Ionospheric and Magnetospheric studies with incoherent scatter radars

Dr. Anja Strømme

EISCAT Scientific Association

Currently at

SRI International, Menlo Park, CA USA

Outline

- The Sun-Earth environment and some useful terms and parameters
- Conditions for “Incoherent” Scattering
- Conditions for “Coherent” Scattering
- Standard operation for EISCAT
- Scientific problems for the different altitude regions
- What else - what new?

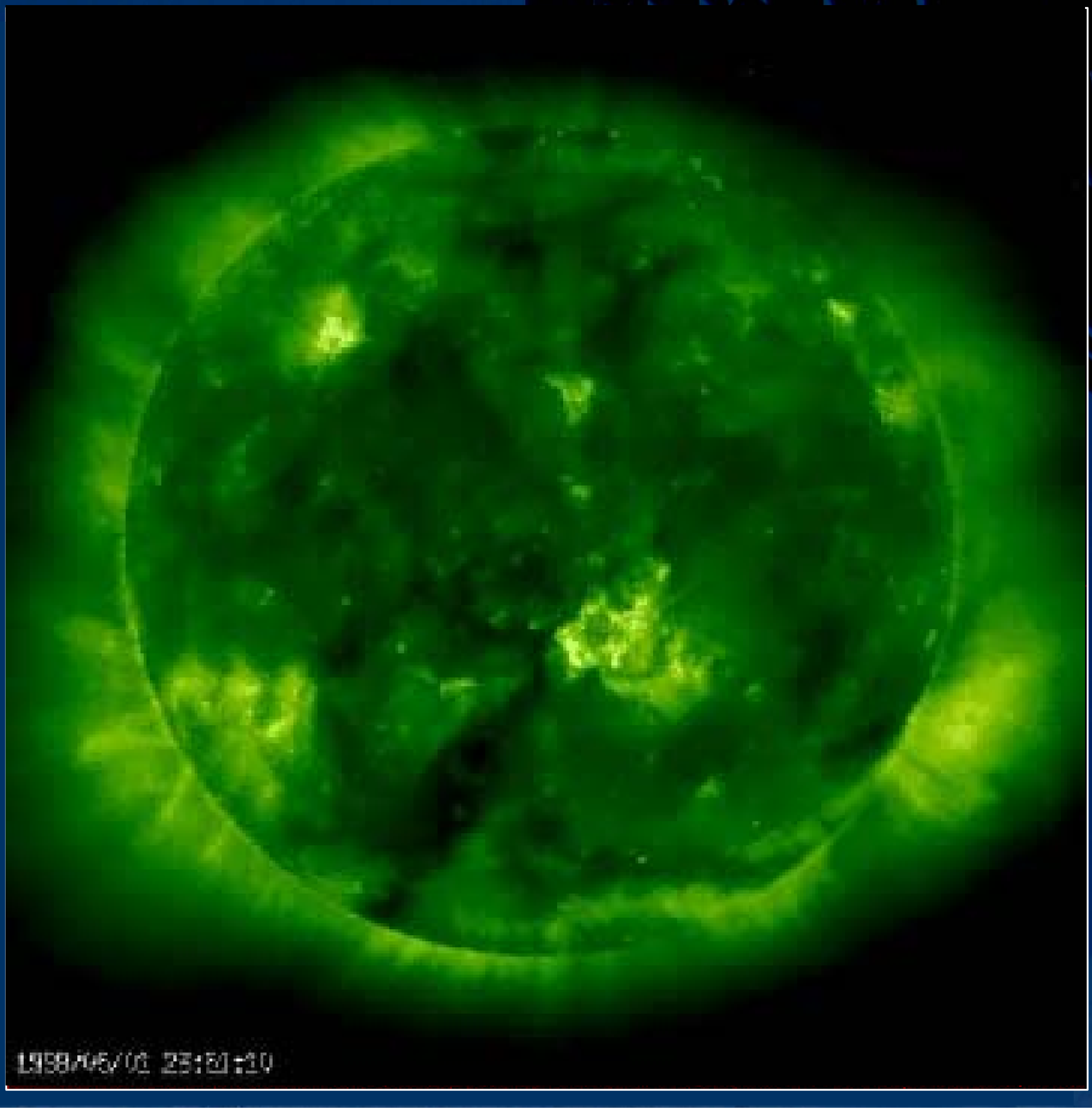
The Sun today…

SOHO-MDI Intensity gram from Stanford University Solar Group

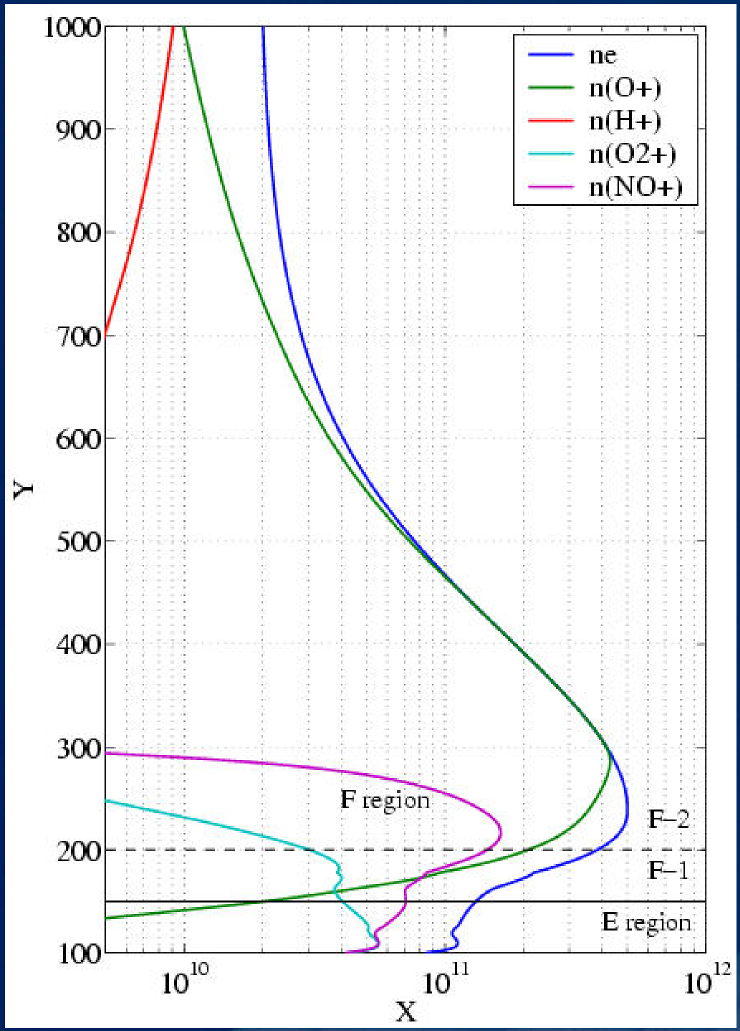
SOHO Extreme ultraviolet Imaging Telescope (EIT) He II 304 Å image from NASA Goddard Space Flight Center

Yohkoh Soft X-ray Telescope (SXT) images from the Hiraiso Solar Terrestrial Research Center/CRL (Japan)

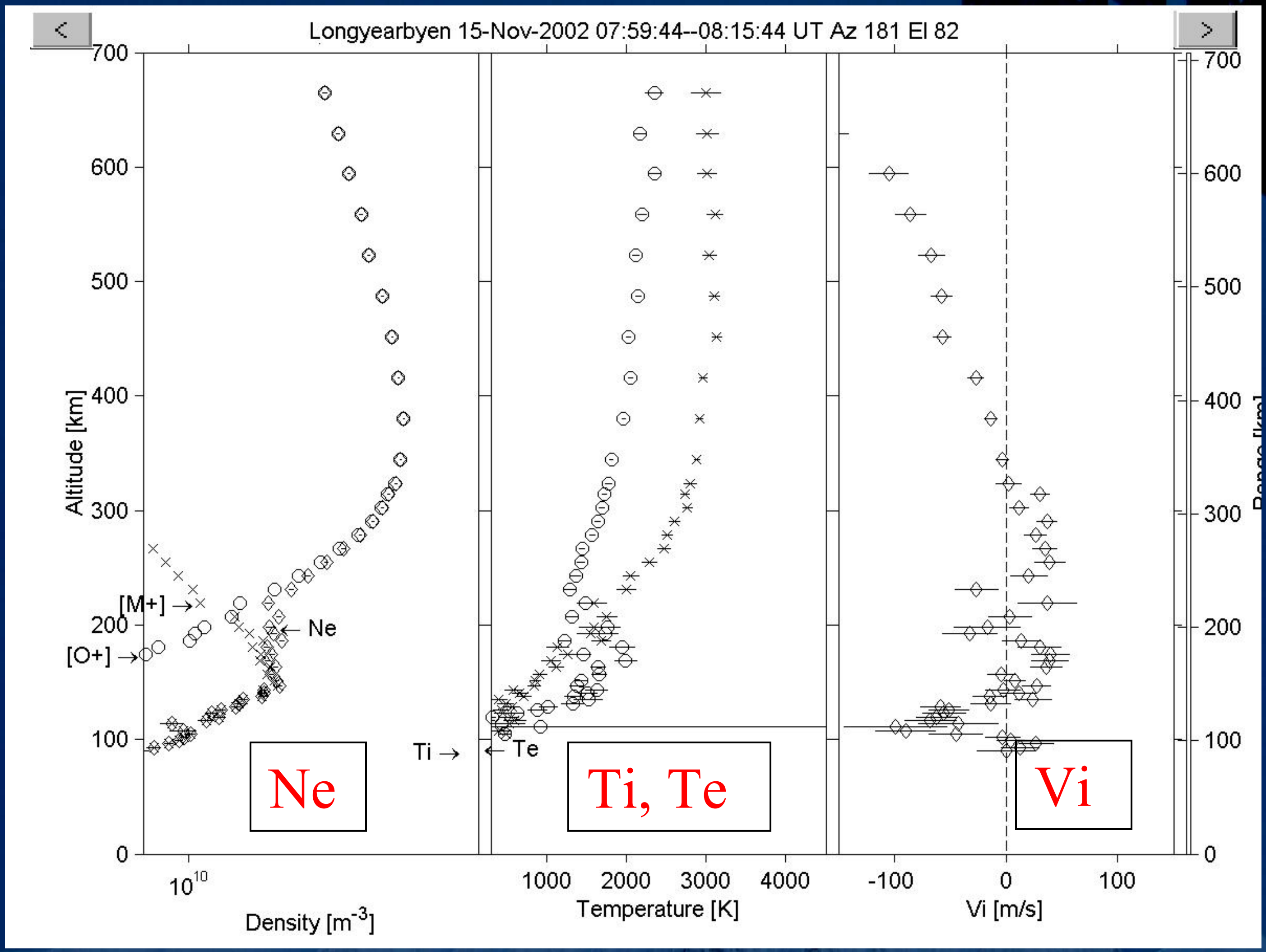
SOHO Extreme ultraviolet Imaging Telescope (EIT) Fe XII 195 Å image from NASA Goddard Space Flight Center (movie)



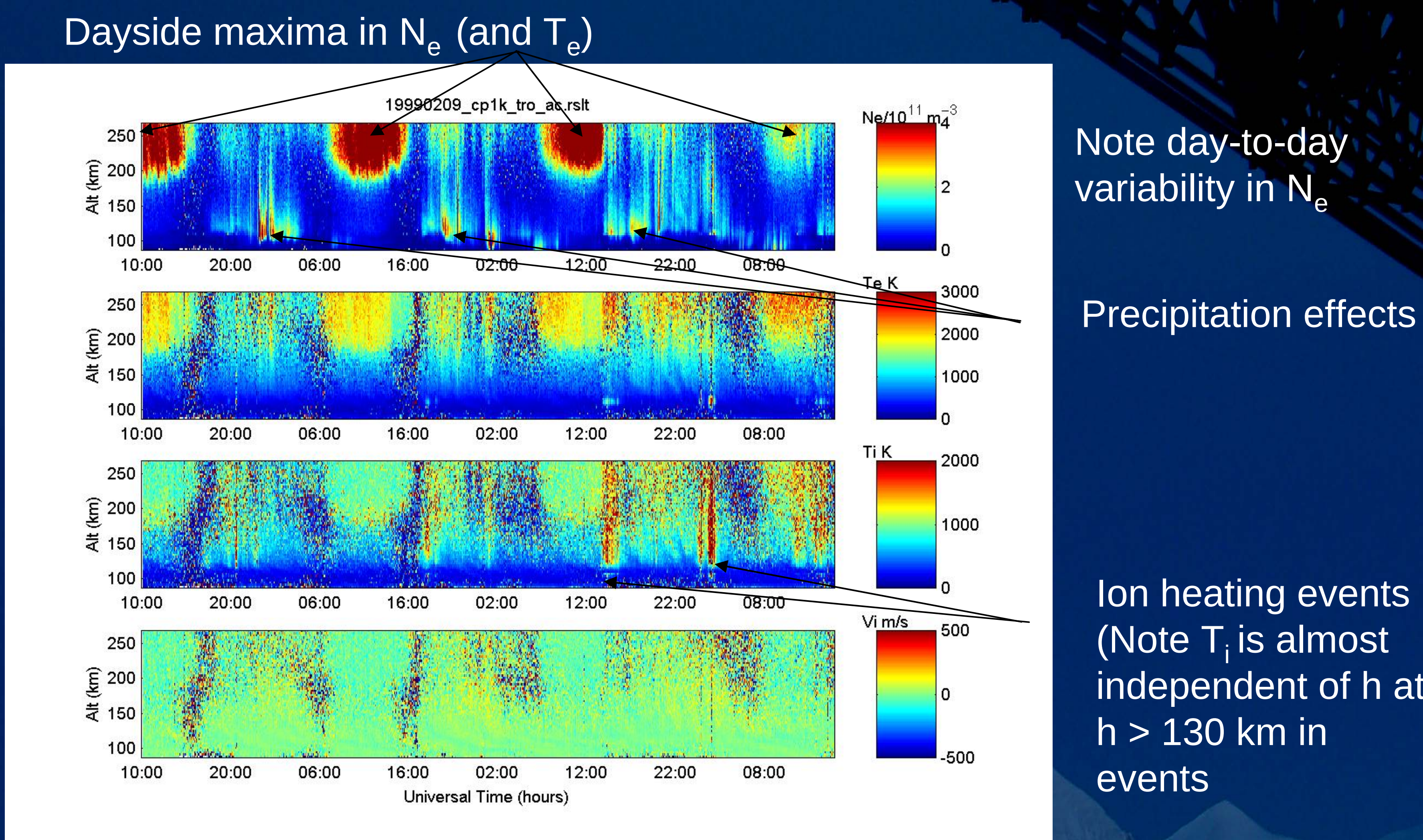
Composition



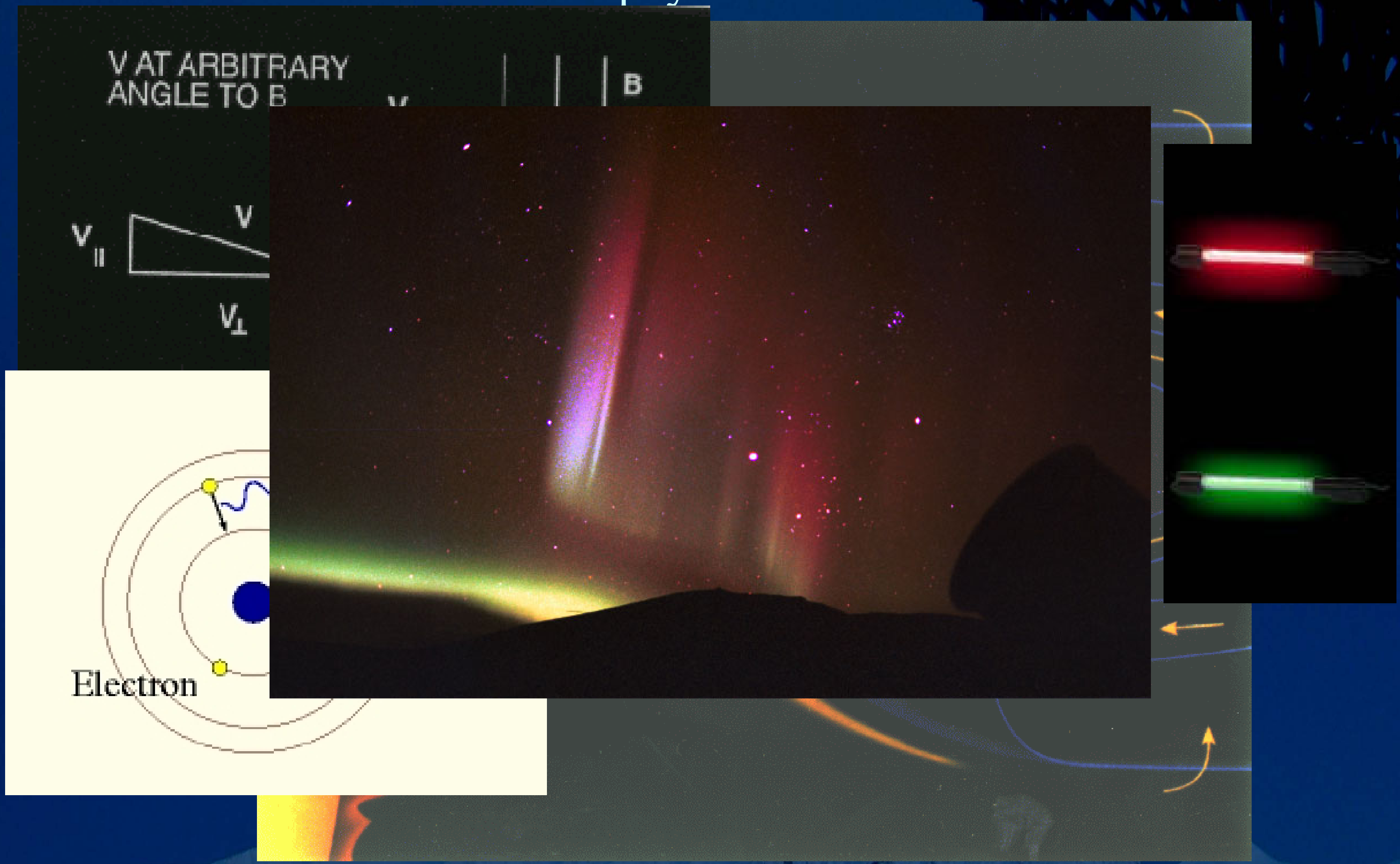
Ionospheric profiles - ESR data



Typical parameter plot

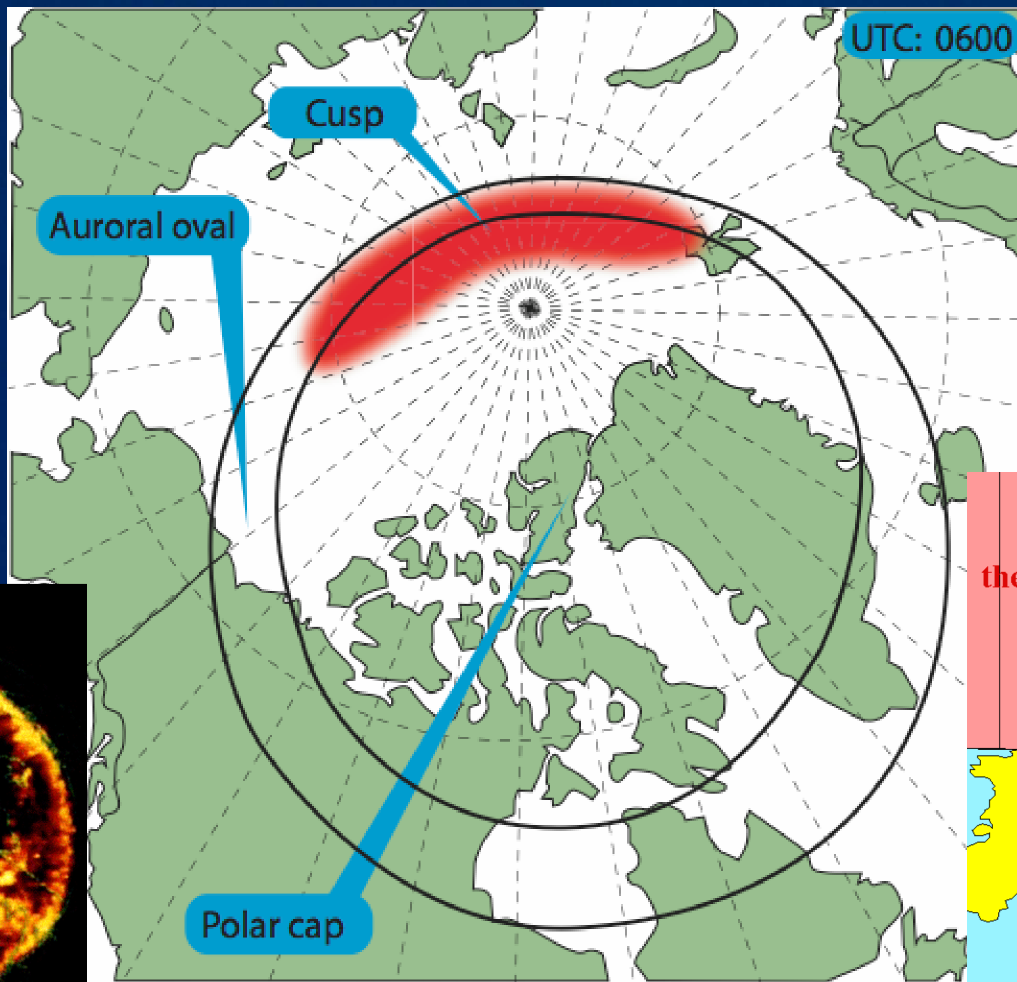


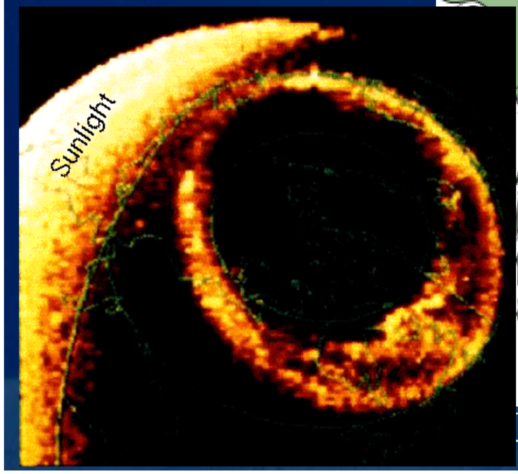
At high latitudes electron (and proton) with solar wind origin creates additional ionization, seen as aurora borealis/australis dispays

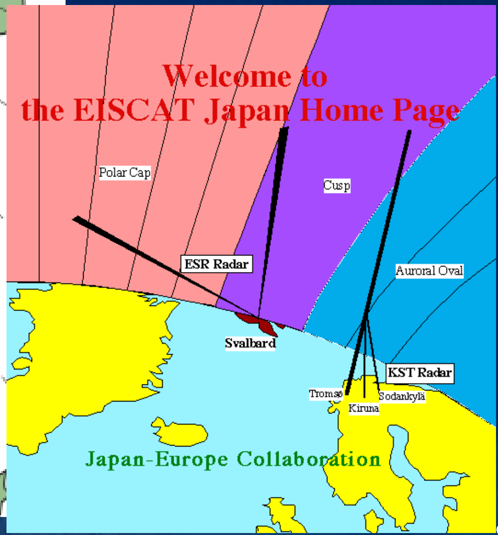


High latitudes are different

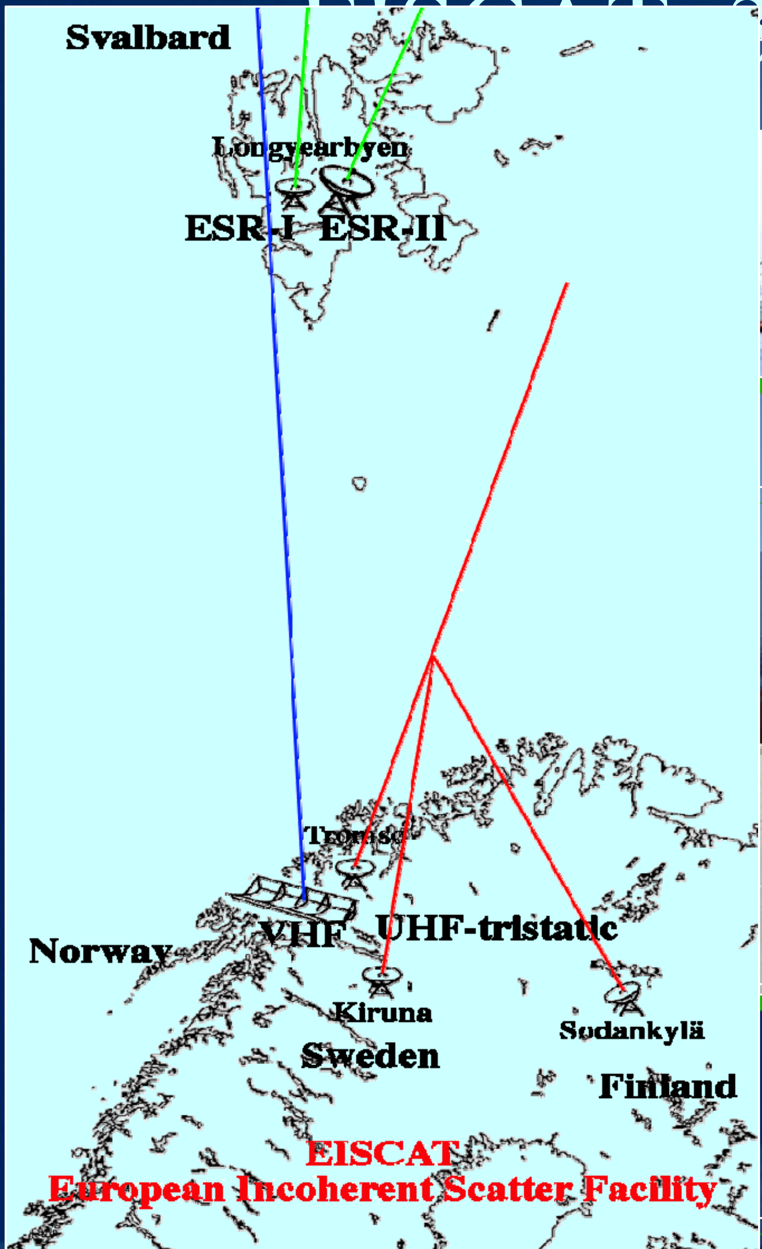
QuickTime™ and a
GIF decompressor
are needed to see this picture.

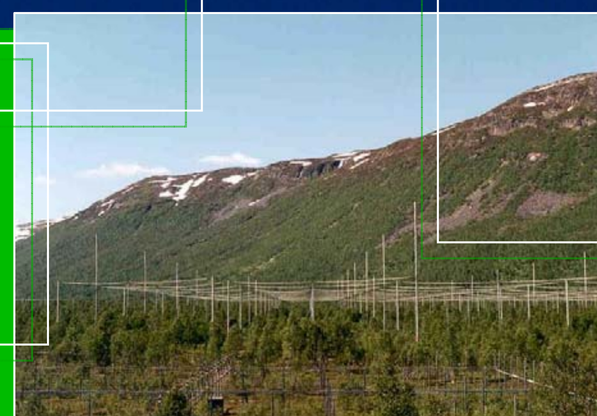




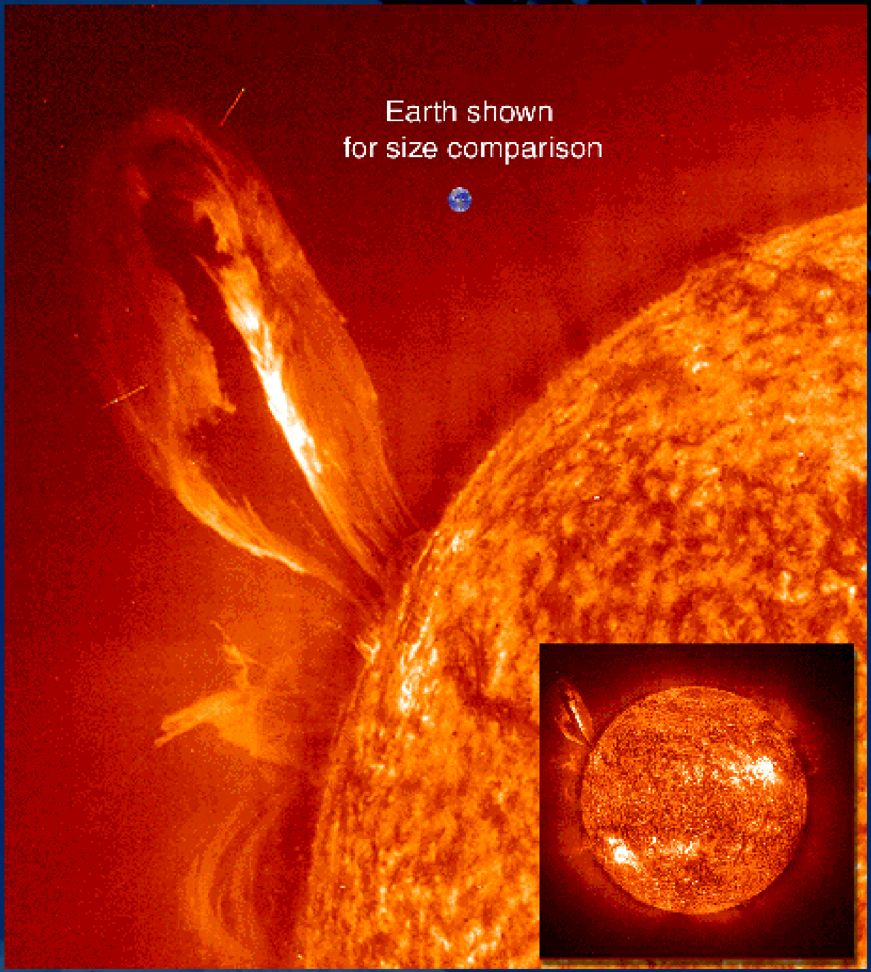


EISCAT: 3 IS Radars + Heater



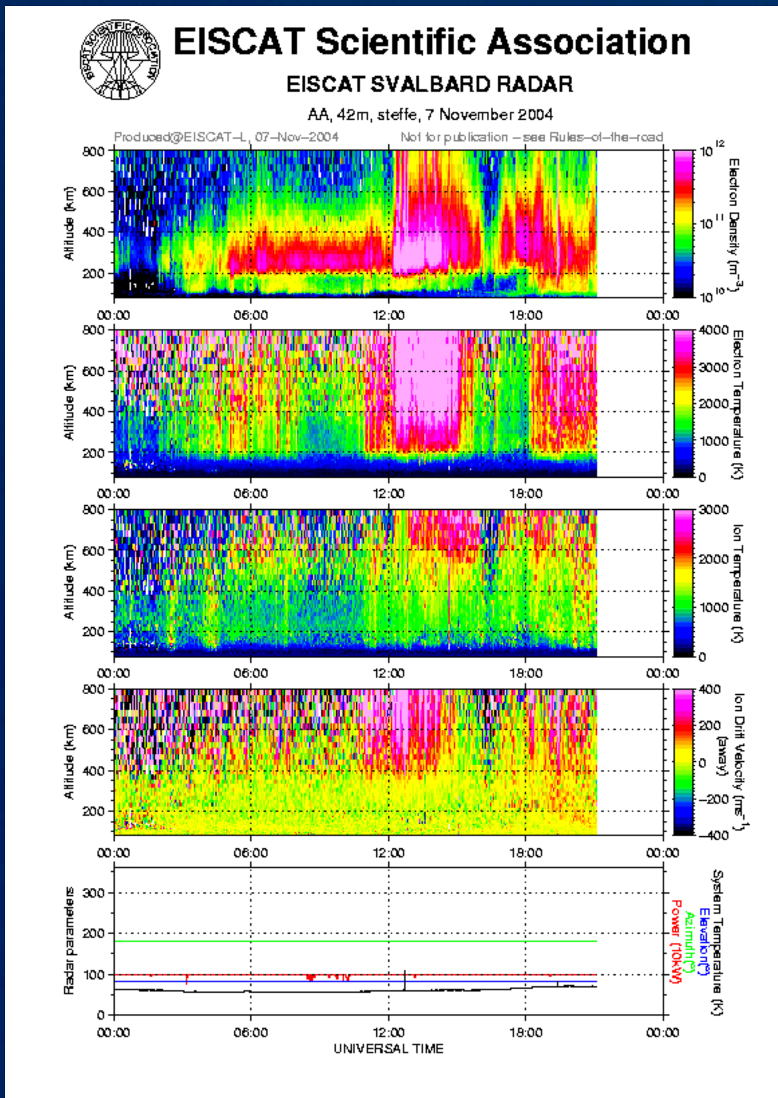


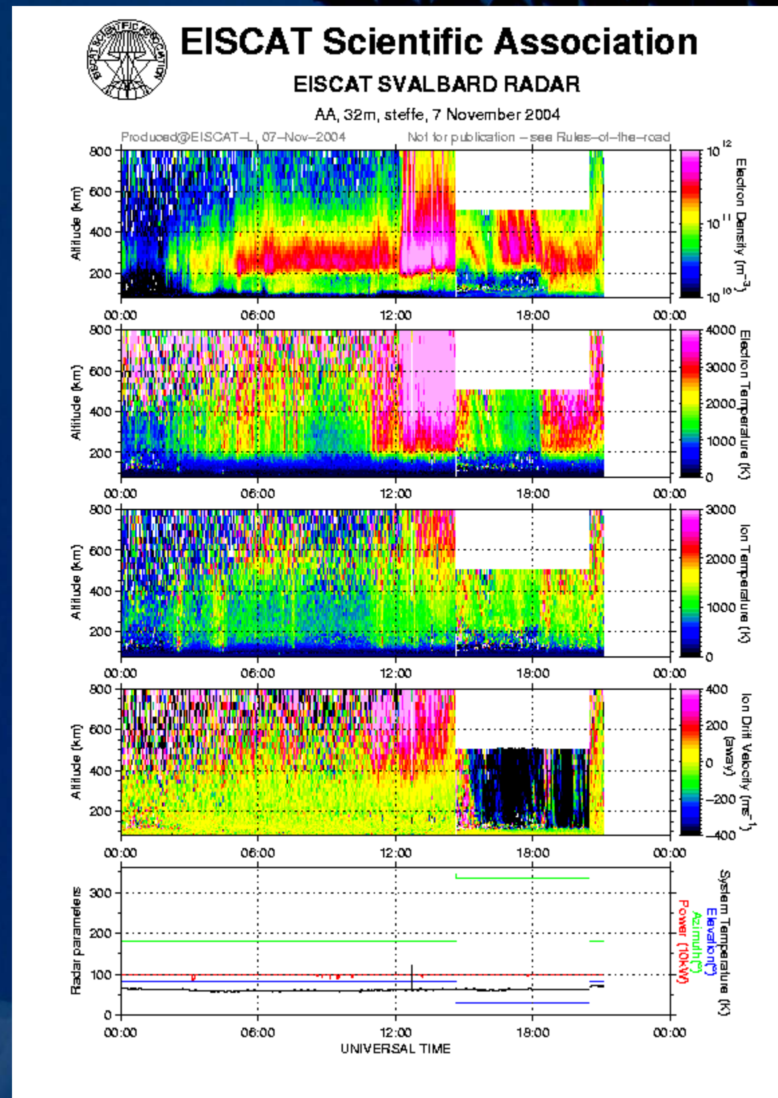
The Sun-Earth environment



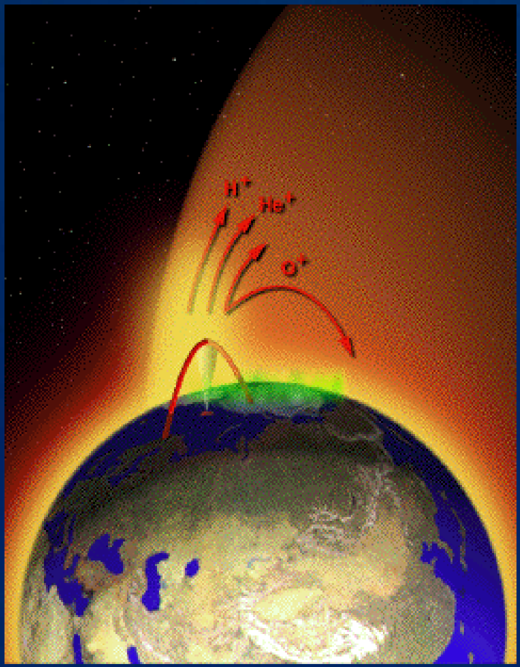
Coronal Mass Ejection (CME)

CME 7. November 2004



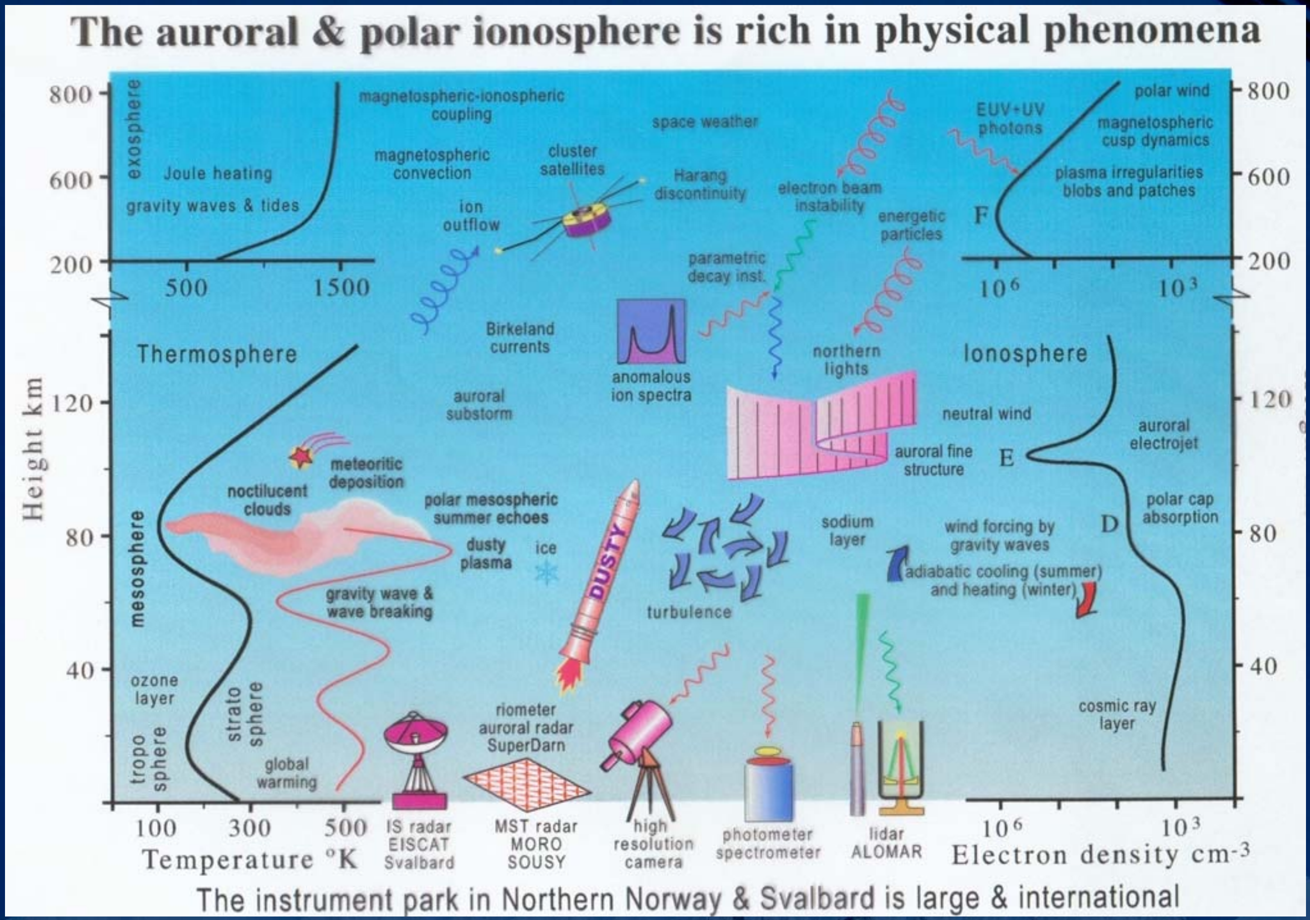


Ion outflow



Not a "one way" system - The interaction between the ionosphere and the magnetosphere is dynamic and complex

The complex ionosphere



Which parameters are varying, and how does that affect matters?

The radar equation

$$P_r = \frac{C c_0 G \lambda^2}{2} \frac{P_t \tau_p}{r^2} \frac{\sigma_e n_e(r)}{(1+(k\lambda_D)^2)(1+(k\lambda_D)^2+T_r)}$$

C: System constant

c_0: Speed of light

G: Gain

λ: Radar wavelength

P_t: Transmitted power

τ_p: Pulse length

σ_e: Scattering cross section of one electron

$n_e(r)$: Electron density

r: Range

k: Wave vector

λ_D: Debye length

$T_r=T_e/T_i$: Temperature ratio

The radar equation

$$P_r = \frac{C c_0 G \lambda^2}{2} \frac{P_t \tau_p}{r^2} \frac{\sigma_e n_e(r)}{(1 + (k\lambda_D)^2)(1 + (k\lambda_D)^2 + T_r)}$$

Predefined by nature

The radar equation

$$P_r = \frac{C c_0 G \lambda^2}{2} \frac{P_t \tau_p}{r^2} \frac{\sigma_e n_e(r)}{(1 + (k\lambda_D)^2)(1 + (k\lambda_D)^2 + T_r)}$$

Predefined by nature

Predefined by radar system

The radar equation

$$P_r = \frac{C c_0 G \lambda^2}{2} \frac{P_t \tau_p}{r^2} \frac{\sigma_e n_e(r)}{(1+(k\lambda_D)^2)(1+(k\lambda_D)^2+T_r)}$$

Predefined by nature

Predefined by radar system

Varying with experiment

The radar equation

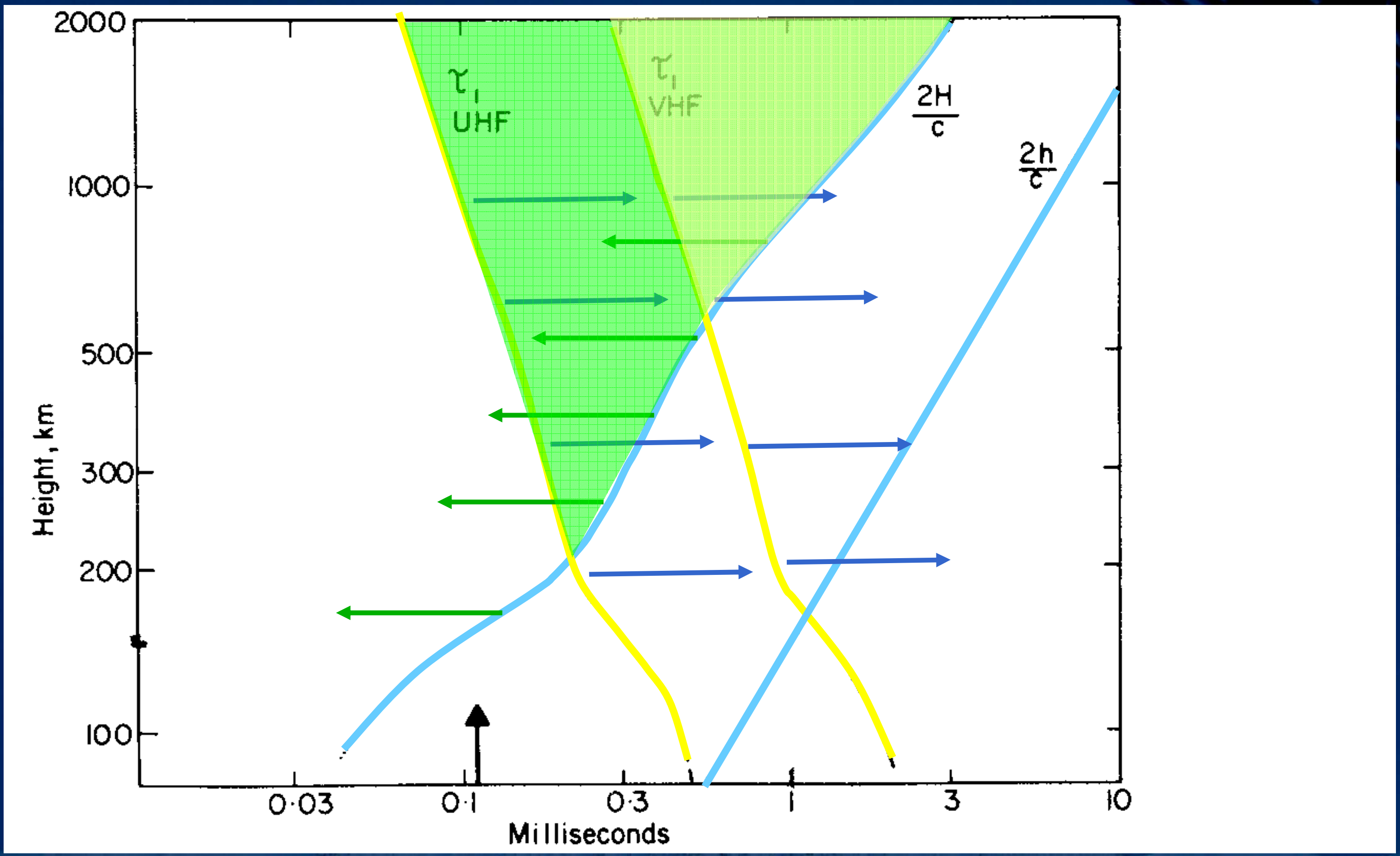
$$P_r = \frac{C c_0 G \lambda^2}{2} \frac{P_t \tau_p}{r^2} \frac{\sigma_e n_e(r)}{(1 + (k\lambda_D)^2)(1 + (k\lambda_D)^2 + T_r)}$$

- Predefined by nature
- Predefined by radar system
- Varying with experiment
- Varying with altitude and conditions

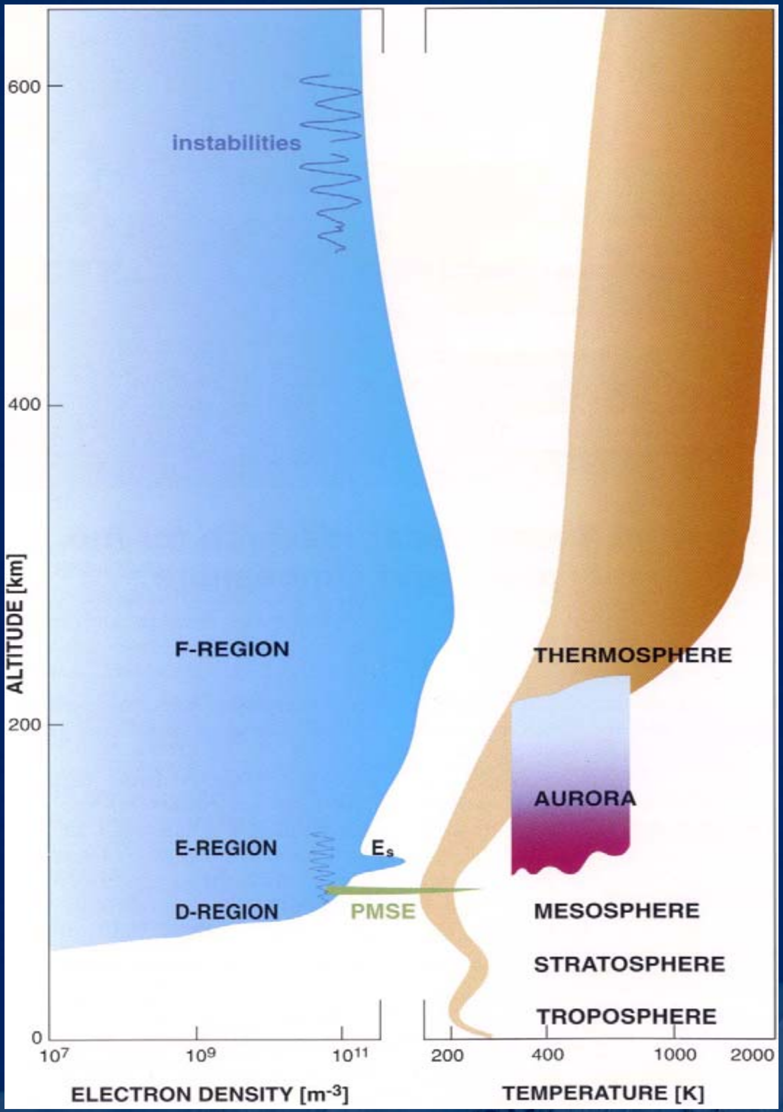
Constrains

- Pulse length
- Degree of ionisation
- Distance
  - Long range R^2 factor
  - Short range Tx/Rx protector and ground clutter
- Debye length
- Bragg condition?

Farley Diagram



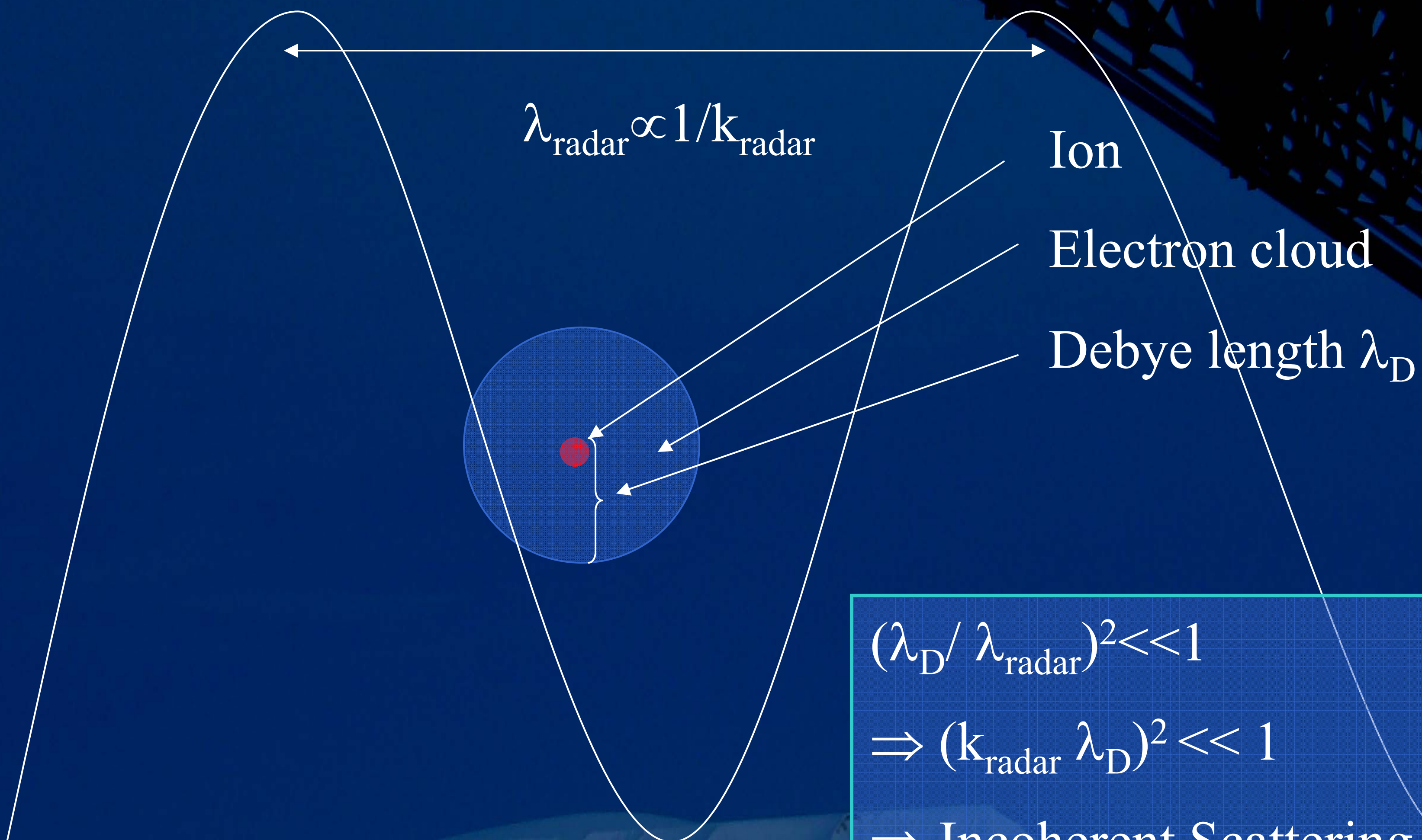
Debye length dependence



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

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

Debye cutoff

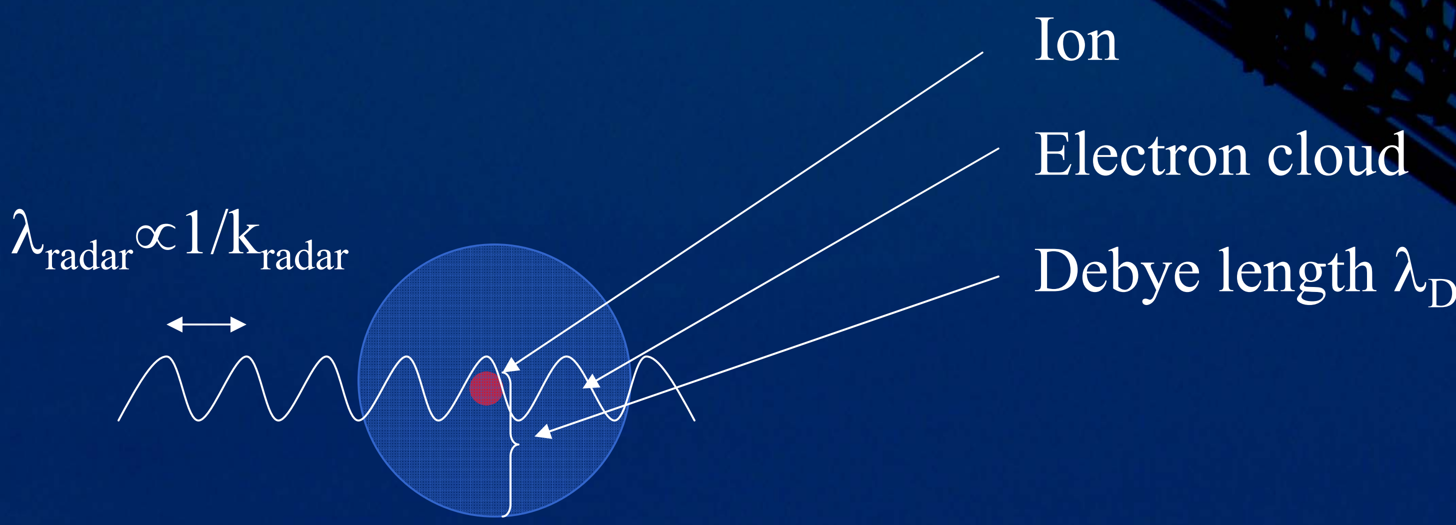


$(\lambda_D / \lambda_{radar})^2 << 1$

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

$\Rightarrow$ Incoherent Scattering

Debye cutoff

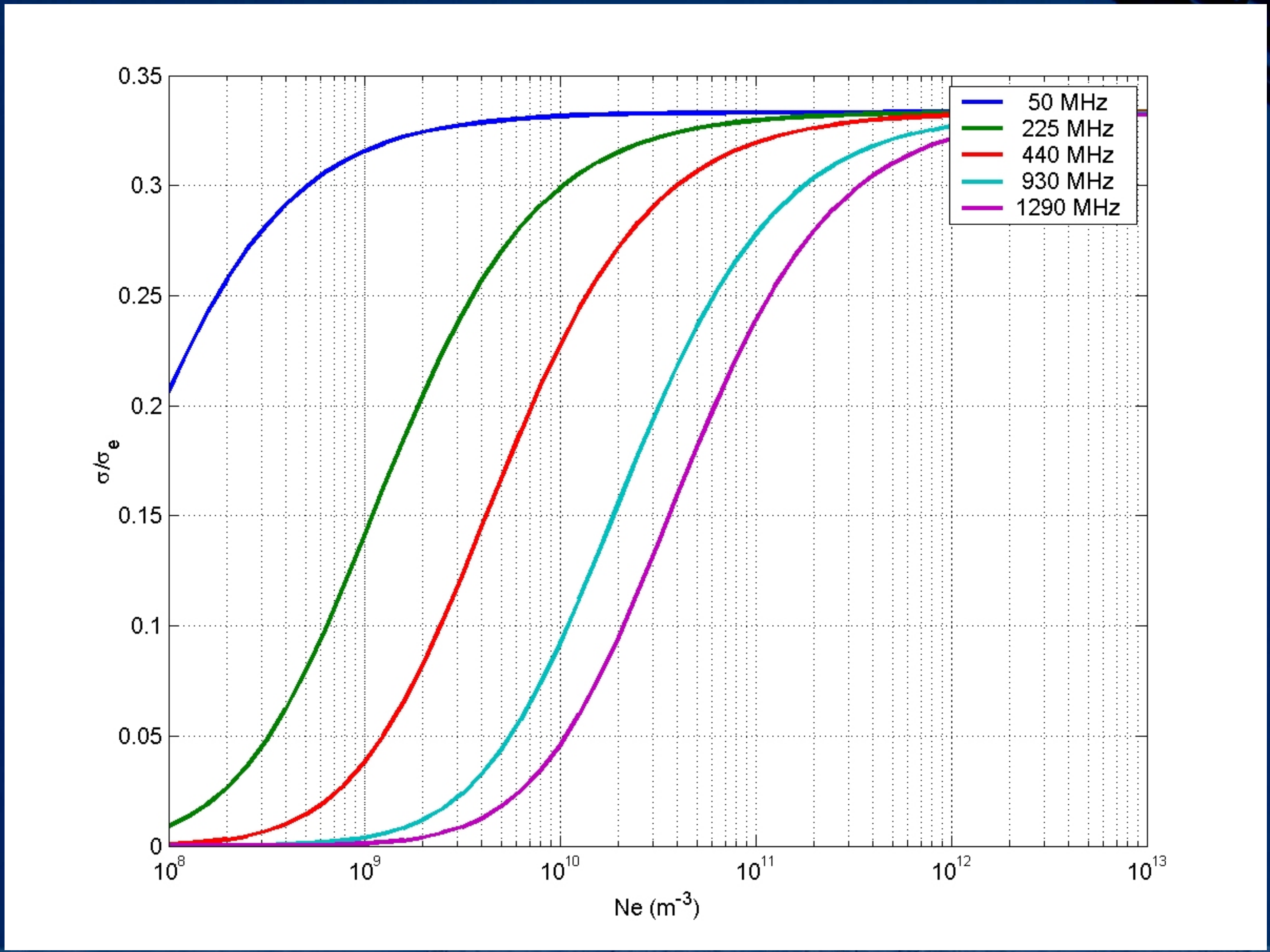


$(\lambda_D / \lambda_{radar})^2 > 1$

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

$\Rightarrow$ Not Incoherent Scattering

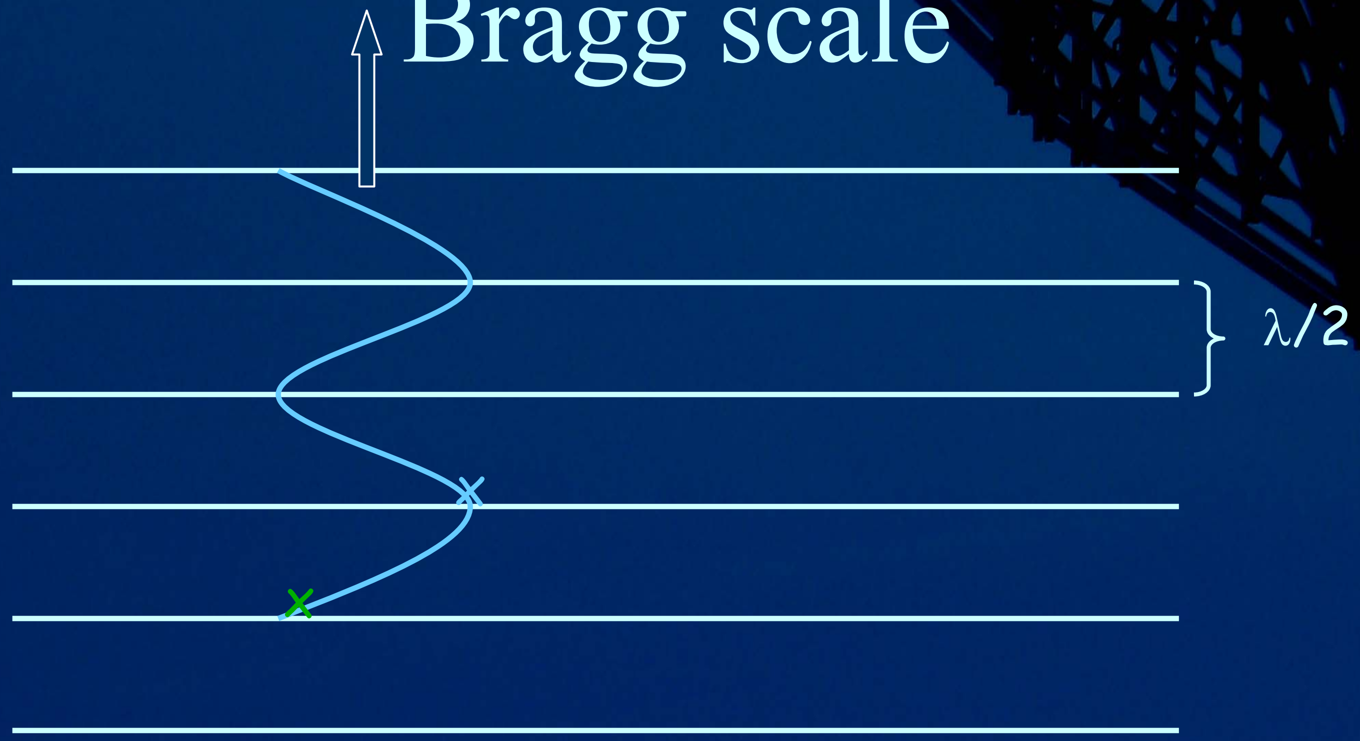
Debye Length Dependencies



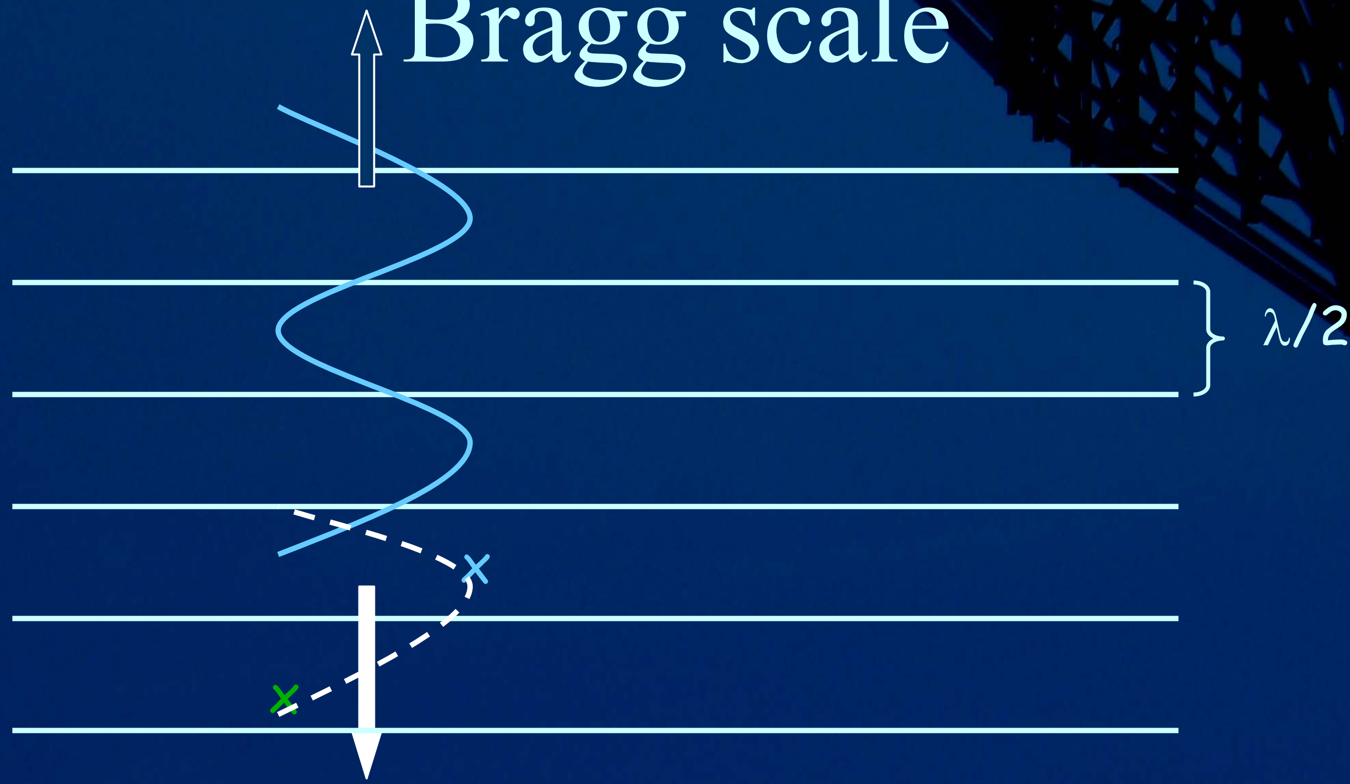
Parameters
Ti: 1000 K
Te: 2000 K

How about "coherent" scattering?

Bragg scale

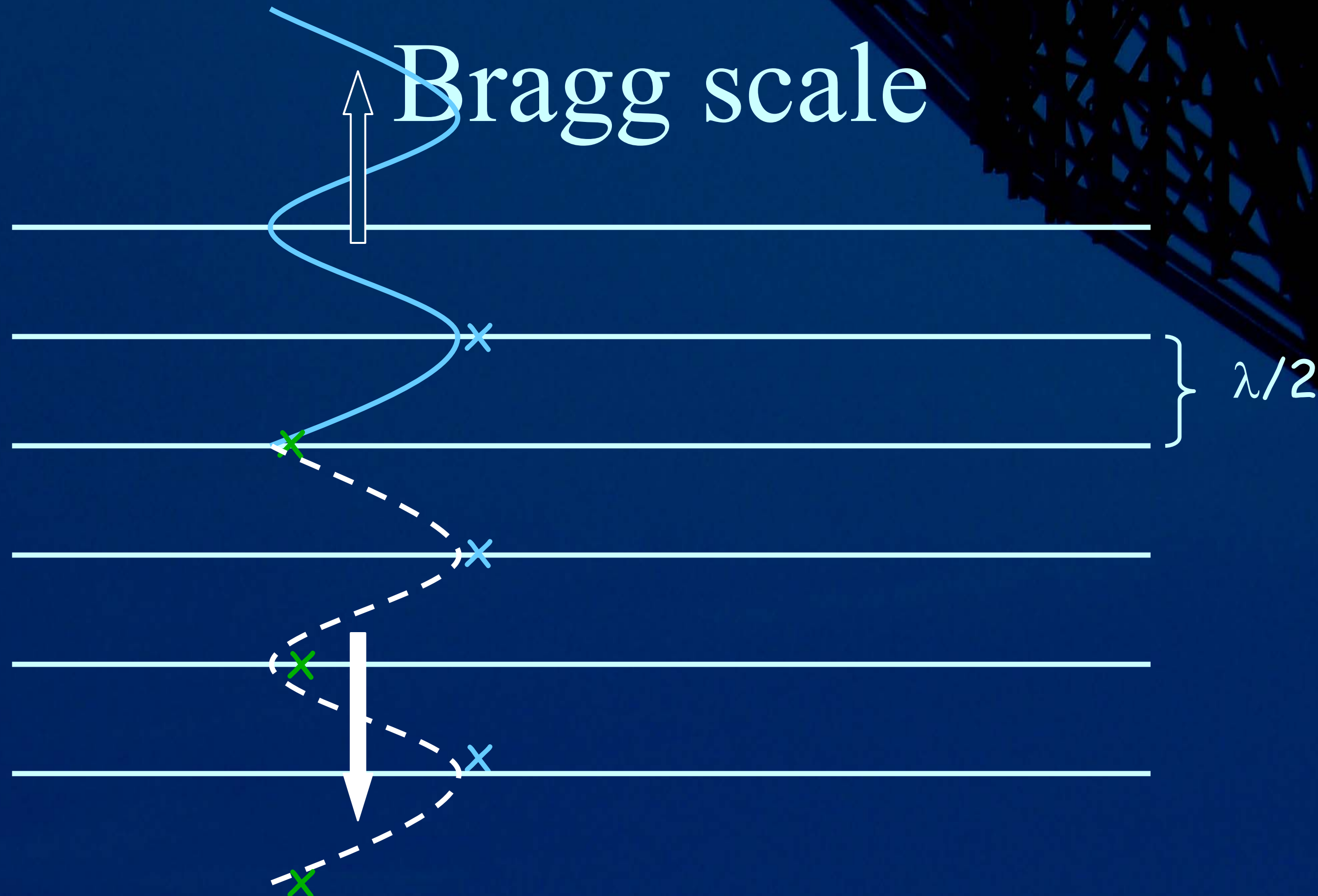


Bragg scale



Bragg scale

Bragg scale



Bragg scale

The Bragg condition for backscatter means that a radar can only observe structures in the refractive index with size close to the half radar wavelength.

Bragg condition

- The Bragg condition for backscatter means that a radar can only observe structures in the refractive index with size close to the half radar wavelength
- This is the case both for the thermal ion acoustic and Langmuir waves causing the “normal” double humped spectra - and for coherent structures and turbulent spectra

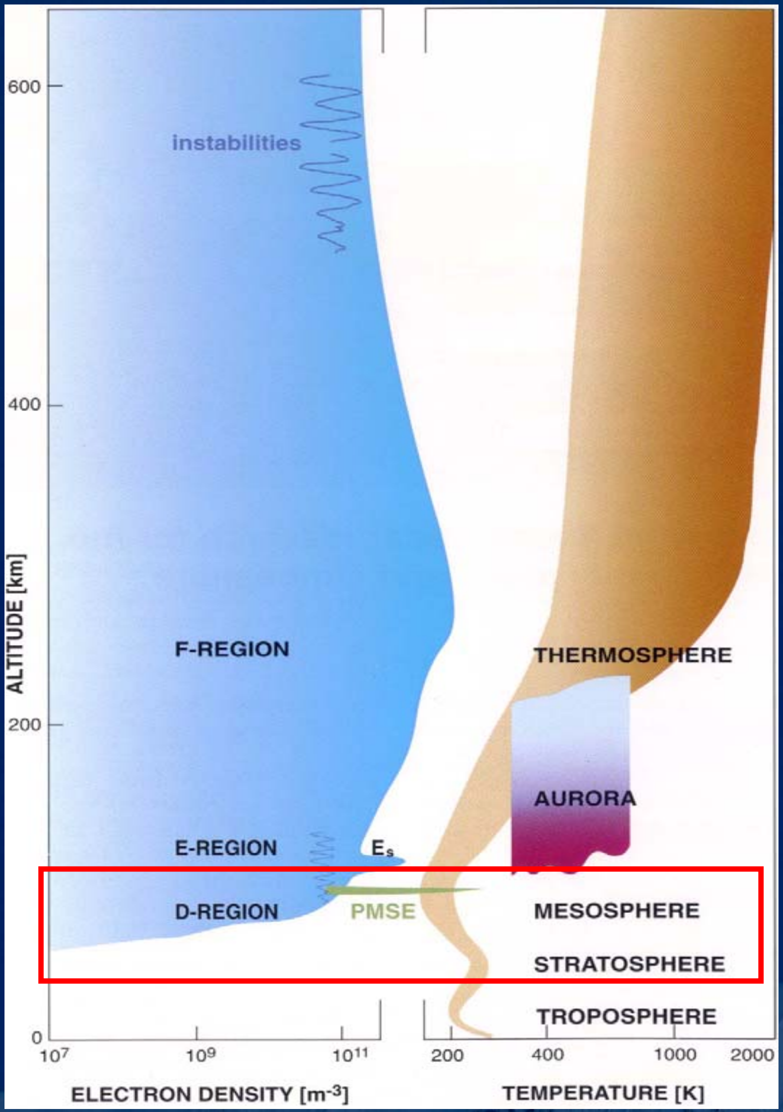
EISCAT experiments

- EISCAT has in place experiments and code sets to study all these different regions and conditions
- Important to pick the right one for the phenomenon one wants to study

D-region

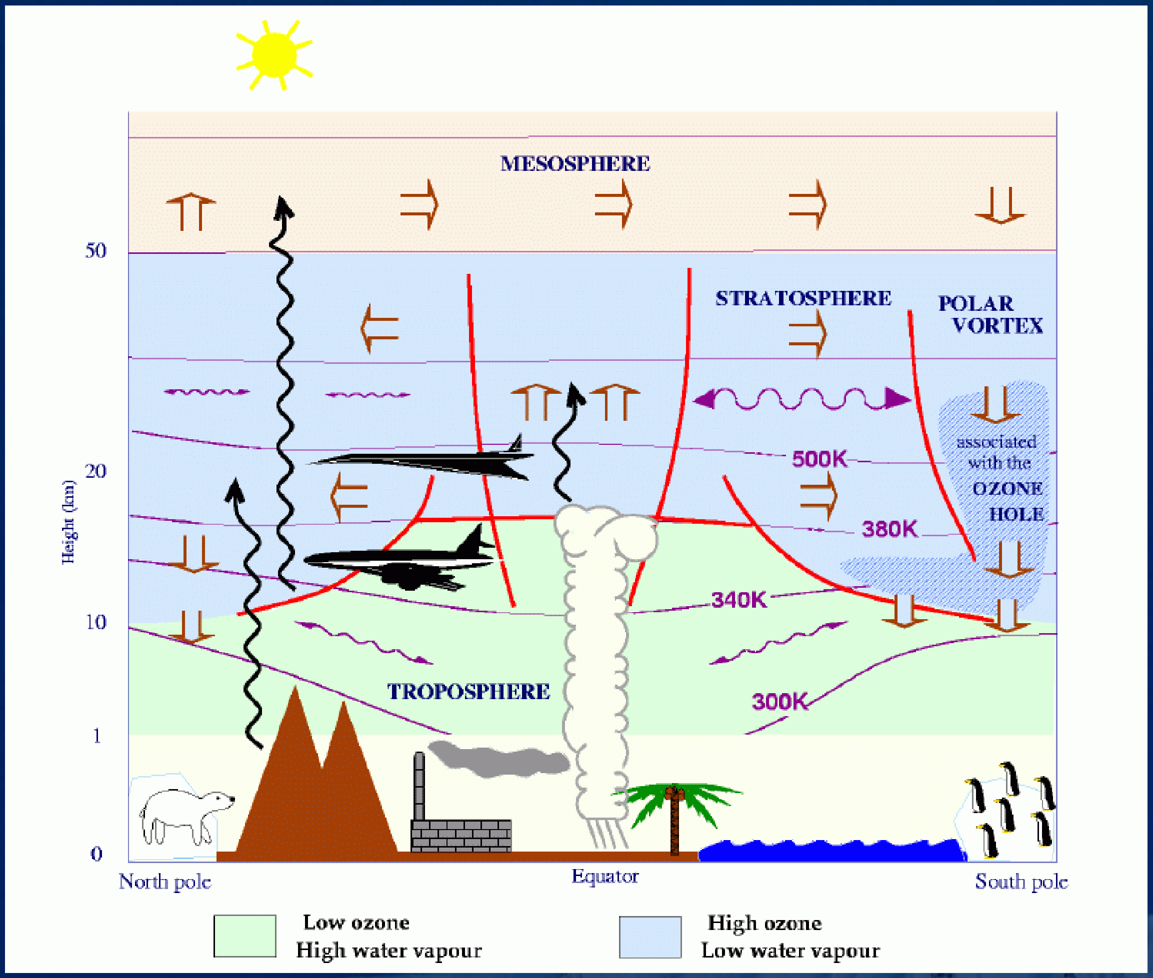
- Altitude range between ~70-100 km
- Very cold - specially in summer (mesopause)
- Generally low degree of ionization
- Affected by ground clutter
- Collision dominated single humped ion spectra
- Narrow spectral width - long correlation time
- Turbulent region due to breaking of gravity waves
- Region where to find Polar Mesospheric Summer Echoes (PMSE) and Polar Mesospheric Winter Echoes (PMWE)

D-region



600
400
200
0
ALTITUDE [km]
instabilities
F-REGION
E-REGION
E_s
D-REGION
PMSE
THERMOSPHERE
AURORA
MESOSPHERE
STRATOSPHERE
TROPOSPHERE
10^7
10^9
10^{11}
200
400
1000
2000
ELECTRON DENSITY [m^{-3}]
TEMPERATURE [K]

Circulation patterns



D-region

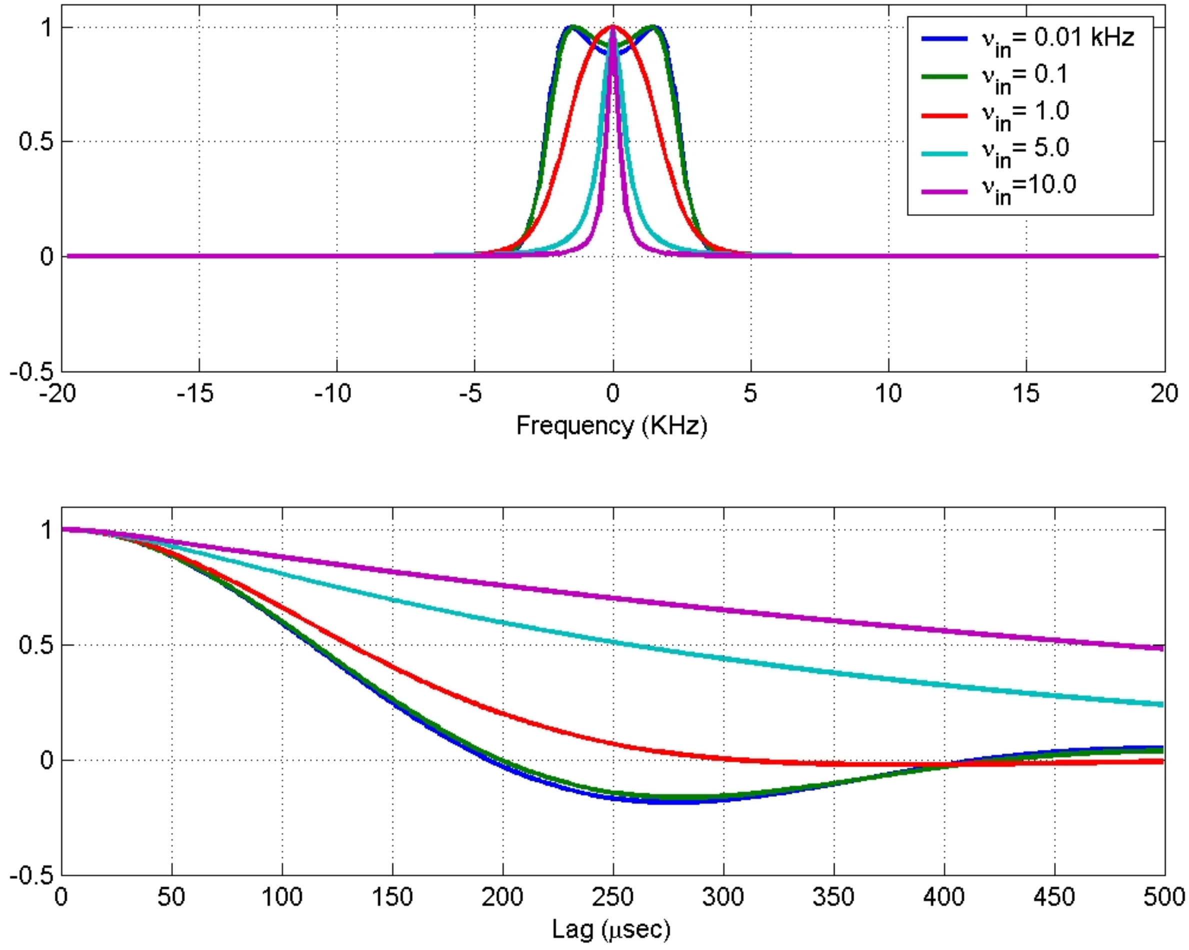
- Altitude range between ~70-100 km
- Very cold - specially in summer (mesopause)
- Generally low degree of ionization
- Affected by ground clutter
- Collision dominated single humped ion spectra
- Narrow spectral width - long correlation time
- Turbulent region due to breaking of gravity waves
- Region where to find Polar Mesospheric Summer Echoes (PMSE) and Polar Mesospheric Winter Echoes (PMWE)

ground clutter...

D-region

- Altitude range between ~70-100 km
- Very cold - specially in summer (mesopause)
- Generally low degree of ionization
- Affected by ground clutter
- Collision dominated single humped ion spectra
- Narrow spectral width - long correlation time
- Turbulent region due to breaking of gravity waves
- Region where to find Polar Mesospheric Summer Echoes (PMSE) and Polar Mesospheric Winter Echoes (PMWE)

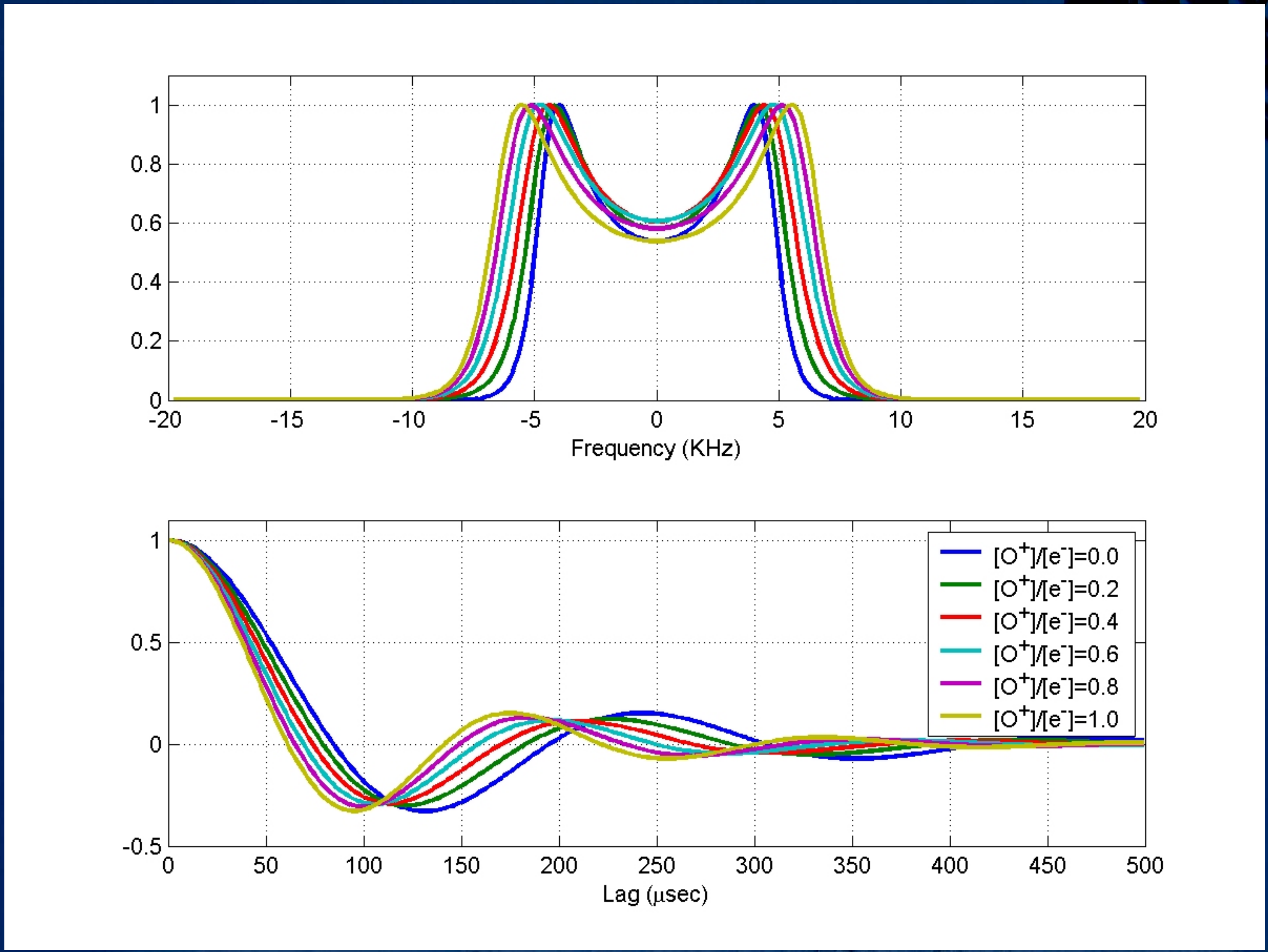
Ion-Neutral Collision Frequency



Parameters
Freq: 449 MHz
Ne: 10^{12} m^{-3}
Ti: 500 K
Te: 500 K
Comp: 100% NO^{+}

Craig Heinselmann

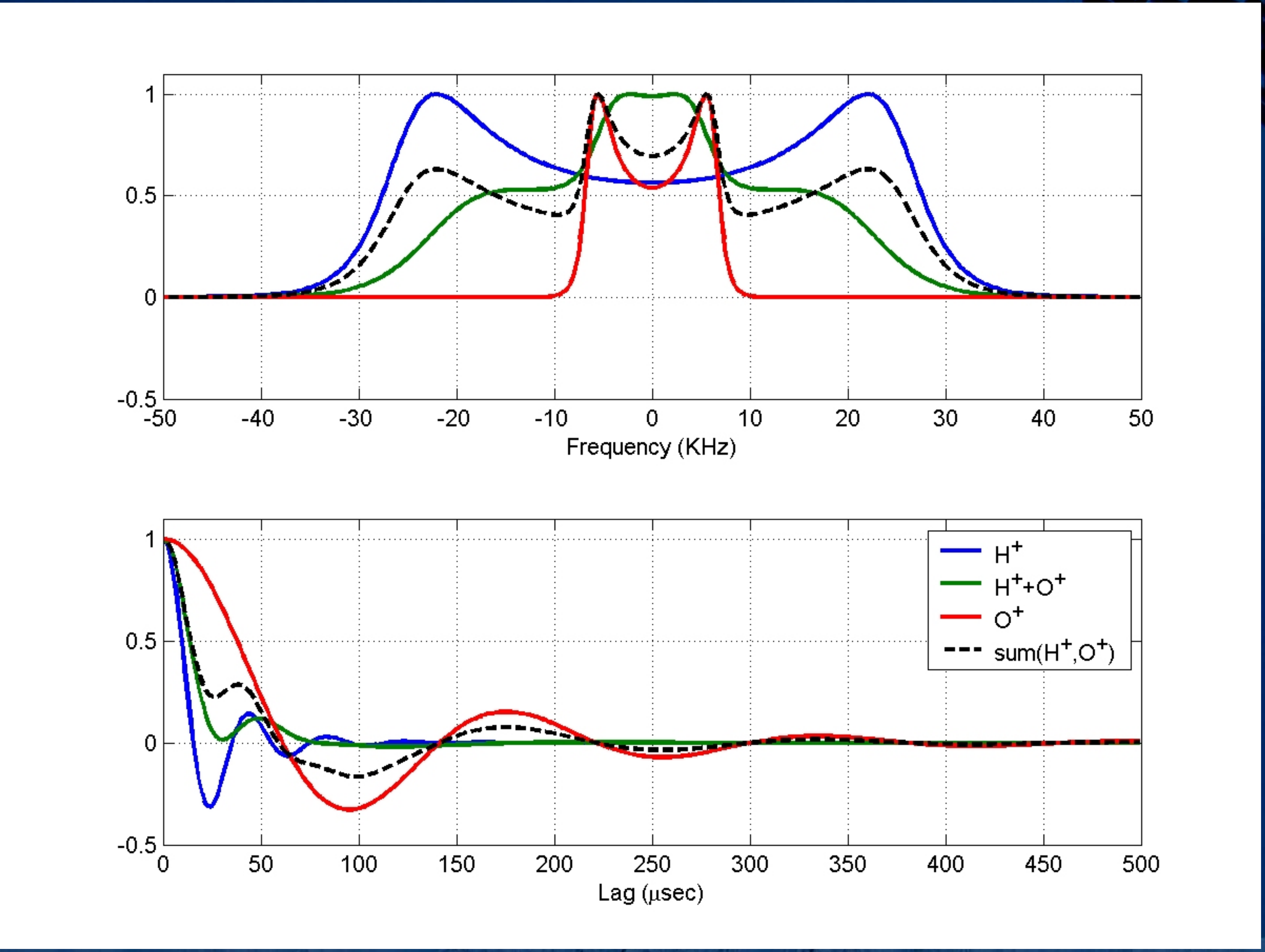
Ion Composition (O^+ vs. NO^+)



<u>Parameters</u>
Freq: 449 MHz
Ne: 10^{12} m^{-3}
Ti: 1500 K
Te: 3000 K
ν_{in}: 10^{-6} KHz

Craig Heinselmann

Ion Composition (O^+ vs. H^+)



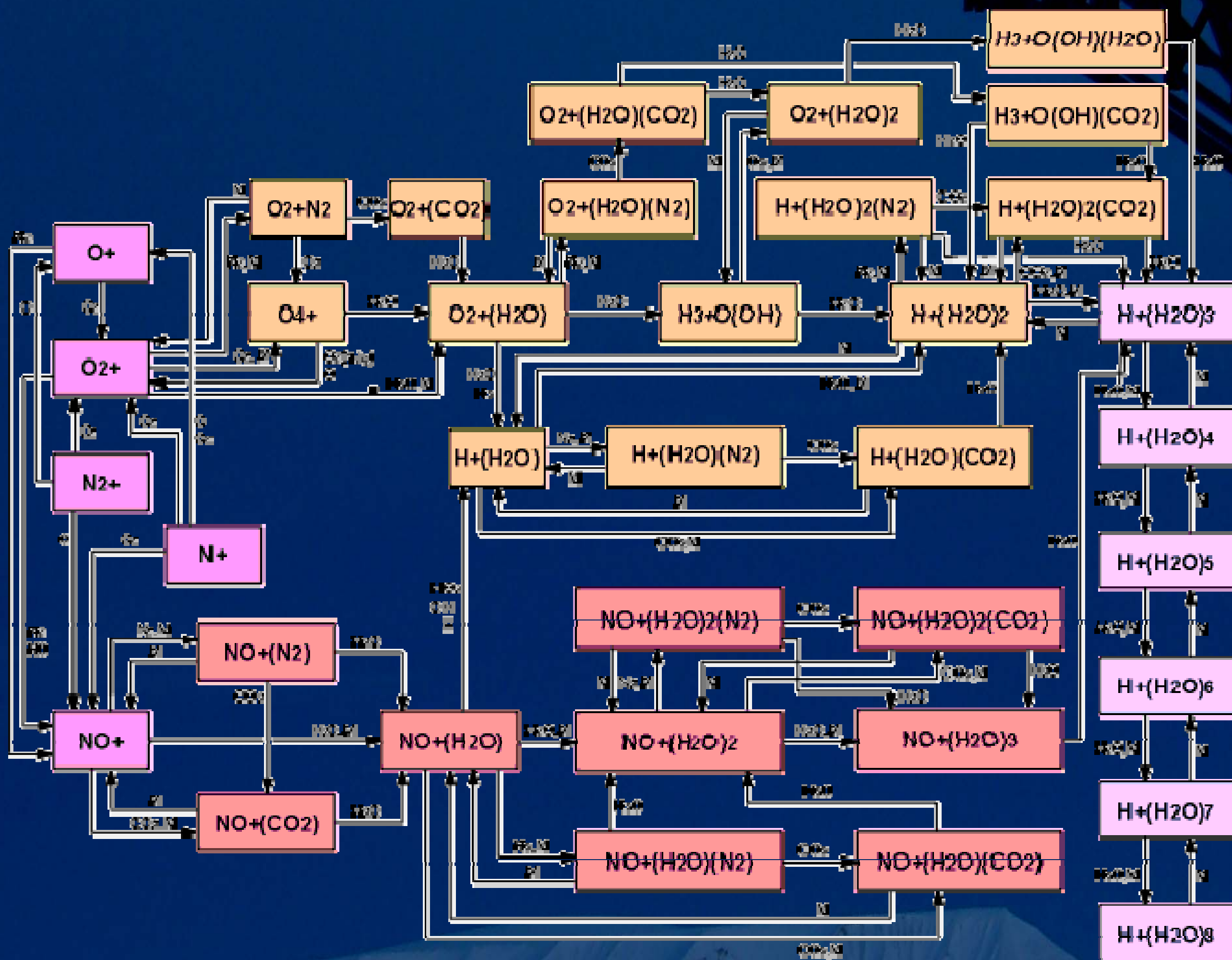
Parameters
Freq: 449 MHz
Ne: 10^{12} m^{-3}
Ti: 1500 K
Te: 3000 K
ν_{in}: 10^{-6} KHz

Craig Heinselmann

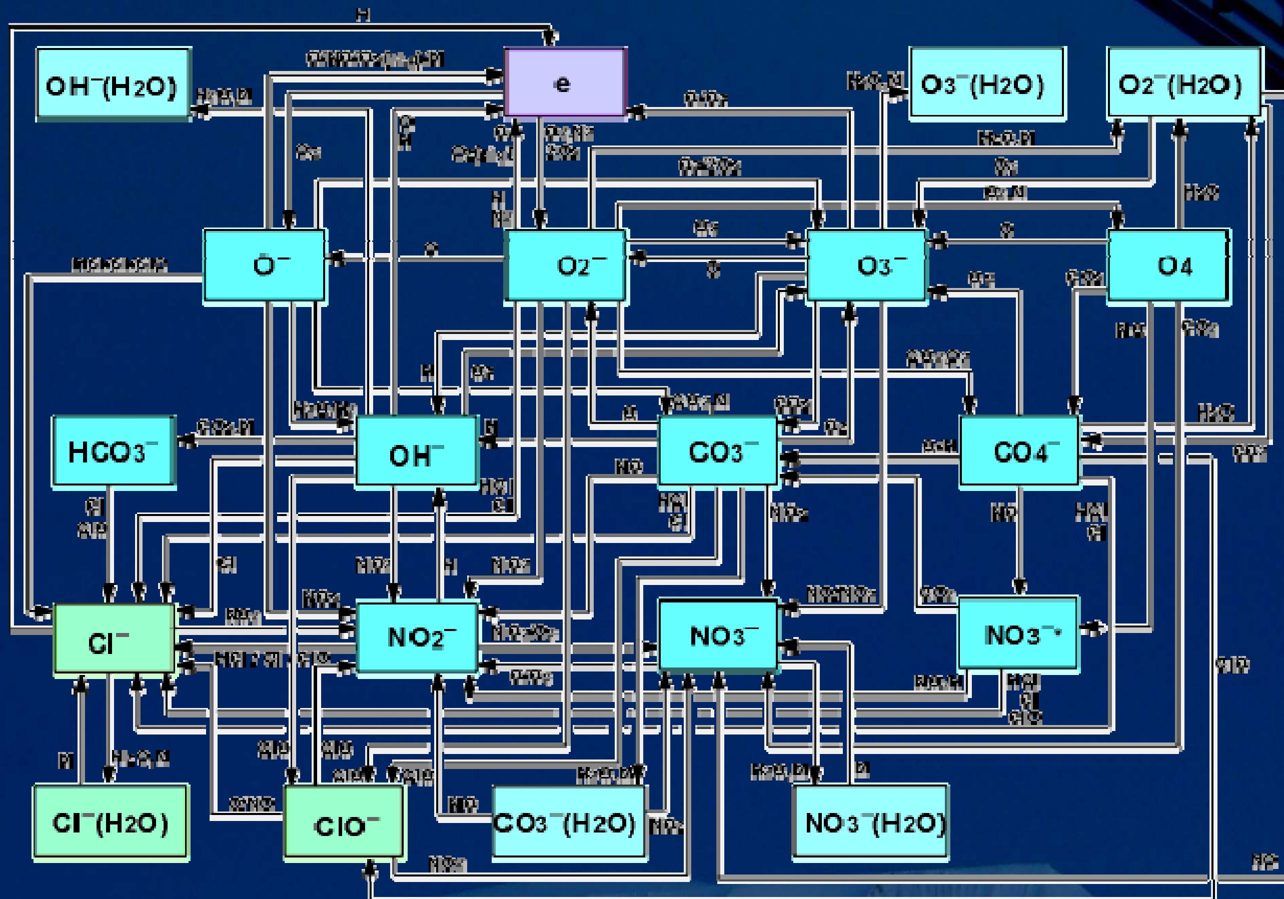
D-region - problem:

- The width of the ion spectrum in the D-region will vary both as a function of collision frequency and ion composition - need more info in order to draw anything but velocity from the thermal IS spectra

SIC - Positive Ion Chemistry



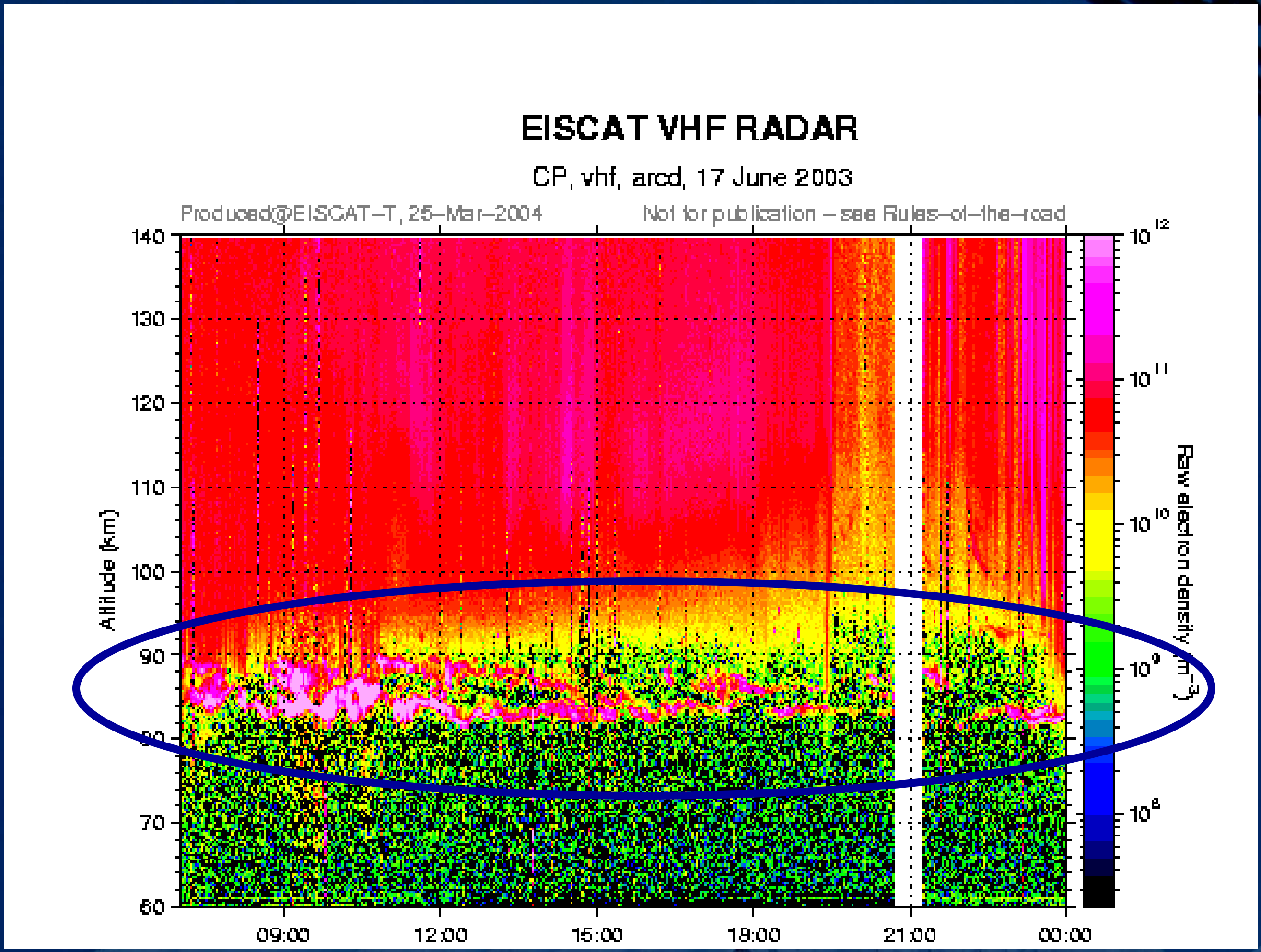
SIC - Negative Ion Chemistry



D-region

- Altitude range between ~70-100 km
- Very cold - specially in summer (mesopause)
- Generally low degree of ionization
- Affected by ground clutter
- Collision dominated single humped ion spectra
- Narrow spectral width - long correlation time
- Turbulent region due to breaking of gravity waves
- Region where to find Polar Mesospheric Summer Echoes (PMSE) and Polar Mesospheric Winter Echoes (PMWE)

Polar Mesospheric Summer Echoes - PMSE



PMSE / PMWE - when?

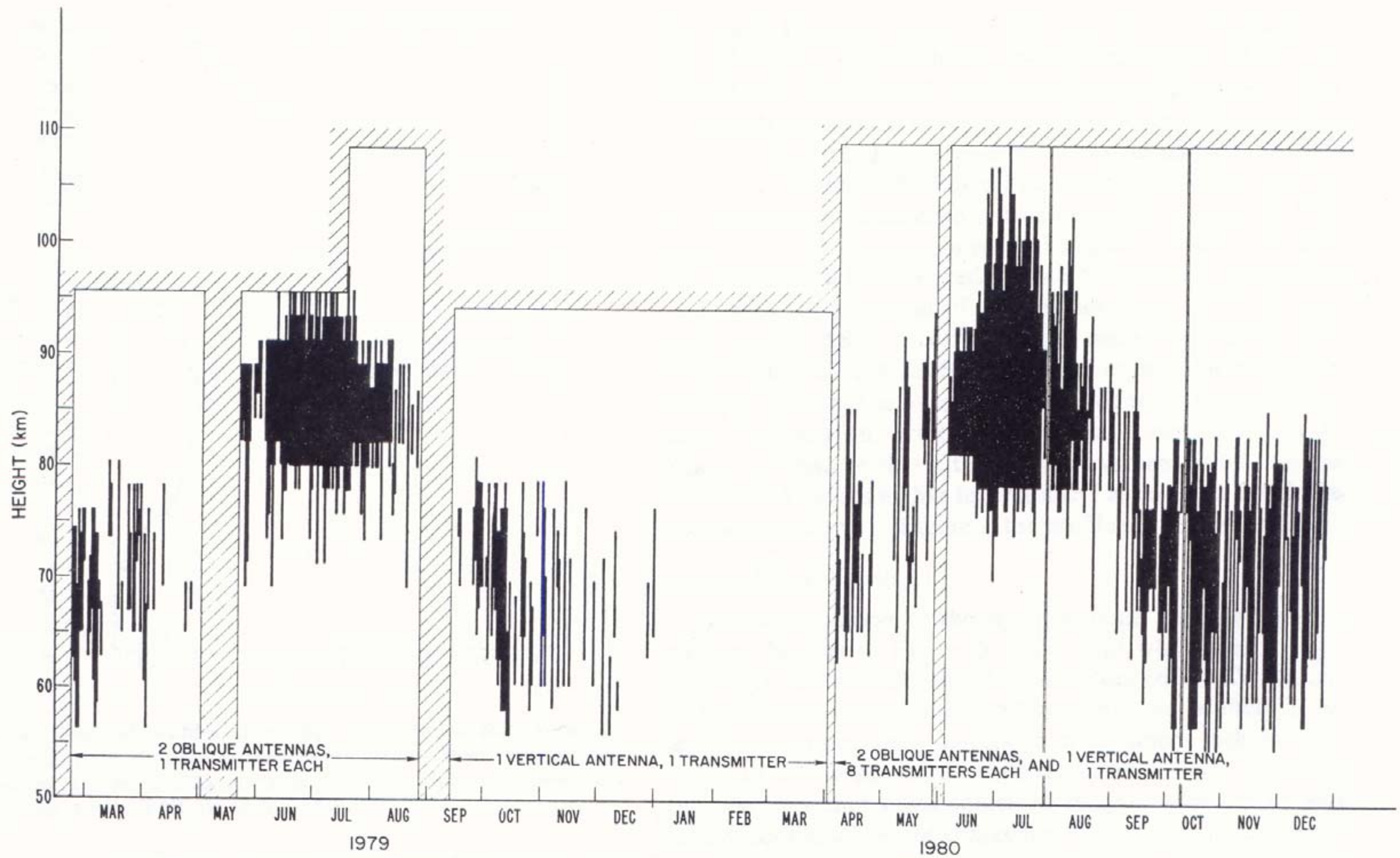
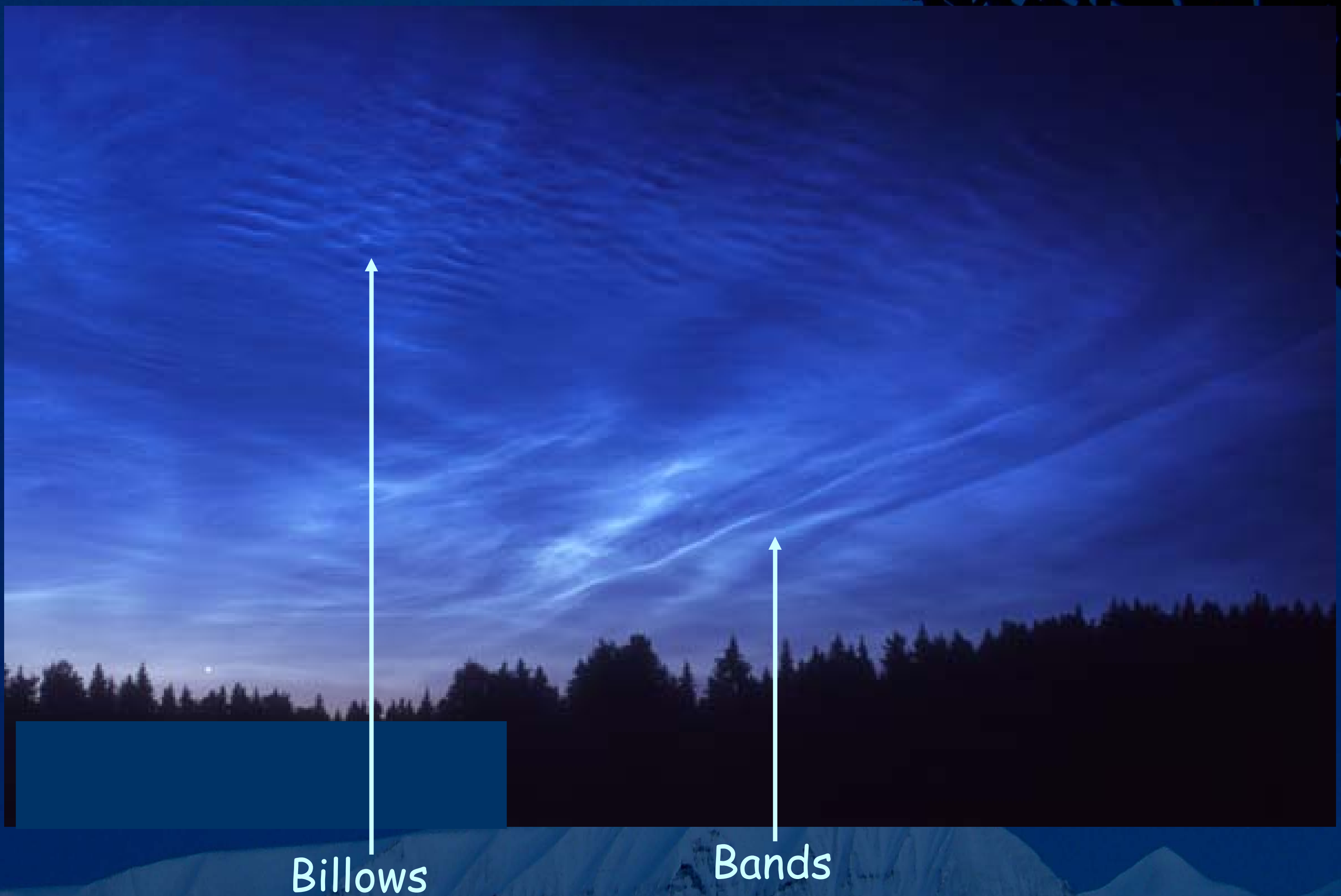
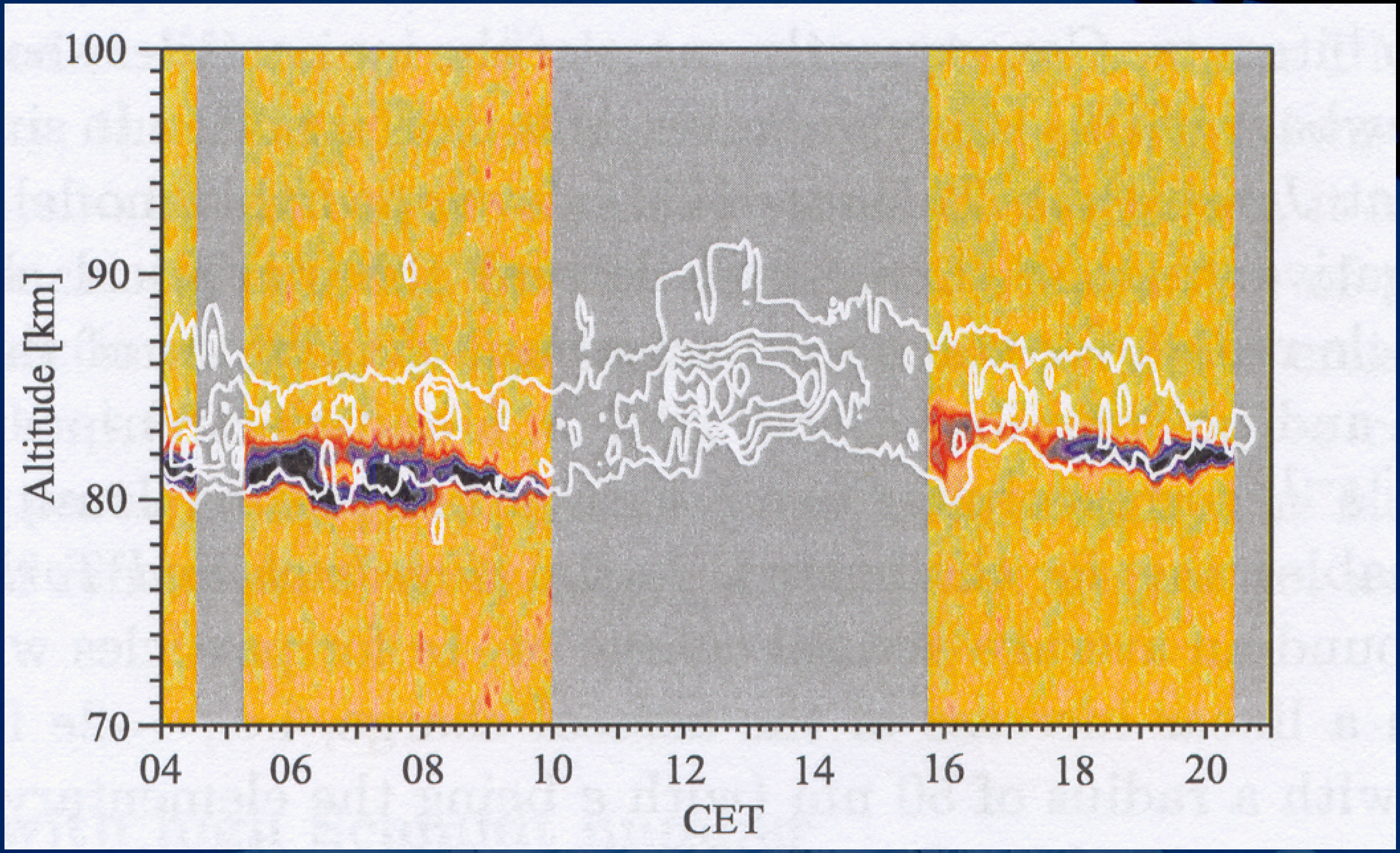


Fig. 1. Height of occurrence of mesospheric echoes on a daily basis from February 1979 to December 1980.

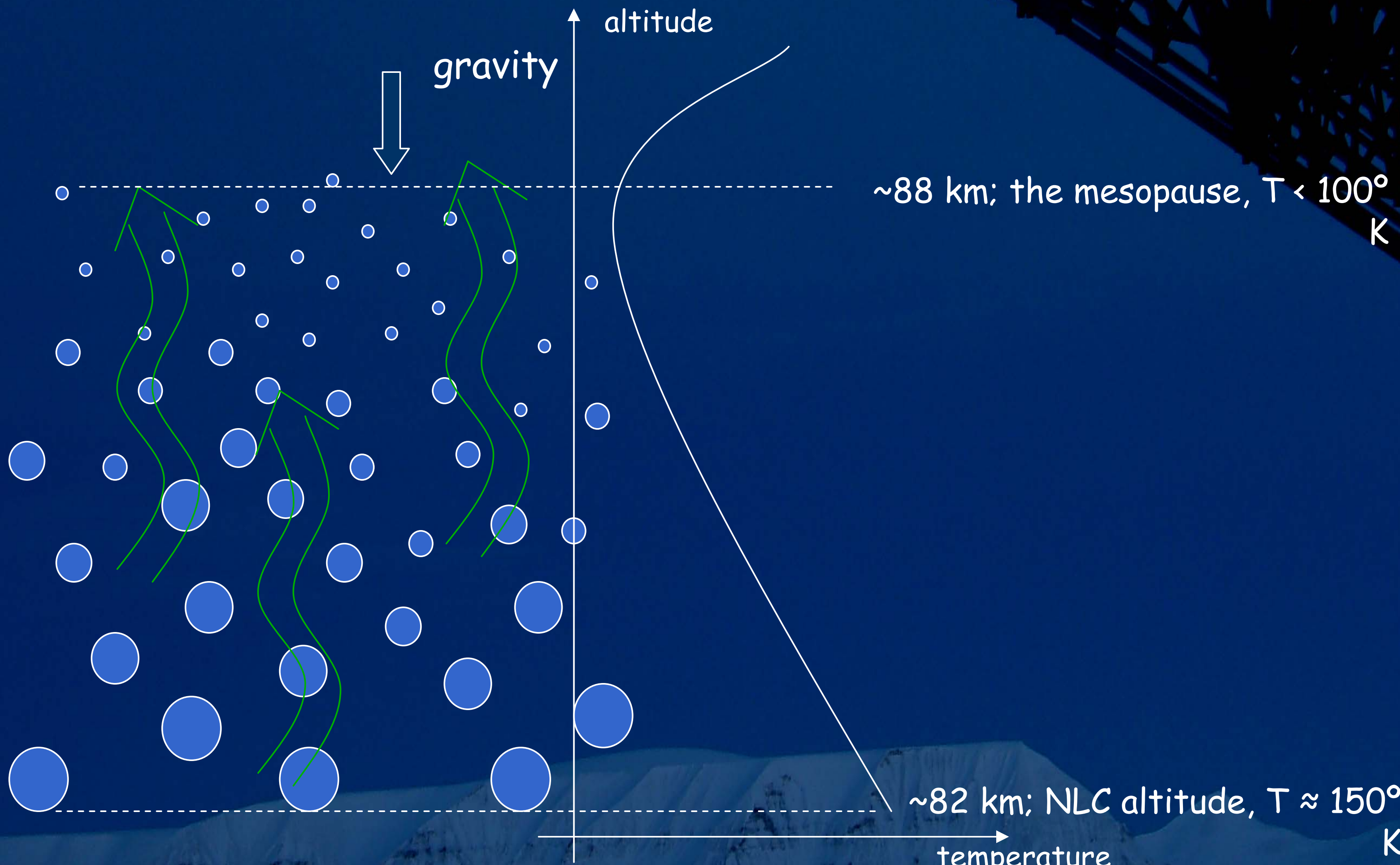
NLC - often correlated to PMSE



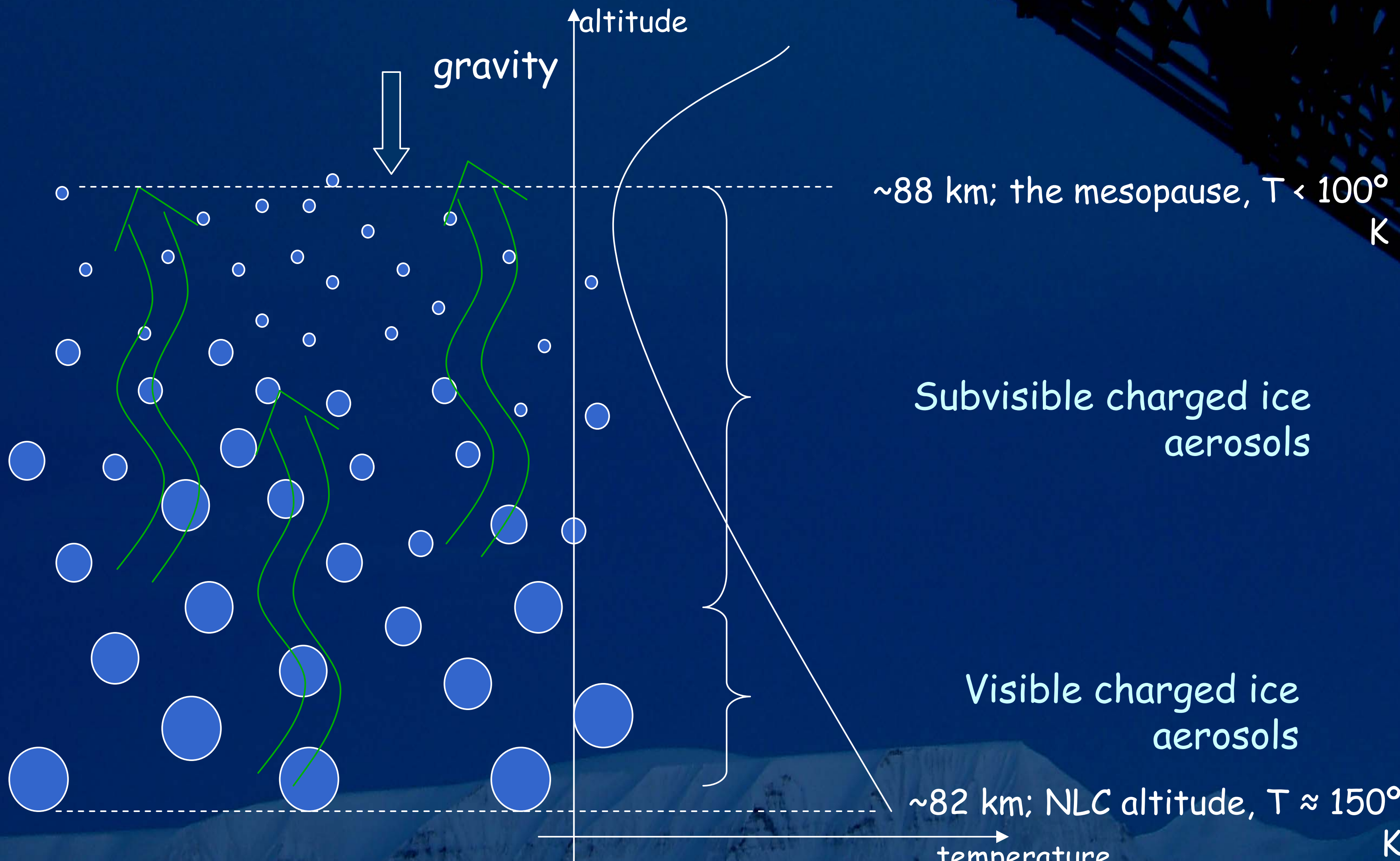
Relative location of NLC and PMSE



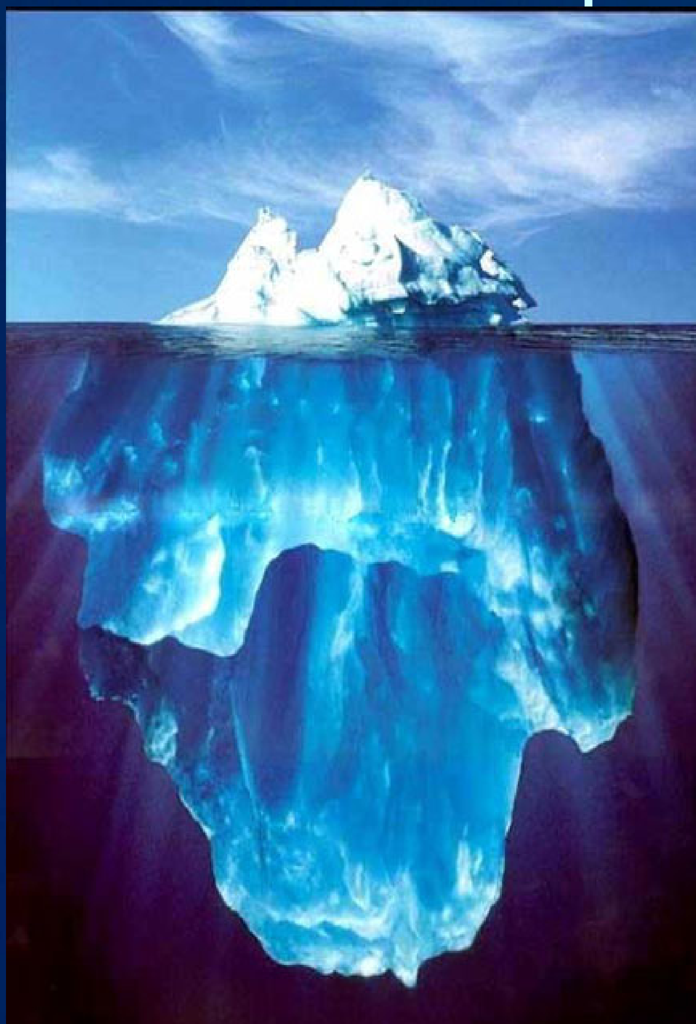
Sedimentation of aerosols



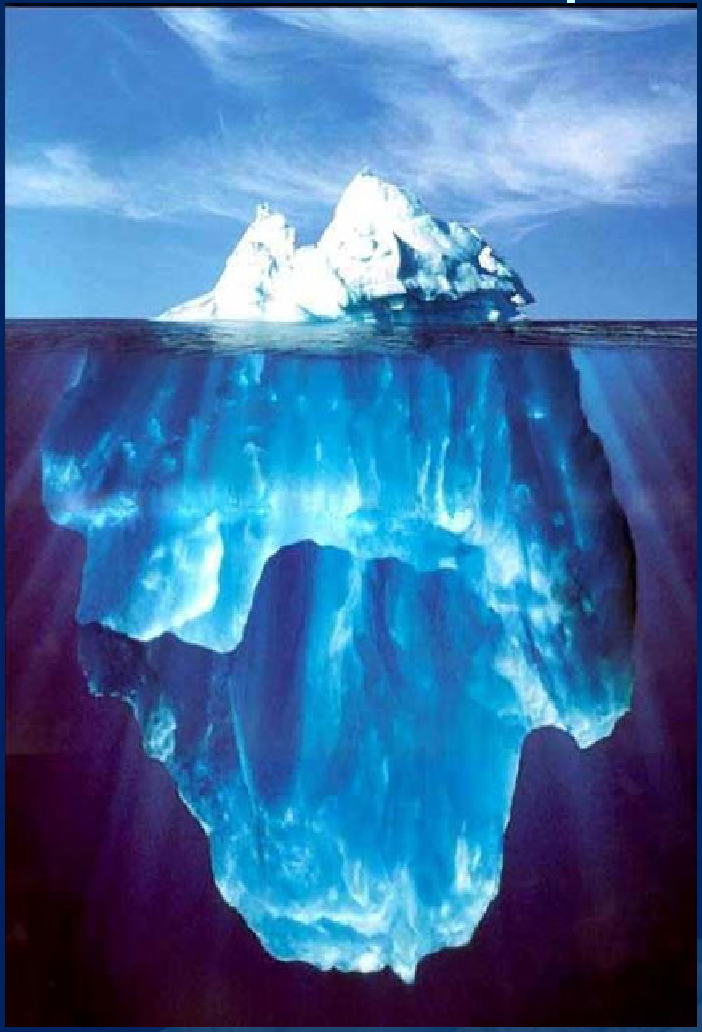
Sedimentation of aerosols

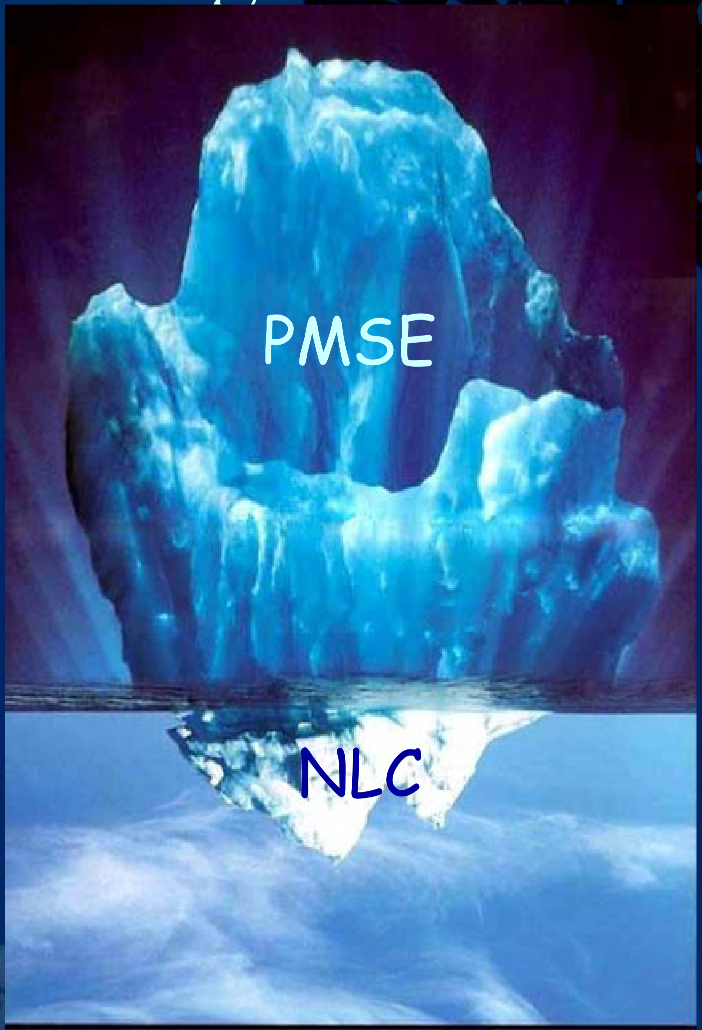


With the naked eye, we can only see the tip of the iceberg

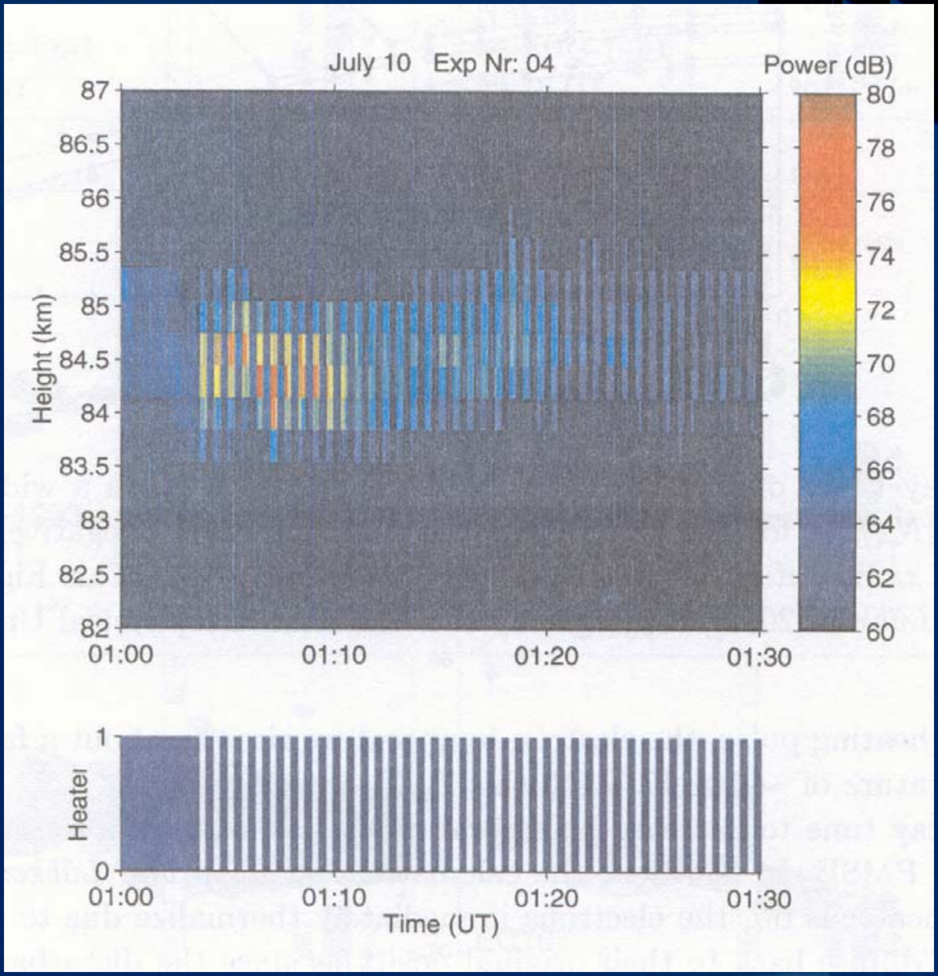


With the naked eye, we can only see the tip of the iceberg



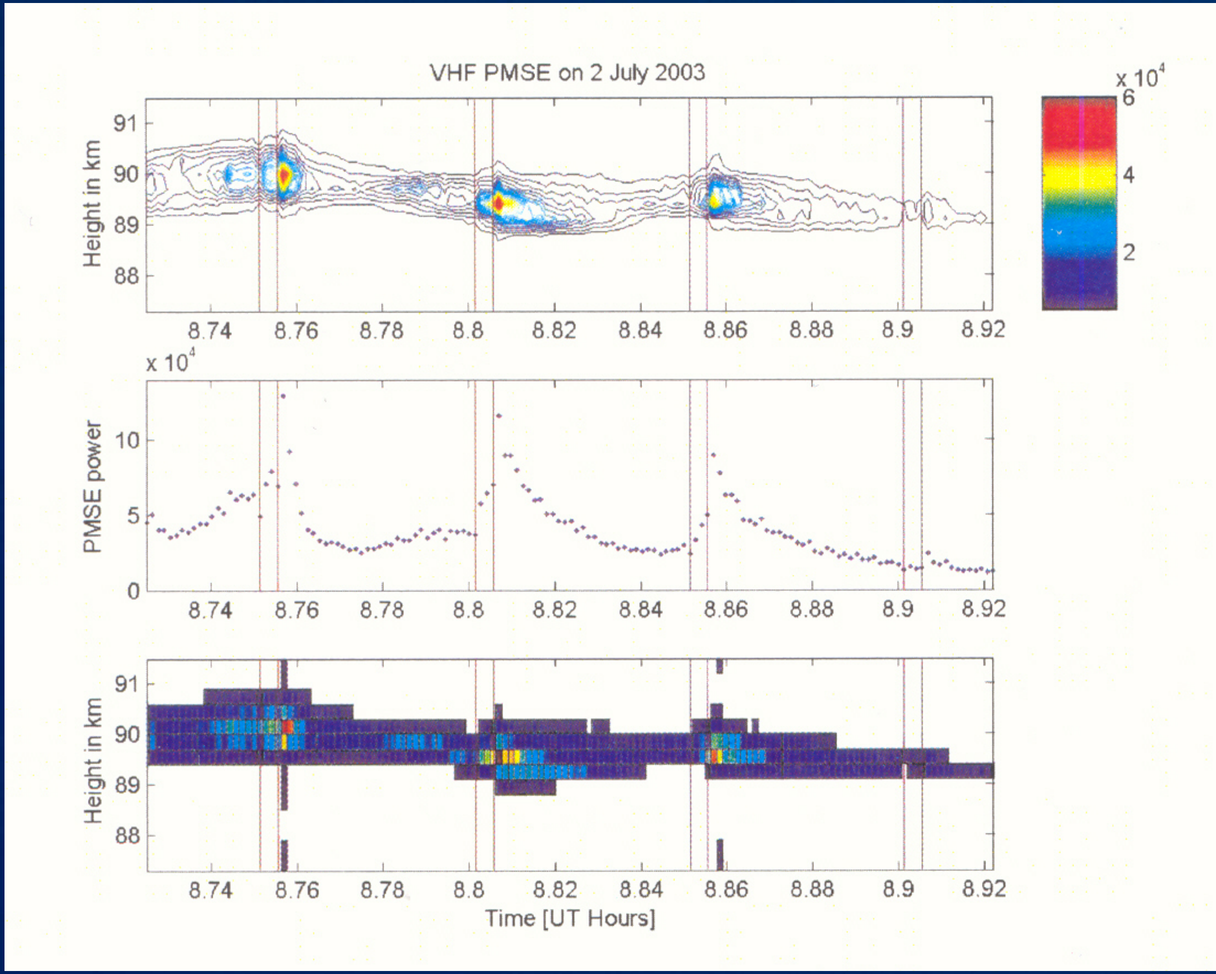


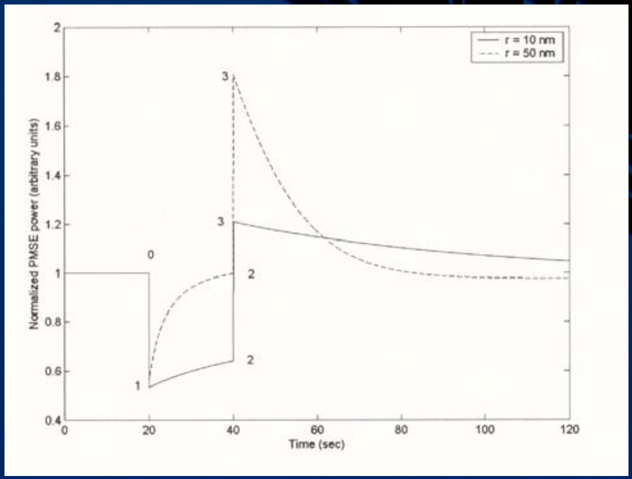
Heating modified PMSE



The heater turns the PSME off!

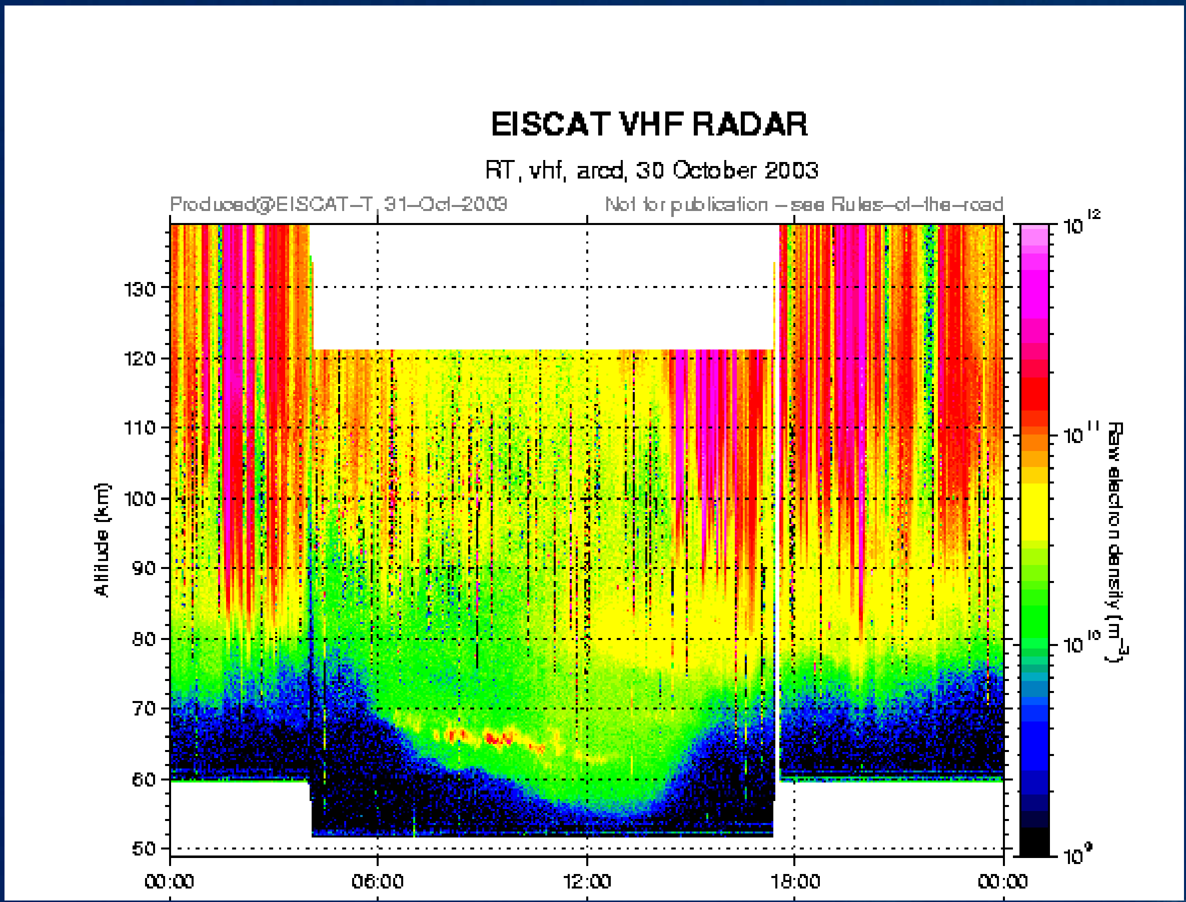
The Overshoot effect





The heater turns the PSME off - but the density “overshootes” right after heater on again!

PSWE



- Weaker than PMSE
- Lower altitude than PMSE
- Not followed by NLC
- Not during extreme cooling

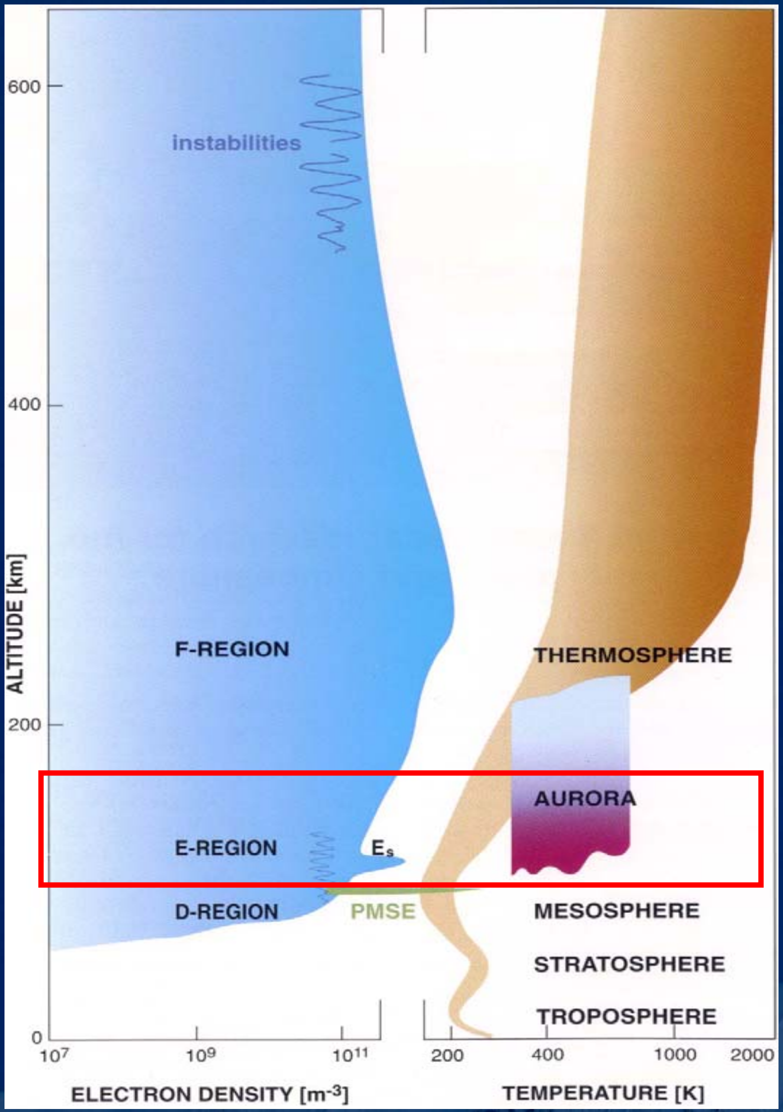
E-region

...the aurora region...

E-region

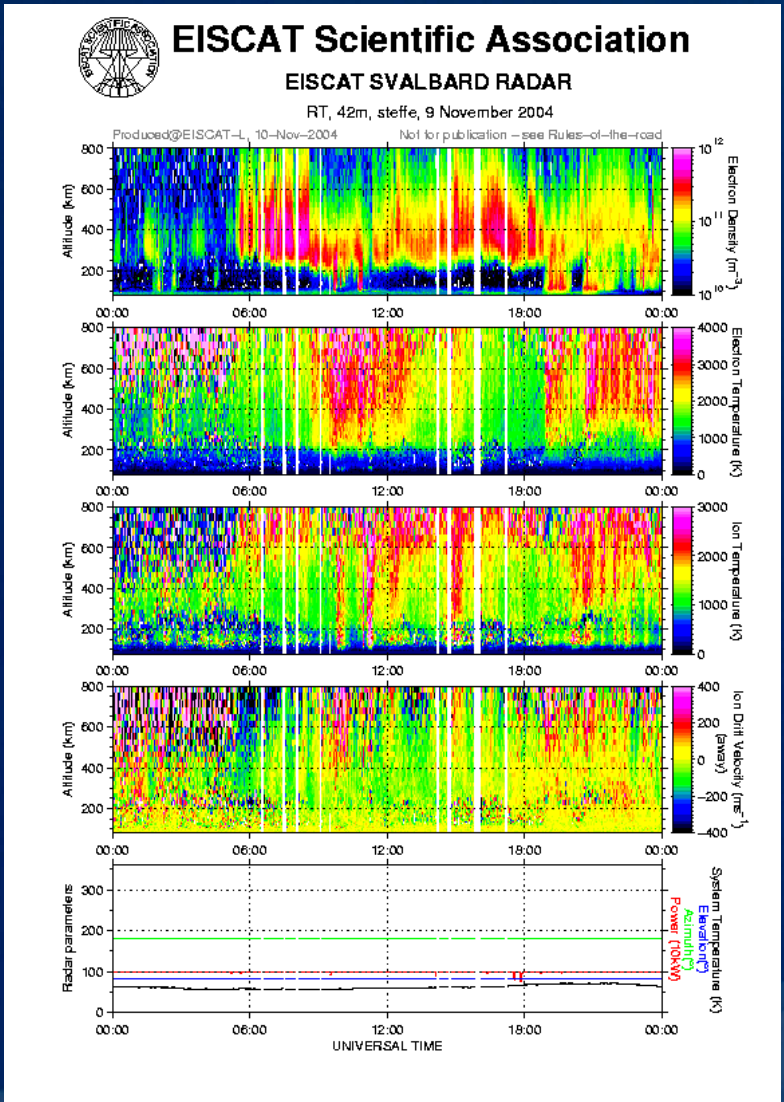
- Altitude region between ~100 - 150 km
- Collision gets less important
- Transition from single to double humped spectra
- Wider spectra than D-region
- Deposition region for auroral particles
  - 2 keV (100 keV) electrons at about 130 km (85 km)
- Horizontal (Hall and Pedersen) currents
- Sudden changes in Ne and Te
- Sporadic E

E-region



600
400
200
0
ALTITUDE [km]
instabilities
F-REGION
E-REGION
E_s
D-REGION
PMSE
THERMOSPHERE
AURORA
MESOSPHERE
STRATOSPHERE
TROPOSPHERE
10^7
10^9
10^{11}
200
400
1000
2000
ELECTRON DENSITY [m^{-3}]
TEMPERATURE [K]

E-region deposition



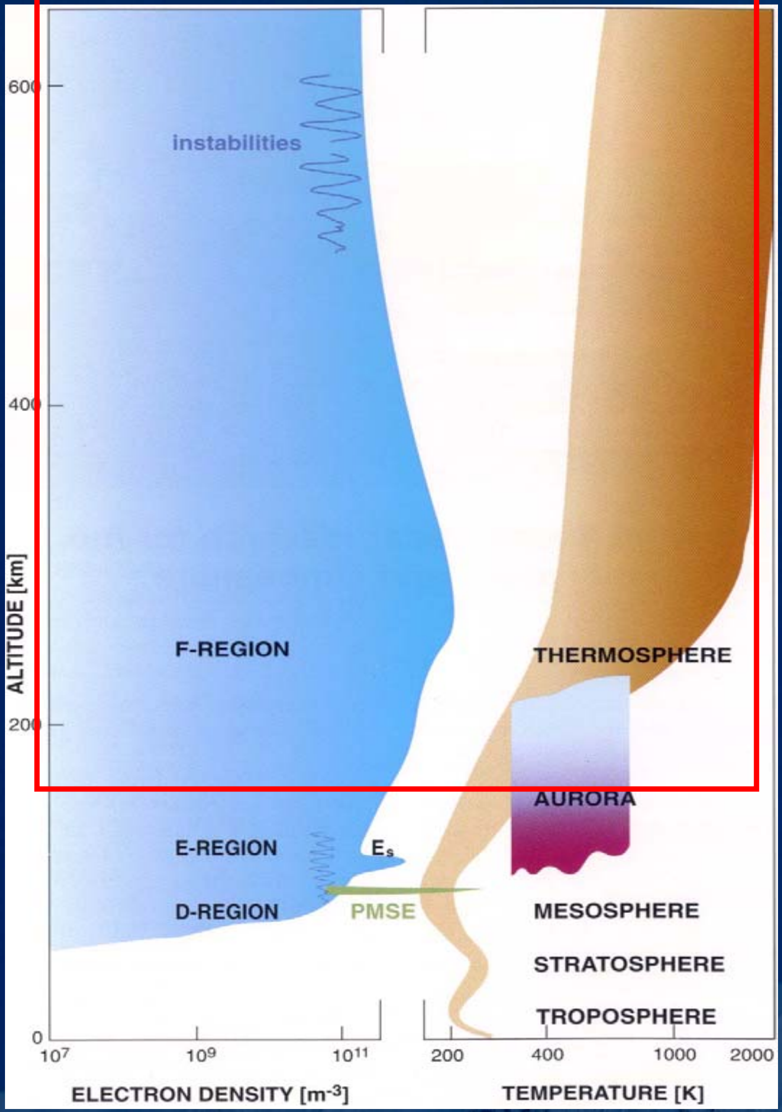
Aurora


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

F-region

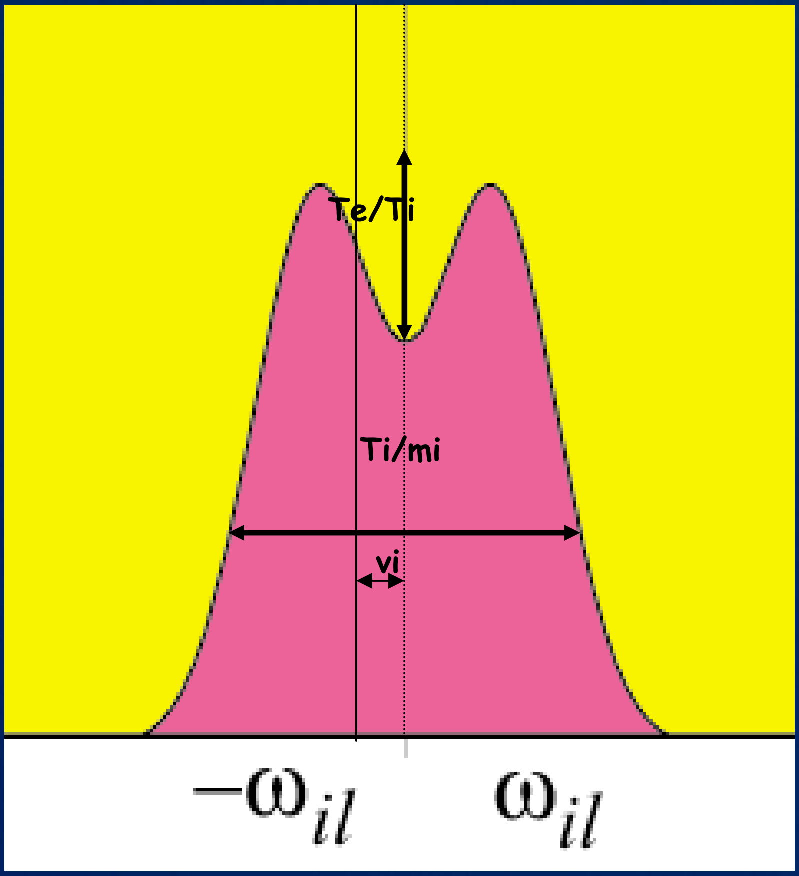
- Altitude region between ~200-2000(?) km
- Collision less plasma
- Spectral width proportional to the local ion acoustic frequency for the radars k-vector
  - can “easily” solve for several parameters
- Decreasing densities with altitude
- Generally increasing temperatures with increasing altitudes
- At high latitude a dynamic region which couples to the magnetosphere

F-region



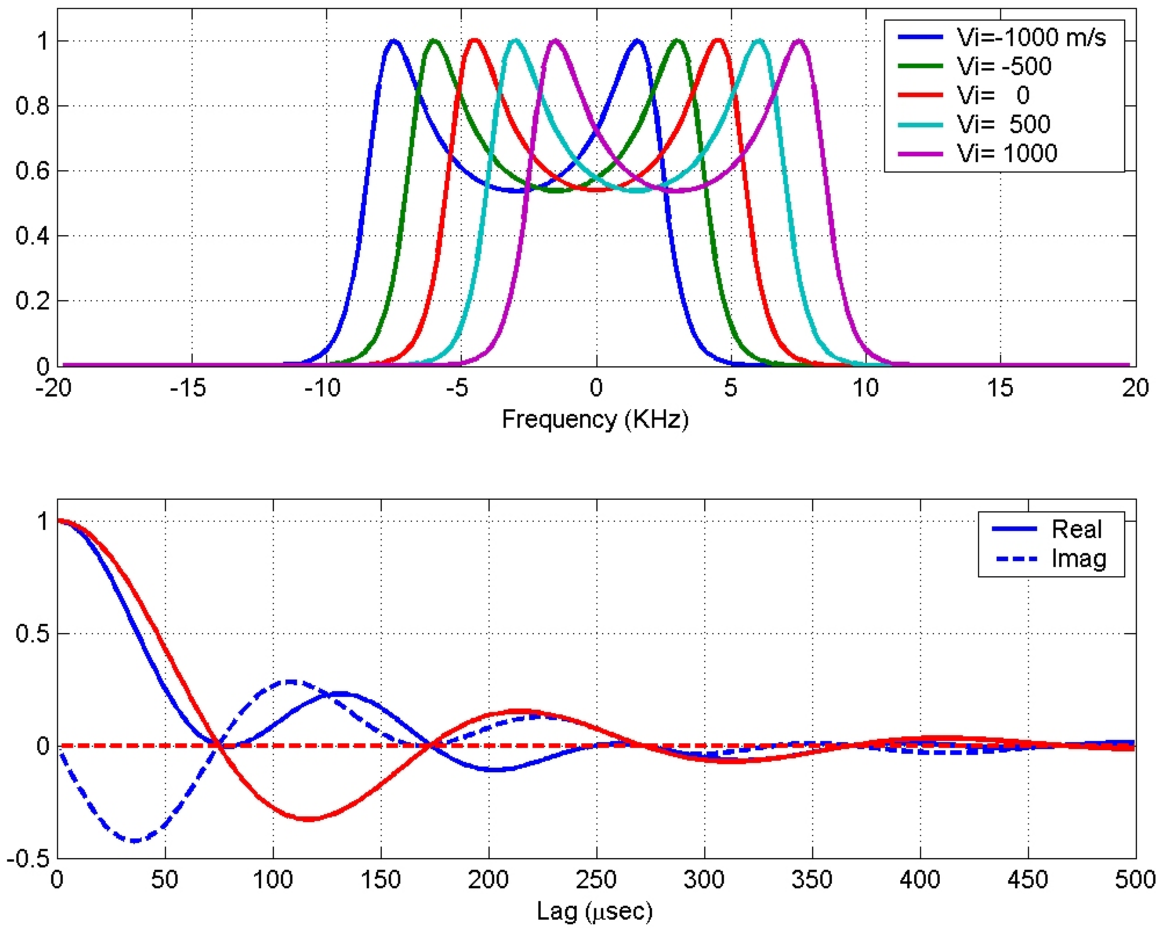
600
400
200
0
ALTITUDE [km]
instabilities
F-REGION
E-REGION
E_s
D-REGION
PMSE
THERMOSPHERE
AURORA
MESOSPHERE
STRATOSPHERE
TROPOSPHERE
10^7
10^9
10^11
200
400
1000
2000
ELECTRON DENSITY [m^-3]
TEMPERATURE [K]

Standard parameters found from IS ion line:



- Ion temperature (Ti) to ion mass (mi) ratio from the width of the spectra
- Electron to ion temperature ratio (Te/Ti) from "peak_to_valley" ratio
- Electron (= ion) density from total area (corrected for temperatures)
- Ion velocity (vi) from the Doppler shift

Ion Velocity



Parameters

Freq: 449 MHz

Ne: 10^{12} m^{-3}

Ti: 1000 K

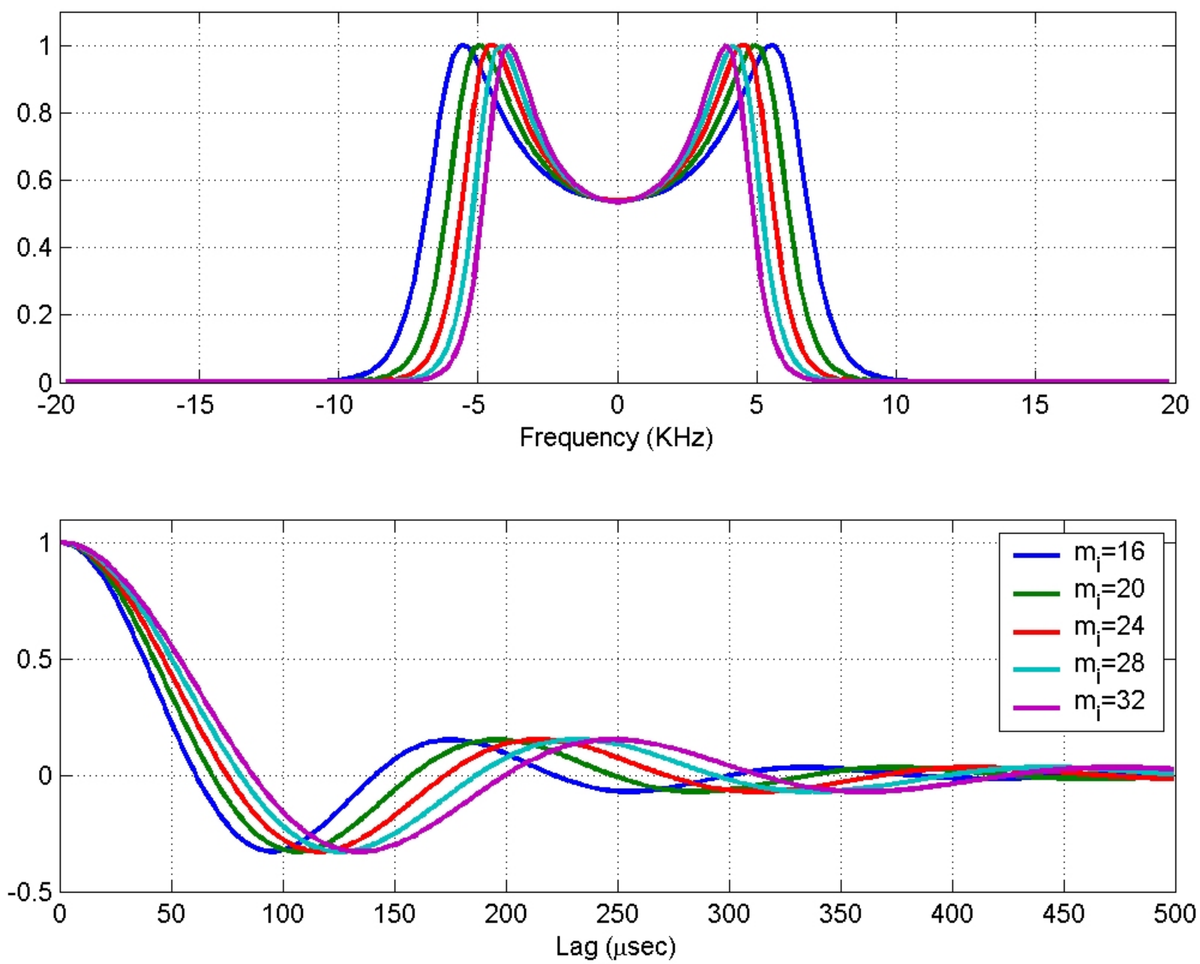
Te: 2000 K

Comp: 100% O^+

ν_{in}: 10^{-6} KHz

Craig Heinselmann

Ion Mass



Parameters

Freq: 449 MHz

Ne: 10^{12} m^{-3}

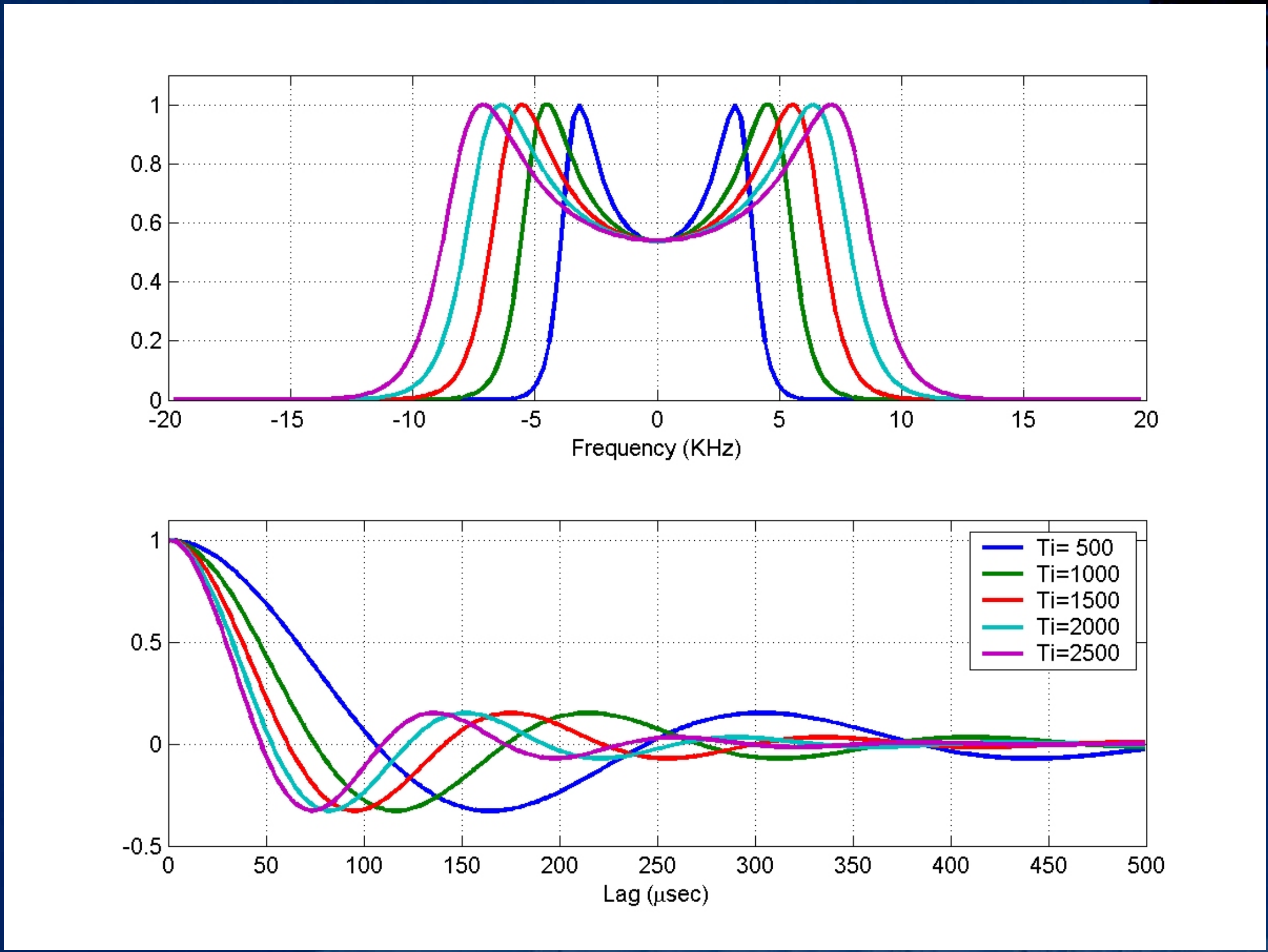
Ti: 1500 K

Te: 3000 K

ν_{in}: 10^{-6} KHz

Craig Heinselmann

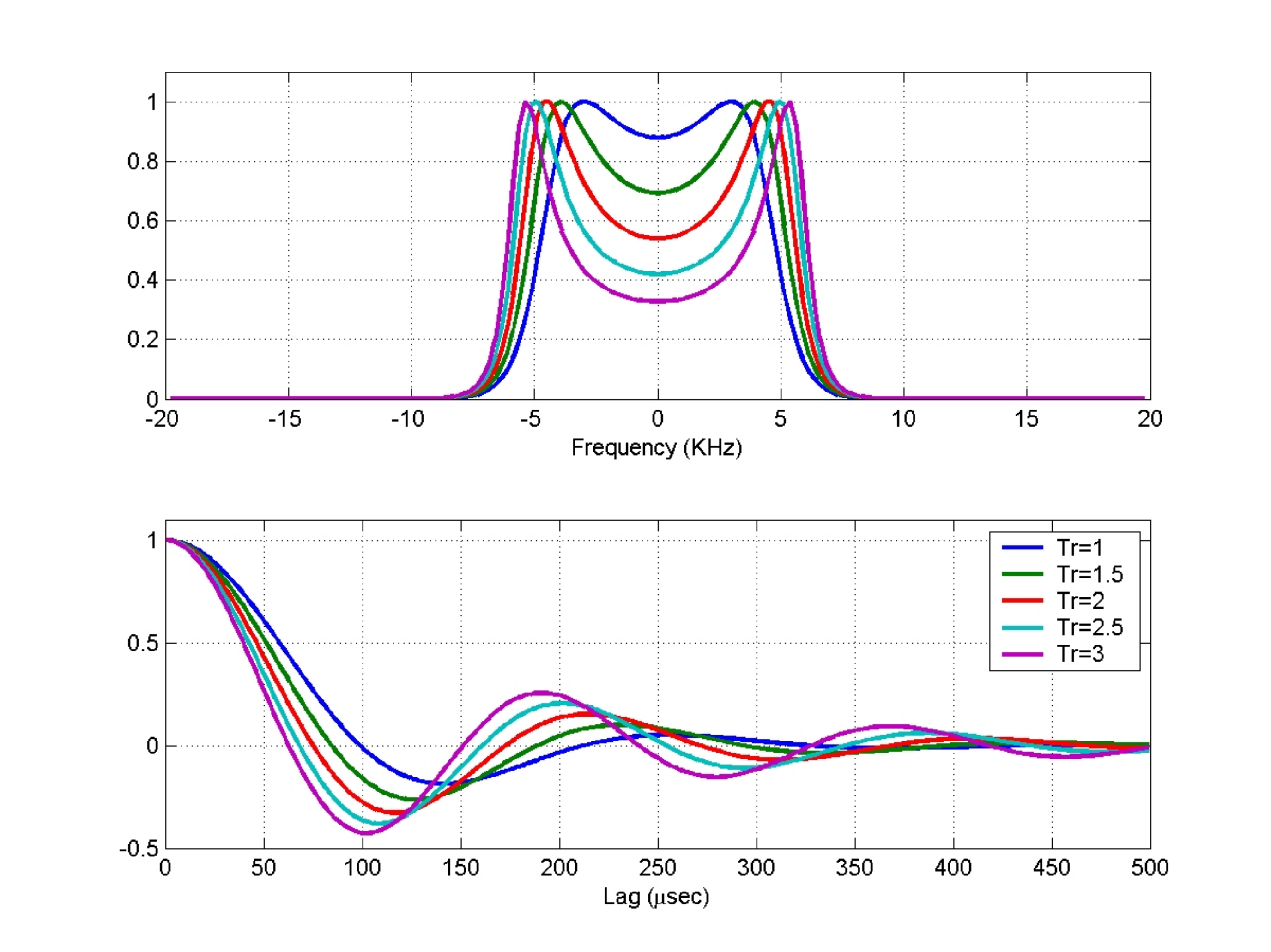
Ion Temperature



Parameters
Freq: 449 MHz
Ne: 10^{12} m^{-3}
Te: 2*Ti
Comp: 100% O^{+}
ν_{in}: 10^{-6} KHz

Craig Heinselmann

Electron/Ion Temperature Ratio

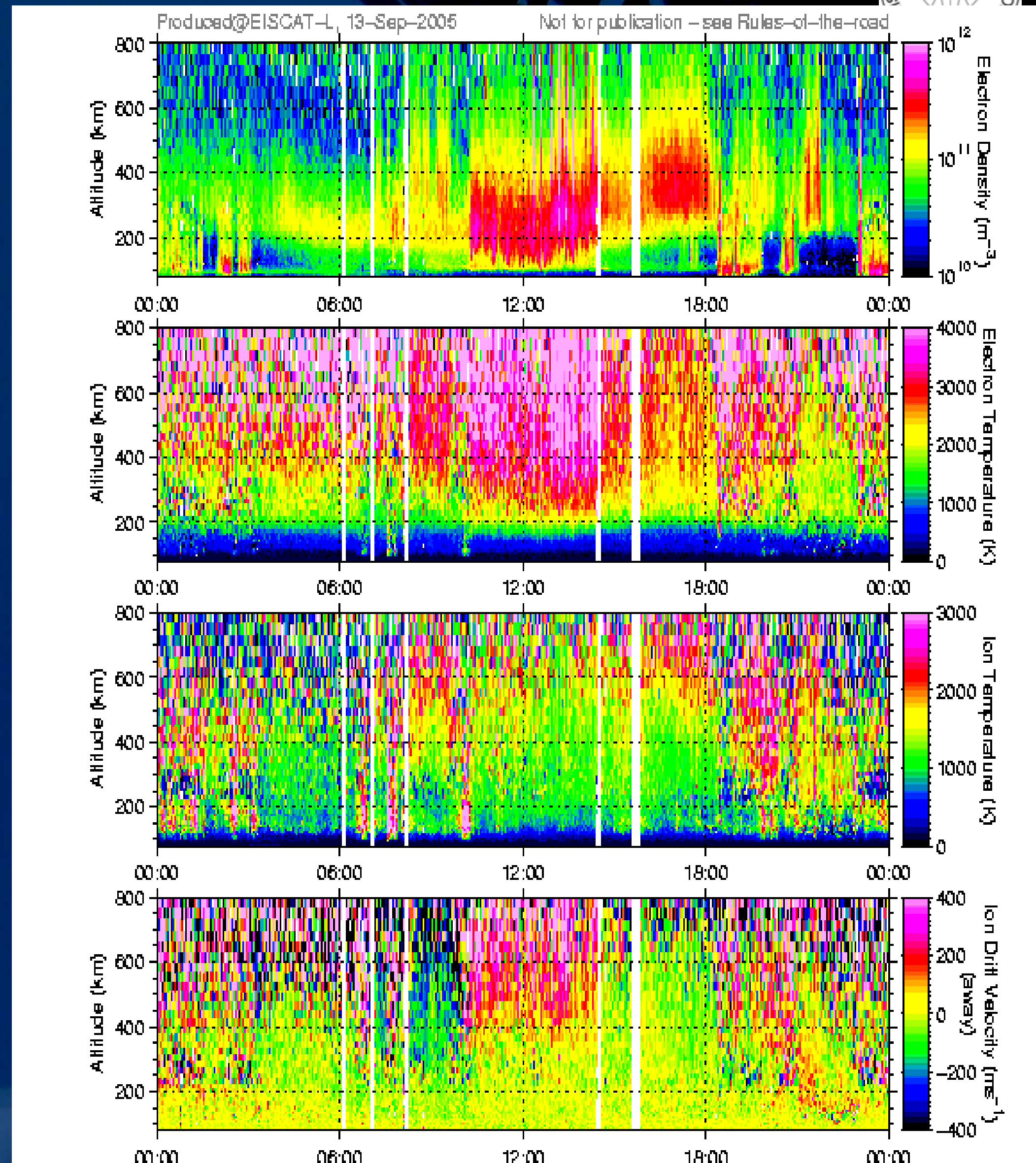


Parameters
Freq: 449 MHz
Ne: 10^{12} m^{-3}
Ti: 1000 K
Comp: 100% O^{+}
ν_{in}: 10^{-6} KHz

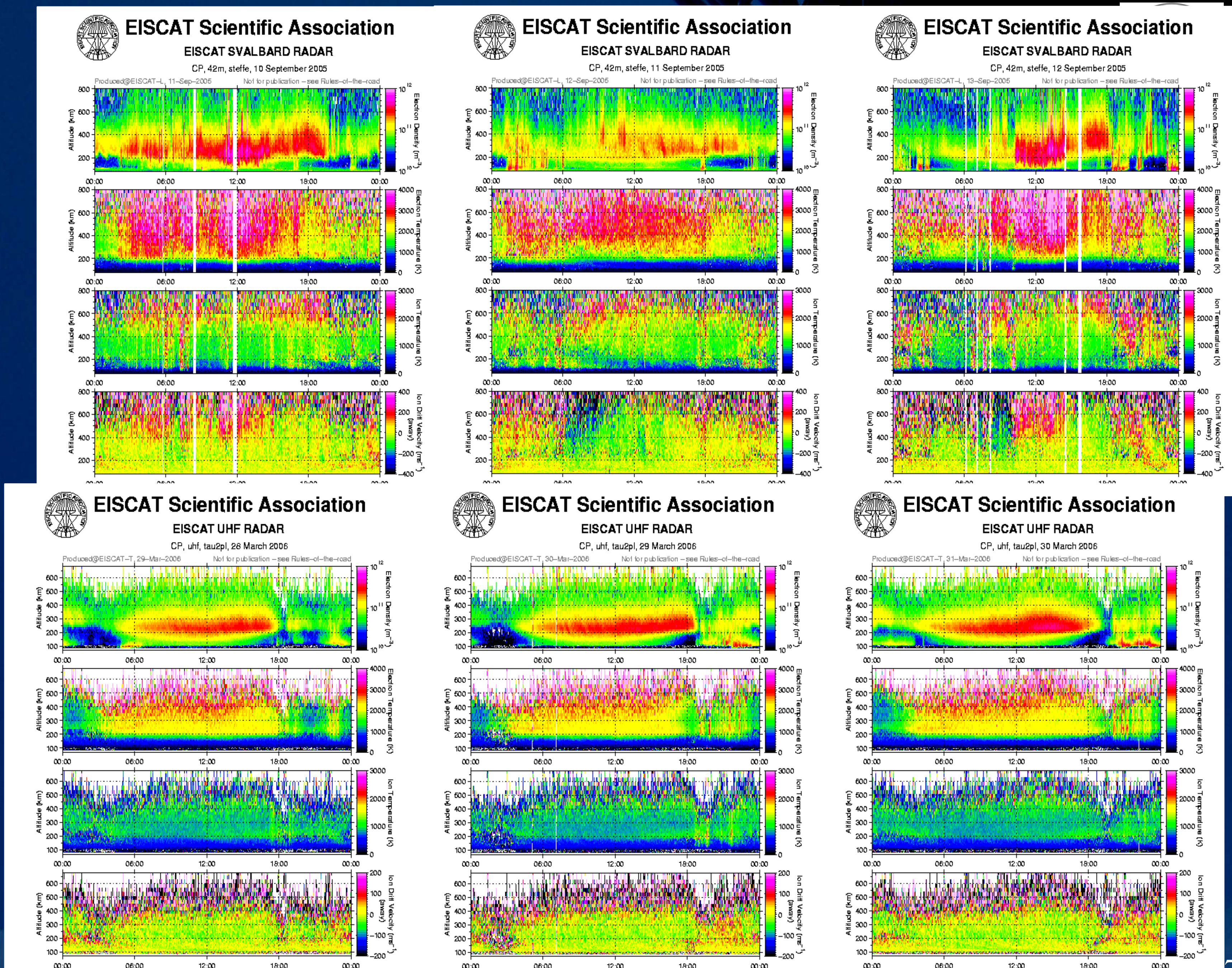
Craig Heinselmann

Summary Data

- Four basic parameters:
  - Electron density
  - Electron Temperature
  - Ion temperature
  - Ion velocity
- Raw data available for further analysis:
  - shorter integrations
  - different gating
  - different weightings
  - other parameters
  - etc.



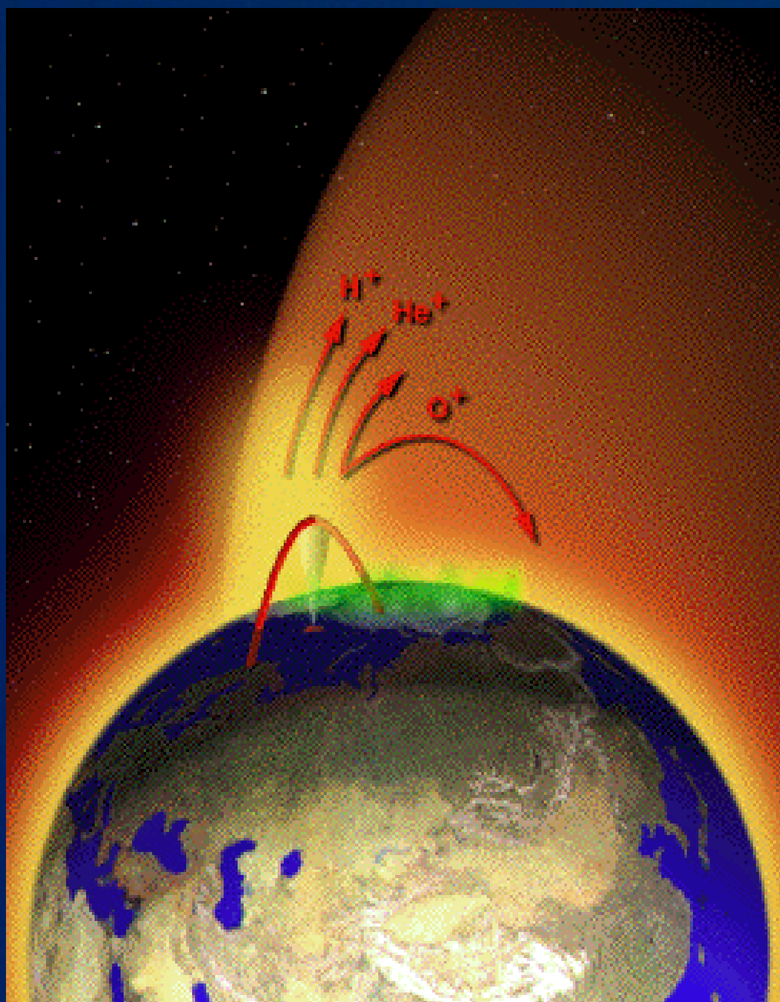
'IS radar is the most powerful ground-based tool'

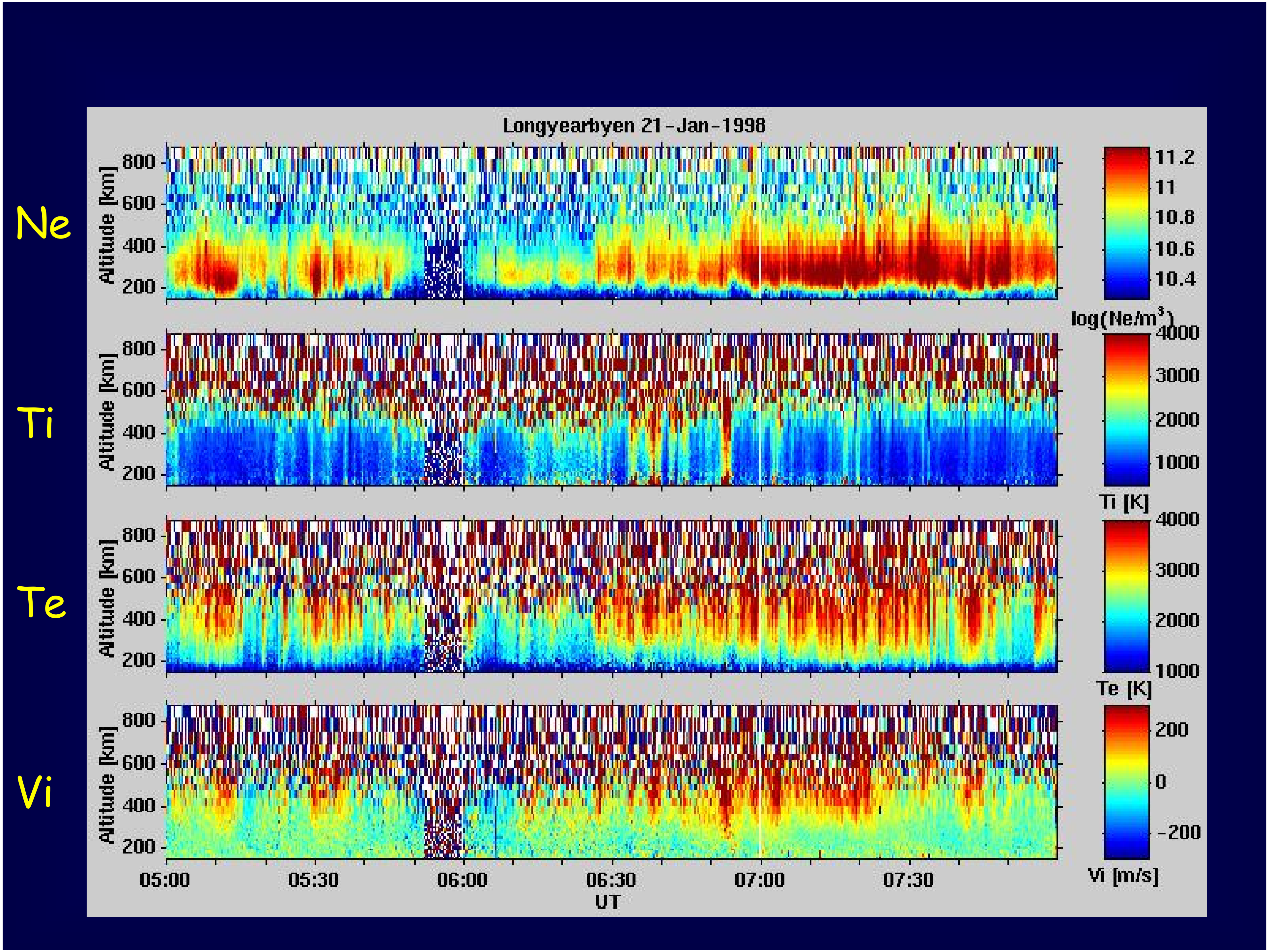

EISCAT Scientific Association
EISCAT SVALBARD RADAR
CP, 42m, steffe, 10 September 2005
EISCAT Scientific Association
EISCAT SVALBARD RADAR
CP, 42m, steffe, 11 September 2005
EISCAT Scientific Association
EISCAT SVALBARD RADAR
CP, 42m, steffe, 12 September 2005
EISCAT Scientific Association
EISCAT UHF RADAR
CP, uhf, tau2pl, 28 March 2006
EISCAT Scientific Association
EISCAT UHF RADAR
CP, uhf, tau2pl, 29 March 2006
EISCAT Scientific Association
EISCAT UHF RADAR
CP, uhf, tau2pl, 30 March 2006
Electron Density
Electron Temperature (K)
Ion Temperature (K)
Ion Drift Velocity
Altitude (km)

42 days of ESR data, 17. May-28. June 2004

Ion outflow

ion outflow





Longyearbyen 21-Jan-1998
Ne
Ti
Te
Vi
Altitude [km]
800
600
400
200
11.2
11
10.8
10.6
10.4
log(Ne/m³)
4000
3000
2000
1000
Ti [K]
Te [K]
200
0
-200
Vi [m/s]
05:00
05:30
06:00
06:30
07:00
07:30
UT

Type I ion outflow

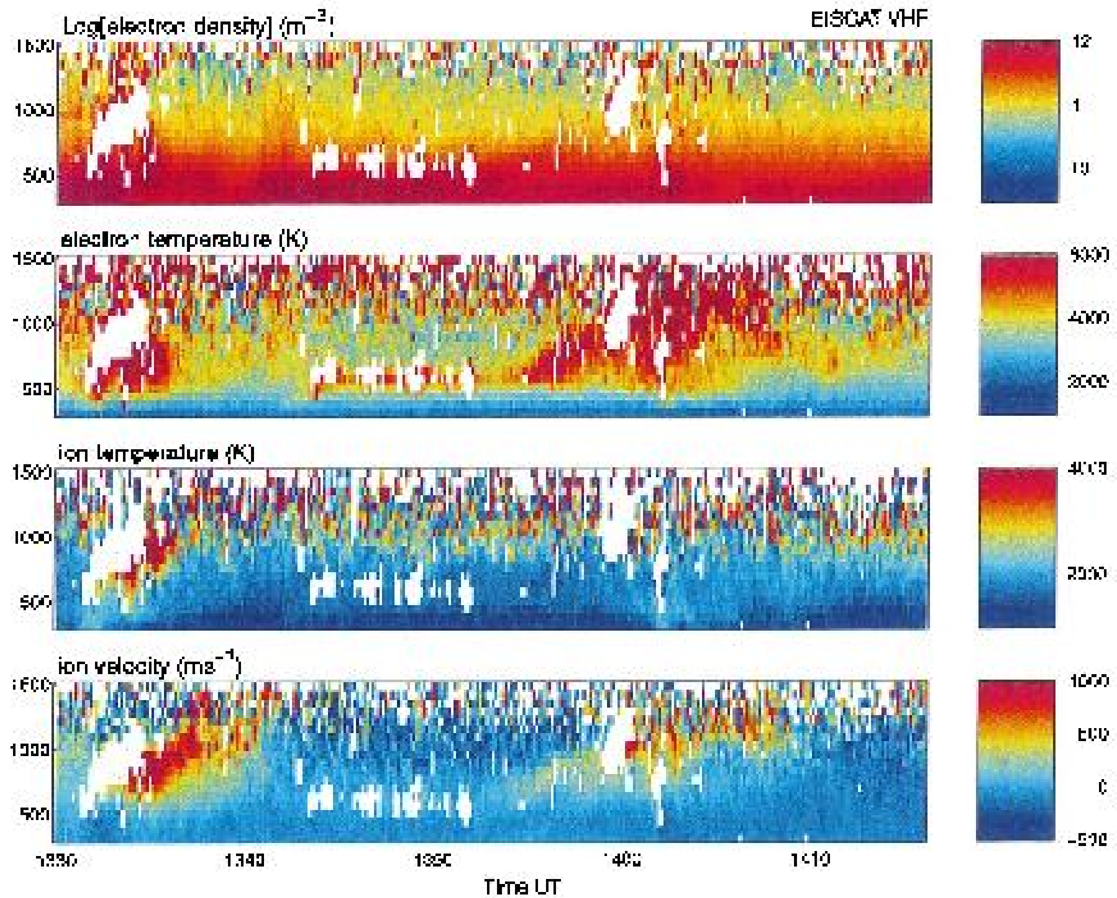


Fig. 1. Data derived from the VHF EISCAT radar during the time period 1330 to 1430 UT. *Panel 1* shows an overview of the electron density, *panel 2* the electron temperature, *panel 3* the ion temperature and *panel 4* the vertical ion velocity (*positive upward*) between altitudes 280–1500 km (Forme *et al.*, 1995)

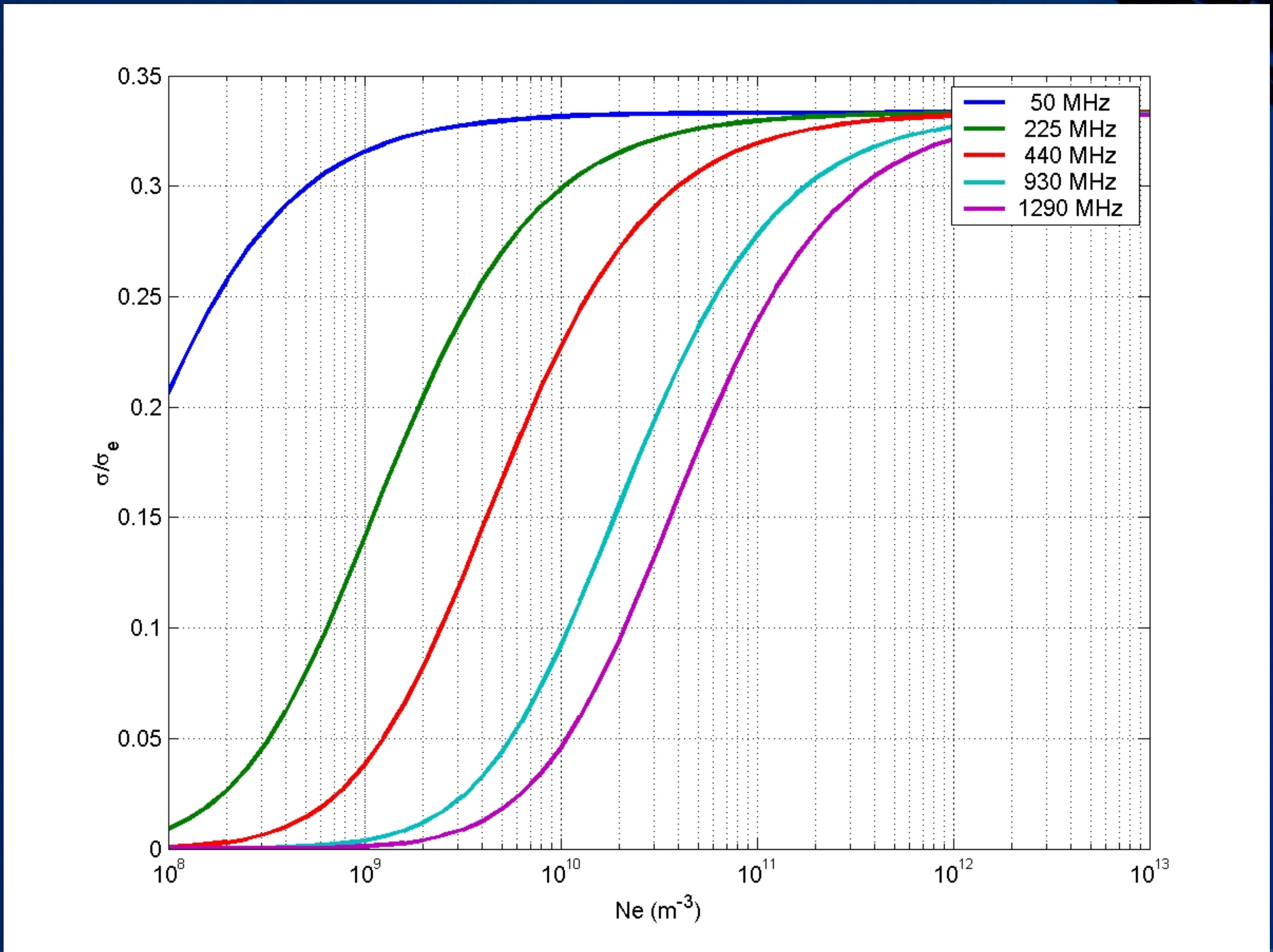
Magnetospheric studies

- Direct "incoherent" scatter from the ionosphere?
- Scattering off coherent structures in the magnetosphere
- Ionospheric response to magnetospheric processe

Direct incoherent scattering?

- Due to the Debye cutoff - the frequency of most incoherent scatter radars are too high (have too short wavelength) to do incoherent scattering in the ionosphere.

Debye Length Dependencies



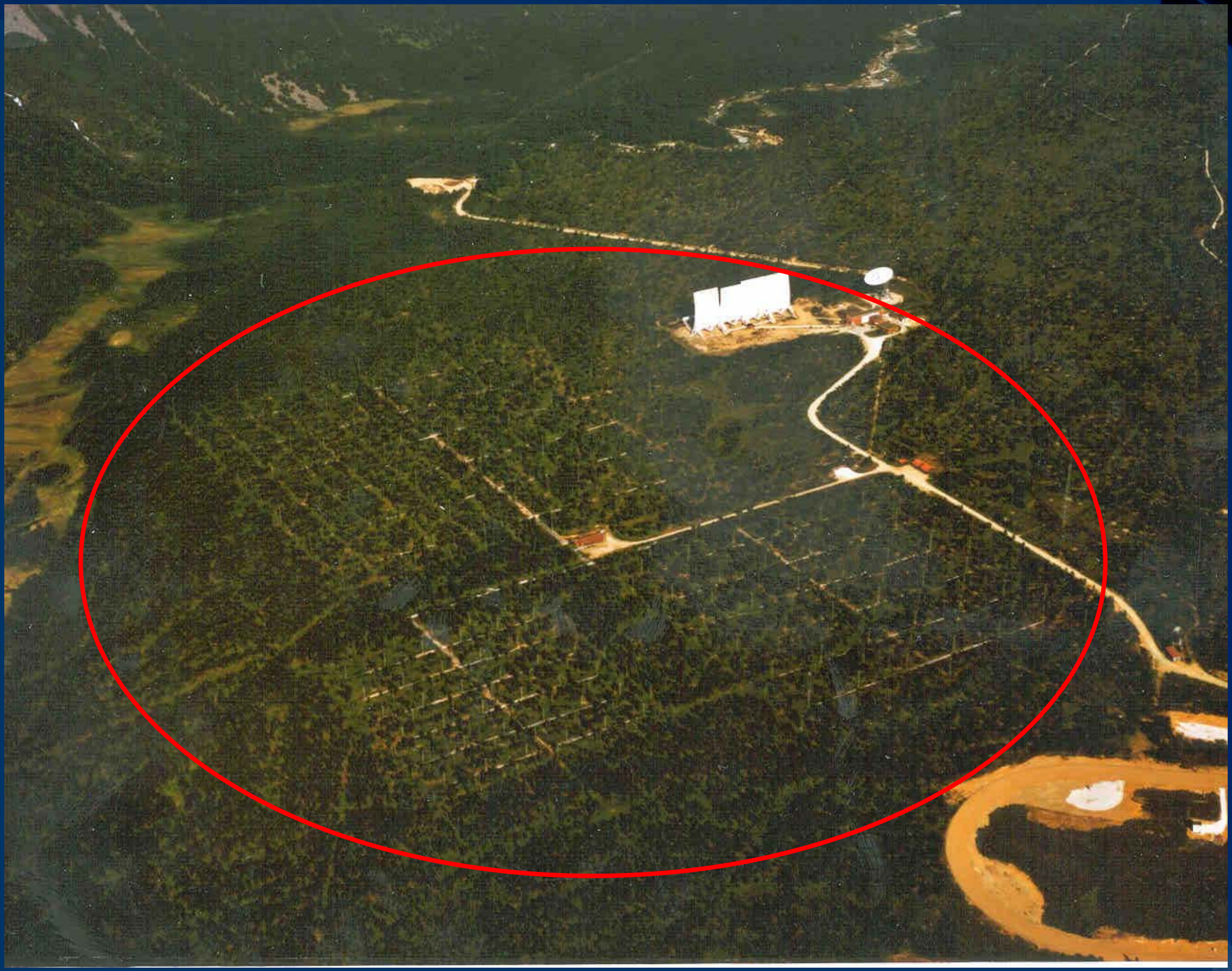
Parameters
Ti: 1000 K
Te: 2000 K

Craig Heinselmann

Direct incoherent scattering?

- Due to the Debye cutoff - the frequency of most incoherent scatter radars are too high (have too short wavelength) to do incoherent scattering in the ionosphere.
- However - the EISCAT HEATER (~4-8 MHz) could in theory receive “incoherent” scattering from magnetospheric regions (however very weak!)

Heating as an IS radar?



Coherent Solar Wind(!) scattering

- *Genkin and Erukhimov 1983* showed that a powerful and sensitive radar, operated in the upper HF range, may produce detectable echoes from ion-acoustic turbulence in fast solar wind streams.
- A tentative experimental detection of such turbulence was made in the summer of 1986 with the Sura facility operated at 9 MHz. Echo bursts with a Doppler shift of $f_{Dop} \approx 19$ kHz, a delay time of $\tau \approx 1.2$ s and an averaged scattered signal power of 2×10^{-14} W, were observed. The receiver bandwidth used was 1.5 kHz. The conjectured scattering region was on the day-side at a distance of 33 Earth radii. The solar wind velocity, as determined from f_{Dop}, was estimated at about 400 km/s.

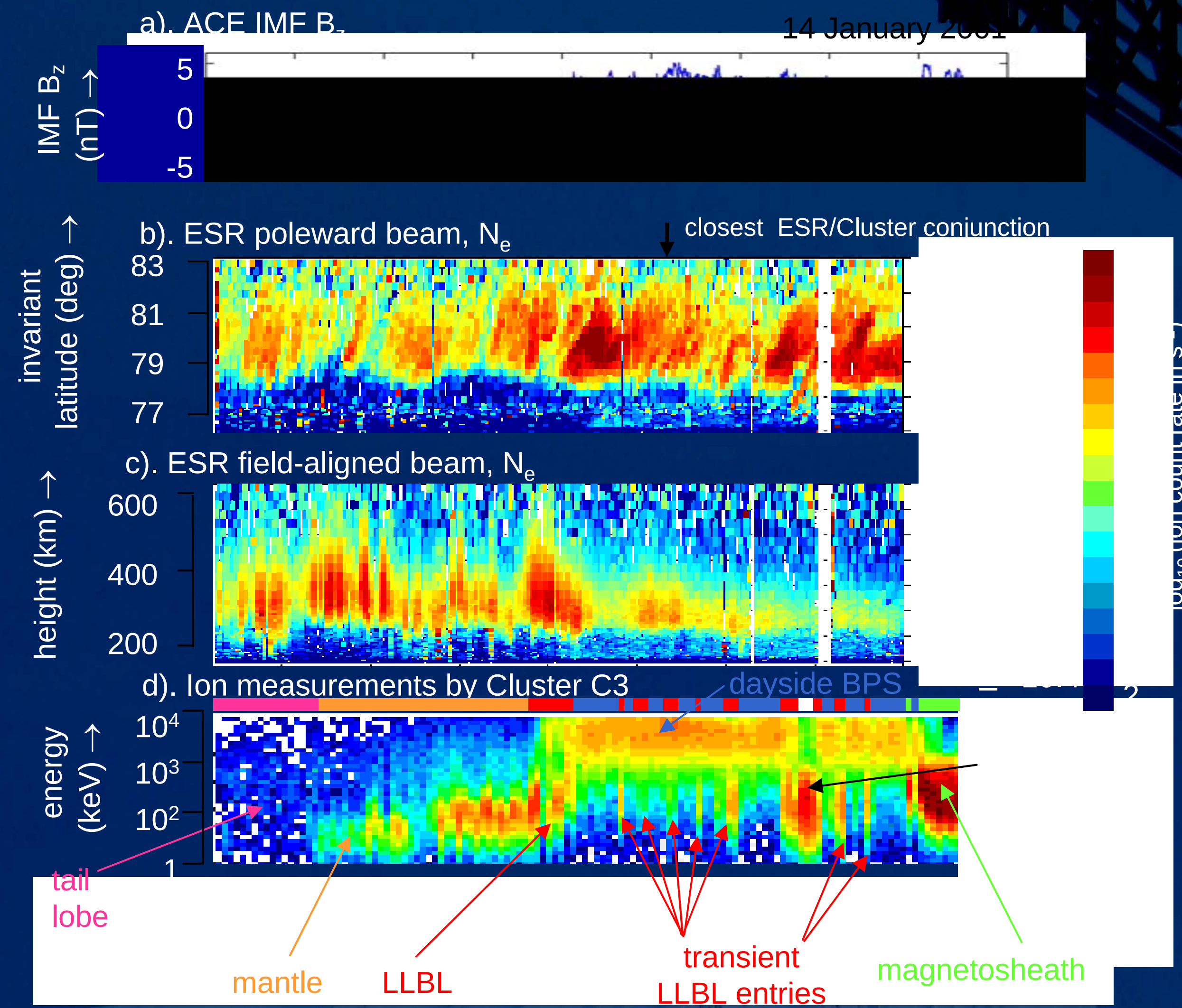
From "Radio Studies of Solar-Terrestrial Relationships" by LOIS Science Team Edited by Bo Thidé 2002

Coherent scattering in the magnetosphere

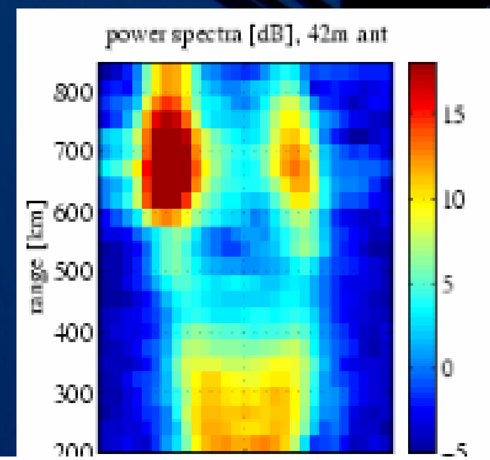
- Theoretical arguments by *Ginzburg and Rukhadze 1975* suggest that the optimum scattering occurs when $\lambda_{radar} \approx 5\lambda_{D.}$ which means that a radar frequency of 85 MHz would yield maximum echoes from altitudes around 3000 km; lower frequencies will scatter off magnetospheric ion-acoustic turbulence at higher altitudes.
- The first tentative observation of coherent HF radar scattering off magnetospheric ion-acoustic turbulence was made at the Russian Sura facility in 1991 by *Gurevich et al. 1992*. Later, in 1995, scattering off magnetospheric turbulence at about 6000 km was observed in experiments performed at Tromsø where the EISCAT HF facility was operated in a radar mode. The echoes were typically a factor 10^{-20} weaker than the transmitted pulses.

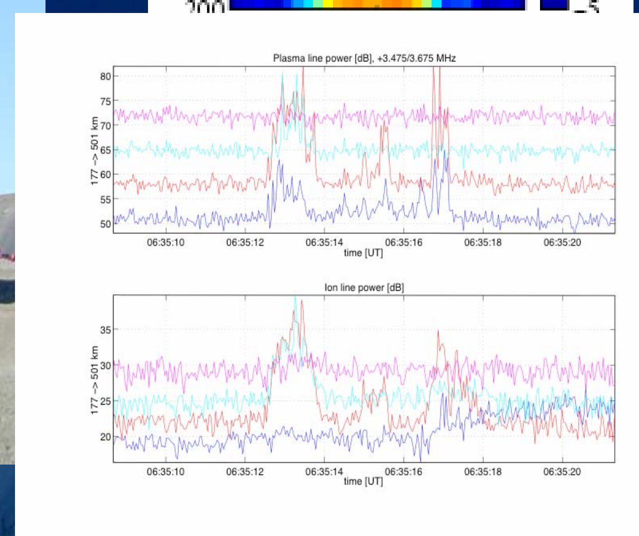
From "Radio Studies of Solar-Terrestrial Relationships" by LOIS Science Team Edited by Bo Thidé 2002

magnetosphere



Small Scale Observations with the EISCAT Radars



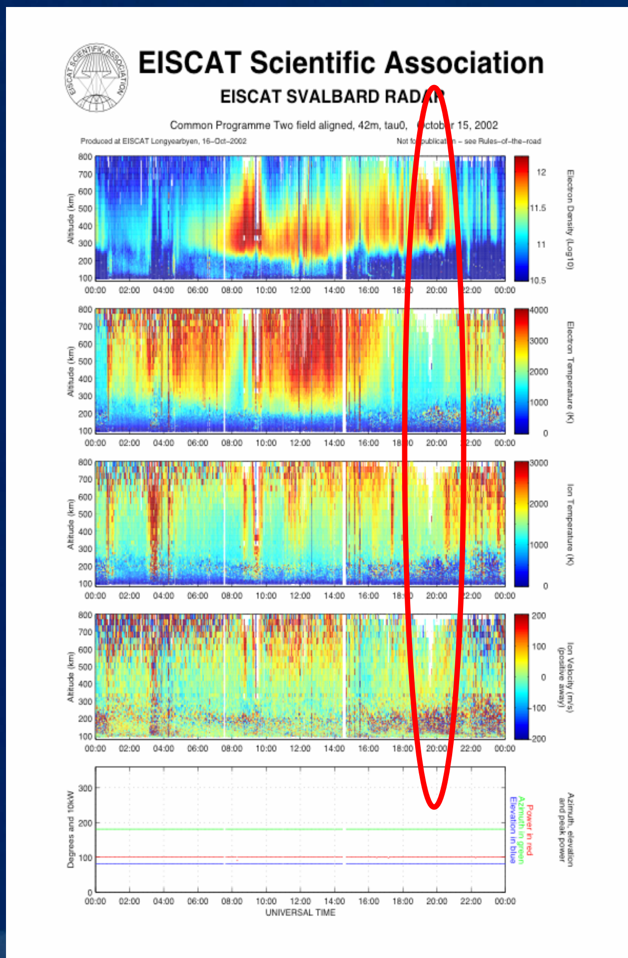


How small are "small scales?"

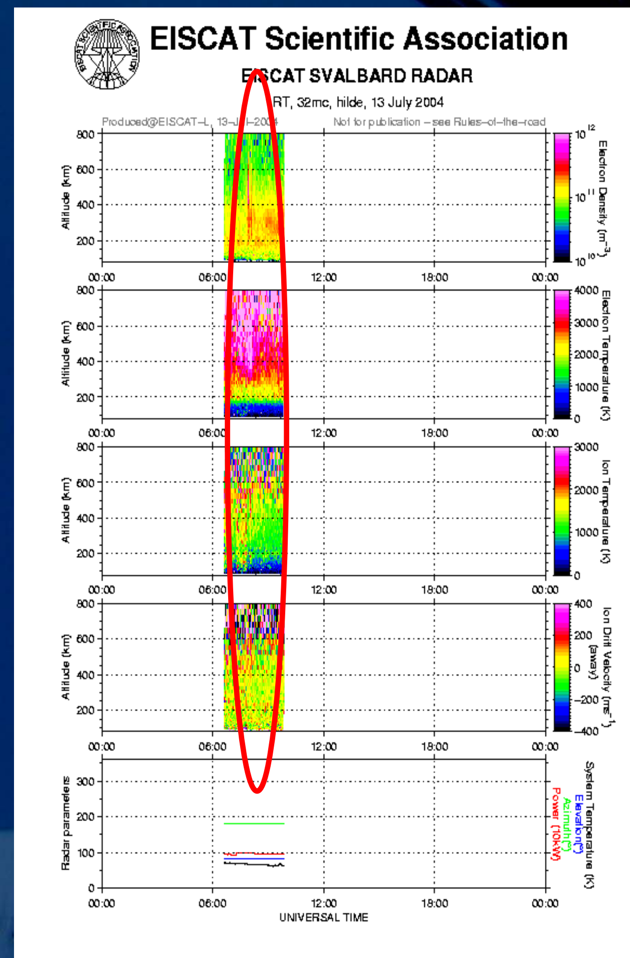
- In this talk, the term small scales refers to both spatial and temporal structures
  - Spatial: Significantly smaller than the radar beam
    - horizontal width of ~10-100 meters
  - Temporal: Shorter than traditional pre-integration time - on the order of a few IPP-length
    - temporal variations of ~0.1 seconds

Motivation for Small Scale Studies (1)

Guisdap does not fit

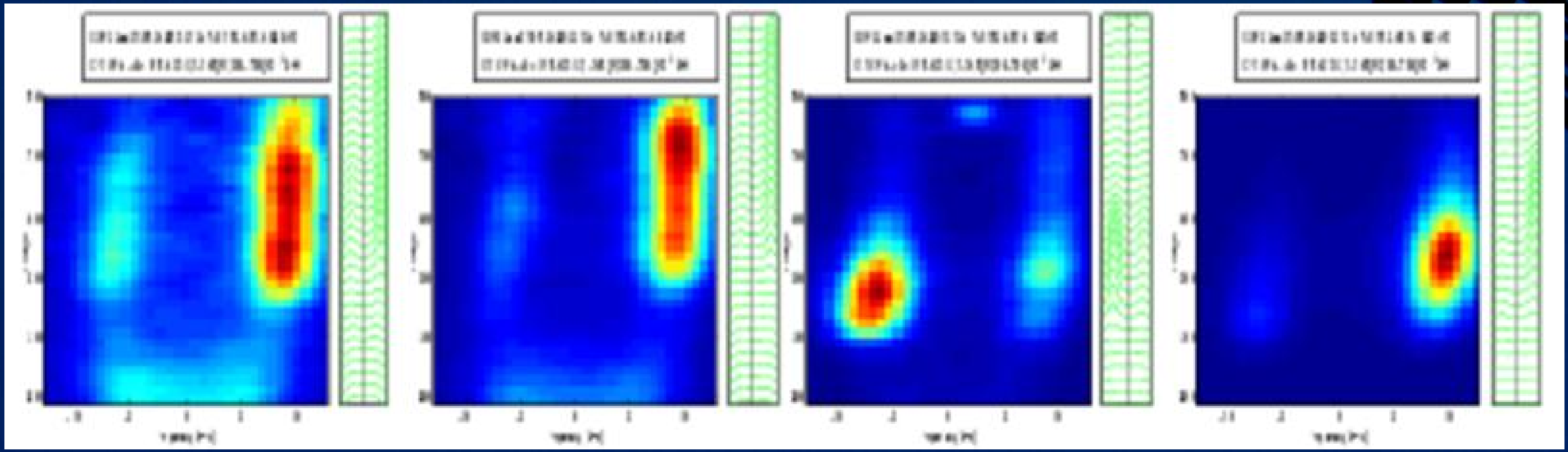


...or even worse: it does!



Motivation for Small Scale Studies (2)

Temporal......



Ion line spectra from the EISCAT Svalbard Radar for 4 consecutive 10s data dumps

Motivation for Small Scale Studies (3)

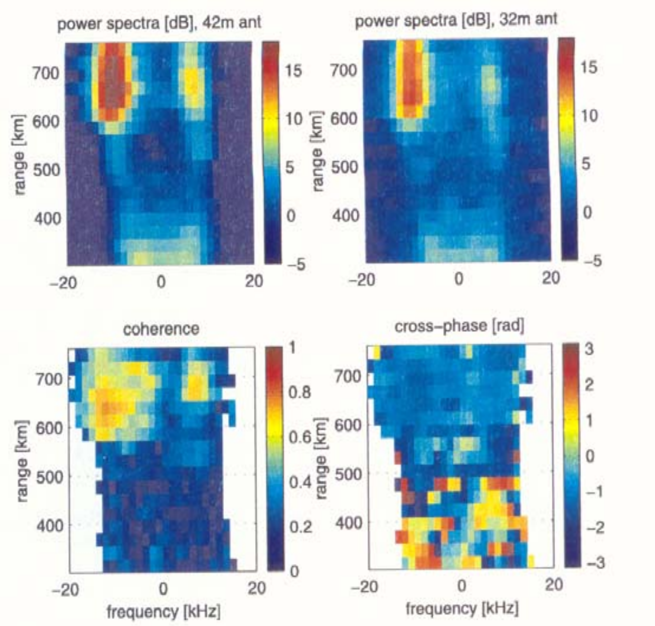


Figure 4. Powerspectra for the two antennae, the coherence and the cross-spectrum phase for an entire profile, this one from a 0.2 s integration starting at 06:46:20.60 UT.

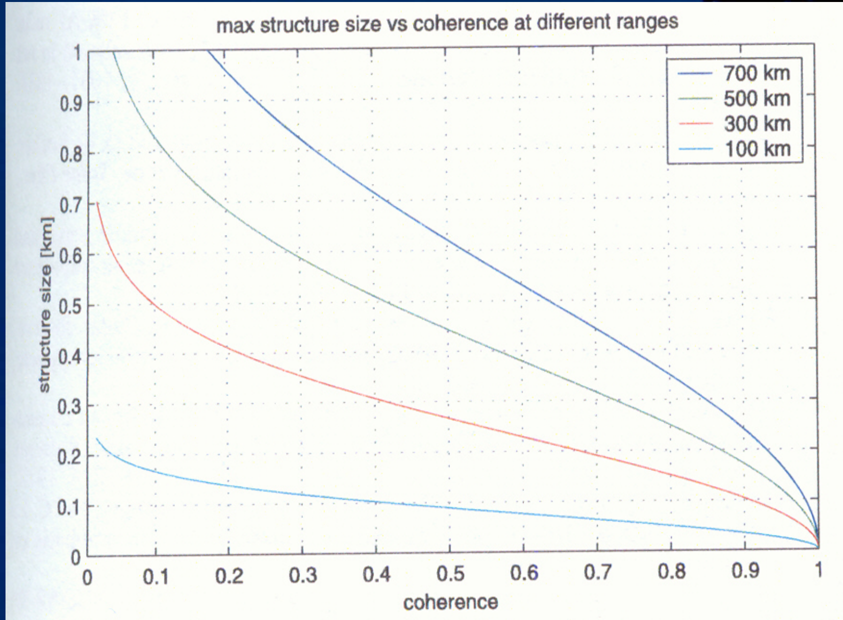
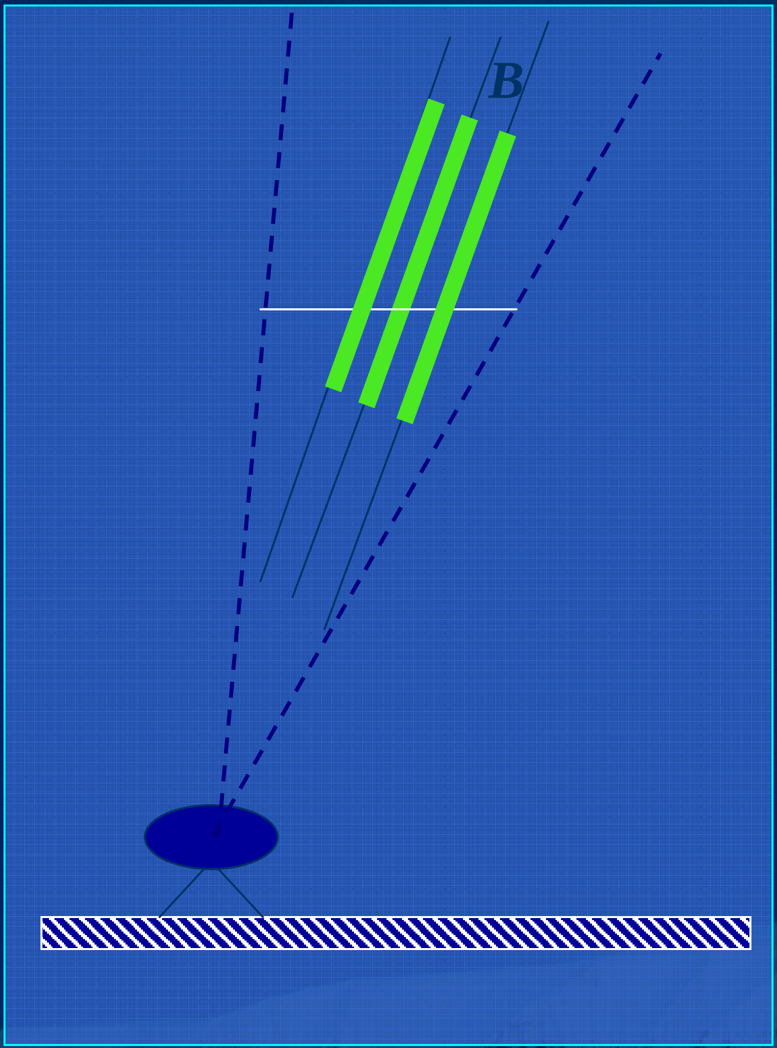


Figure 3. Structure size (in km) vs. coherence for altitudes 100, 300, 500 and 700 km, disregarding all other sources of lowered coherence.

Grydeland et al. 2003 (GRL)

Grydeland et al 2004 (Ann. Geophys.)

Interferometry



An IS radar can not directly resolve structures smaller than the radar beam, given by beam width and pulse length

If coherent structures exist within the radar beam, interferometric methods can be used to resolve them

Observations with the ESR 2 antenna interferometer, estimating the horizontal size of the scattering structure to be on the order of a hundred meters. The increased scattering hence originates from as little as 0.3% of the scattering volume, giving a actual enhancement of 4 to 5 order of magnitudes.

Conclusion