SHORT REPORT

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The manifestations of geomagnetic activity (solar flares and magnetic storms) in the change of electrotelluric potentials according to measurements at the Yuzhno-Sakhalinsk geophysical test site

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Abstract. The results of the analysis of changes in electrotelluric potentials (ETP) during the observation of intense solar flare events and intense magnetic storms on Sakhalin are presented. The data were studied in the period from July 20 to October 12, 2023. The absence of characteristic changes in the ETP (integral amplification or attenuation of noise in the low-frequency region) depending on the presence or absence of a solar flare event is shown. At the same time, in some cases, the strongest flashes were found to coincide with the appearance of signals of the GUV type (Geyser type ULF Variation). For almost three months of observations, five cases of quasi-periodic GUV series have been identified, four of which coincide completely or partially with the times of solar flares and magnetic storms. It should be noted that earlier in the literature, the appearance of these signals was not correlated with any physical process. At the same time, the identification of such patterns is an integral part of extensive work on identifying predictive signs of earthquake preparation in the ETP.

Keywords: a series of electrical signals, solar flare, telluric potentials, magnetic storm, GUV

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Introduction

The mechanisms of interaction between the Earth and the surrounding macrocosm, between geospheres and inside each of them, are determined by the diversity of geophysical fields and their nature. The electric field of the Earth is of particular interest for research, since electric effects not only have a significant impact on the course of natural phenomena and processes but are also significant for modern man in the organization of industrial and technological cycles [1]. In applied geophysics, special attention is paid to regional-scale electric fields, since they cover large volumes of the Earth's crust and troposphere adjacent to the surface, where the conditions for human life are formed. Regional fields of electrotelluric currents are complex current systems formed under the influence of external and internal factors. Solar corpuscular radiation has a significant impact on the change in the components of the field of electrotelluric currents. As a result of the interaction of the supersonic solar wind

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A translation from Russian: Закупин А.С., Стовбун Н.С., Гуляков С.А., Казаков А.И., Дудченко И.П. Проявления геомагнитной активности (солнечные вспышки и магнитные бури) в изменении электротеллурических потенциалов по данным измерений на Южно-Сахалинском геофизическом полигоне. Геосистемы переходных зон, 2024, т. 8, № 2, с. 91–103. https://doi.org/10.30730/gtrz.2024.8.2.091-103. *Translated by Valeria Maksimova.*

with the magnetosphere and ionosphere, electromagnetic field oscillations from 0.0001 Hz to the first hundreds of hertz arise.

For instrumental observations of non-stationary variable regional electric fields of the Earth's crust, the method of telluric currents and its modifications are used, the theoretical foundations of which were laid back in the 1930s under the leadership of K. Schlumberger [2]. In generalized form, the installation for recording the field of telluric currents consists of recording equipment and two pairs of grounding electrodes, located perpendicularly. Despite the relative simplicity, the network of electrometric stations on Earth is very rare [3].

In the Sakhalin Oblast, there have never been any permanent stations for registering the electrotelluric field. In 2023, the first such station began operating at the Institute of Marine Geology and Geophysics of the Far Eastern Branch of the Russian Academy of Sciences (IMGG FEB RAS). By June, a measuring module was developed at the institute, based on which an autonomous station for registering telluric currents was deployed [4]. Over almost a year of continuous operation, significant volumes of data have been accumulated, including signals from various sources, including those induced by anthropogenic factors, as observations are carried out on the territory of the IMGG FEB RAS, which is located near Yuzhno-Sakhalinsk. The majority of publications and manuals recommend placing the registration station in areas with low industrial noise [1, 5], but in the era of rapid industrialization and urbanization, implementing this without government support is not easy. However, there are known cases when such research has been successfully conducted even in urban conditions. For example, the electrotelluric station opened in 1958 in the town of Gurbanovo on the territory of the geomagnetic observatory [6]. The processing of the registered phenomena in [6] was carried out statistically, classifying them into groups: 1) special phenomena, 2) short-period oscillations (with a period of more than 100 seconds), 3) storms, 4) disturbances. Based on the processed results, bulletins were compiled, in which, using typical designations, the type of phenomenon, quality, start and end times, maximum amplitude and average (maximum, minimum) period were indicated [6]. Such an approach is relevant today, as the accumulated database of events can be used in conjunction with artificial intelligence algorithms to automate the processing and correlation search process, for example, with seismic waves. In the work [7], based on the results of comprehensive analysis, numerical modeling, laboratory and field tests using existing global technological methods, the authors propose solutions for implementing electrical monitoring when observing engineering-geological processes in urban and industrial areas.

Taking into account the above, it is of interest to analyze the telluric monitoring data from the IMGG FEB RAS observation point in order to search for possible correlations with magnetic storms from solar flare events.

We should note that these events do not always coincide, and the geomagnetic indices should be considered decisive, but observatories are not available everywhere, and therefore, along with the planetary Kp index, the moments of the high-class flares themselves should be included in the consideration. A similar analysis was recently carried out by the authors [8] for the city of Yakutsk during the large magnetic storm of September 07–09, 2017. A sufficiently high correlation coefficient of 0.5–0.9 was found. The same high correlation coefficient was obtained using the technique described in [9], when studying the influence of geomagnetically induced currents on the electrical networks of the Kamchatka region [10].

Unlike the listed works, in which the measuring system included magnetometers, only electric dipoles are possible at our point. Despite this, we consider it advisable to carry out such a study. One of the reasons is the use of new approaches in data acquisition and processing. Thus, in our recent work [4], it was shown that a significant increase in the sampling rate when measuring the electrotelluric potential (ETP) makes it possible to detect signals that were previously simply impossible to register. Moreover, thanks to new solutions in electrotelluric observations, correlations have been probably established between quasi-periodic series of such signals and an earthquake in the near zone [4]. This made it possible to take a different look at the data obtained and pay attention to other interrelated processes, which together can contribute to solving the problem of earthquake forecasting. Relying, among other things, on a deep review of the state of research in geoelectrics, recently published by V. Pilipenko [12], we can state the relevance of our work, despite the short observation periods from the geophysicists' point of view.

Data

Electrotelluric measurement data

Electrotelluric measurements at the IMGG FEB RAS test site represent a new level, taking into account the achievements of modern science in instrumentation and software for processing long time series.

Prior to this, the study of ETP was carried out in the field measurement mode and had a number of practical disadvantages. The new concept, hardware and software components of the ETP measurement complex, as well as the first results, are described in detail in [4]. Let us note the key aspects of the hardware solutions: high-speed analog-to-digital converters, minimal hardware noise, and high sampling rate. Naturally, mathematical packages (currently foreign) are used in processing, which can perform the construction and fast Fourier transform (FFT), filtering of time series in tens of millions of samples. ETP measurement data are presented in separate text format packages, which contain measurements from three channels (three dipoles, NS, WE, NWSE) taken at a sampling rate of 300 Hz. Based on the maximum possible number of samples for processing in the Origin Pro package (92 million), one package can contain several days of measurements. The ETP measurement database includes continuous recordings from July 20, 2023, to the present. In this work, for the analysis, we selected data up to the date of the last record in the flare catalog, i.e. October 12, 2023. The data were pre-filtered using a 0.01–1 Hz bandpass filter. We should note that this step significantly improves the quality of the analysis, since there is quite a lot of interference in the high-frequency region, and the noise level for the broadband signal is 4 times higher than the noise of the filtered signal in the band from 0.01 to 1 Hz.

Table 1. X-ray-class solar flare events from M5 from July 20 to October 12, 2023

Date, dd.mm.yyyy	Time, h:m			Class, X-ray/opt	L ($J \cdot m^{-2}$)
	to	tm	te		
05.08.2023	21:45	22:21	22:44	X1.6	0.3
06.08.2023	18:20	18:40	19:11	M5.5/SN	0.06
07.08.2023	20:30	20:46	21:18	X1.5	0.28
03.09.2023	08:09	08:36	08:56	M6.0	0.064
20.09.2023	14:11	14:19	14:25	M8.2	0.036
21.09.2023	12:42	12:54	13:02	M8.7	0.001

Notes. Date (dd.mm.yyyy) of implementation of the solar flare event. Time (UTC): to, tm, and te indicate the time of the beginning, maximum, and end of the full flare event, respectively; a flare in Hα (spectral line of the Balmer series of the hydrogen atom) and a burst in the soft X-ray range (1−8 Å = 12.5−1 keV). Accordingly, to and te are determined by the earlier start and later end in these ranges, tm – by the burst in X-rays. If only an X-ray burst is observed, then the end of the event is determined by the point where the intensity decreases by half from Imax to the background. Class: X-ray/opt is X-ray class and optical score of the flare event. L ($J \cdot m^{-2}$), – integral flux in the standard X-ray range from the beginning of the burst through the maximum to 1/2 of the maximum intensity.

Data on solar flare events

The cumulative catalog of solar flare events of X-ray class M1–X > 17.5 of solar activity cycle XXV (I.2020 – VI.2030), which is freely available (author V. Ishkov, Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation of RAS; The Geophysical Center of the Russian Academy of Sciences), was used for the analysis. The catalog was downloaded in version 5 (October 2023), and, accordingly, the latest data in it are dated October 12, 2023. For our study, records from July 20, 2023, i.e., from the moment of the beginning of ETP registration at the IMGG FEB RAS test site, were used. In this work, we focused our attention on large flares that are capable of causing noticeable ionospheric disturbances. Table 1 shows the few events of M-class with an index of 5 or more that were recorded from July 20 to October 12, 2023. The time is given in UTC format for ease of comparison; to obtain local (Sakhalin) time, 11 hours must be added.

As can be seen from Table 1, three periods of activity stand out, with 5 out of 6 events occurring in two of them, from August 5 to 7 and from September 20 to 21. One event, the weakest (M6), occurs on September 3. The first period stands out most with two X-class flares. It is also possible to note the low intensity of the flux from the events of September 20 and 21 despite their sufficiently high class.

Magnetic storms data

The Internet project “Laboratory of Solar Astronomy” of the Space Research Institute of the Russian Academy of Sciences and the Institute of Solar-Terrestrial Physics of the Siberian Branch of the Russian Academy of Sciences (https://xras.ru/magnetic_storms.html) was used as the data source. The laboratory provides information on the geomagnetic activity of the Earth, as well as on solar phenomena, and is freely available. The data are presented in histograms containing information on the dynamics of the planetary Kp index. Based on this index, the G scale of the geomagnetic storm intensity was calculated. Data on magnetic storms of G1 index and above for the period from July 20 to October 12, 2023, were selected from the archive and summarized in a table. During this period, 9 magnetic storms were observed, 7 of which were of G1 level and 2 of G2 level (Table 2). The period of maximum activity of each storm and the corresponding value of the Kp index are entered in the table. In Figure 1, we demonstrate 6 periods that included 9 magnetic storms from Table 2.

The correlation between solar flares and magnetic storms is a very complex topic, and it is the subject of separate studies by specialists. A clear connection is not observed from a simple comparison of solar flares and magnetic storms. Even the first entries in Tables 1 and 2 raise ques-

Table 2. Magnetic storms from July 20 to October 12, 2023

№	Date, dd.mm.yyyy	Time, h:m			G-index	Kp-index
		Start	Maximum	End		
1	05.08.2023	01:00	01:00–07:00	13:00	G2	6.67
2	02.09.2023	04:00	04:00–10:00	13:00	G1	5.33
3	02–03.09.2023	19:00	22:00–04:00	04:00	G1	5.67
4	12.09.2023	10:00	13:00–19:00	19:00	G1	5.67
5	18–19.09.2023	16:00	01:00–07:00	07:00	G2	6.67
6	19.09.2023	10:00	Absent	19:00	G1	5.33
7	24–25.09.2023	16:00	16:00–01:00	07:00	G1	5.67
8	26.09.2023	07:00	Absent	16:00	G1	5.33
9	05.10.2023	01:00	Absent	07:00	G1	5

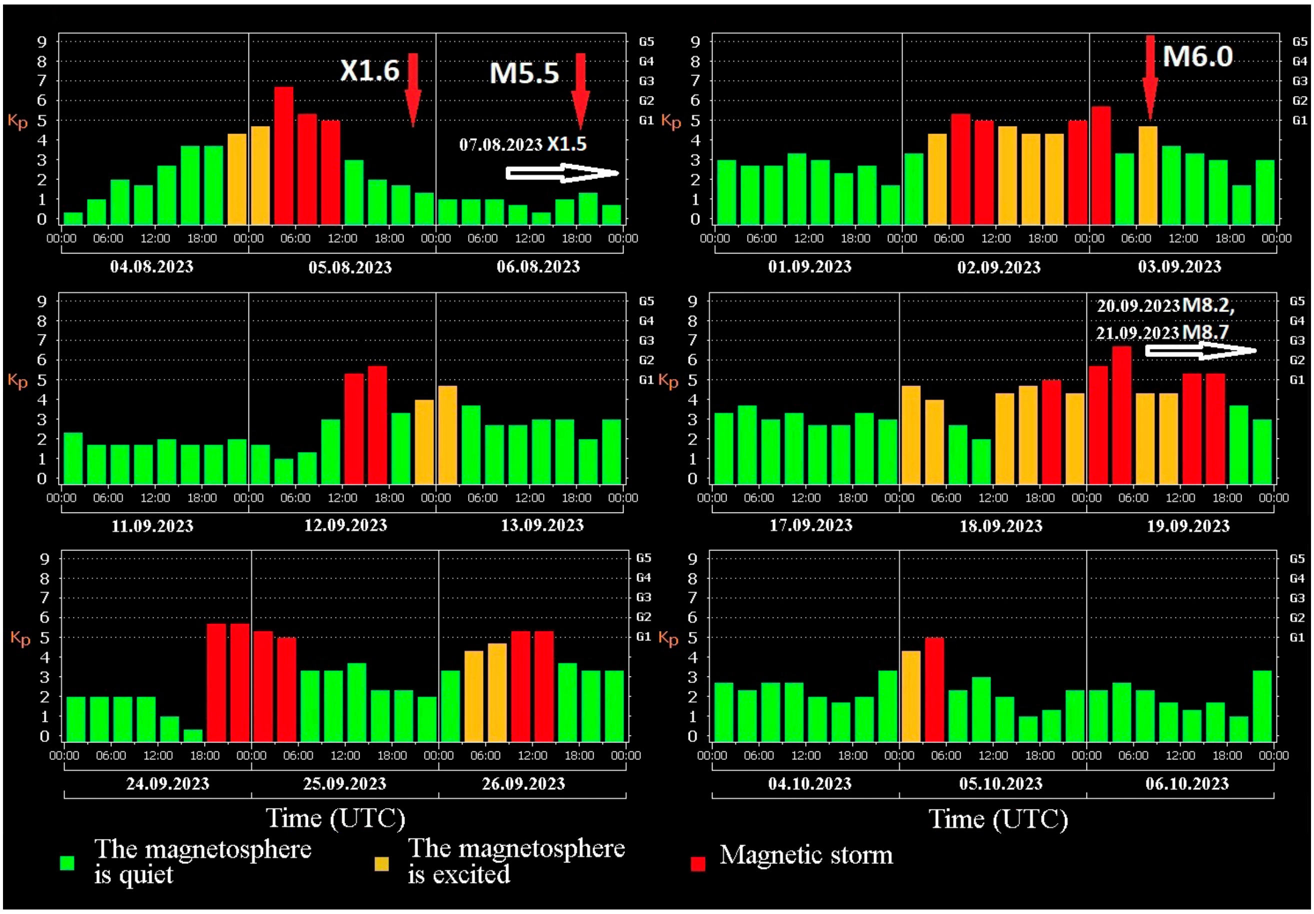


Fig. 1. Periods with magnetic storms for which the G-index is greater than or equal to 1 from July 20 to October 12, 2023. The arrows show the flash points from Table 1. The intensity of the magnetic storm: G1, weak; G2, medium; G3, strong; G4, very strong; G5, extremely strong.

tions. However, we do not consider these questions in this work. Our purpose is to compare ETP variations with the moments of solar flares and then with magnetic storms. We should note that comparing data with magnetic storms, of course, has much more physical meaning than with solar flares; however, this does not deprive the comparison of all three phenomena simultaneously of meaning and interest.

Results

To demonstrate the large periods of time in which solar flares occurred, and on which the prolonged influence of magnetic storms could be assessed, data cuts with a duration of 3-4 days were prepared. These cuts do not always end on whole days, but they clearly follow each other in time. In total, it was possible to fit approximately 10 days into three graphs. In all the following graphs with variations of the ETP, a single scale is observed for each channel, and, in addition, key events (flares and earthquakes) are plotted. The graphs are oriented to periods that cover all events from Table 1, but they also include the majority of the events from Table 2. Despite the fact that the analysis of possible relationship of seismicity to variations of the ETP is not part of the work (this is the task of further research), we consider it useful to show significant earthquakes (with a magnitude greater than 3) that occurred within the study area (within a radius of 25–30 km) on the graphs. A list of these earthquakes is presented in Table 3, and a seismicity map for the period from July 20 to October 12, 2023, is shown in Figure 2.

The Figure 2 and Table 3 show local magnitudes. The dynamics of seismicity over such

Table 3. Earthquakes with M > 3 within a radius of 0.25° from the measurement point

Date, dd.mm.yyyy	Time, h:m:s	Coordinates		Depth, km	Magnitude, M
08.08.2023	18:14:34	47.02°N	142.56°E	6	3.8
18.09.2023	15:49:33	47.12°N	142.61°E	9	3.1

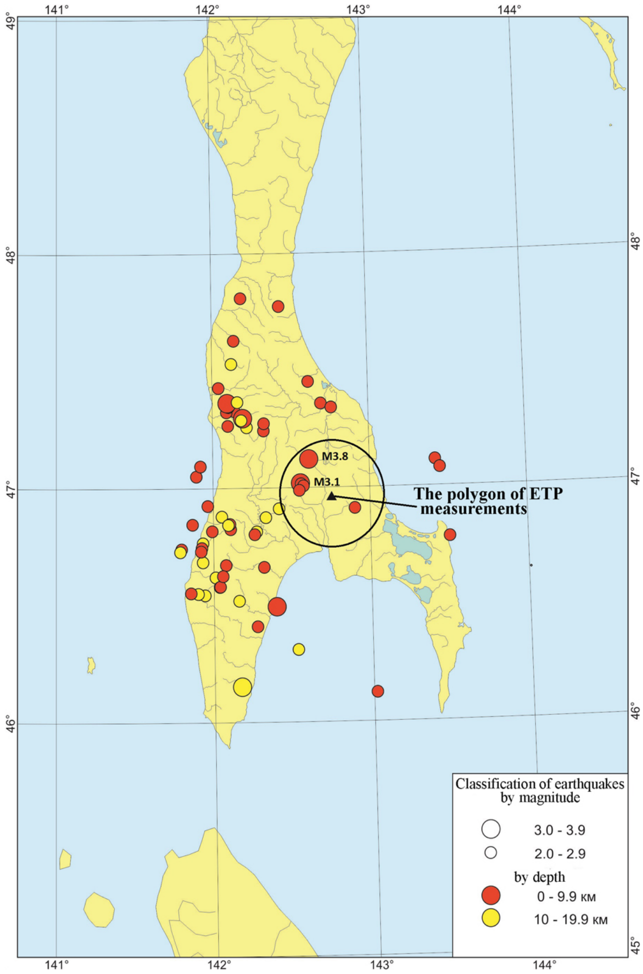


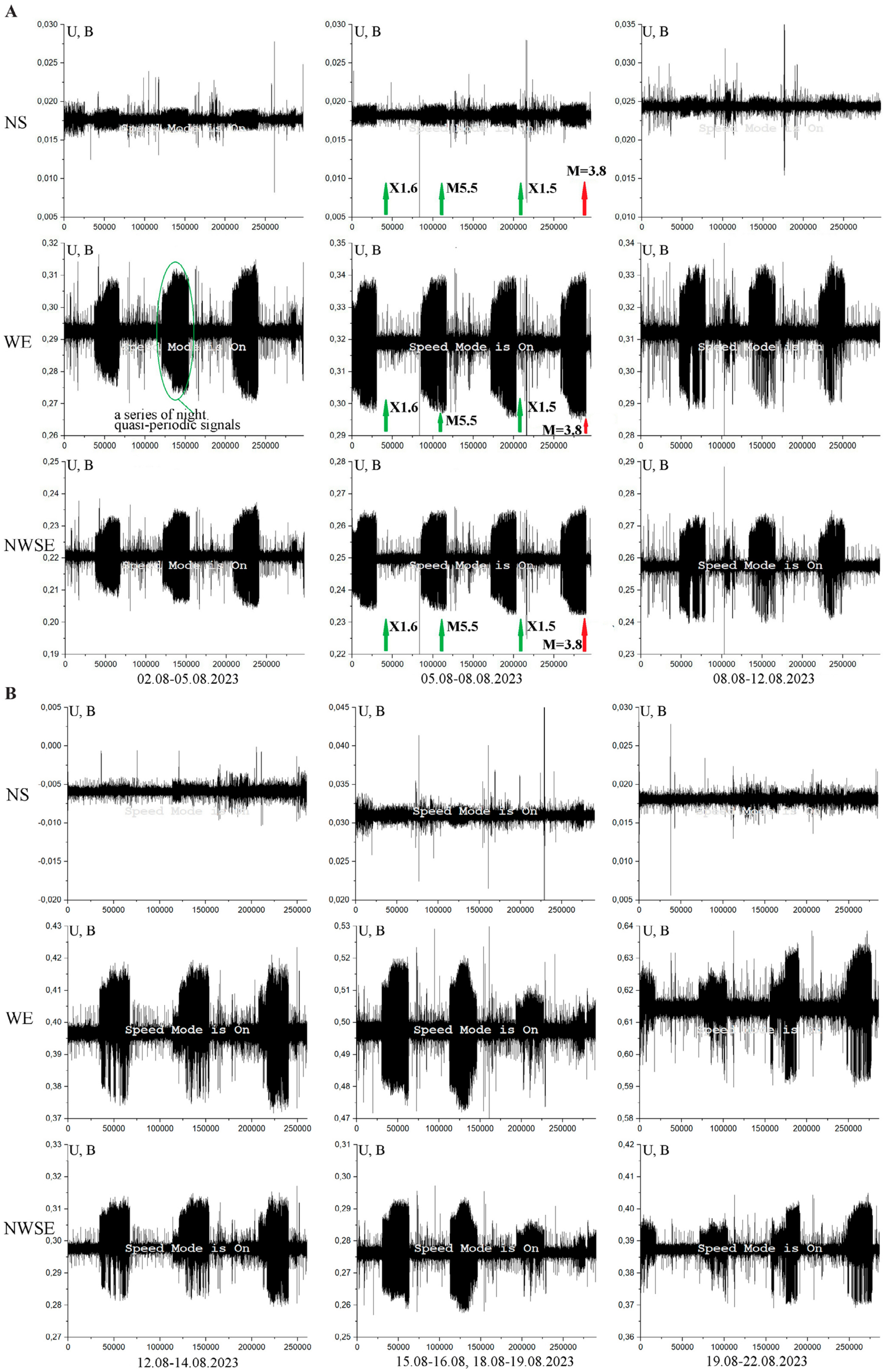
Fig. 2. Seismicity map of the South Sakhalin Island from July 20 to October 12, 2023.

a short period of time is not particularly remarkable, but two earthquakes with M > 3 in the vicinity of the test site are a very rare occurrence, which we noted in our work [4]. So, regarding the ETP data (Fig. 3). The first period of flare activity (Fig. 3 A) coincides with one of the key events of our first study [4] – the earthquake of August 8, 2023, with M = 3.8.

We should note (although this has nothing to do with the issues of this work) that Figure 3 A clearly shows the nocturnal series of signals that were detected in the study [4] from 20.07 to 11.09.2023, and every day for the entire period were observed. It was noted in [4] that during this period, nocturnal series of quasi-periodic pulses changed parameters before and after a seismic event in the area of the landfill (08.09.2023). And on our charts, this key moment just turned out to be captured. We see an increase and stabilization of the signal amplitude, and then, after the earthquake, a disruption of the integrity of the signals that make up the series. The two strongest flare events during the 82-day period occur one day and three days before one of the two strongest earthquakes in the study area. This is undoubtedly an interesting observation and even a subject of future research, but the task of this work is to determine the possible influence of flares on the variation of telluric potentials. Upon detailed examination of ETP variations on all channels and over the entire time period (Fig. 3 A), we were unable to detect any noticeable increase in the number or amplitude of the variations, as well as signals of a certain shape or periodicity (or quasi-periodicity, as in the nocturnal series).

Figure 3 C shows the period from August 31 to September 9, 2023, during which a flare occurred that was close to the lower boundary of our selected range in terms of class, but comparable in radiation intensity to stronger flares (Table 1).

This period is also notable in that the nocturnal series of signals have already significantly weakened (they are no longer visible on the NS channel). We remind you that these episodes after September 11 (until 01.05.2024) were no longer registered by us. However, in these charts, attention is drawn to the strengthening of the signal level on September 3. On the WE channel, we marked this event as GUV. The GUV mark was not chosen by chance. The abbreviation translates as Geyser type


A
NS
WE
NWSE
U, B
0,030
0,025
0,020
0,015
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0,005
0,035
0,32
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0,30
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0,19
0
50000
100000
150000
200000
250000
Speed Mode is On
X1.6
M5.5
X1.5
M=3.8
a series of night quasi-periodic signals
02.08-05.08.2023
05.08-08.08.2023
08.08-12.08.2023
B
0,005
0,000
-0,005
-0,010
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-0,020
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15.08-16.08, 18.08-19.08.2023
19.08-22.08.2023

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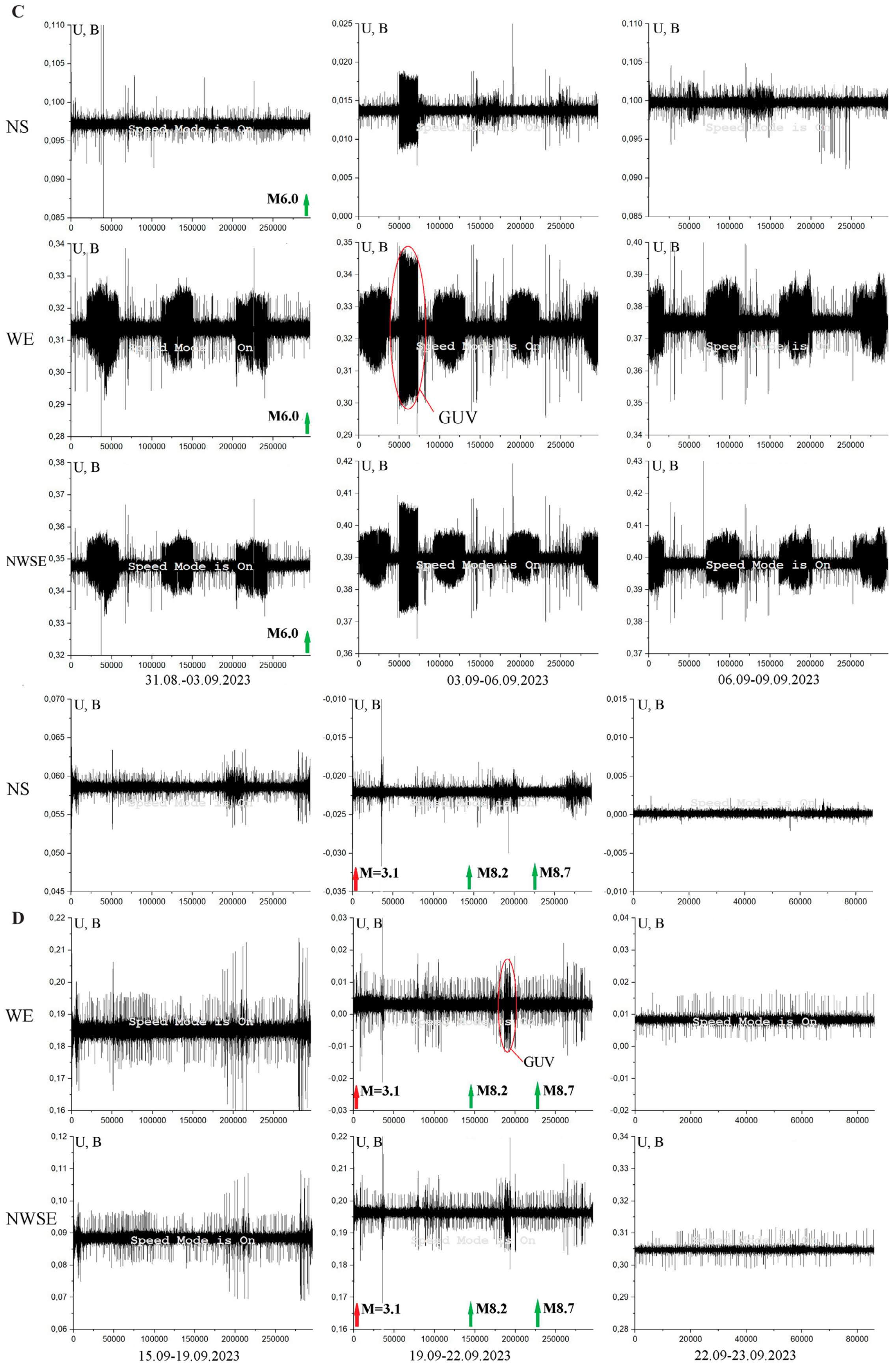

Fig. 3. Potential changes on the NS, WE, and NWSE dipoles: (A) 02.08–12.08.2023; (B) 12.08–16.08 и 18.08–22.08.2023; (C) 31.08.2023 – 09.09.2023; (D) 15.09–23.09.2023. Green arrows show the moments of flare events (*t*0) and their class. A series of quasi-periodic signals is marked with a red outline and the GUV symbol.

ULF Variation. Such a name was given to signals at ultra-low frequencies because of the similarity of the temporal variation of the electric field strength to the change in the height of the water in the geyser [11]. However, the work [11] does not reveal their connection with any physical phenomenon.

In our graph, we see not just an increase in the noise component, but a series of typical quasi-periodic GUV signals (an enlarged fragment is shown in Fig. 4). We have previously mentioned that these signals are present in our measurements [4], although at that time we did not set ourselves the task of finding out their origin or identifying any correlations with other phenomena. As can be seen from Figure 4, the GUV signals in our case have a variable polarity, their amplitude on the NS channel is about 5 mV, their duration is about 5 s, and their period for unipolar signals is about 95 s (c).

In total, the series lasted for about 6 hours and began approximately 14 hours after the solar flare occurred. The last flares from Table 1 also occurred in September 2023 (Fig. 3 D).

During the same period, the second earthquake from Table 3 was observed, which occurred at 15:19 UTC on September 19, 2023, and had a magnitude of M = 3.1. However, the first event occurred exactly after two X-class flares, while the second occurred one day before two M8-class flares. On the graphs, one can note a significant decrease in the level of variations and their number one day after the last flare. However, the most interesting observation is the detection of a series of GUV signals (the series is marked on the WE channel, Fig. 3 D) on September 21, which, although significantly weaker than on September 3 (on the NS channel, the signals are generally indistinguishable), stand out reliably (Fig. 5).

The series was detected 12 hours after the first flare event on September 21 and lasted only about 2 hours. This is already the second case, and despite the fact that nothing similar was observed after the X-class flares in early August (Fig. 3 C), there is a need to consider the issue in detail. We will do this later, but first, we propose to consider a comparable time segment when the solar activity was at a minimum (Fig. 3 B), i.e., there were no flares, and the geomagnetic index was in the green zone (Kp < 4).

A detailed analysis of the graphs revealed no significant changes in the variations of the ETP compared to previous periods. Notably, the degradation of nighttime series, which began to be disrupted on August 10, persists. Furthermore, no other quasi-periodic series of signals of a specific and consistent form, similar to GUV, were detected.

We will now examine the time periods when the most intense magnetic storms were recorded. All nine magnetic storms were success-

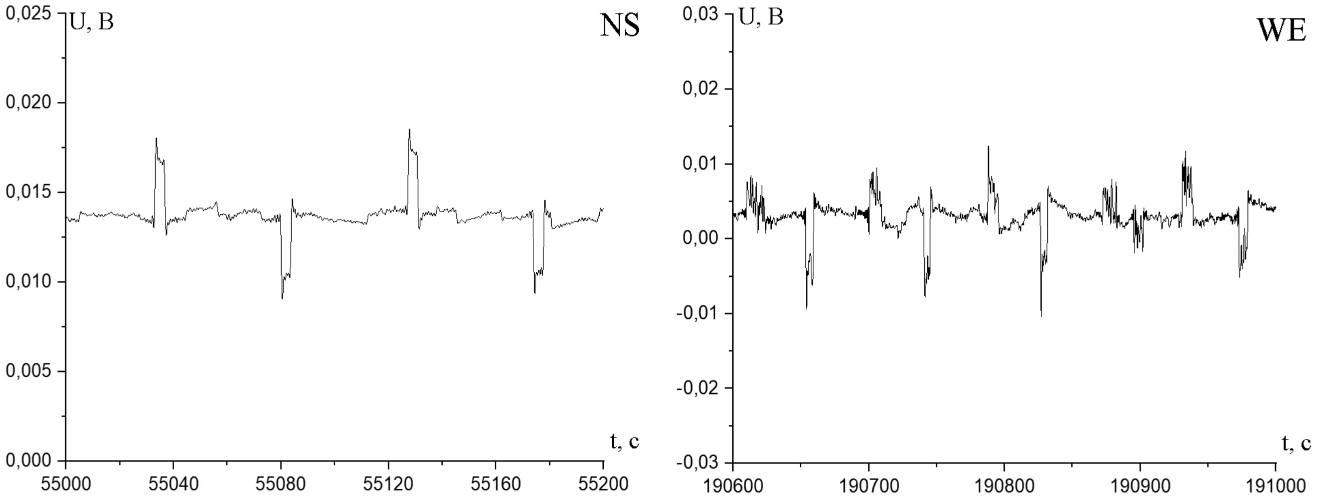

Fig. 5. Fragments of potential changes on the NS channel on September 3, 2023 (on the left) and on the WE channel on September 21, 2023. Separate GUV type signals are presented, which make up quasi-periodic series.

Table 4. Parameters of GUV series

№	Date (dd.mm.yyyy) and time (h:m) Start	End	T (c)	t (c)	A(NS), B	A(NWSE), B	A(WE), B	Channels
1	03.09.2023 22:25	04.09.2023 4:31	87 c	4.21	0.00451	0.0173	0.0241	NS, WE, NWSE
2	21.09.2023 2:14	21.09.2023 4:24	82 c	5.3	–	0.0108	0.0126	WE, NWSE
3	25.09.2023 1:02	25.09.2023 5:12	82 c	4.23	0.0015	0.012	0.015	NS, WE, NWSE
4	02.10.2023 1:30	02.10.2023 5:00	85 c	4.64	0.00195	0.0104	0.0117	NS, WE, NWSE
5	05.10.2023 3:55	05.10.2023 4:51	86 c	4.24	0.00239	0.0106	0.017	NS, WE, NWSE

Note: T, period between signals of the same polarity; t, pulse duration; A, pulse amplitude.

fully mapped onto six three-day periods (Fig. 1). As shown in Tables 1 and 2, and Fig. 1, magnetic storms precede solar flares in almost all cases. However, for instance, on September 12, 24–26, and October 5, when magnetic storms were recorded, no significant flares were observed at all. We analyzed the ETP data during these periods as well. Aside from the already familiar series of GUV signals, we found no novelties related to the passage of storms. We should immediately note that we will not provide ETP graphs for magnetic storms that did not appear in the drawings, as well as similar graphs of the new GUV series, since the results are identical.

Let us return to the question of the possible connection of GUV with geomagnetic manifestations. To address this, we meticulously reviewed the data collected during the entire study period, from July 20 to October 12, 2023. This involved scaling all three channels daily to search for the presence of GUV signals. We should note that this effort was substantial, considering the time required to load daily files containing recordings from three channels with a sampling rate of 300 Hz into a mathematical package, and the need to scale data in packages of several dozen minutes. The results of this analysis are presented in Table 4.

A total of five series of GUV-type signals were observed, with two appearing 12–14 hours after a flare event (Table 4, No. 1, No. 2; Fig. 3 C, D). On average, the series last for several hours, the shortest lasting approximately 1 hour and the longest almost 6 hours. The amplitude and duration of the pulses, as well as the period between them, fluctuate slightly. There is no selectivity with respect to days of the week. The onset of the series varies, while the termination occurs around 15–17 hours Sakhalin Standard Time. The period between GUV signals in our measurements is nearly half the period between the signals we recorded at night in August-September [4], but comparable to them in pulse duration and amplitude. A comparison of data from Table 2 and Table 4 reveals additional information. We will examine each GUV series individually.

1. The series begins on September 3 at 22:25 after magnetic storms No. 2 and No. 3, essentially 12 hours after the end of the storms and the emergence of the flare.

2. The series begins on September 21 at 2:14, while magnetic storms had ended by the evening of September 19 (Table 2, No. 5, 6), and flares of M8.2 and M8.7 occurred on September 20 and 21.

3. The series on September 25 exhibits a clear correlation with magnetic storm No. 7 from Table 2, not only in terms of date but also aligning with its time interval. Notably, there are no flares during this period.

4. The series on October 2 does not coincide with any events.

5. The series on October 5 aligns clearly with storm No. 9 (Table 2) in terms of both date and time. No flares occur during this period.

It turns out that four out of the five GUV series correlate with magnetic storms and/or flares. Moreover, this correlation exhibits intriguing characteristics. In cases 1 and 2, there is a delay, but also a lead by the storms in relation to the flare events. In the absence of flares, magnetic storms perfectly coincide with the GUV series. Two storms, on August 5 and September 12, did not accompany series of signals. This suggests that if correlations exist, they are at least non-linear.

Thus, based on the obtained results, some coincidences exist between ETP variations, solar flares, and magnetic storms. These connections, likely, manifest in the ETP as series of GUV signals.

Of course, according to data from only three months of measurements in a zone with a high level of interference, it is premature to conclude that magnetic storms and the GUV series do have a clear connection. We would just like to draw attention to the form in which this supposed influence may manifest itself. Many were suspicious of the nightly series of signals [4], which appeared as if instantly and stopped in the same way. Now we have seen GUV-type series, which, although filled with signals of a different form, accurately repeat the behavior of night series (quasi-periodicity, abrupt appearance), and most importantly, perhaps correlate with the source that could generate them – variations in the Earth's magnetosphere.

Conclusion

This work considers variations in electrotelluric potentials at the geophysical test site of the Institute of Marine Geology and Geophysics FEB RAS in Yuzhno-Sakhalinsk during periods of intense solar flare events and/or magnetic storms. No integral enhancement or attenuation of telluric noise was detected during flare events or during the passage of magnetic storms in the low-frequency spectrum. For some events, coincidences were found with the appearance of quasi-periodic GUV-type (Geyser type ULF Variation) signal series in the telluric potential field. However, no such series were recorded for the strongest X-class events. GUV series were also identified that were recorded in the absence of flares but in the presence of a magnetic storm. Only four out of five GUV signal series coincided entirely or partially with storms and flares. At this stage of the research, it can be assumed that it is likely to detect significant correlations between intense solar flares (from M5), magnetic storms (G1 and more) and variations of ETP when analyzing a larger volume of data. We believe that this work will be an additional incentive to use the proposed new hardware solutions in the task of searching for earthquake precursors in variations of the ETP.

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