Equipment and method for remote monitoring of seismic activity by VLF electromagnetic signals

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Abstract. A one-point system equipment and a method used for remote monitoring of seismic activity in the lower ionosphere by electromagnetic signals of lightning discharges with observations in Northern Asia are described. Experimental results of detecting of ionospheric effects of strong earthquakes are considered. The effects of shallow-focus earthquakes with magnitudes larger than 5.0 and their precursors manifest themselves in the amplitude characteristics of atmospherics. It is assumed that the variations in the signal characteristics are related to disturbances in the lower ionosphere. Statistical studies of the detection of ionospheric effects during strong earthquakes are carried out. To increase the accuracy and statistical significance of the results, it is proposed to use a multi-point system. A new software-hardware complex called «Sensor signal analysis network» (SSAN), whose endpoints are located in the territory of Northern Asia for synchronous recording of VLF/LF electromagnetic signals of lightning discharges and VLF-transmitters, is planned to be used to study lithospheric-ionospheric disturbances in the main zones of seismic activity.

1. Introduction

The study of lithospheric-ionospheric relations is one of the directions of seismic processes in the Earth's crust. The identification and justification of earthquake precursors is one of the main scientific tasks of these studies. One of the methods for studying the lithospheric-ionospheric relations is the use of observations of electromagnetic signals in very low-frequency (VLF) and low-frequency (LF) ranges for remote monitoring of seismic effects in the lower ionosphere when passing these signals of natural (lightning discharges) and artificial (VLF-transmitters) sources over seismically active regions. In a large number of studies it has been shown that the phase variations of signals of low-frequency radio transmitters [1-3] and the average amplitude of atmospherics [4] observed a few days before seismic events can be used as precursors of earthquakes.

In this paper, the equipment and methods used for remote monitoring of the seismic activity in the lower ionosphere by electromagnetic signals of lightning discharges from observations in Northern Asia and the main experimental results of detecting the ionospheric effects of strong earthquakes are described. The new software-hardware complex «SSAN» for synchronous recording of VLF/LF electromagnetic signals of atmospheric, magnetospheric, and anthropogenic origin is planned to be used for studying lithospheric-ionospheric disturbances in the main zones of seismic activity. Its endpoints are located in the territory of Northern Asia, which is very important for covering a sufficiently large region with seismically dangerous zones.

2. Method

To reveal the effects caused by seismic activity, atmospherics have been measured in the wintertime in Yakutsk using a one-point lightning location system with increased sensitivity in order to increase the range of operation as compared to the summer period [5]. The lightning discharge direction is found...
using three antennas that receive the vertical electric and two horizontal magnetic components of the electromagnetic field. A signal in the range of 0.5–15 kHz enhanced in the receiving channels is digitized by the ADC and entered into the personal computer. The direction toward lightning discharges is determined relative to the rms signal values coming from the magnetic antennas (Figure 1). The ambiguity of direction determination is eliminated by comparing the signs of the mutual correlation between the signal electric and magnetic components of an atmospheric. The maximal standard error in the direction determination is ~2.5°. The temporal signal waveform, i.e. the number of positive and negative half-periods of the electric component exceeding the level equal to 0.1 of the signal maximal value, is used to roughly estimate the distance to a remote lightning discharge. The range coefficient is determined by converting the summer threshold values into the winter ones and is specified by comparing these values with the data of the satellite system for registering lightning discharges (Lightning Imaging Sensor (LIS) [6]) and the worldwide ground based network (World Wide Lightning Location Network (WWLLN) [7]).

![Figure 1. One-point lightning location system installed on autonomous radio-physical station «Oibenkel» in Yakutsk (Yu. G. Shafer Institute of Cosmophysical Research and Aeronomy SB RAS). 1 - east-west loop antenna; 2 - north-south loop antenna; 3 - vertical whip antenna; 4 - preliminary amplifier; 5 - separating transformers; 6 - final amplifier; 7 - analog-to-digital converter; 8 - personal computer.](image-url)
Figure 2. Location of earthquake epicenters and lightning discharges in March 2011 (Japan).

We can anticipate that the effect of impending earthquake processes on the level of VLF signals received in Yakutsk will manifest itself if the dimensions of the disturbed region in the lower ionosphere correspond to those of the first Fresnel zones in the thunderstorm source–receiving point signal propagation path. As is known [8], the dimension of the Fresnel zones \( F \) depends on the distance \( d \) and the electromagnetic signal wavelength \( \lambda \):

\[
F = \left( \frac{n \cdot \lambda \cdot d_1 \cdot d_2}{d} \right)^{1/2},
\]

where \( d = d_1 + d_2 \) (\( d_1 \) and \( d_2 \) are the distances from the epicenter to the thunderstorm source and receiver, respectively, and \( n \) is the zone number).

The method of analysis is as follows: The azimuth and distance to Yakutsk are determined for each selected earthquake. For an initial analysis, we select atmospherics whose the propagation paths are located at a distance not more than the fifth Fresnel zone from the epicenter, and the distances of their thunderstorm sources are larger than the distance to the earthquake. To calculate the Fresnel zones we accepted 10 kHz as the center frequency of the spectrum of atmospherics. The average amplitude of atmospherics registered during an hour is determined (about and more than 1000 atmospherics are, as a rule, registered). The rms amplitude values are averaged, since the signals are received in a broad band. The signal amplitudes have been led to the amplitude of one distance (the distance to an earthquake source) by using the dependence of the damping factor on the distance (inversely proportional to the distance) in a first approximation. This procedure is performed to decrease the effect of smearing and the displacement of signal sources (lightning discharges) from day to day. Azimuthal scanning with a shift of one–two Fresnel zones is subsequently performed to specify the effective dimensions of the disturbed zones in the ionosphere [10].

3. Basic results

A peculiarity of the event is that two strong EQs occurred one after another (9 March, 2011 and 11 March, 2011) practically at the same place, i.e. not far from the coast of Honshu, Japan (\( \phi_1 = 38.44^\circ\text{N}, \lambda_1 = 142.84^\circ\text{E}, \phi_2 = 38.297^\circ\text{N}, \lambda_2 = 142.372^\circ\text{E}, \) the distance between the epicenters is about 40 km). The magnitude of the first EQ was 7.3 and that of the second one, 9.0. The depth of the EQ centers was almost the same: 32 and 30 km. The daytime difference between these events was 3h. These EQs were followed by a long series of aftershocks. The distance to the mentioned epicenters was about 2800 km; and the azimuth (relative to the northward direction) was 155°. In accordance with the sizes
of the area of seismic activity during the EQs of March 9, 2011 and March 11, 2011 and the subsequent aftershocks, the “center” of this area with coordinates $\phi_c = 38.44^\circ$N, $\lambda_c = 142.84^\circ$E was introduced into the analysis. The azimuthal scanning of the dimensions of ionospheric disturbances was carried out with regard to this center. In the direction of the EQ epicenters during the considered period there were two major thunderstorm centers located behind the seismically active area: the neighboring center at distances of 2500–3000 km and the distant one (or rather, the distant centers) at a distance of 6000–8000 km. As seen in Figure 2(a), which presents the spatial distribution of lightning discharges in the maximum of thunderstorm activity (15:00–18:00 LT) on the day of the strongest EQ (11 March, 2011) by the network WWLLN data (http://webflash.ess.washington.edu), the main contribution into the flux of atmospherics was made by the distant centers. First let us consider the variations of the hourly average AA defined at 16:00–17:00 LT (this hourly interval is within the usual time of maximum thunderstorm activity during the day). Figure 3(a) shows the variations of the average amplitude for the monthly period (February–March). Atmospherics were received from the direction of the epicenter from the strongest EQ on 11 March 2011 with $M = 9$, i.e. from the azimuth (with numbers 1 and 2) and interpreted by us as EQ precursors. Assuming that the first increase in the amplitude corresponds to the first EQ of 9 March 2011 and the second increase, to the EQ of 11 March 2011, we concluded that the first precursor was observed 12 days before the event, and the second precursor 11 days before the event. Thus, in spite of the fact that the two EQs proceeded one after another with a small time gap, the effects of the EQs and their precursors turned out to be typical for each event.

Figure 3. Variations of average amplitude of atmospherics for monthly period (February–March) received from the direction of the epicenter from the strongest EQ on 11 March 2011 with $M = 9$ (a). Variations of average amplitude of atmospherics passing over the epicenter of the earthquake in Indonesia on 07.01.09 (b).
Another earthquake took place in Indonesia with the epicenter coordinates 1.788° N; 127.318° E, 07.01.09. Its magnitude was 5.0. Variations of the mean amplitude of the night atmospherics (00-01 LT) in this event are shown in Figure 3(b). A comparison with the above-considered event of 14.03.12 shows that the effect of the earthquake following the next day after the event is also well expressed: the peak of amplitude is nearly 2 times above the level of the amplitude in the previous week interval before the earthquake. The sharp increase in the amplitude of atmospherics observed on 30.12.09, which is also almost 2 times higher than the level in the preceding days, can be seen as a precursor of the earthquake.

Figure 4(a) presents the variations of the amplitude leaded to median values obtained using the superposed epoch technique for 17 earthquakes whose magnitude is more than 5.0 and the depth does not exceed 50 km. The day of lithospheric disturbance has been taken as a zero day. The method of obtaining the variations of signal amplitude is in the following. The change in the amplitude of the thunderstorm signals passing over the epicenter of this lithospheric disturbance, for the interval of -20, +10 days relative to the event has been obtained for each earthquake separately. Further we have led the amplitude of each day to the median value, which was found for the considered period, except...
for the days of the earthquake effects and their precursors. The obtained variations of the amplitude values led to the median for each earthquake using the superposed epoch technique.

It is seen from Figure 4(a) that there is an increase in the amplitude values on the next day after an earthquake was observed. This increase is an effect of these lithospheric events. The increase in the average amplitude which is in the marked box is considered as a precursor of the forthcoming earthquake. In this case it is necessary to take into account that in each separate event the average amplitude increases, as a rule, within one day in the range of 4 to 10 days before the event that leads to «smoothing» of the precursor if the superposed epoch technique is used. In Figure 4 the vertical lines present the mean square error of the average value. One can see that there is a possibility to detect both the effects and precursors of lithospheric disturbances in the amplitudes of thunderstorm discharge signals.

When studying the effects and precursors of earthquakes, the question arises as to the degree of probability of their observation. In our studies, this is the number of lithospheric disturbances that appear in the signals of lightning discharges. Since the manifestation of earthquakes in signals is mediated through the seismic effects in the ionosphere, first of all it is necessary to take into account the fact that the parameters of the lower ionosphere are subject to variations associated with various geo-heliophysical processes [9]. Geomagnetic disturbances, solar flares, and precipitation of particles (in the high latitudes) affect the parameters of the ionosphere and, thereby, change the propagation conditions of VLF electromagnetic signals in the Earth-ionosphere waveguide. Therefore, the study of variations in the parameters of atmospheric signals due to earthquakes should generally be carried out in the absence of geomagnetic and other perturbations in the ionosphere (also associated with lithospheric processes) on the signal propagation paths. Actually, this amounts to the fact that in the experiment the events of earthquakes were considered when these disturbances in the ionosphere on the signal propagation path above the epicenter of the earthquake should be absent 12–15 days before the event and 3–5 days after it. Considering that the technique of remote monitoring of seismic effects in the lower ionosphere presented in this paper is also determined by the presence of a sufficiently high thunderstorm activity in areas on the routes behind the epicenters of earthquakes, it is obvious that with a significant number of earthquakes the number of events considered is not that great.

As an example, consider the earthquakes in the Japanese Islands and their environs in 2014. In total, about 1024 earthquakes with different magnitudes and depths of the outbreaks occurred in this year. According to the results of our studies [10], the greatest impact on the ionosphere is exerted by strong lithospheric disturbances, with magnitudes greater than 5, of which 81 occurred in the region under consideration. Of these, 13 disturbances were deep-focus ones (depths over 70 km) which, according to the results of [11, 12], probably have a different impact on the ionosphere, in contrast to small-focus earthquakes. Then, for the remaining 68 small-focus earthquakes with magnitudes more than 5 we take into account the geomagnetic situation and the required interval for data analysis. As a result, we find that for a detailed analysis for this year there are only 17 earthquakes (Figure 4(b)).

4. Future research
The one-point system described in Section 2, in view of its independence compared to multi-point systems, is much easier for directing-finding of thunderstorm discharges, and it is cheaper. However, the main problem of single-point systems is the accuracy of determining the distance to a lightning discharge at a point of observation. In addition, an increase in the observation area for such systems leads to an increase in the error in determining the coordinates of the lightning discharge. Most accurate in locating a lightning discharge are multi-point systems. They can also give a complete and more accurate picture of the dynamics of the movement of thunderstorm focuses. A multi-point system requires precise timing and the ability to quickly transfer data to an analysis center.

The new software-hardware complex «Sensor Signal Analysis Network» (SSAN) for distributed, time synchronized monitoring of very low frequency (VLF) radiation allows us to solve a number of problems associated with the investigation of lightning activity, monitoring of whistlers, and search for their lightning sources [13,14]. At present the SSAN endpoints are set in Paratunka (KAR),
Yakutsk (OIB), and Neryungri (NER). It is planned to install registration endpoints in Tomsk (TOM), Vladivostok (VLD), and Tiksi (TIX). Table 1 lists the SSAN endpoints.

Table 1. List of SSAN endpoints.

| Call sign | Status     | Latitude     | Longitude    | Location                                                  |
|-----------|------------|--------------|--------------|-----------------------------------------------------------|
| KAR       | Operative  | N 52° 49'   | E 158° 07'   | Radiophysical station «Karimshino», Paratunka, Kamchatka region, Russian Federation |
| OIB       | Operative  | N 61° 55'   | E 129° 21'   | Radiophysical station «Oibenkel», Yakutsk, Republic of Sakha (Yakutia), Russian Federation |
| NER       | Operative  | N 56° 39'   | E 124° 42'   | Neryungri, Republic of Sakha (Yakutia), Russian Federation |
| VLD       | Planned    | N 43° 07'   | E 131° 55'   | Vladivostok, Primorsky Krai, Russian Federation            |
| TOM       | Planned    | N 56° 27'   | E 084° 56'   | Tomsk, Tomsk Oblast, Russian Federation                    |
| TIX       | Planned    | N 71° 35'   | E 128° 46'   | Tiksi, Republic of Sakha (Yakutia), Russian Federation    |

The spatial configuration of the network is shown in Figure 5 (a). Each SSAN endpoint can analyze time synchronized signals and transmit the collected information to one or several collecting centers. A signal from the antenna comes to the pre-amplifier and then to the sound card linear input (applied as one of the ADC variants). A PPS signal from the Glonass/GPS module also comes to the sound card linear input that allows us to make time synchronization of measurements at different sensor network F-nodes. A NMEA 0183 signal comes to the mini-PC to set the system time and to determine the F-node location. After digitization the general signal from the sound card linear input comes to the mini-PC for stream processing. Several programs are launched on the mini-PC working under the Linux operating system. They are: 1) program for data reading from the ADC; 2) program of stream analysis (SA) of natural electromagnetic radiation sources based on the data registered in the VLF range [13].

The registration of atmospherics from distant lightning sources whose propagation paths pass over seismically active regions will allow remote monitoring of lithospheric-ionospheric disturbances in the main zones of seismic activity, including those in Kamchatka and Japan, using the method described in Section 2. In addition, the SSAN allows one to register the amplitude and phase of signals of the VLF-transmitters for various propagation paths in the Earth-ionosphere waveguide.

Table 2 lists the main VLF-transmitters planned to be used for remote monitoring of earthquakes. Signals of the radio transmitters have MSK modulation, which imposes requirements on the network for continuous registration in order to accurately determine the phase of the signals whose response to disturbances in the lower ionosphere is more sensitive than the amplitude. Figure 5(b) schematically shows the propagation paths (green lines) of signals from the VLF-transmitters (green points) and lightning discharges (black points) to the SSAN endpoints. The use of signals from the transmitters allows one to cover a sufficiently large region where there are seismically dangerous zones.
Table 2. List of VLF-transmitters planned to be used for remote monitoring of earthquakes by SSAN.

| Call sign | Frequency, Hz | Modulation | Latitude      | Longitude      | Location                          |
|-----------|---------------|------------|---------------|----------------|-----------------------------------|
| VTX       | 18200         | FSK        | N 08° 23’     | E 077° 45’     | South Vijayanarayananam, India    |
| NWC       | 19800         | MSK        | S 21° 48’     | E 114° 09’     | Harold E. Holt, North West Cape, Exmouth, Australia |
| NPM       | 21400         | MSK        | N 21° 25’     | W 158° 09’     | Pearl Harbour, Lualuahei, HI      |
| DHO38     | 23400         | MSK        | N 53° 04’     | E 007° 36’     | Rhauderfehn, Germany              |
| JJY-40    | 40000         | FSK        | N 37° 22’     | E 140° 50’     | Mount Ootakadoya, Fukushima Prefecture, Japan |
| JJY-60    | 60000         | FSK        | N 33° 27’     | E 130° 10’     | Mount Hagan, Fukuoka Prefecture, Japan |

Thus, the complex using low-frequency signals of natural and artificial sources with the help of the SSAN will increase the accuracy of determining the dimensions of lithospheric-ionospheric disturbances and expand the area of observations of seismic activity zones.

5. Conclusions
A one-point system equipment and a method used for remote monitoring of seismic activity in the lower ionosphere by electromagnetic signals of lightning discharges with observations in the Northern Asia were described. Experimental results of detecting the ionospheric effects of strong earthquakes were considered. The results of a statistical study of earthquakes with the help of the above-proposed method showed that 17 of 1024 earthquakes were identified as associated with strong earthquakes in the absence of other factors affecting the Earth-ionosphere waveguide. Using the method of superimposing epochs for these 17 events, it was found that the earthquake precursors can be identified 12-15 days before and 3-5 days after the events. A small statistics of event detection was obtained using the current one-point system. The new software-hardware complex «Sensor Signal Analysis Network» (SSAN), whose endpoints are located in the territory of Northern Asia for synchronous recording of VLF/LF electromagnetic signals of lightning discharges and VLF-transmitters, is planned to be used to study lithospheric-ionospheric disturbances in the main zones of seismic activity. This system can be used to increase the accuracy of determining the dimensions of lithospheric-ionospheric disturbances and to expand the area of observations of the seismic activity zones.

Acknowledgments
This work was supported under Project II.16.2.1 (registration number AAAA-A17-117021450059-3). The creation of the software-hardware complex SSAN was supported under VarSITI Grant on “Creation of a Database for Atmospheric and Whistler Events Detected in the Russian Far East”.

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