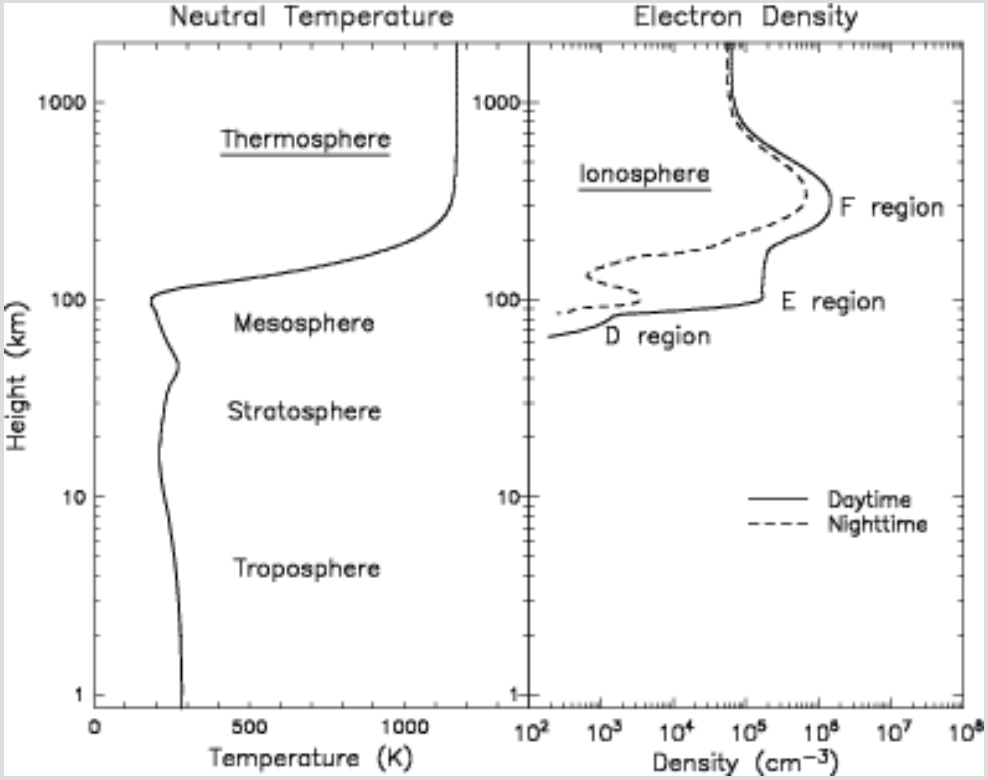
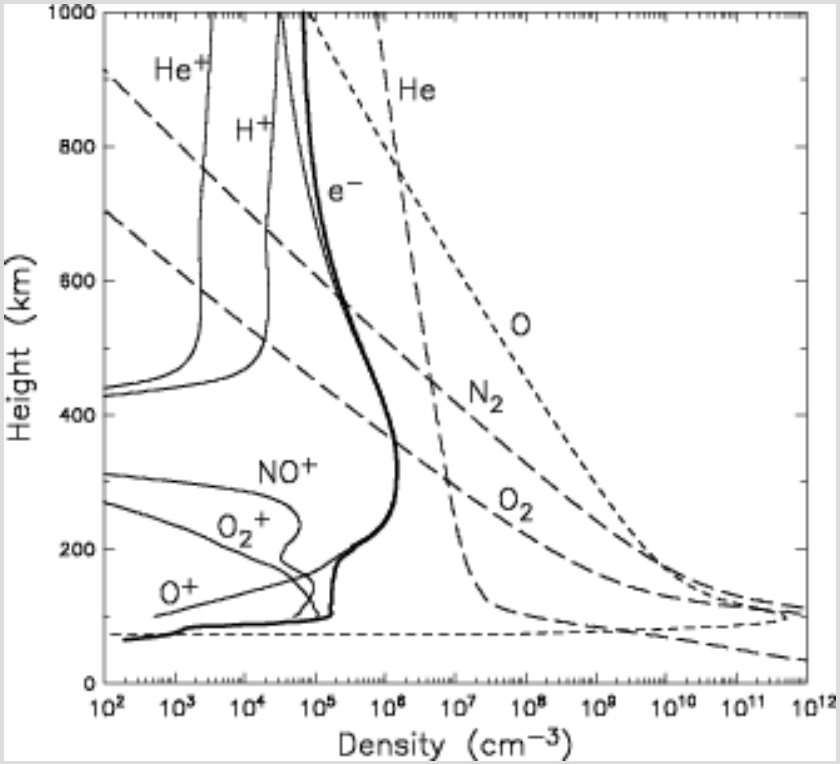
プラズマバブルシミュレーションの高解像度化

横山 竜宏

情報通信研究機構

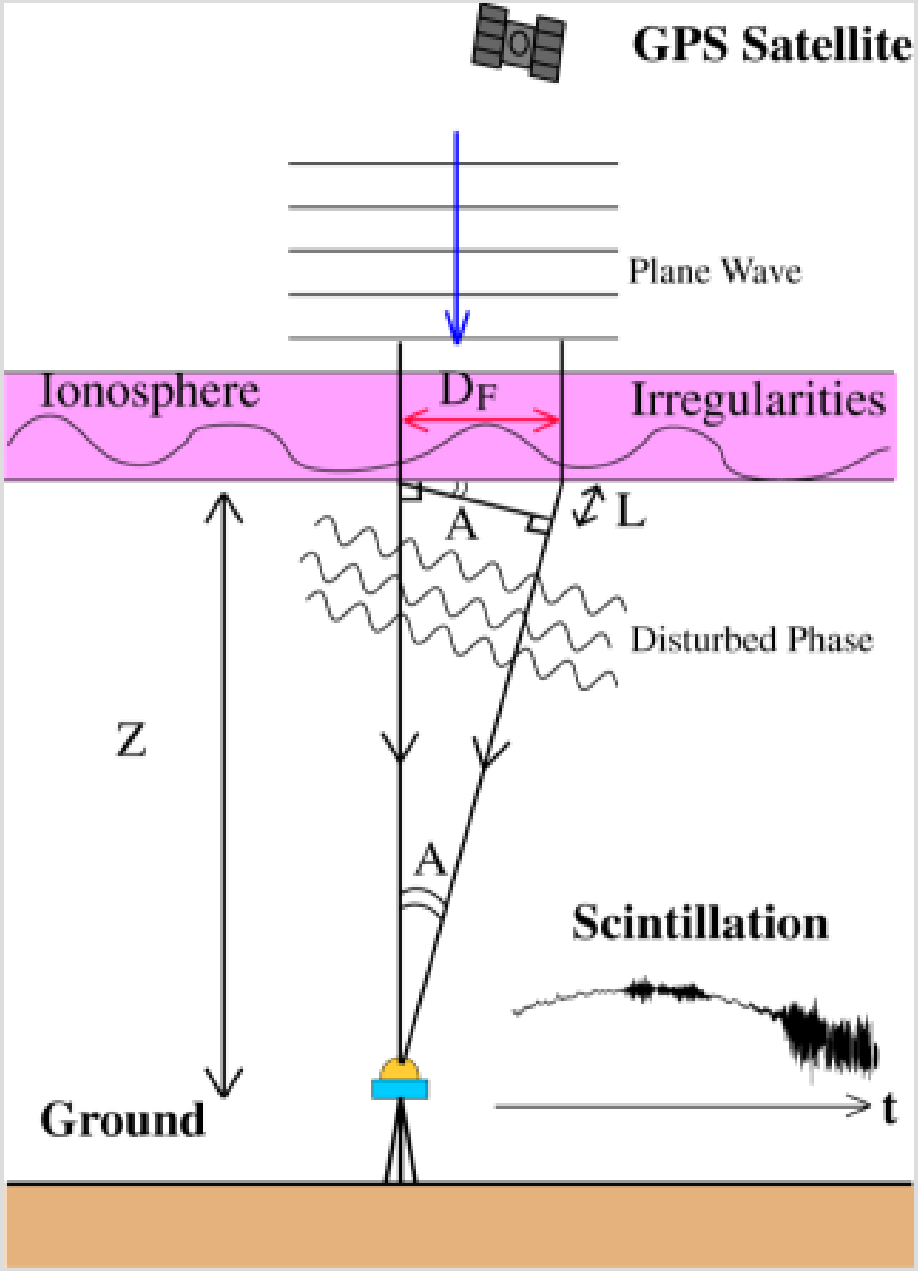
Ionosphere

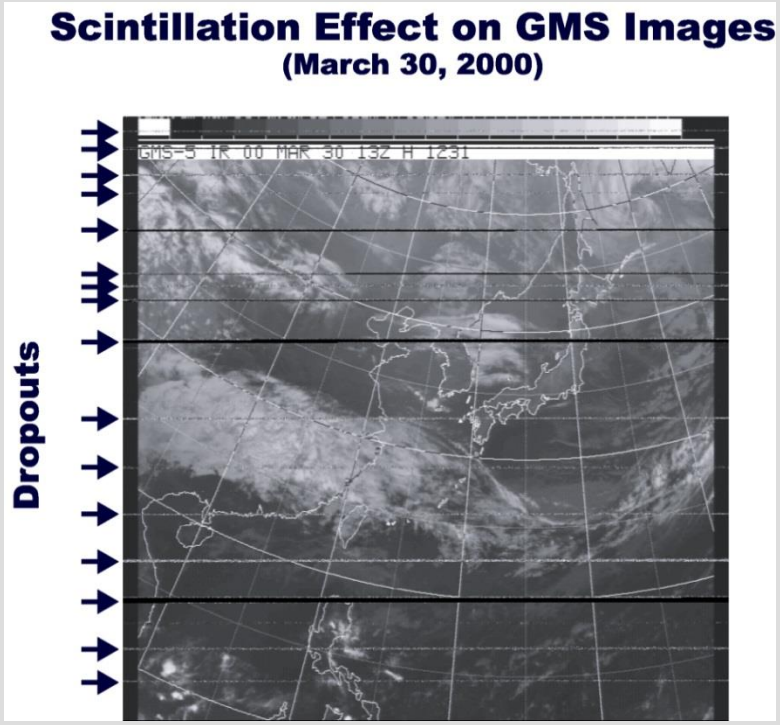




- Plasma density is several orders lower than neutrals.
- Atmosphere-Ionosphere coupling is very important.
- 80-300km: too high for balloon, too low for satellite.

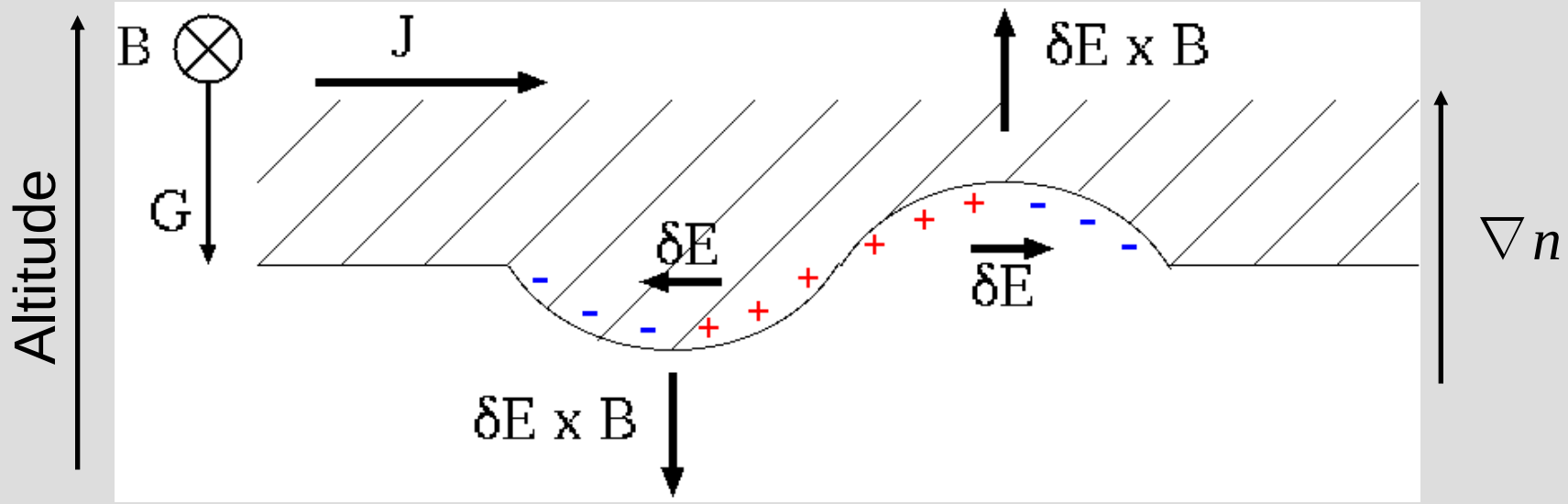
Scintillation





- Fresnel diffraction
  $\sqrt{2}D_F = \sqrt{2\lambda z} \approx 400\text{m}$
- Serious problem for communication and navigation.

Linear Growth Rate of Rayleigh-Taylor Instability



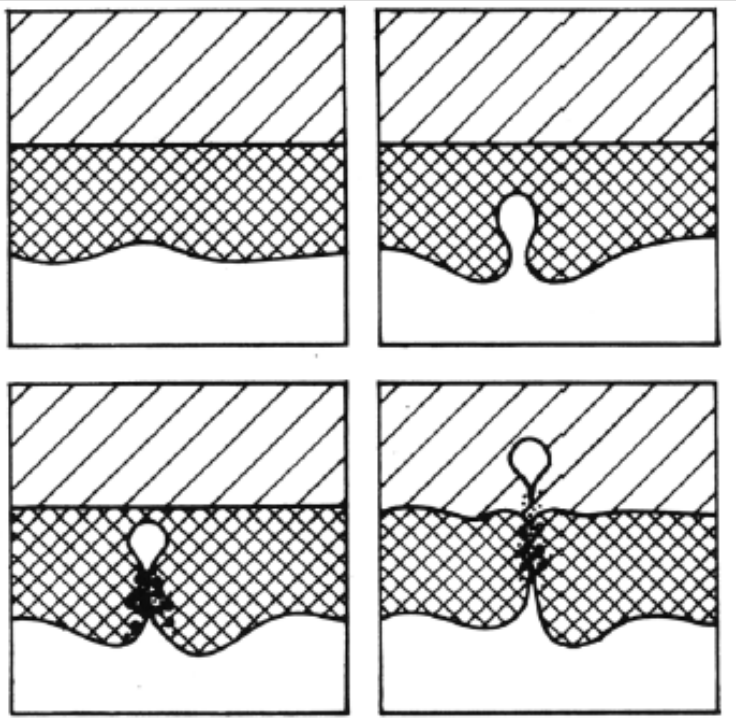
$$\gamma_L = \frac{1}{n_0}\frac{\partial n_0}{\partial z}\left(\frac{E}{B} - \frac{g}{\nu_{\text{in}}}\right) - \beta_L$$

Local

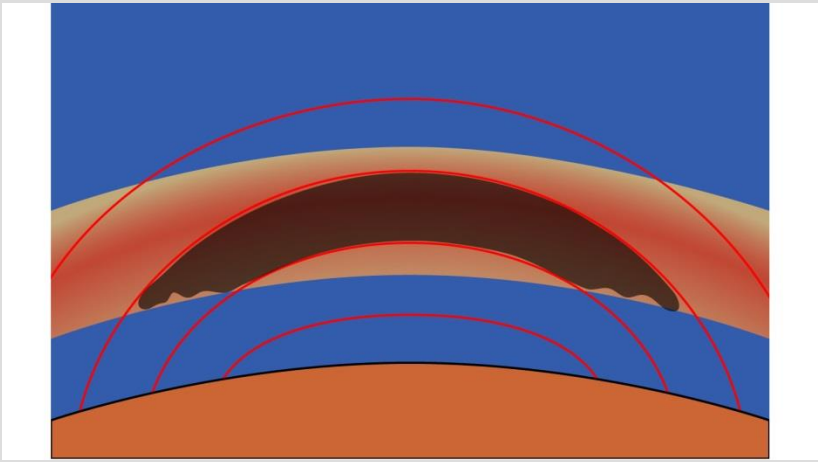
$$\gamma_{FT} = \frac{\Sigma_P^F}{\Sigma_P^E + \Sigma_P^F}\left(\frac{E}{B} - \frac{g_e}{\nu_{\text{eff}}} \cdots\right.$$

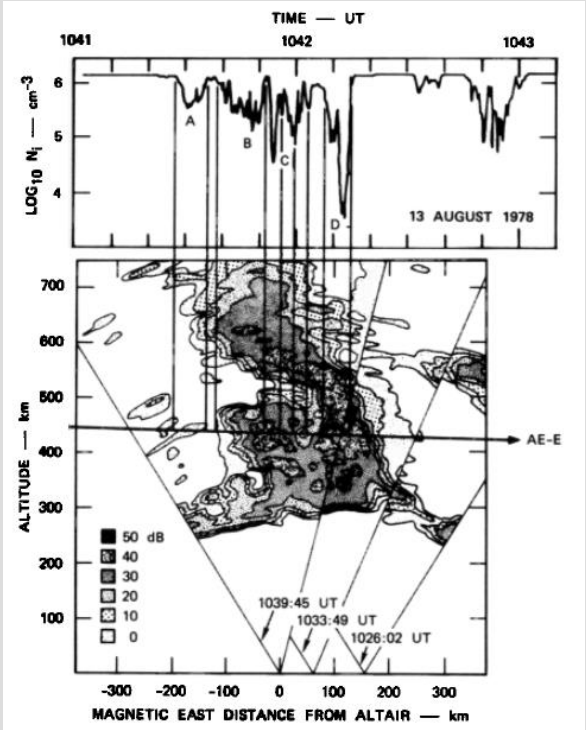
Flux-tube integrated

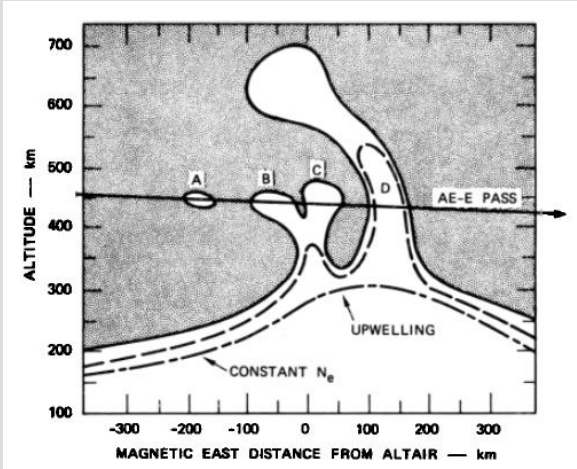
Plasma Bubble



Woodman and LaHoz (1976)

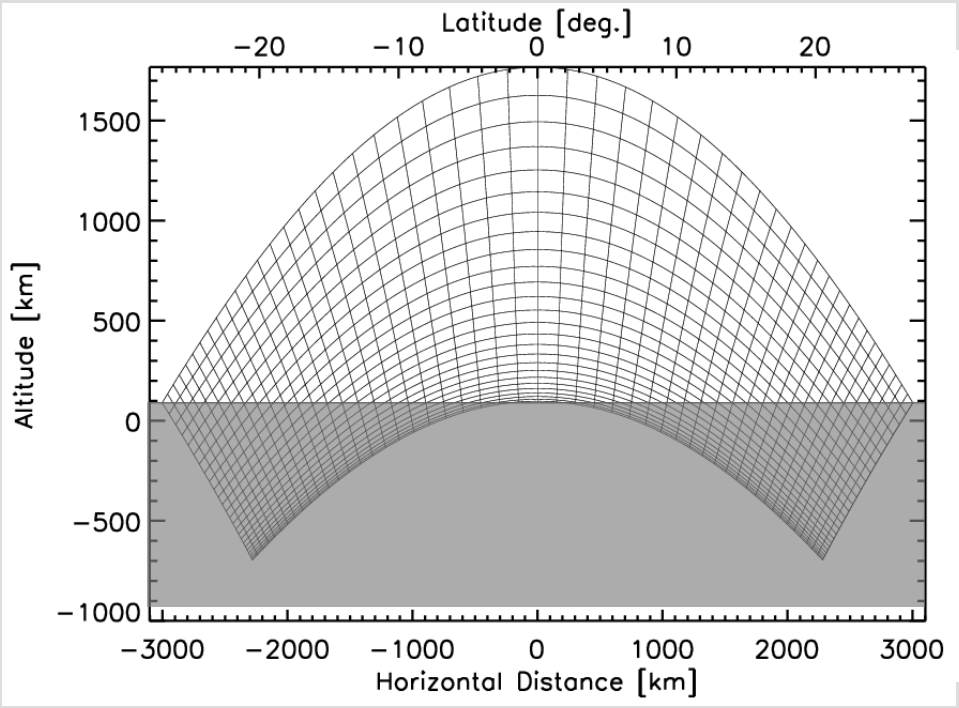


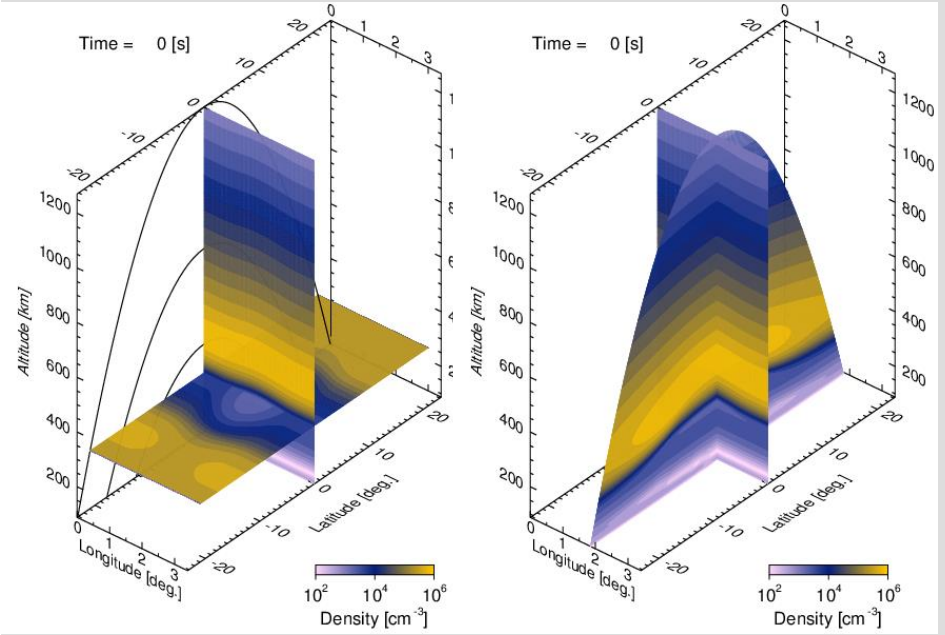




Tsunoda et al. (1982)

High-Resolution Bubble (HIRB) Model





- Dipole orthogonal coordinate
- Grid size is 300 m in zonal, 700m in vertical around F peak.
- $(NX(B_{||}), NY(B_L), NZ(B_\phi)) = (501, 1821, 1120)$
- O^+ (F region), NO^+ (E region)

Equations

$$\frac{\partial N_i}{\partial t} + \nabla \cdot (N_i \mathbf{V}_i) = S_i \tag{1}$$

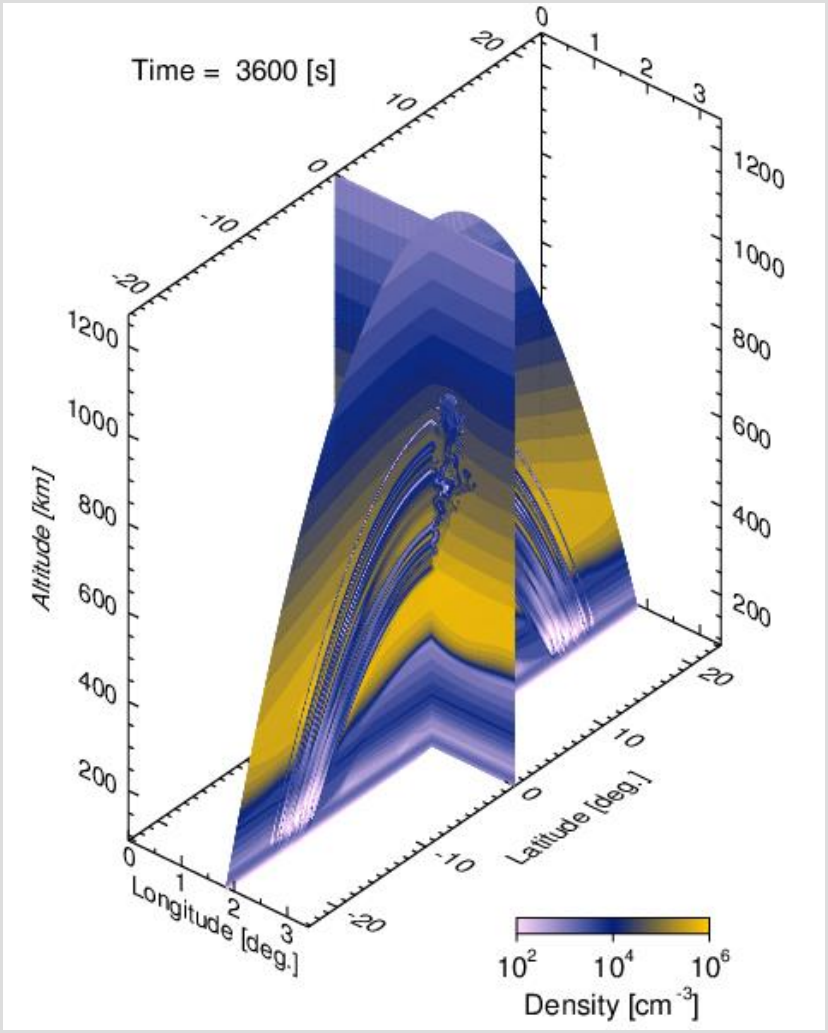
$$e(\mathbf{E} + \mathbf{V}_i \times \mathbf{B}) + M_i \boldsymbol{g} - \frac{\nabla(N_i k_B T)}{N_i} + M_i \nu_{in}(\mathbf{U} - \mathbf{V}_i) = 0 \tag{2}$$

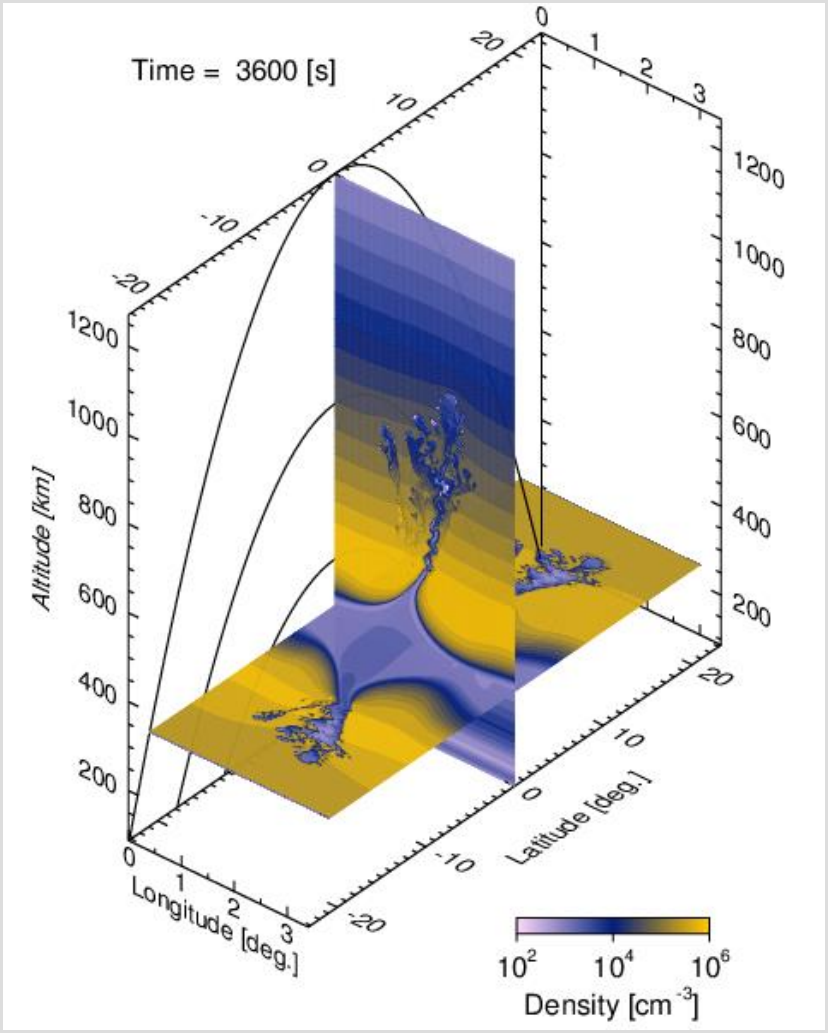
$$-e(\mathbf{E} + \mathbf{V}_e \times \mathbf{B}) + M_e \boldsymbol{g} - \frac{\nabla(N_e k_B T)}{N_e} + M_e \nu_{en}(\mathbf{U} - \mathbf{V}_e) = 0 \tag{3}$$

$$\nabla \cdot \mathbf{J} = \nabla \cdot \left[e \left(\sum_i N_i \mathbf{V}_i - N_e \mathbf{V}_e \right) \right] = 0 \tag{4}$$

- Plasma density is updated by CIP method from Eq. (1)
- Polarization electrostatic potential is solved from (2)-(4).

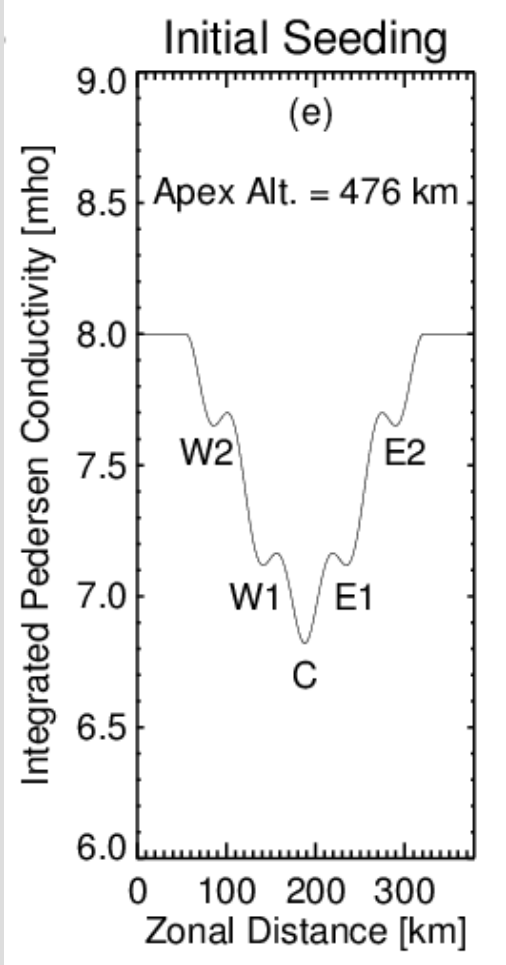
Vertical/Horizontal Density Distribution

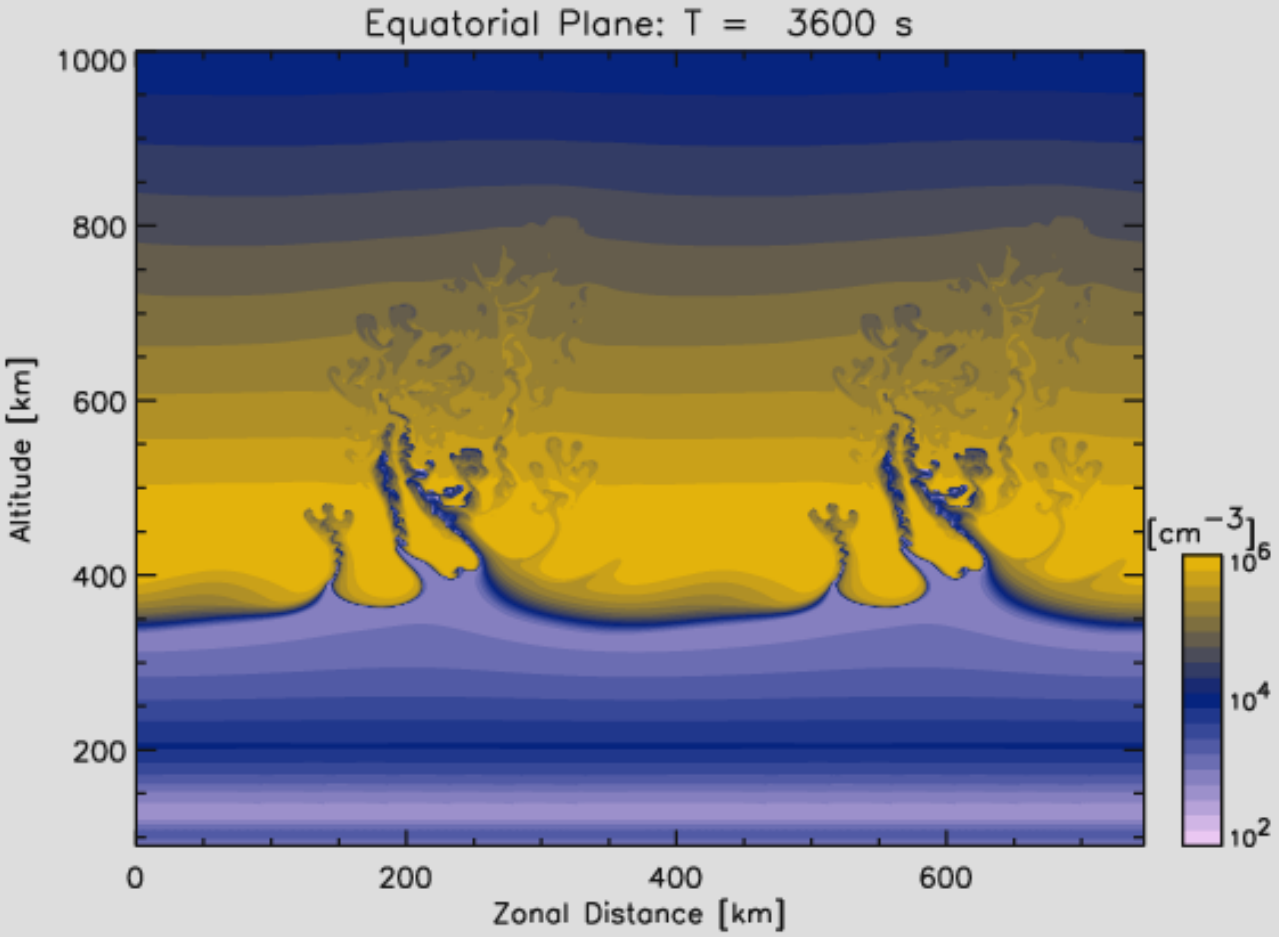




Yokoyama et al. (2014)

West Wall Structuring





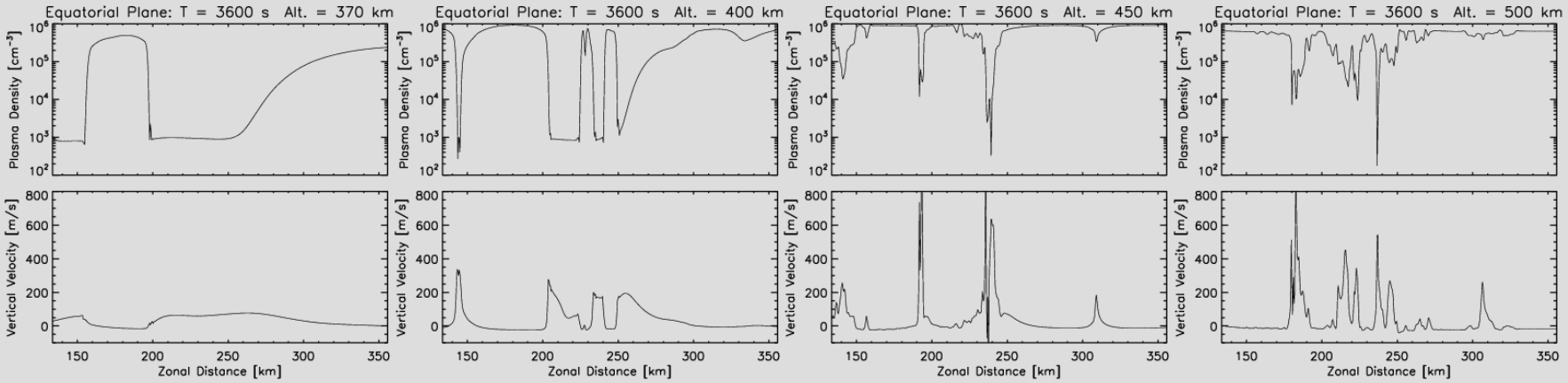
Yokoyama et al. (2015)

- Two seeding wavelength + eastward E field + eastward neutral wind (low resolution (~1km))

Density and Upward Velocity (Zonal cut)

370 km 400 km 450 km 500 km

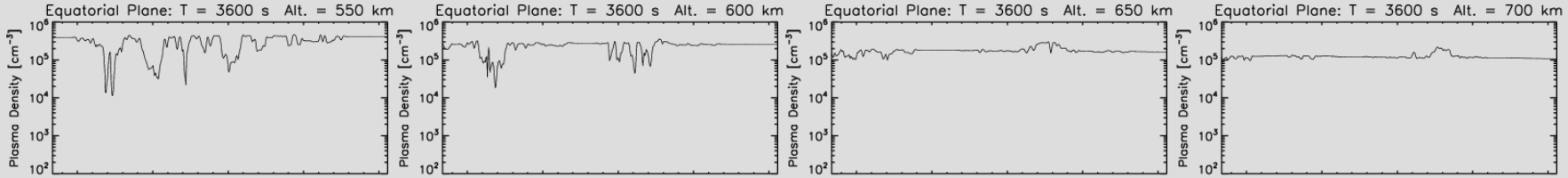
N



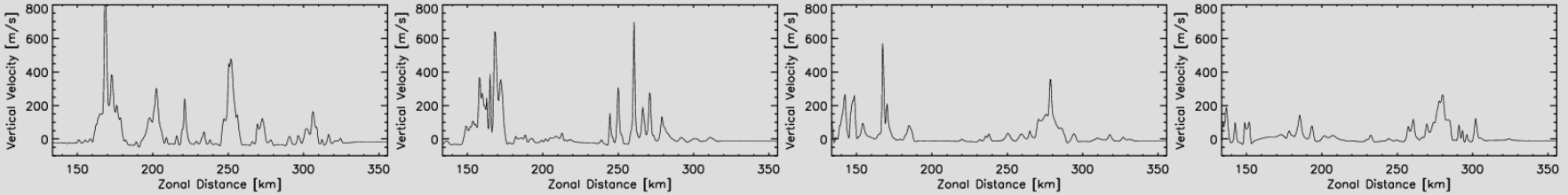
Vz

550 km 600 km 650 km 700 km

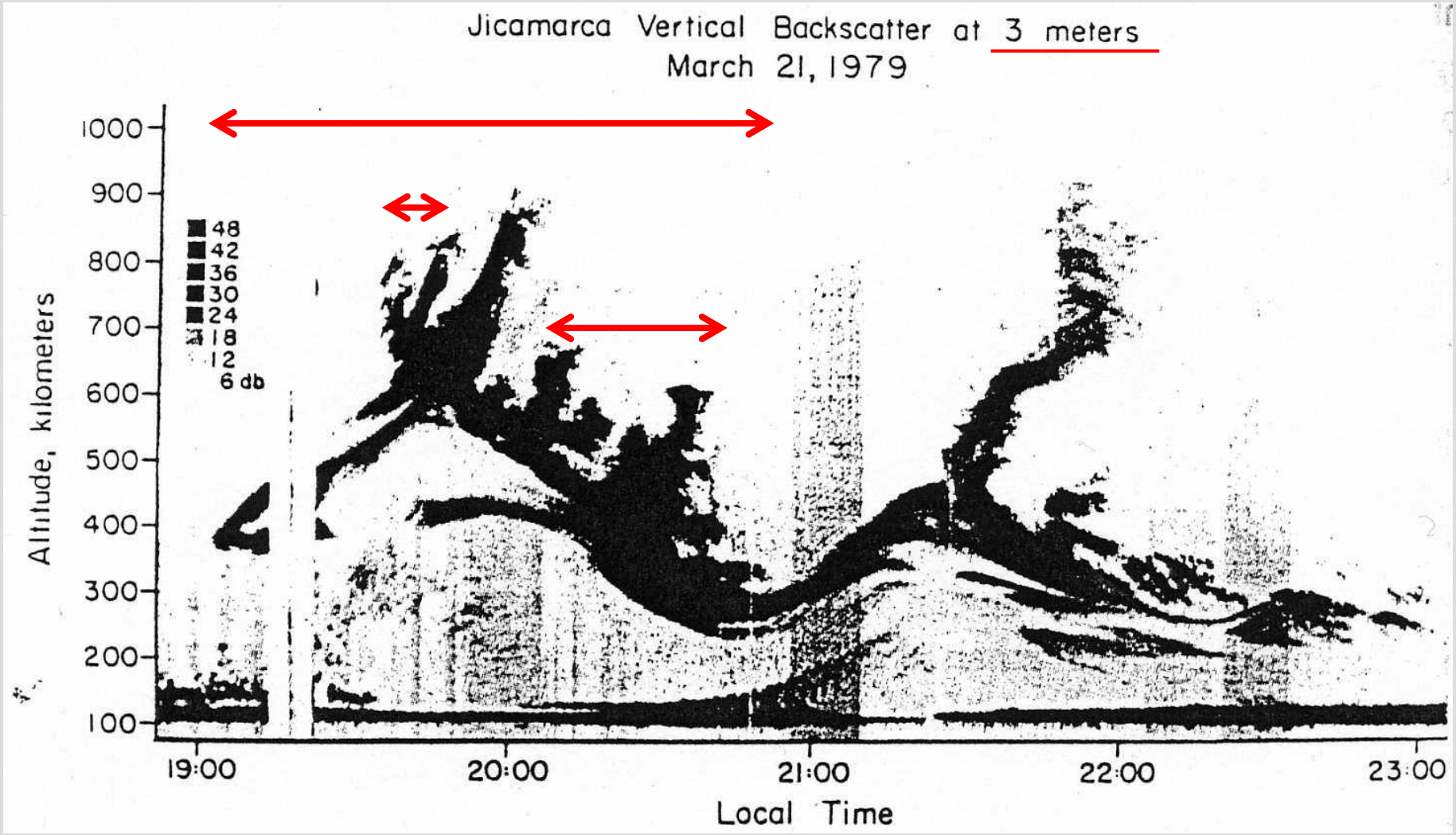
N



Vz

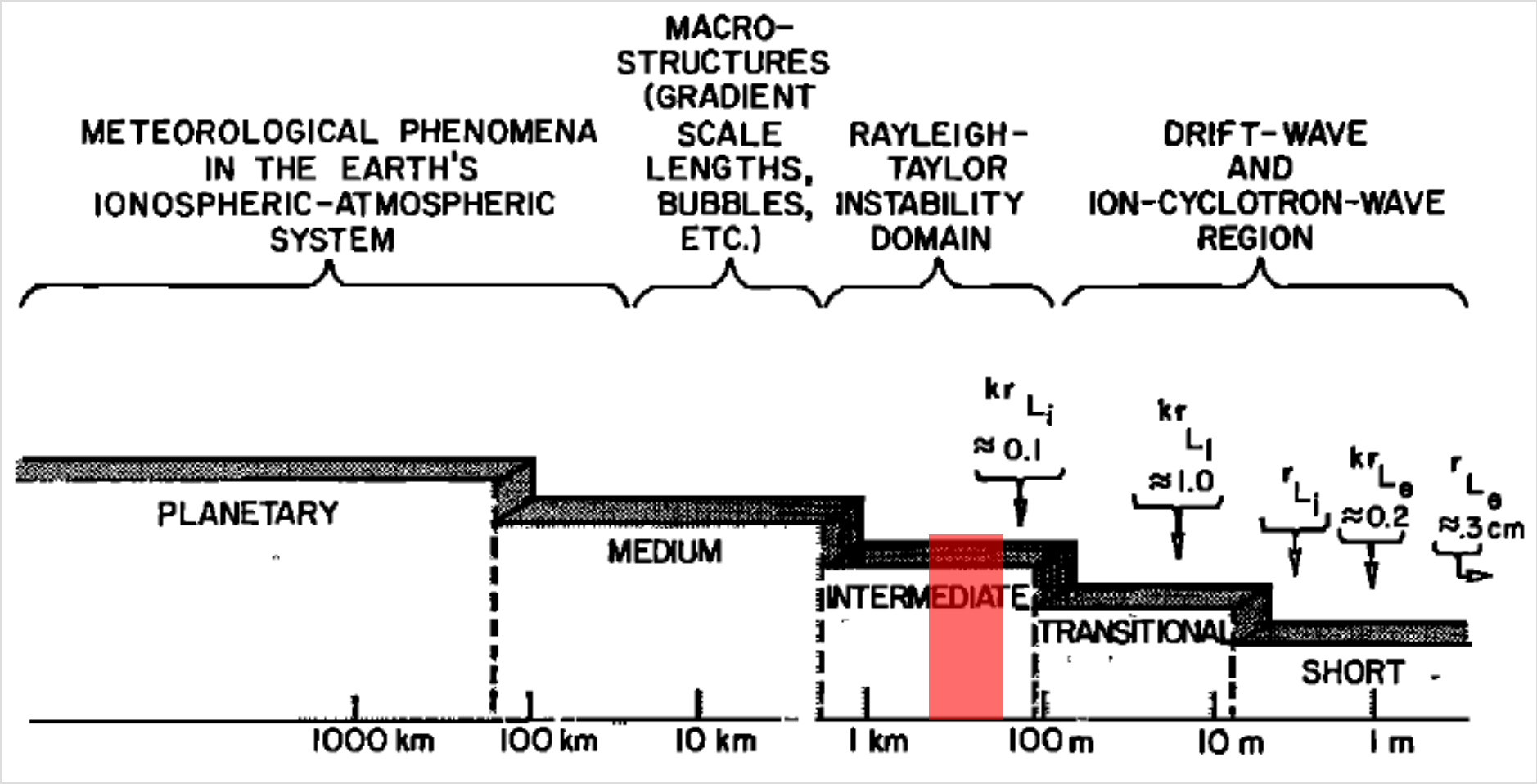


Jicamarca 50MHz Radar Observation



Kelley et al. (1981)

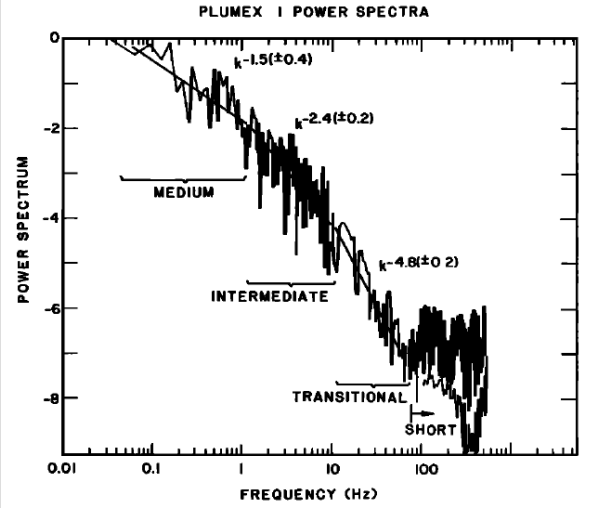
Irregularity Scales and Potential Mechanisms

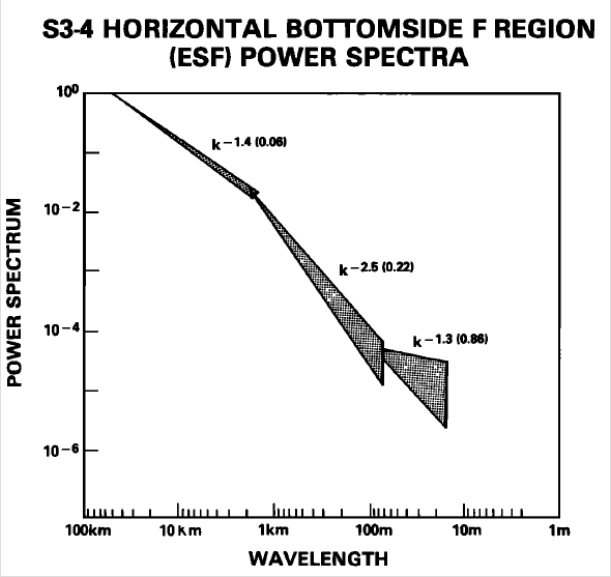


Singh and Szuszczewicz (1984)

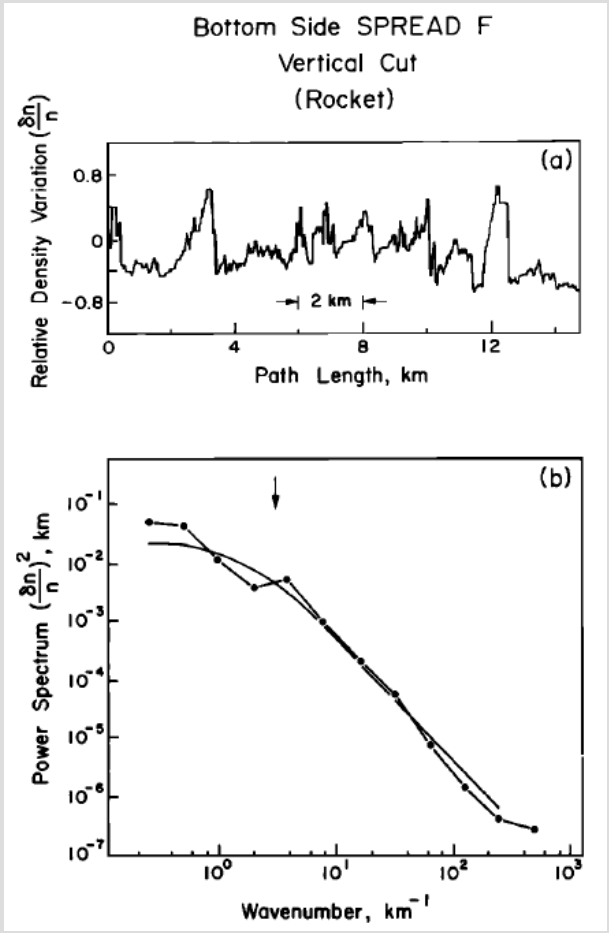
Fresnel scale for GPS scintillation

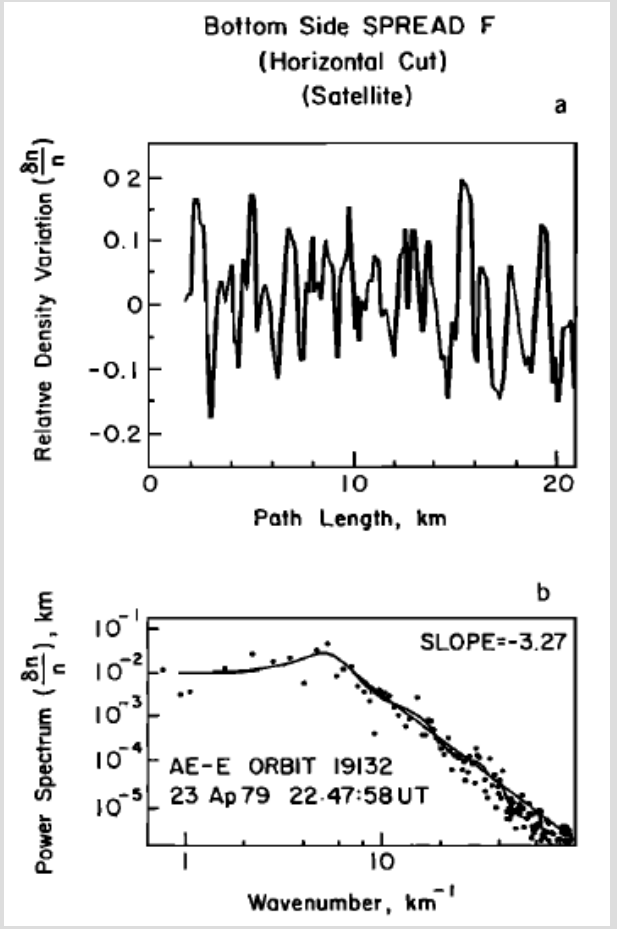
Spectral Characteristics from In Situ Observations





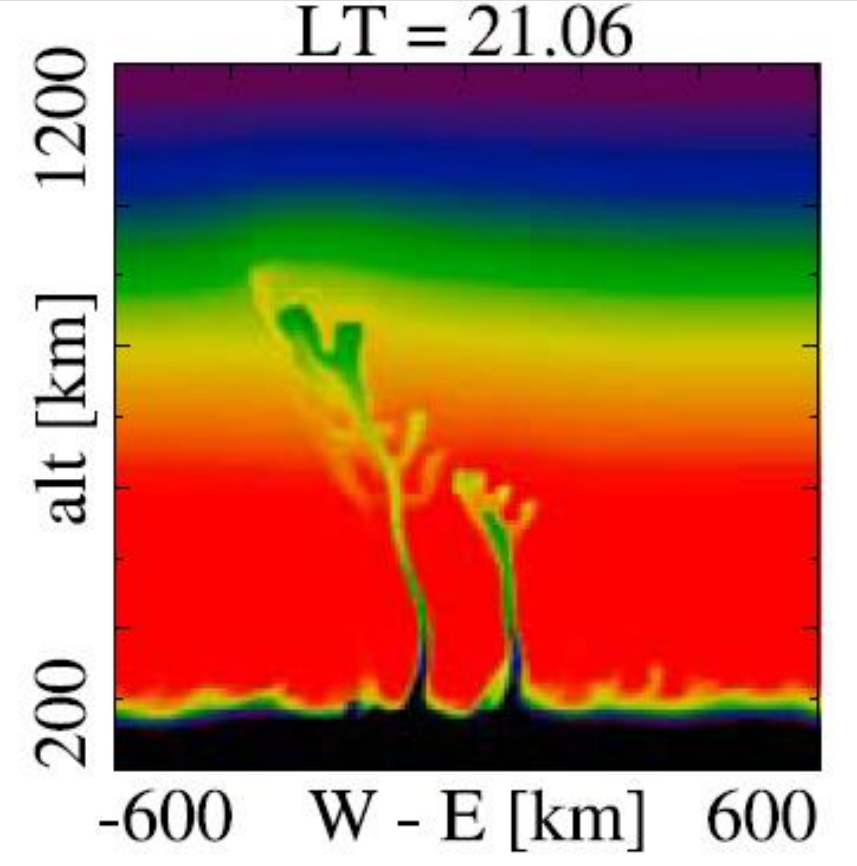
Singh and Szuszczewicz (1984)

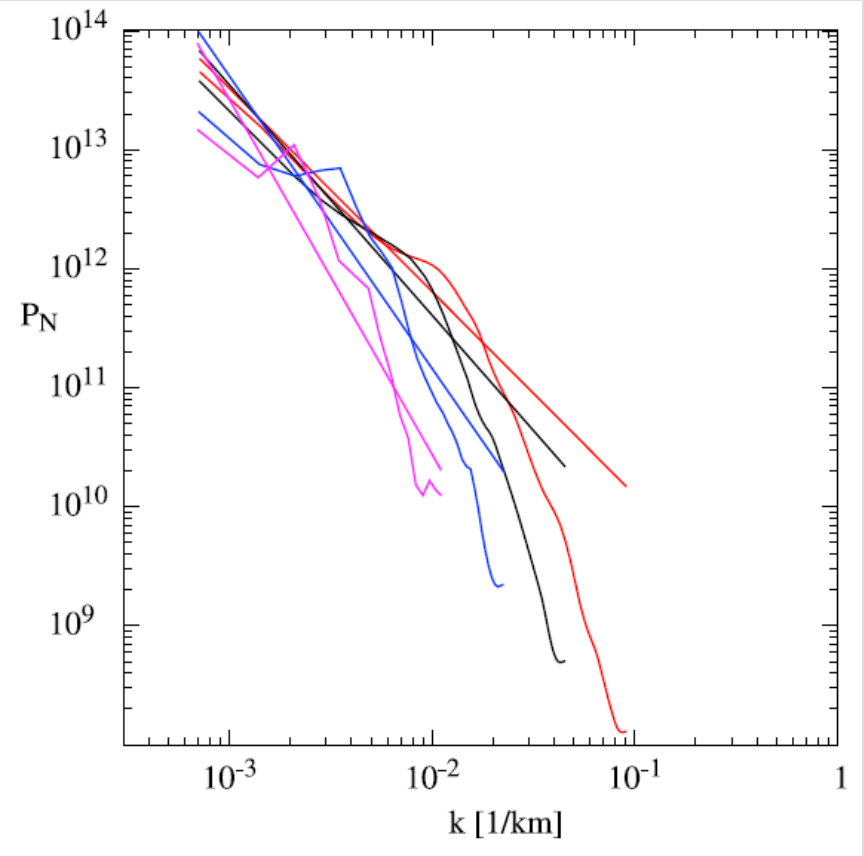




Kelley et al. (1987)

Spectral Estimation from Past Model

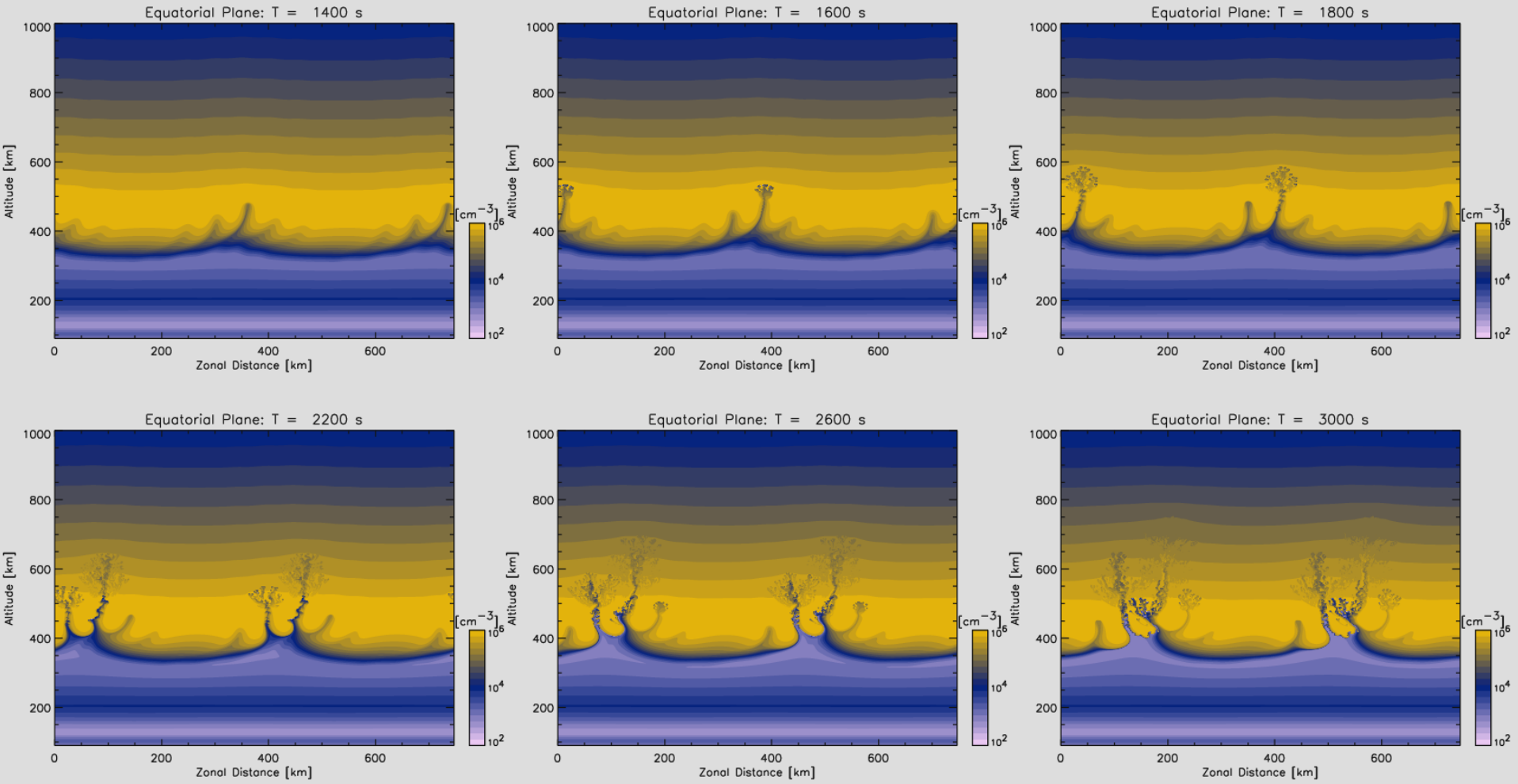




Retterer (2010)

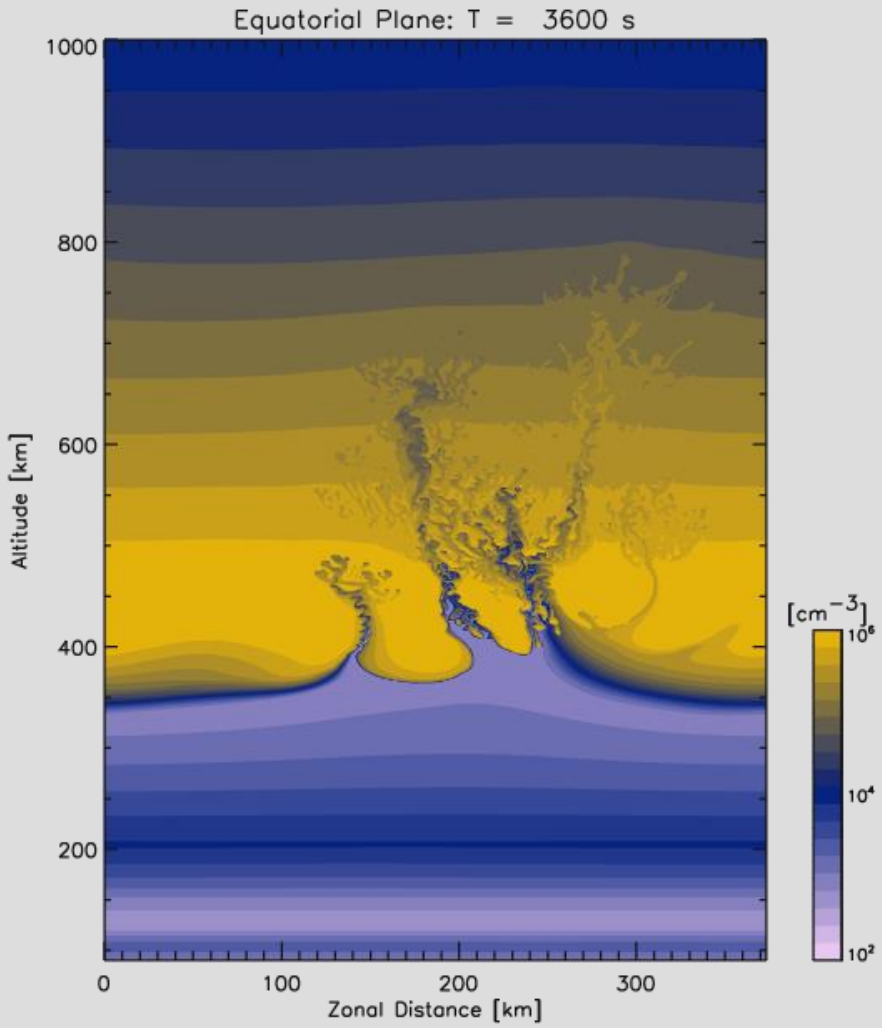
- Minimum grid size was 2.5km.
- Extrapolate spectrum down to Fresnel scale, then apply phase screen model to estimate S4 index.

Test Cases

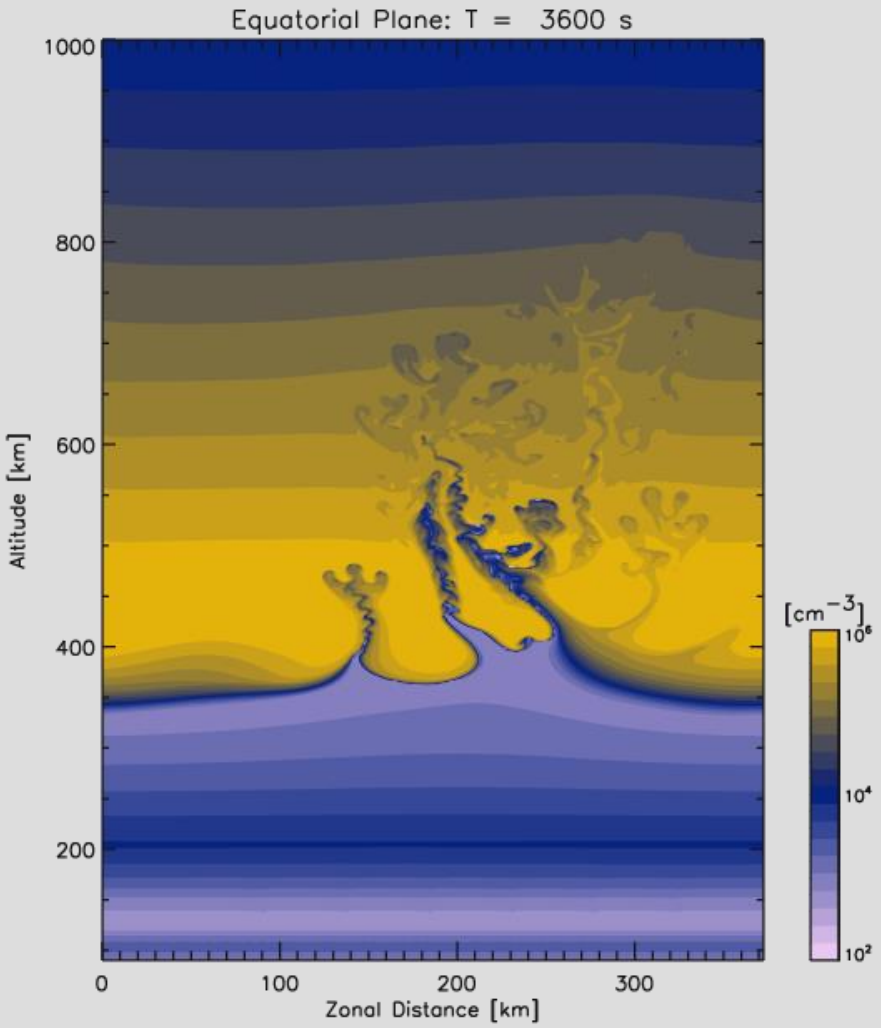


- Two seeding wavelength + eastward E field + eastward neutral wind

Low Resolution vs High Resolution

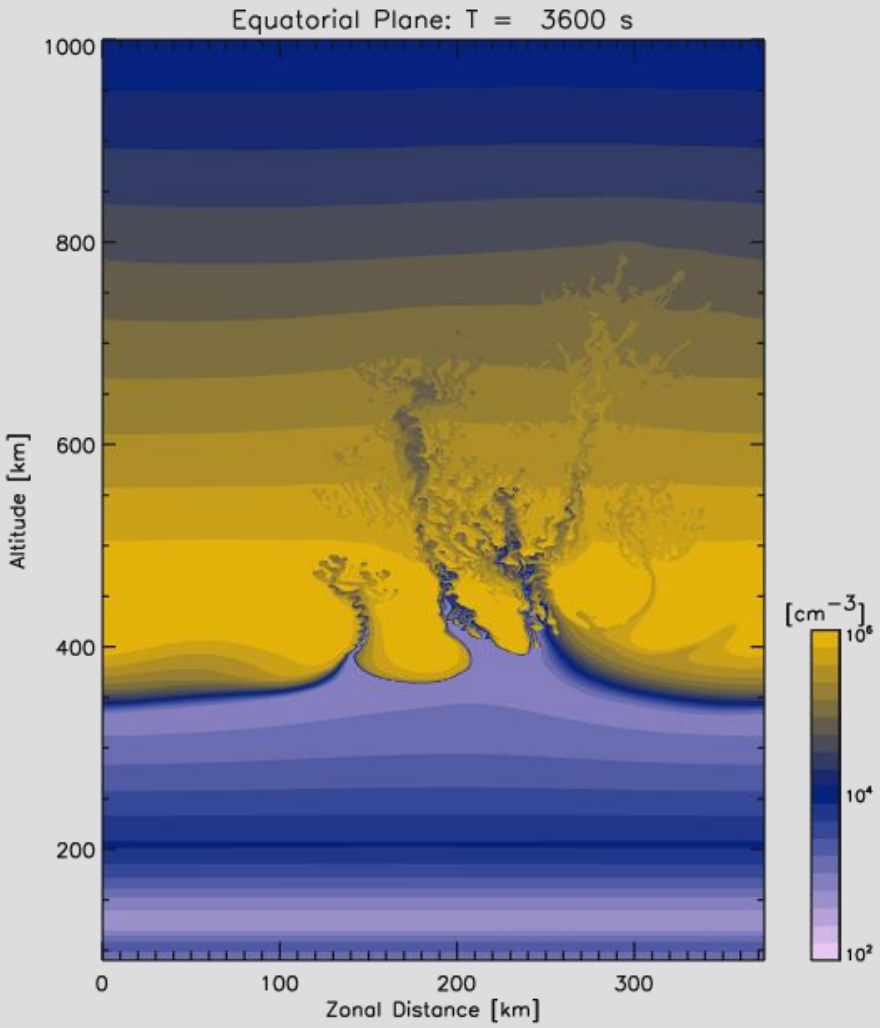


Δx = 300m

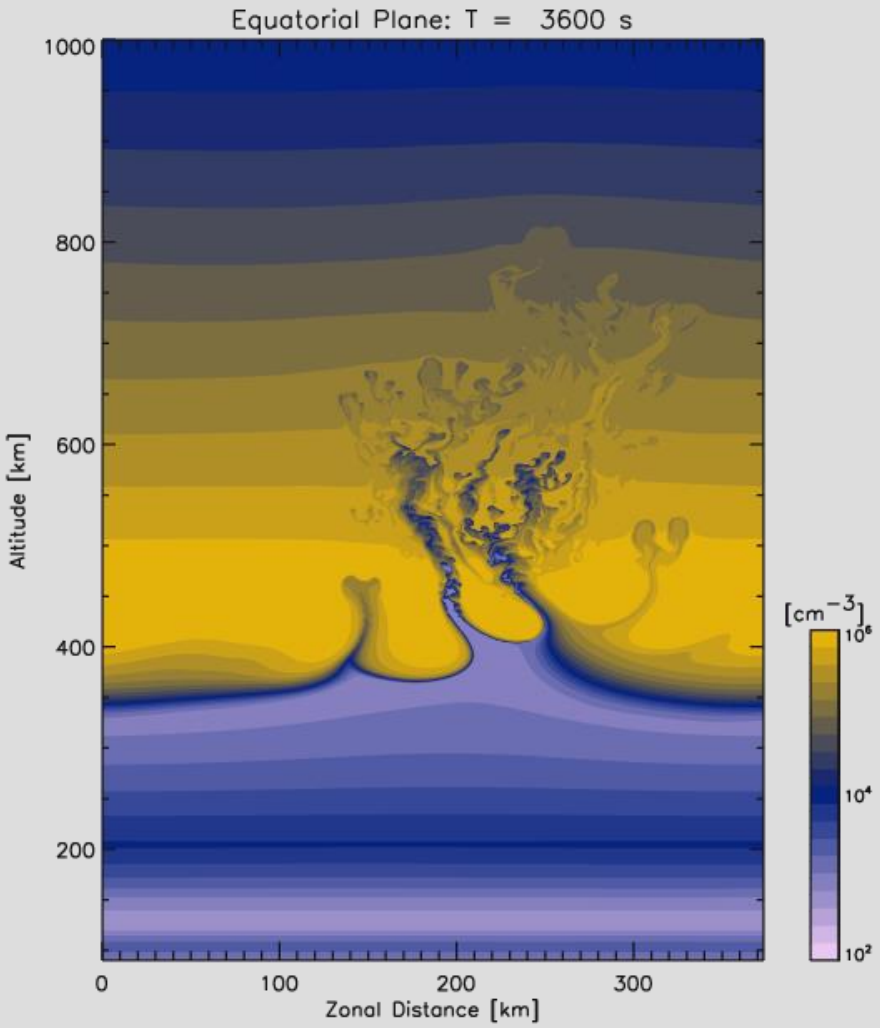


Δx = 1000m

Effect of Cross-Field Diffusion

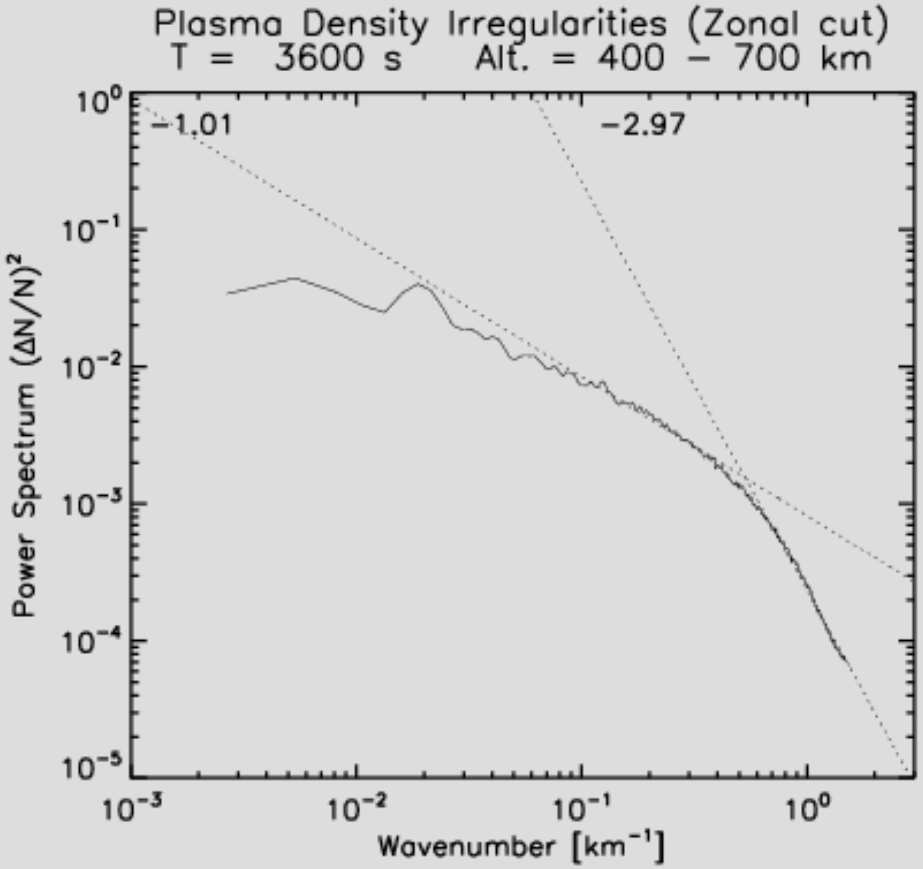


Normal case

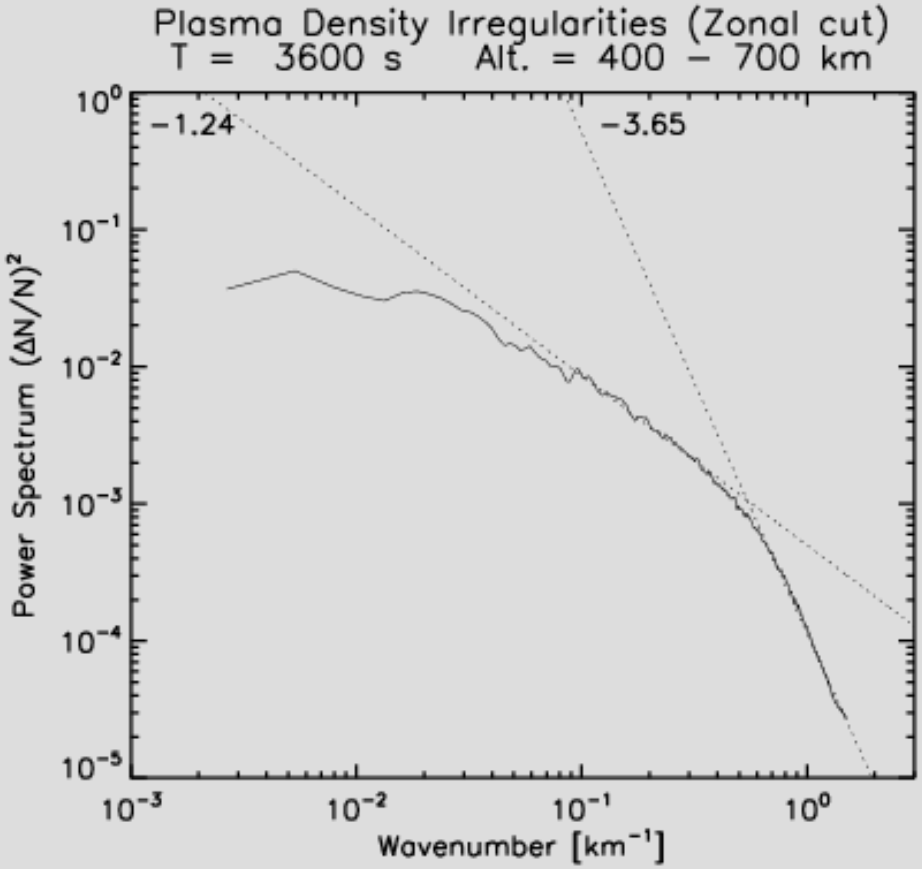


x1000 cross-field diffusion

Zonal Spectral Characteristics

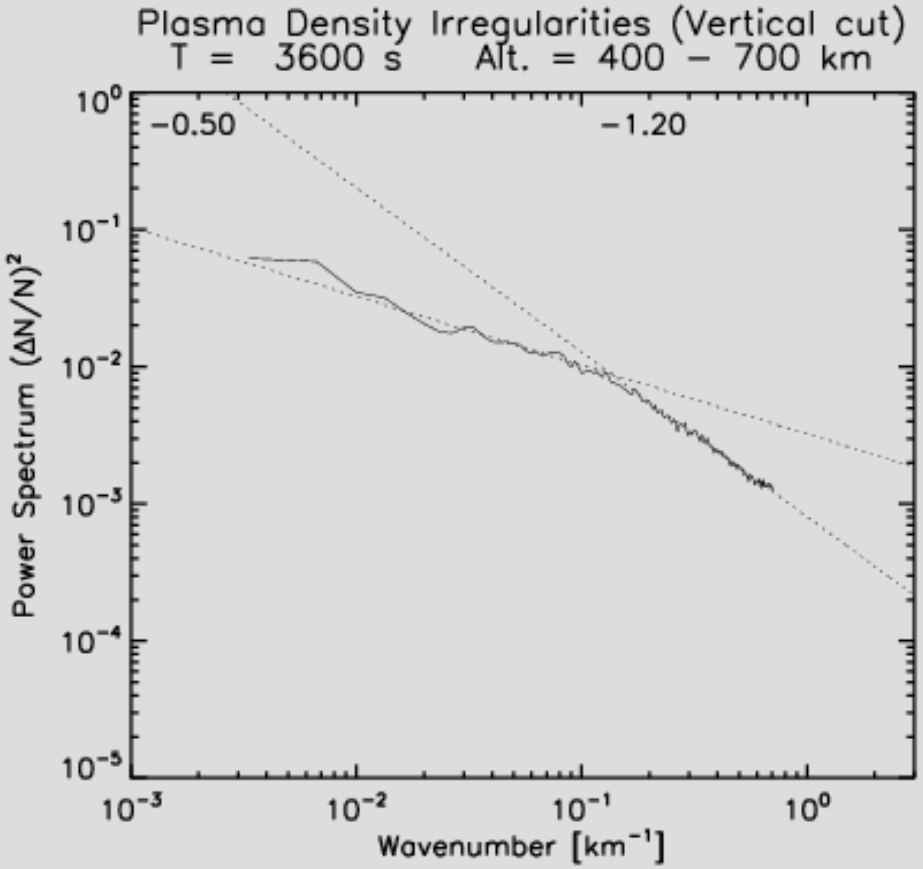


Normal case

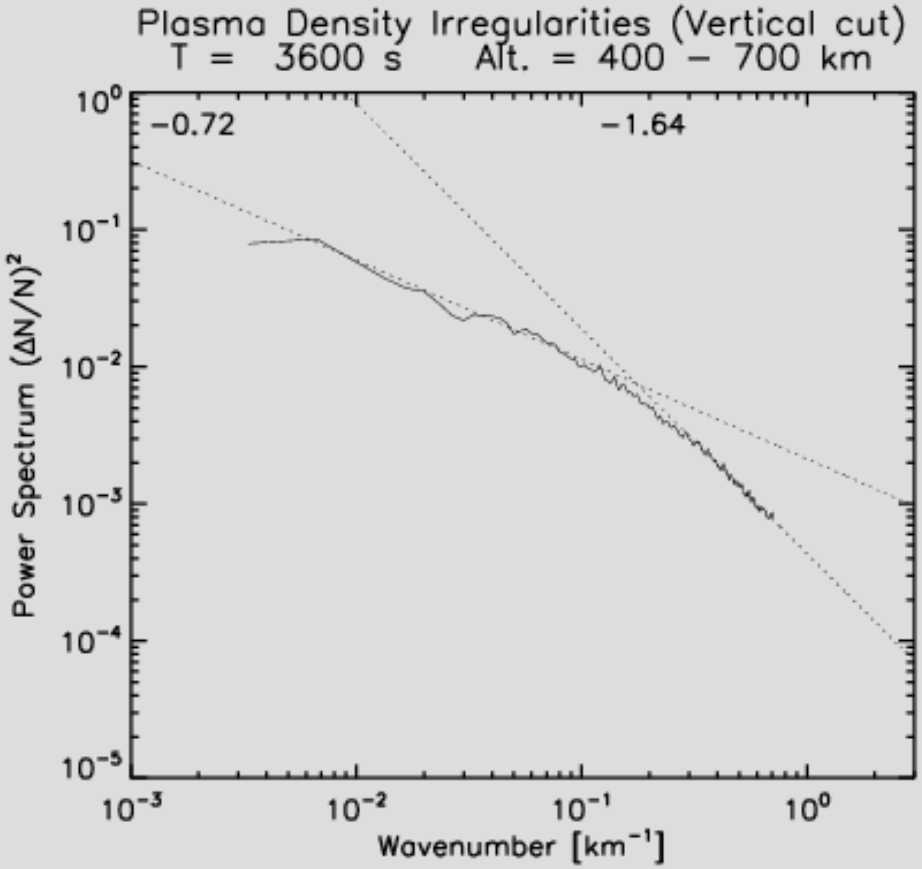


x1000 cross-field diffusion

Vertical Spectral Characteristics

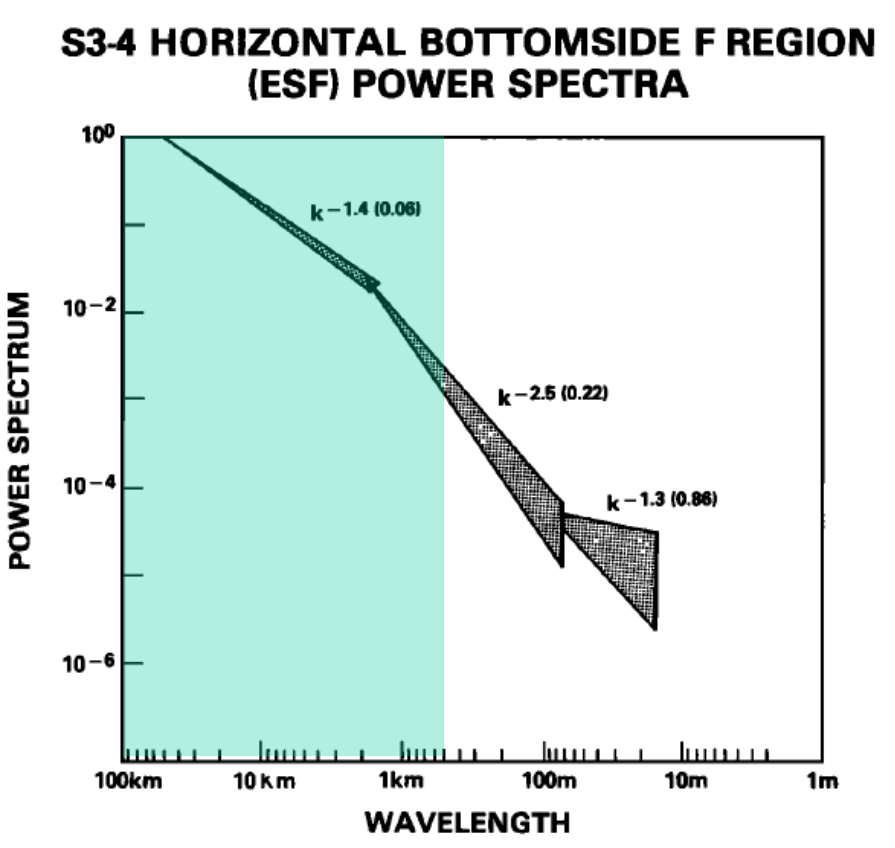


Normal case

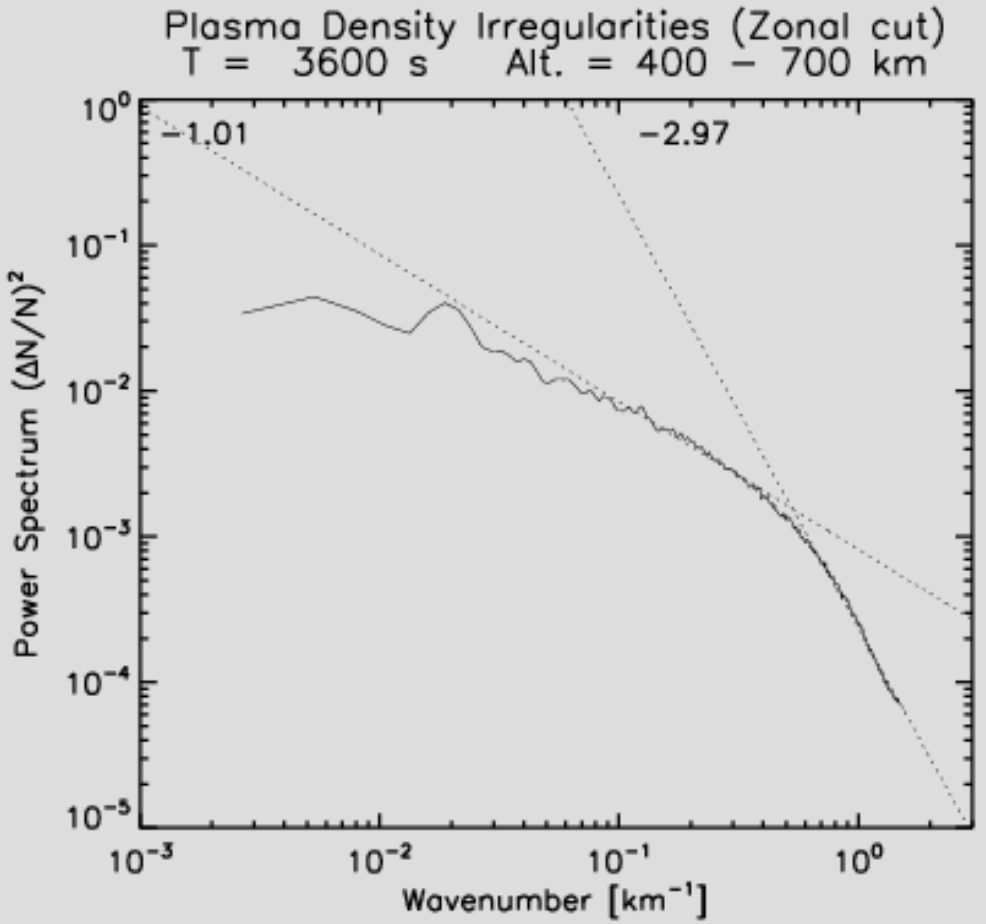


x1000 cross-field diffusion

Comparison with Past Satellite Observations



Singh and Szuszczewicz (1984)



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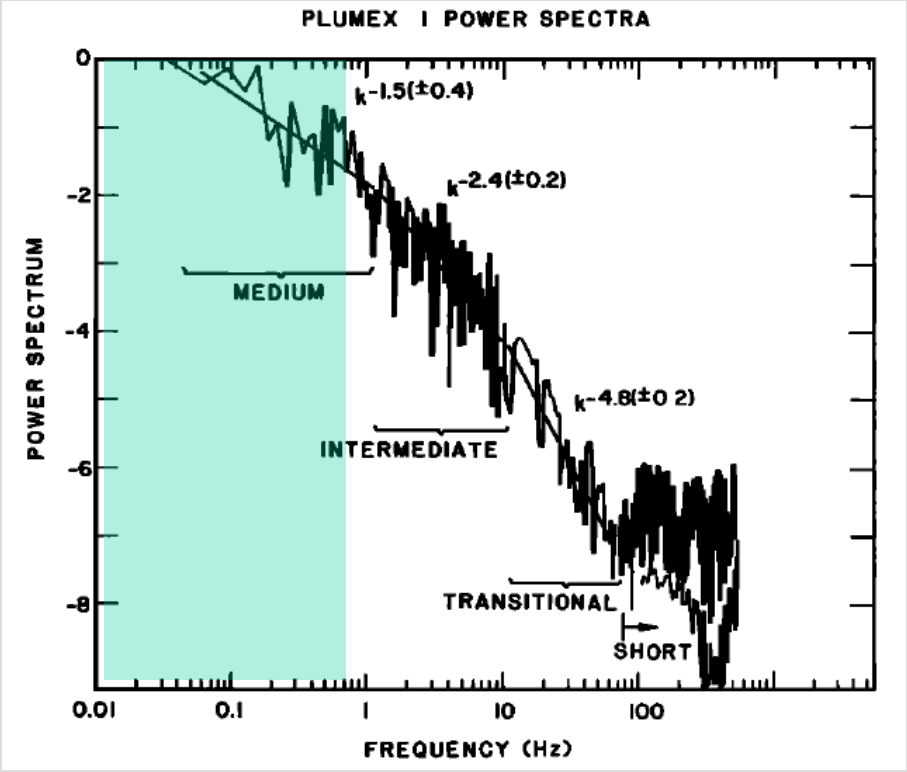
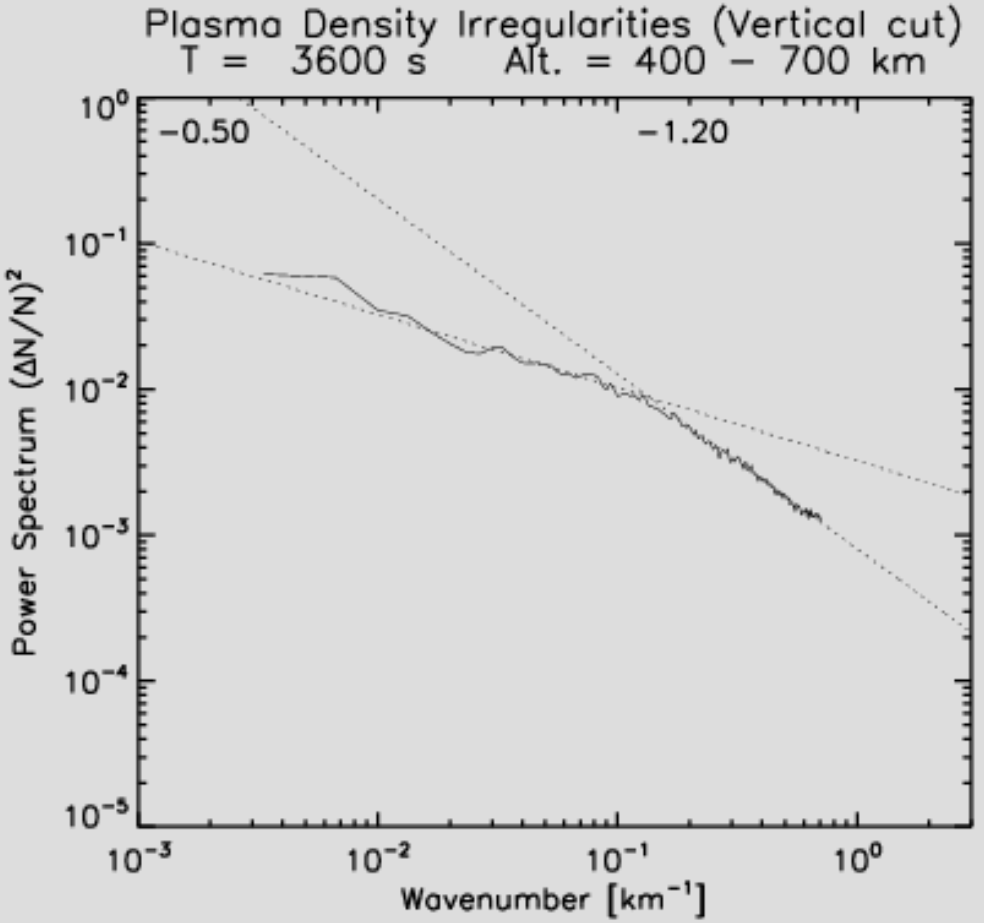


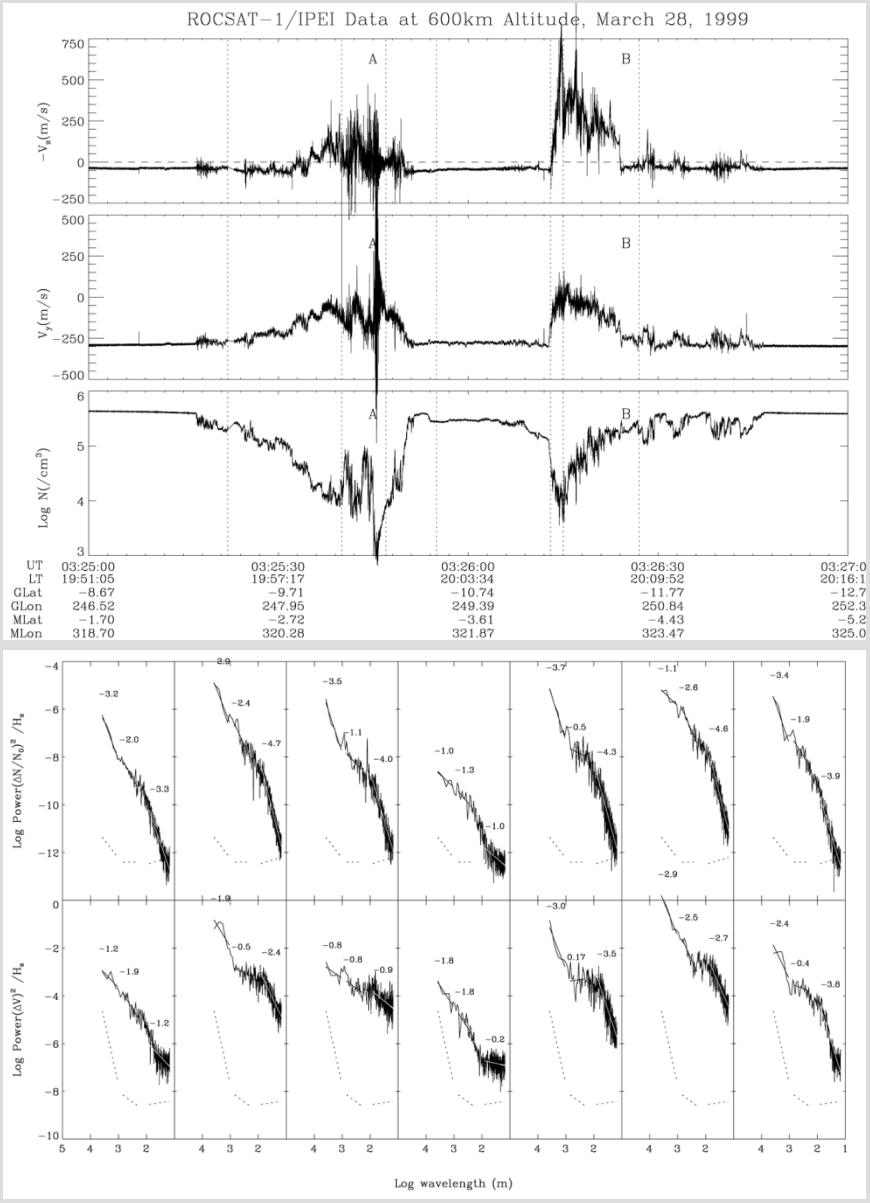
Singh and Szuszczewicz (1984)



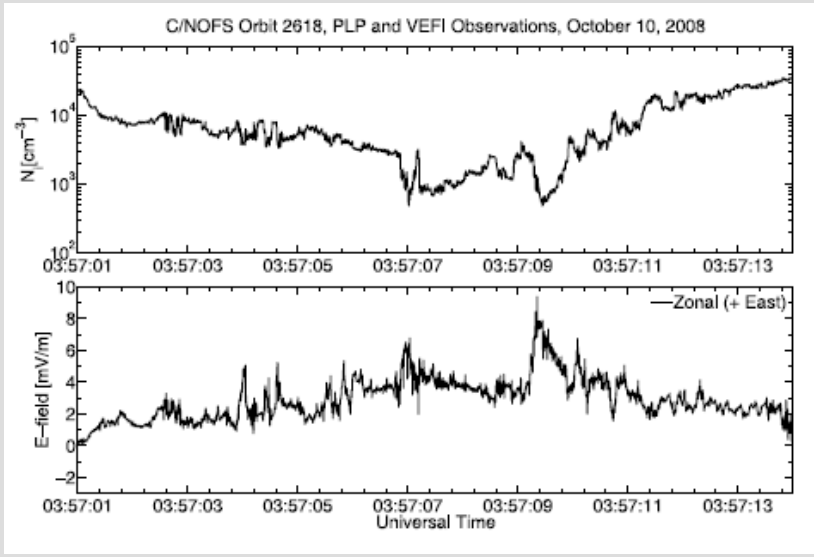
100km 10km 1km

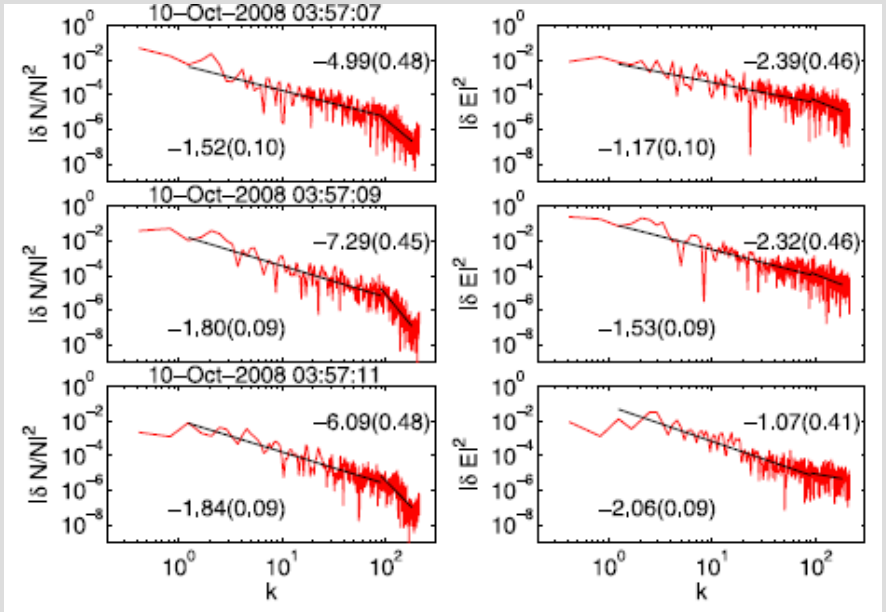
Wavelength

Spectral Characteristics from Recent Observations



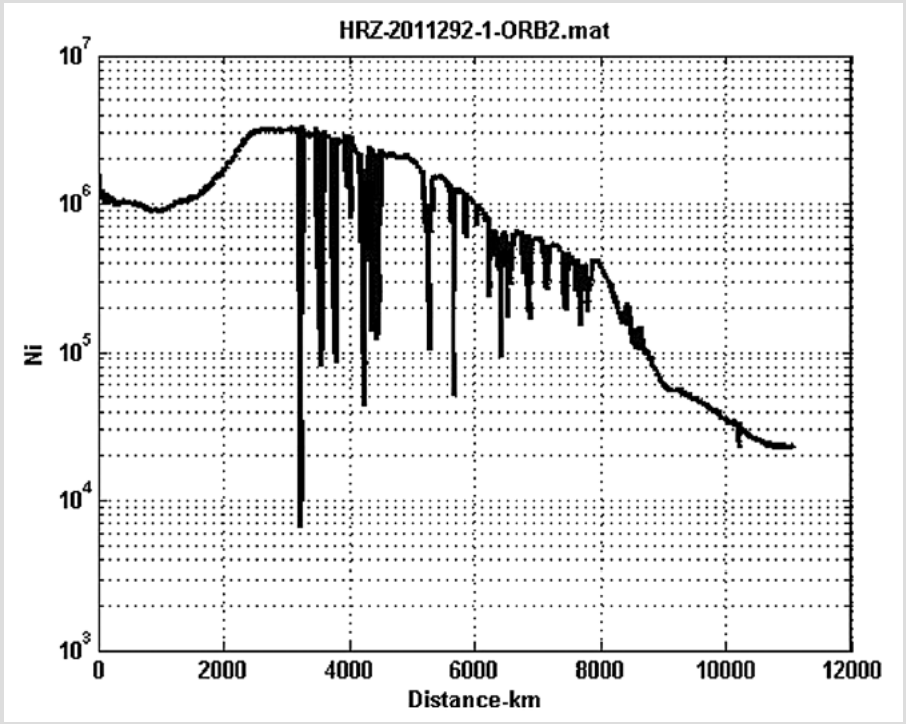
ROCSAT-1 (Su et al., 2001)

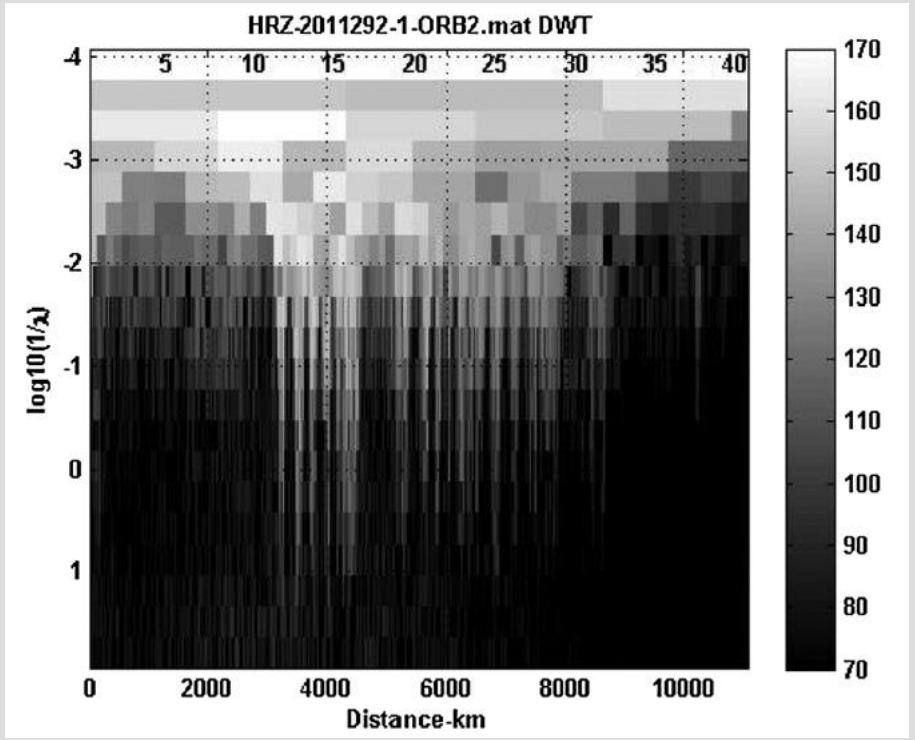




C/NOFS (Rodrigues et al., 2009)

C/NOFS Data Analysis by Discrete Wavelet Transform



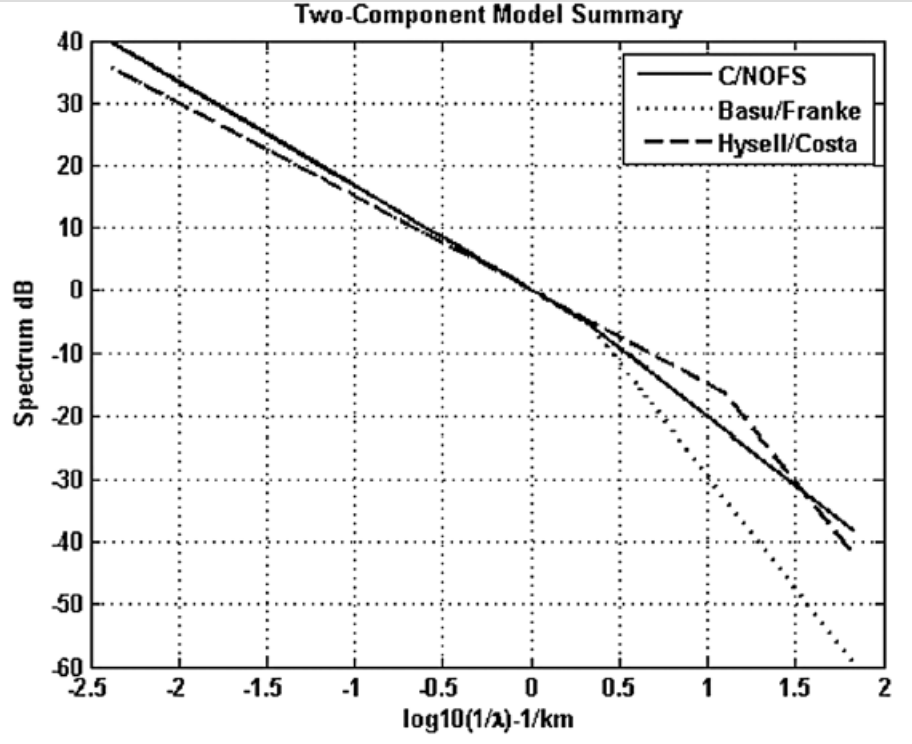


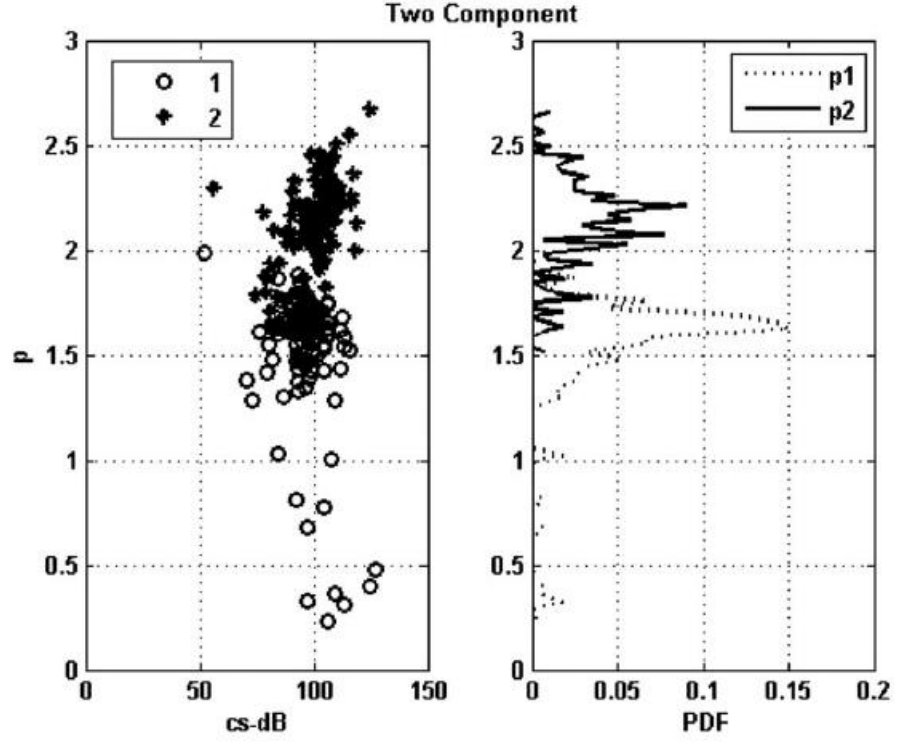
Rino et al. (2014)

C/NOFS Data Analysis by Discrete Wavelet Transform

$$S(k) = \begin{cases} C_1 k^{-p_1} & (k < k_0) \\ C_2 k^{-p_2} & (k > k_0) \end{cases}$$

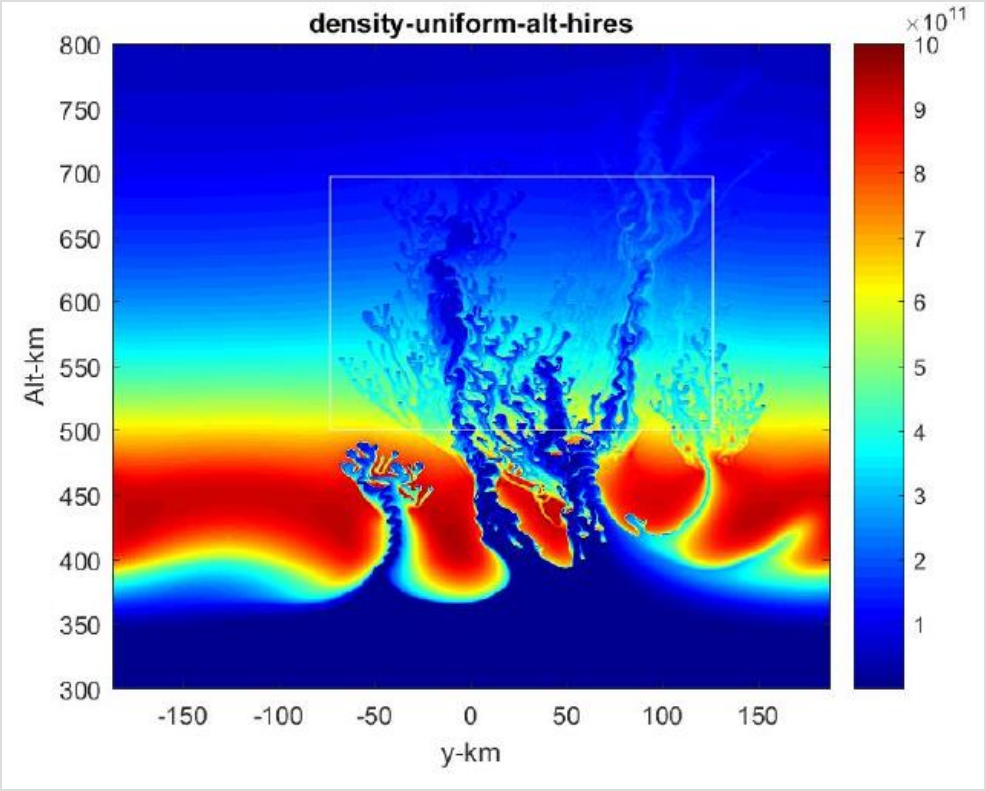
k_0 is the break scale wavenumber

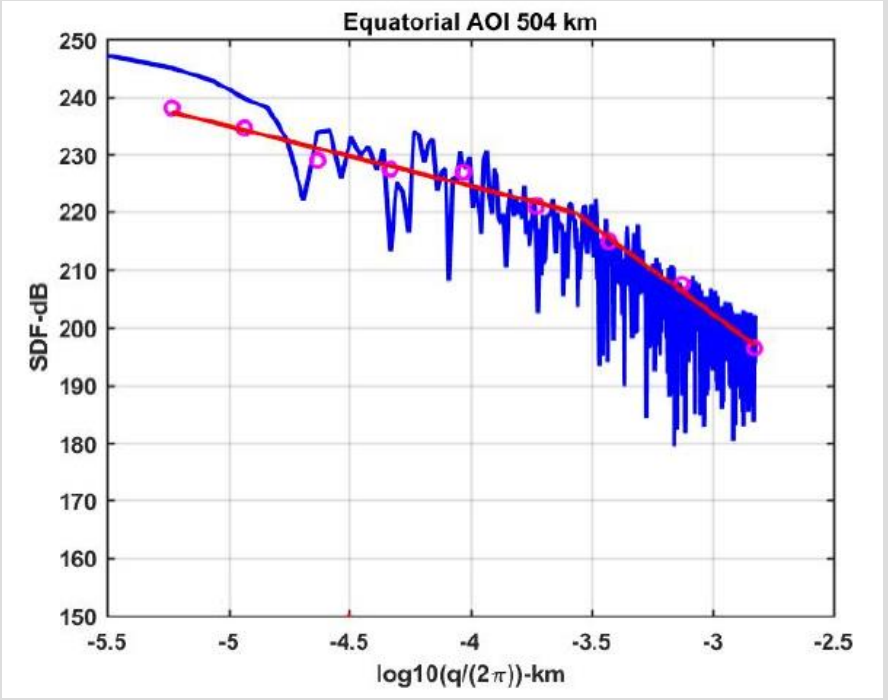




Rino et al. (2014)

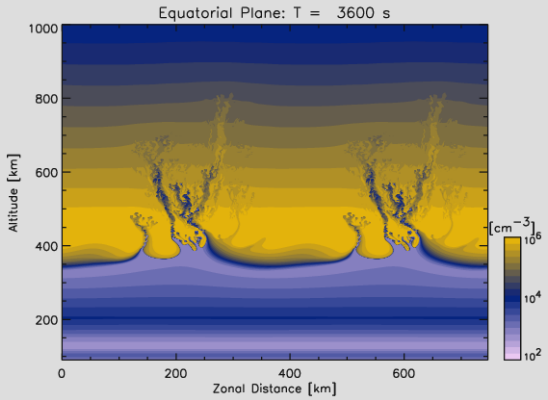
Preliminary Wavelet Analysis on Simulation Data





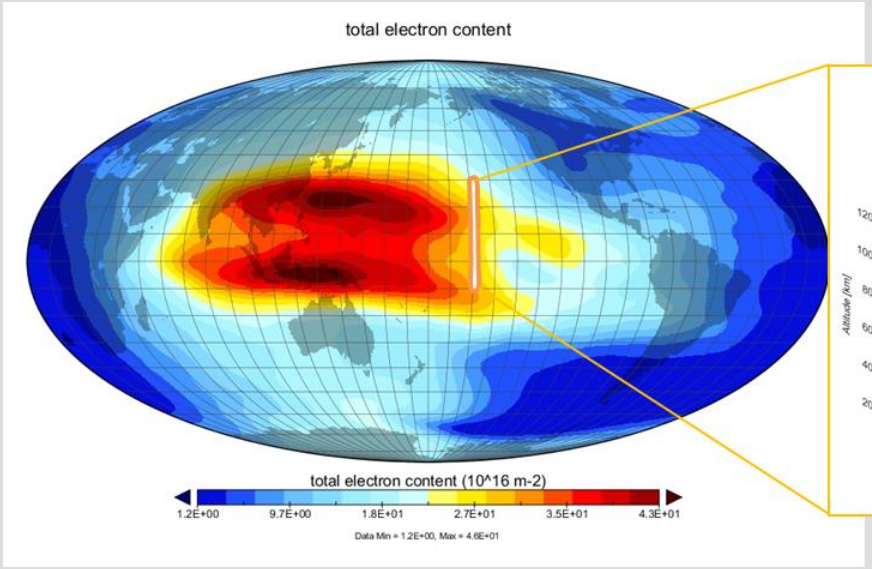
- Two-component power-law is seen in both C/NOFS and simulation data.
- More analyses are still ongoing.

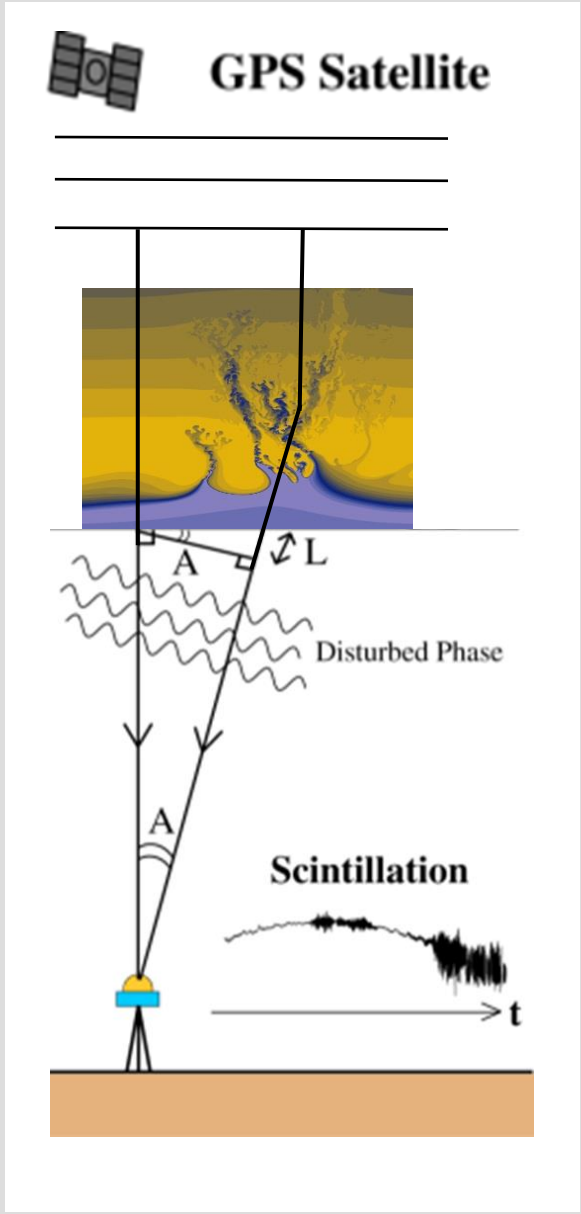
Future Directions



Higher resolution to evaluate scintillation

Couple with global model to understand day-to-day variability





Summary and Future Work

- The spatial resolution of the high-resolution bubble (HIRB) model has been improved to be as small as 300m.
- Intermediate scale irregularities (~1km) are well developed in the model. Spectra have two power-law indices with a break scale at around 2-5 km.
- The spectral characteristics are generally consistent with C/NOFS in situ observations.
- What determines the power-law indices and the break scale is not clear.
- Fresnel scale irregularities that cause GPS scintillation (300-400m) may be directly simulated in the near future.