Validation of Special Sensor Ultraviolet Limb Imager (SSULI) Ionospheric Tomography using ALTAIR Incoherent Scatter Radar Measurements

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Introduction

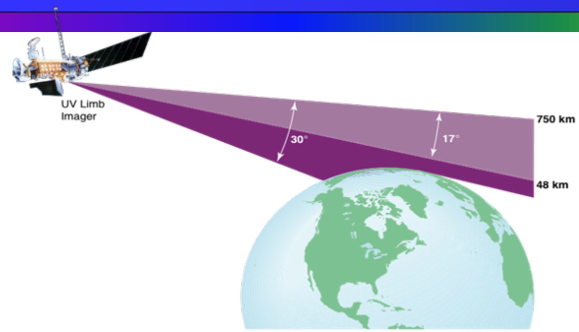
- Data assimilation models are used to specify and forecast ionospheric conditions
  - *These models rely heavily on data accuracy*
  - *Requires validation to ensure consistency between measurement sets*
  - *Requires assessment of measurement strengths and weaknesses*

- UV limb-scanner measurements of emissions that originate in the ionosphere are useful for specifying the latitude-altitude distribution of plasma along the orbit plane
  - *Difficult to validate because measurements for direct comparison do not exist*

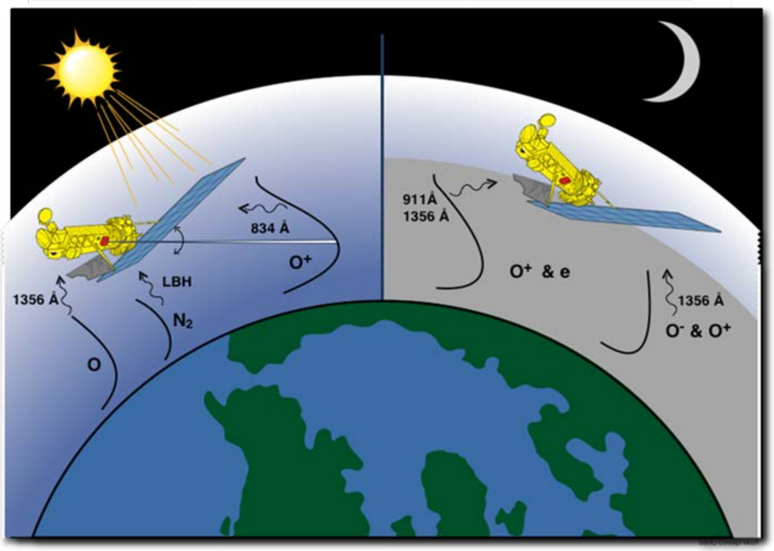
- What are we trying to learn?
  - *How well do the UV measurements capture the underlying distribution of plasma in the ionosphere?*
  - *How are the measurements affected by illumination and ionospheric gradients?*
  - *How well do the UV measurements compare to other measurement techniques?*

- We used coincident measurements of the latitude-altitude distribution of electrons using the incoherent scatter radar at ALTAIR to assess how accurately UV measurements can specify the ionospheric plasma distribution.

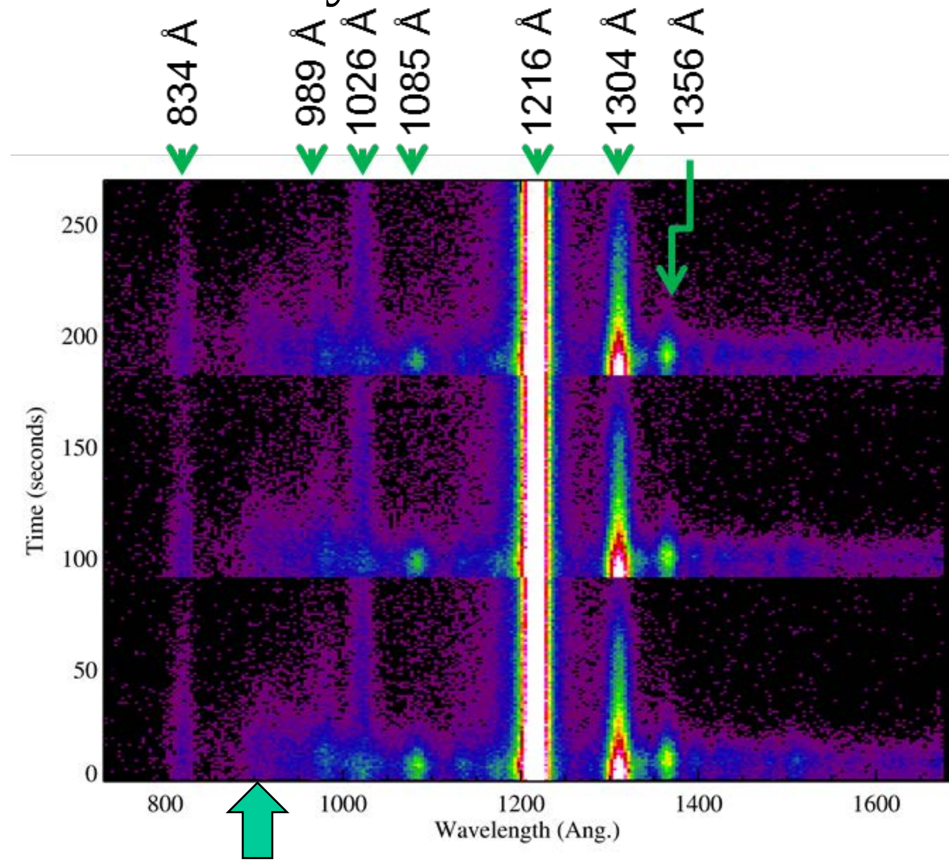
SSULI Measurement Scenario



SSULI Processing Algorithm and Data Products		
Solar Zenith Angle	**Algorithm**	**EDR Data Products**
SZA < 85°	Dayside Ionosphere Algorithm (Requires 834 SDRs)	O+ Density Profile. hmF2, nmF2
SZA >= 108°	Nightside Ionosphere Algorithm (Required 1356 and 911 SDRs)	O+, O Density Profiles, hmF2, nmF2
SZA < 85°	Dayside Neutral Density Algorithm (Requires 1356 and LBH SDRs)	O, N_2, O_2 Density Profiles. Temperature Profile.



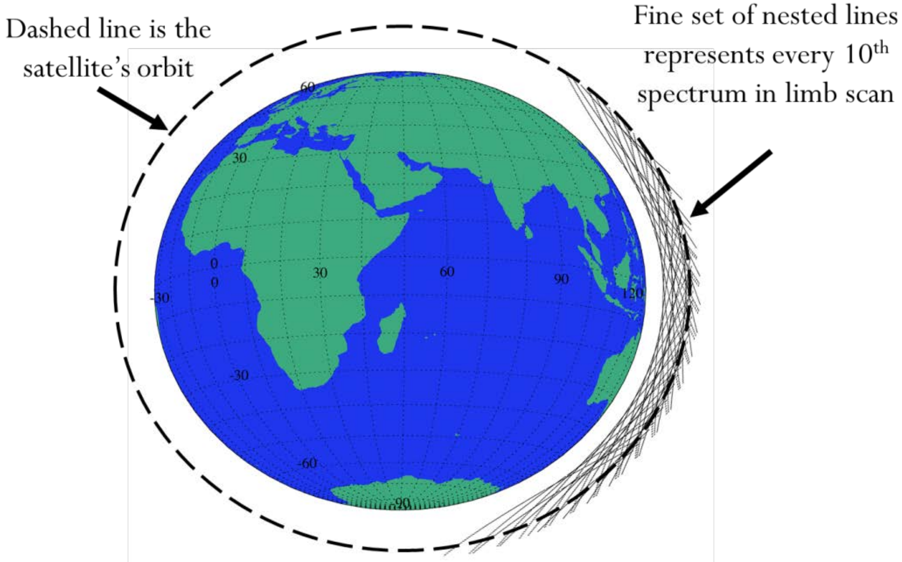
3 Daytime Limb Scans



911 Å, Focus of this talk

Overview

- What are we trying to do?
  - *Specific application: Demonstrate and validate on-orbit specification of the ionosphere*
  - *Approach: Use aggregates of limb scan information to infer the 2-D distribution of O^+ ions in the ionosphere*
- Brightness measurements are linear in the volume emission rate
  - *Analogous to Computerized Ionospheric Tomography → linear in the electron density*
  - *Noise on brightness measurements obeys Poisson statistics – not the Normal Distribution*



Volume emission rate, ε:

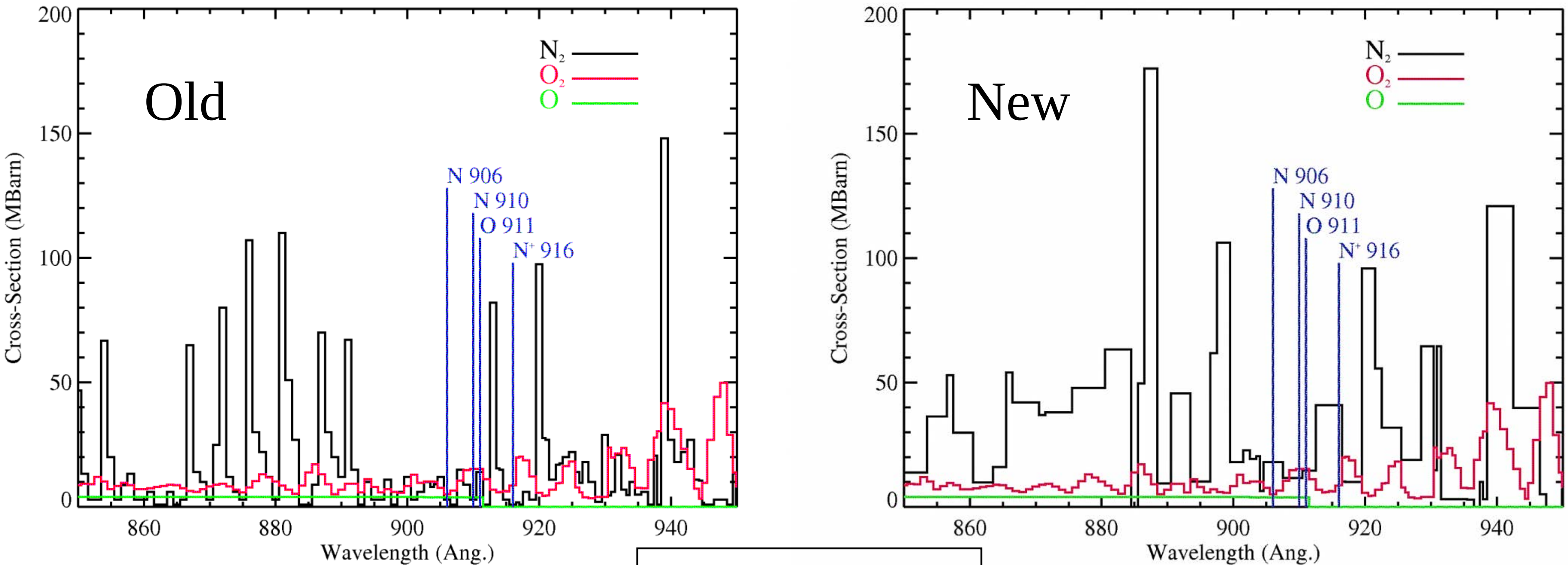
$$\varepsilon(z,\lambda,\phi) = \alpha n_e(z,\lambda,\phi) n_{O^+}(z,\lambda,\phi)$$

$$4\pi I = 10^{-6} \int_0^\infty \varepsilon(s,z,\lambda,\phi)\ \exp(-\tau(s,z,\lambda,\phi))\, ds(z,\lambda,\phi)$$

O I 911 Å Emission & Absorption

- The 911 Å emission is only excited by radiative recombination of F-region O^+ ions and electrons:
  - *$O^+ + e^- \rightarrow O + h\nu$ (911 Å)*
  - *Rate coefficient: $\alpha = 3.5\times10^{-13}$ $(1160./T[K])^{1/2}$ cm^{-3} s^{-1} (Melendez-Alvira et al, 1999)*
- The 911 Å emission is attenuated by atomic oxygen, molecular oxygen, and molecular nitrogen:
  - *O: Photoionization (Conway, 1989, scaled)*
    - $O + h\nu$ (911 Å) $\rightarrow O^+ + e^-$
    - Cross-section: $\sigma = 3.93\times10^{-18}$ cm^2
    - This has not been previously identified as a loss process
  - *O_2: Photoionization & absorption (Conway, 1989)*
    - $O_2 + h\nu$ (~900 Å) $\rightarrow O^+ + O + e^-$
    - $O_2 + h\nu$ (~900 Å) $\rightarrow O_2^*$
    - Cross-section: $\sigma = 15.34\times10^{-18}$ cm^2
  - *N_2: Absorption (Kirby et al., 1979)*
    - $N_2 + h\nu$ (~900 Å) $\rightarrow N_2^*$
    - Cross-section: $\sigma = 14.50\times10^{-18}$ cm^2

Total Cross-sections for O, O_2 & N_2 near 911 Å



1 Barn = 10^{-24} cm^2

For Comparison: Peak of Schumann-Runge O_2 Absorption ~14.8 MBarn

Factors to Consider

- Inversion of 911 Å measurements requires:
  - *Accurate calibration*
  - *Accurate model of the measurements*
    - Line-of-sight integration (quadrature scheme)
    - Accurate physics: absorption, photochemical process
    - Statistical representation of measurement noise

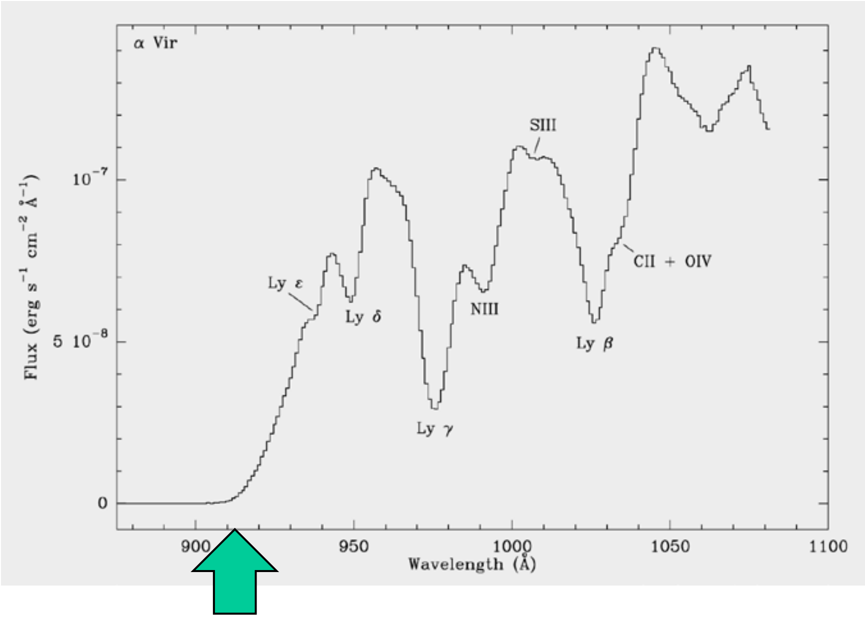
- Calibration
  - *Cannot use stars to calibrate at 911 Å because there are no stellar photons that reach the Earth due to interstellar absorption*
  - *Affects the magnitude of the retrieved density, <u>not the morphology</u>*

- Model of the measurements
  - *Measurement model affects the morphology, <u>not the magnitude</u>*
  - *Quadrature scheme needs to reproduce expected variations*
  - *Measurement statistics guide where the algorithm attributes*
  - *emission*
  - *Absorption determines where the emission can be attributed*
  - *Photochemical process converts the volume emission rate to the product: electron density*

Interstellar Absorption

- ➢ There is essentially zero stellar flux at wavelengths shorter than 912 Å
  - *There is flux at much shorter wavelengths*
  - *Also, dwarf stars in the solar neighborhood can be seen, but their fluxes are low*
- ➢ Figure at left shows a stellar spectrum used to calibrate the SSULI instruments at longer wavelengths
  - *Taken from: Morales et al., "Far-ultraviolet absolute flux of α Virginis", The Astrophysical Journal, 530:403-407, (2000)*
- ➢ How do we calibrate SSULI at 911 Å?
  - *We use ground truth radar measurements.*

EUV Spectrum of Spica (α Viginis)



Interstellar absorption
Cut-off ~920 Å

The Approach

- Because UV measurements for comparison do not exist
  - *Need to validate measurements by deriving a product that can be measured by an alternative means*
  - *This approach provides an end-to-end test from the measurements through the interpretation process*
    - Assessment of calibration
    - Assessment of observation scenario

- ALTAIR Incoherent Scatter Radar
  - *Measures two-dimensional electron density distribution along the orbit plane*
  - *Beneath the Equatorial Ionization Anomaly*
    - High densities
    - Structure and gradients

Ionospheric Tomography Algorithm

$$4\pi I = 10^{-6}\sum_i \varepsilon(z,\lambda,\phi)\left[\exp\left(-\tau(s,z,\lambda,\phi)\right)\Delta s_i(z,\lambda,\phi)\right]$$

- Line-of-sight integrals are replaced by summations assuming constant volume emission rate in a voxel weighted by optical extinction

- The result is a large sparse linear system of equations

$$Ax = b$$

- This system is solved using the iterative Richardson-Lucy algorithm
  - *Non-negative*
  - *Tailored to Poisson random deviates*

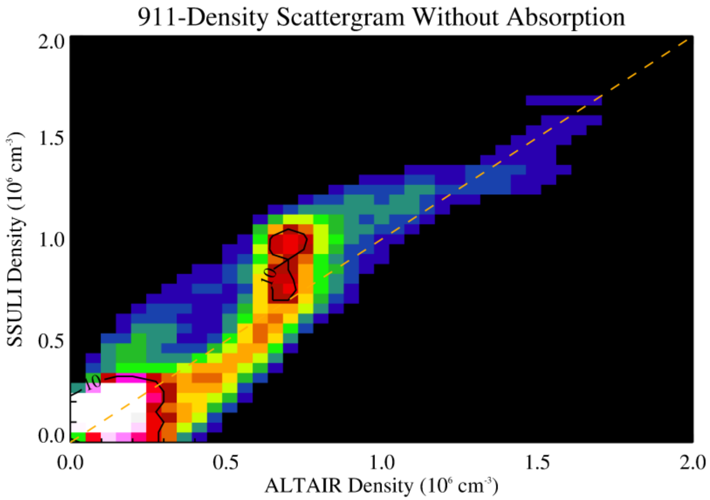
$$x_{j+1} = x_j \otimes \frac{A^T}{A^T\left(\bar{1}\right)}\left(\frac{b}{Ax_j}\right)$$

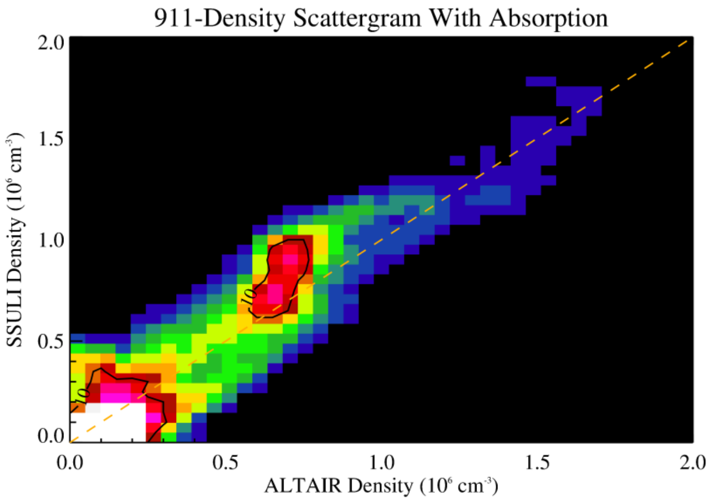
- Solution physicality is ensured by regularizing to a partial differential equation: The diffusion equation

$$\frac{\partial n}{\partial t} = \nabla\cdot\left(\overline{\overline{D}}\nabla n\right) \Rightarrow 0 = \nabla^2 n$$

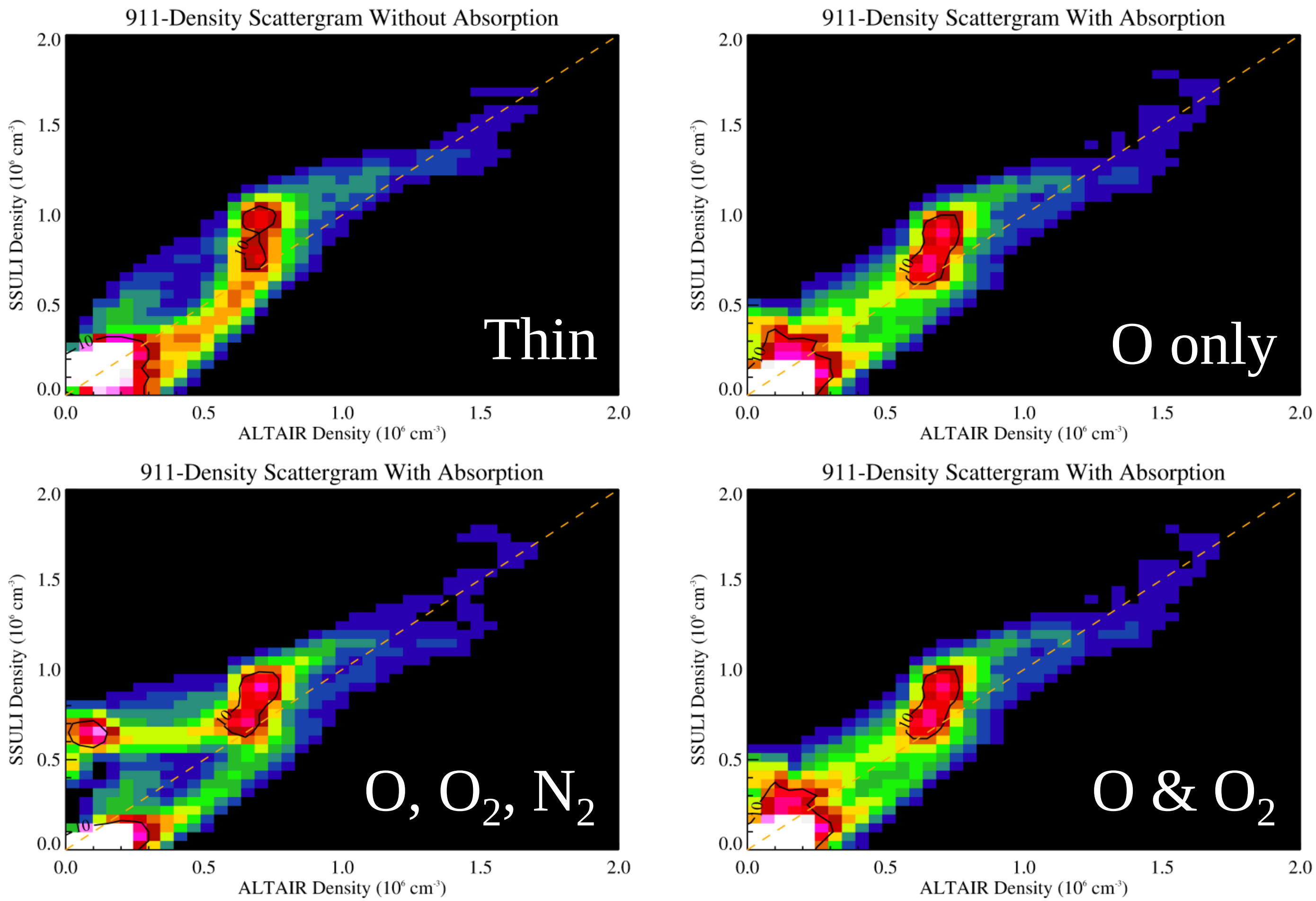
Scatter Plots: Optically Thick and Thin
August 19, 2014

- Plotted scatter plots of corrected SSULI data versus ALTAIR data
  - *Dashed line is the unity slope line indicating perfect agreement*
- Calibration scale factor determined for each inversion
- Top: scatter plot without absorption
  - *SSULI overestimating highest densities by ~50% when density is near 7×10^5 cm^{-3}*
- Bottom: scatter plot with re-ionization of O
  - *Better agreement at all densities*
  - *SSULI overestimating highest densities by ~30% when density is near 7×10^5 cm^{-3}*
  - *Scatter of distribution is tighter than it is without the re-ionization*





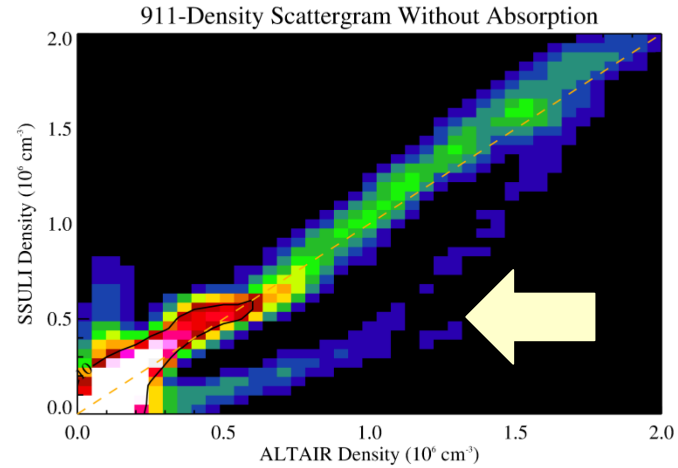
Scatter Plots: Pure Absorption
August 19, 2014

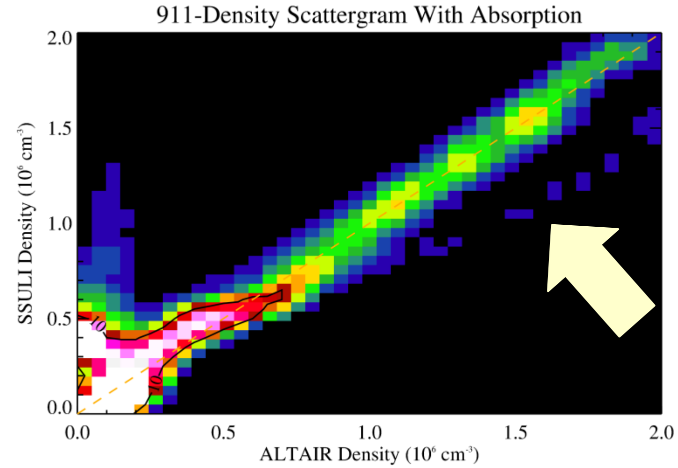


Model with absorption by O & O_2 has lowest scatter

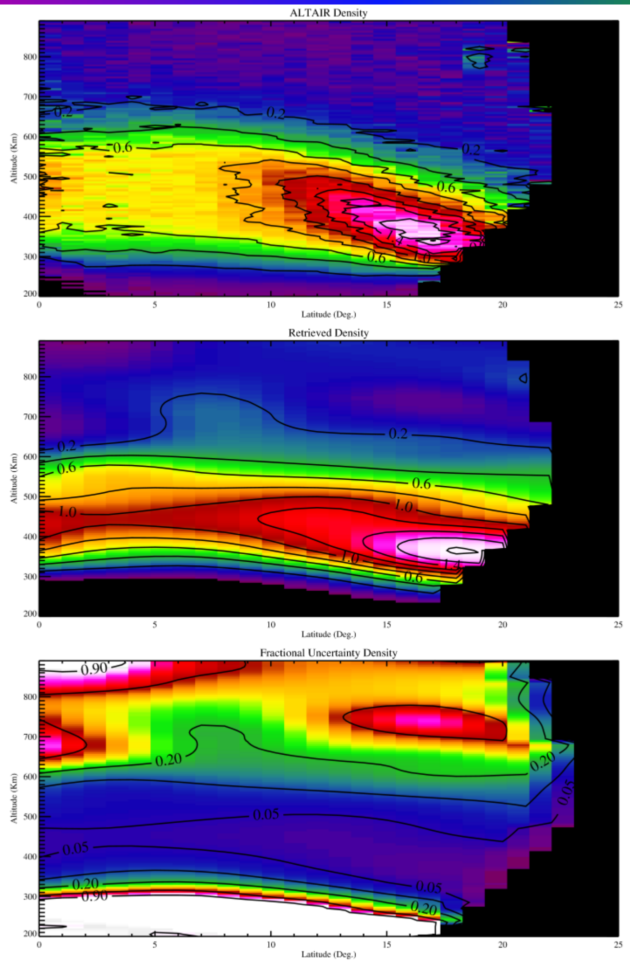
Scatter Plots: Optically Thick and Thin October 12, 2014

- Plotted scatter plots of corrected SSULI data versus ALTAIR data
  - *Dashed line is the unity slope line indicating perfect agreement*
- Calibration scale factor determined for each inversion
- Top: scatter plot without absorption
  - *Correlation is good, but there is an outlier population*
- Bottom: scatter plot with re-ionization of O & O_2 absorption
  - *Better agreement at all densities*
  - *Scatter of distribution is tighter than it is without the re-ionization*
  - *Outlier population is significantly reduced*

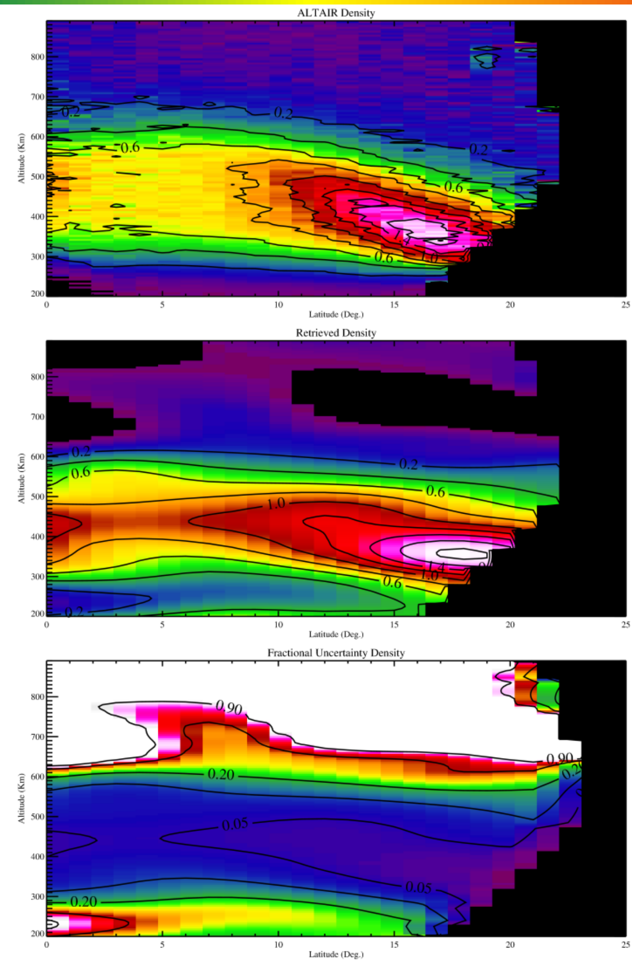




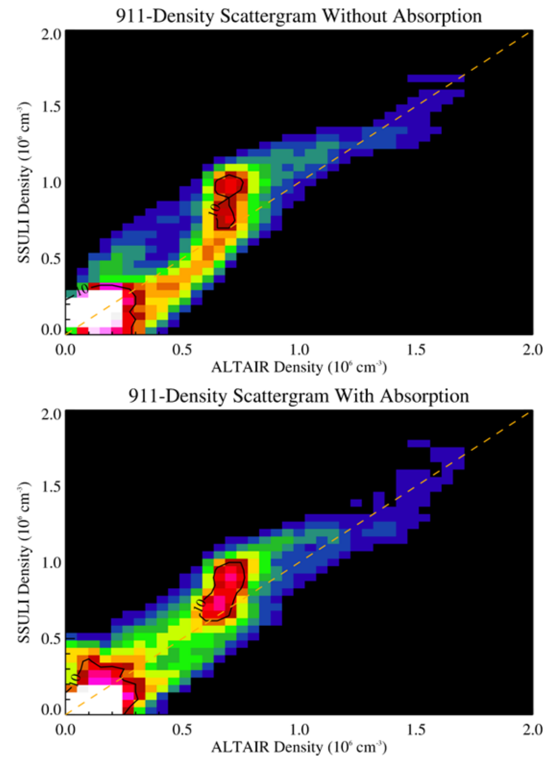
SSULI/ALTAIR: August 19, 2014
-Dusk Pass-



No absorption

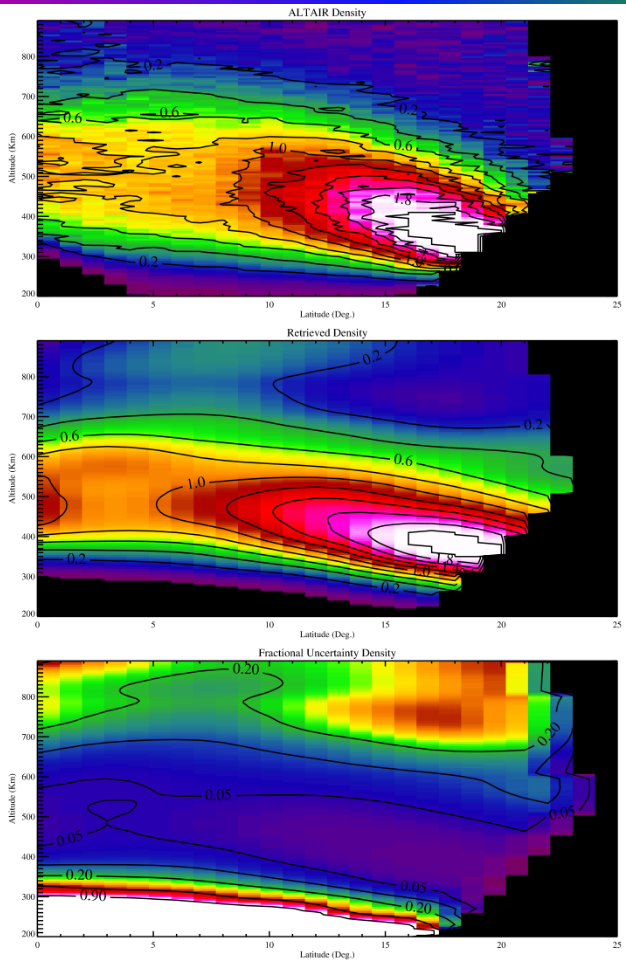


With absorption

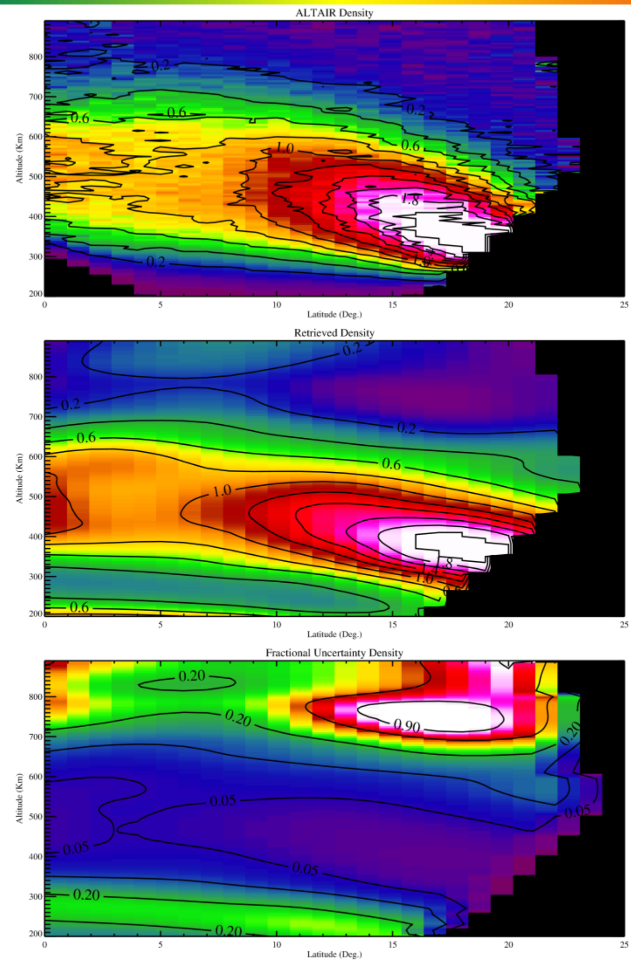


Very good agreement at all densities

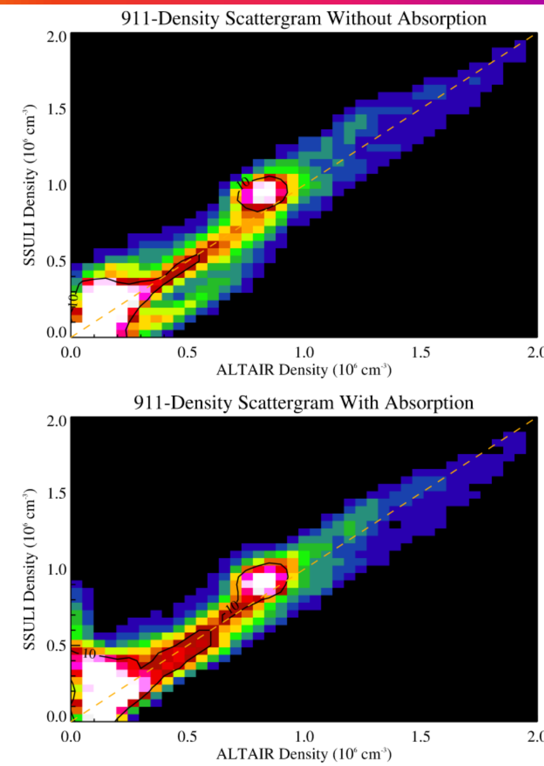
SSULI/ALTAIR: September 4, 2014
-Dusk Pass-



No absorption

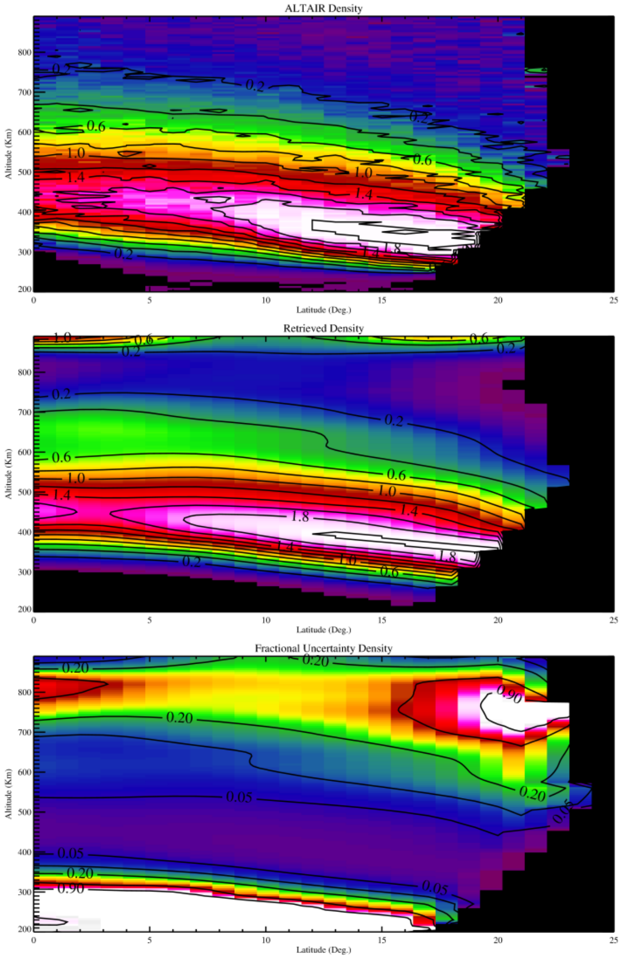


With absorption

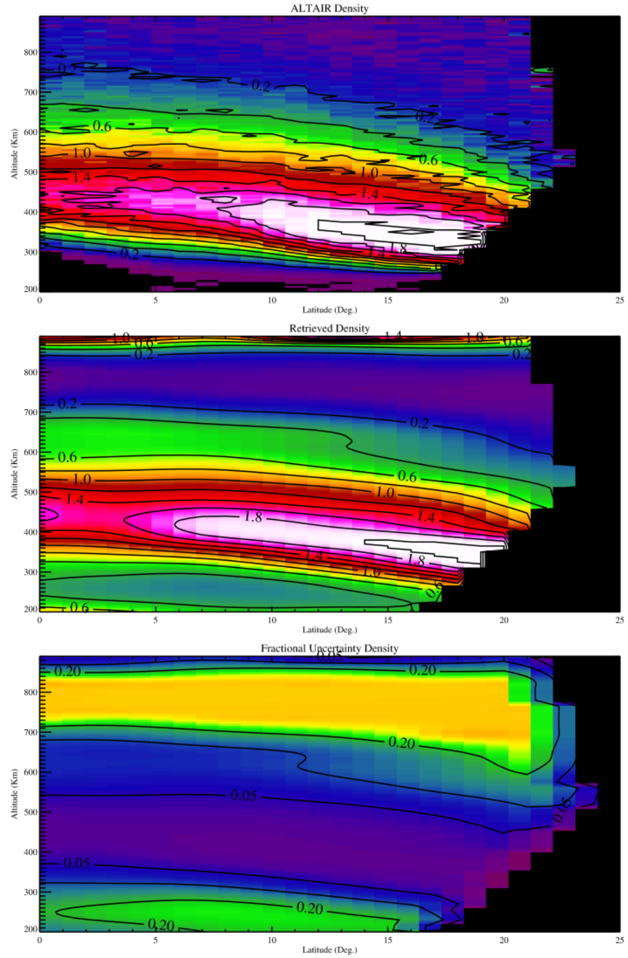


Very good agreement at all densities

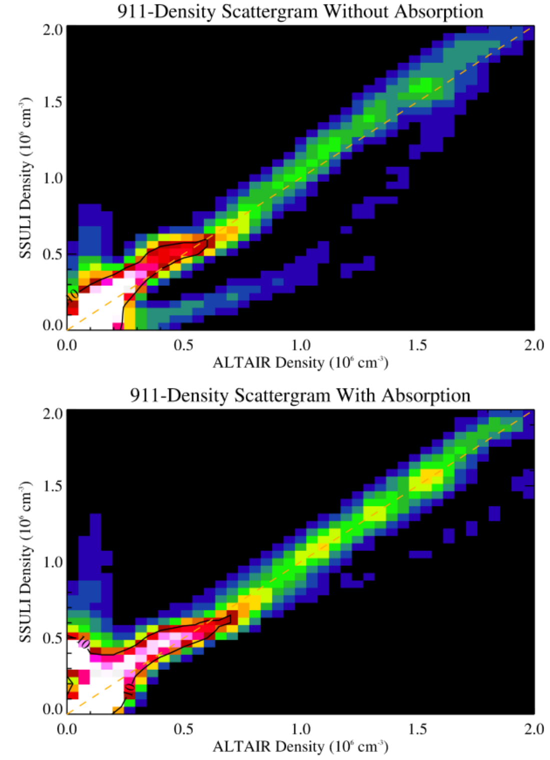
SSULI/ALTAIR: October 12, 2014
-Dusk Pass-



No absorption

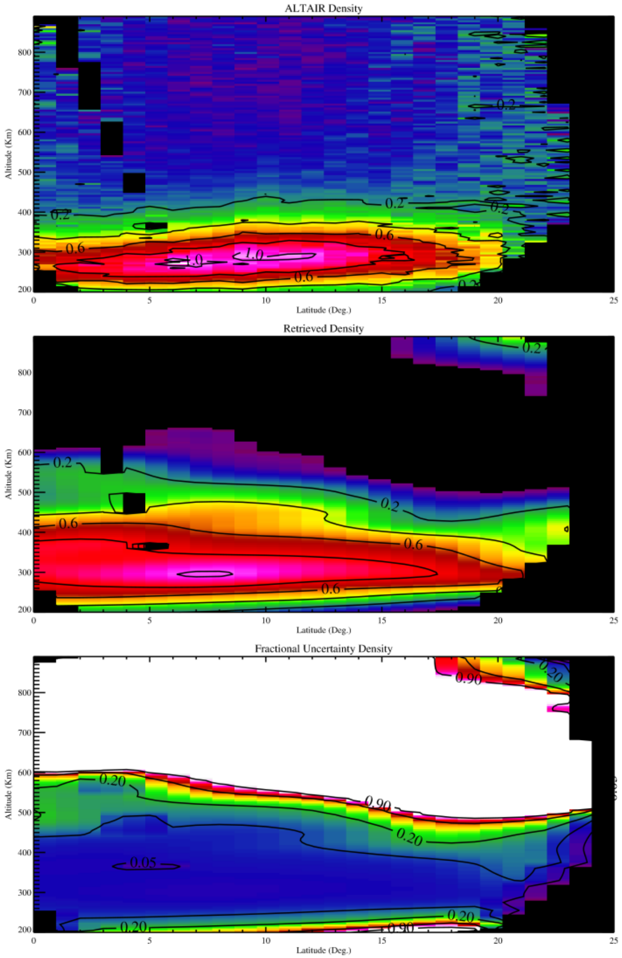


With absorption

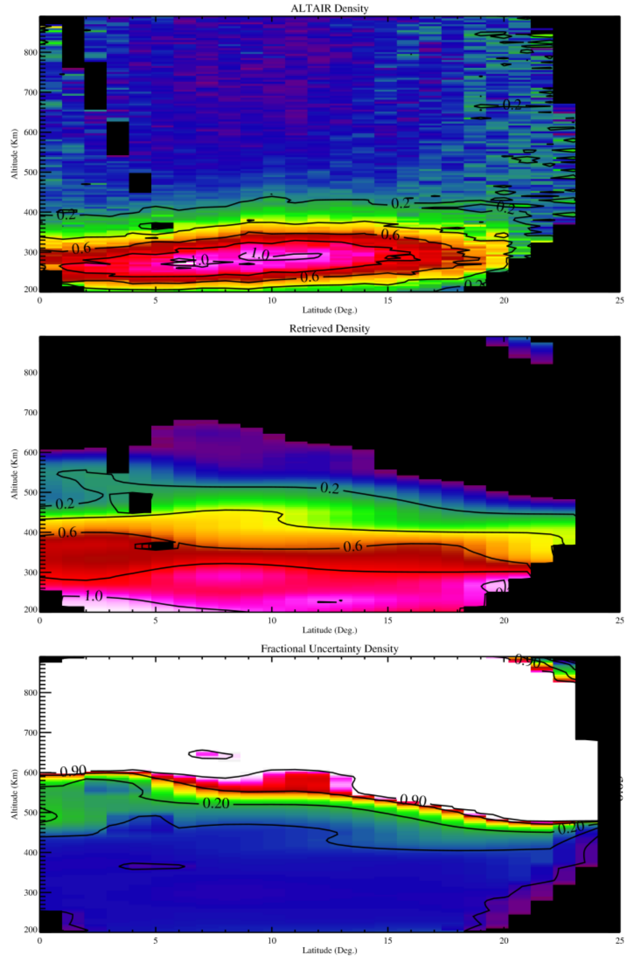


Very good agreement at all densities

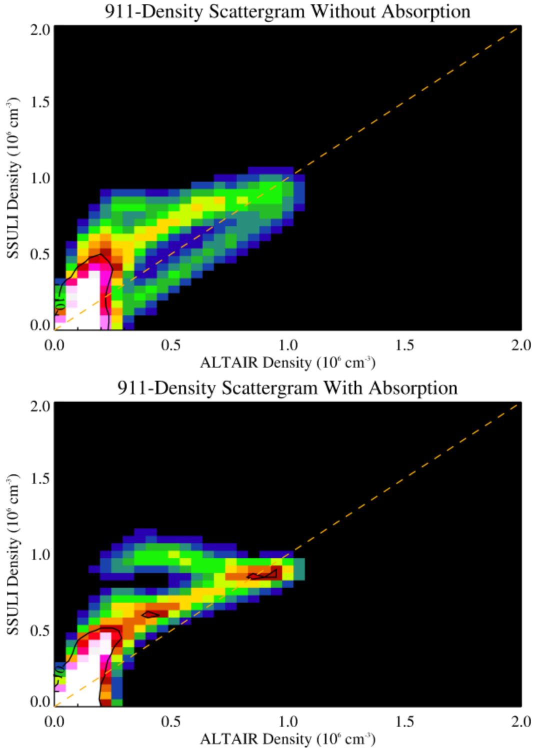
SSULI/ALTAIR: September 29, 2014
-Dawn Pass-



No absorption



With absorption



Poor agreement at all densities: SSULI/algorithm putting ionosphere at higher altitudes

Summary

- We compared the results of UV tomography using UV measurements made by the SSULI sensor to ALTAIR
  - *Excellent agreement with the altitude/latitude distributions from the two measurements for the dusk passes*
    - Dawn passes are still under investigation
  - *The measurements were made in the terminator region, which are typically not used because they are difficult to interpret*

- Our analysis approach entailed
  - *New iterative Image Space Reconstruction Algorithm -- Richardson-Lucy technique -- handles Poisson noise explicitly and is non-negative*
    - Can work on data with very low signal-to-noise ratio
  - *Physicality constraint using regularization to the isotropic diffusion equation*
  - *Inclusion of re-ionization of O & absorption by O_2 by the 911 Å emission – found to be important by this analysis*

Conclusions

- Tomography approach produces accurate electron density distribution
  - *Calibration of the UV data determined during the process*
  - *Good agreement between tomography products and ALTAIR measurements validates the measurements ➔ good for use by GAIM model*

- Neutral absorption is an important consideration for interpretation of the UV measurements
  - *Results are improved when absorption by O and O_2 are included*
  - *When absorption by N_2 is included in the model, the agreement with ALTAIR is degraded*
    - Suggests that N_2 cross-sections near 900 Å need further investigation

Acknowledgements

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Physicality Constraint

- Regularization to a differential equation is an approach used in the computer graphics modeling community
  - *Improves computer rendering by generating a smooth surface from facet information*
- We use the time independent diffusion equation

$$\frac{\partial n}{\partial t} = \nabla \cdot \left(\overline{\overline{D}} \nabla n \right) \Rightarrow 0 = \nabla^2 n \quad (time \;\; independent)$$

- Currently, we assume uniform, isotropic transport
  - *Permits the algorithms to produce reasonable results during daytime and at night*
    - Will work for either ionospheric emissions (nighttime ionosphere) or for emission generated by neutral species (O and N_2 in the dayglow)
  - *However, some emissions, for example O I 1356 Å, have both ionospheric and thermospheric components during the daytime*
    - Drives eventual need for non-isotropic, non-uniform diffusion approximation
- Implemented using the Successive Over-Relaxation approximation
  - *Makes small steps to "relax" solution to the diffusion approximation*

Successive Over-Relaxation (SOR)

- We chose this iterative approach to solve the diffusion equation
  - *Desired a method with low computational overhead*
  - *Wanted a means to guide the algorithms to a physically meaningful solution*
- Approximating the diffusion equation at time step k+1 by finite difference equations (assuming $\Delta x = \Delta y$, i & j are cell indices):

$$n_{i,j}^{k+1} = n_{i,j}^{k} - \frac{D\Delta t}{(\Delta x)^2}\left(n_{i-1,j}^{k} + n_{i+1,j}^{k} + n_{i,j-1}^{k} + n_{i,j+1}^{k} - 4n_{i,j}^{k}\right)$$

- To ensure a stable solution, the maximum time step size allowed is limited by the diffusion time across the cell:

$$W \equiv \frac{D\Delta t}{(\Delta x)^2} \leq \frac{1}{4}$$

  - *We refer to W as the diffusion weight and use it to tune the weighting of the physicality constraint*