TEC variation over Europe during the intense tectonic activity in the area of S Turkiye on February of 2023.

Contadakis M.E.[(1)], **Pikridas C.**[(1)], **Bitharis S.**[(1)], **Scordilis, E.**[(2)]

[(1)] Department of Geodesy and Surveying, Aristotle University of Thessaloniki, Greece
[(2)] Department of Geophysics, Aristotle University of Thessaloniki, Greece

This paper is one of a series of papers dealing with the investigation of the Lower ionospheric variation on the occasion of an intense tectonic activity. In the present paper, we investigate the TEC variations during the intense seismic activity in the westrnmost part of the East Anatolian fault (EAF, SE Turkiye), near the transition zone between EAF and the Dead Sea fault, on February 6th, 2023. The Total Electron Content (TEC) data are been provided by the EUREF Network. These data were analysed using Discrete Fourier Analysis in order to investigate the TEC turbulence band content. The results of this investigation indicate that the High-Frequency limit f_o of the ionospheric turbulence content, increases as aproaching the occurrence time of the earthquake, pointing to the earthquake epicenter, in accordane to our previous investigations. We conclude that the Lithosphere Atmosphere Ionosphere Coupling, LAIC, mechanism through acoustic or gravity waves could explain this phenomenology.

Keywords: Seismicity, Lower Ionosphere, Ionospheric Turbulence, Brownian Walk, East Anatolian Fault.

1.Introduction

It is argued that tectonic activity during the earthquake preparation period produces anomalies at the ground level which subsequently propagate upwards in the troposphere as Acoustic or Standing waves (Miyaki et al. 2002, Hayakawa et al. 2011, Hayakawa 2011, Hayakawa et al. 2018). These Acoustic or Standing 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. The inherent frequencies of the acoustic or gravity wave range between 0.003Hz (period ≈ 5min) and 0.0002Hz (period ≈ 80min), which according to Molchanov et al. (2004, 2005) correspond to the frequencies of the turbulent produced by tectonic activity during the earthquake preparation period. During this propagation 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 paper we investigate the Lower ionospheric variations from TEC observations during the intense seismic activity of the first quarter of 2023 in the transition between the Dead Sea fault and the East Anatolian fault (SE Turkiye) The Total Electron Content (TEC) data are been provided by the EUREF Network. These data were analysed using Discrete Fourier Analysis in order to investigate the TEC turbulence.

2. Seismotectonic Information of the Study Region

On February 6, 2023 a series of devastating earthquakes struck S Turkiye, near the Turkish-Syrian border region. The strongest event of the sequence of magnitude M=7.8 occurred at 01:17 (UTC time) in the region between the cities of Kahramanmaraş and Gaziantep, in south-central Turkiye. Four earthquakes of M≥6.0 followed within the same day, the strongest of which occurred about nine hours later with magnitude M=7.5 (figure 1). The focal parameters of the strongest (M≥6.0) events of the sequence are listed in table (1).

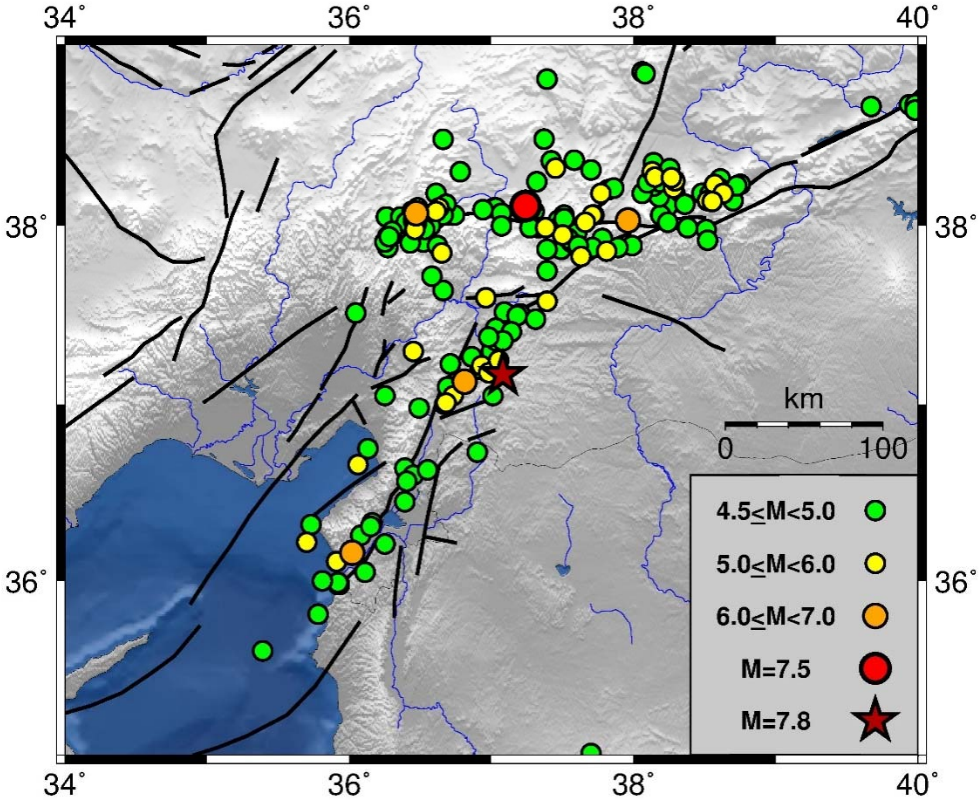


Figure 1. *Spatial distribution of the sequence of the M7.8 (February 6), main shock. Different dimensions/colors of the symbols correspond to different magnitude classes. The dark red star denotes the epicenter of the mainshock while the red circle is the epicenter of the second very strong earthquake of the sequence (February 6, M7.5).*

Table 1. *Focal parameters of the strongest (M≥6.0) earthquakes of the sequence under study.*

Date	Time (UTC)	Lat (°N)	Lon (°E)	M
February 06, 2023	01:17:36	37.170	37.080	7.8
February 06, 2023	01:28:17	37.130	36.810	6.7
February 06, 2023	10:24:49	38.110	37.240	7.5
February 06, 2023	10:26:48	38.030	37.960	6.0
February 06, 2023	12:02:11	38.070	36.470	6.0
February 20, 2023	17:04:29	36.160	36.020	6.3

The epicenter of the mainshock is located in the southwesternmost part of the East Anatolian Fault system (EAF) while its strongest aftershock occurred on a secondary branch to the north of the mainshock's epicenter. The map of figure 1 shows the spatial distribution of the epicenters of the strongest events (M≥4.5) of the sequence that occurred during the period February 6 – December 31, 2023. Their focal parameters come from the online catalogue of

the European Mediterranean Seismological Center (EMSC, https://www.emsc-csem.org/Earthquake_information/
The EAF is a ~700 km long SW-NE trending faulting system that connects the Dead Sea transform fault to the south with the North Anatolian Fault zone to the North. The region is dominated by a N-S compressional stress (e.g. Allmendinger et al., 2007) which results in left-lateral faulting along the EAF.
The fault plane solutions of the M7.8 earthquake, published by reliable sources (e.g. GCMT, INGV, GFZ, NEIC, IPGP, KOERI, ERD), are all related to each other. They show a seismic fault striking at an azimuth of ~55° and dipping to the SE at an angle of ~70° (https://www.emsc-csem.org/Earthquake/tensors.php), with a rake angle of ~11°, indicating left lateral faulting with thrust component

3. 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 mainshock 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 the seismic activity of the first quarter of 2023 in the transition between the Dead Sea fault and the East Anatolian fault (SSE Turkey). Thus, we use the TEC estimations from EUREF stations with distances ranging from 0 km to 4268.9km from active areas, for the period 10/01/2023-10/02/2023.

Table 2. *Distance of GPS stations from the epicenter of the earthquake of Kahramanmaraş*

GPS Station	Longitude (°E)	Latitude (°N)	Epicentral distance (km)
PAZARTZIK (Turkiye) Kahramanmaras	37.080	37.170	0.0
NICOSIA (Cyprus)	33.365	35.1725	402.5
ANKR (Turkiye)	32.759000	39.888000	403.5
ISTA (Turkiye)	28.979870	41.016791	975.3
SOFIA (Bulgary)	23.321867	42.699792	1746.9
ORID (North.Macedonia)	20.801771	41.123657	1784.5
MATG (Italy)	16.604398	40.667598	2268.0
TLFM (France)	1.444209	43.606979	3747.6
YEBE (Spain)	-3.111166	40.533649	4268.9

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 the sites of these stations and of the mainshock as well.

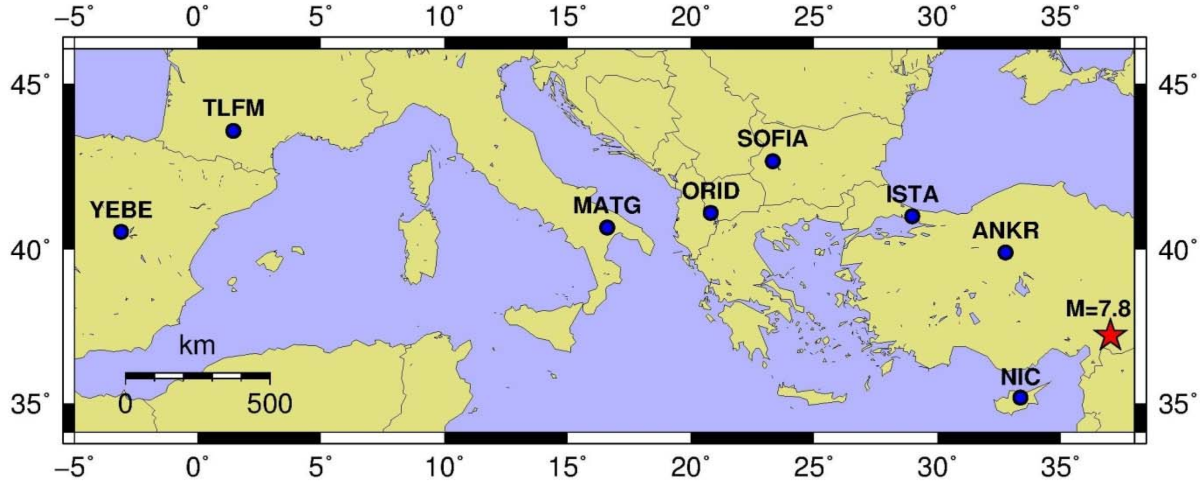


Figure 2. *The 9 GPS stations (blue circles) and the epicenter of the strongest earthquake (red star) of the sequence.*

4. 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 of Kyoto University (http://swdcwww.kugi.kyoto-u.ac.jp/index.html) for the period of our data *(Figure 3 presents the Dst-index variations during February 2023).*

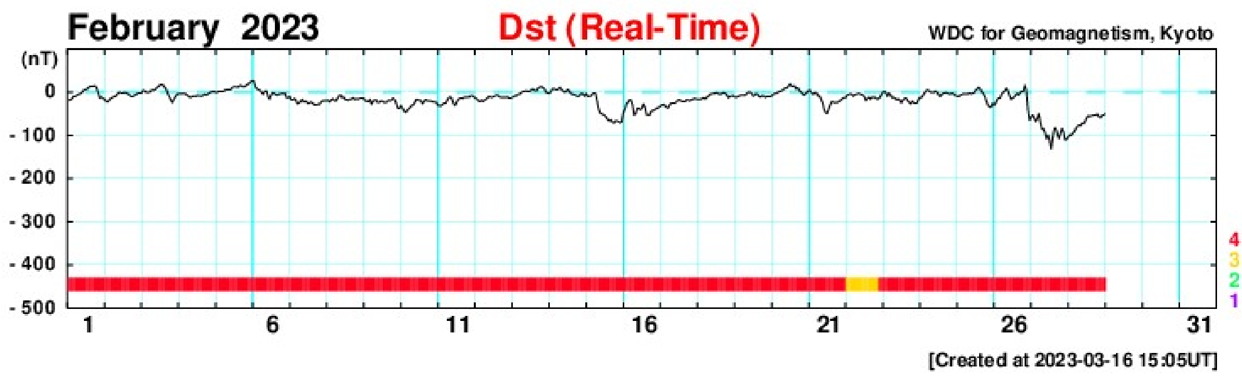
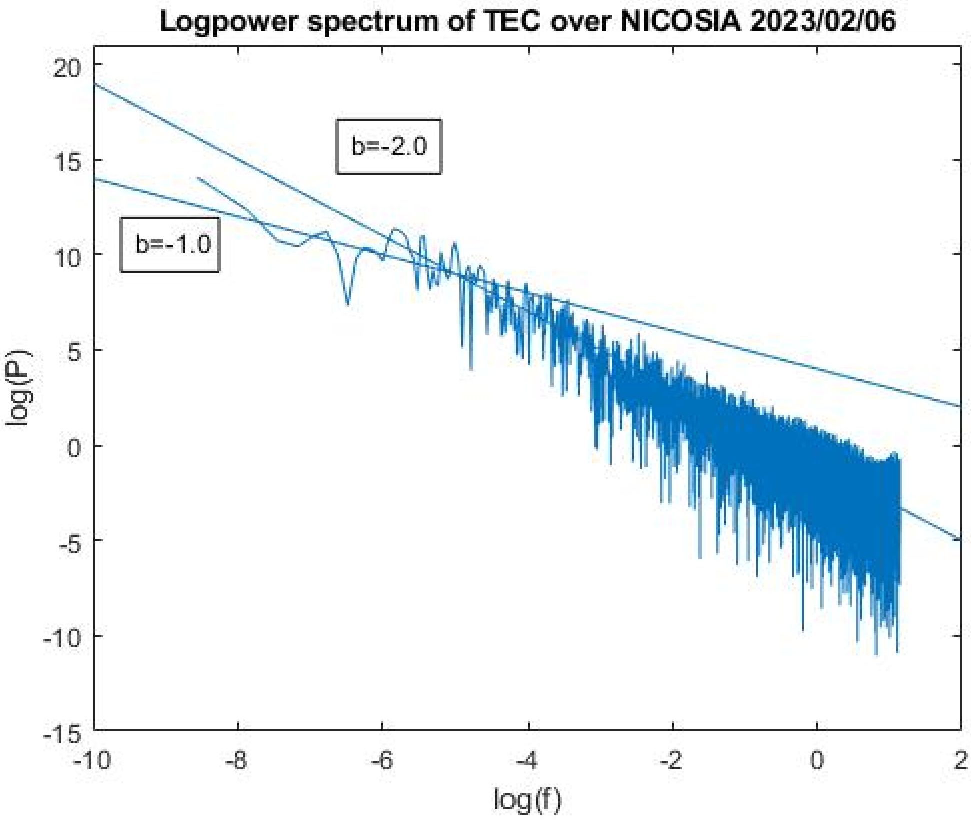


Figure 3. Dst-index variation during February of 2023

5. Data Process

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)=0.0180cycl/(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 4. Logarithmic power spectrum of TEC variations over Nicosia on 06/02 2023

6. Results

Figure 5 displays the variation of the TEC turbulence frequency band upper limit f_o with time distance, in days, from the Kahramanmaraş mainshock of 06/02/2023, while Figure 6 displays the variation of the TEC turbulence frequency band upper limit f_o with epicentral distance, in km, from the Kahramanmaraş main shock. Figures 7 and 8 display the respective variation of the period lower limit T_o with time and epicentral distance respevtively, from the Kahramanmaraş mainshock. It is shown that a strong dependence of the upper frequency f_o limit (lower period limit T_o) of the ionospheric turbulent band content with time and with epicentral distance is observed. In particular, the closer in time or in space to the active area the higher frequency f_o limit/lower period T_o, is. The observed frequencies (and the respective periods) are in the range of the observed Acoustic Gravity Waves on the occasions of strong earthquakes, which correspond to periods 30-100min (Molchanov et al., 2004; Molchanov et al., 2005) or 20-80min (Horie et al., 2007).

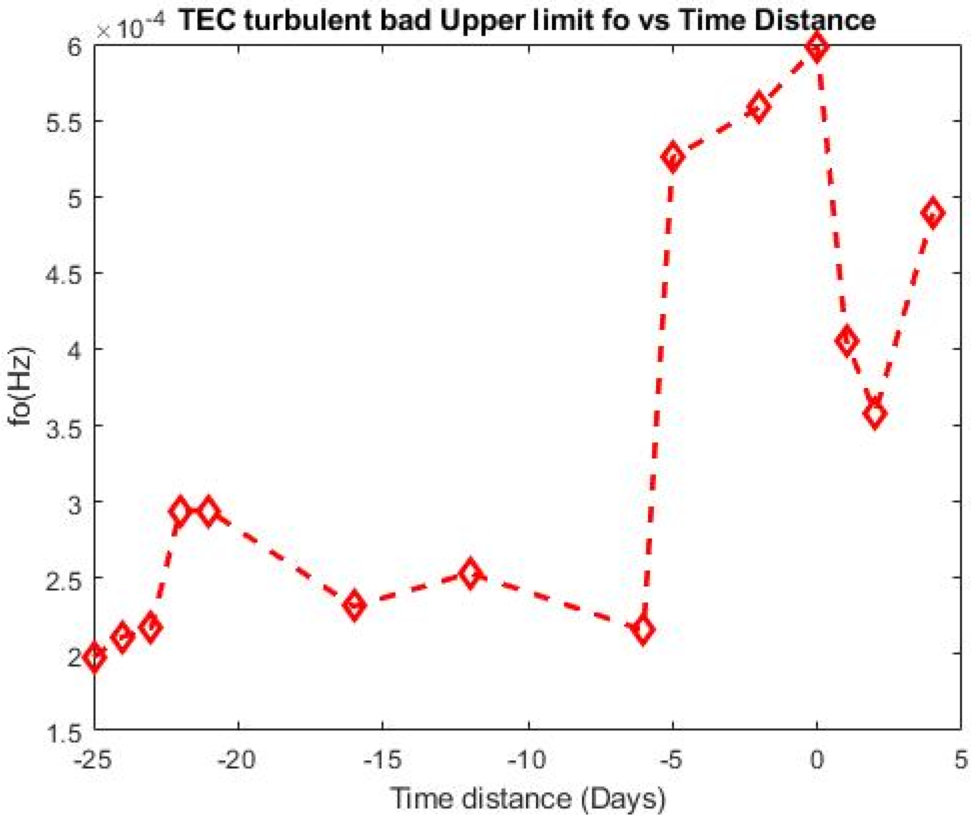


Figure 5. TEC turbulence frequency band upper limit f_o versus time distance from Kahramanmaraş main shock

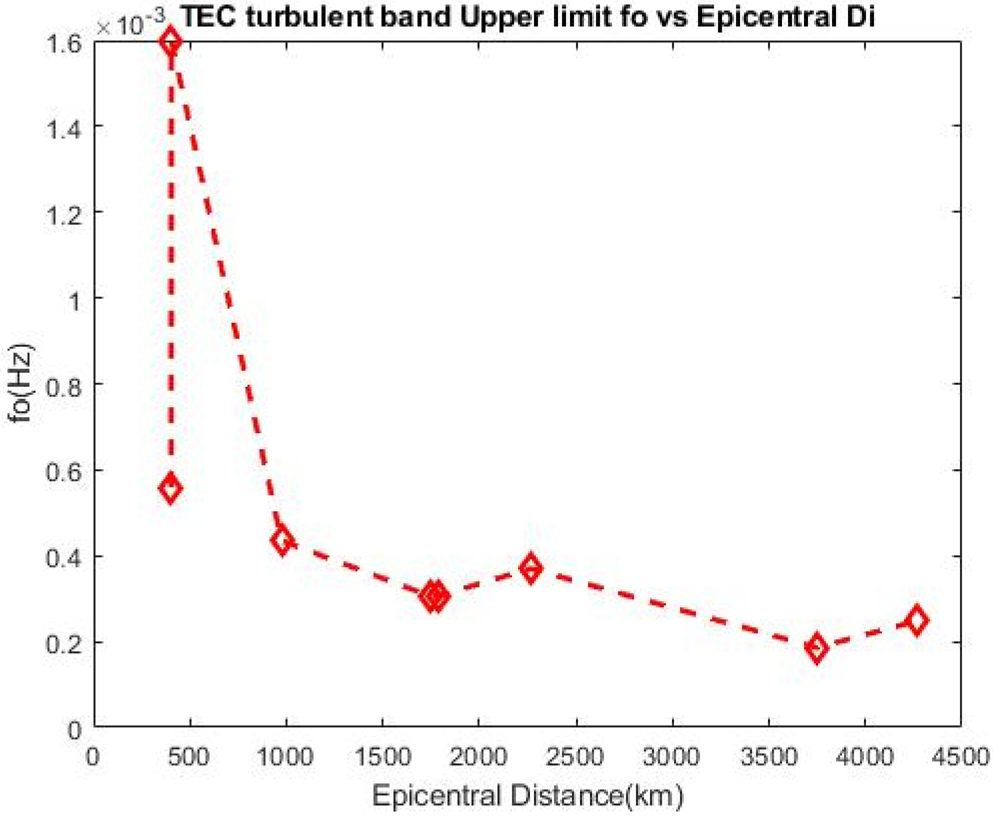


Figure 6. TEC turbulence frequency band upper limit f_o versus epicentral distance from Kahramanmaraş mainshock

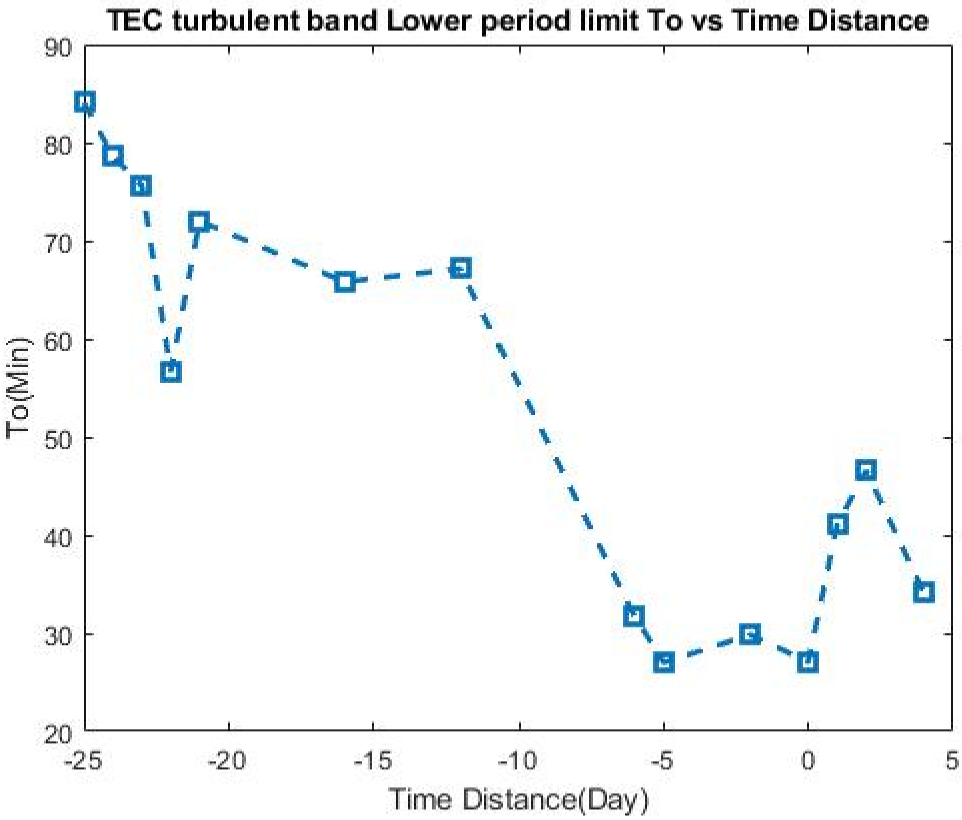


Figure7. TEC turbulence band lower period limit T_o versus time from Kahramanmaraş mainshock.

\

\\

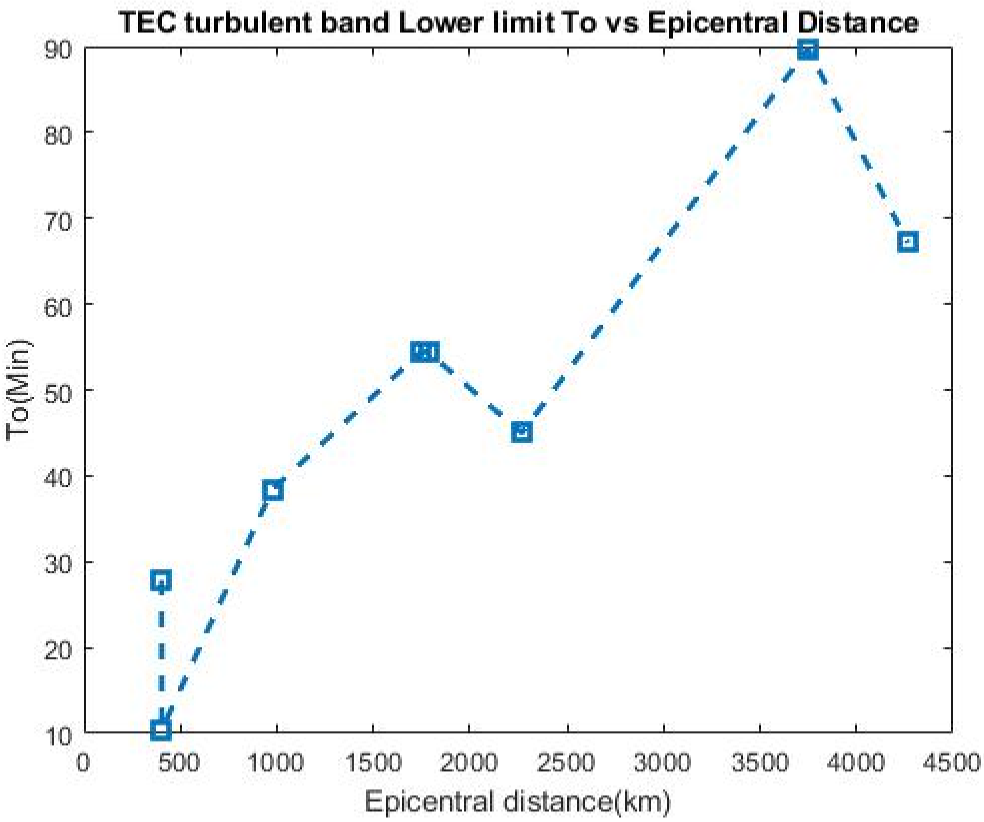


Figure 8. TEC turbulence band lower period limit T_o versus epicentral distance from Kahramanmaraş mainshock.

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 is not conclusive. Nevertheless in our case, the steady monotonic, in time and space, convergence of the frequency band upper limit f_o increment, with the occurrence of the examined strong earthquakes is a strong indication that the observed turbulence is generated by the respective earthquake preparation process.
The qualitative explanation of this phenomenology can be offered on the basis of the Lithosphere Atmosphere Ionosphere Coupling, 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 both, the turbulence of the lower ionosphere, where sporadic Es-layers may appear too (Liperovsky et al., 2005), and the turbulence 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 waves 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, 2005) and Horie et al. (2007), 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) variations are progressively attenuated.

7. Conclusions

The results of this investigation indicate that the High-Frequency limit f_o of the ionospheric turbulence content, increases as we aproach, in time and in space the point of the occurrence of the earthquake, pointing to the earthquake epicenter, in accordance to our previous investigations (Contadakis et al., 2015; Scordilis et al., 2020). We conclude that the LAIC mechanism through acoustic or gravity waves could explain this phenomenology.

References

Allmendinger , R.W. , R. Reilinger and J.P. Loveless (2007). Strain and rotation rate from GPS in Tibet, Anatolia, and the Altiplano, *Tectonics*, 26, TC3013.

Bitharis, S. (2021). Study of the geodynamic field in Greece using modern satellite geodetic methods. *PhD Thesis, School of Rural and Surveying Engineering, Aristotle University of Thessaloniki, Greece*.

Contadakis, M.E., D.N. Arabelos, G. Vergos, S.D. Spatalas and E.M. Scordilis (2015). TEC variations over the Mediterranean before and during the strong earthquake (M=6.5) of 12th October 2013 in Crete, Greece, *Physics and Chemistry of the Earth*, Volume 85, p. 9-16.

Hayakawa, M. (2011). On the fluctuation spectra of seismo-electromagnetic phenomena, *Nat.Hazards Earth Syst.Sci.*, 11, 301-308.

Hayakawa, M., Y. Kasahara, T. Nakamura, Y. Hobara, A. Rozhnoi, M. Solovieva, O.A. Molchanov and V. Korepanov (2011). Atmospheric gravity waves as a possible candidate for seismo-ionospheric perturbations, *J. Atmos.Electr.*, 32, 3, 129-140.

Hayakawa, M., T. Asano, A. Rozhnoi and M. Solovieva (2018). Very-low- and low-frequency sounding of ionospheric perturbations and possible association with earthquakes. In: *Pre-earthquake Processes: A multidisciplinary approach to earthquake prediction studies*, Ed. by D. Ouzounov et al., 277-304, AGU Book, Wiley.

Hobara, Y., F. Lefeuvre, M. Parrot and O.A. Molchanov (2005) Low-latitude ionospheric turbulence observed by Aureol-3 satellite, *Annales Geophysicae*, 23, 1259–1270.

Horie, T., S. Maekawa, T. Yamauchi and M. Hayakawa (2007), A possible effect of ionospheric perturbations associated with the Sumatra earthquake, as revealed from subionospheric very-low-frequency (VLF) propagation (NWC-Japan), *International Journal of Remote Sensing*, vol. 28, issue 13, pp. 3133-3139.

Liperovsky, V.A., C.V. Meister, E.V. Liperovskaya, N.E. Vasileva and O. Alimov (2005). *Nat. Hazards Earth Syst. Sci.*, Vol. 5, No 1, 59-62.

Miyaki, K., M. Hayakawa and O.A. Molchanov (2002). The role of gravity waves in the lithosphere-atmosphere-ionosphere coupling, as revealed from the subionospheric LF propagation. In *Seismo Electromagnetics: Lithosphere-Atmosphere–Ionosphere Coupling*, Ed. by M. Hayakawa and O.A. Molchanov, TERRAPUB, Tokyo, 229-232.

Molchanov, O., P.F. Biagi, M. Hayakawa, A. Lutikov, S. Yunga, D. Iudin, S. Andreevsky, A. Rozhnoi, V. Surkov, V. Chebrov, E. Gordeev, A. Schekotov and E. Fedorov (2004). Lithosphere-atmosphere-ionosphere coupling as governing mechanism for preseismic short-term events in atmosphere and ionosphere, *Nat. Hazards Earth Syst. Sci.*, 4, 5/6, 757-767.

Molchanov, O., A. Schekotov, M. Solovieva, E. Fedorov, V. Gladyshev, E. Gordeev, V. Chebrov, D. Saltykov, V.I. Sinitsin, K. Hattori and M. Hayakawa (2005). Near seismic effects in ULF fields and seismo-acoustic emission: statistics and explanation, *Nat. Hazards Earth Syst. Sci.*, 5, 1-10,

Schaer, S., G. Werner and J. Feltens (1998). IONEX: The ionosphere map exchange format, version 1. *Proceedings of the IGS AC workshop*, Darmstadt, Germany. Vol. 9. No. 11.

Scordilis E.M., M.E. Contadakis, F. Vallianatos and S. Spatalas (2020). Lower Ionospheric turbulence variations during the intense tectonic activity in Eastern Aegean area, *Annals of Geophysics*, 63, 5, PA544.

Turcotte, D.L. (1997). Fractal and Chaos in Geology and Geophysics (2nd Edition), *Cambridge University Press*, Cambridge U.K.