Ionosphere and Ionospheric Delay

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Acknowledgement to:
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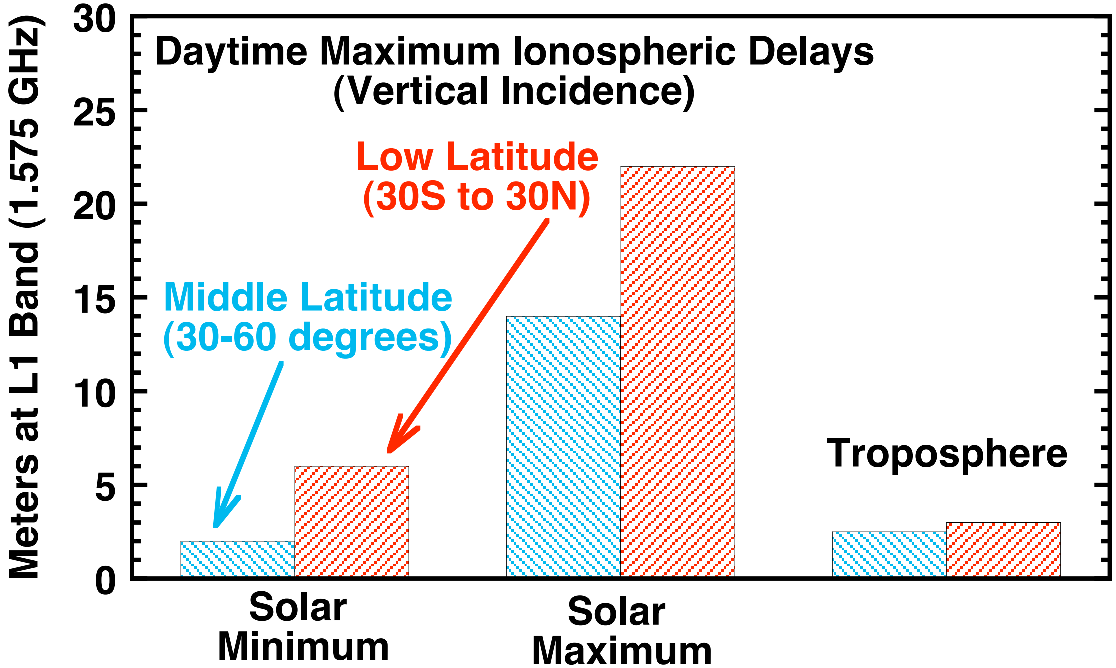
Motivation

- **Ionospheric delay has a major effect on the L-band GPS signal**



Density:
Troposphere $1\text{x}10^{-3}$ g/cm^3
Ionosphere $1.4\text{x}10^{-14}$ g/cm^3

- **GPS is a powerful remote sensing tool for the ionosphere**

Overview

1. The upper atmosphere
2. Ionization and creation of the ionosphere
3. Radiowave propagation in the ionosphere
4. Measuring total electron content with GPS
5. Scintillation
6. TEC science

1. The Upper Atmosphere

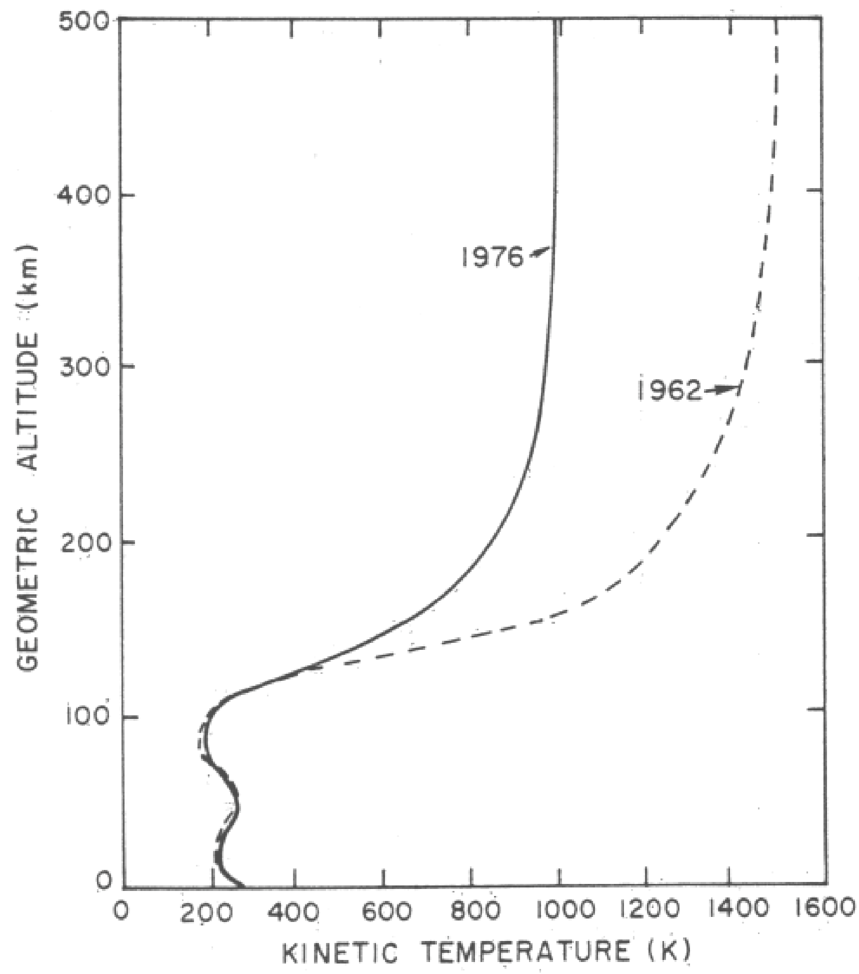


Figure 14-2. Kinetic temperature as a function of geometric altitude.

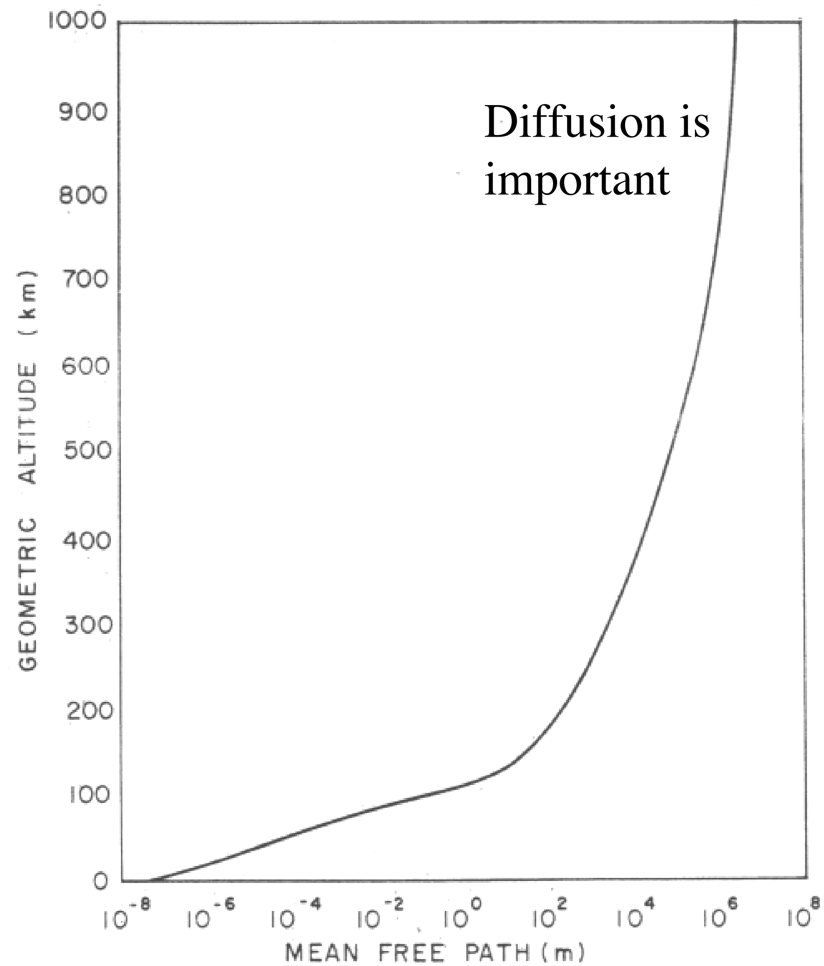


Figure 14-6. Mean free path as a function of geometric altitude.

Hydrostatic Balance/Scale Lengths

$$\frac{dp}{dz} = -\rho z$$

z = altitude

p = pressure

ρ = mass density (g/cm^3)

$$\rho = \sum_i m_i n_i$$

n_i = number density for i

m_i = mass for i

$$p = nkT$$

$$\frac{dp}{p} = -\frac{\rho g}{nkT} dz = -\frac{\overline{m} g}{kT} dz$$

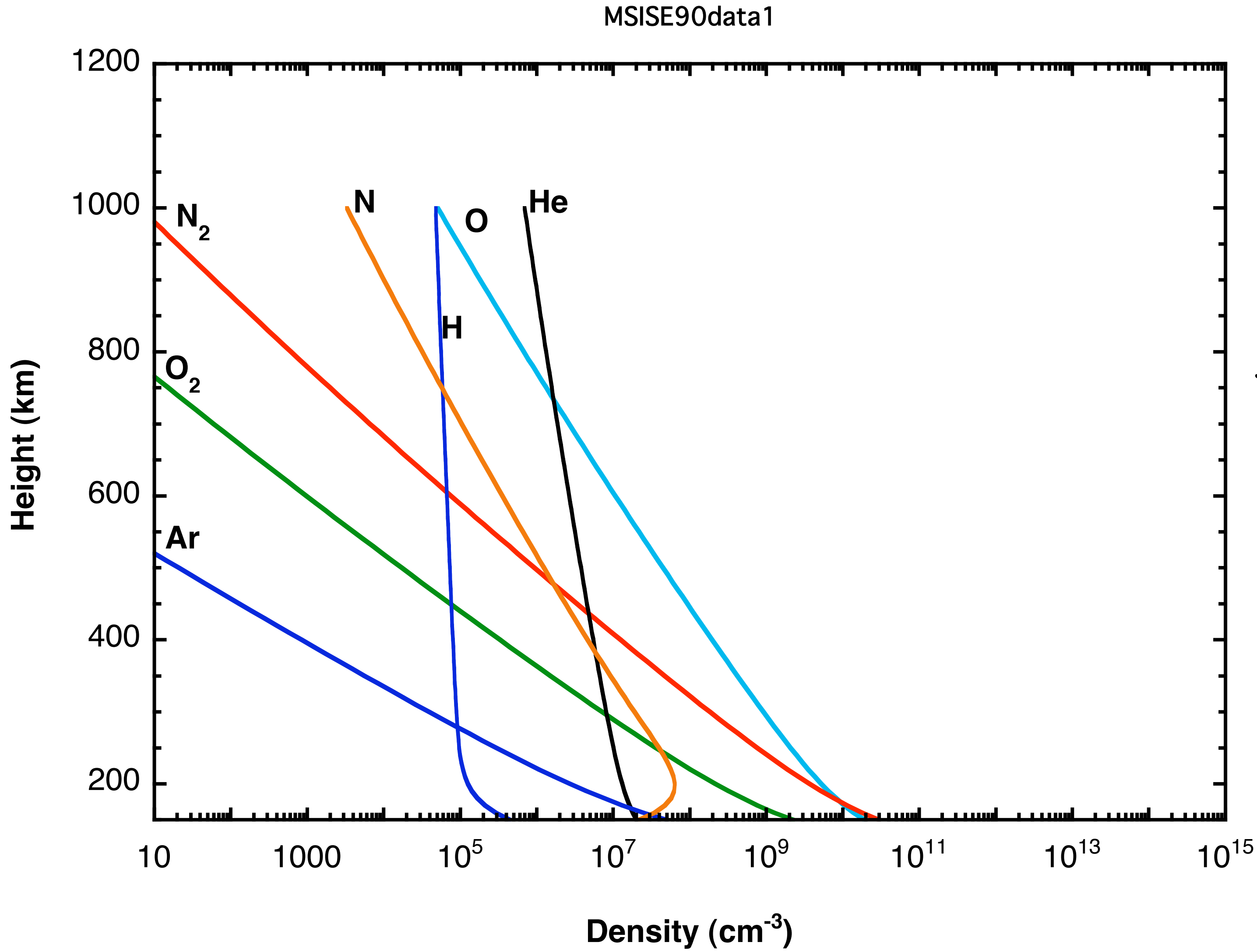
$$\ln p - \ln p_0 = -(z - z_0)/H$$

$$H = kT/\overline{m} g$$

$$p = p_0 e^{-z/H}$$

$H \sim 60$ km at 350 km altitude

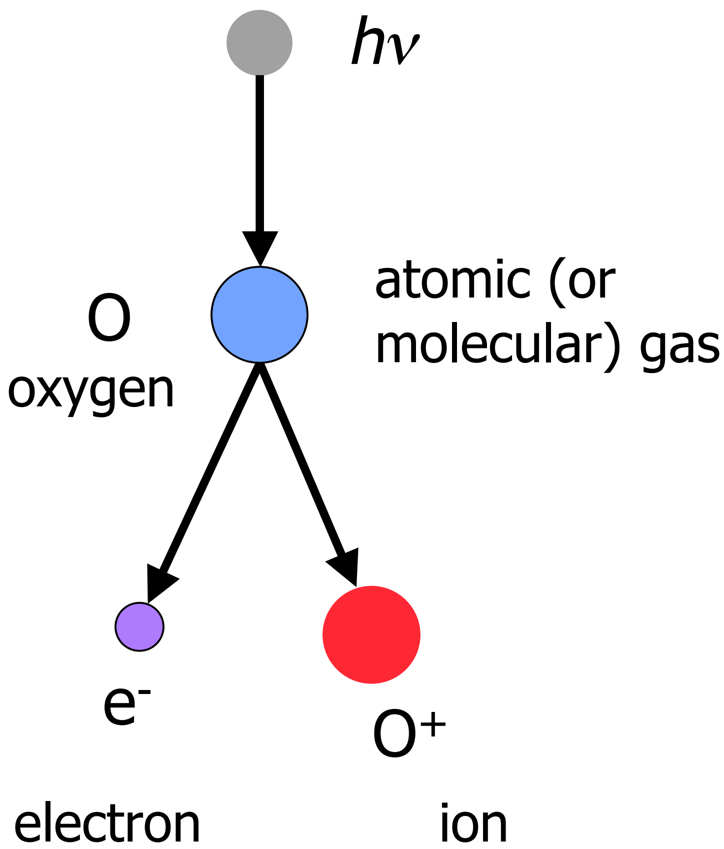
Model Thermosphere Densities



Note:
Different scale length for each species

Here Comes The Sun: Photoionization

Photon from the Sun



Examples of Photoionization

$$O + h\nu(< 911\text{A}) \rightarrow N_2^+ + \text{e}$$

$$N_2 + h\nu(< 796\text{A}) \rightarrow N_2^+ + e$$

$$O_2 + h\nu(< 1026\text{A}) \rightarrow O_2^+ + e$$

Examples of Dissociative Ionization

$$O_2 + h\nu(< 662\text{A}) \rightarrow O^+ + O + e$$

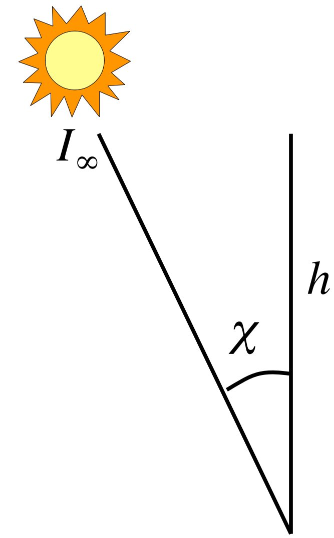
$$N_2 + h\nu(< 510\text{A}) \rightarrow N^+ + N + e$$

Ionization Threshold Energies

	Ionization		Dissociation	
Species	(eV)	λ(Å)	(eV)	λ(Å)
N_2	15.58	796	9.76	1270
O_2	12.08	1026	5.12	2422
O	13.61	911		
N	14.54	853		
NO	9.25	1340	6.51	1905
H	13.59	912		
He	24.58	504		

Altitude Distribution Of Ions: Chapman Layer (1)

$dI = \sigma_a n I dl$	I = intensity [J/m^2-sec] σ_a absorption cross section (m^2) n absorber density dl element of path l
$dI = \sigma_a n I \sec\chi dz$	Change of variable to vertical coordinate z, assuming solar zenith angle χ
$\int_z^\infty \frac{dI}{I} = \sigma_a \sec\chi \int_z^\infty n dz$	Integrate from above the atmosphere to altitude z
$I(z) = I_\infty \exp\left(-\sigma_a \sec\chi \int_z^\infty n dz\right)$	Intensity as a function of altitude



Chapman Layer (2)

$$q(z) = \frac{\sigma_a n(z) I(z)}{W}$$

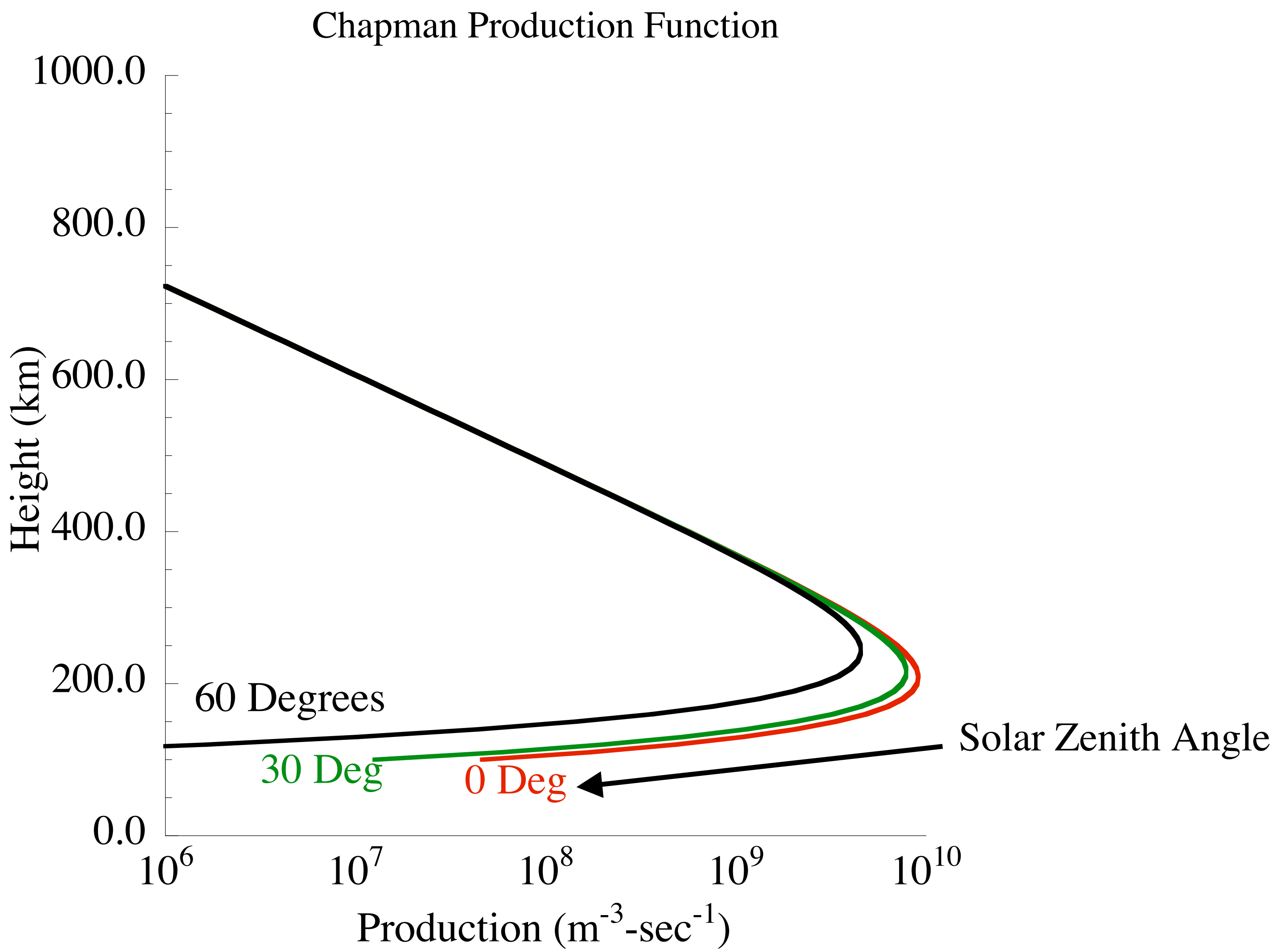
q(z) = ionization production rate
versus altitude
[1/m^3-sec]
1 electron per *W* of absorbed radiation *I*

$$n = n_0 e^{-z/H}$$

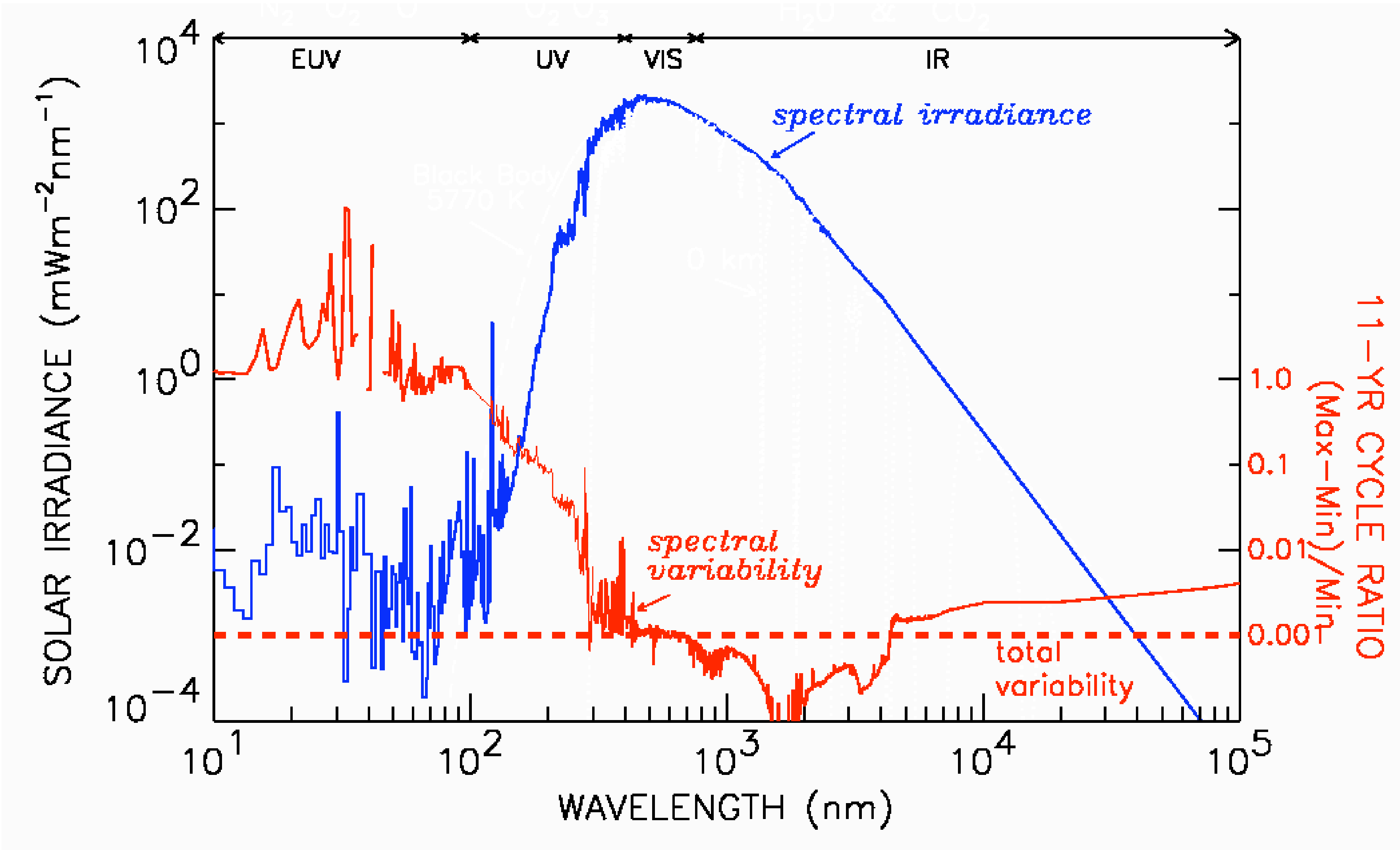
Assume exponential atmosphere

$$q(z) = \frac{\sigma_a n_0 I_\infty}{W} \exp\left(-\frac{z}{H} - \sigma_a n_0 H \sec\chi \exp(-z/H) \right)$$

Chapman Production Function

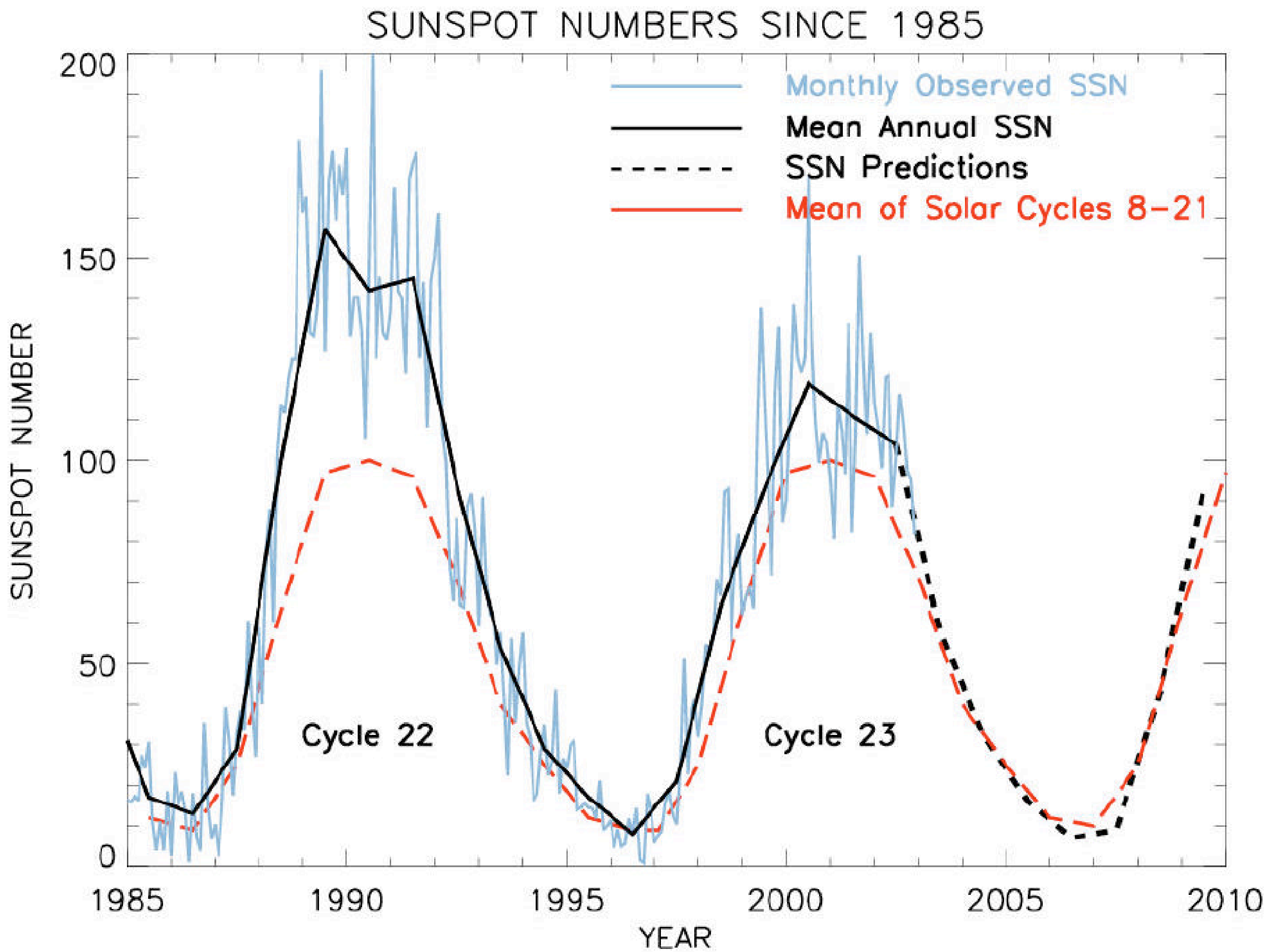


The Variable Sun:
Solar Spectrum and Solar Cycle

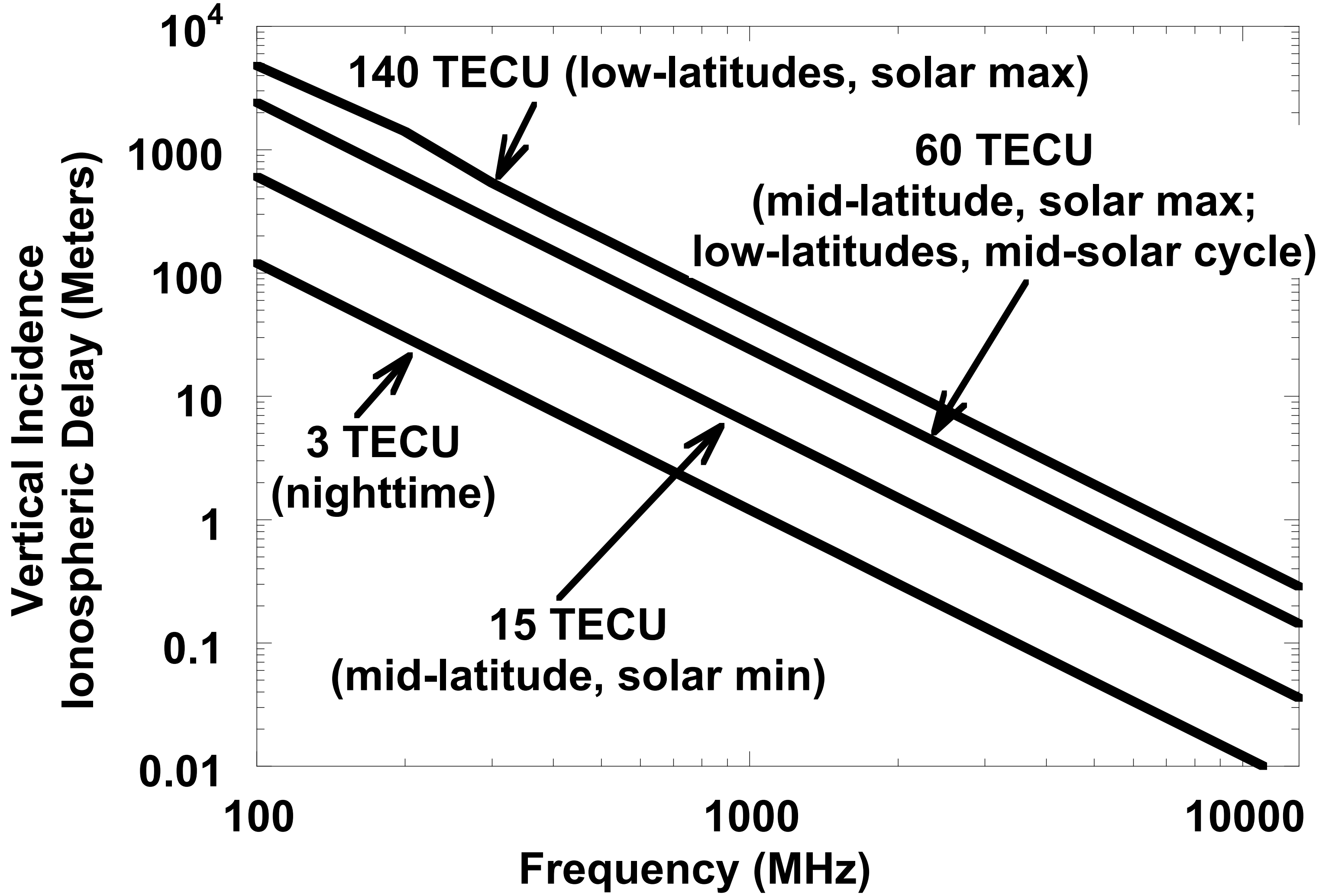


Solar Cycle

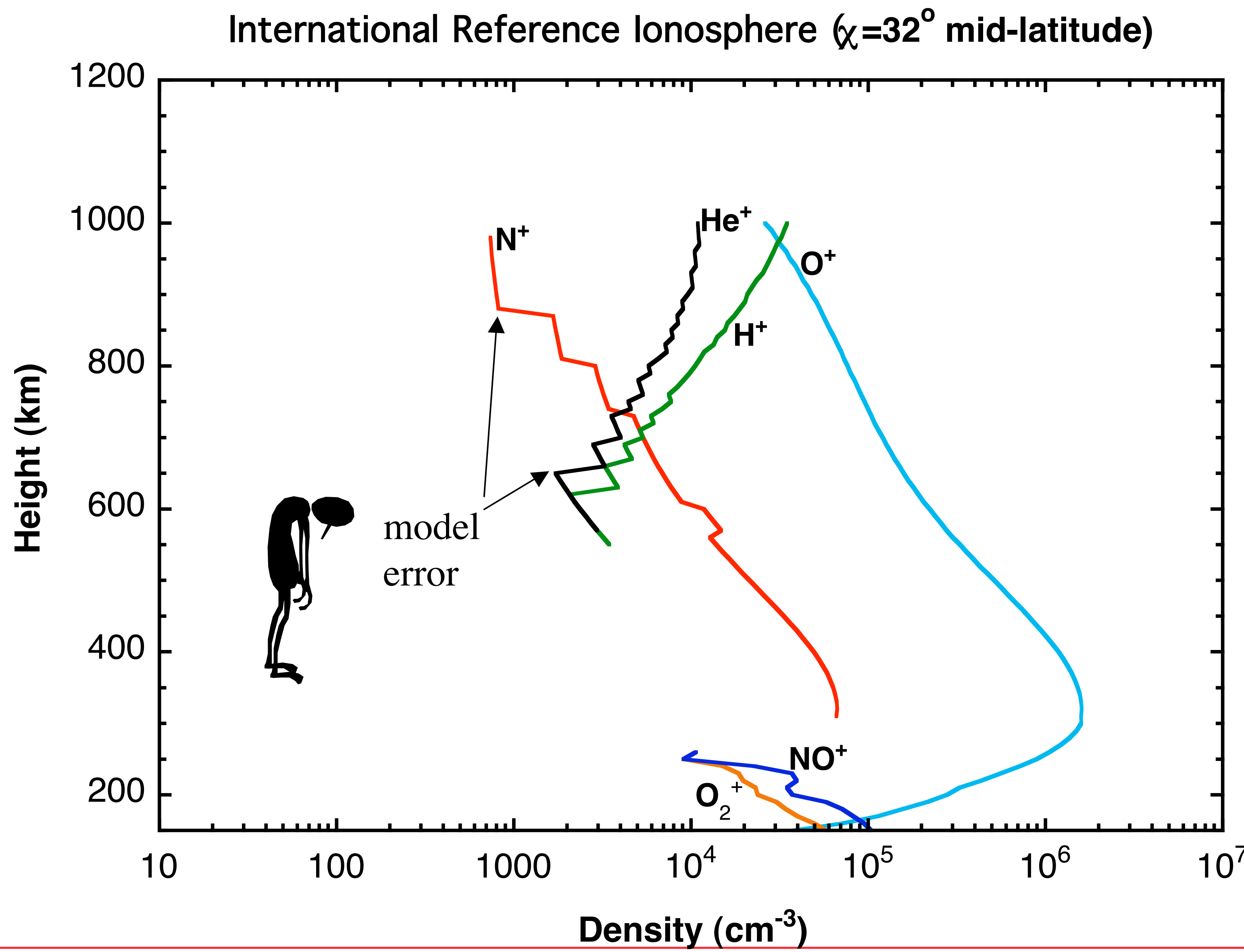
Sunspot number is a proxy for UV flux



TEC Versus Frequency

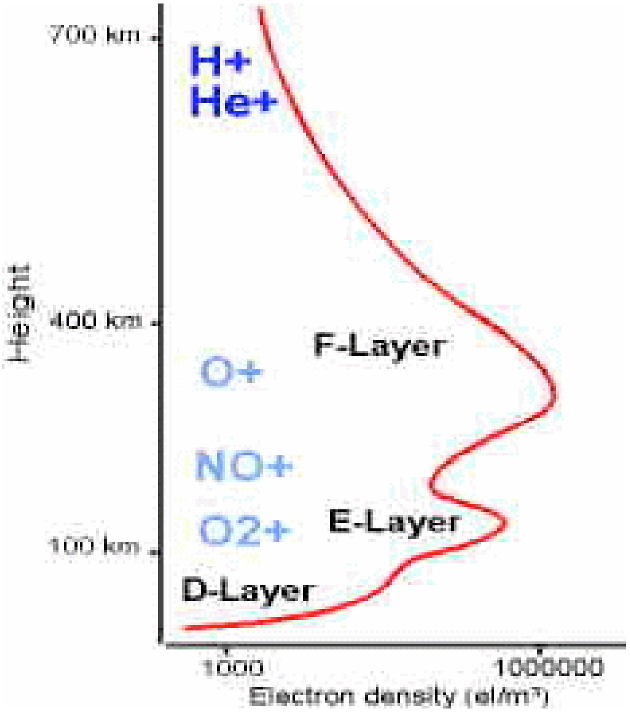


Model Ionization By Species



Production, Loss and Ionospheric Layers

- **F-layer**
  - **Photoionization**
  - **Vertical diffusion important**
  - **Slow chemical recombination process**
- **E and D layers**
  - **Photoionization**
  - **No diffusion**
  - **Fast chemical recombination**
    - Loss ∝ n^2



Radiowave Propagation

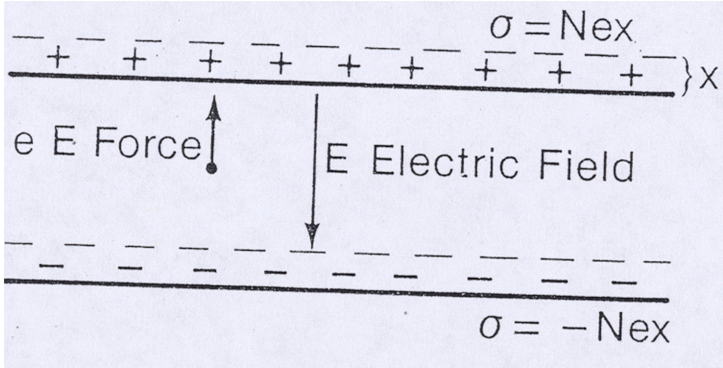
Appleton-Hartree Formula

$n_{\pm}^2 = 1 - \dfrac{2X(1-X)}{2(1-X) - Y_T^2 \pm \sqrt{Y_T^4 + 4(1-X)^2 Y_L^2}}$ $X = \left(\dfrac{f_p}{f}\right)^2 = \dfrac{\left(n_p e^2 / 4\pi^2 \varepsilon_0 m\right)}{f^2}$ $Y_T = Y \sin\theta_B; \quad Y_L = Y \cos\theta_B$ $Y = \dfrac{f_g}{f} = \dfrac{\left(\lvert e \rvert B_0 / 2\pi m\right)}{f}$	Appleton-Hartree: electromagnetic wave (carrier) propagating in a magnetized plasma, neglecting collisions

$n_{\pm}^{group} = 1 + \dfrac{1}{2} X \mp XY \lvert\cos\theta_B\rvert + \dfrac{3}{4} X \left[\dfrac{1}{2} X + Y^2 \left(1 + \cos^2\theta_B\right)\right]$	Energy travels at group speed

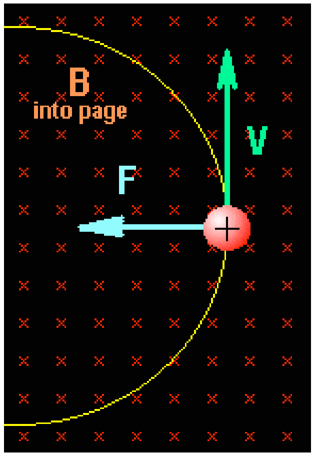
Plasma and Gyro Frequencies

Restoring forces
in a plasma

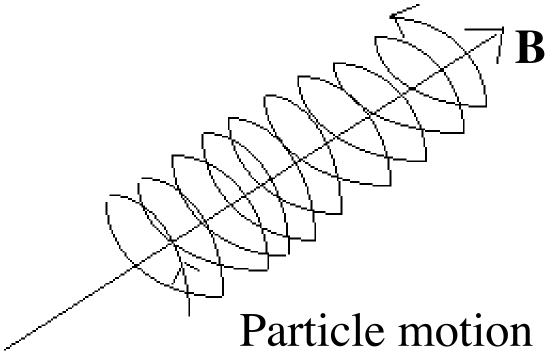


- **F-layer plasma frequency ~ 9 MHz (depends on density)**
- **Gyro frequency ~ 1.4 MHz (depends on magnetic field strength**

Gyration
about magnetic field
line



Magnetic Field



Particle motion

Phase and Range Ionospheric Observables

$$PI = P_2 - P_1 = 40.3TEC\left(\frac{f_1^2 - f_2^2}{f_1^2 f_2^2}\right) + b_I^r + b_I^s$$

$$LI = L_1 - L_2$$

$$= 40.3TEC\left(\frac{f_1^2 - f_2^2}{f_1^2 f_2^2}\right) + n_1\lambda_1 + n_2\lambda_2 + b_I'^r + b_I'^s$$

$f_1 = 1575.42$ MHz
$f_2 = 1227.60$ MHz

Pseudo-range and phase observables. ρ includes non-dispersive terms, including geometry, troposphere and clocks. $b_I^{r,s}$ represents hardware delays that can vary between the two GPS frequencies. $\lambda_{1,2}$ is the GPS wavelength. $n_{1,2}$ are unknown phase integer cycles

- **In direct TEC observations (single-difference), phase level is assumed unknown**
- **Pseudorange level is absolute, except for instrumental biases**
- **Pseudorange noise >> carrier phase noise**

Units Cheat Sheet

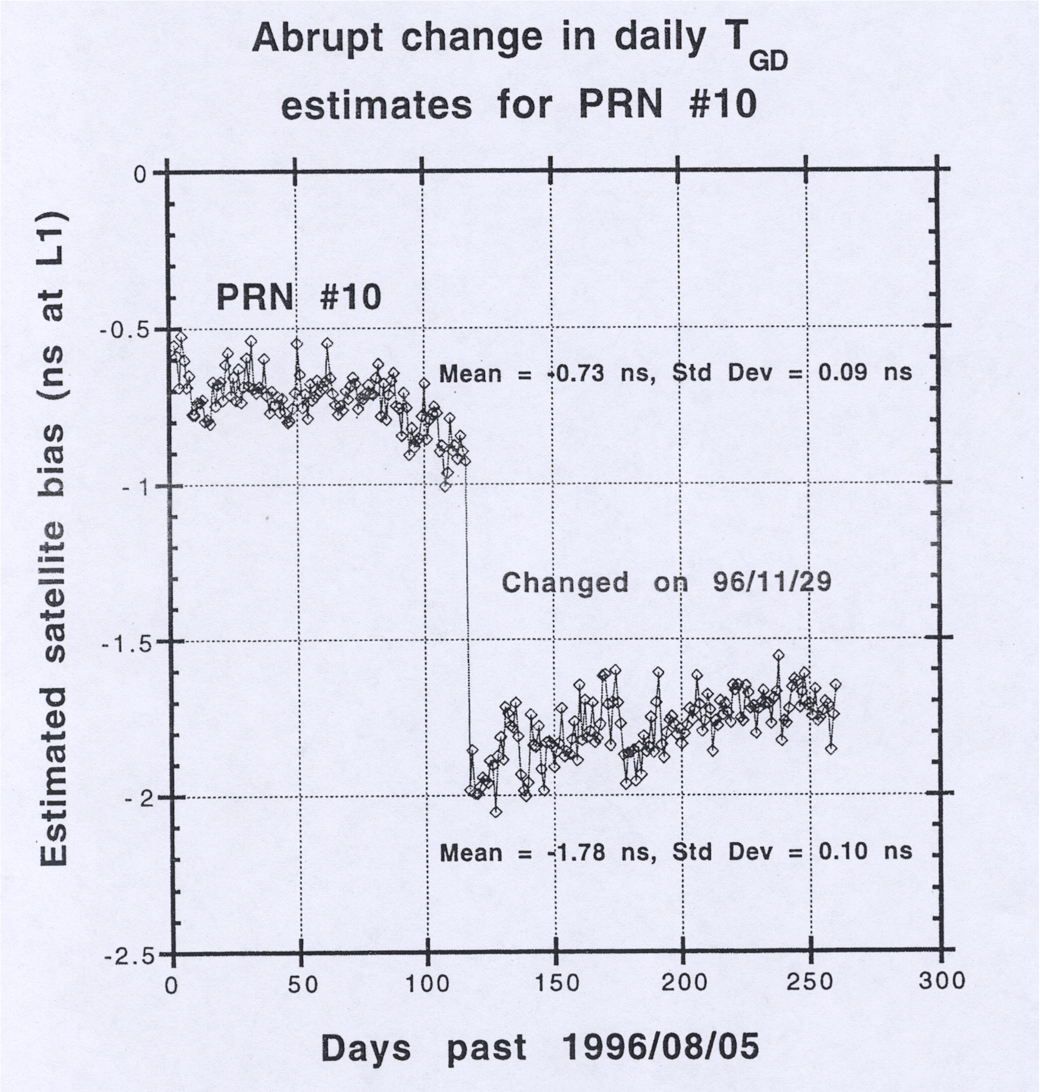
$$\int N\,dL = 40.3\,TEC$$

TEC: Total Electron Content is the integral of electron density along the line of sight between GPS transmitter and receiver (TEC in TEC Units)

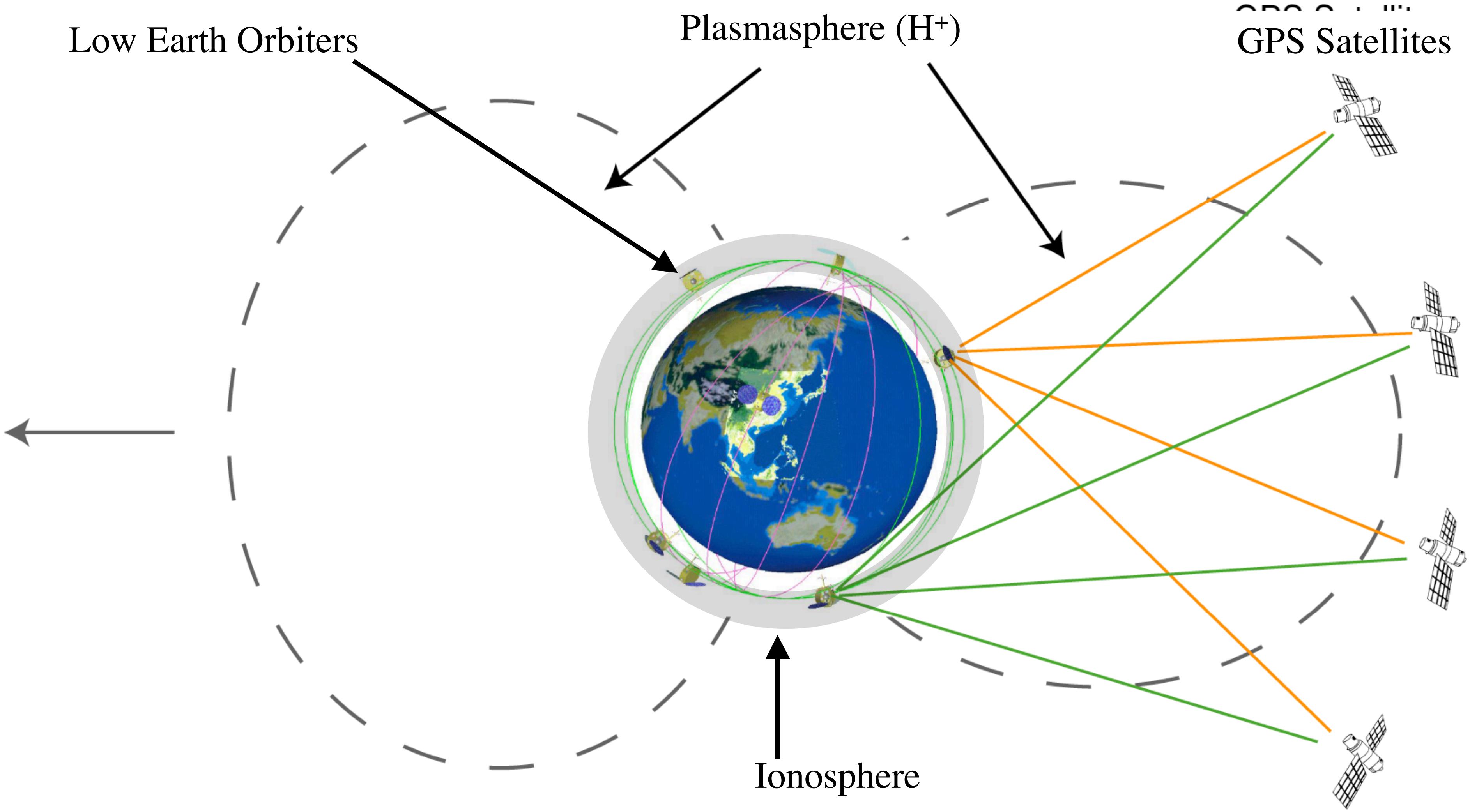
N measured in electrons/meter^3

- **1 TECU = 10^{16} electrons/m^2**
- **1 TECU = 16.2 cm of delay at L1**
- **1 TECU = 10.5 cm differential delay (L1-L2)**
- **1 TECU = 0.35 nsec differential delay (L1-L2)**

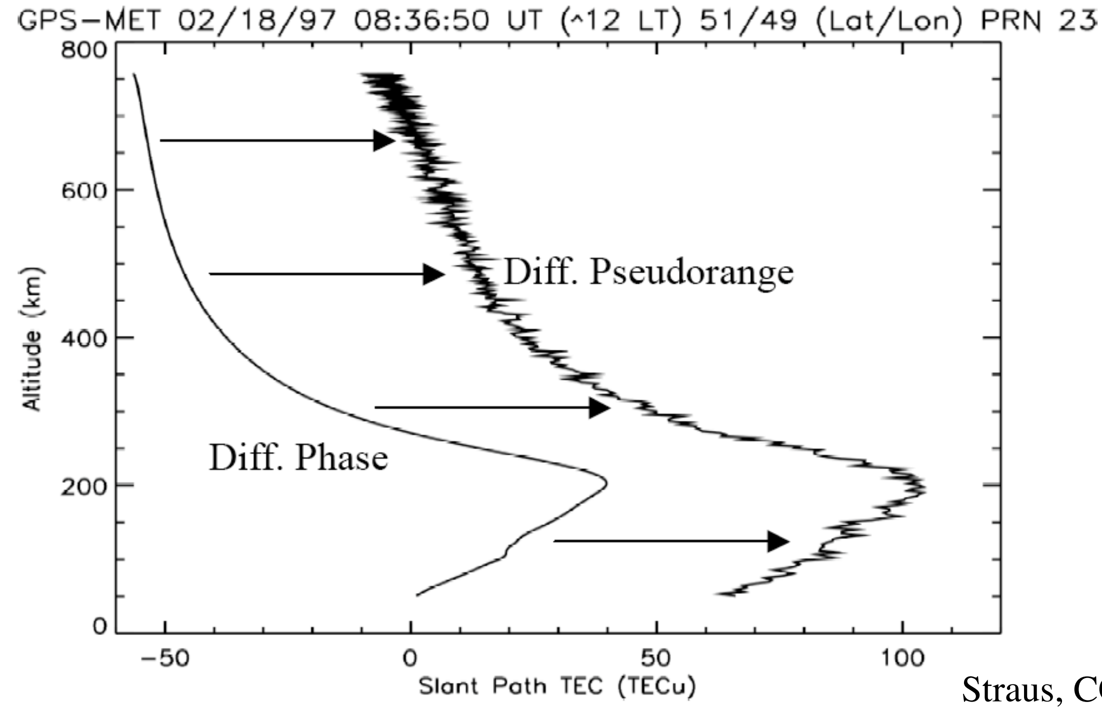
Bias Stability: Satellite



Electron Content In The Ionosphere/Plasmasphere System



Formation of Precise TEC: "Leveling"

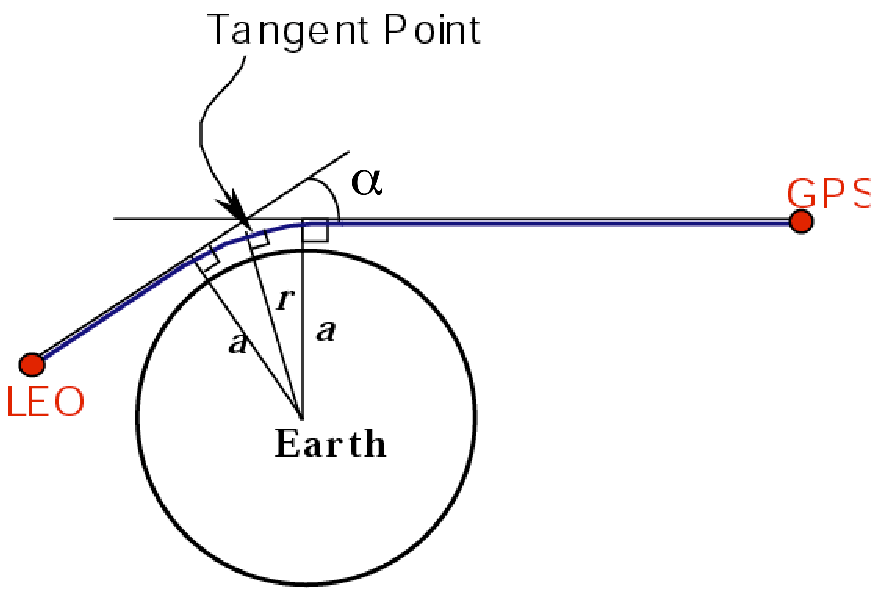


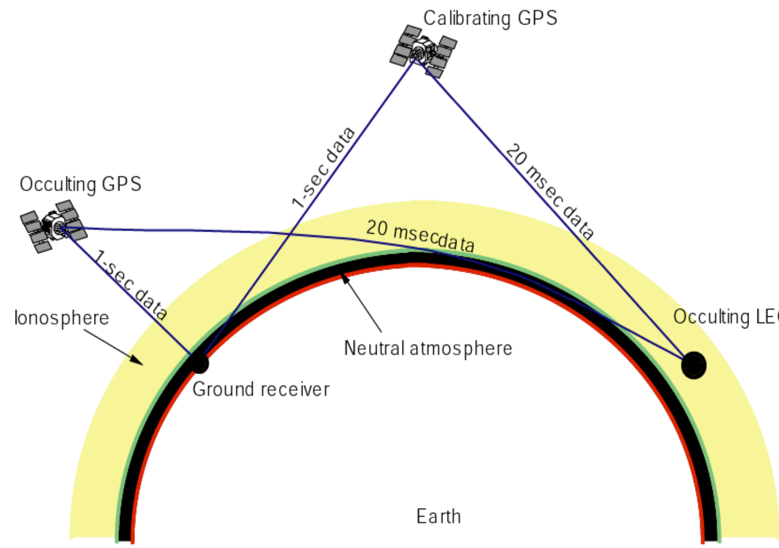
Straus, COSMIC Colloquium 2004

$$B_{rs} = \frac{\sum_{i=1}^{M} \frac{1}{\sigma_i^2} \left\{ \left(P_{2i} - P_{1i} \right) - \left(L_{1i} - L_{2i} \right) \right\}}{\sum_{i=1}^{M} \frac{1}{\sigma_i^2}}$$

Weighted estimate of leveling adjustment, sum over M measurements i, each with expected error σ_i

Occultation Geometry





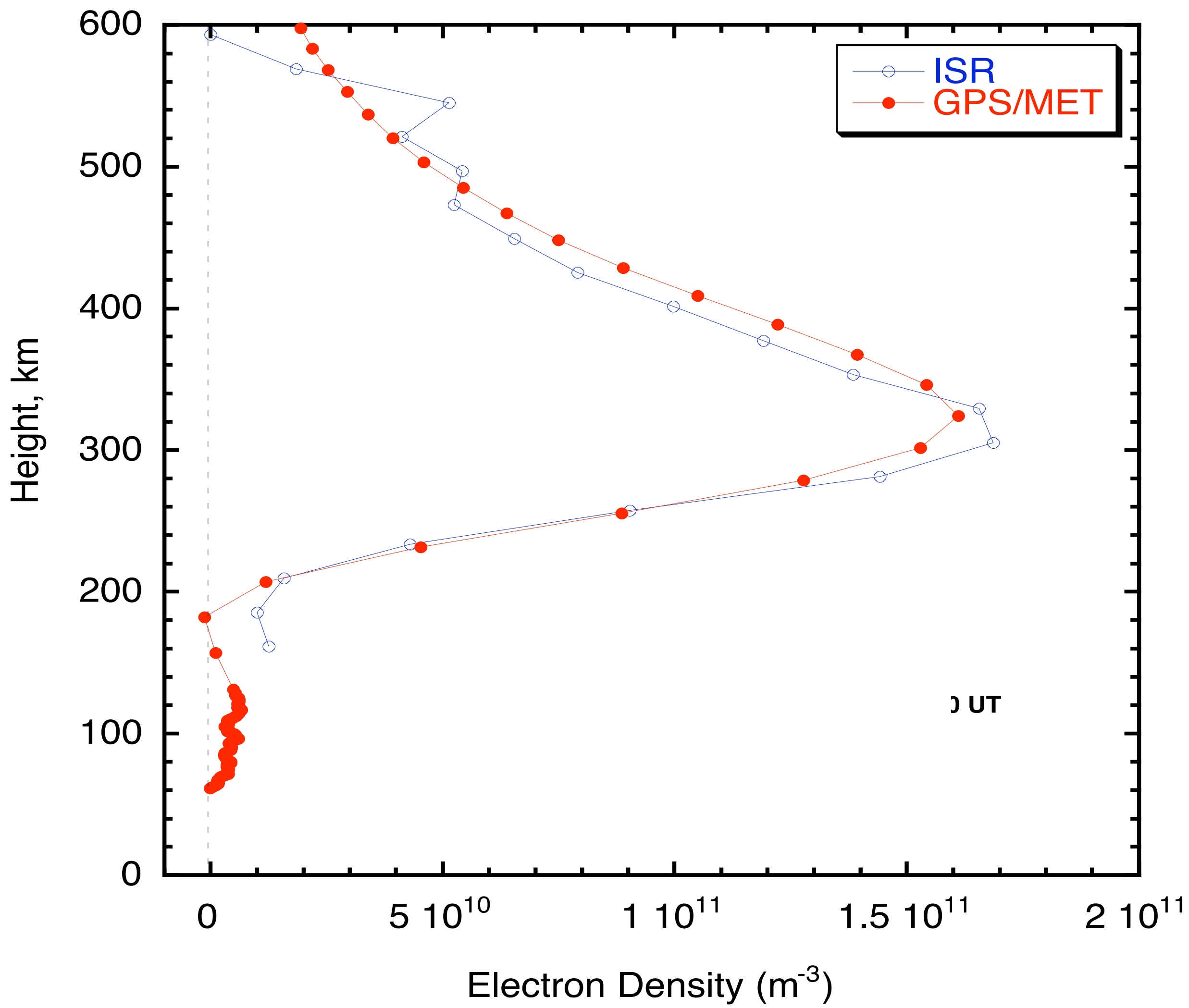
- **Single Frequency Retrievals**
- **Dual Frequency Retrievals**
  - **TEC = const. x (L1 – L2)**
  - **α ~ dTEC/dt**

$$\alpha(a) = 2a \int_a^\infty \frac{1}{\sqrt{a'^2 - a^2}} \frac{d\ln(n)}{da'} da'$$

$$\ln(n(r)) = \frac{1}{\pi} \int_{nr}^\infty \frac{\alpha}{\sqrt{a^2 - r^2 n^2}} da$$

Example of electron density profile

GPS/MET Profile
(Compared to Millstone hill radar)



E-Region Structure

Examples of i onospheric profiles obtained from GPS occultations illustrating how GPS occultations can be used for ionospheric profiling of electron density and the sensitivity to fine structures visible near the E-region [Hajj and Romans, 1998]. The retrieved electron density is labeled as "pseudo-density" because of the simplifying assumptions employed (see text). The lack of fine structures above ~120 km is due to the lower rate (0.1 Hz) data above that altitude limiting the vertical resolution to ~30 km. High rate data for other periods and other satellites are available throughout the ionosphere and can be used.

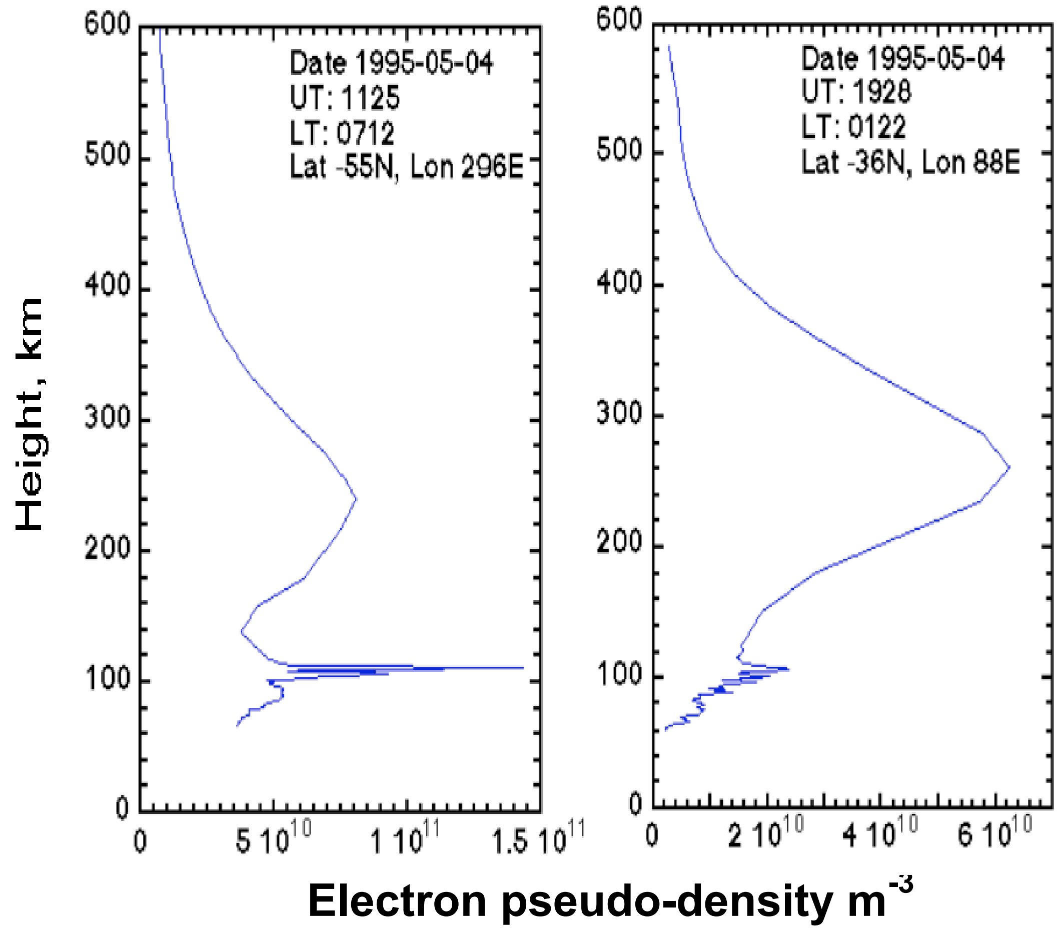
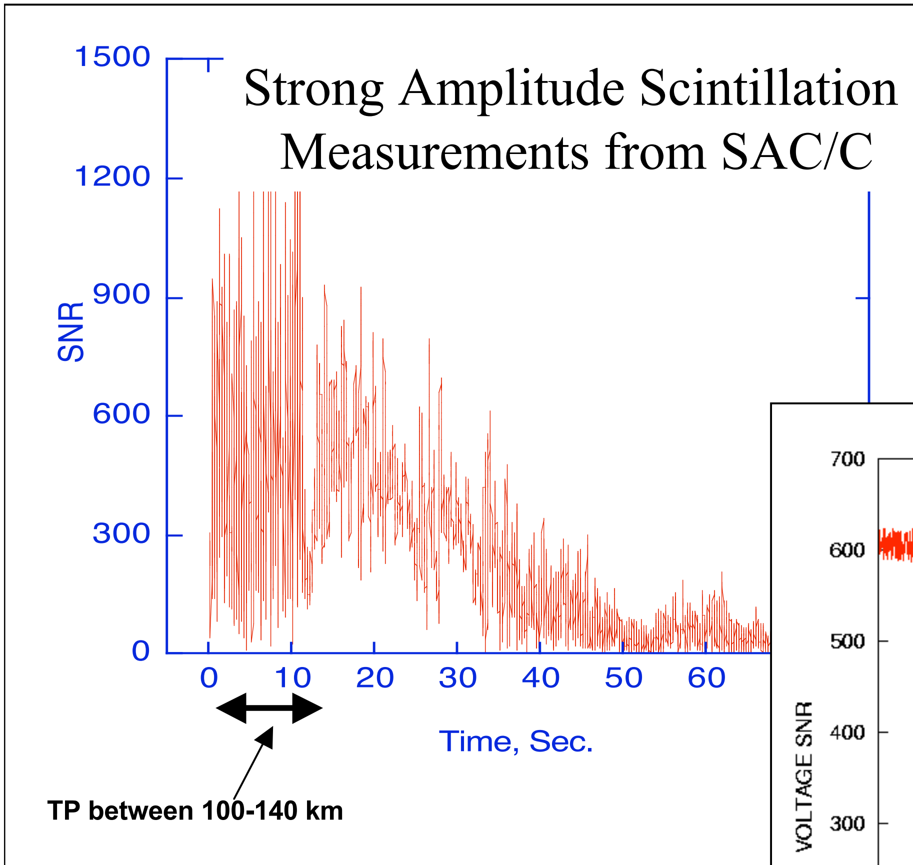


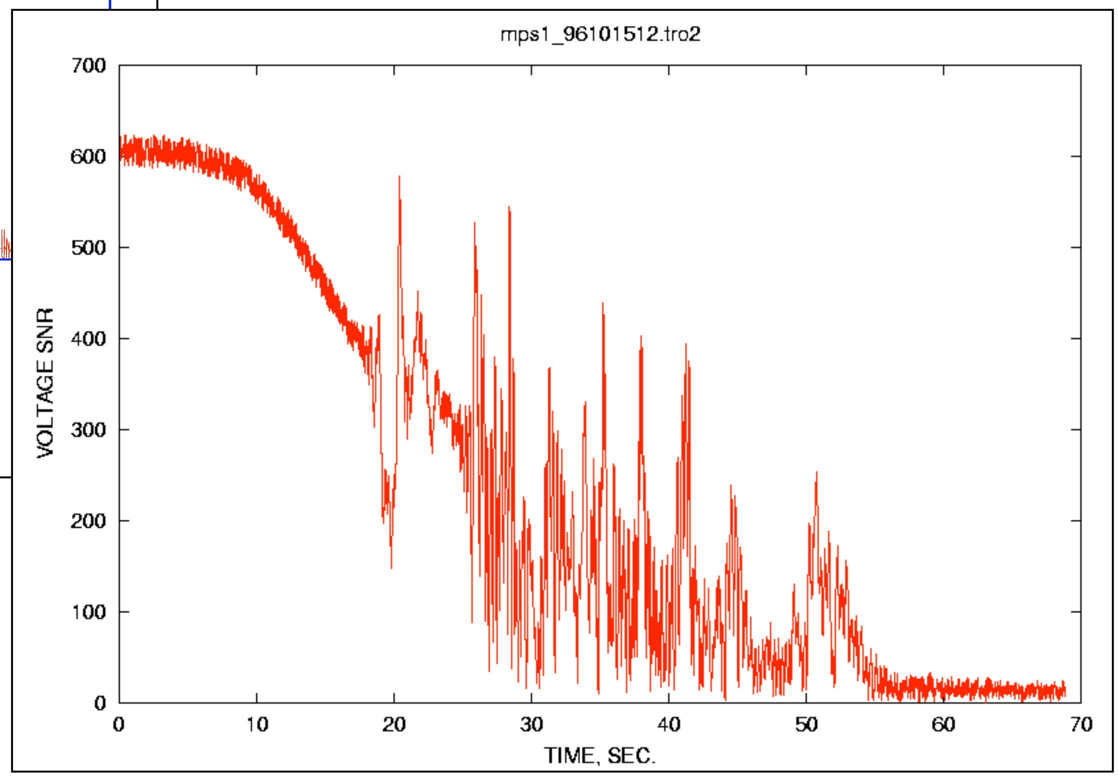
Figure 1

Hajj and Romans, 1998

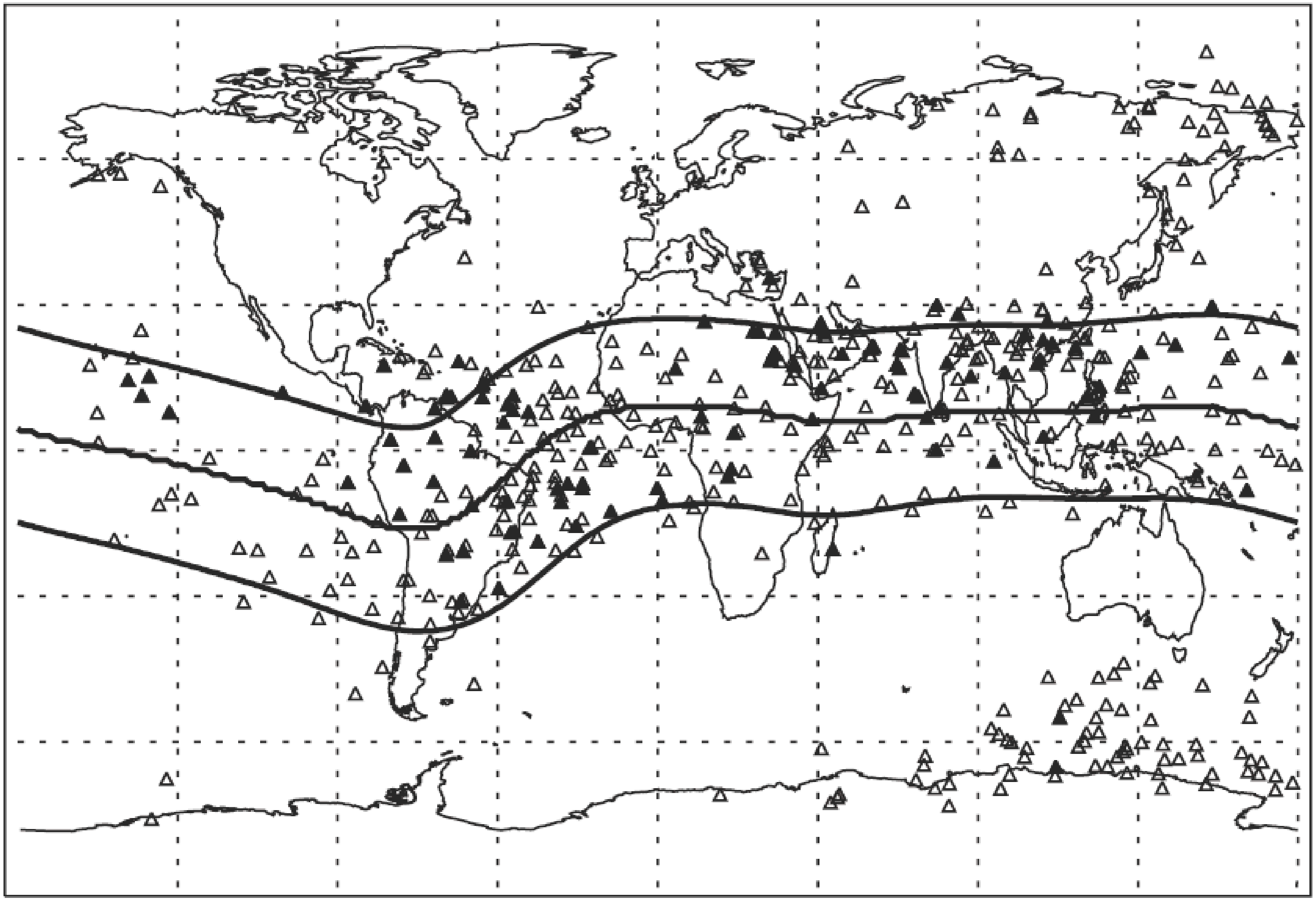
Scintillation



Typical SNR



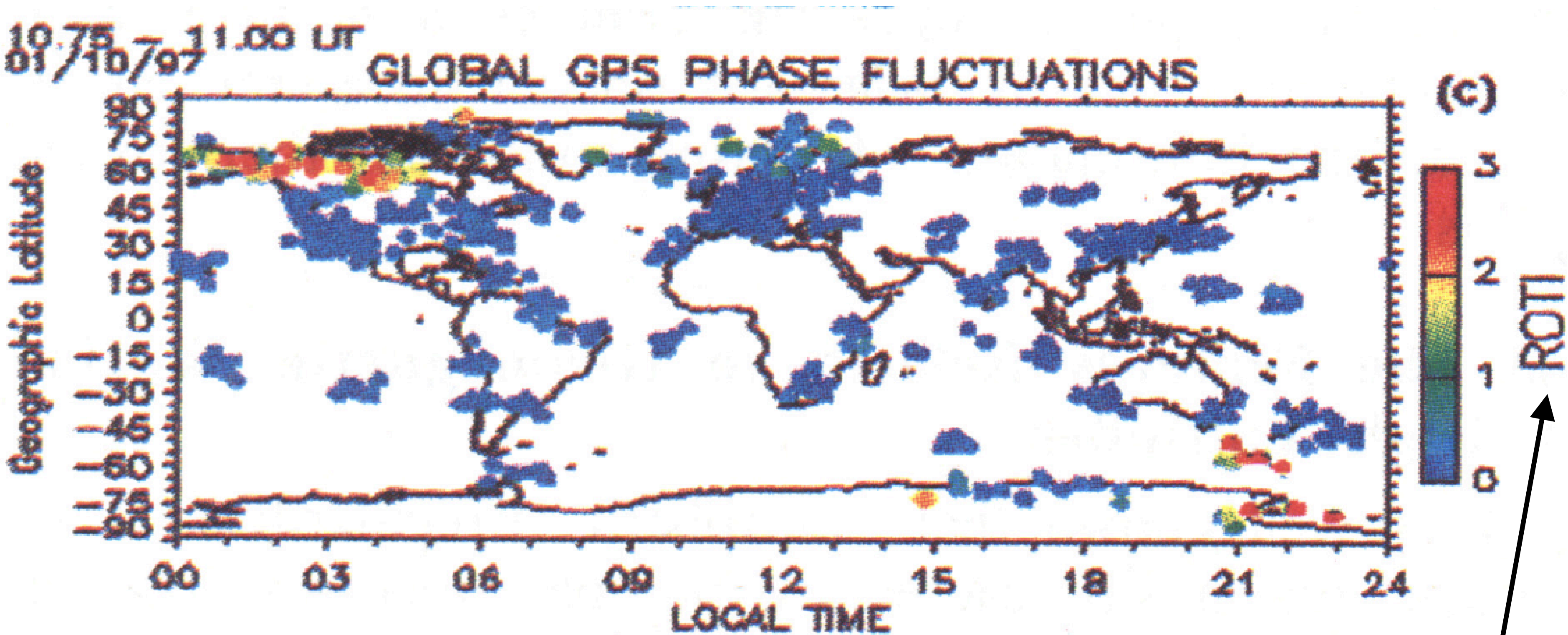
Location Of Strong Scintillation (Amplitude)



Straus et al., GRL 2003

February & March, 2002

High Latitude Scintillation At Solar Minimum (Phase)



Phase fluctuation index

Pi et al., GRL 1997

Global Morphology Of Scintillation

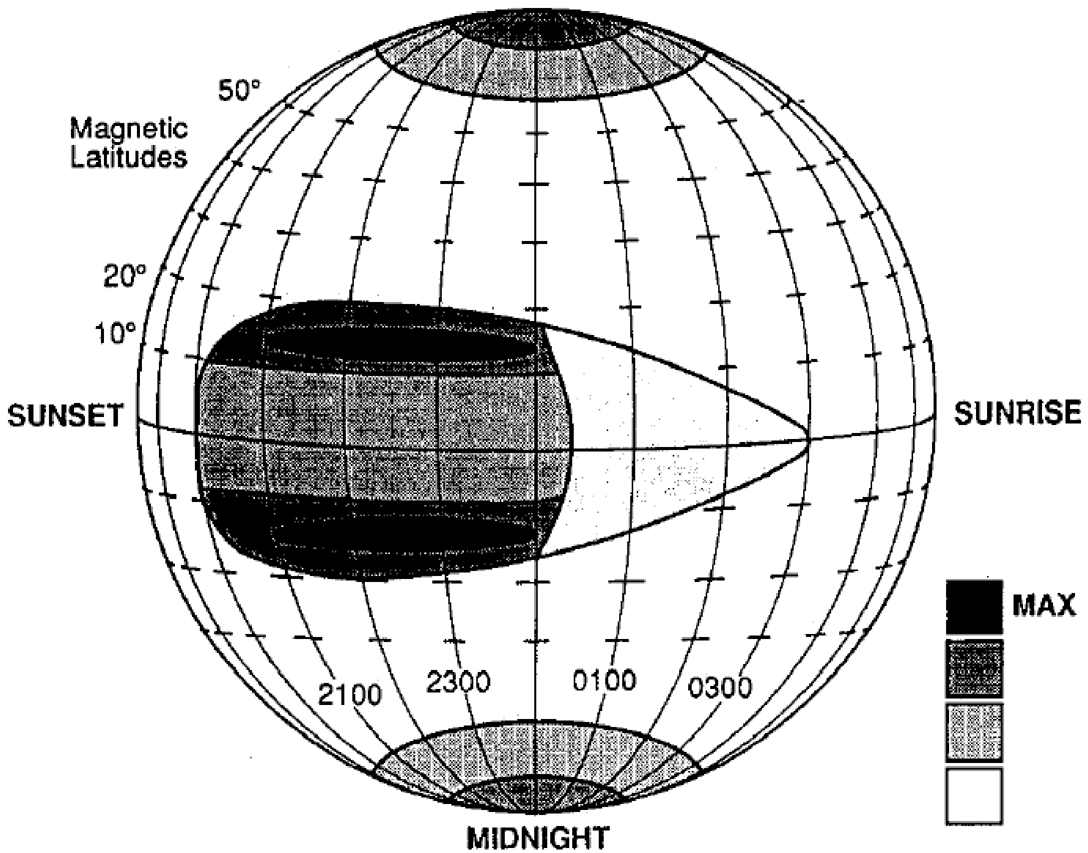
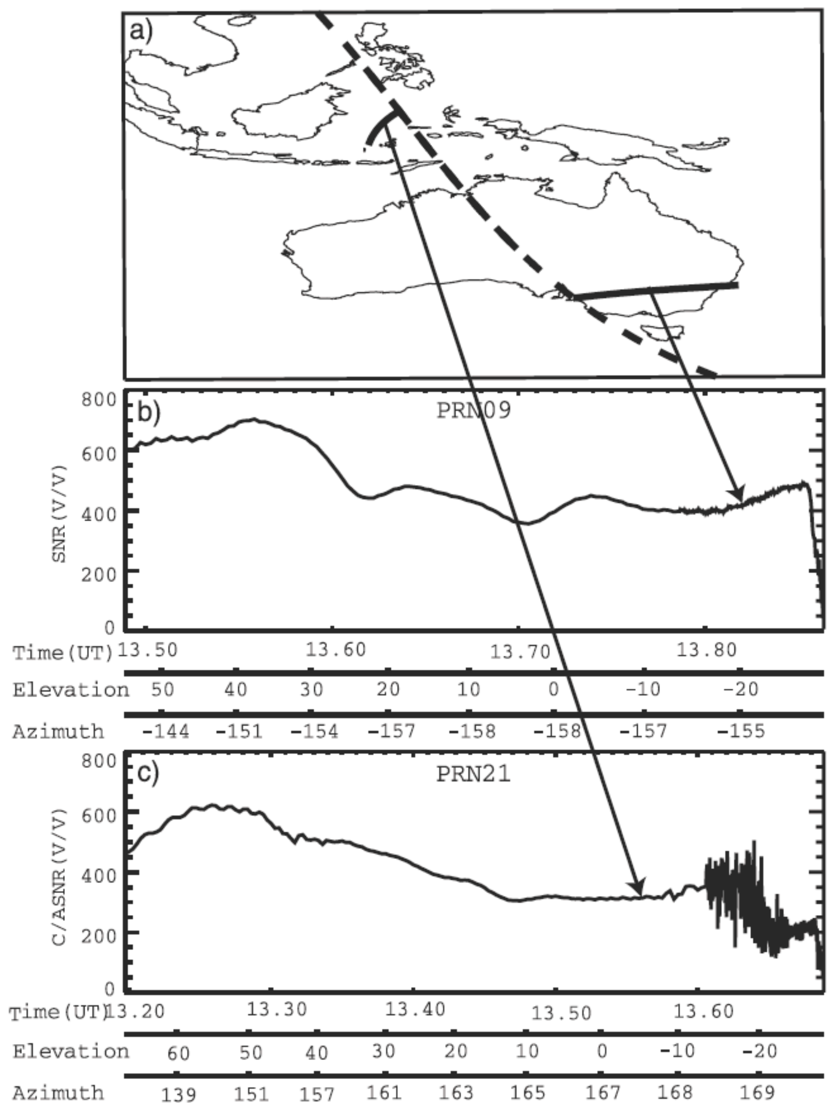


Figure 2. The nighttime scintillation activity during solar maximum. The anomaly regions of the equatorial ionosphere show the most intense scintillation.

Aarons, 1996

Occultations and Scintillation



Straus et al., GRL 2003

TEC Science

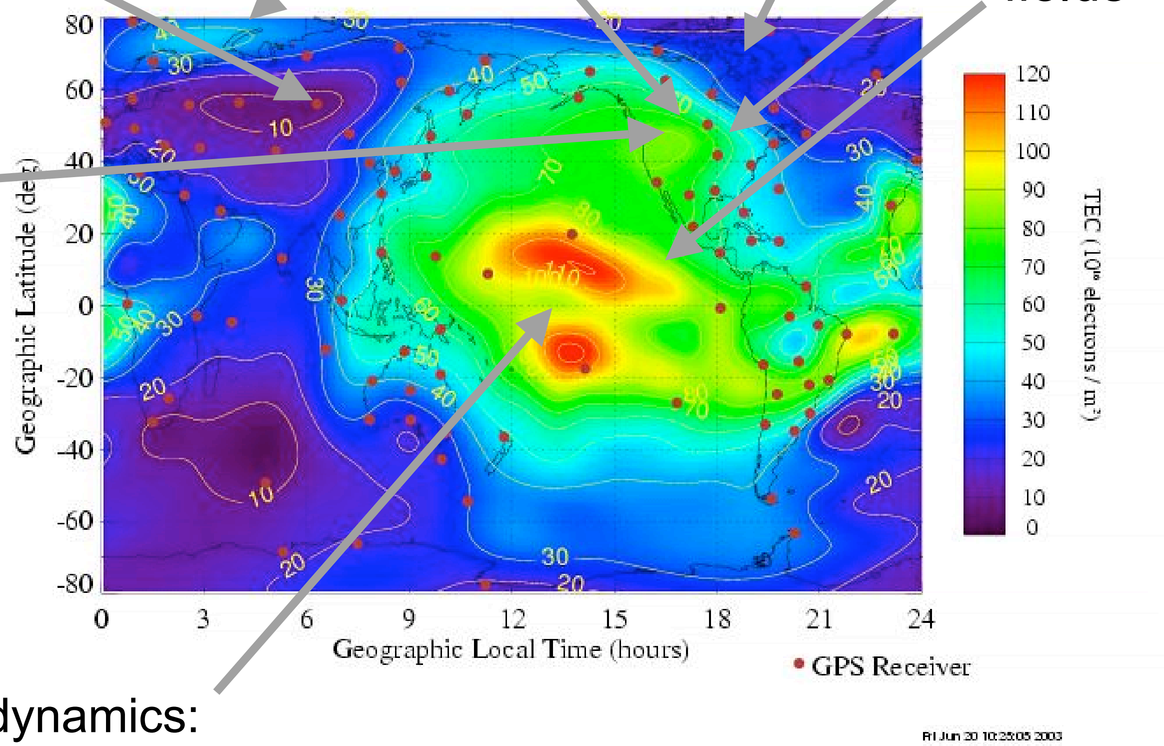
Ionization from particle precipitation

Transport of plasma blobs or patches –
Magnetospheric and solar wind convection

Thermospheric composition changes and dynamo electric fields

Mid-latitude trough
Plasmapause

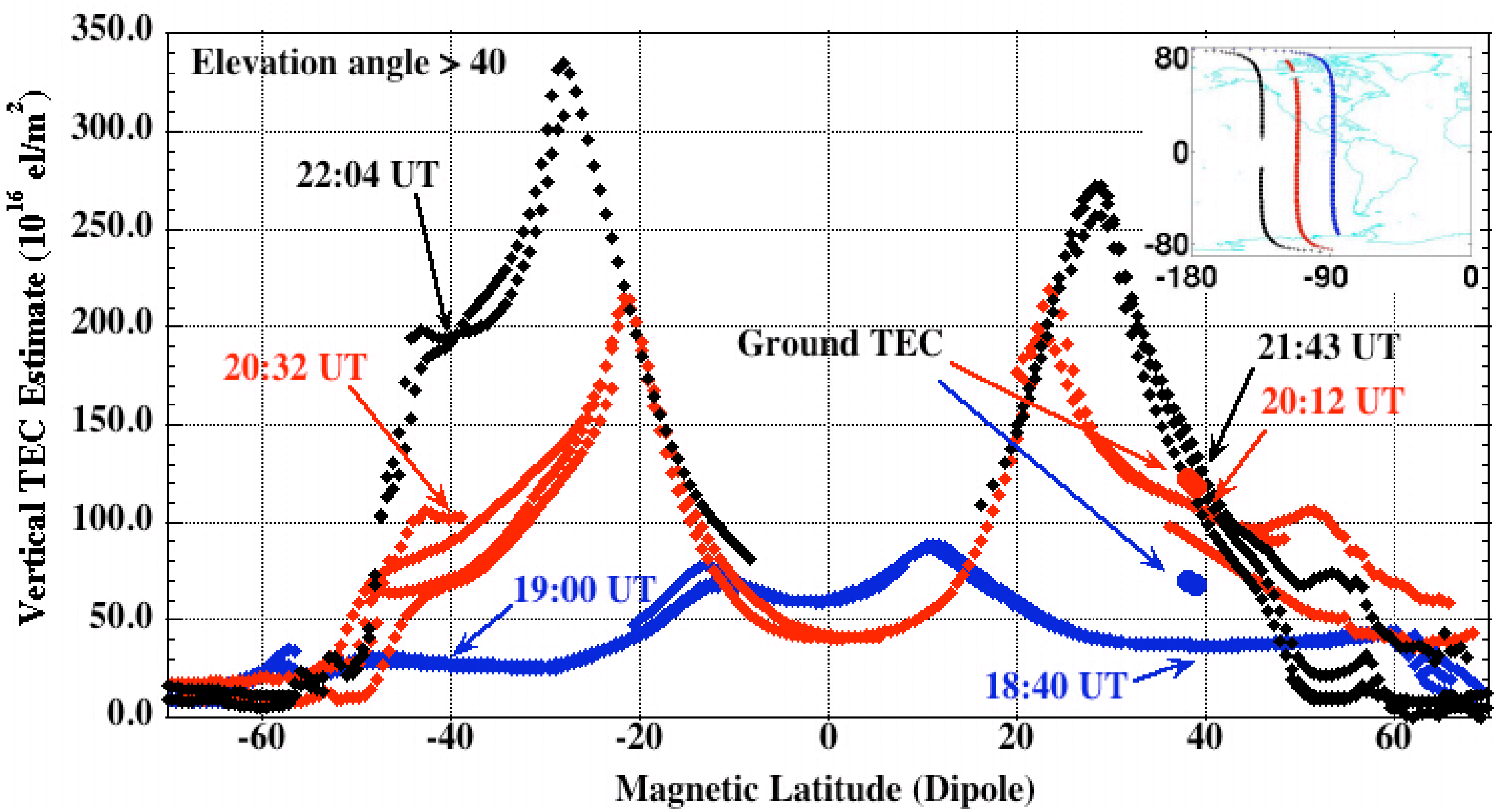
SAID or Polarization Jets?



Equatorial electrodynamics:
magnetospheric, thermospheric

Note: this figure is illustrative

Global Ionospheric Storm Measured From CHAMP



Mannucci et al., GRL 2005

Summary

- **Despite its low density, the Earth's ionosphere has a major impact on GPS signals**
- **Formation of vertical ionospheric structure is a complex process of creation, loss and transport of ionized plasma**
- **The ionosphere varies significantly with solar cycle and with global region**
- **GPS is used to measure total electron content and estimate vertical profiles of electron density**
- **Be aware of the impact of scintillation and *global ionospheric storms***