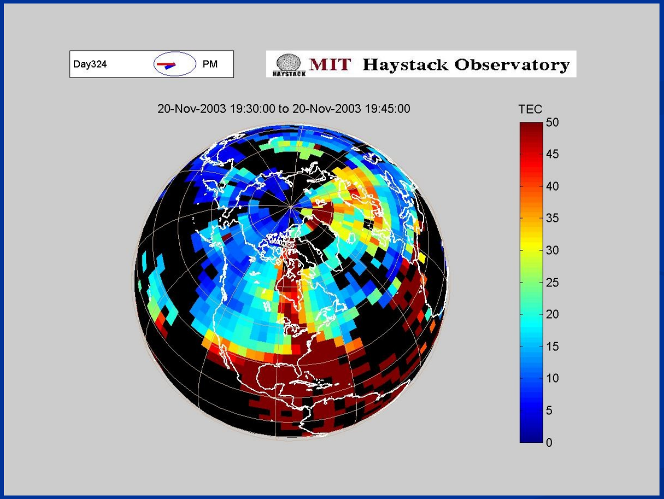
# Introduction to the Ionosphere

Anthea Coster, MIT Haystack Observatory



# References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• Rishbeth, Henry; Garriott, Owen K.
Introduction to ionospheric physics, New, York, Academic Press, 1969. International geophysics series, v. 14

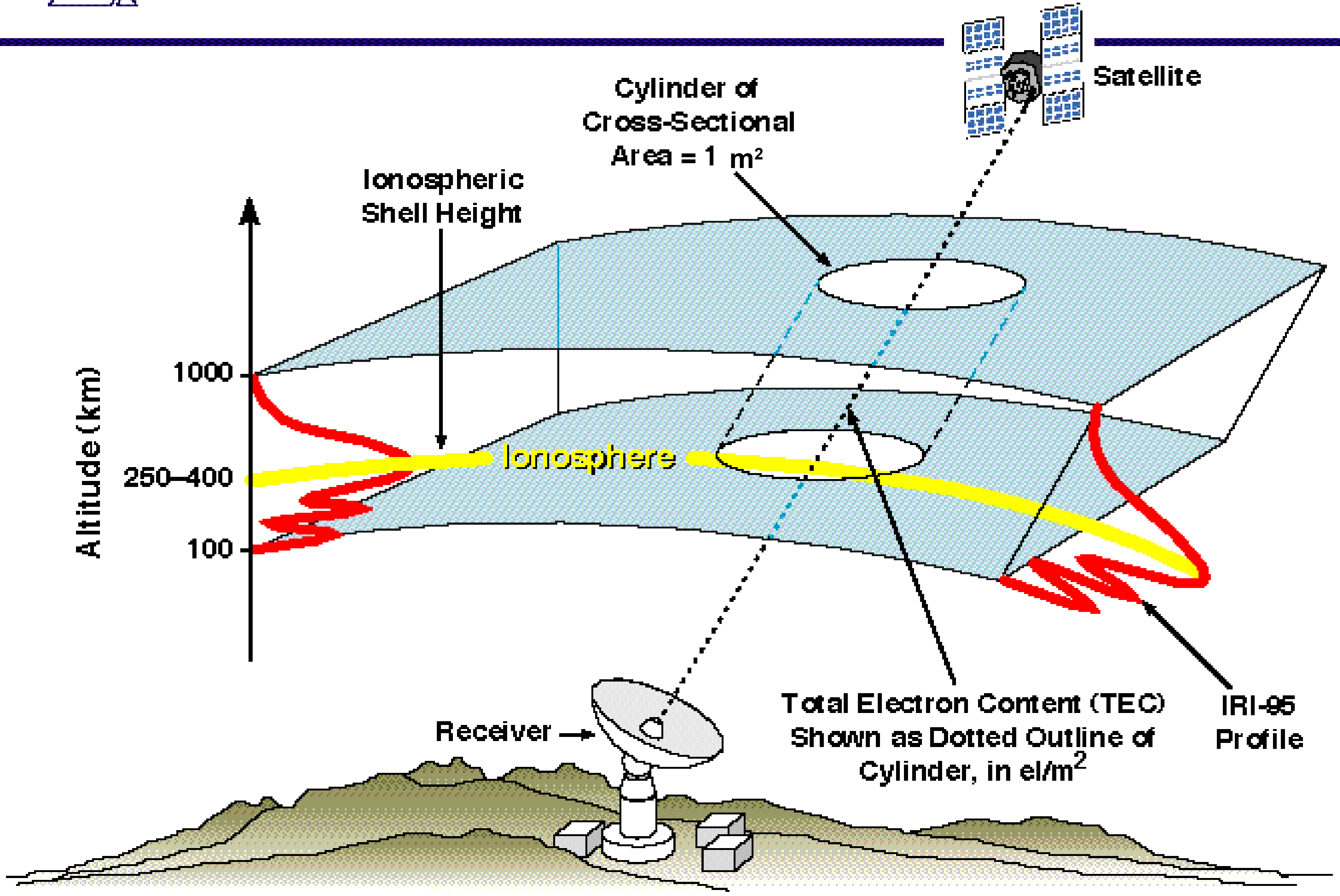
•Jursa, Adolph S., Handbook of Geophysics and the Space Environment, 4th edition, 1985, Air Force Geophysics Laboratory, Hanscom AFB, MA

# Outline

- Definition of Ionosphere
- Basics: Scale Heights/ Production Loss/Conductivities
- Index of Refraction
- Debye Length
- Low Latitudes/Mid-Latitudes/High Latitudes
- Movie

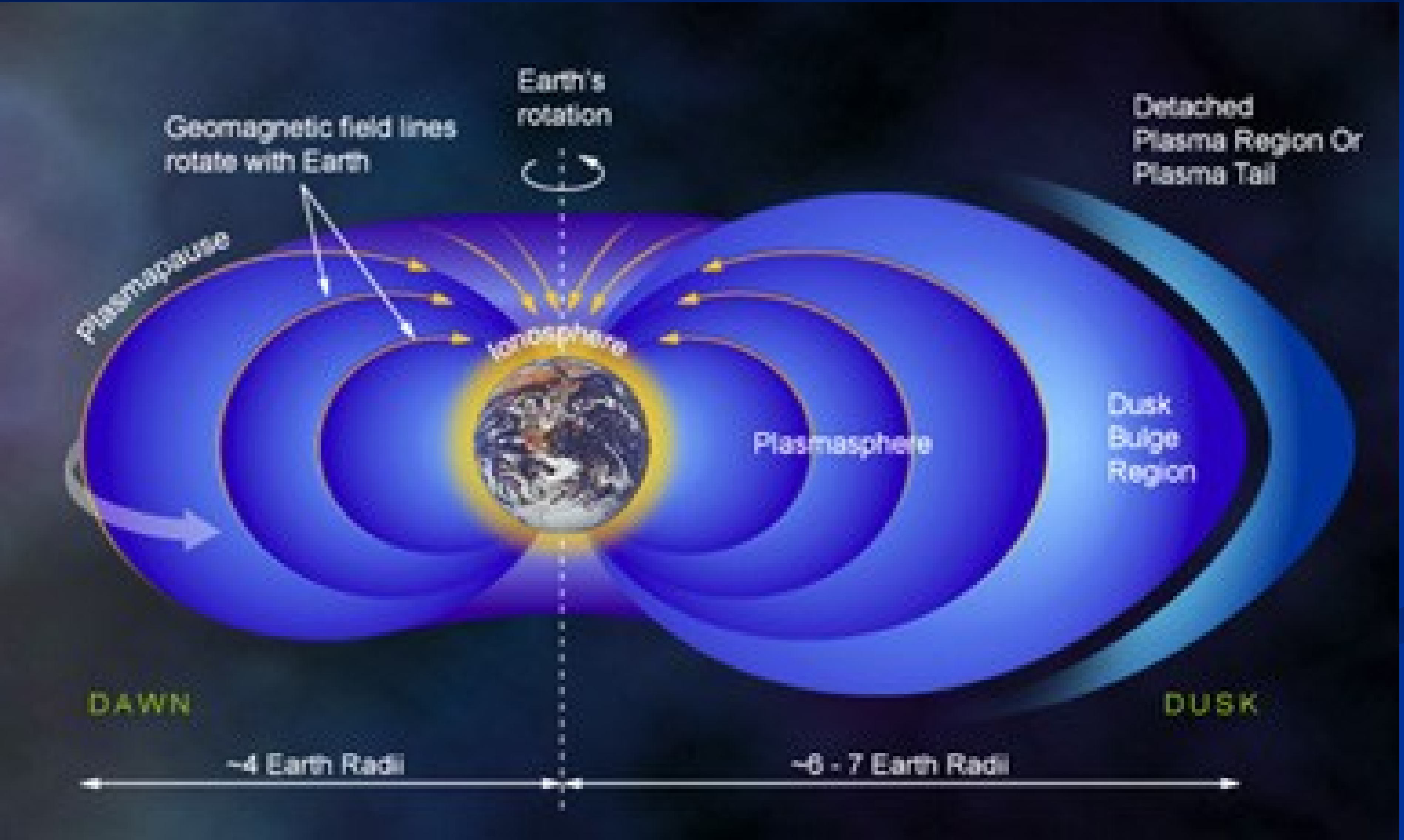
1. Ionosphere – What is it? Where is it? Why do we care?

# Ionosphere



Satellite
Cylinder of Cross-Sectional Area = 1 m²
Ionospheric Shell Height
Altitude (km)
1000
250–400
100
Ionosphere
Receiver
Total Electron Content (TEC) Shown as Dotted Outline of Cylinder, in el/m²
IRI-95 Profile

# Ionosphere and Plasmasphere



# Sun – Earth System Overview

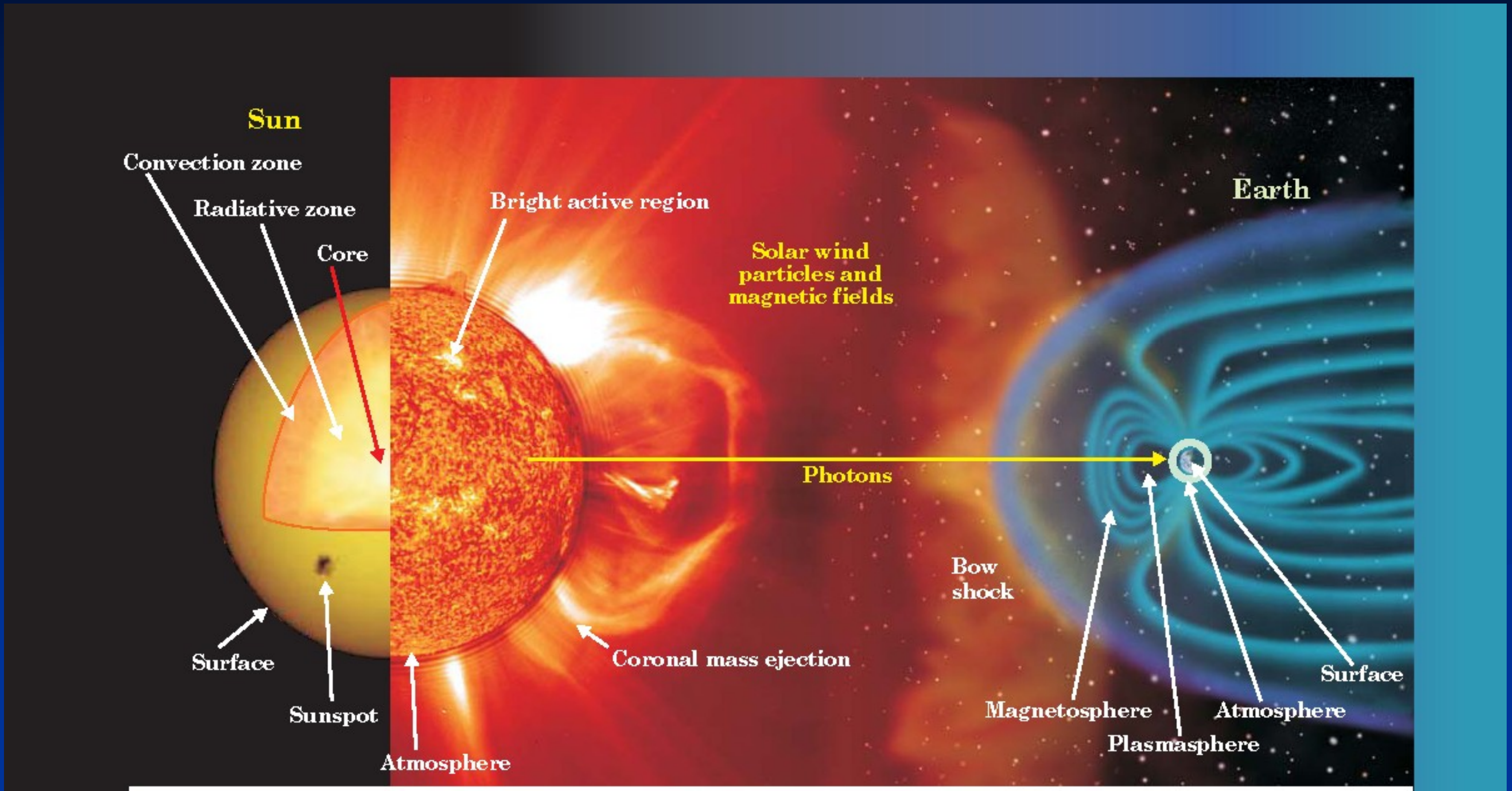
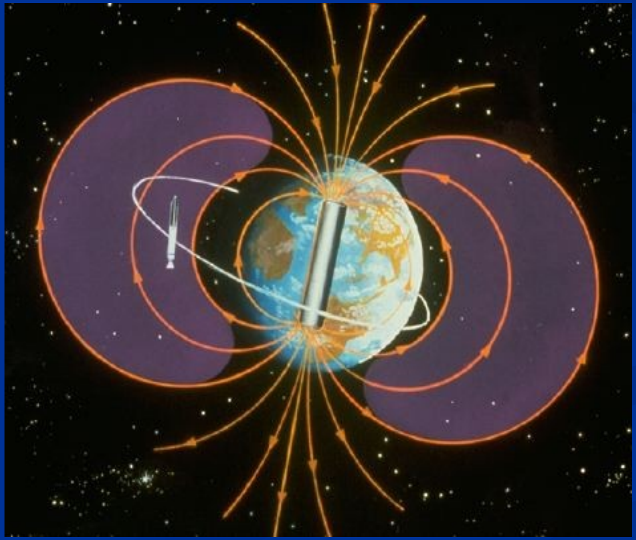



**Figure 1. The Sun–Earth system.** Energy in various forms is constantly flowing from the Sun to Earth. Dynamo action in the convection zone drives variations in this energy flow by producing sunspots and bright active regions. Photons from the Sun's surface and atmosphere reach Earth's surface and atmosphere, but particles and fields that together form the solar wind are intercepted by the magnetosphere (blue). Eruptive events such as coronal mass ejections, shown emerging from the Sun's atmosphere into the solar wind, perturb the magnetosphere and allow energetic particles to penetrate Earth's atmosphere in the polar regions, where the magnetic field lines are anchored. (Figure not to scale.)

# Earth's Upper Atmosphere (and most of the Solar System): A Natural Plasma

- Plasma is the fourth state of matter
- The universe is filled with plasma
- Extreme ultraviolet output from the Sun creates a plasma in Earth's upper atmosphere through ionization



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1. What is it made of? Scale Heights. Different regions (D/E/F - importance of different processes in different regions). How does it form? Production/Loss Mechanisms

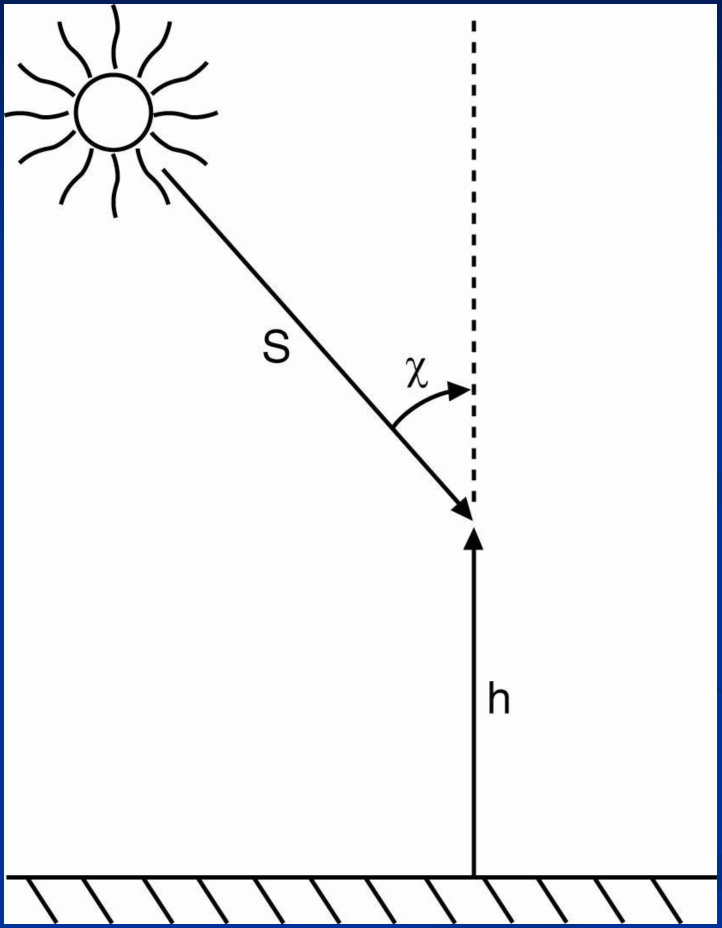
# Distinct Regions in the Ionosphere Form because:

The Solar spectrum deposits its energy at various heights depending on the absorption characteristics of the atmosphere.

The physics of recombination depends on the atmospheric density which changes with height.

The composition of the atmosphere changes with height

# Photoionization



# Scale Height

A **scale height** is a term often used in scientific contexts for a distance over which a quantity decreases by a factor of *e*. It is usually denoted by the capital letter *H*.

For planetary atmospheres, it is the vertical distance upwards, over which the pressure of the atmosphere decreases by a factor of *e*. The scale height remains constant for a particular temperature. It can be calculated by

$$H = kT/Mg \quad \text{where:}$$

$k$ = gas constant = 8.314 J·(mol K)−1
$T$ = mean molecular temperature in kelvins
$M$ = mean molecular mass of dry air (units kg·mol−1)
$g$ = acceleration due to gravity on planetary surface (m/s²)

# Hydrostatic Equilibrium

- The force of gravity on a parcel of air is balanced by the pressure gradient

$$n_n m_n g = \frac{-dp}{dh} = -\frac{d}{dh}(n_n k T_n)$$

- Assume $T_n$ is independent of height and integrate we obtain

$$n_n = n_0 \exp[-(h - h_0)/H_n]$$

- The density of an atmosphere falls off (generally) exponentially.

# Ionospheric Density Profile

- Photochemical equilibrium assumes transport is not important so local loss matches local production.

$$\frac{\partial n_e}{\partial t} = Q - L = 0$$

- If loss is due to electron-ion collisions, we get a Chapman layer

$$Q = L = \alpha n_e^2$$

$$n_e = (Q/\alpha)^{1/2}$$

- If there is vertical transport

$$\frac{\partial n_e}{\partial t} = Q - L - \frac{\partial (n_e u_{eh})}{\partial h}$$

- Treating the pressure forces of electrons and ions and assuming neutrals are stationary, we obtain

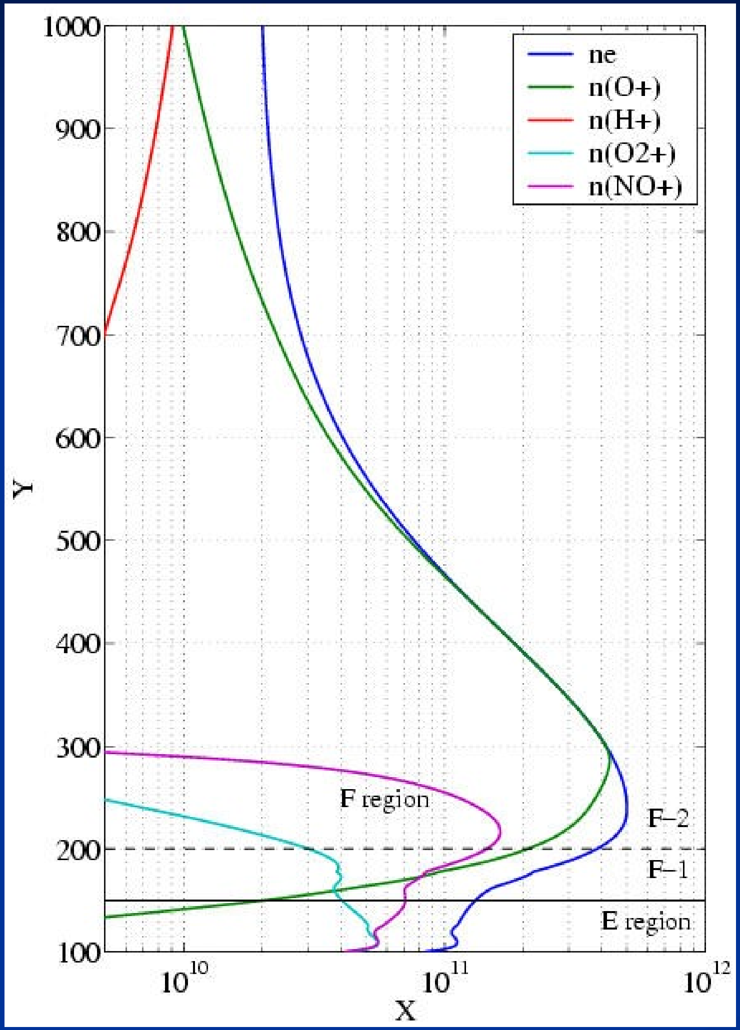
$$n_e u_{pl} = -D\left[\frac{dn_e}{dh} + \frac{n_e}{H_p}\right]$$

- Where $D = k(T_i + T_e)/m_i \upsilon_{in}$ is the ambipolar diffusion coefficient and $H_p$ the plasma scale height

$$k(T_i + T_e)/m_i g$$

- Vertical transport velocity becomes $u_{pl} = -(n_e m_i \upsilon_{in})^{-1}\left[\frac{dp_T}{d_h} + n_e m_i g\right]$

# Composition




**At heights over 100 km, molecular diffusion means that each molecular atomic species has its own scale height.**

**<u>Dominant Constituent</u>**

| | |
|---|---|
| **0-200 Km** | **Nitrogen** |
| **200-1000 Km** | **Oxygen** |
| **1000-2500 Km** | **Helium** |
| **2500 – 8-14 Earth Radii** | **Hydrogen** |

# The Earth's Ionosphere

- For historical reasons, the ionospheric layers are called D, E, F
  - D layer, produced by x-ray photons, cosmic rays
  - E layer, near 110 km, produced by UV and solar x-rays
  - $F_1$ layer, near 170 km, produced by EUV
  - $F_2$ layer, transport important
- .

# Why do we care about conductivities?

Ionosphere is a plasma with an embedded magnetic field.

$$\nabla \cdot [\sigma \cdot (\mathbf{E}(\mathbf{r}, t) + \mathbf{U}(\mathbf{r}, t) \times \mathbf{B}] = 0$$

**“The resulting electric field is as rich and complex as the driving wind field and the conductivity pattern that produce it”, Kelley, Ch. 3**

# Equations of Motion

Parallel equation of motion

$$qE = m_i \nu_{in} u_i \qquad -eE = m_e \nu_{en} u_e$$

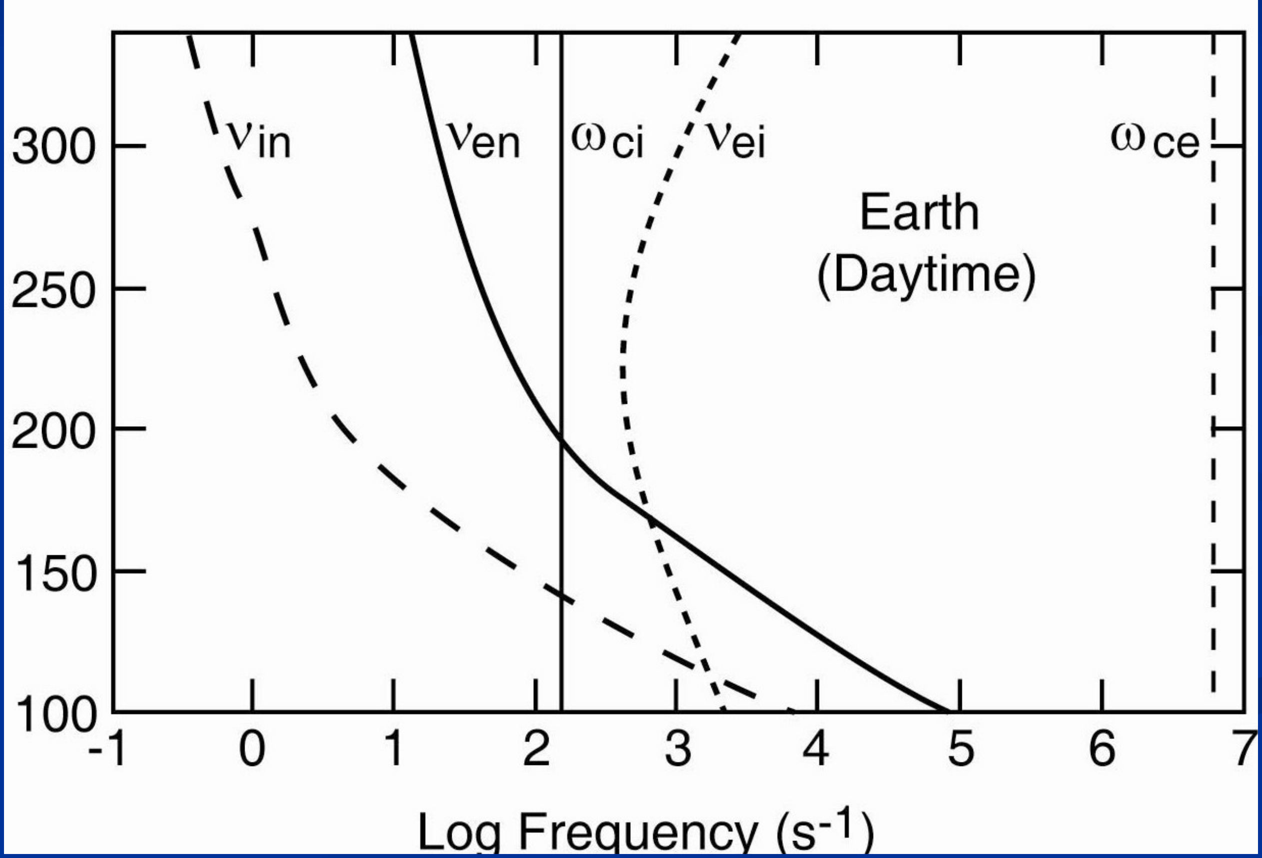
Perpendicular equation of motion

$$q\left(\mathbf{E}_\perp + \mathbf{u}_i \times \mathbf{B}\right) = m_i \nu_{in} \mathbf{u}_{\perp i}$$

$$-e\left(\mathbf{E}_\perp + \mathbf{u}_e \times \mathbf{B}\right) = m_e \nu_{en} \mathbf{u}_{\perp e}$$

# Collision Frequencies

Ion and electrons collide with neutrals as they gyrate. How they move in response to electric fields depends very much on the collision frequency relative to the gyro-frequency.



# Conductivity

$$\sigma_1 = \left[\frac{1}{m_e \nu_{en}}\left(\frac{\nu_{en}^{\ 2}}{\nu_{en}^2 + \Omega_e^{\ 2}}\right) + \frac{1}{m_i \nu_{in}}\left(\frac{\nu_{in}^{\ 2}}{\nu_{in}^2 + \Omega_i^{\ 2}}\right)\right] n_e e^2$$

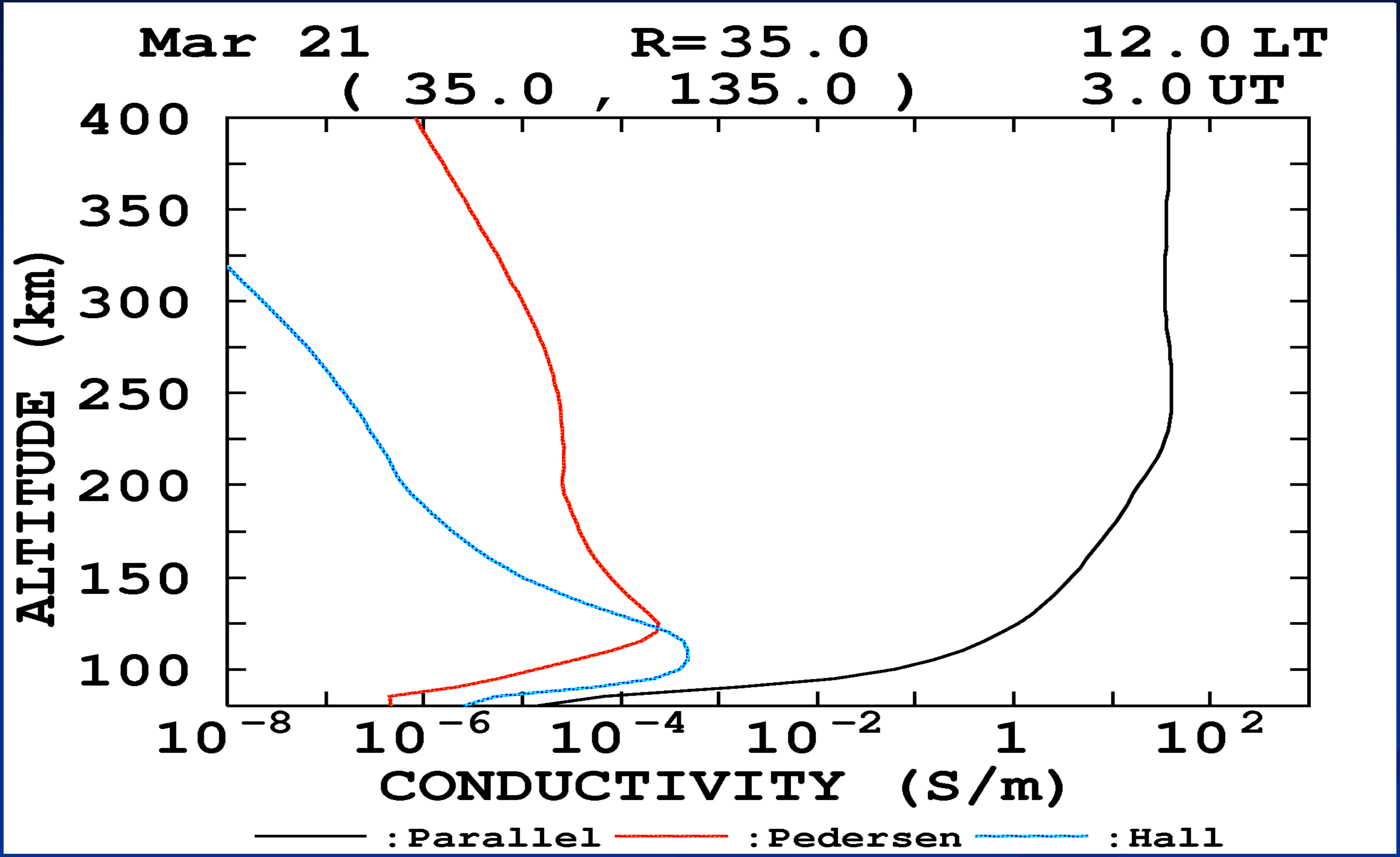
$$\sigma_2 = \left[\frac{1}{m_e \nu_{en}}\left(\frac{\Omega_e \nu_{en}}{\nu_{en}^2 + \Omega_e^{\ 2}}\right) - \frac{1}{m_i \nu_{in}}\left(\frac{\Omega_i \nu_{in}}{\nu_{in}^2 + \Omega_i^{\ 2}}\right)\right] n_e e^2$$

$$\sigma_0 = \left[\frac{1}{m_e \nu_{en}} + \frac{1}{m_i \nu_{in}}\right] n_e e^2$$

$$j = \begin{pmatrix} \sigma_1 & \sigma_2 & 0 \\ -\sigma_2 & \sigma_1 & 0 \\ 0 & 0 & \sigma_0 \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix}$$

- **Pedersen conductivity (along $E_\perp$) perpendicular B, parallel E; horizontal**
- **Hall conductivity (along E x B)**
- **Parallel conductivity**
- Conductivity tensor

http://wdc.kugi.kyoto-u.ac.jp/ionocond/exp/icexp.html



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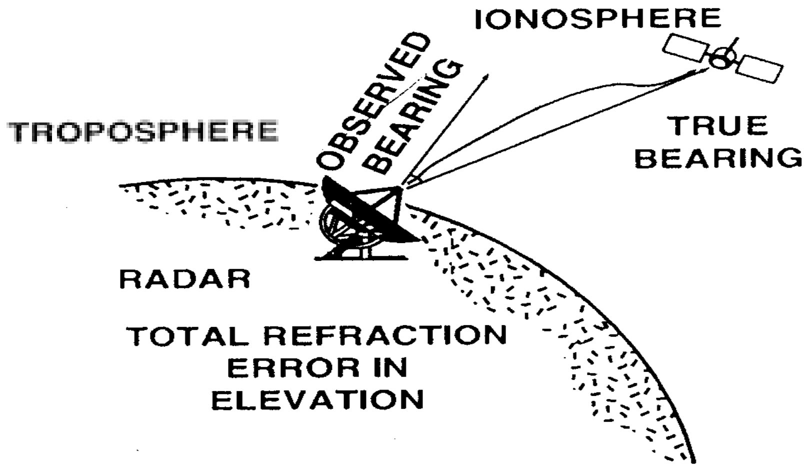
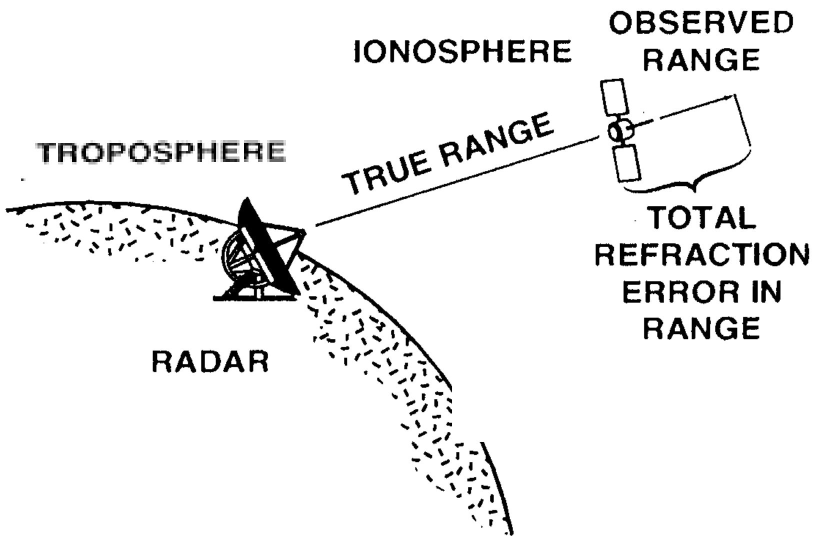
# Introduction to the IONOSPHERE

3. Index of refraction; definition of plasma frequency and gyrofrequency (introduction of magnetic field).

# Radio Waves Refract just like light

# Illustration of Atmospheric Effects



# INDEX OF REFRACTION

$$n^2 = 1 - \frac{X(1-X)}{(1-X) - \frac{1}{2}Y_T^2 \pm \left(\frac{1}{4}Y_T^4 + (1-X)^2 Y_L^2\right)^{1/2}}$$

$$X = \frac{\omega_N^2}{\omega^2} \qquad Y = \frac{\omega_H}{\omega} \qquad \omega_N = \left(\frac{Ne^2}{\varepsilon_0 m_e}\right)^{1/2} \qquad \omega_H = \frac{e|B|}{m_e}$$

$\omega$ = the angular frequency of the radar wave,

$Y_L = Y\cos\theta$, $Y_T = Y\sin\theta$,

$\theta$ = angle between the wave vector $\bar{k}$ and $\bar{B}$,

$\bar{k}$ = wave vector of propagating radiation,

$\bar{B}$ = geomagnetic field, N = electron density

e = electronic charge, $m_e$ = electron mass,

and $\varepsilon_0$ = permittivity constant.

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4. Debye length/Debye sphere why important

# 5. Debye length/Debye sphere

The Debye length is a measure of the plasma’s ability to shield out electric potentials that are applied to it.

The Debye length marks the division between different regimes of plasma’s behavior; i.e. collective plasma motion versus that of individual particle motion.

Plasma phenomenon that take place over distances greater than the Debye length must be described in terms of collective behavior of the plasma.

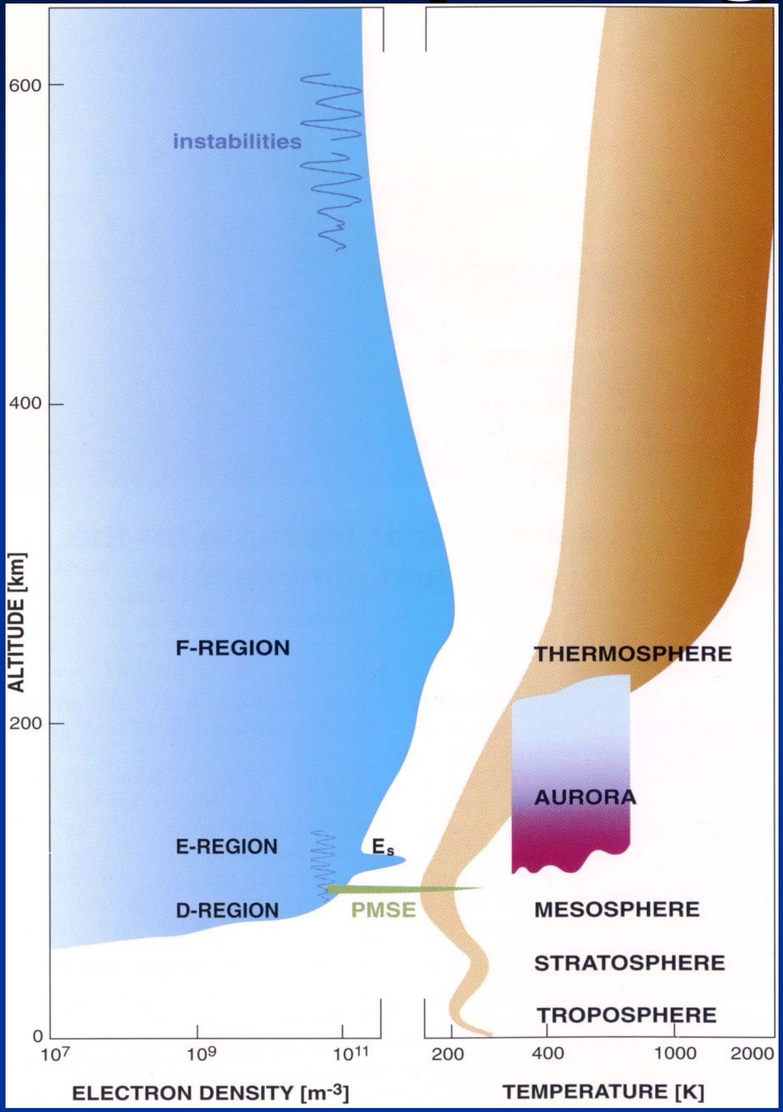
# Debye Length

1. Plasma will not support large potential variations (i.e. will seek to maintain charge neutrality) over distances larger than the Debye length.

2. Potential gradients that do exist have a characteristic length parameter equal to a Debye length

3. These potential gradients are characterized by a natural oscillation frequency known as the plasma frequency.

# Debye length dependence

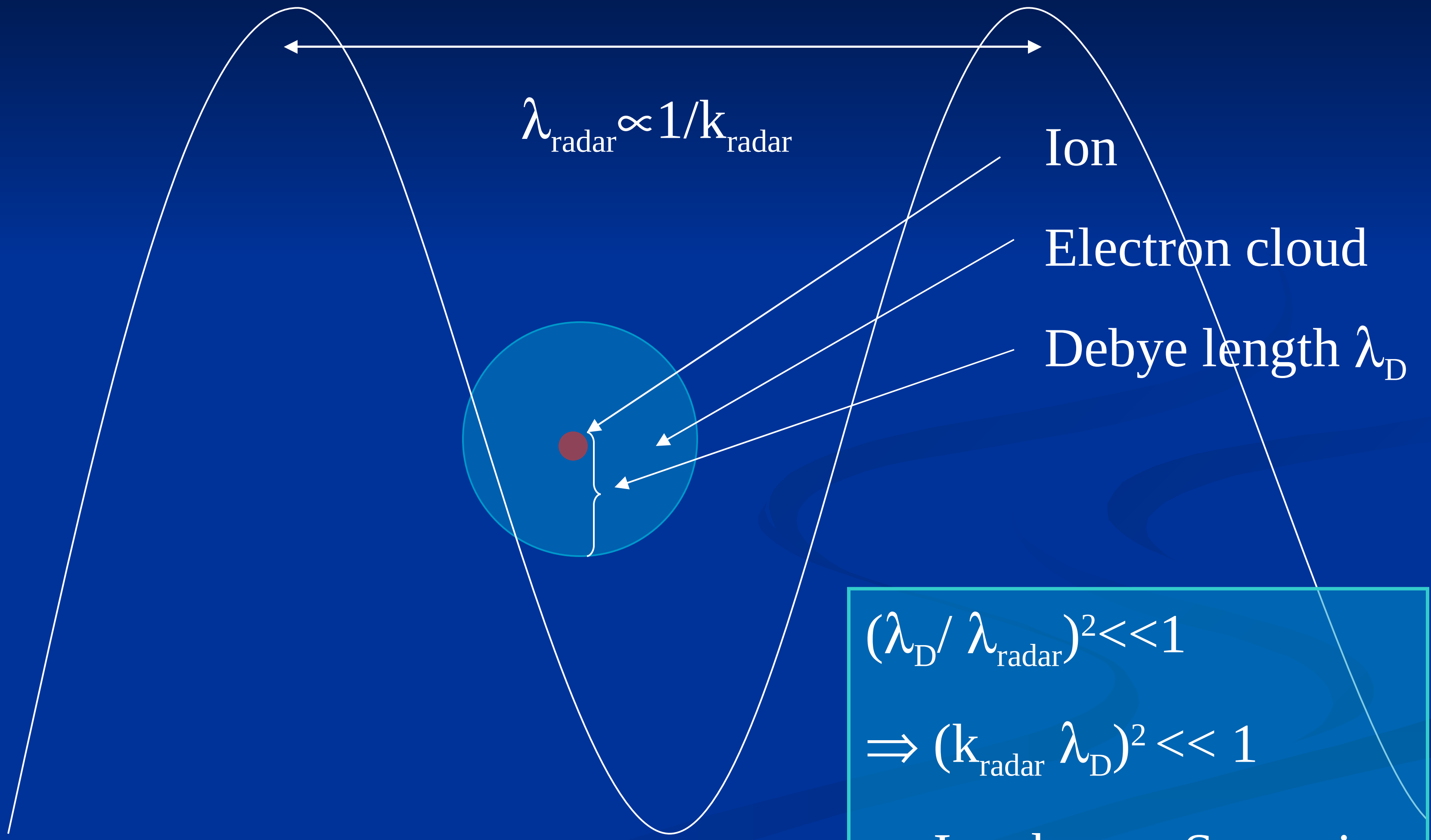



$$\lambda_D \simeq 69\sqrt{\mathrm{T}_e/\mathrm{n}_e}$$

The Debye length is increasing with altitude - from a few millimeter in the D-region up to meters in the magnetosphere

Debye length in E and F region is 0.1 to 1 cm.

# Debye cutoff




$(\lambda_D / \lambda_{radar})^2 << 1$

$\Rightarrow (k_{radar}\, \lambda_D)^2 << 1$

$\Rightarrow$ Incoherent Scattering

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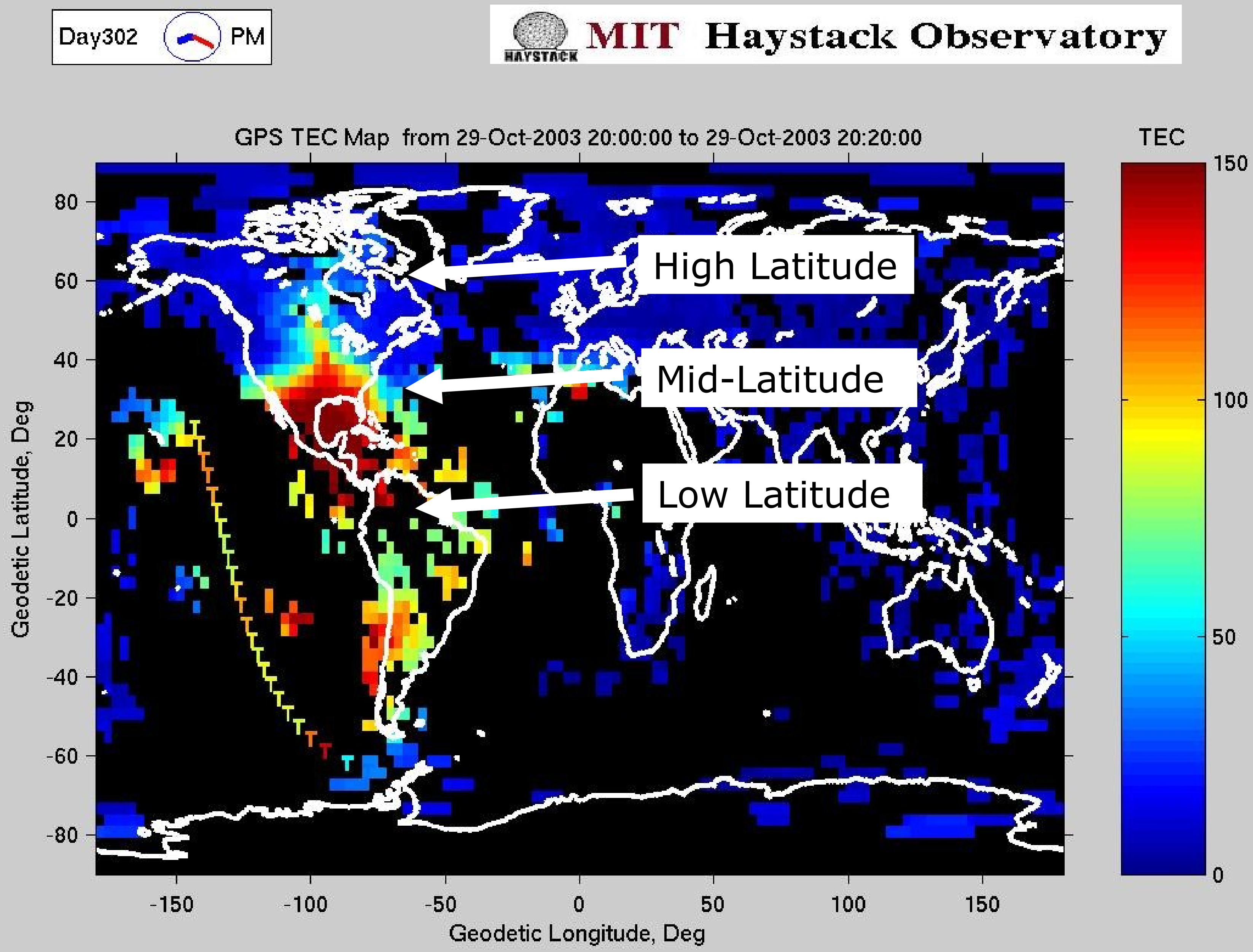
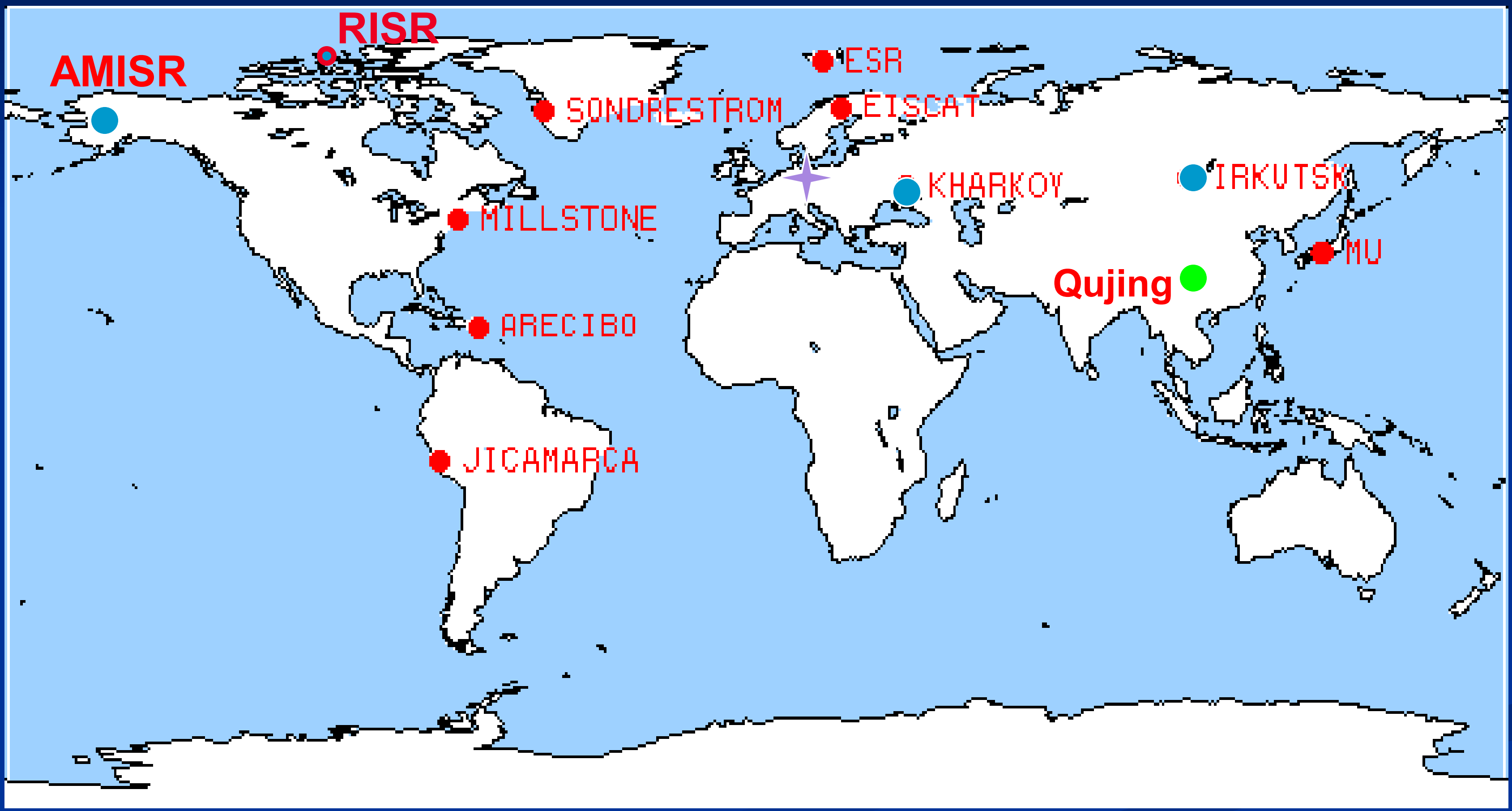
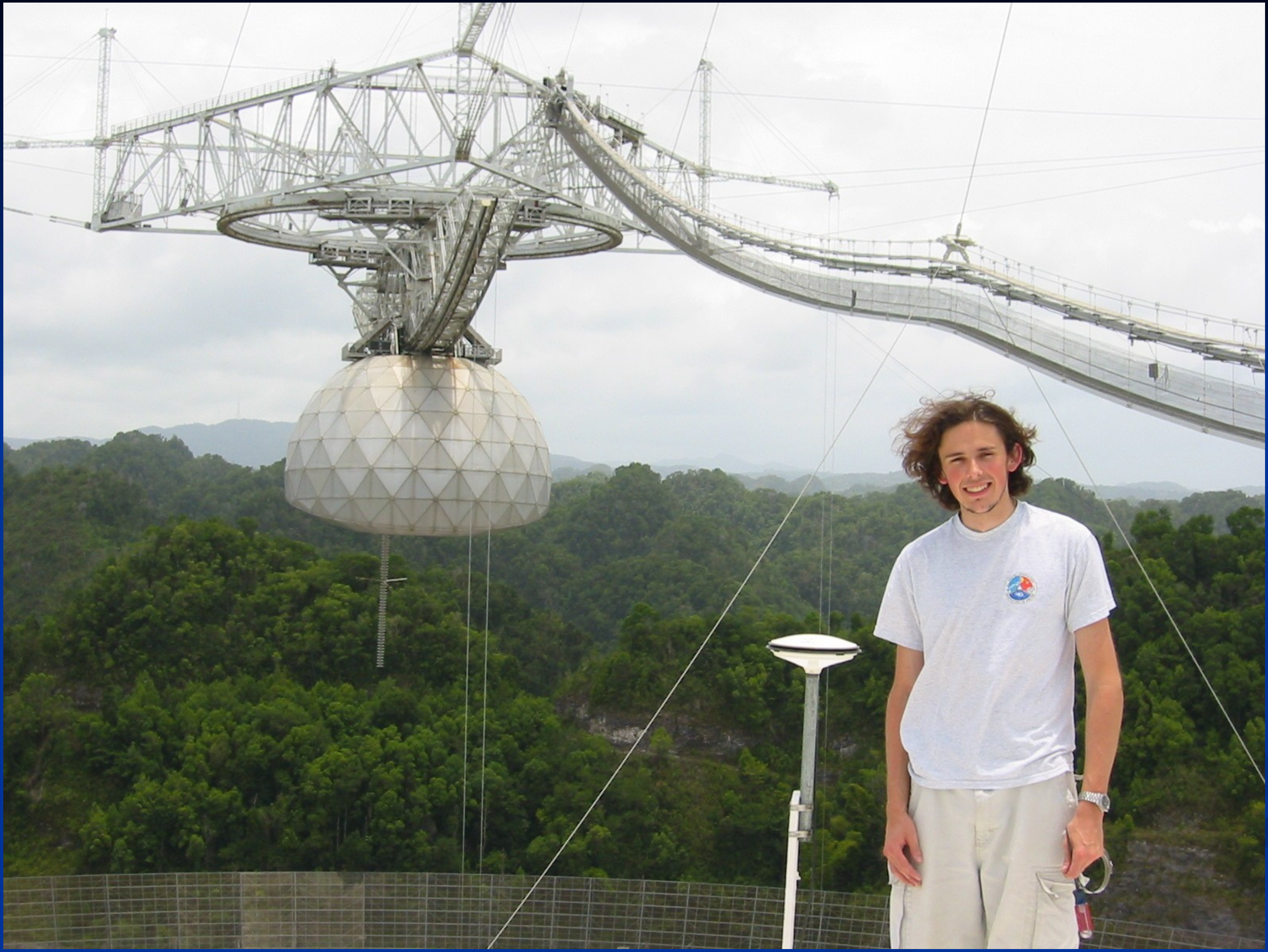

Day302
PM
MIT Haystack Observatory
HAYSTACK
GPS TEC Map from 29-Oct-2003 20:00:00 to 29-Oct-2003 20:20:00
TEC
High Latitude
Mid-Latitude
Low Latitude
Geodetic Latitude, Deg
Geodetic Longitude, Deg
80
60
40
20
0
-20
-40
-60
-80
-150
-100
-50
0
50
100
150
150
100
50
0

# World Incoherent Scatter Radars




Massachusetts Institute of Technology
HAYSTACK

# Jicamarca ISR - Low Latitudes



# Sondrestrom

# AMISR

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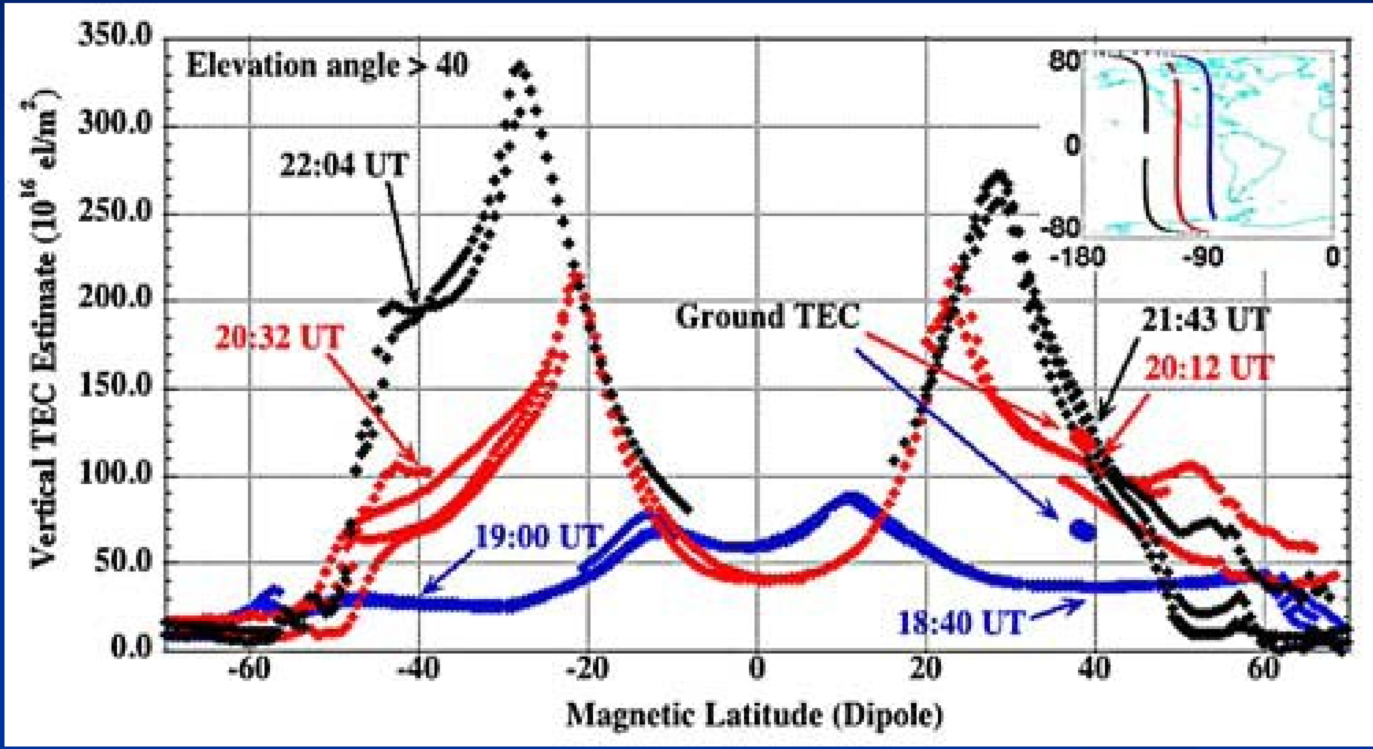
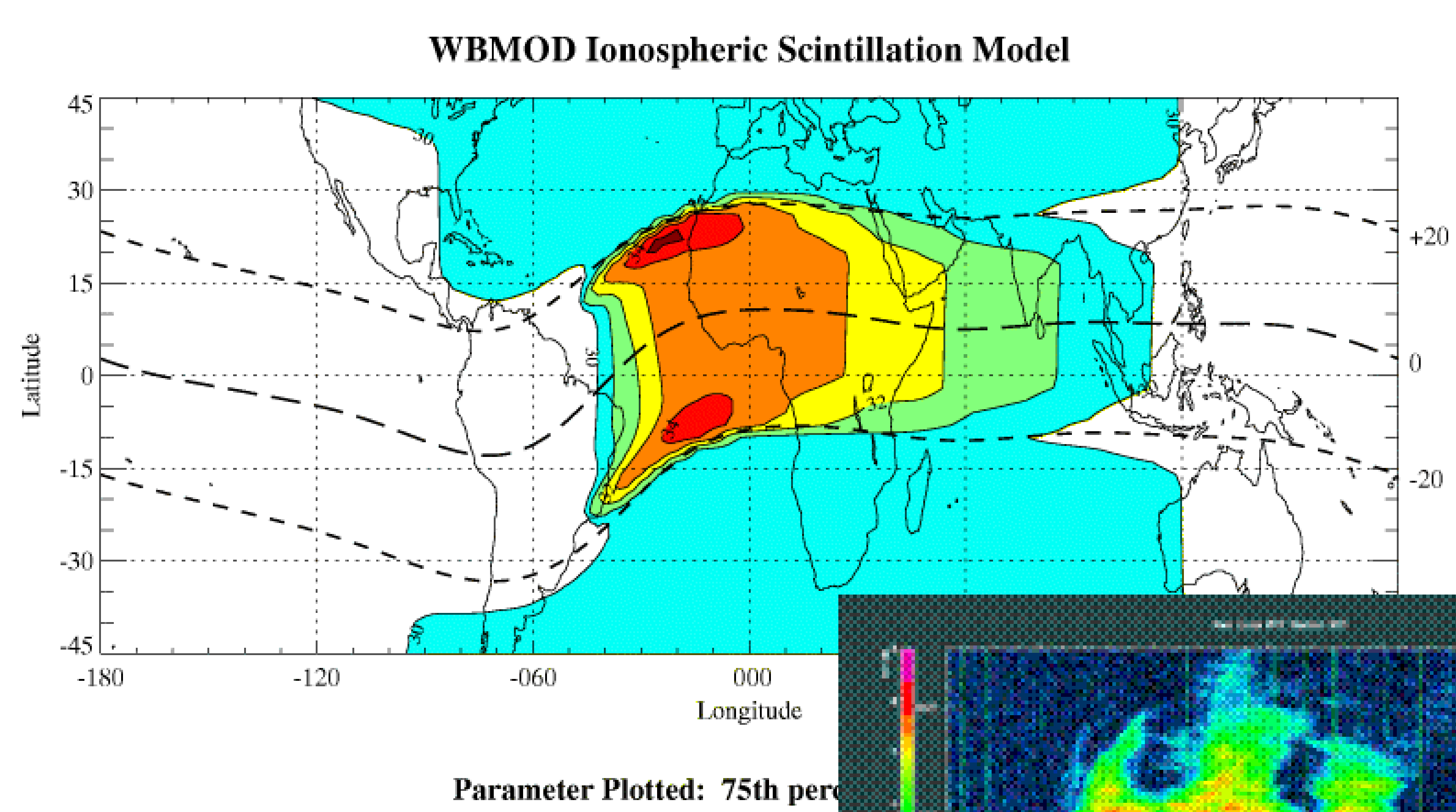
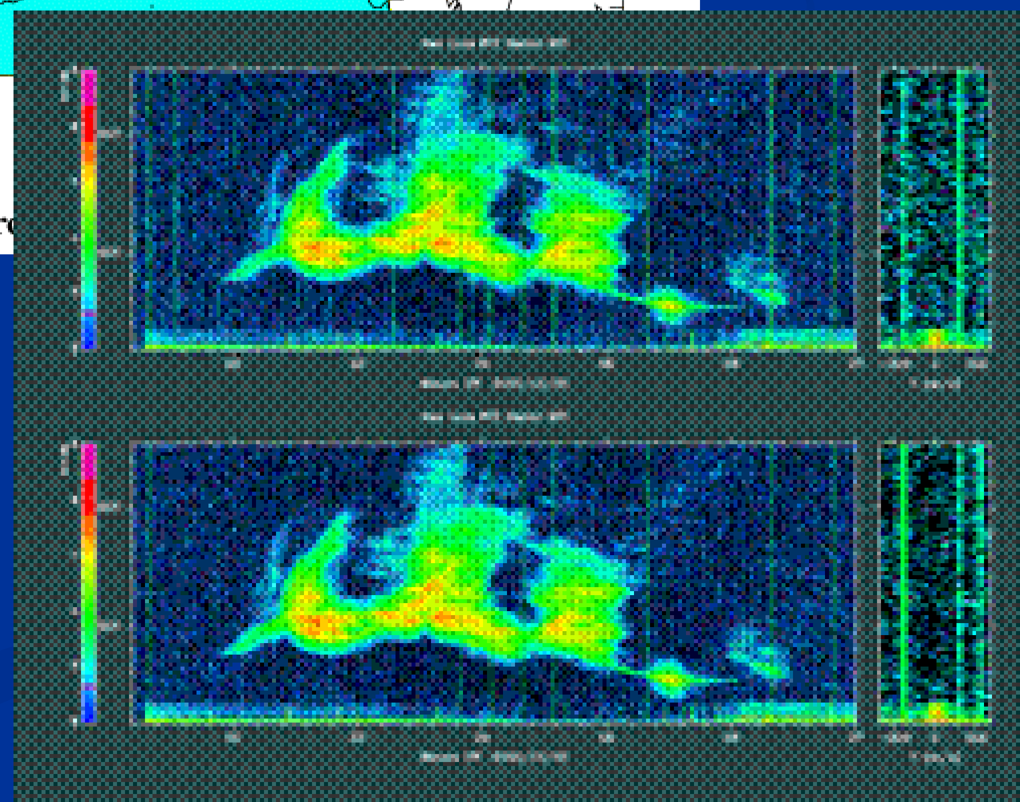
# Storm-time Appelton Anomaly

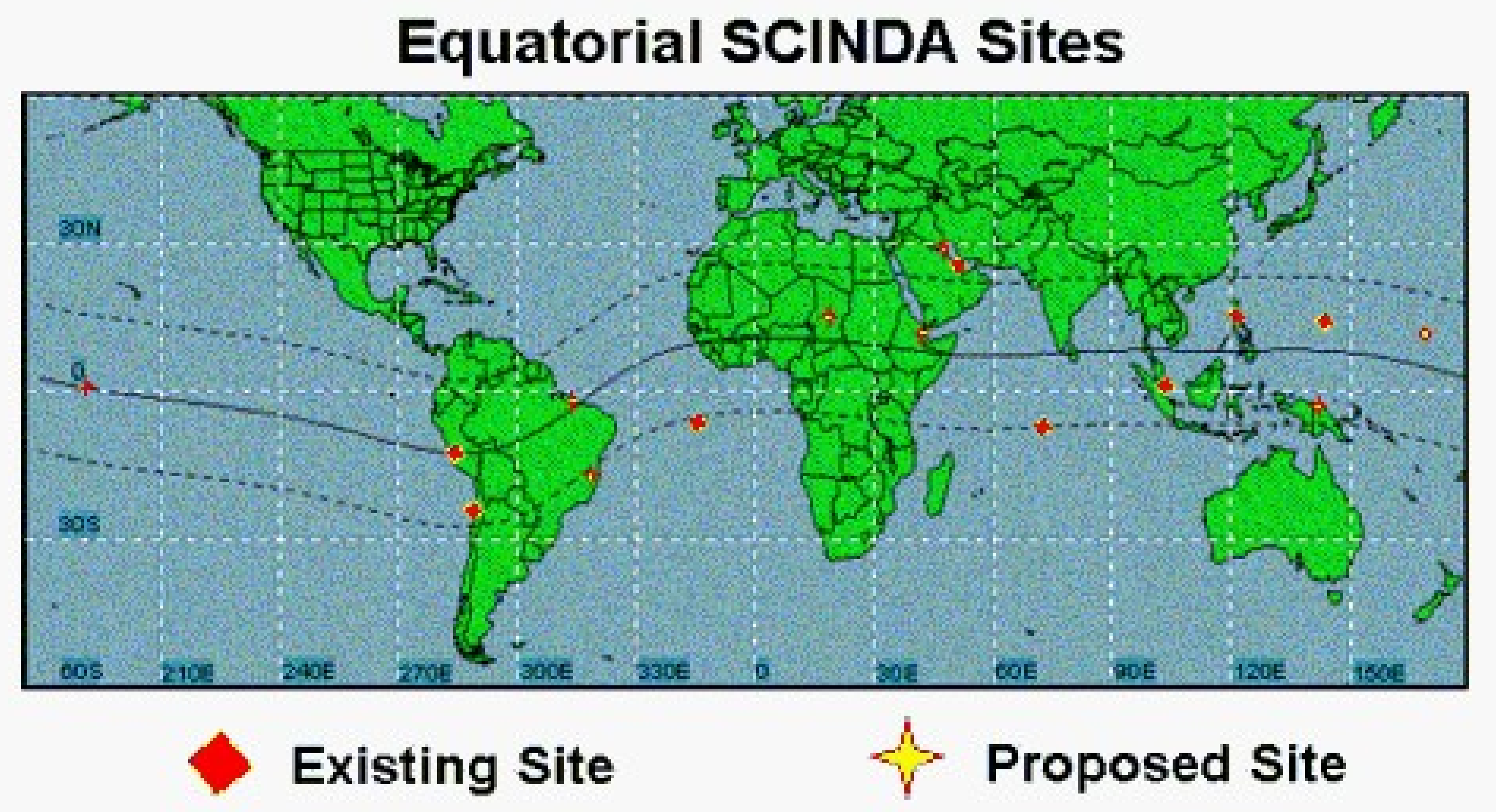


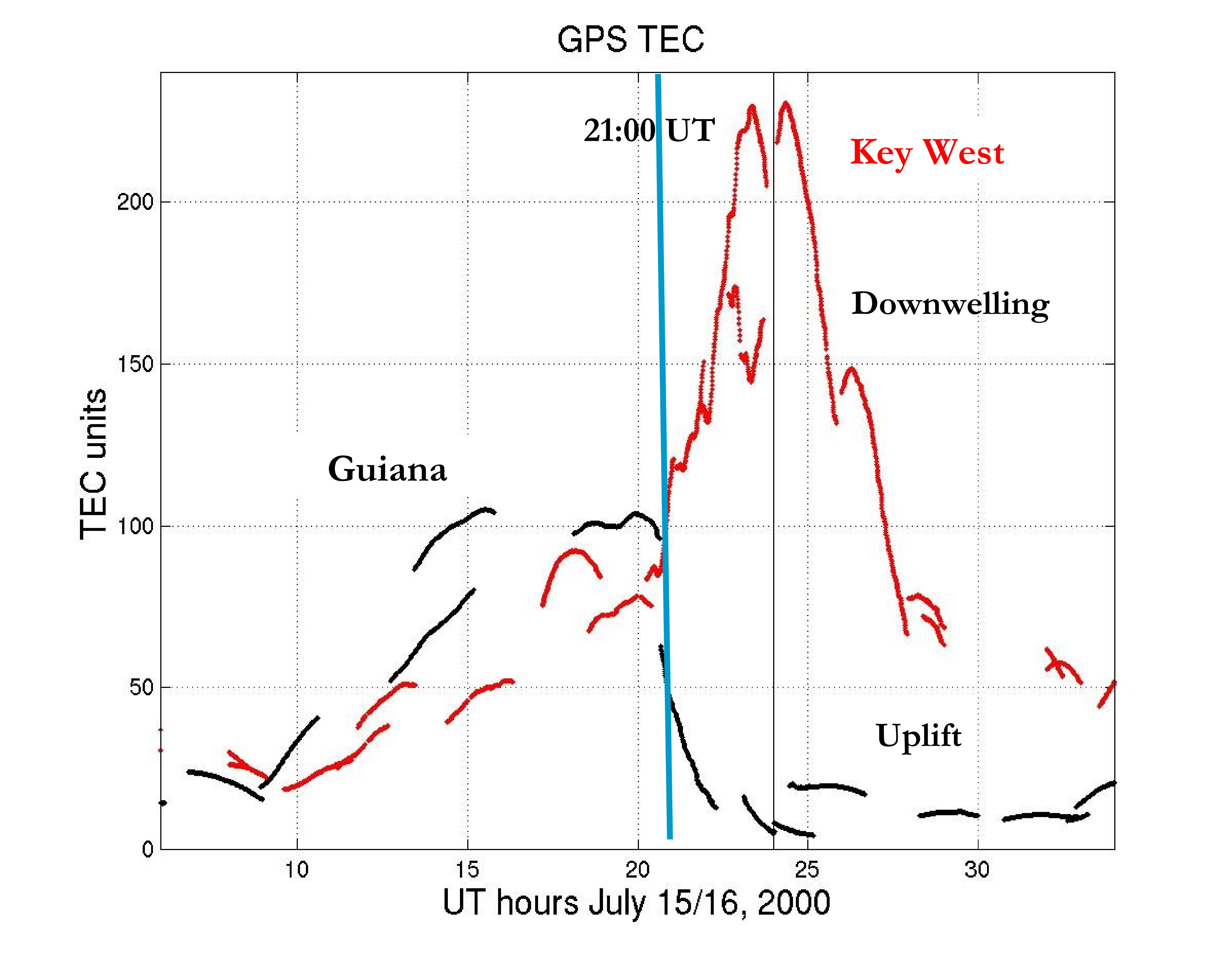

Mannucci et al., 2005, GRL


WBMOD Ionospheric Scintillation Model
45
30
15
0
-15
-30
-45
Latitude
-180
-120
-060
000
Longitude
+20
0
-20
30
32
Parameter Plotted: 75th perc



# SCINDA


Equatorial SCINDA Sites
30N
0
30S
60S
210E
240E
270E
300E
330E
0
30E
60E
90E
120E
150E
Existing Site
Proposed Site



GPS TEC
21:00 UT
Key West
Downwelling
Guiana
Uplift
TEC units
0
50
100
150
200
10
15
20
25
30
UT hours July 15/16, 2000

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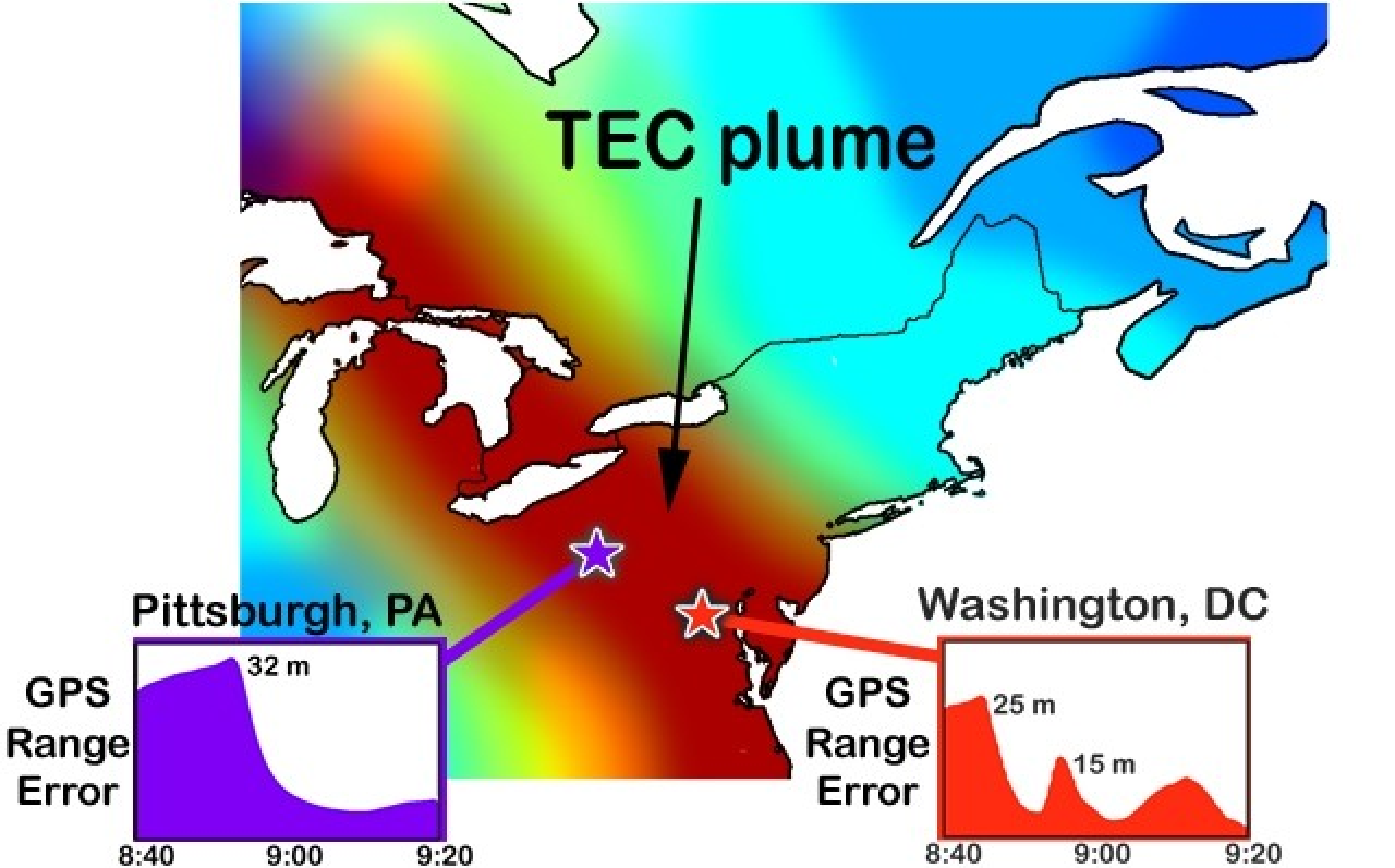
# November 20, 2003



# Socorro New Mexico 20 Nov 2003


(from astronomy picture of the day)

# West Texas 15 Sept 2000 near El Paso Texas

(from astronomy picture of the day)

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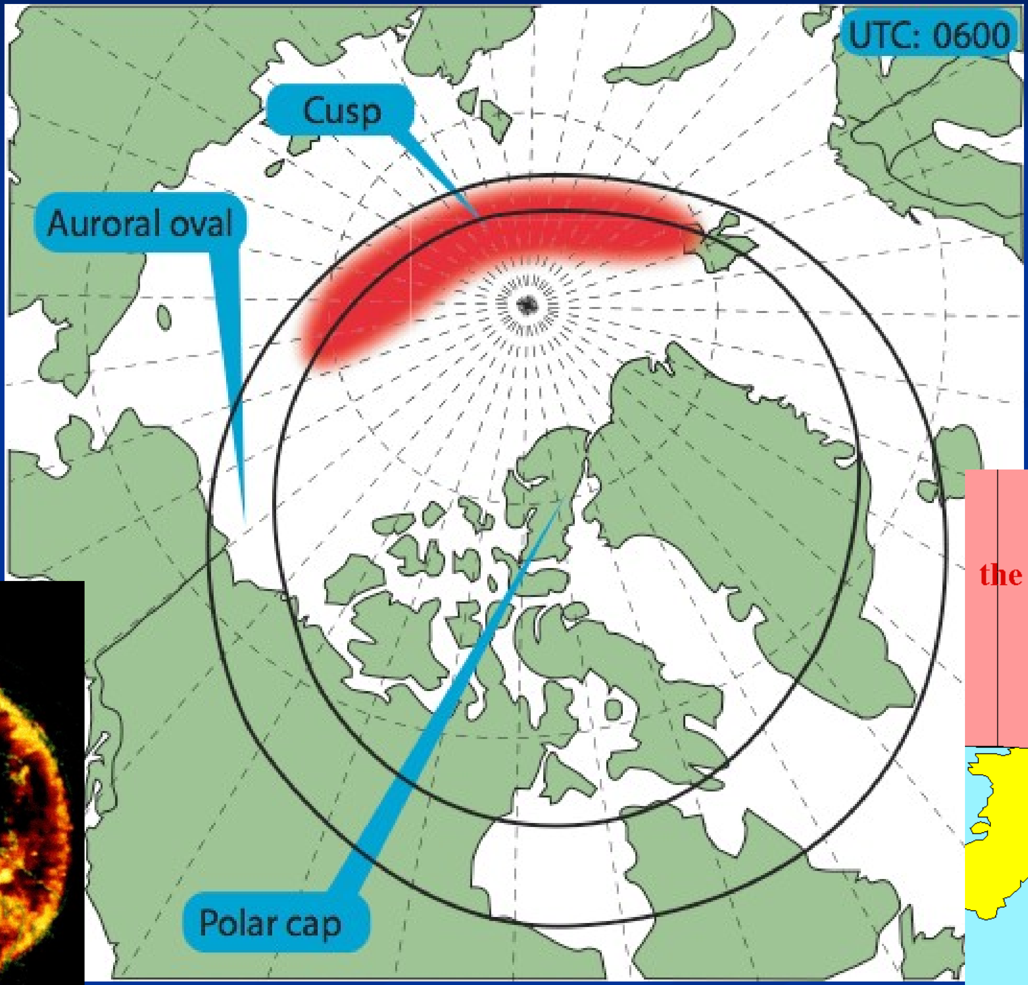
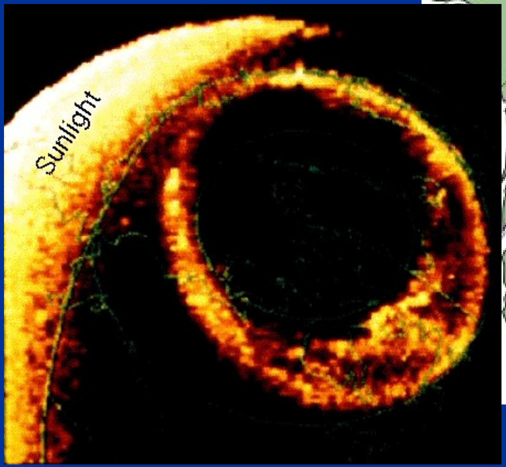
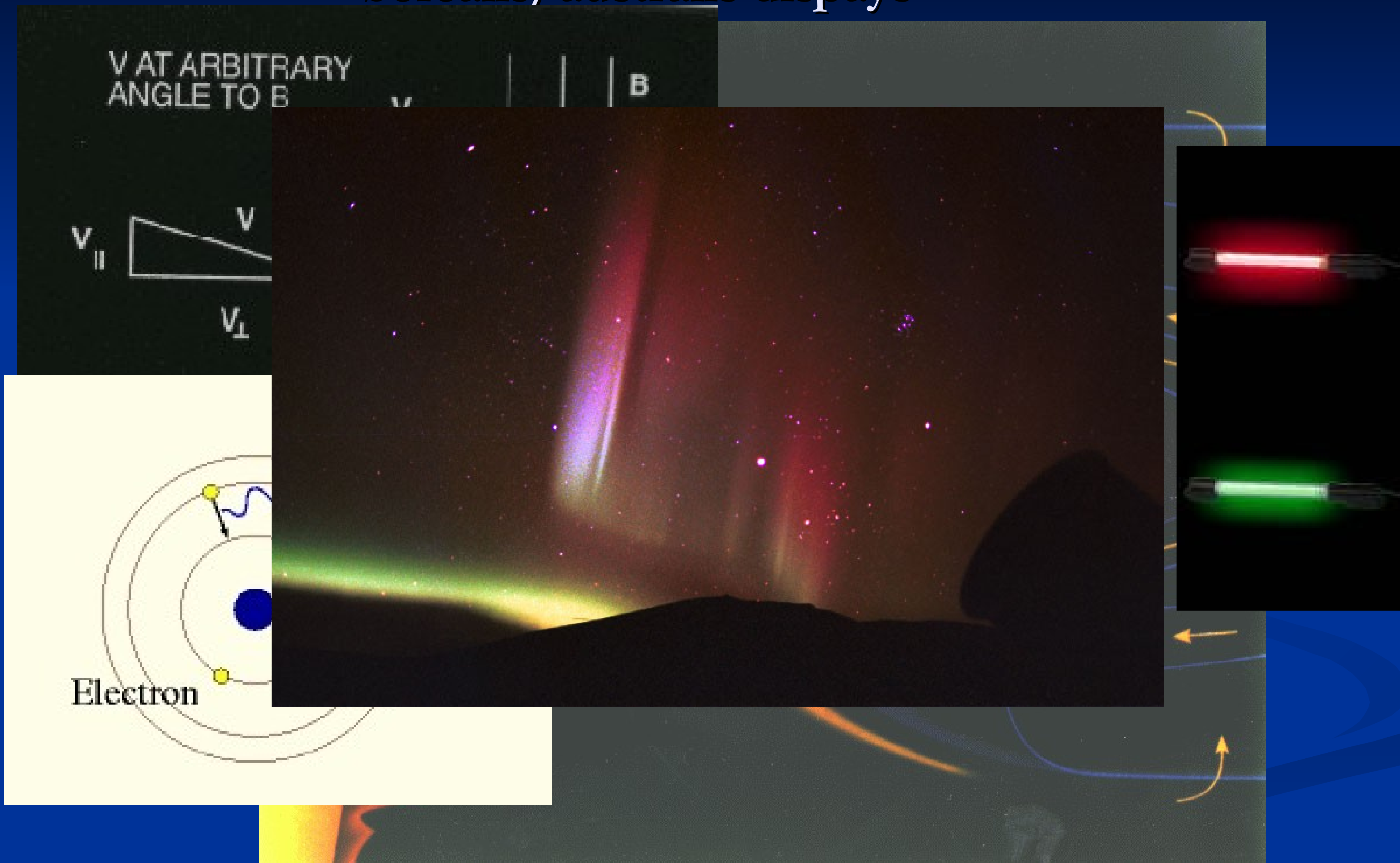
# High latitudes are different

QuickTime™ and a
GIF decompressor
are needed to see this picture.




# At high latitudes electron (and proton) with solar wind origin creates additional ionization, seen as aurora borealis/australis dispays



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