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Ionosphere Scintillation and Earthquakes

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Abstract: Recent theoretical and experimental studies demonstrated the ability of space technologies to identify and monitor the specific variations at near-earth space plasma and atmosphere associated with approaching severe earthquakes, named as earthquake precursors, which appear several days before the seismic shock over the seismically active areas [1].

This paper aims at determining the relationship between ionosphere scintillation of radio waves and earthquakes.

Data for GPS (Global Positioning System) S_4 index have been examined through spatial and temporal correlation. The results showed that the pre-seismic activity can be considered as a source of ionosphere scintillation.

Keywords: Space plasma; Ionosphere; Scintillation; Earthquakes.

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Introduction

Earthquakes are the most fatal natural disasters. Natural tectonic earthquakes are uncontrollable by humans. Therefore the best way to avoid these natural disasters is to predict their occurrence and take precautions. There are many indications that can be observed before an earthquake strikes. These are called precursors. According to Pulinets and his collaborators [2, 3], the scale height changes in the vertical distribution of ions and electrons within the F-layer of ionosphere are due to seismogenic effects.

The critical frequency foF_2 layer data are analyzed with upper and lower bound of inter-quartile range (IQR) and the observed anomalous changes are related to geomagnetic disturbances [4]. The results of the study show some unusual perturbations observed in critical frequency foF_2 region, 1–25 days before and 2–3 days after the main shock.

An additional study shows that critical frequency is reduced both in the pre- and post-midnight hours 0 – 4 days and 1–15 days before the occurrence of earthquakes, respectively. The reduction varies between 24% and 35% in the pre-midnight sector and between 18% and 30% in the post-midnight sector [5].

The mechanism of ULF (Ultra Low Frequency) geomagnetic oscillations is based on the formation of periodic structure of ionosphere conductivity due to acoustic gravity wave instability stimulated by electric field enhancement in the ionosphere [6].

The wave measurements detected by the SORS (Solar Radio Spectrometer) instrument in the 0.1–15 MHz frequency range, as well as the gamma ray fluxes in the energy ranges of 0.12–0.32 and 3.0–8.3 MeV, detected by the SONG (Solar Neutron and Gamma Rays Device) instrument, located on the low orbiting satellite CORONAS-I (Complex Orbital Near-Earth Observations of the Solar Activity) were used to present the ionosphere plasma response to strong seismic activity on 31.03.1994 during quiet geomagnetic conditions and on 6.04.1994 during a

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geomagnetic storm period [7]. In order to better understand the physical conditions and the physical processes in the ionosphere plasma, the characters of typical ionosphere parameters are registered by a network of ground-based ionosondes [8].

In this paper, the ionosphere scintillation index S_4 is thoroughly examined to determine the relationship between scintillation and occurrence of seismic activities. The GPS observations were carried out at a frequency of 1.575 GHz. We tested S_4 index on 3 separate earthquakes in Indonesia, as well as an earthquake in the United States. In the following section, data and results are presented. Then, an analysis of the observed correlation is presented. The conclusion is presented in the last section.

Data and Results

The S_4 index is a statistical parameter; namely the standard deviation of the received power of the signal coming from GPS satellite passing through the ionosphere normalized by its mean value.

$$S_4 = \frac{(\langle P^2 \rangle - \langle P \rangle^2)^{1/2}}{\langle P \rangle}$$

where P is the received power of the signal coming from the satellite. It is the most commonly used parameter for indicating the intensity variation.

The severity of the earthquake can be described according to Dobrovolsky's empirical formula [9]

$$\rho = 10^{0.43M}\ km$$

where ρ is the radius of the preparation zone of the earthquake and M is the earthquake's magnitude. Previously, no earthquake severity under a magnitude of 6.0 was tested. This is due to the fact that an earthquake of a magnitude of 6.0 or lower cannot generate enough impact to affect the ionosphere [2].

For data collection, the following steps are completed.

1. We determine the coordinates (longitude/latitude) of the GPS receiver's location.
2. We collect information of earthquakes within a circular region with a radius of about 7000 km, its median point being the GPS receiver, using Earthquake Hazard Program [10]. The lower limit of earthquake's magnitude $M = 6$ is adopted.
3. Upon selection of the earthquake that affects the GPS receiver, we compare the distance between the earthquake's center and the location of the GPS receiver. On the other hand, we estimate the radius of the region affected by the earthquake (according to Dobrovolsky's formula [9]). When both distances are comparable, we include that earthquake in our analysis. Following this procedure, just few earthquakes are selected, which are shown with their characteristics in Table 1.
4. As for S_4 index, data are available from GPS Scintillation Data in Indonesia web site which belongs to Solar-Terrestrial Environment Laboratory/ Nagoya University [11]. Additional data are available from the web site that belongs to Bear Lake Observatory/ Utah State University [12].

TABLE 1. Characteristics of the selected earthquakes.

Number	Date	Time	Latitude in degrees	Longitude in degrees	Magnitude	Distance from receiver (km)
1	22/2/2004	6:46	-1.56	100.49	6.0	180
2	11/5/2004	8:28	0.41	97.82	6.1	245
3	25/7/2004	14:35	-2.43	103.98	7.3	517
4	15/6/2005	2:51	41.29	-125.95	7.2	1228

The severe scintillations with $S_4 > 0.5$ are selected.

If we attempt to analyze data from earthquakes in a period of time that is too long, we will not be able to see the deeper details. On the other hand, if we take a look at data from earthquakes in a period of time that is too short, we will not be able to collect enough information. We have found that a two-to three-month period of time proves to be an excellent interval.

For the earthquake in Indonesia that occurred on 22/2/2004, S_4 data were collected for the period between 1/1/2004 and 1/3/2004 (Table 2), and those of Indonesia earthquake of 11/5/2004 were collected for the period between 1/3/2004 to 31/5/2004 (Table 3). With respect to Indonesia earthquake of 25/7/2004, S_4 data were selected for the time interval between 1/6/2004 and 31/8/2004 (Table 4). Those of Utah State earthquake of 15/6/2005 were collected between 1/5/2005 and 31/7/2005 and are presented in Table 5. Columns of Tables 1 to 5 are self-explanatory.

TABLE 2. Number of severe scintillations for the period from 1/1/2004 to 1/3/2004 which includes Indonesia earthquake of 22/2/2004.

Date	No. of severe scintillations	Date	No. of severe scintillations
1	2	3	4
1/1/2004	8	1/2/2004	7
2/1/2004	4	2/2/2004	9
3/1/2004	2	3/2/2004	7
4/1/2004	2	4/2/2004	6
5/1/2004	5	5/2/2004	12
6/1/2004	1	6/2/2004	10
7/1/2004	3	7/2/2004	13
8/1/2004	2	8/2/2004	14
9/1/2004	5	9/2/2004	14
10/1/2004	4	10/2/2004	18
11/1/2004	6	11/2/2004	21
12/1/2004	4	12/2/2004	19
13/1/2004	5	13/2/2004	18
14/1/2004	4	14/2/2004	16
15/1/2004	4	15/2/2004	15
16/1/2004	4	16/2/2004	14
17/1/2004	3	17/2/2004	14
18/1/2004	7	18/2/2004	16
19/1/2004	5	19/2/2004	n.a.
20/1/2004	5	20/2/2004	13
21/1/2004	8	21/2/2004	18
22/1/2004	8	22/2/2004	19
23/1/2004	6	23/2/2004	13
24/1/2004	5	24/2/2004	13
25/1/2004	7	25/2/2004	13
26/1/2004	5	26/2/2004	15
27/1/2004	n.a.	27/2/2004	9
28/1/2004	n.a.	28/2/2004	7
30/1/2004	6	1/3/2004	7
31/1/2004	5		

The relationships between scintillation S_4 indices (left axis), earthquake magnitude (right axis) and time for Indonesia earthquakes on 22/02/2004, 11/05/2004 and 25/07/2004 are presented in Figure 1, based on Tables 2 to 4. Figure 2 shows the same relationships for Utah earthquake based on Table 5. The tight correlation between occurrence of earthquakes and severity of ionosphere scintillation is evident.

From (Figs. 1 and 2), we can see that the daily number of occurrences for severe scintillations begins to increase approximately two weeks before the main shock, as well as a few days after it. This is due to the fact that there are pre-seismic activities preceding the earthquake, as well as relay waves (acoustic waves that travel through the atmosphere and reach the ionosphere) following the earthquake.

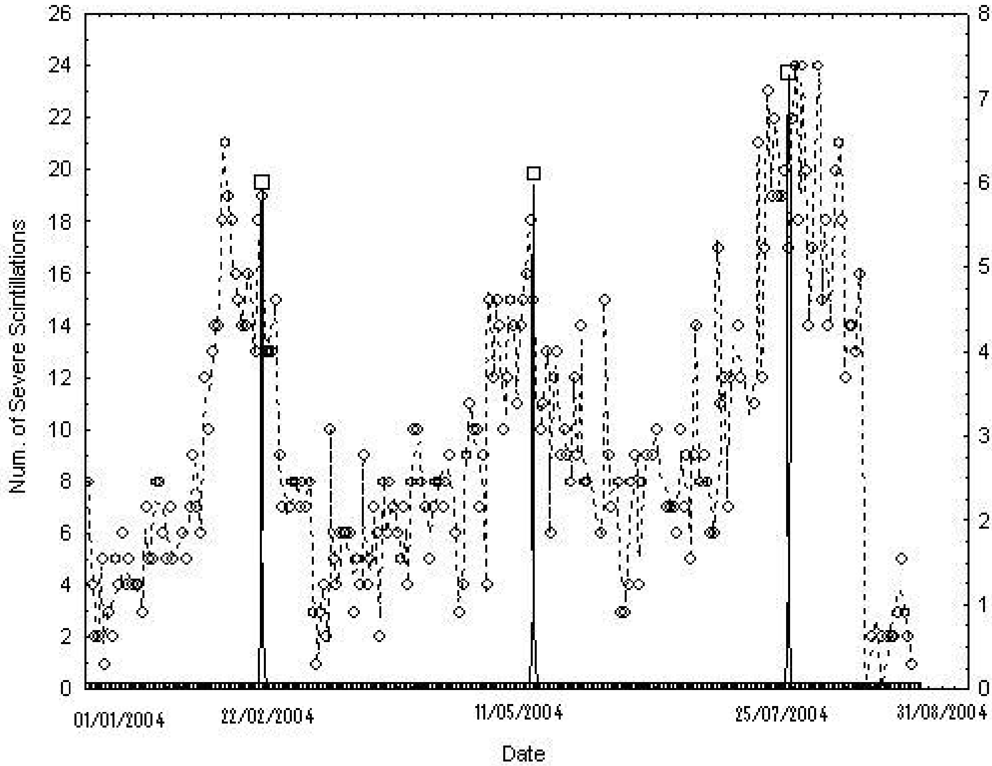

FIG. 1. The relationship between the number of severe scintillations (left axis) represented by circles and the magnitude of an earthquake (right axis) represented by squares. The results for Indonesia earthquakes of 22/2/2004, 11/5/2004 and 25/7/2004 are presented.

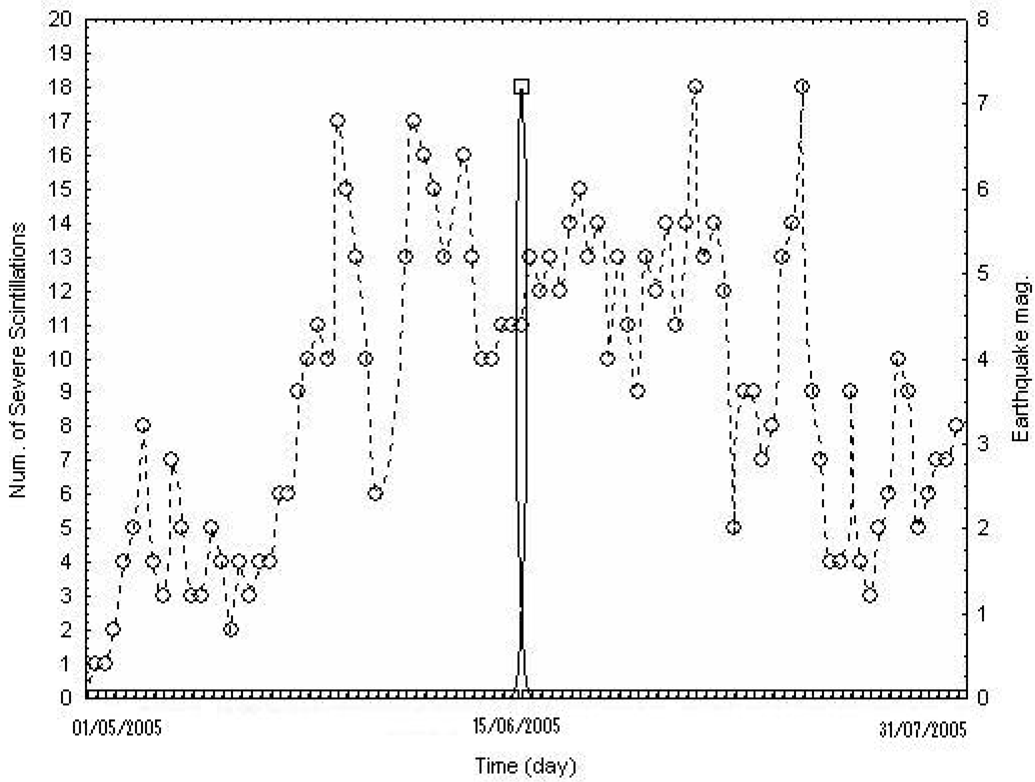

FIG. 2. The relationship between the number of severe scintillations (left axis) represented by circles and the magnitude of an earthquake (right axis) represented by squares. Shown are the results for Utah State earthquake of 15/6/2005.

TABLE 3. Number of severe scintillations for the period from 1/3/2004 to 31/5/2004 which includes Indonesia earthquake of 11/5/2004.

Date	No. of severe scintillations	Date	No. of severe scintillations
1	2	3	4
1/3/2004	8	16/4/2004	9
2/3/2004	8	17/4/2004	n.a.
3/3/2004	7	18/4/2004	6
4/3/2004	8	19/4/2004	3
5/3/2004	7	20/4/2004	4
6/3/2004	8	21/4/2004	9
7/3/2004	3	22/4/2004	11
8/3/2004	1	23/4/2004	10
9/3/2004	3	24/4/2004	10
10/3/2004	4	25/4/2004	7
11/3/2004	2	26/4/2004	9
12/3/2004	10	27/4/2004	4
13/3/2004	5	28/4/2004	15
14/3/2004	4	29/4/2004	12
15/3/2004	6	30/4/2004	15
16/3/2004	6	1/5/2004	14
17/3/2004	6	2/5/2004	10
18/3/2004	6	3/5/2004	12
19/3/2004	3	4/5/2004	15
20/3/2004	5	5/5/2004	14
21/3/2004	4	6/5/2004	11
22/3/2004	9	7/5/2004	14
23/3/2004	4	8/5/2004	15
24/3/2004	5	9/5/2004	16
25/3/2004	7	10/5/2004	18
26/3/2004	6	11/5/2004	15
27/3/2004	2	12/5/2004	n.a.
28/3/2004	8	13/5/2004	10
29/3/2004	6	14/5/2004	11
30/3/2004	8	15/5/2004	13
31/3/2004	7	16/5/2004	6
1/4/2004	6	17/5/2004	12
2/4/2004	5	18/5/2004	13
3/4/2004	7	19/5/2004	9
4/4/2004	4	20/5/2004	10
5/4/2004	8	21/5/2004	9
6/4/2004	10	22/5/2004	8
7/4/2004	10	23/5/2004	12
8/4/2004	8	24/5/2004	9
9/4/2004	7	25/5/2004	14
10/4/2004	5	26/5/2004	8
11/4/2004	7	27/5/2004	8
12/4/2004	8	28/5/2004	n.a.
13/4/2004	8	29/5/2004	n.a.
14/4/2004	7	30/5/2004	n.a.
15/4/2004	8	31/5/2004	6

TABLE 4. Number of severe scintillations for the period from 1/6/2004 to 31/8/2004 which includes Indonesia earthquake of 25/7/2004.

Date	No. of Severe scintillations	Date	No. of Severe scintillations
1	2	3	4
1/6/2004	15	17/7/2004	12
2/6/2004	9	18/7/2004	17
3/6/2004	7	19/7/2004	23
4/6/2004	n.a.	20/7/2004	19
5/6/2004	8	21/7/2004	22
6/6/2004	3	22/7/2004	19
7/6/2004	3	23/7/2004	19
8/6/2004	4	24/7/2004	20
9/6/2004	8	25/7/2004	17
10/6/2004	9	26/7/2004	22
11/6/2004	4	27/7/2004	24
12/6/2004	8	28/7/2004	18
13/6/2004	9	29/7/2004	24
14/6/2004	n.a.	30/7/2004	20
15/6/2004	9	31/7/2004	14
16/6/2004	10	1/8/2004	17
18/6/2004	n.a.	3/8/2004	24
19/6/2004	7	4/8/2004	15
20/6/2004	7	5/8/2004	18
21/6/2004	7	6/8/2004	14
22/6/2004	6	7/8/2004	n.a.
23/6/2004	10	8/8/2004	20
24/6/2004	7	9/8/2004	21
25/6/2004	9	10/8/2004	18
26/6/2004	5	11/8/2004	12
27/6/2004	9	12/8/2004	14
28/6/2004	14	13/8/2004	14
29/6/2004	8	14/8/2004	13
30/6/2004	9	15/8/2004	16
1/7/2004	8	16/8/2004	n.a.
2/7/2004	6	17/8/2004	0
3/7/2004	6	18/8/2004	2
4/7/2004	17	19/8/2004	n.a.
5/7/2004	11	20/8/2004	n.a.
6/7/2004	12	21/8/2004	2
7/7/2004	7	22/8/2004	0
8/7/2004	12	23/8/2004	2
9/7/2004	n.a.	24/8/2004	2
10/7/2004	14	25/8/2004	2
11/7/2004	12	26/8/2004	3
12/7/2004	n.a.	27/8/2004	5
13/7/2004	n.a.	28/8/2004	3
14/7/2004	n.a.	29/8/2004	2
15/7/2004	11	30/8/2004	1
16/7/2004	21	31/8/2004	n.a.

TABLE 5. Number of severe scintillations for the period from 1/5/2005 to 31/7/2005 which includes Utah State earthquake of 15/6/2005.

Date	No. of severe scintillations	Date	No. of severe scintillations
1	2	3	4
1/5/2005	n.a.	16/6/2005	13
2/5/2005	1	17/6/2005	12
3/5/2005	1	18/6/2005	13
4/5/2005	2	19/6/2005	12
5/5/2005	4	20/6/2005	14
6/5/2005	5	21/6/2005	15
7/5/2005	8	22/6/2005	13
8/5/2005	4	23/6/2005	14
9/5/2005	3	24/6/2005	10
10/5/2005	7	25/6/2005	13
11/5/2005	5	26/6/2005	11
12/5/2005	3	27/6/2005	9
13/5/2005	3	28/6/2005	13
14/5/2005	5	29/6/2005	12
15/5/2005	4	30/6/2005	14
16/5/2005	2	1/7/2005	11
17/5/2005	4	2/7/2005	14
18/5/2005	3	3/7/2005	18
19/5/2005	4	4/7/2005	13
20/5/2005	4	5/7/2005	14
21/5/2005	6	6/7/2005	12
22/5/2005	6	7/7/2005	5
23/5/2005	9	8/7/2005	9
24/5/2005	10	9/7/2005	9
25/5/2005	11	10/7/2005	7
26/5/2005	10	11/7/2005	8
27/5/2005	17	12/7/2005	13
28/5/2005	15	13/7/2005	14
29/5/2005	13	14/7/2005	18
30/5/2005	10	15/7/2005	9
31/5/2005	6	16/7/2005	7
1/6/2005	n.a.	17/7/2005	4
2/6/2005	n.a.	18/7/2005	4
3/6/2005	13	19/7/2005	9
4/6/2005	17	20/7/2005	4
5/6/2005	16	21/7/2005	3
6/6/2005	15	22/7/2005	5
7/6/2005	13	23/7/2005	6
8/6/2005	n.a.	24/7/2005	10
9/6/2005	16	25/7/2005	9
10/6/2005	13	26/7/2005	5
11/6/2005	10	27/7/2005	6
12/6/2005	10	28/7/2005	7
13/6/2005	11	29/7/2005	7
14/6/2005	11	30/7/2005	8
15/6/2005	11	31/7/2005	n.a.

Discussion

The ionosphere is not strictly uniform, but contains irregularities of different sizes. The effects of these irregularities on propagation of radio waves may be treated by the diffraction theory. As a wave travels through an irregular medium, it will accumulate changes of amplitude and phase. According to Huygens's principle, each part of the wave front may be regarded as a source of secondary wavelets, the superposition of which builds up the wave front at a point further along. In diffraction theory, one applies this principle to determine how the amplitude and phase of a received signal are affected by passing through a region of irregularity.

Most scintillations arise in the F region of the ionosphere, although they are also found in the E and D regions. The intensity of scintillation is quantified by means of S_4 index.

The theoretical formula for S_4 index is given in reference [13]. One may omit from the theoretical formula parameters that are either constants or unchanged during observations. We can say that S_4 index is a function of electron density of ionosphere plasma, $S_4 = f(N_e)$. Therefore, the main variable that can affect the scintillation index is the electron density (see [13] for more details).

The motion of electrons in the ionosphere is controlled by the earth magnetic field. Therefore, any variation of geomagnetic field may stimulate variation of electron density. Thermally driven convection in the Earth's core bends and twists magnetic field lines leading to electric current and large magnetic fields.

Conclusion

The results of this work indicate that there is a tight correlation between the occurrence of a strong earthquake and ionosphere scintillation.

The S_4 index can be a promising factor in predicting earthquakes. This is due to the fact that there is an obvious increase in the S_4 index up to two weeks preceding an earthquake.

Natural radio sources, like radio-galaxies and quasars, can be used to monitor and analyze ionosphere scintillations, instead of GPS satellites. For this propose, it will be enough to locate small radio telescopes (e.g. 10 m diameter) in seismically active regions and perform real time monitoring.

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