Response to the reviewers

The authors would like to thank the reviewer for constructive comments and suggestions that have helped improve the quality of this manuscript which will be revised accordingly. Please see below our responses. Reviewer comments are reproduced, and our responses are given in blue below each comment.

Reviewer 1

Summary: This paper presents new methods for detecting and analyzing plasma lines with the EISCAT radar. One method involves supervision and hand tuning of parameters but accurately extracts any plasma lines present. The second method is fully automated and can be applied unsupervised to a large data set, but suffers from failed detections. The authors apply these new algorithms to 5 days of plasma lines observed by the EISCAT UHF radar. The extracted plasma line frequency and intensity are then analyzed, showing the dependence of the radar pointing direction and ionospheric density.

This is a well written paper that showcases a new method for plasma line extraction and further shows how plasma lines are influenced by radar and ionospheric parameters. I recommend this paper for publication with some revisions.

Reviewer Comment 1: — In Section 3.3, it is mentioned that the plasma lines are fit to Gaussian functions. Can the authors comment on why a Gaussian is chosen instead of a Lorentzian? From Perkins and Salpeter (1965), the frequency spectrum of a plasma line is expected to be a Lorentzian shape.

Reply: While Lorentzian functions are theoretically expected for plasma line spectra (Perkins and Salpeter, 1965), we think Gaussian functions are easier for interpretation since they provide parameters such as plasma line frequency, width, and intensity in a straightforward manner. In addition, as shown in Figure 4, there is quite a lot of noise as soon as the Gaussian fits fall to zero. Because Gaussian functions decay more rapidly to zero than Lorentzians, they are less sensitive to this noise and therefore do not overestimate intensity. Furthermore, the observed spectral width is not the natural width of a plasma line at a specified frequency and height, but rather a smeared version resulting from frequency variations across the radar range gate and the finite integration time. For these reasons, we consider Gaussian fits to be the more reliable choice for the present analysis, a choice also adopted by Guio et al. (1996).

Reviewer Comment 2: — Figure 4 shows the fitted plasma lines, but this is hard to see as the red curves are thick and cover most of the data. This figure would be more clear if modified so that both curves are visible. Suggestions are to plot the red curve underneath the black curve, reduce the thickness of the red curve, or make the red curve a dashed line.

Reply: In the revised manuscript, we will improve Figure 4 by placing the red curve beneath the black curve and reducing its thickness. This will make both the experimental data and the fitted plasma lines more clearly visible.

Reviewer Comment 3: — In Section 3.4, the phase energy is given by equation 16. First, it is not necessary to approximate the Bragg wavelength as $2f_{\text{radar}} + f_{\text{offset}} \to 2f_{\text{radar}}$. Second, as shown in Longley et al. 2021, the phase energy has a strong dependence on aspect angle. This dependence is given in equation 2 of Longley et al. 2021 (ignoring the gyro terms):

$$E_\phi = \frac{1}{2} m_e \left(\frac{\omega}{k \cos^2 \theta} \right)^2 \tag{1}$$

It is recommended the authors correct equation 16 for both of these changes, while also commenting on the aspect angle changing what electron energies are resonant with the plasma line. Note that this effect is small for the experiments in this paper, but may change how Figures 10 and 11 look.

Reply: We agree that the approximation of the Bragg wavelength as $2f_{\text{radar}} + f_{\text{offset}} \to 2f_{\text{radar}}$ is not strictly necessary. Nevertheless retaining the offset frequency f_{offset} of the receiver with respect to the transmitted frequency f_{radar} is important to understand the physics of the scattering process where the scattering wavevector is

$$\vec{k_s} = \vec{k_r} - \vec{k_t}. \tag{2}$$

The received and transmitted wavenumbers are $k_r = 2\pi(f_{\text{radar}} + f_{\text{offset}})/c$ and $k_t = 2\pi f_{\text{radar}}/c$ respectively. For backscattering the wavevectors are colinear and the scattering wavenumber is $k_s = k_r + k_t = 2\pi(2f_{\text{radar}} + f_{\text{offset}})/c$ which can be written $k_s = 2k_r + \Delta k$ with the fractional correction

$$\frac{\Delta k}{k_r} = \frac{f_{\text{offset}}}{f_{\text{radar}}}. \tag{3}$$

Since in our experiment $f_{\text{radar}} = 931$ MHz and f_{offset} is only a few MHz, the correction introduced by the frequency offset at which plasma line is observed is of the order or less than 1%.

We will clarify this point to make explicit that, while preferable to retain the full Bragg expression for lower-frequency radars, such as VHF, its impact is negligible for this study with the UHF radar.

Regarding the aspect-angle dependence, we note that the expression quoted in the reviewer's comment contains a $\cos^2\theta$ term in the denominator. We believe this may have been a typographical error and interpret the intended form as

$$E_\phi = \frac{1}{2} m_e \left(\frac{\omega}{k \cos \theta} \right)^2. \tag{4}$$

We believe this expression refers to only the parallel component of phase energy. In our analysis, however, we consider as the main parameter the total phase energy, defined as

$$E_\phi = \tfrac{1}{2} m_e v_\phi^2 = \frac{1}{2} m_e \left(\frac{\omega}{k_s} \right)^2, \tag{5}$$

where k_s is the scattering wavenumber defined above. The expression for the phase velocity v_ϕ is the same as specified in Eq. (4) of Akbari et al. (2017). The phase velocity of the scattered wave is defined in Eqs. (14)—(15) in our manuscript. The data are then binned with respect to both total kinetic energy and aspect angle, so the aspect-angle dependence is naturally accounted for in the results. Therefore, we consider it most appropriate to retain the total phase energy and not multiply the wavenumber by $\cos\theta$.

Reviewer Comment 4: — In line 235, it is mentioned that plasma lines are only detected in the 1.7–3.4 eV range. Can the authors comment of where the ionospheric densities were high enough to observe plasma lines at the upper limit of the filter band (7.65 MHz)? Also, it should be noted that the plasma lines with phase energies below 1.7 eV correspond to a lower density plasma, and therefore lower SNR.

Reply: The highest-frequency plasma line observed in our dataset occurred at 6.7598 MHz (line 224) at an altitude of 245.6 km, which lies near the middle of the altitude range where plasma lines were detected. Plasma frequencies above 6.74 MHz were observed between approximately 245.6 and 260.3 km.

We agree that plasma lines with phase energies below 1.7 eV may be present but obscured by noise. In principle, plasma lines from the E-region should also be observable, but in our measurements, they were not detected. This might be because for the relatively low electron densities in the E-region, the corresponding plasma line frequencies could fall outside the receiver filter band (below 2.75 MHz). Also, the E-region is characterised by larger electron-neutral collision frequency which can weaken the suprathermal enhancement mechanism, so that any signal would remain below the noise floor. These might be the reasons that all plasma lines detected in this study were confined to the F-region.

Reviewer Comment 5: — The interpretation of plasma line enhancement given in lines 286–293 is not consistent with the derivations of Longley et al. 2021. There is a distinction between the total damping of Langmuir waves and the individual contributions: collisional damping, thermal Landau damping, and photoelectron Landau damping. Plasma lines are enhanced above thermal levels because the photoelectron Landau damping term flips signs at photoelectron peaks and generates waves through inverse Landau damping. It is suggested that the authors revise this paragraph.

Reply: We agree that plasma line enhancement involves several distinct damping and excitation mechanisms, namely collisional damping, thermal Landau damping, and photoelectron Landau damping, as outlined in Longley et al. (2021).

In a 1D reduced velocity distribution obtained by integrating an approximately isotropic 3D electron VDF, the classical inverse Landau damping mechanism described by Longley et al. (2021) does not strictly occur, as fine structures in the velocity distribution (peaks and valleys) are largely averaged out during the integration.

However, we would like to emphasise that the phase energies investigated in our study (less than 4 eV) are lower than those discussed in Longley et al. (2021). In this regime, the dominant effects are Landau damping and Cerenkov excitation (Nilsson et al., 1996), rather than variations in the suprathermal tail. As summarised by Akbari et al. (2017):

"variation of T_p with phase velocity generally abides by the following trend: at the lowest phase velocities (i.e., highest probing wavenumbers, assuming a fixed electron density) thermal electrons and their Cerenkov excitation and Landau damping are the dominant terms and T_p is close to its thermal level T_e. As the phase velocity increases, the suprathermal electrons become increasingly important and T_p increases as the excitation and damping by suprathermal electrons dominate the numerator and the denominator, respectively. At sufficiently large phase velocities, where the number of resonant electrons significantly drops, on the other hand, the collisional terms dominate both the excitation and damping and the plasma line temperature approaches T_e once again."

Given our relatively high probing wavenumbers, the observed enhancements are most consistently explained by Landau damping and Cerenkov excitation at low phase energies (lifting of the tail of electron VDF), rather than by inverse Landau damping of photoelectron peaks. We will revise lines 286–293 to clarify this interpretation.

Reviewer Comment 6: — A similar issue of interpretation comes in the paragraph around line 295. Yngvesson and Perkins 1968 assumed suprathermal electrons would be unmagnetized, and therefore their claims about changes with aspect angle are not valid. This was corrected with a fully magnetized derivation in Longley et al. 2021, which has some plots showing that plasma line intensity is roughly constant from 0 to 10 degrees aspect angle, then increases from 10 to 20 degrees. However, the full understanding of the presented EISCAT UHF observations is difficult as a good photoelectron model is needed for plasma line power calculations. The authors should revise the discussion in this paragraph to avoid repeating the incorrect conclusions of Yngvesson and Perkins.

Reply: We would like to clarify that the analysis in Yngvesson and Perkins (1968) does account for the magnetisation of photoelectrons, as reflected in their Eq. 20. Therefore, their treatment of aspect-angle dependence is valid and should not be considered incorrect.

In our study, for the phase energies and probing wavenumber considered (less than 4 eV), the dominant mechanisms explaining the observed plasma line enhancements are Landau damping and Cerenkov excitation, as highlighted in the previous comment.

Reviewer Comment 7: — Lines 306-307 state "we aim to further develop an aspect angle dependent plasma line intensity model and apply it to the current dataset." Can the authors clarify how such a model would be different from either Enger 2020 (https://hdl.handle.net/10037/19542) or Longley et al. 2021?

Reply: The key difference in our approach compared to Longley et al. (2021) lies in the treatment of the photoelectron distribution. Longley et al. used a distribution derived from AE-C and AE-E satellite measurements at a single altitude and solar zenith angle from a time (Figure 1 adapted from Hernandez, 1983) years before the plasma line observations (March 17, 2015). Moreover, in their figure, the distribution does not appear to include pitch-angle dependence.

In the MSc thesis of Enger (2020), the electron transport model code Aurora was used, but pitch-angle variation in the electron VDF was not accounted for, with only the component along the magnetic field considered. Both studies, therefore, effectively assume isotropy in their calculations.

In contrast, our model is a direct extension to directions oblique to the magnetic field of the framework published in Guio et al., 1998 and Guio and Lilensten, 1999 which treated the field-aligned direction only. Our model uses the latest version of the multistream numerical electron transport model that was used by Guio, 1998 and Guio, 1999 based on Lummerzheim et al., 1994. The model provides the electron VDF as a function of altitude, energy, and a discrete set of pitch angles spanning 0–180°, taking into account local conditions, Ap, and F10.7 indices. This allows us to capture fine-scale variations in the electron distribution that are relevant to the observed plasma line intensities.

Additionally, we will implement a dynamic calculation of the summation limits of the scaled Bessel functions used in the theoretical incoherent scatter spectral modelling. Unlike Longley et al., who used fixed limits ($\ell = \pm 30$), our approach dynamically calculates the limits based on the electron VDF and the wavenumber and aspect angle, ensuring that all relevant features of the electron distribution are included in the calculation, while avoiding unnecessary computations when the distribution becomes negligible.

Overall, our model will extend previous work by incorporating both anisotropic electron distributions and a more flexible computational framework.