HF Ray Tracing of the Artificially Disturbed Ionosphere above Sura Heating Facility

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Abstract

We present the results of high-frequency (HF) ray tracing of a pumping wave in an artificially disturbed ionosphere above the Sura heating facility applying parameters that are reconstructed using the radiotomography (RT) approach with the signals of the Parus and CASSIOPE beacon satellites. We also discuss the possibility of generating atmospheric gravity waves (AGWs) with special regimes of ionospheric heating and present the examples of such structures in radiotomographic reconstructions.

1. Introduction

Numerous experiments on modifying the Earth's ionosphere by high-power HF radio waves showed that artificial ionospheric disturbances with-sizes ranging from a few fractions of a meter to dozens of kilometers are most intensely generated in the F2 layer close to the reflection height of the high-power ordinary (O-) mode pumping wave (PW) [1]. The latest studies also showed that the 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 but occupies a larger space. In particular, the experiments revealed generation of the ducts of enhanced plasma density in the outer (~700 km) ionosphere [2,3]. Moreover recent experiments [4,5] showed that the periodic modification of the ionosphere by a high-power O-mode HF radio wave with the square- modulated effective radiated power (ERP) at a frequency below or of the order of the Brunt-Vaisala (BV) frequency at the ionospheric heights leads to the generation of AGW/travelling ionospheric disturbances (TIDs), 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 RT of the ionosphere [6], the method that has been efficiently applied in the experiments at the Sura heater [4]. The variations in plasma density yielded by RT may at the same time serve as a basis for modeling the HF propagation in the ionospheric disturbed volume with 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 ionospheric plasma.

2. Description of the experiments

The experiments considered in this paper were carried out at the Sura heating facility during several campaigns in 2011 and 2014. The Sura Heater is located at (56.15N, 46.1E); the geomagnetic inclination is 71° . The heater consists of three HF transmitters with output power 3x250kW, each one feeding its own antenna array in a 4.3-9.5MHz frequency range. Coherent operation of all three transmitters provides a maximum ERP of 80-280MW depending on the selected frequency. The heater beam can be inclined ±40° in the plane of geomagnetic meridian, and both O- and X-mode pumping waves can be used, though we only used O-mode (resonant interaction) with beam inclination 12° to the south taking advantages of the magnetic zenith effect [1] during these campaigns. The experiments were conducted under nighttime conditions, the pumping frequency f_0 was chosen to fulfill the reflection condition $f_{OF2} \geq f_0$. In order to generate AGWs the ERP was modulated with a square wave with a frequency less than or of the order of the BV frequency of the neutral atmosphere at the F2 layer height.

Radio transmissions from Parus (Russian LEO navigational satellites, coherent transmissions at 150/400MHz) and CASSIOPE [7] (Canadian CAScade, Smallsat and IOnospheric Polar Explorer, ePOP/CER coherent transmissions at 150/400/1066,67MHz) recorded at a specially installed receiving network were used for the remote sensing of the heated ionosphere. Three ITS33S receivers were located directly at the Sura facility and approximately 100 km south- and northward, at the villages of Galibikha (56.75N, 45.6E) and Sechenovo (55.21N, 45.88E), respectively, providing a 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. The heating itself started well (up to 4 hours) before satellite passes.

RT inversion of the relative phase measurements was conducted applying the phase difference approach [6] providing 2D height-latitude ionospheric electron density distributions along satellites passes.

The geometric optics approach has been invoked to study propagation of the PW in the disturbed ionosphere. Rays have been traced for heating frequencies through reconstructed 2D distributions of electron density solving Haselgrove's equations [8]. The WMM 2015 [9] model was used to describe geomagnetic field.

3. Results

One of the interesting results was obtained in the heating experiment carried out at the Sura heater on August 18, 2011 [4]. The experiment was conducted in geomagnetically quiet conditions (Kp ~3). The O-mode PW was radiated at a frequency f_{PW} = 4.785 MHz (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 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 BV frequency of the neutral atmosphere at the reflection height of the PW.

Figure 1 (top) shows the RT reconstruction of the ionospheric electron density above the Sura heater during this experiment. A narrow trough with a width of ~60 km and a depth of electron density depletion of ~15-20% are clearly seen on this reconstruction. This trough corresponds to the radiation diagram of the Sura heater and stretches 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-intense 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.

Figure 1 (bottom) 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. At the same time, the narrow trough in electron density forms the artificial waveguide for the PW and lets it penetrate into the topside ionosphere along the geomagnetic field lines.

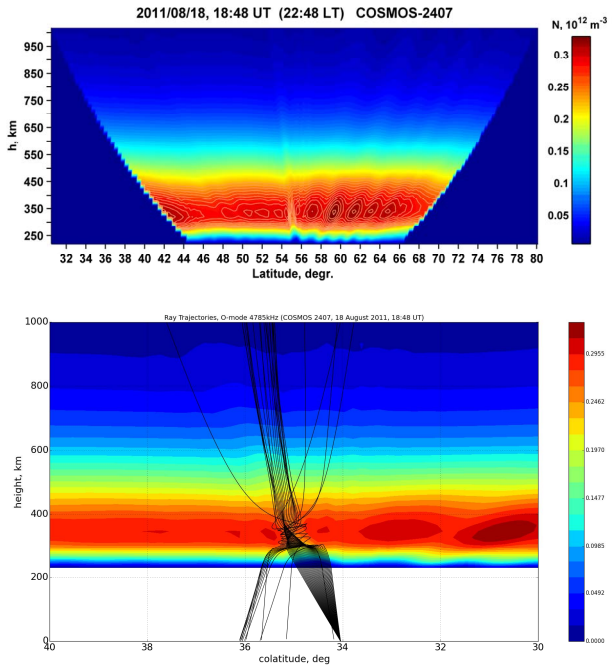

Figure 1. RT crossection of the ionosphere above Sura heater for Cosmos 2407 pass on August 18, 2011, 18:48UT (top) and corresponding ray trajectories for PW (O-mode, 4785kHz) (bottom).

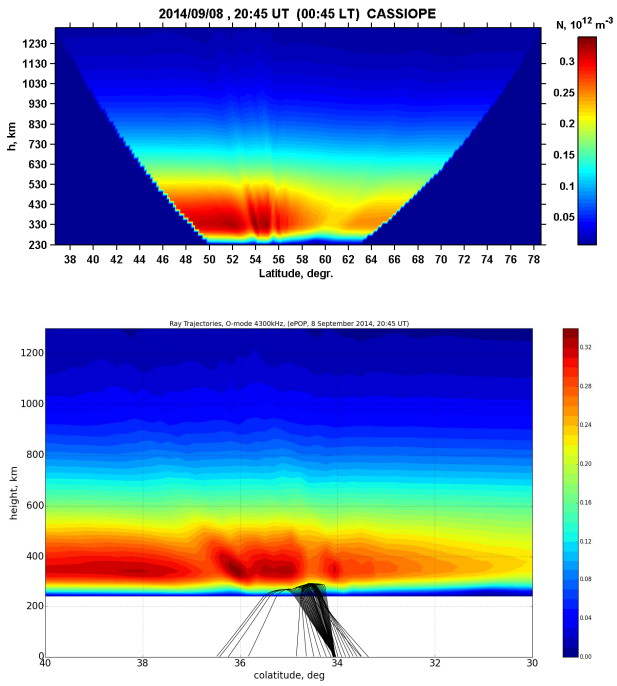

Figure 2. Radiotomographic crossection of the ionosphere above Sura heater for ePOP pass on September 8, 2014, 20:45UT (top) and corresponding ray trajectories for PW (O-mode, 4300kHz) (bottom).

Figure 2 (top) presents the results of the experiment of the same type conducted on September 8, 2014, using 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 19:04 to 20:19 UT (23:04 to 00:19 LT) [15 min radiation; 15 min pause], from 20:34 to 20:54 UT (00:34 to 00:54 LT) [9 sec radiation; 1 sec pause]. The pierce point of the CASSIOPE satellite intersected the center of the ionospheric disturbed volume at 20:46 UT (00:46 LT). The wavelike pattern of ionospheric disturbances is also prominent in this example, but this time it is more intensive to the south of the heater. Note also the presence of the main ionospheric trough on the reconstruction at ~60N.

Figure 2 (bottom) shows the ray structure for the PW. It can be seen that the high-power HF wave is fully reflected from the ionospheric F2 layer and there is no penetration of PW energy up to the outer ionosphere due to large scale irregularities revealed by RT as in previous example. Even so, small (kilometer) scale density-depleted field-aligned irregularities, of cross-field dimension below the resolution of RT, could be responsible for the PW energy penetration up to the outer ionosphere. To verify it one should measure PW intensity at the satellites height which is now possible with RRI instrument onboard CASSIOPE.

4. Conclusions

In this work, we present the results of RT imaging of the large-scale artificial irregularities generated in the nighttime mid-latitude ionosphere in response to its modification by high-power O-mode HF radio waves. It is shown that the long-lasting periodic heating of the ionosphere at frequencies below the BV frequency of the neutral atmosphere results in the excitation of AGW/TIDs with spatial periods of ~200 km that are observed up to 1000 km from the heater.

In the case of formation of the narrow irregularities (~60 km) with ~15-20% electron density depletion, that stretch along the entire F2 layer and serve as artificial waveguides, the PW energy penetrates to the outer ionosphere propagating along the geomagnetic field lines.

In the context of the results presented in this paper, it appeared interesting to conduct the experiments on RT imaging of the disturbed ionospheric region above the heating facility with simultaneous measurements of the PW signal at the same satellite. As of now, such experiments can be carried out e.g. using the CER beacon and RRI onboard the Canadian CASSIOPE satellite [10]. Recent studies [11] showed that, in the presence of rather large scale structures, which could be revealed by RT methods, small scale density-depleted field-aligned irregularities, with cross-field dimensions below the resolution of RT, could be responsible for the PW energy penetration up to the outer ionosphere.

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