Predicting earthquakes by anomalies in the ionosphere

Daria Chaplygina
Saint Petersburg State University
Saint Petersburg, Russia
das9884@gmail.com

Natalia Grafeeva[1,2]
[1]*Saint Petersburg State University*
[2]*ITMO University*
Saint Petersburg, Russia
n.grafeeva@spbu.ru

***Abstract*—Since earthquakes are a global-scale problem, humanity has been attempting to predict them for a long time. Earlier [1], it was shown that machine learning can be used to predict earthquakes. Nevertheless, a sufficiently accurate and complete predictive model could not be obtained, which may be due to an insufficient number of features.**

In this paper, anomalies in the ionosphere preceding seismic activity are considered as earthquake precursors. Two existing approaches to detecting ionosphere anomalies were considered; a third one was proposed, using readings of several ionosondes located in the neighborhood of the earthquake area or in a ring around such neighborhood. To test these approaches, a collection of ionosphere characteristics data, obtained from ground ionosondes, was gathered and processed. In the future, discovered anomalies are planned to be used as features for machine learning models.

***Index Terms*—earthquake prediction, data mining, time series, seismology, ionosphere anomalies**

I. INTRODUCTION

Over the last 5 years (2014–2018), on average, 1,673 earthquakes of magnitude 5 or higher are registered each year. Such earthquakes are considered strong (ranked VI or higher on the Mercalli scale [2]) and can potentially cause damage ranging from broken dishes to human casualties and subsequent technological disasters. Timely prediction of earthquakes could reduce the damage or even avoid it completely, which is why, for a long time, humanity has been attempting to predict seismic activity. For this purpose, seismologists study anomalies which precede earthquakes: foreshocks (small earthquakes occurring shortly before stronger ones), electromagnetic anomalies, radon emissions, unusual animal behavior, and so on. But the use of such precursors has a number of problems: lack of specificity (anomalies might not appear before an earthquake or might appear independently from one) and difficulty of detection (insufficient number of measuring devices and/or their insufficient accuracy).

In 2019, an attempt was made to unify all available knowledge and construct a predictive model of earthquakes [1]. As a result of that work, it was shown that machine learning methods are applicable to this problem, but a prediction algorithm that would be simultaneously accurate and complete could not be obtained. As an area of further research, it was suggested to use ionosphere parameters as an indicator of seismicity.

The goal of this work is to study anomalies in the ionosphere as a precursor to earthquakes. For this purpose, a collection of data containing readings of ground ionosondes was obtained; studies describing ionosphere changes before an earthquake were examined; and three approaches to detecting ionosphere anomalies were considered.

II. IONOSPHERE

The ionosphere is the upper part of Earth's atmosphere, heavily ionized under the influence of solar radiation. The state of the ionosphere can significantly vary depending on *time*: it's affected by the cycle of solar activity, season of the year, and time of day; and also on *geographical location*: there are polar regions, auroral zones, mid-latitudes, and equatorial regions.

The ionosphere is divided into three layers, D, E, and F, depending on the density of charged particles. In turn, the F layer can be subdivided into F1 and F2 layers, and the E layer is considered to contain the sporadic E layer (Es). As the distance to the surface of Earth increases, so does the ion density, from the D layer to the F layer.

To study the ionosphere, the vertical sounding method is used. An *ionosonde* generates a high-frequency vertical radio impulse and records the height where it is reflected. The reflection height, as a function of radio impulse frequency, is recorded in the form of an *ionogram*, an example of which is shown in Fig. 1.

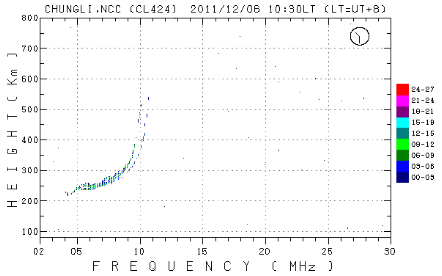

Fig. 1: An example of an ionogram. Color indicates the intensity of reflection. This is the form in which an ionosonde initially receives the data; all other parameters are determined from this image.

All parameters describing the state of the ionosphere are subsequently obtained from the processing of an ionogram.

The graph of the relationship between impulse frequency and reflection height can be used to calculate such characteristics as, for example, virtual heights ($h'E$; $h'F$; $h'F2$; etc.) or critical frequencies (foE; $foF1$; $foF2$; etc.) of various levels of the ionosphere.

III. REVIEW OF LITERATURE

A. Biryukov et al., 1996. One of the first papers that showed a connection between ionosphere variations and seismic activity was published in 1996 [3]. The authors of that article studied experimental data obtained from satellites that detected effects of an upcoming earthquake on the ionosphere. It was shown that seismic waves cause such ionospheric effects as: a glow of the night sky, a change of the properties of ionospheric plasma (its concentration, composition, and heating), and low-frequency magnetic oscillations. As a result, researchers concluded that, even though disturbances that precede earthquakes have low amplitudes and can be caused by other factors, existing diagnostic equipment could detect earthquake precursors from satellites.

S. A. Pulinets et al., 2003. In the paper by S. A. Pulinets et al. [4], the authors published the results of a ten-year study of variations in the ionosphere in seismically active regions shortly before an earthquake. The goal of the study was to determine the main characteristics of ionospheric precursors of an earthquake. In particular, an attempt was made to detect characteristics that could distinguish earthquake precursors from variations that had other causes. As the study showed, before an earthquake, the $foF2$ parameter (critical frequency of the F2 layer of the ionosphere) deviates from its monthly median. The authors reached the following conclusions:

- phenomena in the ionosphere that precede earthquakes can be observed *between 5 days and a few hours* before the earthquake;
- the deviation from the median can be either positive or negative;
- these phenomena can be detected for earthquakes of *magnitude 5 or higher.*

The primary result was the conclusion that, *given a fixed relative position of the earthquake's epicenter and the observation point (in our case, the ionosonde), ionospheric precursors will be similar for all subsequent earthquakes with a close epicenter.* In turn, the existence of consistent patterns of earthquake precursors can enable prediction of future catastrophes.

Chen et al., 2004. Conclusions about the changes of $foF2$ were statistically confirmed in the study [5], whose authors proposed and conducted two tests: the first checks that occurrence of anomalies in $foF2$ is connected with a subsequent earthquake more often than it would be for a random event (coin toss); the second checks the effectiveness of $foF2$ anomalies as an earthquake precursor compared to other indicators. The hypothesis of $foF2$ anomalies before earthquakes being random was rejected with $p - value \leq 0.0052$. The effectiveness test also confirmed the possibility of constructing a predictive model for earthquakes based on $foF2$ deviations.

Thus, studies indicate that ionospheric precursors of earthquakes exist and manifest themselves in the form of anomalies of the values of the F2-layer critical frequency, or $foF2$. But it is also known [6], that the value of $foF2$ depends on the time of day and the season, as well as on solar and geomagnetic activity, which in turn makes it non-trivial to detect anomalous values of $foF2$. The works described below suggested two algorithms for detecting non-typical variations of $foF2$.

S. A. Pulinets et al., 2002. The article [7] suggested the use of 24×6 matrices A_{ij}, where the value in the i-th row and the j-th column indicates the deviation of $foF2$ from the median value for the i-th hour of the j-th day. The study showed that such matrices, when computed for a period of 6 days before an earthquake, turn out to be similar for earthquakes occurring in identical regions. Thus, earthquake prediction becomes a problem of comparing $foF2$ deviation matrices constructed for earlier earthquakes with the current state matrix.

S. A. Pulinets, 2004. Another approach was demonstrated in the article [8]. The method proposed by the authors assumes two ionosondes: one in the *earthquake preparation zone* [9], the other outside that zone, but close to the first ionosonde ($\sim$ *500–700 km*). Data obtained from such ionosondes, in the absence of seismic activity, will be highly correlated due to their proximity, as all external factors will affect them equally. During earthquake preparation, however, one ionosonde falls into the zone of seismic activity, which reduces the correlation indicator. An advantage of this method compared to the previous one is that there is no need to process historical data.

Xia et al., 2011, L. P. Korsunova and V. Hegai, 2018. In later years, attempts were made to use other characteristics of the ionosphere as earthquake precursors. Thus, for example, the study [10] demonstrates the existence of anomalies in TEC (*total electron content*). These anomalies were detected by the authors a few (2–9) days before three earthquakes of magnitude ≥ 7.2. Another article [11] studied anomalies in the Es layer of the ionosphere, specifically, the *virtual height of the Es layer* ($h'Es$). Just like in the previous paper, a significant deviation of this parameter from its typical value was detected prior to an earthquake. Results like this indicate that $foF2$ may not be the only earthquake precursor; however, there is a need for statistical confirmation of observations that currently exist only for particular cases.

D. Davidenko and S. Pulinets, 2019. Recent works also developed the previously described method that uses $foF2$ deviation matrices. The paper by D. Davidenko and S. Pulinets [12] subjected it to slight modifications: instead of 6 days, it considered 10 days before and 4 days after an earthquake, and the deviation was measured from the sliding average of 15 previous values at the same moment in time. The article studied variations in the ionosphere that preceded earthquakes in regions of Greece and Italy. The consideration of a narrow region was motivated by the idea (mentioned in the paper [4]) that earthquake precursors have a pattern that repeats for a particular region.

IV. DESCRIPTION OF DATA

A. *Earthquake data*

The earthquakes information was obtained from the website of United States Geological Survey (USGS) [1]. Data was downloaded for all earthquakes over the period from 1970 to 2019 with magnitudes ≥ 4.5. In total, 78,433 earthquakes were downloaded.

B. *Ionosonde data*

Data about the state of the ionosphere was obtained from the website of the United States National Centers for Environmental Information (NCEI)[2]. As of the time of searching (November 2019) this website had the most complete set of ionosondes data: an information obtained from over 100 ground ionosondes in various places on Earth (ionosonde locations are shown in Fig. 2).

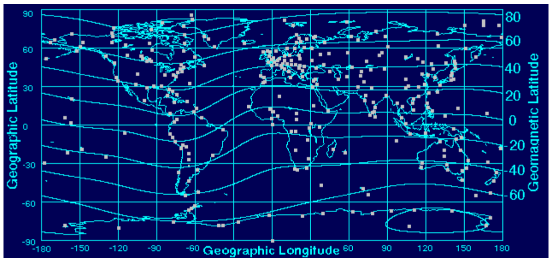

Fig. 2: Locations of ionosondes available in the NCEI dataset. Image taken from the website of the United States National Centers for Environmental Information (NCEI).

For most ionosondes, readings were collected starting in 2000. Every 15 minutes, ionograms were constructed, which were used to calculate up to 49 parameters describing the state of the ionosphere. However, it is worth noting that the dataset that we found is not complete: it has many gaps and missing days. In addition, in order to find earthquake precursors, it is necessary to have an ionosonde in the earthquake preparation zone, which is not always the case for the current ionosonde location grid. An additional difficulty for working with this dataset is the format in which they're stored: each data point is placed in a separate file, which may be in up to three formats (.SAO, .SAO.XML, .EDP). For some time slices, ionosphere characteristics were not calculated, and the data is stored in the form of unprocessed ionograms.

C. *Data processing*

For further study, we filtered and processed the data. From all the ionosondes, we picked those that were:

- located in the preparation zone of one of the earthquakes (in the radius of $10^{0.43M}$, where M is the earthquake's magnitude, [9]; only earthquakes of magnitude ≥ 5.0 were considered);
- were recording ionosphere data on the day of the earthquake.

Such filtering criteria significantly decreased the dataset: of the 78,433 earthquakes, only 891 had at least one corresponding ionosonde. In addition, the amount of data available for earthquake analysis will later decrease even further, because in order to determine earthquake precursors, a few more criteria need to be satisfied:

- ionosphere characteristics are known for a perionod of at least 25 days before the earthquake (necessary for deterimining the sliding average during "calm" days and days of seismic activity);
- data covers a sufficient number of hours per day (the threshold is to be determined).

Even greater difficulty is posed by the second approach to anomaly detection, which attempts to correlate readings of two ionosondes. Only for 156 earthquakes could we select *appropriate* ionosonde pairs (in accordance with the description found in subsection V-B of this paper). For such pairs, filtering criteria are:

- ionosphere characteristics are known for a period of at least 10 days before the earthquake;
- time intervals when data from both ionosondes are known cover a sufficient number of hours per day (the threshold is also to be determined).

For appropriate ionosondes, data for a period of 50 days before and after an earthquake was downloaded and processed. The processing consisted of converting the data to a unified format convenient for later use. The resulting dataset is freely available (https://github.com/DaryaChaplygina/ionoshpere_dataset) and contains ionosonde data in the following form:

TABLE I: THE FORMAT OF THE PROCESSED DATASET. FOF2 AND TYPE ES ARE IONOSPHERE PARAMETERS (49 IN TOTAL)

Ionosonde	**date**	**hour**	**minute**	**foF2**	...	**Type Es**
CL424	2019-01-01	0	0	8.157	...	9
CL424	2019-01-01	0	15	8.55	...	9

V. DETECTING IONOSPHERE ANOMALIES

In our work, we decided to reproduce three approaches to detecting ionospheric precursors of earthquakes. As literature analysis has shown, changes most characteristic of seismic activity is occur in the $foF2$ indicator (the F2-layer critical frequency). Therefore, earthquake prediction is reduced to the problem of finding anomalies in $foF2$.

Two of the anomaly detection methods listed below have been previously described in literature: in the first method, we consider the **deviation from the sliding average**, in the second one, the **decrease in the correlation coefficient** of nearby ionosondes. We also propose a third method, which uses data from multiple ionosondes to predict earthquakes.

A. *Deviation from the average. Ionospheric precursor mask*

In the first approach [12], for every time point i we calculate the value

$$\Delta foF2 = 100(foF2 - foF2_A)/foF2_A \tag{1}$$

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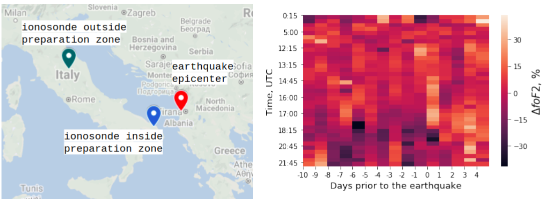
[1] https://www.usgs.gov/natural-hazards/earthquake-hazards/earthquakes

[2] https://www.ngdc.noaa.gov/stp/iono/ionogram.html

Here $foF2_A$ is the average value of the $foF2$ indicator at the same time i over the last 15 days.

These values are used to construct the earthquake mask A^n: an array consisting of values $a_{i,j} = \Delta foF2$ at time point i of day j (where n is the earthquake's index). To construct the array, we use a period of 10 days before and 4 days after the earthquake (Fig. 3b).

The *ionospheric precursor mask* contains the averages of earthquake masks $A^1 \dots A^n$ calculated for seismic activity events of the studied region. Later, earthquakes in a particular region are predicted by comparing the ionospheric precursor mask constructed from historical data with the mask of the current ionosphere state. A match indicates, with a certain probability, an upcoming earthquake.



(a) (b)

Fig. 3: An example mask for an earthquake that happened in Albania on September 21, 2019. (a) the locations of the earthquake's epicenter and the closest ionosonde located in the earthquake preparation area; (b) the earthquake mask constructed from the readings of the closest ionosonde.

We obtained that an ionospheric precursor mask was closer to earthquake masks than to masks constructed at "calm" days for 72% of regions. The distance between masks A and B was calculated as $d(A, B) = median(|a_{i,j} - b_{i,j}|)$. This method of masks comparison is not sufficiently precise, since it does not consider possible time shifts of anomalies appearing or missing values. Still it does show that this method of anomalies detection has potential as an earthquake predictor.

B. Decrease of the correlation coefficient

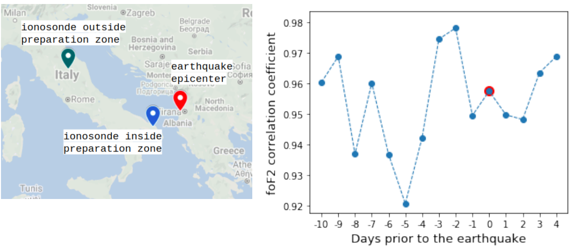
This approach [8] is motivated by a previously mentioned feature of ionosphere data: its dependence on time and location. This requires processing of historical data (in case of the first approach). But this can be avoided if we have a pair of ionosondes $(s1, s2)$ satisfying the following conditions:

- both ionosondes were recording data simultaneously during the earthquake period;
- $s1$ is located inside the earthquake's preparation area, and $s2$ is located outside it;
- the distance between $s1$ and $s2$ does not exceed 700 km.

In this case, an earthquake precursor is the decrease of correlation of the two ionosondes' readings. Correlation is calculated for each day using the formula:

$$\frac{\sum_{i=0..k}(f_{1,i} - af_1)(f_{2,i} - af_2)}{k\sigma_1\sigma_2} \tag{2}$$

In this formula, indices 1, 2 correspond to ionosondes; the sum is calculated over all time points for which data from both ionosondes is available; $f_{j,i}$ is the $foF2$ indicator at time point i for ionosonde j; af_j is the average value of $foF2$ over the day being considered; σ_j is the standard deviation.



(a) (b)

Fig. 4: Example of correlation of ionosonde readings for an earthquake that happened in Albania on September 21, 2019. (a) the locations of the earthquake's epicenter and the closest ionosondes located inside and outside the earthquake preparation area; (b) daily correlation of ionosonde readings for 10 days before and 4 days after the earthquake.

Anomalous decrease of correlation coefficient, on average, two times more frequent in the days preceding earthquake. Moreover, by varying the definition of "anomalous decrease" (in other words, the difference between the current correlation coefficient and the average), we were able to achieve 100% of precision in 25% of regions. That means the most strong anomalies occur only before earthquakes.

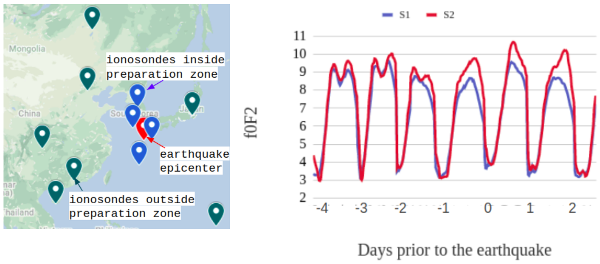
C. Earthquake precursor based on data from several ionosondes

When studying data obtained from ionosondes before an earthquake, we observed a pattern which may, in our view, enable more stable predictions of earthquakes, provided there are enough ionosondes in the neighborhood of a supposed earthquake. To detect it we need data from two groups of ionosondes such that each group satisfies the conditions:

- data from all ionosondes are recorded simultaneously;
- the first group $S1$ contains all ionosondes located no farther than 750 km from the earthquake's epicenter;
- the second group $S2$ contains all ionosondes located between 750 km and 1,500 km from the epicenter.

Then, for each group, we consider 15-minute ionosonde readings ($foF2$ indicator) and smooth them using a sliding average with the window width of 10 readings (this way, we get rid of various noises that are always present in readings). Then, for each group, we construct a time series based on average values of the readings of all ionosondes in the group, up to 15-minute intervals. Fig. 5 shows the time series constructed in this manner for an earthquake in Japan.

Fig. 5 clearly shows stable distinctions between the behavior of time series during the approach of an earthquake. As a formal indicator, we can use the correlation of the last 40 points of the time series corresponding to the groups $S1$ and $S2$. The decrease of the indicator below a certain threshold (for example, 0.9) can be considered one of the precursors of a potential earthquake. Fig. 6 shows a graph of the correlation of such series in the neighborhood of the aforementioned earthquake in Japan.



(a) (b)

Fig. 5: An example time series of ionosonde readings for an earthquake that occured in Japan on November 13, 2015. (a) locations of the earthquake's epicenter and the closest ionosondes; (b) average ionosonde readings for groups S1 and S2.

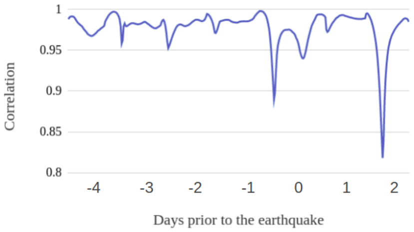


Fig. 6: Correlation of average readings of ionosondes from the two groups for the November 13, 2015 earthquake in Japan.

As in the previous case, anomalous decrease of correlation coefficient begin to occur two times more frequent before most of earthquakes. We could predict earthquakes even better using absolute difference between groups average values of $foF2$ – its anomalous increase occurs from 2 to 20 times more frequent in the days preceding earthquakes.

VI. CONCLUSION

In order to study ionospheric precursors of earthquakes, we gathered and processed a collection of data obtained by ionosondes before an earthquake. This data was used to test ionosphere anomaly detection methods described in section V. The future stages of the work are:

- constructing a predictive model of earthquakes based on the described features;
- comparing the predictive capabilities of the three described precursors and determining their statistical significance (by analogy with paper [5]);
- combining ionospheric indicators with other earthquake precursors to increase the accuracy of predictions.

In conclusion, we would like to add that real-time earthquake prediction requires a more regular network of ionosondes. Since our paper uses data collected from ground ionosondes, this condition is not met, as many earthquakes occur in places where it is difficult to place equipment. The ability to obtain regular data from satellite-based ionosophere sounding would significantly increase the number of regions available for monitoring. As of the time of this article's writing (February 2020), regular satellite-based sounding of the ionosphere is not being conducted. However, satellite sounding of the ionosphere is planned as part of the space complex "Ionozond" [13] and the "Ionozond-TGK" experiment [14]. The measurements are slated to begin in 2021–2022. The "Ionozond" complex will enable the collection of data from any point on Earth, and the "Ionozond-TGK" experiment, from the band between 51.63 degrees northern latitude to 51.63 degrees southern latitude. We hope that by the time when ionosphere data is being regularly obtained from satellites, we will have prepared and confirmed a methodology for predicting earthquakes based on data about the state of the ionosphere.

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