Special Issue: "25th anniversary of the Russian Journal of Earth Sciences"

A Closer Cooperation between Space and Seismology Communities – a Way to Avoid Errors in Hunting for Earthquake Precursors

V. A. Pilipenko[1,2], K. Shiokawa[3]

[1]Schmidt Institute of Physics of the Earth, RAS, Moscow
[2]Geophysical Center of RAS, Moscow
[3]Nagoya University, Japan
* **Correspondence to:** V. A. Pilipenko, pilipenko_va@mail.ru

Abstract: The space physicists and the earthquake (EQ) prediction community exploit the same instruments – magnetometers, but for different tasks: space physicists try to comprehend the global electrodynamics of near-Earth space on various time scales, whereas the seismic community develops electromagnetic methods of short-term EQ prediction. The lack of deep collaboration between those communities may result sometimes in erroneous conclusions. In this critical review, we demonstrate some incorrect results caused by a neglect of specifics of geomagnetic field evolution during space weather activation. The considered examples comprise: Magnetic storms as a trigger of EQs; ULF waves as a global EQ precursor; Geomagnetic impulses before seismic shocks; Long-period geomagnetic disturbances generated by strong EQs; Discrimination of underground ULF sources by amplitude-phase gradients; Depression of ULF power as a short-term EQ precursor; and Detection of seimogenic emissions by satellites. To verify the reliability of the above widely disseminated results data from available arrays of fluxgate and search-coil magnetometers have been re-analyzed. In all considered events, the "anomalous" geomagnetic field behavior can be explained by global geomagnetic activity, and it is apparently not associated with seismic activity. This critical review does not claim that ULF electromagnetic field cannot be used as a sensitive indicator of the EQ preparation processes, but we suggest that both communities must cooperate their studies more tightly using data exchange, combined usage of magnetometer networks, organization of CDAW for unique events, etc.

Keywords: seismo-electromagnetic phenomena, earthquake prediction, geomagnetic pulsations.

Citation: Pilipenko V. A., Shiokawa K. (2024), A Closer Cooperation between Space and Seismology Communities – a Way to Avoid Errors in Hunting for Earthquake Precursors, *Russian Journal of Earth Sciences*, Vol. 24, ES1001, https://doi.org/10.2205/2024ES000899

Research Article

Received: 15 October 2023
Accepted: 15 January 2024
Published: 29 February 2024

1. Introduction: seismo-electromagnetic ULF phenomena

Monitoring of the near-Earth electromagnetic environment in various frequency bands by ground and satellite sensors is the main research tool for the space physics community and the seismic community, though it is used for different tasks. Space physicists are interested to know how electromagnetic disturbances and emissions convey information about dynamic processes in the near-Earth plasma. The seismic community attempts to develop the detection methods of the electromagnetic signatures of the ongoing crust destruction. A useful signal for one community is an interference for the other, whereas industrial and lightning sources obscure all desired signals. A zoo of natural electromagnetic emissions, noise, impulses, and waves is enormous, so any progress in the hunt for seismic-associated disturbances is possible only with the close collaboration of both communities. However, such collaboration is still insufficient, and in this critical review, we demonstrate how seemingly amazing discoveries have turned out to be errors or misinterpretations.

A search and recognition of electromagnetic precursors of EQs remain one of the hot topics in geophysics. The observational results indicated that it is promising to study such phenomena in the ultra-low-frequency (ULF) range (10 mHz–10 Hz) [*Petraki et al.*, 2015]. The signatures of anomalous electromagnetic ULF activity near the epicenter hours – days before EQs were reported (see numerous articles in monographs [*Hayakawa*, 2009, 2013; *Hayakawa and Molchanov*, 2002]). Several types of ULF geomagnetic anomalies were noticed: the appearance of broadband electromagnetic noise [*Molchanov et al.*, 1992]; a change in the spectral composition [*Hayakawa et al.*, 1999]; changes in the polarization structure [*Hayakawa et al.*, 1996]. Enhancements of broad-band electromagnetic noise recorded during periods preceding EQ were suggested to be associated with the irregular flow of the crust fluid [*Fedorov et al.*, 2001; *Fenoglio et al.*, 1995], micro-cracking of the rock medium [*Molchanov and Hayakawa*, 1995], acoustic impulsive background [*Surkov and Hayakawa*, 2006]. These effects were observed only for strong EQs in the immediate vicinity (up to several hundred kilometers) from the epicenter [*Hattori*, 2004].

A surprisingly large number of electromagnetic phenomena can occur within a few minutes in the temporal vicinity of a seismic shock. A seismic wave propagating from the quake hypocenter excites a transient burst of the electromagnetic field due to induction or electrokinetic effects [*Surkov et al.*, 2018]. A few seconds before the arrival of a seismic wave at the registration point, its electromagnetic "forerunner" may begin to grow, excited by currents at the wavefront [*Surkov and Pilipenko*, 1997]. Such a preliminary growth of the magnetic disturbance immediately ahead of the seismic wavefront was observed by Iyemori et al. [*Iyemori et al.*, 1996]. In addition, a rapid movement of crustal blocks at the time of an EQ can cause the appearance of isolated electromagnetic pulse that are several seconds ahead of the front of a seismic wave [*Guglielmi and Levshenko*, 1996]. If this pulse is strong enough, then it will presumably cause a burst of the vertical electric field and light flash in the near-surface atmosphere (EQ light) [*Lockner et al.*, 1983].

Yet, the situation with ULF electromagnetic precursors remains ambiguous. The results of disparate observations cannot be considered strictly substantiated, and some of them are disputed [*Masci and Thomas*, 2015; *Thomas et al.*, 2009a,b]. Various manifestations of electromagnetic effects in different events, poor repeatability of the results, and the absence of a confirmed generation mechanism raise doubts about the reliability of the relationship between the detected geomagnetic phenomena and EQs.

In this review, we re-analyze some observational results and suggested hypotheses, published by leading experts in top-level geophysical journals. We consider the following specific examples: Magnetic storms as a trigger of EQs; Global ULF waves before strong EQs; Global geomagnetic impulses preceding quakes; Long-period geomagnetic disturbances generated by strong EQs; Discrimination of underground ULF sources by amplitude-phase gradients; Depression of ULF power as a short-term EQ precursor, and Feasibility of ULF precursor detection by satellites. To verify the reliability of the above phenomena, we have used available data from the existing fluxgate and search-coil magnetometer databases: INTERMAGNET [*Love and Chulliat*, 2013], IMAGE [*Tanskanen*, 2009], PWING [*Shiokawa et al.*, 2017], and Russian Arctic stations [*Kozyreva et al.*, 2022].

2. Magnetic storms as a trigger of EQs

The possibility of a triggering effect of solar activity and associated space weather disturbances (magnetic storms) on the Earth's seismicity is actively discussed. When the accumulated stress along the fault is close to the critical level, even a weak external impact can provoke instability of lithospheric blocks and serve as an EQ trigger. This concept is based on the assumed excitation during magnetic storms of telluric fields and currents flowing along faults, affecting the dynamics of the pore fluid. It was reported that after magnetic storms with sudden commencement (SC), the number of weak EQs in Tajikistan and Kyrgyzstan increased by 3–4 per day in an area with a size of about a hundred km [*Sobolev et al.*, 2001; *Zakrzhevskaya and Sobolev*, 2002, 2004]. An increase in the daily number of local EQs in Kyrgyzstan and Carpathians on the 2nd day after the solar flare was found [*Kuznetsova et al.*, 2005]. A high correlation was found between the diurnal variation of weak seismicity and the geomagnetic Sq variation [*Duma and Ruzhin*, 2003].

To substantiate the idea of a triggered release of energy accumulated in the crust in the form of weak EQs, experiments were carried out in Tajikistan and Kyrgyzstan with the magnetohydrodynamic (MHD) generator. Powerful electromagnetic pulses from an MHD generator were found to cause a noticeable activation of seismicity, which was most pronounced in its upper 5-km layer [*Tarasov*, 1997]. The intensity of the EQ flux increased sharply 5–6 days after the impact, and the release of the seismic energy turned out to be 5 orders of magnitude greater than the pulse energy. These results were confirmed in the Northern Tien Shan, where similar changes in the seismic regime after the MHD impact were revealed [*Tarasov et al.*, 1999]. Later, instead of an MHD generator, a capacitor-thyristor source was used, but, as in previous works, a noticeable activation of seismicity after impact was revealed [*Smirnov and Zavyalov*, 2012; *Tarasov et al.*, 2001]. The fundamental possibility of the initiating effect of electrical impulses on microcracking processes and the level of acoustic emission was confirmed in laboratory experiments with rock samples under load [*Zeigarnik et al.*, 2022].

Often the literature presents the observations of possible triggered phenomena related to a selected event [*Straser et al.*, 2015]. Despite the importance of case studies, this approach does not provide reliable evidence in favor of the trigger effect reality and should be supplemented by statistical analysis. Kozyreva and Pilipenko [*Kozyreva and Pilipenko*, 2020] tested the idea of a magnetic storm as an EQ trigger for a region of Alaska with high seismicity, and where magnetic activity is much stronger than at low latitudes. They used the super-posed epoch (SPE) method for the College magnetometer data, whereas the moment of a quake was chosen as a reference zero point. To characterize the central trend in the sample, the median value was used, which (unlike the mean value) is resistant to outliers, and only for a normal distribution coincides with the mean value. If the magnetic field variations are in no way associated with seismic activity, the dynamics of the magnetic variation intensity on the SPE plot before and after an EQ will be the same. If strong field variations are an EQ trigger, then the dynamics in the previous 10 days should show a systematic increase in the disturbance and variability of the geomagnetic field. The SPE graphs of the magnetic activity parameters (hourly Dst-index, $|\Delta X|$, and $|dX/dt|$), before "strong" ($M > 5$) EQs did not show any statistically significant enhancement before the seismic shock that goes beyond the dispersion. Similar negative results were obtained for weak (3<M<5) near-surface (H<5 km) EQs, weak small-depth (H=5-10 km) EQs, and weak shallow (H = 10-30 km) EQs. The obtained negative result casts doubt on the hypothesis of a magnetic storm as a possible EQ trigger.

The question under consideration is part of the fundamental problem of the impact of solar activity on geophysical processes. Analysis of long-term archives of solar and geophysical data led to completely different conclusions. On long time scales (tens to hundreds of years), global seismicity was found to be higher either during periods of solar maxima [*Han et al.*, 2004; *Odintsov et al.*, 2006], or minima [*Simpson*, 1967]. On smaller time scales (monthly and annual variations), it was argued that global seismicity correlates with geomagnetic variations [*Duma and Vilardo*, 1998; *Rabeh et al.*, 2009]. At the micro level, high-frequency seismic noise was claimed to be sensitive to magnetic storms [*Adushkin et al.*, 2012; *Sycheva et al.*, 2011], but the connection between background seismicity and geomagnetic variations was denied in [*Desherevskii and Sidorin*, 2016]. At the same time, the statistical relationships between seismicity and solar activity were refuted in [*Love and Thomas*, 2013; *Stothers*, 1990].

Nonetheless, attempts to reveal a hypothetical relationship between the solar activity and seismic process still go on. [*Doda et al.*, 2013] developed the forecasting scheme based on the empirical fact that a strong EQ happens on 14-th day after the solar ejecta (flare or coronal mass ejection) in the region of intersection of lithospheric fault with the meridian with most intense geomagnetic disturbance. Dedicated experiments indicated that "laboratory EQs" (disruption of samples under load) can be triggered by electromagnetic impulses [*Sorokin et al.*, 2019]. Authors supposed that similar electromagnetic triggering of EQs by solar flare or sudden impulses preceding the magnetic storm onset may operate in the terrestrial lithosphere as well. Thus, a large work is still ahead to validate the reported solar-seismic relationships an comprehend their mechanisms (if any).

3. Global ULF wave precursors of strong EQs

The possibility of sporadic quasi-monochromatic signals before an EQ deserves special consideration. There were a number of reports on the observation of "precursory" ULF signals. At low-latitude station Dusheti before several strong (M>6) EQs in the world, [*Gogatishvili*, 1984] observed specific geomagnetic pulsations with a duration from several minutes to several hours with an amplitude of ~10–15 nT and periods of 1–20 s (range of Pc1-2) several tens of minutes or several hours before the quake. [*Bortnik et al.*, 2008] examined the association between EQs and Pc1 pulsations observed for 7.5 years at a low-latitude station in California. They found a statistically significant enhanced occurrence probability of dayside Pc1 pulsations 5–15 days in advance of EQ (M>3) within 200 km around the magnetometer. However, [*Guglielmi and Zotov*, 2010] from the catalogues of Pc1 and earthquakes, revealed that diurnal Pc1 activity in the middle latitudes is statistically higher when the global seismic activity is lower. Before the strongest EQ off the coast of Antarctica on March 25, 1998 ($H = 10$ km, $M = 8.8$) at station Vernadsky, a series of intense pulsations with periods of several tens of seconds (Pc3-4 range) was recorded [*Bakhmutov et al.*, 2003]. A possible mechanism of "anomalous" ULF signal generation has not been even suggested.

The most active searches for "precursory" ULF signals have been carried out at the Caucasian Geophysical Observatory (CGO), located at a depth of 3.5 km. In a series of publications [*Sobisevich et al.*, 2009a,b, 2010a, 2012, 2013] the detection of quasi-periodic short-term signals with periods of 50–150 s before large EQs ($M > 5.5$) in the world a few hours before the shock was reported. However, in [*Kosterin et al.*, 2015] the registered "precursory" signals were compared with the data of other magnetic stations. The set of morphological properties of the observed global "precursory" signals – impulsive waveform, characteristic frequencies, decrease in amplitude with decreasing latitude, confinement to the night sector – was in good agreement with the characteristic features of magnetospheric Pi2 pulsations. In a similar way, the reported by [*Sobisevich et al.*, 2017; *Sobisevich*, 2020; *Sobisevich et al.*, 2010b] daytime long-term quasi-monochromatic "precursory" signals turned out to be Pc3-4 pulsations of the magnetospheric origin. Thus, it can almost certainly be asserted that the recorded signals are magnetospheric ULF pulsations and are not related to seismic activity.

4. Geomagnetic impulses before quakes

Anomalous ULF disturbances during the activation of seismic activity may have an impulsive character [*Bleier et al.*, 2009; *Naumov*, 1999]. An amazing phenomenon was described in a series of papers [*Dovbnya*, 2011, 2014, 2021; *Dovbnya et al.*, 2006, 2008, 2019] – the appearance of global magnetic impulses a few minutes before the seismic shock (see example in Figure 1). The effect was found from the data of induction magnetometers at stations Borok and College, separated by 12 h in longitude and 10° in latitude. Precursory pulses with an amplitude not exceeding 20 pT in the frequency range from 0 to 5 Hz appeared at both stations almost simultaneously at significant distances from the epicenter (up to 10^4 km). This intriguing hypothesis may be a truly major discovery in geophysics, so its critical consideration should be taken carefully.

In [*Martinez-Bedenko et al.*, 2023] the hypothesis about the appearance of a pulsed magnetic precursor was suggested to test using the network of induction magnetometers PWING at Far East. Indeed, the appearance of impulse disturbances synchronously at several stations was detected. However, the waveforms of the pulses indicate that they can be associated with the excitation of the Schumann Resonance (Figure 2). This resonant electromagnetic structure with a fundamental frequency of 7.8 Hz is formed by the Earth's

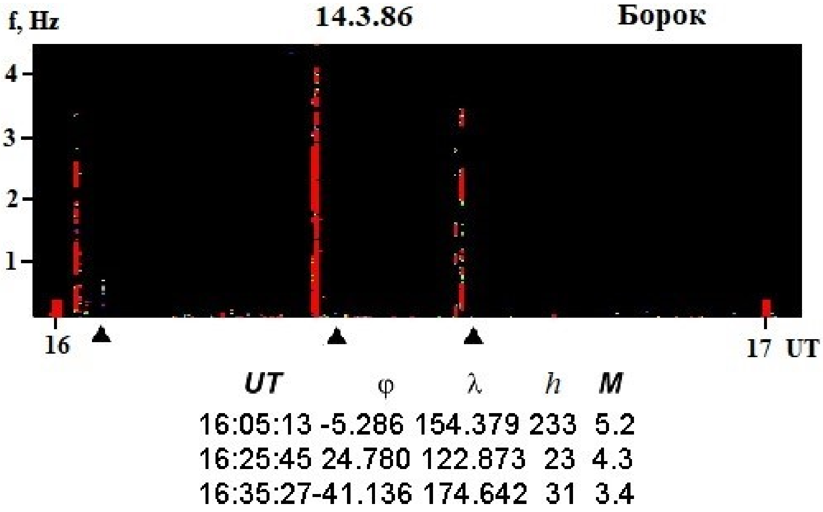

Figure 1. The appearance of global magnetic impulses few minutes before the seismic shocks in dynamic spectra from Borok observatory (from [*Dovbnya*, 2021]).

surface and conductive layers of the upper atmosphere (~80 km) and is effectively excited by lightning discharges. Comparison with the world-wide lightning monitoring system WWLLN shows that at least a part of the pulses is a response to a lightning discharge (Figure 3). Statistics based on automatic calculation of the number of impulses before and after a seismic shock in a 5-min interval has not shown any predominance of impulse disturbances before local EQs.

Although the detailed analysis did not confirm the hypothesis of ultra-short ULF pulses as a precursor of EQs, their physical nature was established – they are caused by atmospheric electric discharges [*Marchuk et al.*, 2022]. In principle, it can be suggested that the appearance of a lightning discharge before an EQ is not just a coincidence, since a seismic process can cause changes in the electrochemical properties of the lower atmosphere due to the release of radioactive emanations [*Harrison et al.*, 2010; *Pulinets and Davidenko*, 2014]. Additional ionization of the lower atmosphere by aerosols and Rn emanations can trigger lightning discharges under favorable conditions [*Yagova et al.*, 2019]. In general, the question of the connection between the process of EQ preparation and atmospheric electricity remains poorly studied, and any reasonable assumptions in this area are hard to make. The WWLLN data on global lightning activity may be used to construct the index characterizing a possible contribution of ULF noise at a particular site produced by distant atmospheric discharges. This new index may help to avoid confusion about magnetospheric, atmospheric, and lithospheric sources.

5. Long-period geomagnetic disturbances generated by strong EQs

The study of the Earth's magnetic field variations accompanying seismic phenomena is important for understanding the mechanisms of inter-geosphere interactions. Besides the co-seismic magnetic effect, long-period geomagnetic disturbances (time scale of a few tens of minutes) around the main shock were noticed [*Adushkin and Spivak*, 2021]. It was suggested that the probable mechanism of this effect is the excitation of the ionosphere in the epicentral region by acoustic-gravity waves (AGWs) resulting from movements of the earth's crust [*Adushkin and Spivak*, 2021; *Chernogor*, 2019]. Based on observations at mid-latitude station Mikhnevo (MKH) [*Spivak and Ryabova*, 2019] claimed that strong EQs are accompanied at far-distant stations by geomagnetic long-period disturbances (period ~5–20 min) with amplitude 2–4 nT (see example in Figure 4, where the reported mid-latitude long-period disturbance is marked by the rounded red box). The authors suggested that these disturbances of the magnetic field are caused either by underground dynamic processes or disturbances in the Earth's ionosphere over the epicenter. This interesting

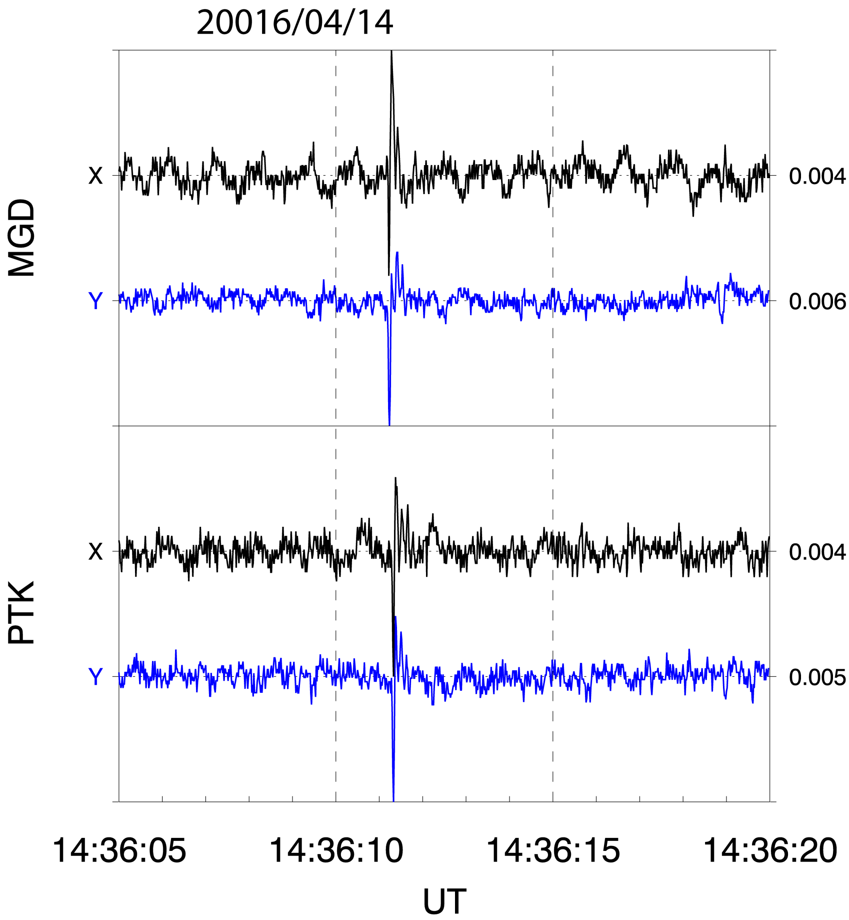

Figure 2. The example of impulse disturbances synchronously recorded at stations MGD and PTK (X and Y components).

hypothesis certainly requires a detailed discussion from various points of view [*Nosikova et al.*, 2023].

All the results presented in those studies were obtained at low- and mid-latitude stations. We have performed an extended analysis of published events, using additional data from stations at auroral latitudes in the same longitudinal sector, where anomalous disturbances were detected. The consideration of magnetograms from a latitudinal profile of stations from low-latitude up to auroral latitudes evidence that the reported "seismogenic" disturbance is just a weak low-latitude response to an intense disturbance at higher latitudes (Figure 4). Thus, the long-period "seismic-associated" geomagnetic disturbances are just accidentally coincided with EQs.

Moreover, there are no physical grounds to expect the appearance of harmonic ULF signals before an EQ, which propagates over the entire globe. Excitation of geomagnetic Pc5 pulsations in the ionosphere above the epicenter by acoustic waves generated by oscillations of the earth's surface was indeed observed after some intense EQs [*Iyemori et al.*, 2005], but distant propagation of such a disturbance along the ionosphere over vast distances is hardly possible. An MHD waveguide in the upper ionosphere capable of propagating ULF waves over distances of up to several thousand km has a critical frequency of ~0.5 Hz, which is much higher than the considered frequency range. Although AGWs can reach the conducting E-layer (~120 km) and induce periodic currents, thereby creating magnetic disturbances [*Zettergren and Snively*, 2015], the propagation of AGWs along the earth's surface occurs at low speeds ~100 m/s, and their magnetic signatures can be revealed after intense quakes or volcano eruptions on a regional scale only [*Gavrilov et al.*, 2022].

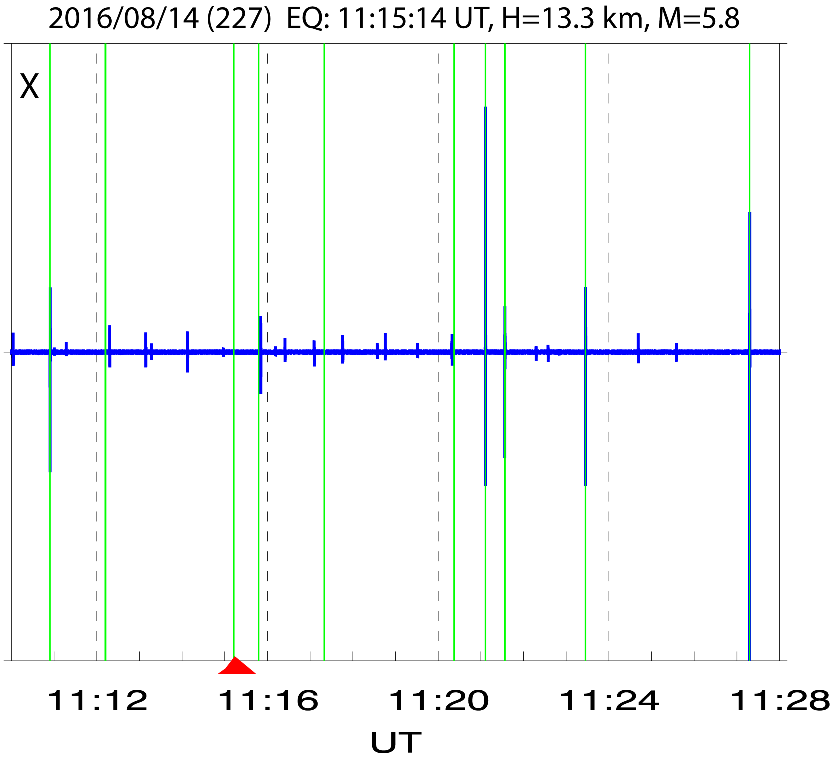

Figure 3. Comparison of discharge moments from the WWLLN database (green vertical lines) and geomagnetic impulses (blue) around EQ (marked by red triangle).

6. Discrimination of underground ULF sources by amplitude-phase gradients

The situation with ULF electromagnetic precursors remains ambiguous to date, as the amplitude of possible electromagnetic noise caused by seismic activity is apparently small. Therefore, for confident discrimination of seismogenic disturbances, the development of special methods for recording and analyzing data is required. There were proposals to use gradient measurements with a small baseline (no more than a few km), which would suppress the contribution of large-scale disturbances of ionospheric origin [*Ismaguilov et al.*, 2003].

The approach used in [*Ismaguilov et al.*, 2003, 2006; *Kopytenko et al.*, 2006] is based on the premise that an electromagnetic field propagates in the conductive Earth in a wave manner with strong attenuation. The amplitude-phase gradient method assumes that ULF wave horizontal propagation velocity is determined by crust conductivity as follows $U = \lambda/T = \sqrt{10\rho/T}$, where the relation of the wavelength with resistivity was used $\lambda = \sqrt{10\rho T}$. The gradient method enabled to seemingly successfully retrieve seismogenic signals several months before nearby EQs with $M = 5$–6 in Japan at a distance <100 km [*Kopytenko et al.*, 2012]. The measured amplitude gradient in the band 0.03–0.1 Hz (Pc2-3 band) was typically around G ≈ 0.1–1 pT/km, and phase velocity U ≈ 20–100 km/s.

However, amplitude/phase gradients of ULF field can be created by the magnetospheric wave conversion process in the resonant region, where the period of source T tends to Alfven period T_A of local field line oscillations. The latitudinal structure of ULF wave amplitude and phase in the resonant region has been modeled using the numerical solution of the equations for coupled MHD modes [*Pilipenko et al.*, 2016]. The modeling results in Figure 5 demonstrate that the resonant component By (corresponding to the ground H-component) in the meridional direction has a strong gradient of amplitude ∇B and phase difference $\Delta\phi$ up to 180^{o}. The spatial-frequency ULF wave structure in a vicinity

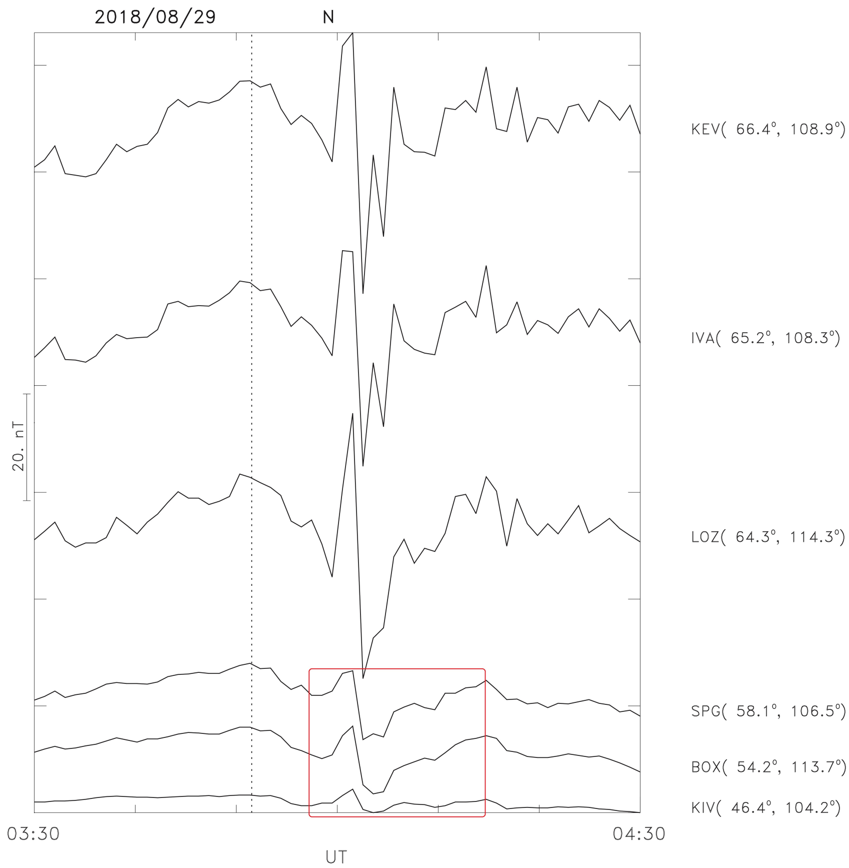

Figure 4. The long-period geomagnetic disturbance detected at mid-latitudes (marked by a red empty box) that was claimed in [*Spivak and Ryabova*, 2019] to be associated with strong EQ (marked by a vertical dashed line). The geomagnetic latitude and longitude are indicated near the station codes at left-hand vertical axis.

of the Alfven resonance is described analytically by asymptotic decomposition [*Best et al.*, 1986]. The phase gradient reaches an extreme value at $x \to x_A(f)$ as follows

$$\frac{\partial \phi}{\partial x} = (a\Gamma)^{-1}, \tag{1}$$

where $a^{-1} = \partial \ln V_A / \partial x$ is the latitudinal scale of the Alfven velocity inhomogeneity, and Γ is the normalized wave dissipation coefficient. The relationship (1) can be used to estimate the phase gradient from the data from stations separated by distance $\Delta x, \Delta\phi(\text{rad}) = \Delta x / a\Gamma$. The sign of phase shift corresponds to an apparent poleward propagation. The phase shift $\Delta\phi$ corresponds to an apparent phase velocity $U = \omega(\partial\phi/\partial x)^{-1}$. The measurements in [*Ismaguilov et al.*, 2003; *Kopytenko et al.*, 2002] were made for Pc3 frequency band (0.05 Hz). For the reasonable values $\Gamma \sim 0.1$, $a \sim 10^3$ km, the apparent phase velocity in the resonant region is to be U~25 km/s. This estimate is close to the observational results, presented in Figure 6.

The latitudinal structure of magnetospheric ULF waves with significant amplitude/phase gradients is formed in the resonance region, therefore, the gradient method of the seismogenic pulsations detection must be applied only in the frequency band far from the magnetospheric field-line resonator frequency. To choose a proper frequency range not contaminated by the resonant effect, the theoretically calculated latitudinal profile of fundamental Alfven period $T_A(\Phi)$ can be used [*Menk and Waters*, 2013]. Notice, the results presented in [*Ismaguilov et al.*, 2003; *Kopytenko et al.*, 2012] were obtained at low latitudes for geomagnetic signals with periods around the resonant periods. Thus, the gradient method of seismic-related signal detection must be supported by the examination of reso-

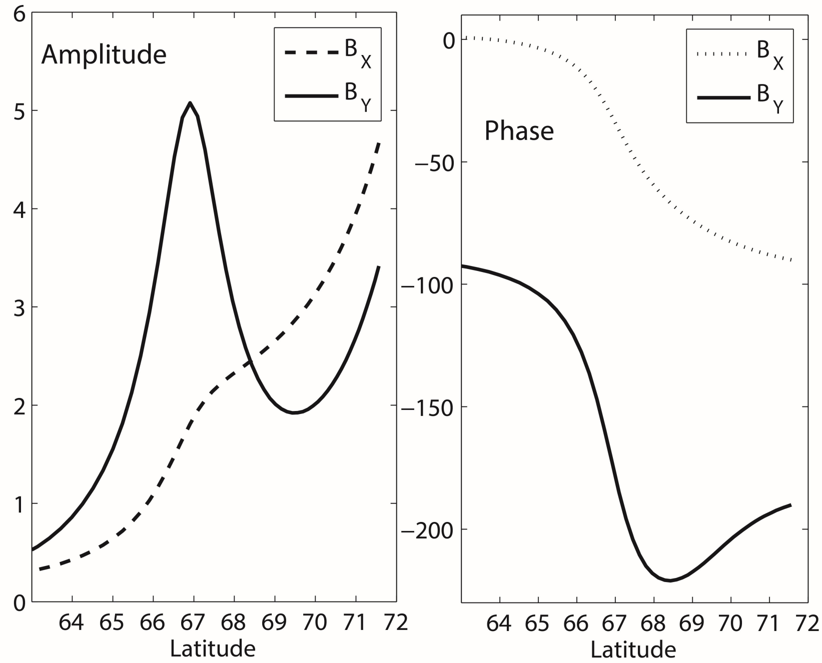

Figure 5. The numerically modeled resonant structure of ULF waves in the magnetosphere: the left-hand panel shows the latitudinal profile of amplitudes, and the right-hand panel shows the phase profile. The magnetospheric $B_Y(B_X)$ components correspond to the components $H(D)$ on the ground.

nant effects, and can be performed only in a frequency-space domain far from the resonant region.

The ground magnetic effect of an underground source (e.g. current along a fault) is a mixture of the source current produced mechano-electrical transformations and the spreading conductive currents. Moreover, for ULF range the propagation inside the crust has a diffusive character. Therefore, the reliable gradient method must be augmented by a numerical model of ULF emission from an underground horizontal current of a finite length.

7. Depression of ULF power as a short-term EQ precursor

Most of the research on the search for electromagnetic precursors was aimed at detecting radiation caused by mechano-electromagnetic converters in the earth's crust. At the same time, the opposite phenomenon was unexpectedly discovered - depression of ULF noise intensity of the geomagnetic field in the frequency band 0.01–0.1 Hz a few days before EQs [*Hayakawa*, 2013; *Li et al.*, 2015; *Molchanov et al.*, 2004; *Schekotov and Hayakawa*, 2017; *Schekotov et al.*, 2006, 2008]. This interesting new phenomenon could be applied to short-term EQ prediction [*Hayakawa et al.*, 2015; *Schekotov et al.*, 2013]. The ULF depression may be caused by an enhancement of ionospheric turbulence before an EQ, which leads to additional absorption of magnetospheric noise upon passing through the ionosphere [*Sorokin et al.*, 2004]. Additional turbulence of the ionosphere can be caused by the action of AGWs excited by seismic activity.

If the effect of geomagnetic depression is really associated with the processes of preparation of a seismic event, then the same effect should be absent at observatories remote from the epicenter. To test this assumption, we have used data from the entire PWING network of induction magnetometers for the EQ event on April 14, 2016 ($M = 6.2, H = 32$ km) in Kamchatka, previously described in [*Schekotov et al.*, 2020]. In the latter study, in the period from April 06 to April 14, 2016, anomalies in the behavior of ULF noise were detected – the depression of the noise intensity several days before the EQ. To identify anomalies, the parameter ΔS was used, which is the reciprocal value of the

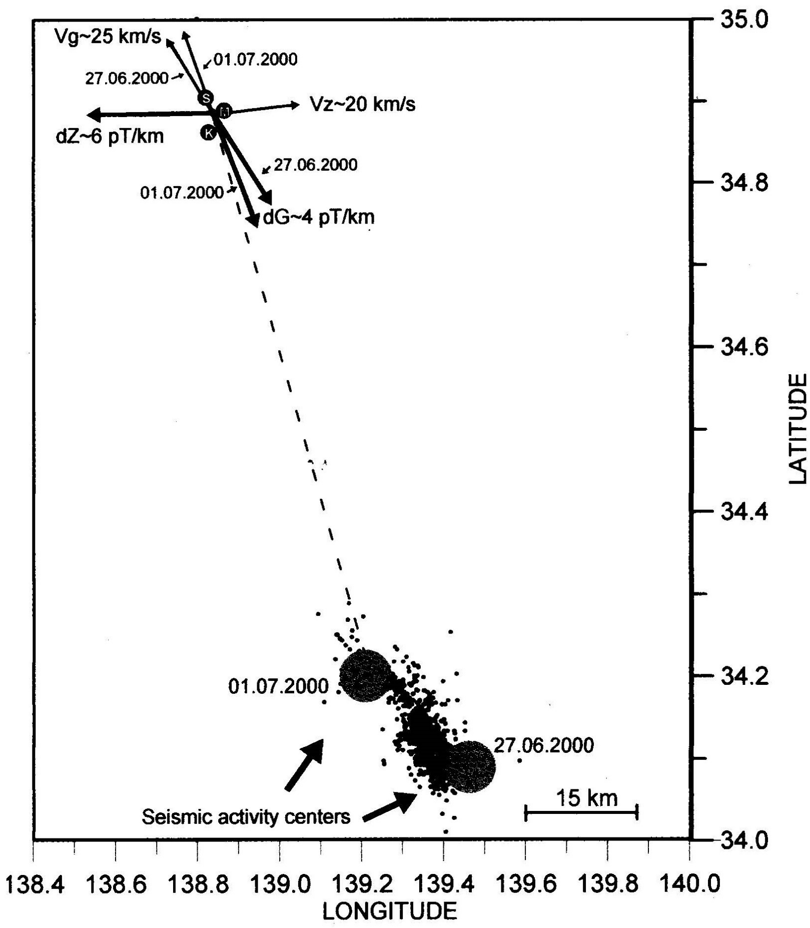

Figure 6. The gradients and phase velocities of anomalous ULF signals in Pc3 frequency band (0.05 Hz) detected before EQ by gradient method in [*Ismaguilov et al.*, 2003; *Kopytenko et al.*, 2002].

band-integrated spectral density W of the horizontal component, calculated over 3-hour nighttime intervals. Comparison of the ΔS parameter with the seismicity index showed that the largest depression value preceded the moment of the EQ by 4 days (Figure 5). Using a similar scheme, we have calculated the variations in the spectral power W(t) in the band 0.01–0.8 Hz for the horizontal Y component at night hours for all PWING stations (Figure 7). Since the equipment at each station has its own sensitivity, the time series of W(t) at each station has been normalized separately to the maximum value during the entire interval. At two nearby stations KRM and PTK, located not far from the epicenter, the depression was most clearly observed on the nights of April 8–9 and April 10–11. This behavior of $W(t)$ coincides with the results from [*Schekotov et al.*, 2020]. But if the effect of geomagnetic depression is really associated with pre-EQ processes, then the same effect should be absent at observatories far from the epicenter. Therefore, the same method was used to analyze the data from the distant MSR and MGD stations located 1514 km and 915 km away from the epicenter. Comparison of W(t) variations at different stations shows that noise intensity depression is observed synchronously both at nearby to the epicenter and at remote (farther than ~1000 km) stations. Thus, depression turns out to be a general magnetospheric process, apparently unrelated to seismic activity.

The reason for the global depression of ULF noise is clearly seen in Figure 8, which shows the planetary geomagnetic index AE, characterizing the disturbance of the geomagnetic field at auroral latitudes. During the periods of April 8–9 and April 10–11, the planetary magnetic situation was exceptionally calm, so even at auroral latitudes the AE index dropped to about several tens of nT. Only after April 11 the geomagnetic activity begins to increase, which can be seen from the behavior of the AE index.

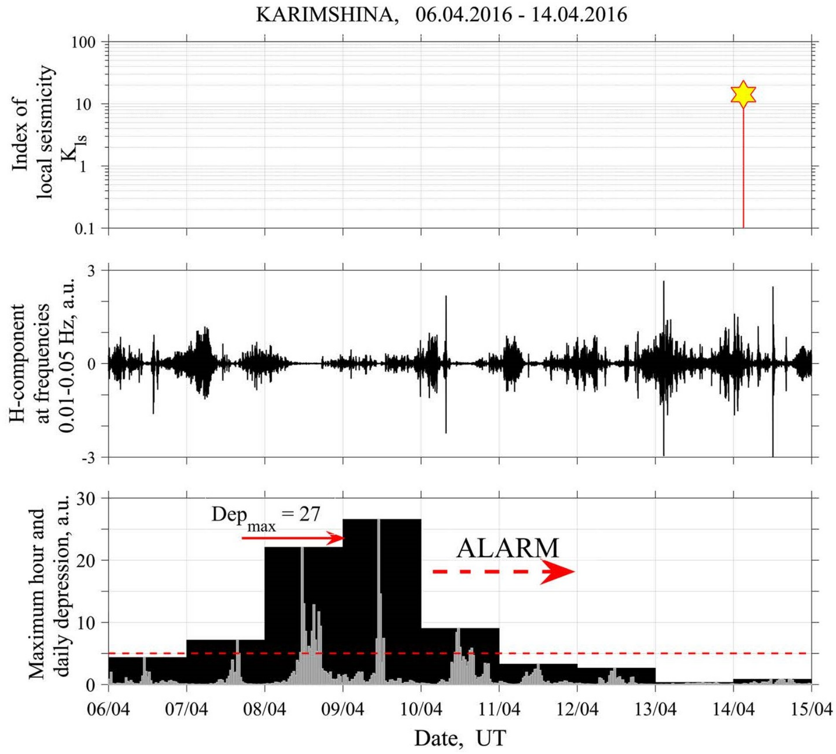

Figure 7. Comparison of the ΔS parameter (bottom panel), characterizing the depression of the ULF noise intensity at night, with the seismicity index (top panel) before the EQ on April 14, 2016 with $M = 6.2 and H = 32$ km in Kamchatka from [*Schekotov et al.*, 2020].

8. Feasibility of the seismogenic ULF disturbance detection by satellites

Attempts are being made to detect seismogenic ULF disturbances on low-Earth-orbit (LEO) satellites [*Kodama et al.*, 2000; *Picozza et al.*, 2021]. The number of reports of "anomalous" electromagnetic disturbances in the ULF range, detected by satellites in the upper ionosphere, is constantly growing [*Bilichenko et al.*, 1990; *De Santis et al.*, 2015; *Huang et al.*, 2020; *Zhu et al.*, 2021]. The most cited pioneering results of EQ precursors detection in the upper ionosphere were obtained on the OREOL-3 and IKB-1300 satellites [*Chmyrev et al.*, 1986, 1989]. During the nighttime flight of IKB-1300 (altitude 800 km) above the EQ source, 15 minutes before the main shock variations were recorded in the range of 0.1–8 Hz in the horizontal magnetic components with typical amplitude about several nT and in the electric field component with amplitude about few mV/m. [*Gousheva et al.*, 2008] revealed the enhancement up to ~5–15 mV/m of the quasi-DC electric field in the upper ionosphere at ICB-1300 over epicenters during seismic activity over various regions. In many studies bursts of electromagnetic noise in the ionosphere in the ELF and VLF frequency bands were noticed in the vicinity of epicenter before the seismic shock.

These encouraging results have stimulated the development of specialized satellite missions for detecting seismo-electromagnetic emissions – DEMETER (orbit altitude ~660 km) [*Parrot and Lil*, 2015], CSES (orbit altitude ~500 km) [*Zhima et al.*, 2022], ESPERIA [*Sgrigna et al.*, 2008], QUAKESAT [*Warden et al.*, 2020]. Besides, data from the multi-probe mission SWARM were used for the search of seismogenic ULF disturbances [*De Santis et al.*, 2019]. In the specialized satellite project DEMETER the sensitivity of the electromagnetic complex was so high that at auroral latitudes the sensors went into saturation. Before an EQ with $M = 7.9 and H = 10$ km, an increase in the electrical component of the noise was found in the vicinity of 5.8 Hz [*Walker et al.*, 2013]. [*Zhang et al.*, 2014] introduced a new parameter for the ULF/ELF electric field perturbations, which includes not only the intensity, but also its attenuation character. After processing the local nighttime DEMETER data during 5 days around 25 seismic events with $M > 6.0$

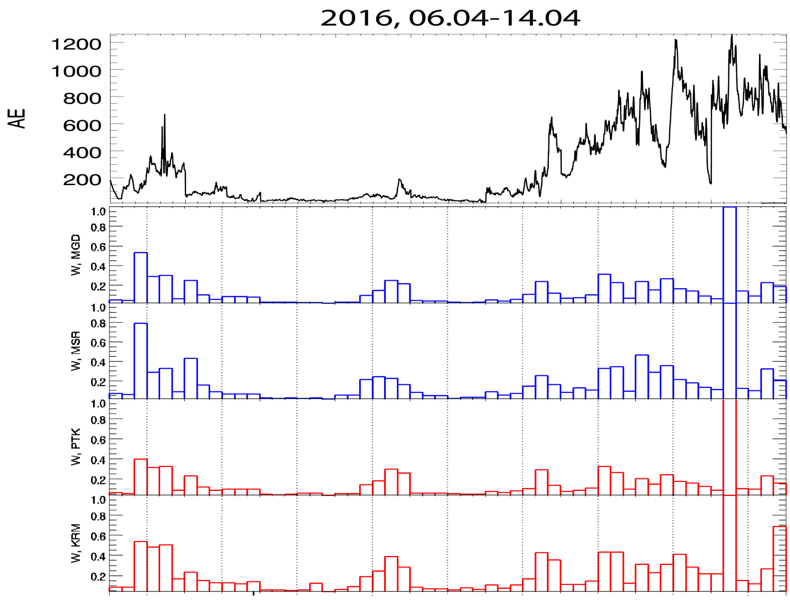

Figure 8. Variations in the spectral power W in the band 0.01–0.8 Hz for the horizontal Y component at night hours for PWING stations. The red color corresponds to nearby stations, blue color denotes distant stations. The upper panel shows the planetary geomagnetic index AE, characterizing the disturbance of the geomagnetic field at auroral latitudes.

in Chile they found precursory anomalies before 2/3 of EQs. Clear temporal and spatial statistical correlations between ULF wave activity in the nighttime ionosphere and EQs ($M \geq 5.0, H \leq 70$ km) were found in the electric field data from DEMETER [*Ouyang et al.*, 2020]. The enhanced ULF wave occurrence rate happened ~1 day and ~1 week before the EQs at distance <200 km from the epicenters. [*Zhang et al.*, 2014] presented ULF electric field (DC-15 Hz) observations during local nighttime by DEMETER satellite around seismic regions of Indonesia and Chile. Anomalous ULF electric field perturbations were revealed with amplitudes ≤ 10 mV/m before some large EQs. [*Akhoondzadeh*, 2013] observed anomalies in the ULF magnetic and electric components a few days prior to the strong earthquake. Electromagnetic measurements on the CSES satellite in the band 75–90 Hz revealed an increase in noise power in the nighttime ionosphere by 10–30% a few days before EQs with $M = 6.4$ and $M = 7.4$ [*Wang et al.*, 2021]. Zhima et al. [2022] suggested that the possible abnormal emissions in the ULF band recorded by CSES satellite were emitted during the EQs.

It is implicitly assumed that the emission from an underground ULF/ELF source directly reaches a LEO satellite upon propagation through the ionosphere as illustrated in Figure 9. To estimate the necessary intensity of a seismic source of anomalous radiation that can be detected at LEO, one has to model the response of the ionosphere to a large-scale underground emitter. The obtained estimate can be compared with the observational results, so a conclusion about the prospects of satellite observations for the search for seismo-electromagnetic emissions may be given. The problem cannot be reduced to the classical problems of electromagnetic radiation from a dipole buried in a conducting half-space. In the situation under consideration, the system of oscillating currents in the earth's crust has a length comparable to the height of the ionosphere, so its finite scale must be taken into account. Such numerical calculations of the penetration of ULF fields from an underground source into the ionosphere were performed in [*Molchanov et al.*, 1995; *Wang et al.*, 2021], but these models have certain significant limitations and cannot provide a comprehensive solution to the problem.

The advanced numerical model that makes it possible to estimate the ULF fields generated by an underground horizontal current of finite length both on the earth's surface and in the upper ionosphere was elaborated in [*Fedorov et al.*, 2023; *Mazur et al.*, 2024].

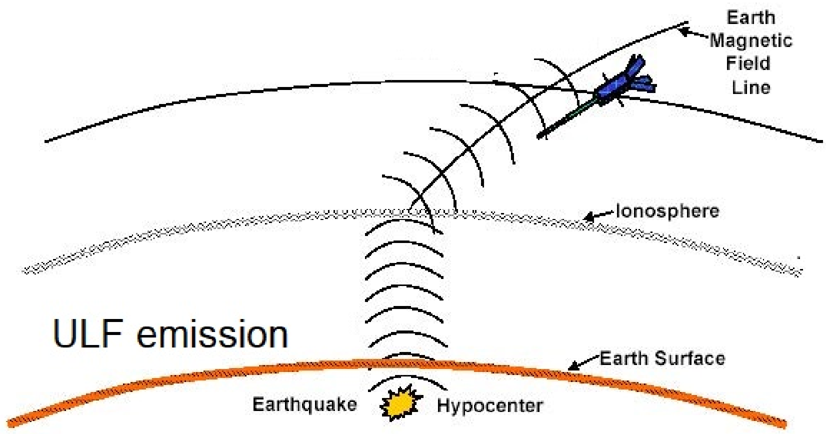

Figure 9. A schematic illustration of the satellite experiments to detect ULF electromagnetic emission from the EQ hypocenter.

This model includes the atmospheric conductivity profile and realistic vertical structure of the ionospheric parameters derived from the IRI model. With the use of this model, the spatial structure of the amplitude of the 0.1-Hz radiation field is calculated simultaneously for the upper ionosphere ($z = 500$ km) and on the ground (Figure 10). The underground current with intensity 1-A, length 20 km, at depth 20 km in the crust with conductivity 10^{-3} S/m, was taken. The maximum disturbance of transverse electric components directly above the source current ($y = 0$) reaches $|E| \sim 2 \times 10^{-3}$ µV/m. The underground current that is capable to produce the observed in early satellite mission E-field disturbance > 1 mV/m in the upper ionosphere is to be $>10^6$ A. However, according to the numerical model, in this case, a perturbation of the geomagnetic field $B \sim 10^3$ nT arises on the earth's surface (see the bottom panel in Figure 10). Such geomagnetic disturbances, comparable to disturbances during strong substorms, would be detected by the existing network of magnetometers. Therefore, ULF disturbances before EQs recorded onboard early satellites can hardly be associated with direct radiation from underground sources of a seismic nature. Only modern observations with sensitivity better than 1 µV/m may produce trustworthy observations because the associated ground signature is to be around 1 nT.

9. Prospects of future research

The most decidedly adverse perspective in EQ studies, mainly from the seismology and geodesy point of view, is that such complex system as EQ is inherently unpredictable because of the highly sensitive nonlinear dependence on initial conditions. The situation is similar to the following example. Having a dense array of all necessary meteodata one can reliably predict an occurrence of severe weather. However, even with most complete set of data it would be hardly possible to predict exactly the place and time where lighting strike. Hopefully, overturning the situation with seismic process is possible through multidisciplinary science. We believe that a critical analysis of all published results is as important as a search for new seismo-electromagnetic effects. This may help to shut down unpromising and misleading directions and thus save time and resources.

The elusive seismogenic ULF emissions are weak, so a simple monitoring of the ULF power is not sufficient to reveal them from other sources. Advanced methods of time series analysis may be helpful to resolve this issue. Some encouraging attempts have been undertaken. [*Serita et al.*, 2005] applied the principal component analysis (PCA) to ground measurements of magnetic field in order to point out earthquake related anomalies. The authors extracted the first two principal components related to geomagnetic variation and anthropogenic sources, while the third component pointed out the possible seismo-associated disturbances. By applying PCA to magnetic data from six observato-

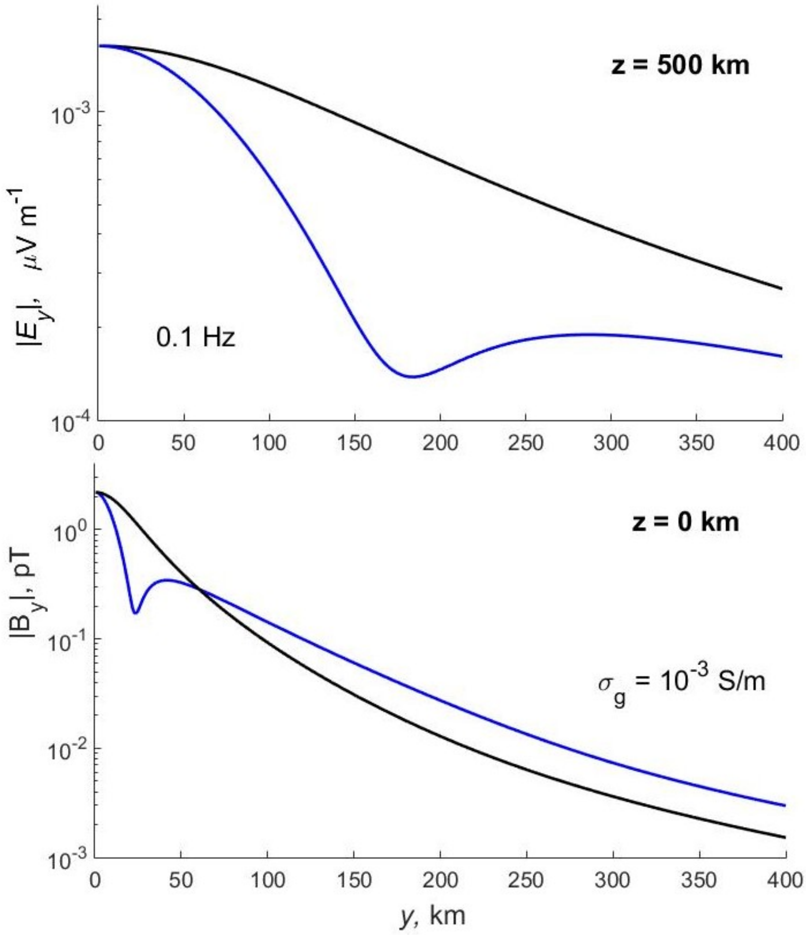

Figure 10. The spatial structure of the amplitude of the 0.1-Hz radiation field calculated for the upper ionosphere (z = 500 km) (electric field components), and on the ground (magnetic field components).

ries [*Kappler et al.*, 2017] were able to identify and distinguish global geomagnetic signals and anthropogenic signals. The application of machine learning methods for automatically classifying and recognizing earthquake precursors on ground and in space have been explored [*Rouet-Leduc et al.*, 2017].

Though the reported results on the effect of magnetic storms on seismicity seem questionable, we do not completely deny the possibility of a relationship between solar activity, the geomagnetic field, and seismicity, and do not deny in principle the possibility of triggered effects in geophysical processes. It is possible that a trigger effect can manifest itself only under a unique combination of favorable factors that are extremely rare and do not appear in general statistics.

Though our analysis has not confirmed the occurrence of impulsive disturbances few minutes before EQs, the study of the generation of electromagnetic pulses at the stage of rock destruction seems to be very promising [*Bleier et al.*, 2010; *Freund et al.*, 2021; *Tsutsui*, 2005]. To isolate unipolar magnetic pulses, presumably associated with an increase in tectonic load on the rock, specialized time series analysis algorithms are to be developed [*Kappler et al.*, 2019].

A comparison of the variations in the integrated spectral power of magnetic noise at array of stations showed that the depression of nighttime magnetic noise, which was previously considered an operative precursor, occurred simultaneously at all nearby and distant stations. Thus, at least for the re-examined event, noise depression cannot be considered as a local short-term precursor. Thus, an additional analysis of all the reported events is required using an extended regional network of magnetometers to validate this effect.

The evident weak point of seismo-electromagnetic studies is the lack of quantitative physical models. Many studies are still based on qualitative concepts, without any estimate of expected effect even with simplified theoretical models. Theoretical modeling would make it possible to discard unrealistic physical mechanisms, otherwise, random coincidences can be perceived as reliable experimental evidence. In particular, a new theoretical formalism is needed for calculating electromagnetic fields in the Earth-atmosphere-ionosphere system, created by an underground current source. This numerical model can be used to indicate characteristic features of such an underground source field that can be used to discriminate disturbances from seismogenic sources. The first application of such model to estimate the self-consistently expected amplitude of ULF emission in the topside ionosphere and on the ground has shown that early "classical" results of satellite observations cannot be interpreted as a result of direct ULF emission from a hypothetical seismogenic source.

In all presented events, the geomagnetic field "anomalies" can be explained by global geomagnetic activity and are apparently not associated with seismic processes. The considered issues are a clear illustration of the fact that the analysis of anomalous disturbances should be carried out jointly by specialists in EQ physics and space weather. We suggest that both communities must cooperate their studies more tightly and perform data exchange. A very effective tool for the in-depth study of geophysical phenomena and the unification of the researcher's expertise is the common data analysis workshop (CDAW). During the CDAW, all participants combine their observational data and modeling efforts for a selected event to achieve the most comprehensive understanding of a phenomena under study.

Acknowledgments. This work was supported by the Russian Science Foundation grant 22-17-00125 and presented at the 7th International Workshop on EQ Preparation Process, Observation, Validation, Modeling, Forecasting (IWEP7) in Chiba.

References

Adushkin, V. V., and A. A. Spivak (2021), Impact of Natural Extreme Events on Geophysical Fields in the Environment, *Izvestiya, Physics of the Solid Earth*, *57*(5), 583–592, https://doi.org/10.1134/s1069351321050037.

Adushkin, V. V., S. A. Ryabova, A. A. Spivak, and V. A. Kharlamov (2012), Response of the seismic background to geomagnetic variations, *Doklady Earth Sciences*, *444*(1), 642–646, https://doi.org/10.1134/s1028334x12050157.

Akhoondzadeh, M. (2013), Novelty detection in time series of ULF magnetic and electric components obtained from DEMETER satellite experiments above Samoa (29 September 2009) earthquake region, *Natural Hazards and Earth System Sciences*, *13*(1), 15–25, https://doi.org/10.5194/nhess-13-15-2013.

Bakhmutov, V. G., F. I. Sedova, and T. A. Mozgova (2003), Morphological analysis of geomagnetic variations in preparation period of the strongest earthquake of 25 March 1998, *Ukrainian Antarctic Journal*, (1), 54–60, https://doi.org/10.33275/1727-7485.1.2003.624 (in Ukranian).

Best, A., S. M. Krylov, I. P. Kurchashov, I. S. Nikomarov, and V. A. Pilipenko (1986), Gradient-time analysis of Pc3 pulsations, *Geomagnetism and Aeronomy*, *26*(6), 980–984 (in Russian).

Bilichenko, S. V., A. S. Inchin, E. F. Kim, O. A. Pokhotelov, P. P. Puschaev, G. G. Stanev, A. V. Streltsov, and V. M. Chmyrev (1990), ULF response of the ionosphere to earthquake preparation processes, *Doklady Akademii Nauk*, *311*(5), 1077–1081 (in Russian).

Bleier, T., C. Dunson, M. Maniscalco, N. Bryant, R. Bambery, and F. Freund (2009), Investigation of ULF magnetic pulsations, air conductivity changes, and infra red signatures associated with the 30 October Alum Rock M5.4 earthquake, *Natural Hazards and Earth System Sciences*, *9*(2), 585–603, https://doi.org/10.5194/nhess-9-585-2009.

Bleier, T., C. Dunson, C. Alvarez, F. Freund, and R. Dahlgren (2010), Correlation of pre-earthquake electromagnetic signals with laboratory and field rock experiments, *Natural Hazards and Earth System Sciences*, *10*(9), 1965–1975, https://doi.org/10.5194/nhess-10-1965-2010.

Bortnik, J., J. W. Cutler, C. Dunson, and T. E. Bleier (2008), The possible statistical relation of Pc1 pulsations to Earthquake occurrence at low latitudes, *Annales Geophysicae*, *26*(9), 2825–2836, https://doi.org/10.5194/angeo-26-2825-2008.

Chernogor, L. F. (2019), Geomagnetic Disturbances Accompanying the Great Japanese Earthquake of March 11, 2011, *Geomagnetism and Aeronomy*, *59*(1), 62–75, https://doi.org/10.1134/S0016793219010043.

Chmyrev, V. M., N. V. Isaev, S. V. Bilichenko, and G. Stanev (1986), Electric fields and hydromagnetic waves in the ionosphere above the earthquake source, *Geomagnetism and Aeronomy*, *26*(6), 1020–1022 (in Russian).

Chmyrev, V. M., N. V. Isaev, S. V. Bilichenko, and G. Stanev (1989), Observation by space-borne detectors of electric fields and hydromagnetic waves in the ionosphere over an earthquake centre, *Physics of the Earth and Planetary Interiors*, *57*(1–2), 110–114, https://doi.org/10.1016/0031-9201(89)90220-3.

De Santis, A., G. De Franceschi, L. Spogli, L. Perrone, L. Alfonsi, and other (2015), Geospace perturbations induced by the Earth: The state of the art and future trends, *Physics and Chemistry of the Earth, Parts A/B/C*, *85–86*, 17–33, https://doi.org/10.1016/j.pce.2015.05.004.

De Santis, A., D. Marchetti, F. J. Pavón-Carrasco, G. Cianchini, L. Perrone, and other (2019), Precursory worldwide signatures of earthquake occurrences on Swarm satellite data, *Scientific Reports*, *9*(1), https://doi.org/10.1038/s41598-019-56599-1.

Desherevskii, A. V., and A. Y. Sidorin (2016), Comparative morphological analysis of the diurnal rhythms in geomagnetic and seismic activity, *Izvestiya, Atmospheric and Oceanic Physics*, *52*(8), 853–861, https://doi.org/10.1134/s0001433816080041.

Doda, L. N., V. L. Natyaganov, and I. V. Stepanov (2013), An empirical scheme of short-term earthquake prediction, *Doklady Earth Sciences*, *453*(2), 1257–1263, https://doi.org/10.1134/S1028334X1312009X.

Dovbnya, B. V. (2011), On the effects of earthquakes in geomagnetic pulsations and their possible nature, *Geophysical Journal*, *33*(1), 72–79 (in Russian).

Dovbnya, B. V. (2014), Electromagnetic precursors of earthquakes and their frequency, *Geophysical Journal*, *36*(3), 160–165 (in Russian).

Dovbnya, B. V. (2021), On the results of remote observation of pulsed ultra-low-frequency electromagnetic signals detected minutes before an earthquake, *Life of the Earth*, *43*(3), 304–313, https://doi.org/10.29003/m2435.0514-7468.2020_43_3/304-313 (in Russian).

Dovbnya, B. V., O. D. Zotov, A. O. Mostryukov, and R. V. Shchepetnov (2006), Electromagnetic signals close in time to earthquakes, *Izvestiya, Physics of the Solid Earth*, *42*(8), 684–689, https://doi.org/10.1134/s1069351306080052.

Dovbnya, B. V., O. D. Zotov, and R. V. Shchepetnov (2008), Connection of ULF electromagnetic waves with earthquakes and anthropogenic impacts, *Izvestiya, Physics of the Solid Earth*, *9*, 3–23 (in Russian).

Dovbnya, B. V., A. Y. Pashinin, and R. A. Rakhmatulin (2019), Short-term electromagnetic precursors of earthquakes, *Geodynamics & Tectonophysics*, *10*(3), 731–740, https://doi.org/10.5800/GT-2019-10-3-0438.

Duma, G., and Y. Ruzhin (2003), Diurnal changes of earthquake activity and geomagnetic Sq-variations, *Natural Hazards and Earth System Sciences*, *3*(3/4), 171–177, https://doi.org/10.5194/nhess-3-171-2003.

Duma, G., and G. Vilardo (1998), Seismicity cycles in the Mt. Vesuvius area and their relation to solar flux and the variations of the Earth's magnetic field, *Physics and Chemistry of the Earth*, *23*(9–10), 927–931, https://doi.org/10.1016/s0079-1946(98)00121-9.

Fedorov, E., V. Pilipenko, and S. Uyeda (2001), Electric and magnetic fields generated by electrokinetic processes in a conductive crust, *Physics and Chemistry of the Earth, Part C: Solar, Terrestrial & Planetary Science*, *26*(10–12), 793–799, https://doi.org/10.1016/S1464-1917(01)95027-5.

Fedorov, E. N., N. G. Mazur, V. A. Pilipenko, and V. V. Vakhnina (2023), Generation of Artificial ULF/ELF Electromagnetic Emission in the Ionosphere by Horizontal Ground-Based Current System, *Journal of Geophysical Research: Space Physics*, *128*(12), https://doi.org/10.1029/2023ja031590.

Fenoglio, M. A., M. J. S. Johnston, and J. D. Byerlee (1995), Magnetic and electric fields associated with changes in high pore pressure in fault zones: Application to the Loma Prieta ULF emissions, *Journal of Geophysical Research: Solid Earth*, *100*(B7), 12,951–12,958, https://doi.org/10.1029/95JB00076.

Freund, F. T., J. A. Heraud, V. A. Centa, and J. Scoville (2021), Mechanism of unipolar electromagnetic pulses emitted from the hypocenters of impending earthquakes, *The European Physical Journal Special Topics*, *230*(1), 47–65, https://doi.org/10.1140/epjst/e2020-000244-4.

Gavrilov, B. G., Y. V. Poklad, I. A. Ryakhovsky, V. M. Ermak, N. S. Achkasov, and E. N. Kozakova (2022), Global Electromagnetic Disturbances Caused by the Eruption of the Tonga Volcano on 15 January 2022, *Journal of Geophysical Research: Atmospheres*, *127*(23), https://doi.org/10.1029/2022jd037411.

Gogatishvili, I. M. (1984), Geomagnetic precursors of intense earthquakes in the spectrum of geomagnetic pulsations with frequencies of 1-0.02 Hz, *Geomagnetism and Aeronomy*, *24*, 697–700 (in Russian).

Gousheva, M., D. Danov, P. Hristov, and M. Matova (2008), Quasi-static electric fields phenomena in the ionosphere associated with pre- and post earthquake effects, *Natural Hazards and Earth System Sciences*, *8*(1), 101–107, https://doi.org/10.5194/nhess-8-101-2008.

Guglielmi, A. V., and V. T. Levshenko (1996), Electromagnetic impulse from the source of an earthquake, *Doklady Akademii Nauk*, *349*(5), 676–678 (in Russian).

Guglielmi, A. V., and O. D. Zotov (2010), Correlation between Pc1 electromagnetic activity and earthquakes, *Izvestiya, Physics of the Solid Earth*, *46*(6), 486–492, https://doi.org/10.1134/S1069351310060030.

Han, Y., Z. Guo, J. Wu, and L. Ma (2004), Possible triggering of solar activity to big earthquakes ($Ms \geq 8$) in faults with near west-east strike in China, *Science in China Series G*, *47*(2), 173, https://doi.org/10.1360/03yw0103.

Harrison, R. G., K. L. Aplin, and M. J. Rycroft (2010), Atmospheric electricity coupling between earthquake regions and the ionosphere, *Journal of Atmospheric and Solar-Terrestrial Physics*, *72*(5–6), 376–381, https://doi.org/10.1016/j.jastp.2009.12.004.

Hattori, K. (2004), ULF Geomagnetic Changes Associated with Large Earthquakes, *Terrestrial, Atmospheric and Oceanic Sciences*, *15*(3), 329, https://doi.org/10.3319/TAO.2004.15.3.329(EP).

Hayakawa, M. (Ed.) (2009), *Electromagnetic phenomena associated with earthquakes*, Transworld Research Network, Trivandrum (India).

Hayakawa, M. (Ed.) (2013), *Earthquake Prediction Studies: Seismo Electromagnetics*, TERRAPUB, Tokyo.

Hayakawa, M., and O. A. Molchanov (Eds.) (2002), *Seismo Electromagnetics: Lithosphere-Atmosphere-Ionosphere Coupling*, TERRAPUB, Tokyo.

Hayakawa, M., R. Kawate, O. A. Molchanov, and K. Yumoto (1996), Results of ultra-low-frequency magnetic field measurements during the Guam Earthquake of 8 August 1993, *Geophysical Research Letters*, *23*(3), 241–244, https://doi.org/10.1029/95GL02863.

Hayakawa, M., T. Ito, and N. Smirnova (1999), Fractal analysis of ULF geomagnetic data associated with the Guam Earthquake on August 8, 1993, *Geophysical Research Letters*, *26*(18), 2797–2800, https://doi.org/10.1029/1999GL005367.

Hayakawa, M., A. Schekotov, S. Potirakis, and K. Eftaxias (2015), Criticality features in ULF magnetic fields prior to the 2011 Tohoku earthquake, *Proceedings of the Japan Academy, Series B*, *91*(1), 25–30, https://doi.org/10.2183/pjab.91.25.

Huang, Q., P. Han, K. Hattori, and H. Ren (2020), Electromagnetic Signals Associated With Earthquakes: A Review of Observations, Data Processing, and Mechanisms in China, https://doi.org/10.1002/9781119127383.ch26.

Ismaguilov, V. S., Y. A. Kopytenko, K. Hattori, and M. Hayakawa (2003), Variations of phase velocity and gradient values of ULF geomagnetic disturbances connected with the Izu strong earthquakes, *Natural Hazards and Earth System Sciences*, *3*(3/4), 211–215, https://doi.org/10.5194/nhess-3-211-2003.

Ismaguilov, V. S., Y. A. Kopytenko, K. Hattori, and M. Hayakawa (2006), Gradients and phase velocities of ULF geomagnetic disturbances used to determine the source of an impending strong earthquake, *Geomagnetism and Aeronomy*, *46*(3), 403–410, https://doi.org/10.1134/S0016793206030157.

Iyemori, T., T. Kamei, Y. Tanaka, M. Takeda, T. Hashimoto, T. Araki, T. Okamoto, K. Watanabe, N. Sumitomo, and N. Oshiman (1996), Co-Seismic Geomagnetic Variations Observed at the 1995 Hyogoken-Nanbu Earthquake, *Journal of geomagnetism and geoelectricity*, *48*(8), 1059–1070, https://doi.org/10.5636/jgg.48.1059.

Iyemori, T., M. Nose, D. Han, Y. Gao, M. Hashizume, and other (2005), Geomagnetic pulsations caused by the Sumatra earthquake on December 26, 2004, *Geophysical Research Letters*, *32*(20), https://doi.org/10.1029/2005GL024083.

Kappler, K. N., D. D. Schneider, L. S. MacLean, and T. E. Bleier (2017), Identification and classification of transient pulses observed in magnetometer array data by time-domain principal component analysis filtering, *Earthquake Science*, *30*(4), 193–207, https://doi.org/10.1007/s11589-017-0191-6.

Kappler, K. N., D. D. Schneider, L. S. MacLean, T. E. Bleier, and J. J. Lemon (2019), An algorithmic framework for investigating the temporal relationship of magnetic field pulses and earthquakes applied to California, *Computers & Geosciences*, *133*, 104,317, https://doi.org/10.1016/j.cageo.2019.104317.

Kodama, T., O. A. Molchanov, and M. Hayakawa (2000), NASDA Earthquake Remote Sensing Frontier Research — Feasibility of satellite observation of seismoelectromagnetics, *Advances in Space Research*, *26*(8), 1281–1284, https://doi.org/10.1016/S0273-1177(99)01219-3.

Kopytenko, Y. A., V. S. Ismaguilov, O. A. Molchanov, E. A. Kopytenko, P. M. Voronov, K. Hattori, M. Hayakawa, and D. B. Zaitsev (2002), Investigation of ULF magnetic disturbances in Japan during seismic active period, *Journal of Atmospheric Electricity*, *22*(3), 207–215.

Kopytenko, Y. A., V. S. Ismaguilov, K. Hattori, and M. Hayakawa (2006), Determination of hearth position of a forthcoming strong EQ using gradients and phase velocities of ULF geomagnetic disturbances, *Physics and Chemistry of the Earth, Parts A/B/C*, *31*(4–9), 292–298, https://doi.org/10.1016/j.pce.2006.02.004.

Kopytenko, Y. A., V. S. Ismaguilov, K. Hattori, and M. Hayakawa (2012), Anomaly disturbances of the magnetic fields before the strong earthquake in Japan on March 11, 2011, *Annals of Geophysics*, *55*(1), https://doi.org/10.4401/ag-5260.

Kosterin, N. A., V. A. Pilipenko, and E. M. Dmitriev (2015), On Global Ultralow Frequency Electromagnetic Signals Prior to Earthquakes, *Geophysical research*, *16*(1), 24–34 (in Russian).

Kozyreva, O. V., and V. A. Pilipenko (2020), On the Relationship of Geomagnetic Disturbances and Seismic Activity for Alaska Region, *Geophysical research*, *21*(1), 33–49, https://doi.org/10.21455/gr2020.1-3 (in Russian).

Kozyreva, O. V., V. A. Pilipenko, E. E. Marshalko, E. Y. Sokolova, and M. N. Dobrovolsky (2022), Monitoring of Geomagnetic and Telluric Field Disturbances in the Russian Arctic, *Applied Sciences*, *12*(8), 3755, https://doi.org/10.3390/app12083755.

Kuznetsova, V. G., V. E. Maksimchuk, Y. M. Gorodysky, and T. A. Klimkovich (2005), Anomalous Effects in the Geomagnetic Field in Relation to the Seismic Regime of the Carpathians, *Izvestiya, Physics of the Solid Earth*, *41*(3), 213–237.

Li, Q., A. Schekotov, T. Asano, and M. Hayakawa (2015), On the Anomalies in ULF Magnetic Field Variations Prior to the 2008 Sichuan Earthquake, *Open Journal of Earthquake Research*, *04*(02), 55–64, https://doi.org/10.4236/ojer.2015.42005.

Lockner, D. A., M. J. S. Johnston, and J. D. Byerlee (1983), A mechanism to explain the generation of earthquake lights, *Nature*, *302*(5903), 28–33, https://doi.org/10.1038/302028a0.

Love, J. J., and A. Chulliat (2013), An International Network of Magnetic Observatories, *EOS, Transactions American Geophysical Union*, *94*(42), 373–374, https://doi.org/10.1002/2013EO420001.

Love, J. J., and J. N. Thomas (2013), Insignificant solar-terrestrial triggering of earthquakes, *Geophysical Research Letters*, *40*(6), 1165–1170, https://doi.org/10.1002/grl.50211.

Marchuk, R., A. Potapov, and V. Mishin (2022), Synchronous globally observable ultrashort-period pulses, *Solnechno-Zemnaya Fizika*, *8*(2), 52–60, https://doi.org/10.12737/szf-82202207.

Martinez-Bedenko, V. A., V. A. Pilipenko, K. Shiokawa, and V. A. Kasimova (2023), Search for Pulsed Ultralow-Frequency Electromagnetic Earthquake Precursors, *Geophysical Research*, *24*(2), 5–24, https://doi.org/10.21455/gr2023.2-1 (in Russian).

Masci, F., and J. N. Thomas (2015), Are there new findings in the search for ULF magnetic precursors to earthquakes?, *Journal of Geophysical Research: Space Physics*, *120*(12), https://doi.org/10.1002/2015ja021336.

Mazur, N. G., E. N. Fedorov, V. A. Pilipenko, and K. E. Borovleva (2024), Electromagnetic ULF fields on the earth's surface and in the ionosphere from an underground seismic source, *Izvestiya*, *Physics of the Solid Earth*, (2).

Menk, F. W., and C. L. Waters (2013), *Magnetoseismology: Ground-Based Remote Sensing of Earth's Magnetosphere*, Wiley, https://doi.org/10.1002/9783527652051.

Molchanov, O. A., and M. Hayakawa (1995), Generation of ULF electromagnetic emissions by microfracturing, *Geophysical Research Letters*, *22*(22), 3091–3094, https://doi.org/10.1029/95gl00781.

Molchanov, O. A., Y. A. Kopytenko, P. M. Voronov, E. A. Kopytenko, and other (1992), Results of ULF magnetic field measurements near the epicenters of the Spitak (Ms = 6.9) and Loma Prieta (Ms = 7.1) earthquakes: Comparative analysis, *Geophysical Research Letters*, *19*(14), 1495–1498, https://doi.org/10.1029/92gl01152.

Molchanov, O. A., M. Hayakawa, and V. A. Rafalsky (1995), Penetration characteristics of electromagnetic emissions from an underground seismic source into the atmosphere, ionosphere, and magnetosphere, *Journal of Geophysical Research: Space Physics*, *100*(A2), 1691–1712, https://doi.org/10.1029/94ja02524.

Molchanov, O. A., A. Y. Schekotov, E. Fedorov, G. G. Belyaev, M. S. Solovieva, and M. Hayakawa (2004), Preseismic ULF effectand possible interpretation, *Annals of Geophysics*, *47*(1), https://doi.org/10.4401/ag-3265.

Naumov, A. P. (1999), Impulsive low-frequency seismo-magnetic signals in geomagnetic variations as an earthquake prediction tool, *Volcanology & Seismology*, *20*, 743–752.

Nosikova, N. S., V. A. Pilipenko, and S. L. Shalimov (2023), On the Magnetic Effects Caused by the Earthquake of March 16, 2022 in Japan, *Izvestiya*, *Physics of the Solid Earth*, *59*(5), 815–820, https://doi.org/10.1134/S1069351323050075.

Odintsov, S., K. Boyarchuk, K. Georgieva, B. Kirov, and D. Atanasov (2006), Long-period trends in global seismic and geomagnetic activity and their relation to solar activity, *Physics and Chemistry of the Earth*, *Parts A/B/C*, *31*(1–3), 88–93, https://doi.org/10.1016/j.pce.2005.03.004.

Ouyang, X. Y., M. Parrot, and J. Bortnik (2020), ULF Wave Activity Observed in the Nighttime Ionosphere Above and Some Hours Before Strong Earthquakes, *Journal of Geophysical Research: Space Physics*, *125*(9), https://doi.org/10.1029/2020JA028396.

Parrot, M., and M. Lil (2015), DEMETER results related to seismic activity, *Radio Science Bulletin*, *355*, 18–25, https://doi.org/10.23919/URSIRSB.2015.7909470.

Petraki, E., D. Nikolopoulos, C. Nomicos, J. Stonham, and other (2015), Electromagnetic Pre-earthquake Precursors: Mechanisms, Data and Models-A Review, *Journal of Earth Science & Climatic Change*, *06*(01), https://doi.org/10.4172/2157-7617.1000250.

Picozza, P., L. Conti, and A. Sotgiu (2021), Looking for Earthquake Precursors From Space: A Critical Review, *Frontiers in Earth Science*, *9*, https://doi.org/10.3389/feart.2021.676775.

Pilipenko, V., O. Kozyreva, E. Fedorov, M. Uspensky, and K. Kauristie (2016), Latitudinal amplitude-phase structure of MHD waves: STARE radar and image magnetometer observations and modeling, *Solnechno-Zemnaya Fizika*, *2*(3), 41–51, https://doi.org/10.12737/19418.

Pulinets, S., and D. Davidenko (2014), Ionospheric precursors of earthquakes and Global Electric Circuit, *Advances in Space Research*, *53*(5), 709–723, https://doi.org/10.1016/j.asr.2013.12.035.

Rabeh, T., M. Miranda, and M. Hvozdara (2009), Strong earthquakes associated with high amplitude daily geomagnetic variations, *Natural Hazards*, *53*(3), 561–574, https://doi.org/10.1007/s11069-009-9449-1.

Rouet-Leduc, B., C. Hulbert, N. Lubbers, K. Barros, C. J. Humphreys, and P. A. Johnson (2017), Machine Learning Predicts Laboratory Earthquakes, *Geophysical Research Letters*, *44*(18), 9276–9282, https://doi.org/10.1002/2017GL074677.

Schekotov, A. Y., and M. Hayakawa (2017), *ULF/ELF electromagnetic phenomena for short-term earthquake prediction*, LAP LAMBERT Academic Publishing.

Schekotov, A. Y., O. A. Molchanov, K. Hattori, E. N. Fedorov, and other (2006), Seismo-ionospheric depression of the ULF geomagnetic fluctuations at Kamchatka and Japan, *Physics and Chemistry of the Earth, Parts A/B/C*, *31*(4–9), 313–318, https://doi.org/10.1016/j.pce.2006.02.043.

Schekotov, A. Y., O. A. Molchanov, M. Hayakawa, E. N. Fedorov, V. N. Chebrov, and other (2008), About possibility to locate an EQ epicenter using parameters of ELF/ULF preseismic emission, *Natural Hazards and Earth System Sciences*, *8*(6), 1237–1242, https://doi.org/10.5194/nhess-8-1237-2008.

Schekotov, A. Y., E. N. Fedorov, Y. Hobara, and M. Hayakawa (2013), ULF Magnetic Field Depression as a Possible Precursor to the 2011/3.11 Japan Earthquake, *Journal of Atmospheric Electricity*, *33*(1), 41–51, https://doi.org/10.1541/jae.33.41.

Schekotov, A. Y., D. Chebrov, M. Hayakawa, G. Belyaev, and N. Berseneva (2020), Short-term earthquake prediction in Kamchatka using low-frequency magnetic fields, *Natural Hazards*, *100*(2), 735–755, https://doi.org/10.1007/s11069-019-03839-2.

Serita, A., K. Hattori, C. Yoshino, M. Hayakawa, and N. Isezaki (2005), Principal component analysis and singular spectrum analysis of ULF geomagnetic data associated with earthquakes, *Natural Hazards and Earth System Sciences*, *5*(5), 685–689, https://doi.org/10.5194/nhess-5-685-2005.

Sgrigna, V., A. Buzzi, L. Conti, P. Picozza, C. Stagni, and D. Zilpimiani (2008), The ESPERIA satellite project for detecting seismo-associated effects in the topside ionosphere. First instrumental tests in space, *Earth, Planets and Space*, *60*(5), 463–475, https://doi.org/10.1186/BF03352813.

Shiokawa, K., Y. Katoh, Y. Hamaguchi, Y. Yamamoto, T. Adachi, and other (2017), Ground-based instruments of the PWING project to investigate dynamics of the inner magnetosphere at subauroral latitudes as a part of the ERG-ground coordinated observation network, *Earth, Planets and Space*, *69*(1), https://doi.org/10.1186/s40623-017-0745-9.

Simpson, J. F. (1967), Solar activity as a triggering mechanism for earthquakes, *Earth and Planetary Science Letters*, *3*, 417–425, https://doi.org/10.1016/0012-821X(67)90071-4.

Smirnov, V. B., and A. D. Zavyalov (2012), Seismic response to electromagnetic sounding of the Earth's lithosphere, *Izvestiya, Physics of the Solid Earth*, *48*(7–8), 615–639, https://doi.org/10.1134/S1069351312070075.

Sobisevich, A. L., K. K. Kanonidi, L. E. Sobisevich, and D. G. Gridnev (2009a), On a class of electromagnetic disturbances preceding strong earthquakes, *Seismic Instruments*, *46*(3), 228–233, https://doi.org/10.3103/s0747923910030047.

Sobisevich, A. L., L. E. Sobisevich, K. K. Kanonidi, and D. V. Likhodeev (2017), Gravimagnetic perturbations preceding earthquakes, *Doklady Earth Sciences*, *475*(2), 891–894, https://doi.org/10.1134/s1028334x17080086.

Sobisevich, L. E. (2020), Seismogravitational processes and gravitomagnetic disturbances accompanying geophysical catastrophes, *Geofizika*, *1*, 70–76 (in Russian).

Sobisevich, L. E., K. K. Kanonidi, and A. L. Sobisevich (2009b), Ultra low-frequency electromagnetic disturbances appearing before strong seismic events, *Doklady Earth Sciences*, *429*(2), 1549–1552, https://doi.org/10.1134/s1028334x09090281.

Sobisevich, L. E., K. K. Kanonidi, and A. L. Sobisevich (2010a), Observations of ultra-low-frequency geomagnetic disturbances reflecting the processes of the preparation and development of tsunamigenic earthquakes, *Doklady Earth Sciences*, *435*(2), 1627–1632, https://doi.org/10.1134/S1028334X10120160.

Sobisevich, L. E., K. K. Kanonidi, and A. L. Sobisevich (2010b), Ultra low-frequency electromagnetic variation observed prior to development of an earthquake followed by tsunami, *Geophysical Journal*, *32*(4), 152–157.

Sobisevich, L. E., A. L. Sobisevich, and K. K. Kanonidi (2012), Anomalous geomagnetic disturbances induced by catastrophic tsunamigenic earthquakes in the region of Indonesia, *Geophysical Journal*, *34*(5), 22–37, https://doi.org/10.24028/gzh.0203-3100.v34i5.2012.116661.

Sobisevich, L. E., K. K. Kanonidi, A. L. Sobisevich, and O. I. Miseyuk (2013), Geomagnetic disturbances in the geomagnetic field's variations at stages of preparation and implementation of the Elazig (March 8, 2010) and M 5.3 (January 19, 2011) earthquakes in Turkey, *Doklady Earth Sciences*, *449*(1), 324–327, https://doi.org/10.1134/s1028334x13030069.

Sobolev, G. A., N. A. Zakrzhevskaya, and E. P. Kharin (2001), On the Relation Between Seismicity and Magnetic Storms, *Izvestiya, Physics of the Solid Earth*, *37*(11), 917–927.

Sorokin, V. M., E. N. Fedorov, A. Y. Schekotov, O. A. Molchanov, and M. Hayakawa (2004), Depression of ULF geomagnetic pulsation related to ionospheric irregularities, *Annals of Geophysics*, *47*(1), 191–198.

Sorokin, V. M., , A. K. Yashchenko, and V. A. Novikov (2019), A possible mechanism of stimulation of seismic activity by ionizing radiation of solar flares, *Earthquake Science*, *32*(1), 26–34, https://doi.org/10.29382/eqs-2019-0026-3.

Spivak, A. A., and S. A. Ryabova (2019), Geomagnetic variations during strong earthquakes, *Izvestiya, Physics of the Solid Earth*, (6), 3–12, https://doi.org/10.31857/S0002-3337201963-12.

Stothers, R. B. (1990), A search for long-term periodicities in large earthquakes of southern and coastal central California, *Geophysical Research Letters*, *17*(11), 1981–1984, https://doi.org/10.1029/gl017i011p01981.

Straser, V., G. Cataldi, and D. Cataldi (2015), Solar wind ionic and geomagnetic variations preceding the Md8.3 Chile earthquake, *New Concepts in Global Tectonics Journal*, *3*(3), 394–399.

Surkov, V. V., and M. Hayakawa (2006), ULF geomagnetic perturbations due to seismic noise produced by rock fracture and crack formation treated as a stochastic process, *Physics and Chemistry of the Earth, Parts A/B/C*, *31*(4–9), 273–280, https://doi.org/10.1016/j.pce.2006.02.019.

Surkov, V. V., and V. A. Pilipenko (1997), Magnetic effects due to earthquakes and underground explosions: a review, *Annals of Geophysics*, *40*(2), https://doi.org/10.4401/ag-3904.

Surkov, V. V., V. A. Pilipenko, and A. K. Sinha (2018), Possible mechanisms of co-seismic electromagnetic effect, *Acta Geodaetica et Geophysica*, *53*(1), 157–170, https://doi.org/10.1007/s40328-018-0211-6.

Sycheva, N. A., L. M. Bogomolov, and V. N. Sychev (2011), On geoeffective solar flares and variations of the seismic noise level, *Izvestiya, Physics of the Solid Earth*, *47*(3), 207–222, https://doi.org/10.1134/S1069351310101027.

Tanskanen, E. I. (2009), A comprehensive high-throughput analysis of substorms observed by IMAGE magnetometer network: Years 1993–2003 examined, *Journal of Geophysical Research: Space Physics*, *114*(A5), https://doi.org/10.1029/2008JA013682.

Tarasov, N. T. (1997), Changes in the seismicity of the crust under electrical action, *Doklady Akademii Nauk*, *353*(4), 542–545 (in Russian).

Tarasov, N. T., N. V. Tarasova, A. A. Avagimov, and V. A. Zeigarnik (1999), The effect of high energy electromagnetic pulses on seismicity in central Asia and Kazakhstan, *Volcanology & Seismology*, *21*(4), 627–639.

Tarasov, N. T., N. V. Tarasova, A. A. Avagimov, and V. A. Zeigarnik (2001), The Effect of Electromagnetic Impacts on Seismicity over the Bishkek Geodynamic Test Ground, *Russian Geology and Geophysics*, *42*(10), 1641–1649.

Thomas, J. N., J. J. Love, and M. J. S. Johnston (2009a), On the reported magnetic precursor of the 1989 Loma Prieta earthquake, *Physics of the Earth and Planetary Interiors*, *173*(3–4), 207–215, https://doi.org/10.1016/j.pepi.2008.11.014.

Thomas, J. N., J. J. Love, M. J. S. Johnston, and K. Yumoto (2009b), On the reported magnetic precursor of the 1993 Guam earthquake, *Geophysical Research Letters*, *36*(16), https://doi.org/10.1029/2009GL039020.

Tsutsui, M. (2005), Identification of earthquake epicenter from measurements of electromagnetic pulses in the Earth, *Geophysical Research Letters*, *32*(20), https://doi.org/10.1029/2005GL023691.

Walker, S. N., V. Kadirkamanathan, and O. A. Pokhotelov (2013), Changes in the ultra-low frequency wave field during the precursor phase to the Sichuan earthquake: DEMETER observations, *Annales Geophysicae*, *31*(9), 1597–1603, https://doi.org/10.5194/angeo-31-1597-2013.

Wang, Z., C. Zhou, S. Zhao, X. Xu, M. Liu, Y. Liu, L. Liao, and X. Shen (2021), Numerical Study of Global ELF Electromagnetic Wave Propagation with Respect to Lithosphere–Atmosphere–Ionosphere Coupling, *Remote Sensing*, *13*(20), 4107, https://doi.org/10.3390/rs13204107.

Warden, S., L. MacLean, J. Lemon, and D. Schneider (2020), Statistical Analysis of Pre-earthquake Electromagnetic Anomalies in the ULF Range, *Journal of Geophysical Research: Space Physics*, *125*(10), https://doi.org/10.1029/2020JA027955.

Yagova, N. V., A. K. Sinha, V. A. Pilipenko, E. N. Fedorov, R. Holzworth, and G. Vichare (2019), ULF electromagnetic noise from regional lightning activity: Model and observations, *Journal of Atmospheric and Solar-Terrestrial Physics*, *182*, 223–228, https://doi.org/10.1016/j.jastp.2018.12.005.

Zakrzhevskaya, N. A., and G. A. Sobolev (2002), On the Seismicity Effect of Magnetic Storms, *Izvestiya*, *Physics of the Earth*, *38*(4), 249–261.

Zakrzhevskaya, N. A., and G. A. Sobolev (2004), The Effects of Magnetic Storms with an Abrupt Start on Seismicity in Different Regions, *Volcanology & Seismology*, (3), 63–75 (in Russian).

Zeigarnik, V. A., L. M. Bogomolov, and V. A. Novikov (2022), Electromagnetic Earthquake Triggering: Field Observations, Laboratory Experiments, and Physical Mechanisms - A Review, *Izvestiya*, *Physics of the Solid Earth*, *58*(1), 30–58, https://doi.org/10.1134/S1069351322010104.

Zettergren, M. D., and J. B. Snively (2015), Ionospheric response to infrasonic-acoustic waves generated by natural hazard events, *Journal of Geophysical Research: Space Physics*, *120*(9), 8002–8024, https://doi.org/10.1002/2015JA021116.

Zhang, X., X. Shen, S. Zhao, L. Yao, X. Ouyang, and J. Qian (2014), The characteristics of quasistatic electric field perturbations observed by DEMETER satellite before large earthquakes, *Journal of Asian Earth Sciences*, *79*, 42–52, https://doi.org/10.1016/j.jseaes.2013.08.026.

Zhima, Z., R. Yan, J. Lin, Q. Wang, Y. Yang, and other (2022), The Possible Seismo-Ionospheric Perturbations Recorded by the China-Seismo-Electromagnetic Satellite, *Remote Sensing*, *14*(4), 905, https://doi.org/10.3390/rs14040905.

Zhu, K., M. Fan, X. He, D. Marchetti, K. Li, Z. Yu, C. Chi, H. Sun, and Y. Cheng (2021), Analysis of Swarm Satellite Magnetic Field Data Before the 2016 Ecuador (Mw = 7.8) Earthquake Based on Non-negative Matrix Factorization, *Frontiers in Earth Science*, *9*, https://doi.org/10.3389/feart.2021.621976.