# Introduction to Ionosphere

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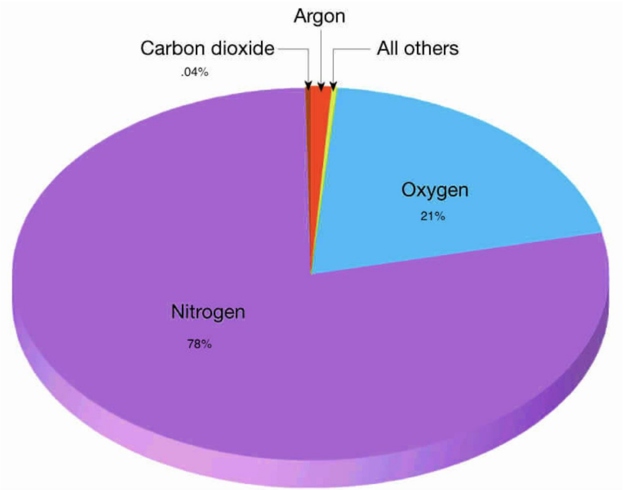
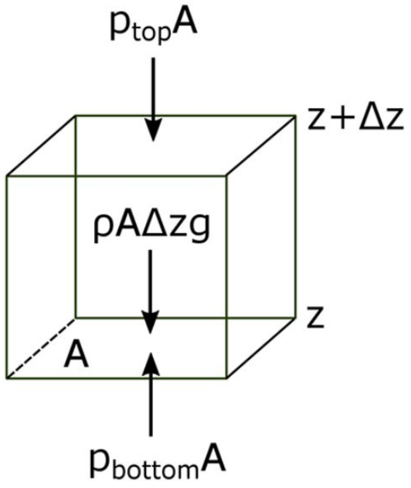
# Outline

- Atmosphere
  - Ionosphere
    - acts as a natural plasma laboratory
    - Important for communications
    - Vertical and latitudinal structure
  - How is ionosphere formed
- Tools to probe ionosphere
  - Radio Techniques
  - Radio wave propagation
- Examples of scientific investigations



# Atmosphere: Pressure Vertical Structure



Forces on an air-parcel at rest

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

Ideal Gas Law: $P = nK_BT$

$$p = p_0 \exp\left[-\int_{z_0}^{z} \frac{mg}{k_B T(z)} dz\right] = p_0 \exp\left[-\int_{z_0}^{z} \frac{dz}{H(z)}\right] \tag{1}$$

and

$$n = n_0 \frac{T_0}{T(z)} \exp\left[-\int_{z_0}^{z} \frac{dz}{H(z)}\right] \tag{2}$$

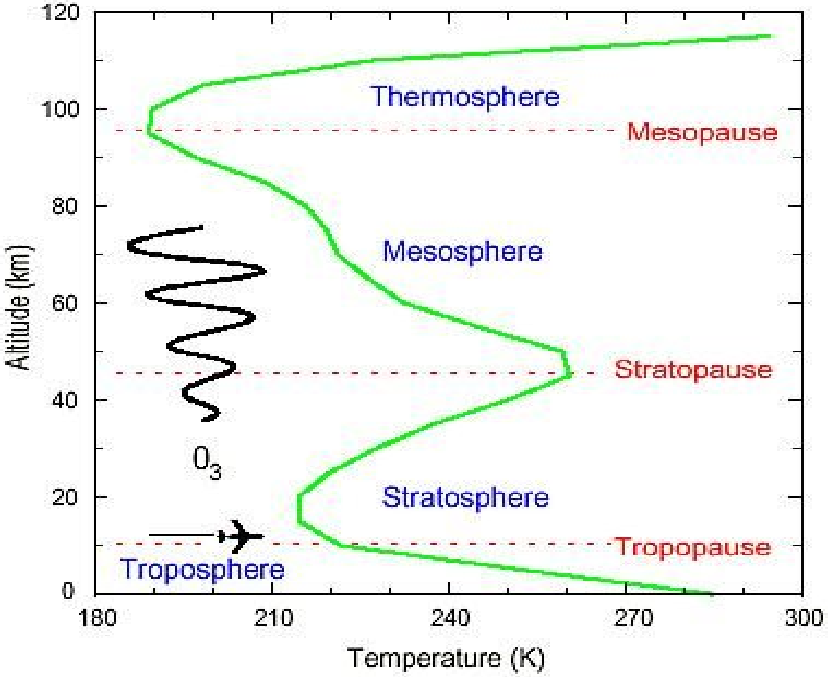
where $p_0$ and $n_0$ are values at a reference height $z_0$.
if the atmosphere is isothermal ($T$=constant), the scale height $H$

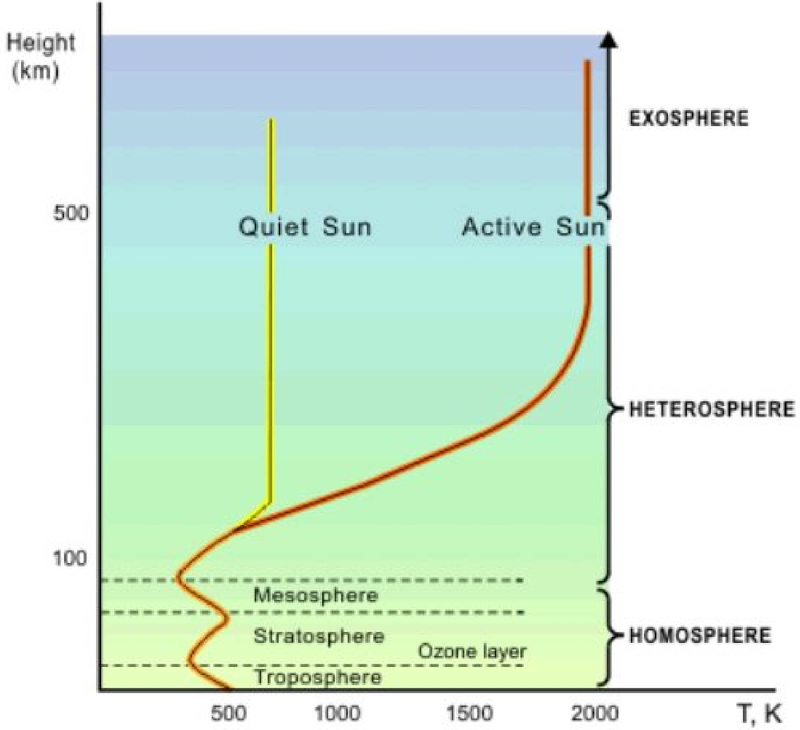
$$H = \frac{k_B T}{mg} \tag{3}$$

is independent of altitude and then the the hydrostatic equations are

$$p = p_0 \exp\left(-\frac{z - z_0}{H}\right), \quad n = n_0 \exp\left(-\frac{z - z_0}{H}\right). \tag{4}$$

# Atmospheric Layers





# Neutral atmosphere

## Composition in the heterosphere

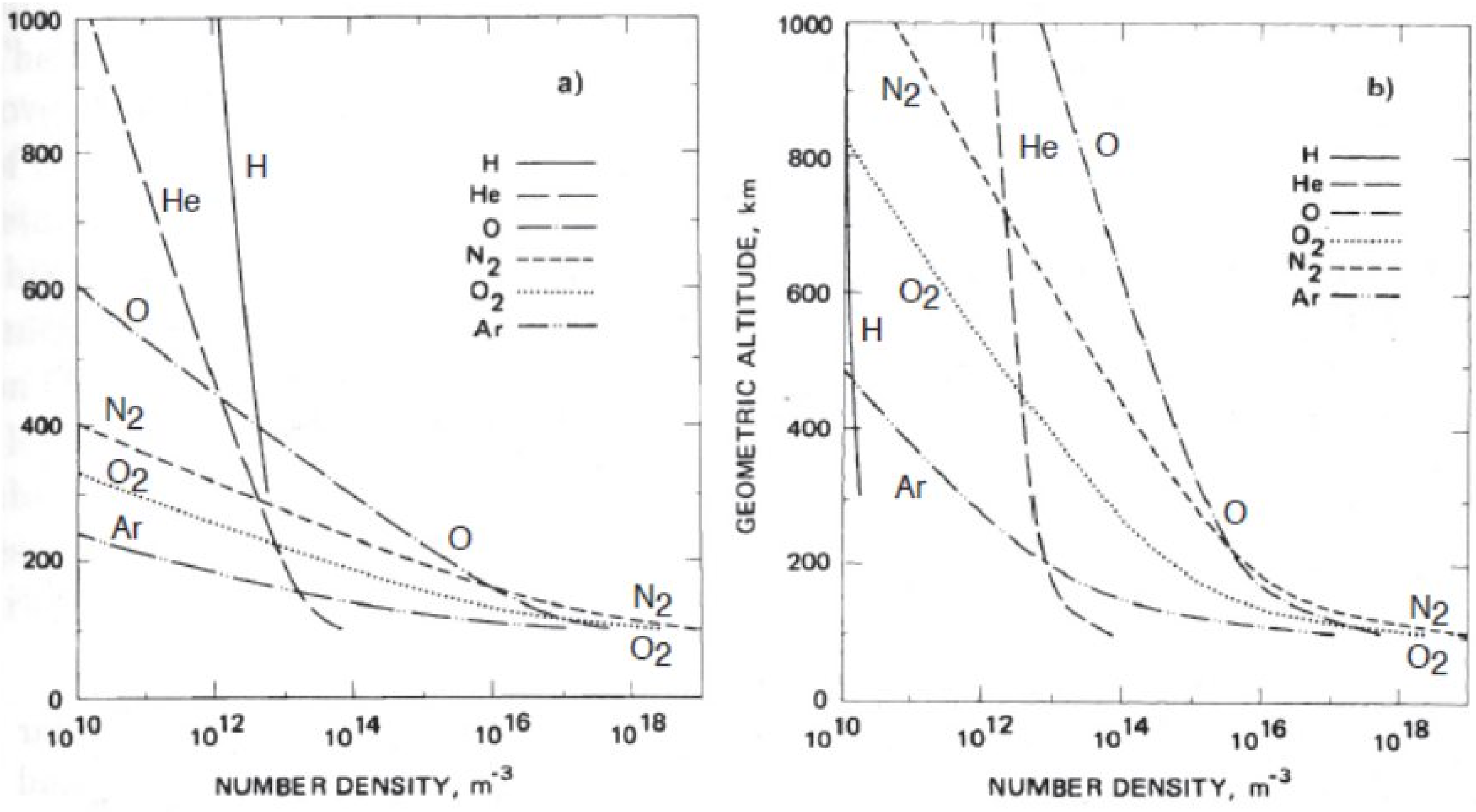


Figure: Atmospheric composition during (a) solar minimum and (b) solar maximum (U. S. Standard atmosphere, 1976).

# Ionosphere: Part of Earth’s Atmosphere

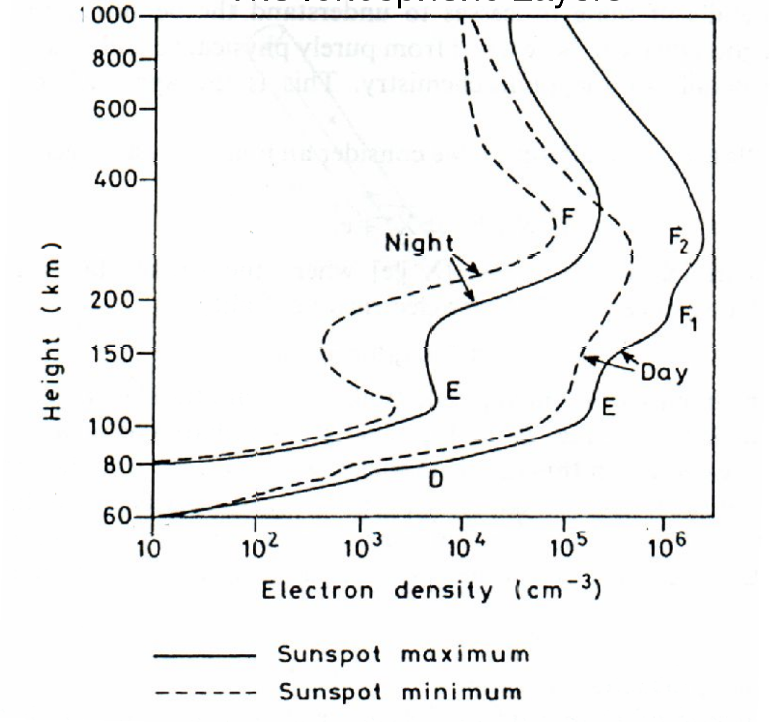
Ionospheric regions and typical daytime electron densities:

- **D region**: 60-90 km, $n_e = 10^8$-$10^9$ $m^{-3}$
- **E region**: 90-150 km, $n_e = 10^{10}$-$10^{11}$ m-3
- **F region**: 150-1000 km, $n_e$=$10^{11}$-$10^{12}$ $m^{-3}$

The ionosphere has great variability:

- Solar cycle variations (in the upper F region)
- Day-night variations in lower F, E, and D regions
- Space weather effects based on short-term solar variability (lower F, E, and D regions)

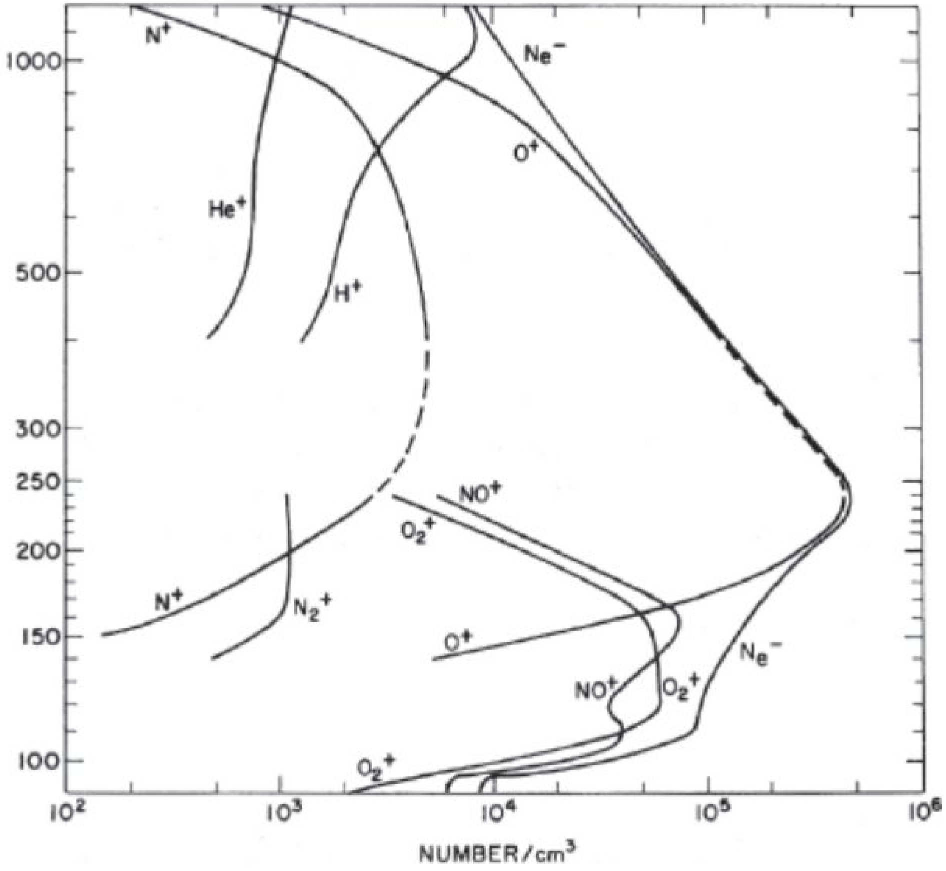
The Ionospheric Layers



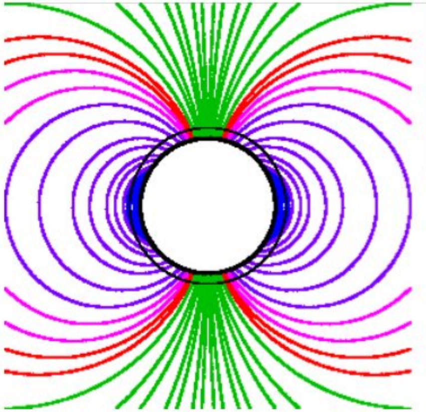
# The ionosphere

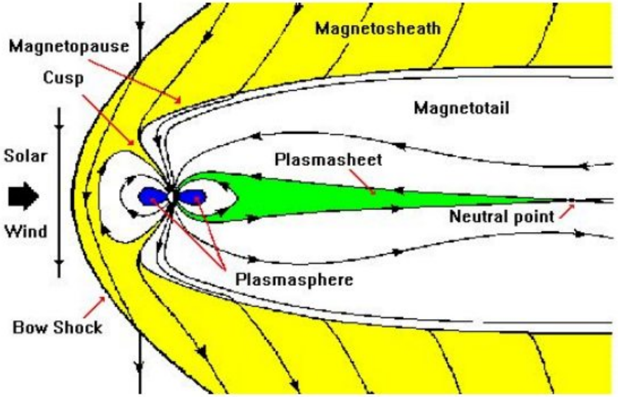
## Composition in the heterosphere

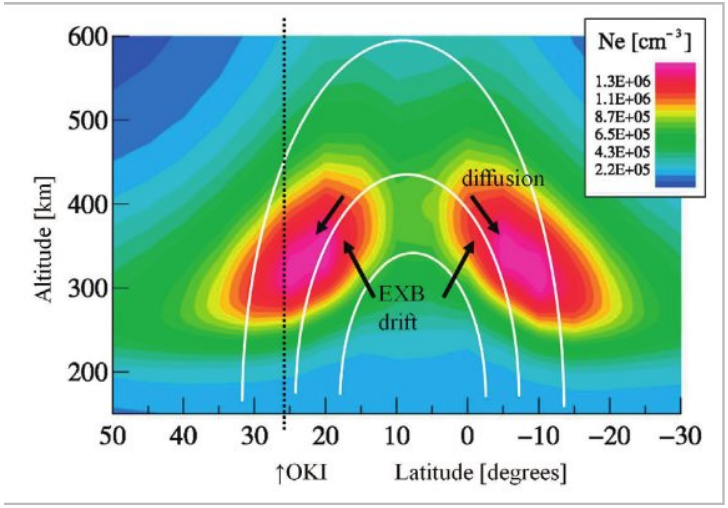
- $O^+$ dominates around the F region peak and $H^+$ starts to increase rapidly above 300 km.
- $NO^+$ and $O_2^+$ are the dominant ions in E and upper D regions (Ion chemistry: e.g. $N_2^+ + O \to NO^+ + N$).
- The D-region (not shown) contains positive and negative ions (e.g. $O_2^-$) and ion clusters (e.g. $H^+(H_2O)_n$, $(NO)^+(H_2O)_n$)



# Ionosphere
# Magnetic Field: Implications







# The ionosphere

## Dynamics of the ionosphere

The important equations for ions (number density $n_i$) and electrons (number density $n_e$) in the ionosphere are the continuity equations:

$$\frac{\partial n_{i,e}}{\partial t} + \nabla \cdot (n_{i,e}\mathbf{v}_{i,e}) = q_{i,e} - l_{i,e},$$

where $q$ is the production rate per unit volume and $l$ is the loss rate per unit volume; and the momentum equations:

$$\begin{aligned} n_i m_i \left(\frac{\partial}{\partial t} + \mathbf{v}_i \cdot \nabla\right)\mathbf{v}_i &= n_i m_i \mathbf{g} + e n_i (\mathbf{E} + \mathbf{v}_i \times \mathbf{B}) - \nabla p_i - n_i m_i \nu_i (\mathbf{v}_i - \mathbf{u}) \\ n_e m_e \left(\frac{\partial}{\partial t} + \mathbf{v}_e \cdot \nabla\right)\mathbf{v}_e &= n_e m_e \mathbf{g} - e n_e (\mathbf{E} + \mathbf{v}_e \times \mathbf{B}) - \nabla p_e - n_e m_e \nu_e (\mathbf{v}_e - \mathbf{u}) \end{aligned}$$

Where **E** is the electric field, **B** is magnetic induction, $p_i$ and $p_e$ are the pressures of the ion and electron gas, and the ion-neutral and electron-neutral collision frequencies are denoted by $\nu_i$ and $\nu_e$, respectively

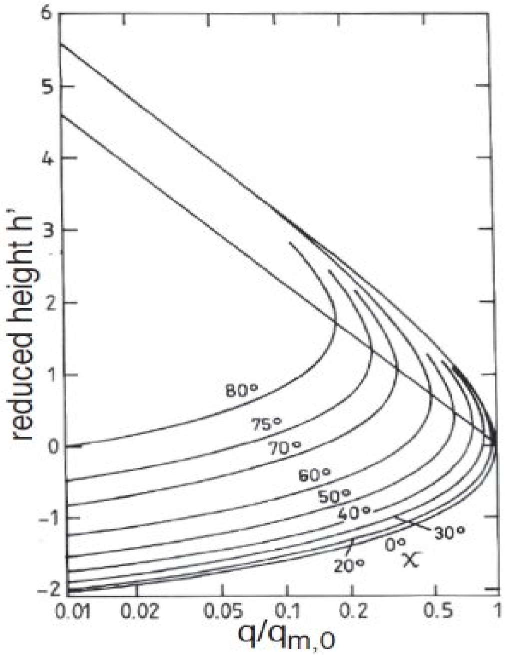
# The ionosphere

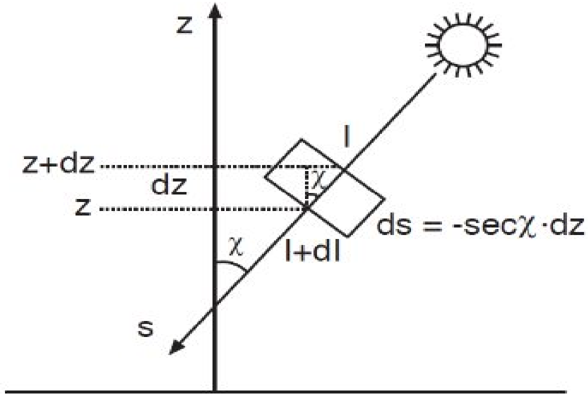
## Ionization source: solar radiation

Chapman production function by using a height variable $h' = h - \ln \sec\chi$:

$$q(\chi, h') = q_{m,0} \cos\chi \cdot \exp\left[1 - h' - e^{-h'}\right] ,$$

where $\chi$ is the solar zenith angle and $h = (z - z_{m,0})/H$, where $H$ is the atmospheric scale height.





With larger zenith angle $\chi$, the peak of ionization rate rises in altitude and decreases by a factor $\cos\chi$.

# The ionosphere

## Ionization source: particle precipitation (electrons)

High-energy electron deposit energy at lower altitudes.

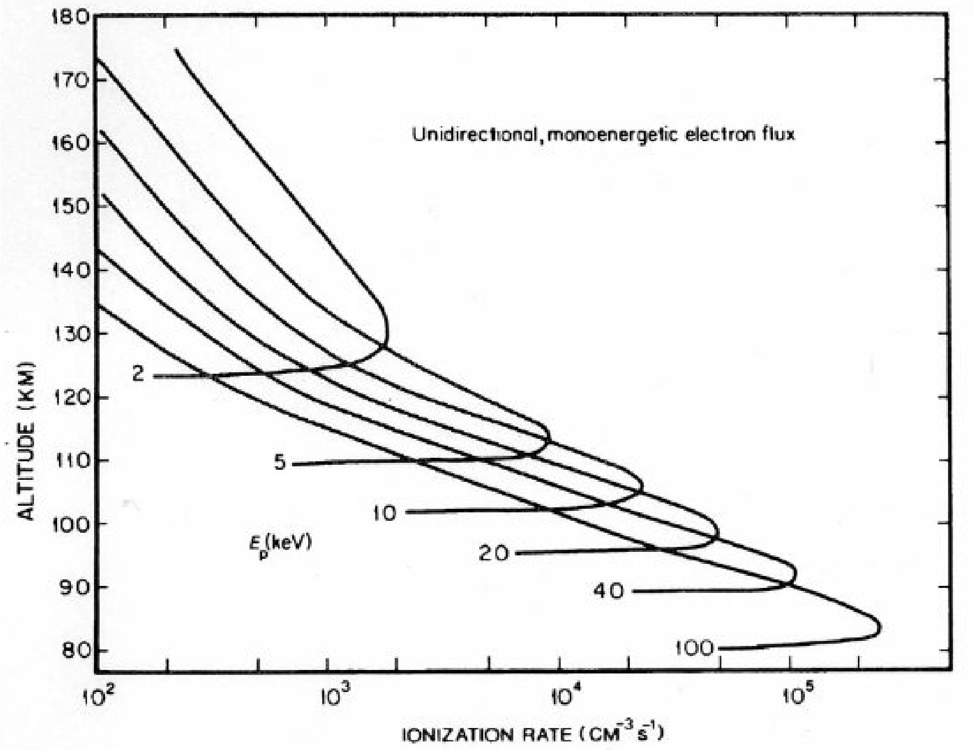


Figure: Ionization rate for monoenergetic electrons with energies 2-100 keV

# The ionosphere

## Ionization source: particle precipitation (protons)

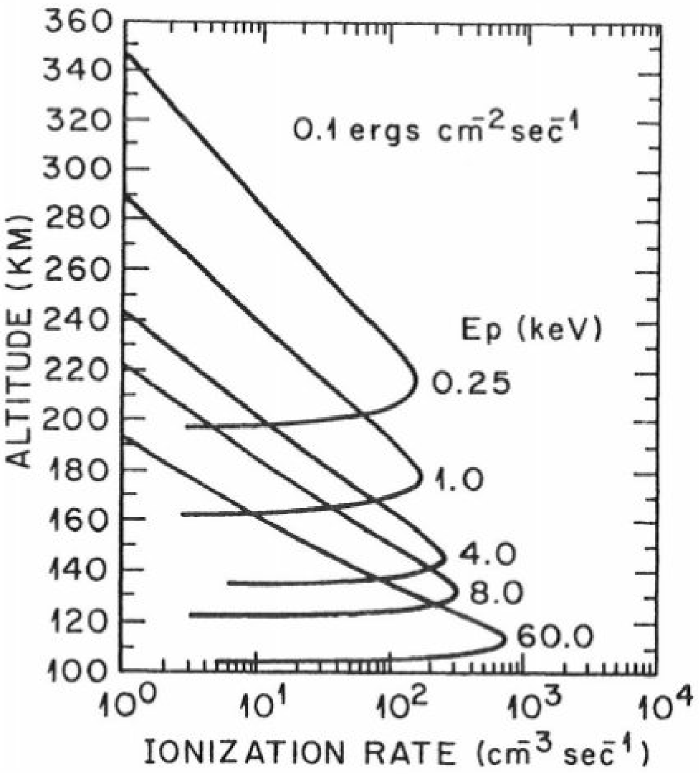


Figure: Ionization rate for monoenergetic protons with energies 0.25-60 keV

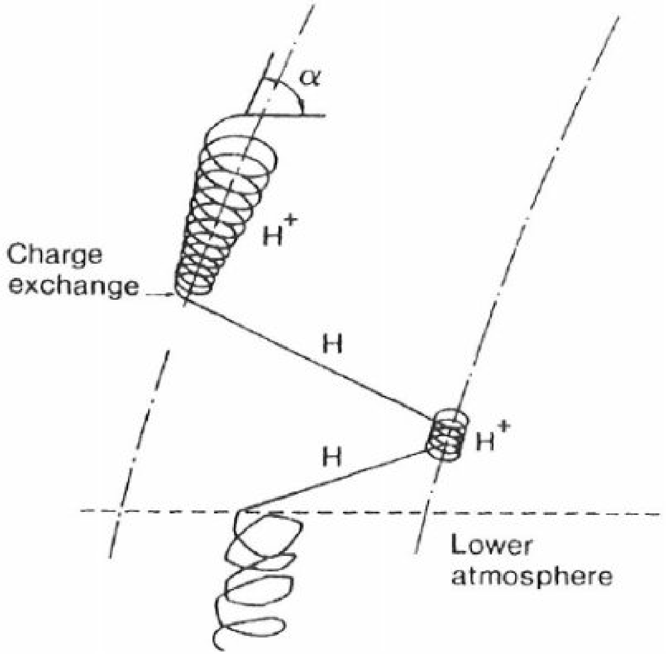


Figure: Protons may make charge exchange with neutral hydrogen.

# The ionosphere
## Loss mechanisms

We have now dealt with the production rate, but there are also loss terms to deal with:

$$\frac{\partial n_{i,e}}{\partial t} + \nabla \cdot (n_{i,e}\mathbf{v}_{i,e}) = q_{i,e} - l_{i,e},$$

1. Recombination
2. Transport/Diffusion

While chemical recombination is very important at lower altitudes (D, E, F1 regions), diffusion plays a larger role at higher altitudes (F2 region) where the densities are very low.

# Ionosphere

## Collision Frequencies

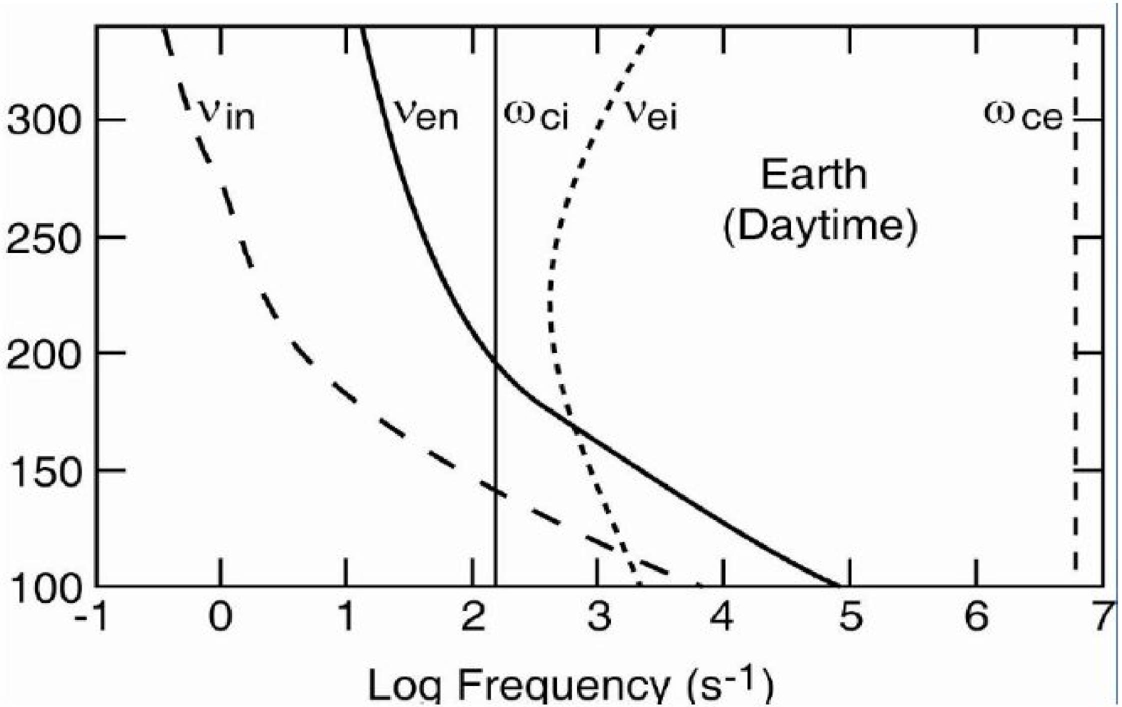
$$n_i m_i \left( \frac{\partial}{\partial t} + \mathbf{v}_i \cdot \nabla \right) \mathbf{v}_i = n_i m_i \mathbf{g} + e n_i (\mathbf{E} + \mathbf{v}_i \times \mathbf{B}) - \nabla p_i - n_i m_i \nu_i (\mathbf{v}_i - \mathbf{u})$$

$$n_e m_e \left( \frac{\partial}{\partial t} + \mathbf{v}_e \cdot \nabla \right) \mathbf{v}_e = n_e m_e \mathbf{g} - e n_e (\mathbf{E} + \mathbf{v}_e \times \mathbf{B}) - \nabla p_e - n_e m_e \nu_e (\mathbf{v}_e - \mathbf{u})$$

# The ionosphere

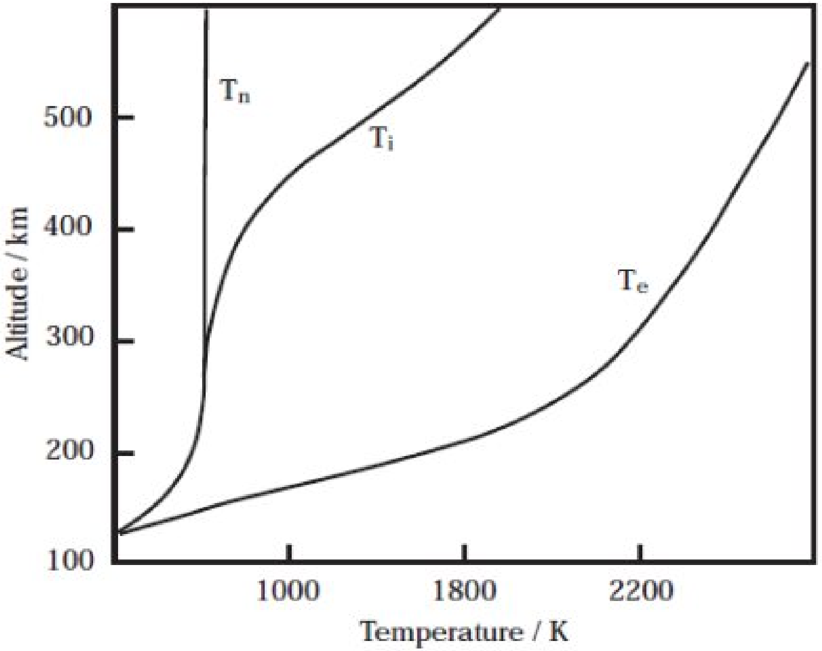
## Collision frequencies

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



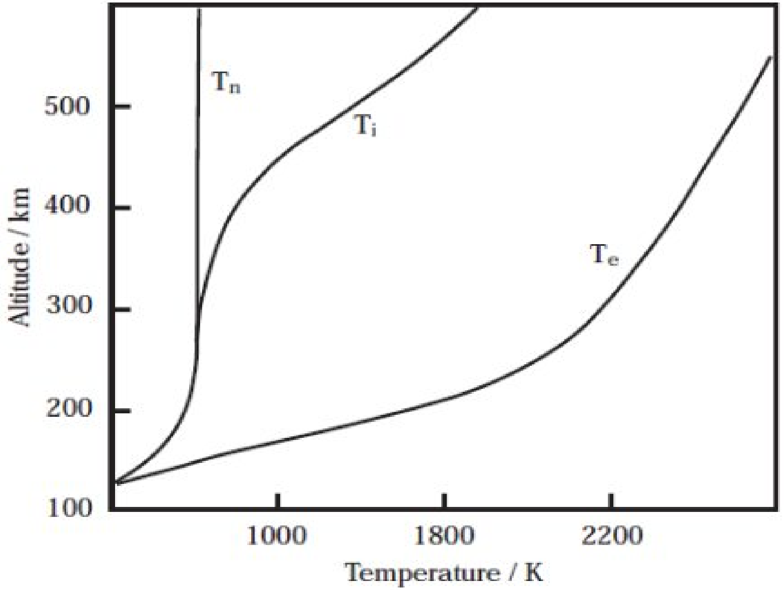
What is the consequence of altitude dependence of collision frequencies?

# The ionosphere



**Question:** Why are $T_n$ and $T_i$ identical at low altitudes? Why is $T_e$ so much higher than either $T_n$ or $T_i$?

# The ionosphere



**Answer:** At lower altitudes, the ions and neutrals have the same temperature due to a high rate of collisions and the high mass of the ions. The electrons have a gyrofrequency much higher than the collision frequency. The electron temperature typically remains higher than the ion temperature due to its much lower mass.

# Ionosphere

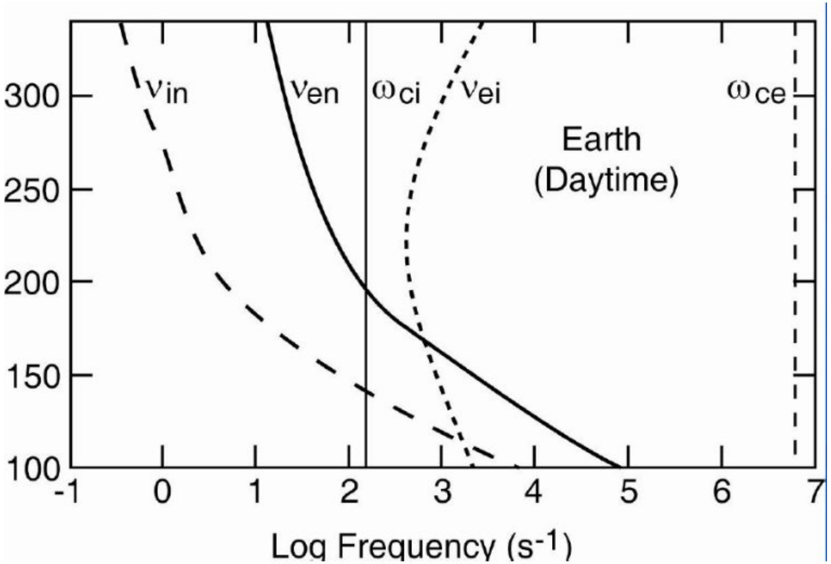
## Collision Frequencies

$$n_i m_i \left(\frac{\partial}{\partial t} + \mathbf{v}_i \cdot \nabla\right)\mathbf{v}_i = n_i m_i \mathbf{g} + e n_i(\mathbf{E} + \mathbf{v}_i \times \mathbf{B}) - \nabla p_i - n_i m_i \nu_i(\mathbf{v}_i - \mathbf{u})$$

$$n_e m_e \left(\frac{\partial}{\partial t} + \mathbf{v}_e \cdot \nabla\right)\mathbf{v}_e = n_e m_e \mathbf{g} - e n_e(\mathbf{E} + \mathbf{v}_e \times \mathbf{B}) - \nabla p_e - n_e m_e \nu_e(\mathbf{v}_e - \mathbf{u})$$

Charged particles are subjected to different forces

Gyrofrequency, $\omega_c$ = qB/m



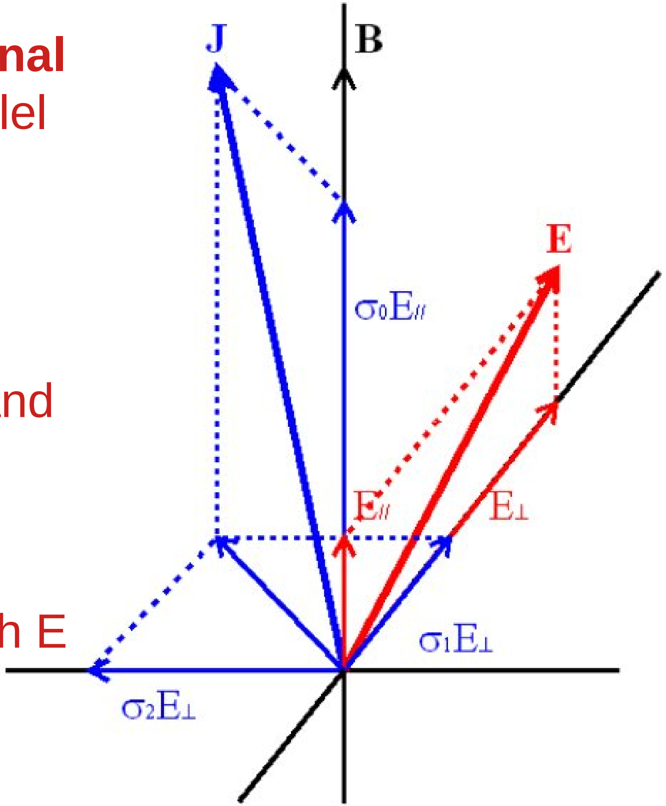
# Ionosphere

## Conductivity

**Direct or Longitudinal Conductivity:** Parallel to B

**Pederson Conductivity:** Perpendicular to B and Parallel to E

**Hall Conductivity:** Perpendicular to both E and B



**B**: Geomagnetic field vector

**E**: Electric field vector

- $E_{\perp}$: Perpendicular component of the electric field
- $E_{/\!/}$: Parallel component of the electric field

**J**: Electric current vector

- $\sigma_0 E_{/\!/}$: Parallel current
- $\sigma_1 E_{\perp}$: Pedersen current
- $\sigma_2 E_{\perp}$: Hall current

# The ionosphere

## Conductivity

- Pedersen conductivity (parallel to E)

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

- Hall conductivity (along EXB)

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

- Parallel conductivity (parallel to B)

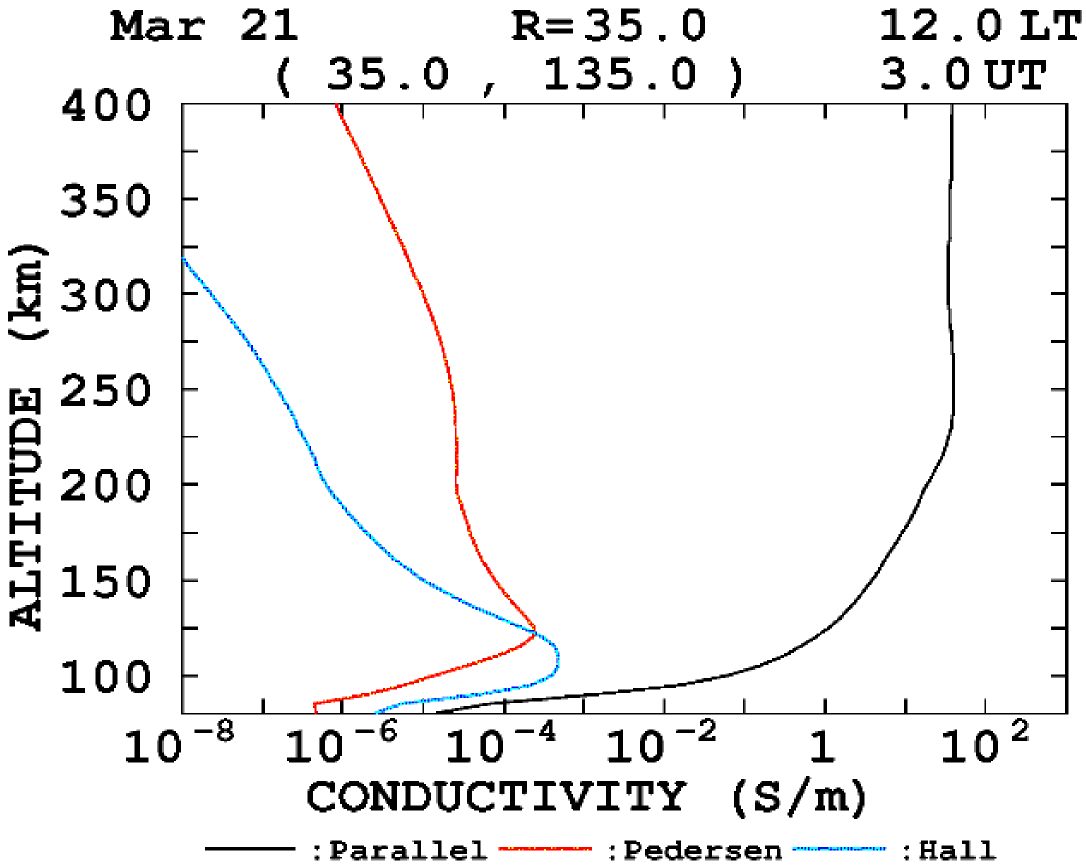
$$\sigma_0 = [\frac{1}{m_e \nu_{en}} + \frac{1}{m_i \nu_{in}}] n_e e^2$$

- Conductivity tensor

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

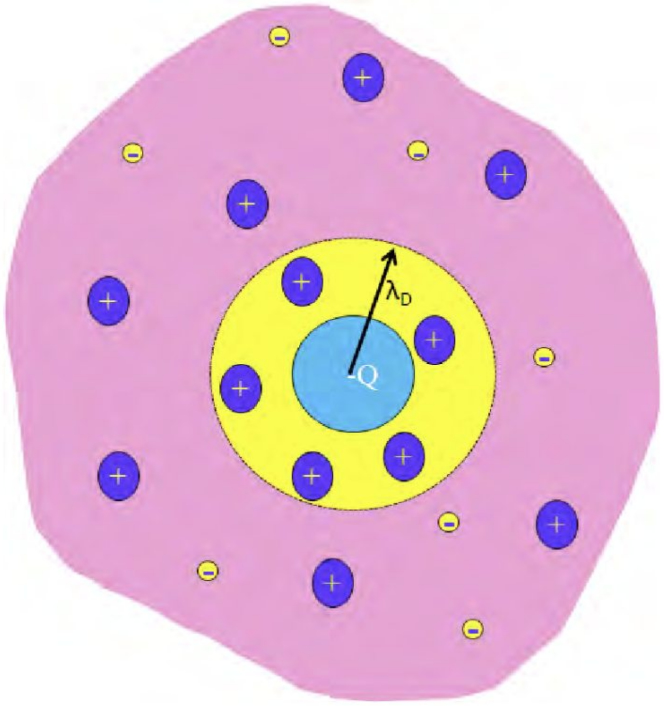
# The ionosphere

## Conductivities



Equatorial and Auroral Electrojets

# Ionosphere
## Debye Length



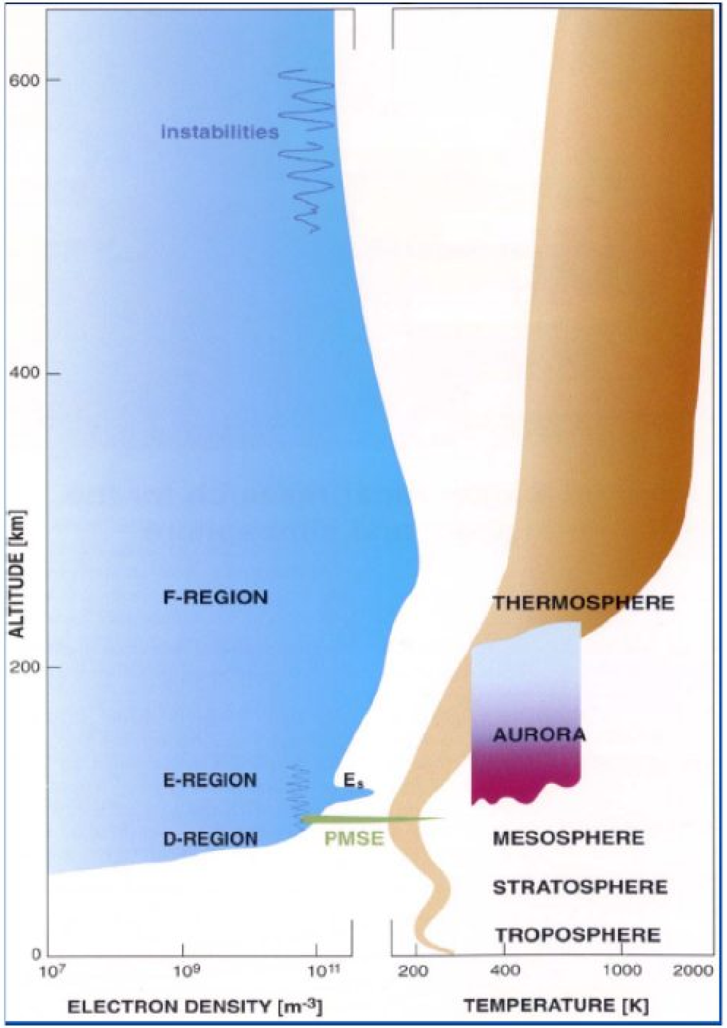
- Debye length is a measure of plasma's ability to shield out electric potential that are applied to it
- It marks the division between the different regimes of plasma's behavior i.e. collective relative to individual particle motion
- At distances > Debye length:
  - Plasma motion needs to be described in terms of collective plasma
  - Plasma will not support large potential variations (i.e. will seek to maintain charge neutrality)

# The ionosphere
## Debye length

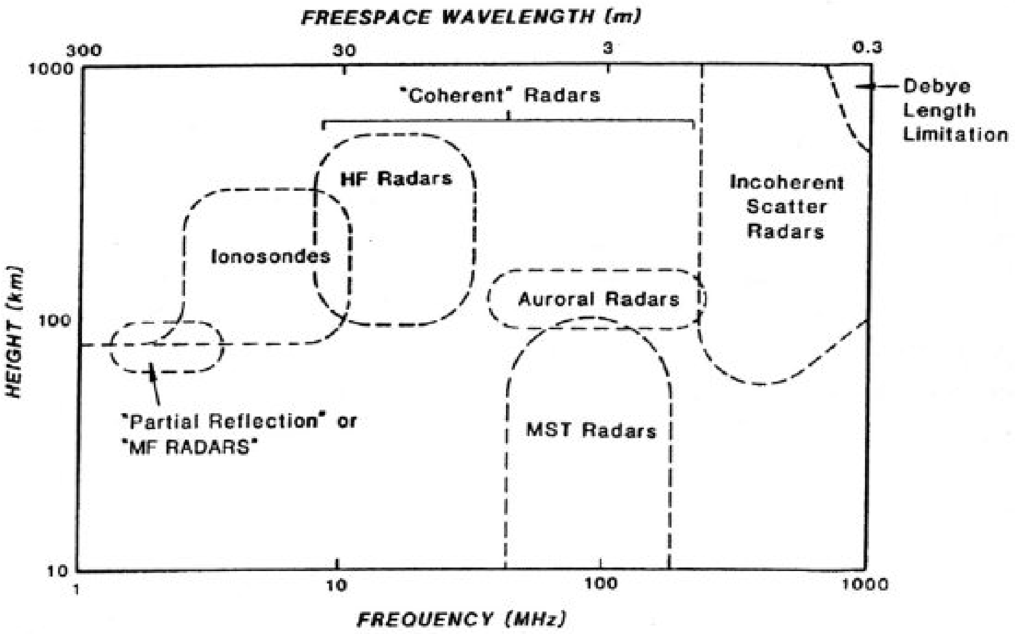
- The  Debye length increases with altitude – from a few millimeters in the F-region up to meters in the magnetosphere
- The Debye length in the E and F regions ranges from 0.1 – 1 cm

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

***Q: If we want to measure the bulk plasma parameters with Incoherent Scatter Radar, how will Delye length affect our choice of radar frequency?***



# The ionosphere



**Answer:** While the radar frequency needs to be higher than that of ionospheric plasma frequencies and irregularities, it should also be chosen with a wavelength greater than the Debye length. This becomes an issue at higher altitudes.

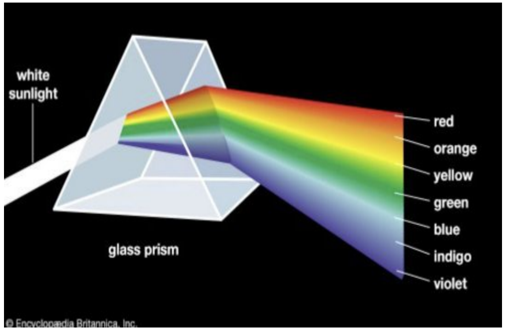
# Summary
# Part 1

- Structure of the Earth’s Atmosphere and Ionosphere
  - Hydrostatic Equilibrium
  - Composition, Temperature
- Formation of Ionosphere
  - Chapman Production Function
  - Electron/proton contributions in ionization
- Dynamics
  - Ion-neutral collision frequencies, conductivity, and Debye Length
- **Part 2 : Radio Techniques**

# Radio Measurements

# Radio measurements of the upper atmosphere

- Propagation and Reflection Experiments:
  - Consider ionospheric plasma as a continuum
  - Ray-bending and reflection governed by variable index of refraction
- Incoherent Scatter Radar:
  - Consider ionospheric plasma as a collection of electron point targets
  - Assume plasma is stable and near thermodynamic equilibrium
  - Use statistical mechanics to describe scatter
- Coherent Scatter Radar:
  - Consider ionospheric plasma as a heterogenous, structured medium
  - Scatter from turbulence, plasma irregularities, etc.



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# The Appleton-Hartree equation

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

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

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

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

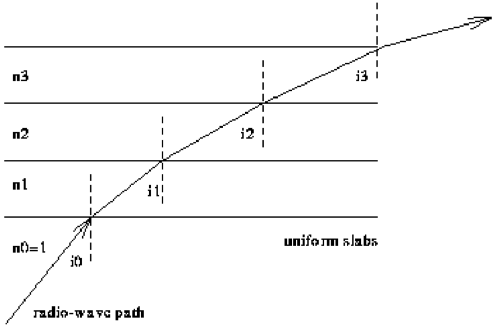
$\theta$ = angle between the wave vector $\bar{k}$ and $\bar{B}$,

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

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

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

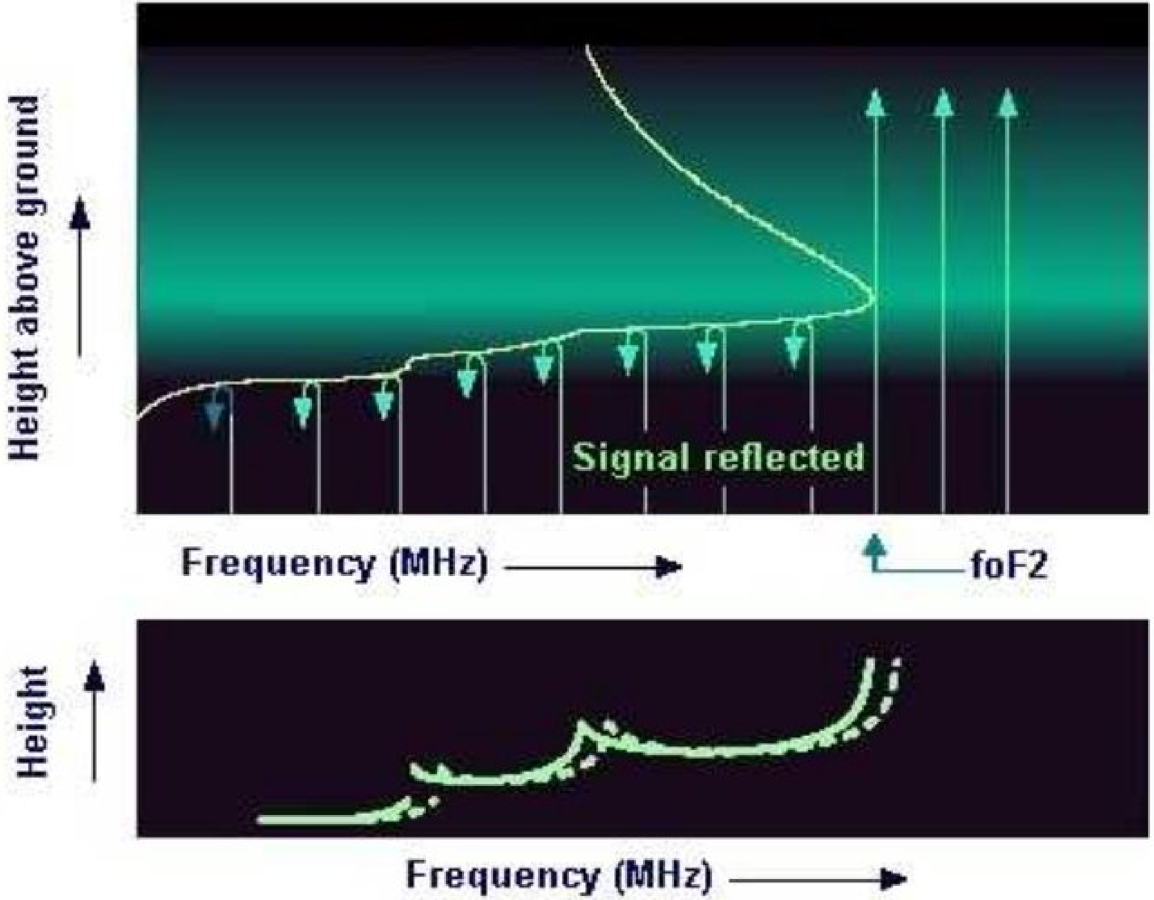
and $\varepsilon_0$ = permittivity constant.



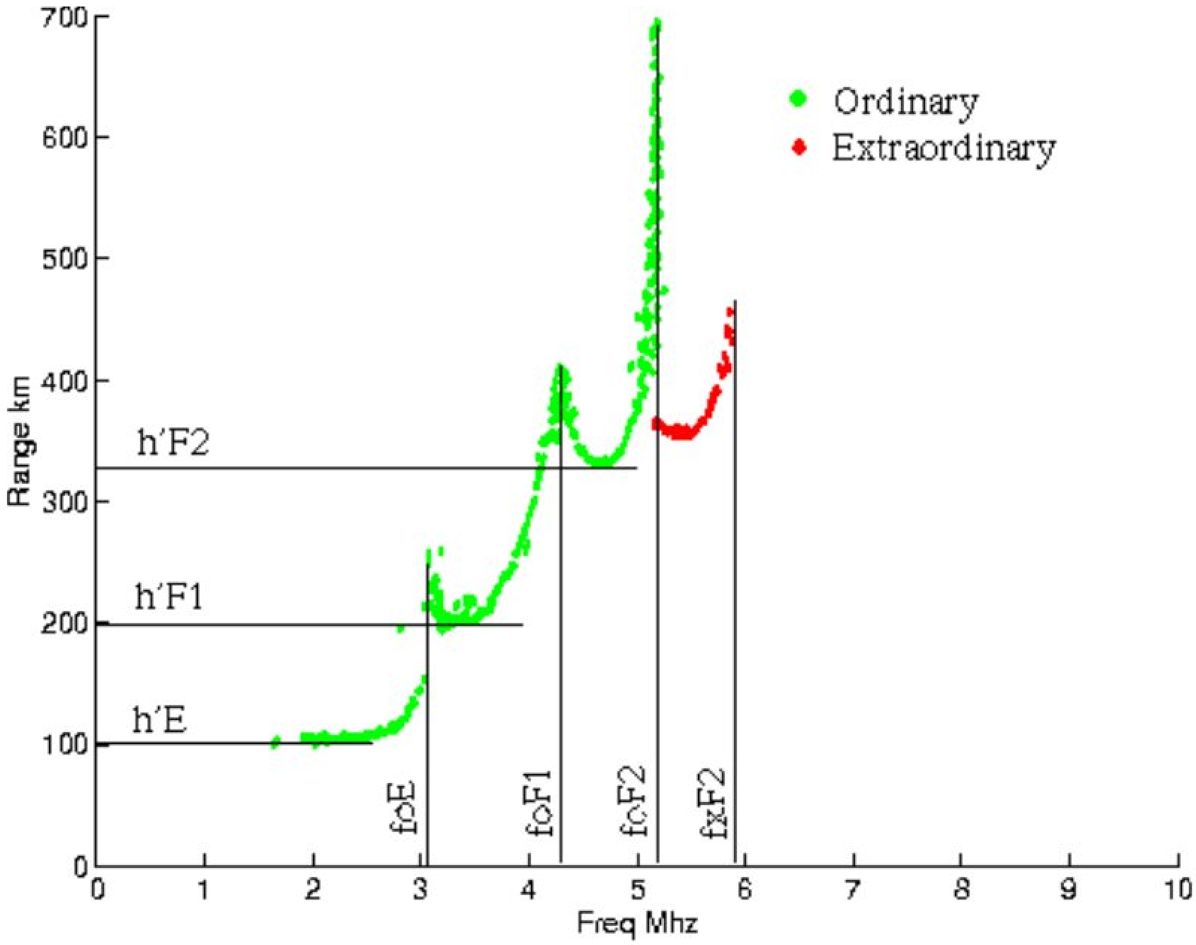
**Simplified Case: $Y_L = Y_T = 0$**

**$n^2 = 1 - X = 1 - \omega_N^2/\omega^2$**

# Reflection experiments: ionosondes

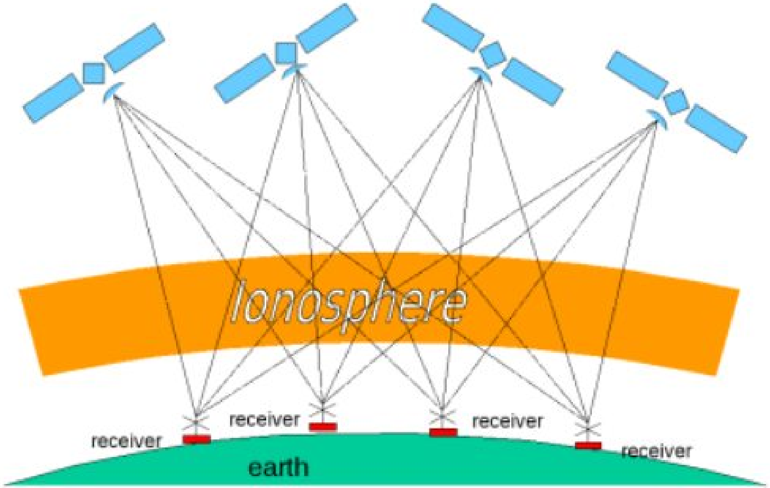


# An Example of Ionogram

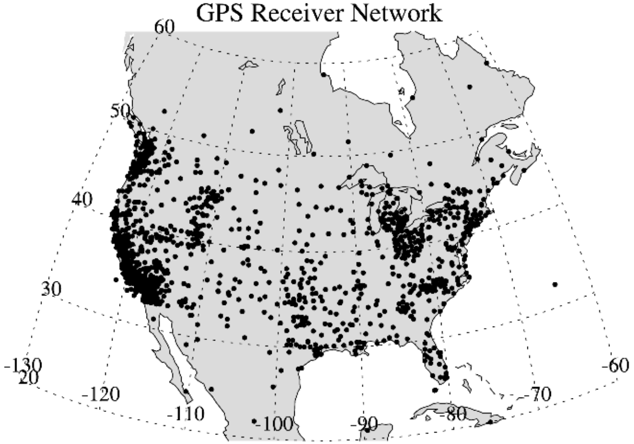


# GPS time difference of arrival

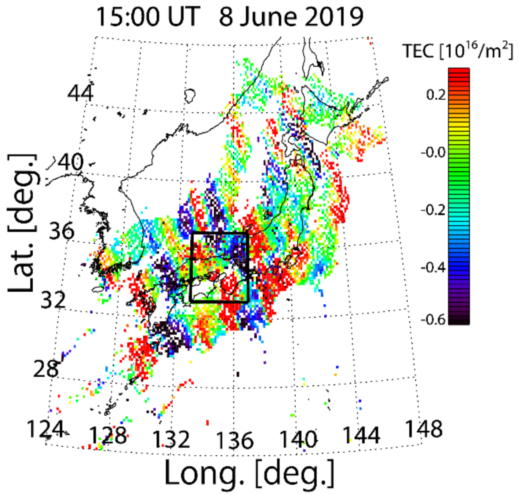
- Satellite radio signals have to traverse the ionosphere to reach the ground.
- Different frequencies travel at different speeds through the ionosphere. A dual frequency GPS receiver can measure the time difference of arrival of signals at different frequencies.
- Time difference of arrival gives the line integral of the electron density along the ray path (total electron content, or TEC).



# TEC Data Examples

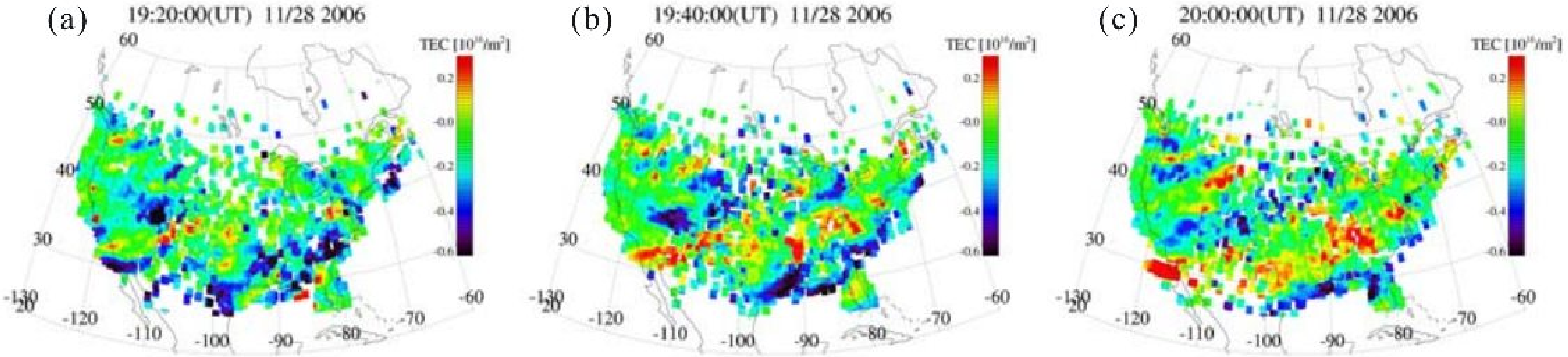


***Dense Network of GNSS receivers in North America and Japan***

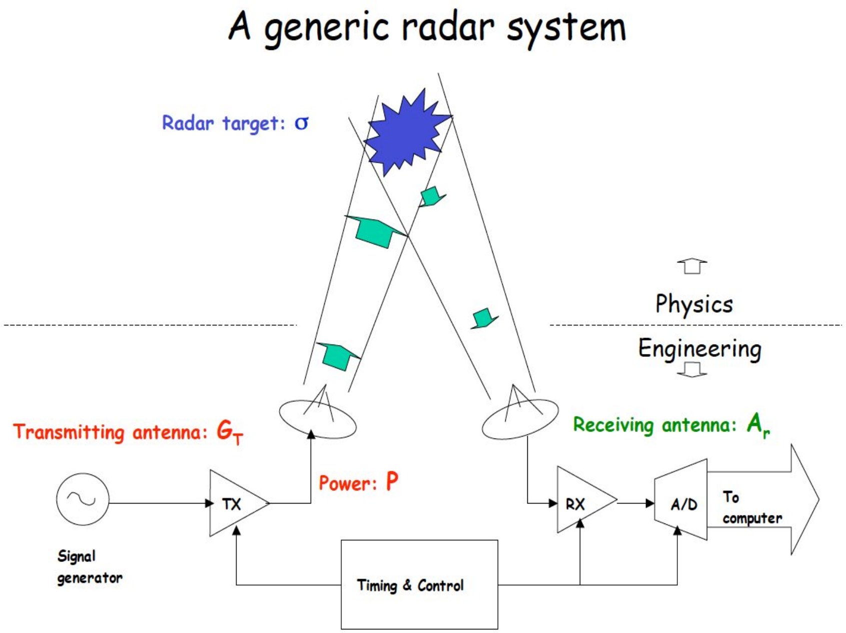


***Tsugawa et al., GRL, 2007***

***Otsuka et al., EPS, 2021***

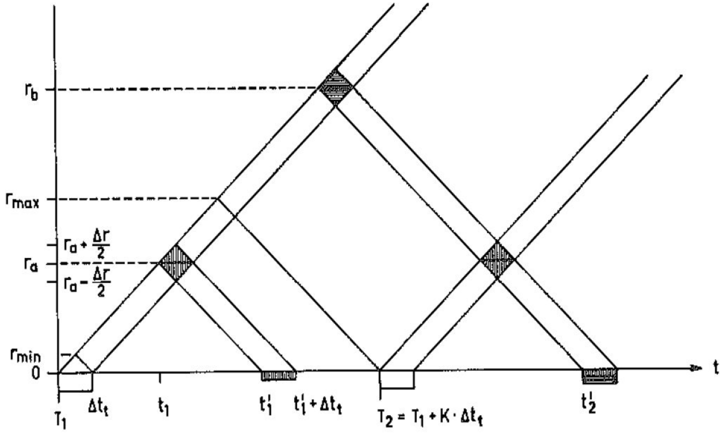


# Radar Concept



*ISR: Scatters from electrons*

$$\mathrm{Pr} = \left(\frac{P_t G_t}{4\pi R^2}\right)\sigma\left(\frac{A_r}{R^2}\right)$$



$$T_1 = {}^{r_a}\!/_{c}$$

$$r_a = {}^{cT_1'}\!/_{2}$$

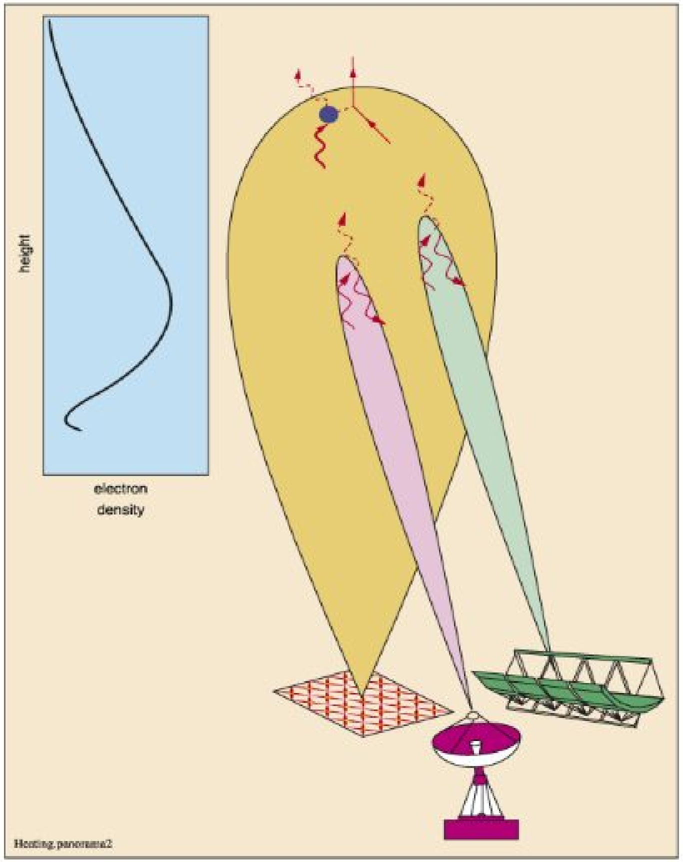
$$T_1' = 2T_1$$

# Coherent Scatter Radar

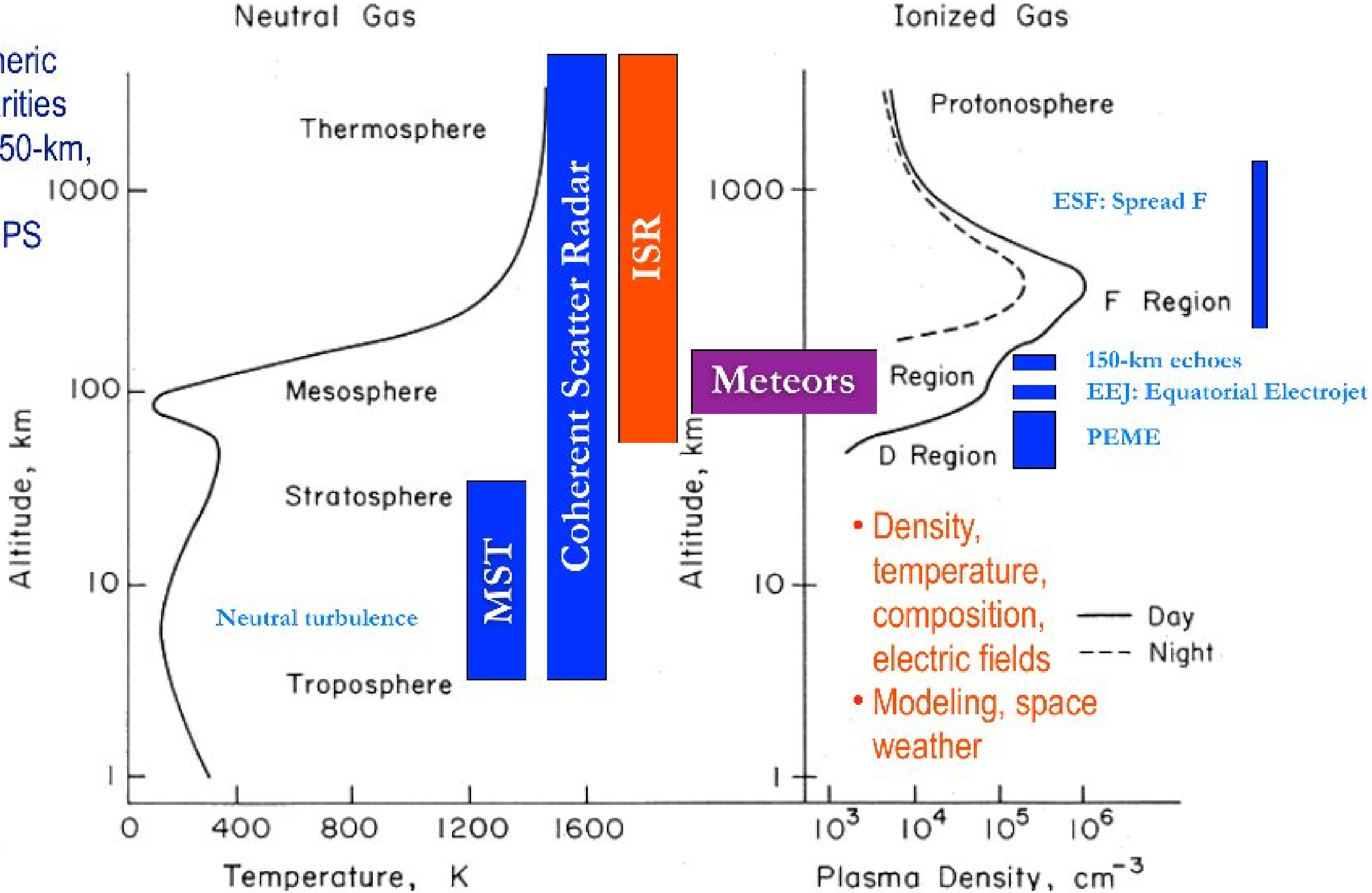
- Any medium with stochastic index of refraction fluctuations can produce coherent scatter.
- Can work in neutral air.
- Works very well in plasmas. Small electron density fluctuations produces significant index of refraction fluctuations.
- Structures must match $\lambda_R/2$ to get constructive interference between the scatter.
- Structures must be aligned $\perp$ to the radar line of sight for constructive interference in the direction back to a monostatic radar.
- Field-aligned irregularities in a plasma are observed when looking $\perp$ to B.

# Incoherent Scatter Radar

- They are big systems with large high-gain antennas.
- Their transmitters deliver power in the order of megawatts.
- Their targets are the electrons moving in the Ionosphere.
- The signal scattered by the electrons is in picowatts, thus the need of sensitive receivers.
- The spectrum of the returned signal provides information about the density, temperature, composition and drift velocity of the Ionospheric plasma as function of height.



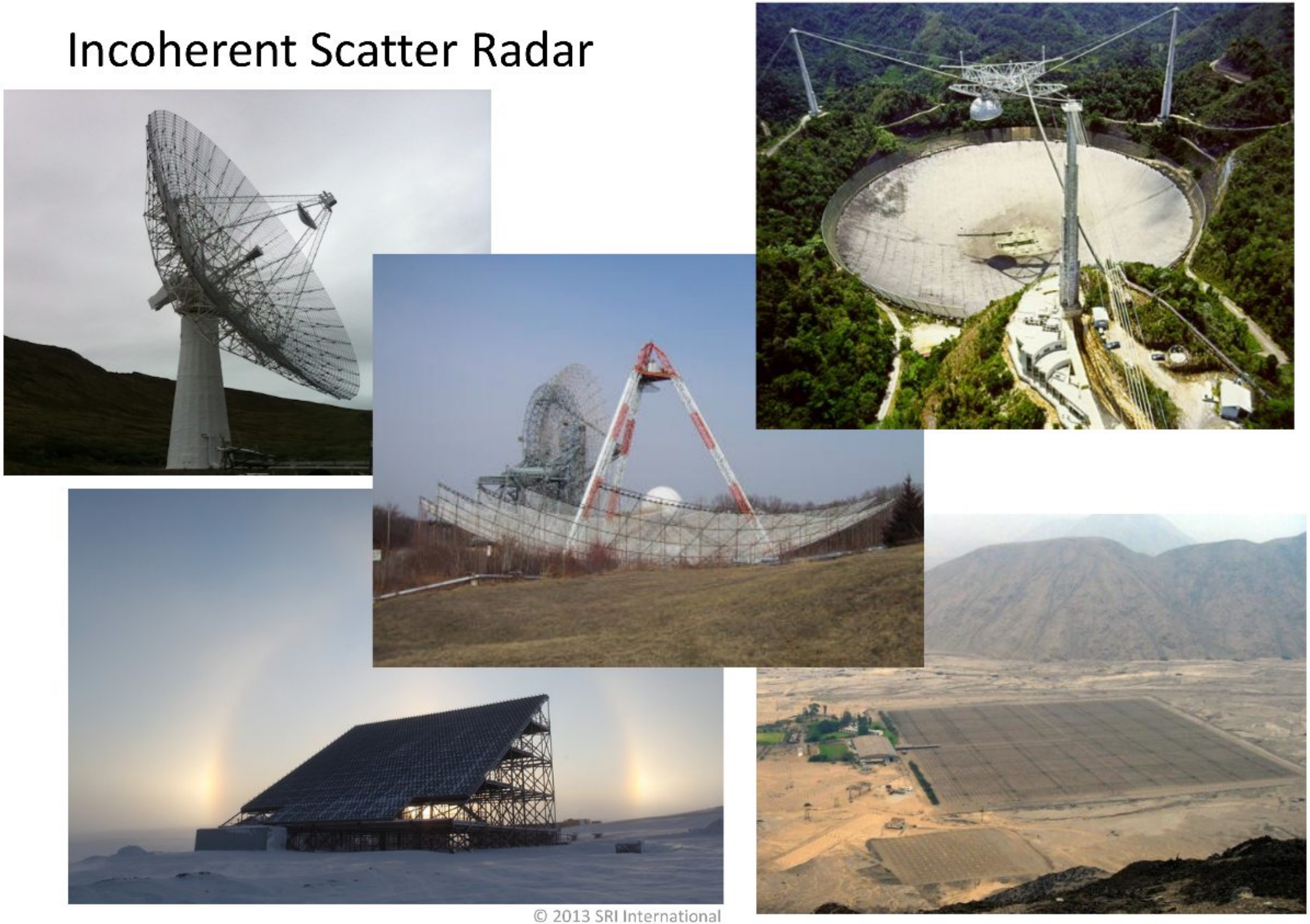
- Ionospheric Irregularities (EEJ, 150-km, ESF).
- SAR, GPS



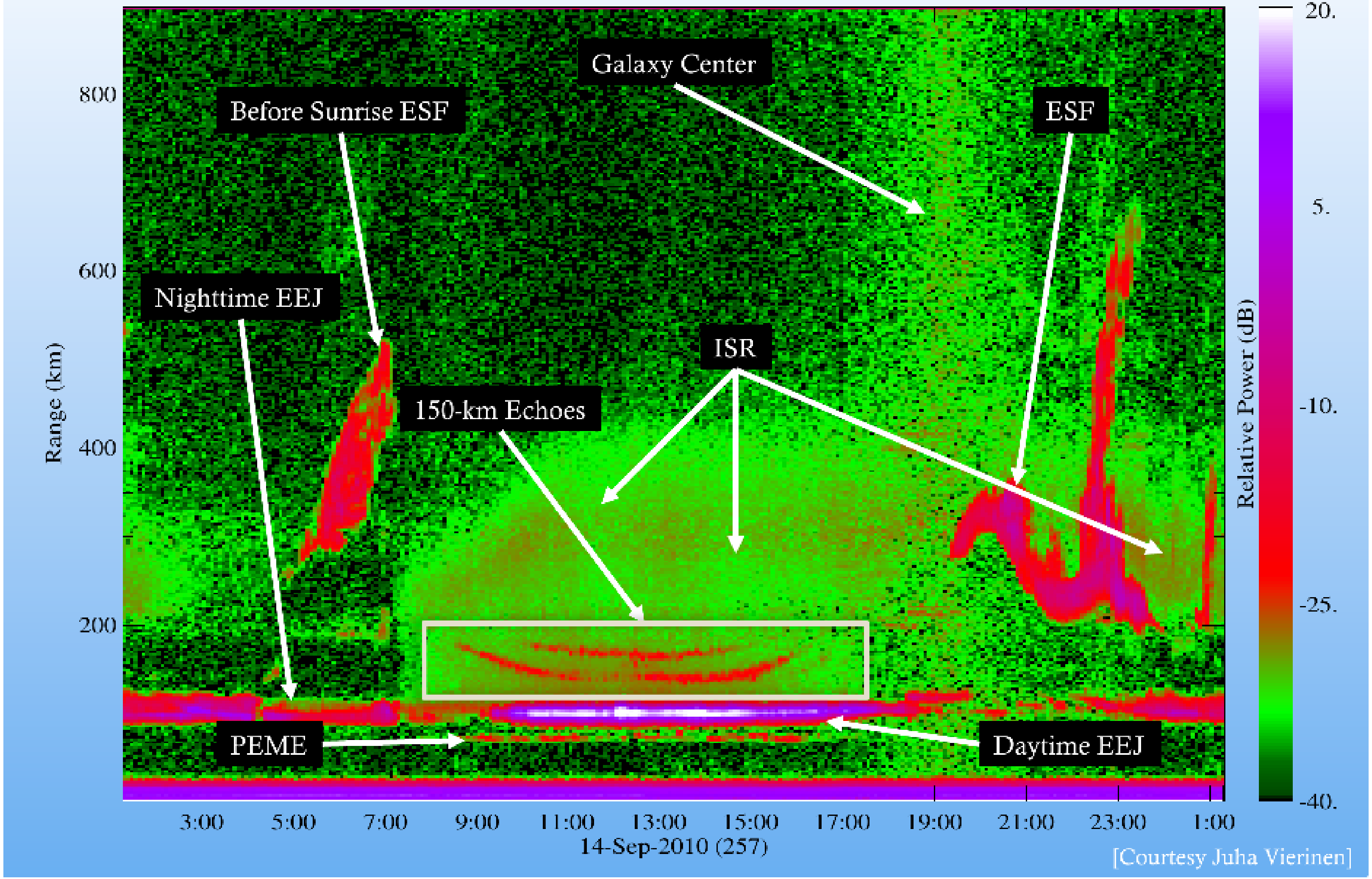
- Neutral atmosphere dynamics (winds, turbulence, vertical velocities)
- Meteorology, aviation.

- Density, temperature, composition, electric fields
- Modeling, space weather

# Incoherent Scatter Radar

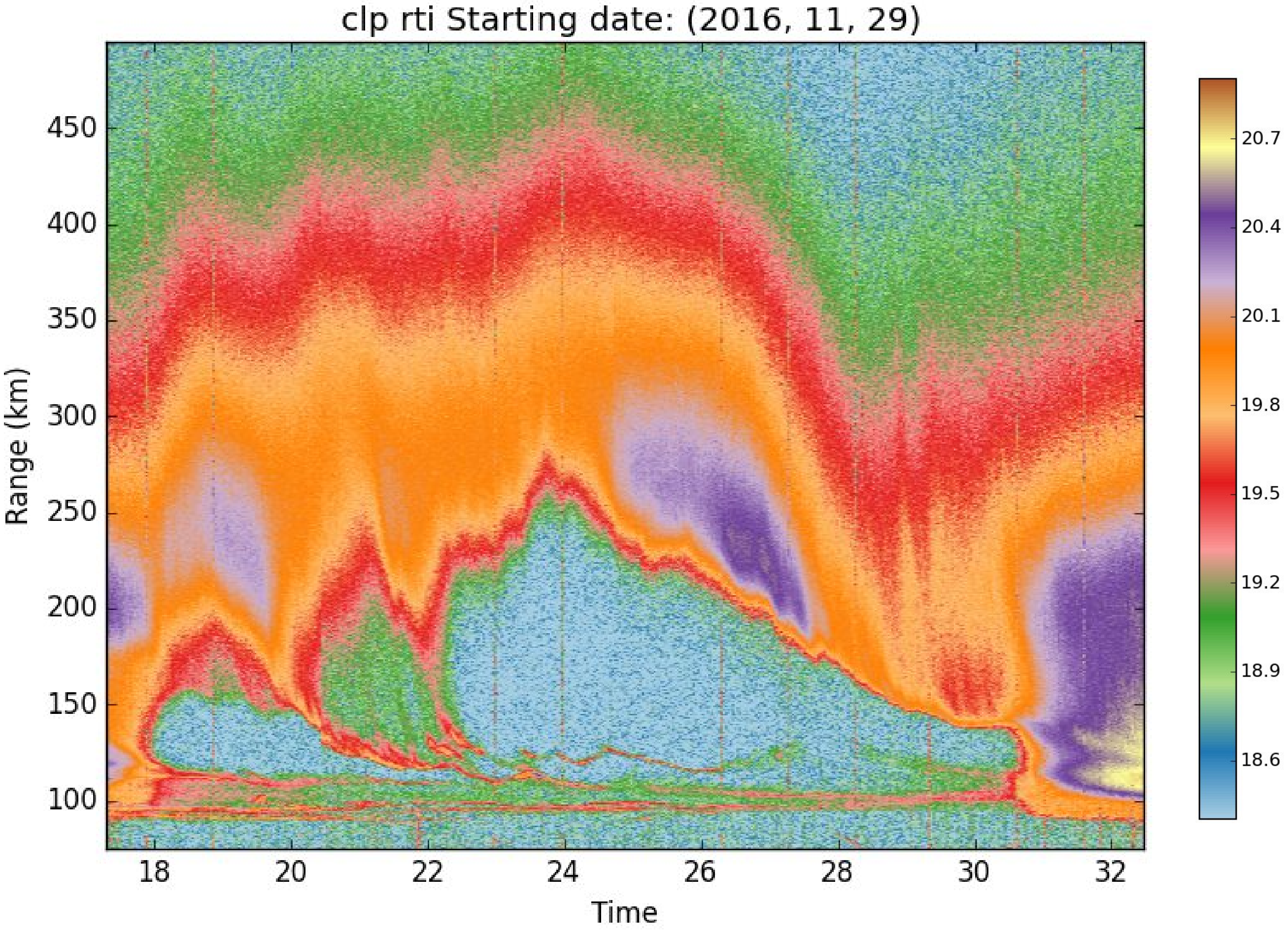


# Incoherent and Coherent Echoes over Jicamarca



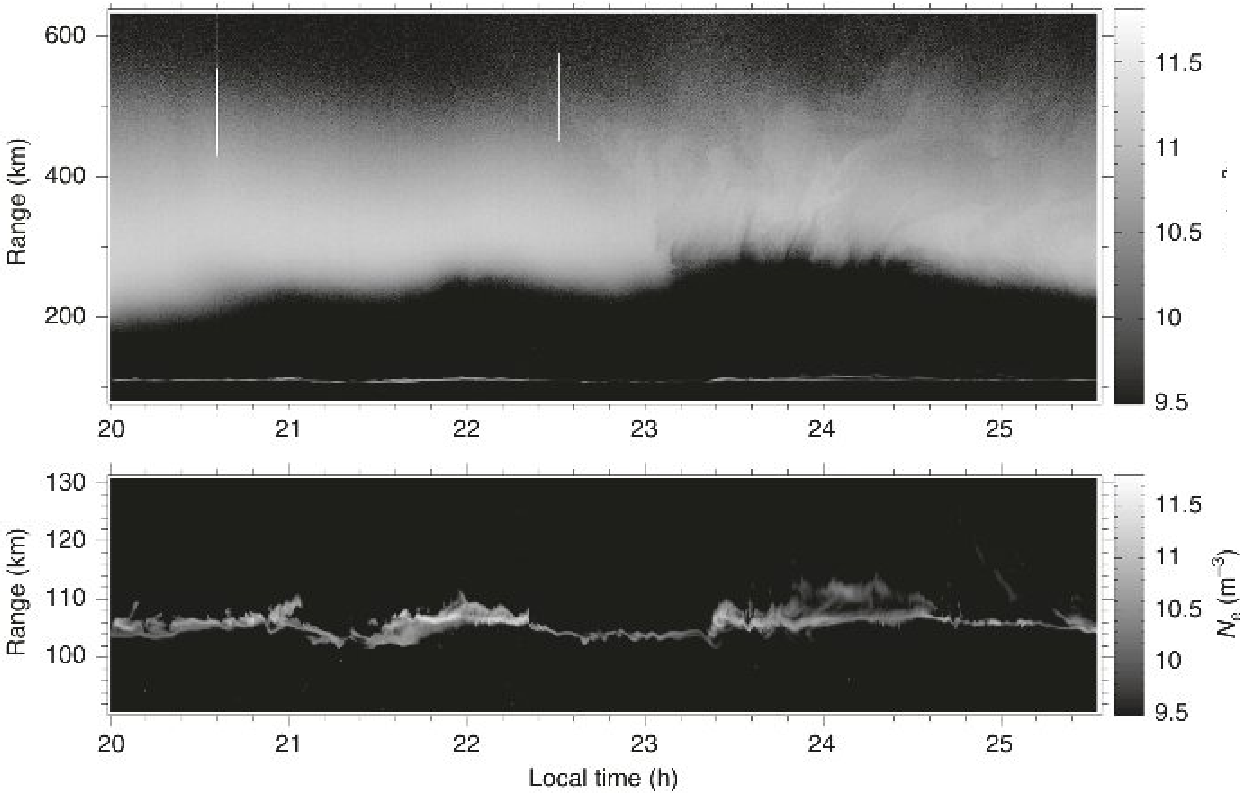
[Courtesy Juha Vierinen]

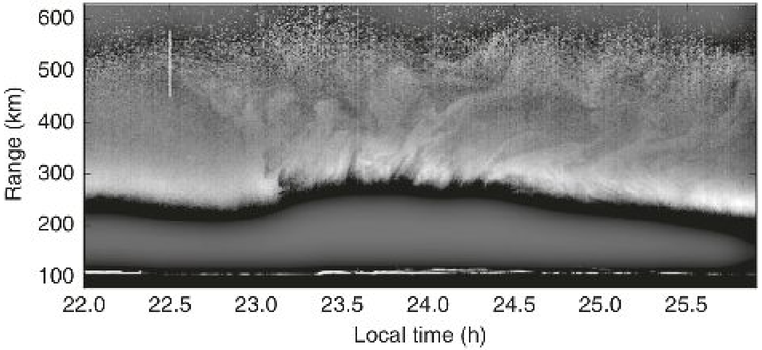
# An Example of ISR Data



# Mid-Latitude Spread-F: Space Weather Phenomena

Arecibo: ISR data; 30 July 2016

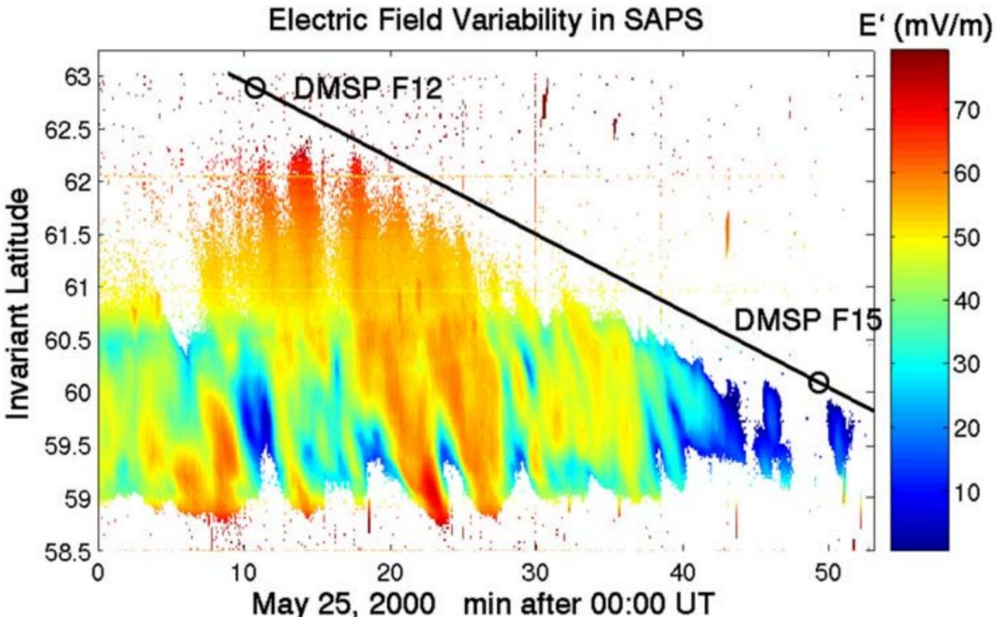




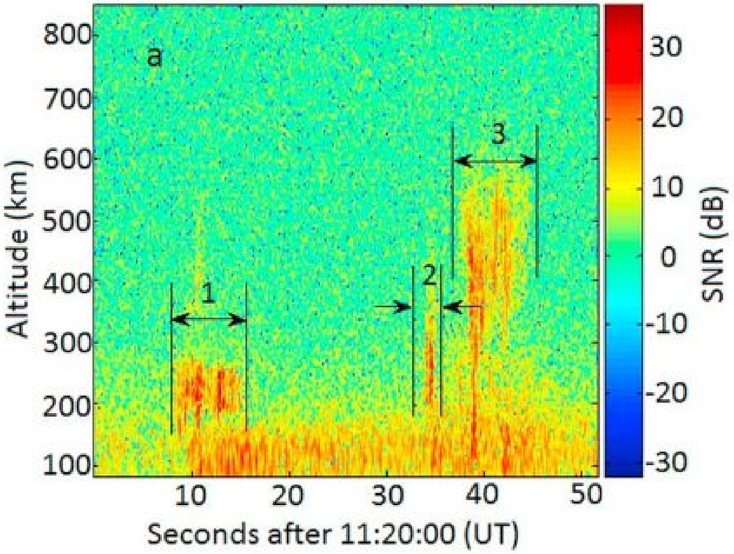
***Numerical simulations suggested that the topside irregularities could be driven by the combined effect of lower atmosphere and plasma dynamics.***

***Hysell et al, Nature Comm., 2018***

# Sub-auroral and auroral Observations



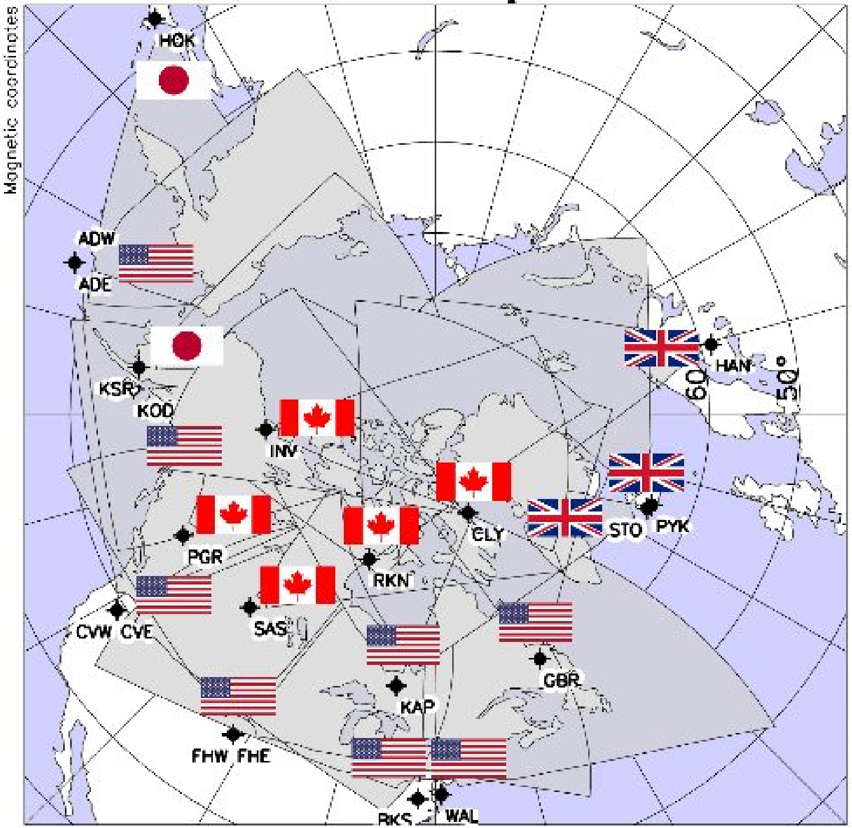
***Foster et al., GRL, 2004***



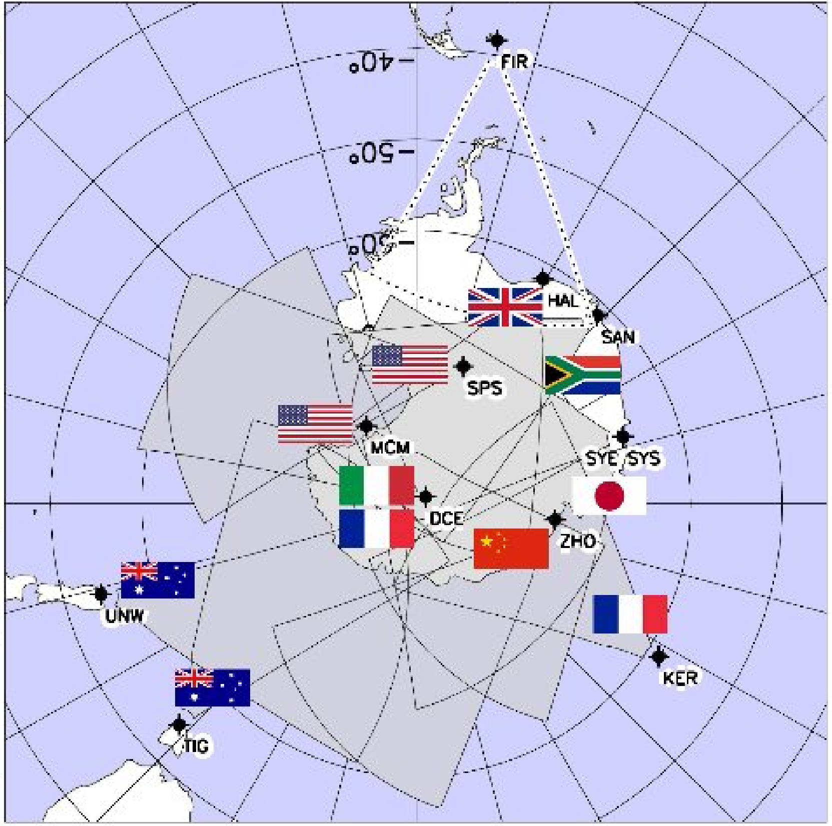
***Akbari et al., GRL, 2012***

# SuperDARN

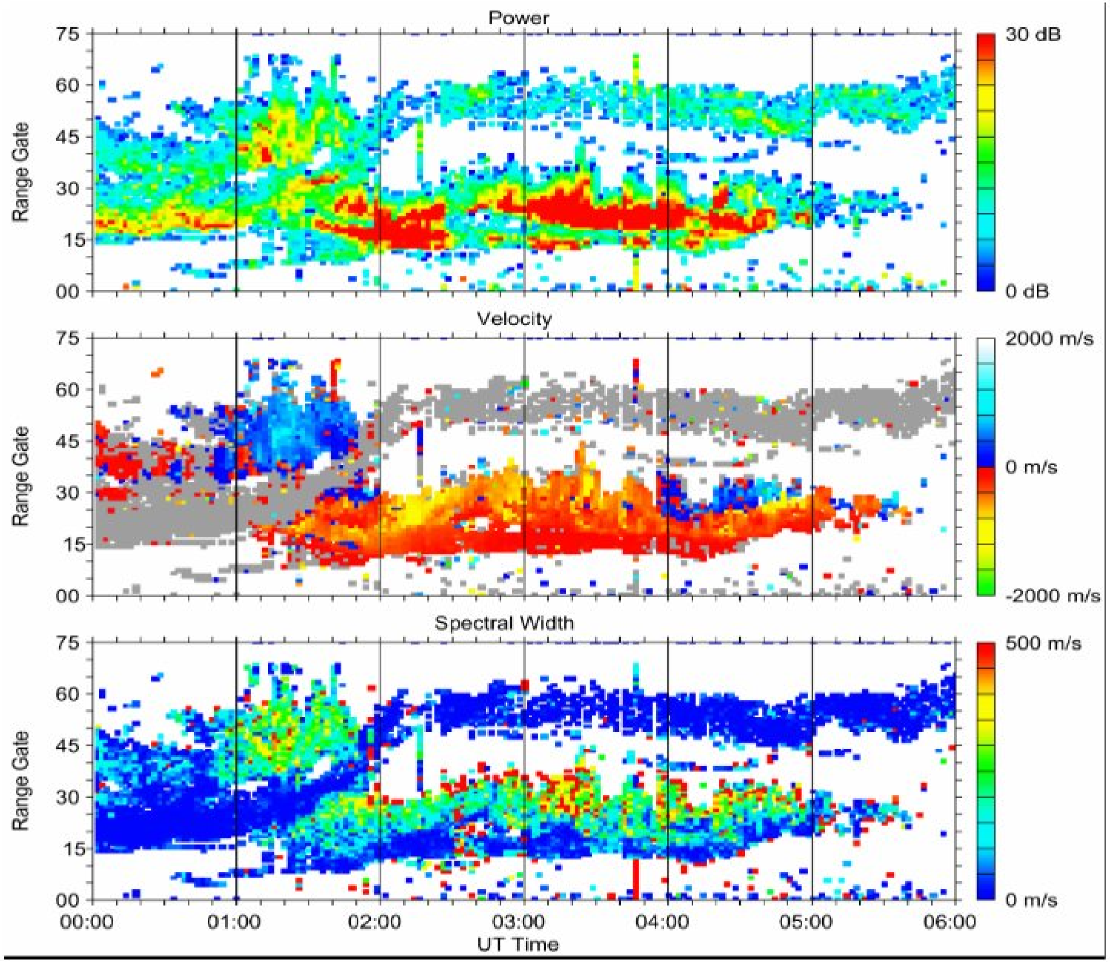
**Northern Hemisphere**



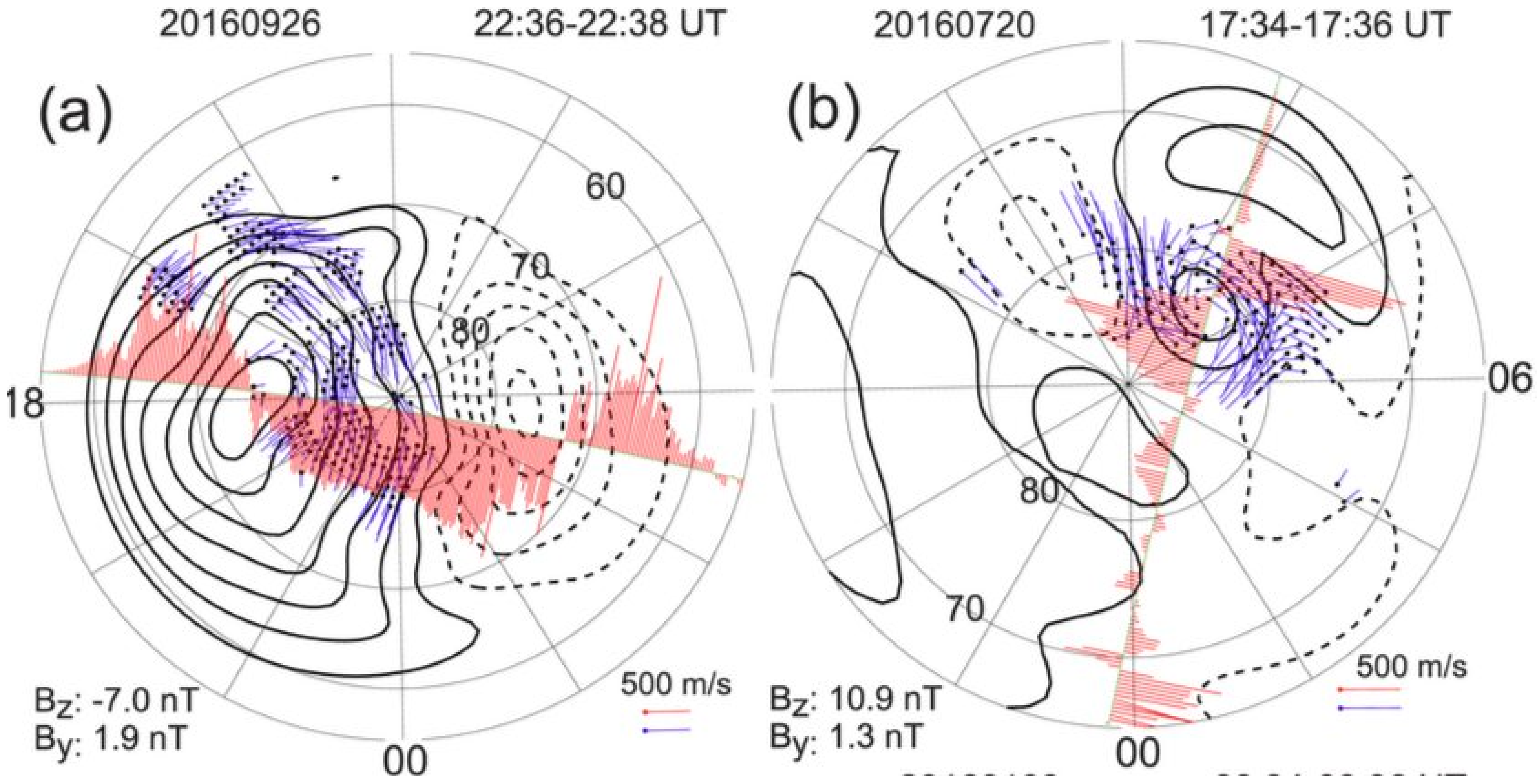
**Southern Hemisphere**



# SuperDARN data



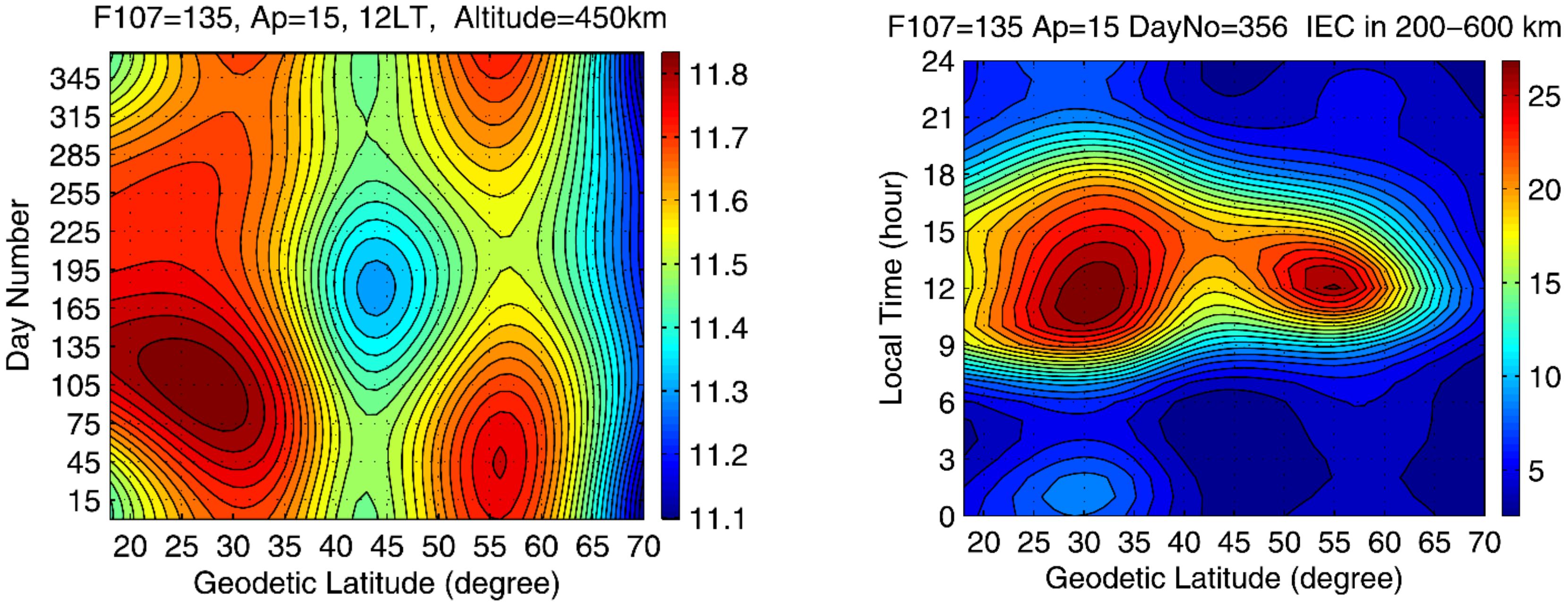
# SuperDARN Data: Convection maps



***Koustov et al., JGR, 2019***

# Climatology inferred using ISRs in US

***Zhang and Holton,JGR, 2007***



*Long Term data sets are useful for investigating the trends, delineating the influence of anthropogenic sources, and other factors.*

# Concluding Remarks

- ISR is the most powerful instrument for ionospheric studies
  - Provides high temporal and range resolution data
  - Infer electron density, drift velocities, electron and ion temperatures
- Ionosphere is highly variable, and many space weather phenomena cannot be accurately predicted
- Long-term data sets are useful to understand the influences of solar-cycle, develop empirical models.
- Combining different techniques allow us to investigate different processes.