Variation of some planetary seismic hazard indices on the occasion of Lefkada, Greece, earthquake of 17 November, 2015.

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Astract: In this work we have show that the "Earth tides-seismicity compliance parameter" *p* may be used as a medium time earthquake forecasting while the frequency content of the ionospheric turbulence over the earthquake epicenter, deduced directly from GPS network TEC observations or indirectly through the VLF transmission network, may be used for the short time earthquake forecasting.

Key words: Seismicity, Ionospheric turbulence, Brownian Walk, Hilbert Huang Transform

1. Introduction

By the term "Planetary seismic hazard indices" we mean parameters or observables which indicate the degree of the mutual interactions of tectonic active areas on the earth surface with some parts or phenomena of the Geosphere and the near Earth space. In this paper we investigate the variation of the tidal triggering effect efficiency, by means of the tidal seismicity compliance parameter *p*, (Arabelos et al. 2016, Contadakis et al. 2009, Contadakis et al. 2012a, Vergos et al. 2015), and the lower Ionosphere variations, by means of the variation of the High-Frequency limit, f_o, of the ionospheric turbulence content (Contadakis et al. 2008, Contadakis et al. 2012b, Contadakis et al. 2015, Roznoi et al. 2012) with the time and space proximity to the site of the earthquake occurrence as well as by the intensity variations of VLF signals transited over the seismic area (Skeberis,et al. 2015). In the following present the results of our investigation: (1) On the maps of the tidal seismicity compliance parameter *p*, over the Greece in order to find any indication of increasing tectonic stress criticality for the year 2015 of the area of Ionian islands in relation to other areas in Greece, which points to the area of a possible strong earthquake. (2) On the High-Frequency limit f_o, of the ionospheric turbulence content, measured analyzing TEC variations, in order to find any increases as the site and the moment of the earthquake occurrence is approaching, pointing to the earthquake locus. (3) On the observational data from the receiver of INFREP network in Thessaloniki, Greece (40.59N, 22,78E), which monitor VLF transmitters based in Tavolara, Niscemi, Italy, Keflavik, Iceland, and Anthorn, UK, in order to see if the signals from the two VLF European transmitters, transmitted over

Lefkada, indicate enhanced high frequency variations, in accordance to the result of the TEC analysis.

2. The Lefkada 2015 earthquake event

On November 17nth, 2015 at 9:10 LMT an earthquake of Magnitude 60 occurred 9km SSW of Lefkada. A large number of aftershocks follow the main shock, 22 of them are of magnitude ranging between M=4 and M=5.1. Table 1 displays the main characteristic of the shocks with M≥4.4. The earthquake source is located on the north segment, the Lefkada segment, of the well known strike slip Cephalonian Transform Fault.

Table 1. The strongest shocks of the 17nth November event

No	Date GMT	Location	Latitude(°)	Longitude(°)	Depth km	Magnitude
1	2015/11/21 00:41:56	1.4 km WSW of Leukada	38.71	20.62	9	4.6
2	2015/11/20 23:37:04	1.4 km WSW of Leukada	38.71	20.62	9	4.4
3	2015/11/20 09:33:14	10.7 km SSW of Leukada	38.63	20.58	11	4.6
4	2015/11/20 05:12:24	30.1 km SSW of Leukada	38.47	20.49	12	4.8
5	2015/11/18 13:03:14	0.5 km NW of Leukada	38.72	20.63	8	4.6
6	2015/11/18 12:15:38	14.2 km NNW of Leukada	38.84	20.59	17	4.9
7	2015/11/18 05:18:13	26.0 km SSW of Leukada	38.50	20.52	14	4.5
8	2015/11/17 19:39:34	3.4 km WSW of Leukada	38.70	20.60	8	4.5
9	2015/11/17 12:37:56	2.4 km SE of Leukada	38.70	20.65	5	4.5
10	2015/11/17 11:57:25	2.7 km SW of Leukada	38.70	20.61	10	4.4
11	2015/11/17 08:33:40	9.8 km SW of Leukada	38.65	20.56	9	5.1
12	2015/11/17 07:10:07	5.9 km SSW of Leukada	38.67	20.60	11	6.0

The area is tectonically very active and has been thoroughly studied by seismologist on the occasion of strong earthquake occurrence (Scordilis et al. 1985, Louvari et al. 1999, Papadopoulos et al. 2003, Valkaniotis et al. 2014). Figure 1 displays the Cephalonian Transform Fault and the locus of the main shock.

3. Earth tide seismicity compliance parameter *p* maps

Based on results of our investigation on earth tide triggering effect on earthquake generation (Contadakis et al. 2008, Contadakis et al. 2012a and Vergos et al. 2015), we consider the confidence level of earthquake occurrence -tidal period accordance, which we call 'earth tide-seismicity compliance parameter *p*", as an index of tectonic stress criticality for earthquake occurrence and we construct maps of *p*'s over all the area of Greece for each year from 2003 to 2015

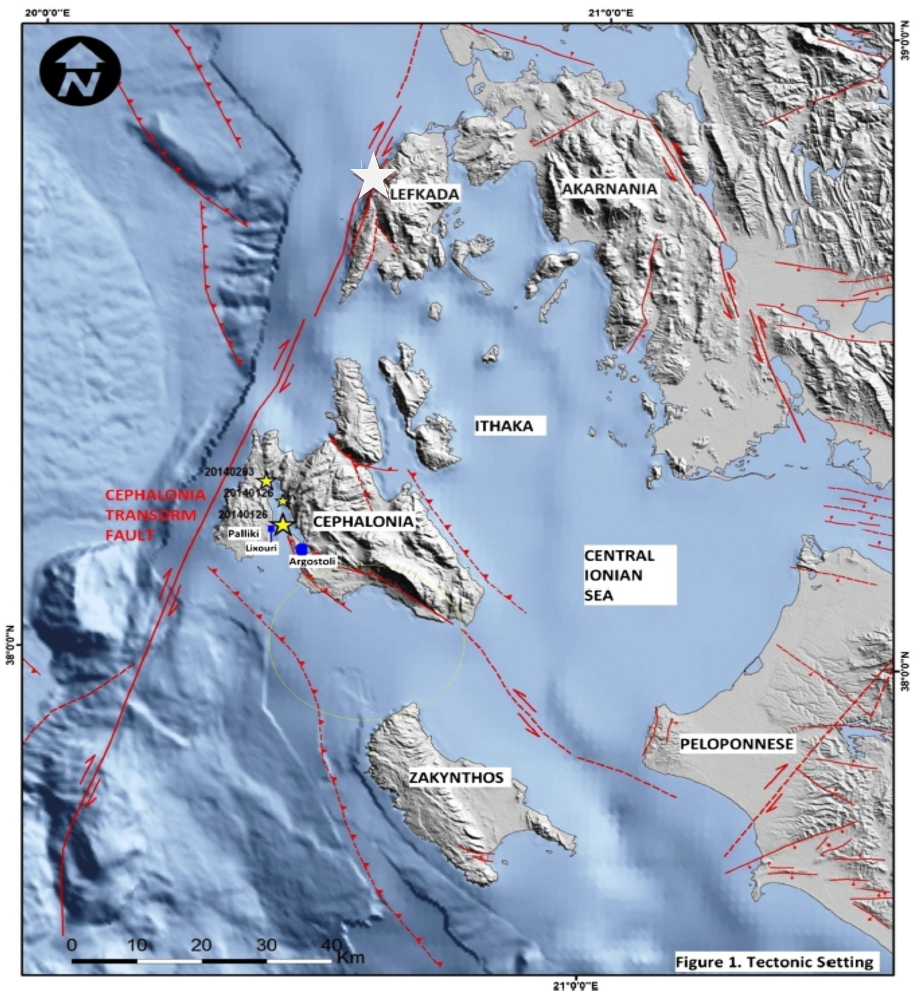

Figure 1. The Cephalonian Transform Fault (quoted from Valkaniotis et al. 2014). The white star indicate the site of the 17/11/2015 event in Lefkada. The yellow stars indicate the sites of the Jan 26-Feb 3, 2014 events of Cephalonia.

For the construction of the "earth tide seismicity compliance parameter" *p* maps we use the NOA -Athens Catalogues. We collected 12424 earthquakes which occurred from 2013.01.01 to 2015.12.31 within the area bounded by $32.5^o \le \varphi \le 42.5^o$, $18.5^o \le \lambda \le 28.5^o$. Table 2 displays these earthquakes. The whole area of Greece is divided in square subareas ($2^o \times 2^o$) and the earth tide seismicity compliance parameter p for each subarea was calculated.

Table 2. The earthquakes occurred in the area of Greece in the years 2013-2015

Year	Events	Focal Depth km	M_L
2013	3737	2-178	2.5-6.2
2014	4940	1-197	2.5-6.3
2015	3737	0-220	2.5-6.1

3.1. Method of Analysis

As we have done in similar studies (Contadakis et al. 2008; Contadakis et al. 2012a; Vergos et al. 2015), 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 investigation, with the simple relation:

$$\phi_i = \{[(t_i - t_0)/T_d]\} - \text{int}\{[(t_i - t_0)/T_d]\} \times 360 \qquad (1)$$

where ϕ_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.

In order to check the compliance of the earthquake frequency distribution periods with the tidal periods 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 $\tilde{a}_{i.}$ The vectorial sum *D* is defined as:

$$D^2 = \left(\sum_{i=1}^{N} \cos a_i\right)^2 + \left(\sum_{i=1}^{N} \sin a_i\right)^2, \qquad (2)$$

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:

$$p = \exp\left(-\frac{D^2}{N}\right) \qquad (3)$$

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. Finally it should be noted that the total number of the shocks for each year is greater than 30 for all the years. This means that the normal distribution approach on which Shuster test is based is valid for all the years.

3.2. Results

Figures 2,3, and 4 display the earthquake seismicity Compliance parameter *p* of the Lunar Monthly Synodic tidal period for the years 2013, 2014, 2015. It is realized that the earth tide-seismicity compliance parameter *p* points to the broader area of significant earthquakes (M≥4.5) with a very high consistency. In particular, while in the year 2013 the tectonic stress criticality index (earthquake seismicity Compliance parameter *p*) is insignificant for the area of Cefalonian Transform Fault, in the years 2014 and 2015 has reach the highest value. In February of 2014 a double strong earthquake of Magnitudes 6.4 and 5.8 occurred on south segment (Cefalonian segment) of the Cefalonian Transform Fault, while on November,17 of 2015 occurred a double strong earthquake of Magnitudes 6.0 and 5.4 on the northern segment (Lefkada segment) of the Cefalonian Transform Fault.

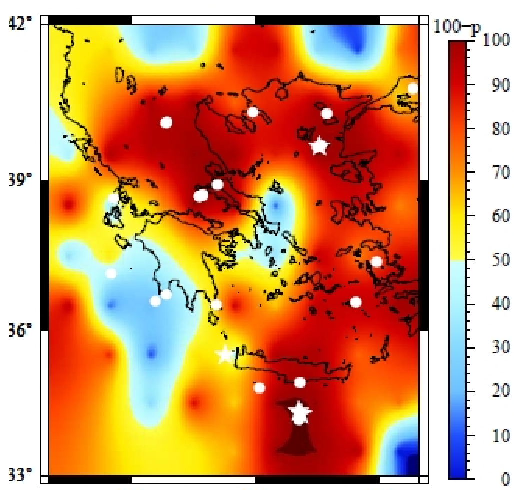

Figure 2. Compliance parameter p of the Lunar Monthly Synodic tidal period for the year 2013. White marks indicate Earthquake epicenters: circles 4.5<M<5.5, stars M≥5.5

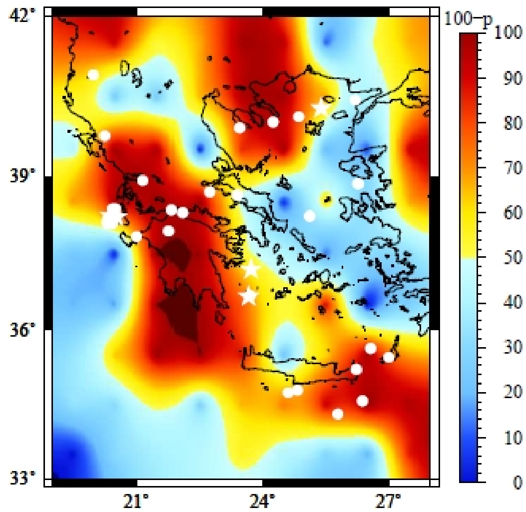

Figure 3. Compliance parameter p of the Lunar Monthly Synodic tidal period for the year 2014. White marks indicate Earthquake epicenters: circles 4.5<M<5.5, stars M≥5.5

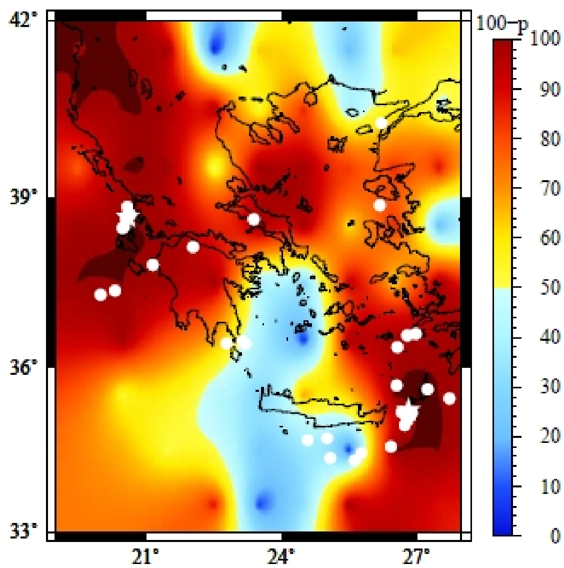

Figure 4. Compliance parameter p of the Lunar Monthly Synodic tidal period for the year 2015. White marks indicate Earthquake epicenters: circles 4.5<M<5.5, stars M≥5.5

4. TEC variation over mid latitude Europe

In the following we investigate the variations of TEC over the broader area of Ionian Islands before and during the seismic activity of 17th of November ,2015 . To this purpose 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 epicentre distances from the active area ranging from 371km to 1862km for the time period between 01//10/2015 and 30/11/2015. 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 3 displays the 8 EUREF stations while Figure 5 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. 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.

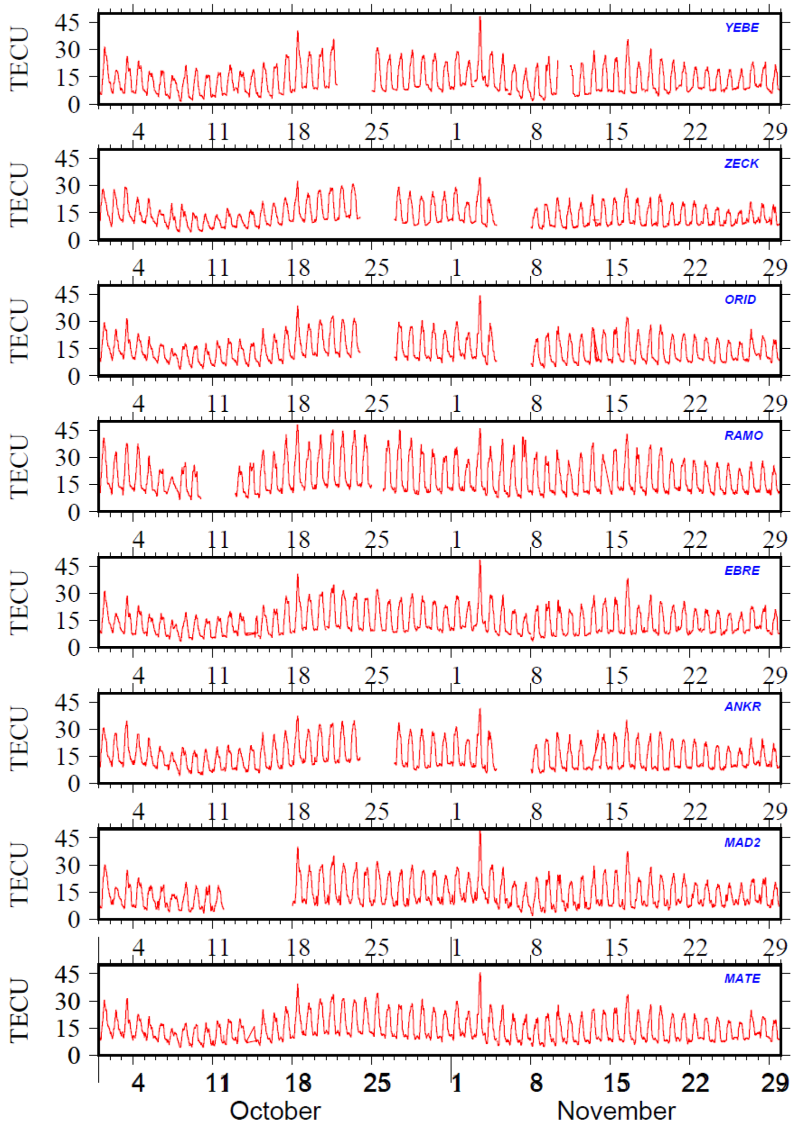

Figure 5. Variations of TEC over the 8 EUREF stations data during the time period of 01/10/ 2015 to 30/11/2015

Table 3. Distance of GPS stations from the epicenter of the earthquake

GPS station	Latitude (degree north)	Longitude (degree east)	Distance (km)
Yebes	40.533615	03.111166	1561.0
Zelenchukskaya	43.916985	41.577686	1861.7
Ohrid	41.123657	20.801771	371.1
Mizpe-Ramon	30.610846	34.802021	1504.6
Roquetes	40.775860	00.431372	1788.5
Ankara	39.936031	32.860733	1061.9
Robledo	38.758064	02.450208	1611.5
Matera	40.666946	16.604445	489.2

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 5 displays the variations of TEC over the 8 EUREF stations data during the time period of 01/10/ 2015 to 30/11/2015, While Figure 6 display the of GPS stations of the 8 EUREF and the site of the earthquake.

Figure 6. The stations of the network (in blue) and the earthquake of November 17, 2015 (in red)

4.1 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 7 displays the Dst-index variations on November of 2015.

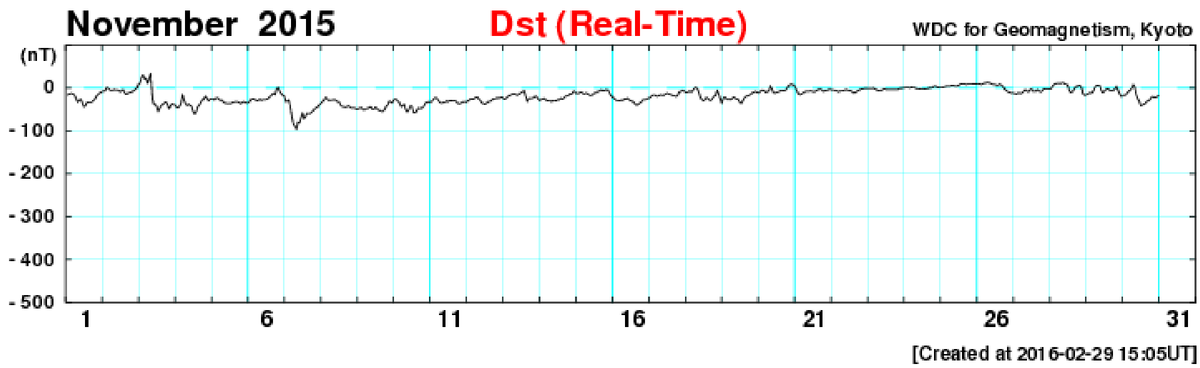

Figure 7 *Dst-index variations on November of 2015*

4.2 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 variations.

This method was successfully applied in our previous work (Contadakis et al. 2008; Contadakis et al. 2012b; Contadakis et al. 2015) in order to find the frequency content of TEC turbidity. It is realized that the upper frequency limit f_o of the spectrum of TEC variations increases as we approach the source of the ionospheric turbidity modulation, in our case the earthquake preparation activity.

The qualitative explanation of this phenomenology can be offered on the basis of the LAIC: 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. 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 ionosphere). As we move far from the disturbed point, in time or in space, the higher frequencies (shorter wavelength) variation are progressively attenuated.

4.3 Results

Figures 8 and 9 display the variation of TEC turbulence frequency limit fo over the selected EUREF GPS stations. Both graphs indicate time and space convergence of increasing frequency limit f_o to the earthquake of 17 November occurrence. Hobara et al. (2005) in a study on the ionospheric turbulence in Low latitudes concluded that the attribution of the turbulence to earthquake process and not to other sources, i.e. solar activity, storms etc are not conclusive. Never the less in our case, the steady monotonic, time and space, convergence of the frequency limit f_o increment, to the occurrence of the Lefkada earthquake is a strong decisive indication that the observed turbidity is generated by the Lafkada earthquake preparation process.

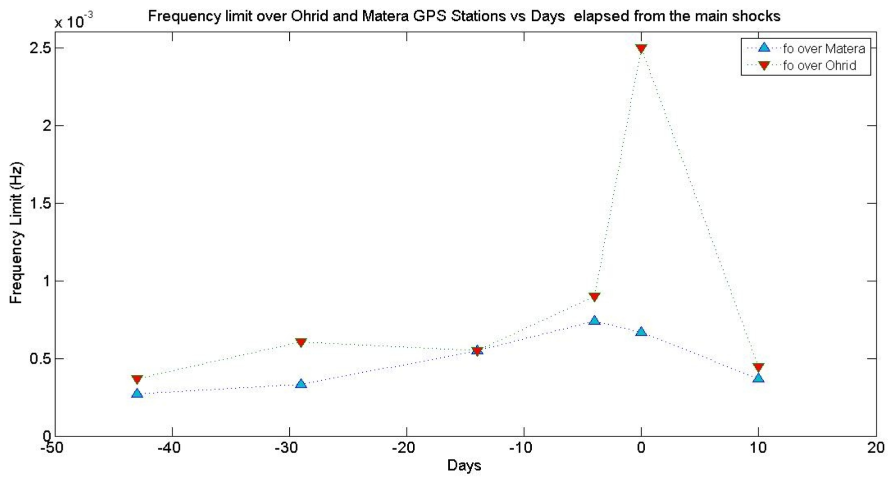

Figure 8. Variation of TEC turbulence frequency limit f_o over the closest to Lefkada GPS Stations of Ohrid and Matera, with the time distance from the day of the earthquake of 17 November, 2015 occurrence

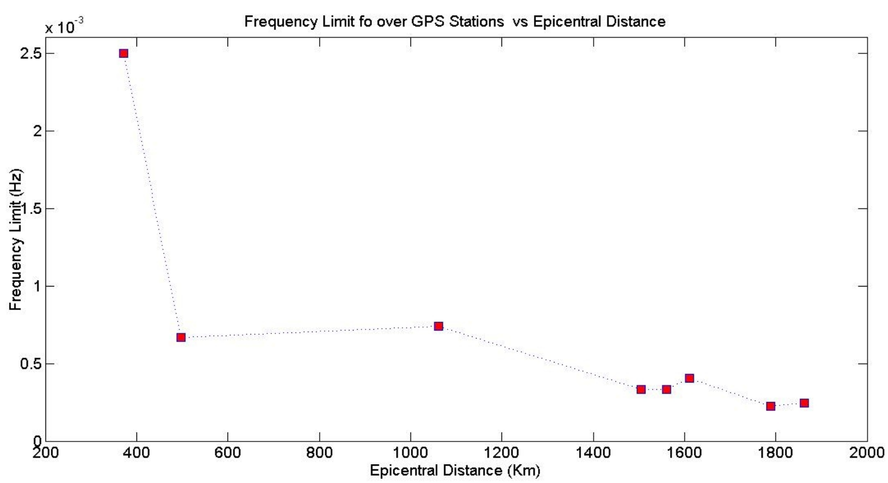

Figure 9. Variation of TEC turbulence frequency limit fo over the GPS Stations of EUREF, with the epicentral distance around the day of the earthquake of 17 November, 2015 occurrence.

5. Detection of VLF/LF disturbances.

As a part of the International Network for Frontier Research on Earthquake Precursors (INFREP) (Biagi et al.2 011) a receiver in Thessaloniki, Greece (40.59N, 22,78E) is monitoring VLF transmitters based in Tavolara, Italy, Niscemi, Italy, Keflavik, Iceland, and Anthorn, UK. The data is being processed by a method of normalization according to the distance between the receiver and the transmitter and then they are processed by the Hilbert Huang Transform (HHT) to produce the corresponding spectra for visual analysis.(Skeberis et al. 2015)
Table 4 displays the characteristic of the transmitters used by the Network of INFREP, while Figure 10 shows the INFREP network and the transmission paths of transmitters to the receiver of Thessaloniki. The nearest to Lafkada transmission paths are shown with white arrows.

Table 4. The Characteristic of the transmitters which are used by the Network of INFREP

Freq. (KHz)	Station	Location	Lat/Lon
19.58	GBZ	Anthorn, UK	54º 54′ 40′′ N 03º 16′ 48′′ W
20.27	ICV	Tavolara, IT	40º 54′ 22′′ N 09º 42′ 48′′ E
23.4	HWU	Le Blanc, FR	53º 04′ 57′′ N 07º 36′ 55′′ E
37.5	ICE	Keflavik, ID	64º 01′ 00′′ N 22º 34′ 00′′ W
45.9	NSY	Niscemi, IT	37º 07′ 32′′ N 14º 26′ 11′′ E
153	ROM	Brasov, RO	45º 45′ 17′′ N 25º 36′ 24′′ E
180	TRT	Polalti, TR	39º 45′ 22′′ N 43º 25′ 05′′ E
183	EU1	Felsberg, DE	49º 16′ 49′′ N 06º 40′ 41′′ E
198	CN1	Berkaoui, DZ	31º 55′ 14′′ N 05º 04′ 03′′ E
270	CZE	Topolna, CZ	49º 07′ 25′′ N 17º 30′ 52′′ E

Figure 10. The INFREP network and the transmission paths of transmitters to the receiver of Thessaloniki

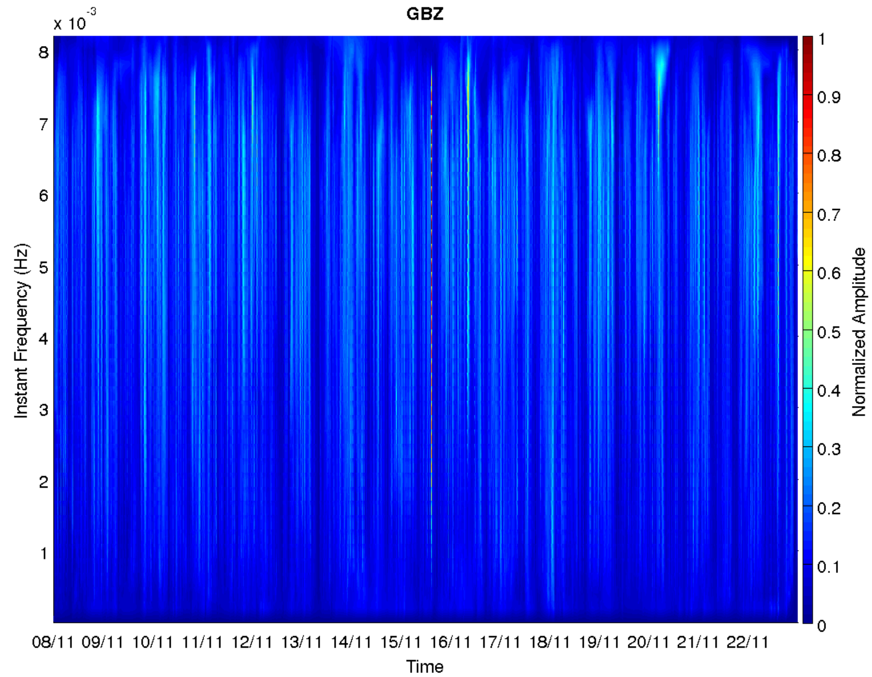

Figure 11. VLF disturbances of the transmission path GBZ-Thessaloniki

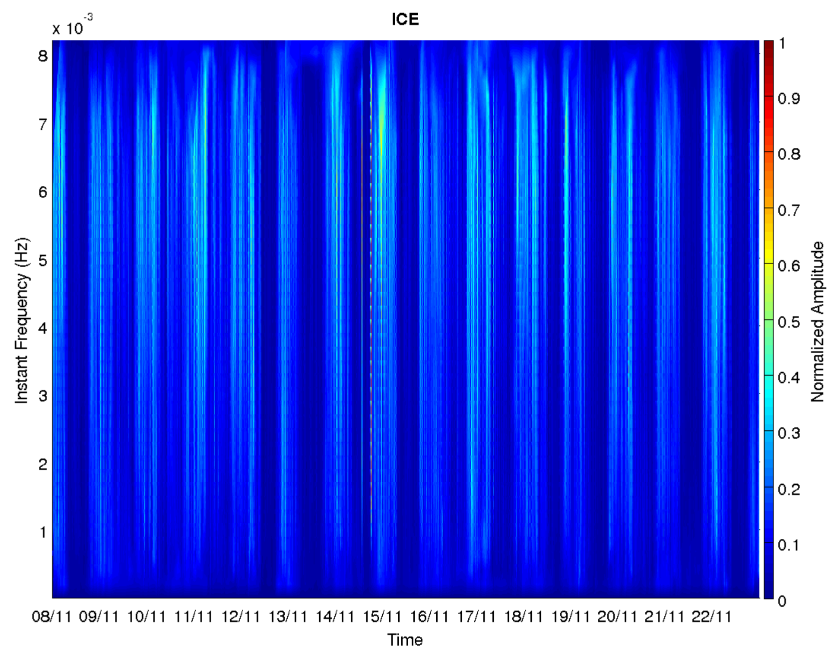

Figure 12. VLF disturbances of the transmission path ICE-Thessaloniki

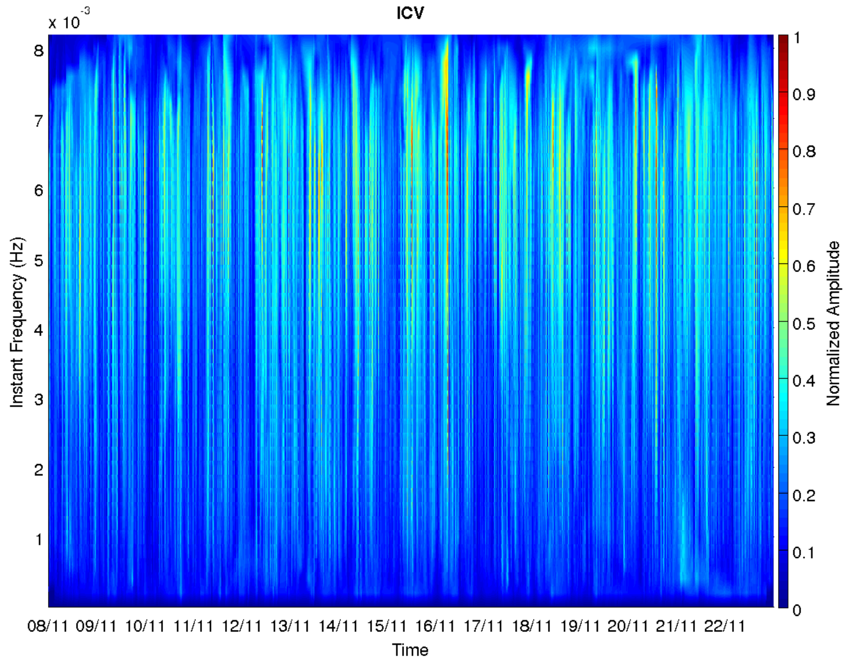

Figure 13. VLF disturbances of the transmission path ICV-Thessaloniki

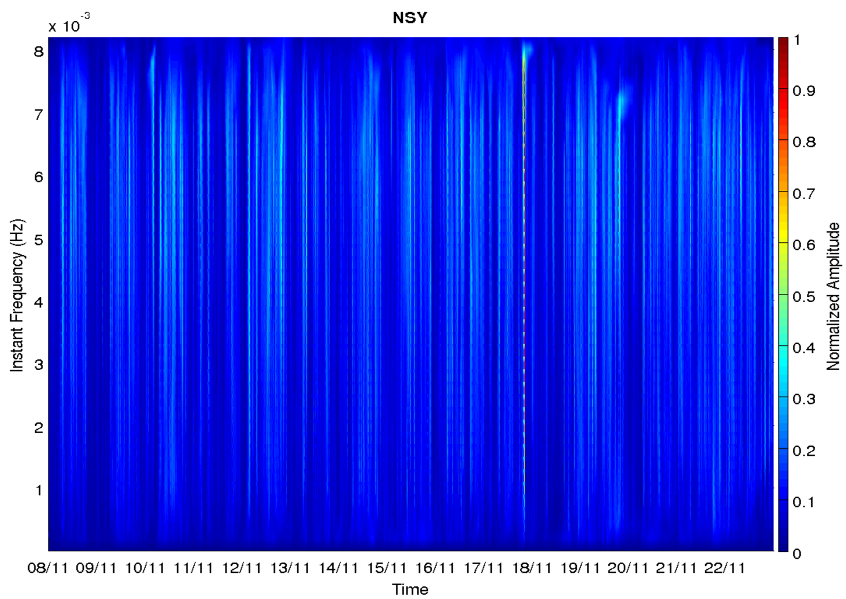

Figure 14. VLF disturbances of the transmission path NSY-Thessaloniki

From Figures 11 to 14 that enhanced signal variations are presented at the closest to the earthquake epicenter transmissions paths the last 10 and even more days before the main shock. The frequency range of the variation is 0.001Hz to 0.009Hz (period 1.66min to16.66min).This results are consistent with the results from the direct observation of TEC variations.

6. Concluding remarks

In this research we show that the “Planetary seismic hazard indices” may be used, in combination with other tectonic information, i.e. tectonic history of the area, for a reliable forecasting of strong earthquakes. In addition they have the great advantage that the relative data are easily accessible as products of national or international multipurpose monitoring campaigns. In particular, in this work we have show that the “Earth tides-seismicity compliance parameter” *p* may be used as a medium time earthquake forecasting while the frequency content of the ionospheric turbulence over the earthquake epicenter, deduced directly from GPS TEC observations or indirectly through the VLF transmission, may be used for the short time earthquake forecasting.

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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