Ionospheric Effects Caused by 40.75 kHz Whistler-mode Waves over Arecibo

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Abstract

We report Arecibo experiments to investigate interactions of 40.75 kHz whistler-mode emissions with ionospheric plasmas, and the subsequent whistler wave-electron interactions in radiation belts. These whistler-modes originate from the Naval transmitter (NAU) in Puerto Rico, emitting radio waves at a power of 100 kW. Based on our theoretical analyses, we show that NAU emissions are intense enough to excite lower hybrid waves in the ionosphere over Arecibo, and precipitate 390 keV electrons from radiation belts to cause the observed plasma line enhancement in nighttime F- and E-regions, respectively.

1. Introduction

Our reported experiments conducted at Arecibo Observatory were aimed at the study of possible ionospheric plasma effects caused by the 100 kW and 40.75 kHz transmitter, code-named NAU, that is operated by the United States Navy at Aguada, Puerto Rico, about 52 km to the west of the Arecibo Observatory. These Arecibo experiments were guided by our earlier theoretical work and laboratory simulation experiments [1-3]. We expect that NAU-launched radio signals can be converted into 40.75 kHz whistler waves with intensities large enough to excite electrostatic plasma waves (i.e., lower hybrid waves) in the ionosphere. Furthermore, the NAU whistler waves can propagate from the ionosphere into the inner radiation belts at L = 1.35 to precipitate trapped energetic electrons into the lower ionosphere over Arecibo. The magnetic conjugate propagation of NAU whistler waves between Arecibo and Trelew, Argentina along the L = 1.35 flux tube was demonstrated in our 1997 Arecibo HF heating experiments [4-5].

2. Interactions of NAU Whistler-mode Waves with Ionospheric Plasmas

Most of NAU's emitted power propagates in the Earth-ionosphere waveguide. However, in the presence of ionospheric plasma irregularities some fraction (~10 % as estimated) of the NAU carrier signal scatters into the ionosphere and magnetosphere to propagate along magnetic field lines in the whistler mode. According to our recent theoretical analysis extended from that of Lee and Kuo and data analyses [6], direct interactions of 40.75 kHz whistlers with ionospheric plasmas can excite meter-scale lower hybrid waves to accelerate electrons and, subsequently, yield enhanced plasma lines with rather broad frequency spectra.

Displayed in Figure 1 is a set of data showing the observed F-region plasma line enhancement in the presence of spread F events, when NAU was on. Shown here are a sequence of three FRI (frequency-range-intensity) plots, acquired at 20:49:07, 20:49:17, and 20:49:27 LT, respectively, on December 25, 2004. This set of data shows sequentially the occurrence of F-region plasma line enhancement at 20:49:17 LT, and disappearance in less than 10 seconds. The enhanced plasma lines appeared at altitudes around 320 ±80 km, having a SNR of ~ 6, and a center frequency at 4 MHz with a bandwidth of ~ 1.5 MHz. No F-region plasma line enhancement events were observed in the absence of spread F activities.

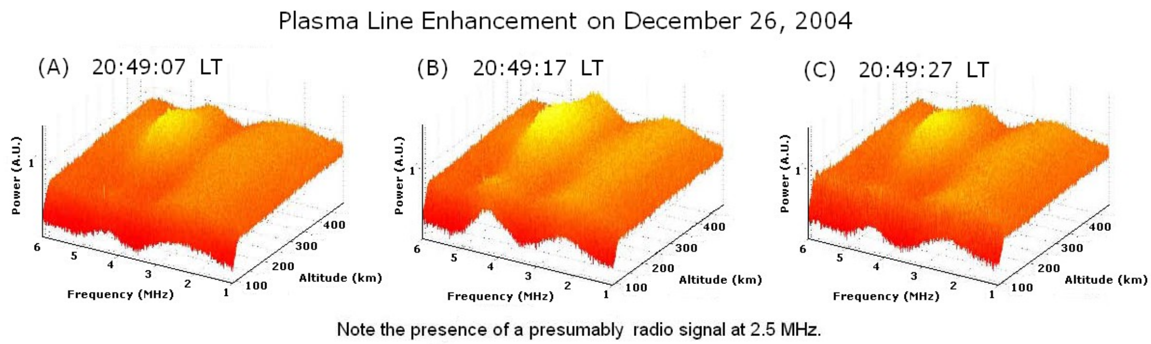

Figure 1. A set of data acquired at 20:49:07, 20:49:17, and 20:49:27 LT, respectively, on December 25, 2004, showing the observed F-region plasma line enhancement in the presence of spread F events, when NAU was on.

As discussed [6], our theoretical and experimental results suggest that the Naval transmitter (NAU) is responsible for causing the enhanced plasma lines, detected by Arecibo 430 MHz radar in the nighttime ionosphere F region, in the presence of spread F events. The NAU-generated 40.75 kHz whistler-mode waves are intense enough to excite meter-scale lower hybrid waves and zero-frequency field-aligned plasma density irregularities in the ionosphere over Arecibo. These lower hybrid waves, generated in a broad range of altitude at the wake of 40.75 kHz whistler mode waves, have a single frequency of 40.75 kHz with a spectrum of wavelengths. They can effectively accelerate electrons continuously along the Earth's magnetic field with energies from a fraction of 1 eV to 10 eV. These energetic streaming electrons, when detected by Arecibo 430 MHz radar, give rise to enhanced plasma lines with a frequency spectrum of ~3.25–4.75 MHz.

3. NAU Whistler-mode Wave-Electron Interactions in Radiation Belts

After 40.75 kHz whistler waves propagate from the ionosphere into the magnetosphere, they will interact and precipitate trapped energetic electrons from the inner radiation belts into the lower ionosphere, generating enhanced plasma lines in the lower ionosphere with relatively narrow frequency spectra. The possible correlation between E-region PL enhancement and NAU operation was established in our early January 2006 experiments [7]. The NAU transmitter was turned off when our experiments began at 22:00 local time (LT) on January 1. It remained off until 01:45 on January 2 when operations resumed and continued uninterrupted through 06:00 when our observation period ended. During the entire 8 hour period the Arecibo ISR looked to local zenith, operating in repeated sequences of 20-minutes backscatter power and 10 minutes PL operations. The average occurrence rate increased from 0.25 event per minute when NAU was OFF to 0.75 event per minute when NAU was ON. The plot of E Region PL Enhancement Event Rate on the night of 1/2 January 2006 is given in Figure 2. We recorded 16 (1.9%) PL enhancement events while NAU signals were absent and 45 (5.35%) after transmissions resumed. This factor of 2.8 increase in PL enhancement rates between NAU ON/OFF periods strongly suggests that a causative relationship between them.

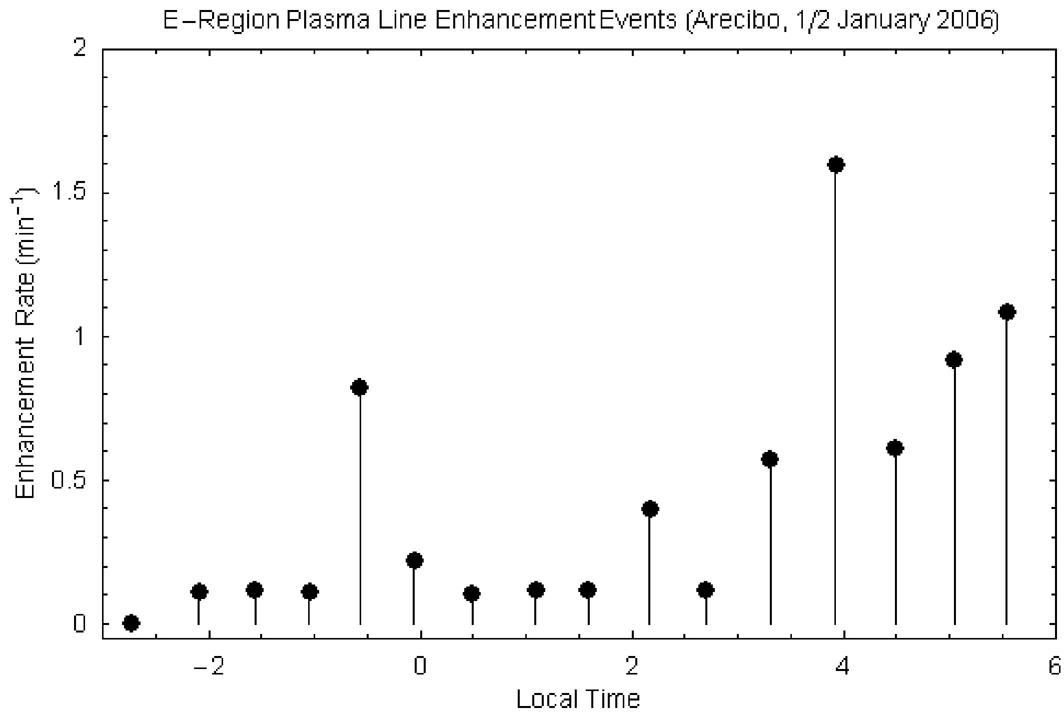

Figure 2. The plot of E Region PL Enhancement Event Rate (i.e., no. of events per minute in each of the 10 minute PL measurement period) on the night of 1/2 January 2006. This is an alternative way to display our 1/2 Jan 2006 PL data, showing that, on the average, the event rate had tripled when NAU was ON in comparison to that when NAU was OFF.

Figure 3 shows a typical set of plasma line (PL) measurements in the form of three frequency-range-intensity (FRI) spectra. From left to right the FRI plots indicate results of PL sequences that began at 05:01:07, 05:01:17, and 05:01:27 LT on January 2, 2006. The middle plot shows an E-layer PL enhancement characterized by spiky bursts that last for a short period of time. Each PL spectrum was acquired over a 10 s integration time. The enhanced PL events have a signal-to-noise ratio (SNR) of 4 to 5 and appeared at altitudes near 120 ± 20 km. Near this time neither the ISR backscatter power profile nor the ionograms showed the presence of significant E-layer or sporadic E plasmas. The enhanced PL spectrum has center frequency of ~2.5 MHz with a ~1.5 MHz bandwidth. Figure 5 also shows no PL enhancements in samples acquired before or after the event recorded between 05:01:07 and 05:01:17 LT. These data suggest that E-layer PL enhancements above Arecibo are episodic phenomena of < 10 s duration.

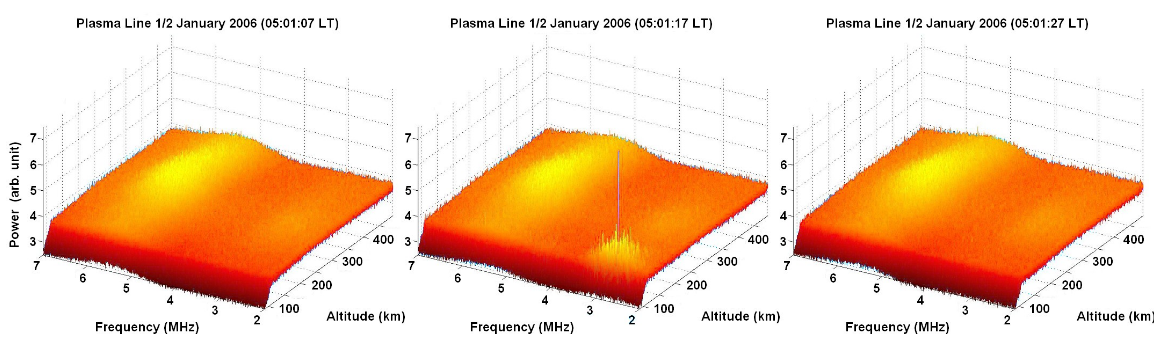

Figure 3. A set of E-region plasma line enhancement data (three FRI plots) recorded at 05:01:07, 05:01:17, and 05:01:27 LT, respectively, on January 2, 2006 when NAU transmitter was turned on

As elaborated in [7], the aforementioned characteristic features of enhanced E-region plasma lines support the following scenario. NAU-generated 40.75 kHz whistlers interact with energetic electrons of ~ 0.4 MeV in radiation belts at L = 1.35, and subsequently cause electron precipitation into the lower ionosphere to ionize neutral particles with ionization energies of ~ 13 eV. The precipitated electrons stream along the Earth's magnetic field, giving rise to enhanced E-region plasma lines with a center frequency of 2.5 MHz and a bandwidth of 1.5 MHz. It indicate that the phase speeds of streaming suprathermal electron-induced waves off which the radar scattered were in the range 6.2×10^5 to 1.2×10^6 m/s. The corresponding energies of resonant streaming electrons fall in the range 2.3 – 8.5 eV [8] in good agreement with the residual energies of those precipitated electrons from the radiation belts.

Acknowledgements

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