

POST-SEISMIC IONOSPHERE EFFECTS AFTER CROATIAN M_W 6.4 EARTHQUAKE ON DECEMBER 29, 2020

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Abstract

The main idea of the present investigation is to study the relationship between post-seismic effects as a result of Petrinja, Croatia earthquake which occurred on December 29, 2020 in some ionospheric parameters. Two types of ionospheric data were used: the critical frequency of the F2 region (foF2), obtained from the vertical sounding of the ionosphere and Total Electron Content (TEC) data. The ionospheric response is studied by the relative deviation of both quantities foF2 and TEC. The results of the ionospheric parameter behaviour show the following: a) a positive anomaly is observed in both ionospheric characteristics; b) the most significant positive response is observed at ionospheric stations closer to the epicentre; c) the delay of the observed post-seismic ionospheric effect increases with distance from the epicentre in both data used. The observed anomalies in the behaviour of considered ionospheric parameters could be associated with the considered lithospheric phenomenon because the selected period is with completely quiet geomagnetic conditions. The results of this research gives additional insight into the Lithosphere-Atmosphere-Ionosphere Coupling during Earthquake processes.

Key words: post-seismic effect, ionosphere, TEC

Introduction. It is well known that earthquakes are one of the most destructive natural phenomena. As a result of earthquakes, energy in the form of

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seismic waves that travel radially around the epicentre and cause a range of damage is released [1]. In recent decades, thanks to the development of the Global Navigation Satellite System (GNSS), ionospheric anomaly scientists have turned their attention to earthquake investigation and prediction [2]. The pre-seismic, co-seismic, and the post-seismic ionospheric anomalies associated with earthquakes are the subject of numerous studies [3–5]. Scientists associate the analysis of polarization fading of different long- and medium-wavelength signal transmissions with the seismic fading. Acoustic energy is transported to the ionosphere, leading to fluctuations in the atmospheric density and hence to fluctuations in electron density and radio absorption [6].

One of the strongest seismic events in Croatia in the last two centuries is that which occurred near Petrinja, Croatia on December 29, 2020. From the analysis made based on the VLF transmitter signals of pre-seismic ionospheric disturbances prior to this earthquake, it is hypothesized that the origin of the recorded earthquake is related to the tectonic activities due to Anatolian plate interactions with African and Arabian plates [3]. Due to the magnitude of 6.4 and the depth of 10 km, significant effects on the environment are also expected. These indicators create conditions for rupture of the ground, cracks and faults, which can lead to major accidents and casualties. The damage assessments after the Petrinja earthquake show that, based on Global Positioning System (GPS) and Interferometric synthetic aperture radar (InSAR) data, fundamental information is provided to improve the interpretation of seismological effects related to natural hazards and society [4, 5].

The main idea of this work is to analyze the presence of coexisting post-seismic effects in some selected geophysical parameters. For this purpose, examples of the variation of the electron density of the ionosphere are shown, which indicate relationships with the earthquake on December 29, 2020 near Zagreb, Croatia with coordinates (45.42°N, 16.21°E).

Data and methods. In the analysis of the considered event, data from Centre Sismologique Euro-Méditerranéen, Euro-Mediterranean Seismological Centre (EMSC) <https://m.emsc.eu/> is used. EMSC is the European infrastructure for seismological products in EPOS (European Plate Observing System). On the basis of the developed open access system, detailed seismological information about the earthquake on the territory of Croatia was obtained.

In order to consider the response of the ionosphere only as a result of the seismological event that occurred, it is necessary to check if a geomagnetic storm, which significantly affects the ionospheric electron density, was not recorded in the considered time interval [7–9]. For this purpose, it is necessary to check the behaviours of the geomagnetic indices Kp and Dst, which are available at the following address: <https://omniweb.gsfc.nasa.gov/>.

In the present work, the ionospheric response is described by two types of data – one is single-station (ionosonde data) and the other is global TEC data.

The used in this study vertical sounding ionospheric data of the F2-layer critical frequency (foF2) values are taken from the GLOBAL IONOSPHERE RADIO OBSERVATORY (GIRO) available at the following link: <https://giro.uml.edu/index.html>. The disadvantage of this type of data is that the ionospheric stations are unevenly located and their number is limited.

Therefore, on the basis of the global data network of the Center for Orbit Determination in Europe (CODE) – <http://ftp.aiub.unibe.ch/CODE/> it is possible to obtain values at the closest possible point to that of the epicentre of the earthquake in order to trace the spatial distribution of the ionospheric response.

In order to define the ionospheric anomalies, which could be a response to the earthquake in Croatia we have to remove in advance all regular variability of the ionosphere. The global scale regular variabilities of the ionosphere are defined by the diurnal variability of the solar ionization and the regular behaviour of the atmospheric tides coming from below and affecting the ionosphere. Such regular variabilities are removed by using relative values of foF2 and TEC defined in [10], where this statement has been proven.

Basic information about the considered earthquake. The destructive earthquake recorded on the territory of Croatia on December 29, 2020 is of primary importance in this research. The event occurred at 11:19:54 UTC (i.e. 12:59:54 local time) with a magnitude of 6.4 and a depth of only 10 km. Its epicentre (45.42°N , 16.21°E) is located at a distance of about 47 km from Zagreb, Croatia and 14.5 km from Sisak, Croatia. The mainshock and most of the aftershocks are located on the Petrinja Fault, which is well documented in the European Seismogenic Fault (EDSF) database. This is the strongest earthquake in Croatia recorded in the last century [11]. Figure 1 presents a map of the lo-

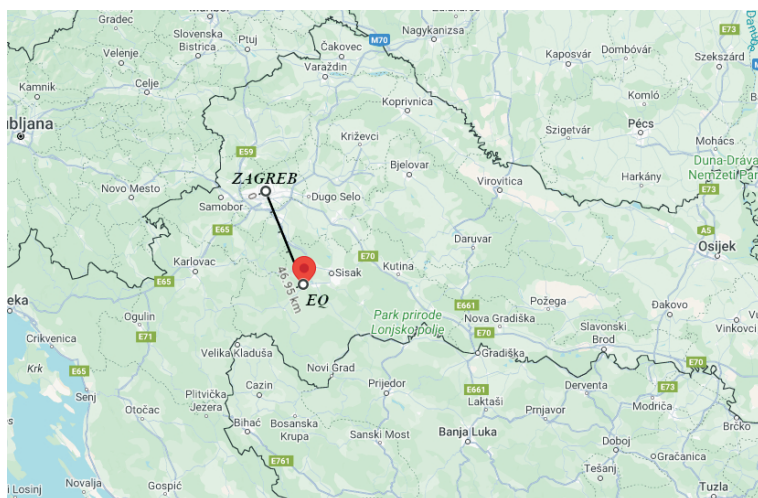


Fig. 1. Earthquake map illustrating the distance between the epicentre of the earthquake and Zagreb

cation of the earthquake and the distance between the epicentre and Zagreb, the capital of Croatia. The distance shown in Fig. 1 allows to investigate the area of the consequences of the Petrinja earthquake related to sliding, rockfall, fracture, sinkhole, and sand volcanism in the epicentral area. The observed geological and surface changes of main roads as a result of the earthquake shows the need for research in the field of natural hazards [3,4].

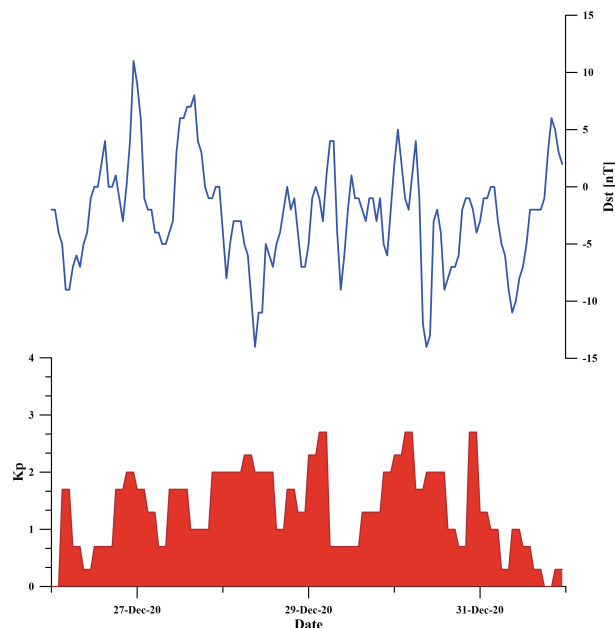


Fig. 2. Variability of geomagnetic indices Kp and Dst

Geomagnetic indices. The established and well-studied effects of the solar influences on the Earth's magnetosphere, ionosphere and atmosphere give reason to analyze the behaviour of the geomagnetic indices before and after the registered earthquake on December 29, 2020. The next step is an analysis of the ionospheric response to search for post-seismic effects. Figure 2 shows the behaviour of the indices Kp (bottom panel) and Dst (top panel) for the period 26–31 December 2020. Selecting this time interval allows the period before and after the recorded event to be considered. As can be seen from Fig. 2, Kp index does not reach 3, and Dst has values up to -15nT . According to the accepted classification for both indices no geomagnetic disturbance was registered during the entire considered interval [12–14]. The obtained results, which show geomagnetically quiet conditions, allow to analyze the geophysical parameters and hypothesize that the obtained anomalies in their behaviour are due to post-seismic effects.

Selection of specific data in the analysis of the ionosphere. Since the behaviour of the geomagnetic indices do not indicate the presence of a geomagnetic storm, the next step is an analysis of the behaviour of the ionospheric

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List of used ionospheric stations received by GIRO

Station code	Country	GEO Latitude	GEO Longitude
RO041	Rome, Italy	41.9	12.5
VT139	San Vito, Italy	40.6	17.8
EB040	Roquetes, Spain	40.8	0.5
DB049	Dourbes, Belgium	50.1	4.6

parameters TEC and foF2. As it was already mentioned in the Data and methods section, when studying the behaviour of ionospheric quantities, their relative deviations, well-known to scientists studying the ionosphere, were used, which allow to evaluate the type of response. The response of the ionosphere can be classified into two categories: positive and negative [15–20]. For this purpose, data from selected ionospheric stations obtained by GIRO were used. Table 1 presents information about the used point data for the foF2 quantity from the ionospheric stations selected as close as possible to the epicentre of the Croatian earthquake.

Besides the ionosonde foF2 data we also use the TEC data from the CODE database as the closest to the epicentre point with coordinates (45°N, 15°E) is selected.

Investigation of the ionospheric response for specific selected points.

The main idea of this study is to analyze the possibility of a relationship between the ionospheric response in the days after the earthquake near Zagreb, Croatia on December 29, 2020. For the purpose Fig. 3 presents the comparison of the behaviour of the relative values of the data from the ionospheric stations and TEC for the available points near the epicentre of the earthquake. From the behaviour of the relative TEC, whose coordinates almost coincide with those of the earthquake (45°N, 15°E), it can be seen that positive values are observed shortly after 12UT on December 29, 2020, i.e. immediately after the seismic event occurred. The quantity has its most significant positive value in the night hours around 03UT on December 30, 2020, reaching around 0.1.

Unlike variations in the relative TEC, which is an integral of the ionospheric electron density for the entire ionosphere along a line vertical to a given point on the Earth's surface, foF2 shows some delay in its response. In addition, for each of the ionospheric stations, the Standard Deviation (STD) is shown, which allows to see what the dispersion of the data is compared to the mean value. The illustrated variations of the individual stations show a similar response to TEC, but with some differences, namely:

- The positive response of all ionospheric stations shows a delay compared to that of TEC. The hypothesis to explain this effect is that the observed delay is most likely related to the distance of the points from the epicentre. Due to the fact that the closest coordinate to the epicentre is the TEC point, it is expected that a response of this parameter will be registered first.

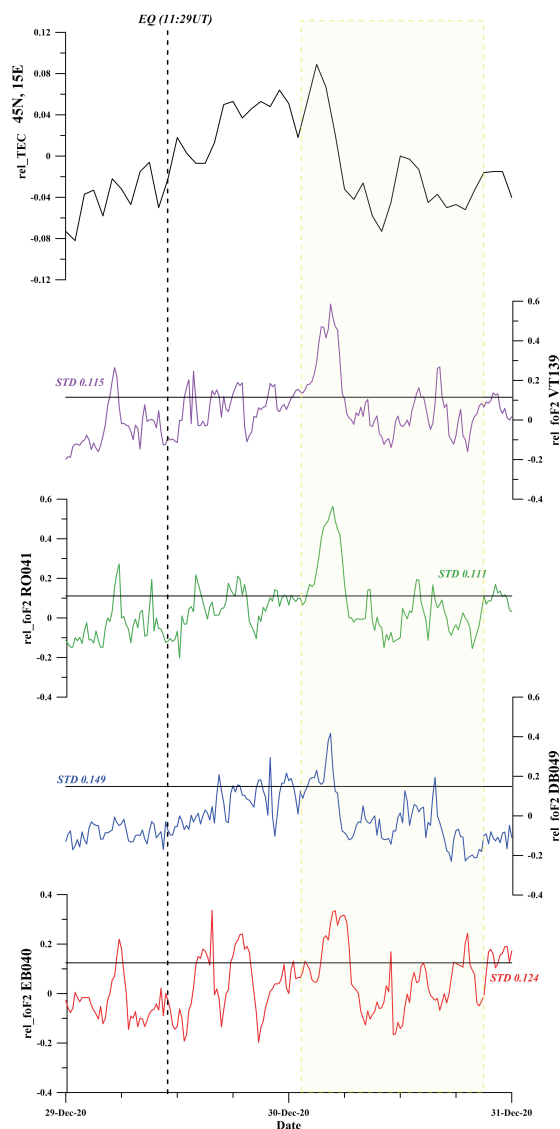


Fig. 3. Behaviour of the ionosphere for the period 29–30 December 2020 according to data of several ionospheric stations and TEC data

- It is noticed that as the selected points move away from the epicentre, the response delay becomes greater. Stations RO041 and VT139 (which are slightly closer in coordinates) show positive relative foF2 values slightly before the other stations DB049 and EB040.
- The maximum positive response also shows some delay in its manifestation with distance from the epicentre. It occurs most rapidly in TEC (around 03UT). After about an hour at 04UT, a maximum in the relative foF2 is observed in the ionospheric data.

- The most significant positive response of about 0.6 is observed at stations RO041 and VT139, while in the more distant DB049 and EB040 stations it reaches about 0.4.

Conclusion. This study presents the ionospheric response most probably produced by the earthquake in Croatia on December 29, 2020. The ionospheric anomaly over European region covered by latitudes of 40.6°N – 50.1°N and longitudes of 0.5°E – 17.8°E are investigated. For this purpose two types of data, foF2 and TEC, have been used for the time interval 29–31 December. The ionospheric response in both parameters is presented by relative deviations of foF2 and TEC. The results clearly show the presence of a positive response in the parameters under consideration. This positive anomaly occurs first at the point with the closest coordinates to the earthquake epicentre and the delay increases away from the epicentre. The larger magnitudes are observed in ionosondes closer to the epicentre and the response decreases with distance to the epicentre.

The results found in the present study give us the opportunity to clarify the view of the ionospheric anomalies most probably related to the Croatian earthquake. The knowledge about the possible sources of the variability of the critical frequency of the ionosphere is extremely important for high frequency radio wave propagation and satellite navigation.

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