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Research paper

IAR signatures in the ionosphere: Modeling and observations at the Chibis-M microsatellite

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ABSTRACT

A peculiar feature of geomagnetic variations at middle/low latitudes in the ULF band, just below the fundamental tone of the Schumann resonance, is the occurrence of a multi-band spectral resonant structure, observed by high-sensitivity induction magnetometers during nighttime. The occurrence of such spectral structure was commonly attributed to the Ionospheric Alfvén Resonator (IAR) in the upper ionosphere. Rather surprisingly, while ground observations of the IAR are ubiquitous, there are practically no reports on the IAR signatures from space missions. According to the new paradigm, the multi-band spectral structure excited by a lightning discharge is in fact produced by a regular sequence of an original pulse from a stroke and echo-pulses reflected from the IAR upper boundary. Upon the interaction of initial lightning-generated pulse with the anisotropic lower ionosphere, it partially penetrates into the ionosphere, travels up the ionosphere as an Alfvén pulse, and reflects back from the upper IAR boundary. The superposition of the initial pulse and echo-pulses produces spectra with multiple spectral peaks. Our modeling of Alfvénic pulse propagation in a system with the altitude profile of Alfven velocity modeling the realistic ionosphere has shown that IAR spectral signatures are to be evident only on the ground and above the IAR. Inside the IAR, the superposition of upward and downward propagating pulses produces a more complicated spectral pattern and the IAR spectral signatures deteriorate. We have used electric field data from the low-orbit Chibis-M microsatellite to search for IAR signatures in the ionosphere. We found evidence that the multi-band structure revealed by spectral analysis in the frequency range of interest is indeed the result of a sequence of lightning-produced pulses. According to the proposed conception it seems possible to comprehend why the IAR signatures are less evident in the ionosphere than on the ground.

1. Introduction: ULF resonators and waveguides in the terrestrial ionosphere

Atmospheric thunderstorms constitute one of the most powerful disturbances in the Earth's environment and provide impulsive electromagnetic coupling of the Earth's atmosphere with the ionosphere/magnetosphere 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 (Füllekrug and Fraser-Smith, 2011). The largest spectral density of the atmospheric electrical discharge is concentrated in the VLF band (~few kHz), though significant spectral power is contained in the lower ELF-ULF bands (from fractions of Hz to few tens of Hz).

Sporadic transients and noise enhancements were observed in the ULF frequency range of several Hz in the thunderstorm proximity (Fraser-Smith, 1993). A feature of geomagnetic variations in the ULF band, just below the fundamental tone of the Schumann resonance (~8 Hz), is the occurrence of a multi-band spectral resonant structure, observed by high-sensitivity induction magnetometers during nighttime at low (Bösinger et al., 2002), middle (Belyaev et al., 1987; Molchanov et al., 2004; Ermakova et al., 2011) and high (Belyaev et al., 1999; Yahnin et al., 2003) latitudes. The lowest frequency of this structure is about fractions of Hz, and the difference between the spectral harmonics is ~0.3–0.5 Hz. Sometimes, at low latitudes up to 15–20 spectral harmonics were observed (Bösinger et al., 2004). Sprite-associated tropospheric lightning flashes, measured ~1900 km from the source by ground magnetometer, exhibited ultra-slow tails with spectral peaks at ~0.7 Hz and ~1.7 Hz (Füllekrug et al., 1998).

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The occurrence of this spectral structure was commonly attributed to the Ionospheric Alfvén 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 the altitude of few thousands km where Alfvén waves are partially reflected from a steep gradient of the Alfvén velocity vertical profile $V_A(z)$. The ionospheric cavity with a minimum of $V_A(z)$ at the maximum of the F-layer works not only as a resonator for Alfvén waves, but as a waveguide for the fast magnetosonic mode. The waveguide modes with frequencies above the critical frequency ~0.5 Hz can propagate over long distances (up to few thousand km) along the ionosphere (Fujita and Tamao, 1988; Kim et al., 2010). The resonant properties of the ionosphere may considerably enhance the electromagnetic coupling between the atmosphere and the topside ionosphere in the ULF frequency range (Pilipenko, 2012; Simões et al., 2012a). Qualitatively, the reflection of atmospheric electromagnetic disturbances from the bottom ionosphere may be imagined as electromagnetic wave reflection from a coat of film with either half-wavelength or quarter-wavelength thickness, like an anti-reflection coating in optics (Nickolaenko et al., 2004).

The spectral IAR properties were well reproduced by numerous analytical and numerical models (e.g., Polyakov and Rapoport, 1981; Lysak, 1993; Prikner et al., 2000; Hebden et al., 2005; Potapov et al., 2014). The damping rates and Q-factors of the IAR modes strongly depend on the Alfvén velocity differential in the upper ionosphere and on the lower ionosphere conductivity. As a possible excitation mechanism, it was suggested that either regional thunderstorms (Sukhorukov and Stubbe, 1997; Fedorov et al., 2006) or world tropical thunderstorm centers (Belyaev et al., 1987) are able to generate signals in the IAR range with sufficient intensities. In general, it is still uncertain how to discriminate the ULF response to distant thunderstorm centers and regional lightning activity, and what is the relative contribution of those sources into IAR stimulation at mid-latitudes.

A resonator response is to be different for a quasi-steady harmonic driving and impulsive excitation. A steady harmonic driver excites a relevant eigenmode of a resonator. An impulsive source produces a pulse oscillating between the upper and bottom boundaries of a resonator, gradually spreading because of dispersion. Upon spectral analysis, a mixture of harmonic oscillations with the frequency gap Δf and sequence of pulses with time delay $\Delta t = 1/\Delta f$ look identical. Fedorov et al. (2014) suggested, in contrast with the traditional view, that multi-band ULF spectra on the ground excited by lightning discharges are in fact produced by a sequence of an initial pulse and echo-pulses, reflected from the IAR upper boundary. Upon the interaction of an initial lightning-generated pulse with the anisotropic lower ionosphere, this pulse partially penetrates into the ionosphere, travels up the ionosphere as an Alfvén pulse, and reflects back from the upper IAR boundary. The superposition of the initial pulse and echo-pulses is separated by time delay $\Delta\tau$ owing to the Alfvén wave propagation up and down in the ionosphere. Indeed, examination of ULF magnetic response to regional lightning activity showed that the mechanism of multiple spectral peak formation was not related to oscillatory response of the ionosphere but caused by a specific multi-pulse structure of geomagnetic disturbances (Schekotov et al., 2011).

The issue of magnitudes of thunderstorm-related ULF-ELF fields in the upper ionosphere is rather controversial. Some studies (e.g., Greifinger and Greifinger, 1976; Molchanov et al., 1995) predicted only a weak strength of ULF fields in the upper ionosphere above an effective electric dipole with typical atmospheric discharge parameters. Thus, according to these theoretical models the IAR signatures could hardly be detected by a low-orbiting satellite (> 400 km). However, the ionospheric response involving the IAR excitation is expected to be more significant. Indeed, Plyasov et al. (2012), using a simplified multi-layered plane model, estimated analytically the IAR excitation rate by an atmospheric electric discharge, and claimed the possibility of IAR detection in the mid- and high-latitude ionosphere by modern electric or magnetic sensors onboard low-orbiting satellites. The effective leakage of 50/60 Hz emission from industrial power lines found by microsatellite Chibis-M also indicates an effective coupling of near-surface ULF-ELF emitters with emissions in the upper ionosphere (Dudkin et al., 2015).

Rather surprisingly, while there are so many ground observations of IAR signatures, there have been practically no dedicated space studies in the frequency range of interest. A search for IAR signatures was made with ELF electric field measurements onboard low-inclination (13°) C/NOFS satellite at altitudes of 400–850 km (Simões et al., 2012b). This study revealed rare short-lived (~10 min) "fingerprint emission" resembling the IAR multi-band spectral structures, when the satellite rapidly changed its altitude. This emission had up to 20 harmonics and was detected near the terminator only. Frequency variations were very fast, about 2–3 times per 10 min. However, frequencies of these structures were at least 5 times larger than model predictions. Thus, an interpretation on the basis of a standard IAR model demands unusually low plasma density in the upper ionosphere, more than an order of magnitude, as compared with existing ionospheric models (e.g., IRI). In our opinion, the fingerprint emissions found by Simões et al. (2012b) are previously unknown spectral structures, but they cannot be interpreted as standard IAR signatures. Dudkin et al. (2014) using the electric field sensor onboard the Chibis-M microsatellite found in the upper ionosphere only few events with signatures of the triggered excitation of the IAR.

In this paper we model the expected waveforms and spectra in the ionosphere resulted from impulsive IAR excitation, and search for these signatures in the electric field data from the low-orbit Chibis-M microsatellite. These modeling results suggest a possible explanation of the rarity of IAR signatures in the data from a low-orbiting probe.

2. Qualitative description of IAR impulsive excitation

Here we describe the notion on the spectral structure formation in the upper ionosphere, which is not related to oscillatory response of the IAR, as has been commonly assumed, but is caused by specific impulsive structure of electromagnetic disturbances produced by regional lightning activity.

There have been extraordinary observations at low latitudes showing that the spectral structure may consist of 20 and more harmonics, even beyond the fundamental tone of the Schumann resonance (Bösinger et al., 2002). So many harmonics could be produced either by a very high IAR Q-factor or an occurrence of sub-resonators. According to the classical theory of the IAR (Polyakov and Rapoport, 1981) the upper threshold frequency of Alfven waves which can be trapped in this resonator is determined by violation of the Wentzel–Kramers–Brillouin (WKB) approximation in the topside ionosphere at altitude h_A: the wavelength becomes comparable to the scale H of the Alfven velocity vertical profile $V_A(z)$, namely $k_A H \sim 1$, where the Alfvenic wave number $k_A = \omega / V_A$ is determined by the Alfven velocity in the topside ionosphere. This condition can be fulfilled under $V_A = 600$ km/s and $H = 100$ km for $f \sim 1$ Hz. Higher frequency waves have wavelengths smaller than H and they should penetrate with just a small reflection into the magnetosphere. Therefore, the occurrence of high-frequency harmonics, up to $f > 10$–15 Hz, seemingly contradicts the standard IAR concept.

According to the new paradigm, suggested by Fedorov et al. (2014), the multi-band structure in dynamic spectra can be the

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