Ionospheric Imaging: From two-dimensional tomography to data assimilation

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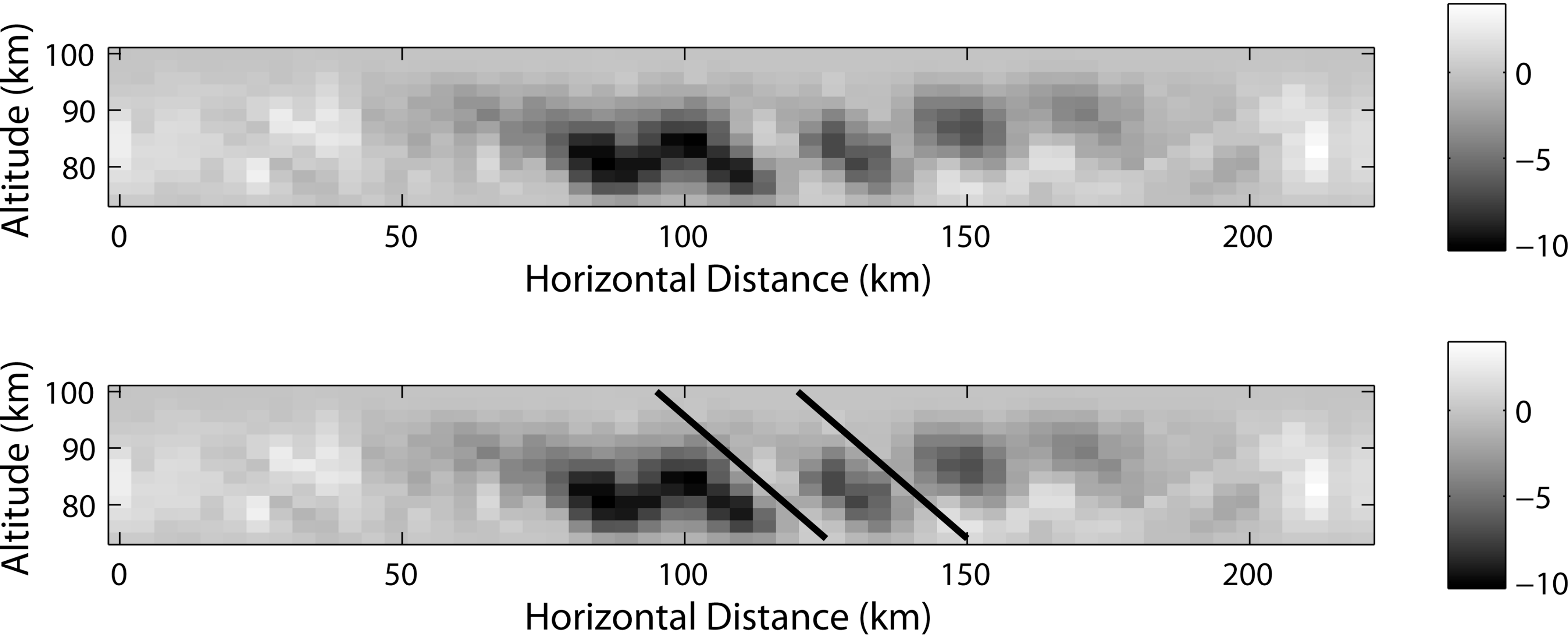
Outline

- A Survey of Tomographic Methods used in the Ionosphere-Thermosphere System
- What are the Fundamentals of Tomography
  - Focus on large scale RF tomographic methods
- Two-dimensional Leo-Satellite Ionospheric Tomography
- 3D Global GPS-based Ionospheric Tomography
- Data Assimilation
  - from the Tomographic Point of View
  - Tomography (or any kind of observations) from the Data Assimilation Point of View
- Future Directions / Conclusions

Tomographic imaging of airglow from airborne spectroscopic measurements

Anderson et al., Applied Optics, V47 13, 2008

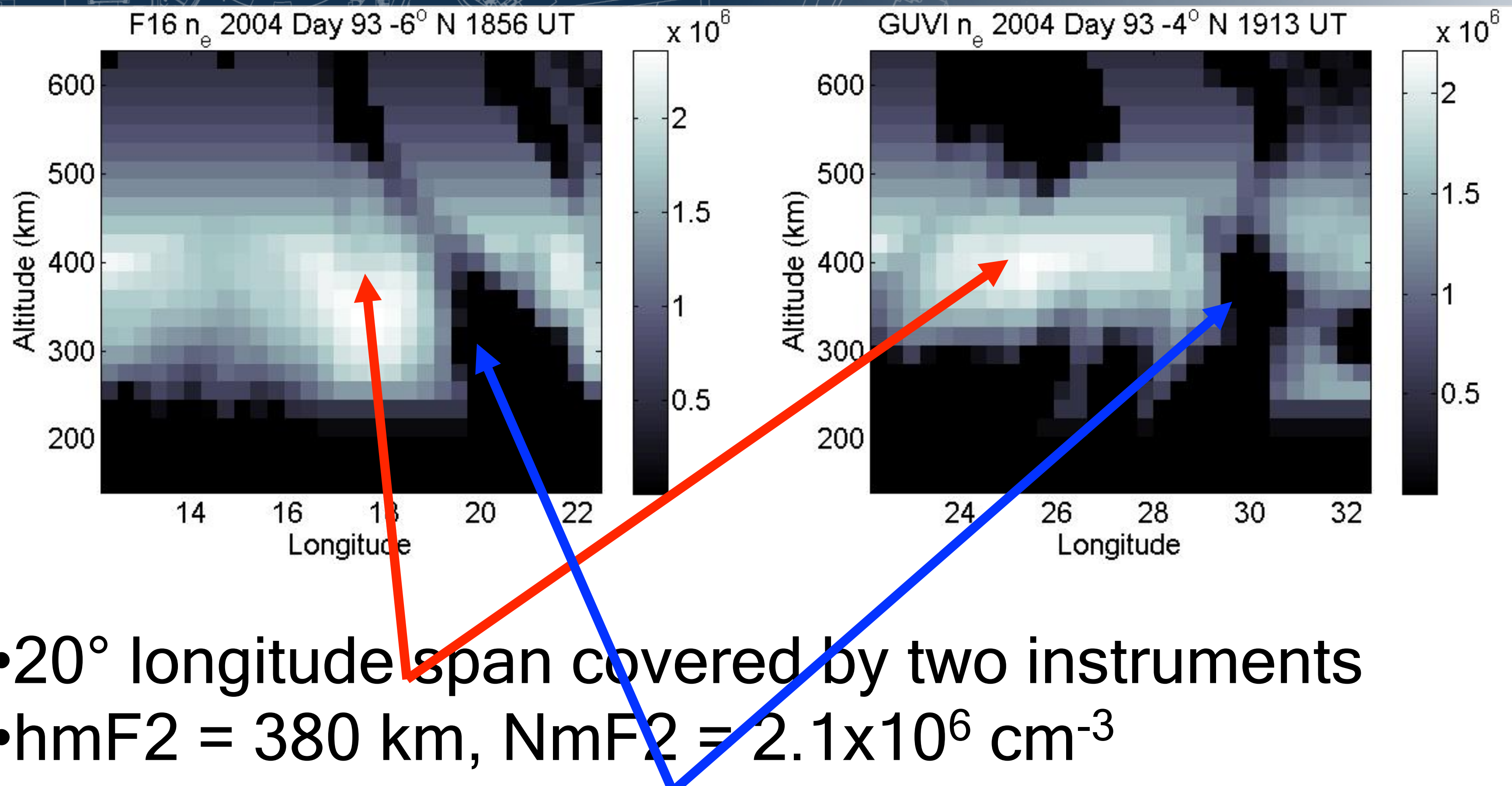


Run 15 perturbation preconstruction. The lines in the bottom panel show two phase fronts of a wave with "25 km for both hor- izontal and vertical wavelengths. These particular wavelengths are some of the most commonly observed in airglow.

APL

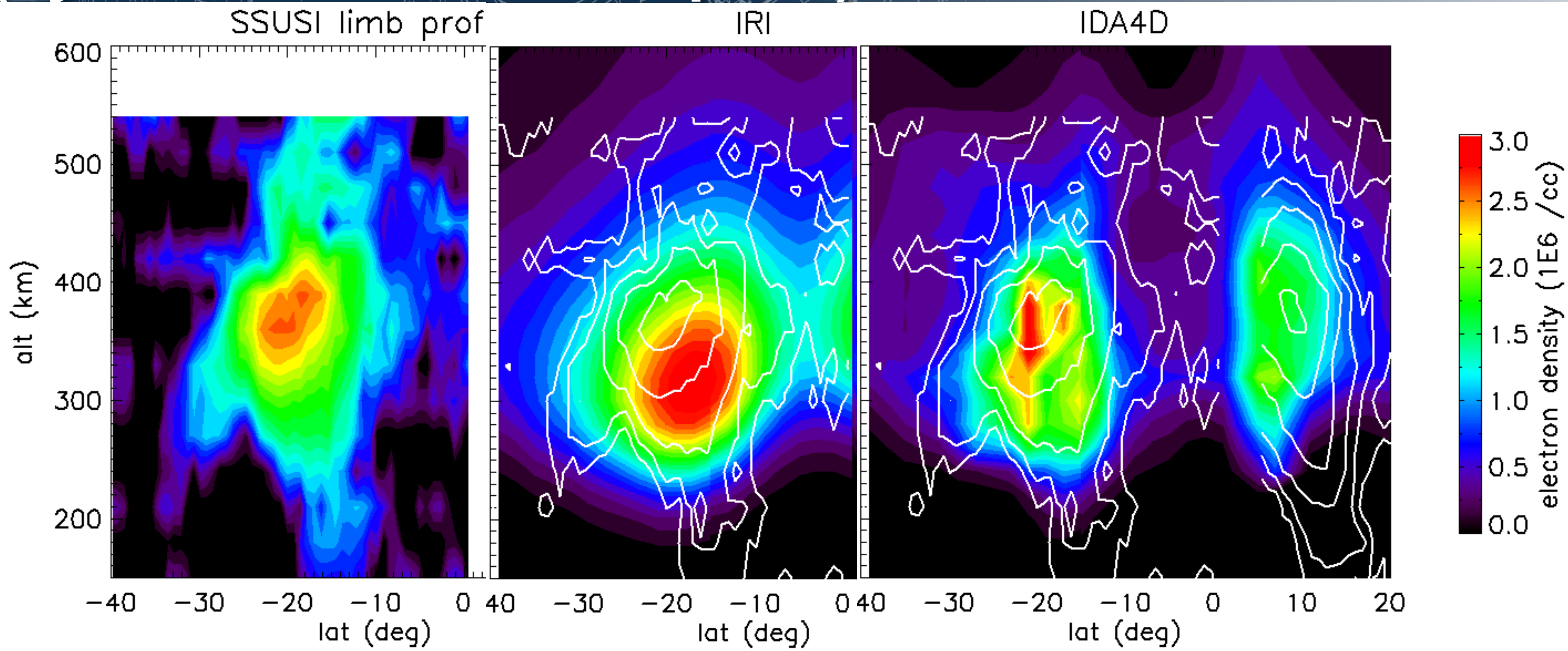
GUVI/SSUSI - Adjoining Images

Dr. Joe Comberiate, JHUAPL (ISEA Presentation



- 20° longitude span covered by two instruments
- hmF2 = 380 km, NmF2 = 2.1×10^6 cm^{-3}
- Multiple plumes visible

Density profiles: SSUSI/SSULI, IDA4D (Lynette Gelinas Aerospace)



SSUSI EDP from APL limb algorithm

IRI

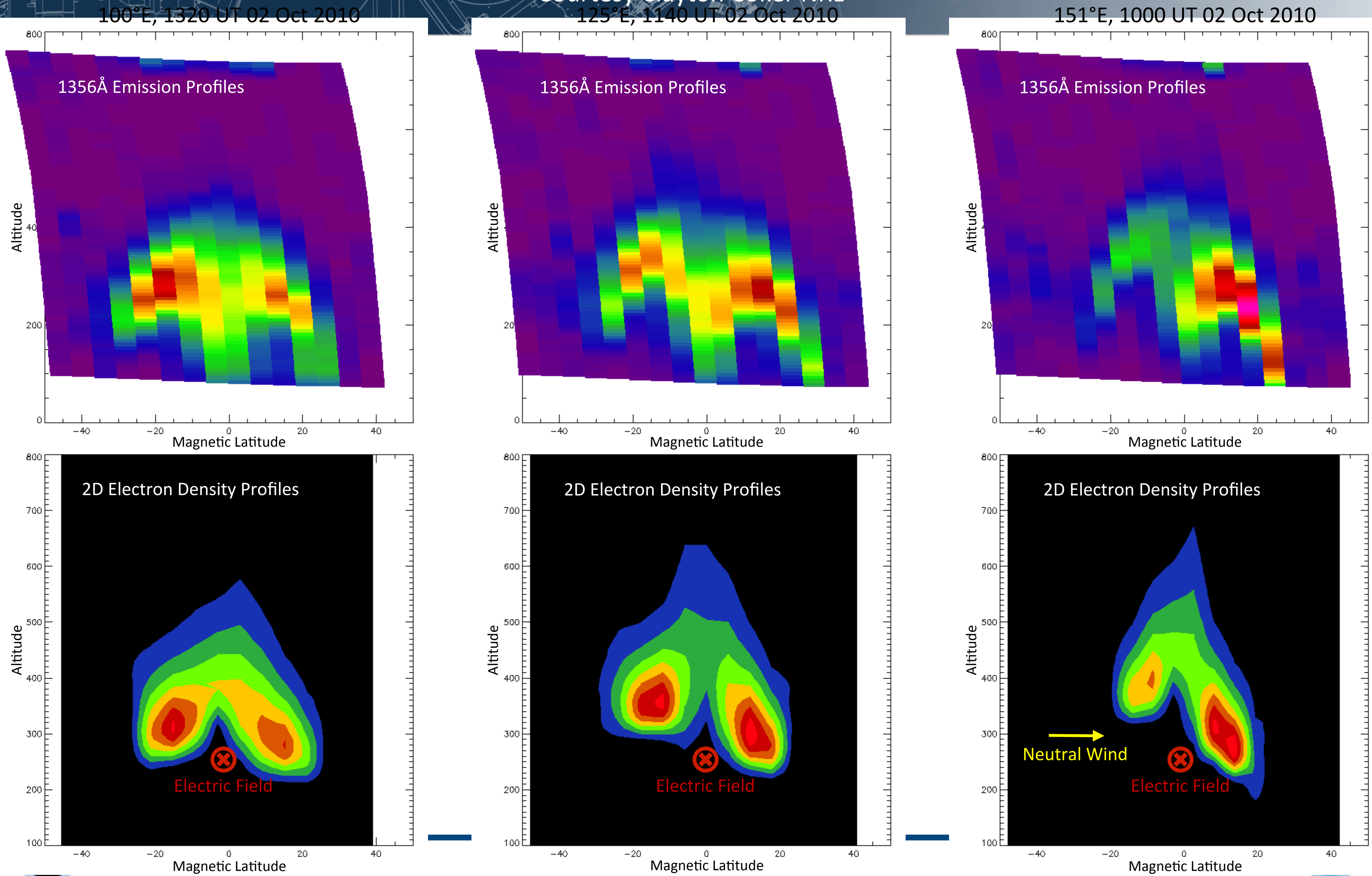
IDA4D, including SSUSI and SSULI limb 1356 radiances: bottomside density not completely "eroded"

SSULI Reveals the Main Features of the Equatorial Ionization Anomaly

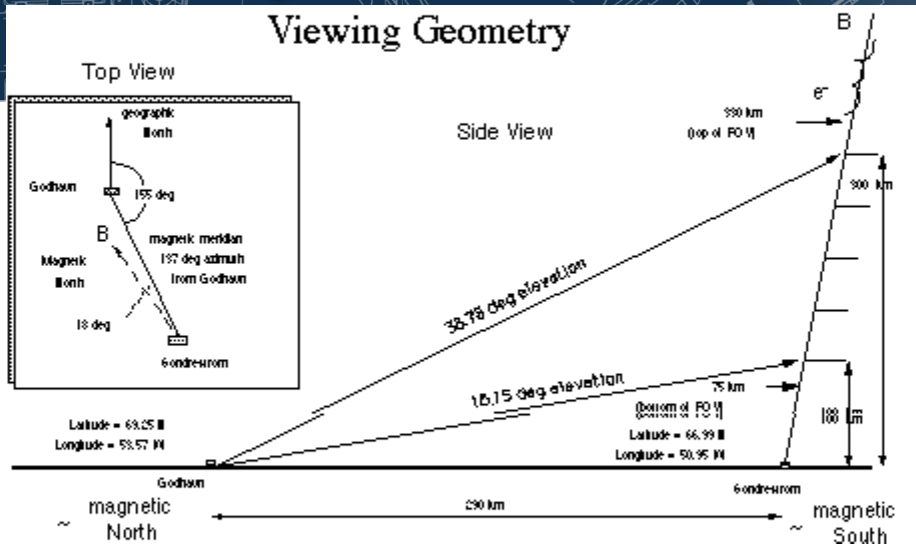
Fully Developed Anomalies – Strong Electric Field

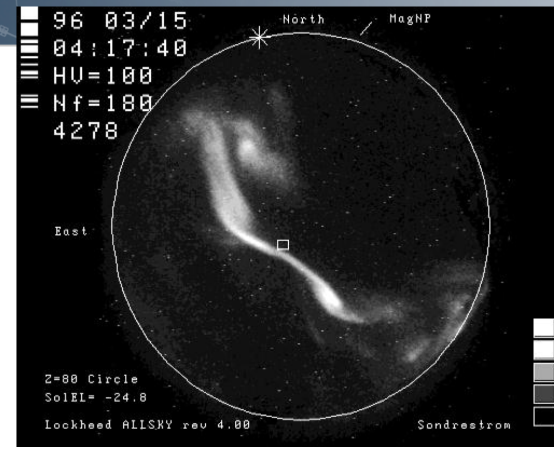
Asymmetric Crests – Meridional Neutral Wind

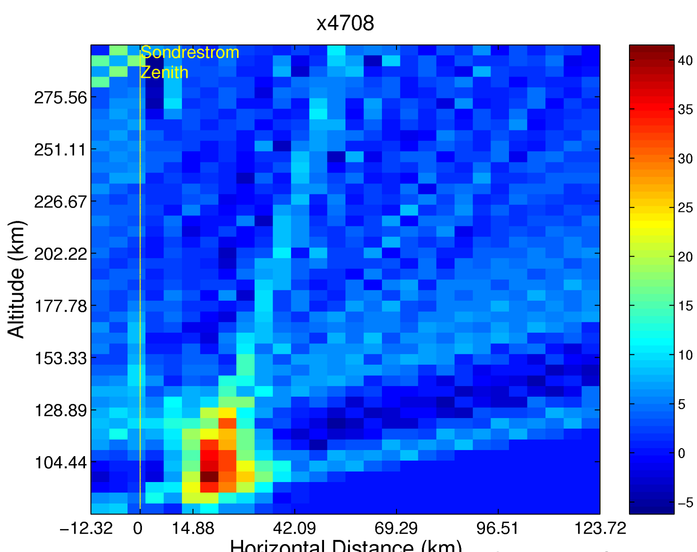
Courtesy Clayton Coker NRL

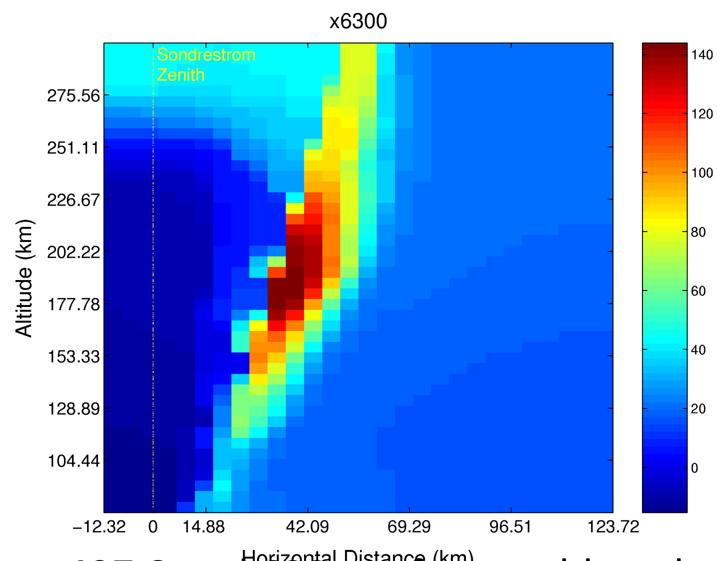


Multi-spectral auroral tomography









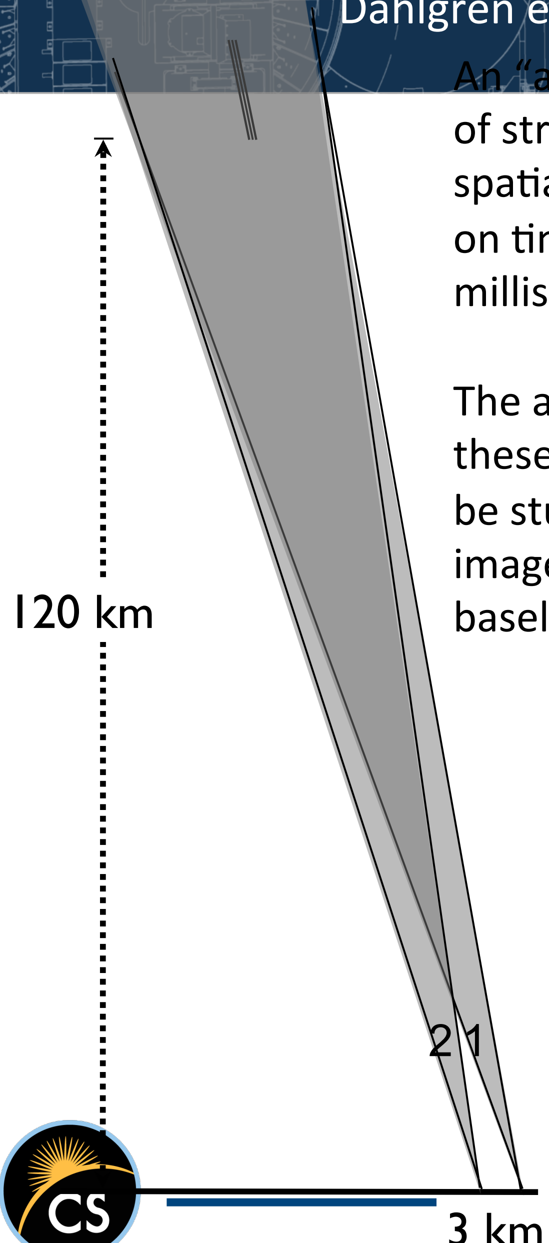
Volume emission profiles estimated simultaneously at 427.8 and 630 nm for a stable poleward boundary arc observed over Sondrestrom, Greenland (Swenson, Kamalabadi, Semeter)

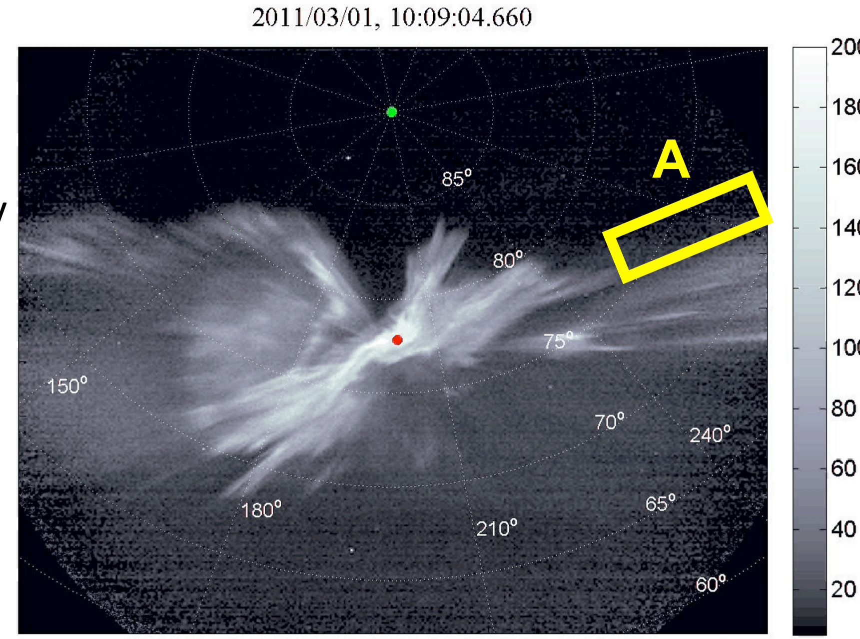
Short baseline auroral tomography

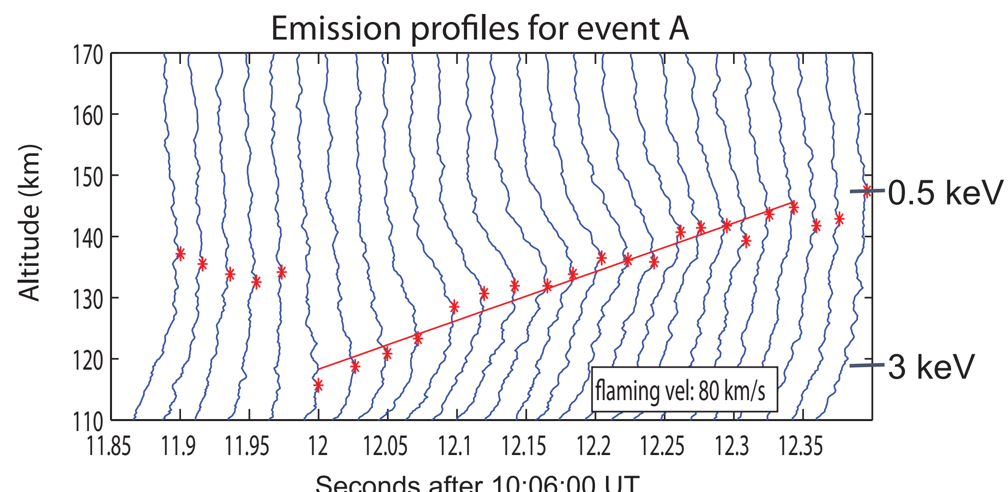
Dahlgren et al., JGR 2013

An "auroral breakup" consists of structure with horizontal spatial scales <100 m that vary on time scales of <1 millisecond.

The altitude characteristics of these fine-scale features can be studied using high-speed imagers at a few-kilometer baseline.







Initial results reveal a change in average energy of precipitating electrons from 3keV to 500 eV over a time sale of 200 ms

Dense GPS Array Tomographic Imaging

Lee, J. K., F. Kamalabadi, and J. J. Makela (2008), Three-dimensional tomography of ionospheric variability using a dense GPS receiver array, Radio Sci., 43, RS3001, doi:10.1029/2007RS003716.

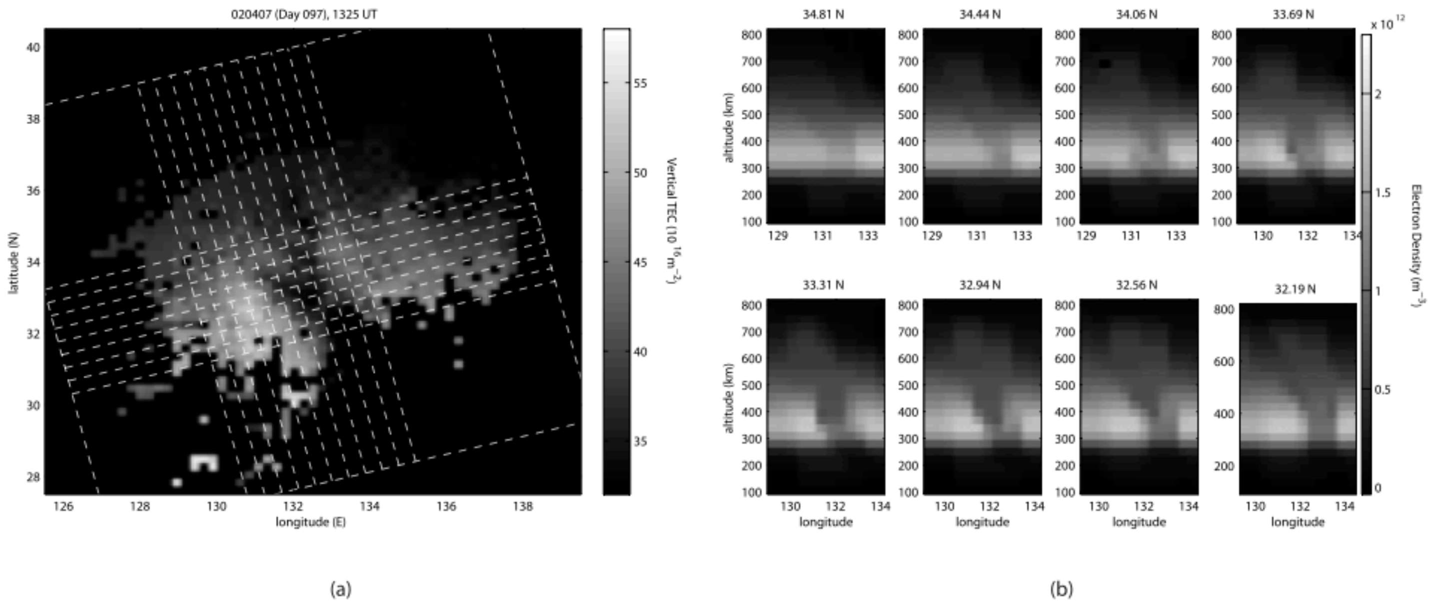
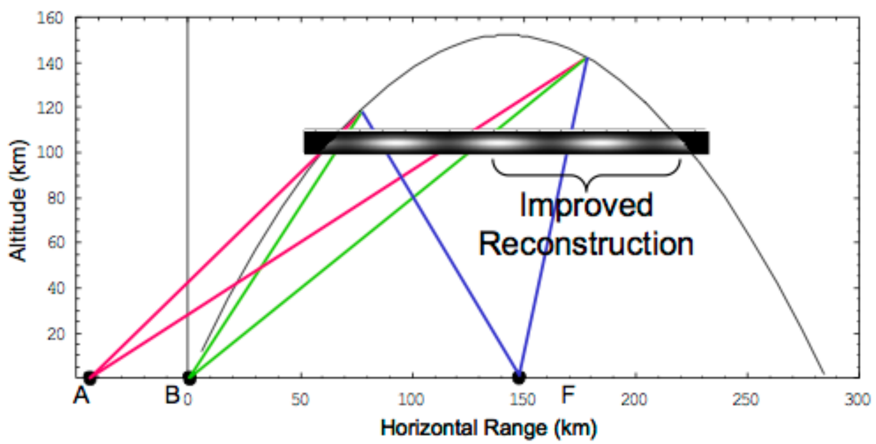


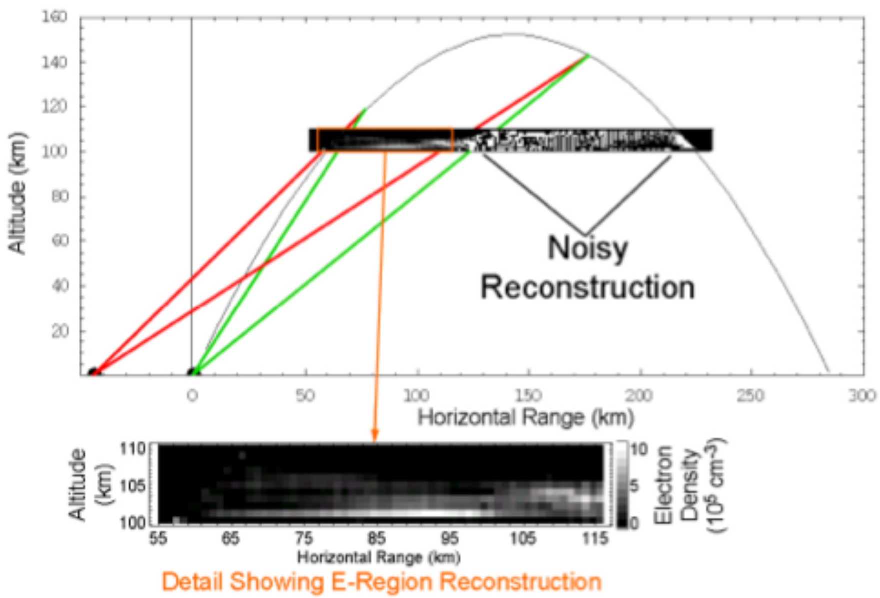
Figure 7. Depletion: (a) nonuniform grid discretization overlayed over VTEC map, and (b) reconstruction at 1325 UT. The longitudinal cross sections are in the inner grid.

SEEK Rocket Campaign Tomography

P. Bernhardt et al.: Radio tomographic imaging of sporadic-E layers during SEEK-2 Part of Special Issue "SEEK-2 (Sporadic-E Experiment over Kyushu 2)"



SVD reconstruction of the test example using data from three receivers.

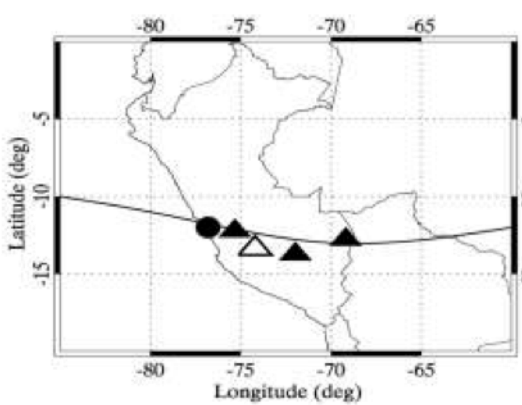


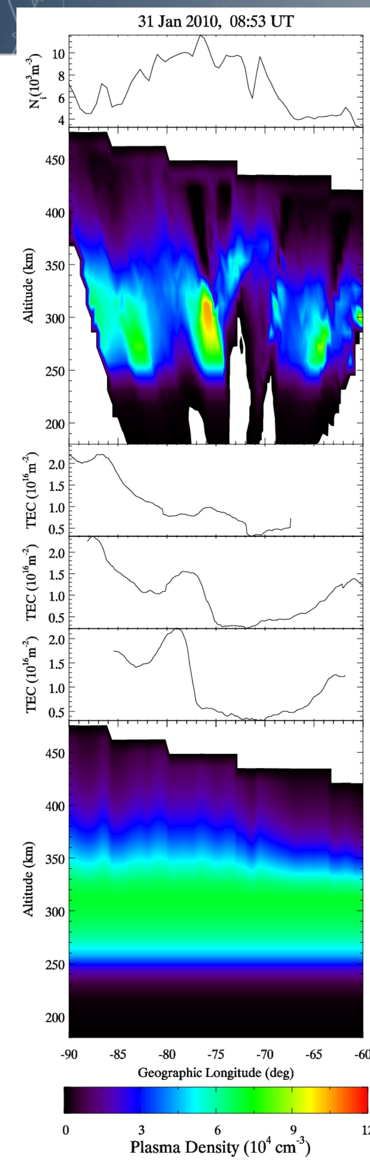
SVD reconstruction of the DBB data during the flight of the SEEK-2-31 rocket using two ground Receivers, 1082 Samples Per Receiver (0.2 s time samples or 158 m horizontal range samples) and a reconstruction grid with 1 km (H)×1 km (V) cell size.

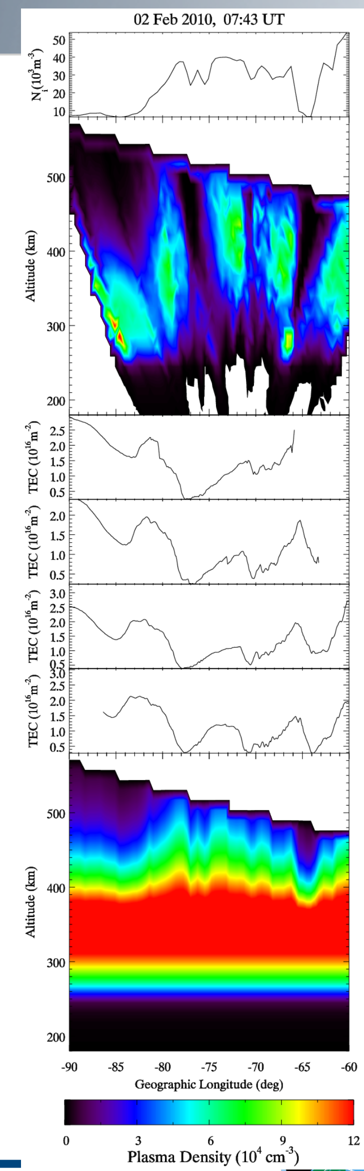
Equatorial Irregularity Reconstruction:

Hei, Bernhardt, Siefring et al. NRL – submitted to JGR

- NRL CERTO Receiver Sites
  - ANCON, Peru
  - Huancayo, Peru
  - Ayacucho, Peru
  - Cuzco, Peru
  - Puerto Maldonado, Bolivia
- Supporting Observations
  - C/NOFS In Situ (PLP)
  - Ground Ionosonde (Jicamarca, Peru)
  - Ground Incoherent Scatter Radar (ISR) (Jicamarca, Peru)
- Reconstruction
  - Initial Layer from ISR, Ionosonde and PLP
  - Algebraic Reconstruction Technique with Relative TEC Data from CERTO
  - Iteration to 2D Images

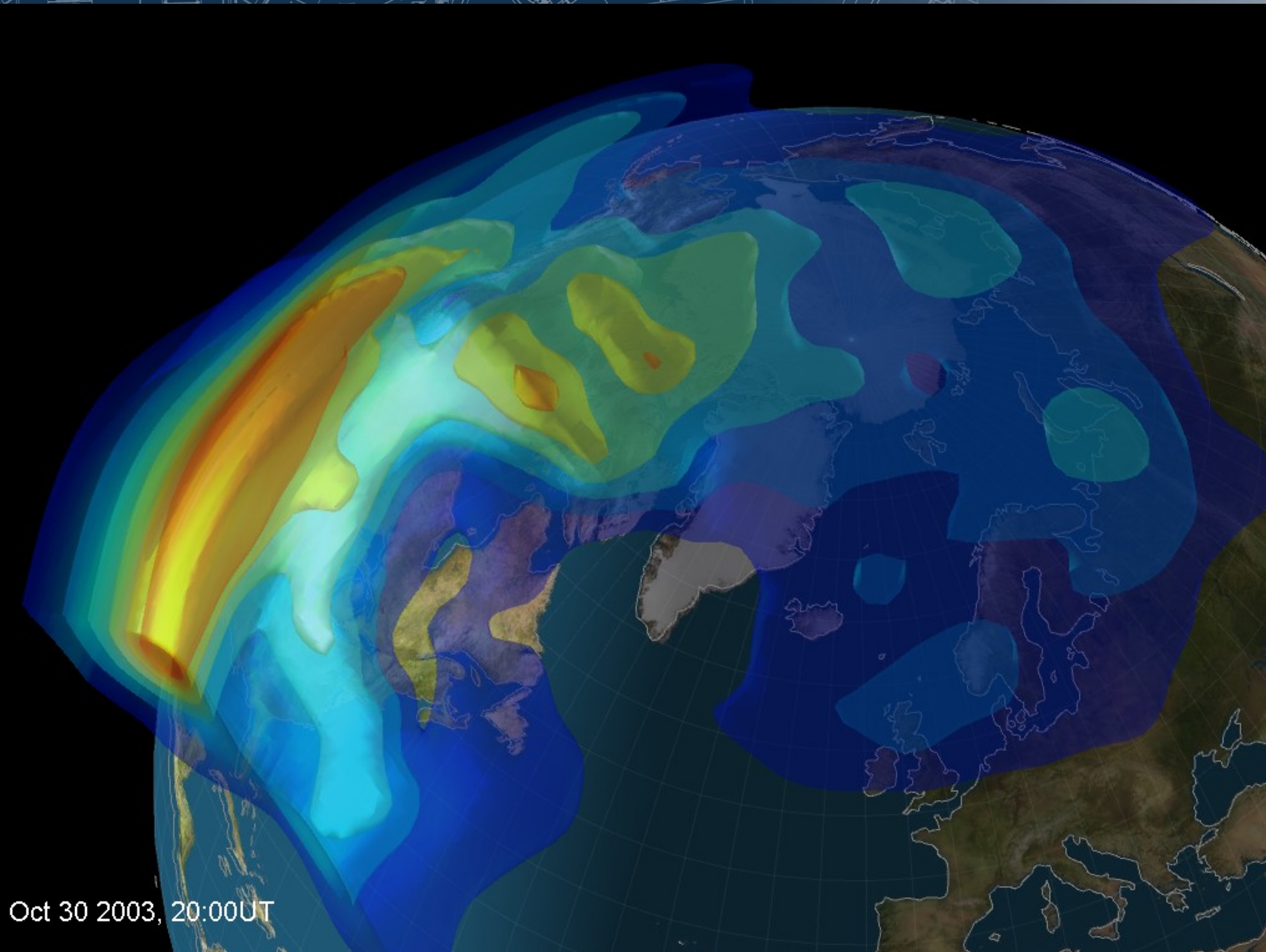






APL

3D Tomographic Image of SED October 30, 2003: MIDAS



Courtesy Dr. C. Mitchell, University of Bath, UK INVERT

Plasmaspheric Imaging

Dr. Romina Nikoukar (NSF #AGS-1231207)

June 19, 2009, which is a relatively quiet day.

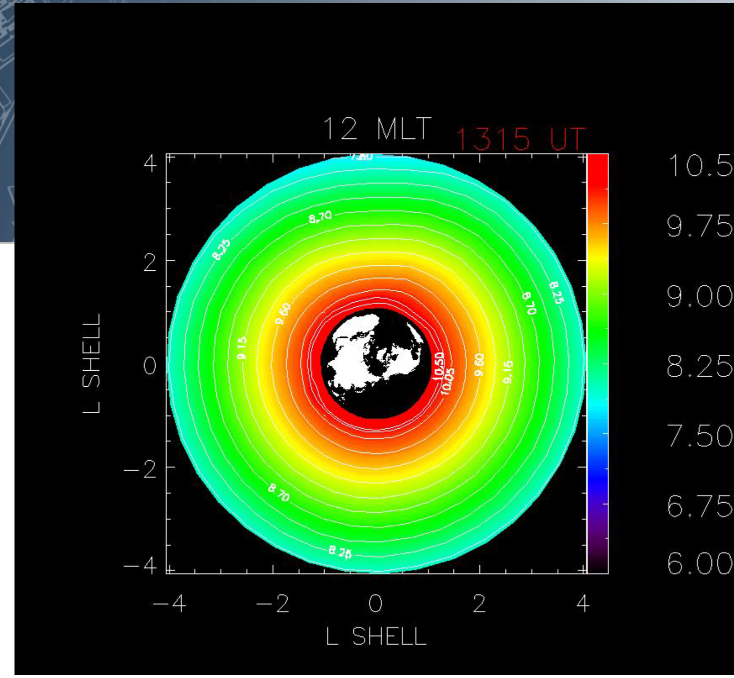
Resolution of the reconstruction grid:

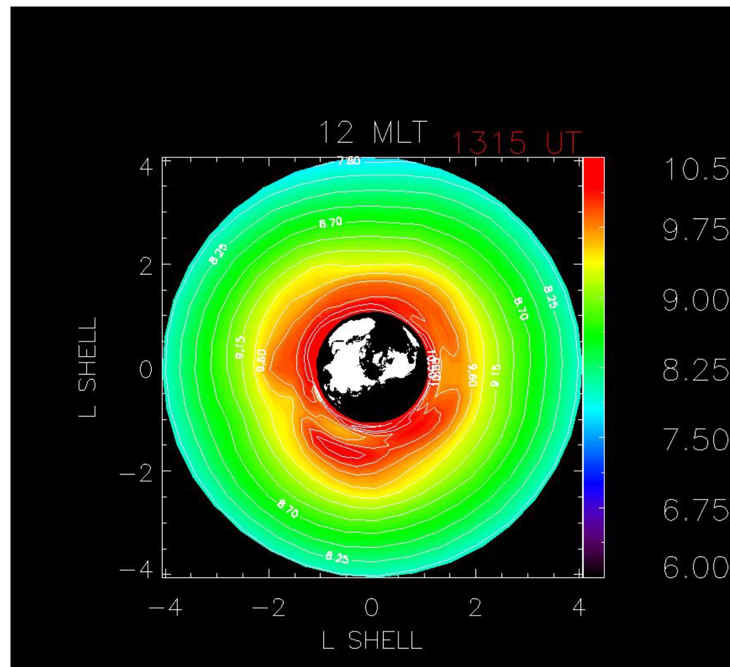
- 10° latitude
- 20° longitude
- 200 km between 400 km and 1000 km 500 km up to 4000 km and 1000 km above

Background plasmasphere model:

- Global Core Plasma (GCP) model

Data: Upward looking GPS data from LEO satellites such as COSMIC, GRACE, and SAC-C

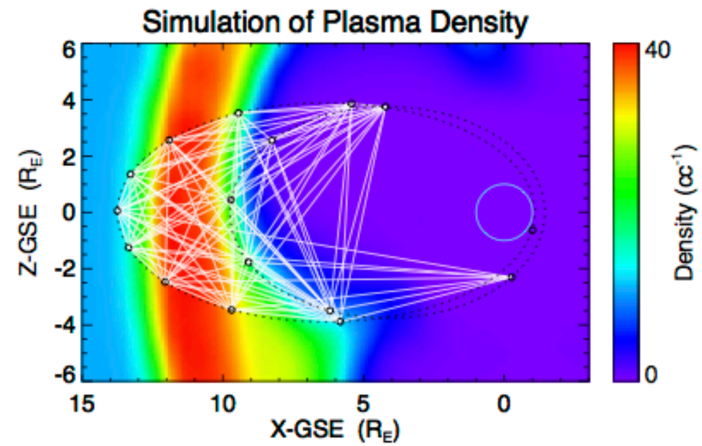




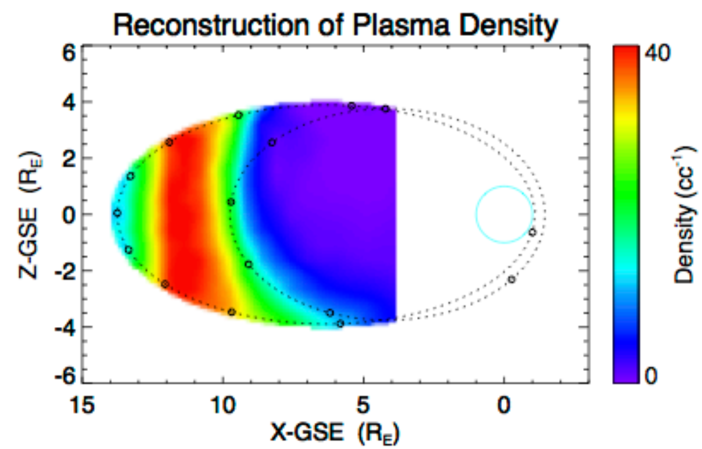
Magnetosphere Constellation and Tomography

Ergun et al., Science Closure and Enabling Technologies for Constellation Class Missions, edited by V. Angelopoulos and P. V. Panetta, pp. 29-35, UC Berkeley, Calif., 1998.

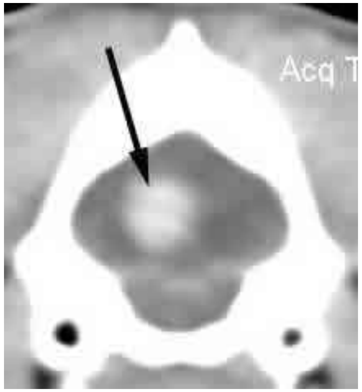
(a)

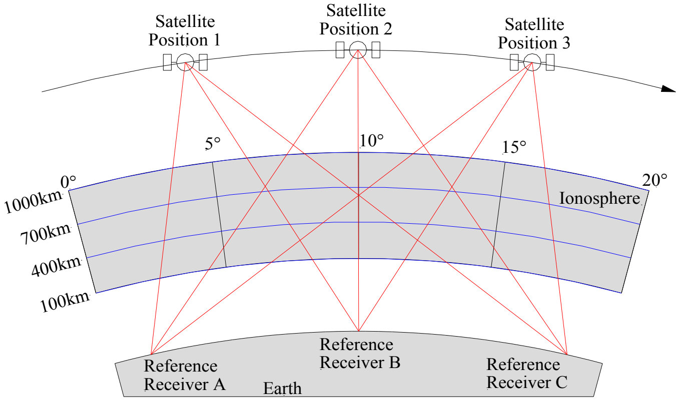


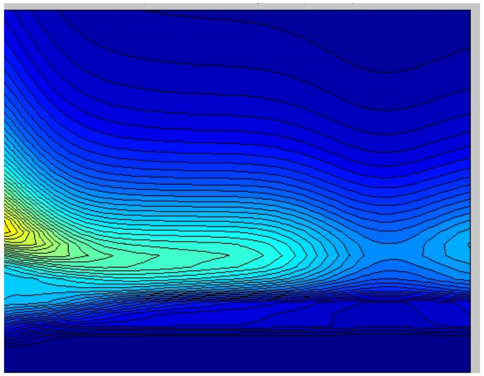
(b)



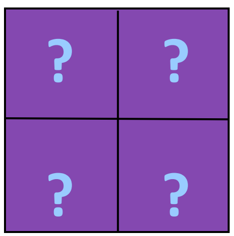
Tomography


Acq T


Satellite Position 1
Satellite Position 2
Satellite Position 3
0°
5°
10°
15°
20°
1000km
700km
400km
100km
Ionosphere
Reference Receiver A
Reference Receiver B
Reference Receiver C
Earth



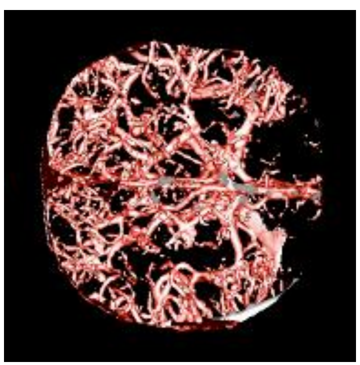
What is tomographic imaging?



e.g. Take a grid containing four numbers

Each number represents the magnitude of the property of the system

For example the density of an object

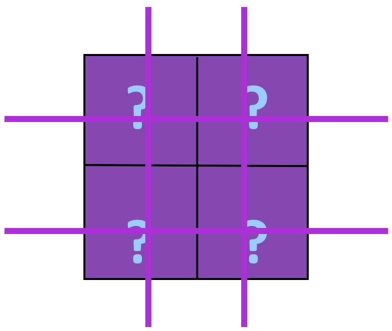


It could be the density of human body tissue

X-ray absorption is proportional to density

(left. Cranial blood vessels imaged by xray tomography)

How does tomography work?

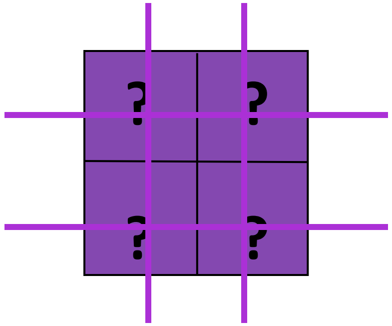


Take measurements that pass through and are affected by an object

By taking many measurements from different angles you can determine the spatial distribution of the integrated quantity

For example if each of the above measurements (integrated quantities) are all equal to 10, find the density in each pixel

Were there enough measurements?



Four equations, four unknowns

… but there are many possible answers

5	5
5	5

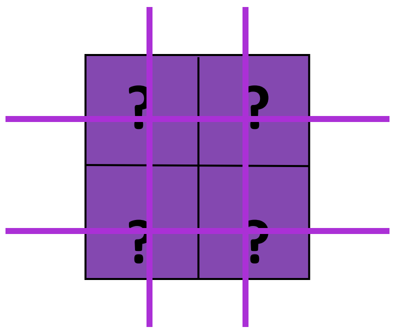
9	1
1	9

7	3
3	7

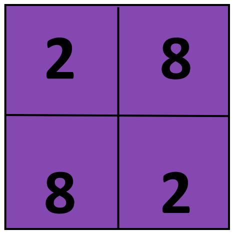
… etc

Equations not all independent

If I can’t change the geometry?

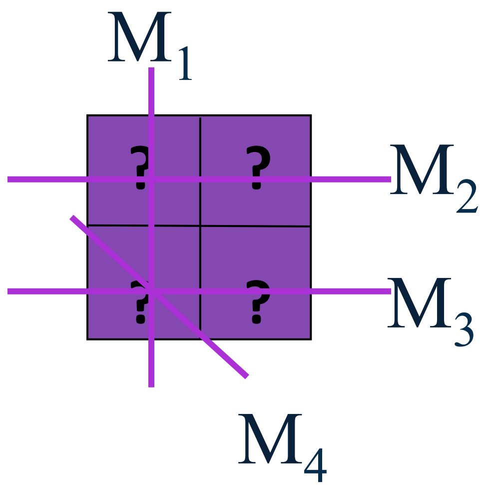


Need some prior information



For example, if you know that the second pixel is four times the value of the first then you can solve the equations with these measurements

If I can choose the geometry? (1)



The influence of each measurement, M, is weighted by its length, A, through each density, x

Formulate as a set of equations, e.g.

$A_{11}x_1+A_{12}x_2=10$

$A_{23}x_3+A_{24}x_4=10$

$A_{31}x_1+A_{33}x_3=10$

$A_{43}x_3=5 * 1.41$

If I can choose the geometry? (2)

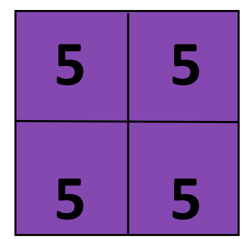
Put in the path lengths and the unknowns are now only the densities

$1\ x_1 + 1\ x_2 = 10$

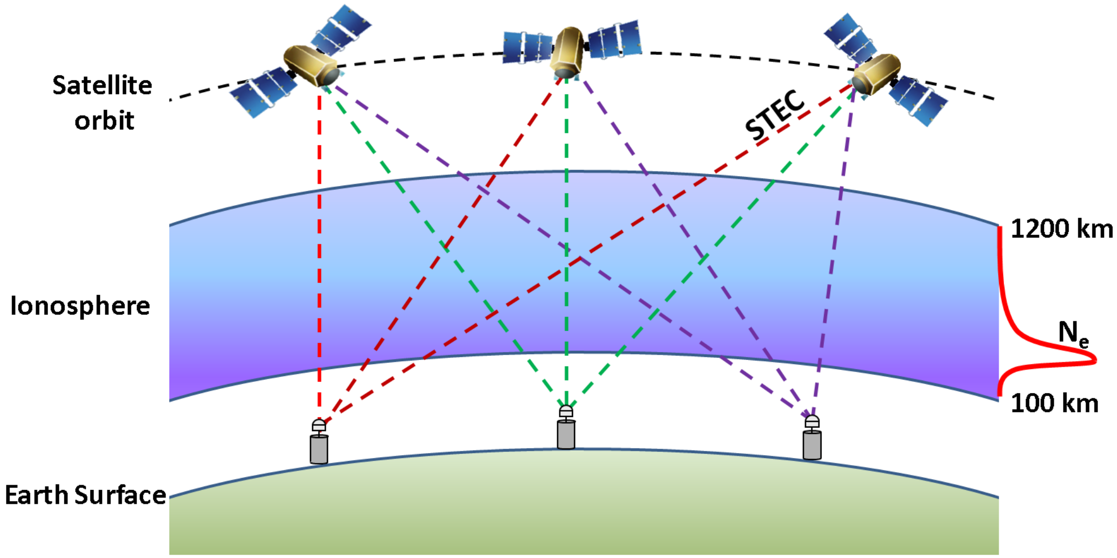
$1\ x_3 + 1\ x_4 = 10$

$1\ x_1 + 1\ x_3 = 10$

$1.41\ x_3 = 5 * 1.41$



Two-Dimensional LEO Tomography



Integrated measurement related to density:

$$T\left(\vec{x}_r,\vec{x}_s\right)=\int_r^s ds N_e\left(r,\theta\right)+\varepsilon_r+C$$

Lots of different look directions.

Represent density as a basis (pixels for example

Compute length of ray through each pixel – matrix relation

$$\vec{y}=\tilde{H}\vec{x}$$

How do we solve for densities ?

ISSUES

1. Limited Angles for Data
2. Data not continuous through image
3. Unknown constant for each receiver
4. Less measurements than unknowns
5. Data not linearly independent
6. Satellite is NEVER directly over receivers, so not a nice 2D (Earth rotates over 20 minutes)
7. Not Continuous in time
8. Regional in space

So, What do We need to do an 2D Ionospheric Tomographic Inversion?

- We need the measurements y
  - The more diversity of angle and direction the better
  - We need to consider the errors – constants of integration how do we deal with those
- We need the geometry matrix H
- We probably need apriori information of some kind to make the solution unique

Dealing with Observations

- Constant of Integration
  - Add constants of integrations as additional unknowns
    - Add complexity to the problem, not clear how to estimate with schemes such as MART, ART
  - Estimate them from a separate technique (Leitinger Method)
  - Only as good as simple ionosphere model
  - Use differential Doppler TEC data
    - Eliminates biases, but now dealing with differences in TEC along the path
- 3D Geometry
  - Satellite not in plane of receivers
  - Receivers not in single plane
  - Rotate / project rays into 2D plane
- Cycle slips
  - Fix or discard
  - Often by hand looking at lots of TEC plots

Early 2D Ionospheric Tomography Inversion Schemes: ART

- Start with an initial guess ionosphere x_j^0
- λ_k, the relaxation parameter, is a number or series of numbers used to control the convergence of the algorithm,
- Δ_{ij} is the length element of ray path *i* through pixel *j* and
- *n* is the total number of pixels.
- One iteration for each ray, cycle several times through all rays till convergence

$$x_j^{k+1} = x_j^k + \lambda_k \frac{y_i - \sum_{m=1}^{n} \Delta_{im} x_m^k}{\sum_{m=1}^{n} \Delta_{im}\Delta_{im}} \Delta_{ij}$$

ISSUES:

- Densities can be negative
- Artifacts in results along ray directions
- Relaxation parameter arbitrary
- Initial guess starts to set solution

Early 2D Ionospheric Tomography Inversion Schemes: MART

- Same parameters as ART
- But now multiplicative.
- No negative densities

$$x_j^{k+1} = x_j^k \left(\frac{y_i}{\sum_{j=1}^{n} \Delta_{ij} x_j^k} \right)^{\frac{\lambda_k \Delta_{ij}}{\max \Delta_j}}$$

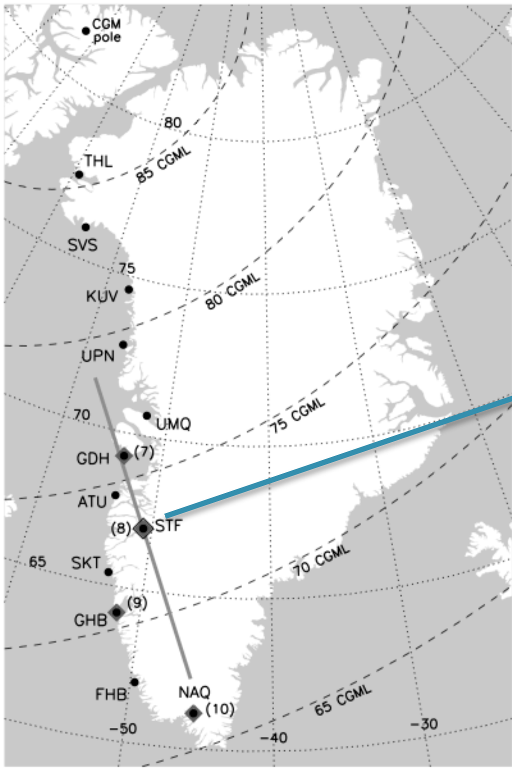
ISSUES:

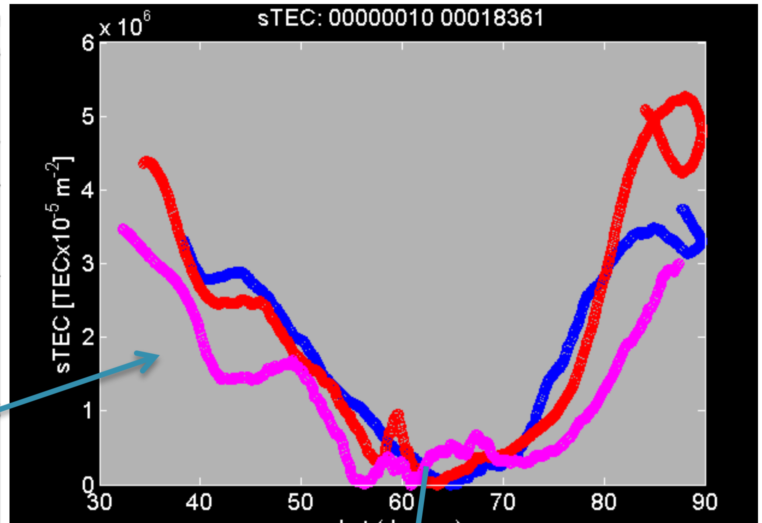
- Initial model very important
- Artifacts in results along ray directions
- Relaxation parameter arbitrary

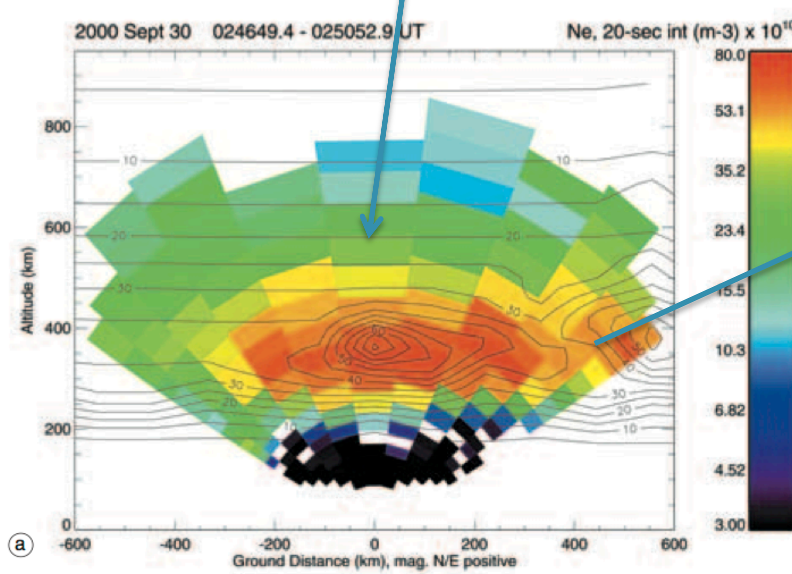
Other 2D Schemes

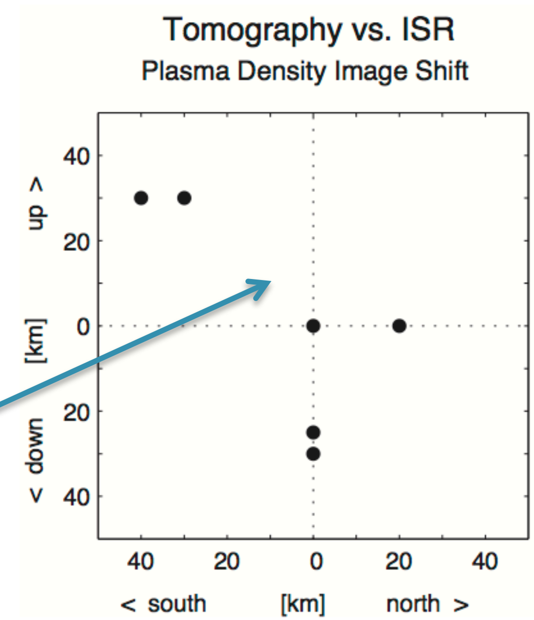
- **Initial basis of models, linear estimation to get background model**
  - Then MART afterwords
- **Linear matrix inversions**
  - Empirical orthogonal functions and Fourier space using (for example) singular value decomposition for the inversion.
- **Regularization / Constraints**
  - Positivity constraints
  - Additional data sources (ionosondes)
  - Tikhonov Regularization

Greenland Tomography Experiment 2002:







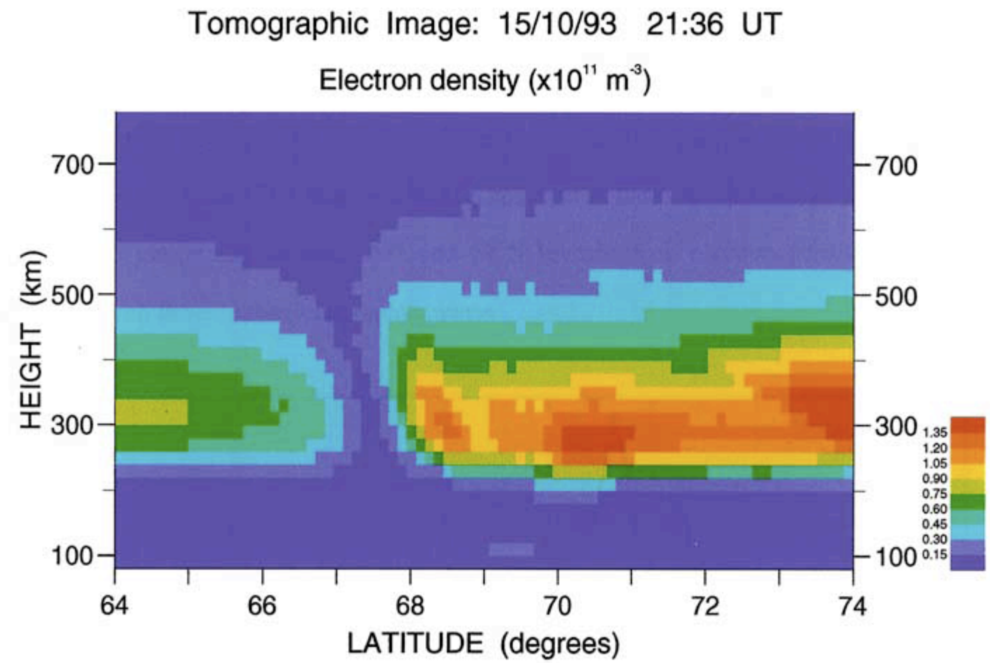


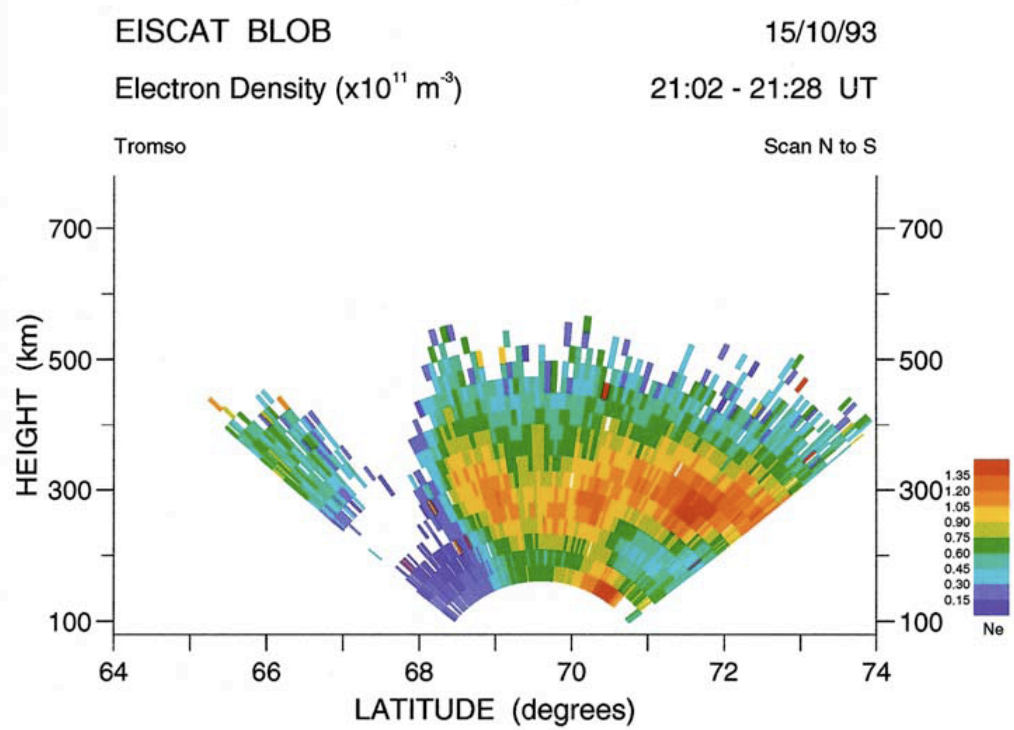
Watermann et al., 2002
NSF #ATM-9813864

Tomographic image of high-latitude trough

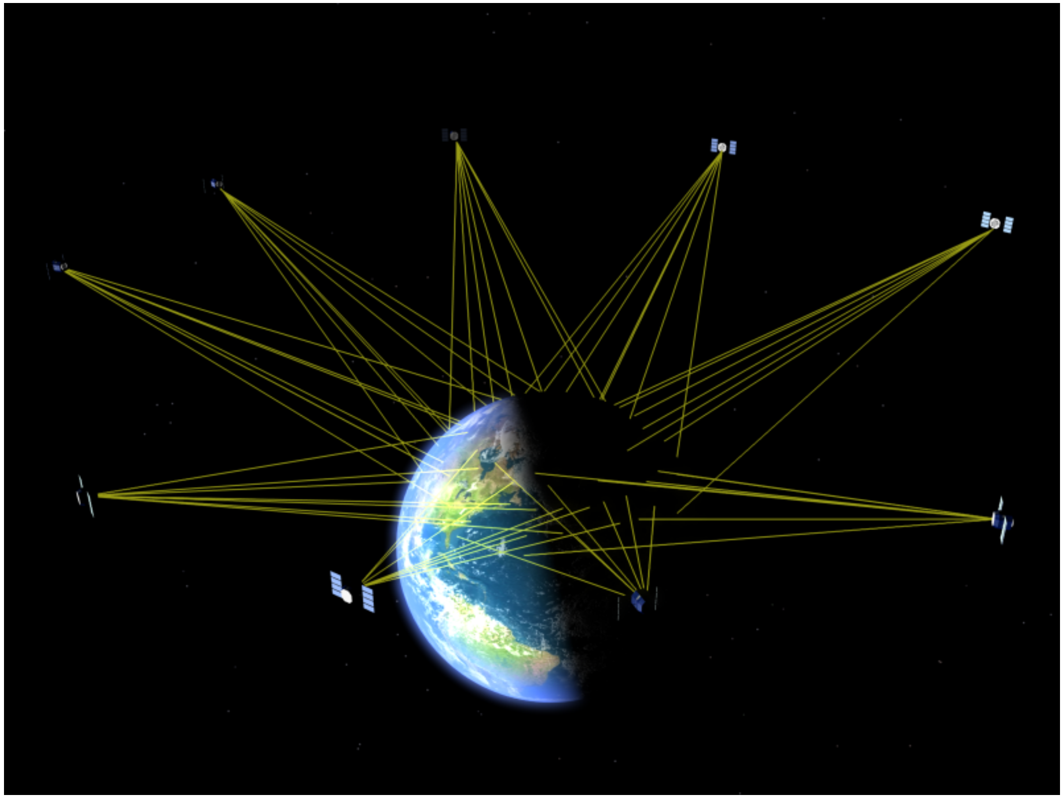
Verification with EISCAT incoherent scatter radar

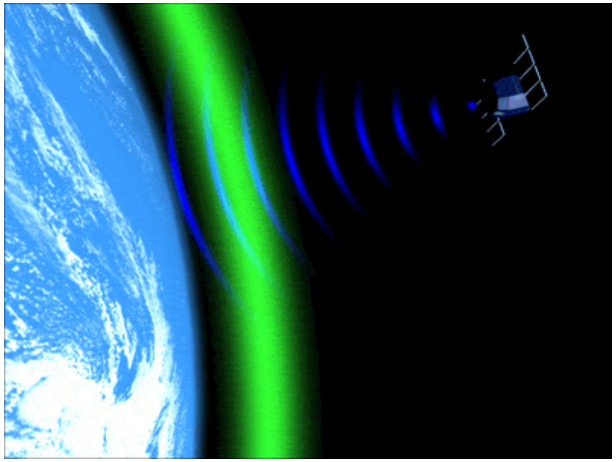
Reprinted from Mitchell et al. [1995]





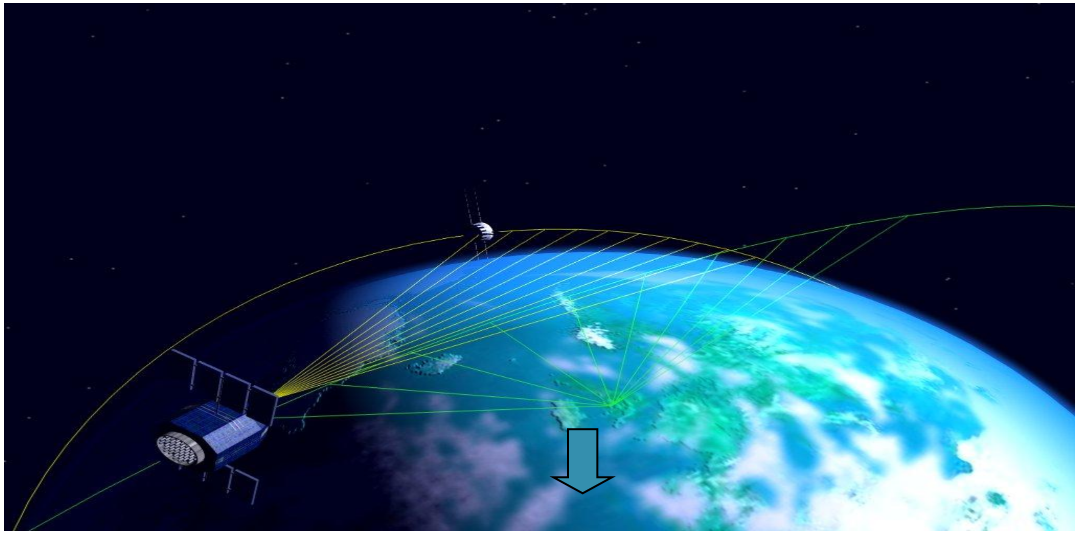
3D Global Imaging: Input Data





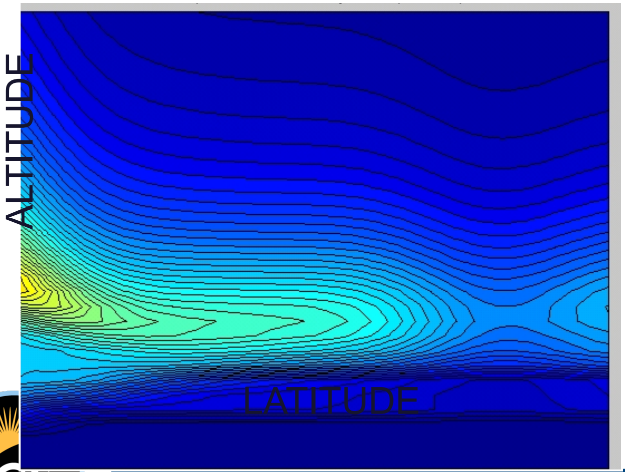
Differential phase gives integrated electron density

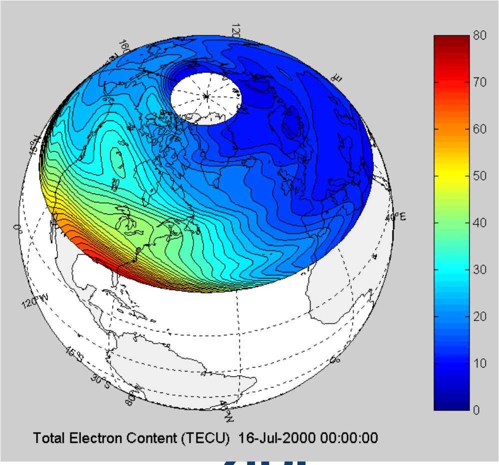
3D Ionospheric imaging



Measured –

relative values of total electron content





Find –

3D time-evolving

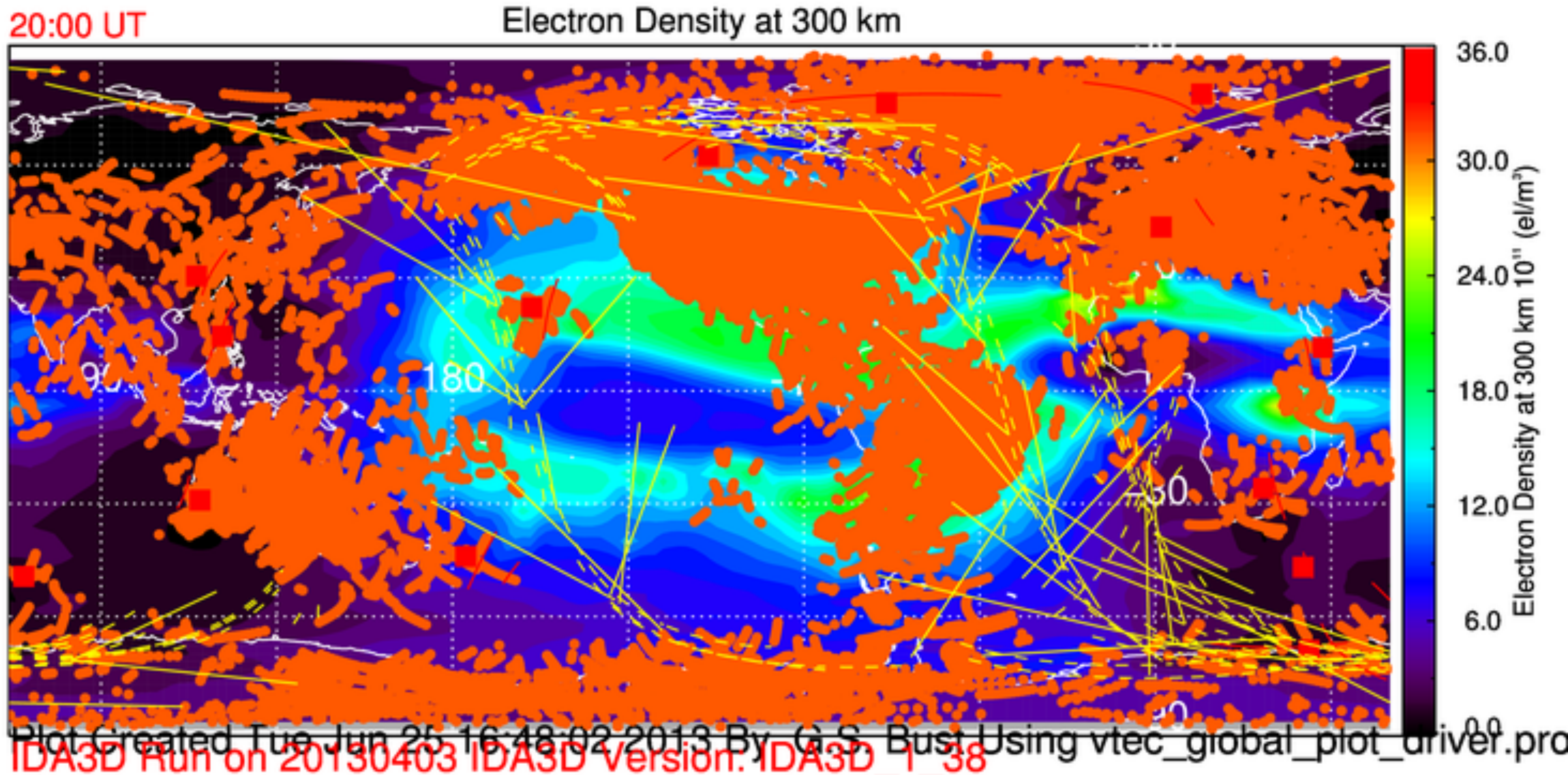
electron density

(Slide courtesy of C.N. Mitchell University of Bath, UK)

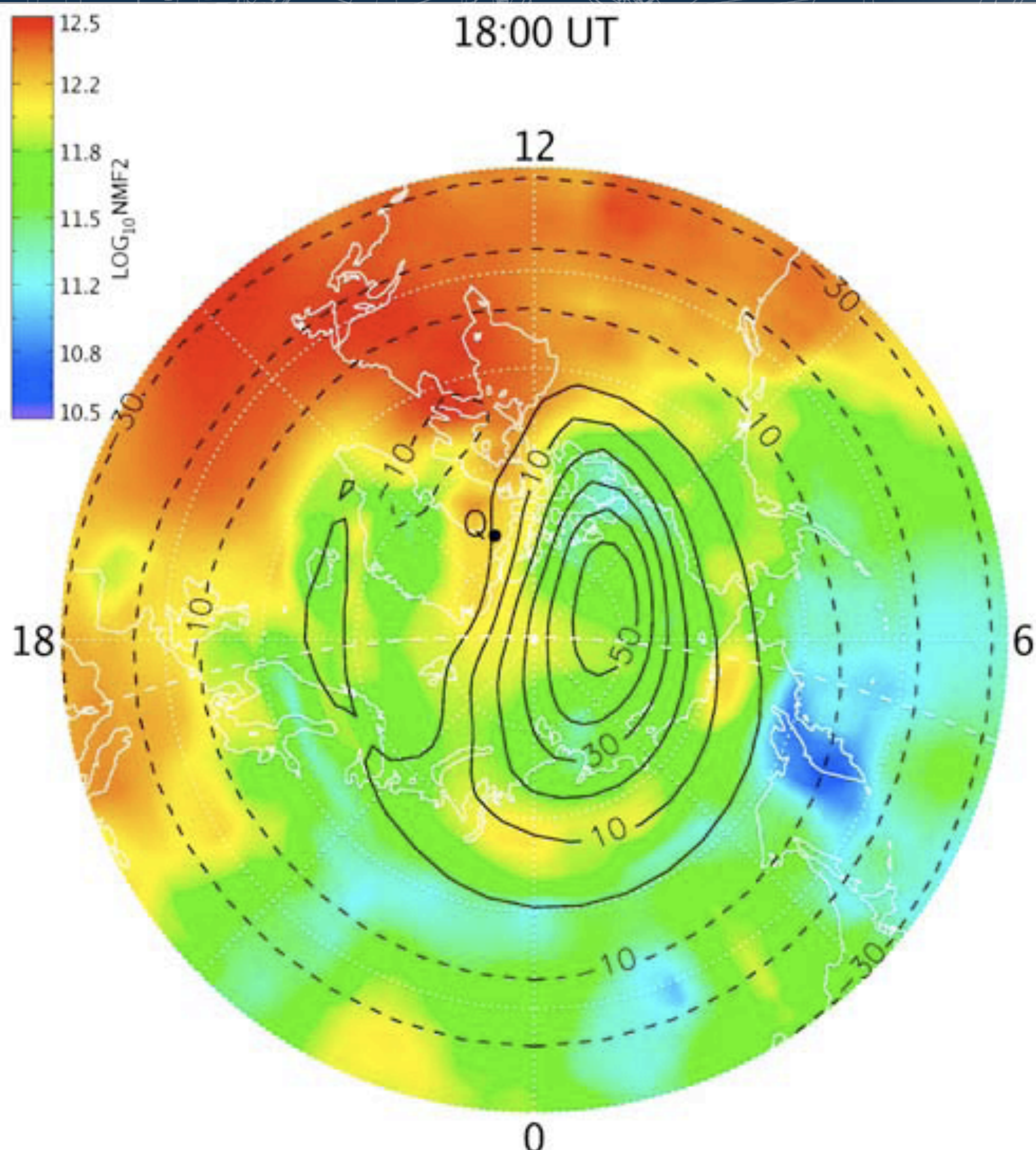
Issues/Methods Time-evolving 3D Imaging

- Issues
  - GPS TEC has receiver and satellite biases
  - GPS TEC moves slowly across ionosphere ~ 100m/s. 6 hours to cross the sky
  - Sparse observations: Only 10-12 satellites visible, large regions (oceans) with no data
  - Under determined
- Methods GPS Biases
  - Remove using JPL satellite estimates (~< 1 TECU residual error)
  - Calculate receiver biases separately (difficult for non IGS/Cors stations)
  - Estimate receiver biases as part of imaging solution
  - Use relative TEC from each receiver – eliminate receiver bias
  - Use phase arc Difference for each satellite – receiver pair
    - Eliminates Bias all together, requires time dependent imaging
- Methods: Time dependence
  - Time dependent algorithm (MIDAS) – also can use phase arcs
  - Kalman Filter to move forward in time (IDA4D, Gauss Markov GAIMS)
  - Physical model to move forward in time (data assimilation) (NCAR TIEGCM, Full Physics GAIM, 4DVAR)
- Methods: Sparse Data / Under determined
  - Expand in basis functions (MIDAS)
  - Background model / Forecast
  - Regularization
  - Other data sets

IDA4D Coverage Plot: 1930-2030



Polar Patches: Dec 12, 2001

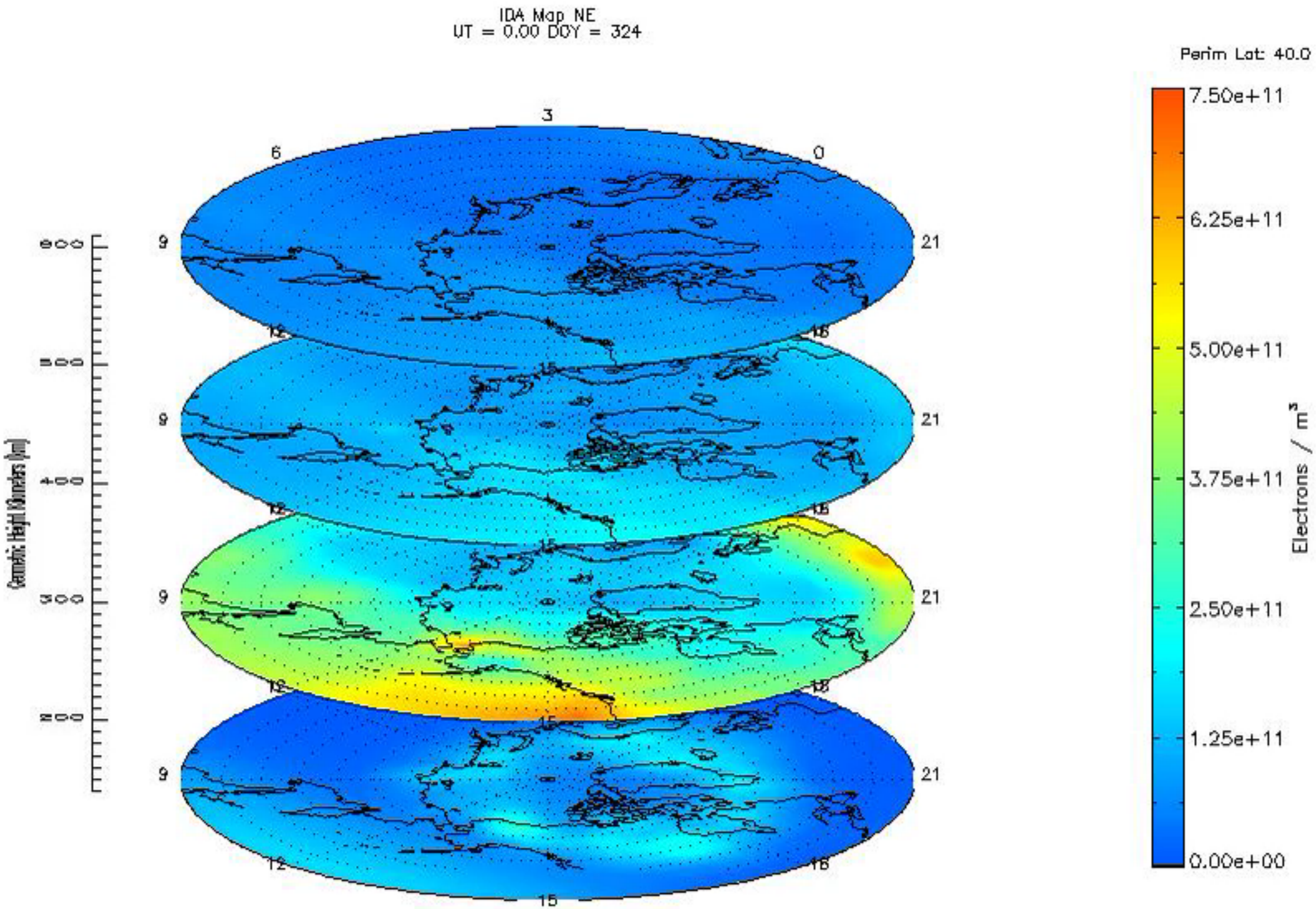


IDA4D electron density distribution as a function of geographic latitude and longitude at 1800 UT with AMIE convection patterns overlaid.

Qanaq is indicated by a black dot. A tongue of ionization extends from the dayside over Qanaq.

Bust and Crowley, 2007

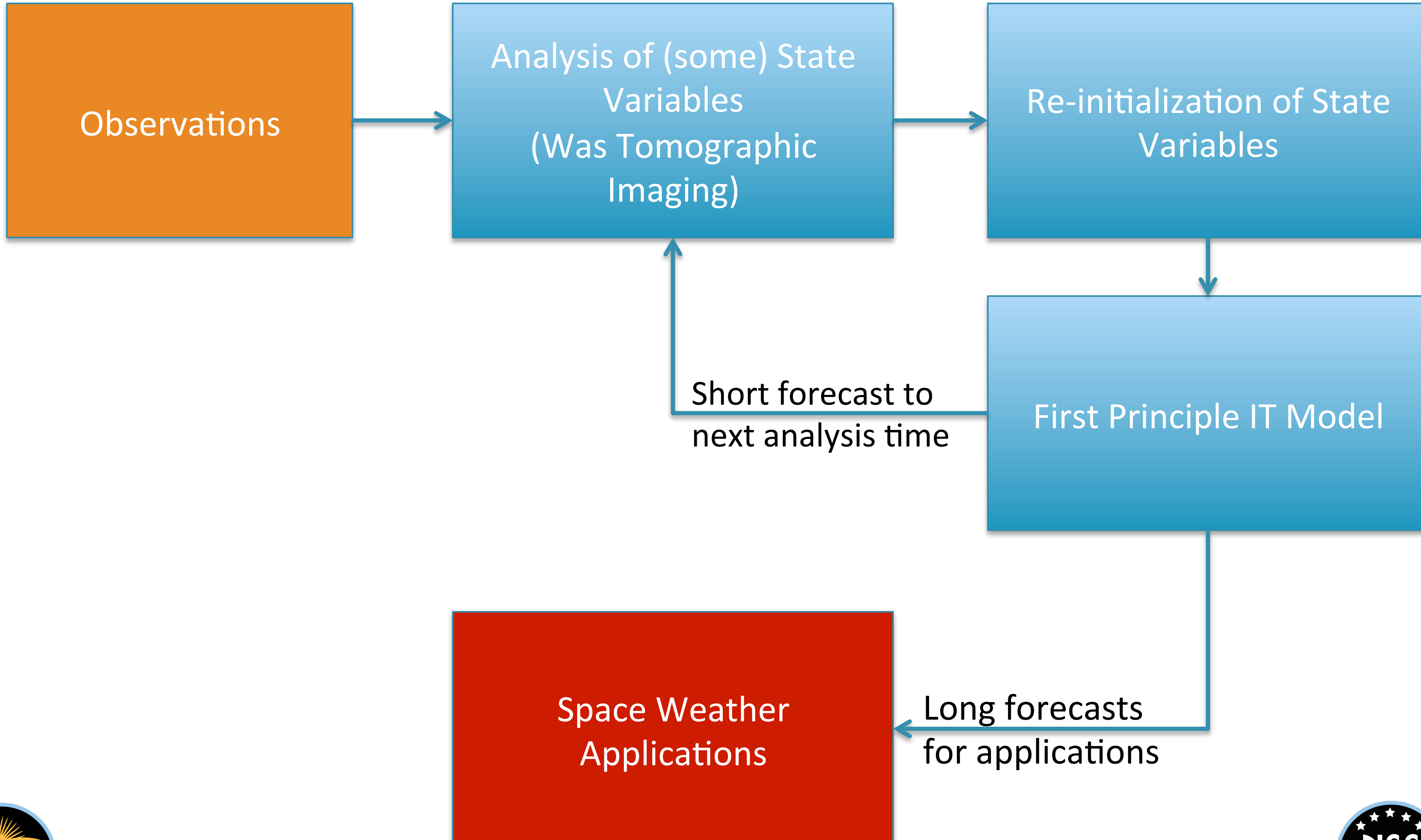
3D Movie Nov. 20, 2003



Data Assimilation

- From Tomography Point of view
  - **PRIMARY GOAL: *accurate estimation of global electron density field***
  - A method of using ***apriori information***
  - Forecast of the Density: better starting condition
  - Error covariances: proper weighting of influence of data and model
- From Data Assimilation point of view
  - **PRIMARY GOAL: *accurate prediction of complete set of state variables – observations used to correct first principle model***
  - Tomography is one formulation of relating observations to state variables
  - Importance is in how well the observations improve model predictions

Data Assimilation Cycle



Future work

- Mesoscale /small scale tomography imaging
- Dense arrays
- Satellite imaging of small scales
- New measurement types
- Optimal methods for each problem to solve
- New platforms
  - Sub-orbital
  - Planes to satellites
  - Balloons
- New regions
  - Plasmasphere
  - Magnetosphere
  - Lower atmosphere
- CEDAR is a great community for these types of problem

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- NSF
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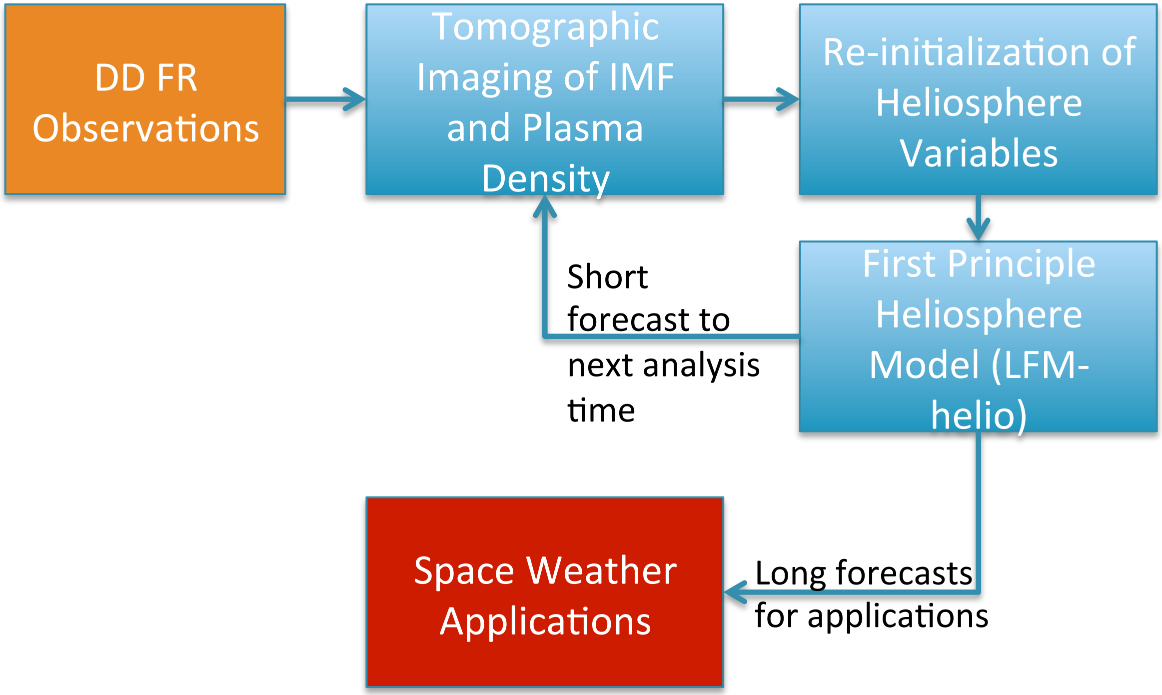
  - AGS0640955
- Friends and Colleagues!


DD FR Observations
Tomographic Imaging of IMF and Plasma Density
Re-initialization of Heliosphere Variables
First Principle Heliosphere Model (LFM-helio)
Short forecast to next analysis time
Long forecasts for applications
Space Weather Applications