Artificial Ionospheric Scintillation Excited during Active Modulation of the Ionosphere

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***Abstract*—Artificial ionospheric scintillation effects excited during fourth gyro-harmonic ($4f_{ce}$) heating at HAARP (The High Frequency Active Auroral Research Program) on the GPS signal along with a theoretical model for the excited ionospheric irregularities are presented in this paper. The generation mechanism and time evolution of Super Small Striations (SSS) responsible for GPS scintillation have been investigated using the simultaneous collected data including GPS scintillation, Wideband SEE (WSEE), ionosonde, and the received signal at the Ukrainian Antarctic Station (UAS). A computational model and theoretical model as well as observational data have been used to study plasma waves associated with SSS.**

I. Introduction

Artificial field aligned irregularities (striations) with spatial scale of the order of several kilometers in the direction of magnetic field and 7-10 m across the magnetic field have been studied extensively over the past few decades. Several theories including thermal parametric instability and resonance instability have been developed to investigate FAIs produced near the upper hybrid resonance level. Variation of ionospheric Total Electron Content (TEC) and GPS/GLONASS signals during mid-latitude ionospheric modification by powerful radiowaves at the Sura facility near N. Novgorod (Russia) are recently observed. The modulation of TEC with the same frequency as the heating pump frequency is reported [1].

The first theory of strong Super Small Striations (SSS) of the order of a few centimeters excited during HF-pump heating of the ionosphere near harmonics of electron gyrofrequency is recently developed [2]. These field aligned density irregularities can scatter UHF radio waves up to a few GHz. The GPS scintillation produced by SSS during third gyroharmonic HF-heating of ionosphere has been observation [3]. Recent observations have shown that the HAARP signal can be detected in Antartica 15.6 Mm from the HAARP facility as a result of scattered waves by the artificial striations into the ionospheric waveguide along Earth's magnetic field [4].

II. Experimental Observations

The experiment on June 7, 2014 started at 02:50 UT and ended at 03:10 UT. The HF beam was directed towards the PRN 25 satellite, the initial angle depends on the day. The HAARP transmitter with the O-mode pulse was at a constant frequency while varying the pump power every 6 seconds. The heating cycle consists of 10 cycles of 100 sec of HF pump heating, and 20 sec of off-time. The first cycle started with pump frequency $f_0 \approx 5.67$ MHz. The pump power 0.9 MW was used at the beginning of the heating cycle. Every 10 sec, the base power is increased by 0.3 MW until max transmitter power (3.6 MW) is reached. For subsequent cycles, the frequency will be increased by 30 kHz, and the same power stepping procedure from .9 MW to 3.6 MW is performed. Every 5 minutes into the experiment, the HAARP beam was re-centered on satellite PRN 25. The HF-beam was directed toward PRN 25 initially at ZA=15.8°, AZ=222.4°. The HF beam angle was changed every 5 min subsequently that to track the PRN 25 satellite. Time series of the received signal (signal to noise ratio SNR) at the Ukrainian Antarctic Station (UAS) during the heating experiment carried out on June 7 is presented in Figure 1a. The strength of DM, UM and BUM versus pump frequency variation are shown in Figure 1b.

III. Summary and Conclusion

To study the ionospheric GPS scintillation produced by SSS, understanding the concept of plasma waves produced through the interaction of HF pump wave with ionospheric plasma is necessary. The UH waves as a product of four-wave decay instability are only trapped inside field aligned striations and can not exist outside resonance region. Therefore, UH waves have a standing wave pattern inside the striations. Trapped UH waves can excite Bernstein wave of a large amplitude inside the striations. The BUM is the signature of Bernstein mode excited through four-wave decay process in the SEE spectrum. The EB mode creates plasma density fluctuations with a transverse scale of 5-10 cm and spatial scale of the order of 1 km along the magnetic field. These plasma irregularities called Super Small Striations (SSS) can cause scattering of UHF signals as well as generating GPS scintillation.

Formation of Super Small Striations (SSS) and associated ionospheric phase scintillation in the GPS signal are studied

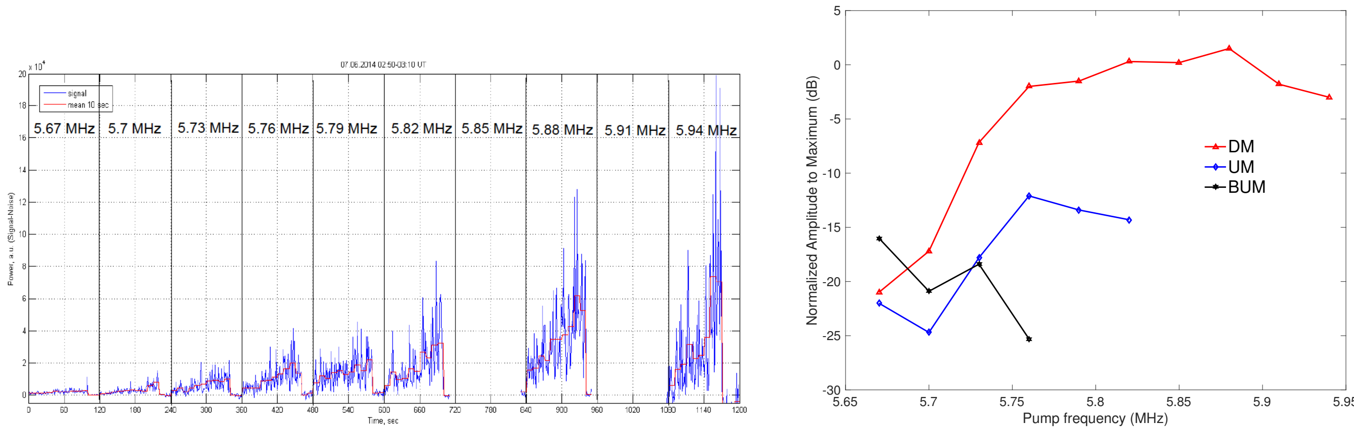

Fig. 1. a) Time history of the HF signal received at the Ukrainian Antarctic Station (UAS) for transmitter frequency variation at HAARP b) Corresponding variation of wideband SEE (WSEE) amplitude including DM, UM, and BUM with f_0 at HAARP.

in this paper using HAARP ionogram, collected data at the Ukrainian Antarctic Station (UAS), Wideband SEE (WSEE) measurements, and STEC data obtained using GPS PRN 25 L1 and L2 signals during heating experiment at HAARP in 2014. The HF transmitter frequency variation near $4f_{ce}$ as well as pump power variation were studied to investigate the modulation of STEC fluctuation and GPS scintillation.

EB waves excited through PDI are assumed to generate SSS of the order of few centimeters. The signature of excited EB/UH associated with PDI manifests itself in BUM feature in the WSEE spectrum. Solution of dispersion relation for 4-wave PDI as the generation source of EB/UH waves, SSS, and GPS scintillation is presented. A comparison of the linear growth time and saturation of STEC fluctuation with the theoretical calculation of growth rate for 4-wave PDI show good agreement. The estimated growth time is about 1 sec.

It has been indicated that the minimum power (0.9 MW) used in the experiment is well above the minimum electric field amplitude required to excite BUM is 0.2-0.6 V/m. Therefore, future experiment starting at lower pump power (0.1 MW) should be carried out in order to determine the threshold amplitude of pump field to generate SSS. As discussed in the introduction, STEC fluctuation are direct indication of GPS phase scintillation. An electrostatic particle-in-cell (PIC) computational results from the previous work [5] were used to study the nonlinear process associated with 4-wave PDI. It should be noted that the main purpose of their work was to show the asymetry in the SEE spectrum not predicted [6]. Computational results show that EB mode decays out after the saturation reached while UH wave stays at about the same amplitude. The STEC data shows a decay and suppression of SSS (and the corresponding EB wave) which matches well the computational results. The decay time estimated by the model is comparable with the observations. This process is attributed to the cyclotron damping of EB waves as the generation source of SSS due to the elevated electron temperature. It should be noted that the linear growth time in the computational results is consistent with the theoretical model as well as the experimental observations. It has been discussed that fututre experiments designed at low power levels should be considered in order to distinguish the generation mechanism of BUM, SSS and GPS scintillation. Considering that the amplitude of electron density fluctuations are small, the amplitude scintillation of GPS signal is negligible in comparision with the phase scintillation.

The data from the HF receiver at UAS showing the signature of HAARP signal is presented. A correlation with the heating cycle and HAARP pump power is observed. The agreement between the amplitude DM in WSEE spectra and SNR of the received signal at the UAS is observed. This validates the theory that scattering of HF pump waves from the decameter scale FAI into the Earth-ionosphere waveguide (EIW) is responsible for the received signal in Antarctica along the ionospheric channel [4].

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