Radiotomographic imaging of the artificially disturbed midlatitude ionosphere with CASSIOPE and Parus satellites

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ABSTRACT

We present the results of the radiotomographic imaging of the artificial ionospheric disturbances obtained in the recent experiments on the modification of the midlatitude ionosphere by powerful HF radiowaves carried out at the SURA heating facility. Radio transmissions from PARUS and CASSIOPE recorded at the specially installed network of three receiving sites were used for the remote sensing of the heated ionosphere.

We discuss the possibility to generate AGWs with special regimes of ionospheric heating (with the square wave modulation of the effective radiated power at the frequency lower than or of the order of the Brunt-Vaisala frequency of the neutral atmosphere at ionospheric heights during several hours) and present radoitomographic images of the spatial structure of the disturbed area of the ionosphere corresponding to the directivity pattern of the heater, as well as the spatial structure of the wave-like disturbances, which are possibly heating-induced AGWs, diverging from the heated area of the ionosphere. The spatial period of observed disturbances is 200–250 km and they are easily traced up to a distance of 700–800 km from the heated region.

1. INTRODUCTION

Starting from the very first ionospheric reconstructions [Andreeva et al., 1990], the low-orbital radiotomography technique is successfully applied during the past decades and provided information on many ionospheric structures such as the ionization troughs, equatorial anomaly, travelling ionospheric disturbances, equatorial plasma depletions, etc. [Kunitsyn and Tereshchenko, 2003; Pryse, 2003; Bust and Mitchell, 2008; Hei et al. 2014]. It was also used for analyzing the structure of the modified ionosphere above the EISCAT/Heating [Tereshchenko et al., 2000] and the Sura [Tereshchenko et al., 2004] heating facilities. The present work is the continuation of the radiotomographic studies of artificially disturbed midlatitude ionosphere [Kunitsyn et al., 2012] with special focus on heating-induced AGW/TIDs.

Numerous experiments on HF heating showed that, besides the Joule heating of the ionospheric plasma, powerful HF impact induces the ponderomotive parametric instability, thermal (resonant) parametric instability, and self-focusing instability in the ionosphere. These phenomena, in particular, cause strong heating of electrons in the resonant area and generation of artificial irregularities of plasma density, which are elongated in the direction of the geomagnetic field. The field-aligned extension of the irregularities could be up to hundred kilometers and their cross-field horizontal dimensions range from less than one meter to a few dozens of kilometers [Gurevich, 1978 and 2007; Erukhimov et al., 1987; Stubbe, 1996; Stubbe and Hagfors, 1997; Belikovich et al., 2007]. The possibility of AGW generation by powerful radio waves was studied theoretically by [Grigor'ev, 1975; Grigor'ev and Trakhtengerts, 1999]. The observations of [Burmaka et al., 2009; Chernogor et al., 2011] have shown detection of AGW-like TIDs caused by the Sura facility at distances of about 1000 km by the incoherent scatter radar and by Doppler HF vertical sounding. Recently [Pradipta et al, 2015] reported on the artificial AGW/TIDs in heating experiments at HAARP. Note that HF heating induced AGWs are obsereved not only in electron density, but also in neutral component [Mishin et al., 2012]. This paper, however, presents one of the first experimental images of the spatial structure of AGW-like TIDs in the artificially disturbed nighttime midlatitude ionosphere during HF-heating experimets at the Sura facility.

2. DESCRIPTION OF THE EXPERIMENTS

The experiments were carried out at the Sura heating facility (Radio Physical Research Institute, Nizhnii Novgorod, Russia) during several heating campaigns in 2011-2014. The Sura Heater is located at φ = 56.15°N and λ = 46.1°E; the geomagnetic inclination is I = 71°. It consists of the three HF transmitters with the output power 3x250kW, each one feeds its own antenna array with 4.3-9.5MHz frequency range (complete antenna field consists of 12x12 dipoles). Coherent opereation of all three transmitters provides maximum effective radiated power (ERP) of 80-280MW depending on the selected frequency. The heater beam can be inclined $\pm 40^0$ in the plane of geomagnetic meridian, both O- and X-mode radiowaves can be used, though we only used O-mode (resonant interaction) with beam inclination 12^0 to the south taking advantages of the magnetic-zenith effect [Gurevich, 2007; Tereshchenko et al., 2004] during these campaings. The experiments were conducted under nighttime conditions, the pumping frequency f_0 was chosen to fullfill the reflection condition $f_O F2 \geq f_0$, in order to generate AGWs the ERP was modulated with a square wave with a frequency less than or of the order of the Brunt-Vaisala frequency of neutral atmosphere at the F2 layer height.

Radio transmissions from PARUS (Russian LEO navigational satellites, coherent transmissions at 150/400MHz) and CASSIOPE (Canadian CAScade, Smallsat and IOnospheric Polar Explorer, ePOP/CER coherent transmissions at 150/400/1066,67MHz) recorded at the specially installed network of receiving sites were used for the remote sensing of the heated ionosphere. Three NWRE ITS33S receivers were located directly at the Sura facility and approximately 100 km south- and northward, at the villages of Galibikha (56.75°N, 45.6°E) and Sechenovo (55.21°N, 45.88°E), respectively, providing rather short but still reasonable tomographic chain. The experiments were designed in such a way that during the heating sessions, the ionospheric pierce points of the considered satellites crossed the perturbed region, and the heating itself started well (up to 4 hours) before satellite passes.

Radiotomographic inversion of the relative phase measuremets was conducted aplying the phase-difference approach [Kunitsyn and Tereshchenko, 2003] providing 2D height-latitude ionospheric electron density crossections along satellites passes.

3. OBTAINED RESULTS

The first experiment considered here was carried out on August 18, 2011 during quiet geomagnetic conditions (Kp~3). The Sura heater operated with two transmitters giving the ERP = 50 MW; the pumping frequency 4785 kHz was lower than f_OF2 throughout the entire experiment. The pump wave was radiated in the following mode: from 14:16 to 16:56 UT (from 18:16 to 20:56 LT) and from 17:01 to 18:51 UT (from 21:01 to 22:51 LT) [10 min radiation, 10 min pause; during the pause 15-s pulses were additionally radiated every two minutes]. The ionospheric pierce points of the Cosmos 2407 satellite crossed the heated region from north to south at 18:49 UT (22:49 LT). Note that, during four hours before the pass the ionosphere was affected by the pumping radio wave with the ERP modulated at a frequency lower than the Brunt-Vaisala frequency of the neutral atmosphere at the reflection height of the pump wave. Figure 1 presents the radiotomographic reconstruction of the electron density distribution above Sura heater for that pass. The features to be noted on this reconstruction are: 1) Narrow trough in electron density with a width of ~60 km and depth of the depletion ~15-20%. This trough corresponds to the radiation diagram of the Sura heater. 2) Wave-like disturbances diverging from the ionospheric region heated by the HF radiation. The spatial period of these disturbances is 200-250 km; they are easily traced up to a distance of 700-800 km from the heated region.

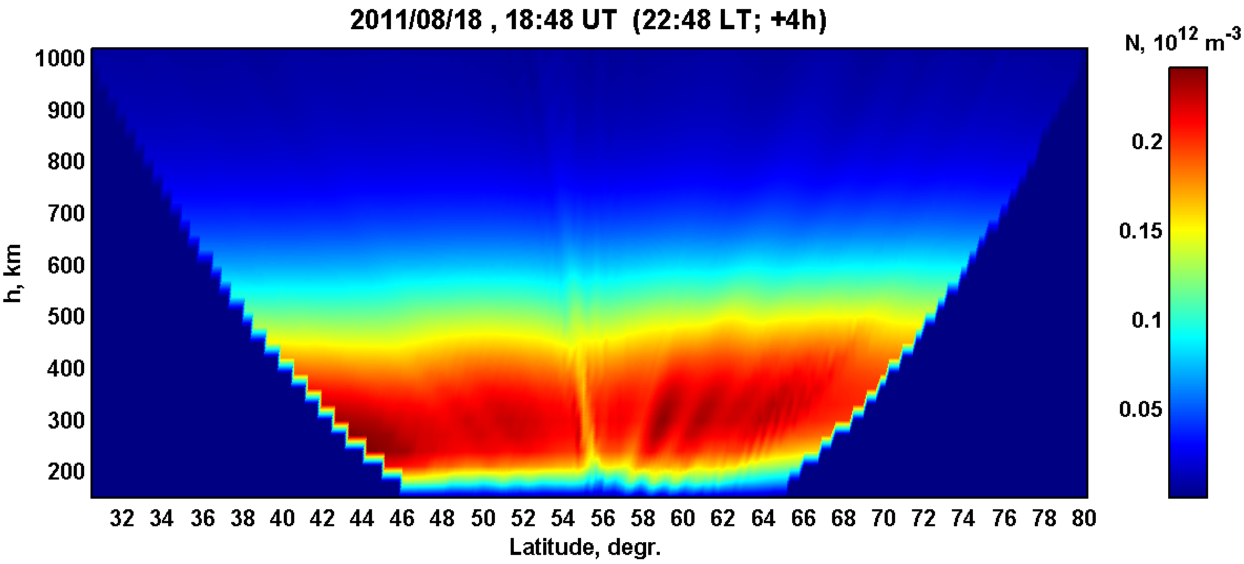

Figure 1. Tomographic crossection of the ionosphere along Cosmos 2407 satellite pass above Sura facility during heating experiment on August 18, 2011.

Almost the same pattern of disturbances (see Figure 2) was obsereved in the heating experiment on March 25, 2014, conducted also in quiet geomagnetic conditions (Kp~2). The pumping frequency was 5455kHz (lower than f_OF2). We used same modulation for ERP: from 15:58 to 18:38 UT (from 19:58 to 22:38 LT) [10 min radiation, 10 min pause] followed by 12 min raduation starting at 18:38 UT (22:38 LT). The ionospheric pierce points of the Cosmos 2407 satellite crossed the heated region at 18:50 UT (22:50 LT). Thus again, for three hours before the pass the ionosphere was affected by the pumping radio wave with the ERP modulated at a frequency lower than the Brunt-Vaisala frequency of the neutral atmosphere.

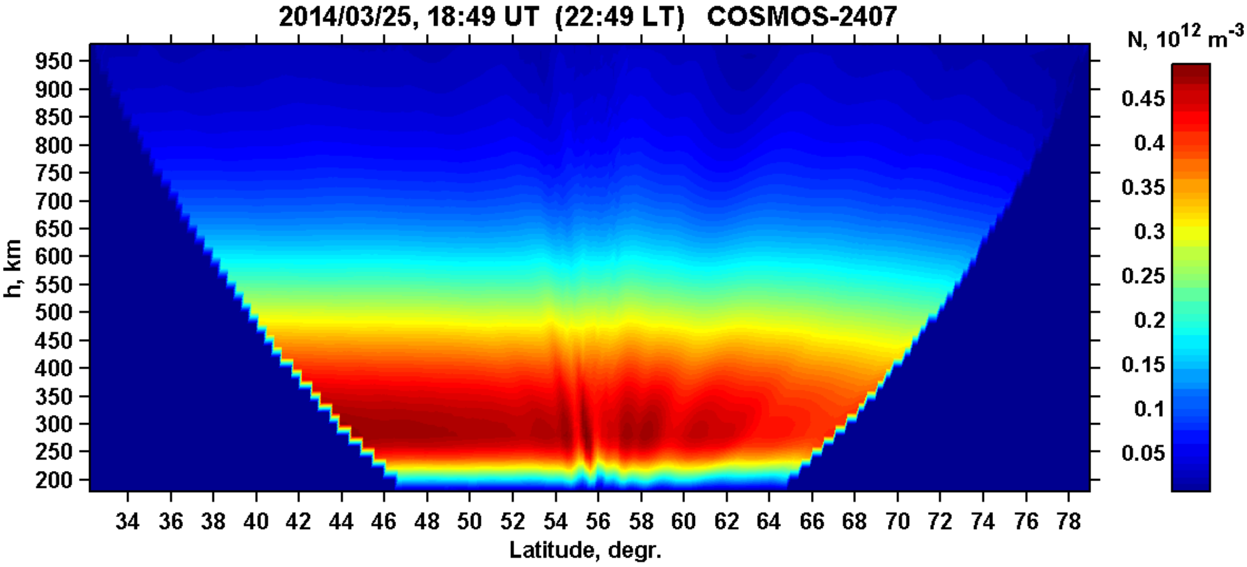

Figure 2. Tomographic crossection of the ionosphere along Cosmos 2407 satellite pass above Sura facility during heating experiment on March 25, 2014.

Figure 3 presents the results of the experiment of the same type conducted on September 9, 2014, using new CASSIOPE satellite. Geomagnetic conditions during this experiment were also quiet (Kp~2), The pumping frequency was 4300kHz, ERP= 55MW was modulated in the following way: from 18:59 to 20:14 UT (22:59 to 00:14 LT) [15 min radiation; 15 min pause], from 20:29 to 20:30 UT (00:29 to 00:30 LT) CW, from 20:30 to 20:49 UT (00:30 to 00:49 LT) [9 sec radiation; 1 sec pause].

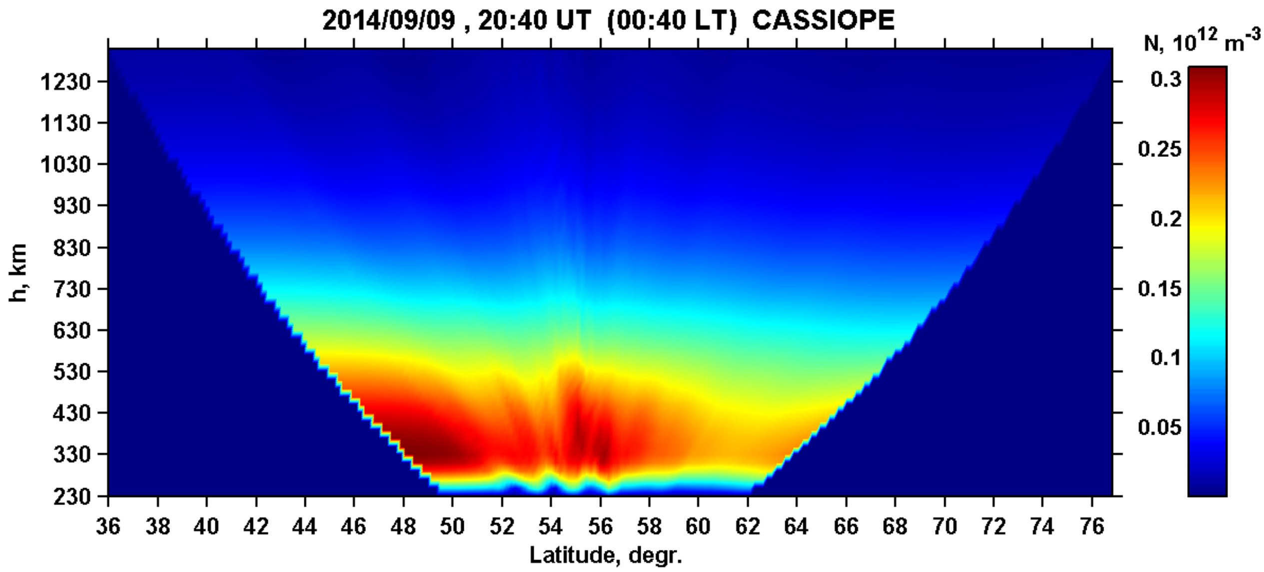

Figure 3. Tomographic crossection of the ionosphere along CASSIOPE satellite pass above Sura facility during heating experiment on September 9, 2014.

The wavelike pattern of ionospheric disturbances is not so prominent in this example as in two previous cases. First of all note that the period of ERP modulation was 1,5 times greater (30 min instead of 20 min) and time of influence was only 1.6 hours instead of 3 hours and 4 hours. So, probably, it was not enough to generate AGWs as in two previous cases. Moreover, starting from

20:35 UT the critical frequency f_OF2 was lower than pumping frequency, thus limiting the efficiency of the heating, so we also didn't observe a distinct trough corresponding to the heater beam, as in two previous cases.

The wavelike disturbances observed in first two presented examples (Figures 1 and 2) might be acoustic-gravity waves generated by the Sura heating facility. This hypothesis is supported by the direction of propagation (in both directions off the heated ionospheric region) and the typical for AGWs inclination of the wave packets. Another possible explanation for the density pattern could be ionospheric modification relaxation oscillator discovered at Arecibo by [Bernhardt et al., 1989] and verified by observations in Sura by [Bernhardt et al., 1991, 2000]. For this model, the HF beam produces a density cavity that drifts off zenith, refracting the radio beam from the vertical. When the cavity drifts far away from the initial beam position, a new cavity is formed at the center of the initial beam and the process repeats. This mechanism could produce a series of large-scale cavities downstream from the heated area and explain the disturbances obsereved in Figure 3.

4. CONCLUSIONS

In this work we present the evedences for the generation of artificial AGW/TIDs in ionospheric heating experiments at Sura heater when the ERP is modulated with a square wave at a frequency lower than the Brunt-Vaisala frequency of the neutral atmosphere at the reflection height of the pump wave. A comprehensive model of HF-induced thermospheric perturbations has not yet been developed. More observational, theoretical and modeling efforts are required to understand the underlying generation processes.

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