Novel ISR electron temperature technique for heating experiments using the Arecibo Legacy

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November 26, 2022

Abstract

The Arecibo Observatory (AO) could modify the ionosphere using high frequency (HF) waves. During the HF experiments, the incoherent scatter radar (ISR) was used to study the behavior of the ion, plasma, and gyro lines with 150m height resolution. One year ago, the AO platform collapsed and put a pause for new experiments. However, the archived ISR data can answer open questions like the electron heating evolution in the interaction region. This paper presents a new methodology to estimate the electron temperature (Te) at the resonance altitude based on the physics of the HF wave-plasma interaction. Estimating Te inside regions where the ionospheric plasma interacts with the powerful HF ground waves is a challenge. Standard ISR techniques to assess the temperatures using the ion line are based on Maxwellian approximations. However, the irregularities generated by HF experiments induce non-Maxwellian behaviors. Therefore, a new approach is proposed using the ion-acoustic phase velocity (C_ia) of the ion-acoustic waves generated during the HF experiments. The ion acoustic velocity can be derived from the ISR enhanced plasma line (HFPL) produced during active experiments. The HFPL is mainly attributed to the HF wave decaying into a cascade of Langmuir and ion-acoustic waves, known as Parametric Decay Instability (PDI). The ion-acoustic waves travel at speed: C_ia=λf_ia, where f_ia is the ion-acoustic frequency, and λ is the radar (Bragg backscatter) wavelength. The PDI signature is characterized at the HFPL by cascaded lines spaced in frequency by multiples of f_ia. After measuring f_ia, Te is obtained using f_ia=1/λ [?](k_B (Te+2Ti)/m_i), where Ti and mi are the ion temperature and mass. Estimates for one particular experiment on June 12, 2019 show that Te is usually higher at the top of the layer and the beginning of every HF pulse. For example, at 280s after 16:43:00LT, it reached a value near 3500 K, when the temperature outside of the interaction region was below 1600 K.

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Abstract:
The Arecibo Observatory had unique instruments to modify the ionosphere using powerful high frequency (HF) waves and diagnose the ionosphere. The most sensitive incoherent scatter radar (ISR) of the world was used to study the behavior of the ion, plasma, and gyro lines with a height resolution of 150 m during the HF experiments. One year ago, the platform of the Arecibo Observatory collapsed and put a pause for new experiments. However, the archived ISR data is a treasure that can help to answer open questions like the electron heating evolution of the interaction region, among many others. New ISR techniques had to be developed to answer these questions. This paper presents a new strategy to estimate the electron temperature at the resonance altitude based on the physics of the HF wave-plasma interaction.

Can traditional ISR techniques be used to estimate the electron temperature at the HF interaction region?

The answer is NO!

Traditional ISR Technique to estimate T_e	Behavior at the HF interaction region
1) Using Maxwellian approximations (Dougherty and Farley, 1960, Fejer 1960, Salpeter 1960, Evans 1969, Hagfords, 1997)	The HF enhanced spectrum is not purely Maxwellian ➢ It can't be used.
2) Using FREE Langmuir waves properties (Showen, 1979, and Nicholls et al., 2006)	HF experiments force the Langmuir waves. ➢ It can't be used.

Estimating the electron temperature (T_e) inside regions where the ionospheric plasma interacts with the powerful HF ground waves is a challenge. Standard ISR techniques to assess the temperatures using the ion line are based on Maxwellian approximations. However, the irregularities generated by HF experiments are known for inducing non-Maxwellian behaviors in the ionosphere. Therefore, a new approach is proposed here by using the ion-acoustic phase velocity C_{ia} of the ion-acoustic waves generated during the HF experiments.

New technique to estimate the electron temperature using the PDI characteristics imprinted in the HF-Enhanced ISR Plasma Line

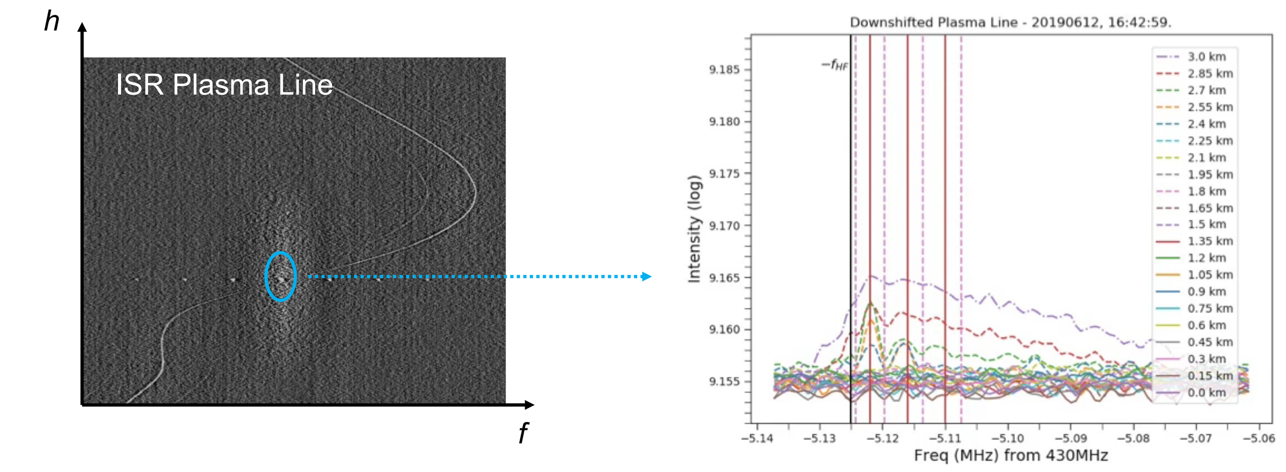

Figure 1. Left Panel: ISR plasma line spectra between 2MHz and 8MHz, collected during an HF experiment. The HF enhanced plasma line (HFPL) is marked with the blue circle. Right panel: Shows the spectra at the HFPL with a bandwidth of 80khz at the HF frequency. Decay lines are observed (near the red lines spaced at ~3kHz). The data corresponds to an experiment performed on June 12, 2019 at 16:43 h (LT). The enhanced line starts at an altitude of 229.1 km, depicted as 0km in the plot. The cadence of the experiment was 10s ON, 10s OFF.

The C_{ia} can be obtained from the ISR enhanced electron (plasma) line produced during active experiments. The enhanced ion and plasma lines (HFIL and HFPL) generated during the HF experiments are mainly attributed to the HF wave decaying into a cascade of Langmuir and ion-acoustic waves, known as Parametric Decay Instability (PDI). The ion-acoustic waves travel at a constant speed with $C_{ia} = \lambda f_{ia}$, where f_{ia} is the ion-acoustic frequency, and λ is the radar wavelength assuming the Bragg backscatter condition. The radar detects the PDIs at the altitude where the Langmuir and ion-acoustic waves match the wavenumber condition in the proximity of the plasma line ($f_{radar} \pm f_{HF}$). The PDI signature is characterized by one mainline and many subsequent cascaded lines spaced in frequency by multiples of f_{ia}. *Perkins et al., 1974* predicted that the frequency separation of the PDI decaying lines during HF experiments is $\Delta\omega \equiv \pm|2k_o|C_{ia}$. Then, the f_{ia} is measured by the average frequency separation of the PDI lines observed in the spectrum of the enhanced plasma line.

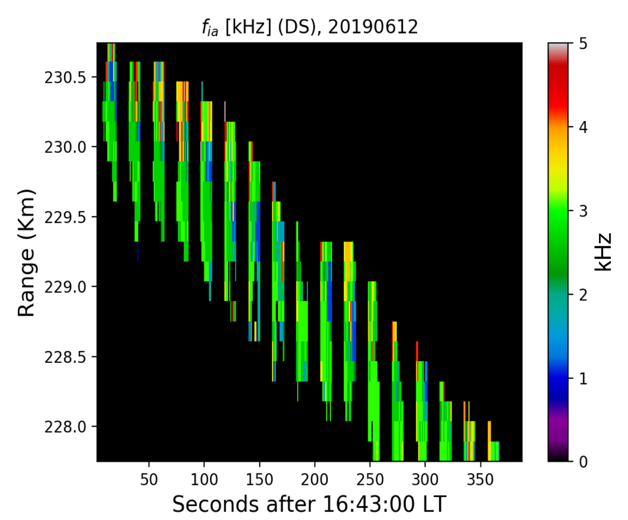

Figure 2. Ion-acoustic frequency obtained by measuring the average spacing of the decaying lines for the experiment presented in Figure 1. The natural ionospheric plasma frequency (f_{pe}) was descending and the altitude of the HFPL was following the matching frequency ($f_{HF} = f_{pe}$) altitude. The ion acoustic frequency is mostly near 3kHz. However, there are increases on the higher altitudes of the HFPL.

The HF electron temperature estimates

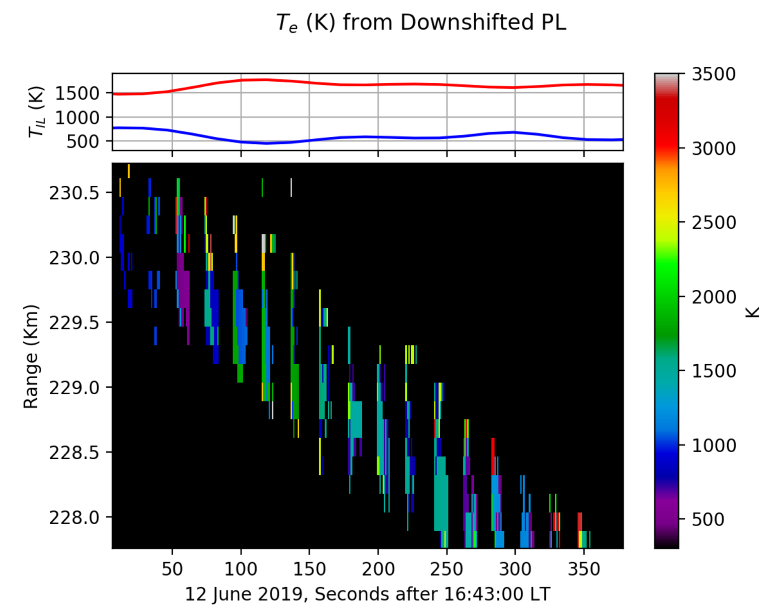

Figure 3. ISR Electron temperature for an HF active experiment on June 12, 2019, during the PRIM campaign at Arecibo. The HF frequency used was 5.125MHz, with a cadence of 10s O and 10s OFF. The ISR time integration used for these estimations is 1s. The quiet natural ionosphere, slightly dropping in altitude, was observed during that time. The first panel shows electron (red) and ion (blue) temperatures obtained with the standard ISR ion line technique for an altitude of 231 km, above and outside the interaction region. The second panel exhibits the electron temperature distribution inside the interaction region estimated using the ISR plasma line, with the methodology proposed in this paper.

T_e is obtained using the definition $f_{ia} = \frac{1}{\lambda}\sqrt{k_B(T_e + 3T_i)/m_i}$, where T_i is the ion temperature, m_i is the ion mass, and k_B is the Boltzmann's constant, assuming an invariant T_i, and an accurate m_i for the resonance region. Estimates for one experiment, are presented in Figure 3. The results show that T_e is usually higher at the top of the layer and the beginning of every HF pulse. For example, at 280s after 16:43:00LT, T_e reached a value near 3500K, when the temperature outside of the interaction region was below 1600K.

Conclusions

1) A method to estimate T_e inside the HF interaction region using the ISR Plasma Line is presented. A T_e distribution (height vs. time) inside of the HF interaction region is obtained.
2) Increase of T_e up to twice the background values is observed at the top of the HF interaction region.
3) Future work: Bernhardt et al., 2009 proposed a technique to estimate the temperatures using the stimulated electromagnetic emission (SEE). We plan to compare temperatures obtained with both techniques.

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Acknowledgments:

The author thanks Dr. Frank Djuth and Dr. Jonathan Krall for the valuable discussions. This research was supported by the US NRL 6.1 Base Program. It was conducted while Eliana Nossa held a NRC Research Associateship with residence at NRL. The Arecibo Observatory is a facility of the NSF operated under cooperative agreement by the University of Central Florida.