Limited Angle Tomography for the 135.6 nm Electron Densities in the F-Layer Atmosphere

Karen Orme
University of Massachusetts, Lowell
Capstone under Prof. Timothy Cook
05/05/16

Image Source: NASA/JSC

I. Project Overview:
The Limited Angle Problem

- ***Objective:*** To demonstrate the limited angle problem in ionospheric tomography for LITES spectrometer

- ***What is the limited angle problem in ionospheric tomography?***
  - Well-known problem in tomography in general
  - Getting an accurate measurement of electron densities in the atmosphere for a full angle can work
  - Where it doesn’t work:
    - Instrumentation limitations
      - Limited look angle due to small aperture size on limb (looking outward just below the surface of the Earth)
    - Physical limitations
      - Noise/interference created from wind, changes/discontinuities in the atmospheric density gradient (aka: plasma drift)
      - Plasma drift can explain why radio signals travel farther at night than during the day

II. Project Overview: Tomography

- ***What is tomography?***
  - Measuring different angles for an object of interest in order to produce cross-sectional image slices of specific areas
  - Useful in medical imaging (CT scans), geophysics, biology, plasma physics, atmospheric sciences, etc.

- ***Why do we care about measuring electron densities in the atmosphere?***
  - The number of free electrons is sufficient enough to affect radio transmission due to plasma drift and irregularities in the ionosphere
  - Improve/study radio communication
    - The ionosphere bounces radio-transmitted signals from a satellite to the ground
    - The denser the atmosphere the more electromagnetic interference occurs

III. Project Overview:
The F-Layer

What is the F-Layer?

- F layer comprised of an F1 and F2 region in the atmosphere
  - Highest concentration of free electrons and ions anywhere in the atmosphere
  - Free electron density is an indicator of the degree of ionization (highest probable)
- F1 Layer Process
  - Production/loss cycle - plasma is formed due to ionized energy present in the layer
  - Highly energetic, negatively charged electrons and positively charged ions interact via electrostatic forces
  - Dissociative recombination - deterioration of atoms giving off highly energetic photoelectrons
- F1-layer at night time merges into F2 (Appleton-Barnett Layer)
  - Optically thin (less dense/less charged)
  - Highest radio signal reflections of all the ionospheric layers
  - Interaction of oxygen atoms and electrons through photoelectron emissions

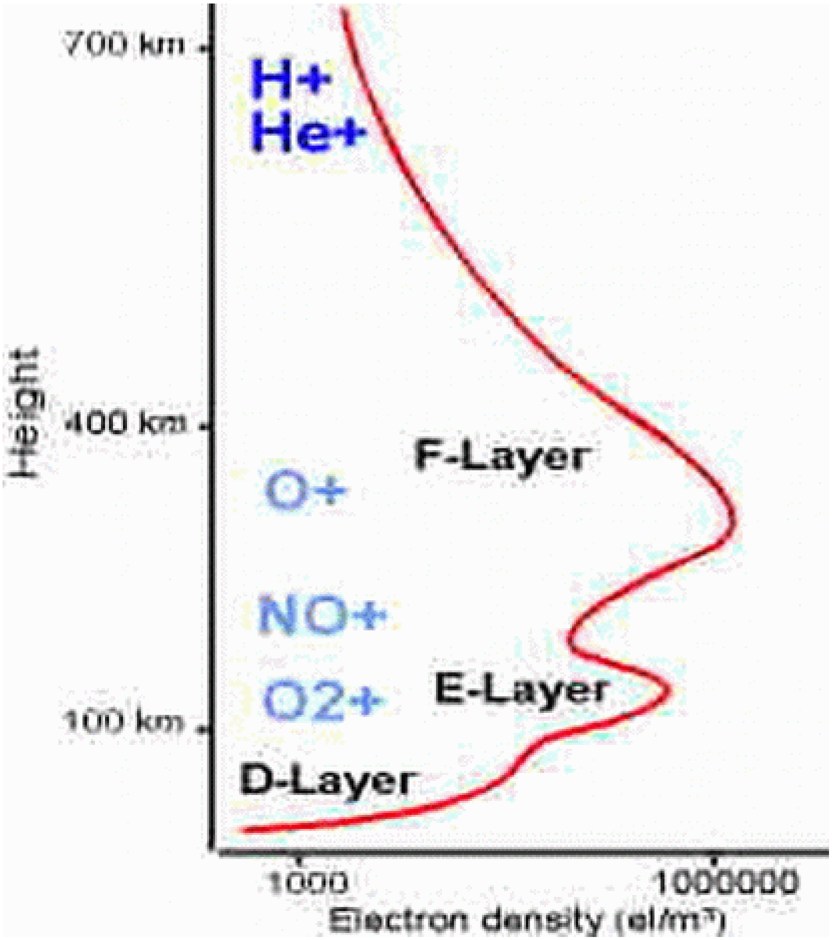


Image Source: Lancaster University

IV. Project Overview: LITES and TIP

What are LITES and TIP?

- LITES - *Limb Imaging Ionospheric and Thermospheric Extreme Ultraviolet Spectrograph*
  - Measures O^+ electron emissions for limb angle (across)
- TIP - *Tiny Ionospheric Photometer*
  - Measures O^+ electron emissions for the nadir angle (down)
- Due for launch in November, 2016 aboard the NASA ISS
- Designed to measure low to mid-latitude ionospheric structures in the EUV spectrum (60-140 nm) using ground-based GPS

The Plan of Action:

- If the electron density of a particular region of the ionosphere is known, then a prediction can be made about what will be observed by LITES
- Create a model atmosphere from AURIC (Atmospheric Ultraviolet Radiance Integrated Code) raw data
- Perform a Radon transform (forward projection) and Inverse Radon Transform (backprojection) on the full angle (0,180) to test if it works
- Calculate the angles for LITES and TIP to view limited angle case
- Perform a Radon and Inverse Radon transform (again)
- See how well it works visually due to information loss generated in the transform by zeroing-out a few column densities (plumes)
- See how well the backprojection preserves the plumes. Is it preserving the information within a reasonable width?
- If not, manipulate the data reasonably to see if the backprojection in LITES works

I. Mathematical Overview:
The Radon Transform (Forward Projection)

- 2D plot is transformed onto a 1D Cartesian plot
- Projection lines summed up as a collection of angles creating a sinogram
- All lines along projection satisfy transform in polar coordinates

$$g(\phi,s) = \iint f(x,y)\delta(x\sin\phi - y\cos\phi - s)\,dxdy$$

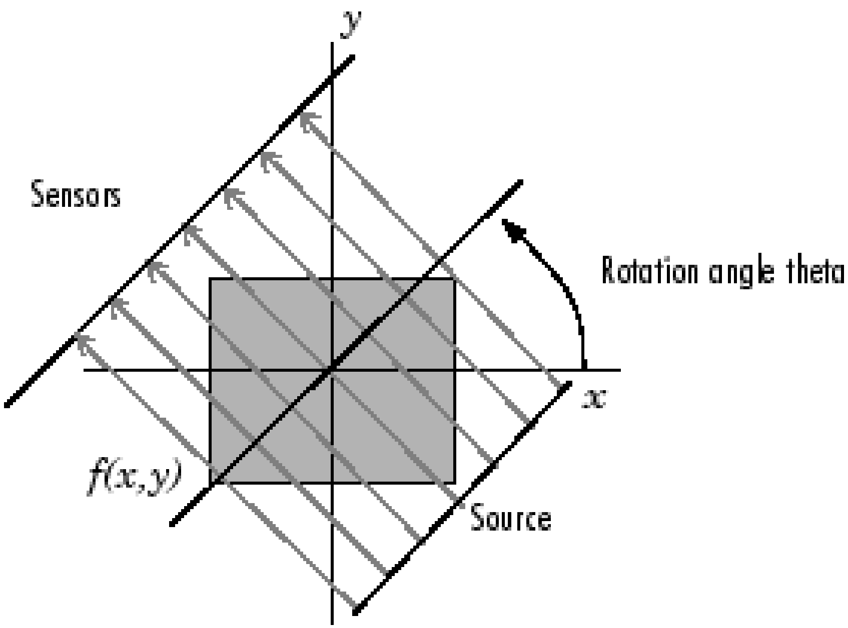


Image sources: Rice University

II. Mathematical Overview:
The Inverse Radon Transform via Fourier Slice Theorem (FST) and Filtered Back Projection (FBP)

- A backprojection reverts sinogram back to the original image (lossy)
- FBP is a combination of backprojection and ramp filtering (less lossy)
- FST is an inverse Radon transformation which slices through an origin parallel to projection line
- Results in projections at an angle in polar coordinates

from Cartesian coordinates: $$f(x,y)=\frac{1}{4\pi^2}\iint F(u,v)e^{j(ux+vy)}dxdy$$

to Polar coordinates: $$f(x,y)=\frac{1}{4\pi^2}\iint G(\phi,\omega)e^{j\omega(x\sin\phi-y\cos\phi)}|\omega|d\omega d\phi$$

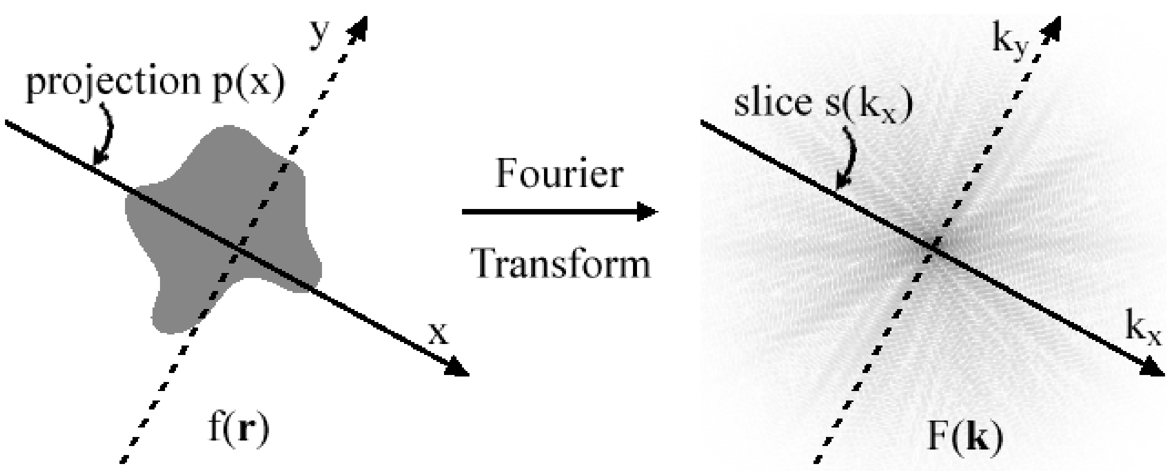


Image source: http://www.wikiwand.com/en/Projection-slice_theorem

II. Mathematical Overview: The Radon Transform (Forward Projection)

- Sample sinogram and FBP (Filtered Back Projection) in medical imaging

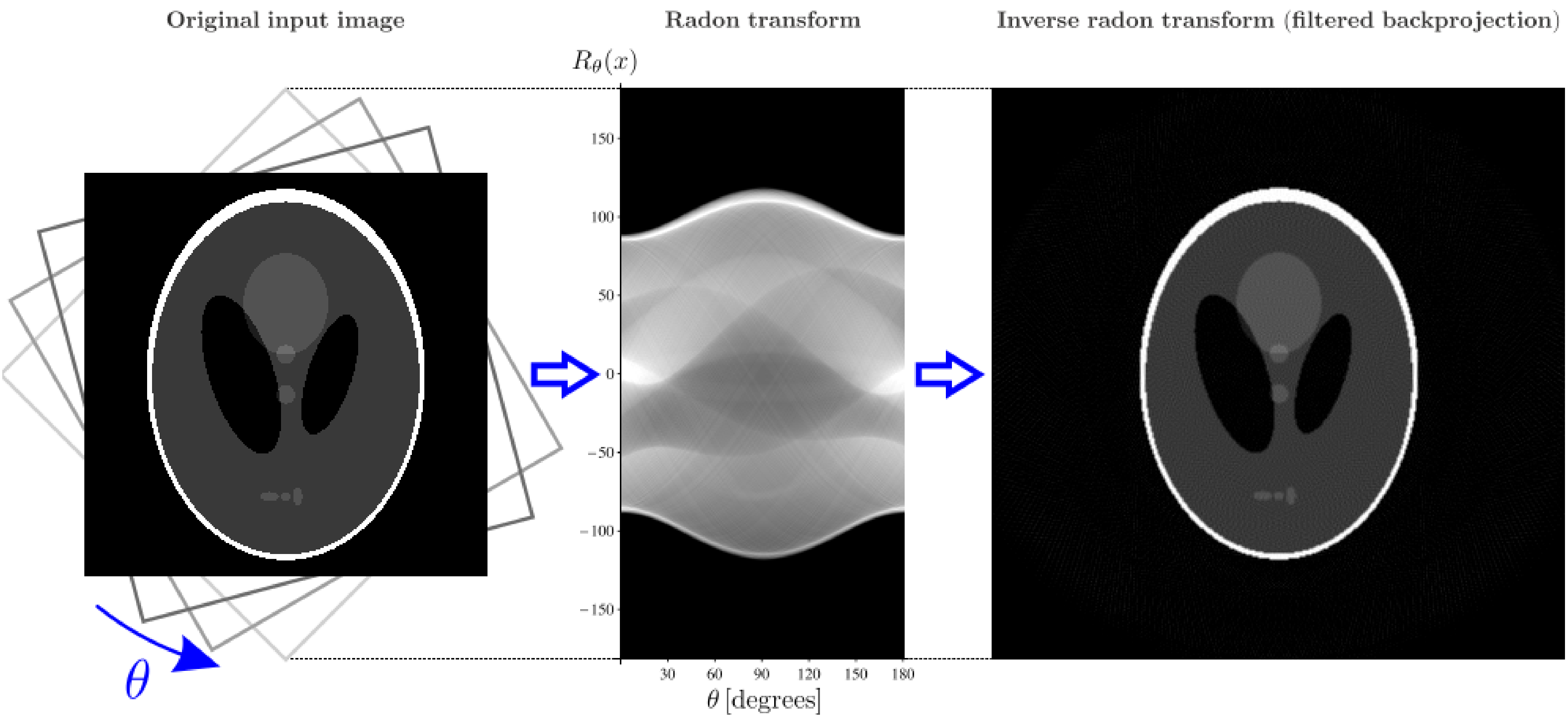
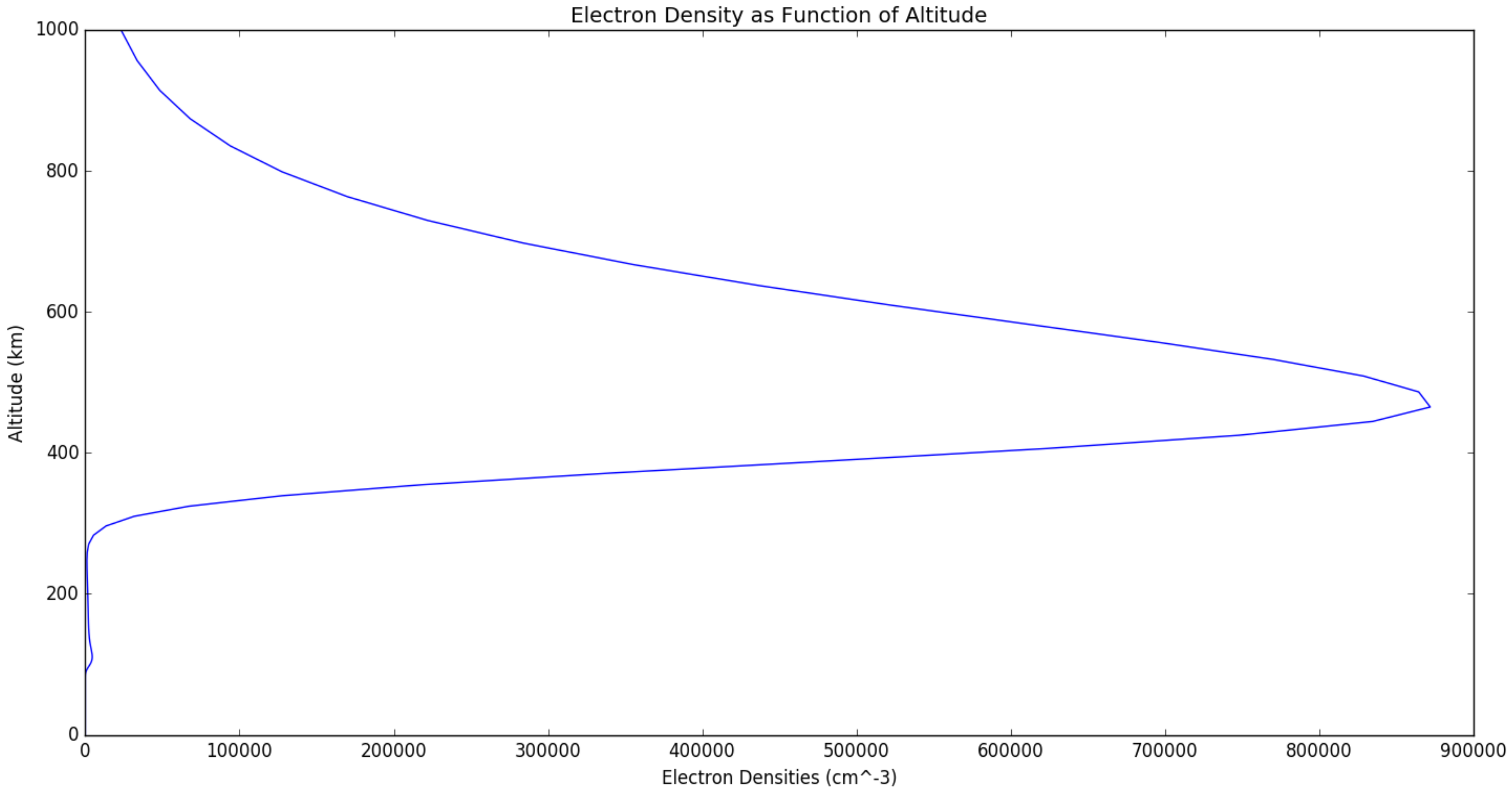


Image Source: Dr. Christian B. Mendl, Phd Stanford University

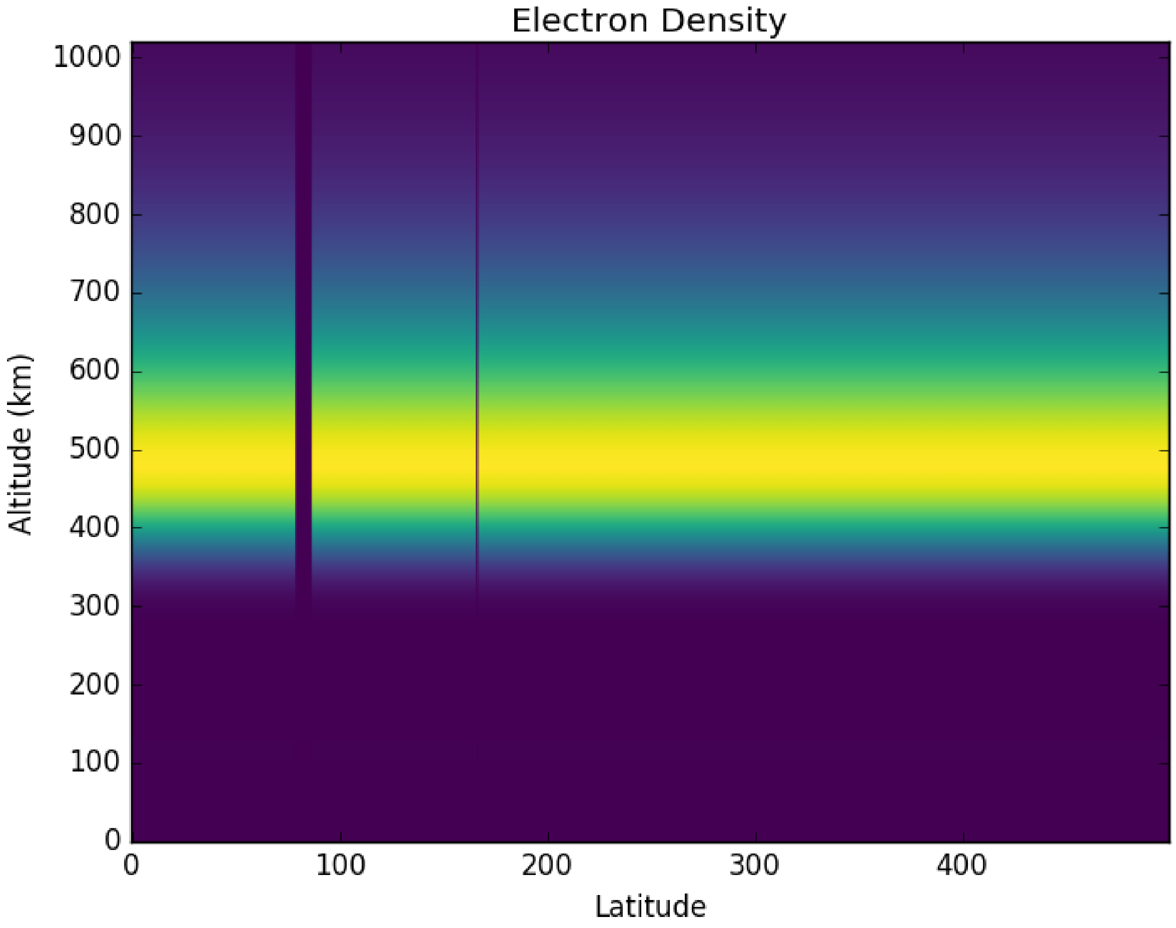
I. Obtaining a model atmosphere
1D Electron Density Plot

- 1D plot of electron densities as a function of altitude taken from AURIC raw data
- 410 km observation height in 135.6 nm spectrum, nighttime F-Layer



II. Obtaining a model atmosphere Creating a 2D Image f(x,y)

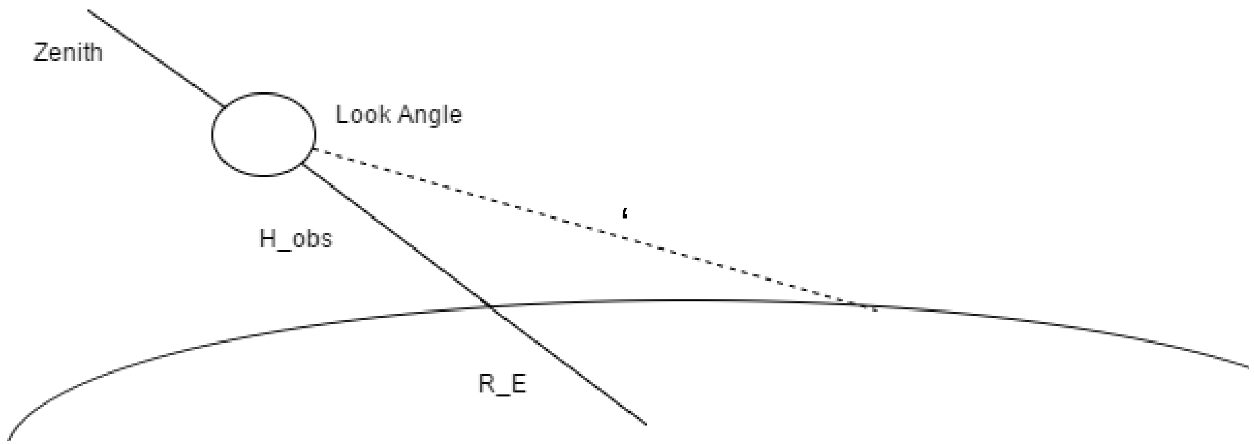
- 2D image processed for f(x,y) for 500 latitudes along the track and a 1000 km altitude
- Zeroed-out column densities (plumes) of 2 and 16 km (1 and 8 px) at points 83 and 250 along latitude



I. Calculations of Respective Angles: Limb

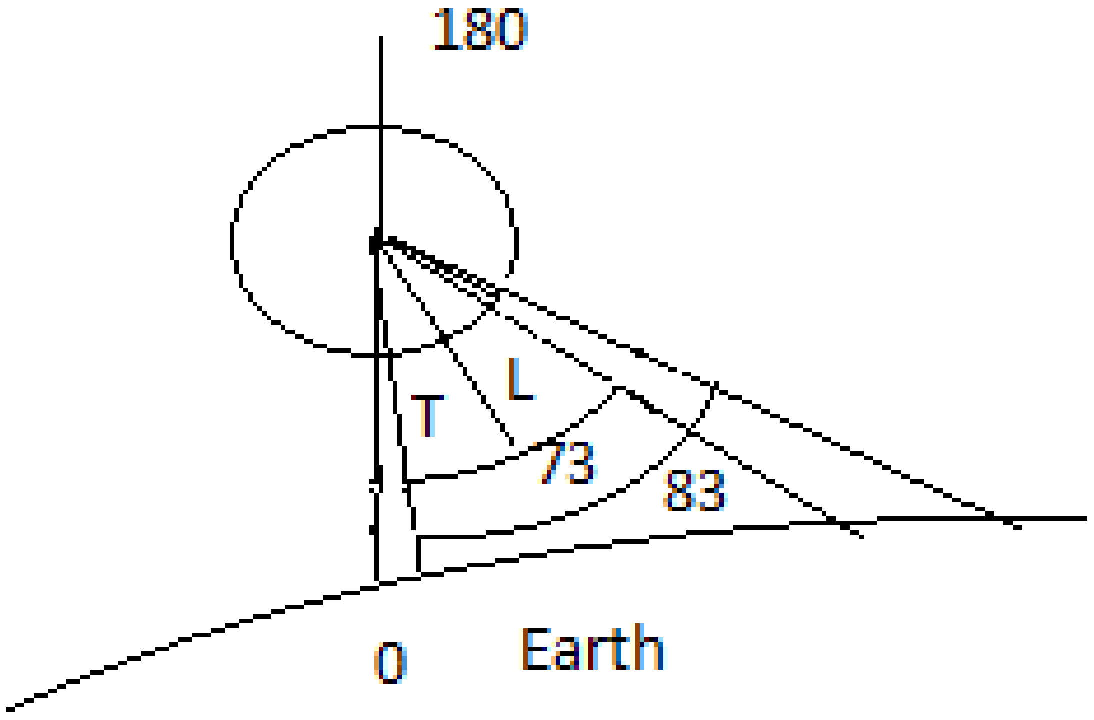
- Zenith altitudes (120-360 km) for LITES
- Calculation of tangent point altitudes
  - R_E = 6371 km, Z = 120-360 km, h_{obs} = 410 km
- Yielded zenith limb angles (180 – tangent point altitudes = 73,83)

$$\theta = \arccos\left(\frac{R_E + Z_{tp}}{R_E + h_{obs}}\right) + \pi/2$$



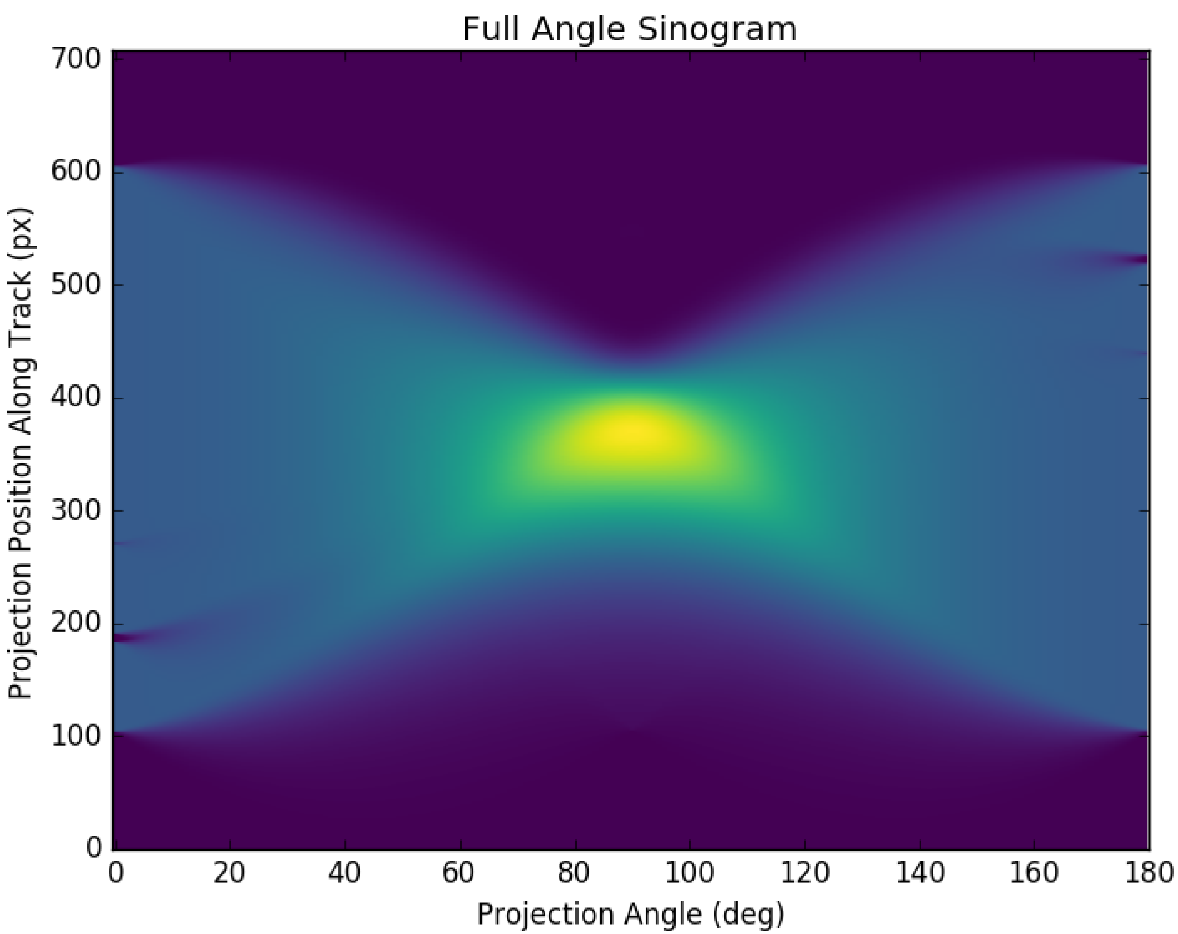
II. Calculation of Respective Angles: Nadir

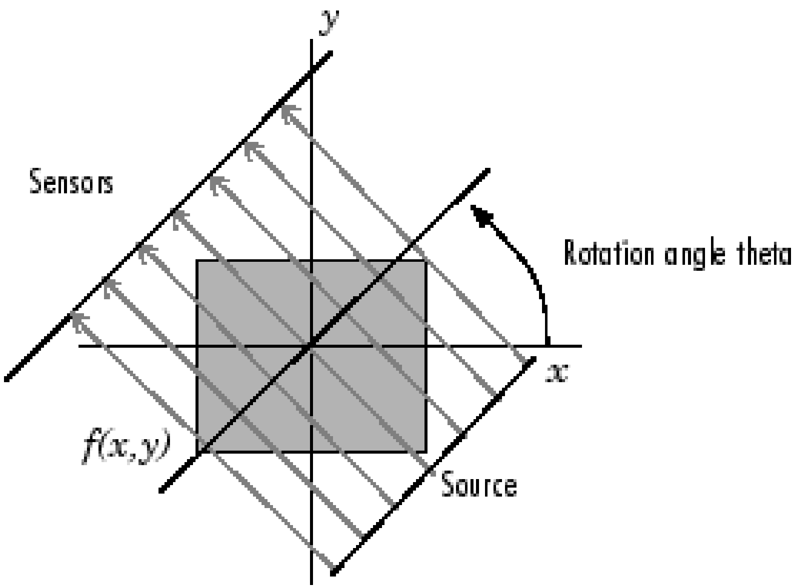
- Limited angles for nadir (TIP) 0-5 degrees
- Earthward orientation



I: The transforms and backprojections: Full Angle Radon Transform

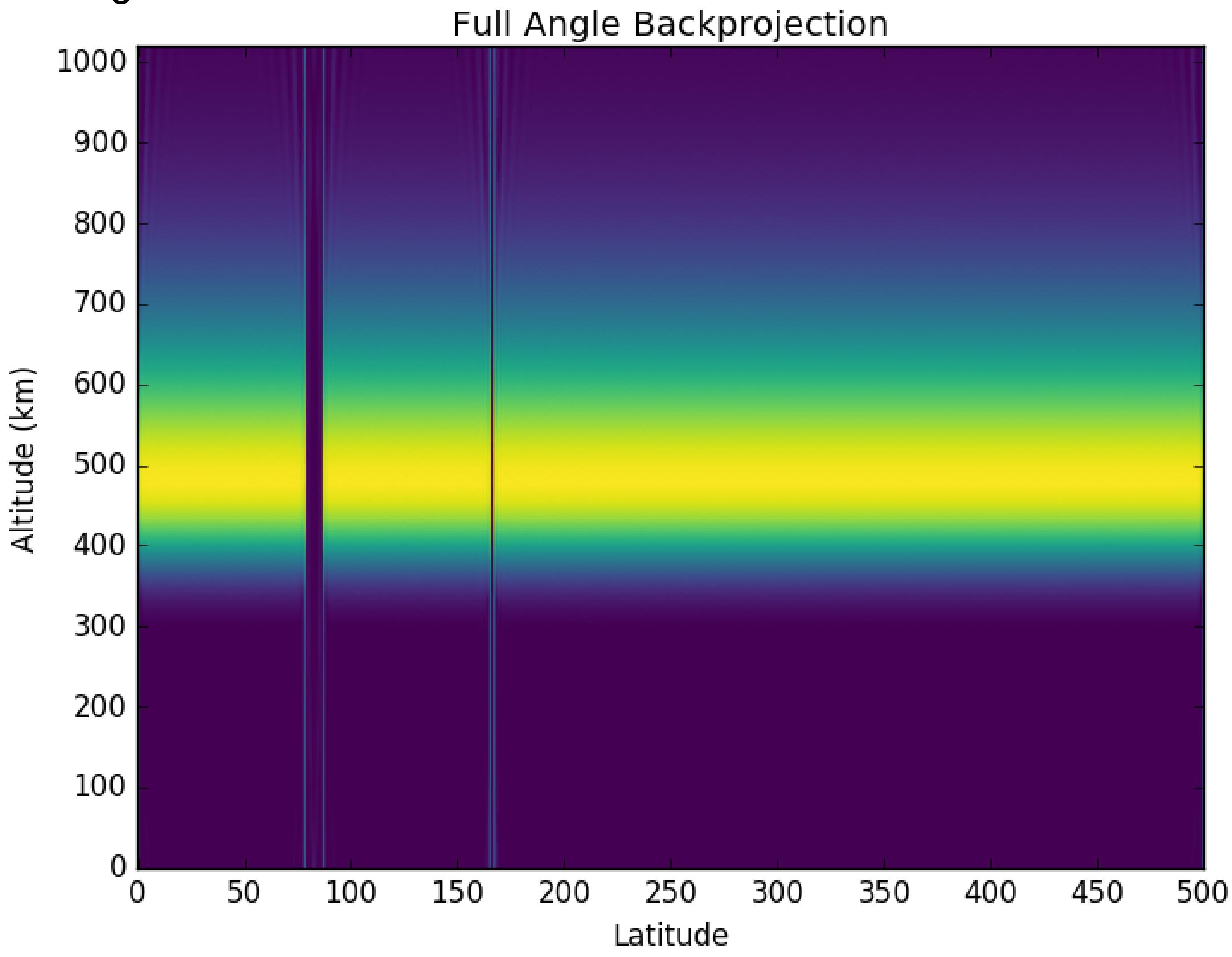
- Full angle transform tests to see if the backprojection actually works
- Each column of original image corresponds to a projection along a different angle
- Position Along Track 700(px):
  - Longest measurable cross section of the plot (length*√2 at 45° rotation)





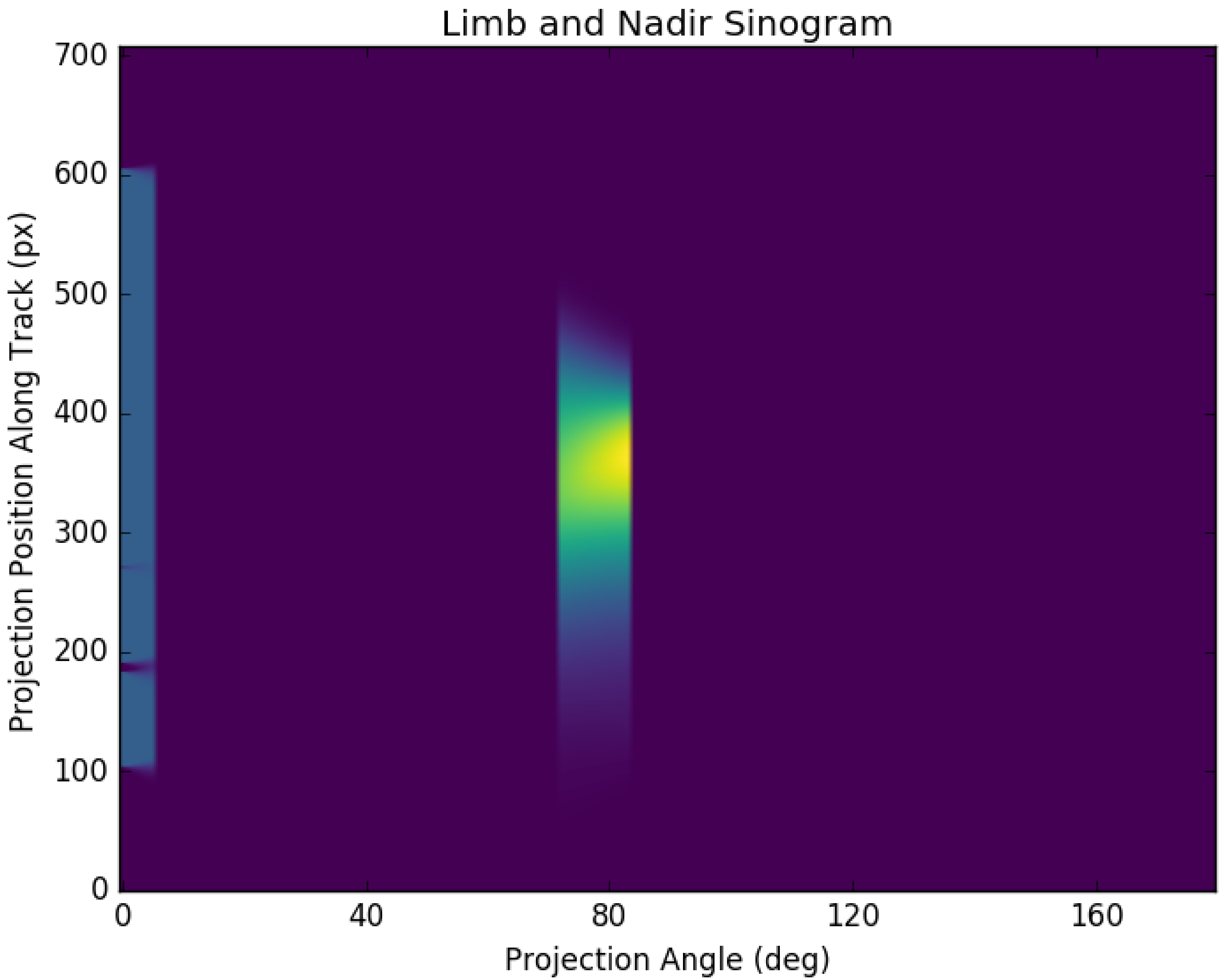
II: The transforms and backprojections: Full Angle Backprojection

Range of angles 0 – 180°

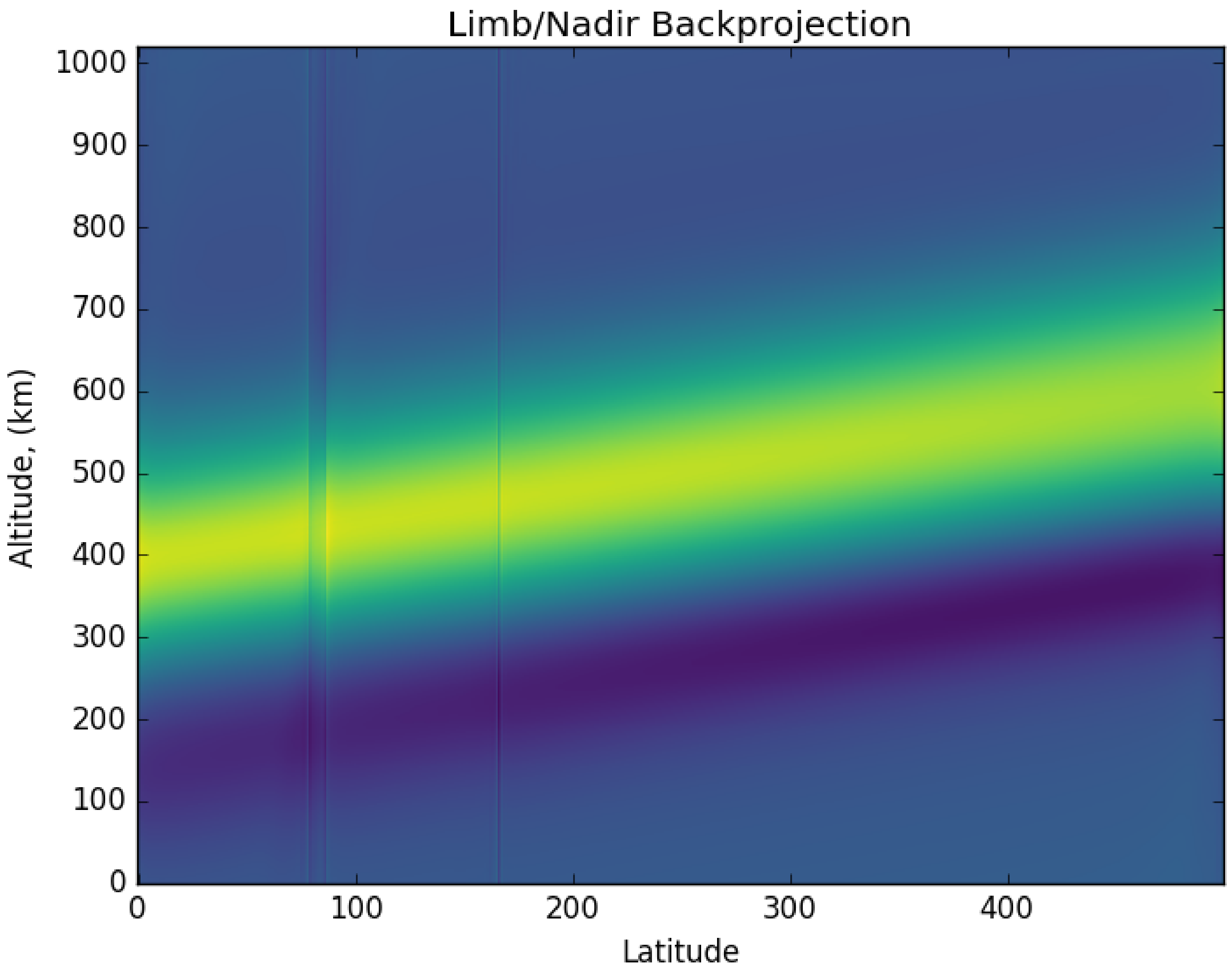


V: The transforms and backprojections: LITES and TIP Sinogram

- Limb 73-83°, Nadir 0-5°

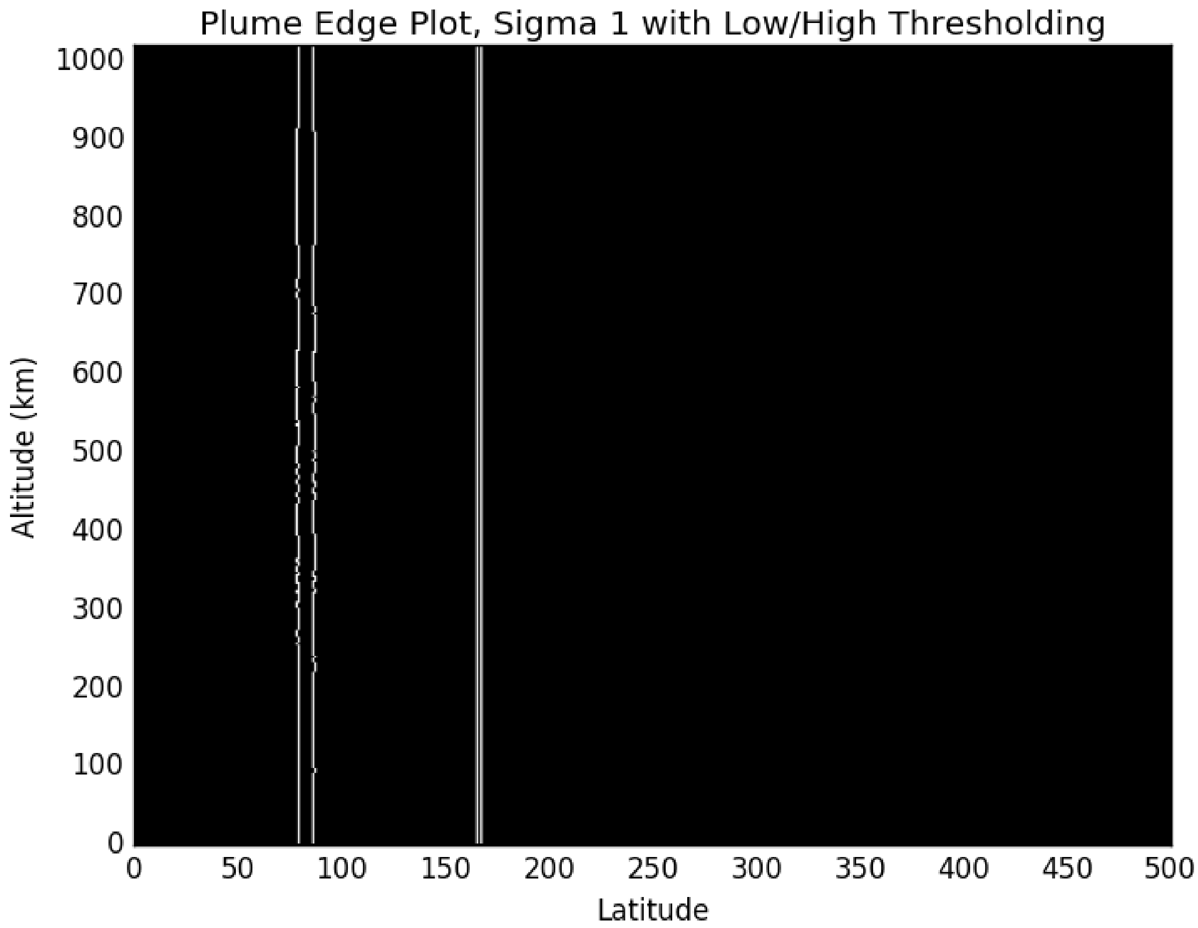


VI: The transforms and backprojections: LITES and TIP Backprojection



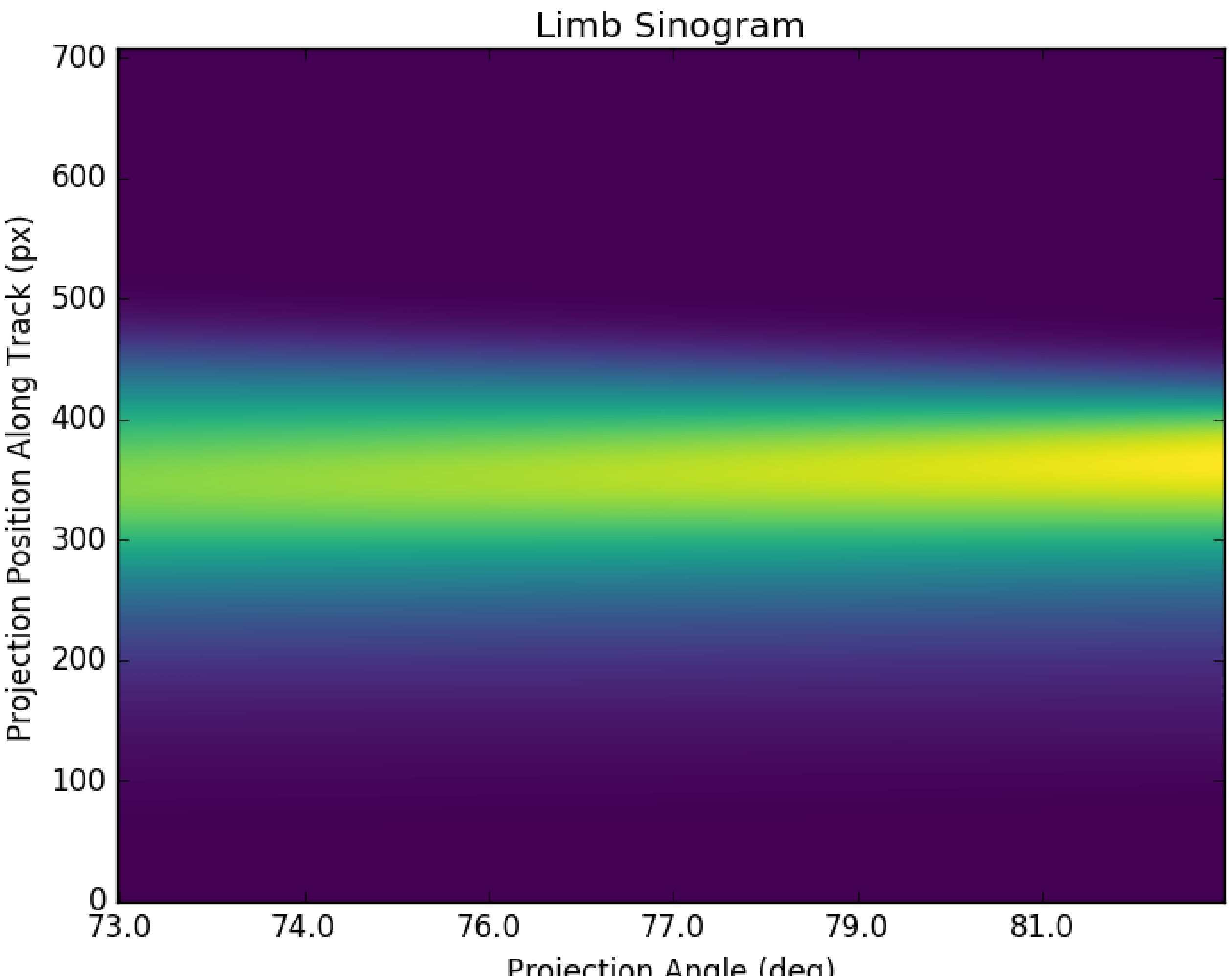
VII: The transforms and backprojections: Canny Edge Detection of Plumes

- Computed width of plumes at 400 km altitude in the LITES/TIP back projection
- Sigma – Gaussian blurring to reduce noise
- High-threshold levels pick out the most prominent edges
- Low-threshold levels toss out the least prominent

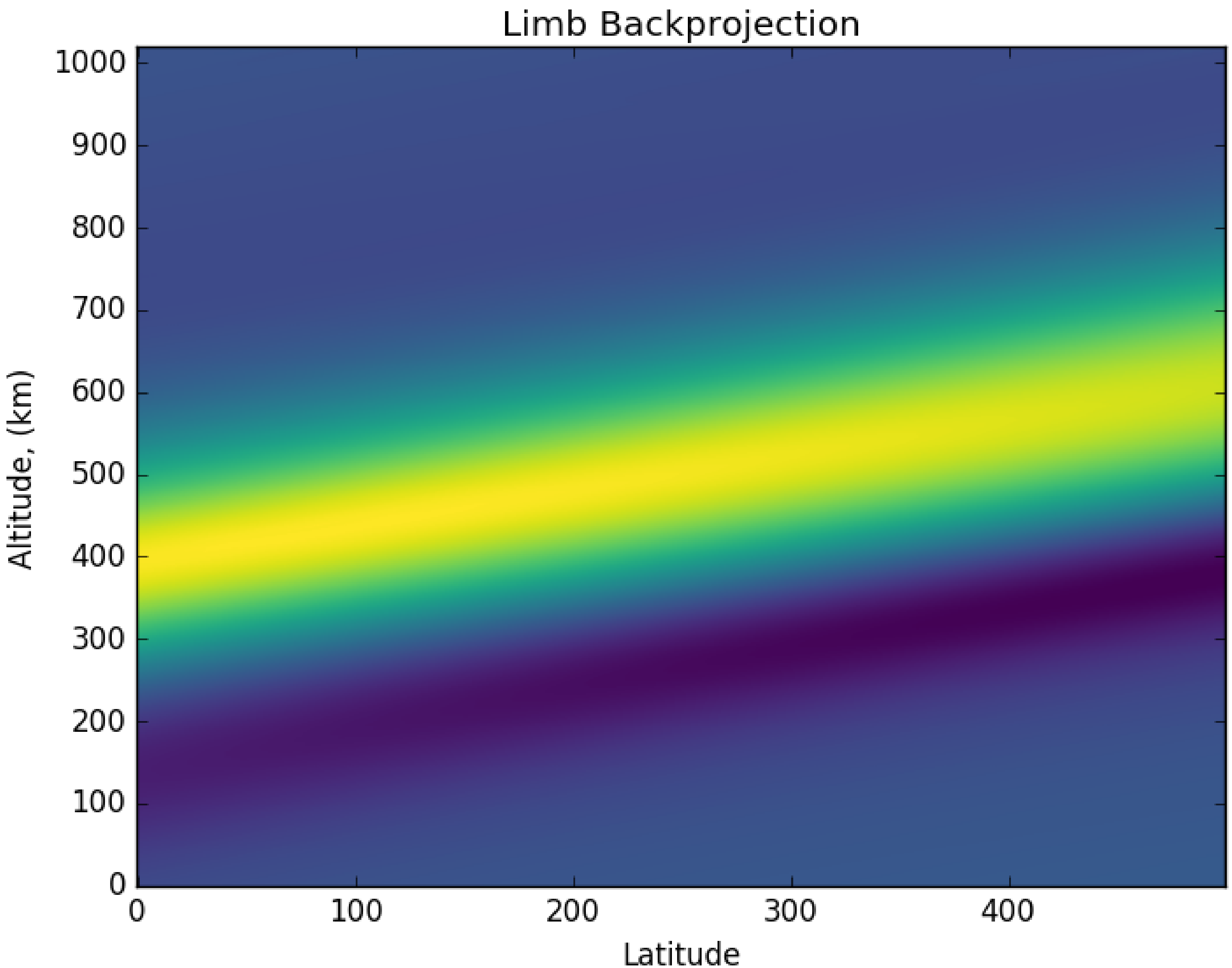


III: The transforms and backprojections: LITES Sinogram

- Limited limb angle from zenith angle calculation (73, 83 deg)



IV: The transforms and backprojections: LITES Backprojection



Analysis: Measurements

- Measured values:
  - Band scale height (Chapman function): 566 km
  - Band width: approx 240 km
  - 1 plume width in back projection was off
    - 4.0, 16.0 km width in original image compared with 2.0, 16.0 km in the backprojection
    - Better measurement in wider plumes
  - Varied plume widths and observation heights (360-405 km), other zenith altitudes to get an idea of how far off it is

Minor Issues, Major Issues:

- Despite attempts to see the plumes in the backprojection, the solution for the limited angle problem remains elusive
- “Band slant”
  - Original program formatted for full angle use only
  - Can possibly be remedied by manipulating source code to use a weighted average
- Washed out intensity in backprojection
  - normalization of pixels poor in original program
  - Tried normalizing the color scheme, but ineffective

Bibliography

1. "Radiative Recombination Process." Applications of Constellation Observing System for Meteorology, Ionosphere & Climate. Ed. L. C. Lee, Robert Kursinski, and Christian Rocken. First ed. Hong Kong: Springer, 2001. 1-385. Print.

2. Berian, James J. Integral Transforms for You & Me (2008): 1-35. Royal Observatory Edinburgh Institute for Astronomy. Web. 02 Jan. 2016.

3. Kamalabadi, F.W.C. Karl, J. L. Semeter, D. M. Cotton, T. A. Cook, and S. Chakrabarti (1999),A Statistical Framework for Space-based EUV Ionospheric Tomography, Radio Sci.,34(2),437–447, doi:10.1029/1998RS900026.

4. Ng, R. (2005). "Fourier Slice Photography". ACM Transactions on Graphics 24 (3): 735–744. doi:10.1145/1073204.1073256.

5. “Integral Transforms for You & Me”. Royal Observatory Edinburgh Institute for Astronomy. J. Berian James. March 2008.

6. Image Projections and the Radon Transform. Rice University. Webpage. 05/02/2016 https://www.clear.rice.edu/elec431/projects96/DSP/bpanalysis.html

7. Real-Time Radon Transform via the GPU Graphics Pipeline. Fall 2010. Webpage. 05/01/2016. http://christian.mendl.net/pages/software.html

8. Publication: E. B. Shume, et al., “Intermediate-scale plasma irregularities in the polar ionosphere inferred from GPS radio occultation,” Geophysical Research Letters, 2015; DOI: 10.1002/2014GL062558

9. The Ionosphere: an Introduction. Lancaster University. Webpage. http://spears.lancs.ac.uk/ionosphere_intro/. 08/10/15