Studies of the Ionospheric Turbulence Excited by the Fourth Gyroharmonic at HAARP

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ABSTRACT

We present the results of a study of the Artificial Ionospheric Turbulence (AIT) induced by HF heating at HAARP close to the fourth electron gyro harmonic in a broad range of radiated powers, using a number of different diagnostics. These include GPS scintillations, ground based SEE, the HAARP ionosonde, Kodiak radar, and most interestingly, received signal at the Ukrainian Antarctic Station (UAS). The latter allowed us to analyze waves scattered by the AIT into the ionospheric waveguide along Earth's terminator, 15.6 Mm from the HAARP facility.

We show nonlinear effects in STEC, SEE, and received signal at UAS due to modulated intensity and frequency of the pump wave. These demonstrate that the scattered waves reach UAS by the waveguide along the Earth's terminator, and that they were injected into the waveguide by scattering off of artificial striations produced by AIT above HAARP, rather than via direct injection from side lobe radiation.

1. INTRODUCTION

The study of the Artificial Ionospheric Turbulence (AIT) generated by HF facilities such as EISCAT and HAARP has a 40-year history. Diagnostic tools to study the AIT have included: coherent and incoherent scattering radars to detect the formation and propagation of artificial striations, ground based electromagnetic receivers to detect stimulated electromagnet emission (SEE), scintillations of the GHz GPS signals, and detection of narrow band electromagnetic emissions via radio telescope.

At the Sura facility, *Ponomarenko et al*. [1999] utilized a distant broadcast station as radar while the scattered signal was received and analyzed by the UTR-2 HF Kharkov Telescope. They found that when the heating frequency exceeded the multiple gyro resonance the scattered signal underwent strong broadening (5-10 Hz), related to the excitation of Super Small Striations (SSS). The experiment stimulated theoretical studies which led to the development of the SSS model [*Gurevich and Zybin*, 2006].

Work by *Bernhardt et al*. [2009], *Thide et al*. [2005] used of Stimulated Electromagnetic Emission (SEE) to probe the AIT. The broadband SEE spectra include features such as the downshifted maximum (DM) and broad upshifted maximum (BUM), both of which are indicators of the processes which occur in the ionopsheric plasma during HF heating [*Leyser et al*., 1994]. The DM is thought to be a signature of the parametric decay of a mode converted upper hybrid wave into another upper hybrid wave and a lower hybrid wave, while the BUM is thought to be produced by a four-wave interaction that includes upper and lower hybrid, as well as electron Bernstein modes.

Additionally, *Zalizovski et al*. [2009] performed O-mode heating at the EISCAT heater and were able to detect HF signals at the Ukrainian Antarctic Station (UAS) located 16.3 Mm away. The HF waves are generated by HAARP and were subsequently scattered into the ionospheric waveguide off of striations excited by AIT.

This paper reports the results of experiments conducted during the HAARP June 2014 campaign, whose objective was to study the development of artificial ionospheric turbulence. The data collected from the different diagnostic tools were analysed.

2. OBSERVATIONS

We report below observations from the daytime experiments conducted in June 6 2014, during the recent HAARP BRIOCHE campaign. The HAARP heater operated in the 0.9-3.6 MW, power range, used O-mode heating. The HF frequency was near the 4th gyroharmonic, and was stepped up from 5.67 to 5.94 MHz in 30 kHz increments. The HAARP antenna array consists of 360 dipoles each fed by 10 kW transmitters. The experiment discussed here lasted 20 minutes, starting at about 3 UT, i.e around 7 p.m. local time. During the day the ionosphere was slightly disturbed (δB~50 nT); a noticeable sporadic E-layer existed (f_0E_s~4.5 MHz); f_OF_2 was in the frequency range 5.6-5.7 MHz while the F2 peak was located at h_mF_2=270 km. Considering the oblique propagation of the heating wave, its frequency was reflected from the F2 peak thus, the heating wave was strongly absorbed in the ionosphere due to anomalous absorption.

Due to regulatory frequency constraints, the minimum heating frequency was 5.67 MHz which was above the 4th gyro resonance. In our March 2013 experiment [*Najmi et al.*, 2014] we have obtained the resonance frequency 5.76 MHz from the SEE spectrum, at which frequency, the DM disappeared. The ionogram shows that 5.76 MHz waves are reflected at 190 km.

An estimate based on the dipole model of the geomagnetic field shows that in the June 2014 experiments the 4th gyro resonance occurs at 5.6 MHz, $4f_{ce} = 5.76MHz\left(\frac{R_E + 190km}{R_E + 250km}\right)^3$, where 250 km is the reflection height of 5.6 MHz taken from ionograms. Thus the lowest heating frequency 5.76 MHz is close to the BUM cutoff, about 8 kHz above the 4th gyroharmonic, i.e. at 5.68 MHz [*Leyser et al.*, 1994].

2.1 GPS OBSERVATIONS

Data collected by the HAARP GPS detector during HF heating experiments on June 6th is presented in figure 1. It shows STEC data in TECU during heating experiments with heated on-off times indicated by solid vertical lines as a function of the elapsed time and heating frequency. The heating at each frequency lasted 100 s while each 10 s the power was stepped up. Thus, the figure shows STEC amplitude as a function of heating power for each of the heating frequencies.

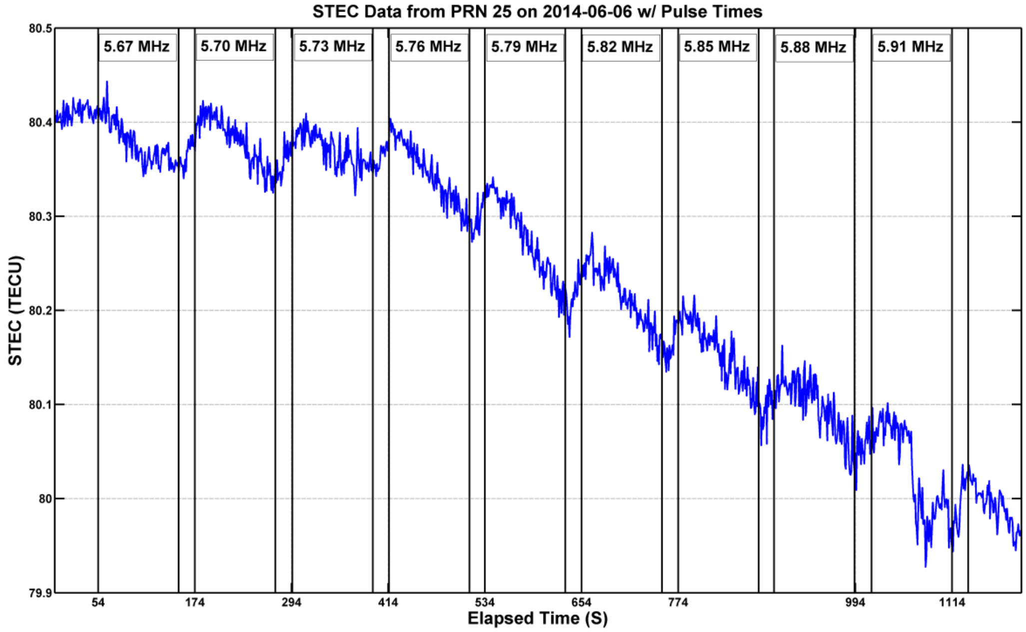

Figure 1: STEC data (in TECU) during heating experiment on June 6th with heated on-off times indicated by solid vertical lines. The heater is first turned on around 20s elapsed. Since the heating at each frequency lasted 100 s and each 10 s the power was stepped up, the figure reveals STEC amplitude vs. power for each of the heating frequencies.

We expected that the STEC amplitude would increase with ERP because larger ERP can lead to production of additional SSS which modulate the GPS signal. Instead, we found that the STEC amplitude initially increased with HF power, but then at each frequency it decayed with power for power levels above ~40-50%.

2.2 SEE OBSERVATIONS

Stimulated Electromagnetic Emission (SEE) signals were measured simultaneously with the STEC using an HF detector operated by the Naval Research Laboratory 15 km away from the HAARP site and shown in Figure 2. It reveals the power spectral density (PSD) of the SEE emission at the selected frequency 5.76 MHz. The traces are averaged over a 10 s portion of the heating period with constant ERP. The heating frequency is shown by the highest peak in the centre at $\Delta_f = 0$, the down shifted maximum (DM) is on the left side of the heating frequency at Δ_F=-10 kHz, while the broad upshifted maximum (BUM) is on the right side of the plots in the range Δ_F=+30-130 kHz. In figure 2, the blue trace corresponds to the per-transmitter power of 2.5 kW, green to 5.0 kW, and red to 10 kW (25, 50, and 100% respectively). The peak amplitude of the SEE signal is saturated at 50% power. On the first time saturation at the 90% level occurs at about 50% of full power for the both DM and BUM amplitude was observed.

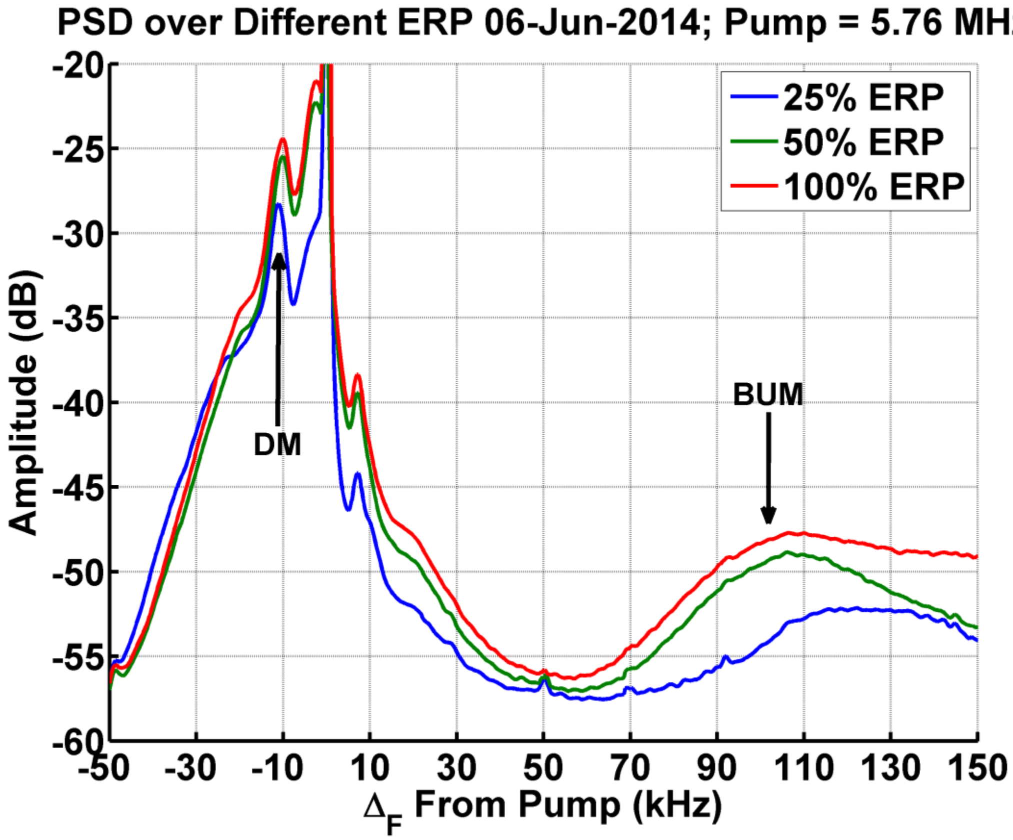

Figure 2. Power spectral densities (PSD) of broadband SEE from 06-Jun-2014 computed for the selected frequency 5.76 MHz. The traces are averaged over a 10s portion of the heating period with constant effective radiated power (ERP). The heating frequency is shown by the highest peak in the center at Δ_F=0, the down shifted maximum (DM) is on the left side of the heating frequency while the broad upshifted maximum (BUM) is on the right side of the plots. The blue trace corresponds to the power 2.5 kW, green to 5.0 kW and red to 10 kW per transmitter (the power level 25, 50, and 100% respectively).

2.3 HAARP SIGNAL DETECTED AT UAS

Monitoring of the HAARP HF signals was carried out at the Ukrainian Antarctic Station (UAS) "Academician Vernadsky". Figure 3 shows the spectrogram of the received signal for June 6, 2014, while figure 4 shows the intensity of the signal detected. The 7th (f_h = 5850 kHz) and 9th (f_h = 5910 kHz) heating cycles, indicated by black arrows at the spectrograms, were contaminated by interference signals and therefore were not processed in Fig. 3 which shows the S/N ratio of the signal intensity. Figure 3 reveals that the intensity of detected signal strongly depends on the heating frequency f_h. In fact, for f_h slightly above the 4th gyro-frequency the intensity of the detected signal was very low, barely above the noise level. The intensity of the detected signal went up with f_h and peaks at 5.79 MHz. We were unable to detect scattered HAARP HF signals from similar detectors in Ukraine and Scandinavia, thus verifying the role played by Earth's terminator in the formation of the waveguide. Figure 4 shows how the signal changes with the intensity of the HAARP heater at the different heating frequencies (the blue lines). The green lines correspond to 4 times increase of the heating power, with the linear interpolation shown by the red lines in Fig. 4.

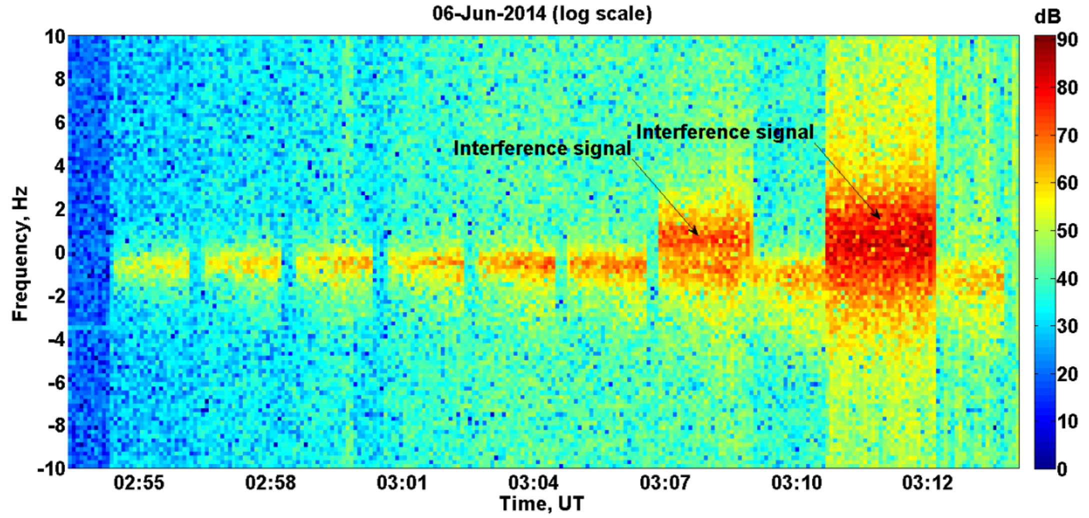

Figure 3: Spectrogram of received HF signal at UAS June 6th. The 7th (f_h = 5850 kHz) and 9th (f_h = 5910 kHz) heating cycles, indicated by black arrows at the spectrograms, were contaminated by interference signals and therefore were not processed.

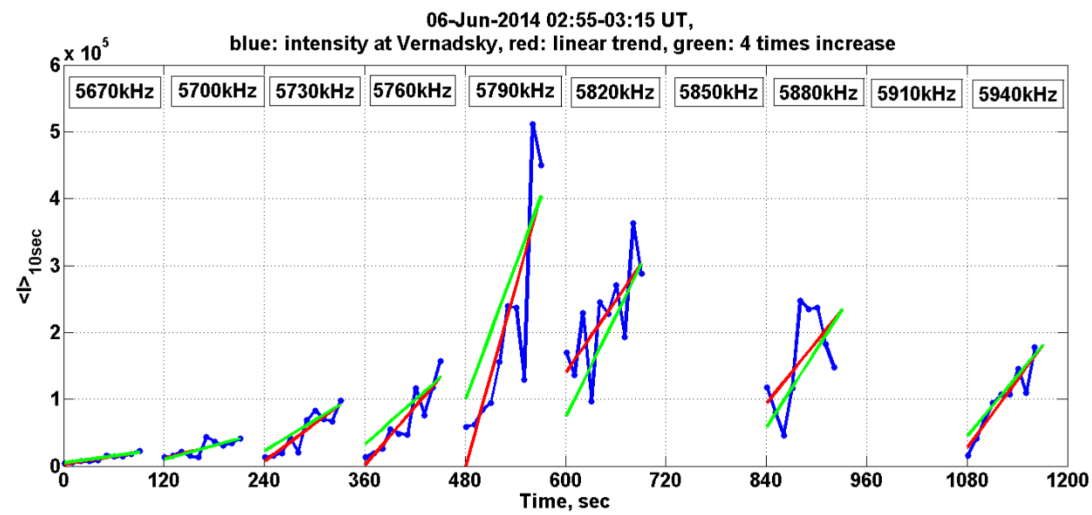

Figure 4: Scaling of Received Power at UAS with ERP. The intensity of the received signals at the different heating frequencies is shown by the blue lines. The green lines correspond to 4 times increase of the heating power, with the linear interpolation shown by the red lines.

We found that the intensity of the signal detected at UAS during the experiments strongly depends on the heating frequency f_h. Figure 5 reveals that when the BUM is dominant in the SEE spectrum, it suppresses the HF signal. The stronger the BUM is, the weaker the HF signal. By contrast, when the DM dominates in the SEE spectrum, the intensity of the detected signal increases with f_h and peaks at 5.79 MHz. Thus the DM and HF peaks occur at the same frequency. Furthermore, it is known that the BUM is associated with the pumping of 10 cm transverse scale striations (SSS) while the DM is associated with the 7-30 m scale striations. Since SSS inefficiently scatter the HF waves compared to the decameter striations related to the DM, this implies that the HAARP signal detected at UAS could be due to the scattering of the HF radiation having the half wavelength of 25 m by the decameter size artificial striations into the ionospheric channel.

The analysis shows that origin of the detected signal at UAS is scattering of the HAARP's HF radiation off of artificially pumped striations and into the ionospheric waveguide. In this process, mirror reflection does not appear to play an important role, as indicated by the low amplitude of received signal at 5.67 and 5.70 MHz. Since the amplitude of the signal varied nonlinearly with the HF power at 5.76, 5.79 and 5.82 MHz, the signal cannot be induced by sidelobe radiation which is known to be linear in the radiated power.

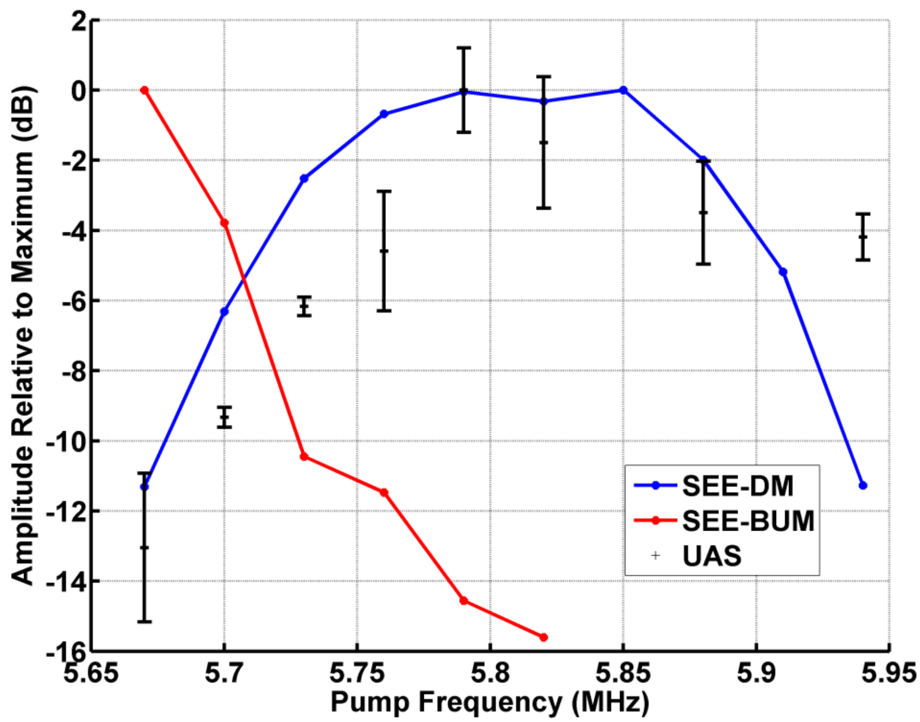

Figure 5: Amplitudes of DM (blue curve), BUM (red curve), and received power at UAS (black points with bars) relative to maximum values, as a function of the pump frequency.

3. CONCLUSIONS

We have presented a study of the artificial ionospheric turbulence (AIT) induced at HAARP by sweeping frequencies near the fourth gyro harmonic. Our study included a number of diagnostics, such as: stimulated electromagnetic emission (SEE), slant total electron content (STEC) and Kodiak radar, to verify the presence of AIT and confirm nonlinear effects related to the variation of the pump intensity and frequency. We added the novel diagnostic of received signal at the Ukrainian Antarctic Station (UAS) 15.6Mm away.

The AIT has a broad wavelength spectrum of which we studied super small striations (SSS) having 10 cm scale, and the decameter scale striations. In the SEE spectrum these striations were manifested by the BUM and DM features respectively.

The SSS were studied with the help of GPS signals. A nonlinear dependence of the STEC amplitude on ERP of the HF heater was obtained. At any heating frequency the STEC amplitude first increases with ERP till it reaches its peak and then decays. This effect is due to the competition between the pumping of SSS and anomalous HF absorption.

On the first time the SEE measurements show saturation of the DM and BUM amplitude that occurs at ½ of the HAARP's ERP. Earlier the saturation could not be observed at Sura facility since its insufficient ERP, less than ¼ of HAARP's. We also observed the dependences of the BUM and DM amplitude on the heating frequency.

We found that HF waves from HAARP were scattered by the AIT into the ionospheric waveguide oriented along Earth's terminator, analogous to a whispering gallery mode, and were subsequently detected at UAS. Attempts to measure the scattered HF signal in Ukraine and Scandinavia were unsuccessful which emphasized the role played by the terminator in the formation of the waveguide.

The intensity of the received signal at UAS has a strong frequency dependence, with the maximum occurring at the same frequency as the peak in the SEE downshifted maximum (DM) and the minimum correlating with the SEE broad upshifted maximum (BUM). The former of which is associated with decameter scale striations which resonantly scatter HF waves, and the latter of which is associated with 10 cm scale striations which do not efficiently scatter HF waves.

In our experiments, the combination of the strong frequency dependence, the presence of ionospheric decameter scale striations shown indirectly by SEE and directly by Kodiak, and the fact that we observed an increased Doppler broadening, which is consistent with scattering off of striations, we conclude that the signal detected at UAS was generated predominantly by the direct scattering of the HF signal into the ionospheric waveguide off of decameter scale artificial striations that were pumped by AIT.

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