Topside F-Region O+ and H+ Drifts Inferred from Arecibo ISR Long Pulse Echoes

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Introduction

Simultaneous measurements of the fluxes of O+ and H+ ions are essential for detailed studies of the morphology of ionospheric-protonospheric coupling.

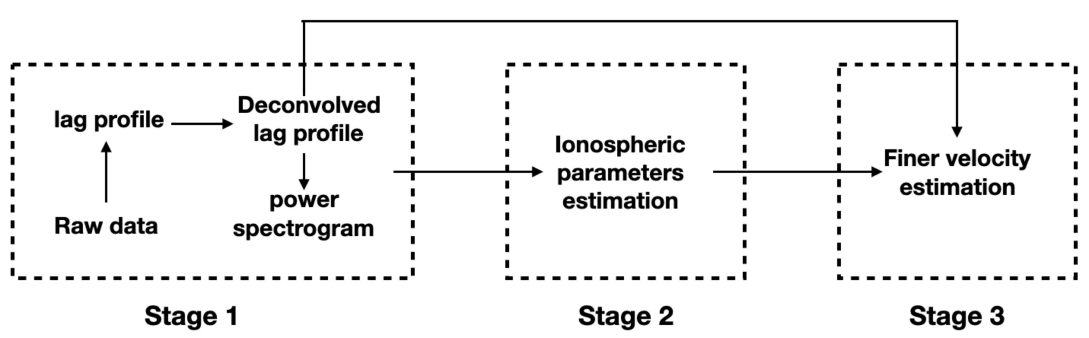

Figure 1: The multi-ion velocity estimation is done using three-stage fitting routine.

We describe a three-stage fitting procedure utilizing spectral and ACF phase model for multi-ion F-region plasmas and its application to Arecibo uncoded long pulse returns to estimate ionospheric composition, temperature, and line-of-sight velocity for all charged species.

Stage 1: Pre-processing

The voltage samples from the receiver are first processed into multiple data products, such as lag profile, power profile and power spectrogram which are used in later stages.

- Consecutive 5000 independent uncoded long pulses (5 minutes equivalent integration time) are integrated to form lag profile to achieve reasonable signal to noise ratio to estimate multi-ion velocities.
- Lag profiles are then either realigned or deconvolved to compensate for height smearing due to the ambiguity from long pulse.

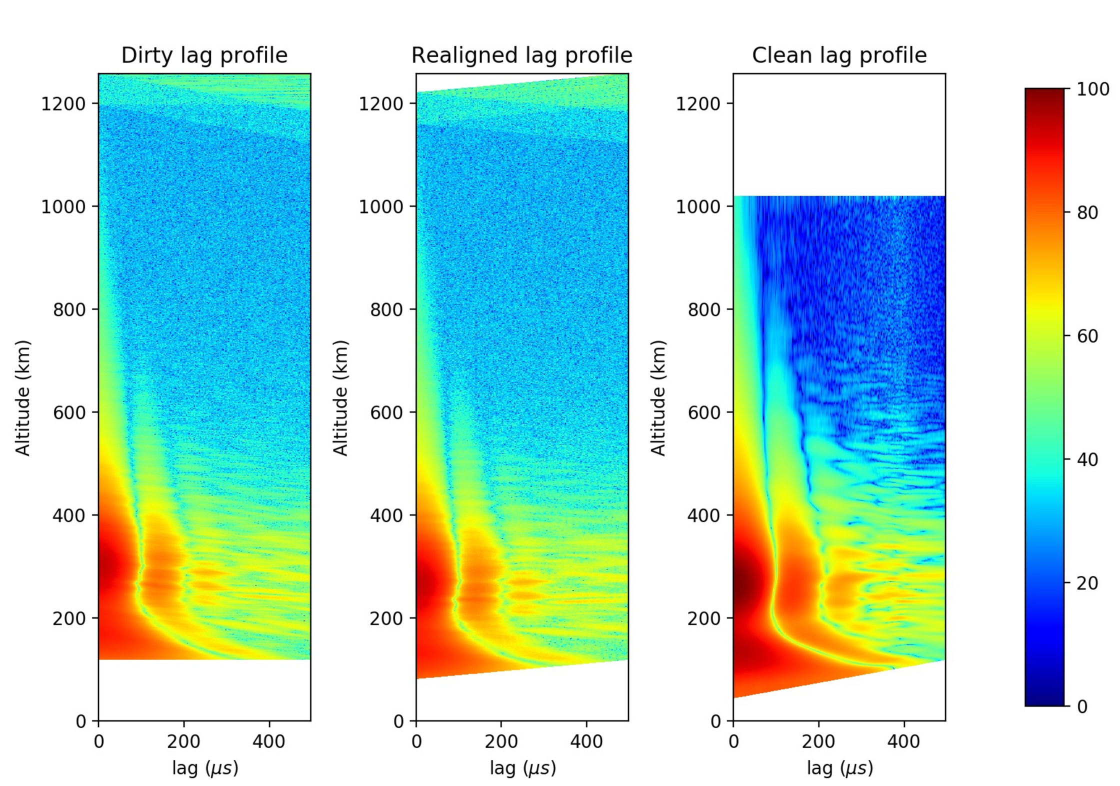

Figure 2: Dirty, realigned and clean lag profiles are compared with magnitude in logarithm with the same color scale. An altitude difference in dirty version is observed due to the poor approximation of height registration while realigned and clean version are consistent in altitude. The pattern in the clean version is more defined, which agrees with the expectation of "sharper" solution before range smeared.

Stage 2: Parameters estimation

Some simplifying assumptions are made in order to reduce the complexity of the fitting.

Electron temperature	T_e	Electrons density	N_e	Electron velocity	V_e
Proton temperature	T_H	Proton density	N_H	Proton velocity	V_H
Oxygen ion temperature	T_O	Oxygen ion density	N_O	Oxygen ion velocity	V_O
Helium ion temperature	T_{He}	Helium ion density	N_{He}	Helium ion velocity	V_{He}

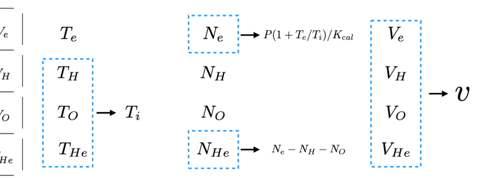

Figure 3: The number of fitting parameters is reduced from 12 to 5 in Stage 2 inversion assuming quasi-neutrality, ions in thermal equilibrium, and a uniform drift velocity for all the charged species.

To fit the spectral model to the measured spectra we minimize the misfit (e.g *Kudeki et al., 1999*)

$$\chi^2 = \sum_m \frac{(\tilde{S}_m - S_m - s_n)^2}{\sigma_m^2}$$

The misfit is minimized using a particle swarm optimization procedure which is gradient free to account for the non-linear dependence of the four parameters.

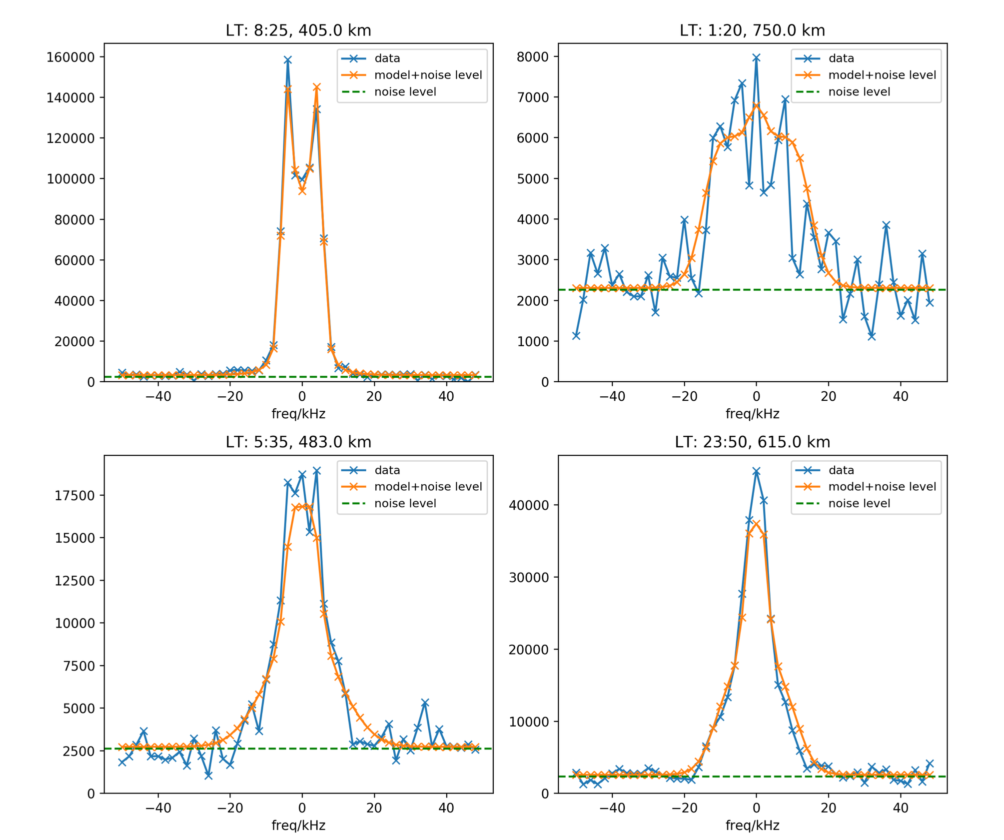

Figure 4: Examples of measured and "best fitted" model ULP power spectra for four different time and heights. The signal part S_m of the model spectrum is normalized by power to match the magnitude of the measured spectrum $\tilde{S}_m$ as well as the noise power level estimate s_n.

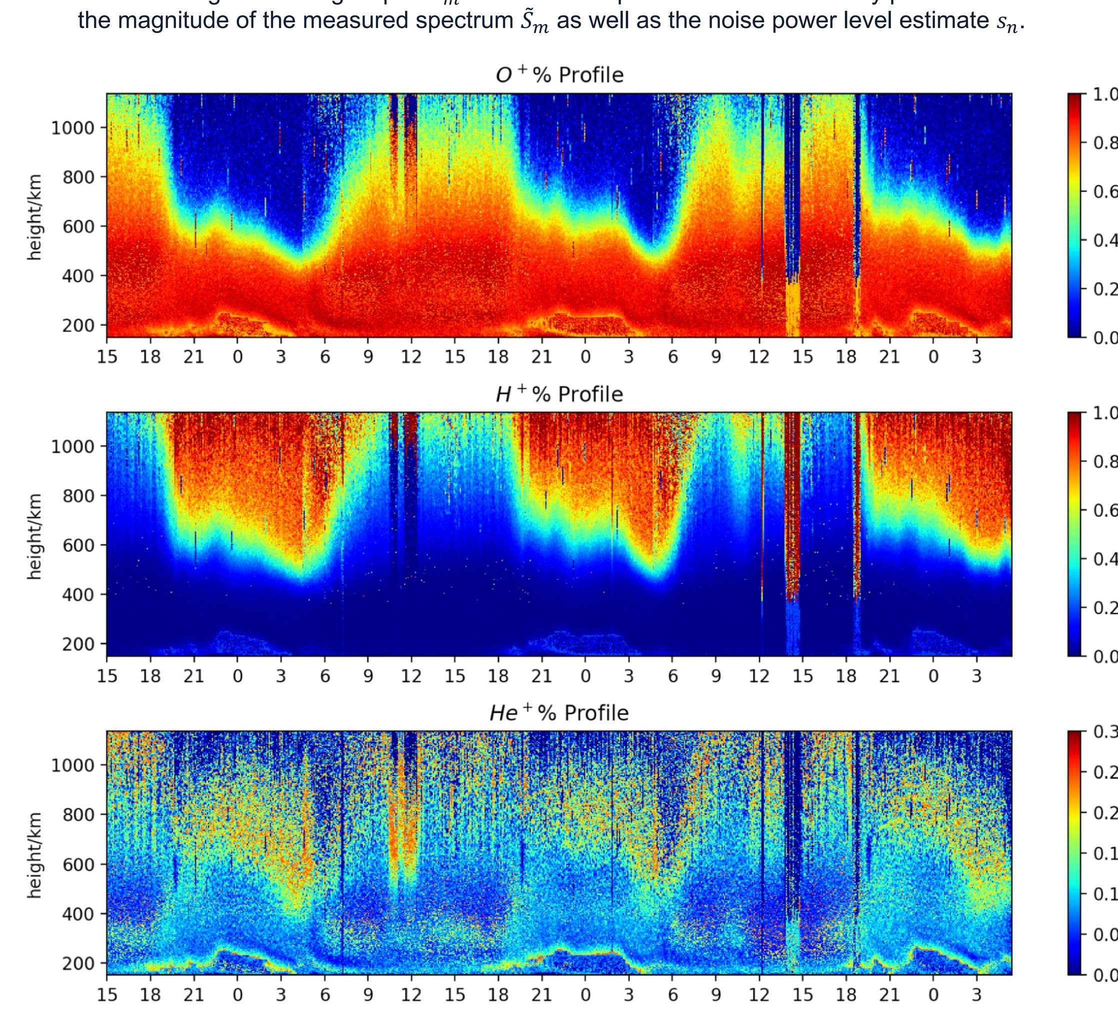

Figure 5: Three maps of composition display a 63 hours observation starting from Sept 23, 2016.

Stage 3: Finer velocity estimation

Ionospheric parameters established in Stage 1,2 are assumed to be valid and are used in a new inversion carried out to identify the possibly differentiated drift velocity V_O and $V_H = V_{He}$ by fitting the phase of the ACF's in each row of the deconvolved lag profile matrix.

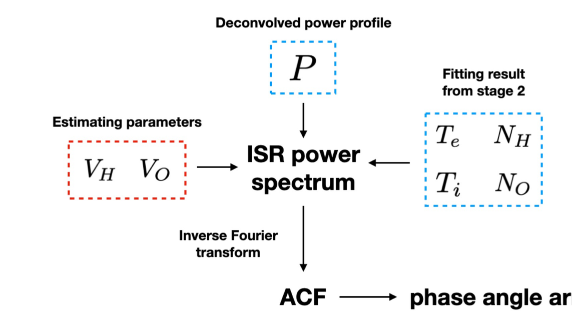

Figure 6: The phase angle is generated via inverse Fourier transform of the ISR power spectrum model whose parameters are partially taken from the fitting results from previous stages.

The cost function is defined as

$$\chi^2 = \sum_m \frac{(\tilde{\phi}_m - \phi_m)^2}{\sigma_m^2}$$

where ϕ_m denotes the measured ACF phase for m-th lag, while

$$\sigma_m^2 \equiv < (\hat{\phi}_m - \phi_m)^2 > = \frac{1}{2K}\left(\frac{1-|\rho_m|^2}{|\rho_m|^2}\right)$$

where ρ_m is the normalized ACF magnitude (coherence)

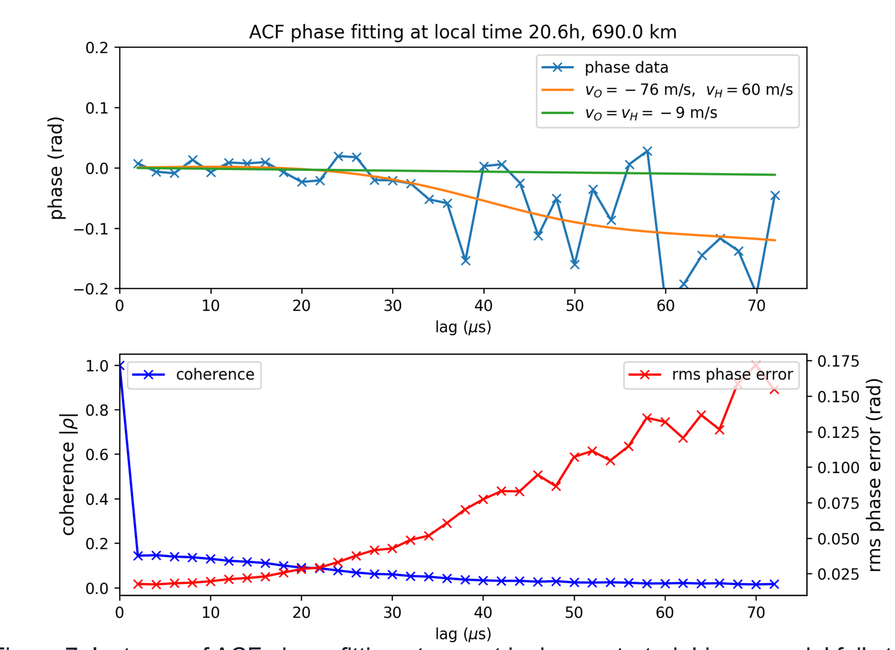

Figure 7: Instance of ACF phase fitting at sunset is demonstrated. Linear model fails to fit the non-linear varying data phase due to the difference velocities of the two types of ions

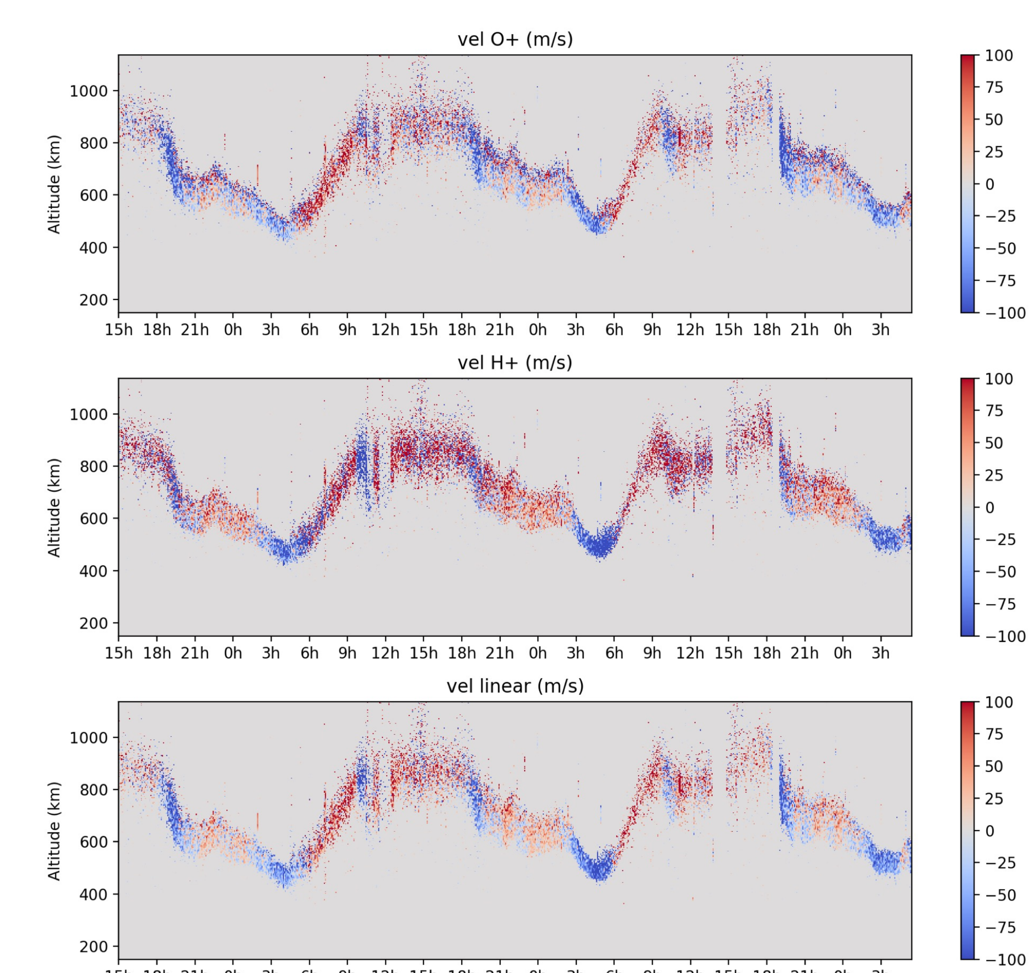

Figure 8: Velocity maps for estimations of linear phase model and two-ion velocity model are displayed for the same 63 hours observation. Only the regions with O+ abundance greater than 30% and less than 70% while the signal level is greater than 0.05 are displayed.

Complementary graphs

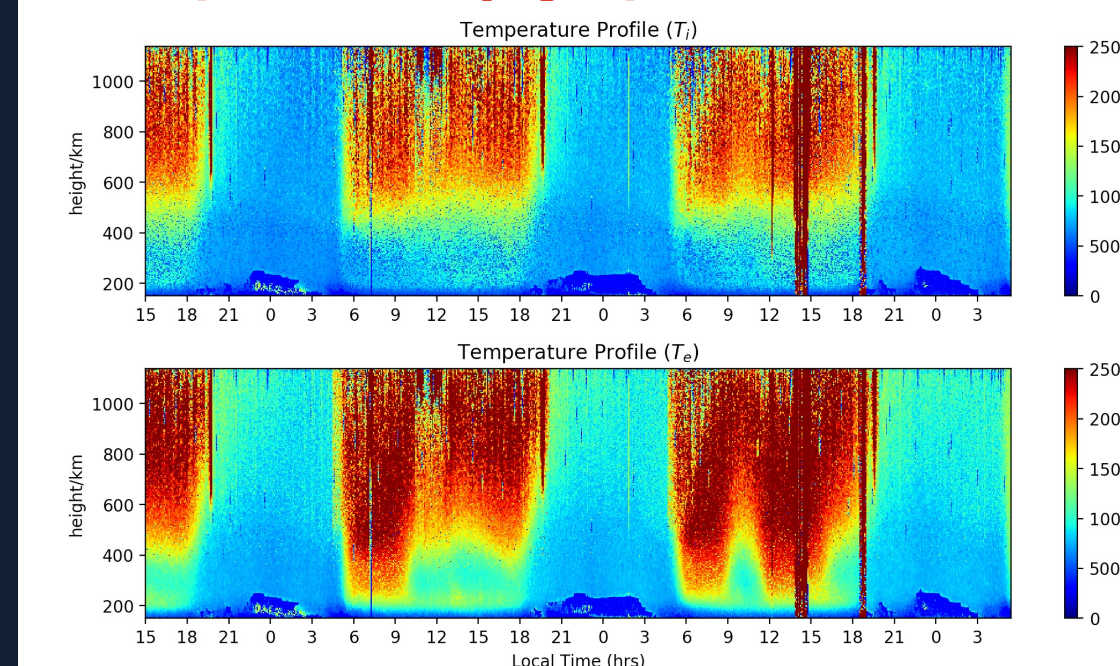

Figure 9: Two maps of ion temperature display a 63 hours observation starting from Sept 23, 2016.

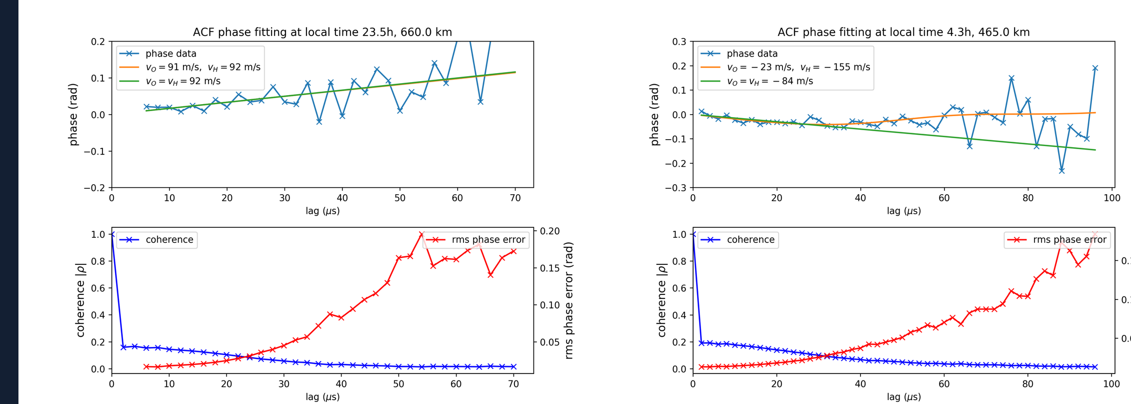

Figure 10: Instances at midnight and sunrise of ACF phase fitting are demonstrated. Linear phase model and two-ion velocity phase model show similar velocity estimation at midnight while the linear phase model fails to fit the non-linear varying data phase at the sunrise.

Conclusion

- A three-stage fitting procedure for Arecibo ISR long pulse spectral data is designed to estimate the draft velocity for H+ and O+ ions
- We presented the result of a 63 hours of observation data in terms of composition, temperature and velocity maps for all charged species.
- Two-ion drift velocities have marginal effect in spectral fitting. There is no benefit to be gained from conducting multiple iterations between Stage 2 and Stage 3

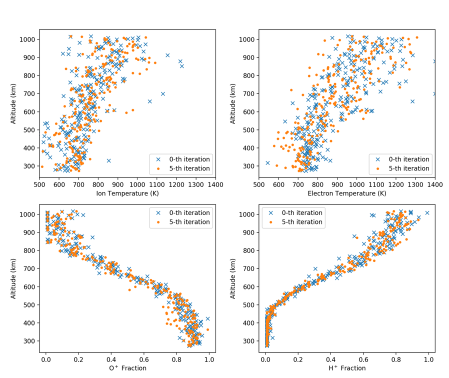

Figure 11: Comparisons are made for temperature and composition profiles for instance at sunset. The routine can be terminated after the first time reaching stage 3

- Counter-streaming of H+ and O+ is spotted in both sunset and sunrise time which has been reported in *Vickrey et al. (1976)*
- In this work, we include He+ in the composition estimation which increases the performance of the fitting and accuracy of estimating the velocity drifts.

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