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International Advanced School
on
Space Weather
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Transionospheric Propagation: Radio tomography, signatures of space weather

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Transionospheric Propagation:

Radio tomography, signatures of space weather

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16 May 2006

Transionospheric Propagation

- Earth / space communication

Outline – Lecture 2

- Radio tomography
  - Imaging ionospheric electron density
- Effects of space weather
  - High-latitude ionosphere

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Tomographic Imaging

- Obtain image from its projections
- Line integrals along intersecting ray paths
- Mathematical ideas long understood
- Development of computers in 1960s
- CAT scanners
- Successes in medical diagnostics
- Applications to geophysics
- Radio tomography of ionosphere
- New experimental technique

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Ionospheric Tomography

- Use radio signals from satellites
- Receive at chain of ground stations
- Measure line integral of electron density (TEC)
- TEC along intersecting ray paths
- Invert data sets in reconstruction algorithm
- Obtain 2D image of electron density
- Large-scale spatial structure of ionosphere

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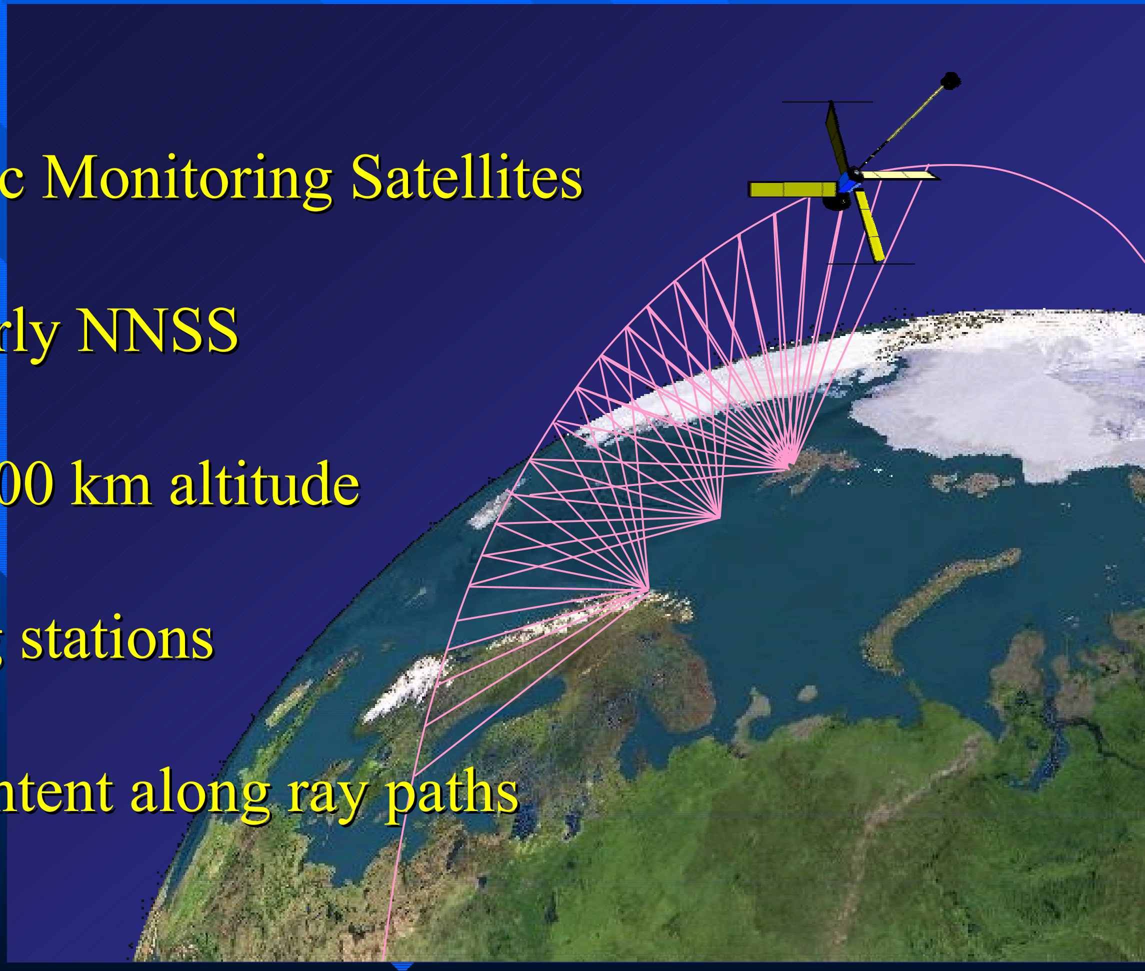
Spatial Structure in Ionosphere

- Why develop radio tomography?
- Most experimental techniques give *time* series
- Tomography gives *spatial* images
- Wide-area cover from limited ground stations
- Remote and inaccessible regions
- TEC gradients important
- Possible errors in radio system operation

Radio Tomography using LEO Satellites

- NIMS – Navy Ionospheric Monitoring Satellites
- up to six satellites, formerly NNSS
- circular polar orbits at 1100 km altitude
- chain of ground receiving stations
- measure total electron content along ray paths



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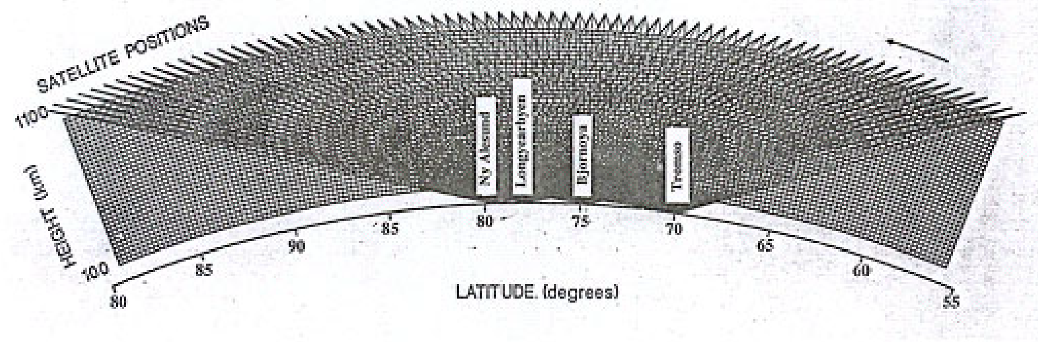
Radio Tomography - Reconstruction



Total Electron Content along Ray Paths	=	Geometry of Path / Pixel Intersections	×	Electron Densities in Pixels
↑		↑		↑
Measured		Calculated from Satellite and Station Locations		Unknowns

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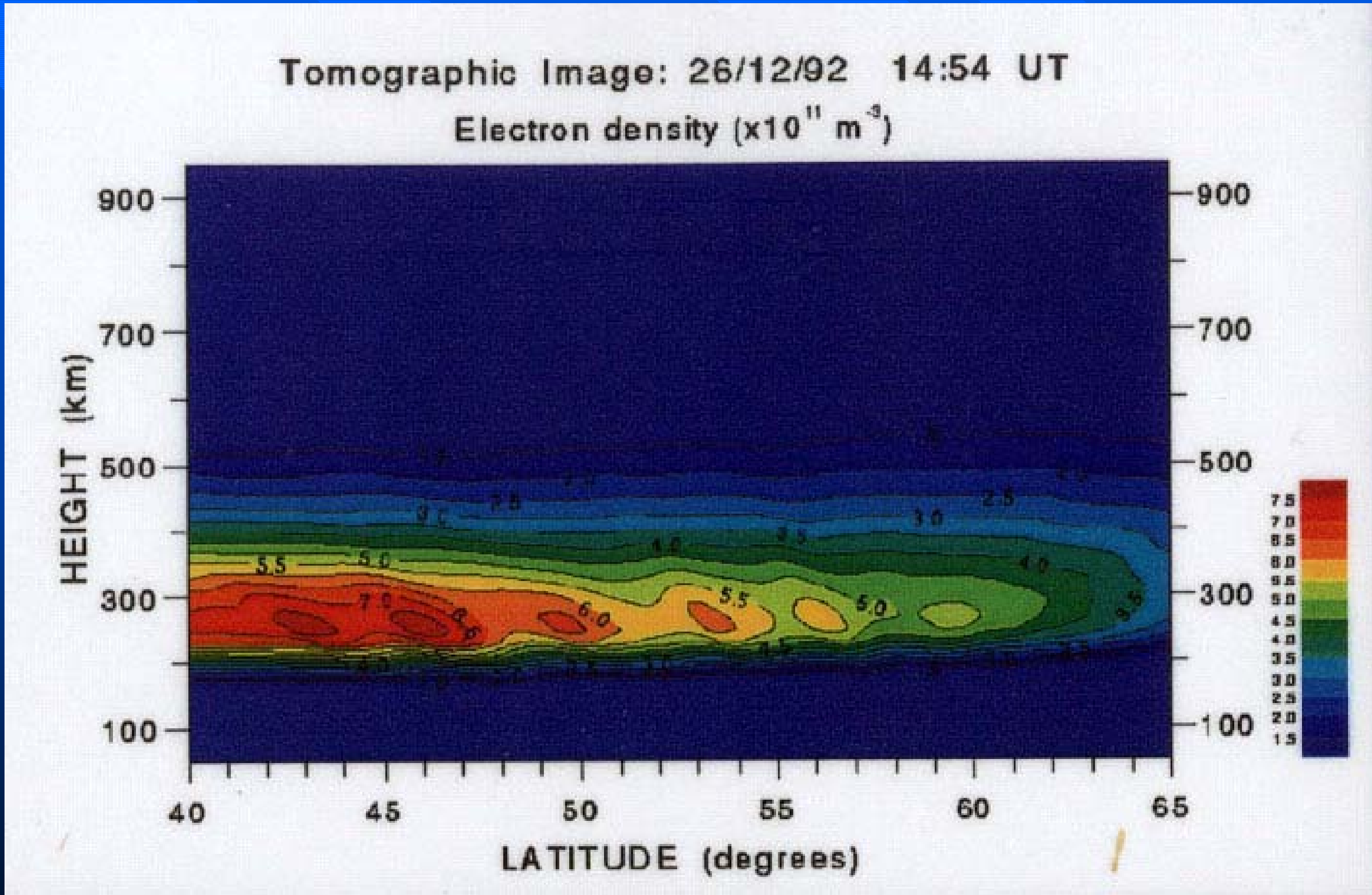
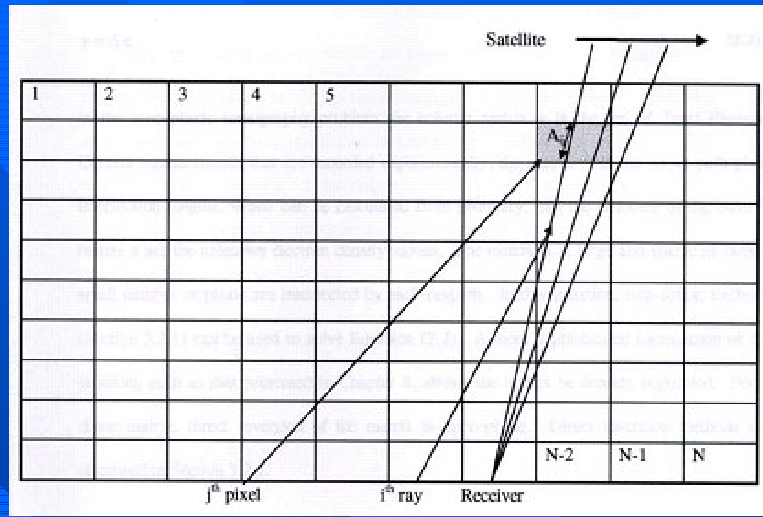
Tomographic Image



Basics of ionospheric tomography - pixels

A_{ij} length of *i* th ray path in *j* th pixel

x_j electron density in *j* th pixel



y_i electron content along *i* th ray path is approximated by

$y_i = \sum A_{ij} x_j$, summed from $j = 1$ to N

For all ray paths between satellite and ground stations

M such simultaneous equations

In matrix notation:

$$\mathbf{y = Ax}$$

y - *slant total electron content measurements*

x - *unknown electron densities*

- ***The problem for ionospheric tomography is to solve this equation to find the electron densities***

Tomographic Algorithms - Iterative

- Early algorithms used *Row Action Methods*
    - *Iterative* solutions
    - Successive corrections to an assumed initial *Background Ionosphere*

- *ART (Algebraic Reconstruction Technique)*

After k iterations the set of electron densities is given by

$$\mathbf{x}_{k+1} = \mathbf{x}_k + \lambda_k \frac{\mathbf{y}_i - (\mathbf{x}_k, \mathbf{a}_i)}{\|\mathbf{a}_i\|_2} \mathbf{a}_i$$

where

$$\|\mathbf{a}_i\|_2 \equiv (\mathbf{a}_i, \mathbf{a}_i) = \left(\sum_j A_{ij}^2 \right)$$

with $\mathbf{a}_i$ representing the *i* th row of **A** and λ_k a relaxation constant <1

Tomographic Algorithms – Direct Inversion
Discrete Inverse Theory (DIT)

- Many different mathematical techniques have been used by different workers
- Finding an appropriate *background ionosphere* to initialise any algorithm is the *key to ionospheric tomography*
- Use extension of DIT method of Fremouw et al. (1992 and 1994) to obtain *background ionosphere*
- Described by linear combination of a number of *basis functions* with different *weightings*

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Two-Stage Reconstruction Process

1. Find *large-scale structure*: Extension of the method of Fremouw et al. (1992 and 1994). Non-iterative approach of Discrete Inverse Theory (DIT).

Vertical structure: Six empirical orthogonal functions (EOFs) obtained from a large set of Chapman profiles. For each 1 degree latitude, the vertical plasma distribution is described in terms of a combination of the EOFs.

Horizontal structure: Plasma distribution represented by Fourier expansion, weighted by the constraint of a one-dimensional power law.

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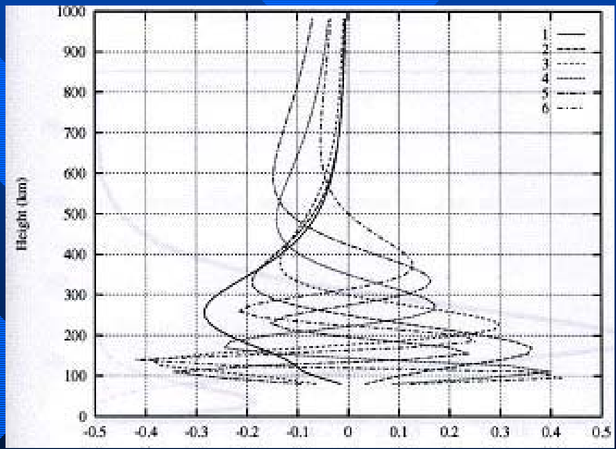
First Stage of Reconstruction

To obtain *basis functions*

- vertical form: Chapman profiles of E and F regions
  - spanning complete range found in data set of
    - peak heights,
    - scale heights and
    - scale-height gradients in topside
- horizontal structure: Fourier series with power-law taper



- Use *truncated Singular Value Decomposition (SVD)* to obtain set of *Empirical Orthonormal Functions* (EOFs) to form *basis.*
- *Background ionosphere* can be described by *linear combination* of these with different *weightings*

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Tomography Algorithms – Discrete Inverse Theory

Background ionosphere described by *linear combination* of a number of *basis functions* with different *weightings*

$$\mathbf{b} = \mathbf{B}\,\mathbf{x}$$

b - the *electron density* values in pixels,
B - *basis functions* representing ionosphere
x - *weight* given to each basis function

Using **H** - *geometry* matrix of path/pixel intersections
y - *measured TEC* ≈ TEC through background (HBx)

Thus $\mathbf{y} = \mathbf{H}\,\mathbf{B}\,\mathbf{x}$ or $\mathbf{y} = \mathbf{A}\,\mathbf{x}$

where now $\mathbf{A} = \mathbf{H}\,\mathbf{B}$

Tomography Algorithms – Discrete Inverse Theory

Need to solve **y = A x**

- Reformulate to avoid need for *absolute calibration* of measured TEC
- Use **y** as *differences* in TEC between successive ray paths, that is, use *relative TECs*

- Solve to find **x** - *the weight given to each basis function in the linear combination that best describes the background ionosphere,* consistent with the measured TEC

$$\hat{\mathbf{x}} = \mathbf{x}_0 + \mathbf{C}_{\mathbf{x}_0\mathbf{x}_0}\mathbf{A}^T\left(\mathbf{C}_{\mathbf{y}_0\mathbf{y}_0} + \mathbf{A}\mathbf{C}_{\mathbf{x}_0\mathbf{x}_0}\mathbf{A}^T\right)^{-1}\left(\mathbf{y}_0 - \mathbf{A}\mathbf{x}_0\right)$$

$$\hat{\mathbf{C}}_{\hat{\mathbf{x}}\hat{\mathbf{x}}} = \mathbf{C}_{\mathbf{x}_0\mathbf{x}_0} - \mathbf{C}_{\mathbf{x}_0\mathbf{x}_0}\mathbf{A}^T\left(\mathbf{C}_{\mathbf{y}_0\mathbf{y}_0} + \mathbf{A}\mathbf{C}_{\mathbf{x}_0\mathbf{x}_0}\mathbf{A}^T\right)^{-1}\mathbf{A}\mathbf{C}_{\mathbf{x}_0\mathbf{x}_0}$$

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Second Stage of Reconstruction

2. Find *smaller -scale structure*:

   Iterative second stage uses *background ionosphere generated by the first stage* as starting condition for *algebraic reconstruction technique (ART)* algorithm.

- Image Grid:

  Altitude: 25 km   Latitude: 0.25 degree

- Can use method to incorporate other types of ionospheric measurements - for example, ionosonde data

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Radio Tomography: Advantages and Limitations

Advantages

- New experimental technique
- Spatial images of large-scale density structures
- Wide coverage from limited ground stations
- Complementary role to other instruments

Limitations

- Understood at early stage
- Limited-angle technique, no horizontal ray paths
- Incomplete information on vertical structure
- Temporal coverage dependent on satellite orbits

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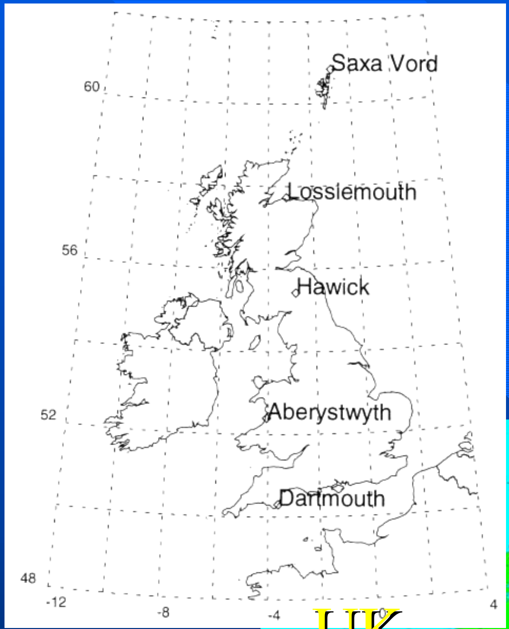
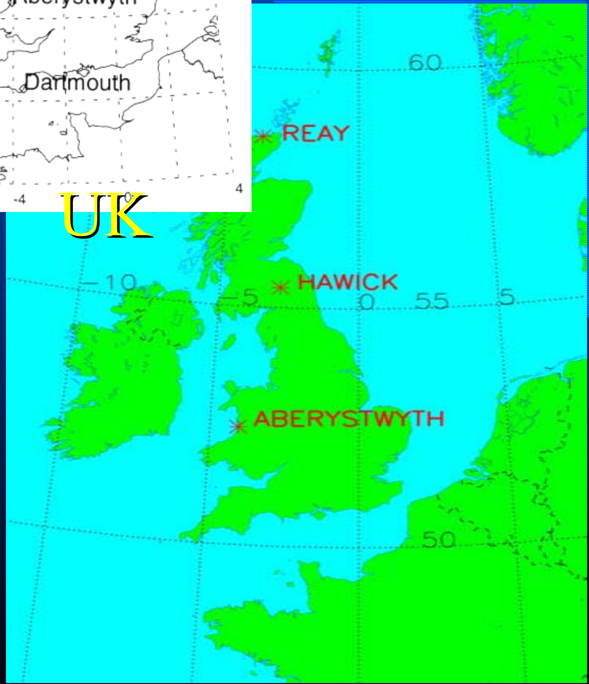
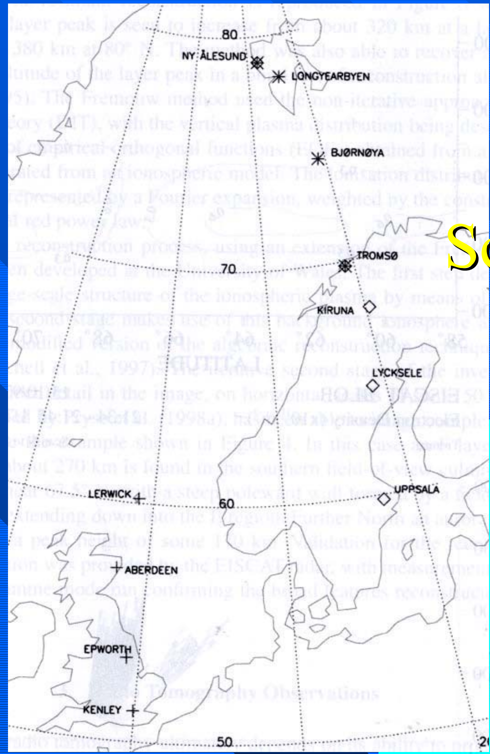
Does it work?
Experimental station chains used by UWA group





UK



Scandinavia

Svalbard

Does it work?
Verification using EISCAT radar

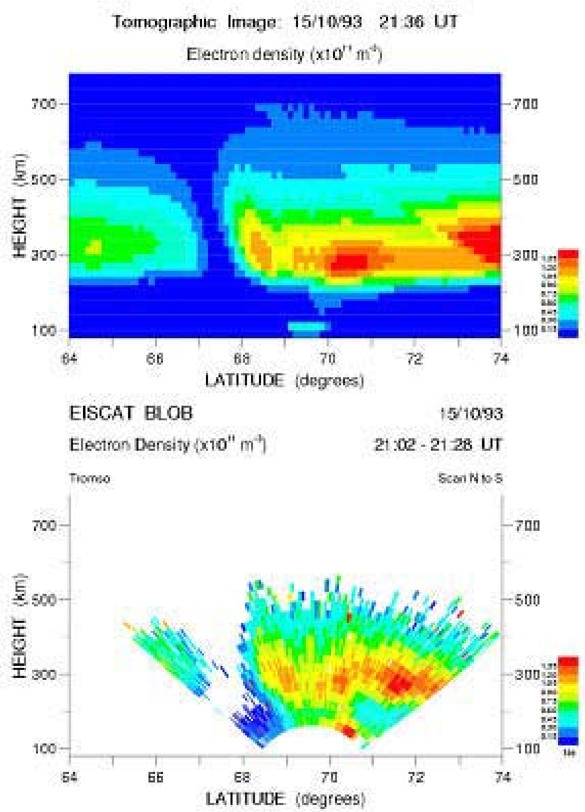


Figure 6.10. Tomographic image of electron density for the pass at 21:36 UT using 20 ray paths per degree movement of the satellite (upper plot) and the electron densities obtained from the EISCAT BLOB scan between 21:02 and 21:28 UT (lower plot) on 15 October 1993.

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Radio Tomographic Imaging: Applications to practical radio systems

- Complementary to ionosonde measurements
- Validation of ionospheric models
- Mapping of ionospheric parameters
- Oblique sounding
- HF ray tracing
- HF direction finding
- Space weather

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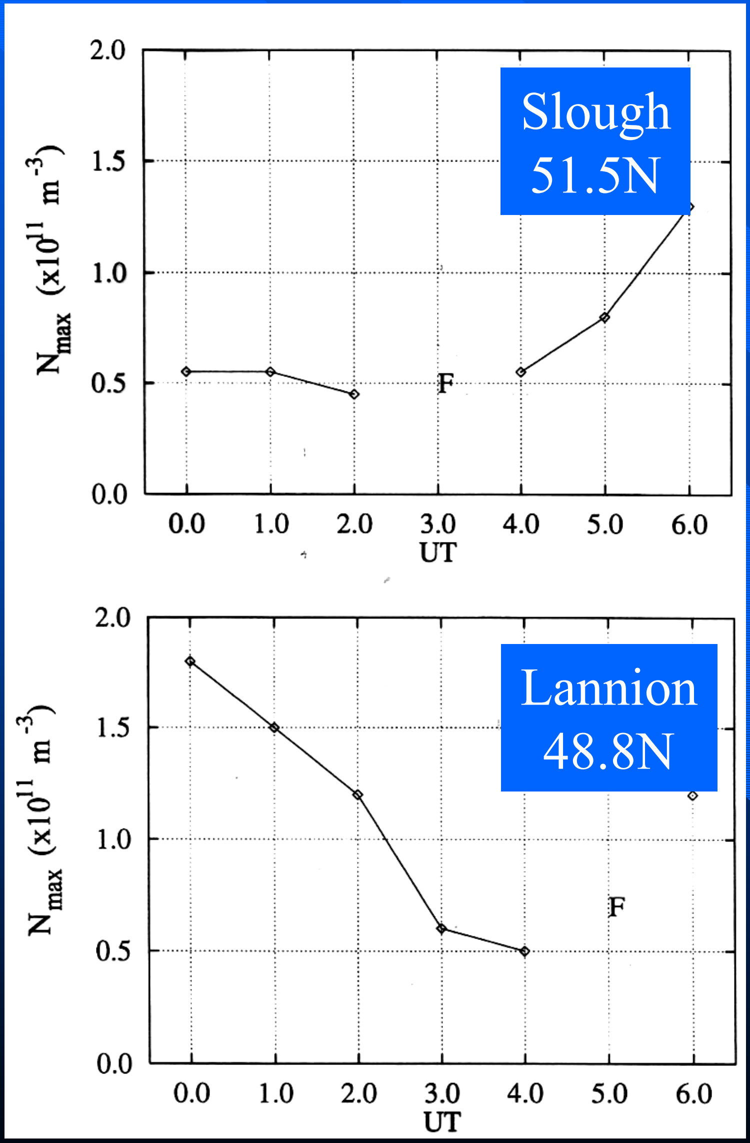
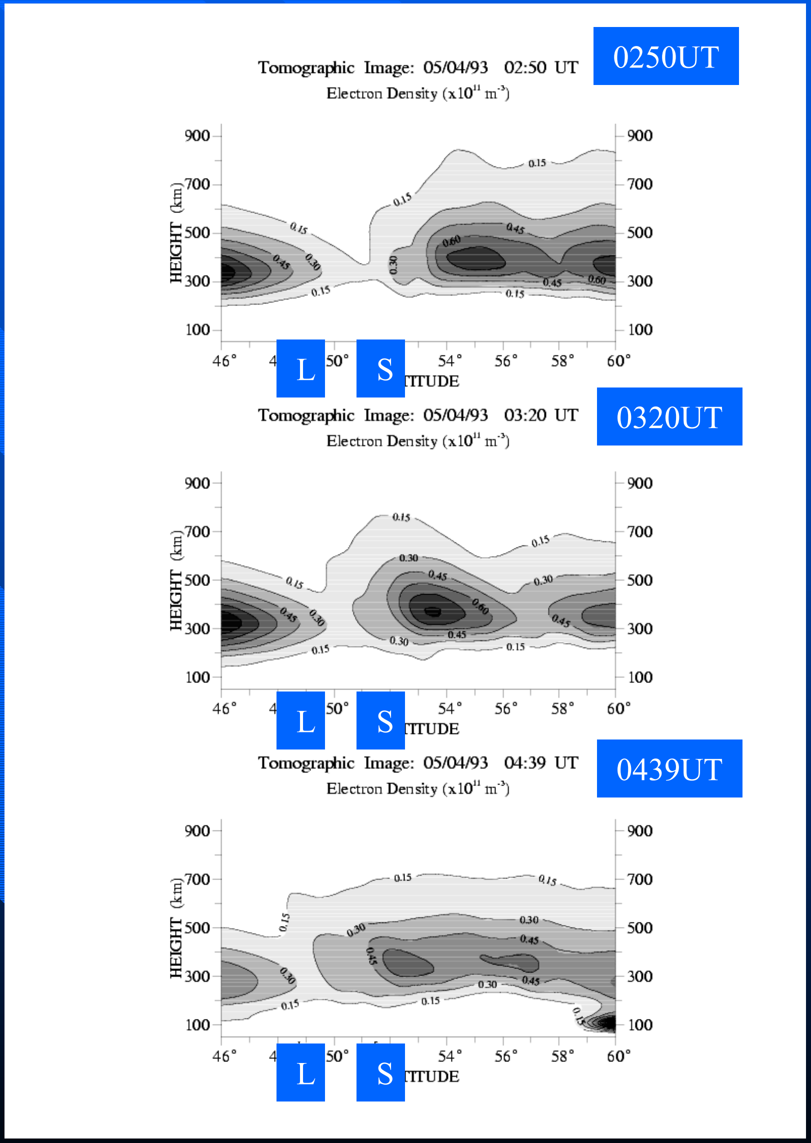
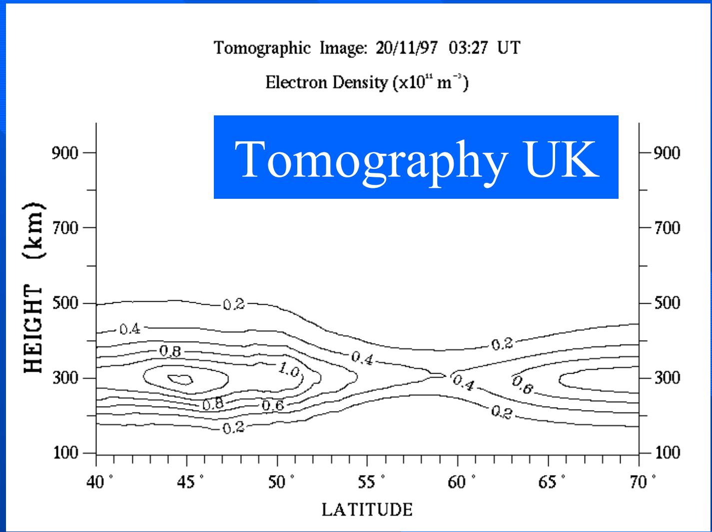
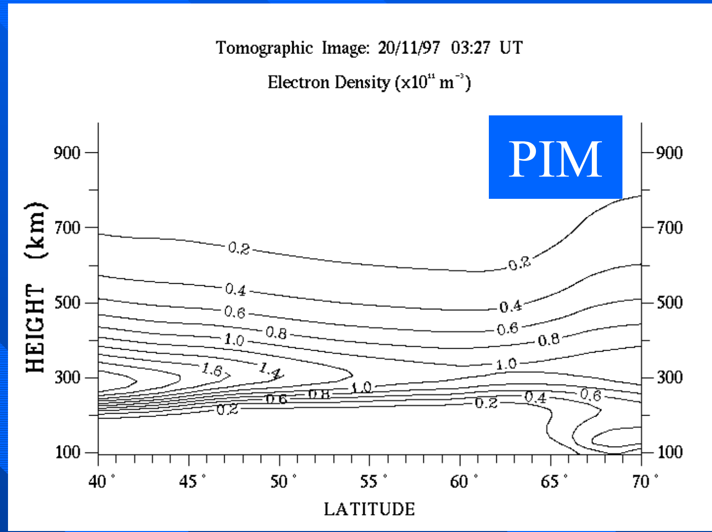
Radio Tomography and Ionosondes

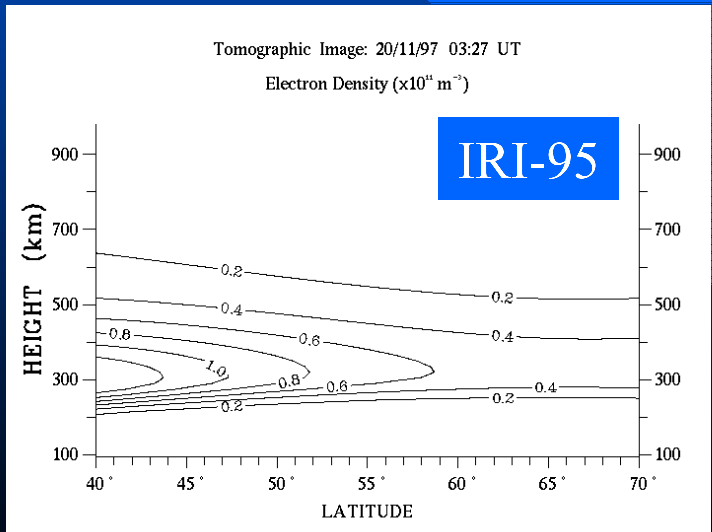


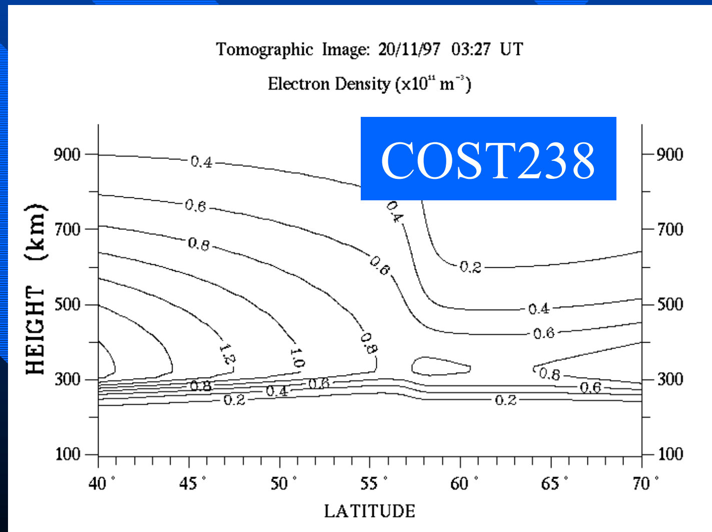


Tomography and Testing of Empirical or Parameterised Models



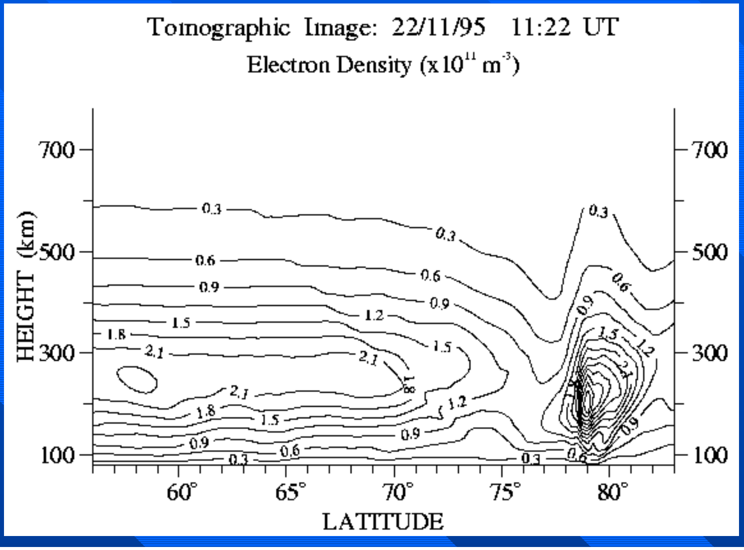


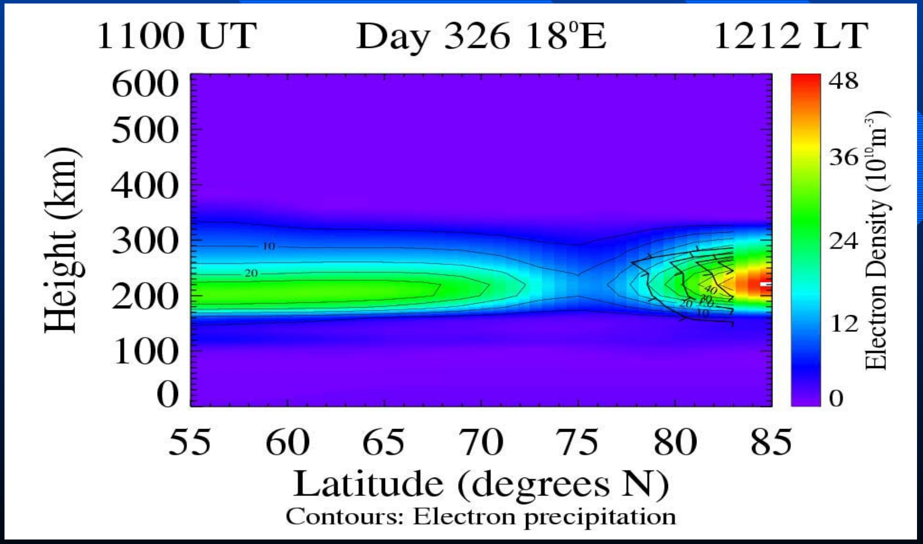




Dabas and Kersley (2003)

Model Validation - Coupled Thermosphere Ionosphere Plasmasphere Model (SUCTIP)

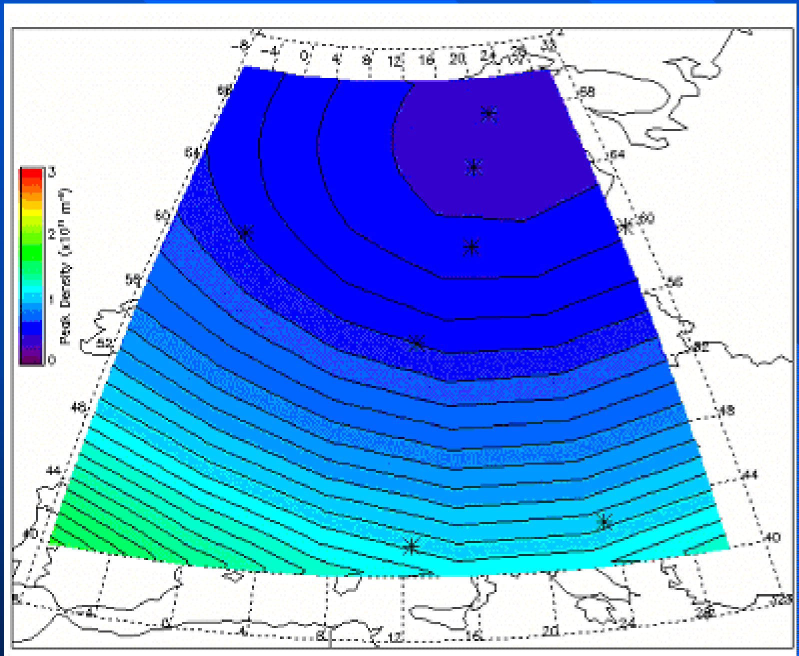




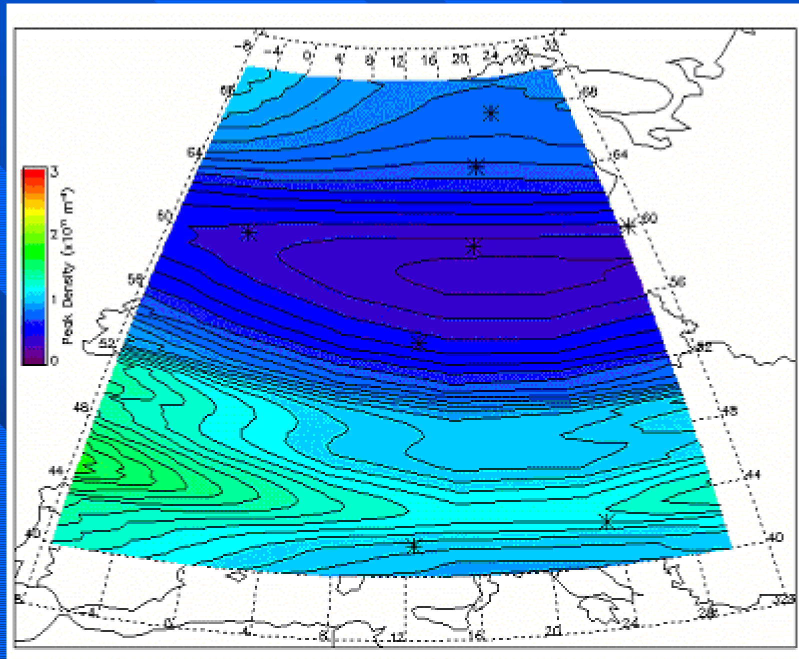
Idenden et al. (1999)

Radio Tomographic Imaging: Applied to mapping of ionospheric parameters

Maps of peak electron density (NmF2) over Europe



a) IRI-95 alone



b) IRI-95 plus tomography

Dabas and Kersley (2003)

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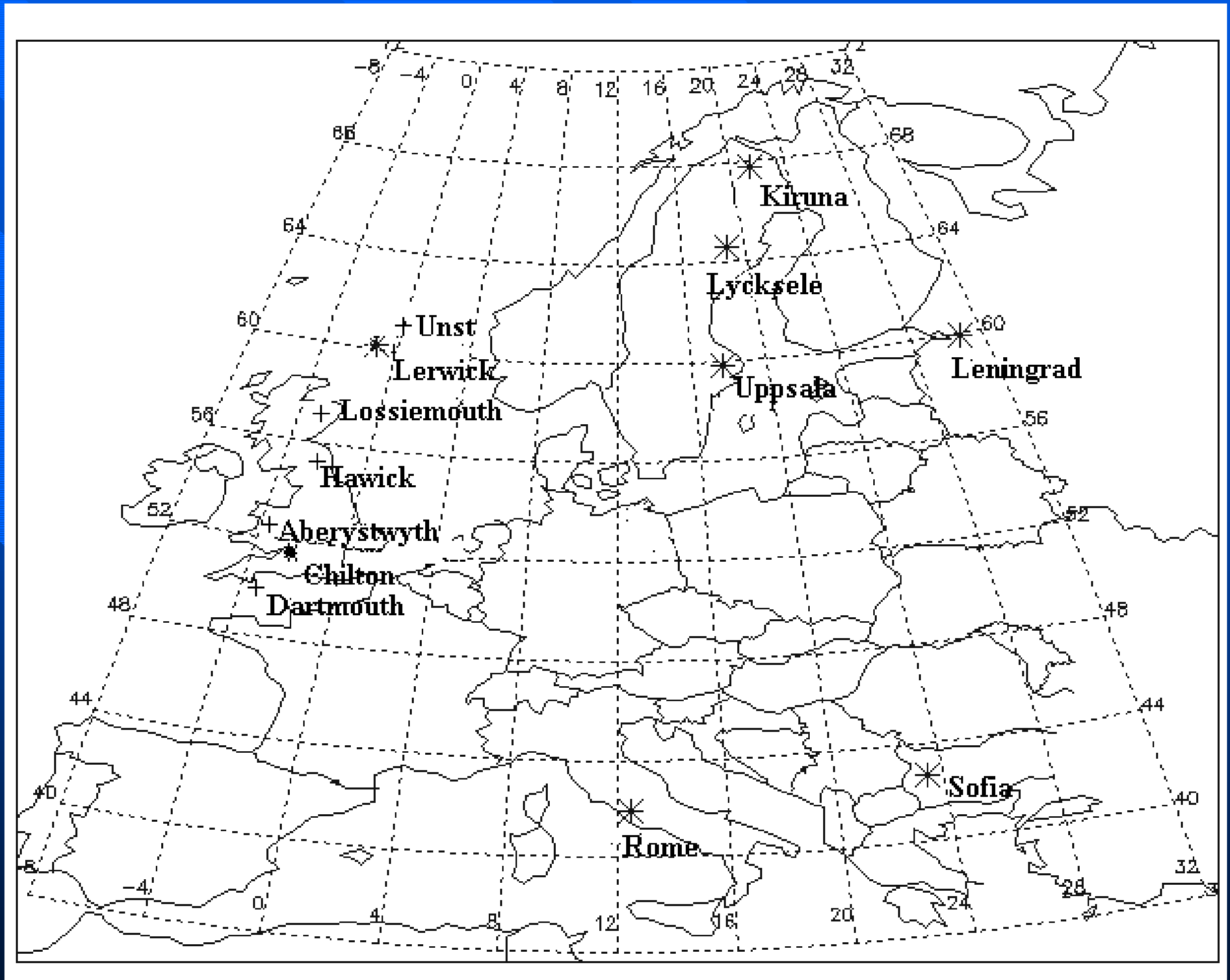
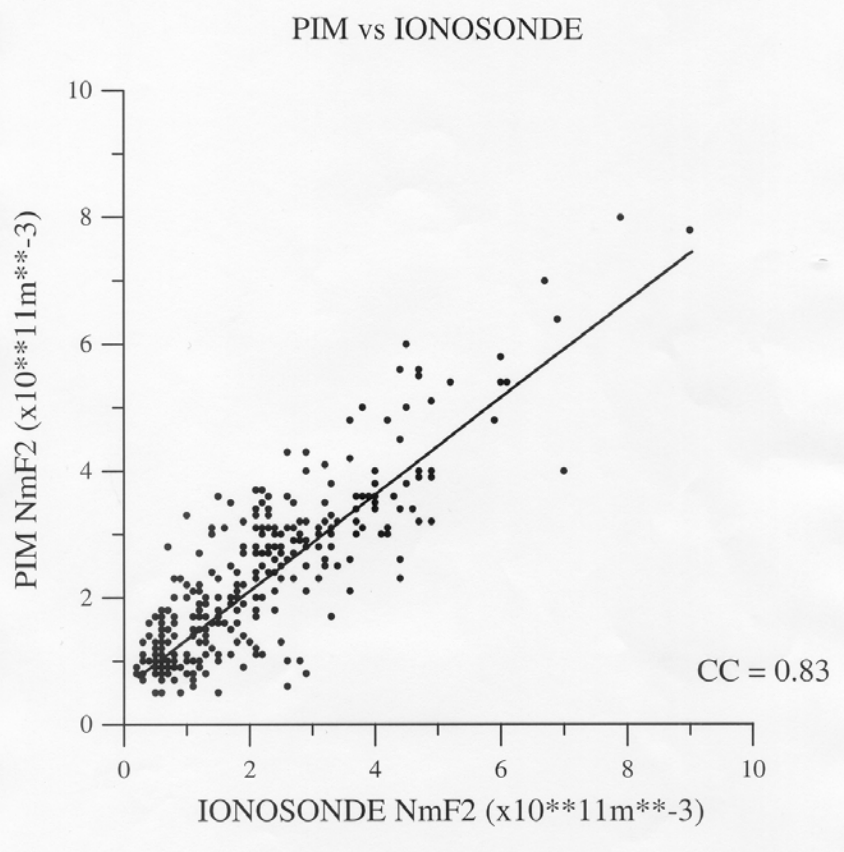
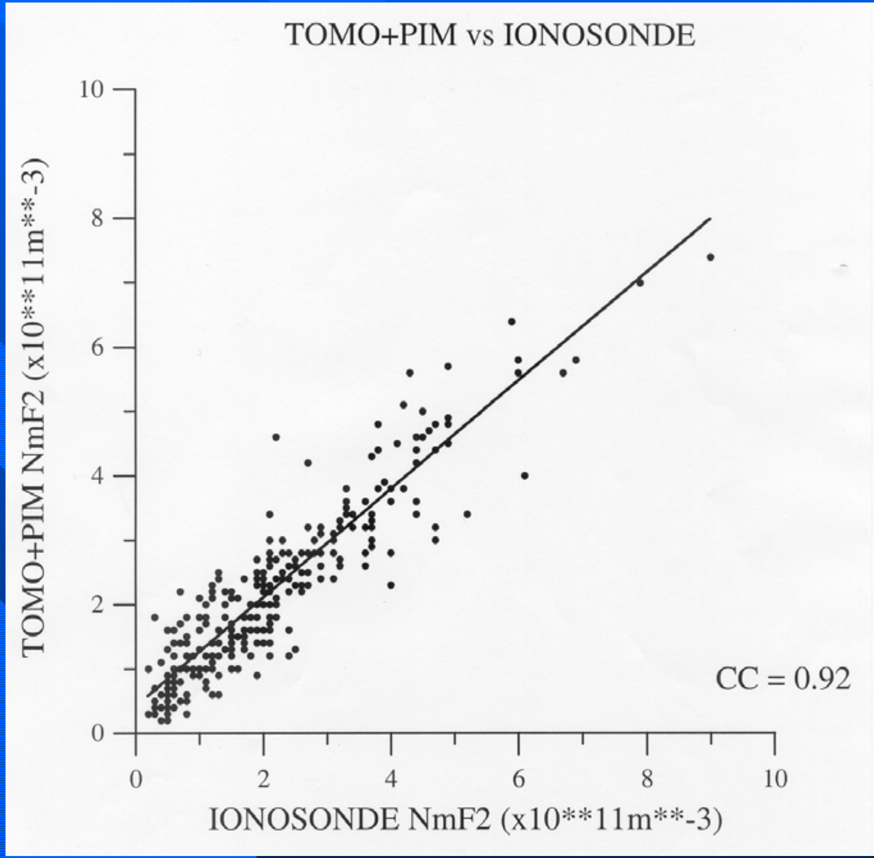
Validation of foF2 Maps

- Tomography from UK stations + Chilton ionosonde
- Validation using ionosondes near trough and at mid-latitudes



Validation of Maps using Ionosondes





- Use of tomographic image gives better agreement with ionosonde foF2 than any of the models alone
- Potential for nowcasting

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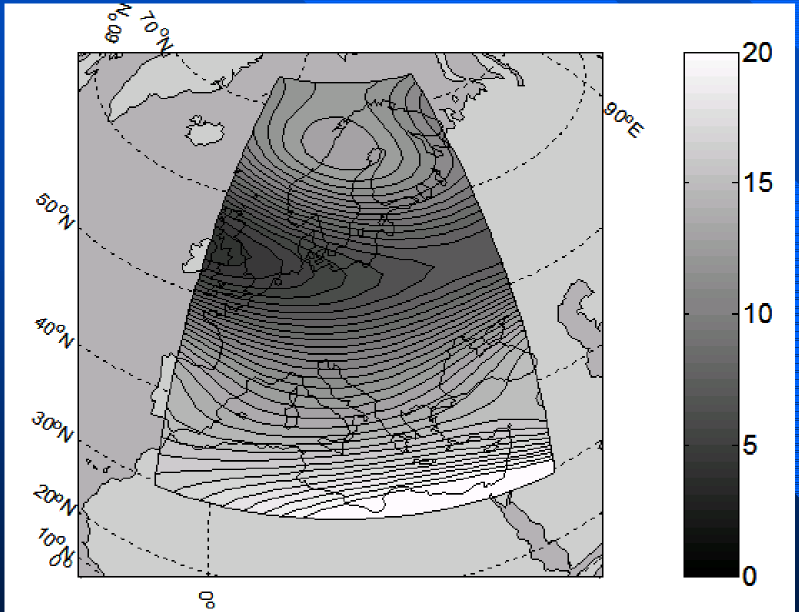
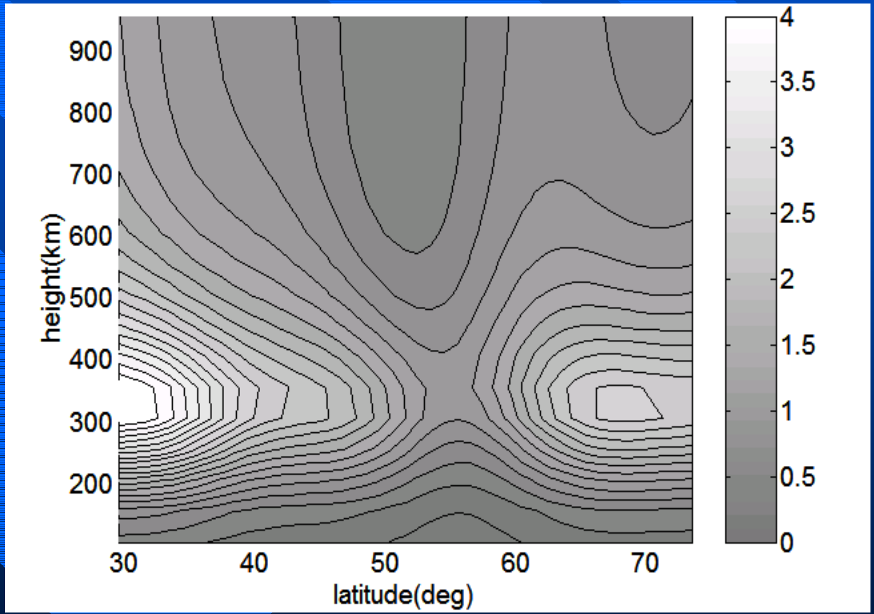
Other forms of ionospheric 'tomography'

- Statistical imaging of ionospheric irregularities
- GPS imaging



TEC map

- Follow temporal changes



Electron density image

- Limited height resolution

Transionospheric propagation and space weather

- Space weather and the solar wind
  - IMF
  - reconnection
  - convection
- Plasma structures at high latitudes
- Signatures of space-weather processes
  - reconnection
  - aurorae
  - tongues, patches and holes
  - main trough and boundary blobs
  - storms, SEDs and mid-latitude features

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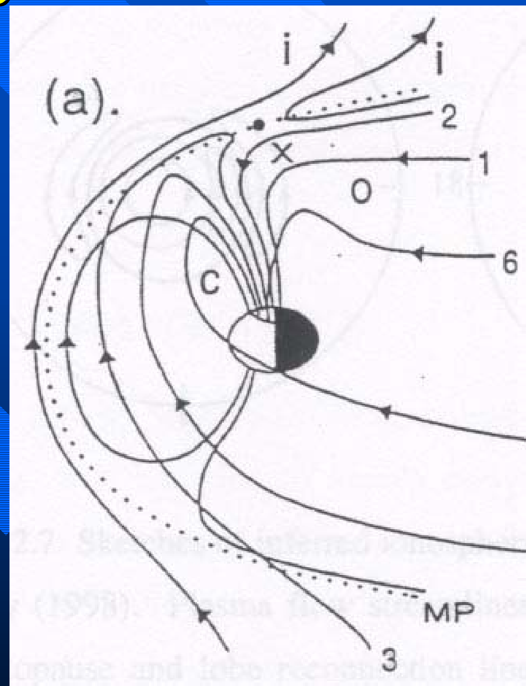
Space weather and high-latitude ionosphere

- Magnetic field lines
  - ‘railway lines’ and ‘telephone wires’ of space

- Field lines converge in high-latitude ionosphere
  - different plasma populations
  - widely separated regions of space
  - in close proximity

- High-latitude ionosphere
  - spatially and temporally variable

- Tomographic images
  - spatial structure of plasma
  - information about space-weather processes far out in space



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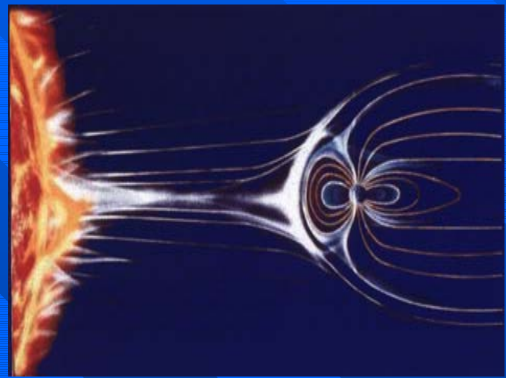
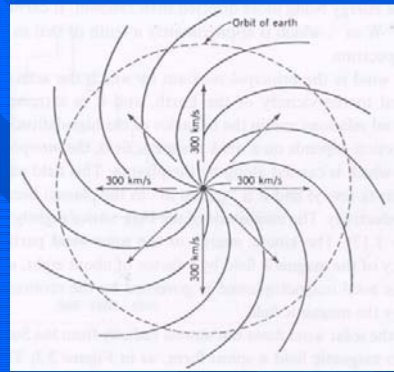
Space Weather

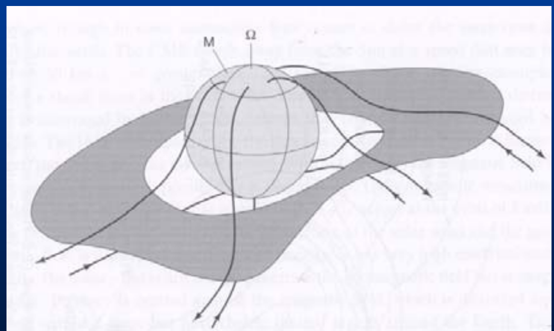




Sun and CMEs

Solar wind

'Garden-hose effect

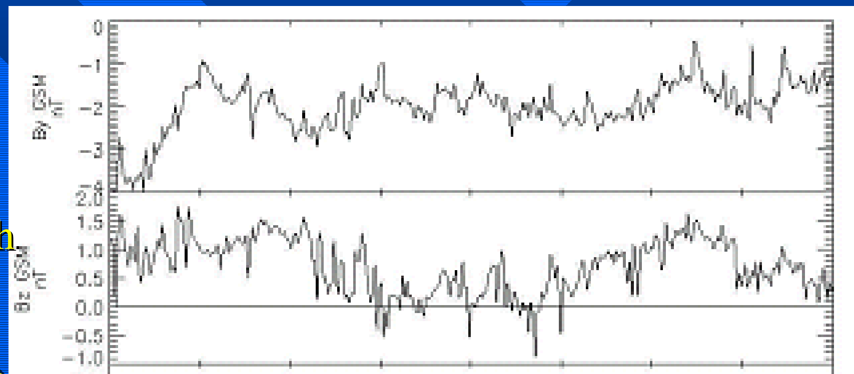


B_y

+north

B_Z

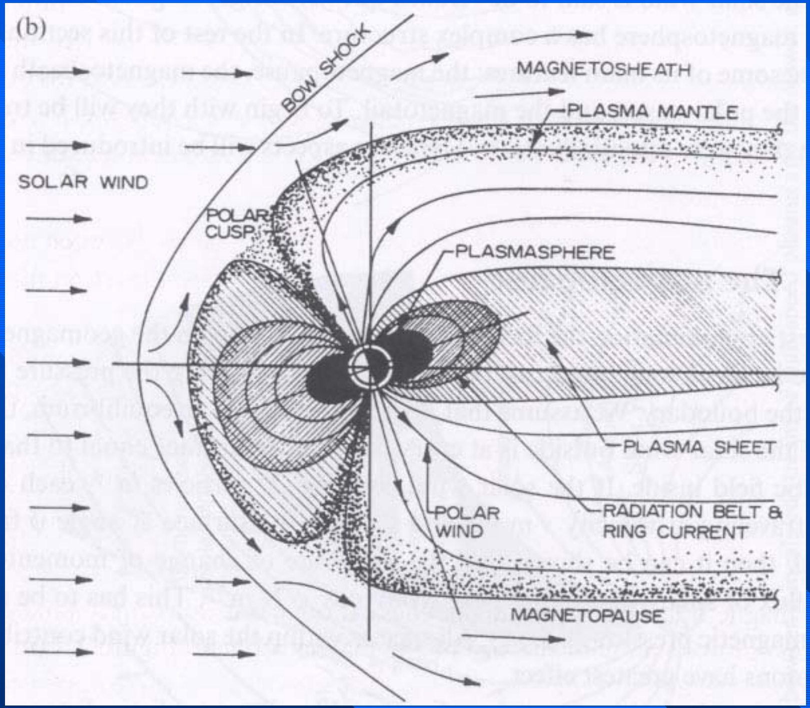
-south



'Ballerina' model

Interplanetary magnetic field (IMF)

Space Weather and the Earth



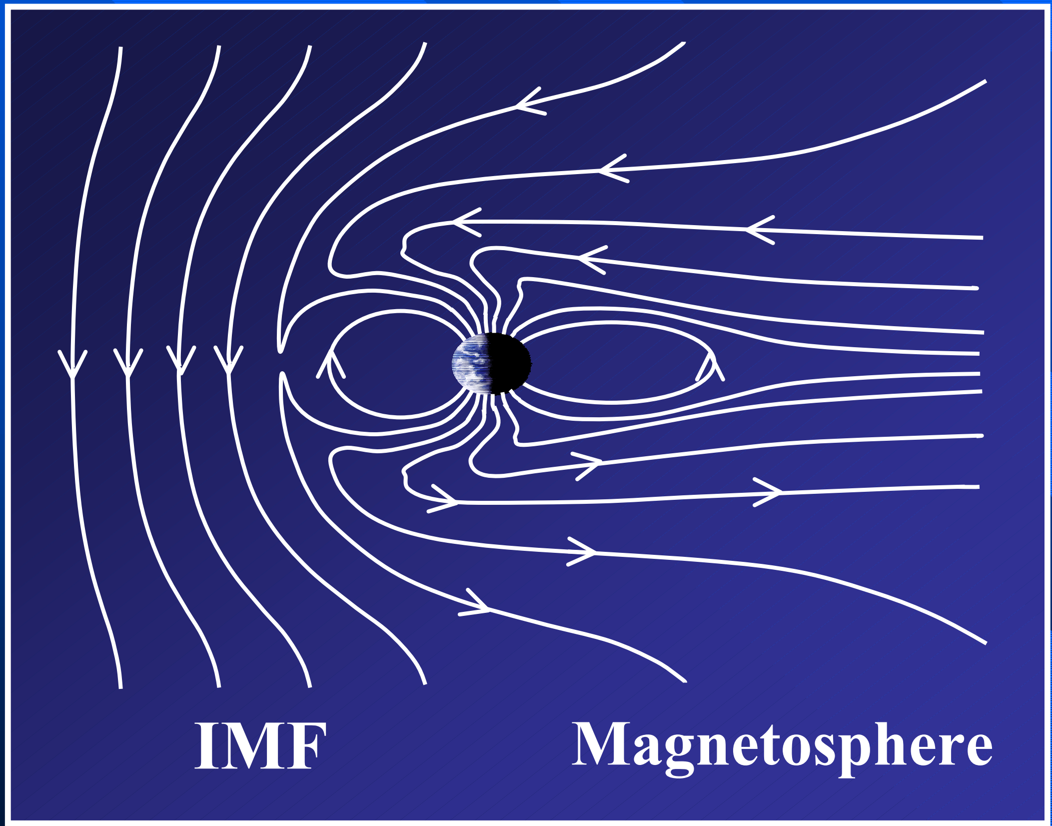
Geomagnetic cavity

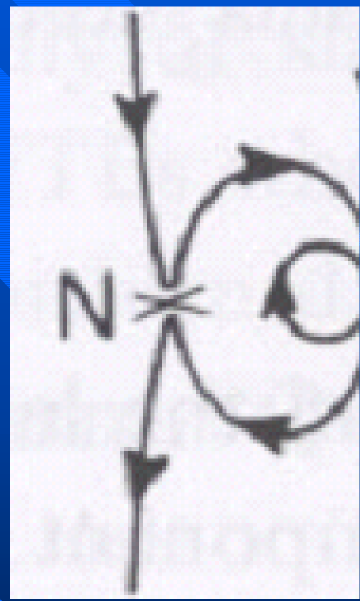
- distortion of geomagnetic field
- polar cusps
- ‘open’ and ‘closed’ field lines
- reconnection

Reconnection

Interplanetary magnetic field (IMF) *southward*

B_Z *negative*



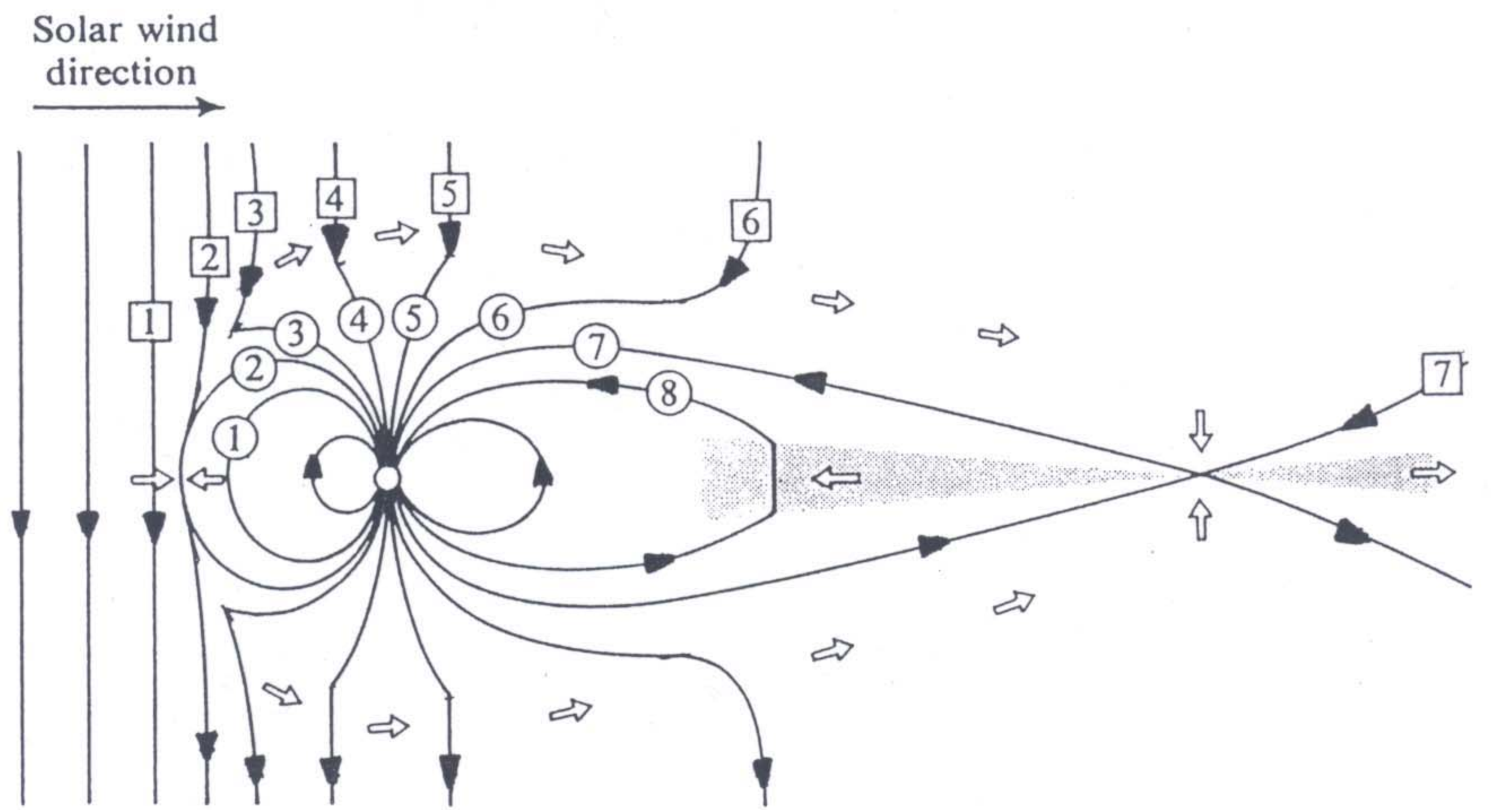


Neutral point

Flux transfer event

FTE

IMF *southward* , B_z *negative*
Reconnection near *equatorial* plane



Evolution of merged magnetic field lines being swept back

Reconnection and the high-latitude ionosphere

↑ Sun

Southward IMF
B_z *negative*

12

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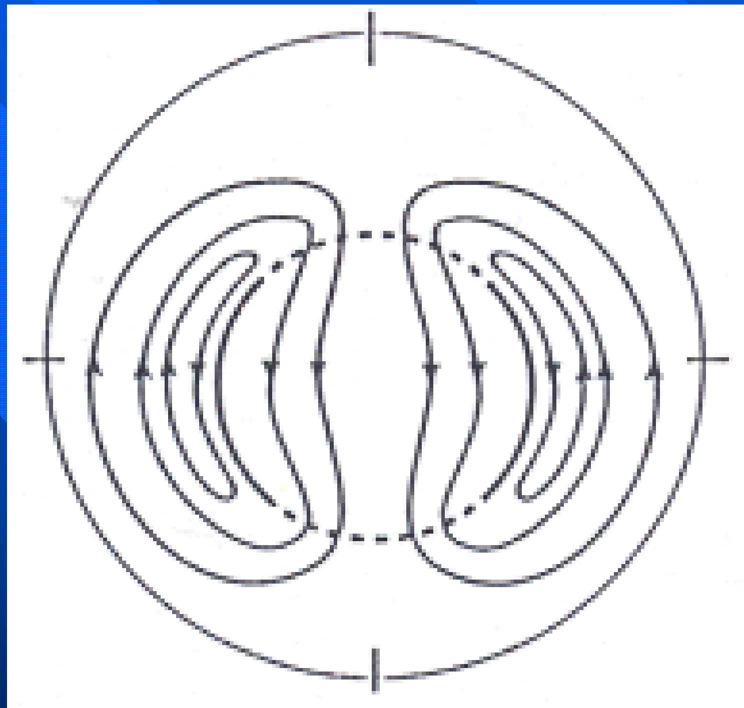

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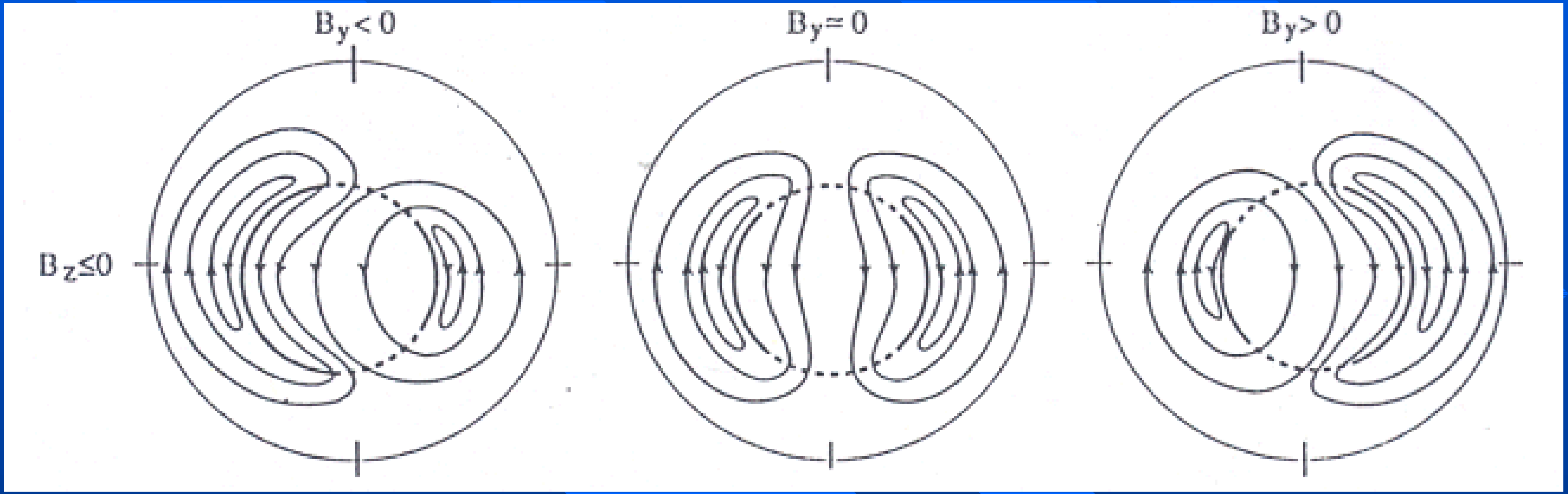
Polar plot

Magnetic Local Time
vs
Magnetic Latitude

- Open polar cap – entry of plasma from dayside
- Fast anti-sunwards flow of plasma across polar cap
- Return flows at lower latitude

ExB plasma convection

Convection patterns and IMF B_y

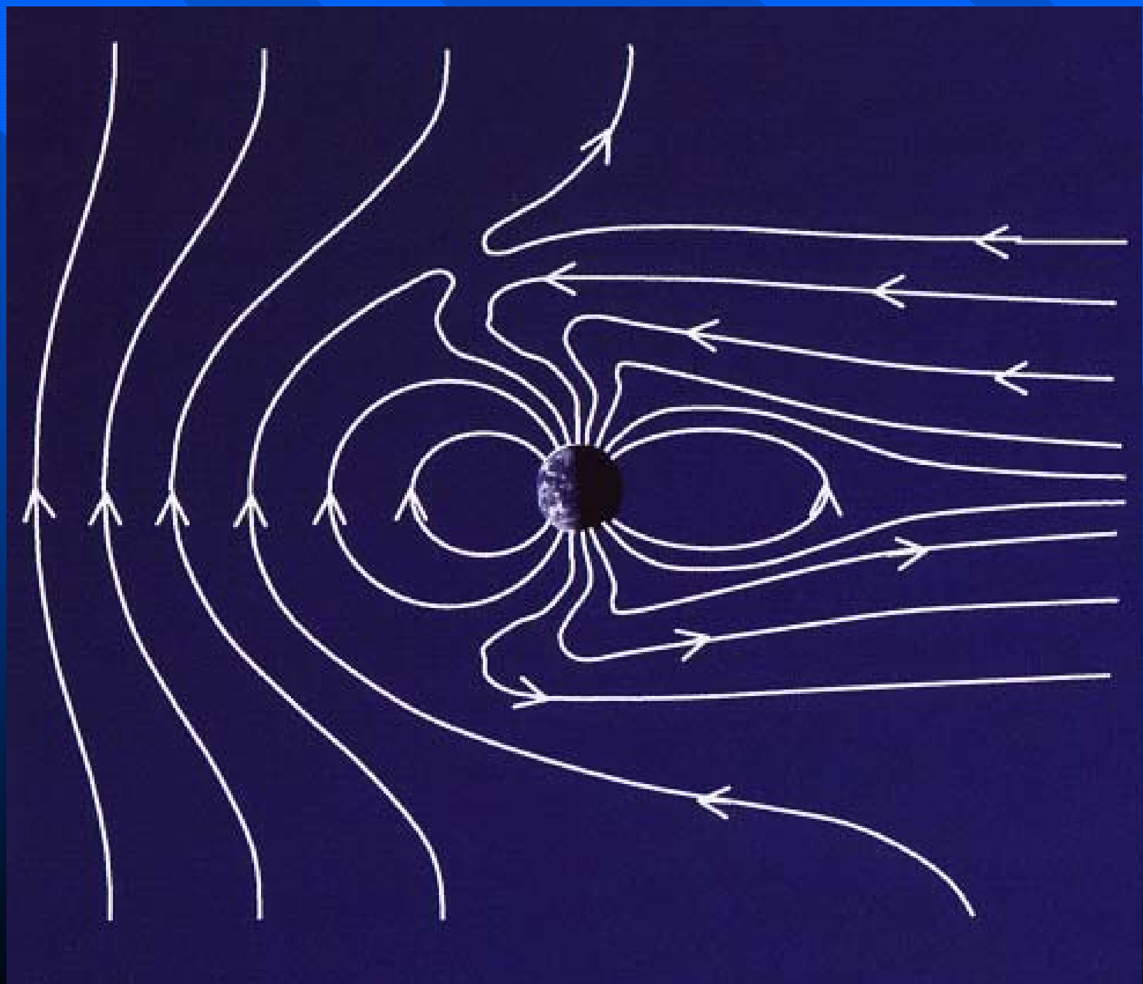


- Cusp rotated from magnetic noon
- Twin-cell patterns

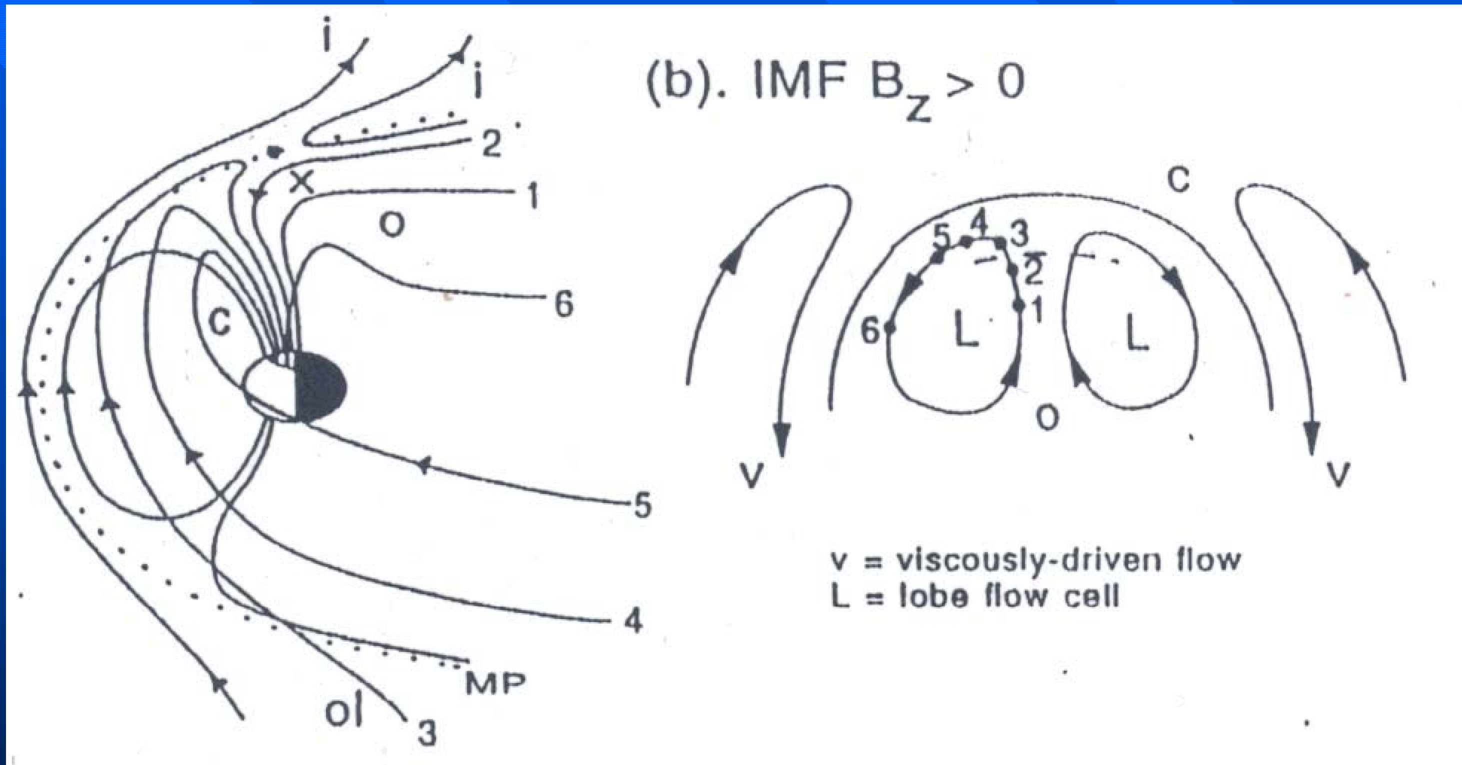
Lobe reconnection

Interplanetary magnetic field (IMF) *northward*

B_Z *positive*

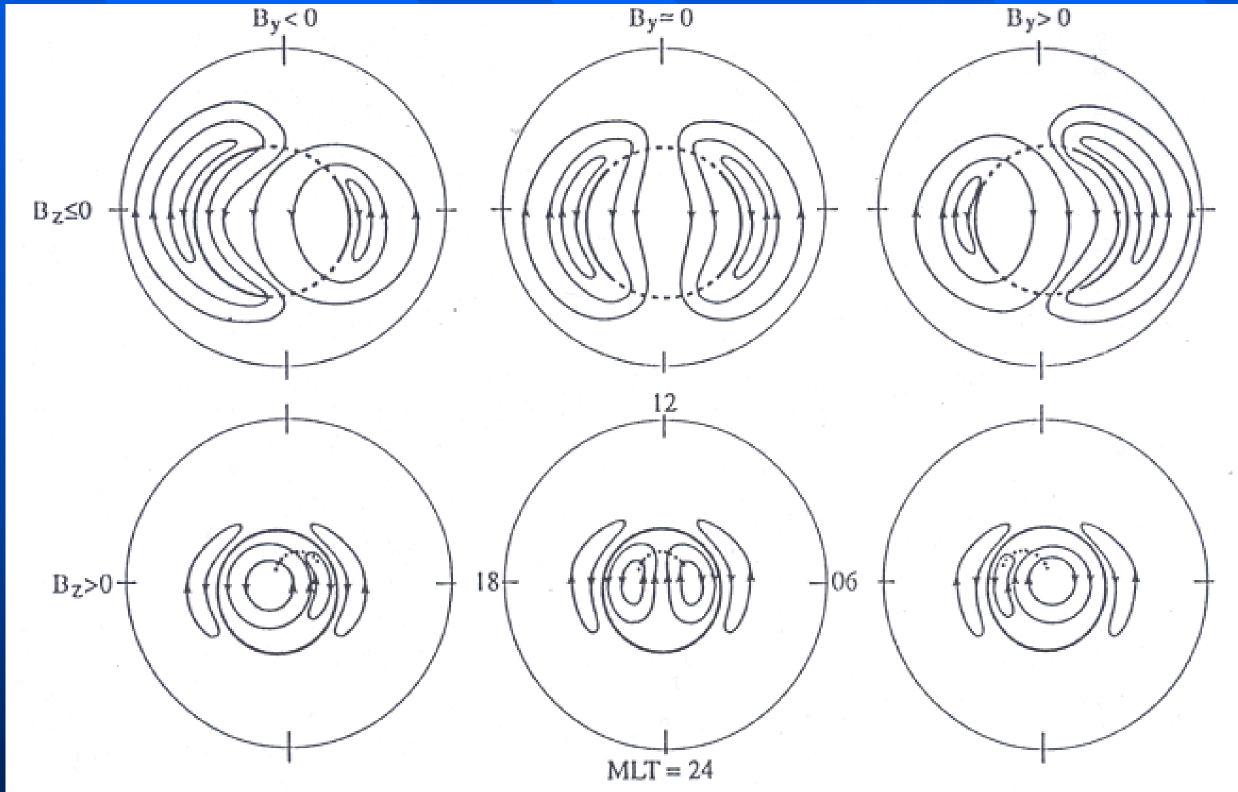


IMF *northward* , B_z *positive*
Reconnection in magnetospheric lobe



- Initial flow sunwards
- Polar cap closed to dayside plasma

Convection patterns for different IMF orientations, B_z and B_y



- Polar cap expands to lower latitudes as IMF B_z increases negative

- Shrunken closed polar cap with B_z positive

- Convection is the key process for understanding of structures in the high-latitude ionosphere

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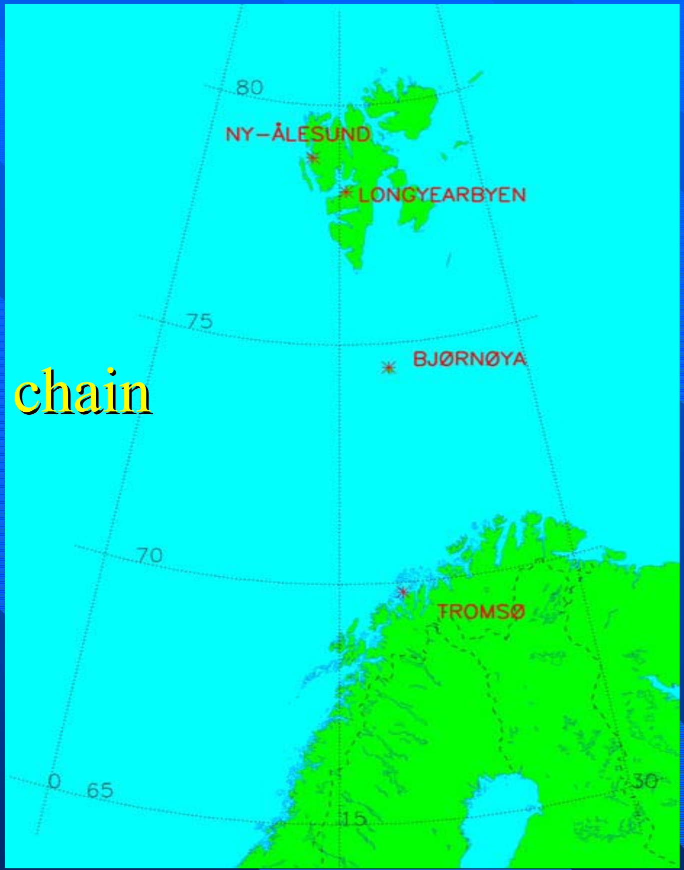
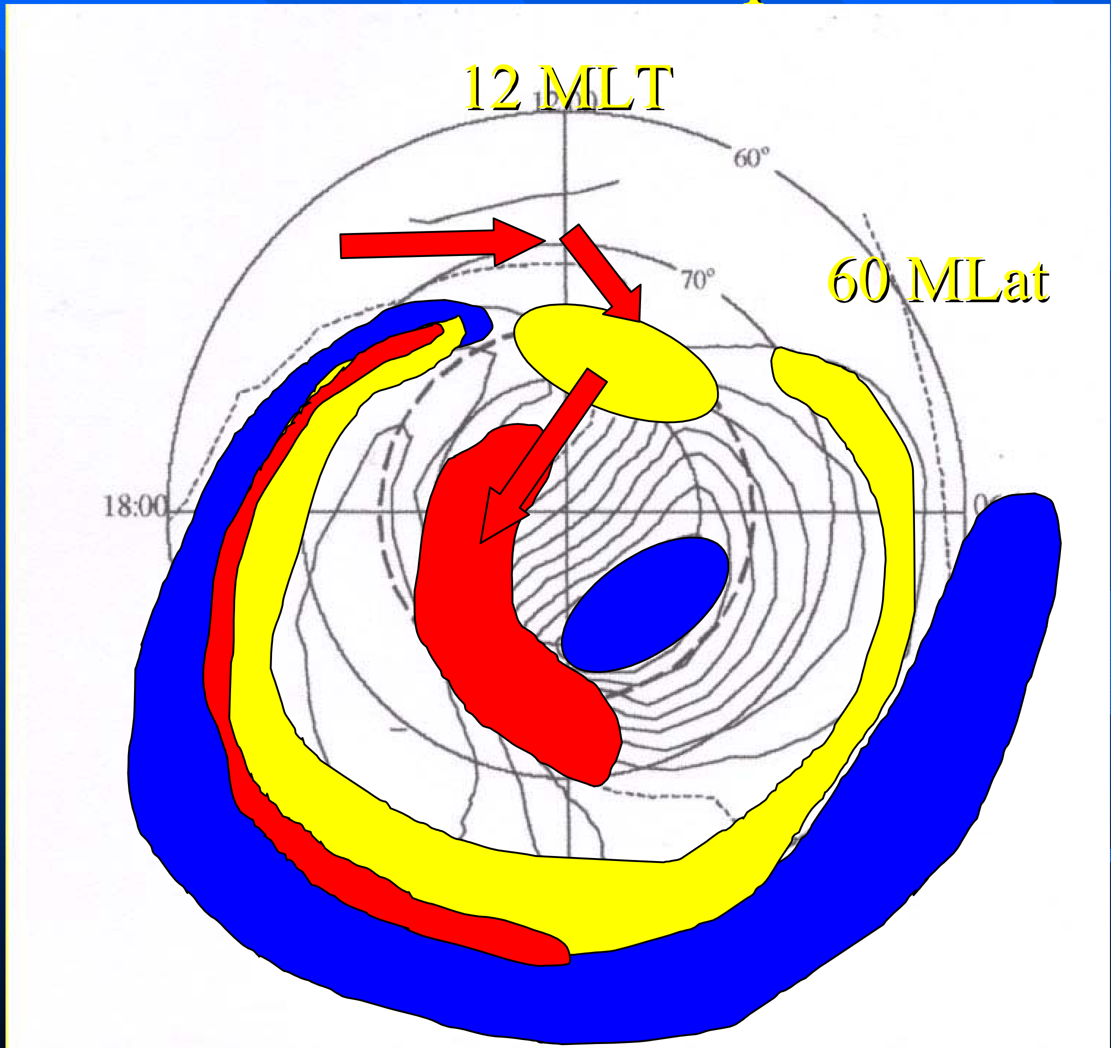
Tomography at high latitudes

UWA station chain

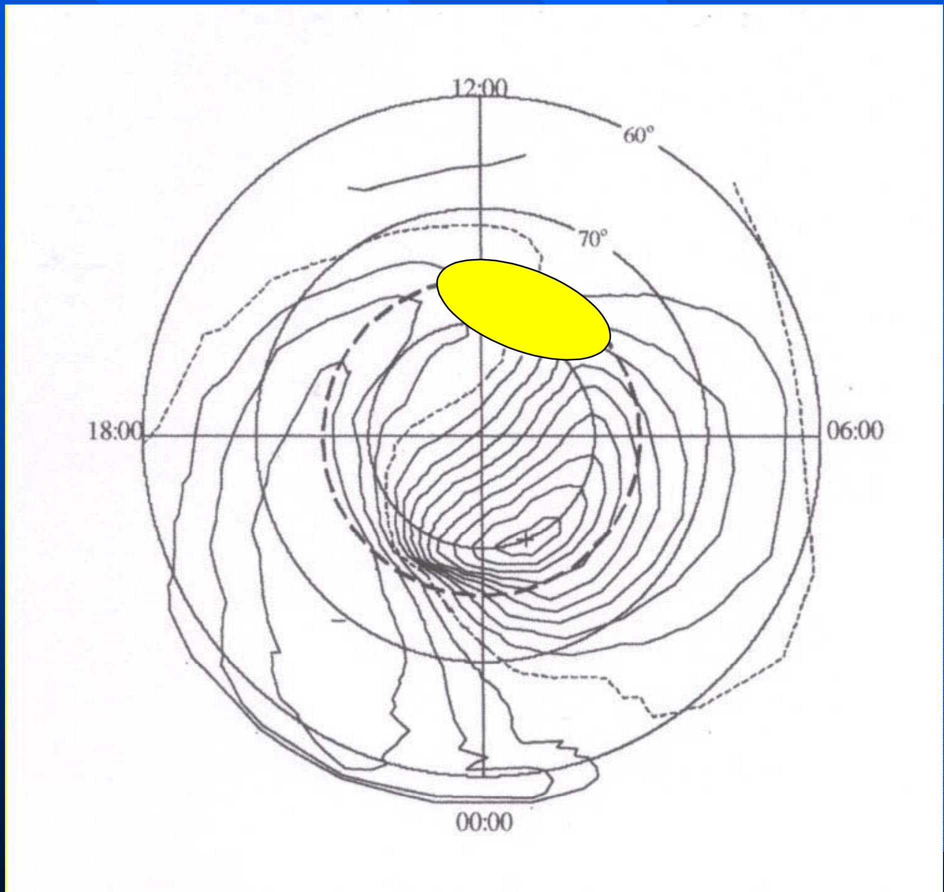


- Svalbard under dayside cusp
- Can study structures linked to space-weather processes - like reconnection

Structures in electron density at high latitudes linked to space weather

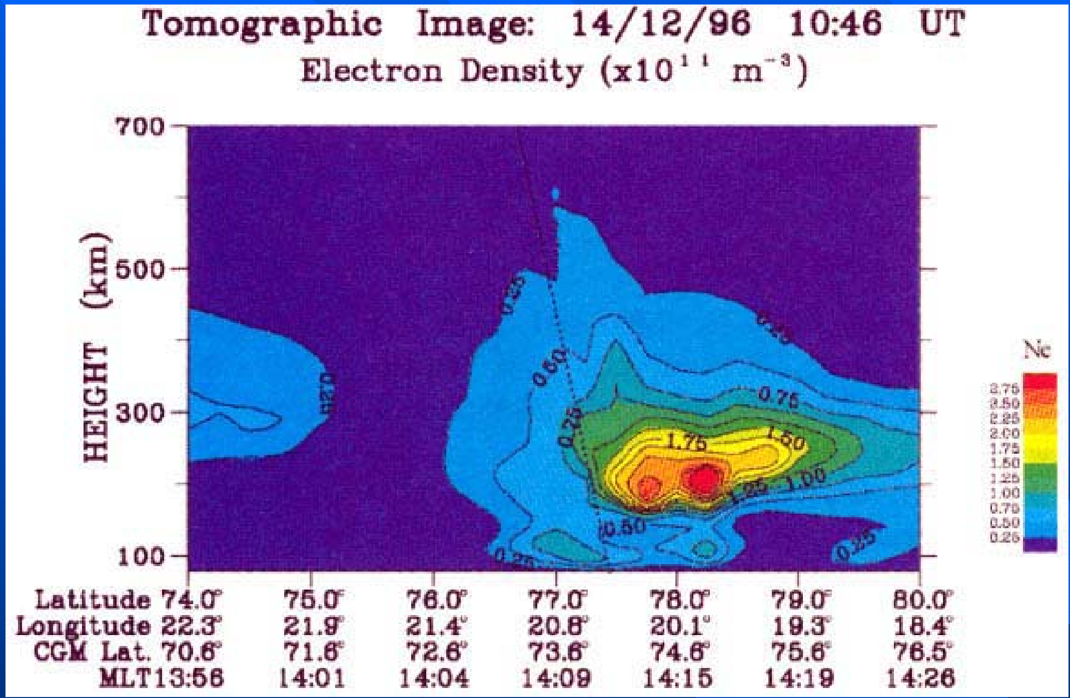


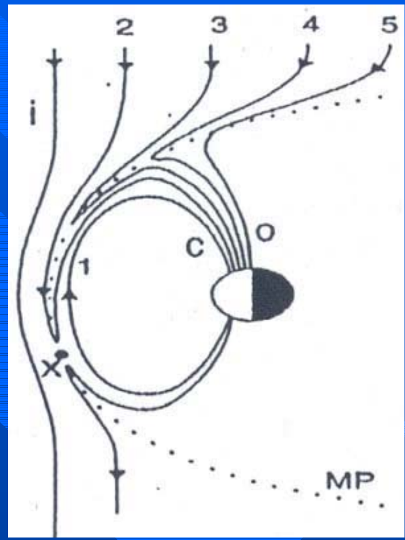
Structures in dayside cusp

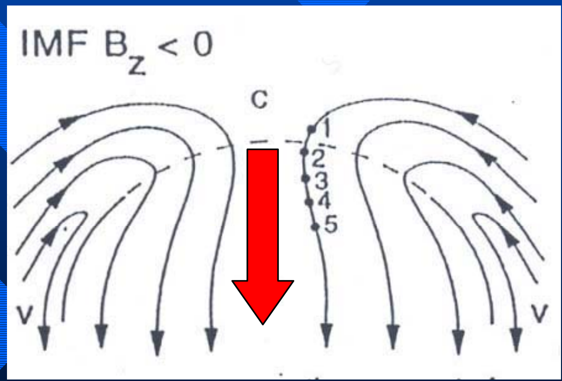


- Signatures of reconnection processes
- Cusp irregularities cause scintillation

Ionospheric Footprint of Equatorial Reconnection

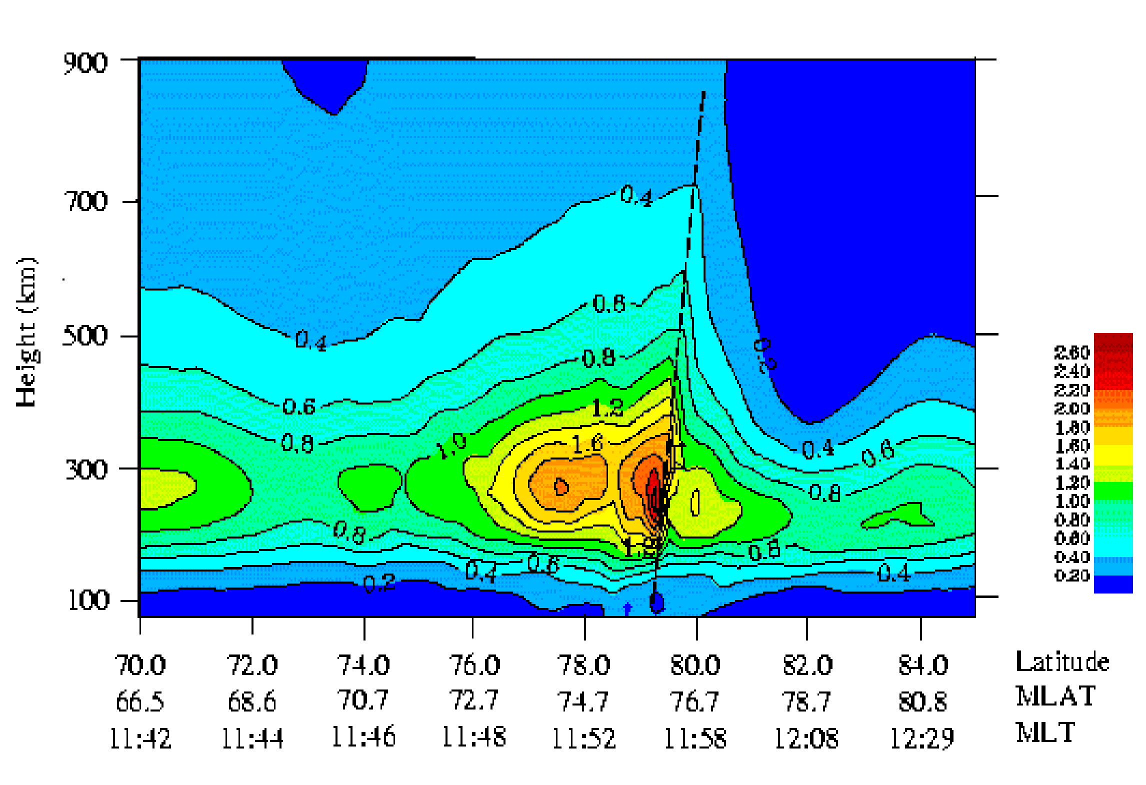


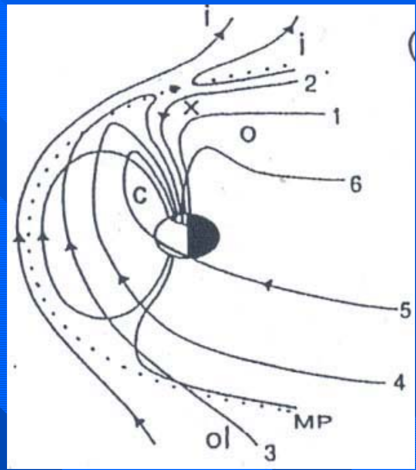


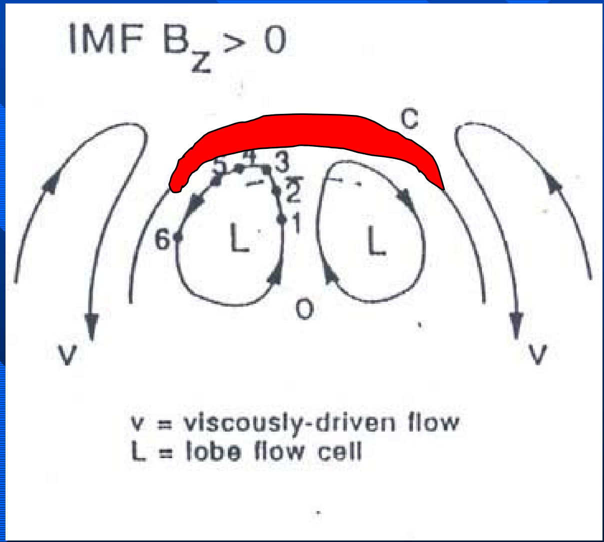


- Open/closed field line boundary
- E-region structures –upwards FAC
- Upper F region – downwards FAC
- Slope in peak height - energy dispersion of FTE precipitation

Ionospheric Footprint of Lobe Reconnection

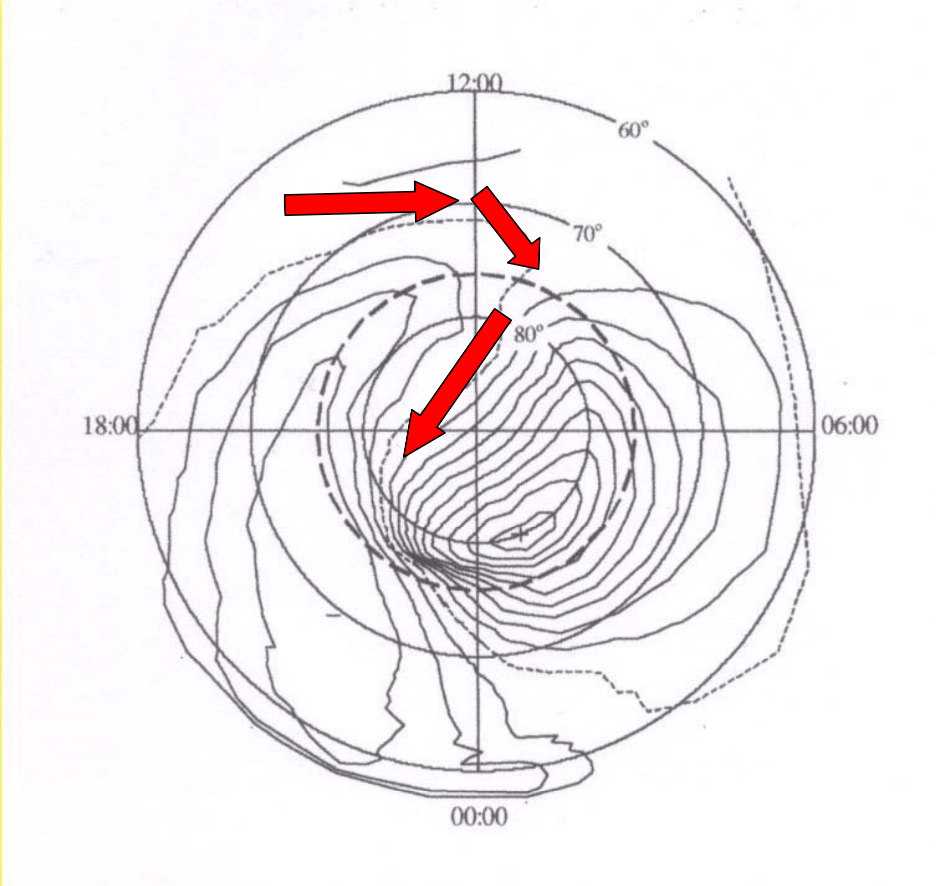






- Adiaroic boundary – no flux transfer
- Reverse dispersion signature

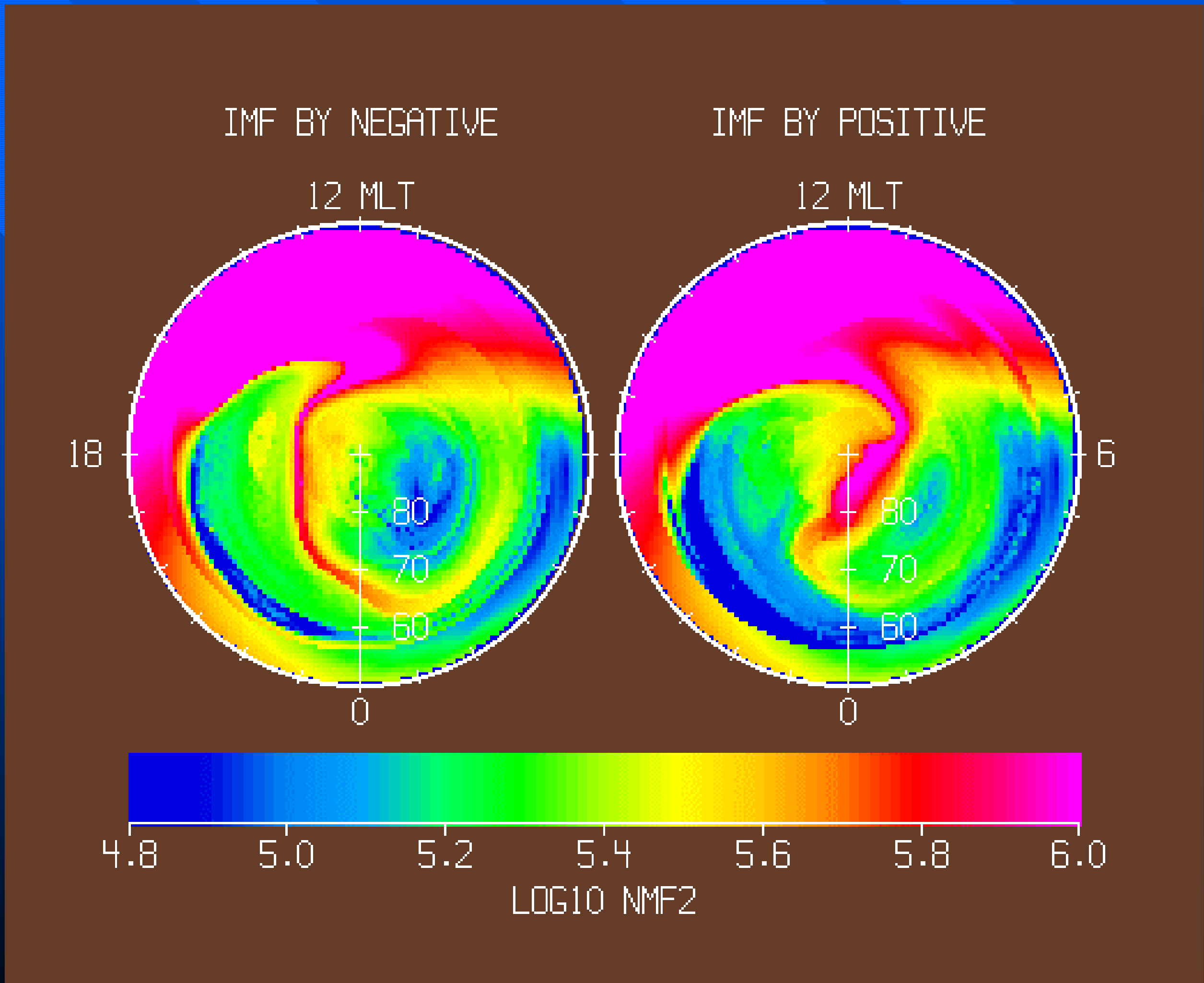
Tongue of ionisation



IMF *negative*
ie *southward*

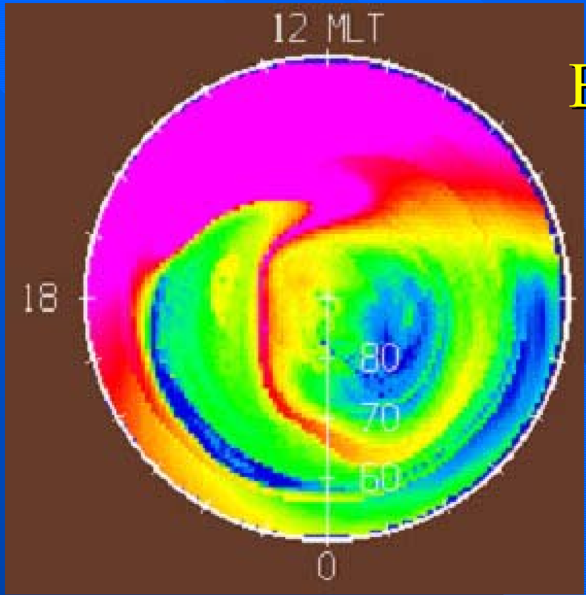
Ionisation from sunlit dayside is convected into polar cap and carried across to nightside in anti-sunward flow

Modelling of tongue of ionisation (TOI)

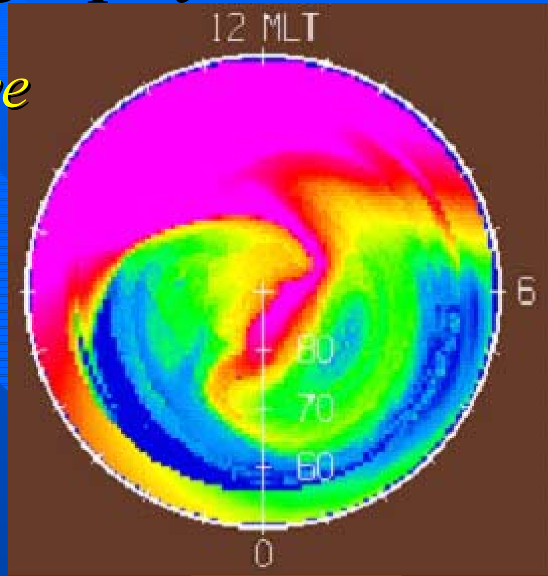


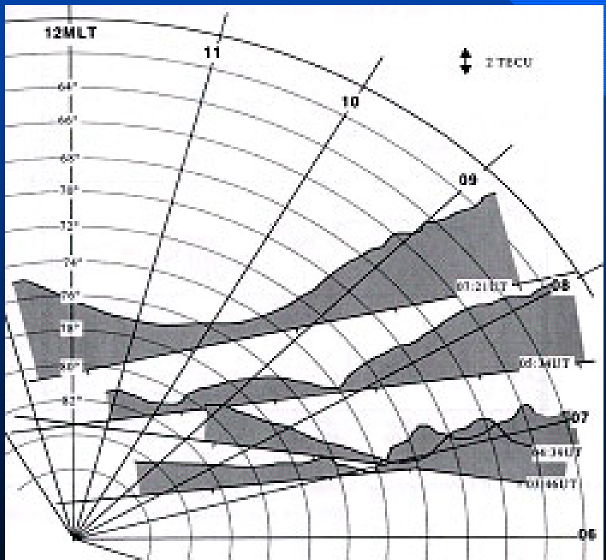
Bowline et al. (1996)

Evidence for TOI from tomography chain

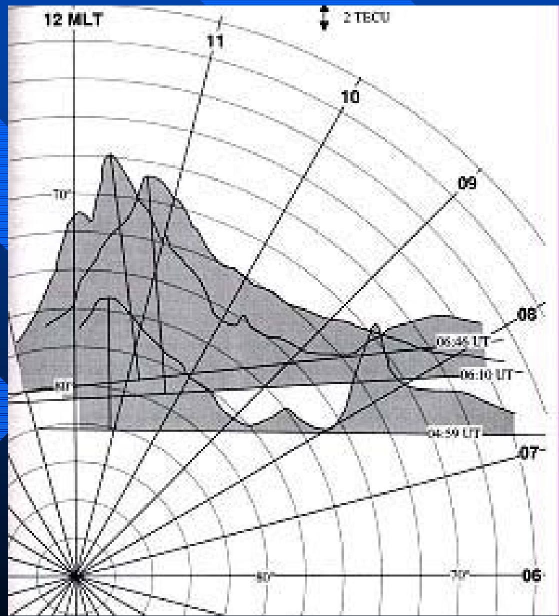


B_y *negative* B_y *positive*





TEC plots



Dayside pre-noon sector

Polar-cap patches

- TOI broken up into patches
- Many different mechanisms proposed
- 100 to 1000 km size
- Electron density may change by > 5x
- Convect at high speed in anti-sunward flow
- Steep gradients
- Instability mechanisms generate irregularities
- Radio-wave scintillation

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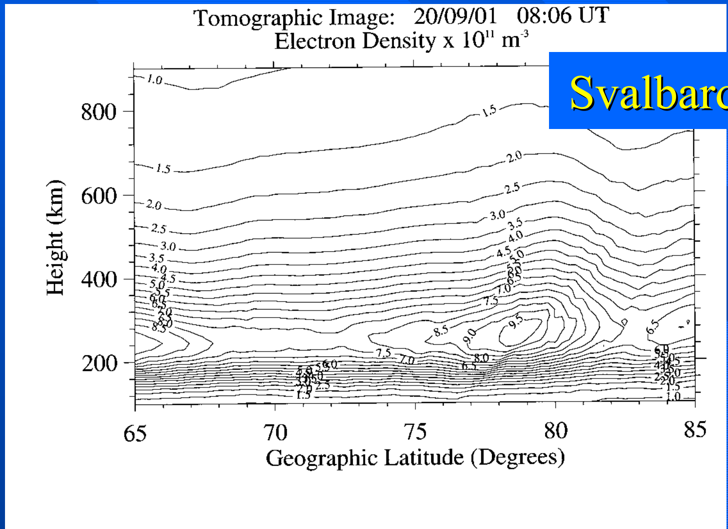
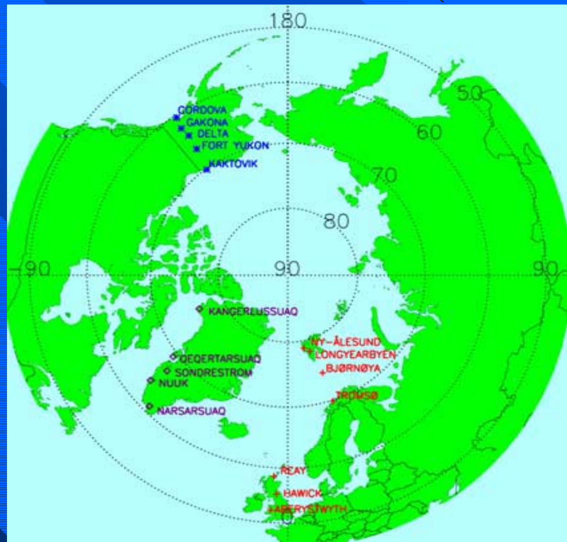
First IITC Campaign

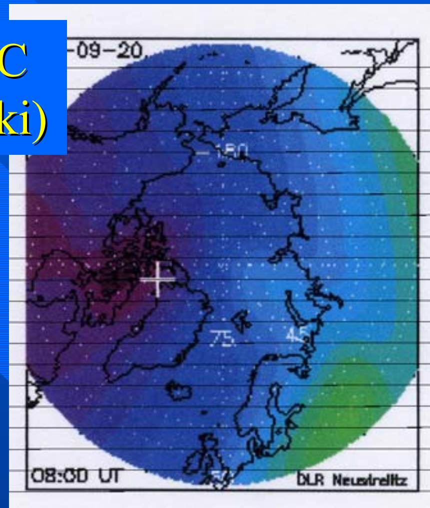
Tongue of Ionisation in the Polar Cap

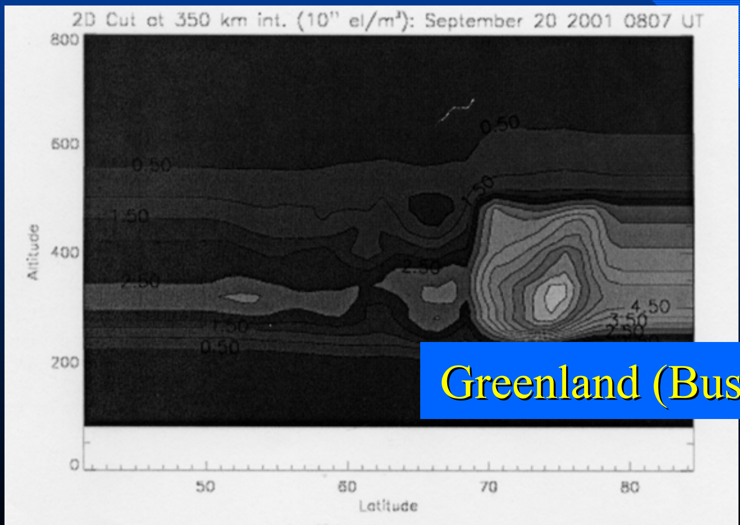


Svalbard (Kersley et al.)

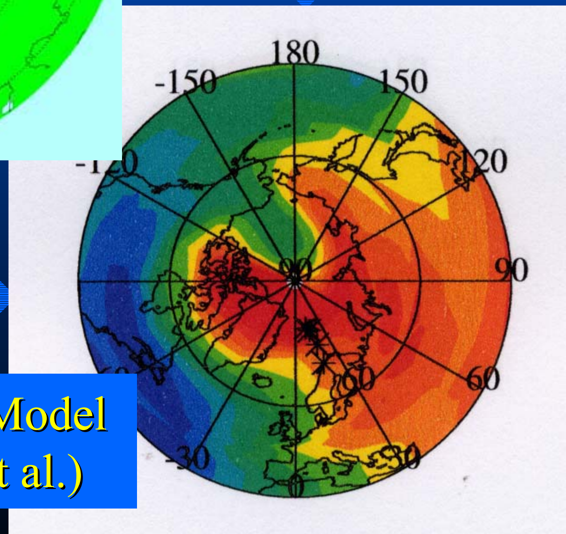


GPS TEC (Jakowski)





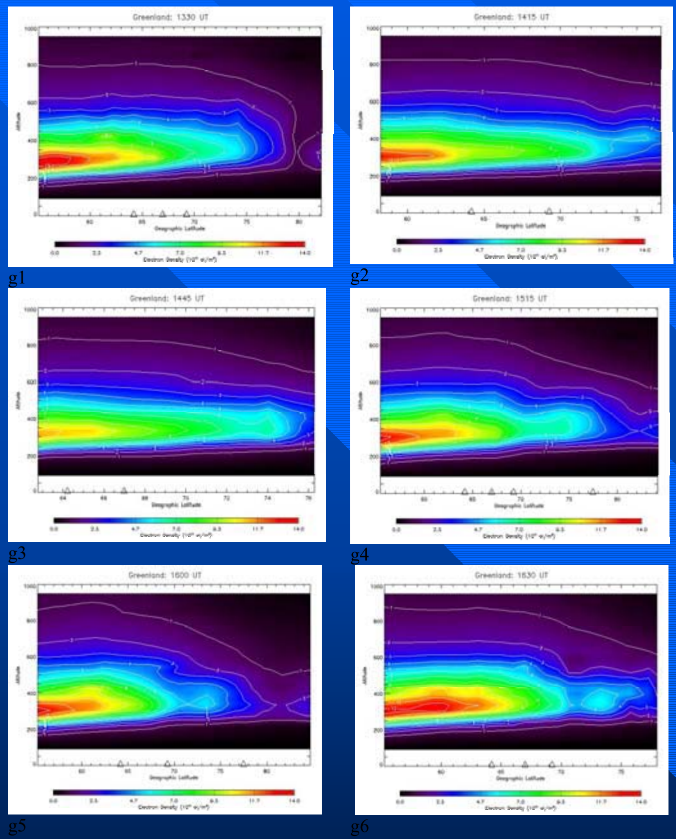
Greenland (Bust et al.)

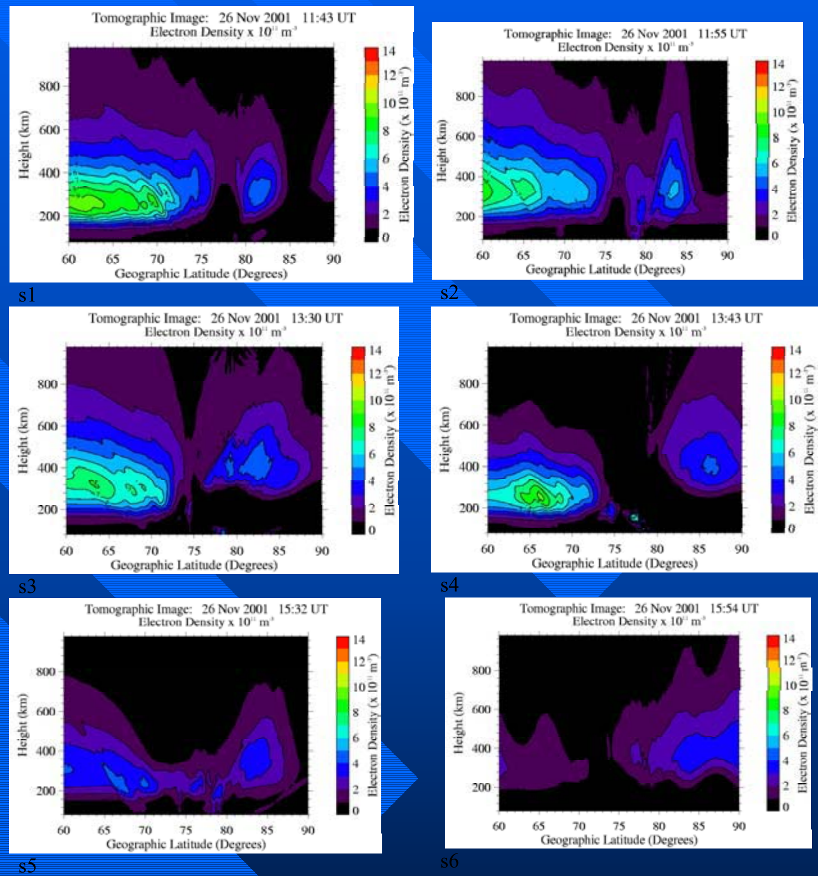


SUCTIP Model (Denton et al.)

Kersley et al., *Radio Sci.*, 2005

Second IITC Campaign





Greenland

Svalbard

Middleton et al., 2005

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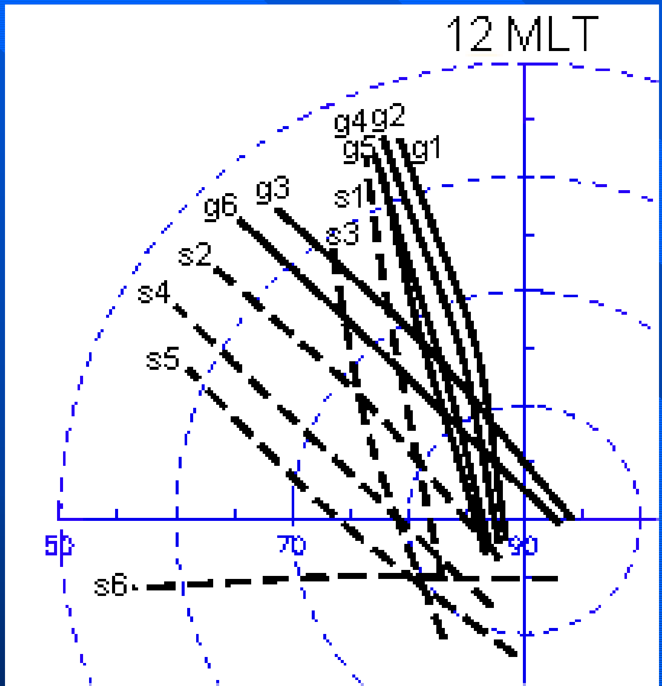
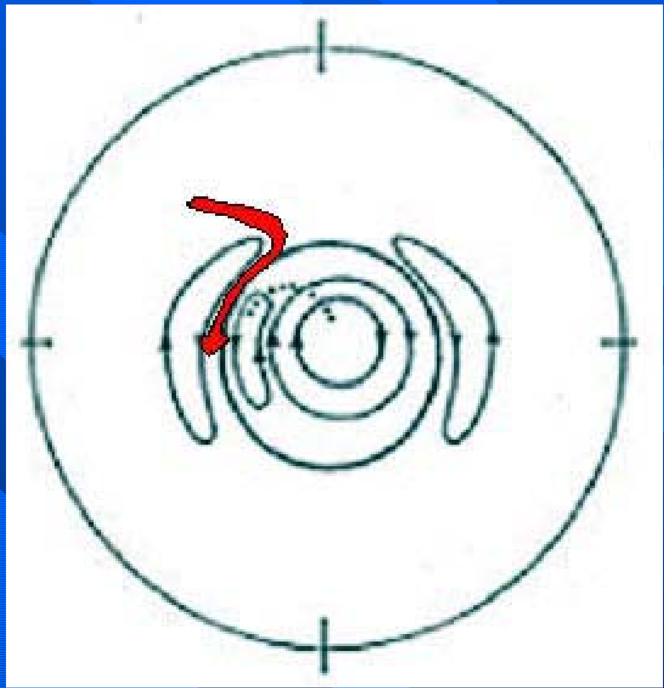
‘TOI’ under northward IMF

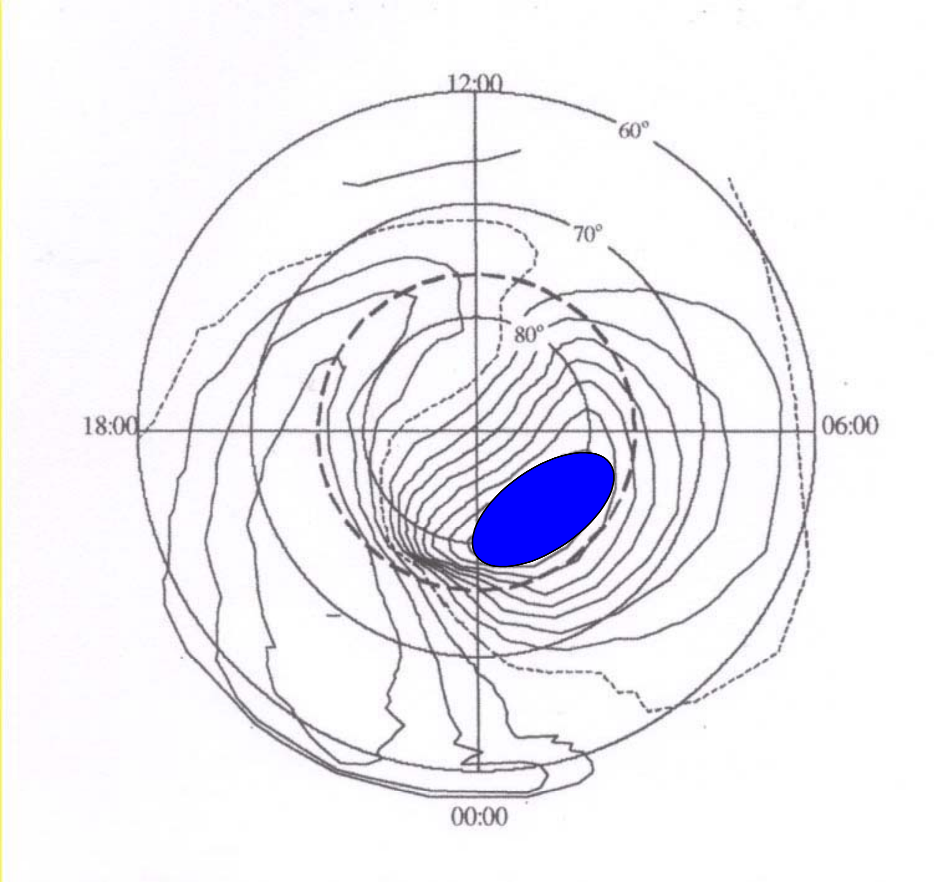




- ‘tongue’ of enhanced ionisation convecting round edge of closed polar cap

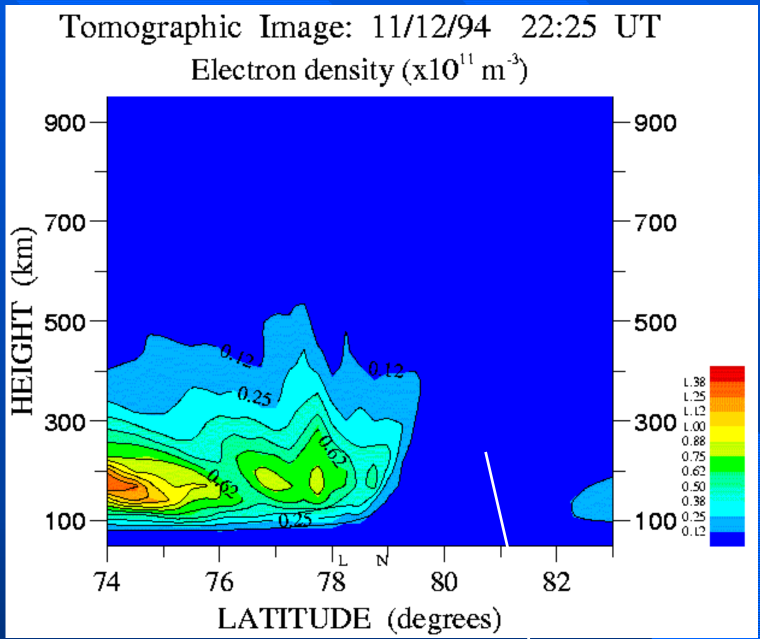
Middleton et al., 2005

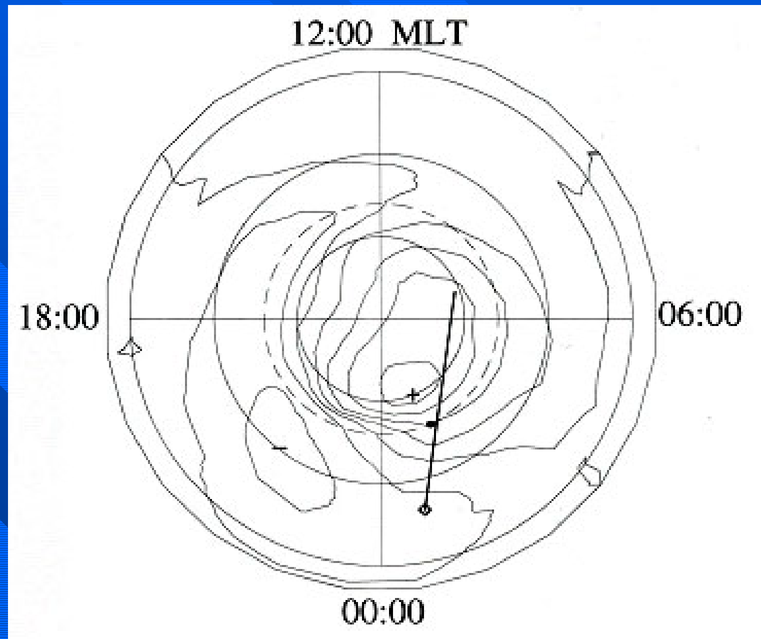
Polar hole in ionisation



- Flux tubes circulating in winter darkness in dawn cell
- No production
- Loss processes dominate
- Very low densities

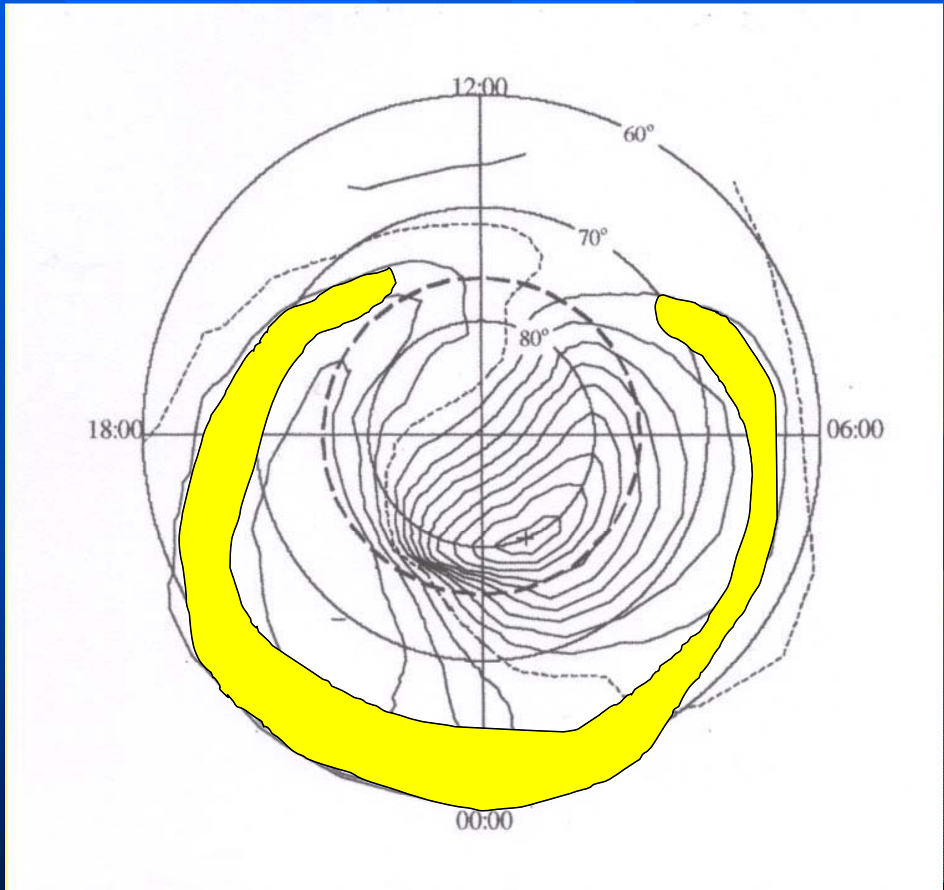
Polar hole





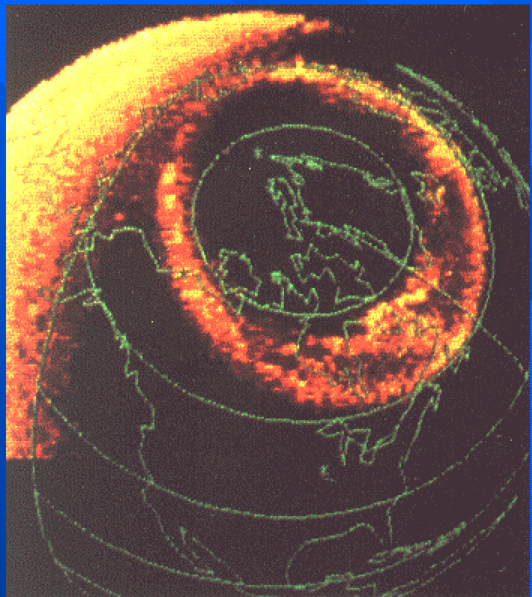
- Very low densities in dawn cell
- Flux tubes circulating in winter darkness

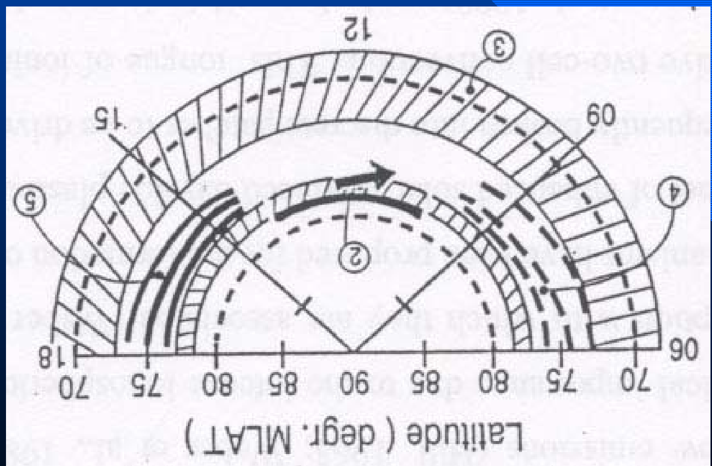
Auroral ionisation

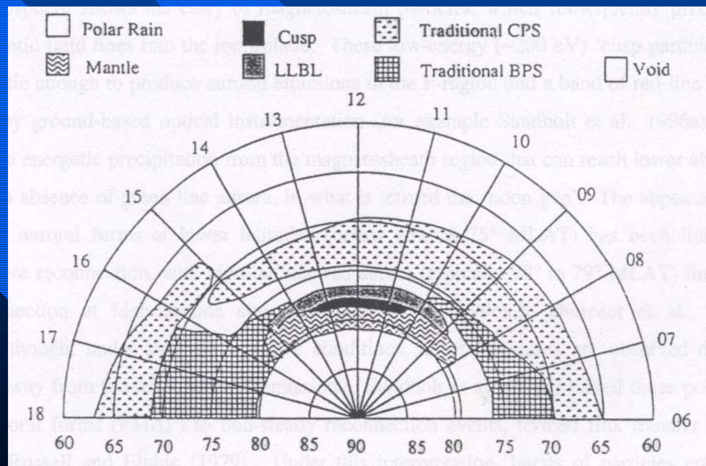


- Precipitation in auroral zone
- Localised and transient structures in electron density
- Small-scales cause scintillation

Auroral ionisation



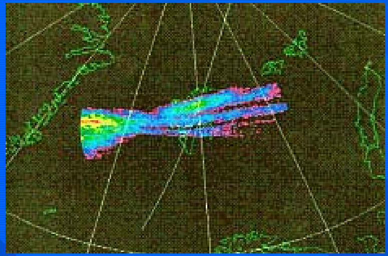




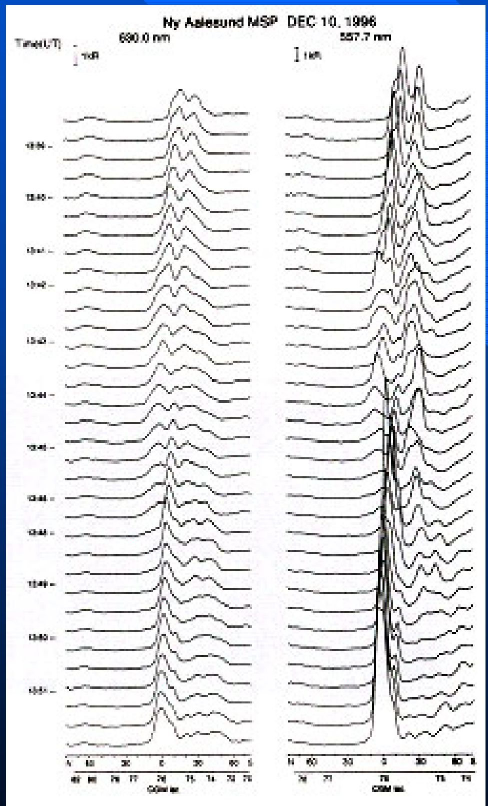
Auroral forms

Precipitation types

Auroral ionisation

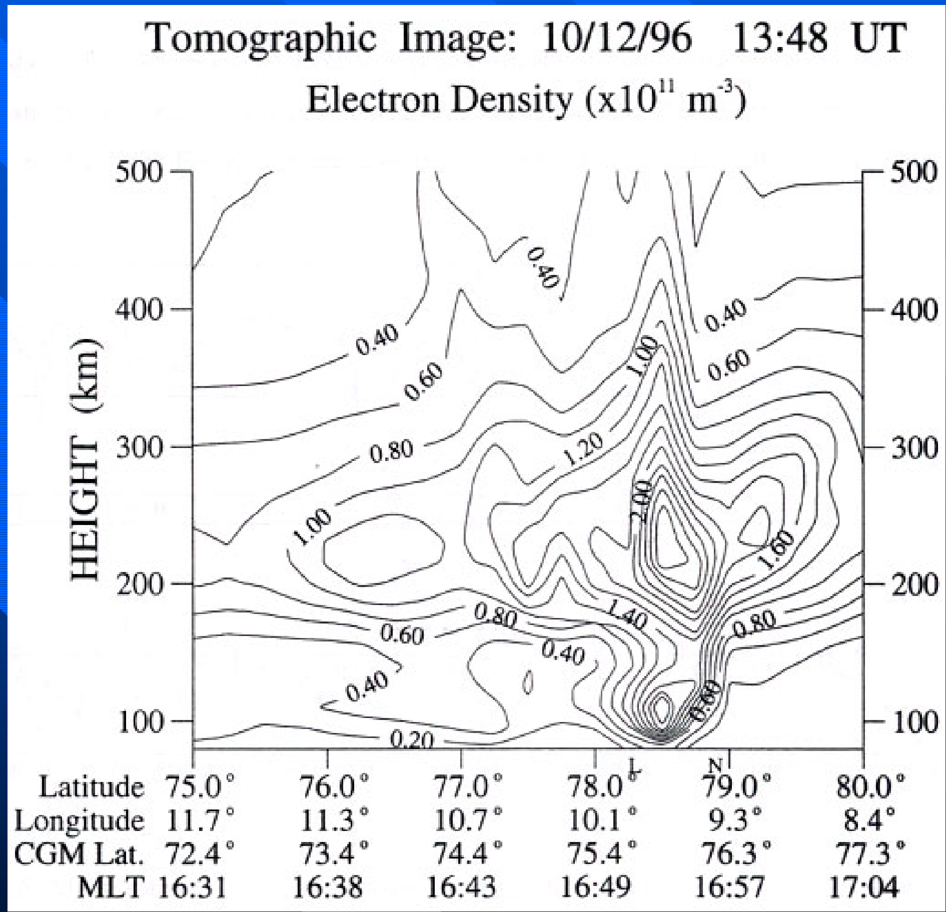


All-sky camera

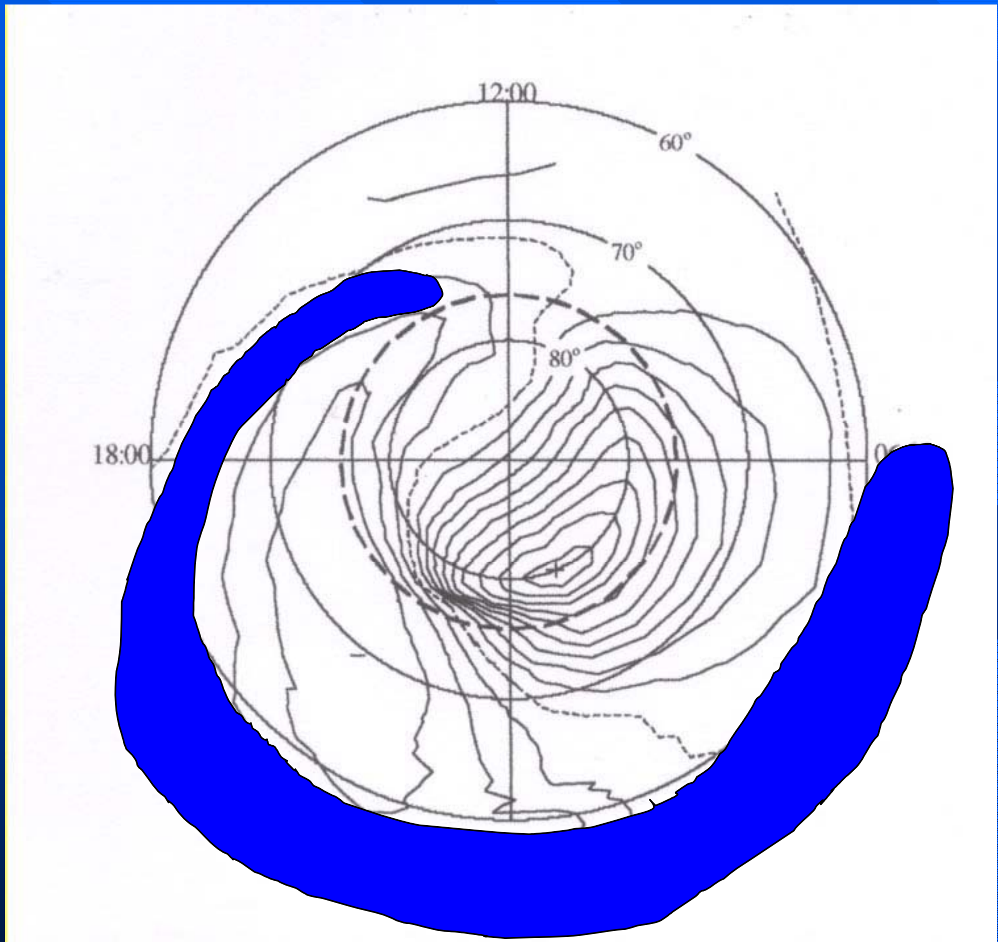


Red 630.0nm

Green 557.7nm

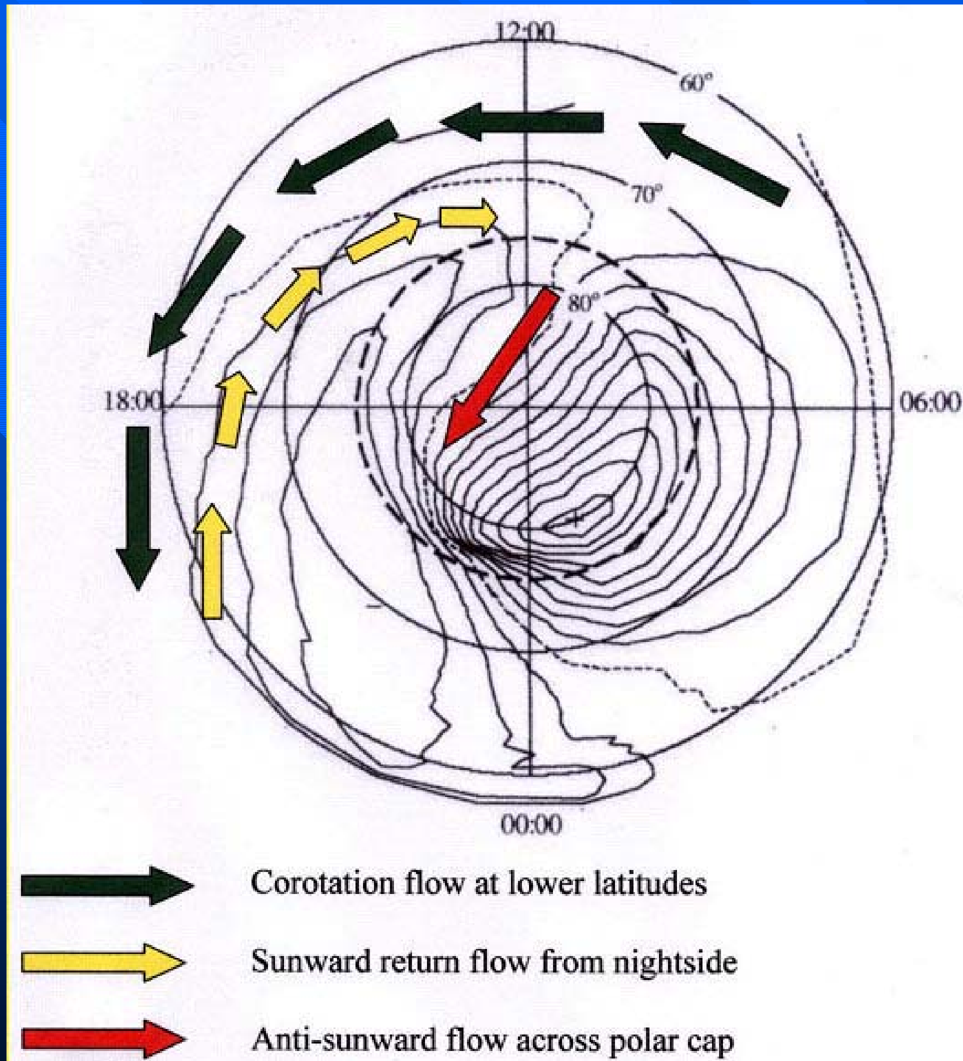


Main trough

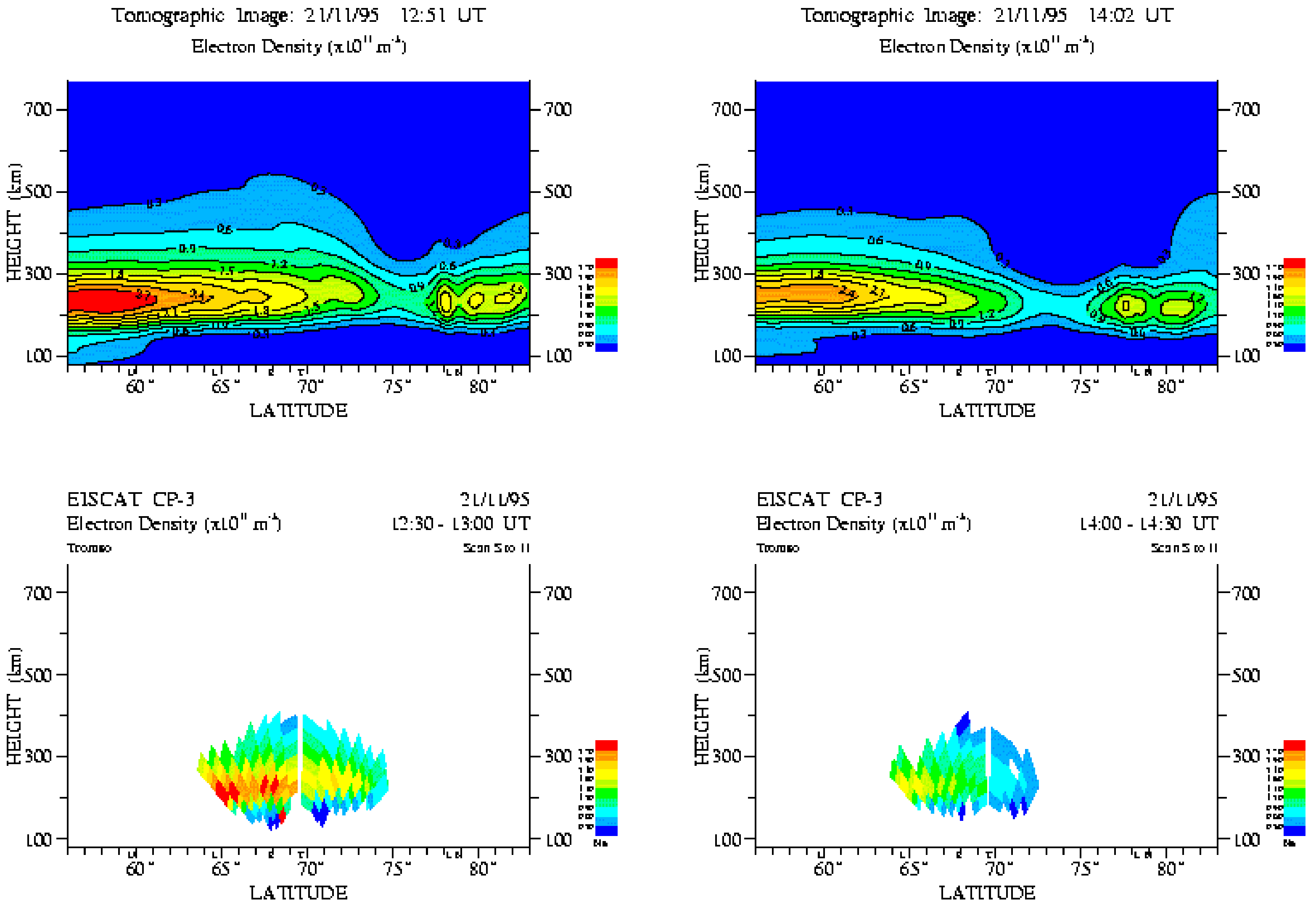


- Main or mid-latitude trough
- Auroral / mid-latitude ionosphere boundary
- Most significant feature of sub-auroral ionosphere at night
- Difficult to model

Formation of Trough

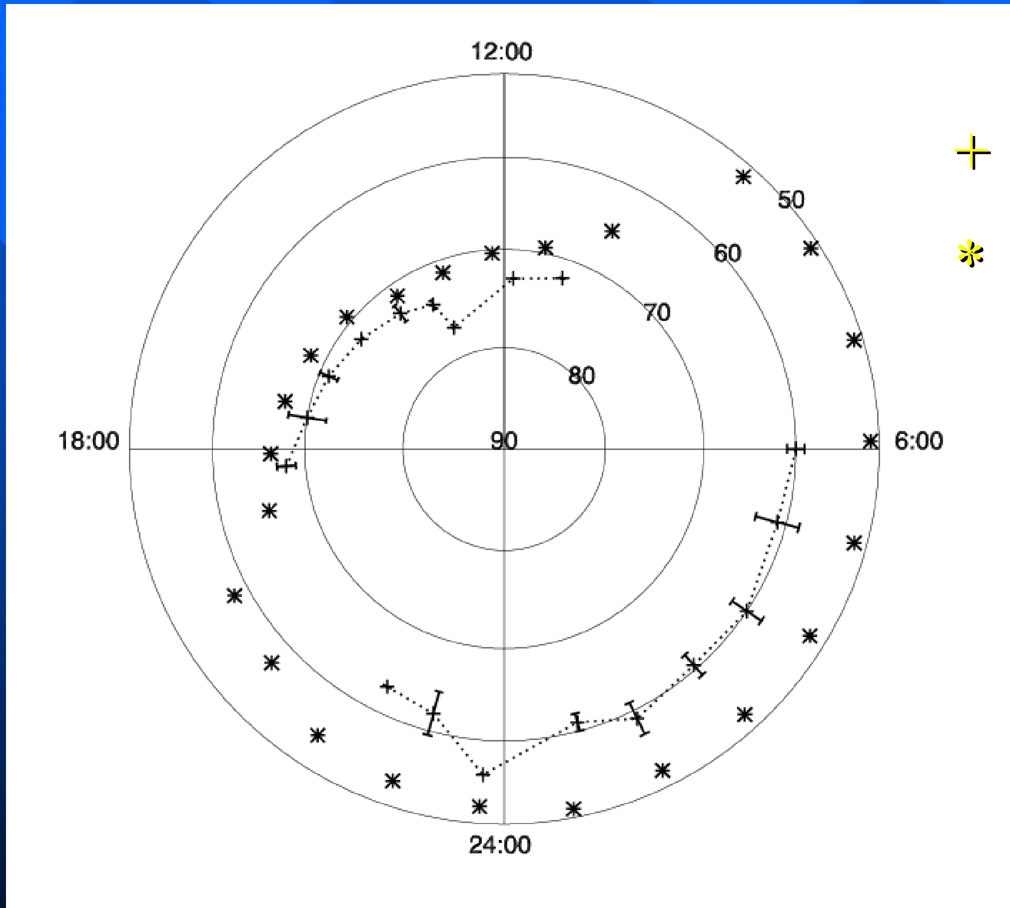


Trough Images



Validation of SUCTIP Model

Latitude of trough minimum vs MLT for quiet geomagnetic conditions



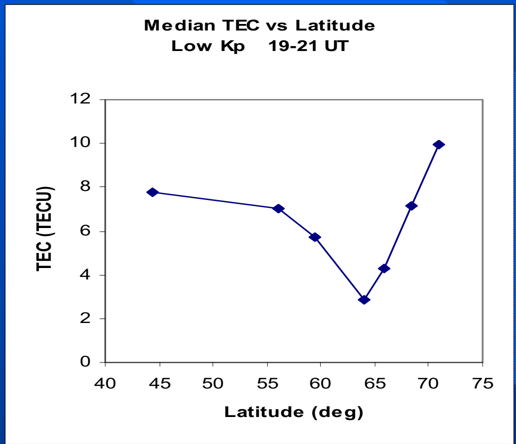
+ Tomography

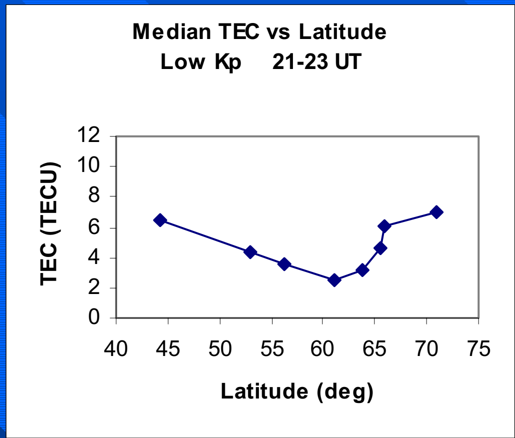
* Model

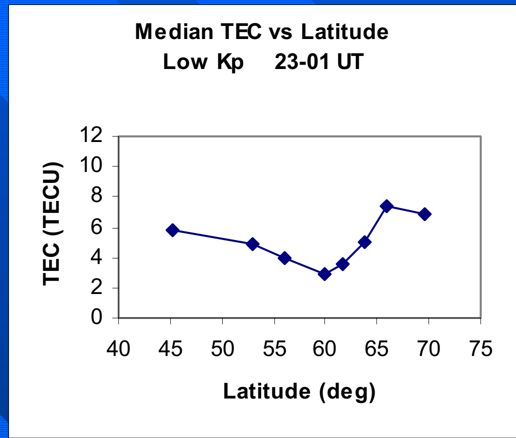
Balthazor et al. (2002)

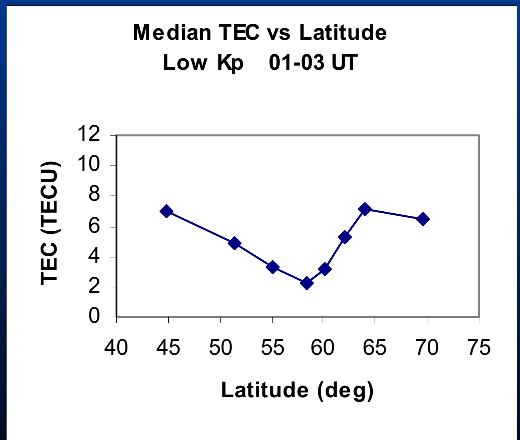
Parameterised trough TECs obtained experimentally for use in model validation

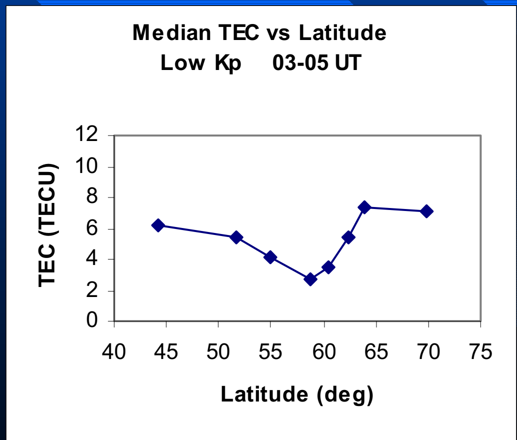
1. Quiet geomagnetic conditions

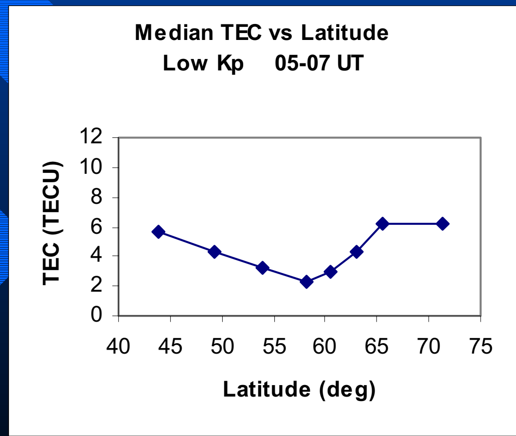












Pryse et al., *Radio Sci.*, 2006

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Ionospheric storms – space weather effects at mid-latitude

- Expansion of polar cap
- Heating in auroral zone
- Equatorward winds
- Lighter oxygen atoms
- Positive phase with increased densities
- Electrodynamic effects
- Storm enhanced densities
- Collapse of ionisation in late afternoon
- Very steep spatial and temporal gradients
- Negative phase
- Molecular rich atmosphere
- Depleted densities
- Last for several days

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Contraction of plasmapause at storm onset

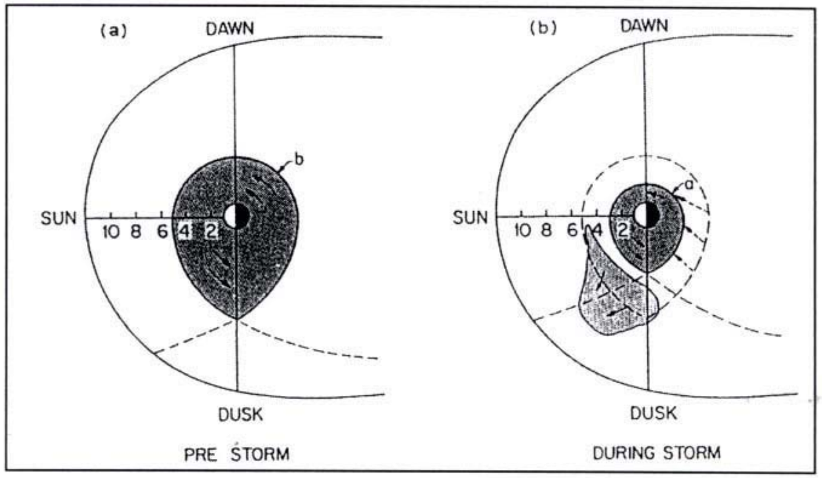
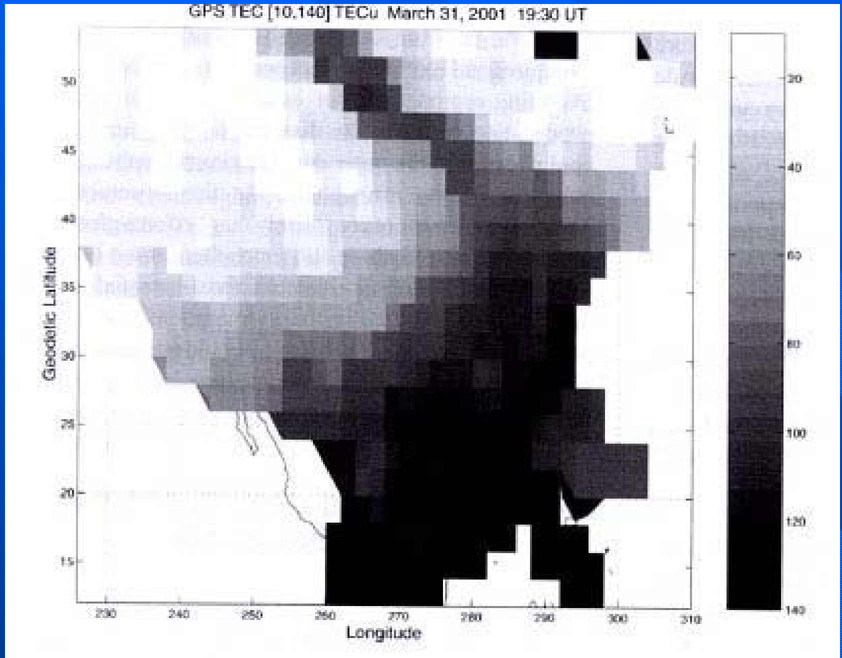
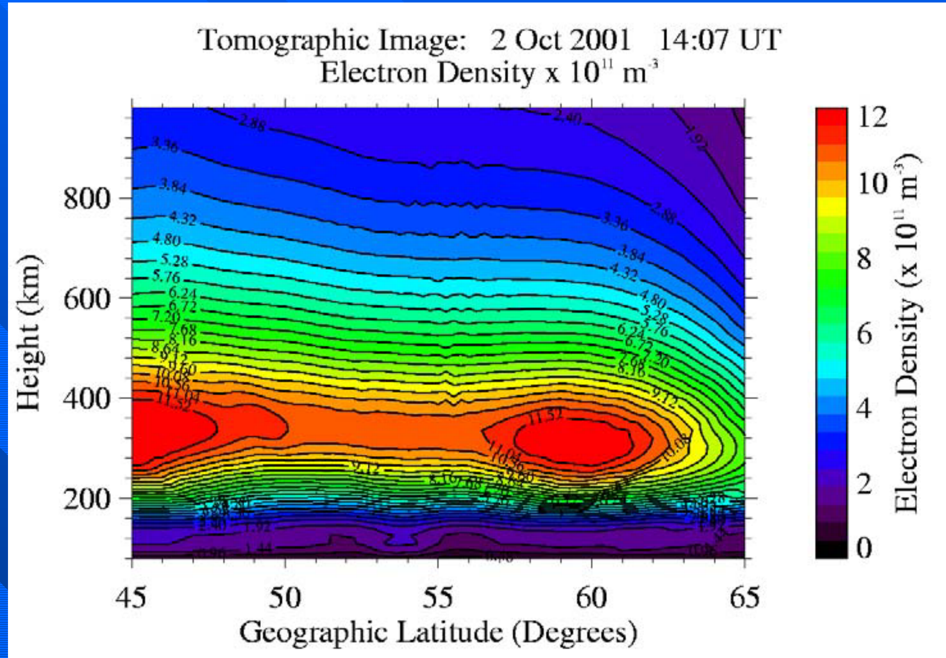


Figure 2.5. Diagram of the plasmasphere, a) quiet period before storm, b) after increased convection has peeled off the outer layers of the region. The grey areas denote high plasma concentrations, filled arrows denote plasma motion, the dotted arrows show the movement of the plasmapause and the scale is in L (Chappell, 1972).

- Very important consequences in mid-latitude ionosphere (SEDs)

Storm enhanced densities (SEDs) at mid-latitudes





GPS TEC map over USA during large storm (Carpenter, 2004)

Tomographic image of SED event over Europe

- Note steep gradients

- Localised features on this kind pose serious potential problems for operation of GPS-based systems like WAAS, EGNOS, etc

Conclusions

- Space weather affects the high-latitude ionosphere
- Many processes cause structures in electron density and TEC
- Steep gradients on many different scales
- Spread to mid-latitudes during disturbed conditions
- Difficult to model complexities
- Important consequences for radio systems using transionospheric propagation

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