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POLARIZATION OF VLF ATMOSPHERICS NEAR THE RESONANCE FREQUENCY OF EARTH – IONOSPHERE WAVEGUIDE BY OBSERVATIONS IN THE AURORAL REGION

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Abstract. Ground-based recording of ELF-VLF waves with right-handed (R) and left-handed (L) circular polarization has been performed at the frequency range of 0-10 kHz in Northern Finland. Monitoring showed a difference in the behavior of VLF waves with R- and L-polarization. The waves with a perfect circular L-polarization were observed at and just above the Earth-ionosphere waveguide cutoff frequency, which is the critical frequency of the first transverse resonance in Earth-ionosphere waveguide (around 1.6-2.3 kHz).
 To study the features of VLF wave propagation near the mode cutoff frequencies, we derived the attenuation of VLF waves with right (R)- and left (L)-polarization from the full wave equation for different models of the ionosphere. Our calculations show that a maximum in the spectra of VLF waves near the critical frequencies of 1.6 – 2.3 kHz due to small absorption of L waves and excitation of resonance waves in Earth – ionosphere waveguide.

Introduction

The atmospheric waveforms are radiated from lightning and able to propagate up to several thousands of kilometers very often. The atmospherics offer an easy way to analyze the effects of Earth-ionosphere wave-guide on propagating ELF-VLF waves. The atmospheric contain a great deal of information about the state of the ionosphere along the propagation path.

Important peculiarities of Earth-ionosphere waveguides have been obtained from the analysis of a special type atmospheric, so-called the tweek ELF/VLF atmospherics. The tweeks have a sharp maximum in amplitude and strong dispersion near the critical frequency of the waveguide, which is ~ 1.6-2.3 kHz (Mikhaylova, 1988). The wave polarization of tweek at the frequency above the cutoff frequency is always left-handed (Yedemsky *et al.,* 1992; Hayakawa *et al.,* 1995).

The propagation mechanism of tweek atmospherics near the mode cutoff frequencies in the presence of an anisotropic homogeneous ionosphere was investigated by Yamashita (1977). Numerical calculations showed very low attenuation in a narrow frequency range just above the mode cutoff frequency. These results are consistent with the observations of a sharp maximum in the tweek spectra. Explanation of the left-handed (L) polarization at the frequency above the cutoff frequency has been given by Ryabov (1992) for a simple model that was earlier used by Yamashita (1977). In the model it is assumed that the Earth-ionosphere waveguide has a plane sharp boundary, and the Earth's magnetic field is vertical.

In this paper we analyze properties of spectrum, and polarization of atmospherics in auroral latitudes and explain the observed features based on the solutions of full wave equation.

Experimental data

The observations of VLF waves were made in Northern Finland during special campaigns (September-October 2005, November 2006). Wideband VLF observations were carried out in the frequency range between 0.5 and 10 kHz using two vertical square loop antennas (the size of the loop is 3×3 m^2, with the effective area being 2300 m^2). The vertical loops were oriented (magnetically) north-south (NS) and east-west (EW). The site was located very far (35 km) from the nearest power line and human settlements during all campaigns. The ELF-VLF signals from the two antennas were fed to the receiver with two independent channels, and the amplified signals were recorded on separate audio tracks of stereo VHS videotapes. Afterwards, one-hour blocks of ELF-VLF data were digitized using a sampling frequency of 40 kHz at 16 or 24 -bit resolution. The sensitivity of the 0.2–10 kHz receiver is about 1 fT at 5 kHz, which is usually below the natural background noise level. More detailed descriptions of the experiment are given by Manninen (2005).

Monitoring showed different behavior of waves with right-handed (R) and left-handed (L) circular polarization in the vicinity of the critical frequency 1.6-2.3 kHz, which is the frequency of first transverse resonance of waveguide Earth-ionosphere. Fig.1 shows typical examples of integrated power from night-time atmospherics recorded on station Siselka (67.82° N, 26.08° E, L=5.47) on October 06, 2005 at 23:00-23:13 UT (top panel), black and grey lines are L and R polarizations, respectively. The ratio of R to L powers is shown on bottom panel. A maximum in amplitude and perfect left-hand circular polarization of atmospherics were registered near critical frequencies 1.6 – 1.8 kHz of Earth-ionosphere waveguide.
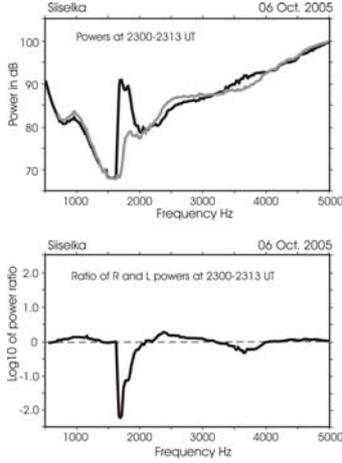
Figure 1. Polarization of night-time atmospherics observed at 23:00-23:13 UT on October 06, 2005 at Siselka. The top panel shows the atmospheric spectrum of left-hand (black line) and right-handed (grey line) polarization. A clear peak in the left-handed circular power at the frequencies of 1.6 – 1.8 kHz is seen. The bottom panel shows the relation of R and L power atmospheric.

Method of calculation of propagation parameters

We have calculated the attenuation of VLF waves with R- and L-polarization by using the wave equation

$$\frac{d\mathbf{e}}{dz} - ik_0 T\mathbf{e} = \mu_0 \mathbf{J}, \tag{1}$$

where $\mathbf{e} = \begin{bmatrix} Ex \\ Ey \\ Hx \\ Hy \end{bmatrix}$ is the vector of amplitudes of wave field

components, z the height of the ionosphere, and matrix T is determined by ionospheric parameters and wave refractive index $n_x = k_x/k_0$. Here k_x is the x-component of the wave vector, and $\mathbf{H} = Z_0 \mathbf{H}$, $Z_0 = \sqrt{\dfrac{\mu_0}{\varepsilon_0}}$. Thus $\mathbf{H}$ measures the magnetic field in terms of the electric field that would be associated with it in a propagating plane wave in free space. This is the same as if the electric field E and magnetic field H were measured in Gaussian units. The vector $\mathbf{H}$ has the same physical dimension as the electric field E, $k_0 = \omega/c$ the wave number in free space, c the light velocity, μ_0, ε_0 the magnetic and electric permittivities of free space [Budden,1961], and $\mathbf{J}$ the external current, which is a source of the wave field

Different ionospheric models have been used in our calculations. If a source of wave field is assumed in the right side of inhomogeneous wave equation (1), this equation describes wave generation, propagation and linear transformation. The boundary conditions include a radiation condition in the upper ionosphere and a perfect conductor condition for the Earth. In the case of non-zero right side of (1), the problem has a unique solution if

$$\begin{vmatrix} E_{x1} E_{y1} \\ E_{x2} E_{y2} \end{vmatrix} \neq 0 \tag{2}$$

Here E_{x1}, E_{y1}, E_{x2}, E_{y2} are the amplitudes of tangential components of the wave, which are obtained after integration of radiation condition from the upper ionosphere to the Earth.

If the right side of (1) is zero (no source), the condition

$$\begin{vmatrix} E_{x1} E_{y1} \\ E_{x2} E_{y2} \end{vmatrix} = 0 \tag{3}$$

describes the eigenmodes of waveguide Earth-ionosphere.

Models of ionosphere

There are different modifications of the IRI model that describe the ionosphere under various conditions. We used the IRI models for geomagnetic latitude 65^0, and for different local times.

The IRI model for 13:00 UT (which corresponds to 15 LT) is shown in Figure 2. The lower axis of abscissas indicates the electron concentration, and the upper one the collision frequency. The ordinate axis marks the height z. The profile of electron concentration is shown by the bold line, and the collision frequency profile by the thin one.

Figure 3 illustrates IRI model for 20:00 UT (22:00 LT). The collision frequency profile in the nighttime model is the same as in the diurnal one.
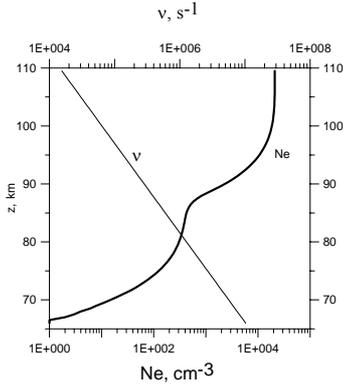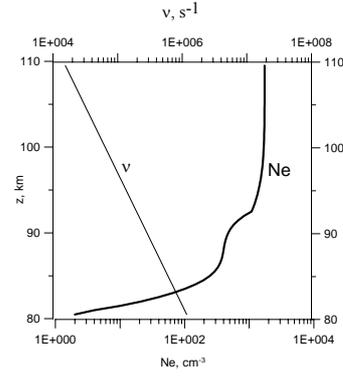
Figure 2. Diurnal model IRI.

Figure 3. Night model IRI.

Results of calculations

As mention above we calculated roots of equation (3). Imaginary part of zeros is attenuation of waves in direction along ground. Tangential electric field on ground is absent but we have two tangential components of magnetic field of wave. We determinate wave rotation (i.e. polarization) from rotation of magnetic field of wave. Polarization in our calculations resulted from ratio of combination

$$H_R = H_x + i \cdot H_y, \quad H_L = H_x - i \cdot H_y, \quad R = |H_R|, \quad L = |H_L|, \quad Polarization = \frac{R-L}{R+L}$$
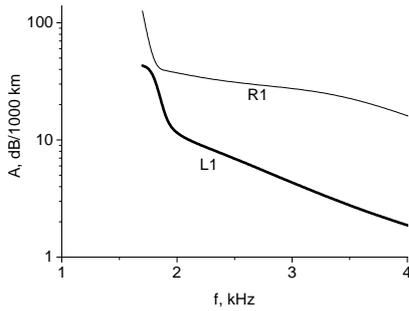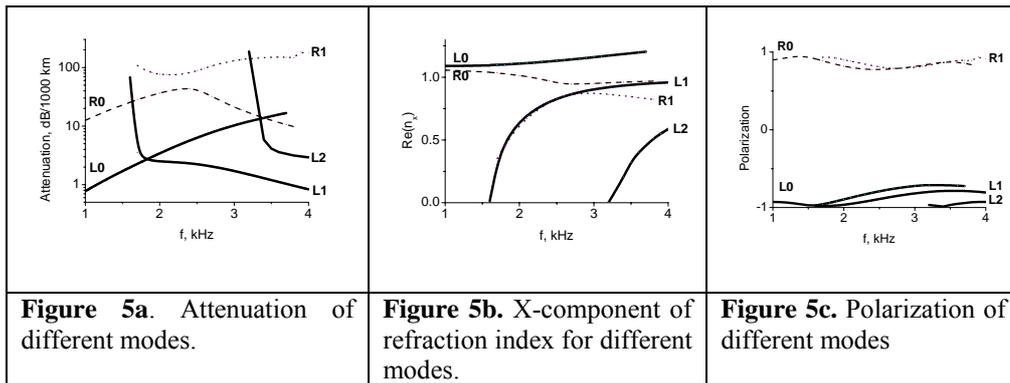

Figure 4. Attenuation of self waves for the diurnal IRI model of ionosphere.

It is shown in figure 4 attenuation of self waves for the diurnal model of ionosphere. From this figure you can see that resonant modes have maximal attenuation and attenuation for left waves (L1, bold line) less than for right waves (R1, thin line). In vicinity of first transverse resonance waves have large attenuation because group velocity is zero. It is seen that left and right waves have large attenuation in day.

Figure 5a. Attenuation of different modes.	**Figure 5b.** X-component of refraction index for different modes.	**Figure 5c.** Polarization of different modes

Parameters of characteristic waves were calculated for the night model of ionosphere. In fig.5a it is shown attenuation for least modes depending on frequency: L0, L1, L2 are left modes (by bold lines), R0, R1, R2 are right modes (by dash lines). In fig.5b it is shown real part of x-component refraction index n_x by same type lines, which are satisfy dispersion relations. Propagate modes must satisfy to relation

$$n^2 = n_x^2 + n_z^2; \quad n_x = 1; \quad n_z = 0. \tag{4}$$

Resonance modes must satisfy to relations

$$k_z = \frac{2\pi}{\lambda_z} = \frac{\pi}{h}; k_x = \sqrt{k_0^2 - k_z^2}; \quad n_x = \frac{k_x}{k_0} = \sqrt{1 - \frac{\pi^2}{(k_0 h)^2}}. \tag{5}$$

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As seen in fig.5b for modes L0, R0 refraction index is $n_x \approx 1$. It means that modes L0 and R0 are propagating modes. Behavior of L1 mode is in agreement with equation (5): component of refraction index $\boldsymbol{n_x}$ for L1mode tend to zero on resonance frequency and tend to 1 when frequencies increase. Polarizations of different mode waves are shown in fig. 5c. Figures 4 and 5a show that least attenuation for all frequencies observed for left waves for night condition.

Discussion

Amplitude maximum in spectrums of VLF waves near critical frequencies 1.6 – 2.3 kHz are detected only for left hand polarization waves during night. However, calculated absorption for L1 mode for the night in Figure 6 don't provide maximum amplitude in vicinity of self waves frequencies of Earth-ionosphere waveguide. Indeed L1 mode absorption have maximum near resonance frequency, when frequency increases absorption decreases quickly, and goes on the plateau. In our opinion maximum in atmospheric spectra near critical frequency due to resonant excitation of self wave of Earth-ionosphere waveguide. The figure 6 presents frequency dependence of amplitude signal in Earth-ionosphere waveguide are excited by plane with current on the height 7.5 km above ground of Earth for night model. The amplitudes of waves with left-hand and right-handed polarizations are shown by bold and thin lines respectively. As seen in Fig.7 amplitudes waves both polarizations have maximums near resonance frequencies. Because attenuation of right waves much more absorption of left waves so far from the source in auroral region we have to observe maximum in spectra only left waves. Note that multiple structure of atmospheric spectra in low latitudes close by source were registered by Lazebnyi (1988) and Belyaev (1991); the frequencies of maximums corresponded to self waves of Earth-ionosphere waveguide. These observations support our conclusion that amplitude maximum of left-hand waves near resonance frequency in auroral region relate to excitation of self waves of Earth-ionosphere waveguide in source region.
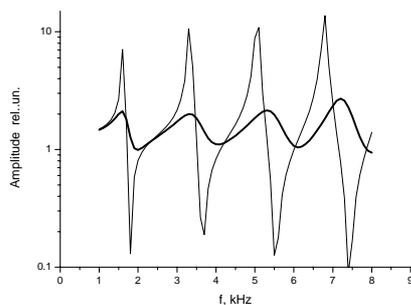

Figure 6. Excitation of self waves of waveguide by plane current. Amplitude of left-hand polarization is bold line and amplitude of right-handed wave is thin line.

Conclusions

Calculations of absorption radio waves for frequencies from 1 to 4 kHz able to explain preferential propagation waves with left polarization in waveguide Earth ionosphere. Left-hand polarization waves not penetrate in ionosphere deeply and absorption for left waves is less than for right waves. Prevalence of left polarization for tweeks was observed earlier in low -latitude region. Our research performed for auroral latitudes shows clearly that amplitude maximum in left-hand polarized waves near critical frequency relate -to least absorption of left waves and excitation of resonance waves of waveguide Earth ionosphere in source region and not connected with the minimum absorption in any frequencies range.

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