Structure of ULF Waves In the Upper Ionosphere: Observations and Model

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Abstract

Recent low-orbiting satellite observations revealed ULF wave structure in topside ionosphere. Pc3 waves were detected very clearly in compressional magnetic component at satellite and in H component on the ground. The following possibilities of ULF compressional disturbance excitation in topside ionosphere are considered: (a) incident Alfven wave upon interaction with the ionosphere generates evanescent compressional mode; (b) transportation of ULF energy to the ionosphere predominantly occurs by fast mode. We estimate quantitatively the expected relationship between Pc3 magnetic components above the ionosphere and on the ground produced by different mechanisms. The modeling results are applied to interpretation of satellite/ground observations.

1. Introduction

Recent advances in precise high-rate measurements of geomagnetic field by low-altitude satellites gave the possibility to detect ULF waves in the top-side ionosphere. These observations showed rather surprisingly the occurrence of significant compressional component $b_{\|}$ of the ULF wave structure [1]. This fact was hard to expect because the traditional notions assume that ULF waves at the ground are mainly produced by transverse field line Alfven oscillations. The structure of ULF waves in the top-side ionosphere may be closely related to their propagation mechanism, and deserves a thorough consideration. The occurrence of the ULF compressional disturbance can be caused by two possible mechanisms: (1) the incident Alfven wave upon interaction with the anisotropically conducting ionospheric layer generates an evanescent fast compressional mode; and (2) the transportation of the ULF wave energy from a distant source to the ionosphere predominantly by a fast compressional mode. The latter notion contradicts the existing theoretical view that Alfven waves only can reach the ionosphere, because fast magnetosonic waves are to be reflected from the regions with high Alfven velocity V_A, so they are to be localized in the near-equatorial plane of the magnetosphere.

In this paper we estimate quantitatively the expected relationship between the Pc3 wave components above the ionosphere and on the ground produced by different mechanisms. The constructed model is applied to the interpretation of satellite observations of Pc3 waves in the upper ionosphere and at mid-latitude stations.

2. Relationship between compressional disturbance above ionosphere and ground signal

We consider the model of the magnetosphere – ionosphere – atmosphere – ground system as a half-space filled with cold plasma immersed in a magnetic field $\mathbf{B}_0$, bounded by the ionosphere - a thin anisotropically conducting layer at altitude h with height-integrated conductances Σ_P and Σ_H. The magnetospheric plasma is characterized by the wave conductance $\Sigma_A = (\mu_0 V_A)^{-1}$. The ground is assumed to be isotropic conductor with conductivity σ_g.

The wave electric and magnetic fields can be decomposed into two modes. The magnetospheric wave fields are a sum of: (A) Alfven mode, where the magnetic field $\mathbf{b}_\perp$ is perpendicular to $\mathbf{B}_0$ and the compressional component is vanishing $b_{\|}$ =0; and (S) fast magnetosonic mode with vanishing field-aligned current $j_{\|} = 0$. In its turn, an electromagnetic disturbance in the atmosphere and in the ground is composed from: (1) magnetic H-mode with vanishing vertical magnetic component bz=0; and (2) electric E-mode with vanishing vertical electric component Ez=0. The general set of Maxwell and MHD equations for the magnetospheric plasma may be decomposed into two uncoupled sets of equations for Alfven and compressional modes. In a similar way, the decomposition into uncoupled equations for E and H modes takes place in the atmosphere/ground.

We consider the harmonic of incident wave $\propto \exp(-i\omega t + ik_x x)$, and neglect the azimuthal variations k_y=0. The boundary conditions for the electromagnetic field at the ground surface are derived via the spectral surface impedances for E and H modes.

The following consideration is based essentially on analytical relationships extracted from the general theory of MHD wave interaction with the thin ionosphere [2]. The electromagnetic field in magnetosphere is a combination of incident (*i*) and reflected (*r*) waves. The wave interaction with the ionosphere is described with the set of the reflection and transmission coefficients

$$\mathbf{R} = \begin{pmatrix} R_{SS} & R_{SA} \\ R_{AS} & R_{AA} \end{pmatrix} \qquad \mathbf{T} = \begin{pmatrix} T_{SS} & T_{SA} \\ T_{AS} & T_{AA} \end{pmatrix}$$

Thus, the coefficient T_{SA} relates the magnetic signal on the ground $b_x^{(g)}$ and the incident Alfven wave $b_y^{(m)}$, as follows $b_x^{(g)} / b_y^{(m)} = T_{SA}$. The E-mode is very weakly excited by the magnetospheric disturbances, so the relevant elements T_{AA} and T_{AS} will not be considered further. Here we estimate quantitatively the expected relationship between the wave magnetic components above the ionosphere and on the ground.

Incident Alfven wave. Upon the reflection of Alfven wave from the ionosphere, an evanescent compressional mode is excited above the ionosphere. The amplitude of this mode $b_{\|}^{(m)}$ is related to $b_y^{(m)}$ via the reflection coefficient R_{SA} as $b_{\|}^{(m)}(z) = b_y^{(m)} R_{SA} \exp(iI - kz)$, where I is the magnetic inclination. As follows from the above

$$\frac{b_{\|}^{(m)}}{b_x^{(g)}} = \exp(iI - kz)\frac{R_{SA}}{T_{SA}}$$

The combination of exact expressions for R_{SA} and T_{SA} from [2] gives

$$\frac{R_{SA}}{T_{SA}} \simeq -\sinh(kh)$$

We have supposed that the terms related to the skin-effect in the Earth's crust were negligeable. Thus, the relationship between the ground magnetic signal and compressional component above the ionosphere does not depend on ionospheric conductance, but is determined by the wave scale *k*.

Incident compressional wave. This possibility assumes that wave energy is transported from a source towards the ionosphere directly by S mode. The ratio of the ground magnetic signal $b_{xS}^{(g)}$ to the incident compressional wave amplitude $b_x^{(i)}$ is determined by the transmission coefficient T_{SS}. The total compressional magnetic field, $b_{\|S}$, in the non-propagation region of S-mode, $k_x >> k_A$, can be found from

$$\frac{b_{xS}^{(g)}}{b_{\|S}} = \frac{-T_{SS}}{\exp(-iI + k_x z) + R_{SS}\exp(iI - k_x z)}$$

Here $R'_{SS} \simeq -\dfrac{k + ik_A\overline{\Sigma}_K}{k - ik_A\overline{\Sigma}_K}$, $T'_{SS} \simeq \dfrac{2(1-i)}{(k - ik_A\overline{\Sigma}_K)[d_g + (1-i)h(1 + k^2h^2/6)]}$, and

$\overline{\Sigma}_K = \overline{\Sigma}_P + \dfrac{\overline{\Sigma}_H^2}{\overline{\Sigma}_P} + \dfrac{2}{k_A d_g[1 - i(1 + 2h/d_g)]}$ is the effective Cowling conductance, modified by the influence of finite ground conductivity, and $\overline{\Sigma}_{H,P} = \Sigma_{H,P} / \Sigma_A$ are the normalized conductances.

3. Numerical Modeling

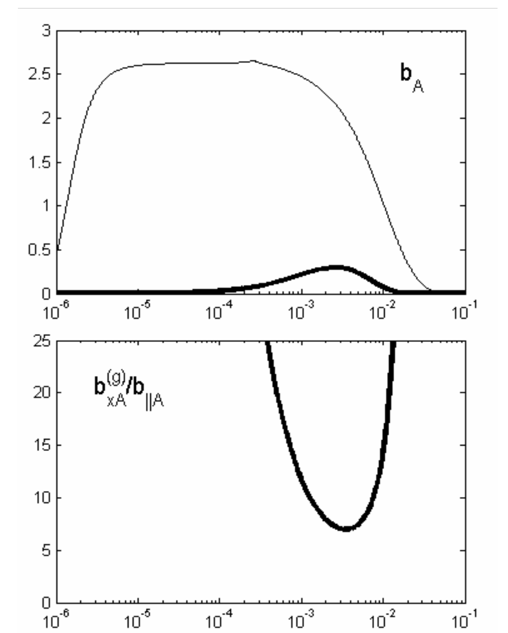

Fig.1.

The critical parameter is the wave transverse scale. So, the relationships between wave amplitudes will be presented as a dependence on k. The total components above the ionosphere are shown, separately for incident S-mode and A-mode. The results of numerical modeling of the Pc3 wave structure (T=30s), based on the exact analytical relationships, are given for the following parameters: V_A=800 km/s, that gives Σ_A=1 Ohm^{-1}. and h=100 km. The model corresponds to the dayside ionospheric conditions Σ_P =5 Ohm-1, Σ_H /Σ_P =2, and inclination I=-90^0. The ground conductivity is high σ_g=0.01 om.m^{-1}, and it corresponds to the skin-depth dg ~ 26 km. We assume that the measurements are made just above the ionosphere (z=0). For low-altitude (~400 km) CHAMP spacecraft the variations of wave components with altitude should not be very significant.

As expected for dayside ionosphere, R_{AA} is high (~0.8) for all scales. The reflection of S-mode, as characterized by R_{SS}, is high for all large scales (k < 10^{-3} km^{-1}). Excitation of reflected A wave by incident S mode, as characterized by R_{AS}, is very weak (<0.1). On opposite, the excitation of S mode by incident A wave grows with k nearly exponentially, and becomes significant at $k \geq 10^{-3}$ km^{-1}.

The transmission coefficient T_{SA}, which characterize the excitation of the H-mode by incident Alfven wave, is high (~2.5), which means that large-scale Alfven waves are easily detected on the ground. However, small-scale structures, k>10^{-2} km^{-1}, are screened by the ionosphere from the ground. The transmission of S-mode through the ionosphere, as characterized by T_{SS} coefficient, is very high. This means that fast compressional waves do not "feel" the ionosphere, and reflect mainly from the highly conductive ground. However, small-scale structures are also screened by the ionosphere from the ground. Conversion of magnetospheric waves, either A or S, characterized by R_{AS} and R_{AA}, into E-mode near the ground becomes noticeable only at very large scales, k<10^{-5} km^{-1}.

The Pc3 wave components in the magnetosphere and on the ground produced by incident Alfven wave with the total unit amplitude 1 nT are shown in Figure 1. The dominant component on the ground is the X component (thin line) $b_{xA}^{(g)} \simeq 2.5$ nT. The scale dependence of compressional disturbance $b_{||A}$ in the ionosphere produced by incident Alfven wave is shown in the upper panel by thick line. The ratio $b_x^{(g)}/b_{||A}$ (bottom panel) shows that the compressional component for a given ground signal becomes noticeable for scales in the range k~10^{-2}-10^{-3}. For the parameters chosen $b_x^{(g)}/b_{||A}$ ~8 at favorable scale $\sim 3\cdot 10^{-3}$ km^{-1}.

The scale dependence of the magnetospheric and ground signals produced by incident S mode with $b_{||S}$ =1 nT is shown in Fig. 2. Because the ionosphere is nearly transparent for a S-mode, the ground magnetic signal $b_x^{(g)}$ has nearly the same amplitude as incident S-wave $b_{xS}^{(g)}$ ~ 1.6 nT.

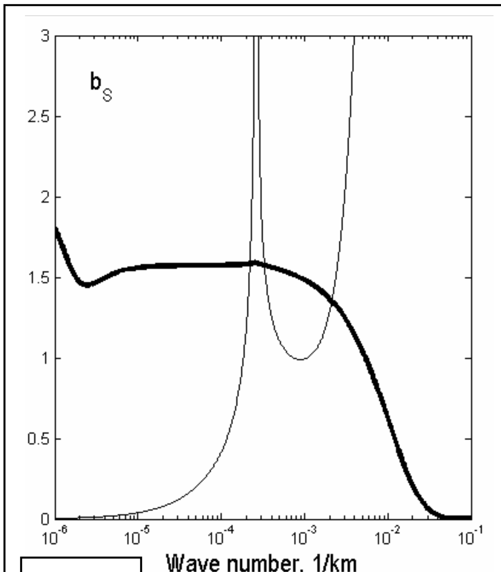

Fig.2.

4. Model validation

To validate the model we have re-examined the Pc3 observations on low-altitude CHAMP satellite in the topside ionosphere. The observations from space are compared to recordings of the mid-latitude ground-based array. Pc3 waves were seen clearly in the compressional component of the satellite magnetic field data, whereas on the ground, their signatures were found in the X component. The coherence between ground and satellite wave signatures was high over wide latitude and longitude ranges.

We have calculated diurnal variations of both the Pc3 wave power in space and on the ground, and the ratio between the satellite compressional signal and ground signal at different magnetic latitudes. The global MLT dependence of the CHAMP compressional power in the 20-70 mHz band has a near-noon (09-14 MLT) and nighttime maxima at low latitudes ($<15^0$). The MLT dependence of satellite and ground power, and satellite/ground amplitude ratio estimated with the data from THY (CGM latitude 42°) and CHAMP for the period Aug-Dec. 2001 are shown in Fig.3a. Comparison of these plots evidences that the Pc3 wave power both in space and on the ground decrease from noon hours to night time hours by about an order of magnitude. At the same time, the ratio between the Pc3 amplitudes on CHAMP and on the ground keeps pretty much the same, varying in the range 1±0.5. Fig. 3b shows the same dependences, but for NUR station at higher latitude (57°). Once again, whereas the Pc3 power varies from dayside hours to nightside hours by about half-order of magnitude, the ratio between the Pc3 amplitudes remains very stable, ~0.5, practically at all MLT. Thus, these dependences show that the ratio between the compressional signal in space and horizontal magnetic disturbance on the ground is not sensitive to the change of the ionospheric conditions. This fact is in an agreement with the proposed model.

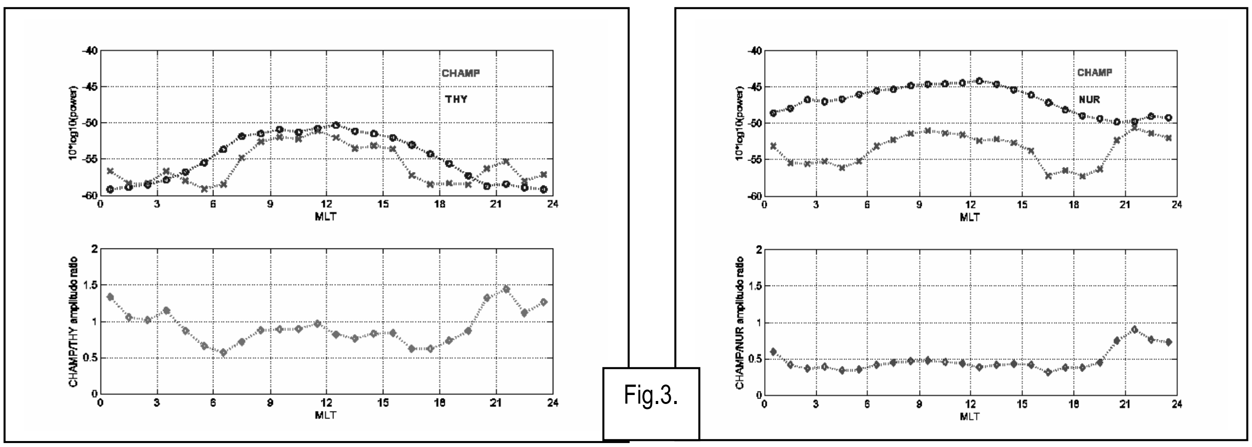

Fig.3.

5. Discussion and Conclusion

With the help of CHAMP high resolution, low noise fluxgate magnetometer measurements at 350–450 km altitude the global distribution of compressional ULF wave activity has been mapped. The observed amplitude ratio between the compressional disturbance in the topside ionosphere and ground response is ~0.5-1.0. This ratio does not match perfectly any of the scenario considered. This fact signifies the in reality both mechanisms: direct fast mode transmission to the ionosphere, and resonant conversion into Alfven waves, contribute to the spatial structure of ULF waves in the top-side ionosphere.

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6. References

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