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The Effect of the Ionosphere on the Controlled-Source Field in the Frequency Range between 0.4 and 95 Hz

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Abstract—The paper addresses the effect of the ionosphere on the ELF and lower frequency waves excited in the Earth-ionosphere waveguide by a controlled source. The experiment carried out on the Kola Peninsula is described and the results of measurements in the frequency range 0.4–95 Hz are presented. Non-monotonic behavior of the magnetic field with time is revealed. It is shown that variations in the magnetic field are related to the state of the ionosphere and depend on the geomagnetic activity. The importance of the effect of the topside ionosphere on the structure of the studied field is discussed.

Index Terms—SLF, ELF, radio waves propagation, ionosphere, magnetic field, conductivity

I. Introduction

Studying the propagation of radio waves in the super low (SLF) and extremely low frequency bands (ELF) (30–300 and 3–30 Hz, respectively, in the International Telecommunication Union designation) in the anisotropic three-dimensional (3D) Earth-ionosphere waveguide is of interest both from the theoretical standpoint and for the practical use in the radiophysical and geophysical applications. In our previous works [1], [2], we considered the influence of the ionosphere on the low-frequency field in the vicinity of the source, i.e., within distances shorter than or comparable to the waveguide height. It was established that the field structure in this region is mainly determined by the conductivity of the lithosphere. Variations introduced in the field by the ionosphere are much smaller than the modulation effects from conductivity distribution in the lithosphere. The calculations have shown that the ionospheric model in the form of a layer with constant conductivity located at a certain height above the Earth fairly well describes the experiments, in particular, the dependence of the field at frequencies below 10 Hz on the state of the ionosphere in the regions with low-conductive lithosphere.

Starting from ULF band and down to lower frequencies, the field reflection mechanism from the ionosphere changes, and the predominant role is played by gradient mechanism associated with spatial variations in permittivity tensor of the ionospheric plasma. Therefore, it is important to identify the ionospheric regions significant

for reflection. This problem is considered in [3]–[5]. The studies of the reflection-significant ionospheric region have shown that its size non-monotonically varies with frequency, substantially increasing in the SLF band and, especially, when passing to ELF and lower frequencies. The top of the region is located at a height of 100–120 km for SLF waves and rises to 2000 km when frequency decreases to 0.1 Hz. The bottom boundary descends to lower heights with the decrease in frequency and reaches 30–40 km in the ELF band. Hence, under certain geophysical conditions, a reflected field can arise in the topside ionosphere (above $maxF_2$) which, together with the field reflected from the bottomside ionosphere, will form a fringe pattern on the Earth's surface.

Calculations [6] show that reflections vanish at frequencies above 8 Hz. It is believed [7] that two reflection regions existing in the bottomside and topside ionosphere form the so-called ionospheric Alfvén resonator (IAR). The reflection region in the topside ionosphere which is associated with the exponentially decreasing plasma conductivity bounds the Alfvén resonator from above, and the conductive gyrotropic E -layer located in the height interval 90–130 km is the IAR lower boundary. The existence of IAR in certain geophysical conditions can be established from the records of the low-frequency electromagnetic noise in the frequency interval 0.5–6 Hz [8], [9]. The morphology of Alfvén resonances is addressed in numerous publications which show that resonance structures are observed at different latitudes mainly in the nighttime in the quiet geophysical conditions. Although the IAR excitation is typically regarded as resulting from global thunderstorm activity, the efficiency of this mechanism in the midlatitudes and, especially, in the high latitudes is challenged in [7] because of the substantial remoteness of the main thunderstorm centers which are located in the equatorial regions.

Instead, it is hypothesized that in these latitudes, the local thunderstorms and the excitation of ionospheric currents feeding the resonator at the E -layer heights are probably more efficient sources. The uncertainty in the type and location of the sources of the electromagnetic field responsible for the emergence of the Alfvén resonances in the records of the electromagnetic noise challenges the use of the resonances or undermines their reliability as an instrument for establishing the conditions in the topside ionosphere. The point is that it is problematic to separate

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two effects, i.e., to elucidate the cause of the absence of the Alfvén waves: is it the switching-off of the source exciting the resonator or the changes in the conductive topside ionosphere destroying the reflection region in the topside ionosphere?

The uncertainty associated with the source can be removed by using a controlled-source low-frequency radiation.

Below, this approach is used to reveal the reflections from the topside ionosphere in the international experiment FENICS-2019 [10]. In contrast to the previous studies [1], [2], this work is based on the measurement results obtained with a receiver-transmitter distance significantly exceeding 100 km at which the waves propagate in a waveguide mode and the effect of the ionosphere is more pronounced. Due to the rapid attenuation of the low-frequency waves, this distance in a real experiment should not be too large so that the signal-to-noise ratio is sufficiently high and the measurement accuracy allows the detection of the ionospheric effect in question.

II. Experiment

The experiment on studying the effect of the ionosphere on the propagation of SLF, ELF, and lower-frequency waves was carried out on the Kola Peninsula in September 2019. A ~ 100 -km long high-voltage line oriented along constant geographical latitude was used as a transmitting antenna (Fig. 1). The signal in the frequency range 0.382–194.2 Hz was produced by a 200 kW mobile generator. The amplitude of the antenna current at the lowest frequency was about 200 A and decreased to 20 A at the highest frequency due to the design features of the transmission system. The magnetic field was measured by the calibrated induction sensors in the vicinity of Varzuga village at distances 314 and 370 km from the ends of the transmitting antenna. Two horizontal sensors H_{SN} and H_{WE} were oriented in two orthogonal directions towards the magnetic north and east, respectively. The third sensor H_Z was installed vertically.

The electric field was measured by the ~ 80 -m long orthogonal lines grounded at the center and at the ends. In the experiment, four field generation sessions were carried out from September 11 to 15 in the interval from 22:21 UT to 02:59 UT (Moscow time MSK = UT + 3) at 11 frequencies (0.382, 0.642, 0.942, 1.942, 3.822, 6.422, 9.422, 19.42, 38.22, 64.22 and 94.22 Hz). The field at a fixed frequency in the lower part of the frequency range was generated for approximately 15 minutes. The exception was the extreme upper frequency where the generation time was increased to half an hour because of the low antenna current. The amplitude of the monochromatic signal was estimated from the average power spectral density in the vicinity of the measured working frequency using Welch's overlapped periodogram averaging estimator with Hamming window [12]. Figure 2a–d shows the measured amplitude of the horizontal magnetic components $|H_{SN}|$ and $|H_{WE}|$ reduced to the antenna current of 1 A for four days. The confidence level of 80% is indicated by

Fig. 1. Scheme of the FENICS-2019 experiment. Estimated conductivity of the Earth's crust [11] 1 – 10^{-4} S/m, 2 – $6 \cdot 10^{-5}$ S/m, 3 – 10^{-3} S/m, 4 – 10^{-2} S/m.

vertical lines. A specific feature of these measurements is the non-monotonic amplitude variations at frequencies below 10 Hz. These variations are most clearly expressed in the $|H_{SN}|$ component in the data for September 11 and 12. The behavior of the field in the region above 10 Hz on different days is similar, without significant differences. In fact, the field is determined by the structure of the lithosphere and weakly depends on the state of the ionosphere [1].

III. Discussion

The field recorded in the experiments is affected by the conditions in the lithosphere and by various heliogeophysical factors. Given that the measurements were carried out on close days and at same time of day for each frequency, the effects associated with the different ionization of the ionosphere by solar radiation can be excluded. The conditions in the lithosphere can be evaluated from the analysis of the electromagnetic impedance on the Earth's

Fig. 2. Amplitudes of the horizontal components of the magnetic field.

Fig. 3. Reduced surface impedances. 1 – 4 estimated in the experiment, 5 – calculated δ .

surface. The surface impedance is determined from the joint measurements of the electric and magnetic field as $|Z| = |E_{WE}/H_{SN}|$. Curves 1–4 in Fig. 3 show the reduced surface impedance $\delta = |Z/Z_0|$ (where $Z_0 = 120\pi$ Ohm is the impedance of free space) calculated from the measurement data. From the figure it follows that the impedance and, accordingly, the conductivity did not change during the experiment and the variations in the field on different days are due to the state of the ionosphere.

For a plane monochromatic wave incident on a two-layer structure with different conductivities of the layers σ_1 and σ_2 , the following expression is valid [13]

$$|Z| = \left| \sqrt{\frac{i\omega\mu_0}{\sigma_1}} \frac{1 + R \exp(-2\kappa_1 d)}{1 - R \exp(-2\kappa_1 d)} \right|,$$

where μ_0 is the permeability of free space, ω is the angular frequency, d is the thickness of the upper layer, and $\kappa_1 = (1 - i)\sqrt{\omega\mu_0\sigma_1}/2$, $R = (\sqrt{\sigma_2} - \sqrt{\sigma_1})/(\sqrt{\sigma_2} + \sqrt{\sigma_1})$. As follows from Fig. 3 (curve 5), the conductivity of the lithosphere is closely approximated by a two-layer structure where a 10-km thick upper layer with conductivity $\sigma_1 = 10^{-4}$ S/m lies on top of a half-space with conductivity $\sigma_2 = 10^{-5}$ S/m. To characterize the geophysical conditions in the region during the experiment, I considered the local hourly magnetic activity indices.

Table I presents the hourly k-indices of magnetic activity at the Lovozero observatory for the period analyzed in this study. The indices corresponding to the time of signal

TABLE I
Geomagnetic k-indices, Lovozero 2019

Day	18	21	24	03
11	211	211	0 00	001
12	112	221	1 11	111
14	100	121	2 32	111
15	124	435	6 32	234

generation by a controlled source are shown in gray. It can be seen that the measurements on September 11 and 12 fell in the magnetically quiet conditions whereas the experiment on September 14 was conducted in a slightly disturbed period. The disturbances on September 15 were observed before the beginning of the experiment while directly during the measurements the magnetic situation was similar to that on September 14. Analyzing Table I and the results shown in Fig. 2a-d, one can see that a correlation exists between the change in the behavior of the field in the frequency region below 10 Hz and the geomagnetic activity.

IV. Conclusions

The experiments on the generation and measurement of low-frequency radiation in the frequency range of 0.4–95 Hz yielded statistically reliable data demonstrating a significant effect of the nighttime ionosphere on the magnetic field excited in the Earth–ionosphere waveguide. Given that the surface impedance measurements have shown the absence of noticeable variations and revealed monotonic behavior with frequency, the main fluctuations in the amplitude of the field can be attributed to the changes in the ionosphere. The analysis of the changes in the frequency dependence of the field for different geomagnetic activity levels supports this conclusion. According to the theoretical models [6], the observed changes in the field cannot be explained by the effects of the bottomside ionosphere alone and need the reflections from the topside ionosphere to be also taken into account. The obtained results suggest that the proposed new experimental method is promising for effective study of ionospheric phenomena.

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