Artificial Ionospheric Perturbations Studied During HAARP May-June 2014 campaign

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ABSTRACT

Preliminary results of the HAARP HF heating campaign in May-June, 2014 are presented. The results concern (i) Doppler (phase) sounding of the ionosphere heated volume and (ii) Broad Downshifted Emission (BDE) feature of the Stimulated Electromagnetic Emission (SEE).

In the experiments performed on June 4, 2014 the short pulse sounding method was implemented for the study of the vertical structure (electron density profile and vertical velocities) with high altitude and temporal resolution. The method comprises of an alternation of quasi-continuous pumping of the ionosphere and sounding by short (wideband) pulses. The use of broadband radio receiver and specially developed signal processing algorithms have allowed us to study evolution of the amplitude and phase of the various spectral components of the reflected probing signals, which passed the perturbed region twice, in a wide (totally ~500 kHz) band. Similar experiments but with lesser ERP were made earlier at the SURA facility [*Shindin et al.*, 2012]. It was found that after pump wave turns on,   the plasma is pushed out from the perturbed region near the wave reflection point. The plasma expulsion stops in 10-15 s, then a much stronger expulsion occurs near the upper hybrid height of the pump wave. The resulted reduction of the plasma density reaches 1-1.5% and disappeared in ~15s after pump wave turns off.

The BDE feature in the SEE spectrum was first detected in 2011 HAARP campaign and found to be in the frequency range $f_{BDE} - f_0 = -$ (50–180) kHz (f_0 is the pump wave frequency). In 2014 campaign BDE was obtained during nighttime (near 00:00 AST) with the pump frequency sweep in the range 5.46 – 5.66 MHz and (near 4th electron gyroharmonic $4f_{ce}$) and 4.15 – 4.35 kHz (near $3f_{ce}$). I was found that near 4th gyroharmonic the BDE appears only at maximum ERP, mainly for the pump frequency below the gyroharmonic. A position of the BDE peak in the SEE spectrum approaches f_0 (moves away from) with increasing (decreasing) frequency according to $f_{BDE} - f_0 \propto \alpha$ (f_0 - $4f_{ce}$) $- df$. The coefficient α and frequency mismatch df vary for different sweeps, and α is larger for decreasing f_0. Near 3rd gyroharmonic the BDE shows up in the SEE spectra only in narrow pump frequency range (few kHz) slightly below $3f_{ce}$.

1. INTRODUCTION

A powerful O-mode electromagnetic pump wave transmitted vertically into the bottomside ionospheric F region excites a wide range of plasma processes leading to the appearance of artificial ionospheric turbulence (AIT), i.e., generation of different HF and LF plasma modes, plasma density inhomogeneities of scales from tens of centimeters to kilometers, enhancement of the electron temperature, electron acceleration and ionization, etc. [*Gurevich*, 2007]. The pump-plasma interaction is known to be strongest near the pump reflection height z_r at which $f_p(z_r)$ equals the

pump frequency f_0, and near the upper hybrid (UH) resonance height z_{UH} where $f_p(z_{UH}) = (f_0^2 - f_{ce}^2)^{1/2}$ [here $f_p = (e^2 N/\pi m)^{1/2}$, and $f_{ce} = eH/2\pi mc$ is the electron plasma frequency and the electron cyclotron frequency respectively, e and m is the electron charge and mass, N the electron density, c the speed of light, H the geomagnetic field strength]. In this paper we briefly describe some results of AIT investigation, obtained during the HF heating campaign at the HAARP facility (62.40°N, 145.15°W) in May-June, 2014 by multi-frequency Doppler (phase) sounding of the ionosphere, and with observation of the Stimulated Electromagnetic Emission (SEE).

2. OBSERVATIONS

2.1 PHASE SOUNDING OF THE HEATED VOLUME

Experiments on multifrequency Doppler (phase) sounding of the ionosphere heated volume was performed on June 4 at 15:00- 16:00 AST. The HAARP transmitter radiation schedule was as follows.

During the 30 second of a long quasi-continuous pumping, high duty cycle pulse (pulse width $t = 70$ ms, interpulse period $T = 100$ ms) was radiated vertically at the frequency f_0=5.5 MHz. Simultaneously, short (20 μs) pulses with the same interpulse period and effective radiated power (ERP) P_{ef}~400 MW at two carrier frequencies $f_{DW} = f_0$ and $f_{DW} = f_0 - 200$ kHz were used for probing structure of the perturbed ionospheric region. The low duty cycle was used during the whole 2 min session including 30 s of the quasi-continuous pumping. During the pumping, the short pulses were radiated within 30 ms pauses. The power of the sounding transmitters was sufficient to create a wide spectrum of diagnostic waves (up to 300 kHz near each carrier frequency), with an average power far below the thresholds of the generation and maintenance of the pump-induced ionospheric plasma instabilities. The use of broadband radio receiver and specially developed signal processing algorithms have allowed the study of the evolution of amplitude and phase (φ) of the various spectral components of the reflected probing signals, which passed the perturbed region twice, in a wide (totally ~500 kHz) band. The frequency resolution of the analysis was 1 kHz, the temporal resolution was determined by the interpulse period T= 100 ms. The results of measurements of the temporal evolution of Doppler frequency shifts $f_{di}(t) = d\varphi_i /dt$ for different spectral components (f_i) of the reflected signal (Figure 1) provided data for further reconstruction of electron density profile in the ionosphere and its temporal evolution $N(z, t)$ by solving the inverse problem of MDS. The initial (reference) profiles were taken from ionograms registered prior to the quasi-continuous pumping session. Temporal variations of the reflection heights $\Delta z_r(f_i,t)$ of different spectral components at f_i, obtained by solving the inverse problem (reconstruction of electron density profile N(z, t)) allows us to calculate vertical velocities of the displacement $\partial \Delta z/\partial t$ at different f_i. Details of the reconstruction algorithm and results of similar experiments at the SURA facility in 2008 and 2010 at f_0=4.785 MHz and at f_0=4.74 MHz [*Shindin et al.,* 2012]. Note that the effective radiated power at SURA experiments P_{ef}≈60 MW was much smaller than HAARP's.

Results of the experiment of 2014/06/04 are presented in figures 1-4. Doppler frequency shifts $f_{di}(f_i,t)$ are presented in Figure 1. Variations of the reflection heights $\Delta z_r(f_i,t)$ are shown in Figure 2. Here black lines correspond to the reflection heights of the pump wave ($z=z_r(f_0)$) and diagnostic wave at $f= f_p(z_{UH})= (f_0^2 - f_{ce}^2)^{1/2}$. Remind, that an increase of electron density N leads to decrease of the reflection height while a decrease of N (expulsion of the ionospheric plasma) leads to decrease in $z_r(f_i)$. Reconstructed relative changes in plasma (electron) density N *vs.* height at the end of quasi-continuous pumping and velocity of the sounding waves reflection height displacement *vs.* time and sounding wave frequency (pulse spectral component) are presented, respectively, in Figures 3 and 4.
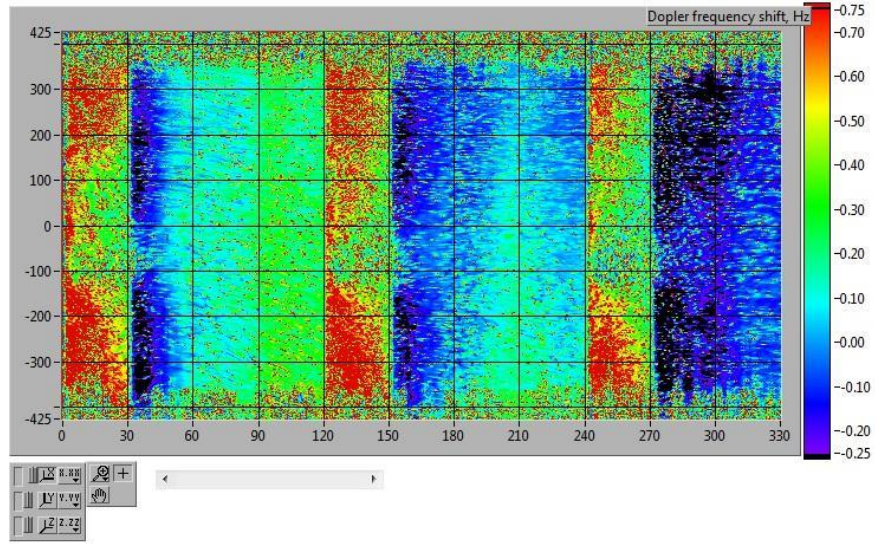
Figure 1. Doppler frequency shifts (Hz, colors) *vs.* time (x-axis, s) and diagnostic wave (diagnostic pulse spectral component) frequency shift from the pump wave $f_i - f_0 - 100$ (y-axis, kHz) for 3 successive quasi-continuous pumping sessions (0-30 s, 120-150 s, 240-270 s). t=0 corresponds to 15:40 AST 2014/06/04. f_0=5500 kHz.
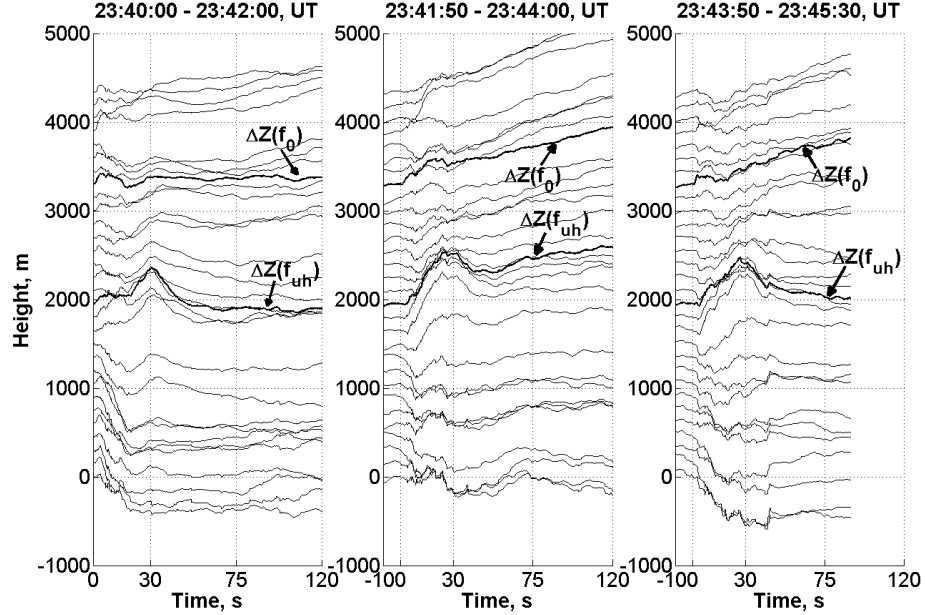

Figure 2. Variations of the reflection heights of different spectral components of diagnostics (sounding) pulses for 3 successive quasi-continuous pumping sessions (0-30 s, left panel, 120-150 s central panel, 240-270 s, right panel). Frequency step Δf_i= 20 kHz, initial diagnostic frequency f_{start} = 5050 kHz, final frequency f_{end} = 5650 kHz. Additional height shift (for clarity) between reflection heights at the successive frequencies is 150 m at t=0. Running averaging over frequency with a window 20 kHz was applied. f_{UH} = 5320 kHz.

It is seen from Figs. 3-4 that after quasi-continuous pump wave is switch on the reflection altitudes of the sounding waves with the frequencies close to the pump frequency, increases. The total uplifting lasts 10-15 s and reaches 150-200 m. In a few seconds plasma expulsion from the upper hybrid height begins. This is accompanied by an increase of the reflection heights of diagnostic waves with frequencies $f_i \gtrsim f_p(z_{UH})$ (up to 500 m) and decrease of the reflection heights of diagnostic waves with frequencies $f_i < f_p(z_{UH})$ (up to 300-400 m). Total drop of the electron density at the upper

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hybrid height reaches 1.2-1.5% during 30 s. Velocity of the reflection height displacement, according to Fig. 4 grows to few tens m/s.
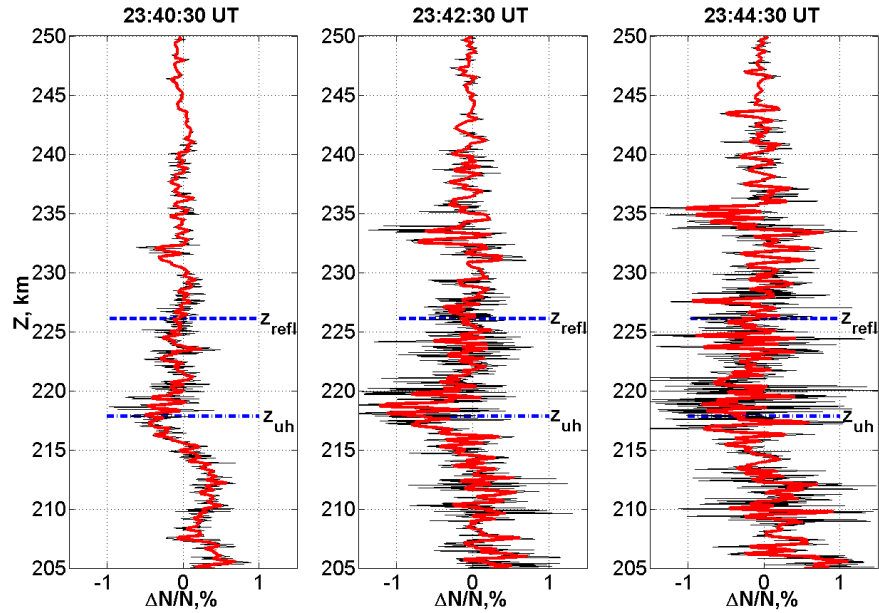

Figure 3. Relative variations of electron density $[N(30\text{ s}) - N(0)]/N(0)$ vs. height at the 30th second of the quasi-continuous pumping. Red line: running averaging with 250 m window.
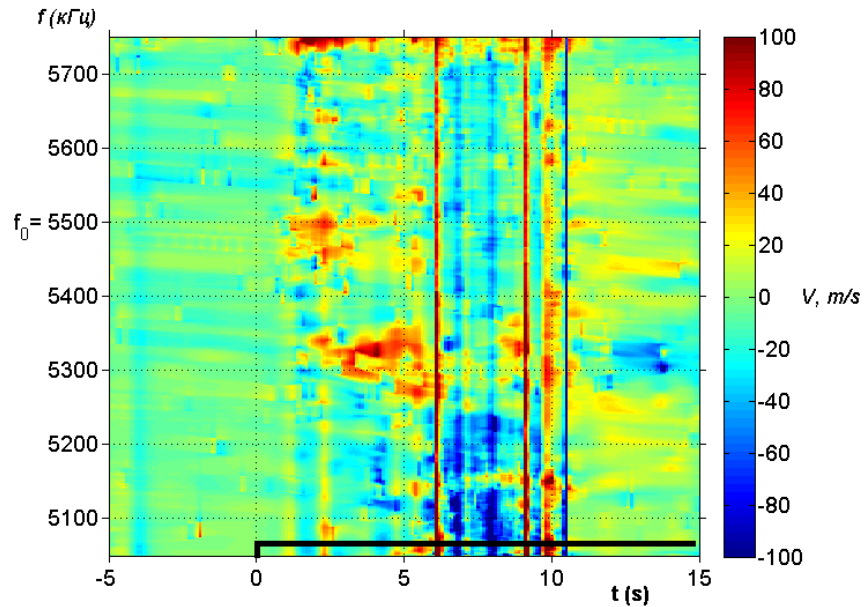

Figure 4. Velocity of the sounding waves reflection height displacement $\partial \Delta z_r(f_i, t)/\partial t$ vs. time and frequency for the pumping session started at 15:40 AST. Black bar corresponds to the time of quasi-continuous pumping. Running averaging over frequency with 21 kHz window is applied.

2.2. Broad Downshifted Emission in the SEE spectrum during the pump wave frequency sweep near the 4th gyroharmonic.

The Broad Downshifted Emission (BDE) in the SEE spectra was identified for the first time during the 2011 HAARP campaign [Grach et. al., 2012]. BDE found to be in the frequency range $f_{BDE} - f_0 =$ – (50–180) kHz. In the 2014 campaign BDE was registered several times in the midnight experiments with pump wave frequency sweep near 4th and 3rd electron gyroharmonics. SEE spectrograms and individual SEE spectra obtained in 2014/06/04 and 2014/06/05 are presented in Figures 5, 6.
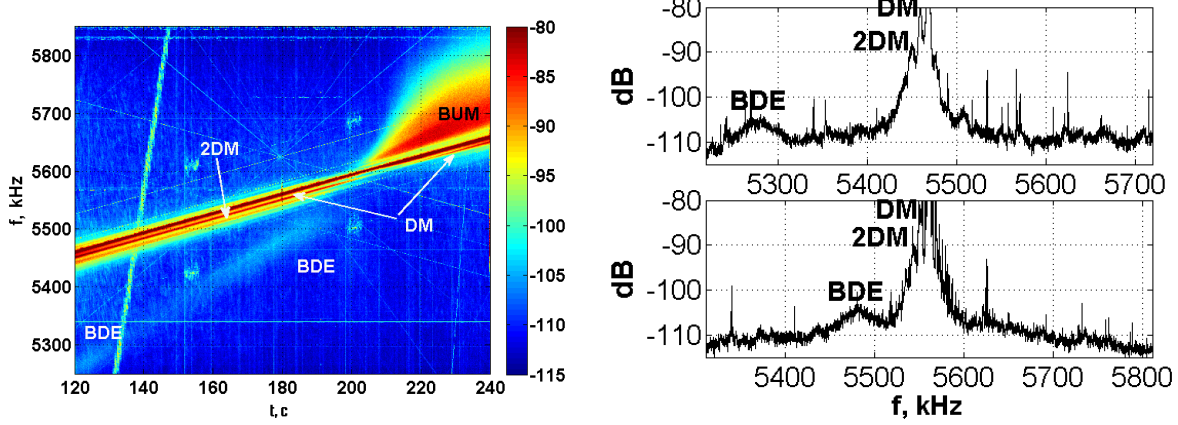

Figure 5. Left: SEE spectrogram obtained 2014/06/04, 00:02-00:04 AST. Pump frequency varied from 5460 till 5660 kHz. Magnetic Zenith, 'twisted mode' of pumping, 7° off zenith. The time t= 120 s corresponds to 00:02 AST. Right: individual SEE spectra obtained at 125th and 180th seconds. Downshifted Maximum (DM), second Downshifted Maximum (2DM), Broad Downshifted Emission (BDE) and Broad Upshifted Maximum (BUM) are marked in the figure.

The 4th electron cyclotron harmonic in the HF-plasma interaction region was estimated by quenching of the Downshifted Maximum SEE feature in the spectrograms. The DM peak situated at $\Delta f_{DM} = f_{DM} - f_0 \approx - 10$ kHz. It disappears when its frequency f_{DM} matches the double resonance, i.e. $f_{DM} \approx f_{uh} (z) \approx 4f_{ce}(z)$, where $f_{uh} = (f_p^2 + f_{ce}^2)^{1/2}$ is the upper hybrid frequency [*Leyser*, 2001, *Grach et al.*, 2008]. In the spectrogram presented in Fig. 5 $4f_{ce} \approx 5600$ kHz, which corresponds to the height $z \approx 270$ km. In Fig. 6 $4f_{ce} \approx 5560$ kHz, which corresponds to the height $z \approx 275$ km. It is seen that the BDE appeared in the SEE spectrum along with such well known features as DM, 2DM and BUM.

Let's enumerate main obtained BDE peculiarities.

(*i*) BDE appears in the SEE spectra in the night time, when the absorption of the pump wave in small. BDE is not observed under a moderate pump wave power; probably the threshold of the BDE generation is close to the maximum ERP of the HAARP facility. Smaller BDE intensity in the Fig. 6 in comparison with Fig. 5 can be attributed to a smaller ERP for the heating twisted mode.

(*ii*) BDE is excited, when the interaction heights are quite large, $z \sim 260$-275 km. According to the measurements of June 5 (not shown in the figure), when the height increases the BDE weakens.

(*iii*) A position of the BDE peak in the SEE spectrum approaches to (moves away from) with increasing (decreasing) f_0 according to $\Delta f_{BDE} = f_{BDE} - f_0 = \alpha (f_0 - 4f_{ce}) - df$; coefficient α and the frequency mismatch df vary for different sweeps and α is larger for decreasing f_0 (Fig.6). E.g., for experiment presented in Fig. 5 $\Delta f_{BDE} = - 1.2(f_0 - 4f_{ce})$ - 36кГц; for the up-sweep in Fig. 6 $\Delta f_{BDE} = - 0.35 (f_0 - 4f_{ce}) - 108$ кГц (left part of the left panel), for the down-sweep in Fig.6 $\Delta f_{BDE} = - 0.9 (f_0 - 4f_{ce}) - 5$ kHz.

(*iv*) BDE is excited mainly for the pump frequency below the gyroharmonic, $f_0 < 4f_{ce}$. However, during up-sweep of the pump wave frequency through the harmonic, the BDE spreads to the frequency range $> 4f_{ce}$, and even continue to present (but much weaker) in the SEE spectrum after replacement of the up-sweep by down-sweep (Figure 6).
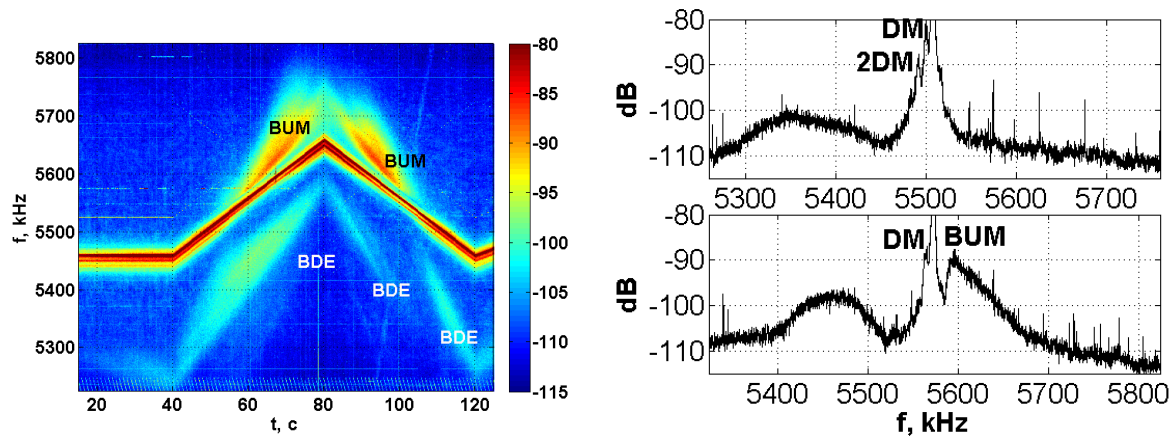
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Figure 6. Left: SEE spectrogram obtained 2014/06/05 at 00:00-00:05 AST. Pump frequency varied in the interval 5460–>5660–>5460 kHz. The time $t = 20$ s corresponds to 00:01 AST. Right: individual SEE spectra obtained at 50th ($f_0 = 5509$ kHz) and 63rd ($f_0 = 5574$ kHz>4 f_{ce}) seconds. The DM, 2DM, BDE and BUM features are marked in the figure.

(v). During the pump frequency sweep near 3rd gyroharmonic, the BDE is observed only for up-sweep in a narrow pump frequency range $f_0 – 3f_{ce}$ ~ -15-25 kHz (not shown in the figures).

3. CONCLUSIONS

In the paper we have presented preliminary results of multi-frequency Doppler sounding of the ionosphere at HAARP conducted on June, 2014. Characteristics of the plasma expulsion from the region near the pump wave reflection point and from the upper hybrid resonance region have been studied.

New data on Broad Downshifted Emission feature in Stimulated Electromagnetic Emission spectra are presented and discussed.

ACKNOWLEDGEMENTS

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