Ionospheric turbulence modulation by intense seismic activity as a tool of Earthquake risk mitigation

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Abstract: According to the well-known Lithosphere Ionosphere Coupling (LAIC) mechanism, 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. 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. Thus observing the frequency content of the ionospheric turbidity in a well extended area, in space and time, around an earthquake event we will observe a decrease of the higher limit of the turbidity frequency band, as a result of the higher damping rate of the higher frequencies, as we move away from the event site. In this article we review the repeated observational accordance to these theoretical explanation, on the occasion of strong earthquakes.

Key words: LAIC mechanisme, Ionospheric turbulence, Seismicity, TEC estimation

1. Introduction

It is generaly accepted that 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. This is the well known Lithosphere Ionosphere Cupling (LAIC) mechanisme. The inherent frequencies of the acoustic or gravity wave range between 0.003Hz (period 5min) and 0.0002Hz (period 100min)), which according to Molchanov et al. (2004, 2006), Rozhnoi et al. 2012, correspond to the frequencies of the turbulent which are produced by tectonic activity during the earthquake preparation period. During this propagration the higher frequencies are progressively dumped. Thus observing the frequency content of the ionospheric turbidity we will observe a decrease of the higher limit of the turbitity frequency band.

In this article we review the repeated observational results in the occation of strong earthquakes in the area of South Europ wich are in accordance to these theoretical explaination.(Contadakis et al. 2012, Contadakis et al. 2015, Contadakis et al. 2017a,Contadakis et al. 2017b, Contadakis et al. 2021, Contadakis et al. 2022, Contadakis et al. 2023, Contadakis et al. 2024)

The ionospheric turbulence before and during intense seismic activity is extracted from the observations of TEC variations of the highest time resolution.There for we use the Total Electron Content (TEC) data of Global Positioning System (GPS) stations of the EUREF network.Figure

1 display the tectonic map of South East area,and the plate movments of South East Europe.The seismic areas are shown as red stars.

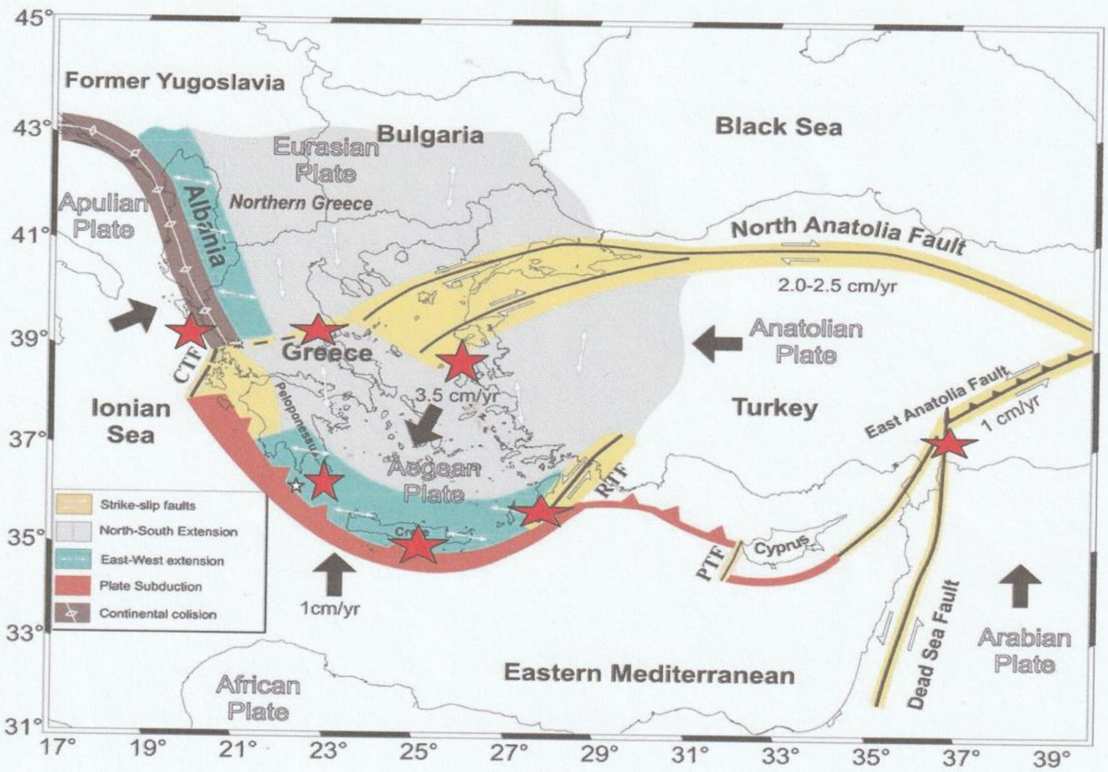

Figure 1. Moves of tectonic plates ruling the active tectonics of Aegean and surroundings (Papazachos et al., 1998).

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Year	Date	Origin Time (GMT)	Lat (°N)	Lon(°E)	M	Region
2020	October 12	00:30:41	35.690	26.276	5.2	Crete
2020	October 21	23:00:56	37.230	20.517	5.2	Ionian Sea
2020	October 30	11:51:26	37.911	26.815	7.0	Samos
2020	December29	11:19:54	45.4232	16.2063	6.4	Croatia
2021	March 03	10:16:08	39.7322	22.2180	6.3	Thessaly
2021	October 12	09:24:04	34.890	26.360	6.4	Crete
2021	October 19	05:32:32	34.745	28.203	5.9	Karpathos
2023	February 06	01:17:36	37.170	37.080	7.8	Southeast Turkiyet

2. TEC Variation Over mid Latitude of Europe

In this study, the TEC values of 8 GNSS permanent stations,belonging to EPN/EUREF network, were estimated before and after the mainshocks under study. The stations are recording satellite data with a 30-sec observation rate.The TEC values were estimated using the IONosphere Map Exchange (IONEX) Format (Schaer et al.1998) file(Bitharis, 2021).For the purposes of our investigation we analyze the variations of TEC over the broader area of Mediterranean before and during activity occurances in the time periods for October 2020 to February of 2023 in the South Eastern Europe.Table 2 displays the a sample of South Europe EUREF stations from wich we select 8 for our porposes. The selected GPS stations have similar latitudes and, therefore, are expected to be affected equally from the Equatorial Anomaly as well as from the Auroral storms.Table 2 lists information about the location of the selected GPS stations while Figure 2 displays an example of the sites of these stations.

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Table 2. The EUREF stations of the Southern Europe

No	GPS Station	Distance (km)	Longitude (deg)	Latitude (deg)	Location
1	YEBES	1400.8	-3.0886	40.5200	Yebes (Spain)
2	LRC	1193.8	-1.2193	46.1589	LaRochelle (France)
3	TLSE	961.0	1.4812	43.5607	Toulouse (France)
4	MARS	650.6	5.3538	43.2788	Marseille (France)
5	AJAC	379.0	8.7626	41.9275	Ajaccio (France)
6	GEN	413.7	8.9211	44.4144	Genova (Italy)
7	CAGL	520.6	8.9728	39.1359	Ajaccio (France)
8	ROM	87.8	12.4900	41.8900	Rome (Italy)
9	NOT1	632.4	14.9898	36.8759	Noto (Italy)
10	MATE	347.0	16.7045	40.6491	Matera (Italy)
11	OHRI	644.4	20.8019	41.1172	Ohrid (FYROM)
12	SOFI	827.0	23.3947	42.5561	Sofia (Bulgaria)
13	BUCU	1043.4	26.1257	44.4639	Bucharest (Romania)
14	ANKR	1683.6	32.7586	39.8875	Ankara (Turkey)

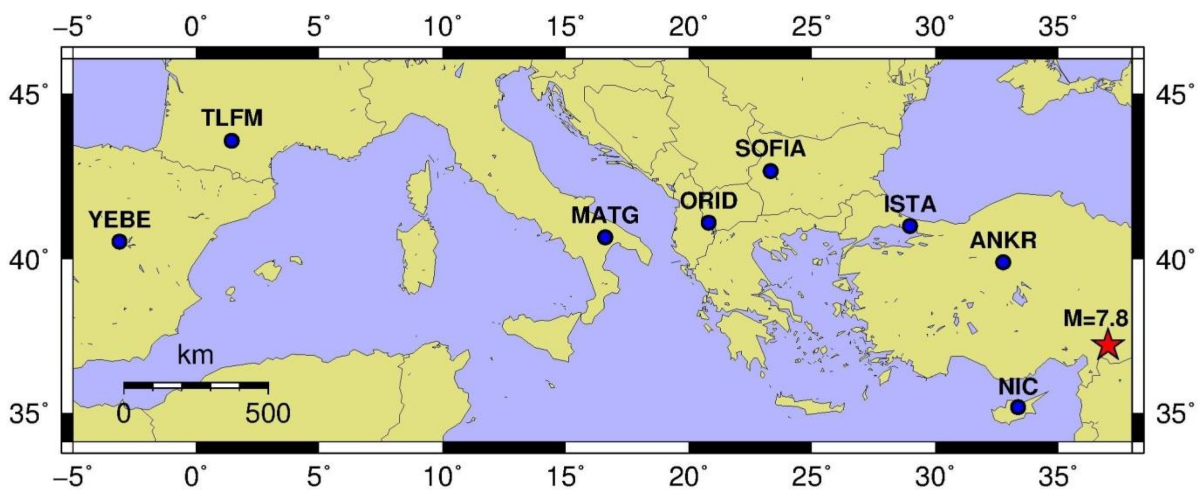

Figure2..*The locus of the GPS stations of the network (in blue) and the locus of the earthquakes of Februar 2023 (in red)*

3. Geomagnetic activity

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) *f*or the time period of our data.In the periods of the seismic activities of our interest,no significant variation of the Geomagnetic field occurred.

4. Data 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 slope of the diagram whether the contributed variations to the spectrum are random or periodical. If they are random the slope will be 0, which corresponds to the white noise, or -2 which corresponds to the Brownian walk noise; otherwise the slope will be different, the so called Fractal Brownian walk noise (Turcotte, 1997). This means that we can trace the presence of periodical variations in the logarithmic power spectrum of TEC variations. As an example, Figure 4 displays the logarithmic power spectrum of TEC variations over the GPS station of Nicosia on 06/02/2023. It is seen that the slope of the diagram up to $\log(f_o)=-4.0174$ is $b=-2$(Brownian walk noise) and from $\log(f_o)<-4.0174$it becomes $b=-1.0$ (fractal Brownian walk noise). This means that, for frequencies higher than $f_o=\exp(-4.0174)$, the TEC variation is random noise. On the contrary, the variation of TEC for lower frequencies contains not random variations, i.e. turbulent. So we conclude that the upper limit of the turbulent band is $f_o=\exp(-4.0174)=0.0180$cycl/(min/2)=>598.4μHz. Or, equivalently, the lower period limit $T_o$of the contained turbulent is 27.85 minutes (it should be noted that the sampling rate is half minute)

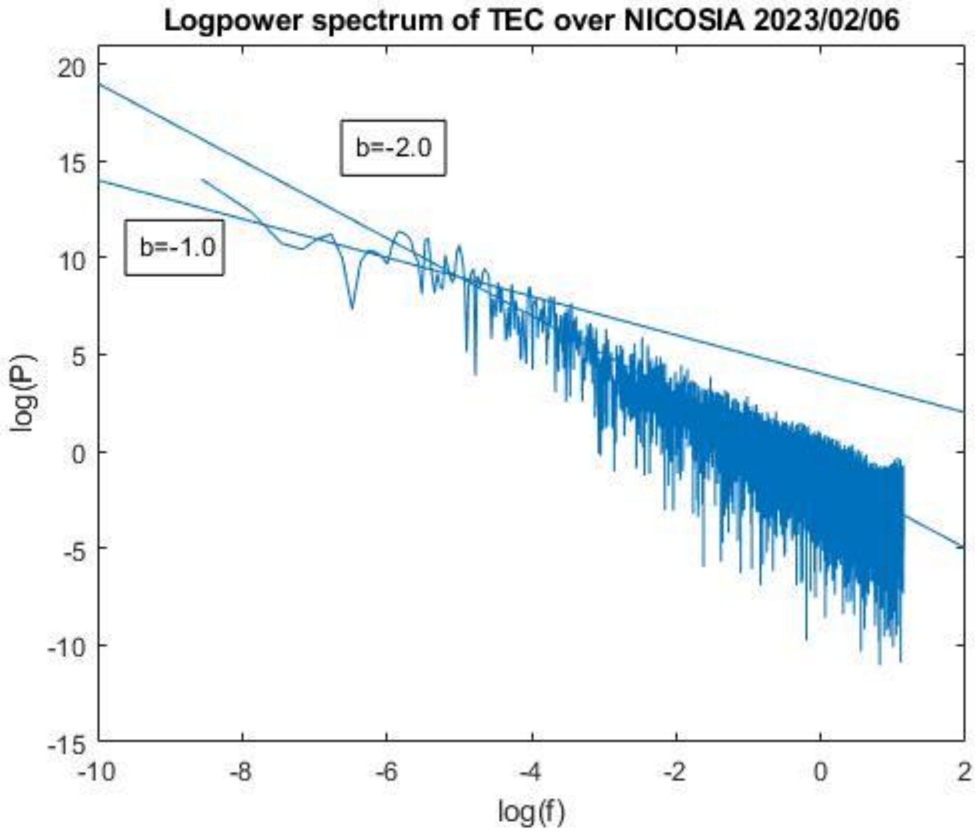

Figure 3. Logarithmic power spectrum of TEC variations over Nicosia on 06/02 2023

This means that using this method we can trace the presence of periodical variations in logarithmic power spectrum of TEC variations and in addition to determine an upper frequency limit of the turbidity frequencies band. This method was successfully applied in our previous work (Contadakis et al. 2008, Contadakis et al. 2012; 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.

5. Results

Figures 4 to 14 summarize the results of our TEC analysis. They display the variation of the upper frequency limit of the Ionospheric turbidity band with the epicentral distance from the main shock. In addition the variation of the upper frequency limit of the Ionospheric turbidity with the time distance from the area of the earthquake occurance is given for all the earthquakes .

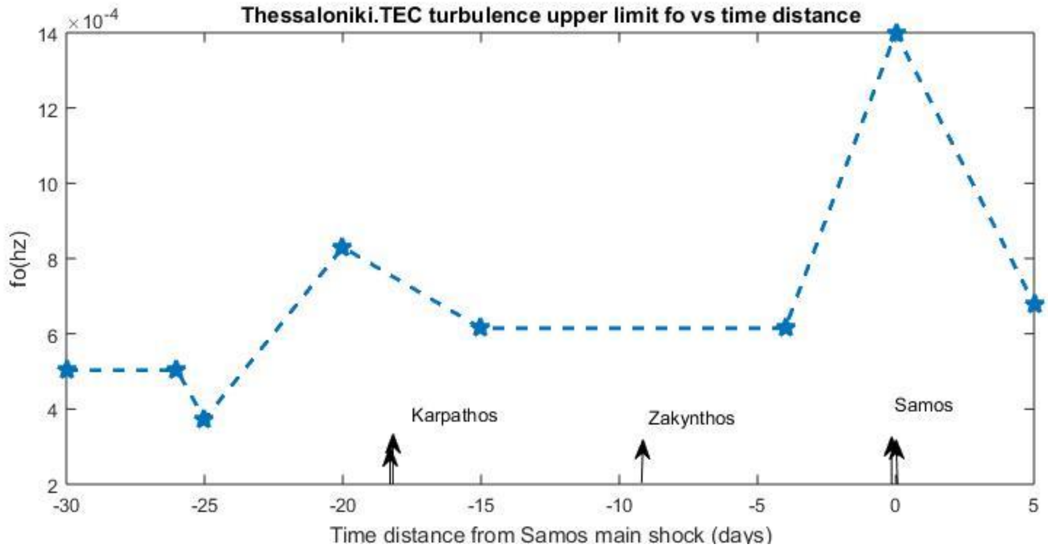

Figure 4. Thessaloniki mean reference site upper limit fo vs Time distance,,Samos Karpathos Zakynthos event

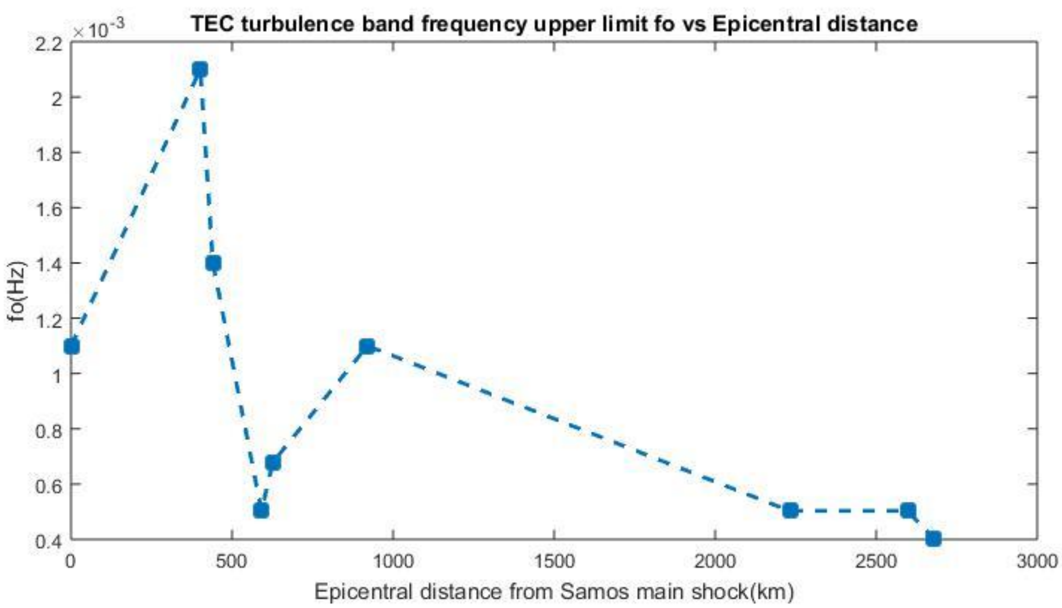

Figure 5.Tec turbulent band upper limit fo vs Epicentral distance, Samos Karpathos Zakynthos event

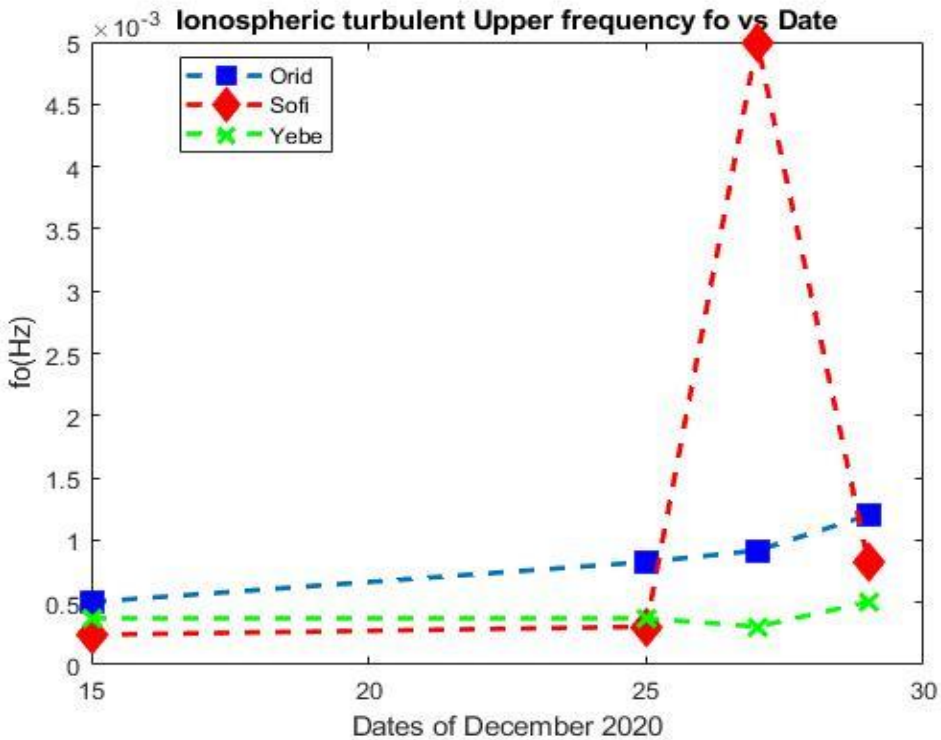

Figure 6. Ionospheric Turbulent band Upper frequency limit fo vs date Croatia event

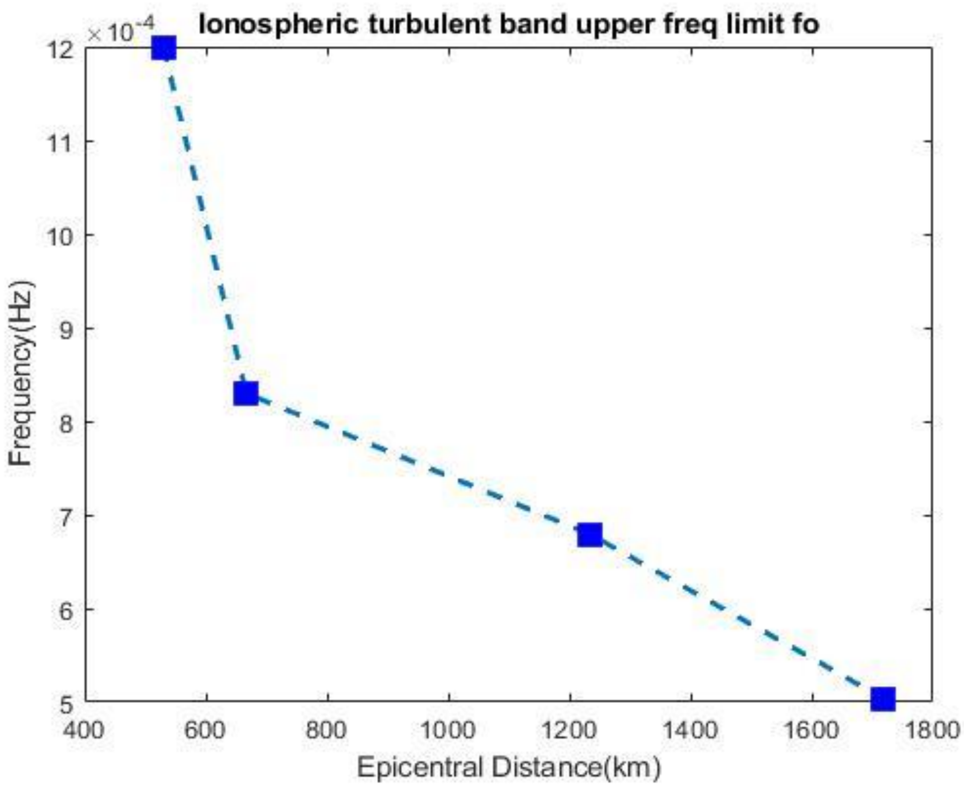

Figure 7. Ionospheric Turbulent band Upper frequency limit fo vs Time distance , Croatia event

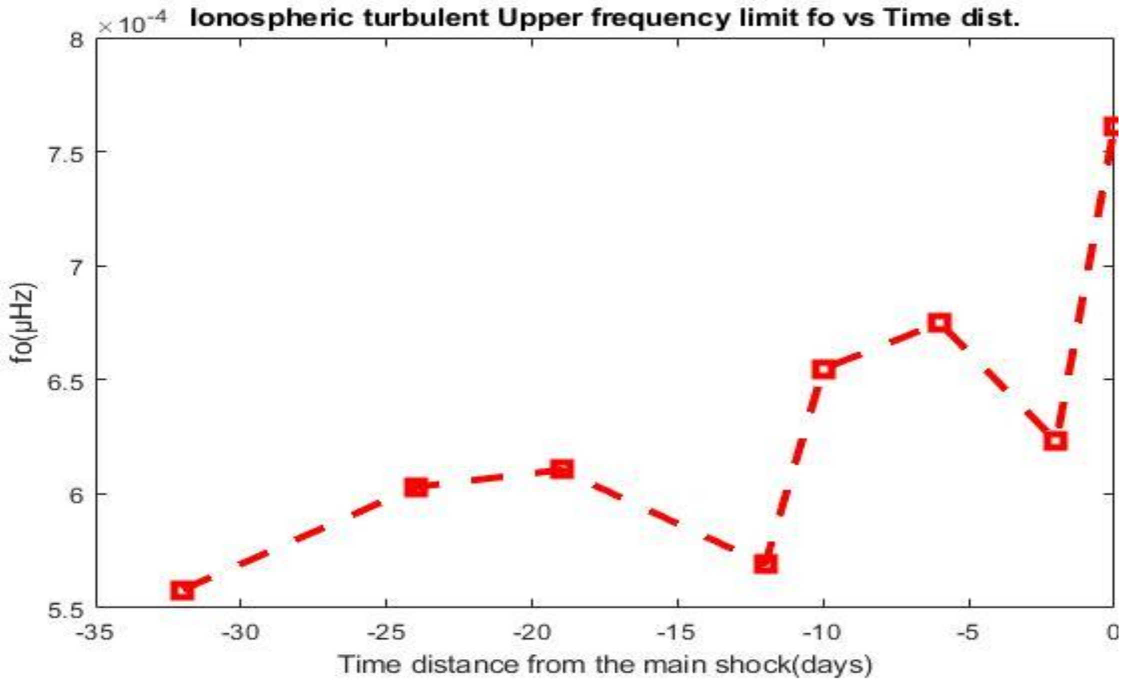

Figure 8. Ionospheric Turbulent band Upper frequency limit fo vs Time distance , Thessalia event

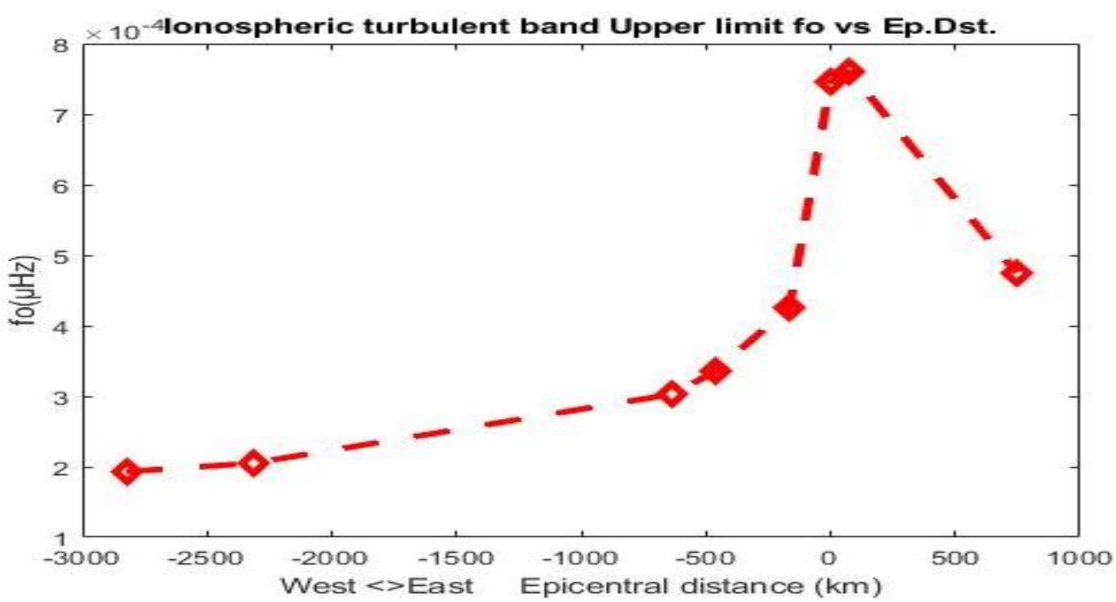

Figure 9. Ionospheric Turbulent band Upper frequency limit fo vs Epicentral distance distance , Thessalia event

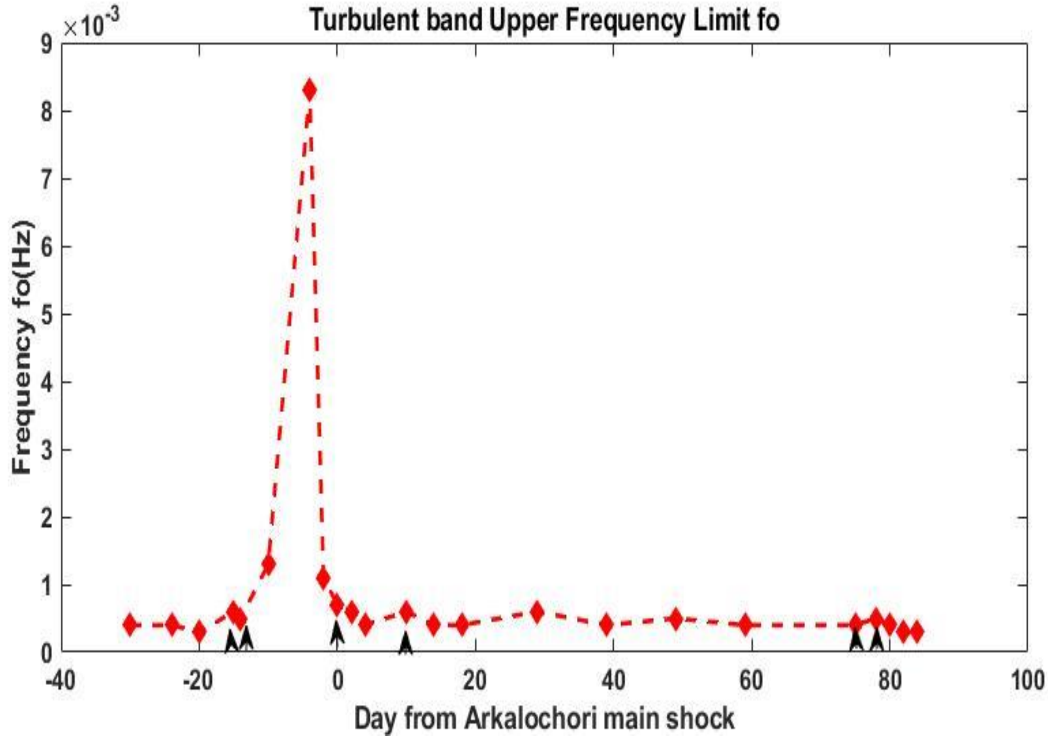

Figure 10. Ionospheric Turbulent band Upper frequency limit fo vs Time distance , Crete Karpathos event

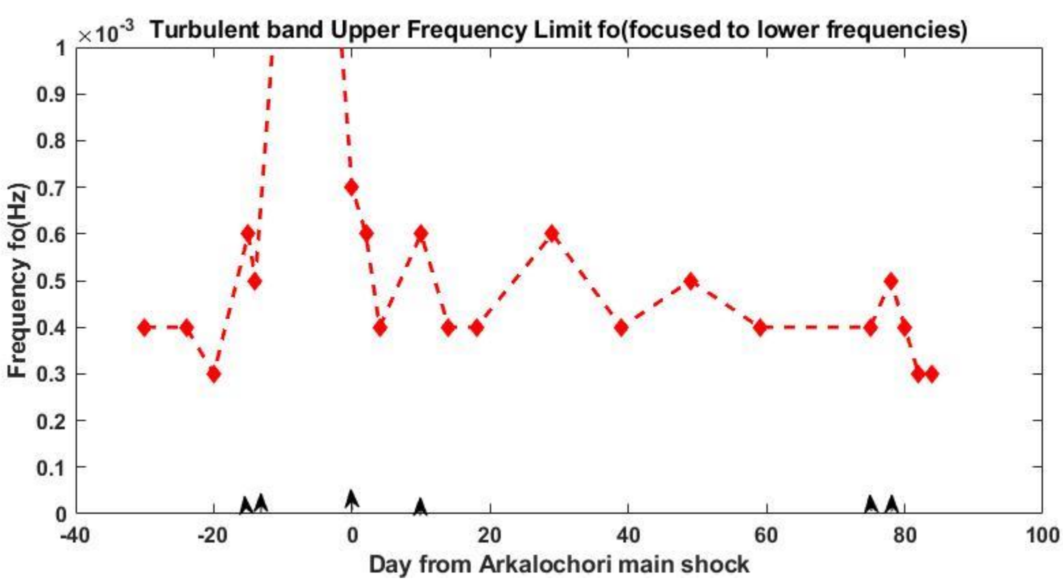

Figure 11. Ionospheric Turbulent band Upper frequency limit fo vs Time distance , Crete Karpathos event(focused)

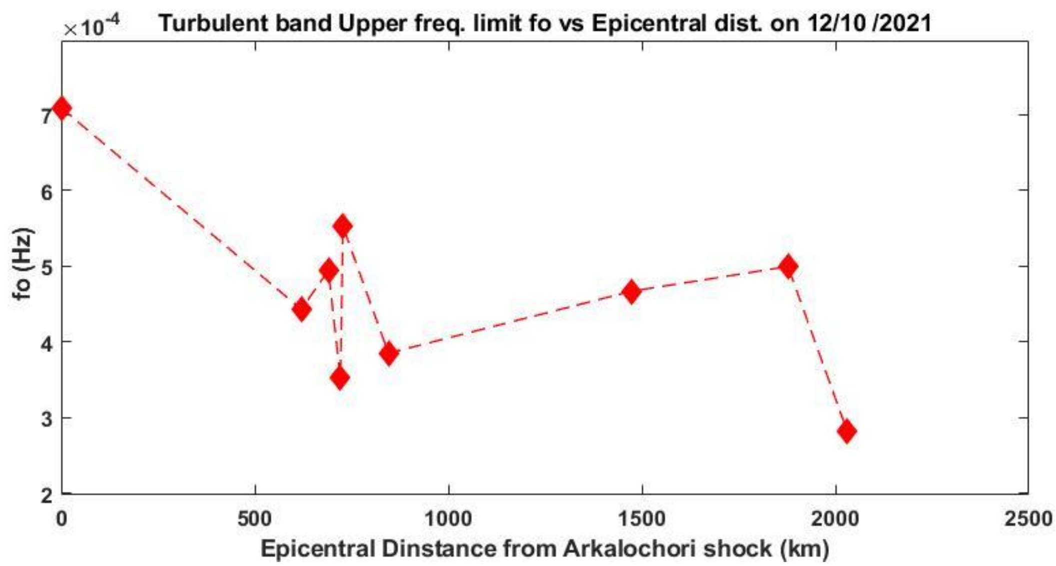

Figure 12. Ionospheric Turbulent band Upper frequency limit fo vs Epicentral distance , Crete Karpathos event

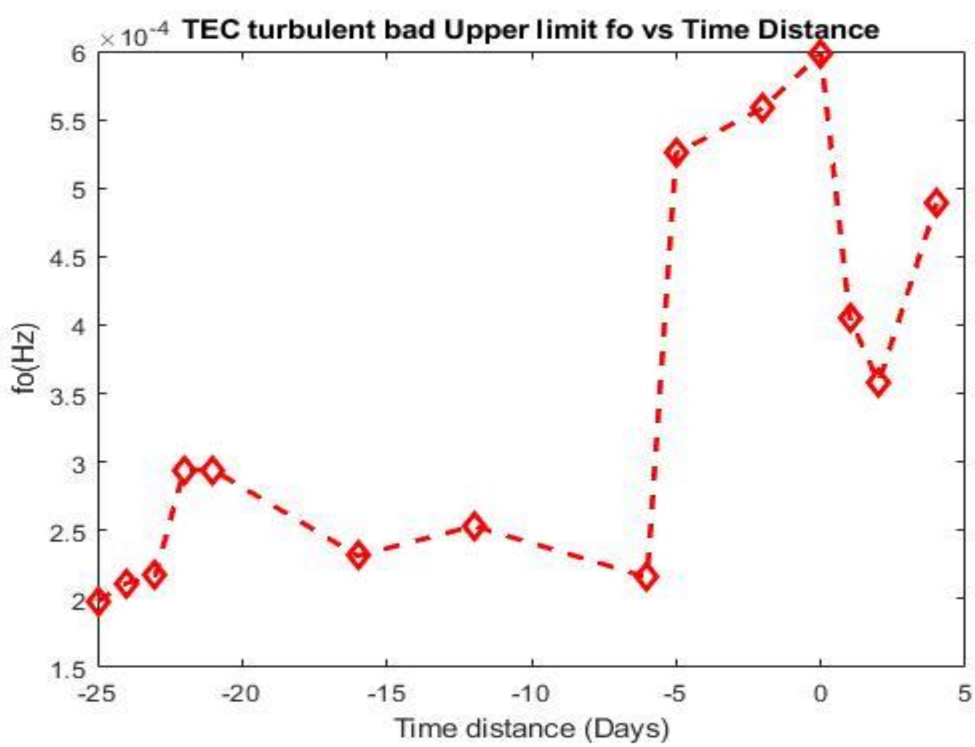

Figure 13. Ionospheric Turbulent band Upper frequency limit fo vs Time distance , Turkiye event

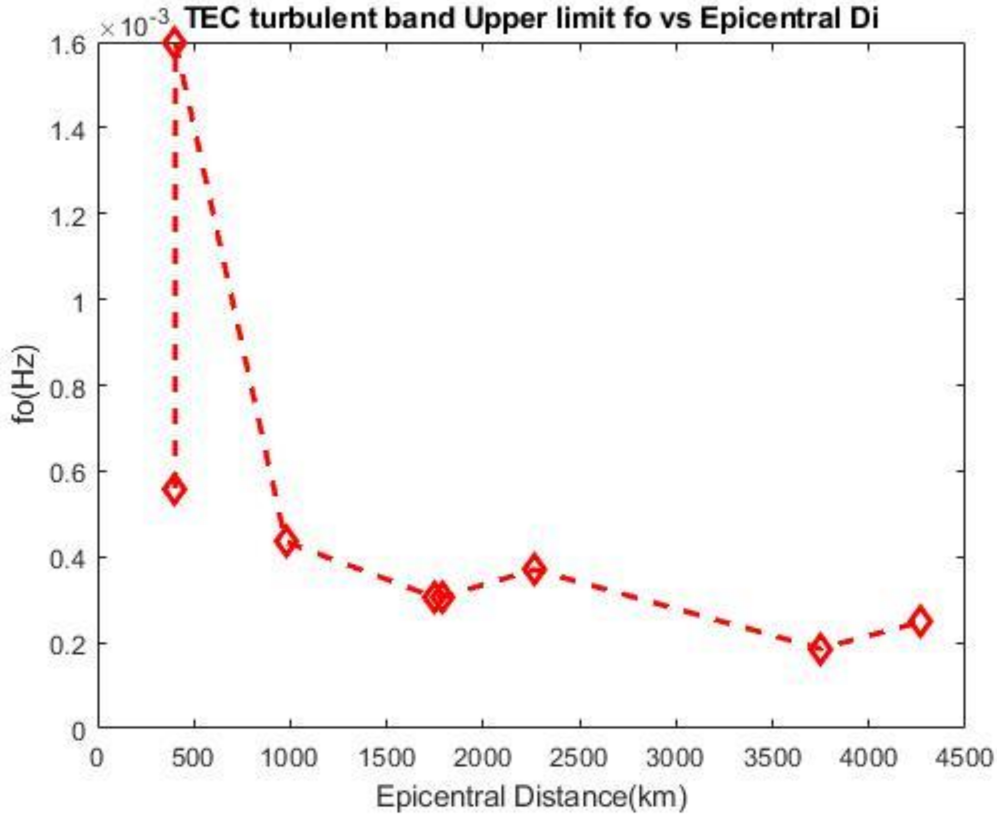

Figure 14. Ionospheric Turbulent band Upper frequency limit fo vs Epicentral distance , Turkiye event

All graphs indicate time and space convergence of increasing turbulene frequency limit fo to the earthquakes of 24 August and 26/30 October, occurrence. Hobarat 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 is not conclusive. Never the less in our case, the steady monotonic, time and space, convergence of the frequency limit fo increment, to the occurrence of the Amatrice earthquakes of 24/08 and 26&30/10 is a strong decisive indication that the observed turbidity is generated by the respective earthquakes preparation processes.

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 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

6. Concluding Remark

In this article we review the repeated observational results in the occation of strong earthquakes in the area of south Europe which are in accordance to the Lithosphere Atmosphere Ionosphere Cupling(LAIC) mechanisme. Thus observing the frequency content of the ionospheric turbidity, we will observe a decrease of the higher limit of the turbitity frequency band, as we move away, in time and space, from the epicenter of a strong earthquake, as a result of a differential dumping phenomeno. This important result may be used for the short term earthquake forcusting. Rigorous earthquake risk estimation can not be extracted from our result since the characteristics of each event is diferent(i.e Magnitude ,epicentral distance of the nearest GPS station ect..). Nevertheless continuous monitoring of the TEC (TBUL) fo and the alarming for further investigation by comparing with the TBUL of distant stations and with the results of seismical monitoring, as well as with the results of other near earth surface precursor methods, if the TBUL tend to around 0.001Hz

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