Response to the reviewers

The authors would like to thank the reviewers 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 2

The manuscript “Data reduction of incoherent scatter plasma line parameters” presents a study of plasma line detection in the EISCAT UHF radar dataset, using two approaches: a supervised (kind of manually adjusted) and an unsupervised technique (with the detection based on the statistical parameters of the data itself).

The manuscript is well written and easy to follow. The figures are generally clear and of good quality. The conclusions are well supported by the data. Minor revisions/clarifications could improve the quality of the manuscript, which is of high standard already.

Reviewer Comment 1: — As the paper provides an important reference for plasma line analysis, it would be good to mention in the introduction plasma lines associated with instabilities and turbulence. The interested reader will find this information in e.g. the review by Akbari et al., but it would be good to mention this fact – and maybe even add references to key publications.

Reply: We will add a short note in the introduction at line 42:

"Plasma lines may also be strongly enhanced by plasma instabilities and Langmuir turbulence. Such processes can lead to intensities several orders of magnitude above the thermal level, and have been studied both theoretically and observationally. For example, Guio and Forme (2006) presented a numerical study of Langmuir turbulence driven by low-energy electron beams, while Isham et al. (2012) reported the first direct evidence of naturally occurring cavitating Langmuir turbulence in the ionosphere. A comprehensive review of these processes is given by Akbari et al. (2017)."

We will include these references in the revised manuscript to provide readers with a starting point to further study.

Reviewer Comment 2: — The discussion of Figure 7 is not very clear in lines 224–227. The description mentions an increase of the plasma line frequency at “about 11:20:15 UT”, and then mentions a “gradual increase” from 10:00-11:20 UT. Both are related to the Sun, one to the “solar EUV radiation” and the other to "sun exposure". In my opinion, this description should be consolidated.

Reply: In the revised manuscript, we will consolidate the description in lines 224–227 to read:
"The plasma line frequency increases gradually from 10:00-11:20 UT (Figure 7), driven by an increase in the photoelectron population from solar EUV radiation."

Reviewer Comment 3: — An interesting phenomenon is observed in Figure 7, namely the undulation of the location of detected plasma line. This would indicate that the peak of the profile is moving up and down in altitude. Some quasiperiodic variations of the lower “boundary” of the F region are seen also in the top panel of Figure 6. While not directly related to main subject of the discussion, the authors may want to comment on possible nature of the variations (could these be related to gravity waves? or variations in the ionospheric convection? Or yet something else?). Are these variations of the electron concentration profile capable of affecting the plasma line enhancement condition?

Reply: We thank the reviewer for highlighting the undulations in the location of the detected plasma line. We agree that this is an interesting feature and note that similar variations were observed on other days of the experiment as well. We are currently uncertain about the exact cause of the observed undulations. If the reviewer is aware of any studies reporting similar variations in background electron density, we would be grateful for references and happy to consider including them. To our knowledge, we are not aware of prior studies documenting this phenomenon, and we are currently investigating it further with colleagues.

The plasma line enhancement condition primarily depends on the presence of suprathermal electrons and the shape of their velocity distribution function (VDF). Variations in the F-region lower boundary or undulations in the electron density profile do not alter this condition.

As discussed in the manuscript, processes such as solar EUV radiation and auroral precipitation generate suprathermal electrons, which lead to observable plasma line enhancements. Therefore, while processes that cause altitude undulations (e.g., gravity waves or ionospheric convection) may affect the local electron density profile, they do not change the fundamental requirement for plasma line enhancement: the presence of suprathermal electrons. The enhancement mechanism itself remains governed by the suprathermal electron VDF.

Reviewer Comment 4: — A note on Fig. 6 is that the date of the production of the figure is not important, and probably should not be included in the plot.

Reply: The production date will be removed from Figure 6 in the revised manuscript.

Reviewer Comment 5: — For Figure 7 it is a good idea to have a better setup of the time labels, having only two of them, at 10:29 and 11:30 does not help in pointing out specific times in the plot.

Reply: In the revised manuscript, we will adjust the time axis of Figure 7 by adding major ticks and labels every 30 minutes and minor ticks every 5 minutes, making it easier to identify specific times in the plot.

Reviewer Comment 6: — The bottom panel indicates the intensity units in eV, is this correct? Figure 4 gives intensity in K/kHz, while there is also an extensive discussion of the phase energy" (eq. 16). In Figure 5 the intensity is in K, and Figures 10 and 11 present $k_B T_p$.

Reply: The units in Figure 7 are correct. Figure 4 shows the plasma line antenna temperature, T_A^p, in units of K/kHz. Integrating this over frequency produces the altitude profiles in units of K shown in Figure 5. These profiles are then converted to plasma line temperature, $k_B T_p$, expressed in eV, which is displayed in Figure 7. We acknowledge that the caption of Figure 7 incorrectly referred to the intensity as A_p. The plotted quantity is actually the plasma line intensity $k_B T_p$, i.e. the plasma line temperature in energy units (eV) derived from A_p expressed in antenna temperature T_A^p and using Eqs. (12)–(13). This will be corrected in the revised manuscript.

$k_B T_p$ is derived from the amplitude of the plasma lines, whereas the phase energy is obtained from the resonance frequency f_r (Figures 4 and 5) using Eqs. (14)–(16). We will harmonise the notation throughout the manuscript to improve consistency.

Reviewer Comment 7: — A minor detail: text predominantly refers to "altitudes", while some of the figures are marked with "height" (while others with "altitude"). This could probably be harmonized.

Reply: We will harmonise the terminology throughout the manuscript and figures, consistently using "altitude" to improve clarity.

Reviewer Comment 8: — The paragraphs in lines 228–236 seem somewhat misplaced. In part they refer to "similar plots" which are not presented, in contrast to the detailed discussion of the even presented.

Reply: The reason for not including plots from all six days in the manuscript was to avoid excessive length, as these additional figures do not provide new information beyond what is already shown. In the dataset and model code, the figures for the other days can already be generated by modifying the argument of the `fitted_params` function in `paper1.m`. We will make these figures available as supplementary material for the reviewer's reference if desired.

Reviewer Comment 9: — They also refer to Figure 10, not to be presented to the reader until later in paper. The consequences of observing a narrower interval of the phase energy range than covered by the system is not very clear at this point. A suggestion would be moving this material to the discussion (line 257 and onwards), rather than having it in Results.

Reply: We will move the lines 233–236 and consolidate them with the discussion of Figure 10, starting from line 279. The intention of mentioning the limited phase energy range in the Results section was to highlight that, even with multiple days of observations, the daytime ionospheric conditions between consecutive days were relatively similar. To explore a wider range of phase energies, it would be necessary to have observations covering a broader range of ionospheric conditions.

Reviewer Comment 10: — I suggest considering renaming the last section to something like "Summary and Discussion". Conclusions would be expected to be a concise summary of the findings, the nature of the presentation here is more of a discussion (among other aspects, four new figures are presented!).

Reply: We agree and will rename the last section to "Summary and Discussion" in the revised manuscript.

Reviewer Comment 11: — The purpose of showing presenting Figures 8 and 9 in the concluding section is not very clear (paragraph in lines 254–256). Probably they would fit better in the analysis section?

Reply: We agree that Figures 8 and 9 would fit better in the Results section. In the revised manuscript, we will move these figures. These figures intend to illustrate the robustness of the methods against some common data analysis challenges encountered in plasma line detection.

Reviewer Comment 12: — Line 262–263 "The absence of upshifted plasma lines means that we cannot use our data to calculate ionospheric currents." – what this ever the intension in this work?

Reply: Initially, the authors intended to calculate ionospheric currents using plasma lines observed at both upshifted and downshifted frequencies. Our methodology is designed to work when plasma lines are detected at either frequency shifts. However, as explained in lines 259-–263, this was not possible due to the absence of upshifted plasma lines in our observations.

Reviewer Comment 13: — Figures 10 and 11 present $k_B T_p$ in eV. These would correspond to temperatures well in excess of those shown in Fig. 5 (left panel). I suspect that the numbers are not directly comparable, but it would be helpful with a clarification in the paper on how they should relate to each other.

Reply: The temperatures shown in Figure 5 correspond to the plasma line antenna temperature T_A^p, whereas Figures 10 and 11 present the plasma line temperature $k_B T_p$. These quantities are related via equations (12) and (13), and Section 3.4 discusses how they are connected. In the revised manuscript, we will clarify this distinction in the figure captions to make it explicit which temperature each figure represents, improving clarity for the reader.

Reviewer Comment 14: — It would be interesting to discuss how the choice of the dataset affects the results. The observations are from several days in a row in January, all during daytime. How would the observations look in a different seasons and/or time of the day?

Reply: In the revised manuscript, we will add this in the "Summary and Discussion" section:

" Plasma line enhancements above the thermal level depend directly on the suprathermal electron flux. During daytime, the prolonged input of solar EUV energy produces suprathermal electron fluxes over an extended period, resulting in more frequent plasma line detections, particularly around the F-layer peak where electron density is highest. At night, suprathermal electron flux is generated through transient auroral activity, resulting in observable plasma line enhancements. For nighttime observations, careful selection of the integration time is necessary, as too long an interval could average out short-lived enhancements and make plasma lines harder to detect.

Regarding seasonal variations, we expect statistical plasma line occurrence to vary in line with the study from Ivchenko et al. 2018 (Figure 2). In particular, May–July will offer the highest number of plasma line observations due to prolonged solar illumination and high suprathermal electron fluxes. Both solar EUV radiation and auroral precipitation can contribute during March–April and August–October, allowing plasma line detection under a wider range of conditions. Therefore, there can be more observations over wider phase energy intervals to build figures similar to Figures 10 and 11 for plasma lines observed due to both solar EUV radiation and auroral precipitation.

The primary objective of the present paper is to develop and demonstrate methodology for plasma line detection and analysis. The methodology presented can be applied in future long-term studies to investigate how plasma line occurrence and phase energy distributions vary with season, time of day, and aspect angle. A proper exploration of the seasonal and diurnal variations would require multiple observations spanning the year under varying conditions, which is beyond the scope of the current work but could be pursued in future studies."