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Radiotomography and HF-raytracing of the Artificially Disturbed Midlatitude Ionosphere.

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Abstract. We present the results of the radiotomographic imaging of the artificial HF-induced ionospheric disturbances obtained in the experiments on the modification of the midlatitude ionosphere by powerful HF radiowaves carried out at the SURA heater and discuss the possibility to generate AGWs with special regimes of ionospheric heating. We also study the HF propagation of the pumping wave through the reconstructed disturbed ionosphere above the SURA heater, showing the presence of heater-created, field-aligned irregularities that are "artificial radio windows".

Key words: Ionosphere, Radiotomography, Raytracing, HF-heating, SURA heater

Numerous experiments on modifying the Earth's ionosphere by the high-power HF radio waves showed that artificial ionospheric disturbances are most intensely generated in the F2 layer close to the reflection height of the high-power ordinary (O-) mode pumping wave (PW), when the pondermotive and thermal (resonant) parametric instabilities, as well as the self-focusing instability are developed. These processes result in almost full absorption of energy of the PW in these resonant area, strong heating of the ionospheric plasma, and generation of artificial irregularities with the sizes ranging from a few fractions of a meter to dozens of kilometers, see for example [4] and references therein. The latest studies also showed that the ionospheric disturbed volume where the intense generation of artificial ionospheric irregularities takes place is not limited to the narrow resonance layer near the O-mode PW reflection height and to the horizontal dimensions of the radiation pattern of the heater antenna at this height level but occupies a larger volume. In particular, the experiments revealed generation of the ducts of enhanced plasma density in the outer (~700 km) ionosphere [1,7]. Moreover, the theoretical studies [3] and recent experiments [5,8,9] showed that the periodic modification of the ionosphere by the high-power O-mode HF radio wave with the square modulated effective radiated power (ERP) with the frequency below or of the order of the Brunt-Vaisala frequency at the ionospheric heights leads to the generation of AGW/TIDs with rather high amplitudes, which can be detected at the distances up to ~1000 km from the heater. These waves can produce plasma density irregularities and significantly affect HF propagation in this region.

A handy instrument for studying spatial structure of heating-induced ionospheric irregularities is provided by the low-orbital radio tomography of the ionosphere, the method that has been widely and efficiently applied in the experiments at the SURA heater [5,11]. The variations in plasma density yielded by radio tomography may at the same time serve as a basis for modeling the HF propagation (the ray tracing for the SURA transmitter using the extended bicharacteristic method for the eikonal equation [6]) in the ionospheric disturbed volume with the allowance for the plasma perturbation parameters measured in the experiment. This is important for improving our understanding of the interaction of the powerful radio wave with magnetized plasma.

One of the interesting results from the standpoint of the above mentioned effects was obtained in the heating experiment carried out at the SURA heater on August 18, 2011 [5]. The experiment was conducted in the geomagnetically quiet conditions (Kp ~3). The O-mode pump wave (PW) was radiated at a frequency f_{PW} = 4.785 MHz (by 0.5 MHz lower than f_{OF2}~5.3 MHz measured just before the beacon satellite pass above the SURA heater). The PW was radiated by two transmitters of the heater (giving ERP=50 MW) 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 - on, 10 min – off]; during the pauses 15-s pulses were additionally radiated every two minutes. The ionospheric pierce point of the Cosmos 2407 beacon satellite intersected the center of the ionospheric disturbed volume from north to south at 18:49 UT (22:49 LT). Note that for 4 hours before the pass the ionosphere was affected by the pumping O-mode radio wave with the ERP modulated at the frequency lower than the Brunt-Vaisala frequency of the neutral atmosphere at the reflection height of the PW.

Fig. 1 (left) shows the tomographic reconstruction of the ionospheric electron density above the SURA heater during this experiment. Narrow trough with a width of ~60 km and depth of the electron density depletion ~15-20% is clearly seen on this reconstruction. This trough corresponds to the radiation diagram of the SURA heater and stretch along the entire F2 region. Note also the presence of the duct of enhanced plasma density in the outer ionosphere at the heights ≥ 500 km. Distinct wavelike disturbances with a period of ~200 km and velocity increasing with height are observed diverging from the disturbed region up to 1000 km north of the SURA heater. These disturbances are much less intensive to the south of the SURA heater, where they become barely distinguished from the natural electron density variations even at a distance of ~600 km from the heater.

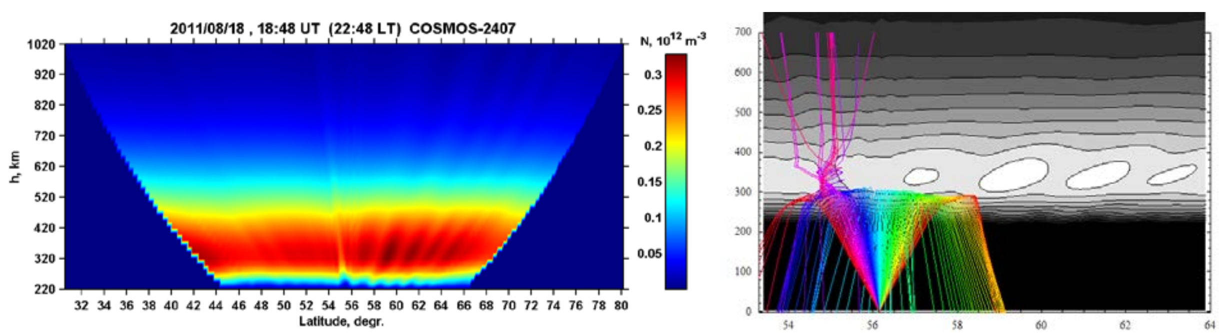

Fig. 1. The tomographic cross section (left) of the ionosphere along the Cosmos 2407 satellite path above the SURA heater and the ray structure (right) for the pump wave (O-mode, f_{PW} =4.785 MHz) during the ionospheric heating experiment on on August 18, 2011.

Fig. 1 (right) shows the ray structure for the PW. Note that for the most of the ray trajectories, the PW reflection from the F2 layer takes place. This is accompanied by the emergence of the caustic focusing regions where the intensity of the PW electric field significantly increases and can produce e.g. irregularity generation. These regions of intensive AIT generation are spaced apart from the center of the heated region by up to ~100 km. Such a cluster structure of disturbed region of the ionosphere was observed for decameter irregularities in [12]. At the same time, the narrow trough in electron density forms the “artificial radio window” (waveguide) for the PW and lets it penetrate into the topside ionosphere along the geomagnetic field lines. Note that the similar phenomenon of the

PW penetration through the F2 ionosphere which was non-transparent before HF heating was previously observed in the experiments at the SURA heater using the radio receiving instruments onboard French DEMETER microsatellite [2].

Conclusions. Our results show that the long-lasting periodical heating of the ionosphere with the modulation frequencies of ERP below the Brunt-Vaisala frequency of neutral atmosphere results in the excitation of AGW/TIDs observed within up to 1000 km from the heater. The results suggest that as the f_{PW} approaches f_{OF2}, the efficiency of this excitation increases. In the case of formation of the narrow troughs with ~15-20% electron density depletion, which stretch along the entire F2 layer and serves as artificial waveguide, the PW energy penetrates to the outer ionosphere propagating along the geomagnetic field lines. In this context, it appears interesting to conduct the experiments on tomographic imaging of the ionospheric disturbed volume above the heater with simultaneous measurements of the PW signal at the same satellite. As of now, such experiments can be carried out e.g. using the e-POP payload onboard the Canadian CASSIOPE satellite [10].

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