Observation of global electromagnetic resonances by low-orbiting satellites

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Abstract. Penetration of Schumann resonances energy from the Earth-ionosphere resonance cavity into the circumterrestrial space is examined. This study focuses on estimates of Alfvén wave amplitude and spectra in the frequency range of 7–50 Hz which can be observed by low-orbiting satellites. Differences in Schumann resonances observation conditions between the nighttime and sunlit sides of the ionosphere are analyzed. Particular emphasis has been placed on the ionospheric Alfvén resonator (IAR) excited by both global thunderstorm activity and individual lightning discharges. IAR spectra in the frequency range of 0.5–10 Hz are calculated for ionospheric altitudes. The calculated spectral amplitudes of IAR and Schumann resonances are compatible with C/NOFS satellite observations. To explain a shift of IAR resonant frequencies observed during C/NOFS satellite passage through terminator region, the IAR model is developed in which an interference of Alfvén waves reflected from the ionospheric E-layer and the IAR upper boundary is taken into account.

1. Introduction

The electromagnetic energy stemming from the global lightning activity of the planet is believed to be the major source for excitation of Schumann resonances (SR) in the Earth-ionosphere resonance cavity. The SR signature can be detected in the frequency range $7-50$ Hz from any place of the Earth away from thunderstorm and man-made electromagnetic sources [1]. The resonant energy transfer from the world-wide electric storms and magnetospheric-ionospheric plasma convective flow can be also accumulated in ionospheric Alfvén resonator (IAR). The lower boundary of IAR coincides with the high-conducting ionospheric E-layer while the IAR upper boundary is due to Alfvén wave reflection from the strong gradient of background plasma density above the maximum of the F-layer [2]. Typically the ground-based observations of the IAR signatures exhibit the spectral resonance structure (SRS) in the frequency range $0.5-5$ Hz.

Recent ELF electric field measurements onboard low-orbiting C/NOFS satellite revealed a distinct picture of the first five SR [3]. Moreover several spectrograms of the electric field meridional and zonal components with "fingerprint" pattern manifest itself similar to typical IAR SRS, although these spectral peaks lie in the frequency band ~1–15 Hz [4]. These abnormal spectra were detected by the C/NOFS satellite in the near-equatorial region near the terminator. A possibility for the SR energy penetration from the Earth-ionosphere resonant cavity into the upper ionosphere has been recently examined by Surkov et al. [5]. The feasibility of the IAR signature detection by low-orbiting satellites with magnetic or electric sensors has been discussed by Plyasov et al. [6].

2. Estimates of Schumann resonance amplitudes in the ionosphere

In order to compare the magnitudes of SR at the ionospheric altitudes and on the Earth surface, we use the simplified plane stratified model which consist of the infinitely conductive ground $(z < -h)$, neutral atmosphere $(-h < z < -h_0)$, conducting atmosphere $(-h_0 < z < 0)$, conducting gyrotropic E-layer of the ionosphere $(0 < z < l)$ and the F-layer $(l < z)$. In this model the F-layer is the semi-space filled with cold collisionless plasma. The origin of the reference frame is placed at the interface between an ionospheric E-layer and the atmosphere, z-axis is vertically upward, x axis is directed from West to East, and y-axis is directed from South to North. At first the individual cloud to ground (CG) lightning discharge flowing vertically upward is considered as a primary source for the electromagnetic perturbations.

To treat the electric and magnetic fields in the E-layer, Maxwell's equations are needed, which, in their full form, are given by

$$\nabla \times \mathbf{B} = \mu_0 \left(\sigma_\parallel \mathbf{E}_\parallel + \sigma_P \frac{\mathbf{B_0} \times (\mathbf{E}_\perp \times \mathbf{B_0})}{B_0^2} + \sigma_H \frac{\mathbf{B_0} \times \mathbf{E}_\perp}{B_0} \right) \tag{1}$$

$$\nabla \times \mathbf{E} = i\omega \mathbf{B} \tag{2}$$

Here $\mathbf{B}_0$ is the unperturbed geomagnetic field; $E_\parallel \mathbf{E}_\parallel$ and $\mathbf{E}_\perp$ denote components of electric field parallel and transverse to $\mathbf{B}_0$, respectively; $\sigma_\parallel$, σ_P, and σ_H are parallel, Pedersen, and Hall conductivities of the ionospheric plasma, respectively. All electromagnetic fields is assumed to vary with time as $\exp(-i\omega t)$, where ω denotes a frequency.

In the F-layer, instead of equation (1) we have to use the following:

$$\nabla \times \mathbf{B} = -\frac{i\omega}{c^2} \left(\varepsilon_\parallel \mathbf{E}_\parallel + \varepsilon_\perp \frac{\mathbf{B_0} \times (\mathbf{E}_\perp \times \mathbf{B_0})}{B_0^2} \right) \tag{3}$$

where $\varepsilon_\parallel$ and $\varepsilon_\perp = (c/V_A)^2$ are parallel and transverse components of the ionospheric plasma permittivity tensor, respectively; V_A is Alfvén wave velocity and c denotes a speed of light in vacuum.

In what follows we study axially symmetric problem assuming that the geomagnetic field $\mathbf{B}_0$ is vertical. Due to the axial symmetry of this model it is suitable to search for the solution of equations (1)–(3) with the proper boundary conditions in the form of Bessel transform with respect to polar radius for all field components. It should be noted that on the ground the azimuthal component b_φ excited by a lightning discharge is usually much greater than the radial component b_r. Analysis of this problem have shown that the ratio of azimuthal magnetic perturbations in ionosphere and on the ground can be roughly estimated through the height-integrated Pedersen and Hall conductivities, Σ_P and Σ_H, as follows [5]:

$$n_b = \left| \frac{b_\varphi(0)}{b_\varphi(-h)} \right| = \left| \frac{i + (1 + \alpha_P) k_A h}{1 + \alpha_P - i k_A h \left\{ (1 + \alpha_P)^2 + \alpha_H^2 \right\}} \right| \tag{4}$$

where $\alpha_P = (\Sigma_P + \Sigma_a)/\Sigma_w$, $\alpha_H = \Sigma_H/\Sigma_w$, $\Sigma_w = (\mu_0 V_A)^{-1}$ is the Alfvén wave conductance, Σ_a is the height-integrated atmospheric conductivity and $k_A = \omega/V_A$ denotes the Alfvén wave number. Substituting the nighttime atmospheric and ionospheric parameters: $\Sigma_a = 0.15$ S, $\Sigma_P = 0.4$ S, $\Sigma_H = 0.6$ S, and $h = 50$ km into equation (4), gives $n_b \approx 0.5$. For daytime conditions ($\Sigma_a = 1.5$ S, $\Sigma_P = 5$ S, and $\Sigma_H = 7.5$ S) this estimate is on one order of magnitude smaller than the above one.

Analogous ratio of the radial electric field in the ionosphere and on the ground is given by

$$\left| \frac{e_r(0)}{e_z(-h)} \right| \approx \frac{V_A(1+\alpha_P)}{c\left[(1+\alpha_P)^2 + \alpha_H^2\right]} \tag{5}$$

Whence it follows that this ratio is about 2×10^{-3} for the night-time ionosphere. Although this estimate decreases by one order of magnitude for the daytime conditions. The C/NOFS satellite measurements have shown that the electric field amplitude of the first SR in the ionosphere is ~ 0.3 μV/(m Hz$^{1/2}$), that is $3-4$ orders lower than the amplitude of the SR vertical electric component $e_z(-h)$ on the ground. Thus, our estimates of SR amplitudes in the ionosphere are in a good agreement with the C/NOFS satellite observations.

3. Analysis of IAR spectra observed by low-orbiting satellite

A simplified plane-stratified model of IAR has been used to study electromagnetic perturbation inside the IAR. This model is different from that used above by incorporating upper IAR boundary at height about 10^3 km. To model the increase in Alfvén wave velocity with height, we assume that the Alfvén velocity has a jump across the upper IAR boundary. The Hall conductivity of the ionospheric E-layer leads to the coupling between shear Alfvén and fast magnetosonic modes inside the IAR. The major source for IAR excitation is supposed to be either a separate intense lightning stroke or stochastic global thunderstorm activity.

In the framework of the above model the ratio between the magnetic disturbance inside IAR and on the ground can be roughly estimated as $B_{\text{IAR}}/B_g = \omega h V_{AM}/V_{AI}^2$ [6], where V_{AI} and V_{AM} are Alfvén wave velocities in the IAR and the magnetosphere, respectively. According to this estimate the peak disturbance inside the IAR can be an order of magnitude larger than that in the atmosphere. In the frequency range of interest, i.e. $0.5-5$ Hz, the spectral amplitudes of electric power spectra are estimated as $W_E \sim 0.1-0.2$ μV/m·Hz$^{1/2}$. This value is thus consistent with the observations during nighttime conditions since the electric field power spectra detected by C/NOFS satellite at the altitude range of $400-850$ km were $\sim 0.05-0.1$ μV/m·Hz$^{1/2}$ [3].

However the dynamic spectra recently observed by the C/NOFS satellite can hardly be interpreted on the basis of standard IAR theory because these spectra were shifted to higher frequencies (up to 15 Hz) as compared with typical SRS on the ground. To study this effect in more detail, we develop a simple one-dimensional model of the field-aligned Alfvén wave propagation inside the IAR. Analysis of this problem has shown that interference between the primary Alfvén wave and the waves reflected from IAR boundaries can greatly affect the power spectra of electromagnetic perturbations detected by satellite. Let H be the length of field line piece bounded by the resonator boundaries and z be the satellite coordinate measured along the field line. The interference effect results in "modulation" of power spectra in such a way that the spectra have a quasi-oscillatory shape with "periods" $f_1 = V_{AI}/(2z)$ or $f_2 = V_{AI}/[2(H-z)]$ depending on the satellite coordinate z and the direction of the primary Alfvén wave propagation. The implication here is that f_1 and f_2 are equal to the

reciprocal propagation delay time between the primary and reflected Alfvén waves. Both these frequencies are greater than the fundamental IAR frequency $f_0 = V_{AI}/(2H) \approx 0.5 - 1$ Hz.

Model simulations have demonstrated that the interference effect can mask the spectral peaks due to excitation of the IAR eigenoscillations. Moreover, the changes in coordinate z due to the satellite movement along orbit can result in temporal variations of the power spectra obtained on the basis of Fast Fourier Transform (FFT) technique. To explain the increase of the spectral peak frequencies detected by C/NOFS satellite when the satellite descended from 650 to 450 km altitude [3], we suppose that the distance (measured along the field line) between the satellite and the ionospheric E-layer; that is the IAR lower boundary, decreased with time thereby producing both the increase in f_1 and the shift of spectral peaks to the higher frequencies.

4. Conclusion

The above theoretical analysis is indicative of the feasibility of detection of both Schumann resonances and IAR signatures in space by modern magnetometers and electric field sensors onboard low-orbiting satellites. However it seems likely that the observed "fingerprint" spectrograms resembling SRS are not typical for IAR eigenmodes because these spectrograms are subjected to the interference effects between primary and reflected Alfvén waves propagating in IAR. The observation onboard low-orbiting satellite can thus provide us with additional information about ULF/ELF electromagnetic fields and noises at the ionospheric altitude.

Acknowledgements

References

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