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EXCITATION OF GLOBAL ARTIFICIAL Pc1 SIGNALS DURING FENICS-2024 EXPERIMENT: 1. OBSERVATIONS

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Abstract. In July–August 2024 on the Kola Peninsula, the FENICS-2024 experiment was conducted to generate artificial electromagnetic signals at night, using two power transmission lines as a horizontal radiating antenna. The generator frequency varied discretely from session to session from 1 to 194 Hz with current amplitude from ~150 A at low frequencies to ~40 A at high frequencies. The paper presents the results of the first stage of the experiment when the power transmission line Vykhodnoy—Olenegorsk with a distance between earth electrodes of substations L=84 km was utilized as a radiating antenna. Magnetic stations, located from ~1200 to ~2100 km from the nodal substation, recorded signals with frequencies from 1 to 9 Hz with ~0.3–~6.0 fT/A amplitudes normalized to the emitter current. The observations have shown the promise of the new type of active experiments on creating a probing signal for magnetotelluric sounding over a large area.

The observation results will be compared with theoretical models in the subsequent work.

Keywords: ULF emissions, distributed network, FENICS, power transmission line, active experiments.

INTRODUCTION: EXCITATION OF ARTIFICIAL ULF EMISSIONS

Ultralow-frequency (ULF) waves in the frequency range from fractions of Hz to a few Hz (Pc1 pulsations) are of particular importance for space physics. Due to the resonant wave–particle interaction, electromagnetic ion-cyclotron (EMIC) waves of the Pc1 range can cause precipitation of relativistic electrons from the outer radiation belt into the atmosphere and thus reduce the "killer" electron flux to a level safe for satellite electronics [Usanova et al., 2014]. In addition, ULF electromagnetic disturbances are widely used for magnetotelluric sounding of the earth's crust [Berdichevskii, Dmitriev, 1992]. The question arises: Is it possible to artificially excite Pc1 electromagnetic waves?

For the first time, artificial Pc1 signals were detected during high-altitude nuclear explosions. For example, the Argus explosion in the ionosphere over the Atlantic caused geomagnetic disturbances with periods 1–3 s and amplitudes 2–5 pT, which spread to almost all parts of the world [Berthold et al., 1960]. As a less extreme method, excitation of artificial Pc1 pulsations by modulated ionospheric radio heating was proposed [Getmantsev et al., 1977; Papadopoulos et al., 2005, Guo et al., 2021]. In the first experiments at the SURA facility with modulated pulsed short-wave (HF) irradiation of the dayside ionosphere, excitation of magnetic pulsations was detected at a modulation frequency of 3 Hz with amplitudes of several nT at ~100 km from the transmitter [Getmantsev et al., 1977]. Presumably, heating of the E layer causes variations in the electron collision frequency, on which the conductivity of collisional ionospheric plasma depends, resulting in periodic modulation of the ionospheric current, which excites geomagnetic pulsations, in the heating region. Modulated HF heating of the F-region can generate ionospheric currents that act as an antenna for injection of Pc1 waves into the ionospheric waveguide [Papadopoulos et al., 2005, 2011a]. The pressure gradient related to pulsating heating of electrons produces a local diamagnetic current at the modulation frequency, which excites a magnetosonic wave [Li et al., 2024]. Artificial ULF waves are thought to propagate along the ionospheric magnetosonic waveguide, whereas ground responses are detected only in those regions where the wave reached the E-region after reflecting from the upper wall of the waveguide. This mechanism for generating artificial Pc1 pulsations has been confirmed in experiments with HAARP, EISCAT, and Arecibo heating facilities. A spatially localized wave response at a modulation frequency of 2.5 Hz was detected by ground magnetometers 20 km from the HAARP facility and by the low-orbit satellite DEMETER within 100–150 km from the heating site [Papadopoulos et al., 2011b]. During another heating experiment, there were spectral peaks at a modulation frequency of 3.8 Hz with 30–40 fT amplitudes in the data from ground magnetic stations [Eliasson et al., 2012]. Several campaigns for modulated heating of the ionosphere with the SURA facility have shown that the ponderomotive force plays a leading part in excitation of artificial signals due to the pressure gradient in the ohmic heating region [Kotik et al., 2013]. Pulsations in the range 2–20 Hz with amplitudes from 0.2 to 0.5 pT occurred only in the vicinity of the heating facility (the first tens of kilometers) and sharply decreased in amplitude with distance from it.

The method of exciting Pc1 emission by radio heating requires enormous expenses and needs a heating facility. The question arises whether another ground antenna can be used to generate artificial Pc1 pulsations in the ionosphere, despite the fact that noticeable efficiency in ultra- and extremely low-frequency (ELF) emissions (from a few to hundreds of Hz) can be expected only for extremely large-scale emitting systems. Indeed, such ULF-ELF transmitters exist — this is an extensive global network of power transmission lines (PTLs). In a balanced mode, radiation from a three-phase PTL at the industrial frequency 50–60 Hz is low, but in an asymmetric unbalanced mode PTL networks become a source of radiation at the industrial frequency that penetrates even into near-Earth space [Pilipenko et al., 2021b]. Consequently, PTL disconnected from the trunk network can be utilized as a controlled source of ULF/ELF radiation [Belyaev et al., 2002; Ermakova et al., 2005; Ermakova et al., 2006].

FENICS (Fennoscandian Electrical conductivity from soundings with the Natural and Controlled Sources) experiments are conducted on the Kola Peninsula with controlled sources of ULF/ELF electromagnetic fields, using PTL as a horizontal radiating antenna [Velikhov et al., 1994; Zhamaletdinov et al., 2015, 2019]. The main objectives of the experiments with artificial signals involve magnetotelluric sounding (MTS) of the Fennoscandian Shield to construct a model of lithospheric conductivity and to study propagation features of the ULF/ELF electromagnetic field in the Earth–ionosphere waveguide. In the period from July 25 to August 8, 2024, another experiment FENICS-2024 was performed using temporarily decommissioned 330 kV PTLs as radiating antennas. The paper presents the results of recording of artificial ULF signals at magnetic stations located at a distance ~300–2100 km from the source.

1. THE FENICS-2024 EXPERIMENT AND RECORDING STATIONS

The FENICS-2024 experiment was conducted in two stages (Figure 1):

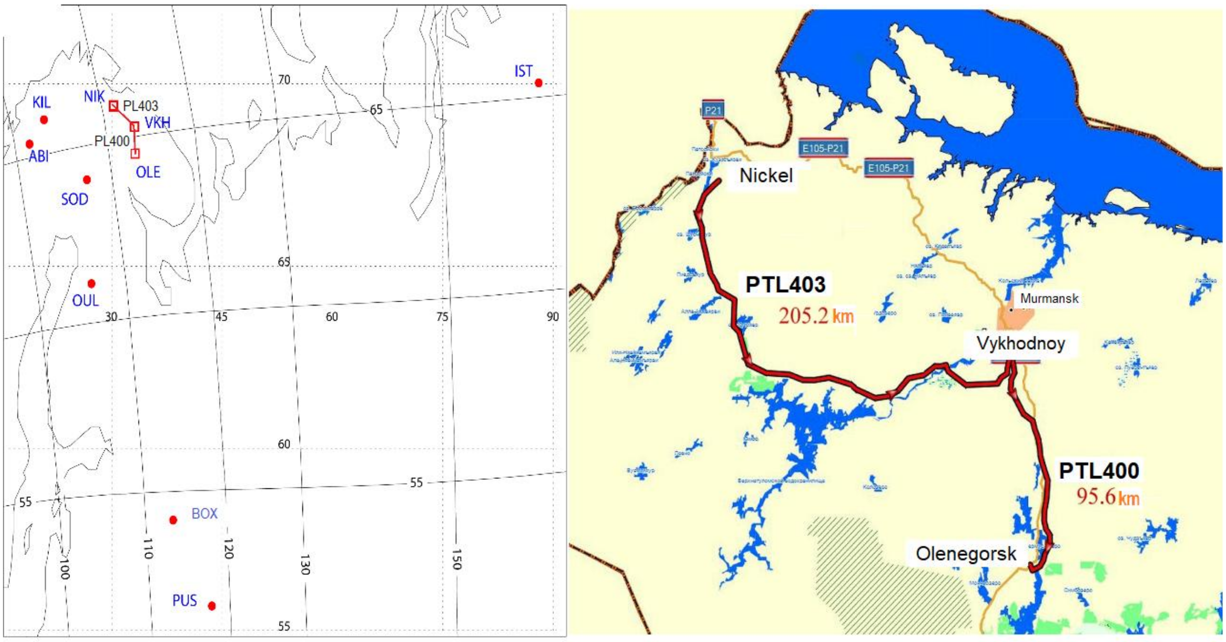

Figure 1. Location of tie stations of the power grid and magnetic stations (*a*): dotted lines are geographic parallels and meridians, dashed lines are corrected geomagnetic lines, as well as PTLs (*b*) used in the FENICS-2024 experiment

- At the first stage, on July 24–25, 2024 according to universal (UT) time, PTL400 Vykhodnoy (VKH) — Olenegorsk (OLE) 95.6 km long with a distance between grounding electrodes of substations L=84 km was used as a radiating antenna.
- At the second stage, on July 30–31 — August 8, 2024 according to universal (UT) time, PTL403 Vykhodnoy—Nickel (NIK) 205 km long with a distance between grounding electrodes of substations L = 130 km was employed.

At both stages, the current source was a generator Energia-2 connected to the grounding device of VKH and to a high-voltage overhead PTL [Barannik et al., 2012; Kolobov et al., 2013]. During the experiment, a 200 kW generator produced alternating current in PTL with an amplitude from ~140–150 A at low frequencies (1–10 Hz) to ~40 A at the highest frequencies (194 Hz). Current with the given frequency was supplied to PTL in 15-min sessions on the schedule from 00 to 04 Moscow time (from 21 to 01 UT). Operating frequencies in the ULF range were 1.0, 1.5, 2.0, 3.0, 4.0, 6.0, 7.5, and 9.0 Hz. The current in the line was recorded using a compensation current sensor up to 0.5 % and linearity of the transfer characteristic of at least 0.1 %. Operating conditions of all PTLs did not change during the experiment. In this paper, we report the results of the first stage of the experiment.

At a relatively small distance from the source (300–550 km), artificial emissions were monitored by induction magnetometers deployed by Sodankylä Geophysical Observatory (SGO) in Finland and Sweden [https://www.sgo.fi]. Most stations of this network operate with a sampling frequency of 250 Hz and have a 35 Hz cut-off filter.

To study features of very long-distance propagation (>1000 km) of ULF signals, two horizontal magnetic field components (B_x — north–south, B_y — east–west) have been observed at several magnetic stations with high-sensitivity equipment.

Borok Geophysical Observatory (BOX) monitors a wide range of geophysical fields [Chulliat, Anisimov, 2008; Anisimov et al., 2008]. Magnetic variations in the Pc1 range are recorded using SMM-009 equipment with a sampling frequency of 100 Hz. The equipment includes a three-component magnetometer based on IMS-010 induction sensors with a flat amplitude–frequency response in the range 2 Hz – 1 kHz and a linear one in the range 0.001–2 Hz at a noise level ~10^{-4} nT/√Hz at 1 Hz [Polyakov et al., 2016]. A signal was identified by spectral accumulation followed by averaging of obtained realizations. BOX is R~1230 km away from VKH.

The station Staraya Pustyn (PUS) is located on the territory of the radio physical facility of SUNN NIRPhI [Ermakova et al., 2019]. Equipment of the receiving station includes an induction magnetometer with a sampling frequency of 64 Hz. The sensors are distinguished by high linearity of conversion, low noise at low frequencies, and a large dynamic range, which allows measurements to be made even at a relatively high noise level. The recording path was calibrated by a narrowband signal from a magnetic current loop. The station is R~1560 km away from VKH.

The station Istok (IST) of the Institute of Solar-Terrestrial Physics SB RAS is located ~100 km north of Norilsk. The induction magnetometer operating at the station with a sampling frequency of 64 Hz has an almost flat frequency response in the 0.3–10 Hz range. The amplitude of the recorded signal was estimated with the following algorithm. For the analyzed interval, the signal spectrum was plotted and a local peak of spectral power was measured. Then, a new spectrum was formed which consists of a peak at the selected frequency, and the inverse Fourier transform was performed into a harmonic signal with the sought-for amplitude. Since the frequency response is flat at frequencies above 1 Hz, the known V–nT conversion ratio was used to estimate the amplitude in physical units. The station is R~2100 km away from VKH.

Geographic coordinates of the stations and the distance R to VKH are listed in Table 1. The location of PTL substations and magnetic stations is shown in Figure 1.

Table 1

Magnetic stations and PTL substations

Station	Code	Latitude	Longitude	R, km
Vykhodnoy	VKH	68.84	33.08	0
Olenegorsk	OLE	68.09	33.17	84
Nickel	NIK	69.40	30.22	130
Kilpisjärvi	KIL	69.05	20.79	493
Sodankylä	SOD	67.37	26.63	314
Abisko	ABI	68.36	18.82	503
Oulujärvi	OUJ	64.52	27.23	546
Borok	BOX	58.03	38.33	1231
Staraya Pustyn	PUS	55.66	43.63	1557
Istok	IST	70.03	88.01	2077

Table 2

Normalized amplitude [fT/A] of artificial signals at different stations (stage 1 of the experiment) July 24–25, 2024 PTL400

f, Hz	BOX	PUS	IST
1.0	6.3	0.41	0.27
1.5	2.0	0.80	0.31
2.0		0.51	0.36
3.0	1.4	0.69	0.37
4.0	1.7	0.65	0.28
6.0	1.8		0.32
9.0	2.2		

2. RESULTS OF RECORDING OF ULF SIGNALS AT DIFFERENT DISTANCES

Geomagnetic conditions during the experiment were quiet. The regional auroral electrojet activity index *IE* [https://space.fmi.fi/image/www/] calculated along the Finnish stations MEK–OUJ–SOD–IVA-KEV–NOR did not exceed 300 nT at night; therefore, the conditions for identifying artificial signals were generally determined by local noise rather than by magnetospheric-ionospheric disturbances. Since signal generation conditions and ionospheric conditions were practically unchanged during this period, recording data is given for one of the days of the first stage of the experiment — July 25, 2024 UT. General information on the total amplitude of the horizontal component of received signals, which was measured in different sessions and was normalized to the emitter current J_0 in the session, is presented in Table 2.

At relatively close stations in Scandinavia, a clear response was recorded on all days of the experiment at all operating frequencies from 1 to 10 Hz. Figure 2 presents spectrograms in the frequency range 1–4 Hz at the stations KIL, ABI, SOD, and OUJ for July 25, 2024 UT (on other days, the received signals were similar). The short horizontal tracks on the spectrograms at 21–22 UT are caused by monochromatic radiation generated in the corresponding sessions. The intensity of artificial signals at 300–550 km from the source is seen to exceed the intensity of natural Pc1 pulsations, as, for example, at KIL at 00–03 UT (Figure 2).

Spectra of the emission recorded at BOX on July 25, 2024 are exhibited in Figure 3. Emission is recorded at all generated frequencies in the range from 1 to 9 Hz, only a narrowband interference ~2 Hz does not allow an artificial signal to be identified at this frequency, and emission at a frequency of 7.5 Hz is suppressed by emission of the fundamental Schumann resonance mode ~7.8 Hz. The normalized amplitude of artificial signals varies from ~6 to ~1.4 fT/A, but the frequency dependence is nonmonotonic (see Table 2).

Artificial signals emitted by PTL were also recorded at PUS, which is more remote from the source, at all frequencies in the range 1–4 Hz, and they are identified quite well against the background of noise. Static spectra of the calibrated recording for July 25, 2024 ~~UT~~ are shown in Figure 4. Signals with comparable amplitude were recorded for both horizontal components, although B_y (channel CH2) slightly predominates over B_x (channel CH1). The characteristic normalized signal amplitudes in all sessions are 0.4–0.8 fT/A (see Table 2).

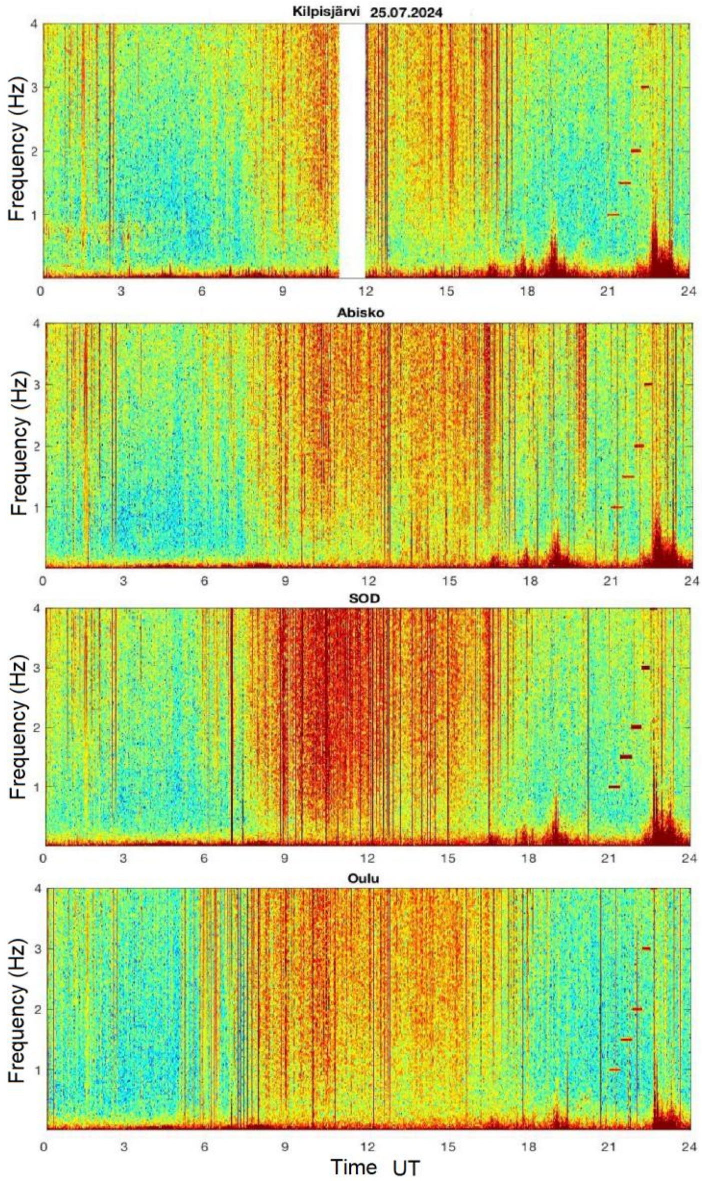

Figure 2. Total power spectrograms of magnetic noise recorded at KIL, ABI, SOD, and OUJ in Finland and Sweden on July 25, 2024

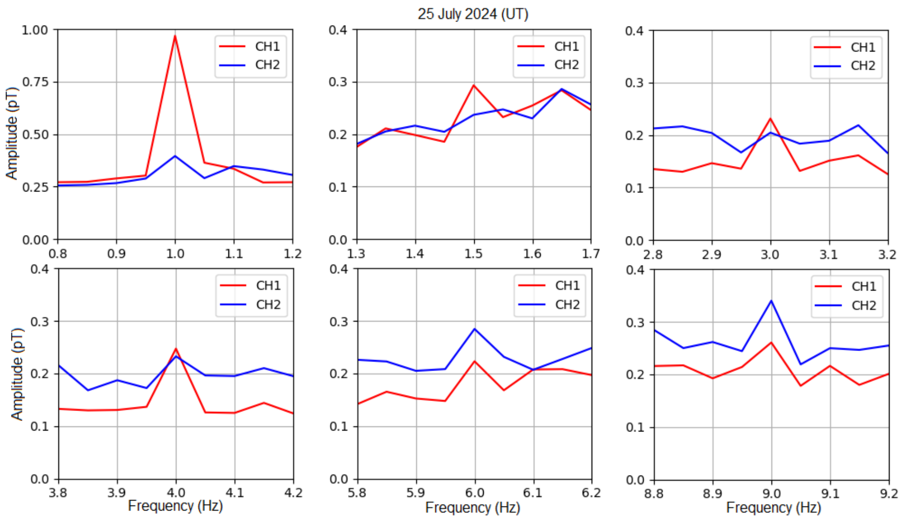

Figure 3. Spectra of artificial emission [pT] recorded at BOX on July 25, 2024 for six intervals of artificial signals with different frequencies (from 1 to 9 Hz). CH1 and CH2 are, respectively, the meridional and azimuthal components of the recorded emission

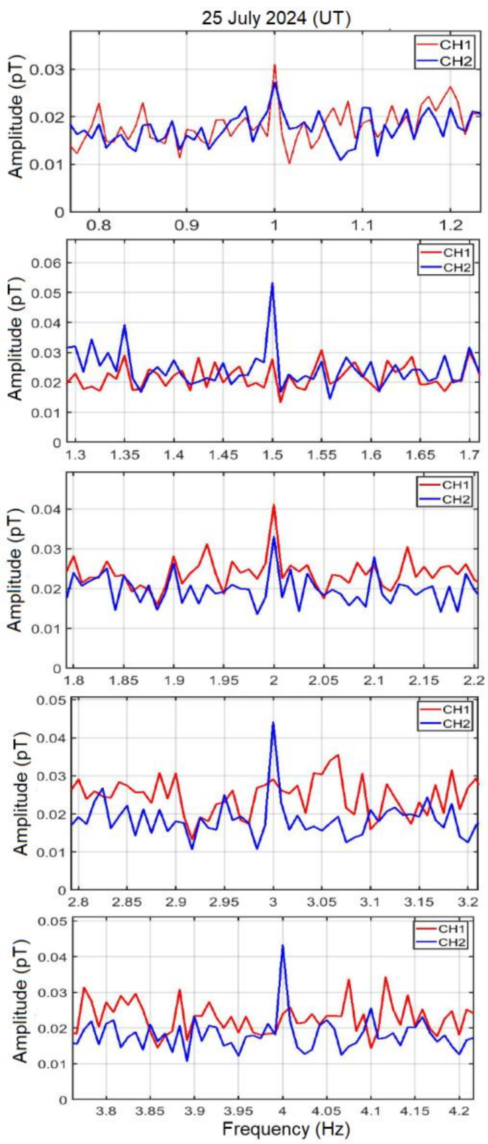

Figure 4. Amplitude spectra [pT] of artificial signals with different frequencies recorded at PUS on July 25, 2024. Channel CH1 corresponds to B_x; CH2, to B_y

At the station IST farthest from the source, there are also peaks corresponding to the occurrence of artificial harmonic emission on the spectra. Spectral peaks can be identified when examining the close vicinity of the frequency set by the facility (Figure 5). Normalized amplitudes of the recorded signal are on average ~0.3 fT/A.

Figure 6 compares amplitudes of artificial Pc1 signals (*D* component) at different frequencies at the distant stations PUS and IST. On average, the amplitude at PUS (0.6±0.2 fT/A) is about twice as high as the amplitude at IST (0.3±0.05 fT/A). Since the signal amplitudes only slightly exceed the noise level, it is difficult to speak about frequency dependence. Most likely, this dependence is non-monotonic.

Compared with the typical amplitude of Pc1 pulsations ~20–40 pT at middle and subauroral latitudes, the amplitude of artificial Pc1 signals at large distances from PTLs turned out to be about two orders of magnitude lower: 0.05±0.01 pT at IST, and 0.04±0.01 pT at PUS. Although the experiment was conducted under magnetically quiet conditions, the artificial signal was at the noise level, but due to the monochromatic emission at a known frequency it was confidently identified both on spectrograms and in static spectra (see Figures 3–5).

3. DISCUSSION

The results of the FENICS-2024 experiment confirm the idea that disconnected PTLs can be used as a controlled source of ULF waves. In the experiment, artificial signals in the frequency range 1–6 Hz were detected at a distance more than 2000 km. Such long-range propagation has never been observed in experiments on ionospheric radio heating [Papadopoulos et al., 2011a]. Thus, the use of the FENICS facility to excite artificial emissions can be a much cheaper and more effective alternative to radio heating. Artificial signals generated by PTLs make it possible to carry out MTS over a vast territory. Similar experiments with signals from large-scale facilities CSELF (Control Source Extremely Low Frequency) [Zhao et al., 2015] and

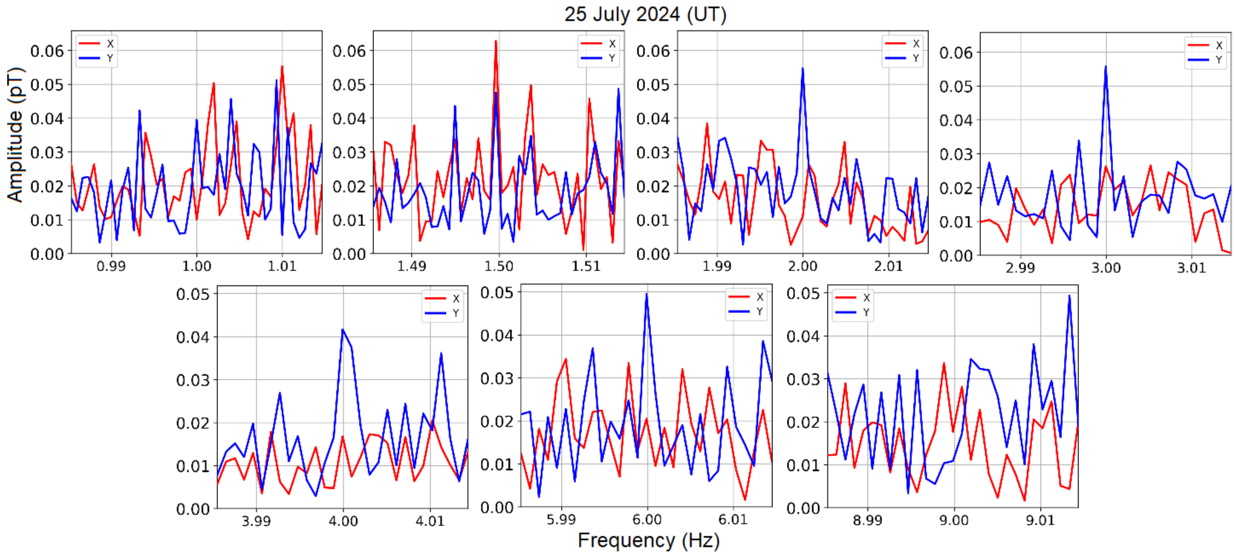

Figure 5. Amplitude spectra [pT] of horizontal components of artificial signals with different frequencies at IST on July 25, 2024

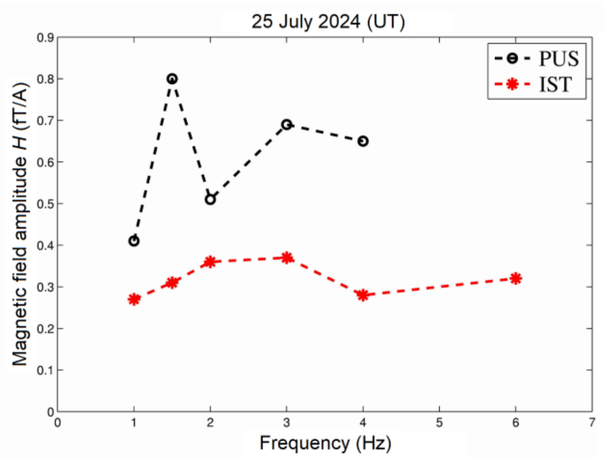

Figure 6. Comparison of normalized amplitudes of artificial Pc1 signals (horizontal *D* component) at different frequencies, recorded on July 25, 2024 at the distant stations PUS and IST

WEM (Wireless Electromagnetic Method) [Su et al., 2012] to monitor the conductivity of the surface layers of the earth's crust are conducted in China.

During MTS, account should be taken of the difference between artificial Pc1 signals and natural ULF pulsations. The magnetic mode prevails in natural ULF pulsations excited by ionospheric currents [Pilipenko et al., 2021a]. Both magnetic and electric modes contribute to the structure of artificial signals generated by a finite-length horizontal antenna. Over high-resistance rocks (such as granites on the Kola Peninsula), surface impedances of these modes differ, and for correct MTS the directional analysis should be used in order to separate contributions of electric and magnetic modes [Chetaev, 1985].

The signal-to-noise ratio in the ULF range can be increased by amplifying the alternating current in 100–200 kW, whereas, for example, for PTL403 with 2.5–5 ohm resistance the generator power should be 2.5–5 MW to amplify the current to 10^3 A, which makes the facility not so mobile and extremely expensive. In this case, the use of MHD generators with a circuit resistance less than 0.1 ohm seems more promising.

The observation results will be compared with theoretical estimates, using various models of ULF field excitation in the atmosphere and ionosphere, in the subsequent work. Artificial signals from the FENICS facility are likely to be emitted into the upper ionosphere too [Pilipenko et al., 2024]. The question as to what amplitudes of artificial Pc1 emission can be expected in the upper ionosphere in the vicinity of the FENICS-2024 facility at the current values in use will also be addressed in the subsequent work.

CONCLUSION

The FENICS-2024 experiment has shown that PTLs with currents 140–150 A are an effective source of 1–10 Hz artificial ULF waves. The use of temporarily decommissioned PTLs can be a much cheaper and more effective alternative to radio heating methods of exciting artificial Pc1 pulsations. Such artificial signals can be employed for near-real-time MTS of the surface layers of the earth's crust over a huge area.

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