SRI International

Introduction to the Ionosphere

2018 ISR Summer School

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Major credits to: Roger Varney, SRI International, Anita Aikio, University of Oulu and Anthea Coster, MIT Haystack

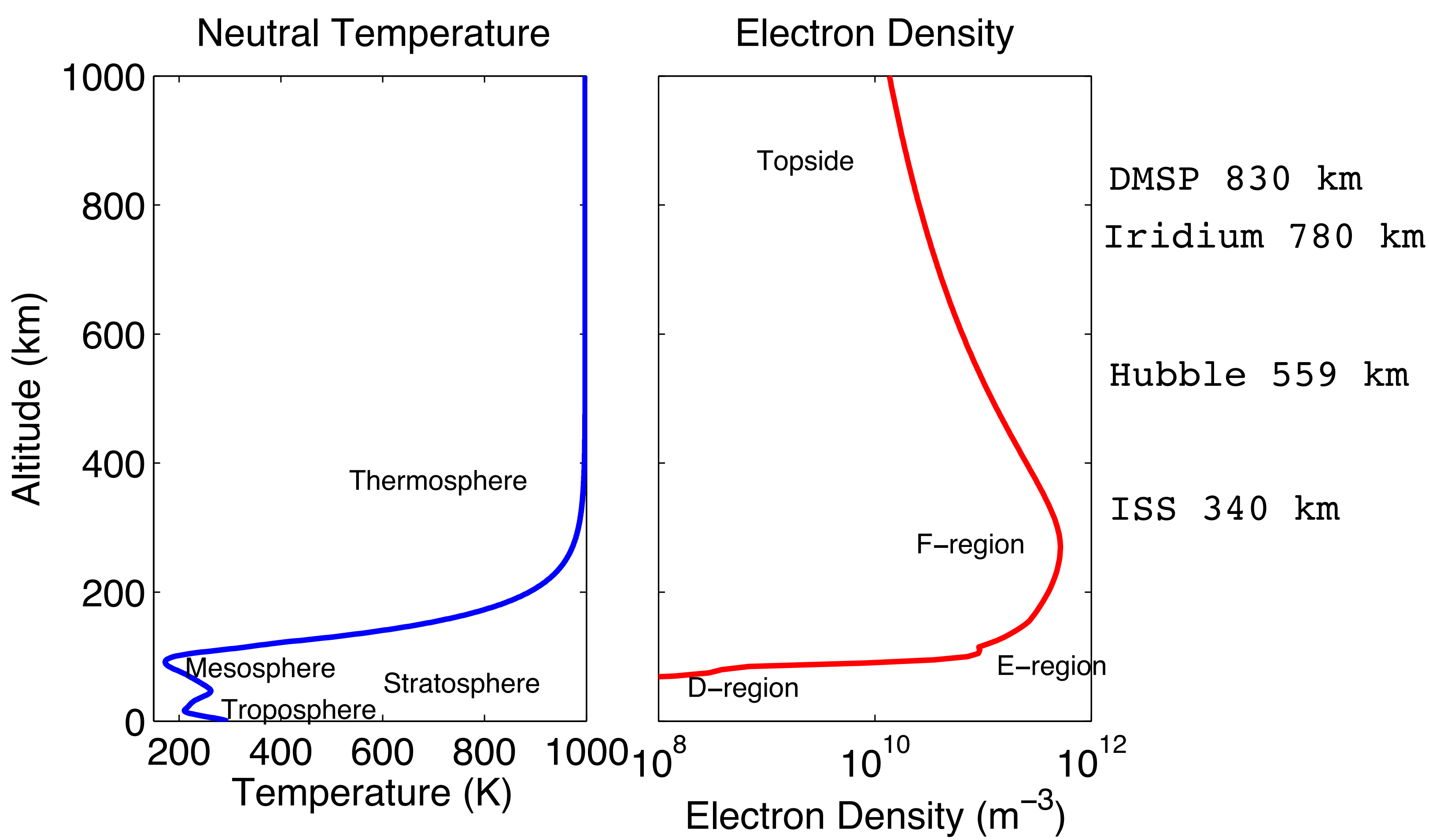
Outline

- General school introduction
- The upper atmosphere
- Using radars to measure ionospheric properties
- The week ahead

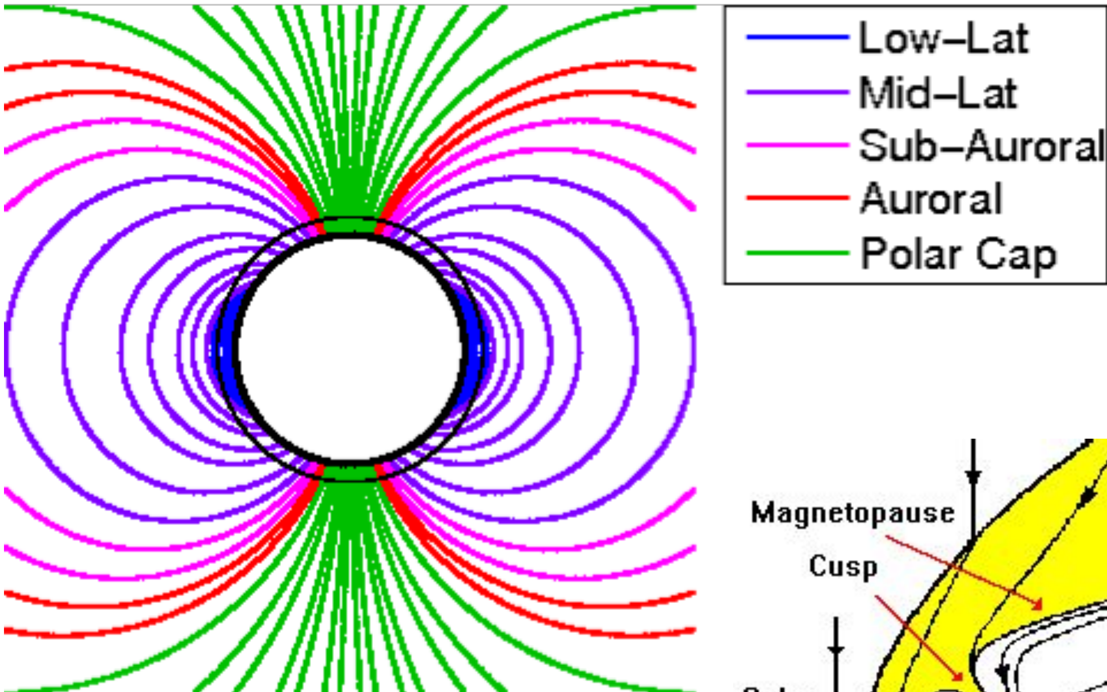
Welcome to the 2018 ISR Summer School!

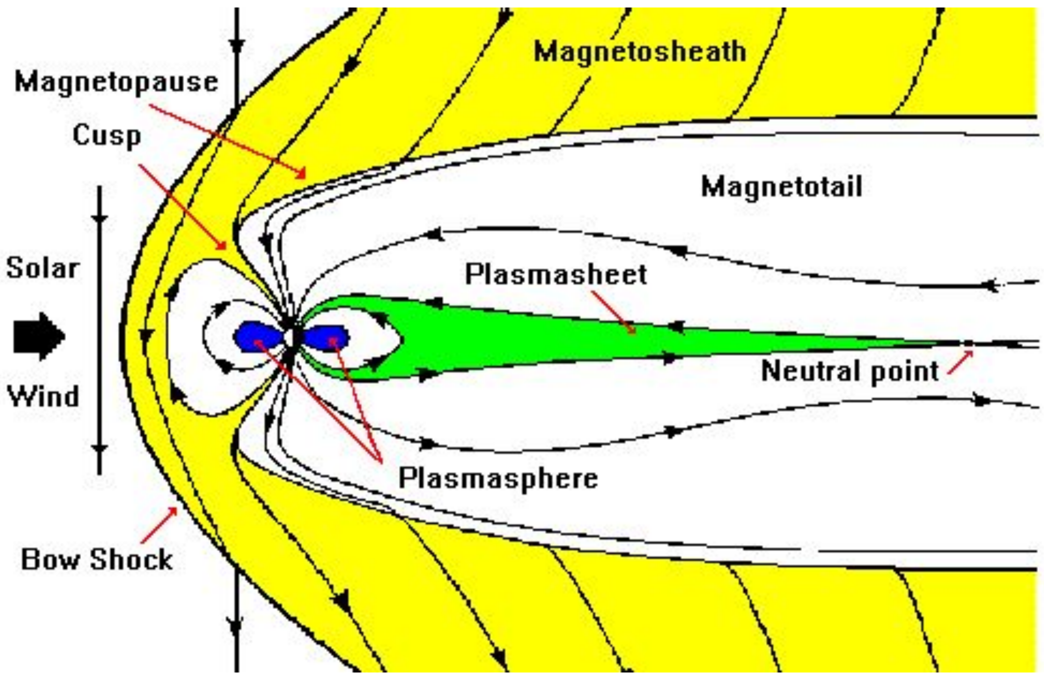
- The mission of this school is to introduce students to basic incoherent scatter radar (ISR) concepts and encourage the use of data products in their ongoing research efforts.
- Every student comes with a slightly different background. Each lecture is structured to come at the ISR concepts from a different angle so you may find some lectures building from your particular education base more than others.
- Ask questions! There will be lots of unstructured time in the afternoons where you can discuss concepts you didn’t understand with the lecturers. If you hear unfamiliar jargon or acronyms during the lectures feel free to ask for a definition – you are likely not alone.
- Even if you don’t become an ISR expert, this school will give you the tools you need to use ISR data in your research and become more familiar with topics you will encounter in future conferences.
- All lectures will be placed on the school wiki for future reference.

The Upper Atmosphere



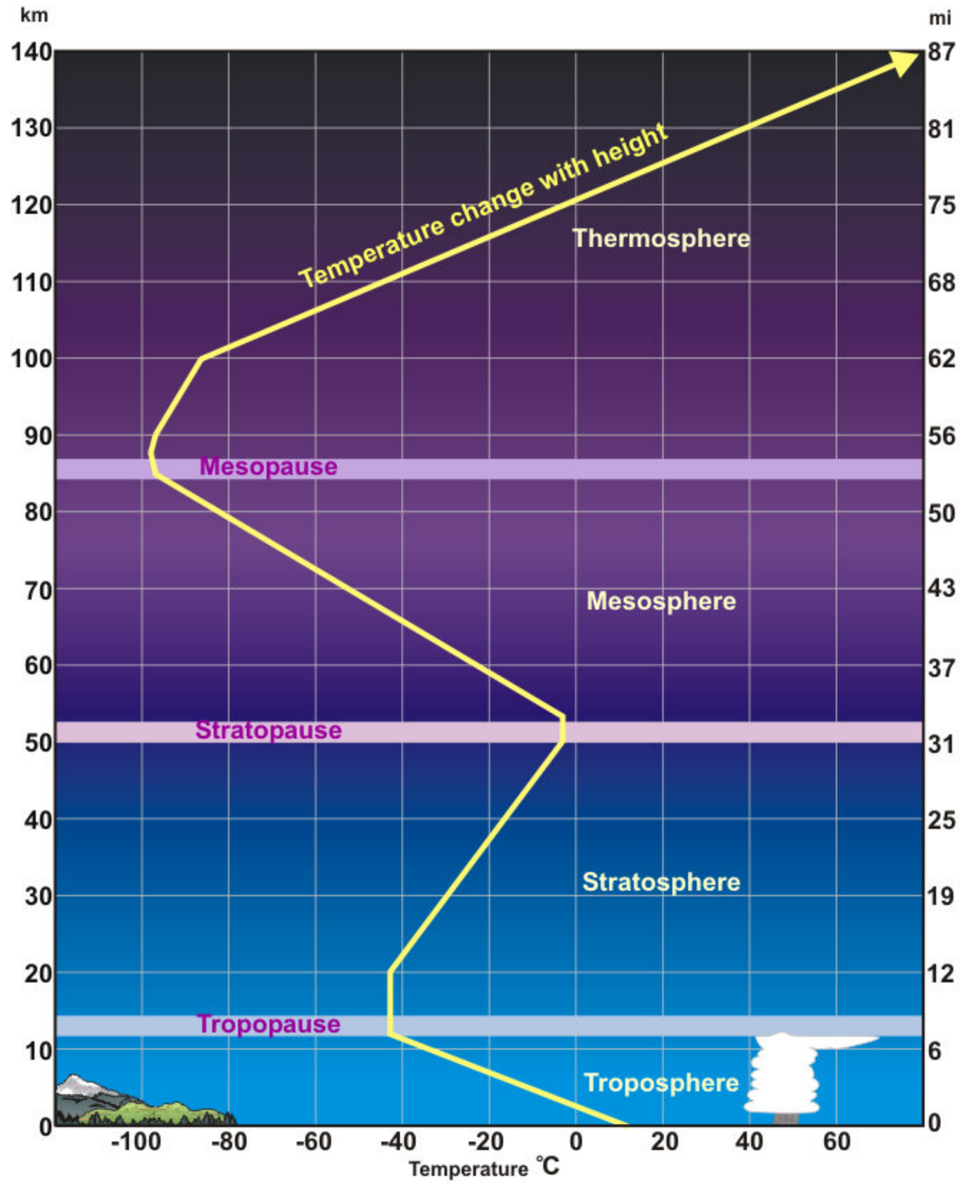
The Magnetic Field





The neutral atmosphere

- The **troposphere** is heated by the warm ground and infrared radiation is emitted radially. T decreases with height. The **tropopause** is at 12-15 km, T_{min} ~ -53C.
- In the **stratosphere**, the ozone (O_3) layer at 15-40 km absorbs solar radiation. The **stratopause** is at 50 km with T_{max}~7C.
- In the **mesosphere**, heat is removed by the radiation of infrared and visible airglow as well as by eddy transport. The **mesopause** is close to 85 km with T_{min} ~ -100C.
- In the **thermosphere**, UV radiation is absorbed and it produces dissociation of molecules and ionization of atoms and molecules.



The neutral atmosphere

Atmospheric gas in a stationary state

Above the surface of the Earth, the atmospheric pressure *p* and density *n* are given

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

and

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

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

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

Is independent of altitude and then the hydrostatic equations are

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

The neutral atmosphere
Atmospheric gas in a stationary state

Since the scale height is in fact dependent on temperature and we now know that temperature increases with altitude in the thermosphere,

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

we will see in upcoming lectures that it is possible to take ISR measurements with lower range resolution in the F-region as compared to the lower E-region.

The neutral atmosphere

Atmospheric regions by composition

- The **homosphere** is the region below about 100 km altitude, where all gas constituents are fully mixed; i.e. the relative concentrations of different molecular species are independent of height. This is caused by turbulent mixing of the air.
- The **turbopause** is the upper boundary of the homosphere at an altitude of about 100 km.
- The **heterosphere** is the region above the homosphere. In the absence of atmospheric turbulence, each molecular species distributes with height independently of the other species (according to its own scale height). At great altitudes light molecular species dominate.

The neutral atmosphere
Composition in the heterosphere

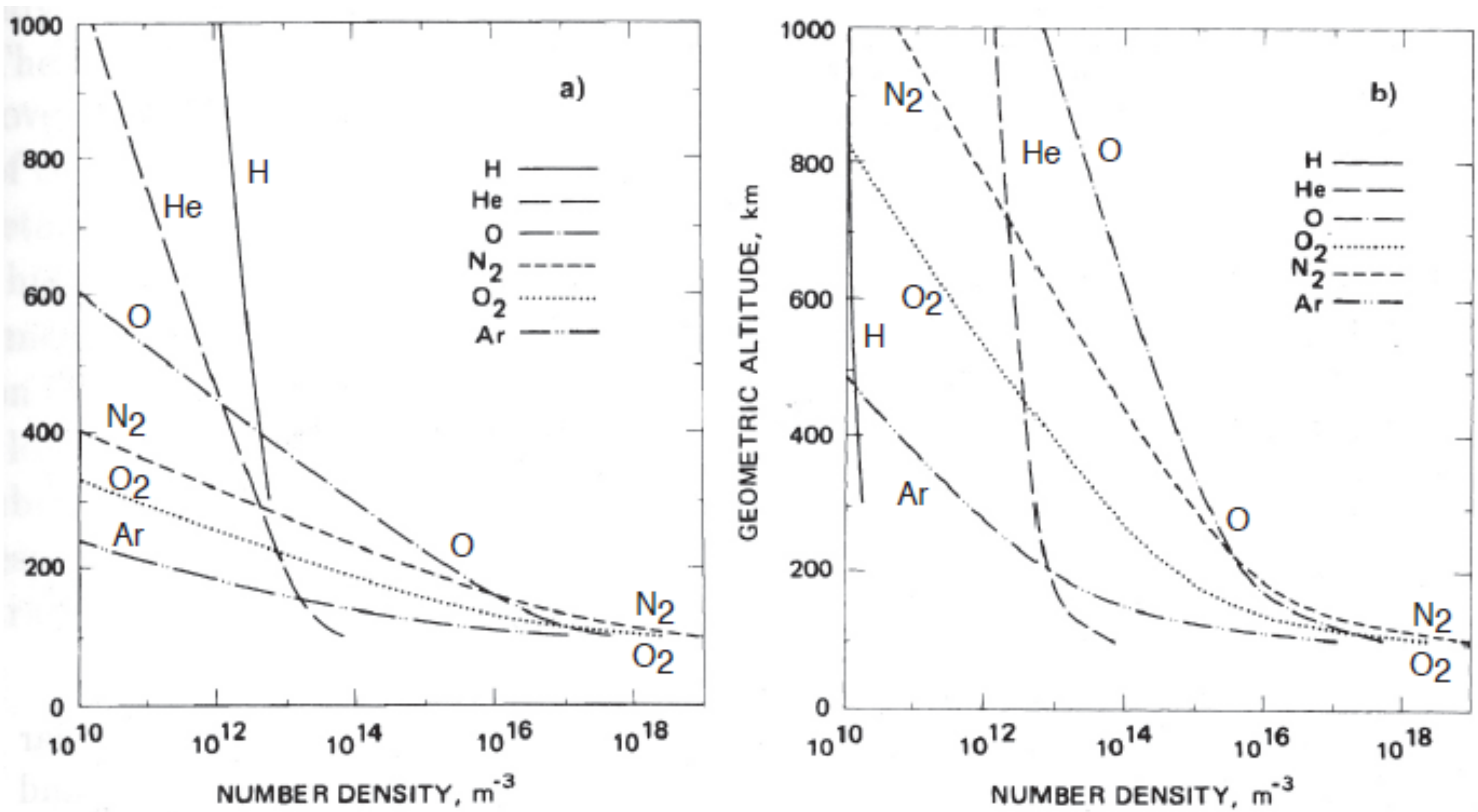


Figure: Atmospheric composition during (a) solar minimum and (b) solar maximum (U. S. Standard atmosphere, 1976).

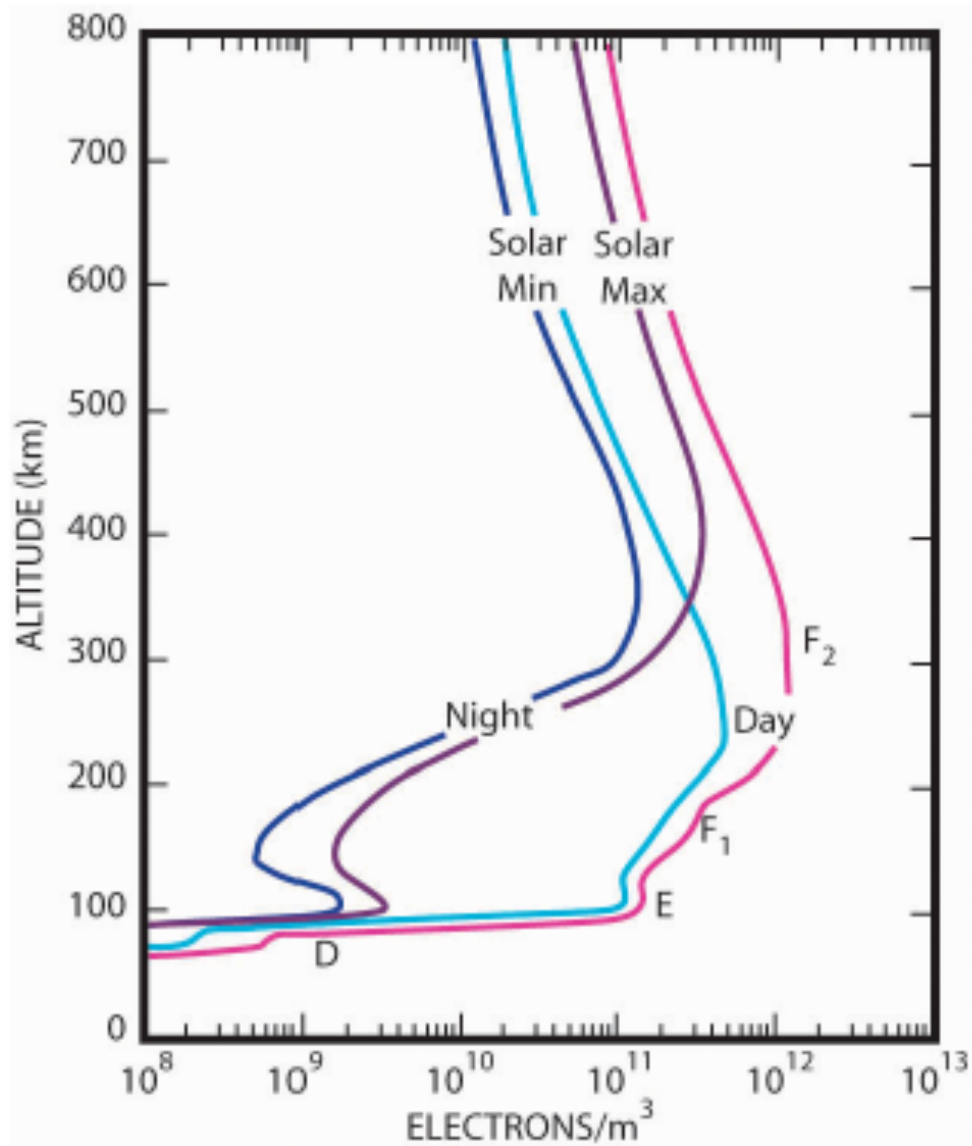
The ionosphere

Ionospheric regions and typical daytime electron densities:

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

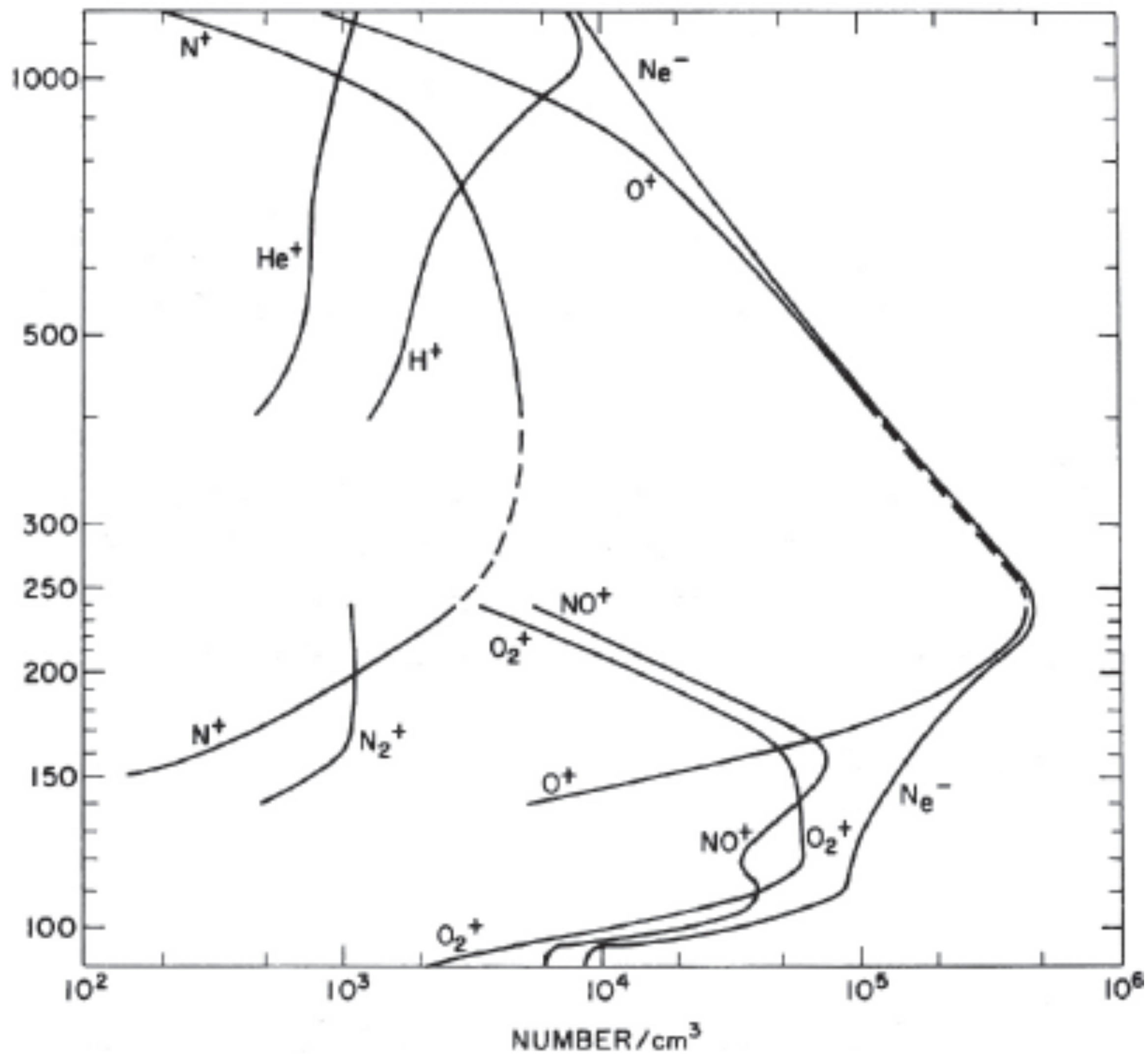
The ionosphere has great variability:

- 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. $H^+(H_2O)_n$, $(NO)^+(H_2O)_n$)



The ionosphere
Ion temperatures

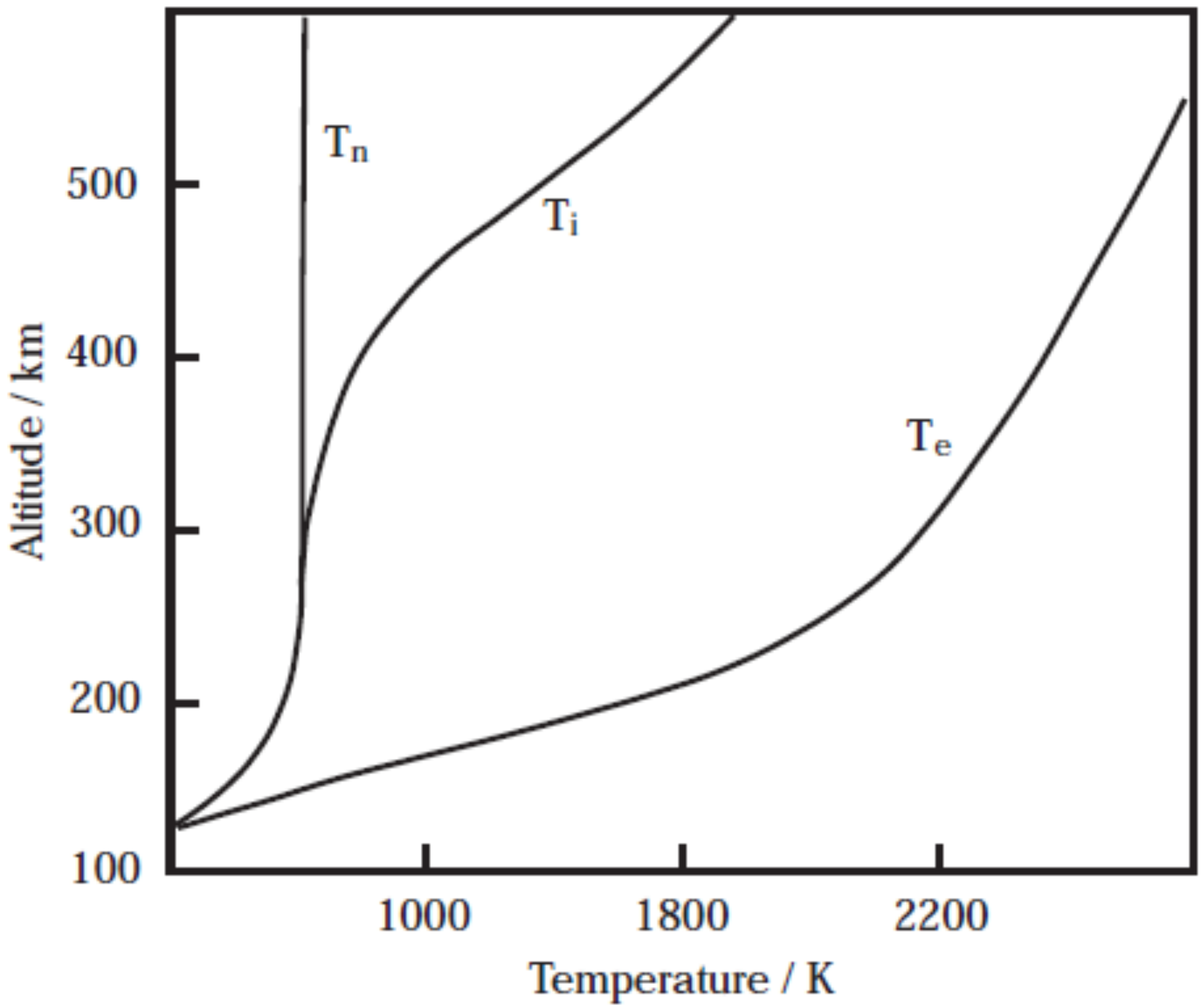


Figure: An example of neutral, ion, and electron temperature profiles

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 **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 ν_i and ν_e, respectively

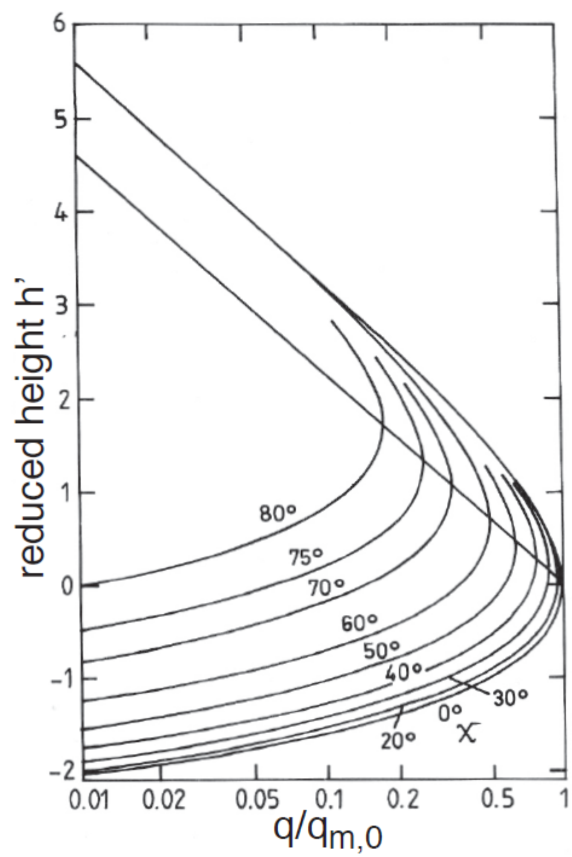
The ionosphere

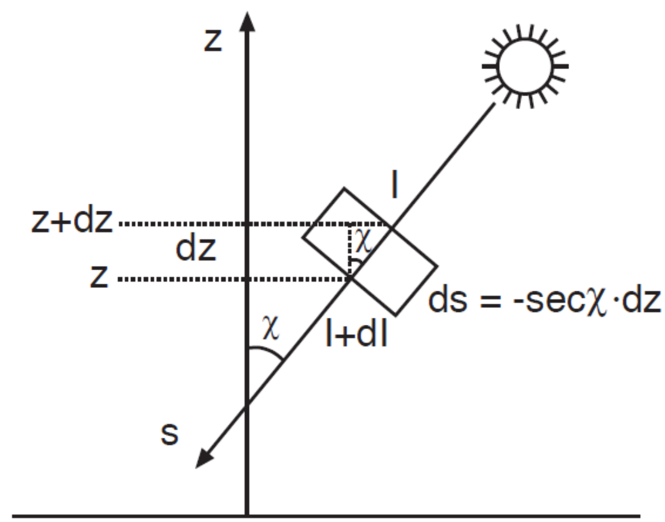
Ionization source: solar radiation

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.

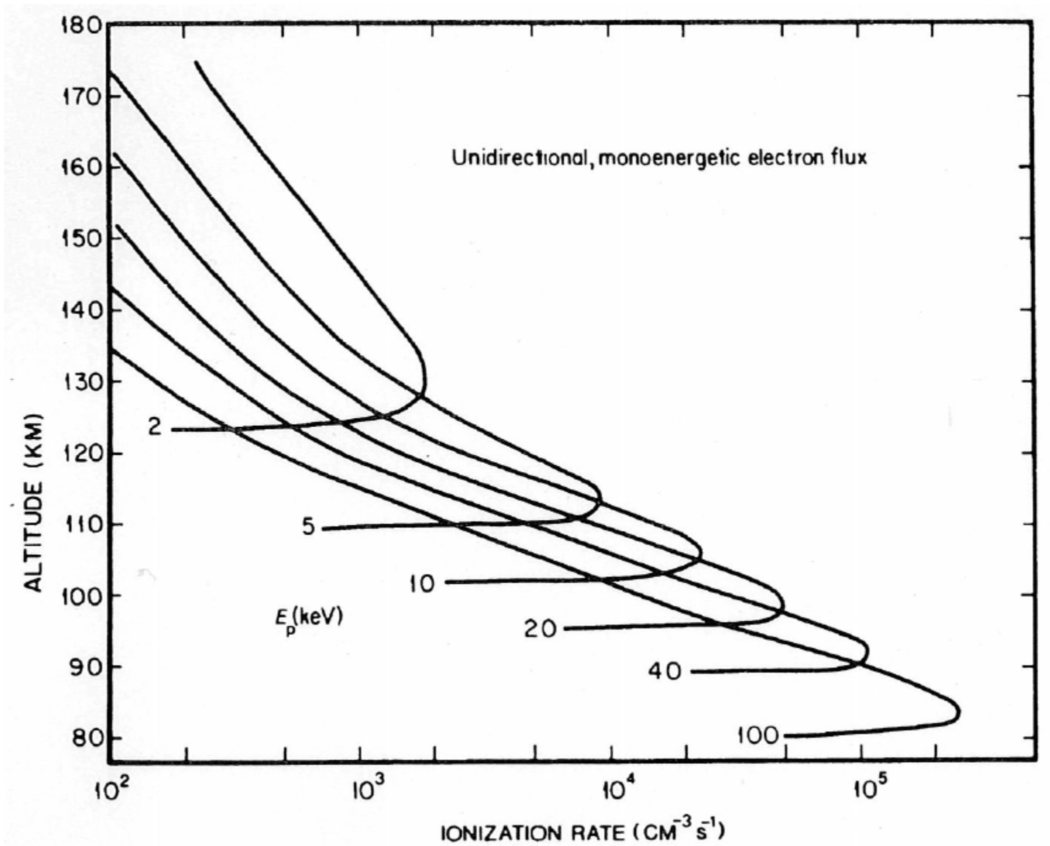


Figure: Ionization rate for monoenergetic electrons with energies 2-100 keV

The ionosphere

Ionization source: particle precipitation (protons)

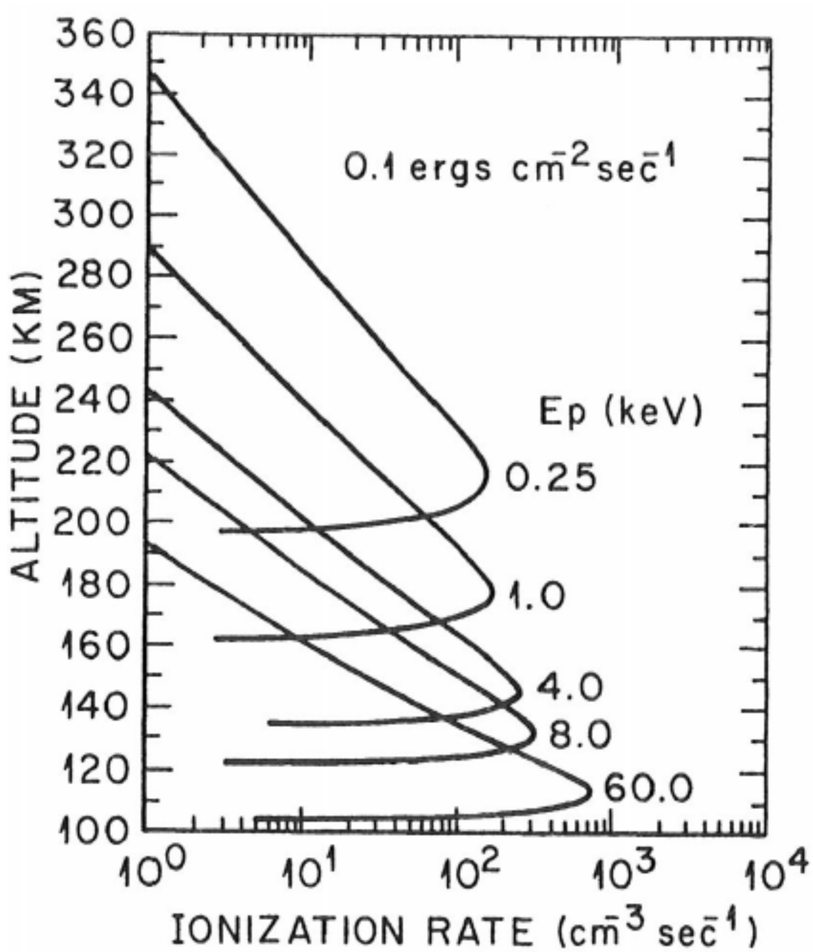


Figure: Ionization rate for monoenergetic protons with energies 0.25-60 keV

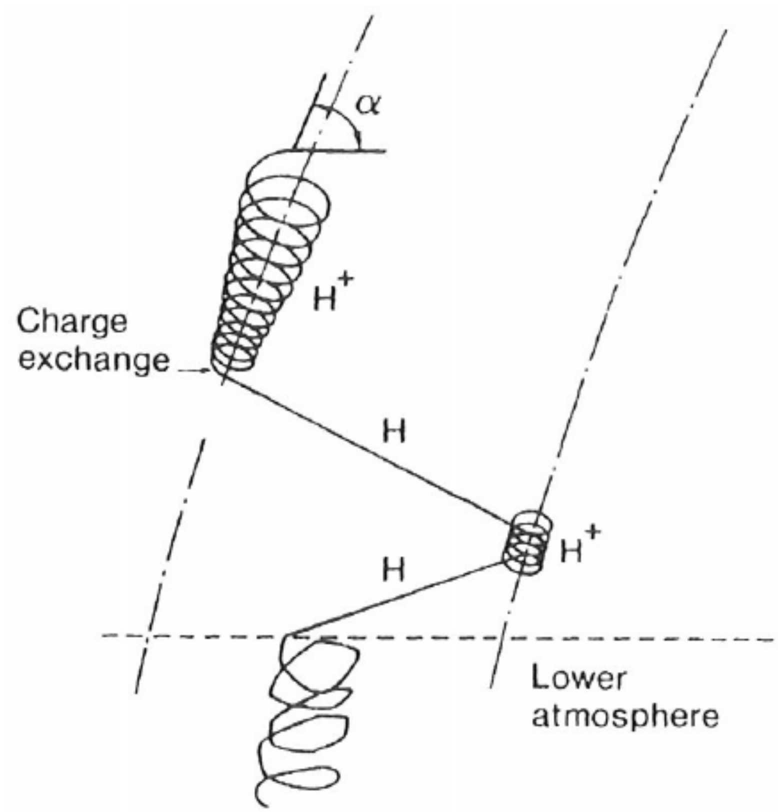


Figure: Protons may make charge exchange with neutral hydrogen.

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.

The ionosphere

Equations of motion

Conductivities matter because the ionosphere is a plasma with an embedded magnetic field.

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

Parallel equation of motion:

$$\mathrm{q\,E} = \mathrm{m_i} \nu_{\mathrm{in}} \mathrm{u_i} \qquad -\mathrm{eE} = \mathrm{m_e} \nu_{\mathrm{en}} \mathrm{u_e}$$

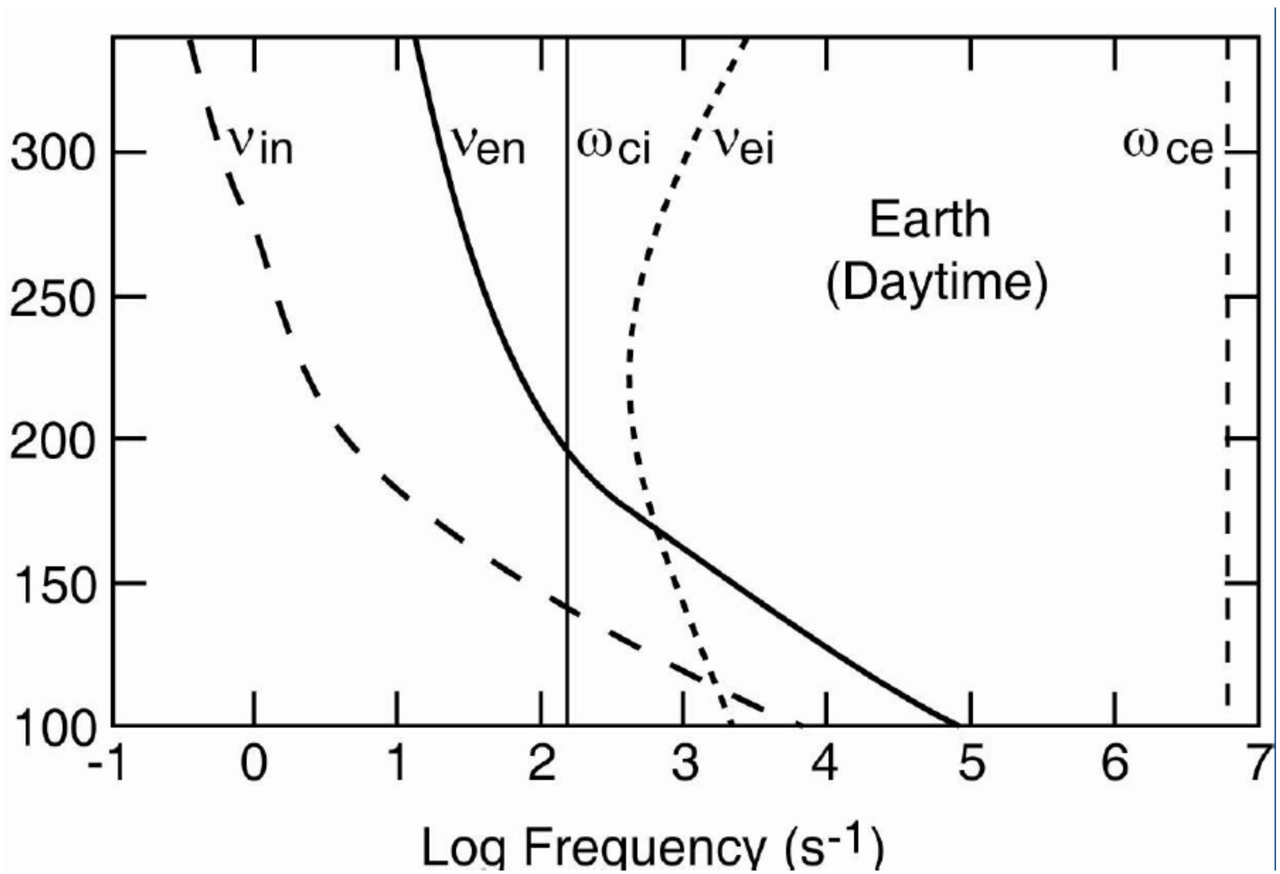
Perpendicular equation of motion:

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

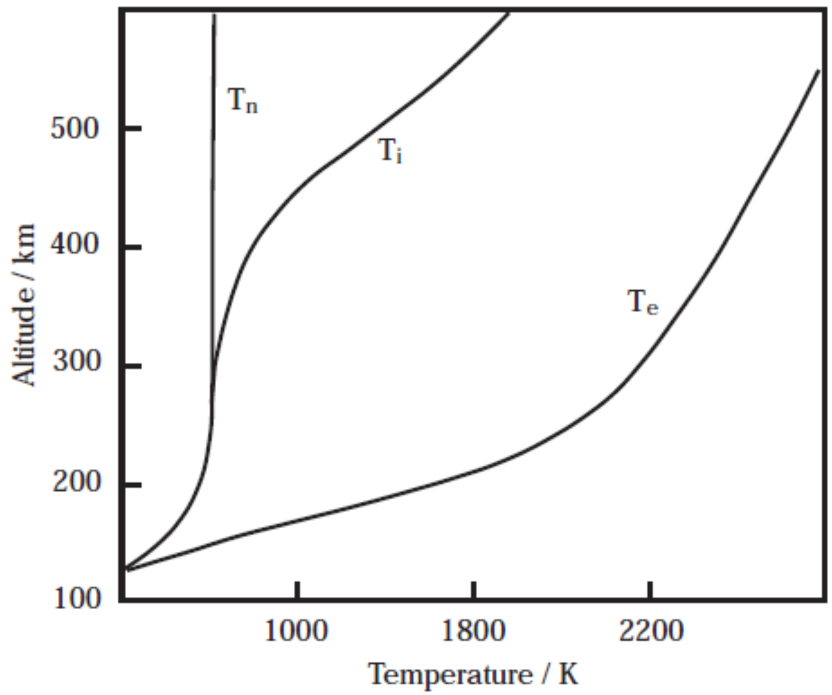
$$-e\left(\mathbf{E}_\perp + \mathbf{u}_e \times \mathbf{B}\right) = \mathrm{m_e} \nu_{\mathrm{en}} \mathbf{u}_{\perp e}$$

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.

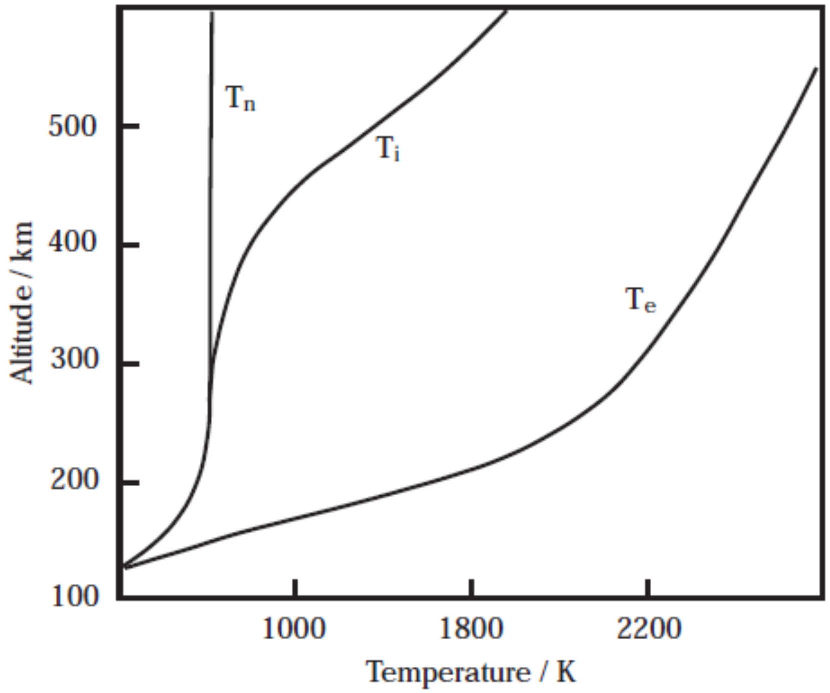


The ionosphere



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.

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)

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

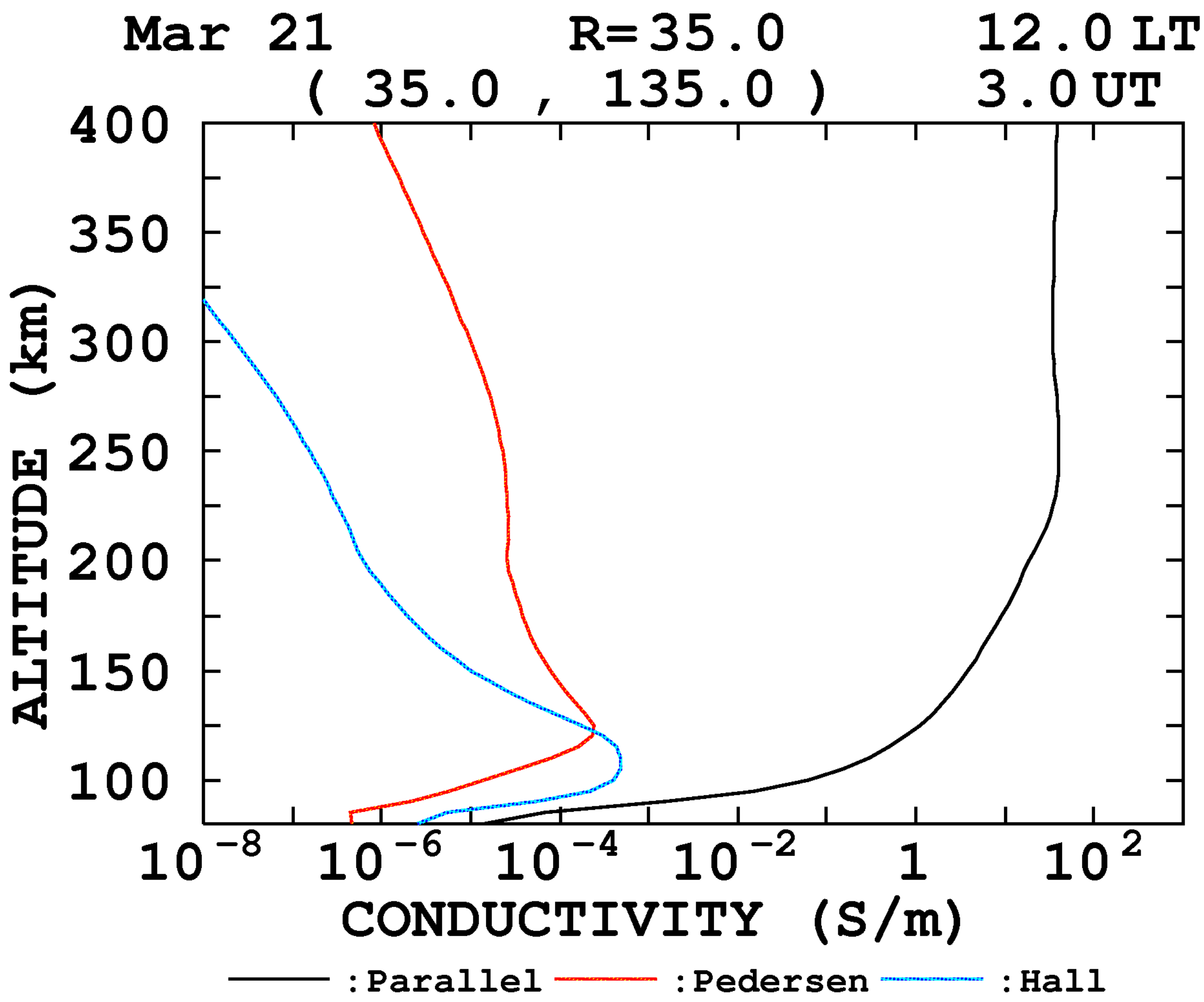
- Parallel conductivity (parallel to B)

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

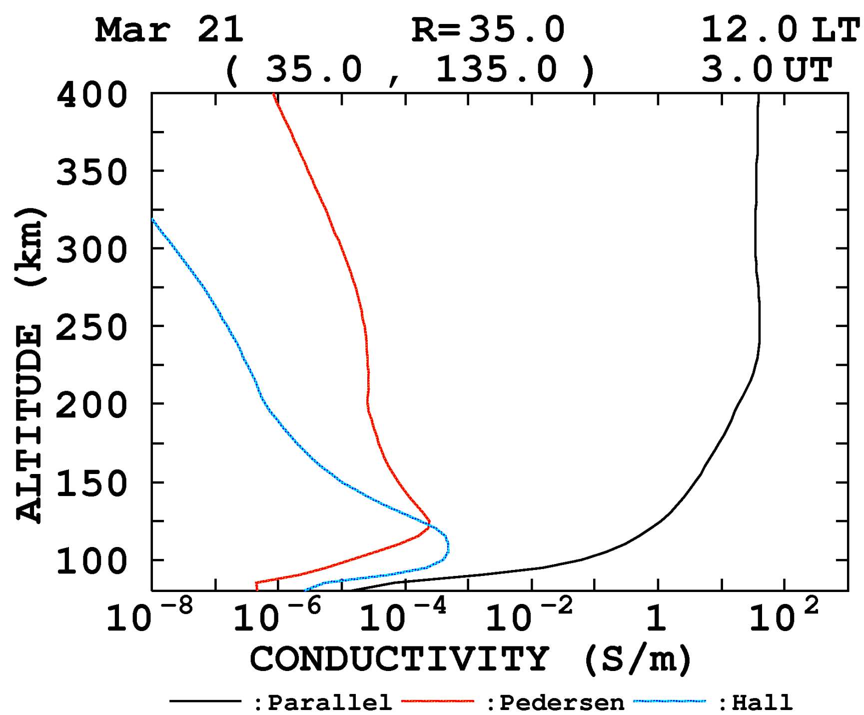
- Conductivity tensor

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

The ionosphere
Conductivities



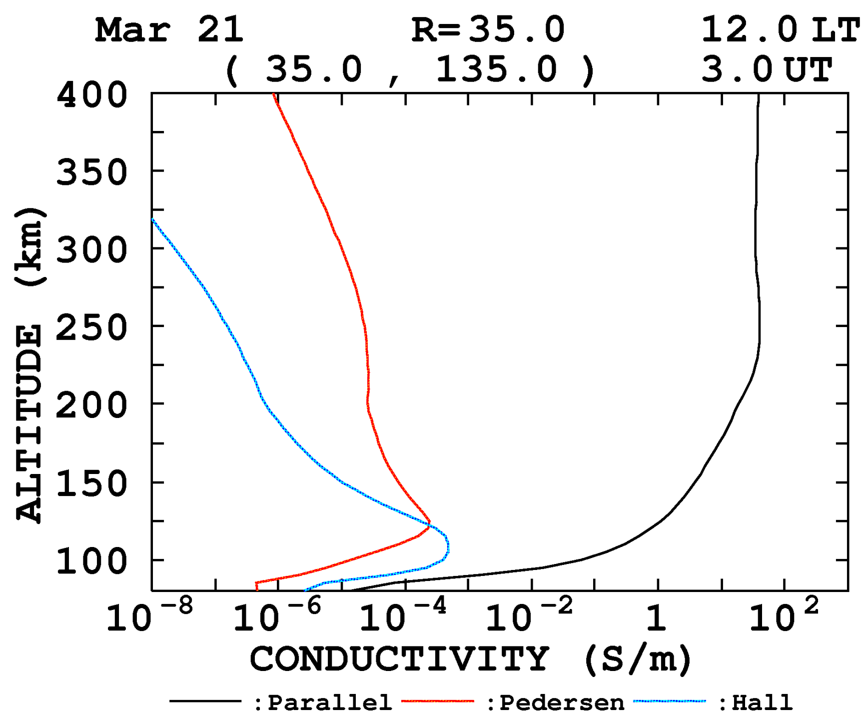
The ionosphere
Conductivities



Question: There is a peak in the Hall and Pedersen conductivities in the E-region. What ionospheric phenomenon also peaks at this altitude?

The ionosphere

Conductivities



Answer: The auroral and equatorial electrojets

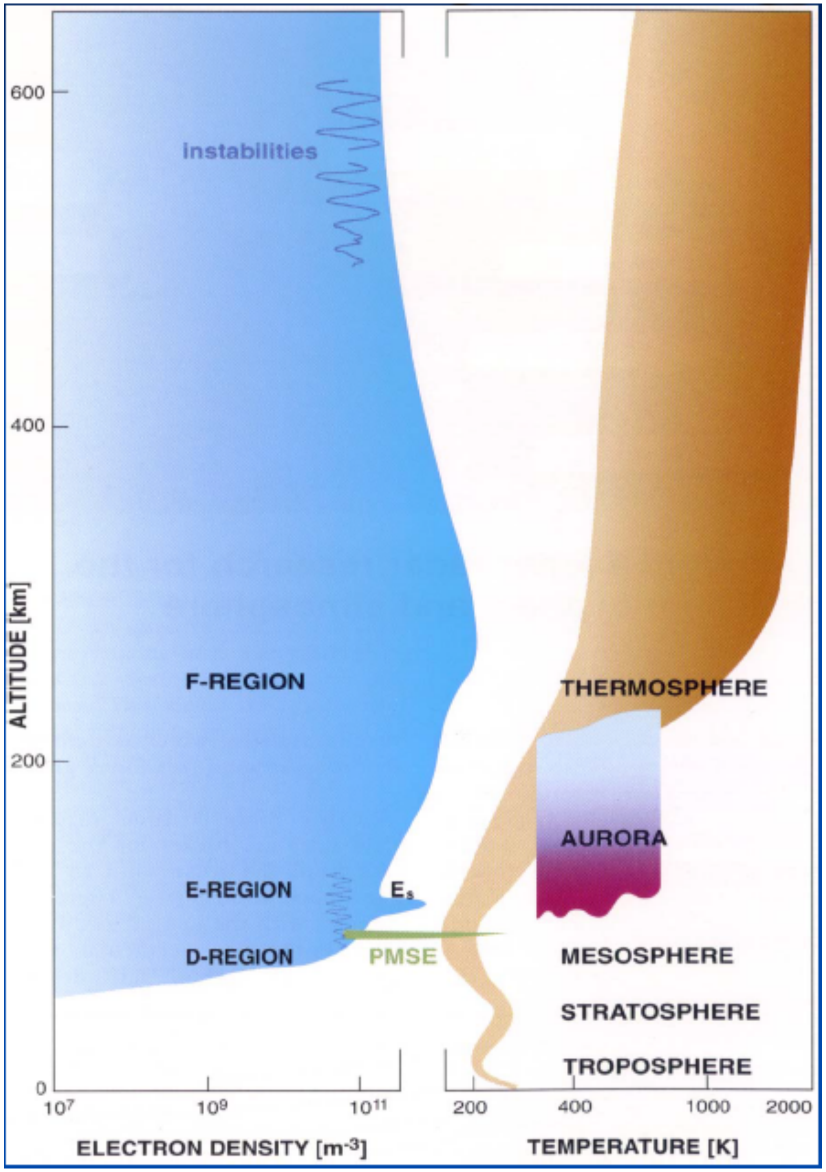
The ionosphere
Debye length

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

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

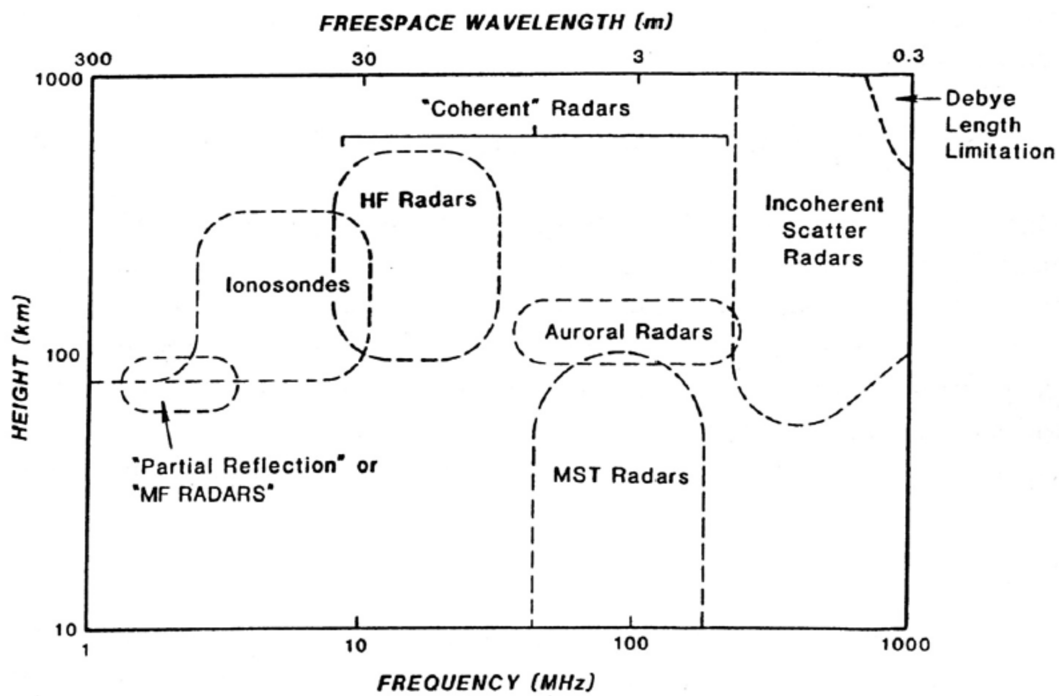
$$\lambda_D \simeq 69\sqrt{\mathrm{T}_e/\mathrm{n}_e}$$



The ionosphere

Question: If we want to measure bulk plasma parameters with an incoherent scatter radar, how will the 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.

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

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

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

ω = the angular frequency of the radar wave,

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

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.

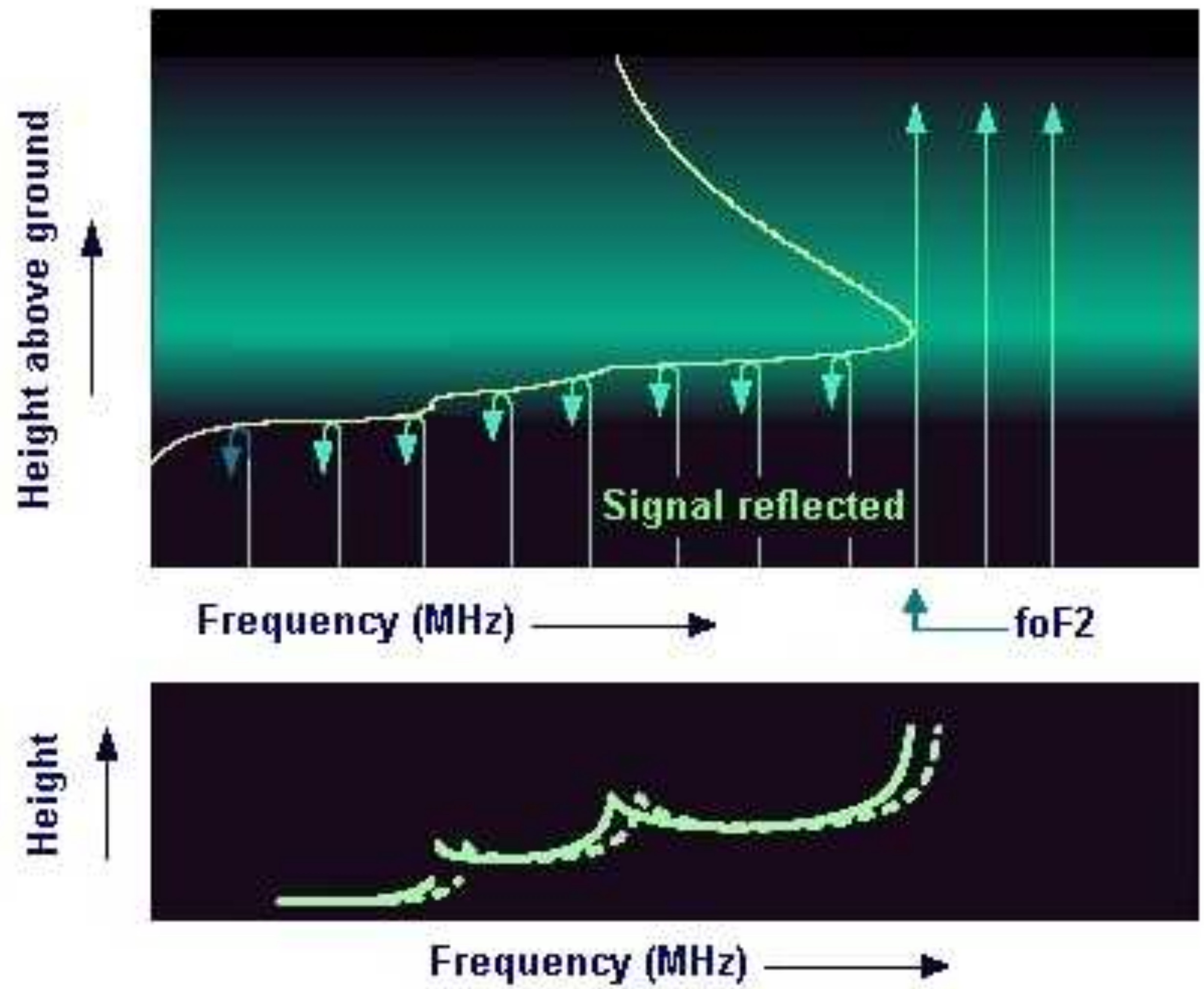
The Appleton-Hartree equation

Index of refraction in an unmagnetized plasma:

$$n^2 = 1 - \omega^2_{pe}/\omega^2$$

Electron plasma frequency: $\omega^2_{pe} = e^2 n_e/\varepsilon_0 m_e$

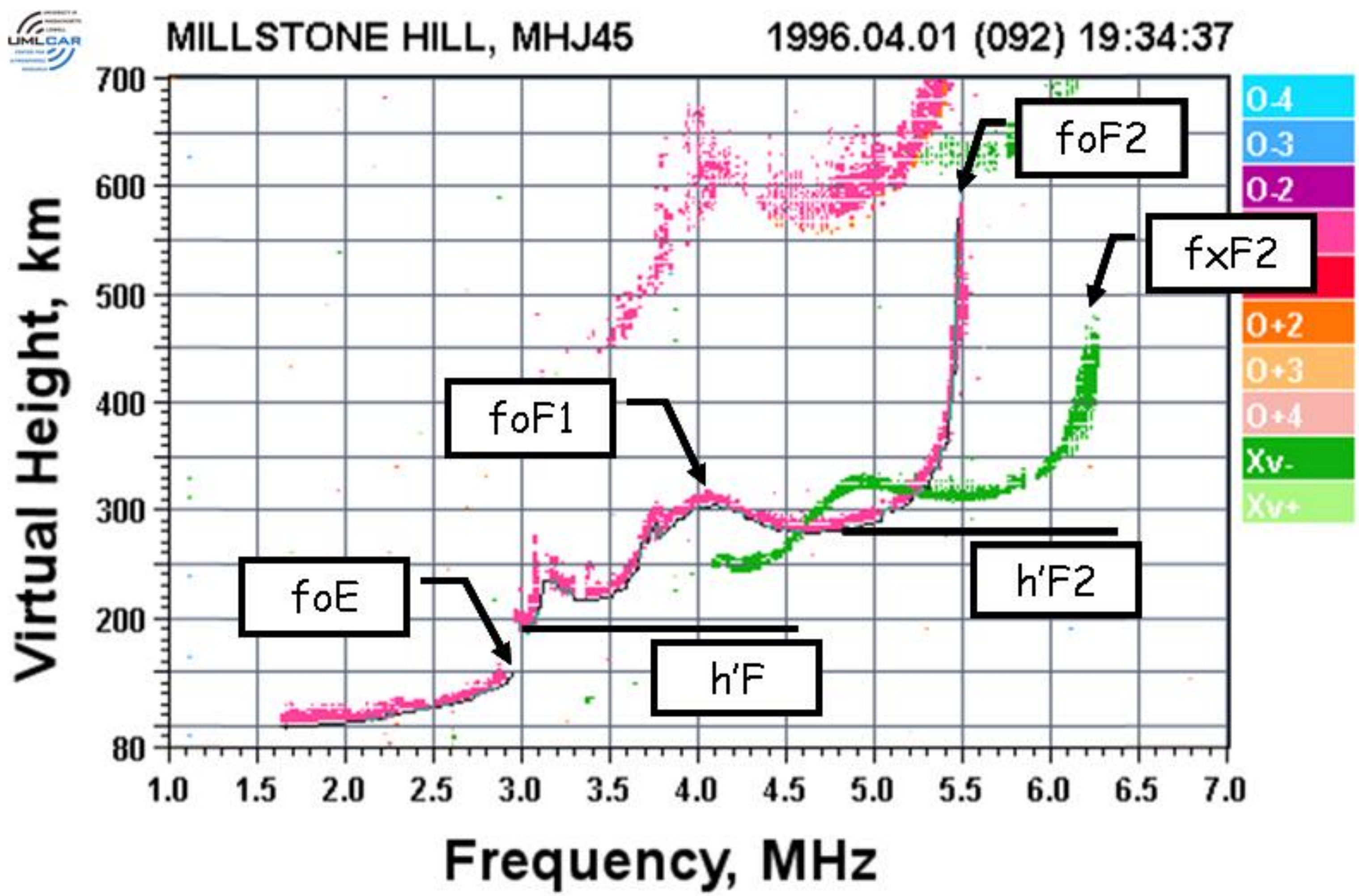
Reflection experiments: ionosondes



Ionograms

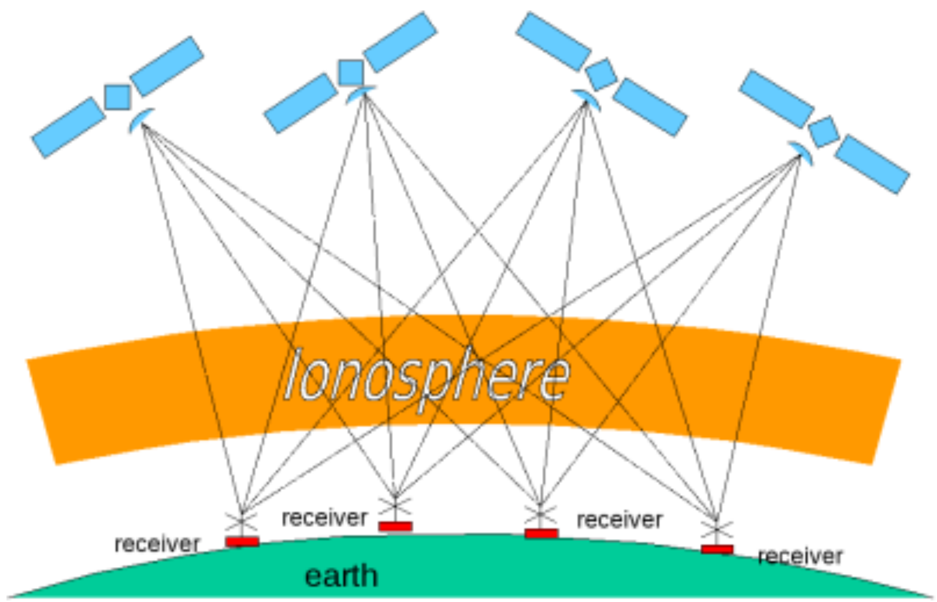
Autoscaled:

foF2	5.49
foF1	4.86
foF1p	4.56
foE	2.96
foEp	3.23
fxI	6.20
foEs	2.95
MUF	18.70
M	3.415
D	3000
h'F	185
h'F2	285
h'E	98
h'Es	98
zmF2	227
zmF1	196
zmE	106
yF2	67
yF1	40
yE	30
C-level	1

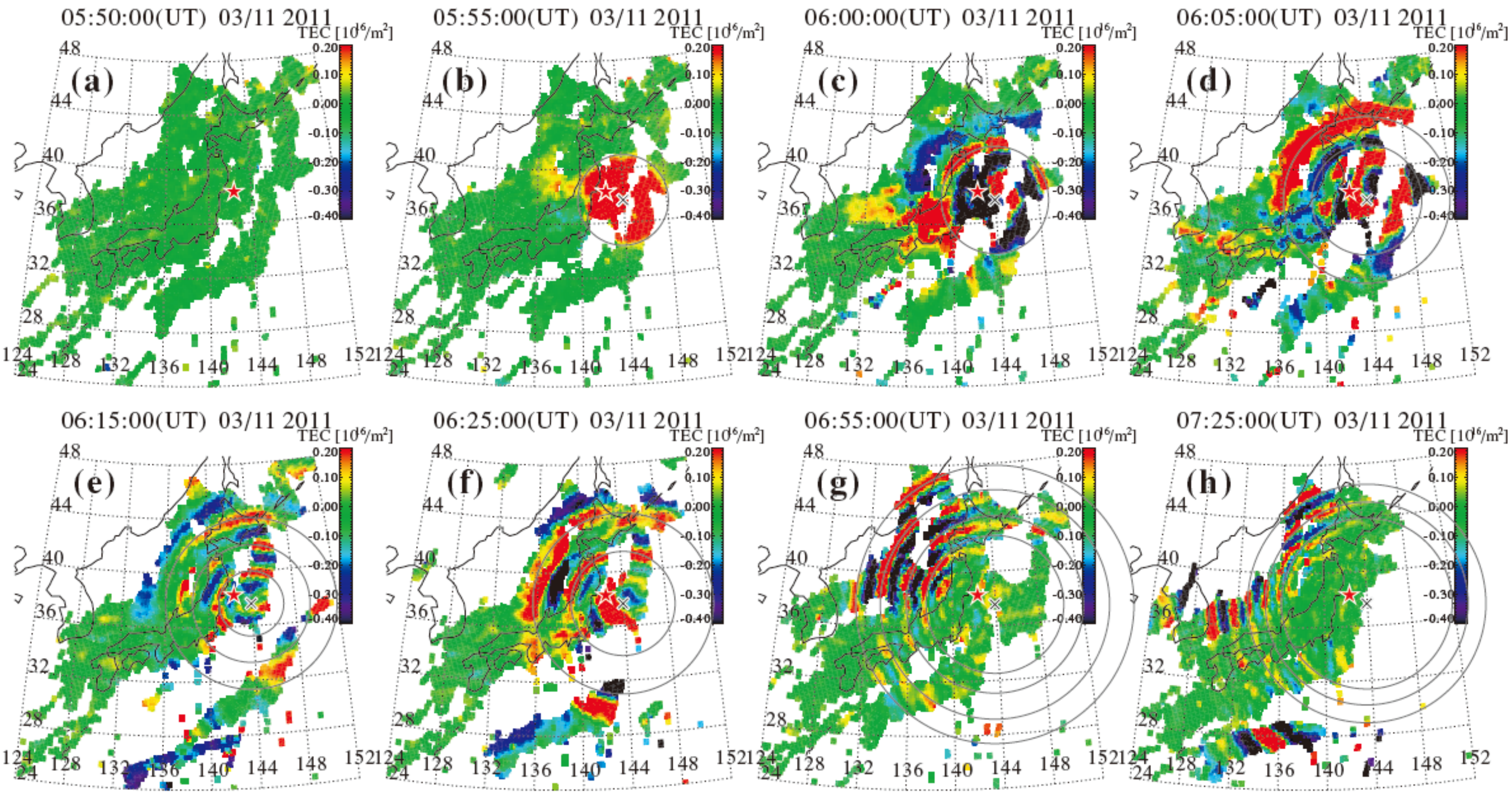


GPS time difference of arrival

- 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).

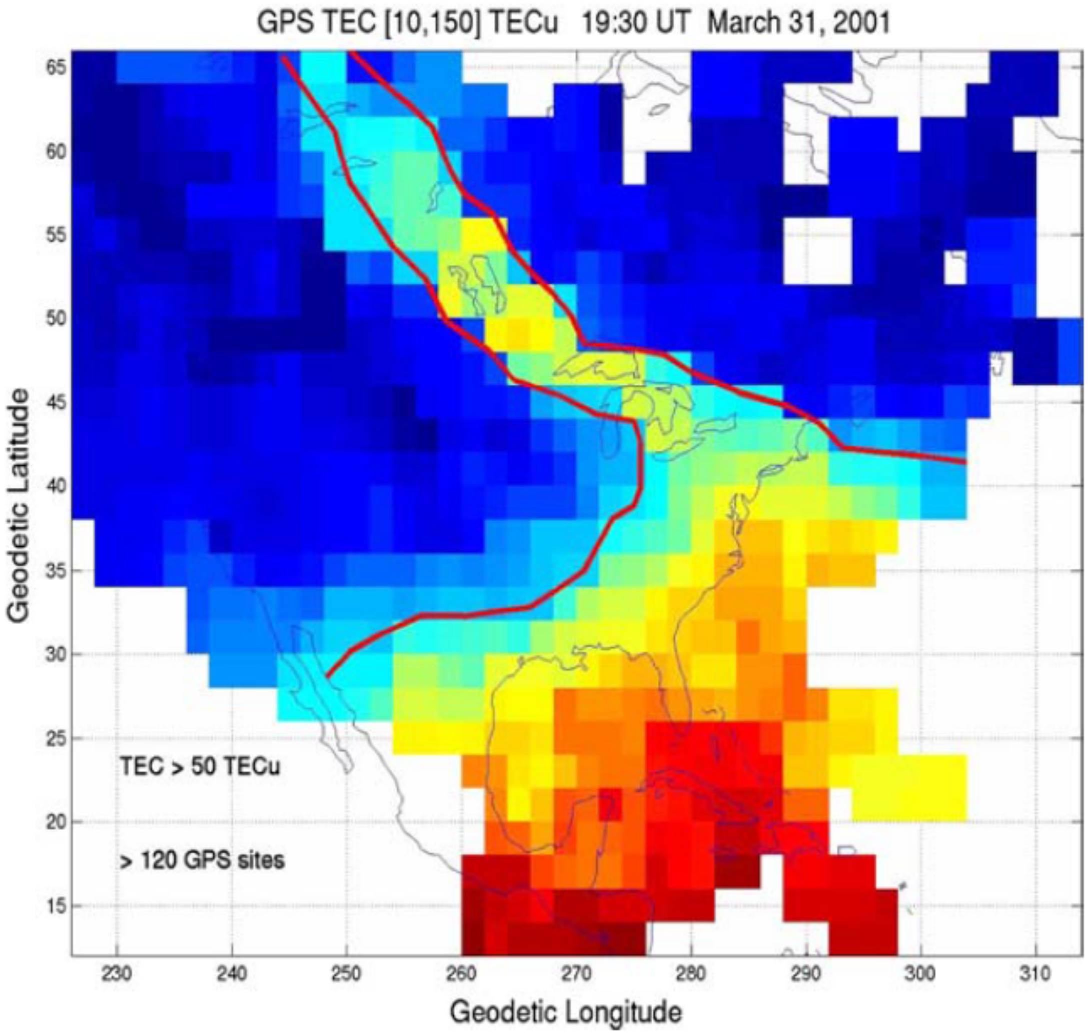


Ionospheric response to 2011 Tohoku earthquake



Tsugawa et al., 2011

Total electron content maps



Coster and Skone, 2009

Incoherent scatter radar

Radar Cross Section of One Electron:

$$\sigma_e = 4\pi r_e^2 \approx 10^{-28}\ \mathrm{m}^2$$

Suppose $N_e = 10^{11}\ \mathrm{m}^{-3}$ and $V = 1\ \mathrm{km}^3$:

$$\sigma = 10^{11} \times 10^{9} \times 10^{-28} = 10^{-8}\ \mathrm{m}^2$$

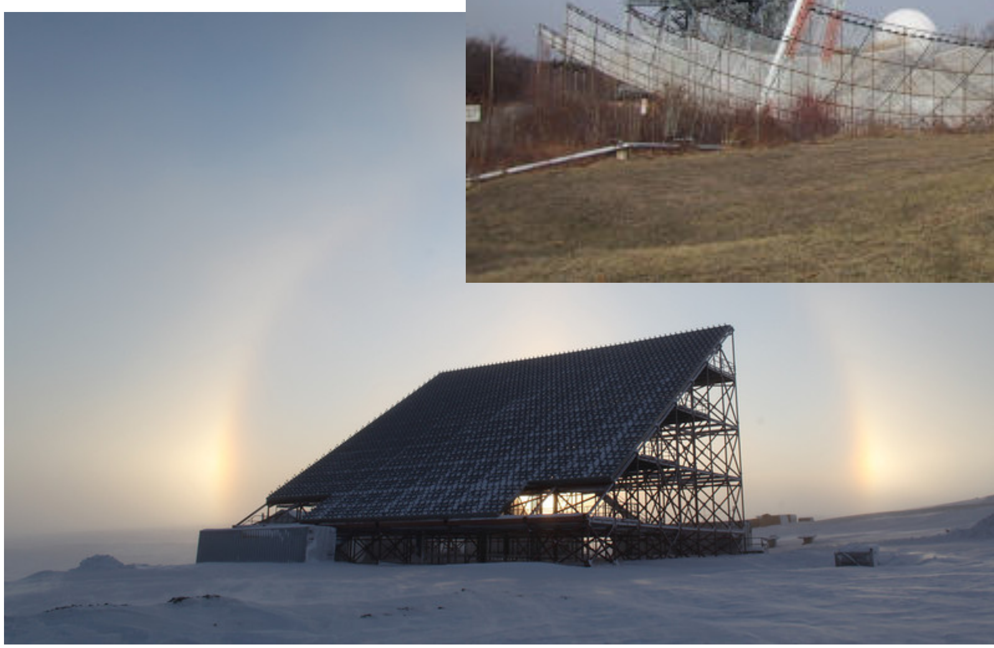
Power received by a 430 MHz, 300 m radar with 1 MW of power and 60% efficiency from a 100 $\mu\mathrm{m} \times 100\ \mu\mathrm{m}$ target at 300 km:

$$P_r = P_t \frac{G}{4\pi R^2} \sigma \frac{A_{eff}}{4\pi R^2} \approx 4 \times 10^{-15}\mathrm{W}$$

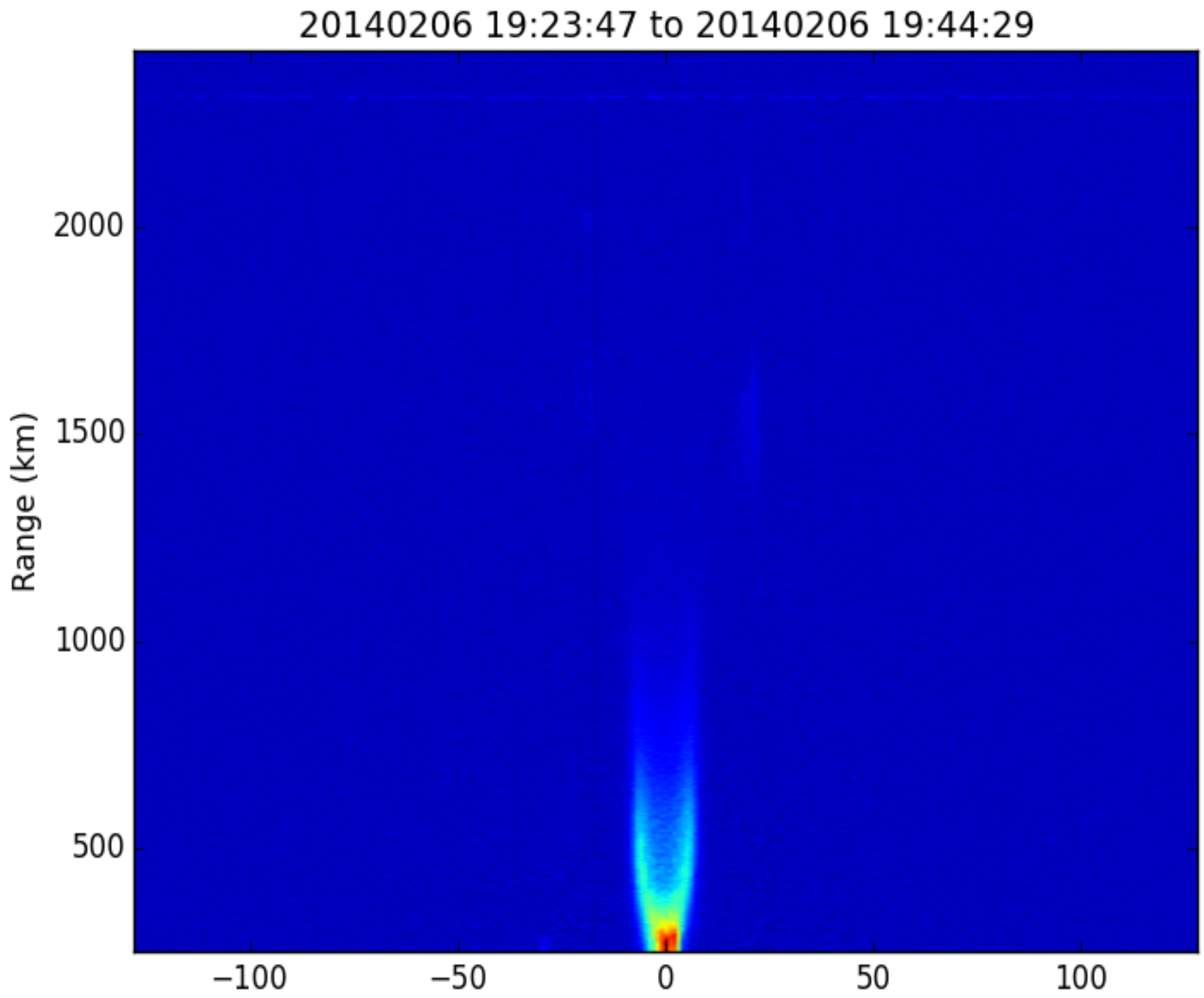
Noise Power for a 200 K receiver with a 500 kHz bandwidth:

$$N = k_B T_{sys} B = 1.4 \times 10^{-15}\mathrm{W}$$

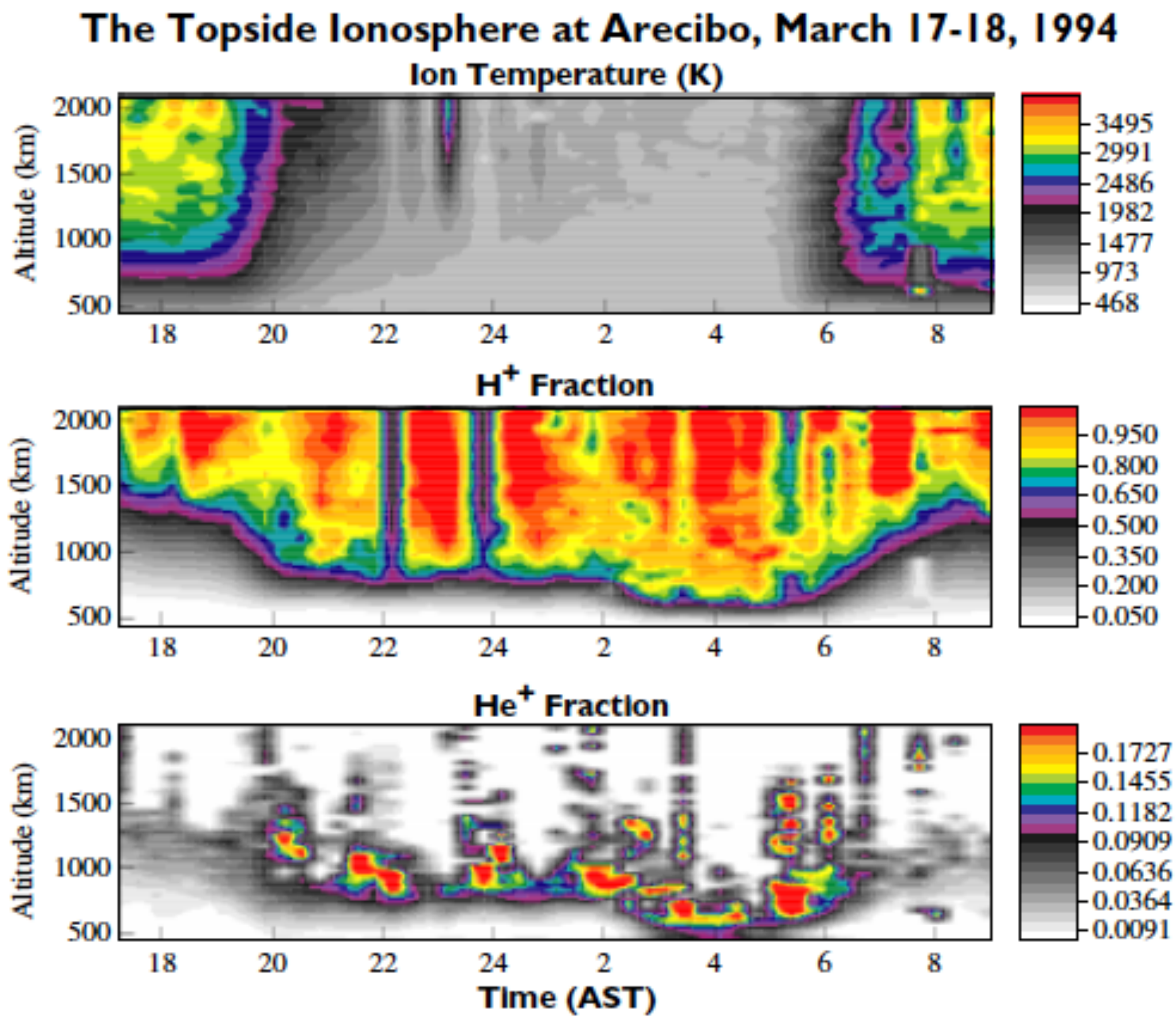
Incoherent Scatter Radar



Incoherent Scatter Radar



Incoherent Scatter Radar

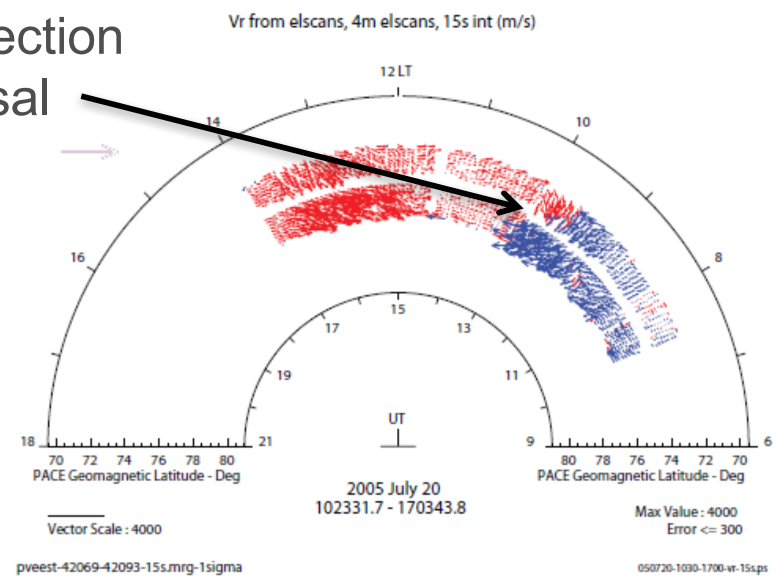


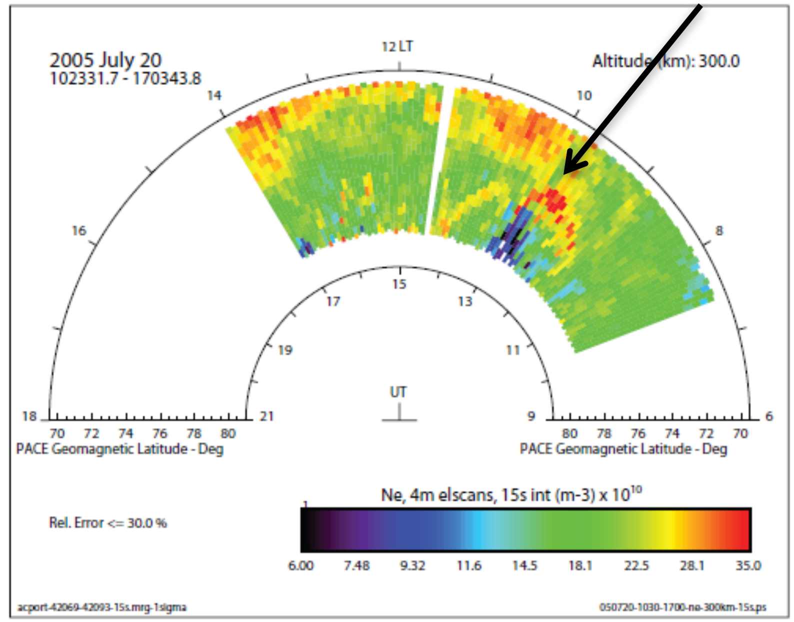
Sondrestrom

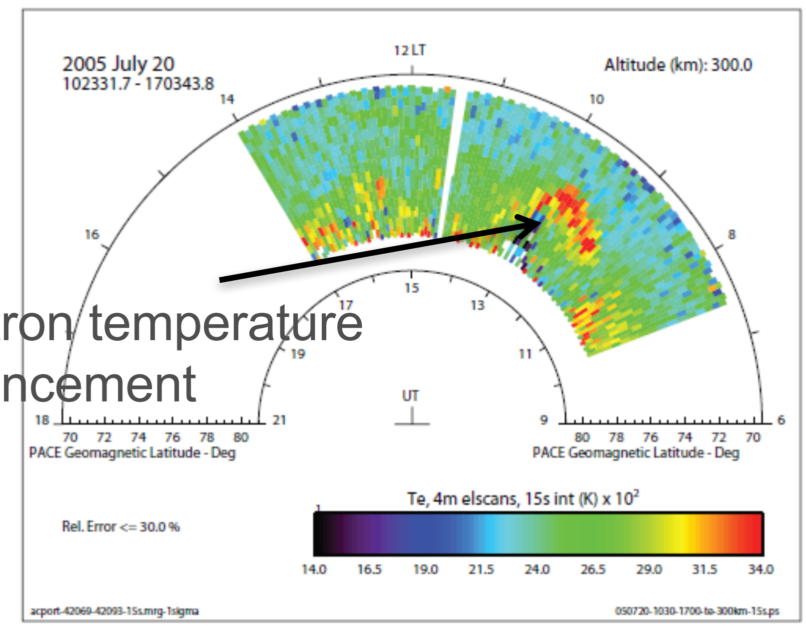
Influx of particles and Joule heating (due to current flow)

Electron density enhancement

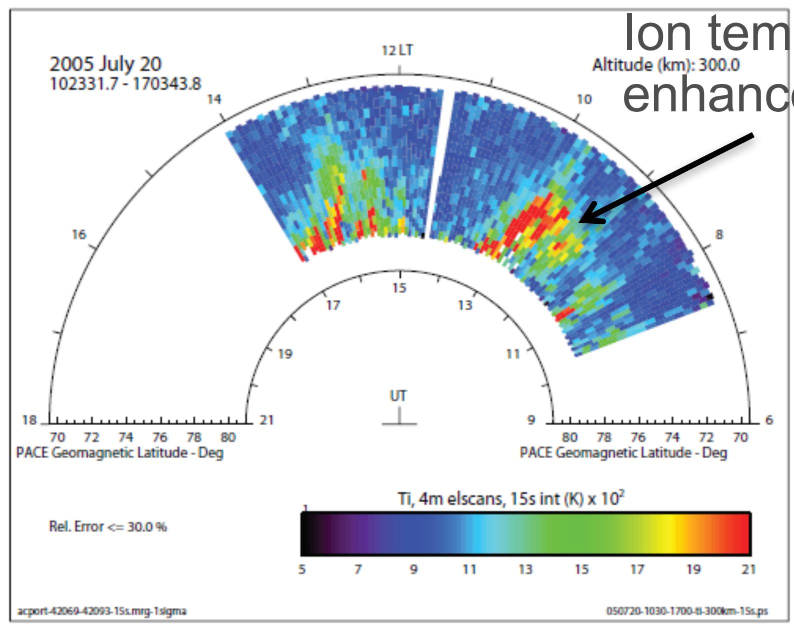
Convection reversal





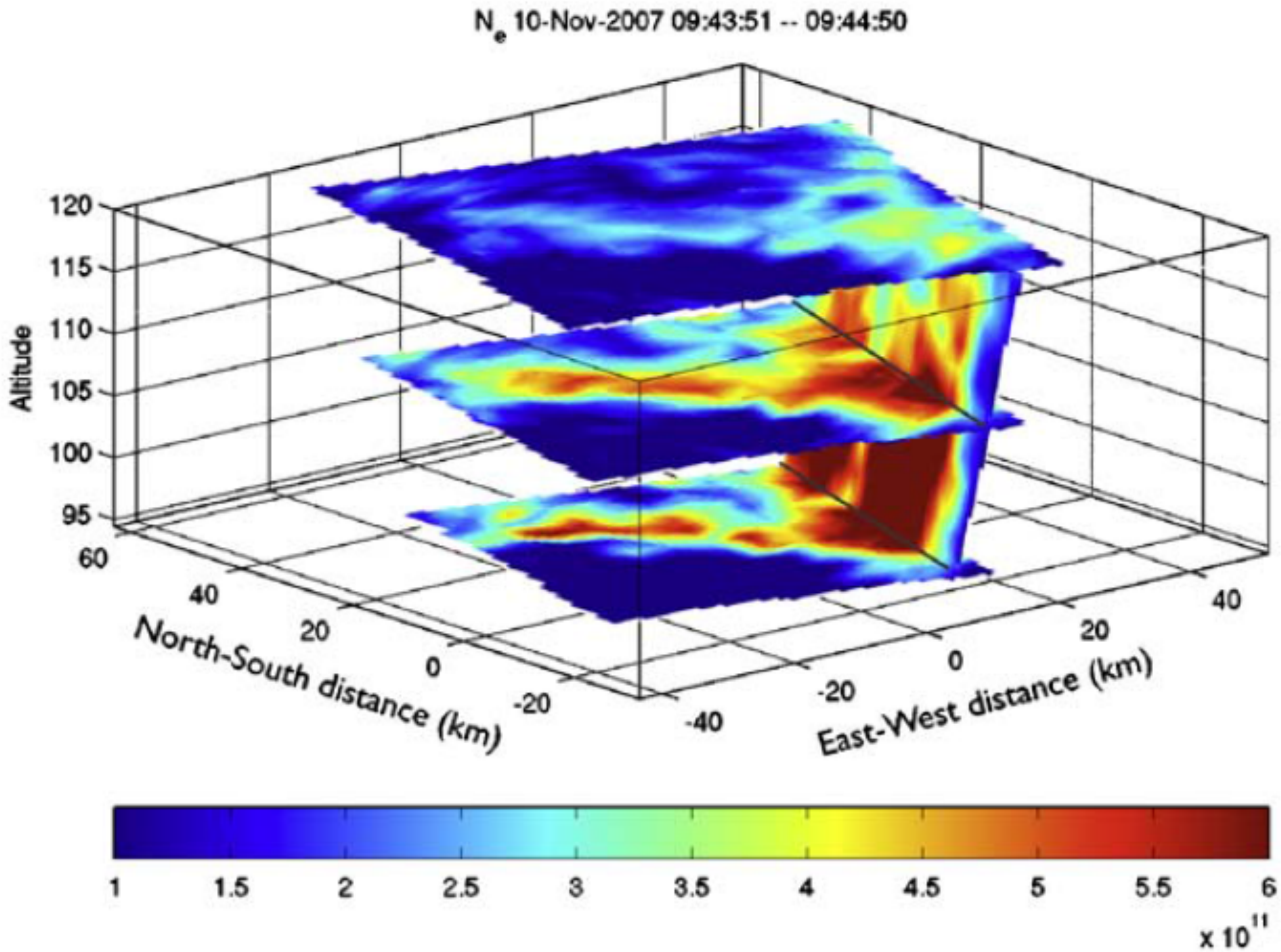


Electron temperature enhancement

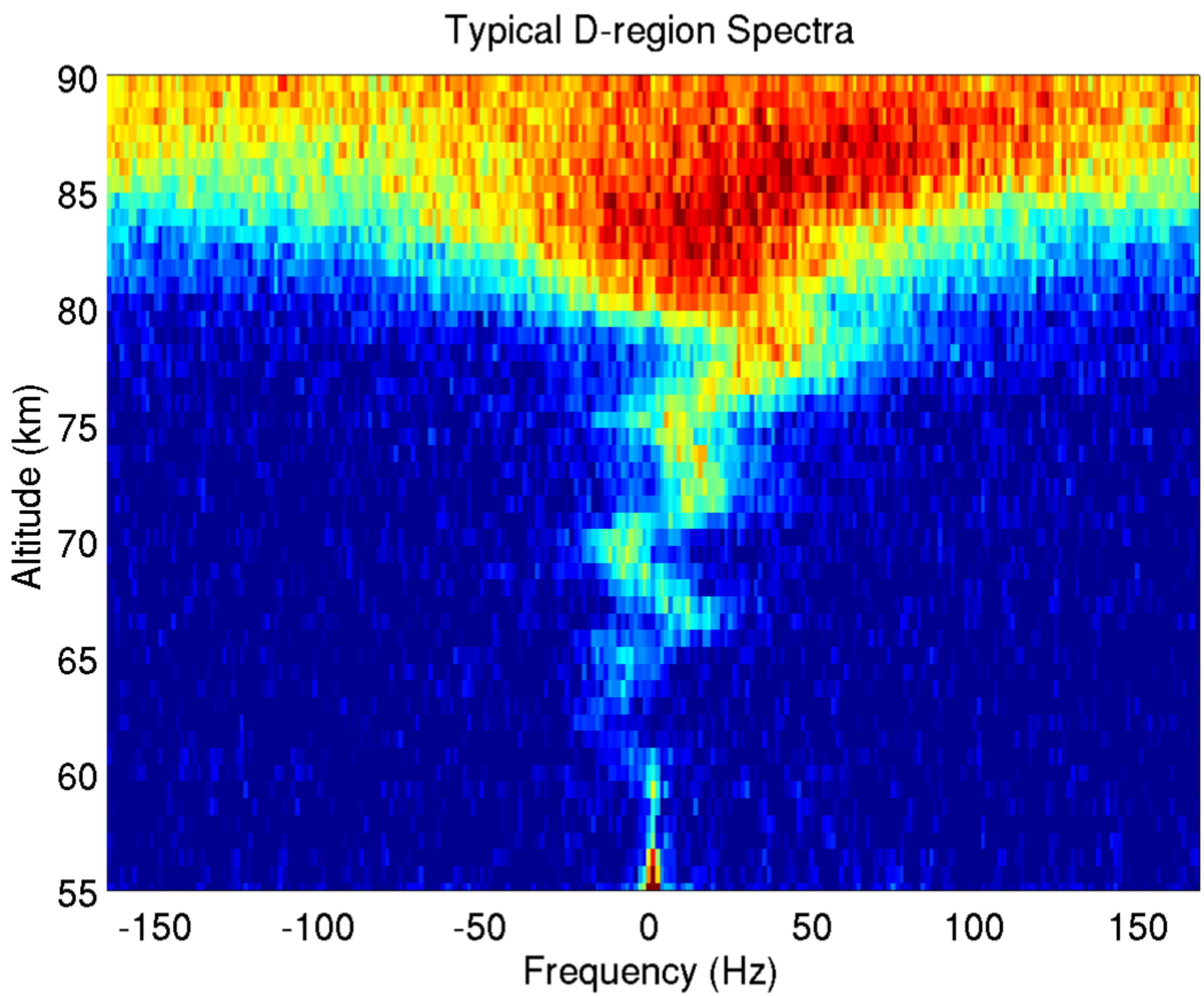


Ion temperature enhancement

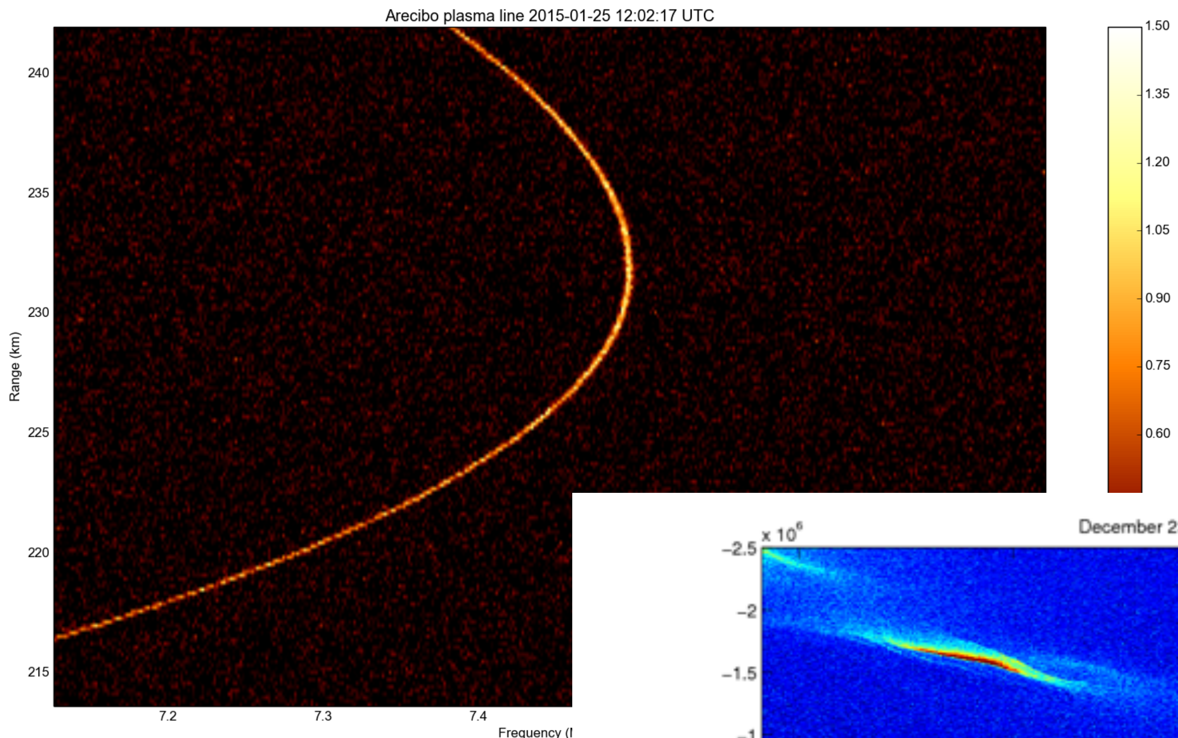
Incoherent Scatter Radar

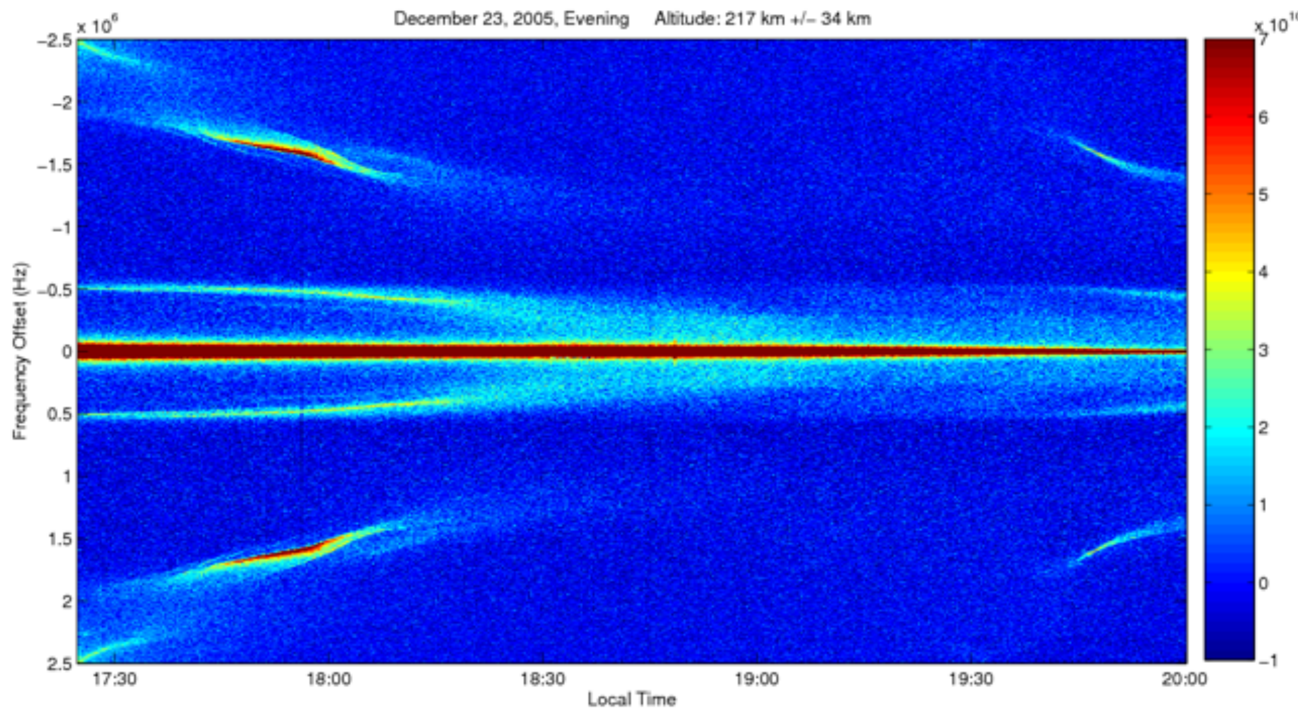


Incoherent Scatter Radar



Incoherent Scatter Radar



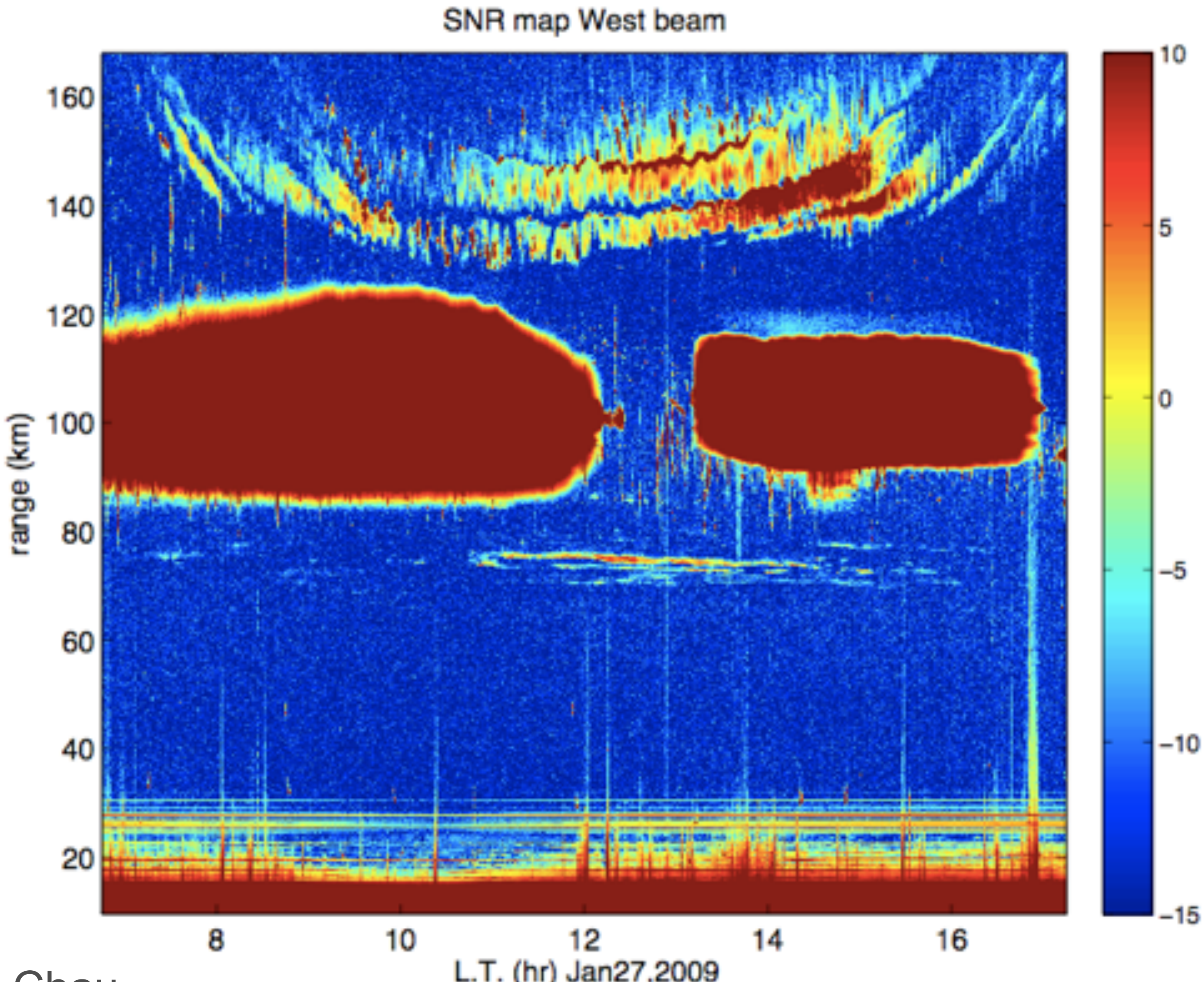


Juha Vierinen
Asti Bhatt

Coherent Scatter Radar

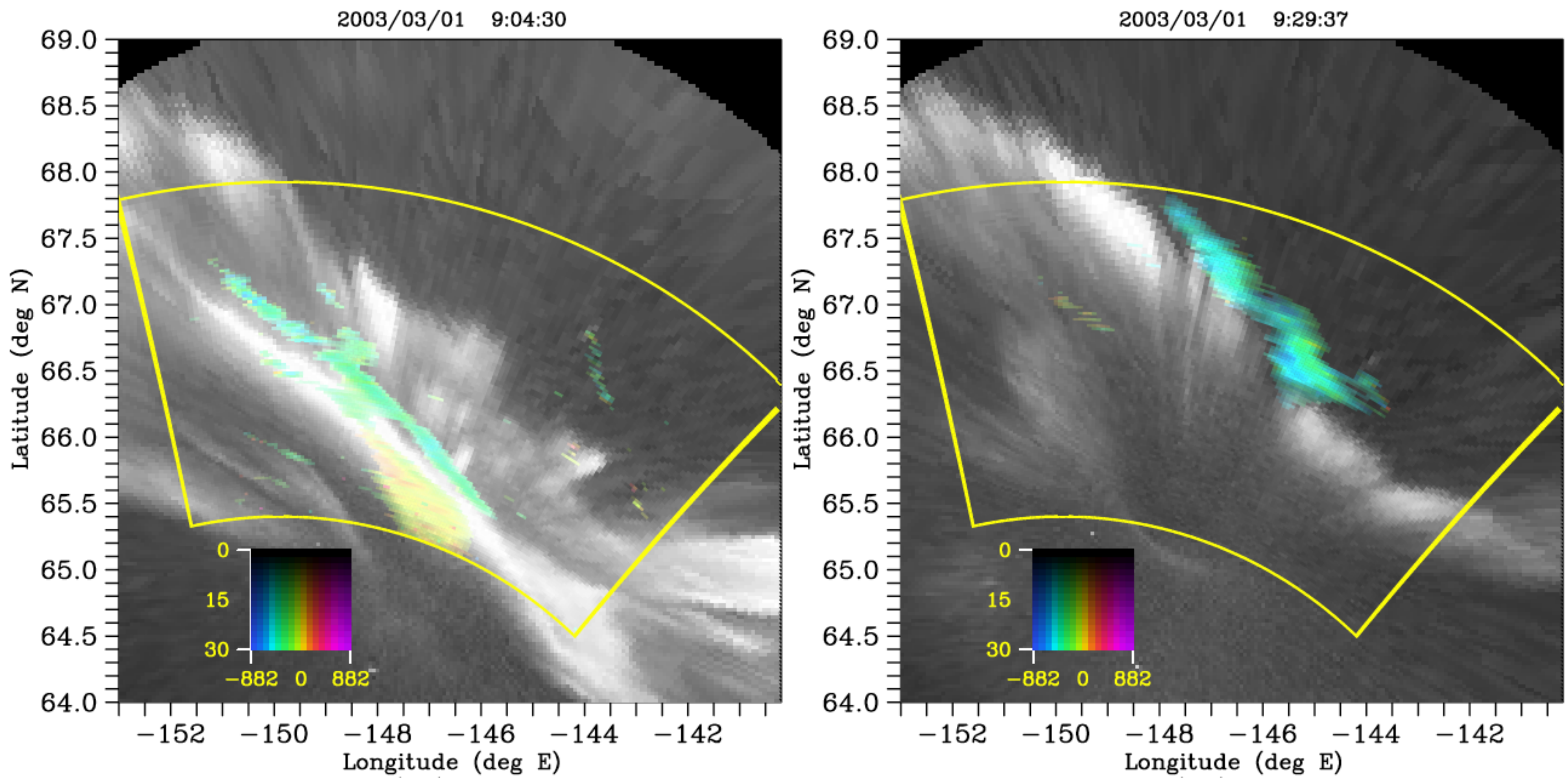
- Any medium with stochastic index of refraction fluctuations can produce coherent scatter.
- Can work in neutral air.
- Works very well in plasmas. Small electron density fluctuations produces significant index of refraction fluctuations.
- Structures must match $\lambda_R/2$ to get constructive interference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

Equatorial electrojet, 150-km echoes, and mesospheric turbulence



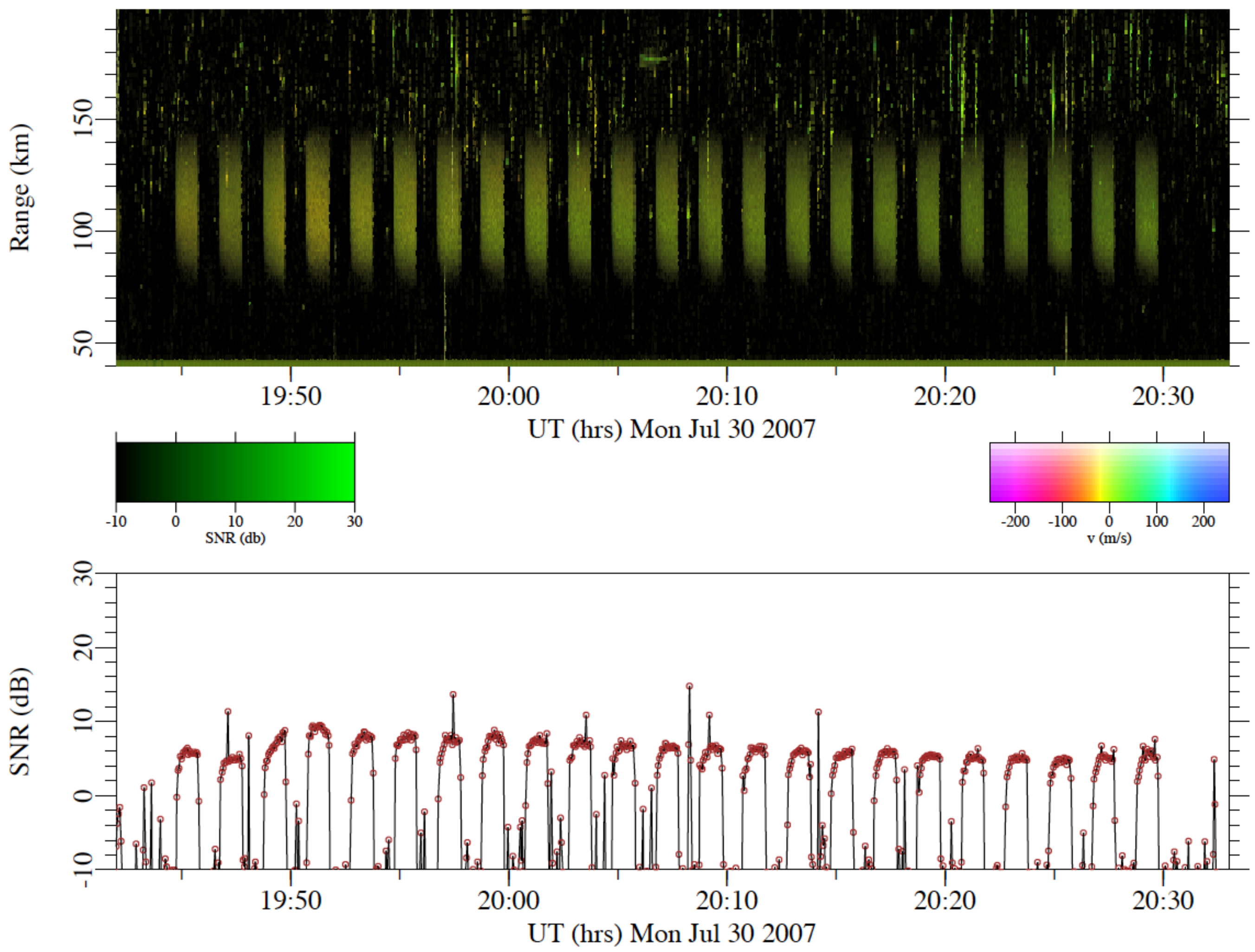
Courtesy J. Chau

Auroral electrojet instabilities



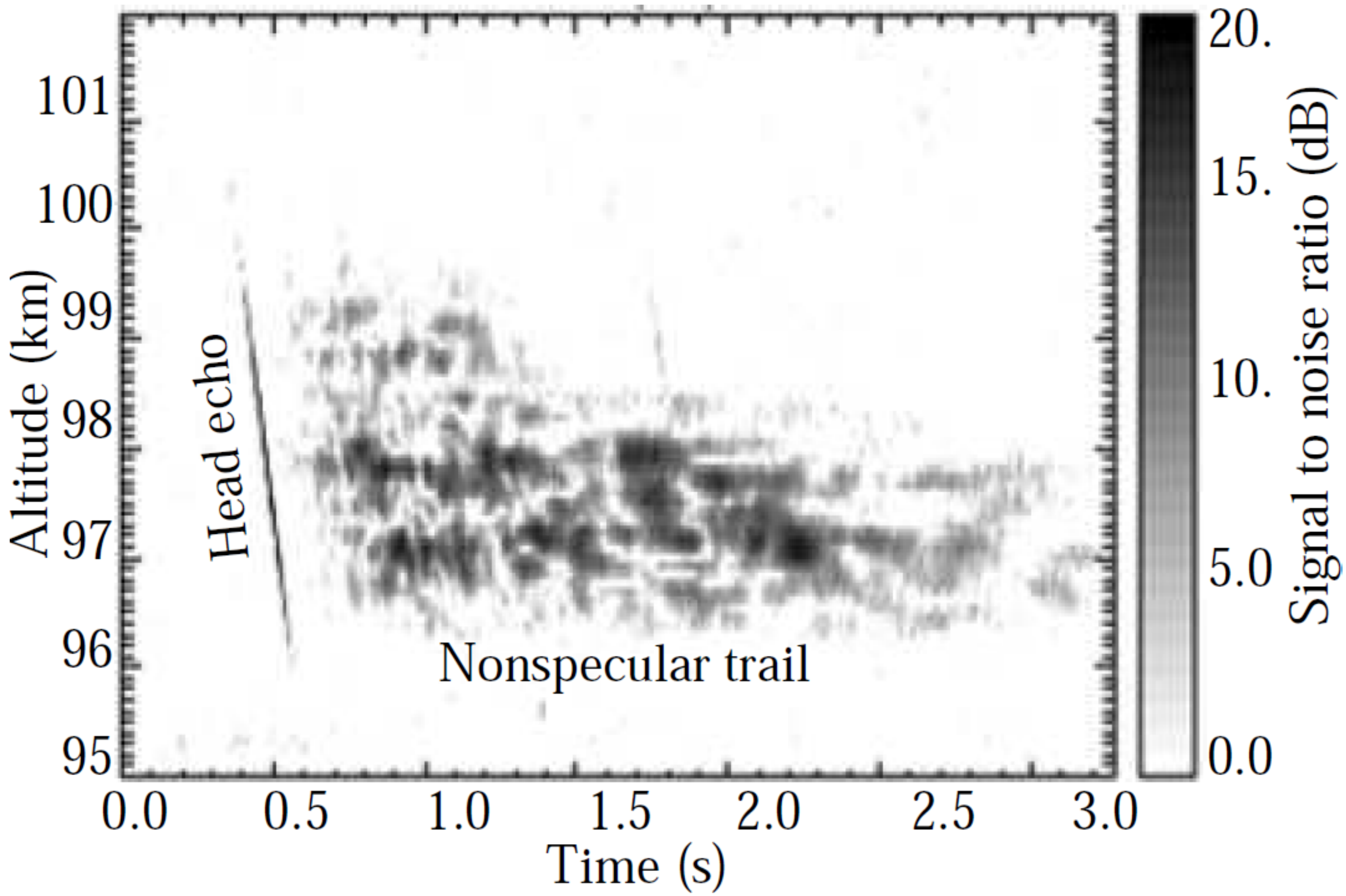
Bahcivan et al, 2006

Ionospheric modification



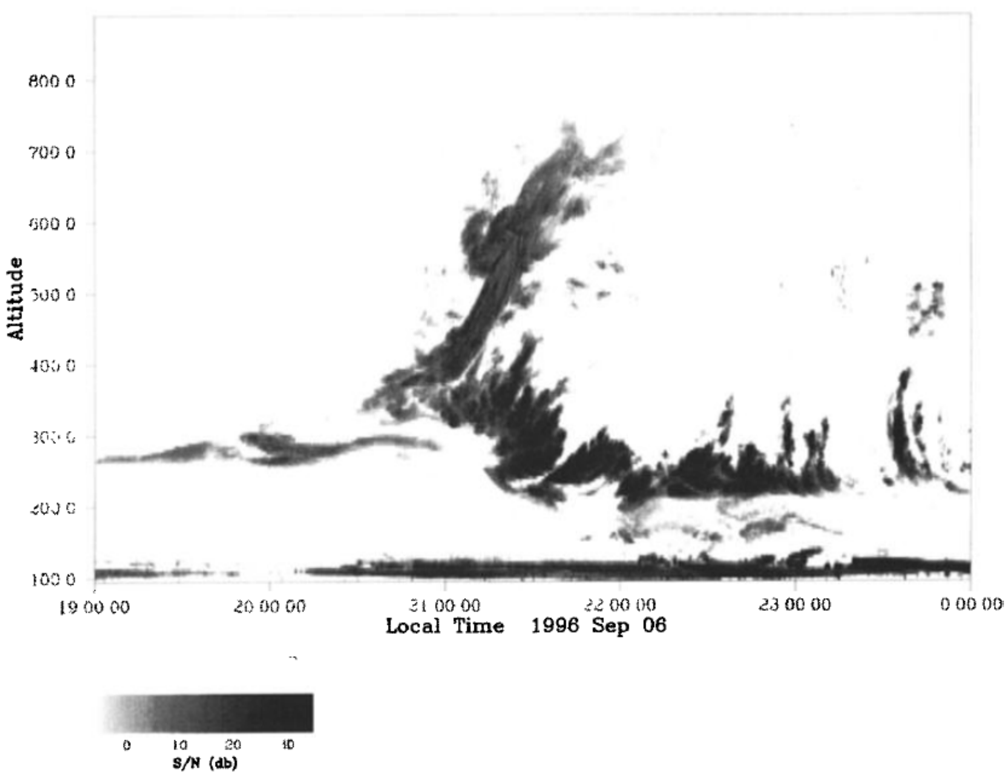
Hysell, 2008

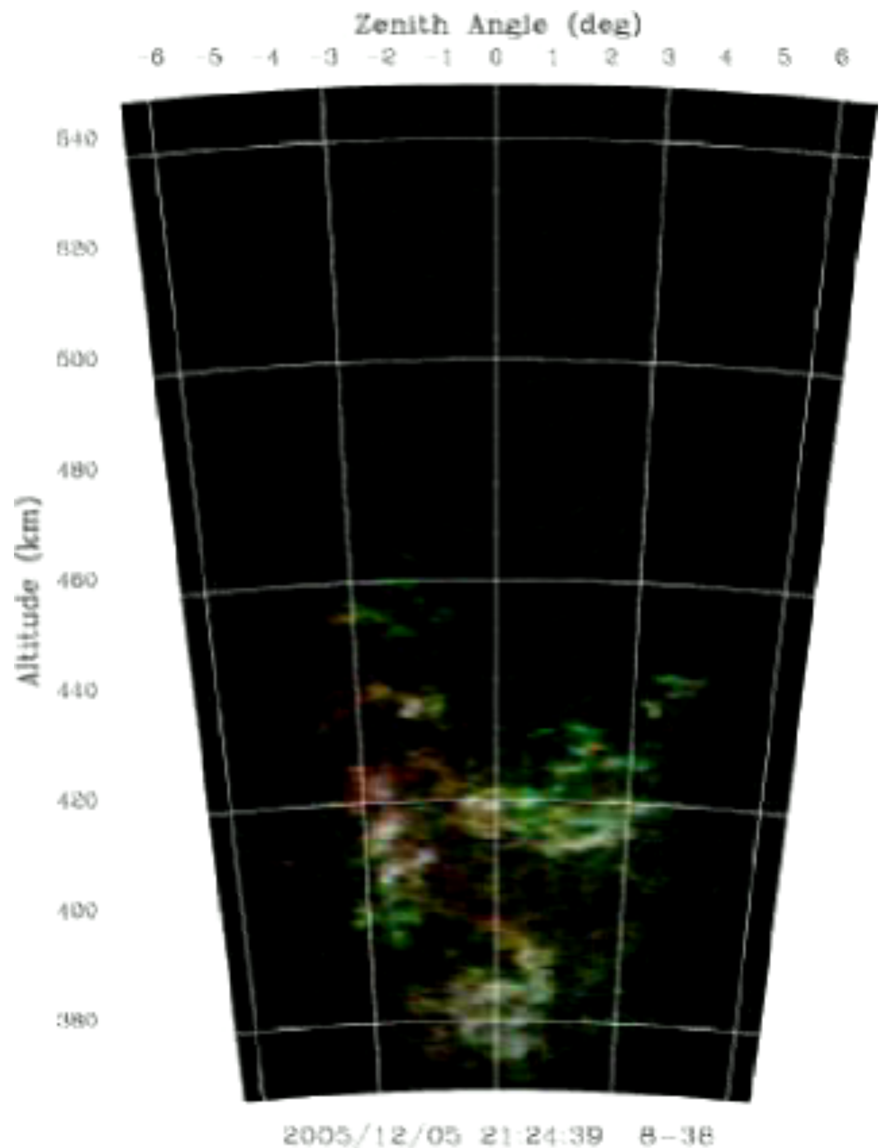
Meteors and meteor trails



Dimant and Oppenheim (2006)

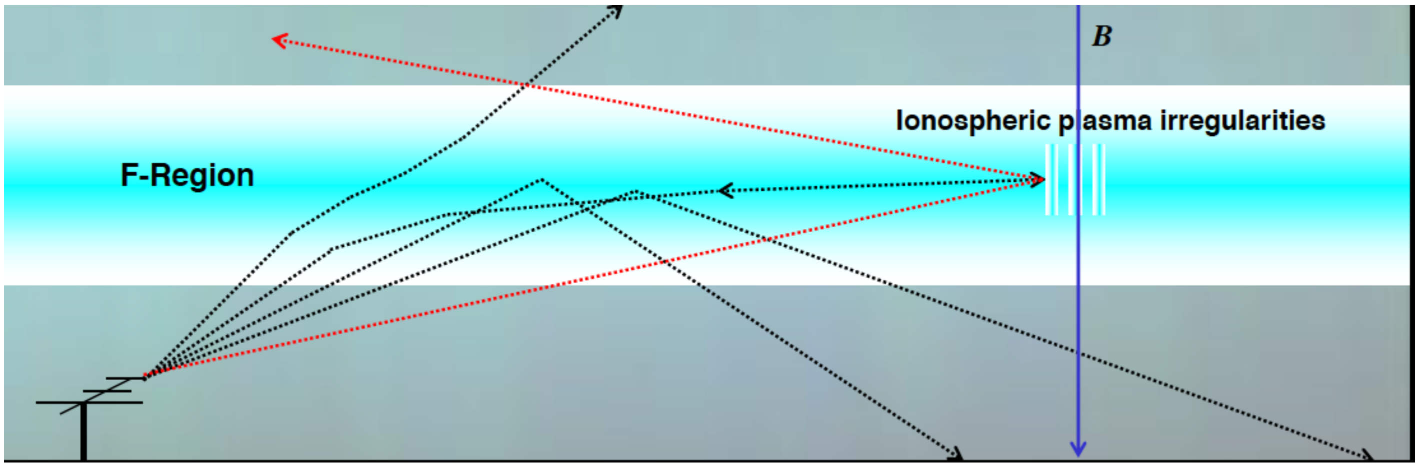
Equatorial spread F

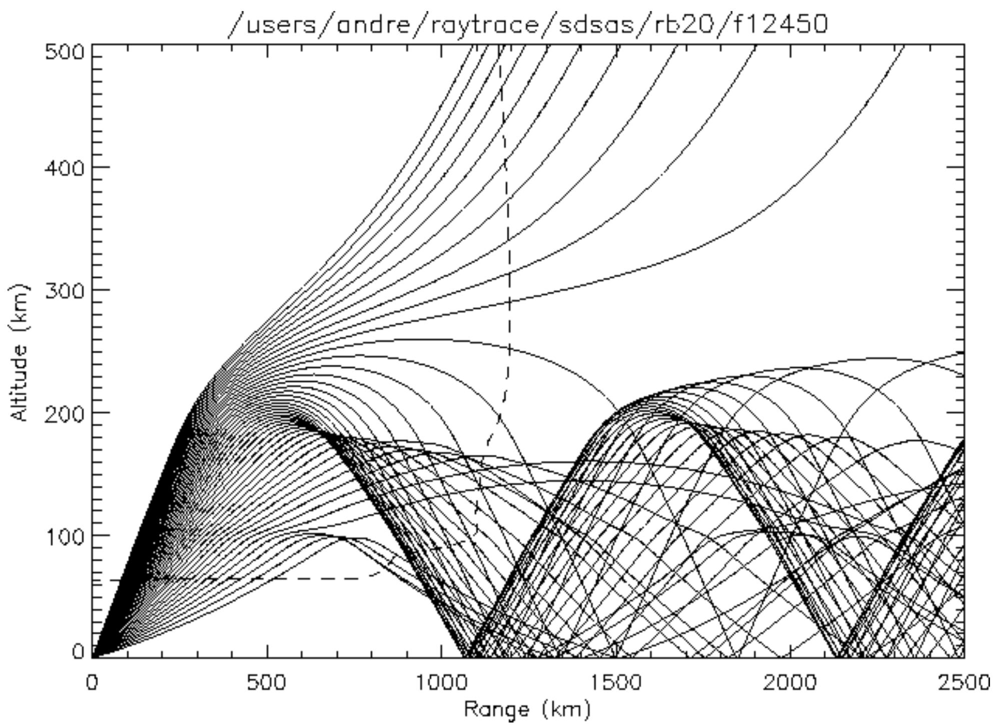




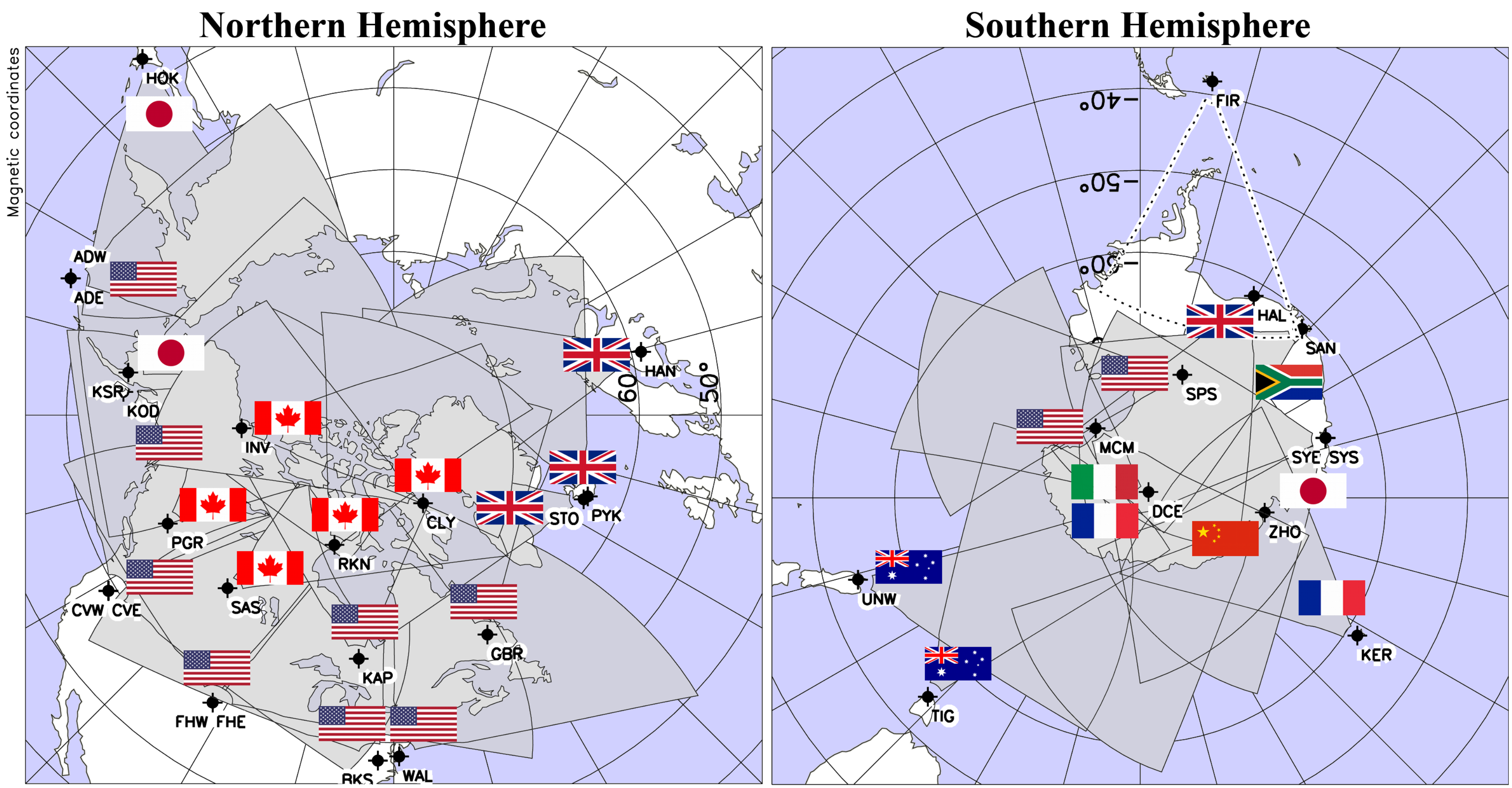
Hysell and Burcham, 1998

SuperDARN


B
Ionospheric plasma irregularities
F-Region

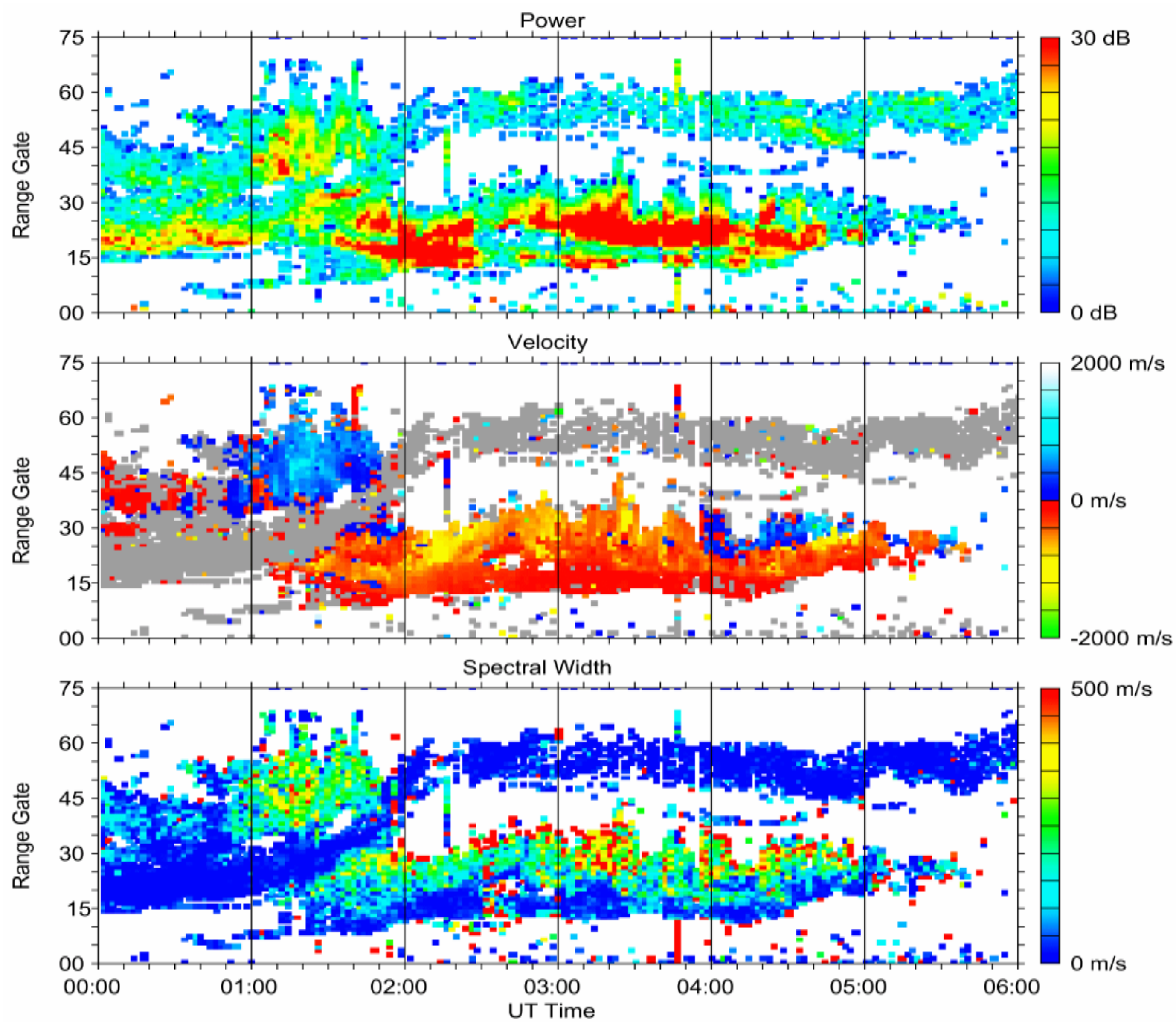

/users/andre/raytrace/sdsas/rb20/f12450
Altitude (km)
Range (km)
0
100
200
300
400
500
0
500
1000
1500
2000
2500

SuperDARN

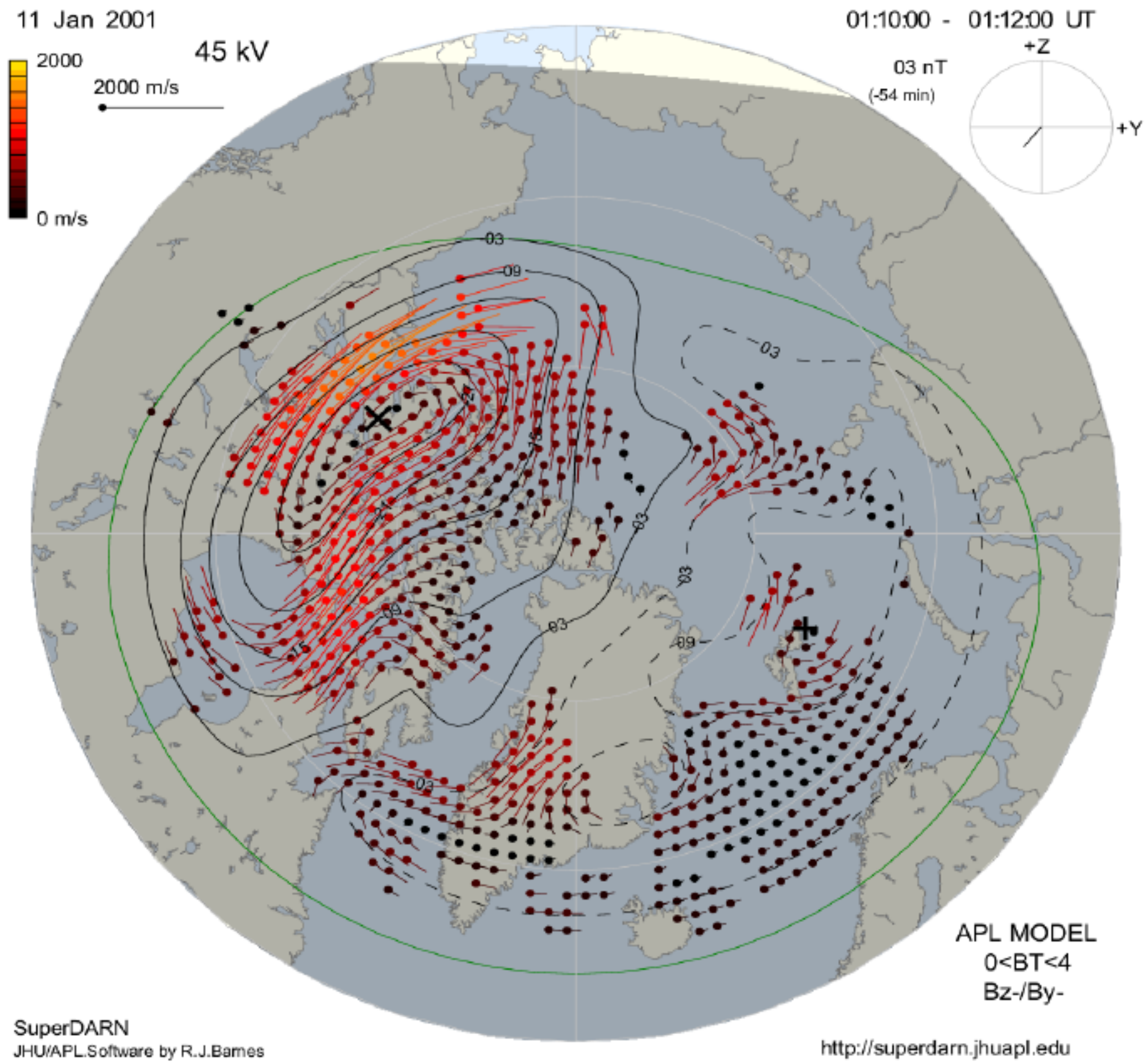


Northern Hemisphere
Southern Hemisphere
Magnetic coordinates
HOK
ADW
ADE
KSR
KOD
INV
PGR
CVW CVE
SAS
RKN
CLY
STO
PYK
HAN
GBR
KAP
FHW FHE
BKS
WAL
60°
50°
-40°
-50°
-60°
FIR
HAL
SAN
SPS
MCM
SYE SYS
DCE
ZHO
UNW
TIG
KER

SuperDARN data



SuperDARN data



The week ahead

- The week is divided up into morning lectures and afternoon group work.
- The lectures will take you through the basics of radar, ISR theory, pulse coding, data analysis and fitting, and data interpretation. Some topics will be iterated to give different perspectives and review material.
- Experiments will be designed on Monday and run that night at the MIT Haystack Observatory.
- On Monday night or Tuesday morning, your group will have the opportunity to go to the radar site and observe your experiment being run.
- Data will be delivered on Tuesday afternoon and the rest of the week's group work will be used to analyze the results.
- Each group will present results from their experiments on Friday morning.
- Now it's time for a group picture outside!

Literature

- Brekke, A.: Physics of the Upper Atmosphere, John Wiley & Sons, 1997.
- Hunsucker, R. D. and J.K. Hargreaves, The High-Latitude Ionosphere and its Effects on Radio Propagation, Cambridge University Press, 2003
- Kelley, M. C.: The Earth's Ionosphere, Academic Press, 1989
- H. Risbeth and O. K. Garriot: Introduction to Ionospheric Physics, Academic Press, 1969
- Hargreaves, J. K., The solar-terrestrial environment, Cambridge University Press, 1992.