

Introduction to Ionosphere

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Acknowledgments:

E. Kendall, M. Sulzer, A. Coster, Roger Varney

Funding Support: NSF

Incoherent Radar Scatter School

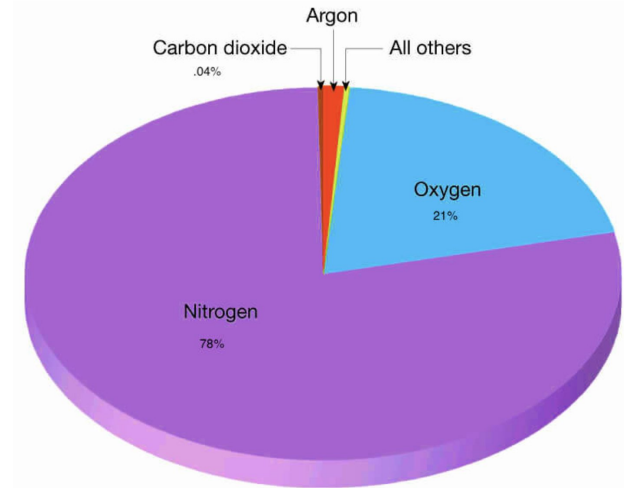
17 – 22 July, 2022

Boston University

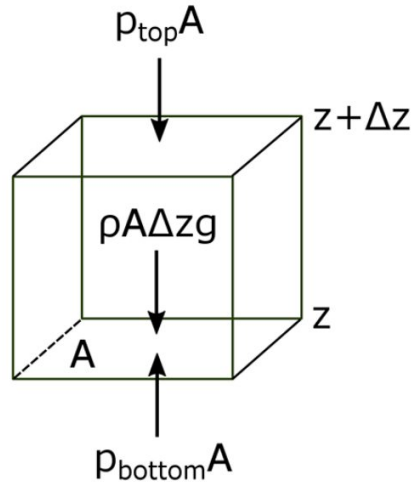


Outline

- Atmosphere
 - Ionosphere
 - acts as a natural plasma laboratory
 - Important for communications
 - Vertical and horizontal 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: $P = nK_B T$

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

and

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

where p_0 and n_0 are values at a reference height z_0 .

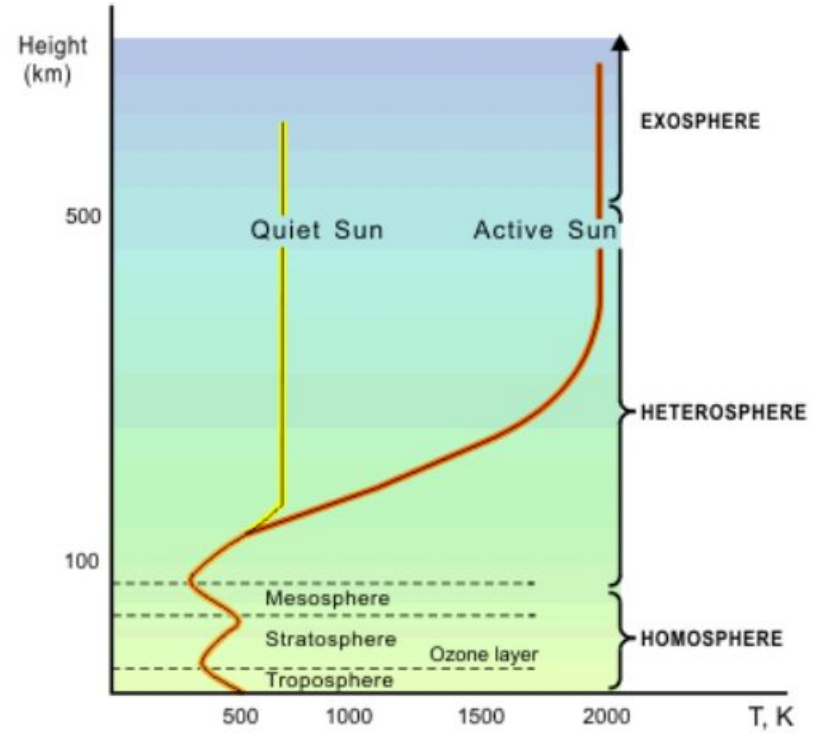
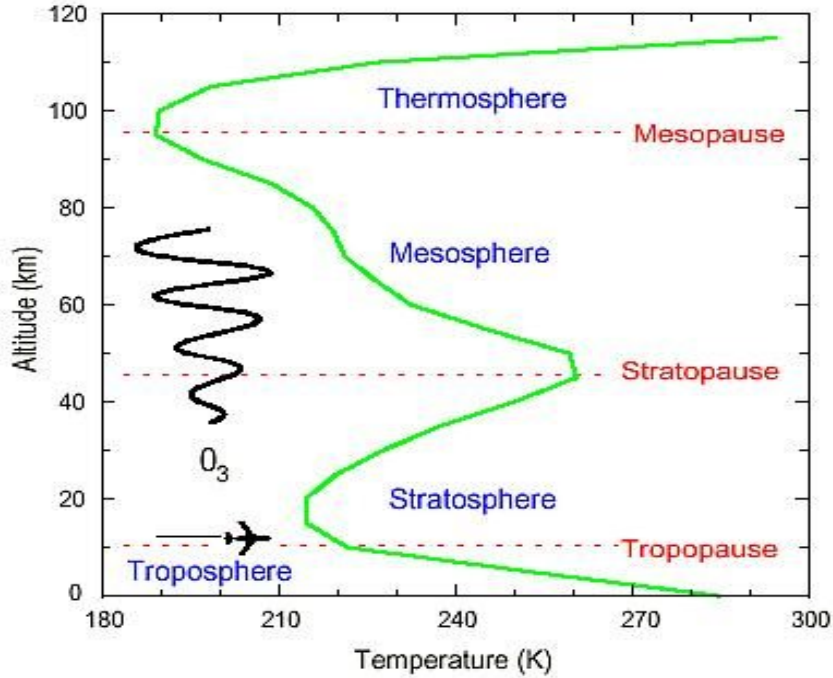
if the atmosphere is isothermal ($T = \text{constant}$), the **scale height H**

$$H = \frac{k_B T}{mg} \quad (3)$$

is independent of altitude and then the hydrostatic equations are

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

Atmospheric Layers



Neutral atmosphere

Composition in the heterosphere

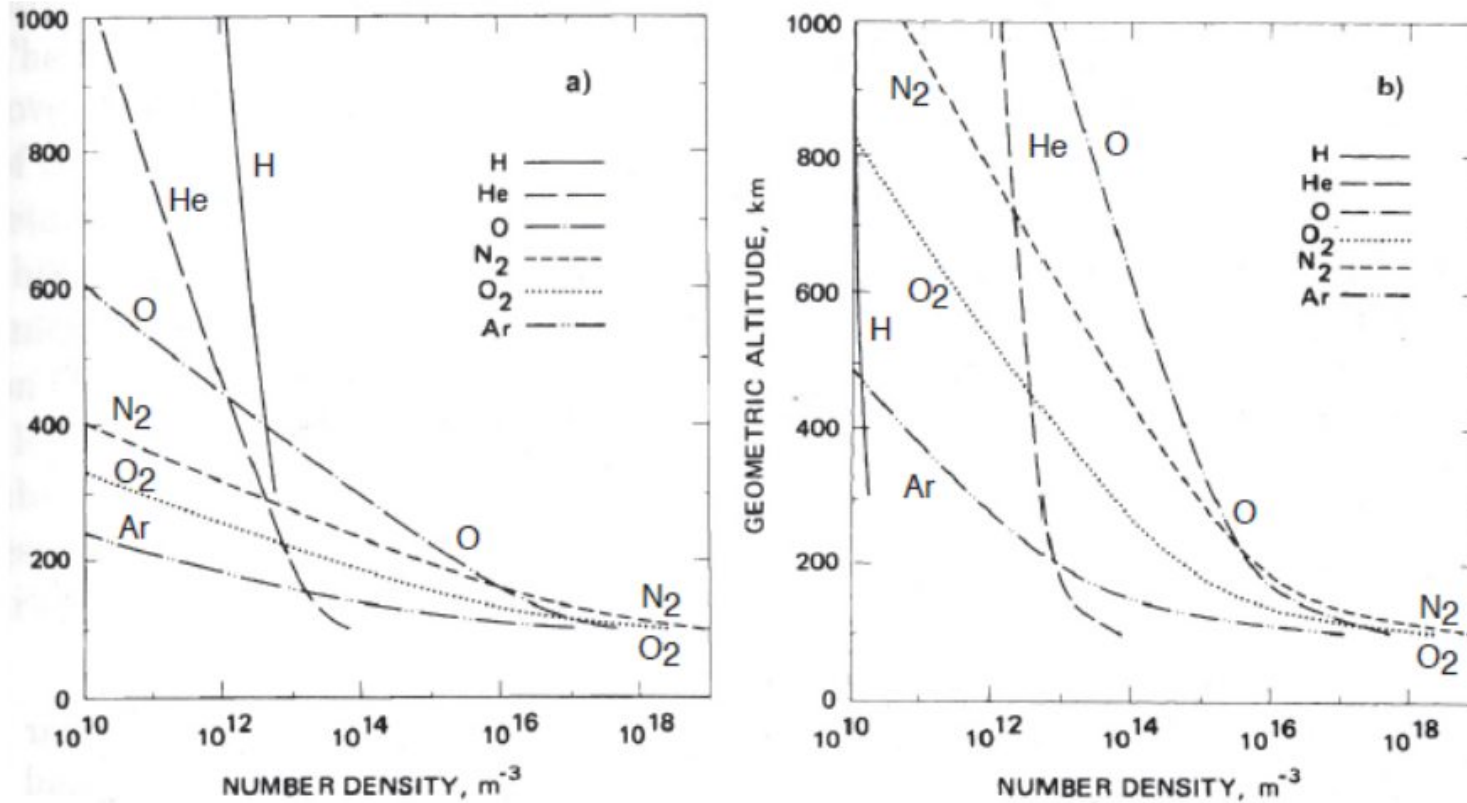


Figure: Atmospheric composition during (a) solar minimum and (b) solar maximum (U. S. Standard atmosphere, 1976).

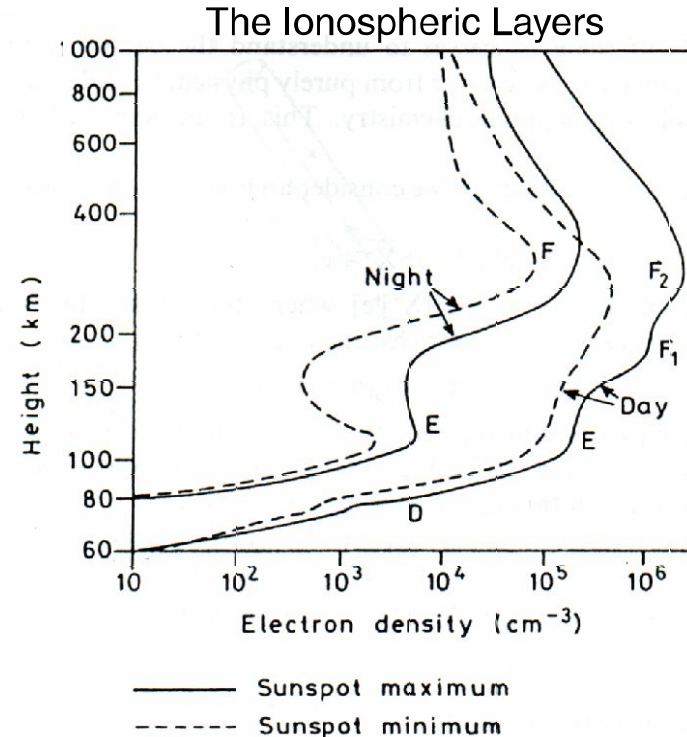
Ionosphere: Part of Earth's Atmosphere

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:

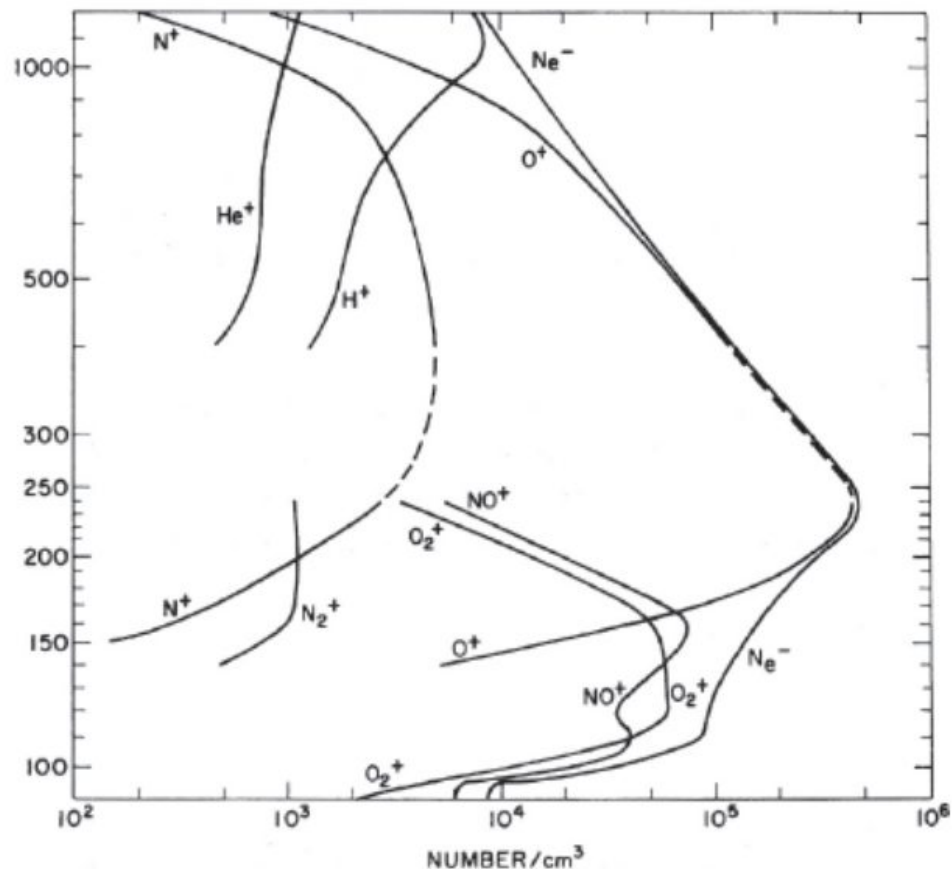
- Solar cycle variations (in the upper F region)
- Day-night variations in lower F, E, and D regions
- Space weather effects based on short-term solar variability (lower F, E, and D regions)



The ionosphere

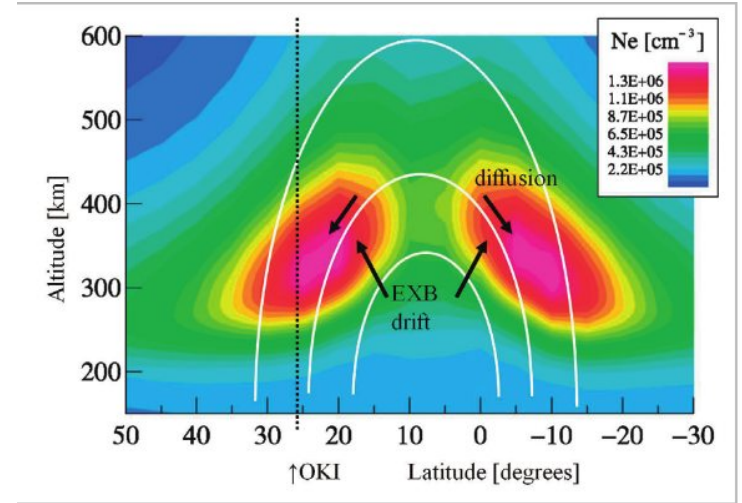
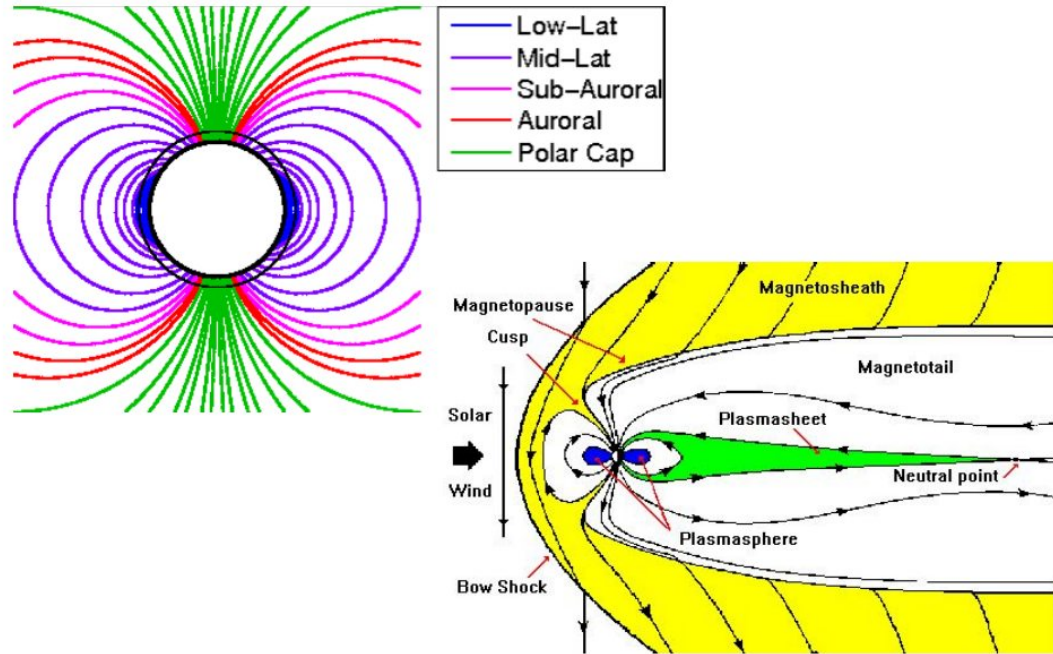
Composition in the heterosphere

- 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. $N_2^+ + O \rightarrow NO^+ + N$).
- 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:

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

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

Where \mathbf{E} is the electric field, \mathbf{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 ν_i and ν_e , respectively

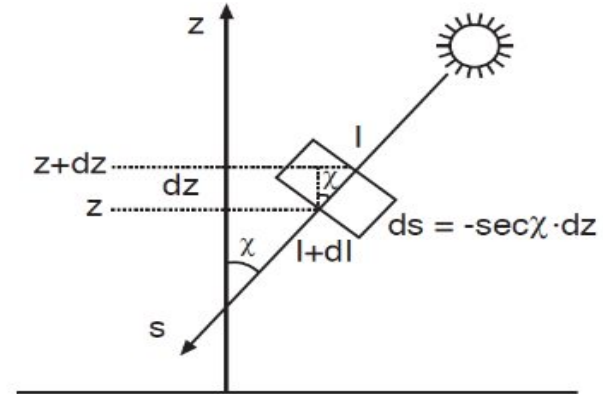
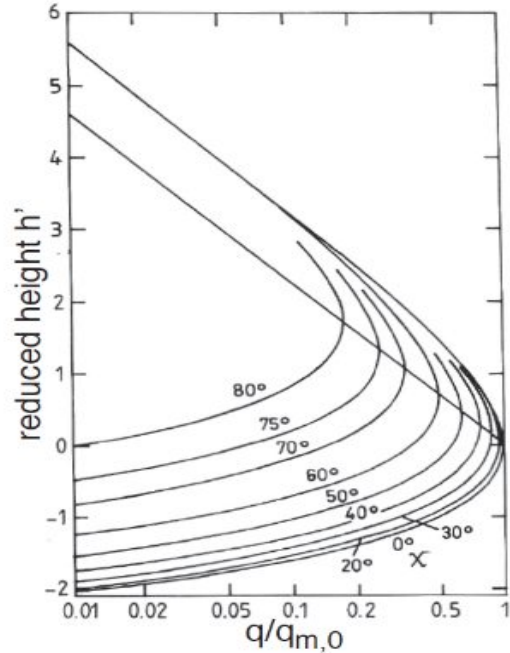
The ionosphere

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



With larger zenith angle χ , 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.

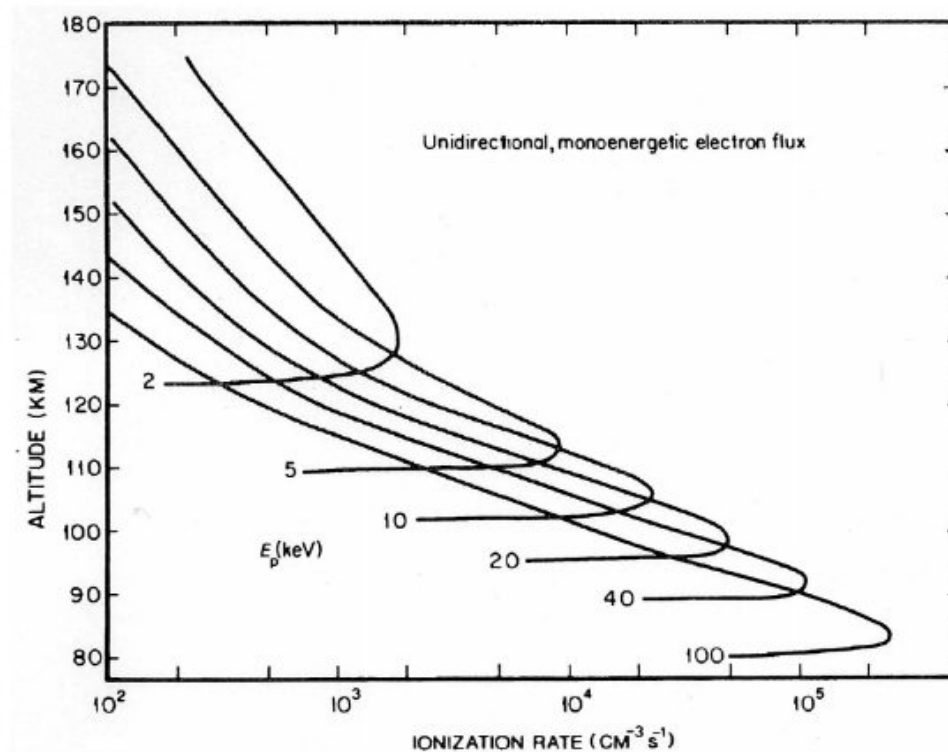


Figure: Ionization rate for monoenergetic electrons with energies 2-100 keV

The ionosphere

Ionization source: particle precipitation (protons)

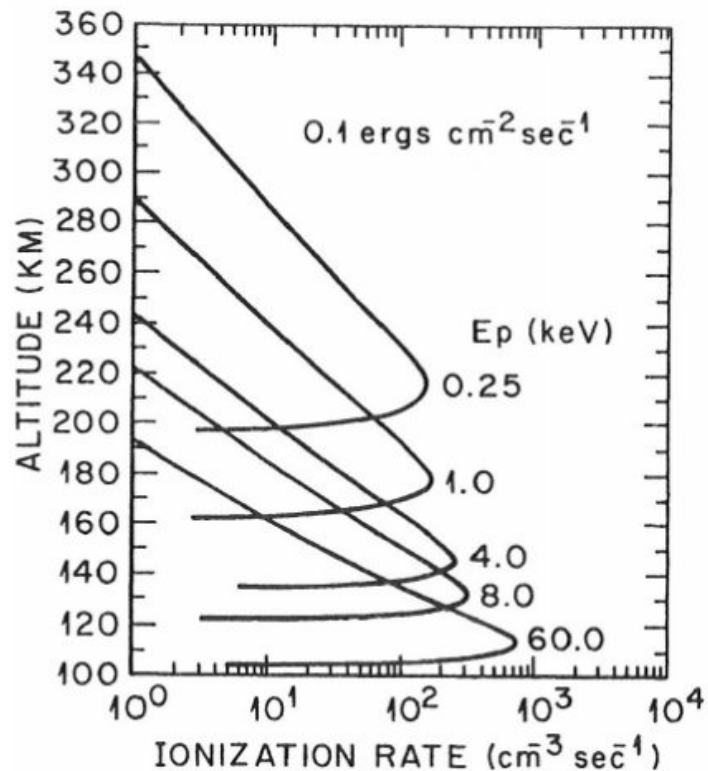


Figure: Ionization rate for monoenergetic protons with energies 0.25-60 keV

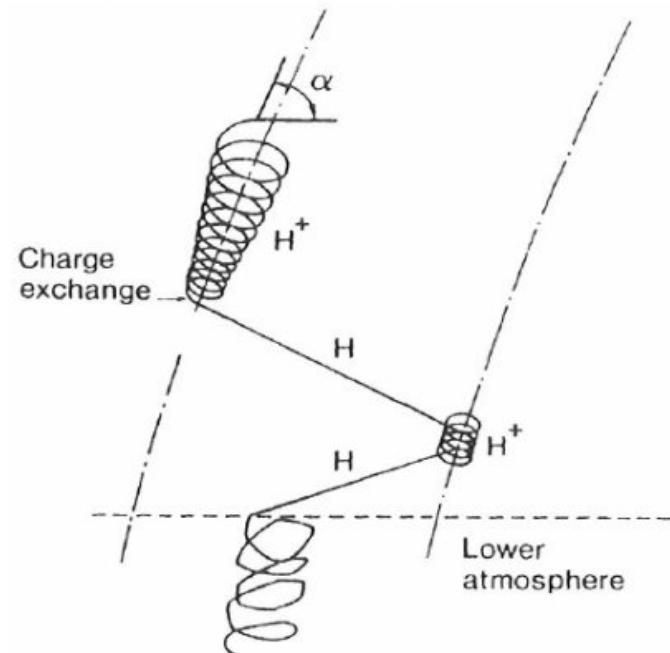


Figure: Protons may make charge exchange with neutral hydrogen.

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

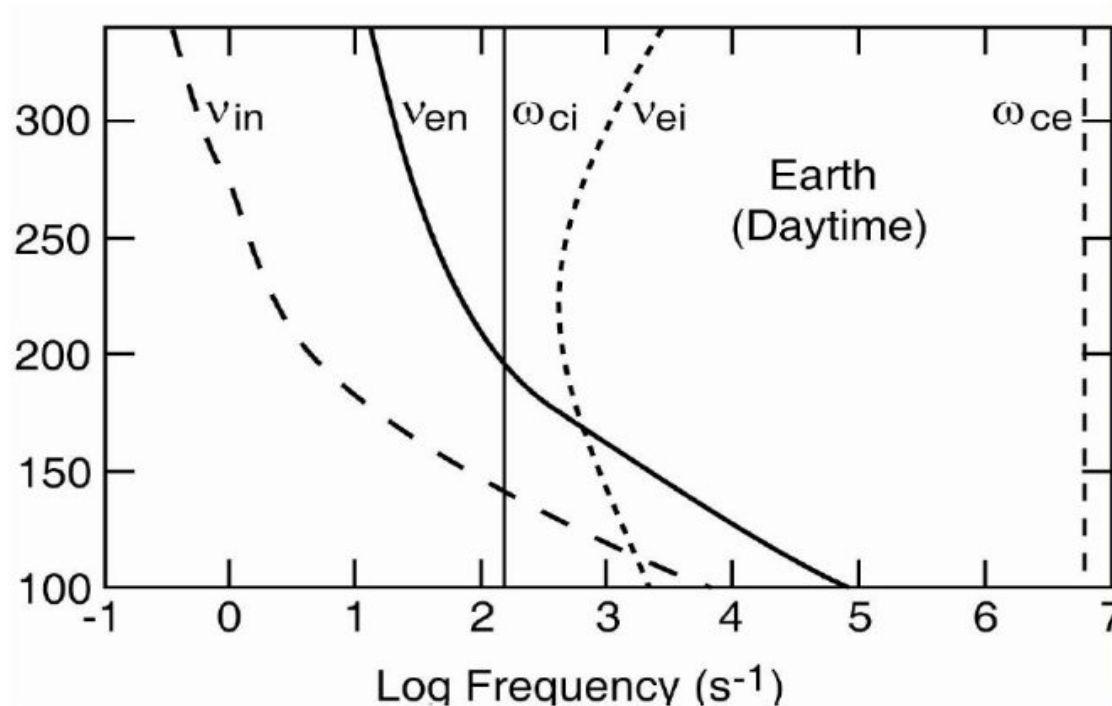
$$n_i m_i \left(\frac{\partial}{\partial t} + \mathbf{v}_i \cdot \nabla \right) \mathbf{v}_i = n_i m_i \mathbf{g} + en_i (\mathbf{E} + \mathbf{v}_i \times \mathbf{B}) - \nabla p_i - n_i m_i \nu_i (\mathbf{v}_i - \mathbf{u})$$

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

The ionosphere

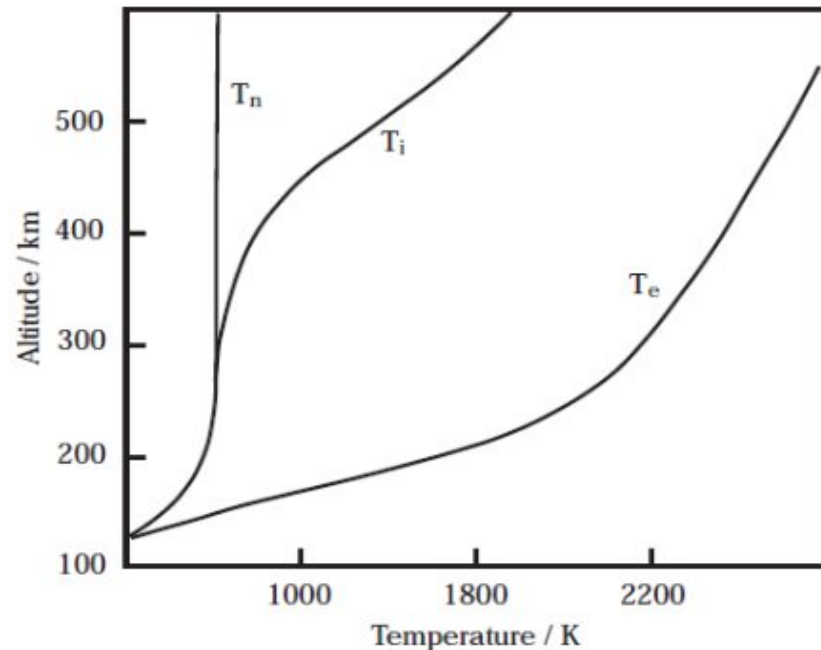
Collision frequencies

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.



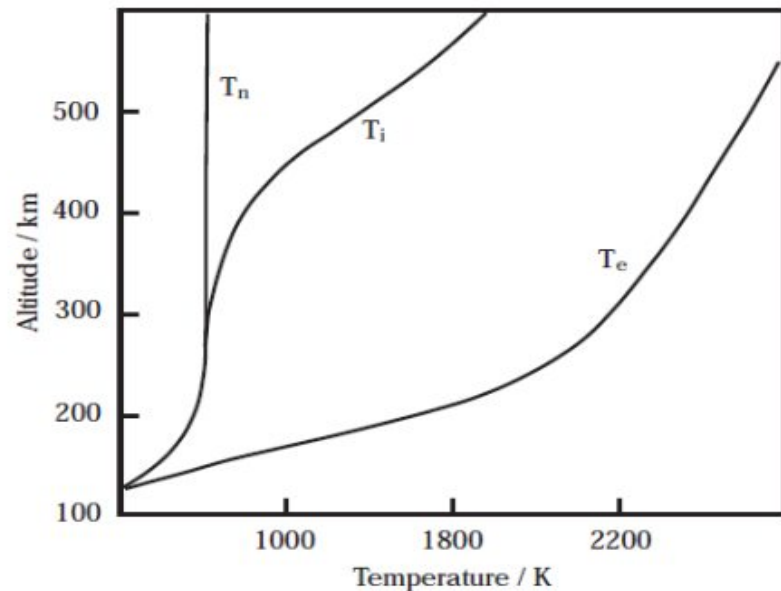
What is the consequence of altitude dependence of collision frequencies?

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

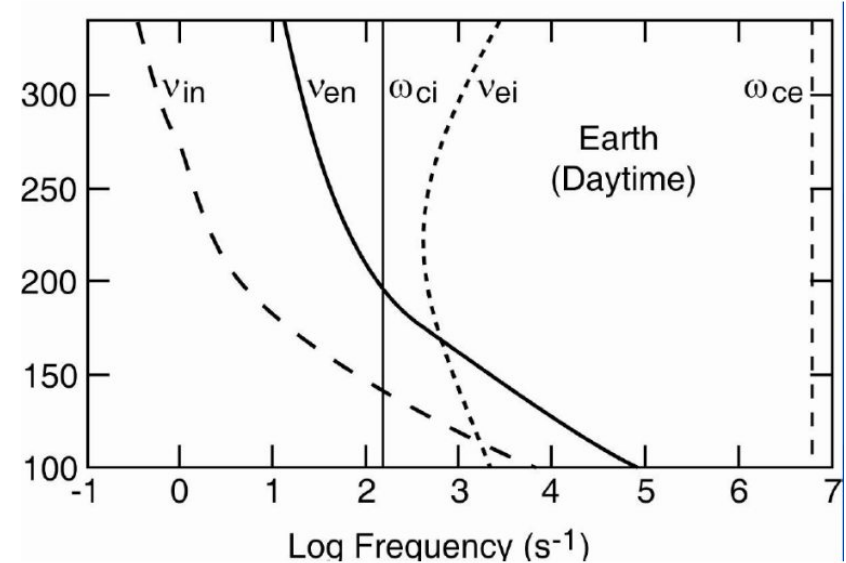
Collision Frequencies

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

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Charged particles are subjected to different forces

Gyrofrequency, $\omega_c = qB/m$



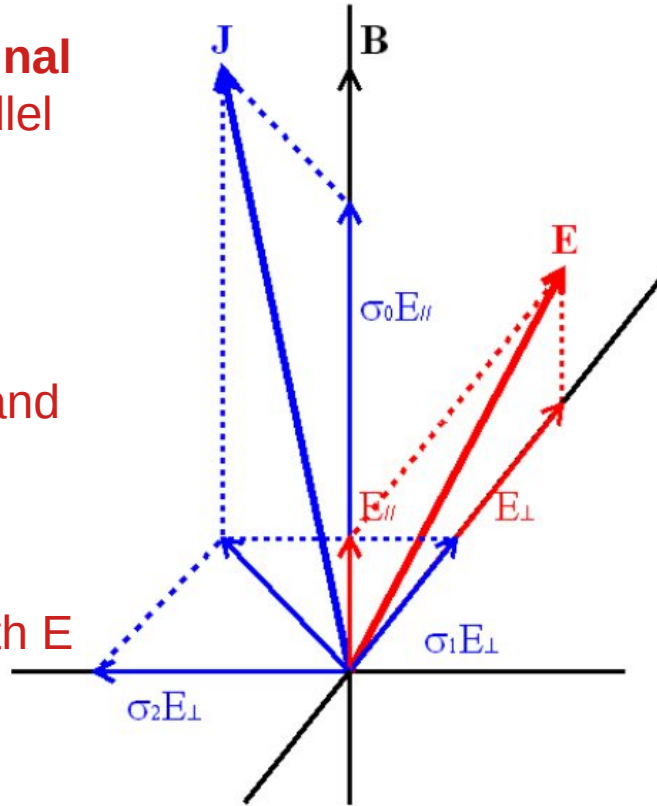
Ionosphere

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} : Parallel component of the electric field

J : Electric current vector

$\sigma_0 E_{\parallel}$: Parallel current

$\sigma_1 E_{\perp}$: Pedersen current

$\sigma_2 E_{\perp}$: Hall current

The ionosphere

Conductivity

- Pedersen conductivity (parallel to E)

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

- Hall conductivity (along EXB)

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

- Parallel conductivity (parallel to B)

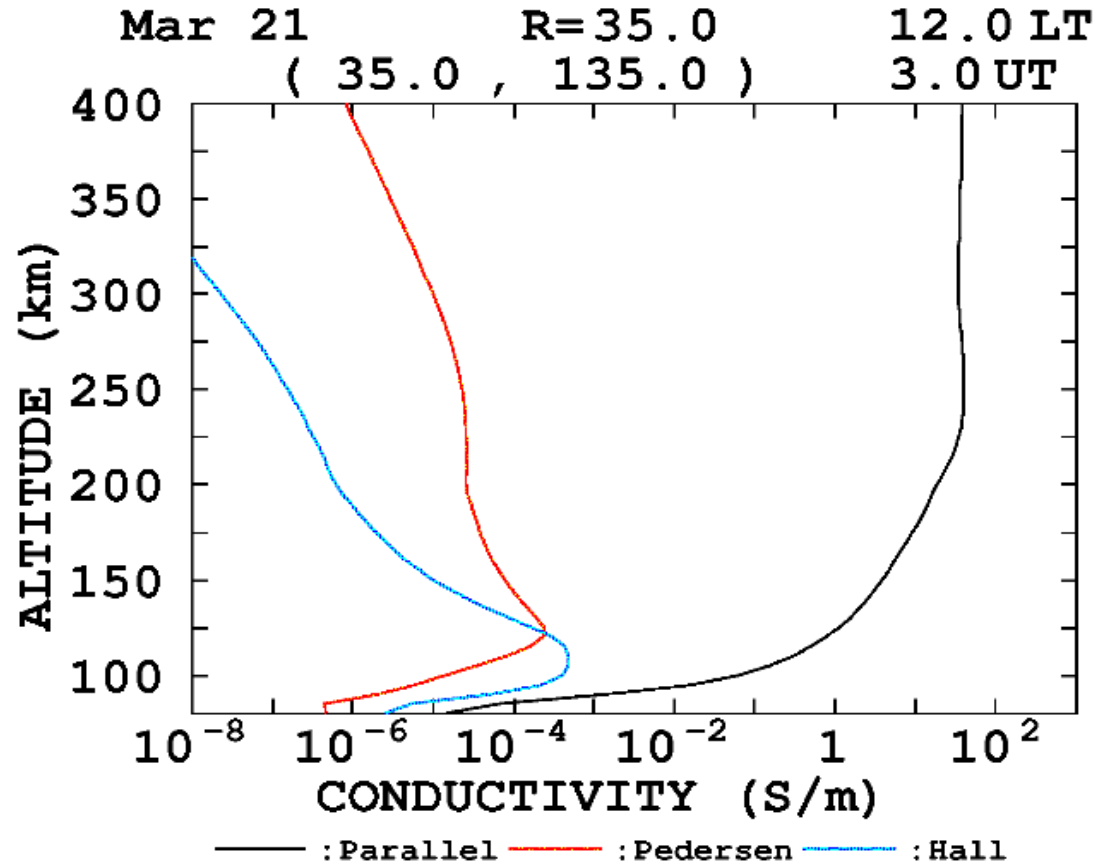
$$\sigma_0 = \left[\frac{1}{m_e \nu_{en}} + \frac{1}{m_i \nu_{in}} \right] n_e e^2$$

- 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

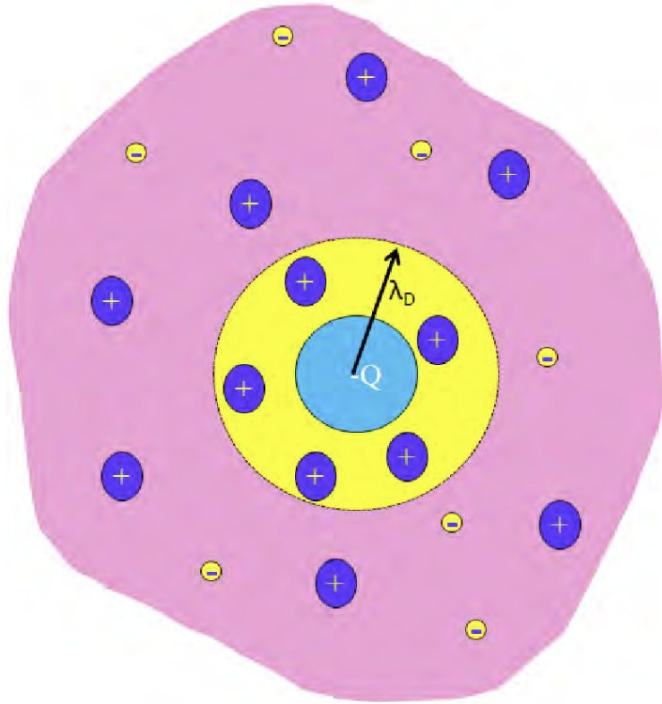
Conductivities



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)

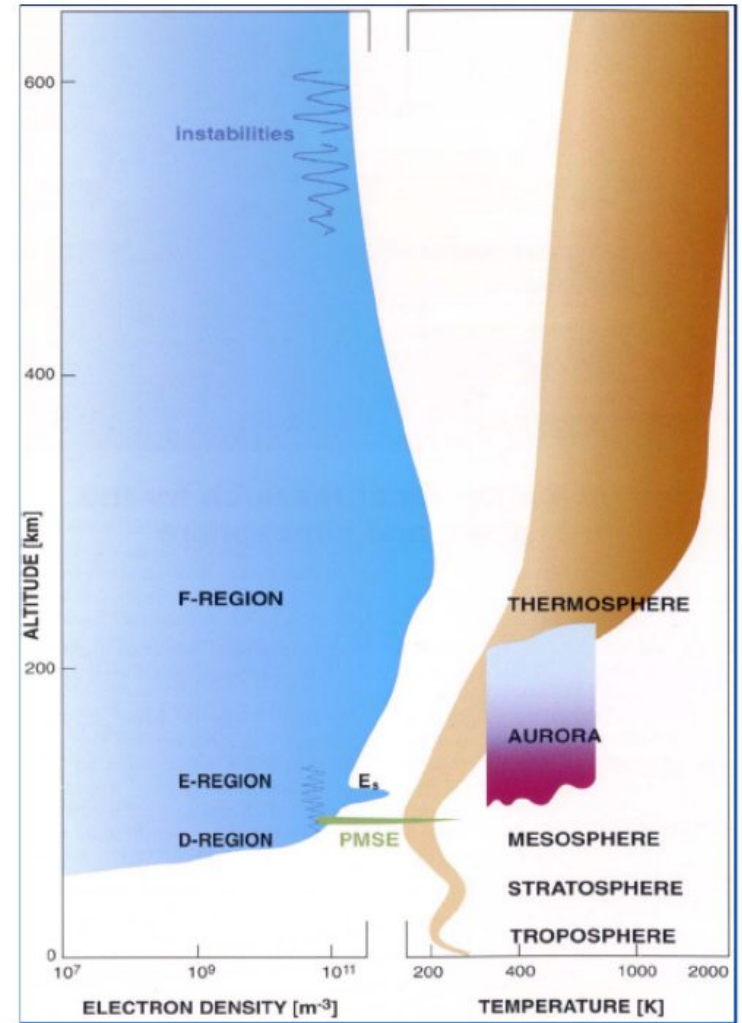
The ionosphere

Debye length

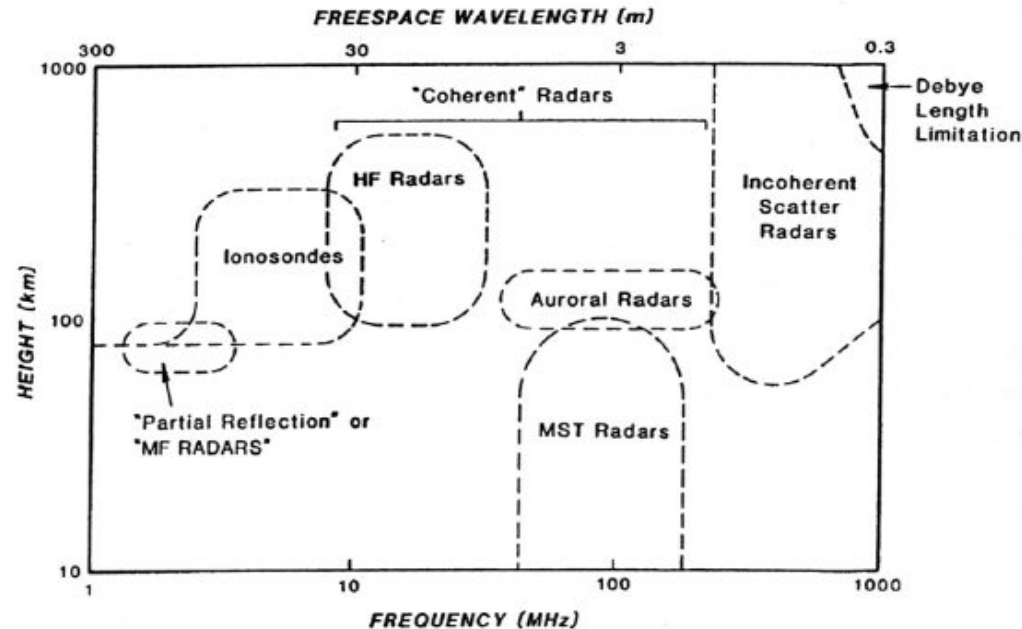
- The Debye length increases with altitude – from a few millimeters in the F-region up to meters in the magnetosphere
- The Debye length in the E and F regions ranges from 0.1 – 1 cm

$$\lambda_D \simeq 69 \sqrt{T_e / n_e}$$

Q: If we want to measure the bulk plasma parameters with Incoherent Scatter Radar, how will Debye 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

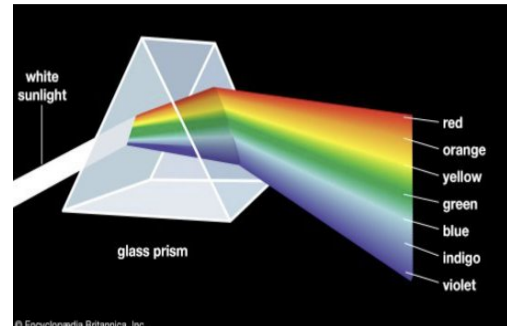
Part 1

- 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.



The Appleton-Hartree equation

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

$$X = \frac{\omega_N^2}{\omega^2} \quad Y = \frac{\omega_H}{\omega} \quad \omega_N = \left(\frac{Ne^2}{\epsilon_0 m_e} \right)^{1/2} \quad \omega_H = \frac{e|B|}{m_e}$$

ω = the angular frequency of the radar wave,

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

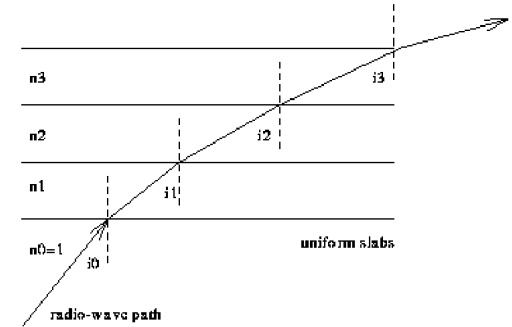
θ = angle between the wave vector \bar{k} and \bar{B} ,

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

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

e = electronic charge, m_e = electron mass,

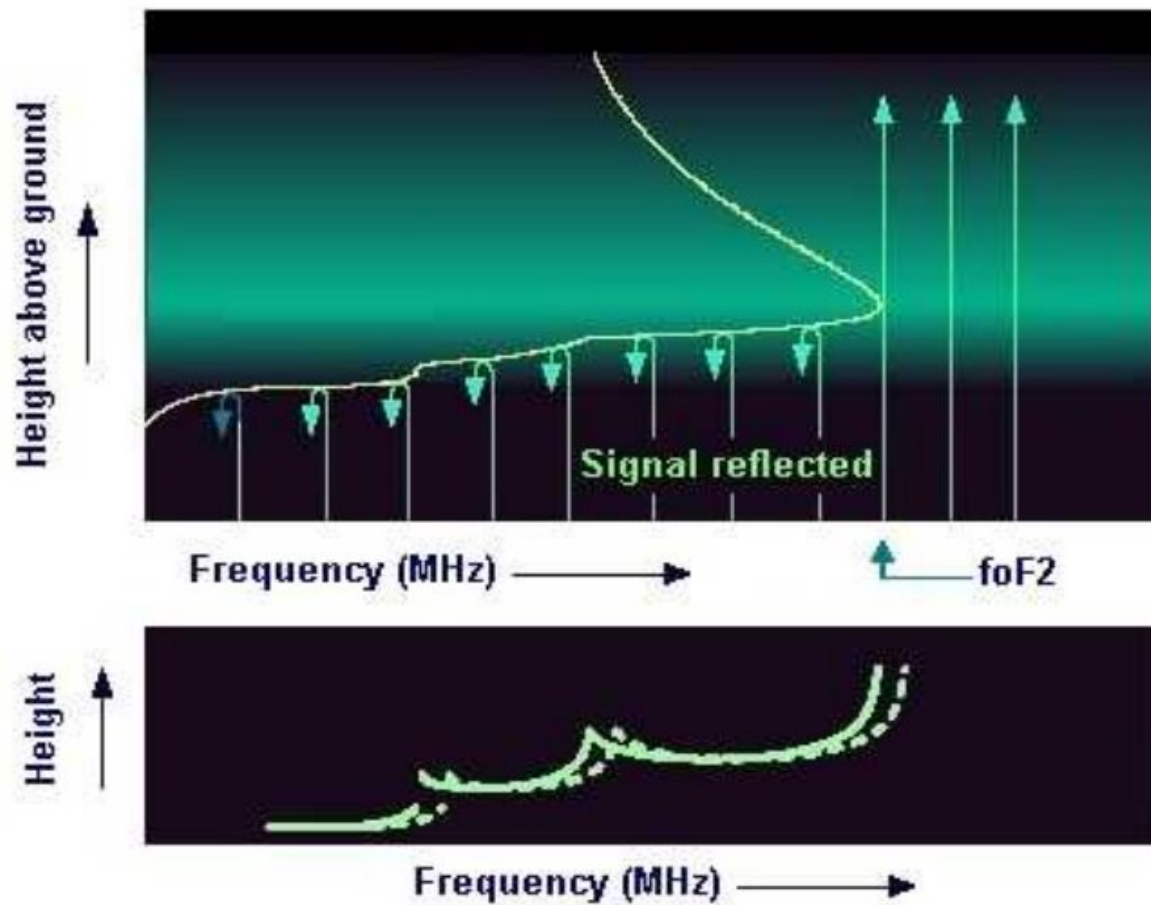
and ϵ_0 = permittivity constant.



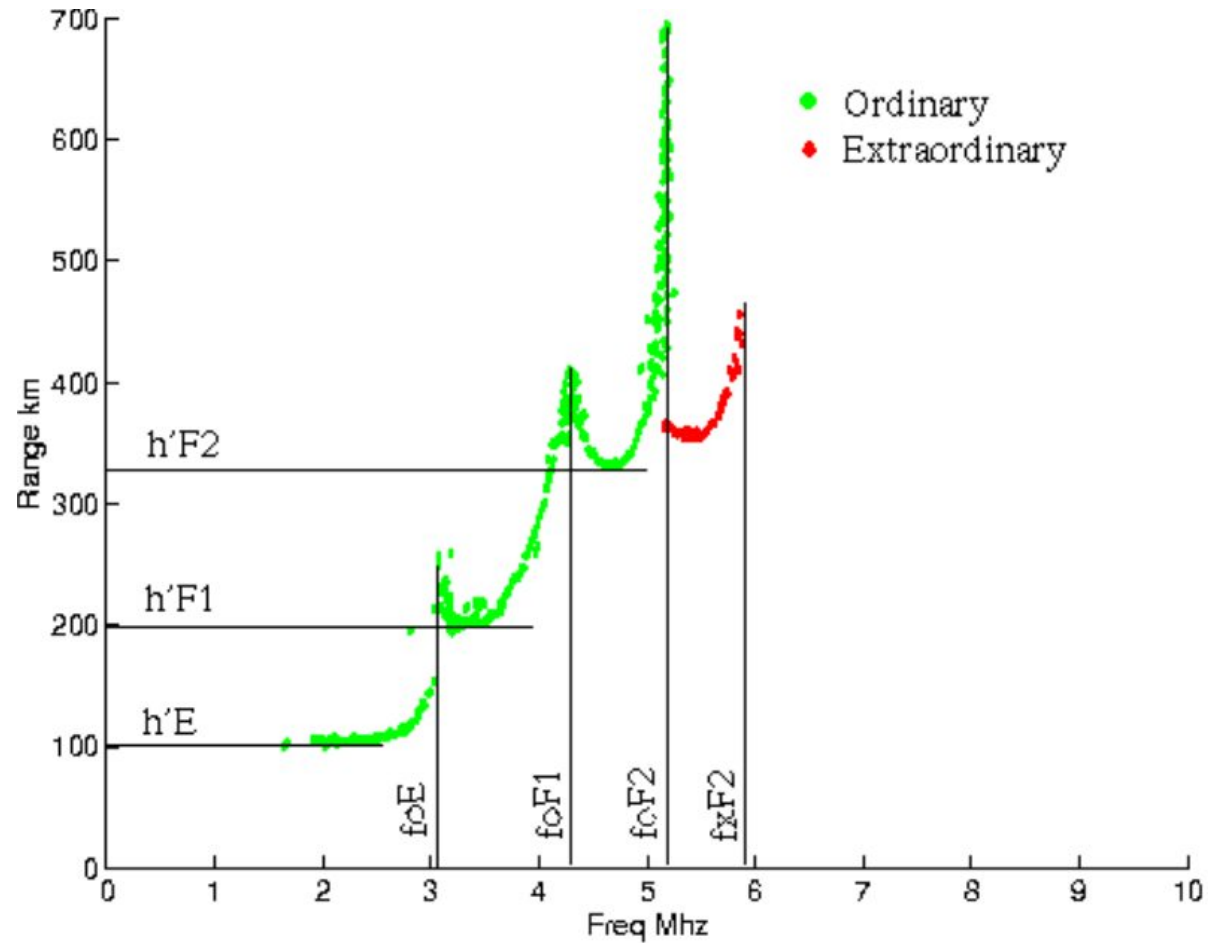
Simplified Case: $Y_L = Y_T = 0$

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

Reflection experiments: ionosondes

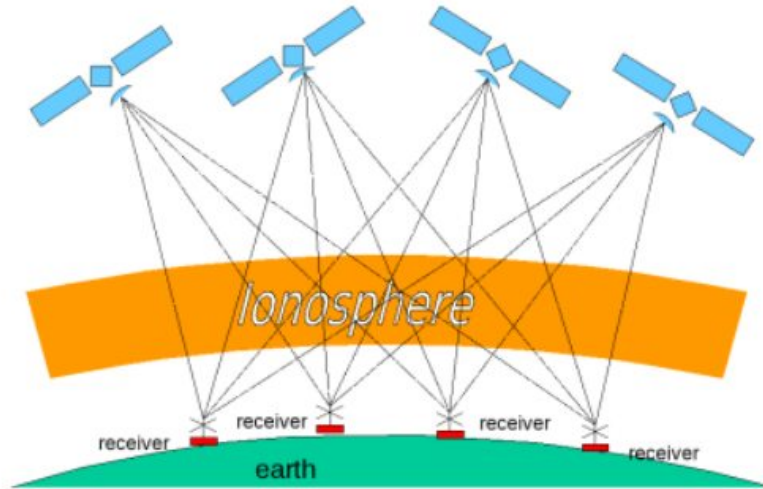


An Example of Ionogram

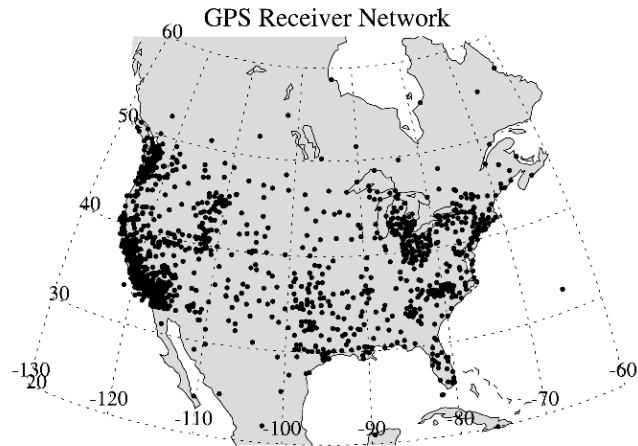


GPS time difference of arrival

- 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).

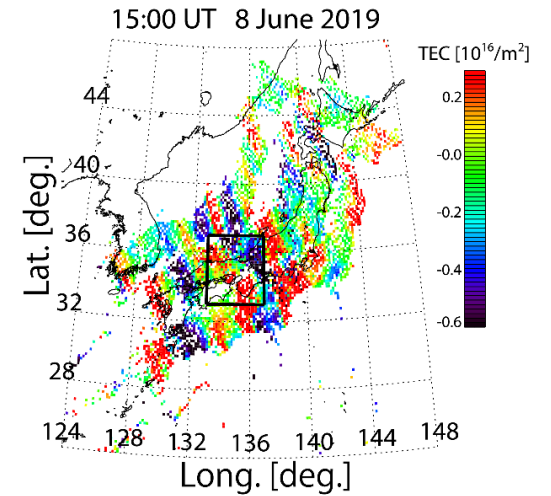


TEC Data Examples

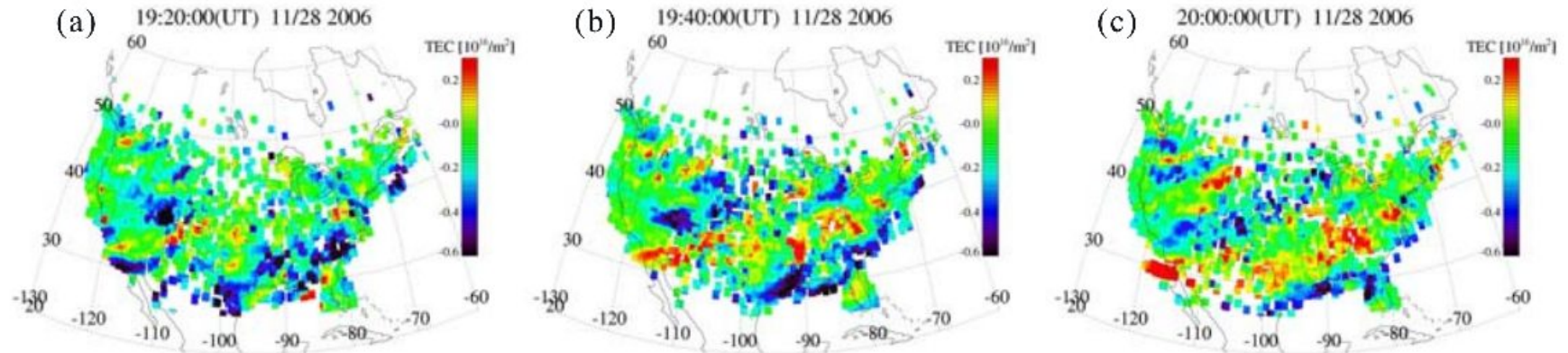


**Dense Network
of GNSS
receivers in
North America
and Japan**

Tsugawa et al., GRL, 2007

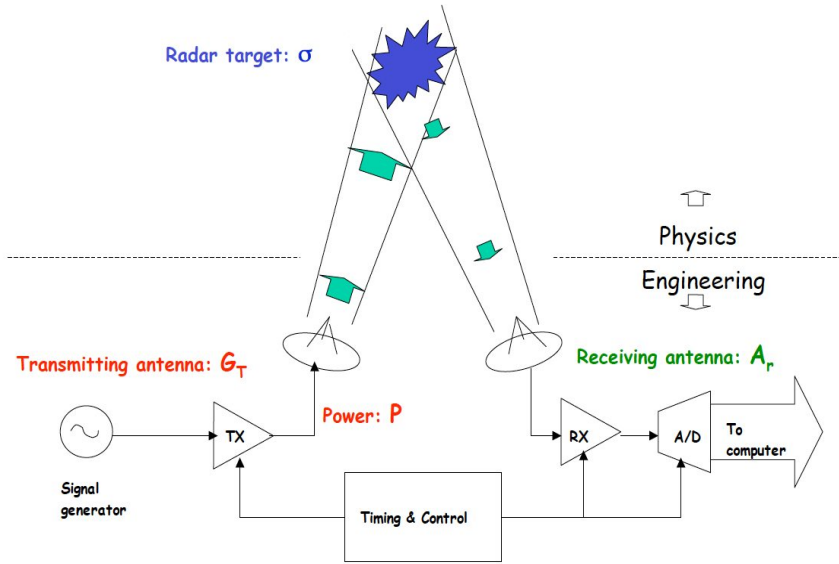


Otsuka et al., EPS, 2021



Radar Concept

A generic radar system



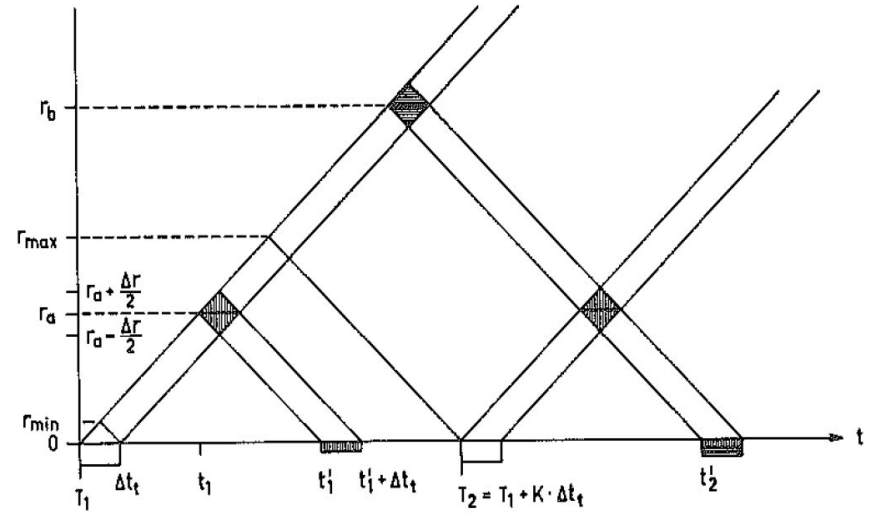
$$r_a = cT_1$$

$$r_a = \frac{cT_1'}{2}$$

$$T_1' = 2T_1$$

Received Power

$$P_r = \frac{P_t G_t}{4\pi R^2} \sigma \frac{A_r}{4\pi R^2} L$$

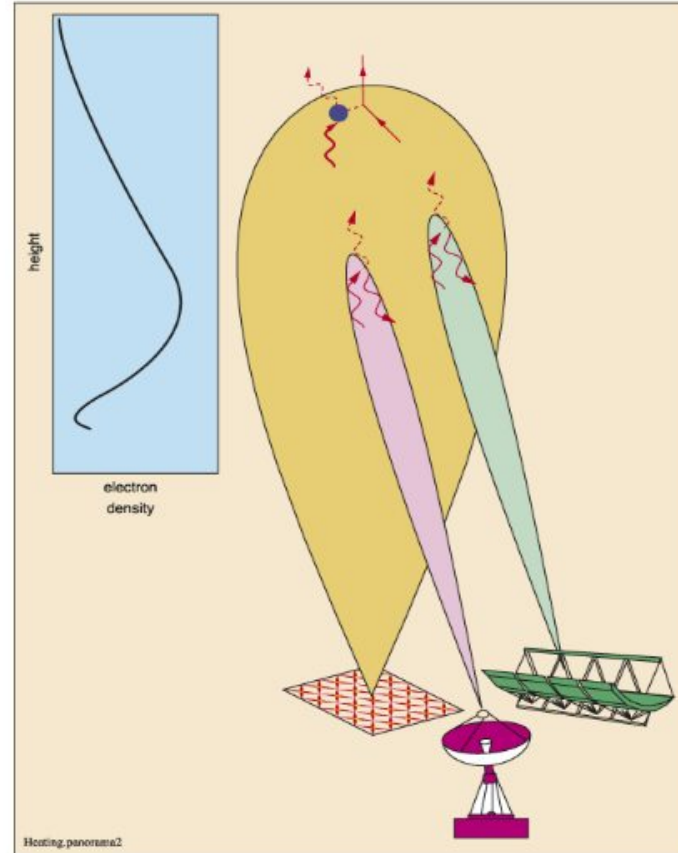


Coherent Scatter Radar

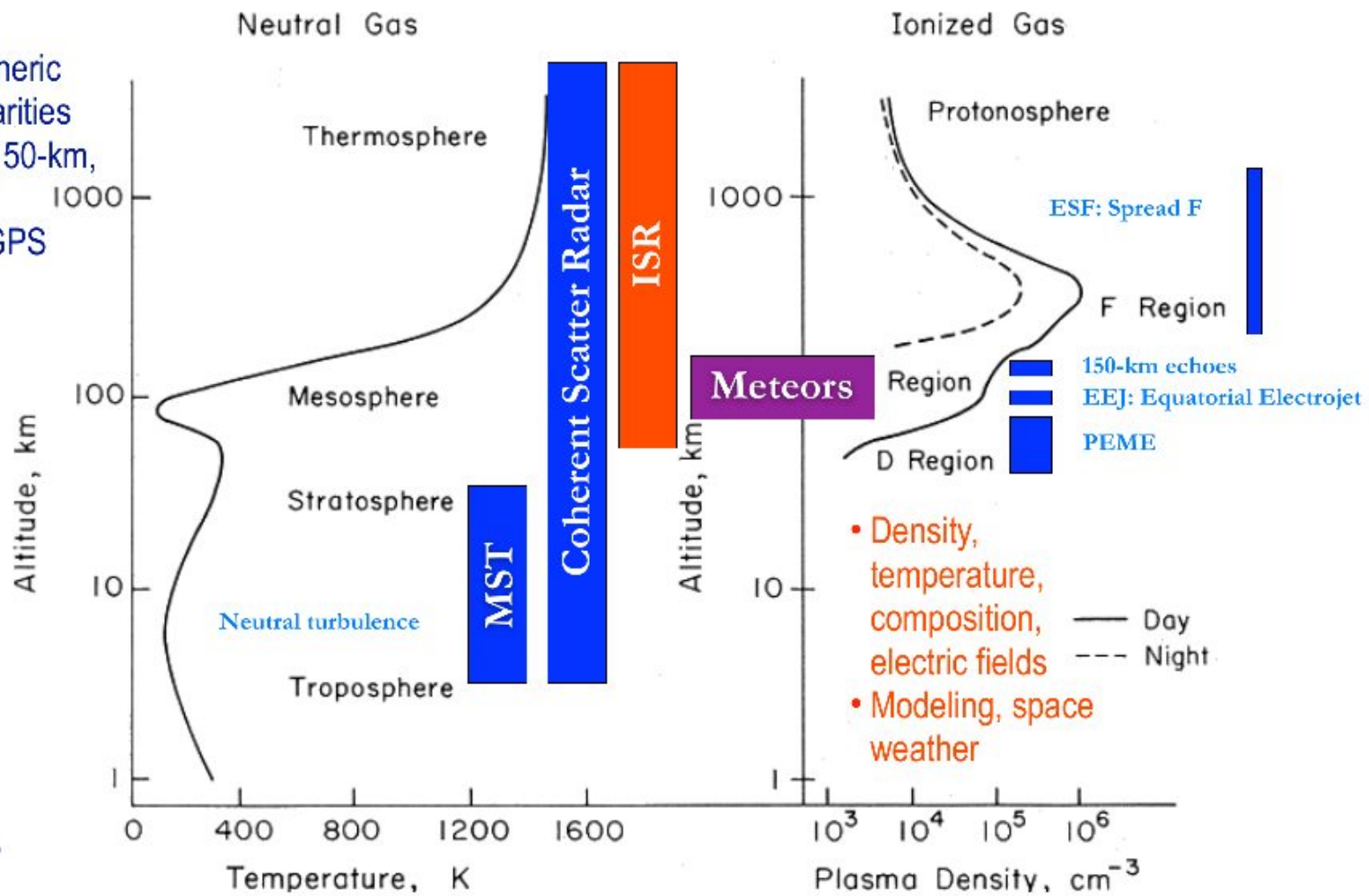
- Any medium with stochastic index of refraction fluctuations can produce coherent scatter.
- Can work in neutral air.
- Works very well in plasmas. Small electron density fluctuations produces significant index of refraction fluctuations.
- Structures must match $\lambda_R/2$ to get constructive interference 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

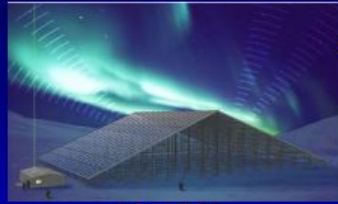
- They are big systems with large high-gain antennas.
- Their transmitters deliver power in the order of megawatts.
- Their targets are the electrons moving in the ionosphere.
- The signal scattered by the electrons is in picowatts, thus the need of sensitive receivers.
- The spectrum of the returned 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.



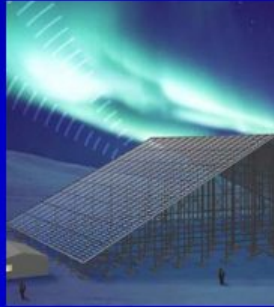
The NSF Incoherent Scatter Radar Chain-2008



AMISR-
Resolute Bay

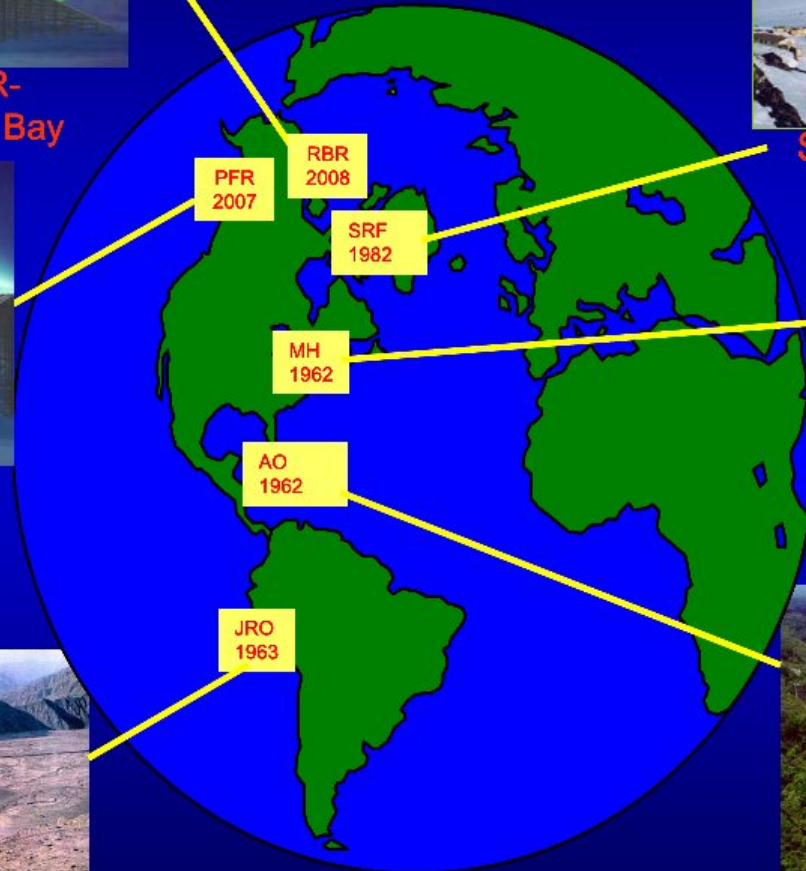


Sondrestrom (SRF)



AMISR-
Poker Flat

Jicamarca (JRO)



PFR
2007

RBR
2008

SRF
1982

MH
1962

AO
1962

JRO
1963

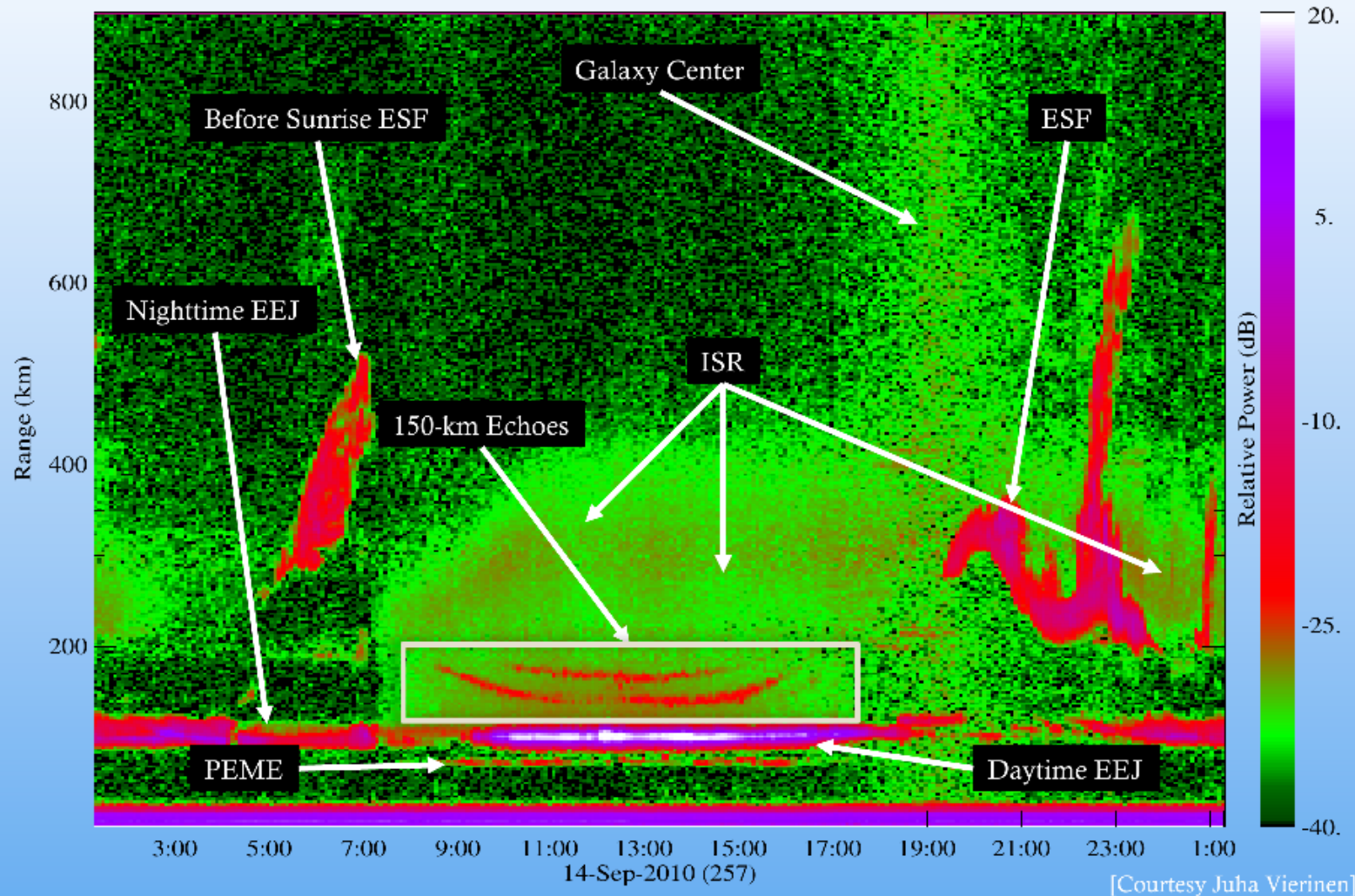


Millstone Hill (MH)

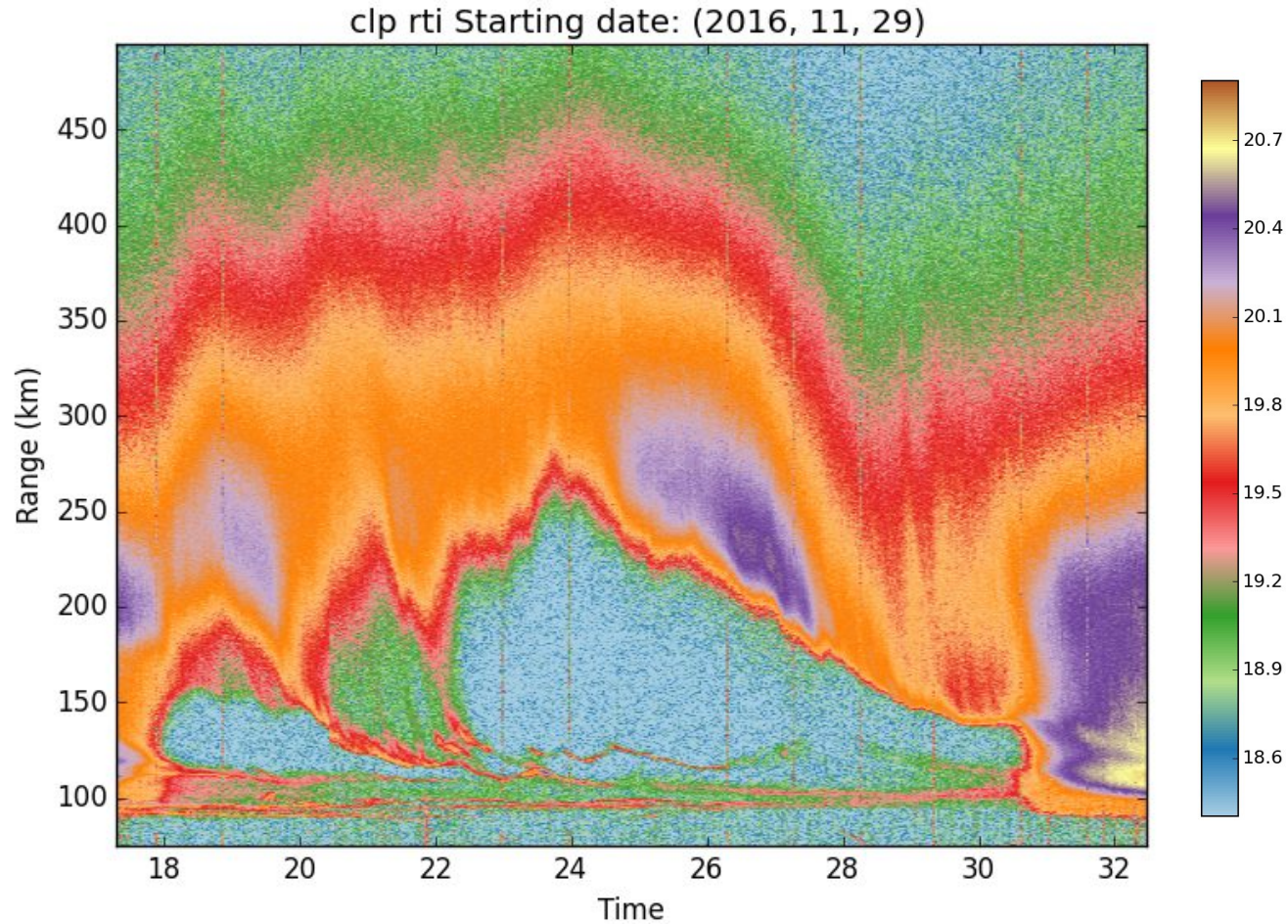


Arecibo (AO)

Incoherent and Coherent Echoes over Jicamarca

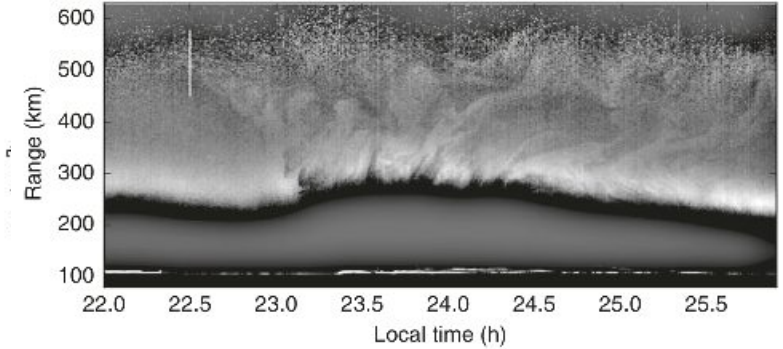
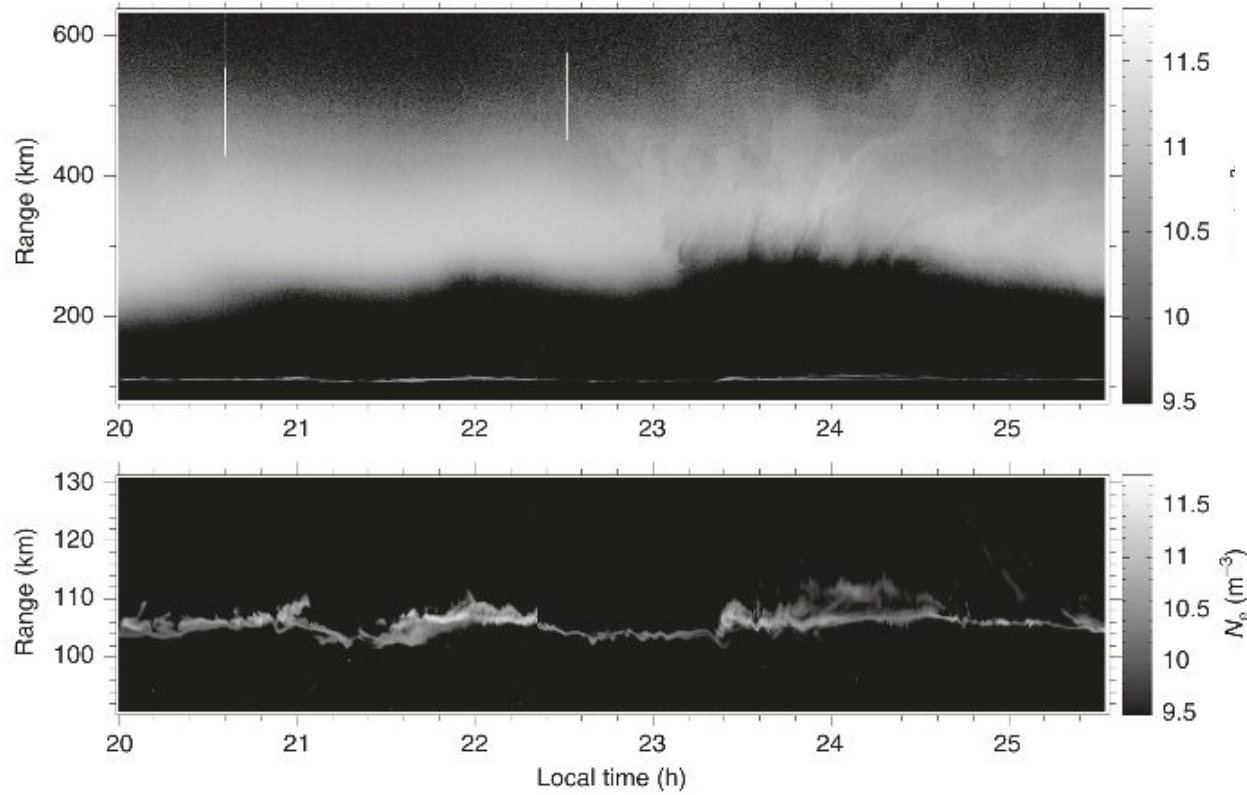


An Example of ISR Data



Mid-Latitude Spread-F: Space Weather Phenomena

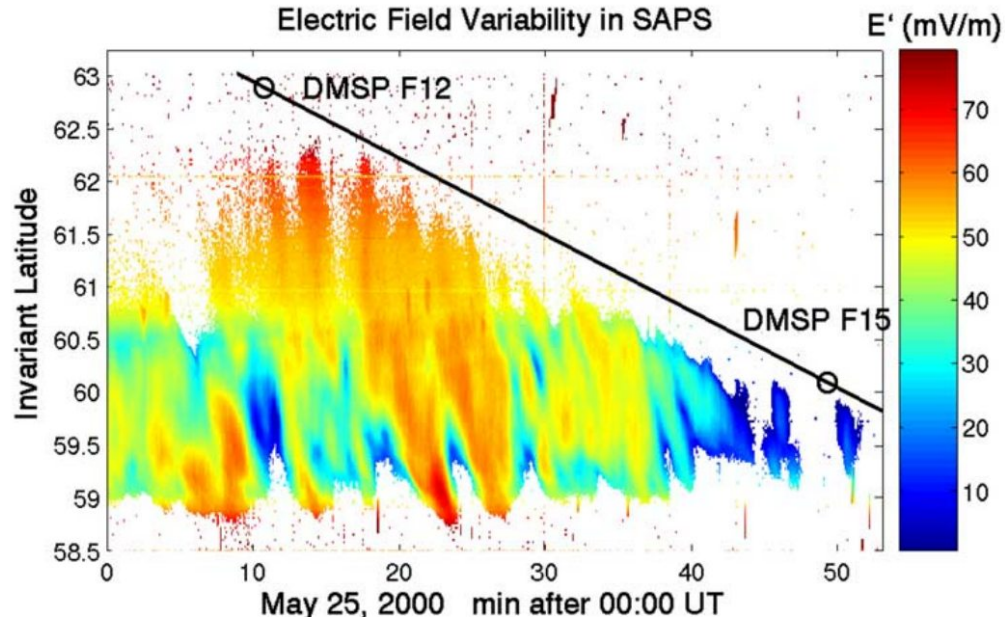
Arecibo: ISR data; 30 July 2016



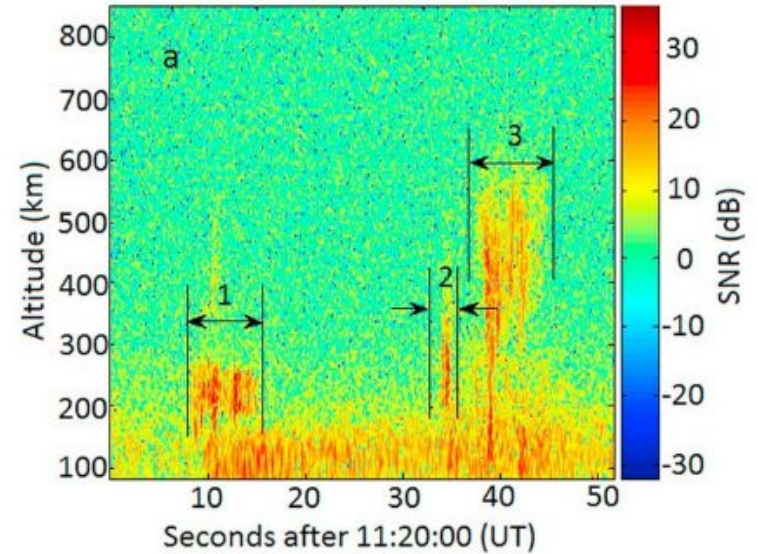
Numerical simulations suggested that the topside irregularities could be driven by the combined effect of lower atmosphere and plasma dynamics.

Hysell et al, Nature Comm., 2018

Sub-auroral and auroral Observations



Foster et al., GRL, 2004



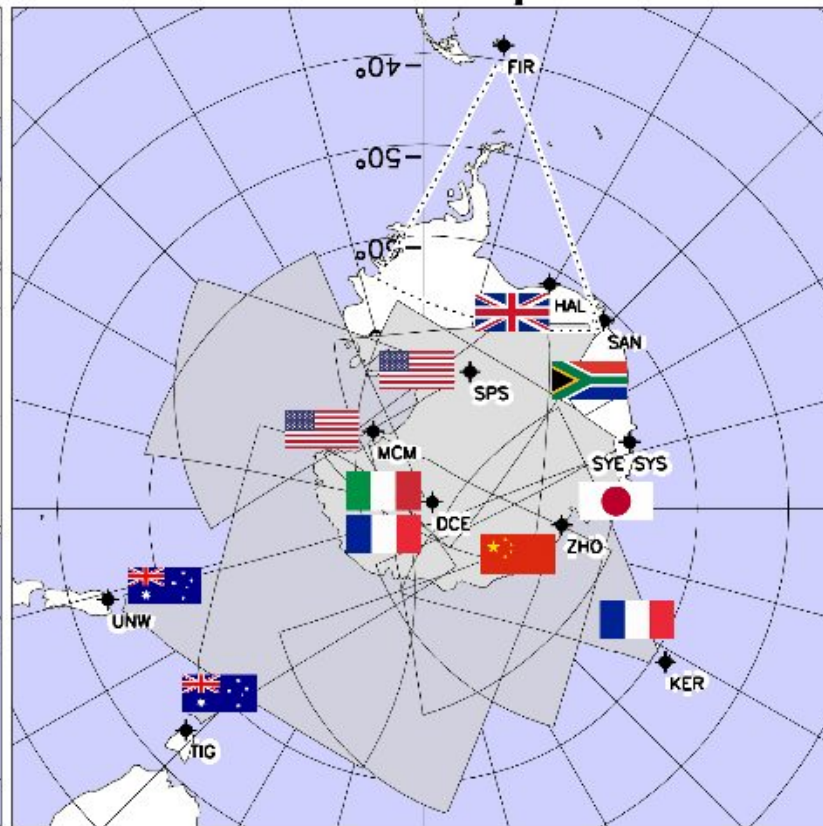
Akbari et al., GRL, 2012

SuperDARN

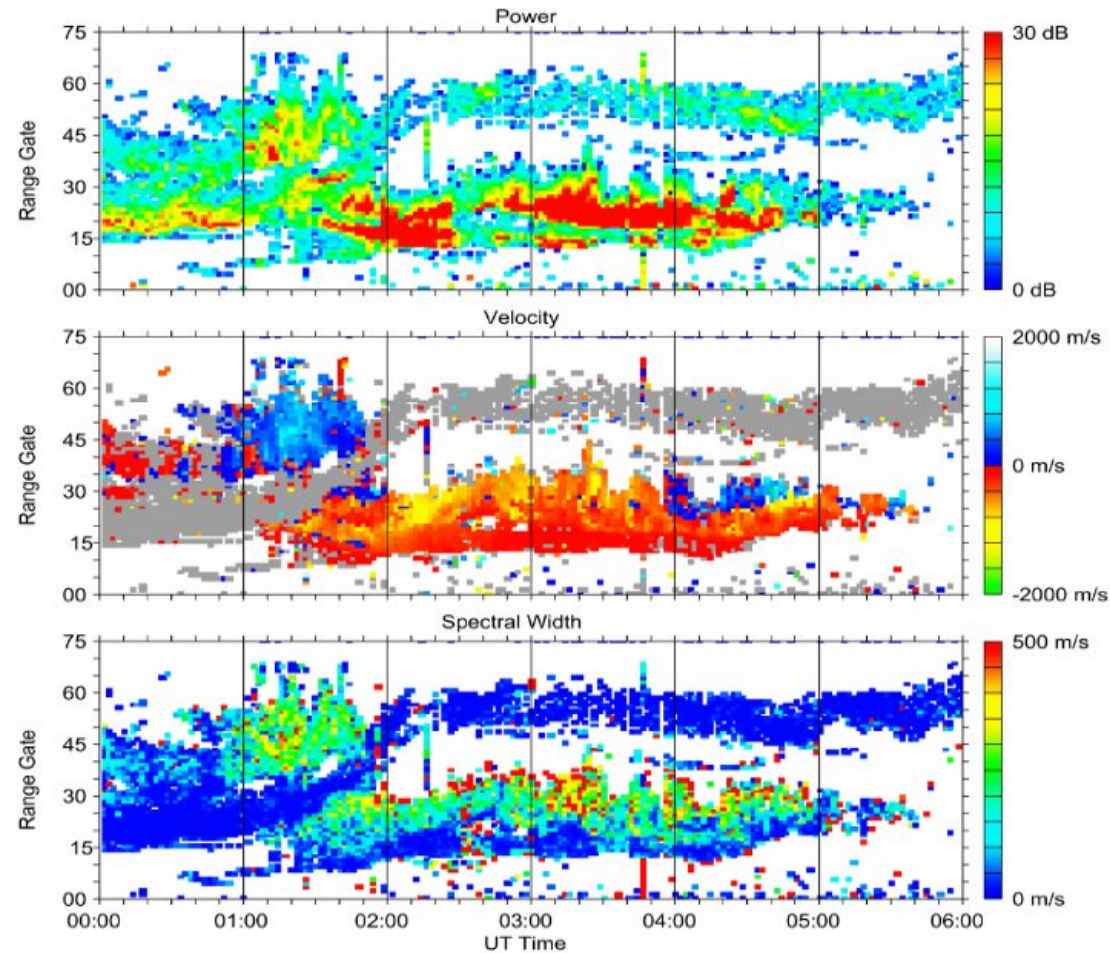
Northern Hemisphere



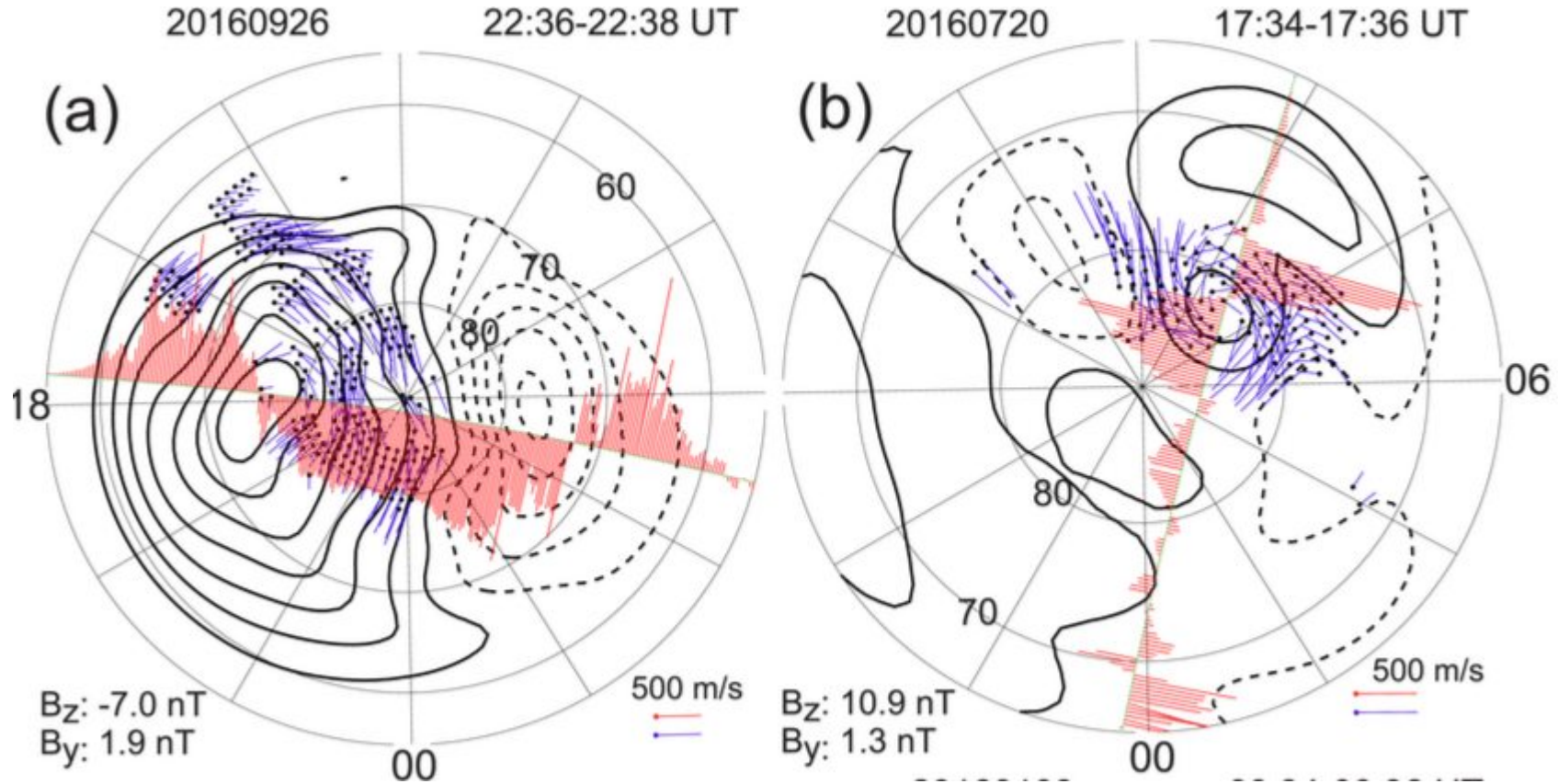
Southern Hemisphere



SuperDARN data



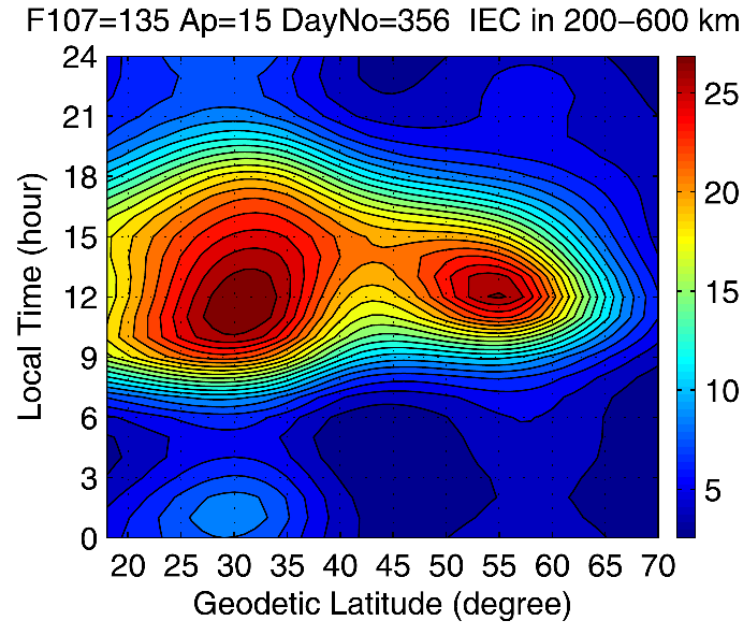
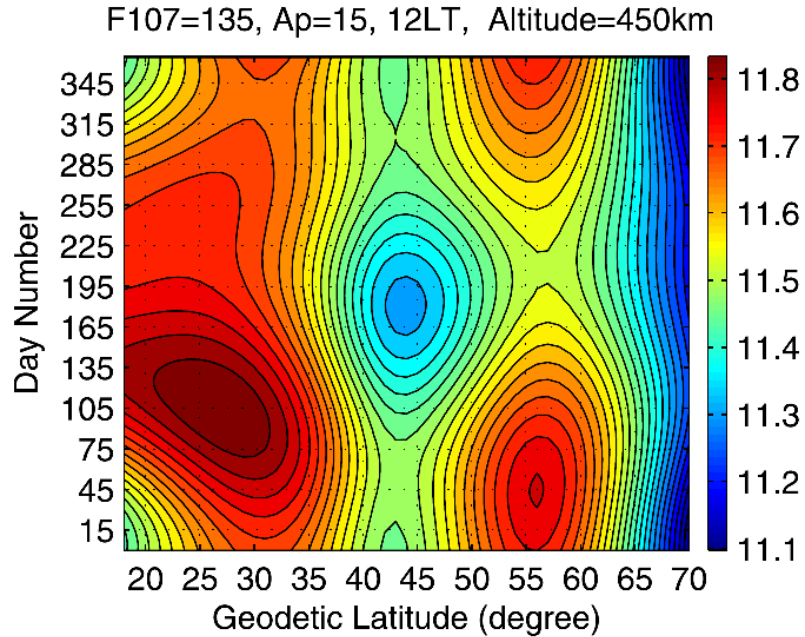
SuperDARN Data: Convection maps



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, composition
- Ionosphere is highly variable, and many space weather phenomena cannot be accurately predicted yet.
- 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.