ULF waves and transients in the upper ionosphere: low Earth orbit observations

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We review new physical results about various types of ULF waves (Pc3, Pi1-2, Pc1-2) in the topside ionosphere stemming from low-orbiting satellite observations. Pc3 and Pi2 waves were detected clearly in the compressional component, whereas on the ground their signature was found in the H component. Relationships between the ULF wave compressional component above the ionosphere and the ground response can be produced by different wave energy transfer mechanisms. Theoretical modeling showed that Pc 3 waves and nighttime Pi2 pulsations observed simultaneously in the upper ionosphere and on the ground corresponded to the scenario of direct fast mode transmission to the ground. The transverse waves dominated only in narrow regions of field line Alfven resonance. Pc1 and Pc2 waves were found to be confined to subauroral and sub-plasmapause latitudes, respectively. The overwhelming fast magnetosonic waves in the near-planet environment could be used as sounding signals for the magnetotelluric sounding of the conductivity of a planet based on the recordings of electric and magnetic components on a low-orbiting probe. The LEO observations make it possible to study ULF response of the upper ionosphere to atmospheric thunderstorm activity.

1. Introduction

The current knowledge of ULF wave physics is mainly based on the electromagnetic observations either in the near-equatorial magnetospheric domain with geosynchronous spacecraft or in the lower ionosphere with radar facilities, or on the ground with magnetometers. The region of topside ionosphere has remained mostly unexplored. Only recently advances in precise high-rate measurements of the geomagnetic field by low Earth orbit (LEO) satellites have made it possible to detect various types of ULF waves in the topside ionosphere. A sensitivity of modern satellite magnetometers and electric field sensors became sufficient to detect waves and transients in a high-frequency part of ULF spectrum. Such LEO missions, like MAGSAT, DE-1, Ørsted, FAST, ST5, C/NOFS, Chibis-M, and especially CHAMP have enabled us to study in situ the ULF waves in the topside ionosphere. These observations cover the ULF range from Pc1/Pi1 waves (fractions of Hz) to Pc3 waves ($f \simeq 20-100$ mHz). Due to the fast motion of a LEO spacecraft, lower frequency Pc4-5 waves (1– 10 mHz) cannot be revealed by such observations. Though Pi2 waves have low frequencies ($\sim 5-25$ mHz), thanks to their large spatial scales at low latitudes, they have also been detected by low-orbiting spacecraft. LEO satellite observations have a unique role in ULF wave physics, bridging the gap between magnetospheric and ground observations, especially in studying the interactions of ULF waves with the ionosphere. These observations have indicated already that some existing theoretical views have to be revised.

2. ULF wave observations in LEO missions

There have been a handful of studies on various types of ULF waves from LEO and we will outline here some of the key studies.

2.1. Pc1 waves

Pc1 waves ($\sim 0.2-5$ Hz) are expected to be highly effective in depleting relativistic electrons from the outer radiation belt and protons from the ring current, therefore studies of these waves became a high priority. According to the present day knowledge [e.g., *Guglielmi and Kangas,* 2007] Pc1 pulsations represent packets of electromagnetic ion-cyclotron (EMIC) waves which are excited as a result of cyclotron instability of energetic ring current protons with anisotropic temperature distribution ($T_\perp > T_\parallel$). It is commonly believed that this EMIC instability is convective, that is, the region of instability at the top of a field line works as an amplifier of running along a field line Alfven waves. The wave packets themselves oscillate between the conjugate ionospheres and are intensified at each passage through the equatorial region of the magnetosphere (the "bouncing wave packet" model), though currently this model casts more and more doubts [*Mursula,* 2007].

Pc1 observations in the ionosphere were first reported during the MAGSAT era (*Iyemori and Hayashi,* 1989). The amplitude of the Pc1 waves on the ground was found to be ~5–100 times smaller than that observed by MAGSAT. However, conjunction studies between space and ground Pc1 waves are not easily done as Pc1 waves are ducted within the ionosphere and appear on the ground over a much wider region than in space [*Fujita and Tamao,* 1988; *Kim et al.*, 2010].

The availability of 10 years of high-quality CHAMP data enabled *Park et al.* (2013) to examine a global climatology of Pc1 pulsations. Diurnal variation of Pc1 occurrence showed a primary maximum early in the morning and a secondary maximum during pre-midnight hours. Annual variations of the occurrence rate exhibited a clear preference for local summer. The solar cycle dependence revealed an occurrence rate maximum at the declining phase (2004–2005), whereas neither magnetic activity nor solar wind velocity controlled the Pc1 occurrence significantly. Pc1 occurrence rate peaked at subauroral latitudes, with the steep cutoff towards higher latitudes. An interesting feature found was that the global distribution of Pc1 exhibited a highest occurrence rate in the longitude sector of the South Atlantic Anomaly.

A successful attempt to identify EMIC waves on the LEO mission ST5 was made by [*Engebretson et al.,* 2008], when 3 identical probes were located in almost identical orbits in a "pearls-on-a-string" configuration with distances between them from first thousands to hundreds of km. The ST5 probes crossing the same spatial region with a delay of $\sim 1-10$ min provided a drastically new possibility for resolving the problem of space-time uncertainty. All EMIC wave packets detected by two ST5 probes were observed at crossing one and the same latitude, which manifested their narrow localization in latitude with characteristic scale $\Delta\Phi \simeq 0.5-0.7^o$ in latitude, or transverse dimension $\Delta x \simeq 50-90$ km.

EMIC emissions were never detected with comparable amplitudes by all three ST5 probes. At the same time, when at the moment of registration of the wave packet the satellite orbit passed in the vicinity of a ground station a prolonged Pc1 emission at the same frequency was observed at the ground. In order to reconcile these observational facts, one may assume that the EMIC instability develops in the near-equatorial magnetosphere in the form of a series of irregular bursts of instability (like "frying pop- corn"). EMIC waves are excited not in the regime of continuous emission, but in the form of relatively short (< 10 min) strongly localized wave bursts distributed chaotically in time and space in a finite region. That is why at a LEO satellite only short bursts of EMIC waves can be observed, while at ground stations prolonged emission collected from a large area is registered. Thus, the EMIC instability of the ring current may work not as a convective amplifier of oscillating wave packets, but as a generator of wave bursts (absolute instability).

The traditional theory of EMIC wave generation was developed under the assumption of their field-aligned propagation at which the packet wave vector remains parallel to the external magnetic field ($k \simeq k_{\|}$), since only these waves can interact efficiently with resonant protons. The critical transverse scale is determined by the value $k_\perp^* = (\omega/\Omega)k_{\|}$ (where Ω is the ion gyrofrequency) [*Leonovich et al.*, 1985]. The small scale of EMIC waves detected by ST5 corresponds to a quasi- perpendicular propagation, since for them $k_\perp \simeq 1/\Delta x > k_\perp^*$. The realistic structure of the radial distribution of the magnetospheric plasma is rather irregular, which allows one to suggest the existence of local waveguides for EMIC waves, not related directly to the plasmapause. A waveguide for EMIC waves can be formed due to the joint action of the transverse wave dispersion and plasma inhomogeneity. The dispersion of the Alfven wave can be caused by: a finite gyro-frequency $\omega/\Omega \neq 0$; a finite Larmor radius of ions $\rho_i \neq 0$; and an electron inertia, characterized by inertial electron length $\lambda_e \neq 0$ [*Dmitrienko et al.,* 1992]. The waveguide nature of EMIC waves was further evidenced by the consideration of polarization features of the wave structures in the topside ionosphere [*Pilipenko et al.,* 2012]. For a typical EMIC wave packet, the polarization ellipticity ϵ changed its polarity in the region of maximum amplitude of the transverse wave component. This polarization reversal may indicate the standing-mode structure of EMIC waves in the transverse direction which are characteristic for waveguide modes. However, comparison of ST5 observations with predictions of waveguide theory showed that none of those mechanisms could explain adequately the observed transverse scale of EMIC trapped modes in the topside ionosphere. The elliptical polarization and changing wave ellipse rotation do not follow from the existing theoretical models of the magnetospheric waveguide for EMIC waves, which indicates the necessity to refine theoretical models for the explanation of this effect. Thus, the question about the instability regime and the mechanism of spatial structure formation of EMIC waves remains open.

2.2. Pi1 bursts

Pi1 bursts in the band 0.1-1 Hz are known to be a signature of the auroral intensifications. However, *Lessard et al.* (2006) suggested that Pi1B could be not just a marker, but even a driver of auroral activations. Using a good conjunction of ground stations, GOES footprint and the track of the low-orbiting FAST spacecraft crossing they found that Pi1b waves propagated past

GOES as a compressional mode earthward and coupled to transverse waves at LEO altitudes. Moreover, Cluster and Polar showed that Pi1b pulsations were associated with plasma fast flows from deep in the magnetotail. The implication is that fast flows trigger compressional wave power that couples to shear mode waves that drive Alfvenic aurora that is observed as the brightening of an existing arc. A possible mechanism responsible for the resonant mode conversion due to the finite frequency effect of a fast mode wave packet into Alfvenic wave packet was proposed by *Pilipenko et al.* [2008]. So far, only one such event was reported, so this hypothesis awaits further validation.

2.3. Pc2 waves

Pc2 waves ($70 - 150$ mHz) are very a rare type of pulsations on the ground. Surprisingly, they were found to be almost always present in the topside ionosphere and magnetosphere as shown by CHAMP and THEMIS data analysis [*Yagova et al.,* 2015]. These Pc2 pulsations occurred mostly just inside the plasmapause ($L \simeq 3.5$). The amplitudes of compressional and transverse components were comparable. The mechanism of these signals is still unknown. The responsible wave mode was interpreted as a waveguide mode of the waveguide formed at the plasmapause, partly converted into Alfven waves. Also, generation of these waves by ion-cyclotron instability of energetic oxygen ions is possible.

2.4. Pc3 waves

Dayside Pc3-4 waves are typically observed for quiet and moderate activity period in the 10–80 mHz range. These waves are commonly considered as a magnetospheric and ground image of upstream waves beyond the bow shock. This conjecture is supported by the linear statistical relationship between the wave frequency and the interplanetary magnetic field (IMF) magnitude B_{IMF} ($f \simeq 6.6 B_{IMF}$), and strong control of Pc3 wave activity by the IMF cone angle. Compressional Pc3 waves in the near-equatorial regions of the magnetosphere were interpreted as fast mode inward transport of upstream wave energy into the inner magnetosphere (e.g., *Kim and Takahashi,* 1999; *Takahashi et al.,* 1994). Because fast waves are to be reflected from regions with high Alfvén velocity V_A, they are expected to be localized in the near-equatorial plane of the magnetosphere only, and they can reach the ionosphere only as an evanescent mode. Therefore, traditional notions assumed that Pc3 waves at the ground were mainly produced by field line Alfvén oscillations, excited by compressional waves in a resonance region.

Heilig et al. (2007) and *Ndiitwani and Sutcliffe* (2009) found that the compressional power was unexpectedly large at LEO. In magnetic field measurements from CHAMP satellite Pc3 waves rather surprisingly were seen clearly in the magnetic field-aligned $b_{\|}$ component, whereas on the ground their signatures were found in the H component. The coherence between ground and satellite wave signatures was high over wide latitude and longitude ranges. Observations of Pc3 pulsations by the scalar magnetometer on the Ørsted satellite ($h = 650 - 900$km) also showed the dominance of the compressional component (*Jadhav et al.*, 2001). Pc3 wave packets were almost simultaneous at Oersted and at ground magnetic stations. In nighttime events the Pc3 packets had about the same amplitude, but during the daytime Pc3 amplitudes at the satellite were larger than on the ground, especially at lower latitudes.

Heilig *et al.* (2007) performed a statistical analysis of compressional Pc3 waves (20–70 mHz) in the topside ionosphere recorded onboard CHAMP (Fig. 1). Observations revealed a clear latitudinal distribution of the Pc3 amplitudes: the average dayside compressional power had a peak near the geomagnetic equator and at high latitudes, and minima showed up at $\sim 40°$ latitude in both hemispheres. The latitudinal characteristic was rather symmetrical about the dip-equator, and peak values at high latitudes and at the equator had similar magnitudes. Additional nighttime maximum at low latitudes and high-latitude maxima on the day- and nightside were probably produced by the contribution by spatial structures sampled by the fast moving satellite, namely the equatorial spread F phenomenon and field-aligned currents.

Sutcliffe et al. (2013) showed that beside the upstream wave related activity with B_{IMF} dependent frequency a typical Pc3-4 pulsation observed at LEO contains a field line resonance contribution with latitude dependent frequency. A case study on a conjunction event between CHAMP satellite and the ground SEGMA network clearly detected the field-line resonance at LEO [*Vellante et al.*, 2004]. The authors succeeded to reveal the characteristic signatures of the Alfvén resonance in the spatial structure of Pc3 wave. The behavior of the azimuthal component showed specific amplitude-phase structure: the reversal of polarization sense through the resonant shell and $\pi/2$ rotation of the polarization ellipse through the ionosphere.

Ndiitwani and Sutcliffe [2009] investigated a similar Pc3 event and found a negative Doppler shift during a poleward section of CHAMP's orbit. *Ndiitwani and Sutcliffe* [2010] reported on two Pc3 events observed by CHAMP with L-dependent Doppler-shifted frequency. These results and especially the results of the statistical survey of *Heilig et al.* [2013] confirmed the flight direction dependent Doppler shift, as well as the $\pi/2$ rotation. Figure 3 shows the power spectrum of the toroidal Alfven waves as a function of latitude averaged from 4 months of daytime (07-15 MLT) observations made by CHAMP along poleward orbit segments around the March equinox in 2003. Field line resonances detected along the MM100 ground magnetometer array with latitude dependent frequency (dashed line) were observed Doppler shifted to lower frequencies by CHAMP (dotted line). No significant dependence of the rotation angle on ionospheric conductivity or horizontal wave scale predicted by the theory was found. All the resonant Pc3 events considered in the above studies were observed during daytime at mid latitudes ($30° - 50°$ magnetic latitude). At higher and lower latitudes transverse components are dominated by magnetic signatures of field aligned currents [*Nakanishi et al.*, 2014; *Heilig and Lühr*, 2013].

The occurrence of a significant compressional component $b_{\parallel}$ of the Pc3 wave structure was unexpected, because it contradicted the assumed Alfvenic nature of Pc3 waves. The main features of the dayside compressional Pc3 activity at LEO were found to be controlled by interplanetary parameters (*Heilig et al.* 2007): Wave amplitudes are controlled by the solar wind speed and IMF cone angle, while the dominant frequency is determined by the IMF strength. All these findings supported the upstream origin of the compressional waves observed at LEO and indicated that the fast mode transfer mechanism from outer magnetosphere to the ground may be important.

Comparison of Pc3 waves at LEO with wave activity observed by magnetospheric satellites may help to estimate the efficiency of possible transmission mechanism. A pioneering study of this type was made by *Balasis et al.* [2012]: they compared strong Pc3 wave signatures during 2003 Halloween storm at CHAMP with observations at CLUSTER mission. Pc3 waves were detected at CHAMP in total B variations, most evident in the auroral zone and dayside equator, while the wave power decreased significantly at mid-latitudes. Clear Pc3 waves were observed simultaneously with comparable magnitudes ($\sim 2 - 4$ nT) both in the topside ionosphere and in the magnetosphere. Therefore, the combined LEO/ground observations clearly showed that the existing theoretical view assuming that only Alfvén waves can reach the bottom ionosphere has to be revised.

The key parameter for comparison of theoretical predictions with ground- satellite observations is the ratio κ of the compressional component above the ionosphere $b_{\parallel}$ to the ground magnetic signal $b_x^{(g)}$ (H component), namely $\kappa = b_{\parallel}/b_x^{(g)}$. The MLT dependence of satellite/ground amplitude ratio κ showed that this ratio remains pretty much the same, varying in the range $\kappa = 1.0 \pm 0.5$ (Fig. 2).

2.5. Pi2 waves

The mid-latitude Pi2 transients are commonly considered as a cavity mode oscillatory response of the inner magnetosphere (plasmasphere) to the substorm activation. This idea was firmly supported by numerous satellite observations in the nightside magnetosphere (*Takahashi et al.,* 1995; *Keiling et al.,* 2001). The signatures of Pi2 compressional mode were observed by LEO DE-1 spacecraft even in the polar cap [*Teramoto et al.,* 2008]. Using data from CHAMP, *Sutcliffe and Lühr* [2003] extracted Pi2 pulsations with a significant compressional component. Simultaneous observations of nightside Pi2 waves at CHAMP and on the ground provided the spectral power ratio $\kappa \simeq 1.0$. The compressional component was in phase with the H component and the poloidal component was in anti-phase [*Sutcliffe and Lühr*, 2010]. Pi2 pulsations observed by the Orsted satellite in a low-latitude region were also nearly pure compressional mode (*Han et al.,* 2004), and Pi2 compressional component mapped directly to the H-component on the ground. These observations interpreted Pi2 waves at low latitudes as the cavity fast mode wave directly transmitted to the ground.

Observations of dayside Pi2s at LEO are much more confusing. While daytime Pi2 pulsations are regularly observed on the ground, *Sutcliffe and Lühr* [2010] found no convincing evidence for their existence in CHAMP data. On the other hand, *Han et al.* [2004] presented two dayside events as candidate Pi2s. For these two events the amplitude at LEO was much smaller than on the ground, and the signals were in antiphase. What is clear from LEO observations, mechanism responsible for the dayside Pi2s should be different from the nightside mechanism. Both *Han et al.* [2004] and *Sutcliffe and Lühr* [2010] argued that the observed behavior can be explained by an ionospheric current excited by an electric field transmitted from nightside auroral latitudes through the ionosphere-ground waveguide. However, the mechanism of the magnetospheric E-field transmission through the atmosphere seems rather questionable [*Yumoto et al.,* 1997]. Thus, the mechanism of daytime Pi2 pulsations still remains unknown.

2.6. Observations of Pc4-5 wave structure

Analyzing ST5 data, *Le et al.* (2011) found transverse ULF wave packets in the Pc2-3 frequency range (∼30-200 mHz) with durations of a few minutes. These waves were typically observed whenever ST5 crossed the dayside subauroral zone. Waves in this band were not seen by ground magnetometers located along the footprint of the ST5 orbit, instead resonant Pc4-5 waves were detected. *Le et al.* (2011) suggested that these unique waves often seen by ST5 are in fact poloidal (small-scale in transverse direction) Pc4-5 wave structures observed Doppler-shifted by ST5 as a result of its rapid traverse across the resonant field lines azimuthally. From the observed Doppler shift, $\Delta\omega \simeq \mathbf{k}_\perp \mathbf{V}_s$ (where V_s is the satellite velocity), the azimuthal angular wave numbers were estimated in the order of 100. These results indicated that high latitude poloidal Pc4-5 waves were much more frequent than previously thought. However, the occurrence of poloidal Pc4-5 waves were not verified yet by magnetospheric satellites.

3. Modeling the relationship between the ULF compressional disturbance above the ionosphere and ground signal

The ULF wave pattern in the topside ionosphere is a complicated mixture of incident, reflected, and mutually converted waves. Interpretation of the low- altitude observations and comparison of satellite/ground measurements demands a relevant model. For low frequencies (Pc3/Pi2 pulsations) an elaboration of such a model is facilitated by the possibility to use the thin ionosphere approximation. Under such an approximation the interaction of a plane wave harmonic with the magnetosphere–ionosphere–atmosphere–ground system can be described analytically (*Alperovich and Fedorov*, 2007). For periods $T > 20$ s the analytical approximation matches well the sophisticated numerical code that links the magnetosphere with the ionosphere and underlying atmosphere and ground [*Waters et al.,* 2013]. However, in the Pc1/Pi1 range the approximation of a thin ionosphere is not valid, and the full wave equations in a realistic ionospheric plasma must be treated. An additional complication arises, which is to be taken into account, that a part of the Pc1 wave energy can be trapped in the ionospheric cavity. This cavity can serve as a waveguide for the fast magnetosonic mode and as a resonator for the Alfven mode. The channeling of Pc1 wave energy in the ionospheric waveguide ensures the propagation of the signal to large distances along the ionosphere (*Fujita and Tamao,* 1988). The partial trapping of the incident wave energy in the ionospheric Alfven resonator results in oscillatory frequency-dependent transmission properties of the ionosphere in the Pc1 band (*Lysak*, 1997).

The occurrence of ULF compressional disturbance in the topside ionosphere can be caused by two possible mechanisms:

- an incident Alfvén wave generates an evanescent fast compressional mode upon interaction with the anisotropically conducting ionosphere (*Hughes and Southwood,* 1976);

- transport of ULF wave energy from a distant source to the ionosphere occurs predominantly via the fast magnetosonic mode.

3.1. MHD wave penetration through the thin ionosphere to the ground

Standard models of the magnetosphere – ionosphere interface consider a half-space filled with a cold magnetospheric plasma bounded by a thin ionosphere - an anisotropically conducting layer at altitude h with height-integrated conductances Σ_P and Σ_H. The magnetospheric plasma is characterized by an Alfvén velocity V_A and a wave conductance $\Sigma_A = 1/\mu_0 V_A$. This multi-layer system is immersed in a straight magnetic field $\mathbf{B}_0$, inclined to the Earth's surface by angle I (vertical $\mathbf{B}_0$ corresponds to $I = \pm\pi/2$, in the equatorial ionosphere $I \to 0$). The atmosphere and ground are assumed to be isotropic conductors with conductivities σ_a and σ_g.

The wave electric ($\mathbf{e}$) and magnetic ($\mathbf{b}$) fields can be decomposed into two modes. The magnetospheric wave fields are the sum of

- Alfvén mode, where the disturbed magnetic field $\mathbf{b}_\perp$ is perpendicular to $\mathbf{B}_0$, whereas the longitudinal component is vanishing $b_\parallel = 0$; and

- Fast magnetosonic (FMS) mode, where the field-aligned component of the current vanishes $j_\parallel = 0$. The field-aligned (compressional) magnetic component $b_\parallel$ is typical for FMS mode and characterizes the plasma and magnetic field compression: $\delta N/N \simeq b_\parallel/B_o$.

An electromagnetic disturbance in the atmosphere and at the ground is composed of

- Magnetic (TE) H-mode, where the vertical component of the disturbed electric field is absent, $e_z = 0$; and

- Electric (TM) E-mode, where the vertical component of the disturbed magnetic field is absent, $b_z = 0$.

Commonly, a harmonic incident wave $\propto \exp(-i\omega t + ik_x x + ik_y y)$ is considered. Here for simplicity the azimuthal variations are neglected, $k_y = 0$, so $k = k_x$ is the component of the horizontal wave vector. The general set of Maxwell and ideal MHD equations for the electromagnetic field in the magnetospheric plasma may be decomposed into two uncoupled sets of equations for Alfven and FMS modes. In a similar way, the decomposition into uncoupled E- and H-modes takes place in the atmosphere/ground region.

The electromagnetic field in the magnetosphere may be presented as a combination of incident and reflected waves. The "thin ionosphere" theory provides analytical expressions for the matrix

R of reflection coefficients, e.g., the ratio of the horizontal magnetic components $\mathbf{b}_\tau$ of the wave magnetic fields after and before reflection. Similarly, for the wave penetration to the ground, the matrix **T** of transmission coefficients for the ratio of the horizontal magnetic field at the ground to the horizontal magnetic field in the ionosphere was calculated. The elements of the reflection/transmission matrices are given in the theory of MHD wave interaction with the thin ionosphere (*Alperovich and Fedorov,* 2007), and they comprise the Hall effect (*Yoshikawa and Itonaga,* 1996), excitation of the ionospheric surface mode (*Pilipenko et al.,* 2000), and the finite conductivity of the atmosphere and ground. In what follows, we consider separately the mechanisms of occurrence of $b_\parallel$ upon incidence of Alfvén and FMS waves onto the ionosphere–atmosphere–ground system.

Alfvén waves. Upon interaction with the anisotropic ionosphere, a compressional component of the reflected evanescent mode can be produced by an incident Alfvén wave. The ratio $\kappa_A(z)$ of the compressional component of an evanescent mode above the ionosphere $b_\parallel(z)$ at altitude z to the ground magnetic signal $b_x^{(g)}$ is (*Pilipenko et al.,* 2008)

$$\kappa_A(z) = \frac{b_\parallel(z)}{b_x^{(g)}} = \exp(iI)kh_* \exp(-kz) \qquad h_* = h + (1+i)\delta_g/2 \tag{1}$$

This relationship is valid for large-scale wave structure, $kh \ll 1$, and when the wave skin-depth $\delta_g = (2/\omega\mu_0\sigma_g)^{1/2}$ in the ground is much less than the horizontal scale of the disturbance, that is $k\delta_g \ll 1$. Thus, the ratio κ_A should not depend on the ionospheric conductance, but it is determined by the wave scale, ground conductivity, and the altitude of the space monitor. In fact, the atmospheric H-mode and reflected fast mode are produced by the same ionospheric Hall current, induced by the incident Alfven wave. As a result, the lower penetration of the magnetospheric Alfven signal to the ground and its lower efficiency of compressional mode excitation exactly compensate each other, and the ratio κ_A remains nearly the same during both nighttime and daytime. The latitude (or inclination) determines the phase shift between the compressional and ground signals ($Arg(b_{\|}, b_x^{(g)}) \simeq I$), but not the amplitude of their ratio.

FMS mode. This mechanism assumes that the wave energy is transported from a source towards the ground by a FMS mode, without conversion into Alfvén waves. Though, FMS waves upon their propagation to the bottom ionosphere encounter a non-propagation (opaque) region, thanks to its large horizontal scale, even an evanescent FMS mode can convey significant wave energy towards the Earth. The factor κ_F characterizing the ratio of the total compressional magnetic disturbance at LEO to the mid-latitude ground magnetic disturbance, induced by the FMS mode, is determined by the transmission properties of the whole ionosphere-atmosphere-ground system. The thin ionosphere theory (Pilipenko et al., 2008, 2011) provides a remarkably simple relationship for a low altitude z and highly-conductive ground ($\sigma_g \to \infty$), as follows

$$\kappa_F(z) = \frac{b_{\|}(z)}{b_x^{(g)}} = (1 - ip)\cos I \qquad (2)$$

The parameter $p = \omega h / V_C$ controls the penetration of the FMS mode through the ionosphere to the ground. Here $V_C = (\mu\Sigma_C)^{-1}$ ($V_C[km/s] \simeq 800/\Sigma_C[S]$) is the ionospheric Cowling velocity, determined by the Cowling-like combination of the ionospheric conductances $\Sigma_C = \Sigma_P + \Sigma_H^2/\Sigma_P$. For the nightside ionosphere the parameter $|p| \ll 1$. Thus, the nightside ionosphere may be considered as transparent for FMS mode, that is $\kappa \simeq 1$, so the incident wave is reflected mainly by Earth's surface. The component $b_{\|}$ is expected to be in phase with H-component on the ground. These theoretical predictions agree with the CHAMP/ground observations of Pi2 waves [*Cuturrufo et al.,* 2014]. At dayside $|p| \simeq 1$, thus, the dayside ionosphere can partially screen the magnetospheric signal from the ground, and introduce a noticeable phase delay.

The relationship (2) predicts that the experimentally measured ratio κ_F should be proportional to $\cos I$, that is, it should decrease away from the dip equator. This prediction agrees with the Pi2 observations by *Han et al.* [2004].

Comparison of two mechanisms. Large-scale Alfven and FMS modes both provide ground response mainly in H- component, so just isolated ground observations cannot resolve them. For interpretation of satellite observations it is necessary to know the relation between the parameters $\kappa_A(z)$ and $\kappa_F(z)$. The numerically modeled behavior of these factors at CHAMP altitude for Pc3 waves at middle latitudes showed that the compressional component produced by an incident Alfvén wave becomes noticeable for wave scales in the range $k \simeq 10^{-2} - 10^{-3}\text{km}^{-1}$ [*Pilipenko et al.*, 2008]. The factor κ_F, characterizing the efficiency of fast mode penetration to the ground, is somewhat higher for the dayside ionosphere than for the night side ionosphere. Comparison of the experimentally observed ratio κ with the modeling results showed a better correspondence with the scenario of direct fast mode transmission to the ground, because $\kappa \simeq \kappa_F \gg \kappa_A$. Thus, this theoretical consideration confirmed the new paradigm of the Pc3 wave energy transmission mechanism to the ground. Throughout mid- and low latitudes, the wave energy is transmitted predominantly by FMS mode, and only a narrow latitudinal region corresponding to the field line resonance, conversion into Alfven mode dominated.

4. Possibility of electromagnetic sounding of planetary interior from a LEO probe

Standard magnetotelluric sounding (MTS) of the crust conductivity profile $\sigma(z)$ is based on the determination of ground impedance Z_g from the data of synchronous magnetic and telluric electric field observations on the ground, whereas ULF magnetospheric waves are sounding electromagnetic signals. When the strong skin-effect approximation (Wait-Price condition) is valid, $k\delta_g \ll 1$, the electric and magnetic components of any electromagnetic wave on the Earth's surface are related by the impedance relationship independent of the wave's spatial structure

$$\mu_0 \frac{E^{(g)}(\omega)}{B^{(g)}(\omega)} = Z_g(\omega) \qquad (3)$$

For any conductivity profiles, an apparent resistivity ρ_T is introduced using the Tikhonov-Caniard formula $\rho_T(\omega) = |Z_g(\omega)|^2/\omega\mu$. *Fedorov et al.* [2014] suggested that a similar MTS approach can be used to find the planetary interior conductivity using the registration of variable electric and magnetic fields on a LEO probe above a planetary ionosphere, while FMS waves in the planetary magnetosphere can play the role of sounding waves. Indeed, any planet with a magnetosphere and detached bow shock constantly generates reflected particles and upstream waves that subsequently penetrate into the magnetosphere and "illuminate" a planet. Observations of upstream Pc3 waves in the terrestrial magnetosphere on LEO satellites indicated that the Alfven mode in the ULF field predominates only in the narrow resonance region, while MHD wave activity above the ionosphere is generally formed by FMS waves. The probe magnetometer measures electric and magnetic wave components above the ionosphere, which enables one using the spectra of tangent to the ionosphere electric $E_\tau(\omega, k)$ and magnetic $B_\tau(\omega, k)$ variations to determine the matrix of an apparent spectral impedance $Z_I(\omega, k)$. The satellite MTS becomes feasible if an adequate theory could provide an estimate of the planet's surface impedance contribution to the apparent impedance of an entire system magnetosphere - ionosphere - atmosphere - ground measured onboard a probe.

There are two conditions when the planet's surface impedance Z_g can be in principle determined from the apparent impedance Z_I measured on a probe above the ionosphere. First, the ionospheric conductance should not be very high, otherwise FMS mode would be totally reflected by the ionosphere and would not reach the ground. Second, the planet's ground conductivity should be high enough, otherwise FMS mode would not reflect effectively from its surface. When both conditions are valid, then, according to the thin ionosphere theory, the planet's surface impedance Z_g can be determined from measured by probe apparent impedance Z_I from the following relationship

$$Z_g \simeq Z_I + i\omega\mu(z + h) \tag{4}$$

The geometrical factor in (4) is easily calculated from frequency of detected waves ω and probe altitude z. The proposed approach can be tested based on electromagnetic Pc3 and Pi2 wave observations on LEO SWARM satellite with electric and magnetic sensors onboard in the Earth's topside ionosphere before it can be applied to sound other planets.

5. ULF response in the upper ionosphere to atmospheric electric discharges

Atmospheric thunderstorms constitute one of the most powerful disturbances in the Earth's environment and provide an impulsive coupling of the Earth's atmosphere with the ionosphere above active storm cells with a considerable energy involved. Electrical storms are known to be one of the natural sources of electromagnetic emissions in a wide frequency range, from 0.1 Hz to hundreds of MHz covering ULF - ELF - VLF - HF - VHF bands. The largest spectral density of the atmospheric electrical discharge is concentrated in the VLF band (∼few kHz), though comparable spectral power is contained in the lower ELF-ULF bands (from fractions of Hz to few tens of Hz).

The characteristic feature of the Earth's atmospheric electromagnetic activity is the world-wide occurrence of Schumann resonance - narrow-band electromagnetic emission at certain frequencies in the ELF range of 8-50 Hz. SR are formed due to the natural spherical resonance cavity between the ground and lower ionosphere, permanently excited by the global thunderstorm activity. Commonly, it is assumed that the resonator upper boundary is a perfectly reflecting conductor.

Nonetheless, a theoretical possibility of electromagnetic energy leakage from the resonator into the upper ionosphere was indicated [*Surkov et al.,* 2013]. This leakage may become noticeable on the nighttime side of ionosphere. Recent electric field measurements onboard LEO C/NOFS and Chibis-M satellites revealed a distinct picture of several Schumann harmonics [*Simoes et al.,* 2013; *Dudkin et al.,* 2014], most evident during nighttime.

A peculiar feature of the geomagnetic variations in the ULF band, just below the fundamental tone of Schumann resonance, is the occurrence of multi-band Spectral Resonant Structure, observed by high-sensitive induction magnetometers during nighttime at low, middle, and even high latitudes. The lowest frequency of this multi-band spectral structure is about fractions of Hz, and the difference between the spectral harmonics is ∼0.3-0.5 Hz. The occurrence of this spectral structure was commonly attributed to the Ionospheric Alfven Resonator (IAR) in the upper ionosphere (see review by *Demekhov,* 2012). The IAR lower boundary coincides with the E-layer, whereas the upper boundary is located at altitude of few thousands km where Alfven waves are partially reflected from a steep gradient of the $V_A(z)$ profile above the maximum of the F-layer. The ionospheric cavity with a minimum of $V_A(z)$ works not only as resonator for Alfven waves, but as a waveguide for the FMS mode. The waveguide magnetosonic modes with frequencies above the critical frequency ∼0.5 Hz can propagate over long distances (up to few thousand km) along the ionosphere. It was suggested that either regional thunderstorms or world tropical thunderstorm centers are able to stimulate the signals in the IAR range with sufficient intensities.

A resonator response is to be different for a quasi-steady harmonic driver and for an impulsive excitation. While the first driver excites a relevant eigenmode of the resonator, an impulsive source produces a pulse oscillating between the upper and bottom boundaries of resonator, gradually spreading because of dispersion. *Fedorov et al.* [2014] suggested, in contrast with the traditional view, that multi-band spectra on the ground excited by lightning discharges are in fact produced by a pair or more pulses, reflected from the IAR boundaries. As illustrated in Fig. 3, upon the interaction of the initial lightning-generated pulse with the anisotropic lower ionosphere, it partially penetrates into the ionosphere, travels up the ionosphere as an Alfvn pulse, and reflects back from the upper IAR boundary. The superposition of initial pulse and echo-pulse separated by time delay Δt owing to the Alfvn wave propagation up and down in the ionosphere, produces spectra with multiple spectral peaks separated by $\Delta f = 1/\Delta t$. Indeed, examination of ULF magnetic response to the regional lightning activity showed that the mechanism of the multi-band spectral structure was not related to the oscillatory response of the upper ionosphere, but was caused by specific multi-pulse structure of geomagnetic disturbances (*Schekotov et al.* 2011).

The issue of the magnitudes of the thunderstorm-related ULF fields in the upper ionosphere is rather controversial. Greifinger and Greifinger (1976) predicted only a weak strength of the ULF fields in the upper ionosphere above the thunderstorm. Thus, according to many theoretical models the IAR signatures could hardly be detected by a low-orbiting satellite. In contrast to the above results, *Plyasov et al.* (2012), using simplified multi- layered plane models, estimated analytically the expected IAR excitation rate by atmospheric thunderstorms, and claimed the possibility of the IAR signature detection in mid- and high latitude ionosphere by modern electric or magnetic sensors onboard LEO satellites.

Rather surprisingly, while ground observations of IAR are ubiquitous, the reports on detection of IAR signatures in the topside ionosphere are rare. The ELF electric field measurements onboard low-inclination (13^o) C/NOFS satellite at altitudes of 400-850 km revealed few shortlived (< 1 s) signatures near the terminator ("fingerprint emission" with up to 20 harmonics) resembling IAR multi-band spectral structure (*Simoes et al.,* 2011). However, frequencies of these structures were at least 5 times larger than model predictions. Thus, an interpretation on the basis of standard IAR model demands more than an order of magnitude lower plasma density in the upper ionosphere as compared with existing ionospheric models. *Dudkin et al.* [2014] using the electric field sensor onboard Chibis-M microsatellite found just several signatures of the triggered excitation of IAR in the upper ionosphere. Thus, the lack of ubiquitous IAR signatures in the topside ionosphere is still to be understood.

6. Discussion: Prospects of further studies

Observations at CHAMP of the global distribution of dayside compressional Pc3 pulsation activity and ground Pc3 waves have shown that a significant part of the magnetospheric fast mode energy can leak to the ionosphere, and eventually to the ground. The statistics of the Pc3 wave events are probably dominated by events with a larger contribution of intervals when CHAMP was away from the local Alfven resonant region. In these events a ground Pc3 signal is expected to be coherent over large distances, and resonant distortions of amplitude/phase behavior will be small. Observational results and theoretical modeling have confirmed the idea of fast mode cavity mechanism of night side low-latitude Pi2 oscillations and Pc3 waves. The transmission channel of magnetospheric Pc3/Pi2 waves to the ground is especially evident at near-equatorial latitudes. The origin of night time Pc3 waves has not been firmly established yet. The coordinated CHAMP-ground observations of nighttime Pc3/Pi2 waves are generally in a qualitative agreement with the predictions of the theory, assuming the incidence onto the upper ionosphere of a pure FMS mode. The daytime CHAMP-ground Pc3 events revealed nearly π-phase difference between the topside ionosphere and the ground [*Cuturrufo et al.,* 2014], which is not consistent with the fast mode transmission mechanism. However, in a general situation, coupled Alfvén and FMS modes may compose an incident ULF wave. Therefore, a situation is possible in which the compressional component in the upper ionosphere is due to FMS mode, whereas the ground signal and ionospheric electric field are produced mainly by the Alfvén mode. This case probably corresponds to the daytime Pc3 wave events observed by CHAMP by *Vellante et al.* [2004] and *Ndiitwani and Sutcliffe* [2009]. Though a close correspondence between the compressional component and ground signal was observed, the behavior of the CHAMP azimuthal component showed specific amplitude-phase structure typical for the field line resonance. The theoretical model for this general situation is still to be developed. The demand for the elaboration of a reliable qualitative model of ULF transmission through the ionosphere to the ground comes not only from ULF wave studies, but from the wider space community. Such model is necessary to evaluate how adequately ground observations of ULF waves correspond to magnetospheric wave activity, which is the important driver/loss factor for ring current protons and relativistic electrons.

The model of a thin ionosphere enables us to couple wave signature in the upper ionosphere and on the ground of Pc3/Pi2 pulsations. For short-period Pc1 waves the problem becomes significantly more complicated due to the ionospheric Alfven resonator excitation and mode trapping into the FMS waveguide. These effects make the ULF wave transmission properties strongly frequency- and scale dependent and demand more sophisticated numerical models for their description (e.g., *Lysak,* 1997; *Prikner et al.,* 2004).

The SWARM multi-probe mission with high-sensitive magnetometers and electric field sensors onboard is capable to solve many remaining problems [*Balasis et al.,* 2013]. A combination of the electric and magnetic field measurements by the fleet of the SWARM mission provides a possibility to identify the direction of the wave energy flow (Poynting vector). A combination of observations at LEO and in the inner magnetosphere will help to determine how effectively the FMS waves can illuminate a whole planet, in particular polar regions, near equatorial, and mid-latitude. What fraction of compressional mode energy can tunnel towards the E- layer? Can compressional waves refract on the night side and produce "night side" Pc3 pulsations?

Pi1b pulsations were suggested to be initially excited by tail fast flows, and when these waves propagate earthward, they mode convert into transverse waves and eventually end up driving Alfvenic aurora. This hypothesis is still to be validated and further examined.

It is theoretically possible to use MTS in order to determine the conductivity of the planetary interior based on registration of variable electric and magnetic fields on a low orbiting space probe, whereas FMS waves in the planetary magnetosphere can play the role of sounding waves. Planets with a magnetosphere and bow shock have a halo of the upstream waves. These waves penetrate into the magnetosphere as FMS mode and illuminate a whole planet. FMS wave apparent impedance registered onboard a probe makes it possible to estimate the planetary conductivity accurately if the geometric correction is taken into account. This idea can be validated using the data from SWARM mission.

The measurements onboard three ST5 micro-satellites showed that in the topside ionosphere the EMIC wave packets are narrowly localized over latitude with a characteristic scale from the first tens to 100 km. The observed transverse scale corresponds not to the regime of quasi-longitudinal wave propagation, as it has been assumed in all theories of EMIC instability, but to the regime of quasi-transverse wave propagation. Thus, the models on generation of EMIC waves by energetic protons in the Earth's magnetosphere should be augmented by a mechanism of formation of their strongly localized radial structure. The probable capture of waves into the magnetospheric waveguide has not been explained quantitatively by available theoretical models. This waveguide, apparently, is formed at the segment of the field line adjacent to its top. The comparison of satellite and ground observations also led to the conclusion that the EMIC instability of the ring current protons works not as a convective amplifier of the multiple oscillating wave packets, but as a system of local generators of short time (< 10 min) wave bursts.

Electromagnetic resonances (like Schumann resonance or IAR) are to be a ubiquitous feature of planetary environments that possess a ionosphere and show evidence for electrical activity, such as Venus, Jupiter, Saturn, and Neptune. A study of the properties of Schumann resonances and other ULF transients could therefore indirectly yield the information on the interiors of these planets and lightning activity. Therefore, examination of electromagnetic response in the terrestrial ionosphere to atmospheric electric discharges by LEO satellites may be considered as a testing ground for the development of tools for the study of Solar system planets.

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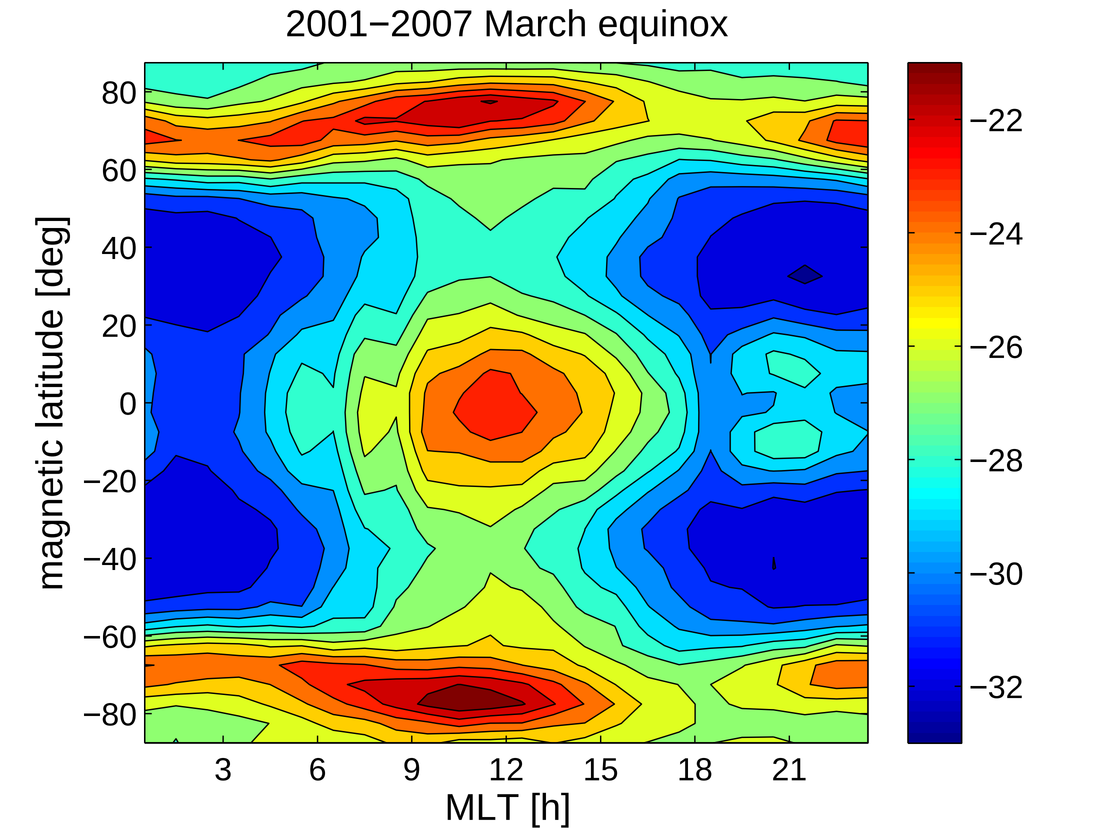
7. Figure captions

F1. MLT-magnetic latitude distribution of the compressional power in the 16- 100 mHz band near March equinox (about 4 month of data centered at March equinox) based on all observations between 2001-2007 by CHAMP. The wave power has been corrected for solar wind speed variation.

F2. The magnetic latitude dependence of κ observed between 0607, 11 12, and 1617 MLT, respectively (adapted from Pilipenko et al., 2008).

F3. Doppler-shifted FLR continuum observed by CHAMP. The dashed black line shows the mean FLR frequencies f_R determined from ground observations. The dotted black line represents a fit to the CHAMP observations made by $0.85 \times f_R - 12$. (adapted from Heilig et al., 2013).

F4. A sketch of the IAR excitation by lightning stroke.



2001−2007 March equinox
magnetic latitude [deg]
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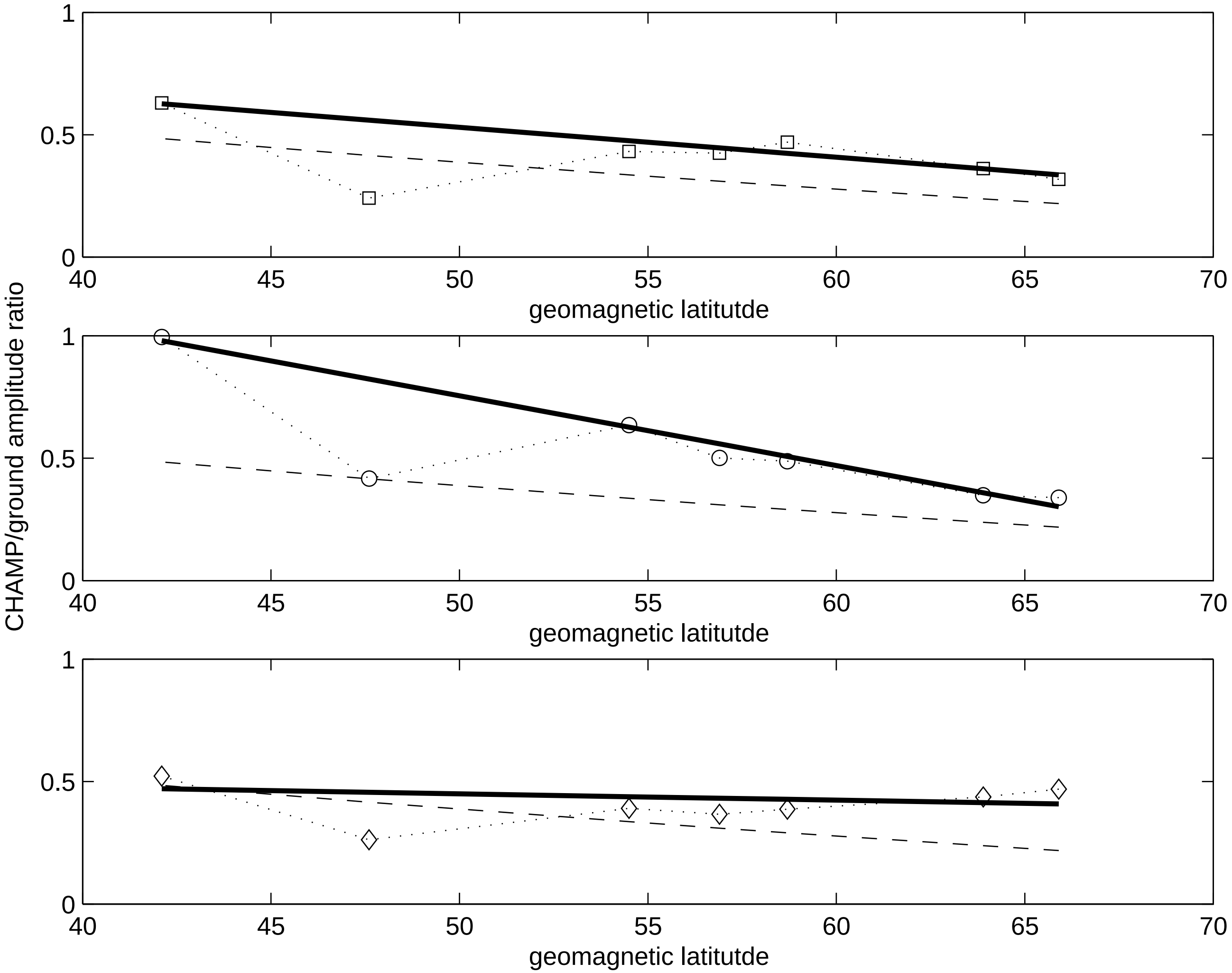
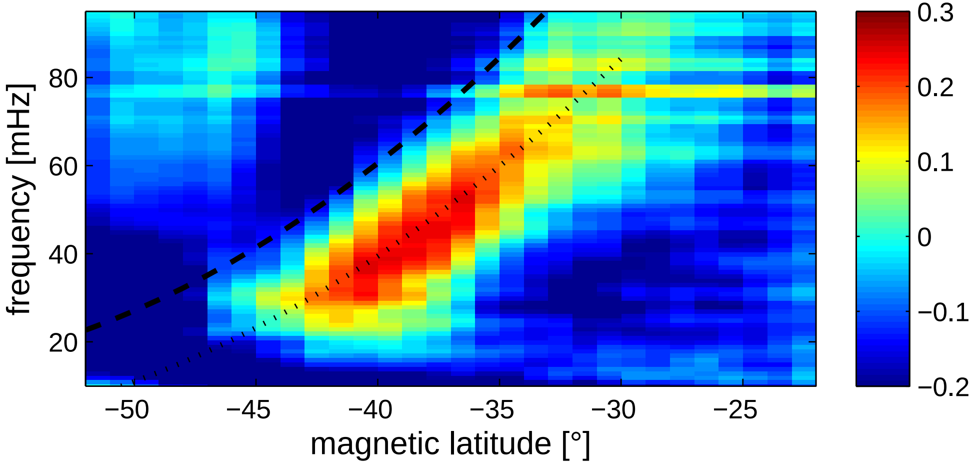
60
40
20
0
−20
−40
−60
−80
3
6
9
12
15
18
21
MLT [h]
−22
−24
−26
−28
−30
−32


CHAMP/ground amplitude ratio
geomagnetic latitutde
geomagnetic latitutde
geomagnetic latitutde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80
60
40
20
−50
−45
−40
−35
−30
−25
magnetic latitude [°]
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0.2
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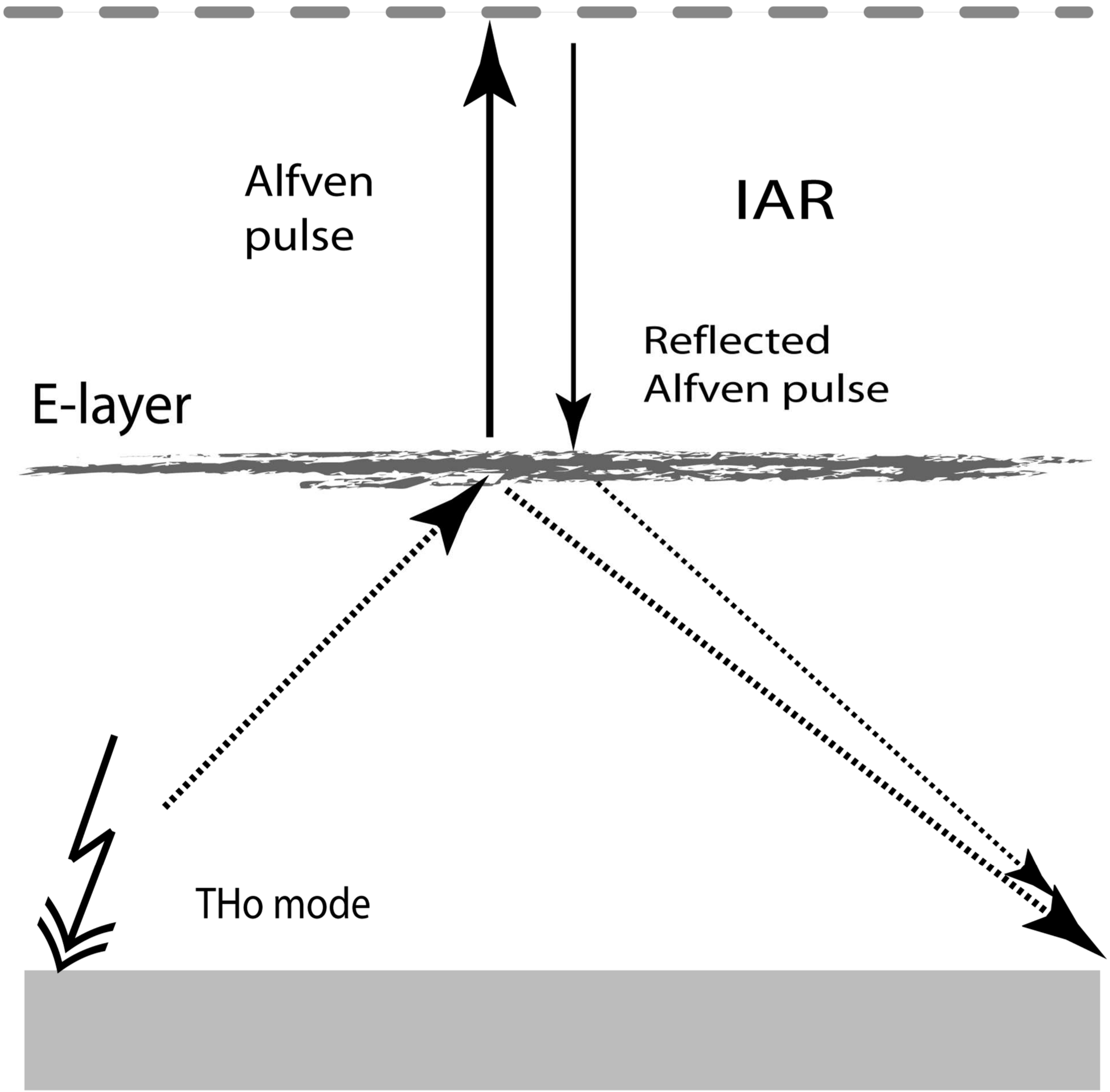
0
−0.1
−0.2


Alfven
pulse
IAR
Reflected
Alfven pulse
E-layer
THo mode