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INFLUENCE OF IONOSPHERIC RESONATORS ON DAILY DYNAMICS OF THE FIRST SCHUMANN RESONANCE SPECTRAL PARAMETERS ACCORDING TO DATA FROM A MERIDIONAL CHAIN OF ULF MAGNETOMETERS

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Abstract. We have experimentally studied the influence of the local ionosphere, namely the ionospheric Alfvén resonator (IAR) and the lower ionospheric resonator at altitudes 80–300 km (sub-IAR) on the amplitude and polarization of the first Schumann resonance. The study is based on spectral analysis of data from simultaneous monitoring of ULF magnetic noise components at a meridional chain of stations: high-latitude stations Barentsburg and Lovozero, mid-latitude observatory NNGU NIRFI (NL, Nizhny Novgorod Region), a low-latitude station in Israel. We have also used monitoring data from the Borok and Crete observatories. At the stations in dark conditions, significant variations were found in the spectrum of the polarization parameter ε at the frequency of the first Schumann resonance (SR). Moreover, these variations had different character at different observatories. Analysis of the daily dynamics of the parameter ε has shown that these variations are associated with the influence of local sub-IAR having different optical thickness and quality factor at these observatories. The influence of sub-IAR on polarization in the SR band was found to depend on the ratio of the boundary frequency f_b (the frequency that separates the negative and positive polarization of ULF magnetic noise) to the frequency of the first SR. The IAR influence on the polarization and amplitude of magnetic fields in the frequency band of the first Schumann resonance was discovered only at the NL and Lovozero stations: a high-quality Alfvén resonator in the ionosphere above the NL station could cause the SR frequency band to change and its central frequency to shift. Analysis of low-frequency data from the observatories separated by distances of 400 km has revealed that the influence of local ionospheric resonators can lead to a difference in the amplitude characteristics of the first SR even at such distances. It has also been shown that the influence of the IAR and sub-IAR resonators on the azimuthal angle of the magnetic field vector in the frequency band of the first SR is less noticeable and can generate variations in this parameter by 10°–20°. Numerical calculations performed for the spherical waveguide model made it possible to adequately interpret the features of the daily dynamics of the parameter ε in the frequency range of the first SR.

Keywords: ionospheric resonators, magnetic noise, Schumann resonance, polarization, spectral parameters, resonance spectral structure.

INTRODUCTION

As is known, the Schumann resonance (SR) occurs at eigenfrequencies of the Earth–ionosphere cavity when excited by its planetary thunderstorm activity and is global. Schumann resonances are linked to oscillations in the Earth–ionosphere cavity with a fundamental frequency of ~8 Hz and higher-order modes spaced ~6 Hz apart. Spectral characteristics of magnetic noise at SR frequencies have been studied in many works, generally based on four-year and one-year averaged data. In [Satori, Zieger, 1996; Price, Melnikov, 2004; Greenberg, Price, 2007], diurnal and seasonal variations in amplitude, central frequency, and Q-factor of the magnetic field in the band of the first three SRs have been examined at observatories in Hungary and Israel. Schlegel and Fullekrug [2000] have for the first time studied diurnal variations in SR parameters from data obtained in two opposite points of different hemispheres, in Antarctica and Greenland. They have found 12- and 8-hr periods in the SR amplitude variations at both stations, as well as its variation depending on season. Roldugin et al. [2004] have examined the diurnal variation in the frequency of the first SR mode from observations at three stations located on Svalbard, Kola Peninsula, and Kamchatka. The frequency varied from 0.2 to 0.3 Hz in all the observatories. Semi-diurnal periods prevailed in the frequency variation. The variation was controlled by local (LT), not universal (UT) time. The frequency of the north–south (NS) component had peaks at about 07:00 and 19:00 LT. The diurnal variation in the frequency of the east–west (EW) component revealed an antiphase behavior such that the maximum frequency of the EW component occurred at ~01:00 and 13:00 LT. In all these works, it is emphasized that since SR is an electromagnetic phenomenon in Earth's atmosphere associated with global lightning activity, variations in its parameters can be an indicator for activity of global thunderstorm cells in Southeast Asia, Africa, and South America. Using the long-term recording of magnetic

ULF noise components in Schumann resonance bands, a number of studies of diurnal variations in SR parameters associated with changes in the position of thunderstorm cells across the globe have been carried out [Ogawa et al., 1969; Nickolaenko, Rabinowicz, 1995; Nickolaenko et al., 1998].

An important SR parameter is magnetic field polarization in respective frequency bands, which is characterized by the ellipticity coefficient and the azimuth angle of the major axis of the polarization ellipse. Experimental studies of polarization parameters have been carried out at low [Sentman, 1987], middle [Rusakov, Bakastov, 1988], and high [Roldugin, Vasiliev, 2012] latitudes. In all the cases, elliptical polarization of ULF magnetic field oscillations at the frequencies of the first and second SRs has been detected, and during the day the polarization coefficient could vary from positive to negative. At middle (Borok Observatory) and high latitudes (Barentsburg and Lovozero observatories), left-handed polarization at the first-SR frequency was generally found (left-handed polarization corresponds to the rotation of the field vector in the same direction in which positively charged particles rotate in the geomagnetic field in the Northern Hemisphere, which corresponds to the counterclockwise rotation of the field vector). Koloskov et al. [2005] report the results of polarization monitoring of the first three SR modes in Antarctica. Diurnal variations of the ellipticity coefficient averaged over four solar cycle periods have been examined from data for 2001–2003. A high degree of ellipticity of the first SR mode with positive values of the polarization coefficient from 0.4 to 0.8 was found. In the same work, by solving the problem of excitation of Schumann resonances it is shown that the polarization vector of magnetic ULF fields in the band of the first SR mode when excited by thunderstorm equatorial sources should rotate clockwise in the Southern Hemisphere and counterclockwise in the Northern Hemisphere.

In [Bösinger and Shalimov, 2004], Figure 1 illustrates polarization parameter variations, especially noticeable at night, at the Crete station for several days in October 1999. The paper comments on polarization variations in the range to 6 Hz; however, this figure indicates that ellipticity coefficient variations in the first-SR frequency band are most pronounced at the same time. Bosinger et al. [2014], through analysis of numerical calculations of horizontal ULF fields from a ground-based source, explain strong variations in the degree of magnetic ULF field ellipticity at night, which are generated by the lower ionospheric Alfvén resonator (sub-IAR) at low latitudes. Sub-IAR occurs when the refractive index of low-frequency waves significantly varies at night at heights from the lower boundary of the ionosphere (~70–80 km) to the lower boundary of the F layer (250–300 km). This variation is related to the so-called valley in the vertical electron density profile. Due to large gradients of the refractive index at boundaries of this region, the entire structure has its own resonance properties, different from IAR, and, in particular, can cause a broadband spectral maximum (BSM) to occur in amplitudes of background noise horizontal components at 1–6 Hz [Ermakova et al., 2007]. According to [Ermakova et al., 2007, 2012], sub-IAR also affects the behavior of the polarization parameter ε (defined below) and leads to a characteristic frequency dependence of this parameter with a change of polarization from left- to right-handed. In these works, it is shown that in the case of a ground-based source of vertical electric dipole type, the local ionosphere makes the most significant contribution to the formation of the polarization parameter spectrum, and the nature of the frequency dependence of this parameter depends slightly on the direction to the source.

Since the occurrence of marked ε variations in the frequency band of the first SR correlates with the occurrence of variations at lower frequencies, we can assume that the local ionosphere also affects polarization parameters of the first SR. Thus, the state of the local ionosphere can be added to the global factors of formation of SR polarization and significantly change its daily dynamics.

In this paper, we study the effect of superposition of three resonators: the global spherical Schumann resonator, the lower ionospheric Alfvén resonator (sub-IAR, 80–300 km heights), and the ionospheric Alfvén resonator (IAR, from 80 to 2000 km) on peculiarities of the daily dynamics of spectral ULF noise parameters in the frequency band of the first Schumann resonance. To determine the local nature of the diurnal variations in the spectral parameters of the first SR, we analyze data from the meridional magnetometer network. The method of averaging data over long periods of time is not suitable for such studies since averaging neutralizes the effect of the variable local ionosphere on background noise parameters. We analyze low-frequency data for individual diurnal periods when the effect of local resonators in magnetic noise spectra was most pronounced. Along with this, we perform model calculations of the spectra of the polarization parameter ε to confirm that local sub-IAR has an effect on ε variations in the first-SR band at night.

1. ANALYSIS OF LOW-FREQUENCY MONITORING DATA FROM THE MERIDIAN NETWORK OF STATIONS

We have used data on magnetic field horizontal components from the meridional chain of stations spaced over long (1500–2000 km) distances: at the high-latitude stations Barentsburg and Lovozero, at the mid-latitude observatory NIRFI New Life (NL), the Nizhny Novgorod Region, and at the low-latitude station Mitzpe-Ramon in Israel. We have also employed data from simultaneous recording at observatories spaced by 400 km apart (NL and Borok) and data from the station on Crete Island. Designations and geographic coordinates of the stations are listed in Table.

Table shows that the stations are widely spaced in latitude and much less in longitude.

The data was obtained in the frequency band 0.1–16 Hz with a sampling rate of 32 Hz by highly sensitive induction sensors (an exception is data from Crete — recording to 10 Hz). Processing consisted in obtaining spectra and spectrograms of polarization and amplitude

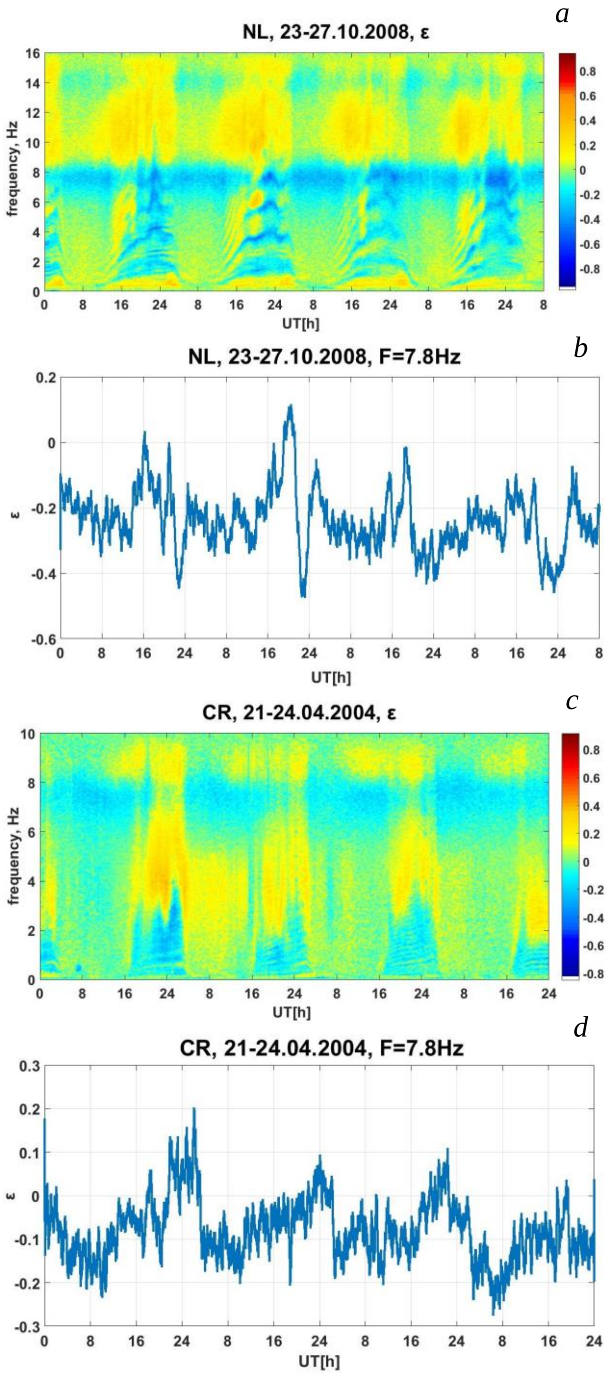

Figure 1. Spectrograms of the ε parameter at the NL and CR stations (a, c); the ε dynamics at the first-SR frequency for October 23–27, 2008 at the NL station (b) and for April 21–24, 2004 at the CR station (d)

Station	Geographic latitude	Geographic longitude
Barentsburg (BAB)	78° N	14° E
Lovozero (LOZ)	68° N	35° E
New Life (NL)	56° N	45° E
Mitzpe-Ramon (MR)	31° N	35° E
Borok (BOR)	58° N	38° E
Crete (CR)	35° N	25° E

parameters at a 10 s interval and their subsequent averaging at a 10–15 min interval. The daily dynamics of different spectral magnetic noise parameters at the first Schumann resonance frequency was also derived and analyzed. Figure 1 exhibits spectrograms of the polarization parameter ε from the NL station for October 23–27, 2008 and from the CR station for April 21–24, 2004. The ε value depends on the ratio of right- to left-polarized noise components:

$$\varepsilon = \frac{|H_\mathrm{R}|/|H_\mathrm{L}|-1}{|H_\mathrm{R}|/|H_\mathrm{L}|+1}. \tag{1}$$

Here, $H_\mathrm{R} = \left(H_\mathrm{NS} + iH_\mathrm{EW}\right)/\sqrt{2}$, $H_\mathrm{L} = \left(H_\mathrm{NS} - iH_\mathrm{EW}\right)/\sqrt{2}$ are the right- and left-polarized magnetic field components respectively, H_NS and H_EW are the magnetic field components along the NS and EW directions. The right-handed polarization corresponds to field vector rotation at the same direction in which negatively charged particles rotate. To ε>0 corresponds the right-handed polarization; to ε<0, the left-handed polarization; to ε=0, the linear polarization. Referring to Figure 1, *a*, *c*, the most intense ε variations at the first-SR frequency occur at night and begin at sunset at each station. Figure 1, *b*, *d* demonstrates diurnal variations in ε over the entire period of time at the NL and CR stations. As can be seen in these figures, after sunset a characteristic dependence of ε on sign change appears which is related to the effect of the lower ionospheric Alfvén resonator [Ermakova et al., 2007, 2012]. Note that sub-IAR is part of IAR since it is located at altitudes that include IAR and is connected with an additional region of ULF wave reflection at the lower boundary of the ionospheric F layer. Reflection of ULF waves from this region also inevitably affects spectra of the magnetic ULF noise recorded on the Earth surface. Since the phase incursion of normal waves when reflected from the F-layer lower boundary is several times less than when reflected from the F-layer upper boundary, sub-IAR does not significantly affect the frequency scales of the resonance spectral structure (RSS). Superposition of the two resonators manifests itself in the background noise spectra on Earth as superimposition of a large-scale variation on smaller-scale RSS. The coefficients of reflection from the F-layer upper and lower boundaries may depend on different heliogeophysical conditions. At midlatitudes, for example, the probability of RSS occurrence is higher at solar minimum. At solar maximum and in summer, the coefficient of reflection from the F-layer upper boundary decreases significantly, which leads to weak RSS oscillations in a narrow frequency range (to 2–4 Hz) or to the absence of RSS at mid-latitude stations [Potapov et al., 2021]. The dependence of the coefficient of reflection from the F-layer lower boundary on the solar activity level is different; therefore, in years close to solar maximum and in summer only a broadband spectral maximum in ε spectra and magnetic components can be observed. The magnetic component spectra presented in [Ermakova et al., 2007] demonstrate only the presence of BSM. The BSM central frequency is generally below the frequency of the first SR mode; however, the sub-IAR effect on the polarization spectra can be noticeable at frequencies higher than 7–8 Hz (the region of positive ε). Since upper walls of IAR and sub-IAR are different, these resonators can be manifested both in the same and in different frequency ranges. In the ε spectrogram at the NL station (Figure 1, *a*), RSS appears in almost the same frequency range as the broadband variation — to 14–16 Hz, except for the first hours after sunset when RSS appears in the frequency range to 8 Hz; and the broadband structure, to 12 Hz. In the ε spectrogram for the CR station (Figure 1, *c*), the lower resonator affects the ε spectra in the frequency range to 9–10 Hz, and the IAR effect is limited to 2–4 Hz, which is due to the absence of violation of geometric optics for normal waves in the outer ionosphere at frequencies above 4 Hz. The manifestation of sub-IAR in the polarization parameter spectra in a wider frequency range confirms the autonomy of its effect on ULF noise spectra on Earth.

To compare the sub-IAR effect at different stations and during different periods of the day, we use the concepts "optical density" and "Q-factor" of the resonator. The sub-IAR Q-factor can be inferred from the depth of the large-scale oscillation in the ε spectrum relative to zero values, i.e. from maximum absolute values of this parameter. The resonator optical density is the optical density of ionospheric layers at its heights, which is determined by phase incursion of normal waves in the resonator. The characteristic of the sub-IAR optical density can be the boundary frequency f_b, which separates the left-handed polarization from the right-handed one in the ε background noise spectrum and is equal to the BSM central frequency [Ermakova et al., 2012]. The spectrograms in Figure 1, *a*, *c* show that at the beginning of nighttime the sub-IAR effect increases ε in the first-SR band at both stations, reducing the degree of magnetic field circular polarization, and at certain hours changes polarization from left- to right-handed (Figure 1, *b*, *d*). During this period, f_b remains lower than f_{1SR}.

After 20:00 UT at the NL station, the polarization parameter decreases sharply to $\varepsilon \le -0.4$ (Figure 1, *b*), which means a sharp increase in the degree of magnetic field circular polarization in the first-SR band. Thus, the absolute values of ε become larger than those during daylight hours; and f_b, higher than f_{1SR}. Note that at the NL station IAR also contributed to the increase in the absolute value of ε after 19:00 UT when the ε resonant structure minima fell into the first-SR band. The CR station observed an increase in ε in the first-SR band, and f_b at night remained lower than the frequency of the first SR mode.

Now, for comparison, we present spectrograms of the polarization parameter at stations located at different latitudes. To do this, we use simultaneous recordings of horizontal magnetic ULF fields at the MR, NL, LOZ, and BAB observatories on October 23, 2008.

The magnetic field in the first Schumann resonance band in the Northern Hemisphere has predominantly left-handed polarization [Roldugin, Vasiliev, 2012; Koloskov et al., 2005], as confirmed by monitoring data from all low-frequency observatories (Figure 2). But the absolute values of ε in the first-SR band at the lower-latitude station are significantly lower than at higher-latitude stations.

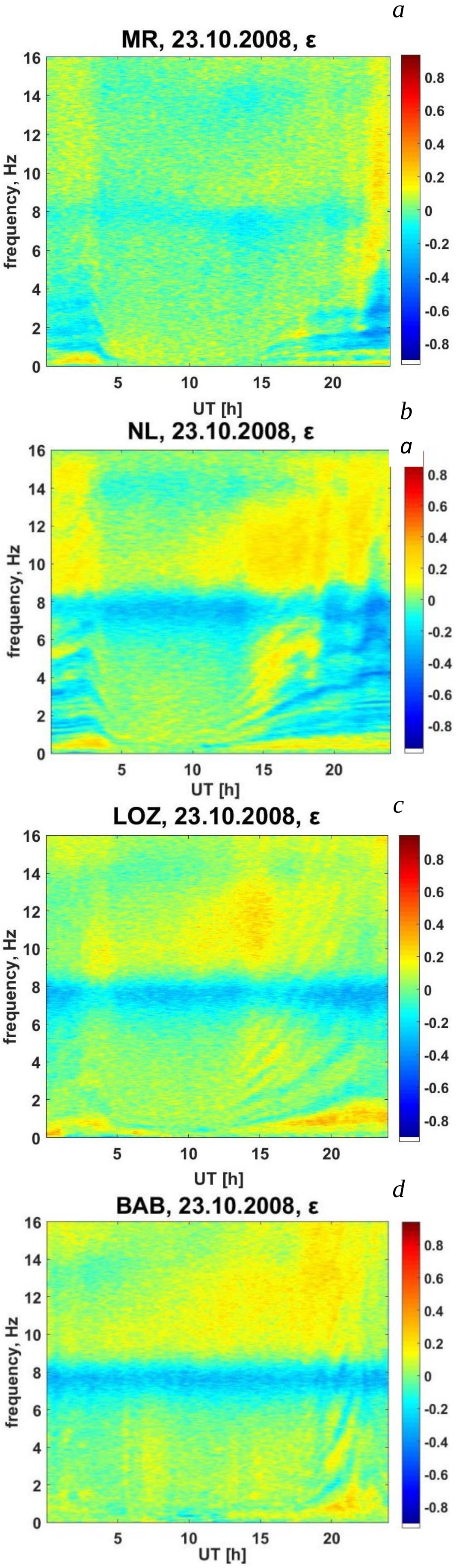

Figure 2. Spectrograms of the ε parameter at the MR (*a*), NL (*b*), LOZ (*c*), and BAB (*d*) stations on October 23, 2008

Figure 2 indicates that ionospheric conditions over the stations were very different: the IAR resonator at the NL and LOZ stations had a higher Q-factor than at the other stations, which manifested itself in a wide frequency range of RSS up to 16 Hz. At the NL station (Figure 2, *b*), the sub-IAR effect was most pronounced throughout the nighttime hours. At the MR station, the sub-IAR effect on ULF noise polarization in the first-SR band was manifested after 21:00 UT when the Q-factor of this resonator increased significantly (see Figure 2, *a*). The upper frequency of the range in which the broadband structure was recorded at this station (to 14–16 Hz) was, as at CR, much higher than the upper frequency of the range in which RSS was recorded (4–5 Hz).

Thus, the occurrence of ε variations at the first-SR frequency at different stations at night correlates with the occurrence of a large-scale alternating-sign frequency dependence and RSS in the spectra of this parameter (Figure 2, *a*–*c*). Figure 3, which illustrates the daily dynamics of ε at the first-SR frequency at all the stations, demonstrates that variations of this parameter differ in all the observatories.

The most intense ε variations are observed in the first-SR frequency band at the NL station at night, which is due to the influence of both resonators. At the lower-latitude station MR, the sub-IAR effect caused a change of polarization in the first-SR band (positive ε after 22:00 UT). The weakest diurnal polarization variations were recorded at the highest latitude station BAB, which is due to the minor effect of ionospheric resonators over this station on the ε spectra those days.

We have also examined the effect of ionospheric resonators on the spectral ULF noise amplitude in the first-SR band and have detected no noticeable sub-IAR effect. Figure 4 exhibits spectra of the NS magnetic component at the NL and BOR stations, demonstrating the influence of local IARs. IAR over mid-latitude stations could lead to a change in the SR frequency band, to a shift in its central frequency (Figure 4, *a*, *b*).

Analysis of the NS magnetic component spectra and the daily dynamics of the SR spectral amplitude for March 17, 2008 at the NL station allows us to conclude that due to variations in the RSS frequency scale after 19:00 UT the NS magnetic component amplitude at the first-SR frequency changed by 20–30 % (Figure 4, *a*, *b*, *d*). Figure 4, *c* displays the NS component spectra simultaneously recorded at the NL

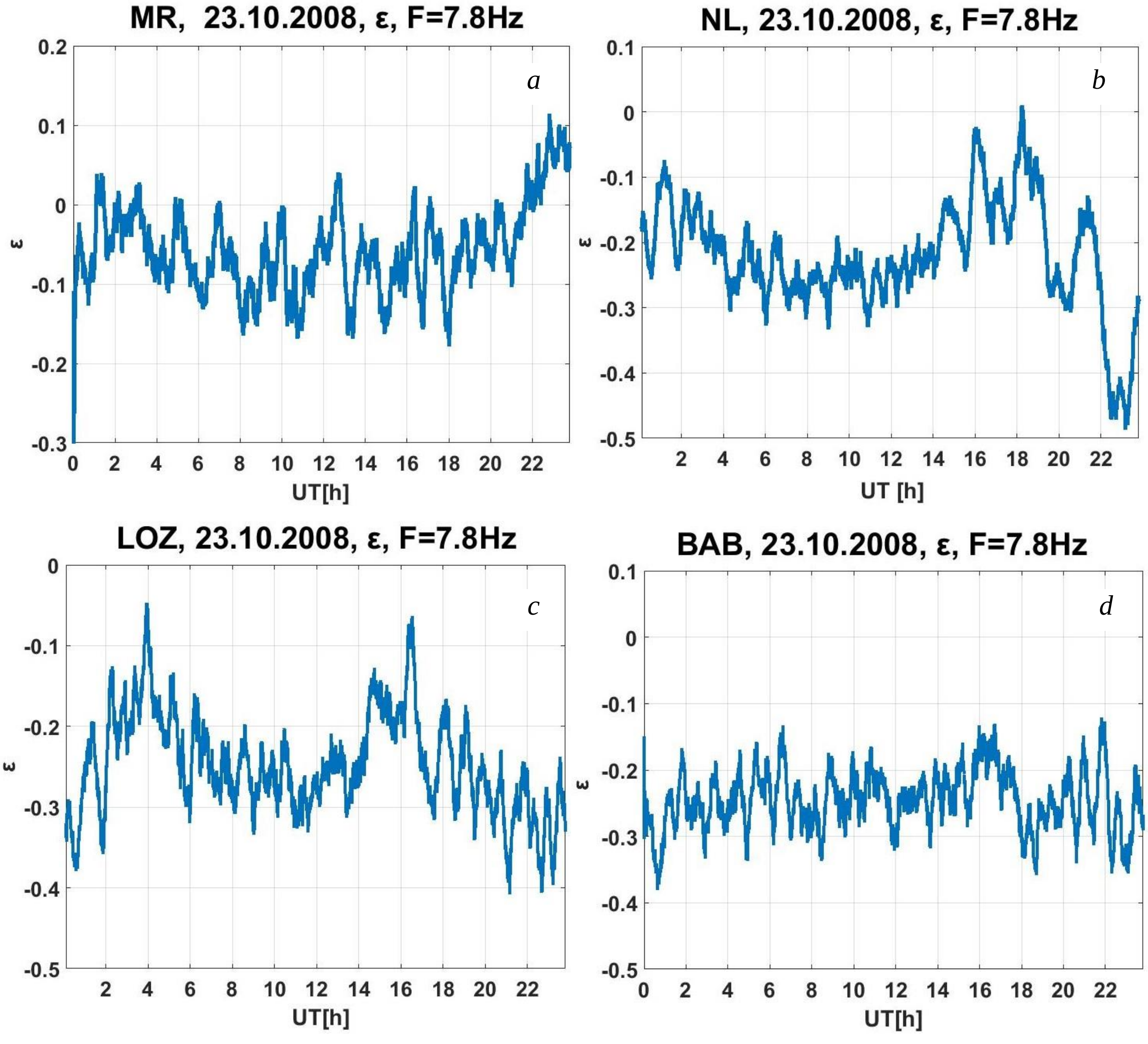

Figure 3. Daily dynamics of the ε parameter on October 23, 2008 at the MR (*a*), NL (*b*), LOZ (*c*), and BAB (*d*) stations

and BOR stations spaced at a distance of ~400 km. The difference between the RSS frequency scales led to different shifts in the amplitude maximum in the first-SR band at these stations. Thus, the effect of local IARs may be the cause for the different amplitude spectra in the band of the first SR mode even at short distances.

For each station, we have also studied the daily dynamics of the modulus of the azimuth angle ψ between the main axis of the polarization ellipse of the magnetic field vector and the EW direction for October 23, 2008 (Figure 5). This parameter was chosen for the analysis to reduce the spread of azimuth angle variations with changes in the intensity of equatorial thunderstorm sources. As follows from Figure 5, at the first-SR frequency large-scale variations in the daily dynamics are determined mainly by variations in the intensity of global thunderstorm cells and are similar at all the stations. There is a difference between ψ values: at low- and mid-latitude stations, the ψ values vary within 40°–60°; at higher-latitude stations, within 30°–55°. This is associated with the fact that for polar observatories the angle between the direction to global thunderstorm sources and the EW direction is greater than for more southern stations. The minimum values of the azimuth angle (30°–40°) at the stations correspond to the predominant influence of the African thunderstorm source; its maximum values (55°–60°), to the influence of the American and Asian thunderstorm sources.

Let us now compare the IAR effect in the first-SR band on the azimuth angle and the polarization parameter. For the analysis we have taken the day when the Q-factor of the lower ionospheric resonator was low — March 17, 2008.

Referring to Figure 6, c, d, due to the low Q-factor of the lower resonator after sunset there was a slight increase (respectively, a decrease in the absolute value) in ε: ε≈–0.2, which slightly exceeded the daily values, in contrast to the October 23, 2008 event (see Figure 3, b) when the parameter ε reached zero values in the first-SR band. After 19:00 UT, there was a sharp increase in the degree of circular polarization in the domain of negative ε values due to the fact that the RSS minimum in the ε spectrum fell on the frequency of the first SR mode. Figure 6 indicates that the IAR effect in the first-SR band led to variations in the angle ψ by 15°–20° and to a significant 2–2.2-fold decrease in ε.

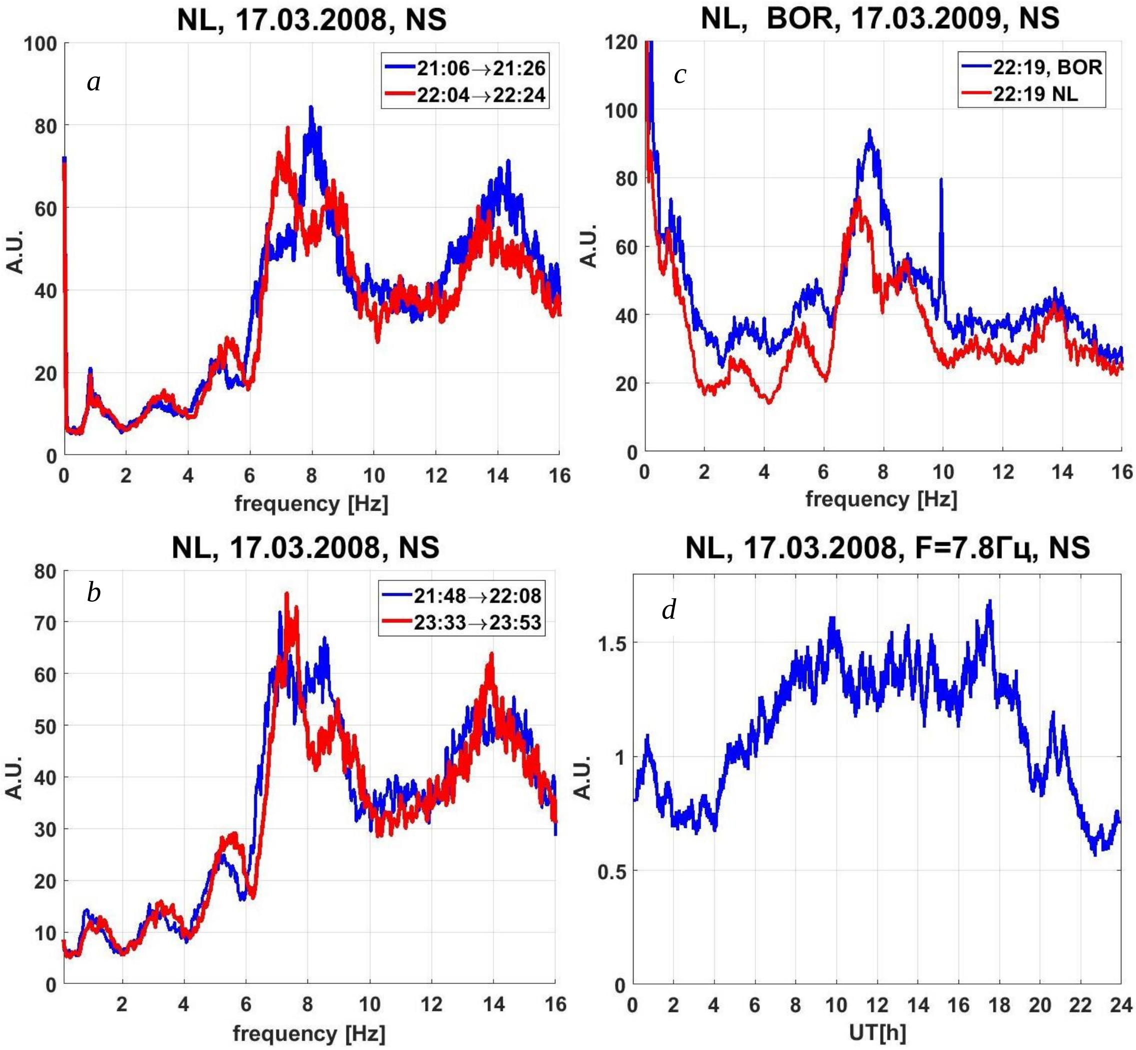

Figure 4. Spectra of the NS component at the NL station on March 17, 2008 (*a*, *b*) and at the NL and BOR stations on March 17, 2009 (*c*), as well as daily dynamics of the NS spectral amplitude at a frequency of 7.8 Hz at the NL station on March 17, 2008 (*d*)

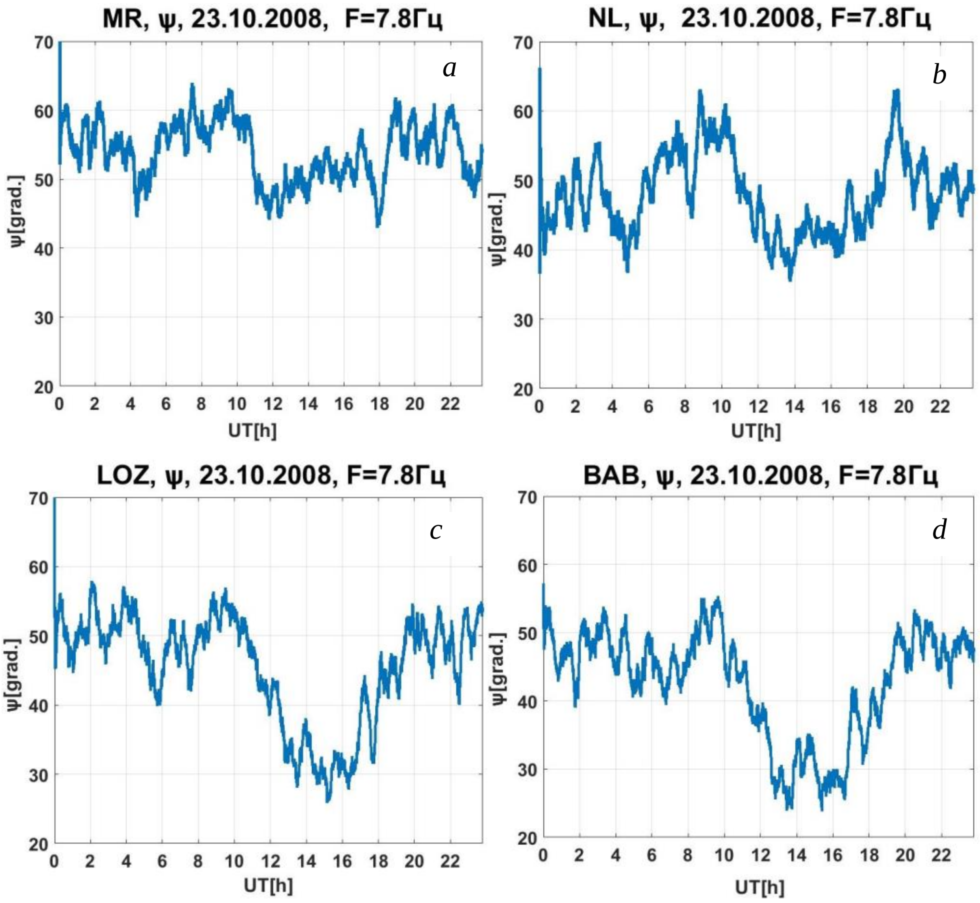

Figure 5. Daily dynamics of the azimuth angle modulus at the MR (*a*), NL (*b*), LOZ (*c*), and BAB stations (*d*) on October 23, 2008

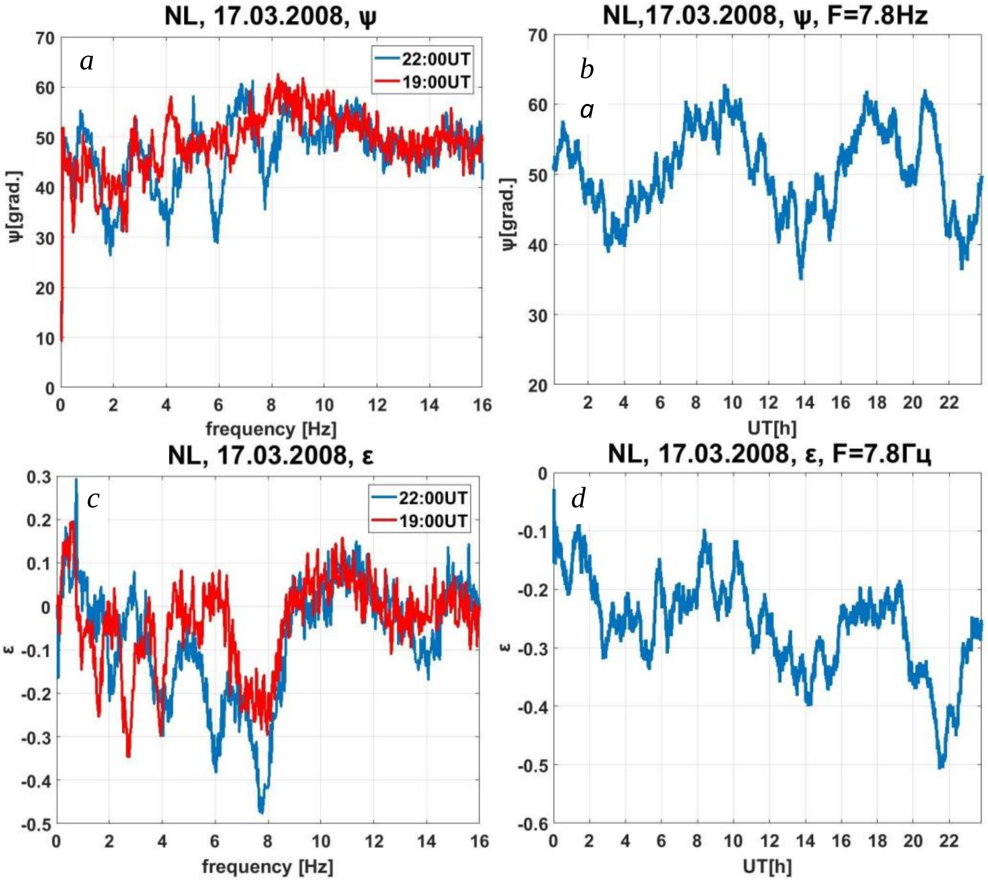

Figure 6. Spectra (*a*, *c*) and daily dynamics (*b*, *d*) of the parameters ψ and ε at the NL station on March 17, 2008

2. DISCUSSION, NUMERICAL CALCULATIONS

The different nature of the formation of ε spectra, magnetic component spectra, and azimuth angle spectra leads to different manifestations of local resonators in the spectra of these ULF noise parameters, in particular in the first-SR band. The polarization parameter spectra are independent of the direction to the source, whereas the magnetic component spectra and the ψ parameter depend on the position of the source. So, the sub-IAR effect, which gives rise to a broadband maximum, is most pronounced in the spectrum of the longitudinal (along the direction to the source) field component [Ermakova et al., 2007]. If there are different thunderstorm sources at a time, the sub-IAR effect on amplitudes of magnetic components can significantly decrease. Figure 7 shows spectra of the magnetic component and the parameter ε for two periods of September 08, 2011. The almost complete disappearance of BSM in the magnetic component spectrum was not accompanied by the disappearance of the sign-variable ε-spectrum dependence characteristic of the sub-IAR effect. So, the sub-IAR effect is most pronounced in the ε dynamics. The azimuth angle and its spectrum also depend on the direction to the source [Ermakova et al., 2014], and when adding fields from different sources the variations of this parameter due to the sub-IAR effect can be significantly lower than the ε variations.

Thus, in the first-SR band the effect of both resonators is most pronounced in the ε spectra

To analyze spectra of the polarization parameters at the first-SR frequency at stations of different latitudes, we numerically calculate these parameters. We use the results of solution of the problem of calculating magnetic components from a vertical electric dipole in the spherical horizontally inhomogeneous Earth-ionosphere waveguide [Kirillov, Kopeikin, 2002] and the method of calculating the surface impedance of anisotropic inhomogeneous ionosphere developed in [Ermakova et al., 2007, 2012]. The longitudinal and transverse magnetic field components are calculated by the following formulas:

$$H_\varphi = \frac{Il\sqrt{D_S}}{4\pi a h(1)} \times$$
$$\times \left(n1_{\mathrm{L}}^{-1}(2)^{\theta\theta} + \frac{h_{Sm,\theta\varphi}}{h_{Sm,\theta\theta}} h1_{\mathrm{L}}^{-1}(2)^{\theta\varphi} \right) \mathrm{ctg}\left(\frac{r}{2a}\right),$$
$$H_\theta = -\frac{Il\sqrt{D_S}}{4\pi a h(1)} \times \tag{2}$$
$$\times \left(h1_{\mathrm{L}}^{-1}(2)^{\varphi\theta} + \frac{h_{Sm,\theta\varphi}}{h_{Sm,\theta\theta}} h1_{\mathrm{L}}^{-1}(2)^{\varphi\varphi} \right) \mathrm{ctg}\left(\frac{r}{2a}\right).$$

Here Il is the current moment of the source; a is the Earth radius; r is the distance from the source to the receiver along the geodetic line; D_S is the matrix determinant $\hat{h}_{Sm}$, $h(1)$ is the height of the lower boundary of the ionosphere at the source point; (2) means that the matrix components $h1_L^{-1}$ are determined at a receiver point, the formulas for calculating matrices $\hat{h}1_L^{-1}$ and $\hat{h}_{Sm}$

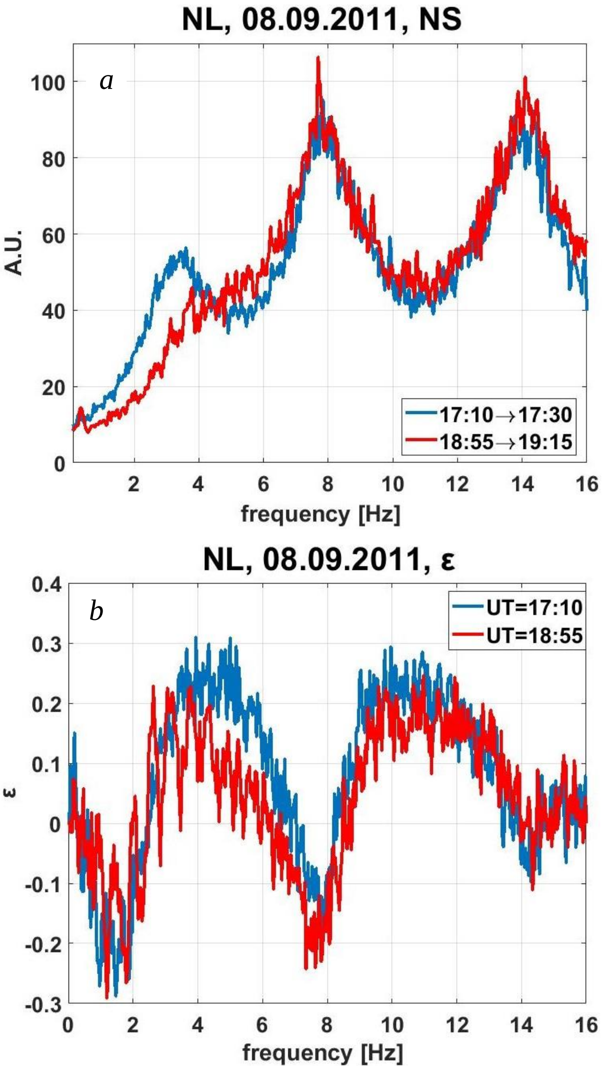

Figure 7. Spectra of the NS magnetic component (*a*) and the polarization parameter ε (*b*) at the NL station on September 08, 2011

are given in [Kirillov, Kopeikin, 2003]. The use of the solution for a spherical waveguide obtained in this work makes it possible to take into account the horizontal inhomogeneity of the ionosphere along the propagation path of ULF waves. However, as is shown in [Ermakova et al., 2011], magnetic noise spectra depend little on the inhomogeneity of ionospheric parameters along the low-frequency wave propagation and is determined mainly by impedance matrix components at the point of recording magnetic fields. Thus, the calculations confirm the conclusions drawn in [Polyakov, Rapoport, 1981; Belyaev et al., 1987, 1989] from experimental data that the RSS formation mechanism is local.

Note that the model spectra ignore peculiarities of the formation of the Schumann resonance, but adequately describe the experimental spectra of ε below and above this frequency range and can explain the diurnal variations of ε in the first-SR band caused by the sub-IAR and IAR effects.

Figure 8 exhibits the model spectra of the polarization parameter ε and the azimuth angle ψ between the main axis of the magnetic field polarization ellipse and the EW direction for different ionospheric plasma conditions at night. These spectra show that the effect of the local ionosphere, in this case sub-IAR, can be significant for a single source at first-SR frequencies. Referring to Figure 8, *a*, depending on the resonator optical density and Q-factor, the sub-IAR contribution to magnetic field polarization in the first-SR band can lead to both an increase and a decrease in the ε modulus (blue and red curves respectively). The sub-IAR effect can also cause a deviation of the magnetic field orientation in the first-SR band from the direction of TH polarization by 10°–20° (see Figure 8, *b*).

Yet, no sub-IAR effect was detected in the experimental spectra of the ψ angle in the first-SR frequency band. This might have been due to the causes analyzed above, namely the presence of several thunderstorm cells.

Let us discuss the causes for the different polarization changes in the first Schumann resonance band at different stations on October 23, 2008. We analyze the daily dynamics of ε at the LOZ and NL stations. Figure 3, *b*, *c* demonstrates a similar pattern of the ε variations at the first-SR frequency at these stations at night. However, due to the low Q-factor of sub-IAR at the LOZ station after sunset, the ε variation in the first-SR band was not as significant as at the NL station: maximum ε values increased to –0.02÷0.1 at NL and to –1.3÷–0.8 at LOZ. Figure 9 presents spectra of the polarization parameter at these stations in the first half of nighttime. The ε spectra confirm that the depth of oscillations of both the large-scale variation and small-scale RSS was much greater at the NL station. The simultaneous IAR and sub-IAR effects caused a sharp increase in ε when the RSS maximum fell on the central frequency of the first SR mode at the NL station (Figure 9, *b*). A decrease in ε in the band of the first SR mode in the second half of nighttime is related to different factors: at the NL station, to the IAR and sub-IAR effects with high f_b (Figure 10, *b*); and at the LOZ station, to the disappearance of the IAR and sub-IAR effects (see Figure 2, *c*). This led to recovery of the parameter ε to almost daily values at the LOZ station (see Figure 3, *c*).

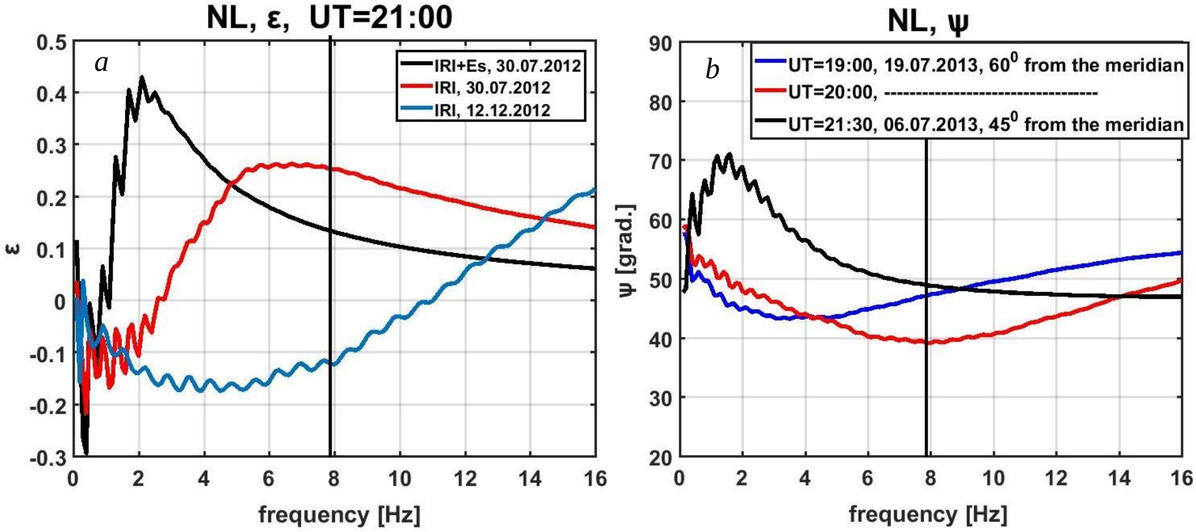

Figure 8. Model spectra of the parameter ε (*a*) and the azimuth angle ψ for different directions to the source (*b*) for the NL station

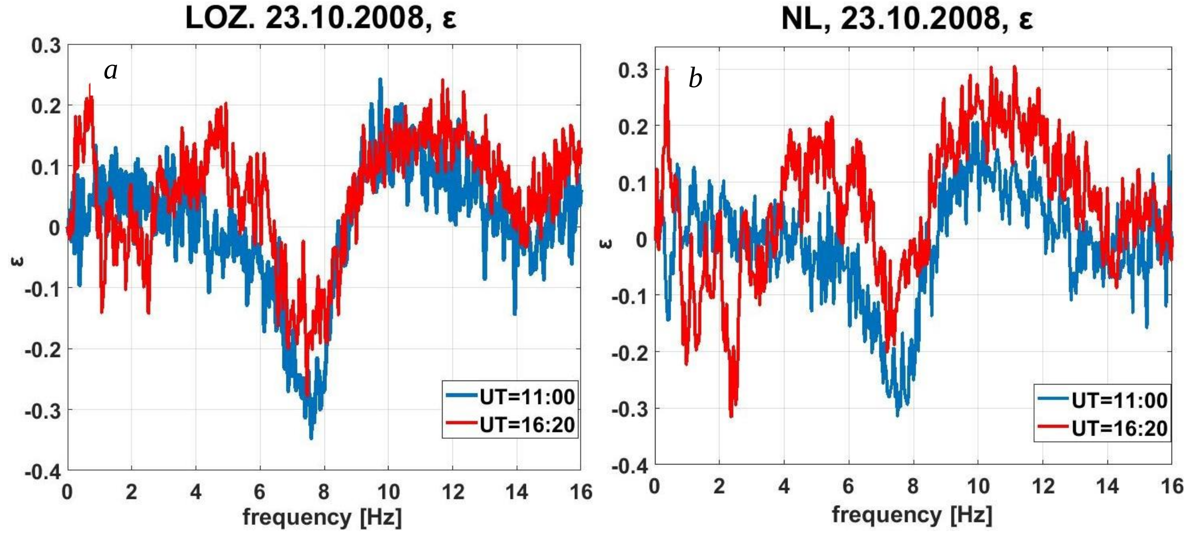

Figure 9. Experimental spectra of the parameter ε at the LOZ (*a*) and NL (*b*) stations on October 23, 2008

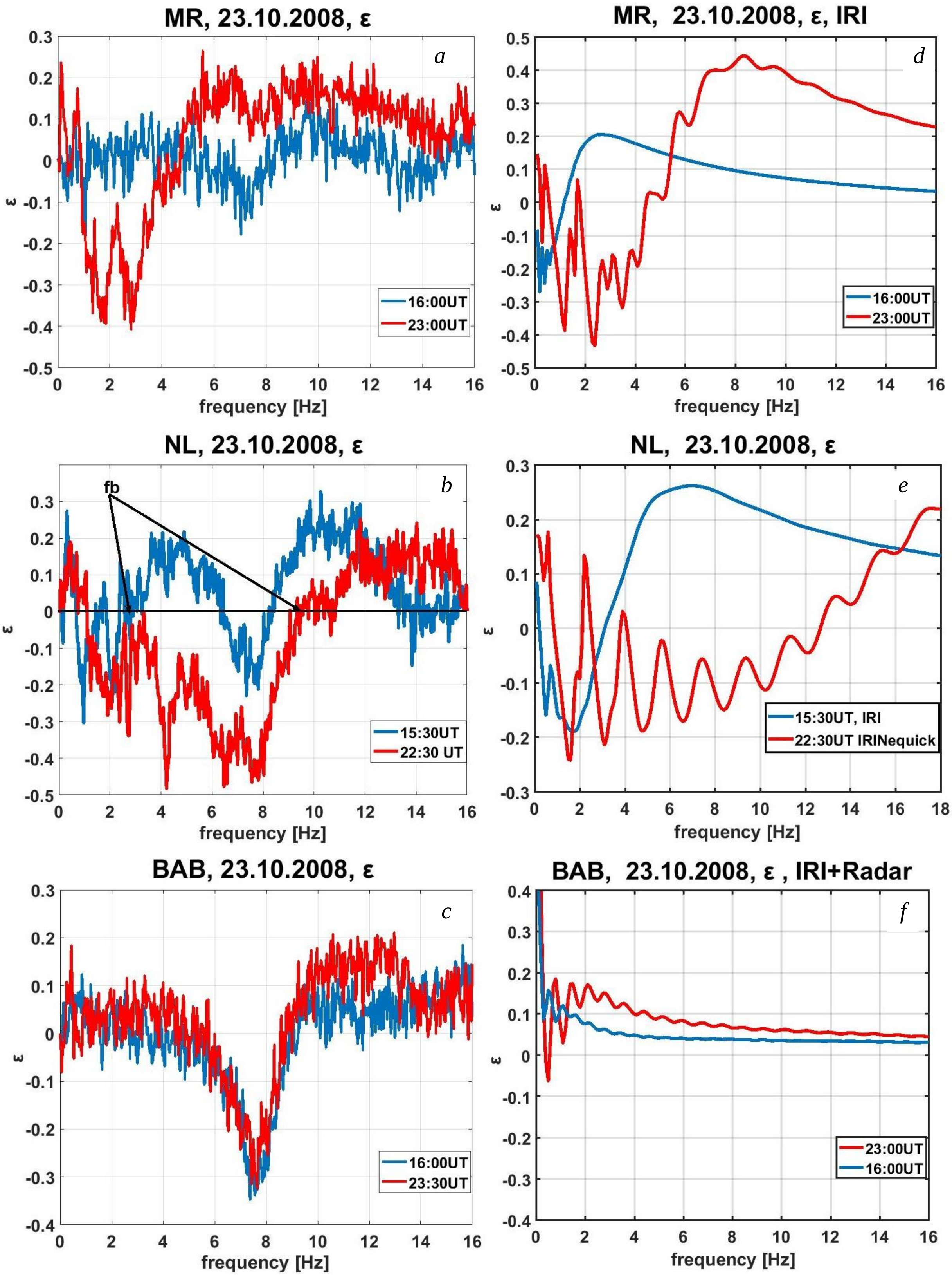

Figure 10. Experimental spectra of the parameter ε at the MR, NL, and BAB stations for October 23, 2008 (left panels), model ε spectra for the same stations (right panels)

Figure 10 (left panels) displays the polarization parameter spectra for the MR, NL, and BAB stations for different time periods on October 23, 2008. As already mentioned above, the different daily dynamics of ε (see Figure 3, *a*, *b*, *d*) at these stations is associated both with lower absolute values of ε at the first-SR frequency at the MR station (including during the daytime) and with different ionospheric plasma conditions over the stations. The latter, in turn, resulted in different parameters of ionospheric resonators over the observatories, as evidenced by the experimental ε spectra. At the MR station, due to an increase in the Q-factor and high optical density of sub-IAR after 21:00 UT ($f_b<f_{1SHR}$), as well as small ε, polarization changed after 21:00 UT from left- to right-handed in the first-SR band (Figure 10, *a*). The most significant variations in the sub-IAR parameters were observed at the NL station: at night, the resonator optical density changed significantly, f_b increased approximately three times and became higher than the first-SR frequency. The simultaneous influence of the two resonators caused a sharp change in ε at the first-SR frequencies after 20:00 UT (Figure 10, *b*). Unlike the case presented in Figure 9, *b*, here RSS minima fell on the central frequency of the first SR mode. The experimental ε spectra for the BAB station (Figure 10, *c*) confirm that no significant changes in the magnitude and nature of the frequency dependence of ε at frequencies below and in the first Schumann resonance band were recorded at this station during the day. This implies that the sub-IAR and IAR effects due to their low Q-factor were negligible.

Right panels of Figure 10 exhibit the model spectra of the parameter ε for different stations according to IRI-2016. For the BAB station, we have also used ionospheric data obtained with the incoherent scatter radar on Svalbard. In these plots, we were interested in the ε variations in the first-SR band at night. The model spectra for the MR station confirmed that f_b was low (~2–4 Hz) and ε increased at the first-SR frequencies at 23:00 UT (Figure 10, *d*). Such changes in the sub-IAR parameters led to a change in the first-SR polarization from left- to right-handed at the MR station after 21:00 UT (see Figure 3, *a*). At the NL station there was a sharp change in the sub-IAR parameters at night, which caused a multiple increase in f_b and a change of ε sign in the first-SR frequency band (Figure 10, *e*). That is why the contribution of the local ionosphere decreased the absolute values of ε at the first-SR frequency immediately after sunset and increased the absolute ε values in the first-SR band with the left-handed polarization after 19:00 UT (see Figure 3, *b*). For BAB, the model ε spectra reveal no significant changes in polarization at the first-SR frequency during the period of interest (Figure 10, *f*), which is due to the small influence of local resonators on spectra of this parameter in the corresponding frequency band.

Thus, the calculated spectra of ε show that the local ionosphere over the observatories can make a significant contribution to the dynamics of ε at the frequencies of the first SR mode at night.

CONCLUSIONS

From comparison between the spectra and daily dynamics of the magnetic ULF noise amplitude and polarization in the frequency band of the first Schumann resonance at stations spaced at long (>1500 km) and short distances (~400 km), we have found out that the local inhomogeneous ionosphere affects the first-SR amplitude and polarization.

This effect is shown to be most pronounced in the spectra of the polarization parameter at night, and the variations depend greatly on sub-IAR parameters. When $f_b<f_{1SHR}$, the degree of magnetic field circular polarization decreases under the influence of the local ionosphere, and in this case polarization may also change from left- to right-handed; when $f_b>f_{1SHR}$, the degree of magnetic field circular polarization may increase, with polarization remaining left-handed.

High-quality IAR can also change the degree of ellipticity of the first SR, the changes depending on the frequency scale of the resonant oscillations driven by IAR.

The IAR and sub-IAR effects on the azimuth angle of the magnetic field vector in the first-SR frequency band are less noticeable and can cause variations of this parameter by 10°–20°.

We have demonstrated that the effect of high-frequency IAR can cause a change in the shape of the amplitude spectrum in the band of the first SR mode: the SR frequency band to narrow or widen and its central frequency to shift.

Analysis of the data from the spaced recording with bases of 400 km has confirmed the effect of local IAR on the magnetic noise amplitude in the first-SR band for a horizontal inhomogeneous ionosphere.

The model spectra of the parameter ε obtained from calculations of the magnetic field in a spherical Earth–ionosphere waveguide from a source such as a vertical electric dipole have confirmed the contribution of local sub-IAR to the formation of magnetic field polarization in the first-SR band at night.

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