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**Key Points:**
- Use of thermal plasma oscillations to measure electron density from bottom side through 1000 km
- New nighttime plasma line capability
- Relative comparison of ion line power to thermal plasma line power

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# Radar observations of thermal plasma oscillations in the ionosphere

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**Abstract** Incoherent scatter radar observations of ionospheric plasmas rely on echoes from electron density fluctuations with properties governed by the dispersion relations for ion acoustic and Langmuir waves. Radar observations of echoes associated with Langmuir waves (plasma lines) from thermal plasma are weak, and only a few near-thermal level measurements have been reported. Plasma line echoes are typically only observed with existing radars only when the Langmuir waves are enhanced by suprathermal electrons. A new observation technique has been developed which is sensitive enough to allow observations of these echoes without the presence of suprathermal electrons up to at least 1000 km. This paper presents recent observations from the Arecibo Observatory 430 MHz incoherent scatter radar which show plasma line echoes during the night when no suprathermal enhancement is expected to be present. The observations are compared with theory, and the results are found to be in agreement with classical incoherent scatter theory for thermal plasmas. The theoretical ratio of the ion line and plasma line power spectral density is within approximately 3 dB of the predicted value. The finding adds a new observational capability, allowing electron density to also be observed at night using the plasma line well into the top side of the ionosphere, increasing the accuracy of the electron density measurement.

**Plain Language Summary** Our results address a fundamental theory of scattering of electromagnetic waves from thermal plasma, which was formulated in the 1960s. The theory has so far been validated only partially, for the ion line component of the theory, which describes scattering from ion acoustic waves. Our new measurements confirm for the first time that the second part of the theory, which describes scattering of electromagnetic waves from thermal plasma waves, also known as Langmuir waves, is also accurate to with a factor of 2, when comparing the relative power of the ion line and the plasma line.

## 1. Introduction

Over 50 years ago, *Dougherty and Farley* [1960], *Fejer* [1960], and *Salpeter* [1960] independently derived the theory for incoherent scattering of radio waves from free electrons in plasmas in thermodynamic equilibrium. The theory describes the shape of the Doppler spectrum of radar scatter from such plasma which is present, e.g., in the Earth's ionized upper atmosphere. The spectrum includes the ion line, a feature associated with ion acoustic waves, and plasma lines, a feature associated with plasma oscillations or Langmuir waves. *Dougherty and Farley* [1960] remark that the plasma line will be "very difficult to observe using present techniques. However, if it could be observed, with improved experimental methods ( … ), the effect would provide another way of determining the electron density."

The theory for incoherent scattering of electromagnetic waves from plasmas was extended soon after inception to include the effects of the magnetic field, collisions, and multiple ions with different masses [*Evans*, 1969]. Recent advances in the theory include the special case of scattering at small magnetic aspect angles [*Sulzer and González*, 1999; *Woodman*, 2004; *Kudeki and Milla*, 2006; *Milla and Kudeki*, 2011]. For the ion line, the theory is experimentally validated and well established. It is used with incoherent scatter radars around the world as a basis for observations of ionospheric plasma state parameters such as electron density, electron temperature, ion temperature, and ion composition. Until now, the near-thermal level plasma line has only been reported in relatively few observations. *Carlson et al.* [1982] reported nighttime observations of plasma lines intensities that "exceed their thermal level by a modest factor (roughly two to four times … )." Slightly enhanced nighttime plasma lines have also been reported by *Carlson et al.* [2015]. The reason for relatively few observations is that the thermal plasma line is a very weak signal, it is difficult to detect, even when using the Arecibo radar.

The theory for plasma lines in the presence of suprathermal electrons was first formulated by *Perkins and Salpeter* [1965]. They found that the plasma line can be greatly enhanced through inverse Landau damping when the electron energy distribution includes a suprathermal component with energetic electrons that are matched in energy to the radar wavelength and plasma frequency. Soon after, observations with the Arecibo Observatory radar confirmed that the enhanced waves can be readily observed [*Perkins and Salpeter*, 1965].

The suprathermal enhancement is so large that even radars far less sensitive than Arecibo can observe plasma lines, and such observations nowadays constitute the most accurate ground-based method for measuring ionospheric plasma density. Measurements of plasma lines have also been used to observe electron temperature [*Hagfors and Lehtinen*, 1981; *Kofman et al.*, 1981; *Nicolls et al.*, 2006] and as a diagnostic tool for suprathermal electrons [*Carlson et al.*, 1982; *Yngvesson and Perkins*, 1968]. Enhanced plasma lines can be used to observe ionospheric electron density variations during auroral precipitation with very high temporal resolution [*Vierinen et al.*, 2016], in some cases surpassing the accuracy of ion line measurements.

Suprathermal enhancements of plasma lines occur primarily during the daytime when suprathermal photoelectrons are created by solar ultraviolet radiation. Photoelectrons can also flow along the magnetic field lines from the magnetically conjugate sunlit hemisphere and cause plasma line enhancements even if the local hemisphere is in darkness [*Evans and Gastman*, 1970]. Secondary suprathermal electrons created by collisions between auroral energetic precipitating particles and the neutral atmosphere are another mechanism for producing plasma line enhancements [*Oran et al.*, 1981; *Valladares et al.*, 1988; *Kirkwood et al.*, 1995].

Suprathermal enhancements of plasma lines at Arecibo were recently found to occur also at night when no significant quantities of suprathermal electrons are thought to be present [*Carlson et al.*, 1982, 2015]. These observations have been attributed to a source of suprathermal electrons, as the plasma line power was enhanced from the thermal levels. Suprathermal enhancements of plasma lines at night are, however, not observed on a regular basis at Arecibo, which indicates that the suprathermal enhancement of plasma lines is not a regular phenomena. Observations at Arecibo have also been used to study suprathermal electrons created by ionospheric heating [*Carlson et al.*, 1982, 2017].

In this study, we show using a new more sensitive observation technique that the Arecibo Observatory radar is routinely capable of observing thermal level plasma lines at night, well into the topside of the ionosphere. These observations are within approximately 3 dB explained using the standard thermal incoherent scatter theory without any plasma line enhancement. We use ion line power as a reference when determining plasma line power, which to our knowledge has not been reported earlier.

## 2. Theory

The theory for incoherent radar scatter from thermal plasmas, using notation from *Kudeki and Milla* [2006], provides an analytic expression for the radar Doppler spectrum as a function of radio wave $\boldsymbol{k}$ vector. The $\boldsymbol{k}$-$\omega$ spectrum of electron density in the probed region is given by

$$\left\langle |\Delta N_e(\boldsymbol{k},\omega)|^2 \right\rangle = \frac{|j\omega\epsilon_0 + \sum_i \sigma_i|^2 \langle |n_{t,e}(\boldsymbol{k},\omega)|^2\rangle}{|j\omega\epsilon_0 + \sigma_e + \sum_i \sigma_i|^2} + \frac{|\sigma_e|^2 \sum_i \langle |n_{t,i}(\boldsymbol{k},\omega)|^2\rangle}{|j\omega\epsilon_0 + \sigma_e + \sum_i \sigma_i|^2}, \tag{1}$$

where $\omega$ is Doppler frequency, $\sigma_e$ and $\sigma_i$ are the electron and ion conductivities, and $\langle |n_{t,e}(\boldsymbol{k},\omega)|^2\rangle$ and $\langle |n_{t,i}(\boldsymbol{k},\omega)|^2\rangle$ are thermally driven $\boldsymbol{k}$-$\omega$ density spectra of "noninteracting" electrons and ions, respectively, that can be expressed as

$$\begin{aligned} \langle |n_{t,s}(\boldsymbol{k},\omega)|\rangle &= N_s 2\mathrm{Re}\left\{J_s(\omega;\boldsymbol{k})\right\} \\ \sigma_s(\boldsymbol{k},\omega) &= j\omega\epsilon_0 \frac{1 - j\omega J_s(\omega;\boldsymbol{k})}{k^2 h_s^2}, \end{aligned} \tag{2}$$

in terms of the Gordeyev integral [*Gordeyev*, 1952]

$$J_s(\omega;\boldsymbol{k}) = \int_0^\infty \mathrm{d}\tau e^{-j\omega\tau}\langle e^{j\boldsymbol{k}\cdot\Delta r_s(\tau)}\rangle \tag{3}$$

for charged particle species $s$—here $k^2 = |\boldsymbol{k}|^2$, $h_s = \sqrt{\epsilon_0 K T_s/N_s e^2}$ is the Debye length, $N_s$ is the average electron density, while $\langle e^{j\boldsymbol{k}\cdot\Delta r_s(\tau)}\rangle$ within the Gordeyev integral is the characteristic function of random particle displacements $\Delta r_s(\tau)$ of at time $\tau$. The form of the characteristic distribution depends on the three-dimensional velocity distribution of the different species (ions and electrons). This can be used to include effects of suprathermal electrons, the magnetic field, and also collisions in the spectral model.

With a radar of a specific frequency and geometry, we observe this spectrum at one $\boldsymbol{k}$ vector which depends on the location of the transmitter, the receiver, and the wavelength. In our case, we used the Arecibo 430 MHz radar to transmit and receive, so our observation is $\langle|\Delta N_e(\omega)|^2\rangle = \langle|\Delta N_e(\boldsymbol{k},\omega)|^2\rangle|_{\boldsymbol{k}=\boldsymbol{k}_r}$, where the monostatic radar wave vector is $\boldsymbol{k}_r = 4\pi\boldsymbol{u}f/c$, with $f = 430\cdot 10^6$ Hz, and $\boldsymbol{u}$ a unit vector pointing toward zenith.

## 3. Method

In a practical measurement, the incoherent backscatter power depends on the size of the scattering volume. The larger the volume, the more electrons from which to scatter. In order to maximize the volume in our experiment (and therefore the sensitivity of the experiment), we utilized a long uncoded pulse which has a volume spanned to first order by the length of the pulse in range multiplied by the area of the radar beam. The long uncoded pulse also has a very narrow bandwidth which allows observing plasma lines very close to the stronger ion line without the spectral sidelobes of the transmitted waveform spreading ion line power on top of the significantly weaker plasma line. In order to reduce the variance of the estimates, we average in power the received Doppler spectrum across a 90 kHz frequency interval at frequency offsets larger than the ion line width. While a long uncoded pulse is a relatively often used radar pulse type, the combination of long pulse with a broad band receiver and sufficient incoherent integration in frequency to improve the sensitivity of the plasma line measurement has to our knowledge not previously been used.

In the delay frequency domain, the power averaged incoherent scatter radar measurement is a two-dimensional convolution of the true range-Doppler radar echo power distribution and the range-Doppler ambiguity function that results from the transmit pulse shape and the averaging of frequency bins:

$$m(\omega,r) = \int\int w(\omega',r')\langle|\Delta N_e(\omega-\omega',r-r')|^2\rangle \mathrm{d}\omega'\mathrm{d}r',$$

where $m(\omega,r)$ is the averaged power as a function of delay $r$ and frequency $\omega$ measured by the radar, $w(\omega,r)$ is the range-frequency ambiguity function, and $\langle|\Delta N_e(\omega,r)|^2\rangle$ is the true range-Doppler spectrum which varies with range due to changes in plasma parameters.

In order to fit plasma parameters to the measurements, we used a full-profile inversion method, which fits altitude profiles of plasma parameters that are smooth in altitude to the measurements [*Holt et al.*, 1992; *Lehtinen et al.*, 1997; *Hysell et al.*, 2008]. This was applied to the full incoherent scatter spectrum, including the ion line shape and the plasma resonance frequency inferred from the plasma lines. The plasma resonance frequency determined from the plasma lines in this case provided a well calibrated electron density profile. We do not use measured plasma line power to constrain the plasma parameter fit.

After producing plasma parameters for the measurement, we forward modeled the full incoherent scatter spectrum, which could be compared with the measurements, to see if the ratio of the power of the plasma lines and the ion lines matched theoretical predictions. To do this, we first evaluate the theoretical incoherent scatter spectrum at a high range and Doppler resolution. This is because the width of the plasma line is much narrower than the measurement Doppler resolution. High range resolution was needed to model the gradients in electron density as a function of altitude. To this high-resolution model, we apply a $1/r^2$ weighting in range $r$ in light of the radar equation for volume filling targets. Then, the theoretical range-Doppler measurement is convolved with the two-dimensional range-frequency point spread function determined by the true recorded transmit pulse. The scale of the modeled measurement is determined using the power of the $F$ region peak echo. The same constant is applied to the whole theoretical range-Doppler radar echo model. This scaling constant is ultimately determined by the radar transmit power, antenna gain, and receiver noise power. To model the antenna sensitivity as a function of frequency, we assumed uniform efficiency across

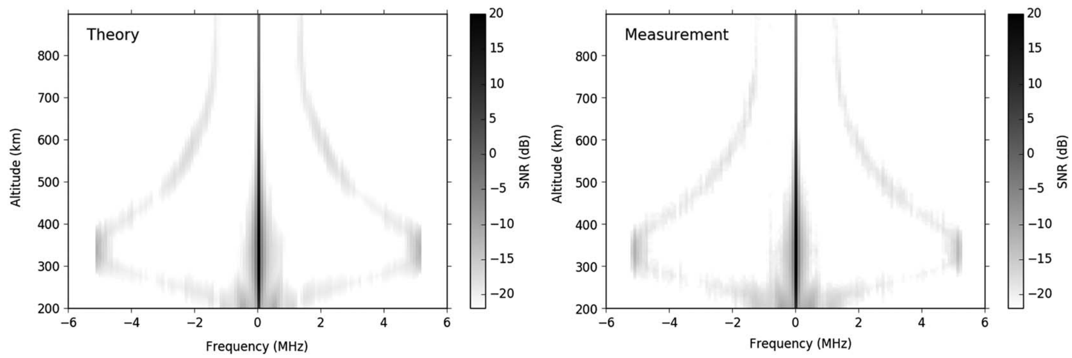


**Figure 1.** Full incoherent scatter radar spectrum as a function of altitude and Doppler shift, measured at night between 13 May 2016 2:14 UTC and 13 May 2016 2:24 UTC. (right) The measurement is shown. (left) A theoretical range-Doppler measurement, produced using plasma parameters determined from the measurement. The theoretical spectrum includes all of the instrumental effects, including simulated measurement noise. The range gate spacing is 1.5 km, and the Doppler resolution is 90 kHz.

the band. Finally, the convolved measurement is integrated in range and Doppler to match the measurement resolution. In the high signal-to-noise ratio ion line portion of the observation, we use 1.5 kHz resolution. In the plasma line portion, we use a 90 kHz frequency resolution.

## 4. Results

Our observations were performed with the Arecibo Observatory 430 MHz radar at night between 12 May 2016, 23 UT and 13 May, 5 UT. We utilized the line feed pointed vertically to obtain maximum sensitivity with a transmit peak power of 1 MW. The radar cycled between two modes of operation: (1) 10 s of 440 μs long uncoded pulses with 10 ms interpulse periods and (2) 10 s of 440 μs pseudorandom coded long pulses with 2 μs baud lengths. Radar echoes were recorded using a newly installed complex baseband digital receiver

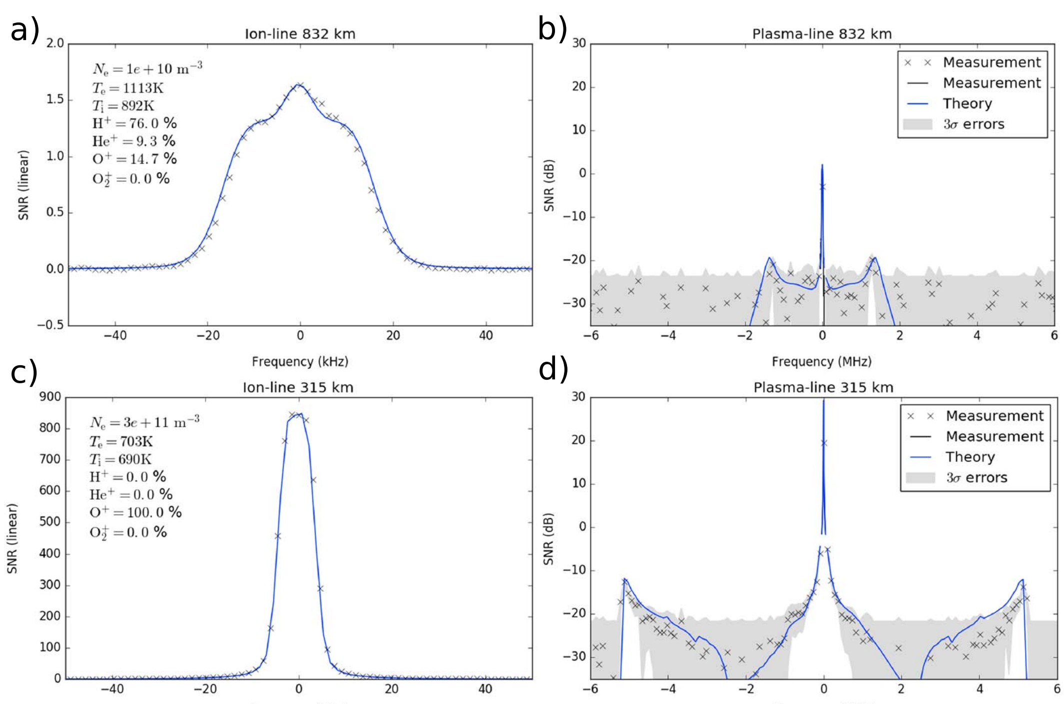


**Figure 2.** (a) Simulated and measured ion line at 832 km altitude, (b) simulated and measured ion line and plasma lines at 832 altitude, (c) simulated and measured ion line at 315 km altitude, and (d) Simulated and measured ion line and plasma lines at 315 altitude. The measurements in Figures 2a–2d are indicated with black crosses, and the theory is shown with a blue line. Error bars of $3\sigma$ are shown with a solid light grey color.

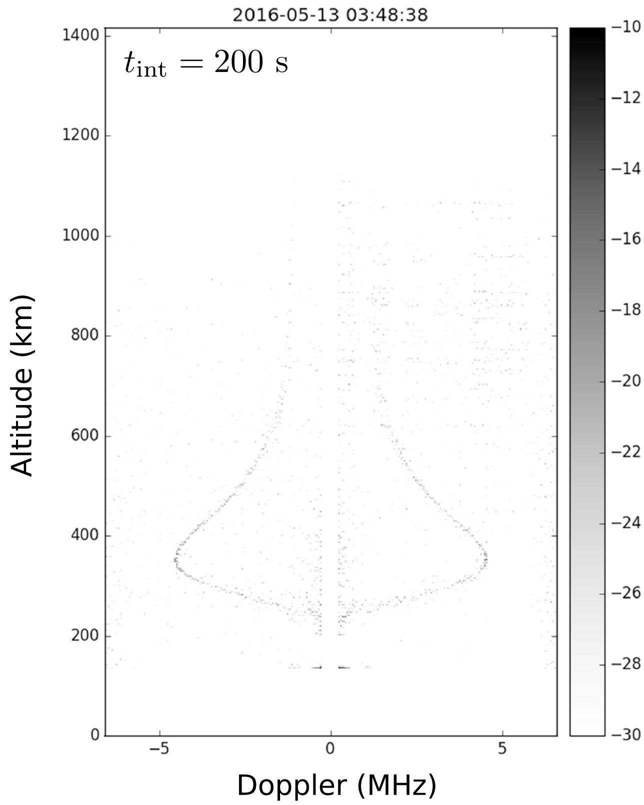


**Figure 3.** Range-Doppler deconvolved long pulse plasma line profile, using the CLEAN deconvolution algorithm. The colorscale is uncalibrated power in decibel scale. An integration time of 200 s is used.

recording signals both with bandwidth of 25 MHz and 16 bit integer samples. The radar echoes, and transmit pulses were recorded digitally and processed off-line.

To form an averaged range-Doppler measurement, we multiply a conjugated copy of the transmit pulse with received echoes offset by the amount of delay expected for the radar echo at each range gate. This vector is then discrete Fourier transformed, and the resulting power is averaged over multiple pulses. This is repeated for each range gate. The end result is a two-dimensional array, which contains range in one dimension and Doppler in the other. We used a 10 μs range step, which results in 1.5 km altitude resolution, but as stated earlier, this measurement is in fact smeared in range and Doppler shift due to the range-Doppler ambiguity function. The procedure is described in more detail in *Vierinen et al.* [2016].

Observations averaged over 10 min were used in this study, which is effectively five minutes of averaging as we only used the long uncoded pulses for this study. Averaging over 1 min or effectively 30 s of long uncoded pulse data already shows a detectable plasma line profile, but we do not show these results here, as they have larger error bars.

Figure 1 (right) shows a representative incoherent scatter radar profile observed at night. The observed returned range-Doppler power distribution is shown as signal-to-noise power in decibel units. This observation contains radar returns averaged between 13 May 2016 2:14 UTC and 13 May 2016 2:24 UTC, which is 22:14 – 22:24 local time, well after the local and conjugate hemisphere sunset, when no suprathermal photoelectrons are expected to be present. Similar profiles were observed throughout the whole night between 12 May 2016 23:00 and 13 May 2016 10:00 UTC, with enhanced plasma lines only observed in the beginning and end of the experiment when the Sun was setting or rising.

Figure 1 (left) shows a simulated measurement corresponding to the measurement in Figure 1 (right) . The simulated measurement is obtained using plasma parameters that have been fitted to the measurement. This simulation contains all of the instrumental effects, including the range-Doppler ambiguity function smearing, and both finite range and Doppler resolutions. Simulated measurement noise is also used. The theory and the measurement are in good agreement with each other. Most importantly, the relative power of the ion line and the plasma line are in good agreement with theoretical predictions, which indicates strongly that the plasma line echoes are not enhanced in power by suprathermal electrons. At the bottom of the profile, one can also see the plasma lines merging into gyrolines [*Bhatt et al.*, 2006] at frequency offsets between 500 kHz and 1 MHz.

Figure 2 also shows sections of the measured spectra and theoretical spectra at various altitudes. Note that also in this case, the instrumental effects are included in the modeling. The ion line measurements and modeling at altitudes 315 and 832 km are shown in Figures 2a and 2c. The measurement is in units of signal-to-noise ratio in linear scale. Figures 2b and 2d show signal-to-noise ratio for the ion line and the plasma line in signal-to-noise ratio units in decibel scale. The measurements are accompanied with 3$\sigma$ error bars, which are shaded grey. The crosses indicate the measurements, and the blue line indicates the theoretically predicted

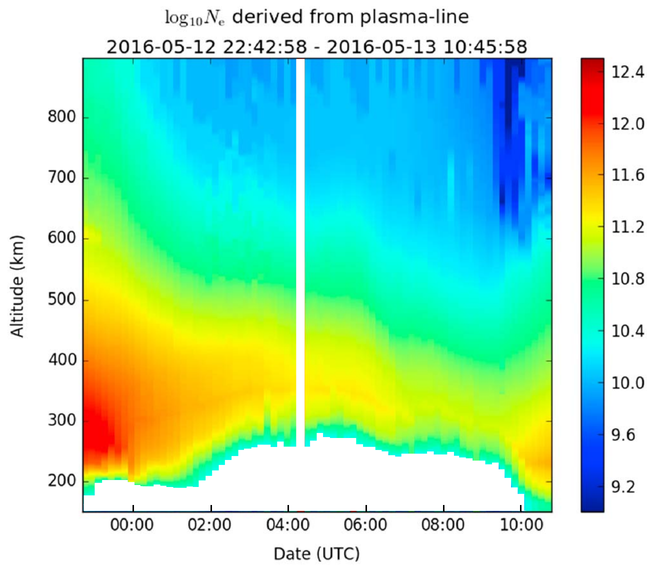


**Figure 4.** Plasma frequency (in units of electron density) measured throughout the night at Arecibo. The poorly determined bottomside portion has been omitted from the plot, as is one integration period during which the radar transmit power was off.

shape of the measurement. The 315 km altitude is dominated by $O^+$ ion plasma near the peak of the *F* region. At this altitude the plasma frequency is at its highest and the ratio of ion line to plasma line power is also at its highest, with the plasma line being nearly 4 orders of magnitude lower in power. The 833 km altitude is well into the $H^+$ dominated plasma on the topside, which a little bit of $O^+$ ions causing a bump in the middle of the spectrum. The plasma resonance frequency is ≈1.5 MHz but still detectable. The reason why the plasma line is still detectable at such high altitude is that the line becomes broader, and the ratio of ion line to plasma line power is only two orders of magnitude.

Figure 3 shows a representative nighttime deconvolved plasma line profile, which is obtained by applying the CLEAN algorithm to remove the range-Doppler smearing due to the long pulse experiment, which is visible in Figure 1. The point is to demonstrate that it is possible to extract a plasma line profile even from long pulse experiments. The deconvolution procedure is identical to that used earlier by *Vierinen et al.* [2016]. Figure 3 does not show the ion line portion of the spectrum, as it is not as easily deconvolved using the method.

Figure 4 shows electron density, derived from the plasma line throughout the whole observation. We have used the formula $f_r = 8.98\sqrt{N_e}$ in the conversion, which is not entirely accurate. Extraction of plasma resonance frequency from the plasma line was not performed optimally, which has resulted in some fluctuations in electron density that are not real. The main point is merely to show that a plasma line profile can be observed throughout the whole night. The *F* region nighttime electron density behavior shown is a typical nighttime ionosphere observed at Arecibo [*Zhang and Holt*, 2007], showing an increase in the *F* region peak altitude post sunset and slow descent toward the presunrise.

## 5. Conclusions

Our observations show that the thermal level plasma line profiles can be observed during the night well into the topside of the ionosphere. Our observations are in agreement with the theory for incoherent scattering of electromagnetic waves from thermal Langmuir waves, i.e., plasma lines. The theory is in agreement with observation when comparing the relationship in power between the ion line and the plasma line. However, the errors are still relatively large (about 3 dB). Reducing these errors is a topic of future work.

We have processed several other nighttime measurements with long uncoded pulse observing mode, and each time found that the plasma lines are observable throughout the night. Our observations indicate that the thermal plasma line at Arecibo is strong enough to be reliably observed up to at least 1000 km altitude and possibly higher. Because thermal plasma lines are significantly weaker than suprathermal electron enhanced plasma lines, the achievable range and Doppler resolution is not as good as it is for suprathermally enhanced plasma lines, but they can still provide an accurate measurement of electron density.

The ability to observe thermal plasma lines opens a new capability for the Arecibo Observatory radar, which can be used to improve plasma parameter measurements at night. For example, the plasma line can be used to better constrain the topside electron density, allowing for improved ion composition and electron temperature determination.

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