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OBSERVATIONS OF IAR SPECTRAL RESONANCE STRUCTURES AT A LARGE TRIANGLE OF GEOPHYSICAL OBSERVATORIES

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Abstract. Examination of spectral resonance structures (SRS) caused by the ionospheric Alfven resonator (IAR) in electromagnetic 0.1÷4 Hz emissions is presented. The data were collected at two distant from each other mid-latitude geophysical observatories (GOs) Borok (L=2.8) and Mondy (L=2.1), and auroral observatory Sodankyla (L=5.2). From 1996 to 1998 more than thirty events were detected at the mid-latitude stations. All events occurred at Borok were always seen at Sodankyla, whereas only a few SRS events were observed in common at Borok and Mondy at nearly the same local time. The SRS dynamical spectrograms consist of well-separated spectral lines, which enables determining the SRS frequency differences between the lines Δf_k and their temporal variations. The observed frequencies grow from the evening to the midnight and then decrease to the early morning, which is coincident with their differences behavior. SRS number distributions over local time obtained at the mid-latitude stations Borok and Mondy are similar to each other, with distribution maxima appearing approximately at the same local time. Moreover, the SRS frequencies and ratio of foF_2 ionospheric frequency to the total electron content in the ionosphere vary during a day in a similar manner. To confirm the IAR origin of the SRS spectra we use both phenomenological formulas for resonator harmonics derived by generalizing some IAR models, and IAR numerical simulations based on height profiles of ionospheric plasma parameters taken from EISCAT radar measurements.

Introduction

A concept of the Ionospheric Alfven Resonator (IAR), which has been introduced in [*Polyakov*, 1976; *Polyakov and Rapoport*, 1981] and verified at middle latitude station Nizhni Novgorod, Russia, and at high latitude station Kilpisjarvi, Finland by *Belyaev et al.*, [1987, 1999], plays an important role in understanding of the physical phenomena occurred in the coupled magnetosphere-ionosphere system [*e.g.*, *Trakhtengertz and Feldstein*, 1991; *Lysak*, 1991, 2002; *Pokhotelov et al.*, 2000, 2001, 2001a; *Prikner at al.*, 2001; *Feygin et al.*, 2003]. Recently experimental evidence for the existence of IAR at high latitudes was confirmed by *Demekhov et al.*, [2000] by using a high sensitive, two component induction magnetometer at Kilpisjarvi observatory (L = 6). A large amount of continuous SRS observations is available from a high-latitude station Sodankyla at L=5.2 [*Yahnin et al.*, 2003]. The high-resolution measurements of IAR signatures were made also at a low-latitude station in Crete (L=1.3) by *Bosinger et al.*, [2002]. In addition to the ground observations confirming operation of the IAR, recently *in situ* observations have been performed from FREJA satellite [*Grzesiak*, 2000], and FAST satellite [*Chaston et al.*, 2002].

In the present study we examine SRS observed at two distant from each other midlatitude stations Borok and Mondy and at high latitude Sodankyla GO (the preliminary discussion of these data was given in *Pokhotelov et al.*, 2001b). From comparing SRS properties we interpret these observations as IAR signatures based on existing IAR models

Experimental data analysis

Low frequency electromagnetic emissions at Borok ($\varphi = 58^\circ$, $\lambda = 38.3^\circ$, L=2.8) and Mondy ($\varphi = 51.8^\circ$, $\lambda = 101.8^\circ$, L=2.1) were registered with search coil magnetometers and recorded by a computer system. The magnetometers installed at Borok and Mondy were designed to detect a signal of a few picoTesla (pT) at 1 Hz. Characteristics of the signals below 4 Hz to be analyzed are clearly seen on spectrograms. In the period from 1996 to 1998, 35 SRS events have been registered at the two midlatitude observatories. All the events occurred in Borok have their counterparts at the high-latitude station of Sodankyla ($\varphi = 67.4^\circ$, $\lambda = 108.9^\circ$, L=5.2), while only a few of the Mondy events have their counterparts at Borok. A typical SRS spectrogram is shown in Fig. 1.

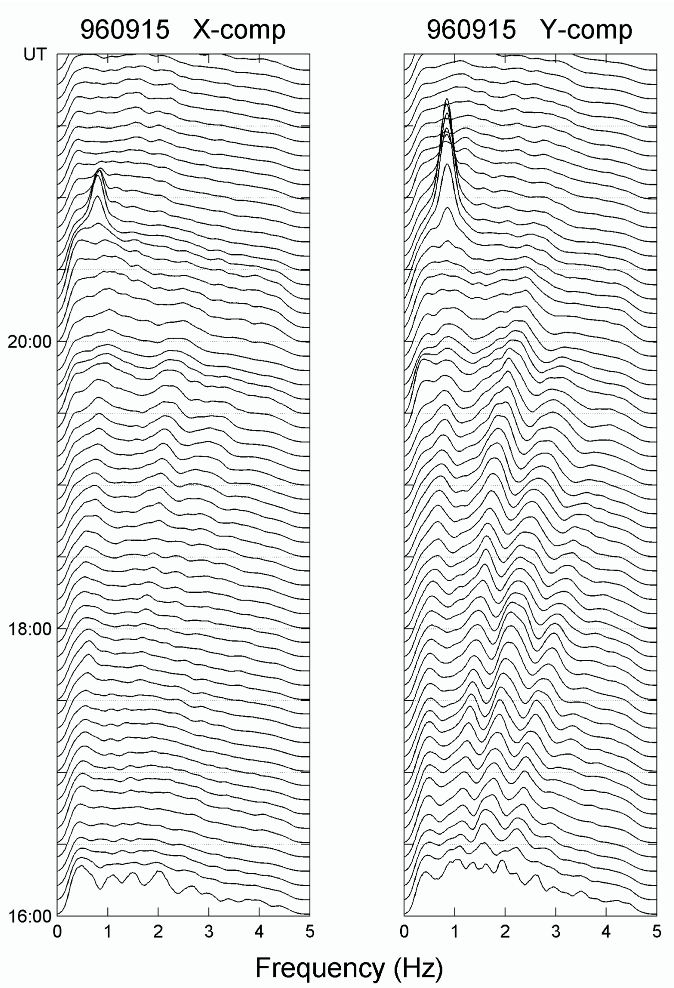

Figure 1. Dynamical spectrum detected on the electromagnetic emission background in the frequency range 0.1 ÷ 4 Hz at Borok on 15.09.96

The diurnal and seasonal distribution of SRS occurrence at Borok and Mondy has been investigated as well. Figure 2 shows the diurnal variation of the SRS number during 1996 -1998 period at these stations, which are similar to each other, with both having a broad maximum (20-24 LT) around 22 LT.

The data obtained make it possible to formulate the following properties of the SRS phenomena: (a) All events occur just after 17:00 LT and continue during several hours up to the local midnight or early morning; (b) The frequencies of the harmonics increase from the evening to local midnight and then decrease to the early morning hours. Similar diurnal behavior is also exhibited by the frequency spacing Δf_k of the SRS detected by *Belyaev et al.* [1987, 1999]; (c) All events are observed under quiet magnetic conditions (K_P< 1); (d) Each event consists of several harmonics (from 3 to 10) in the frequency range from 0.1 Hz to 4 Hz. The duration of each event is more than 5 hours; (e) Each harmonic consists of many detached wave splashes, which are chaotically distributed around the mean frequency; (f) In all cases the simultaneous SRS were detected during summer and autumn periods; (g) The SRS in most cases are more pronounced in the Y - component at Borok and nearly equally well in the X - and Y - components at Sodankyla and Mondy; (h) The comparison of the events at Sodankyla, Borok and Mondy showed that all events registered at Borok are seen at Sodankyla, and that there are only two cases of common occurrence of the SRS at all the three stations at nearly the same local time. In other cases SRS signals are seen at Sodankyla and Borok, but they are absent at the same local time at Mondy and *vice versa*.

Pc1 ("pearl" pulsation) and IPDP characteristic properties considerably differ from the analyzed SRS phenomena [*e.g. Prikner et al*., 2001; *Feygin et al*., 2003], however, if we identify the obtained SRS spectrograms with the signatures of the IAR eigenoscillations then all the above SRS properties can be naturally explained. Appearance of the SRS in Sodankyla and Borok GO in common nearly at the same local time and rather rare common occurrence of these phenomena in Sodankyla, Borok and Mondy suggest that appropriate resonance conditions exist during the night time over large ionospheric region, on the scale of hundreds of kilometers.

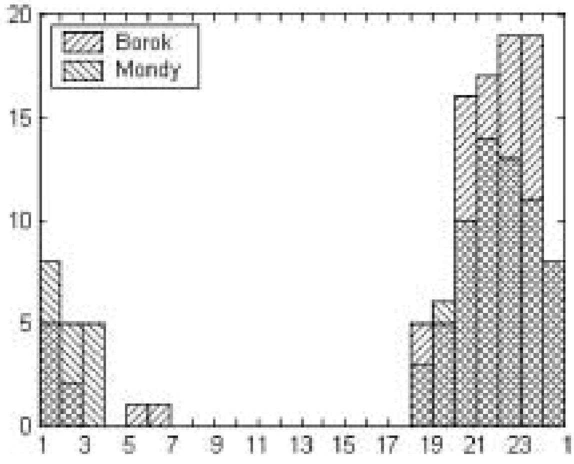

Figure 2. Diurnal variation of SRS event number at Borok and Mondy for the period 1996-1998.

Numerical and analytical simulations of IAR characteristics

We apply the full-wave numerical simulation method of ionospheric filtration of signals [*Prikner and Wagner*, 1991] for the dynamic spectrum observed at Kilpisjarvi, Finland (φ = 69.02° N, λ = 20.86° E, L = 5.9) around 20.00 UT, on September 21, 1998. The EISCAT CP-1 program provided vertical profiles of the ionospheric plasma parameters over Tromso, φ = 69.66°N, λ = 18.95° E, which is close to Kilpisjarvi. The measurements have been performed up to the altitude of 600 km. The input characteristics of the ionospheric medium are realistic altitude profiles of the electron-ion density, mass of the effective ion with respect to the total plasma composition, and profiles of effective ion and electron collision frequencies. The amplitude transmission coefficient (TC) at frequency f on the ground (z = 0) is TC (f) = B_h (f, z=0) / B_h^{inc} (f, z_{max}), where B_h is the horizontal component of the wave transmitted to the ground, B_h^{inc} is the horizontal component of the real B -field amplitude at the incident L-mode wave. The amplitude reflection coefficient (RC) at the upper ionosphere boundary z = z_{max} (an assumed upper boundary of the IAR) is, RC (f) = B_h^{ref} (f, z_{max}) /B_h^{inc} (f, z_{max}), where B_h^{ref} is the horizontal component of the real B-field amplitude at the wave reflected back to the magnetosphere at z = z_{max}. The IAR reflection and transmission coefficients have minimum and maximum values, respectively, at IAR eigenfrequencies, and the evaluated frequencies are equal approximately to the observed ones.

In considering the IAR characteristics it is convenient to use the simplified IAR model [*Pokhotelov et al.*, 2001a, 2001c], in which the domain over the anisotropic conductive E - layer is divided into two regions with the plasma mass densities ρ_I and ρ_M and constant magnetic field B_0. These regions represent the topside ionosphere and magnetosphere, the Alfven velocities being v_{AI} and v_{AM}, respectively. The IAR is localized in a uniform along the magnetic field lines region of the characteristic length L. The anisotropic conductive layer extending from z=-Δz to z=0 serves as a IAR lower wall, having the height-integrated conductivities Σ_P and Σ_H. Further we denote the ratio v_{AI}/v_{AM} as ε, which typical values consistent with the IAR appearance are $\varepsilon \sim 10^{-2}\div10^{-1}$.

The neutral wind with a velocity of v_{n0} and velocity fluctuations δv_n is included into the model. The fluctuations vary in time as ~exp(-iΩ t), while the electric and magnetic field perturbations are supposed to have the form ~exp(-iωt), with Ω<<ω. To describe the plasma dynamics the quasi-hydrodynamic equations of motion and continuity for electrons and one-charged ions as well as the quasineutrality condition $n_e \approx n_i$ are used, only collisions of electrons and one-charged ions with neutral particles being taken into account.

When there is no persistent neutral wind (or having transferred to the neutral wind reference frame), one can get expressions for the IAR eigenfrequencies disturbed by the neutral wind fluctuations δv_n in the following form:

$$\eta = k\pi - \frac{\alpha_P\alpha_L x}{(x^2+y^2)(1-\alpha_P{}^2)}, \ 0<\alpha_P<1 \text{ and } \eta = \frac{(2k+1)}{2}\pi - \frac{\alpha_P\alpha_L x}{(x^2+y^2)(1-\alpha_P{}^2)}, \ \alpha_P>1,$$

where the dimensionless frequency $x_0= \omega L/v_{AI} =\eta+i\gamma$, $\alpha_L=\alpha_P L\rho_{pl}/\Delta z\rho_0$, $\alpha_P=\mu_0\Sigma_P v_{AI}$, , ρ_{pl} is the plasma density, ρ_0 is the unperturbed density of the neutral gas, $x=\Omega L/v_{AI}$. Here we take into account that $\rho_{pl} / \rho_0 \sim 10^{-5} \div 10^{-8}$. When α_P tends to 1, that is, when the ionosphere and magnetosphere are optimally matched, the damping rate γ becomes very large, and the mode frequencies undergo a finite jump. This region with sharp frequency variation is named a transition region [*Yoshikava et al.*, 1999].

Let us compare the values of eigenfrequencies obtained in the above model, which peculiarity is a jump of the Alfven velocity, with those obtained in the model of *Polyakov and Rapoport* [1981] as well as in the model with smooth exospheric profile of the Alfven velocity [*Trakhtengertz and Feldstein*, 1991; *Lysak*, 1991]. In the model of Polyakov and Rappoport the profile of the Alfven velocity is

$v_A{}^2(z)=v_{AI}{}^2$, $h_1<z<h_2$, $h= h_2- h_1$; $v_A{}^2(z)=v_{AI}{}^2(z)/(\varepsilon^2+\exp(-2(z-h_2)/L))$, $z>h_2$.

The IAR resonance frequencies are

$$f_k = \frac{v_{AI}(k+1/4)}{2(h+L)}, \ k = 0, 1, 2,\ldots, \alpha_P< 1; \ f_k = \frac{v_{AI}(k-1/4)}{2(h+L)}, \ k= 1, 2,\ldots, \alpha_P> 1.$$

When the altitude variation of the Alfven velocity is described by the expression [*Greifinger and Greifinger*, 1968]: $v_A{}^2(z)=v_{AI}{}^2(z)/(\varepsilon^2+\exp(-2z/L))$, then, according to *Trakhtengertz and Feldstein* [1991] and *Lysak* [1991], for low (α_P<< 1) and high (α_P>> 1) ionospheric conductivity the IAR dimensionless eigenfrequencies are determined by the roots of the Bessel functions: $J_1(\eta)=0$, which yields 0, 3.83, 7.02, 10.17, 13.32 and $J_0(\eta)=0$, yielding 2.40, 5.52, 8.65, 11.79, 14.93. These are close to kπ, k=0,..., 4, that describe in the main approximation the dimensionless eigenfrequencies of the IAR in the simplified model in the low conductivity case, or (k+1/2)π for highly conductive ionosphere.

Taking into account the above numerical and analytical results for the IAR spectra, we use the following phenomenological expressions for the IAR frequencies: $f_k = (2k+\delta_k)\dfrac{v_{AI}}{4L}$, $\alpha_P< 1$; $f_k =(2k+1+\delta_k)\dfrac{v_{AI}}{4L}$, $\alpha_P> 1$, where k=0,1,2,.... The terms $\delta_k= \delta_k(\alpha_P , \rho_I, v_{n0})$, entering these formulas are purely phenomenological and should be fitted using the data or evaluated numerically or analytically as small corrections in order to describe the deviation of each mode frequency from the equidistant distribution under the condition: $\delta_k(\alpha_P , \rho_I, v_{n0}) < 1$. Typically, each δ_k reaches its maximum in the transition region near α_P =1.

We determinate the value of the Alfven velocity v_{AI} at the level of n_{max}. We take the IAR parameter L to be proportional to the effective thickness of the ionosphere. The latter can be evaluated from the data on the total electron content in the ionosphere I. It is known that F_2-layer critical frequency foF_2 is proportional to $n_{max}{}^{1/2}$, so the frequencies of IAR f^{IAR}_k must be proportional to the ratio foF_2/I, which determines the characteristic scale for the IAR frequencies. Thus these quantities are to have the similar diurnal behavior. The diurnal variation of the SRS frequencies, which were recorded at Borok station on September 15, 1996, and diurnal variation of the IAR frequencies obtained from the phenomenological formula for an insulator, meaning the ionosphere at $\alpha_P < 1$, are presented in Fig. 3.

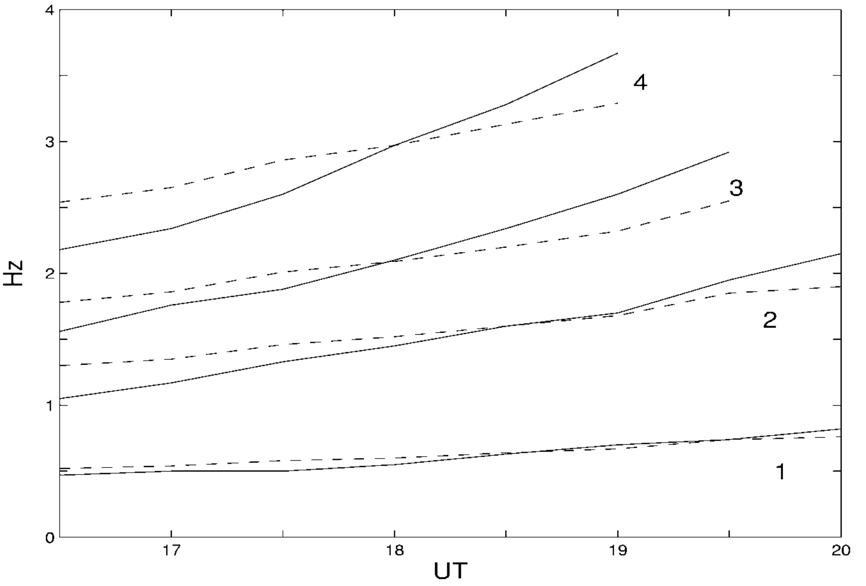

Figure 3. The diurnal behaviour of the experimental values of the SRS frequencies f_k^{SRS} (solid lines) and of the calculated IAR frequencies f_k^{IAR} (dashed lines) for Borok on 15.09.96.

Conclusions

1. Having performed the data analysis as well as numerical and analytical IAR modeling, we can conclude that the SRS signatures seen at Borok, Mondy and Sodankyla stations correspond to the eigenmodes of the local IARs.
2. The IAR frequencies depend on the characteristic IAR parameters v_{AI} and L. Determination of these parameters and their diurnal behavior in environmental conditions is of primary importance for identification of SRS phenomena with IAR signatures.
3. We found that the SRS frequencies and IAR frequencies obtained with the use of the ratio of the F_2-layer critical frequency to the total electron content in the ionosphere exhibit similar diurnal behavior. The evident correlation between these quantities and reasonable numerical evaluation of the SRS frequencies with realistic altitude profiles of plasma parameters confirm the IAR origin of the SRS phenomena.

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