***Limited Angle Tomography for LITES Ionospheric EUV Measurements in the 135.6 nm Spectrum***

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May 5, 2016

## Introduction:

Within the F-region of the atmosphere are two sub-layers: F1 and F2. In the F1 region, there is a production/loss cycle of electron densities where plasma is formed due to ionized energy present in the layer. This occurs when negatively charged electrons and positively charged ions attract via electrostatic forces, yet are too energetic to remain stable. They undergo dissociative recombination which is a breaking up or deterioration leading to unstable atoms and highly energetic photoelectrons.

Airglow is produced at altitudes of 80+ km where the atoms exited by photons relax and emit energy in the visible light spectrum. During the daytime**,** both F1 and F2 regions remain distinct from each other. Photon emissions are produced by the sun when an ion is formed from the interaction of a photon with the atoms in the lower thermosphere in a process called photoionization. Dayglow has very small solar fluorescence; hence, emission is largely from photoelectron impact due to spin-forbidden transitions. P-orbital molecules, like oxygen, have an odd symmetry which means they do not have spin states with the same spin quantum number.

At night time, the F1-layer becomes optically thin as the two regions merge into F2 – known as the *Appleton-Barnett* layer. Optical photoelectron emissions are generated by the interaction of oxygen atoms and electrons. This yields a plasma frequency approximately 35 MHz or less with 106 electrons/$m^3$ density. The ionosphere at night hosts mainly a radiative recombination process. In this process, there is not enough excitation energy to remove the ions from the oxygen atoms. Therefore, there is a change in ionic distributions compared to daytime. Oxygen radiative recombination emission detections are typically unfavorable for daytime, although these particular emissions are always present[1].

LITES (Limb Imaging Ionospheric and Thermospheric Extreme Ultraviolet Spectrograph) and TIP (Tiny Ionospheric Photometer) are designed to measure the $O^+$ emissions in the ionosphere where it has the greatest concentration of free electrons. Its bandpass is designed to filter wavelengths in the EUV range of 60-140 nm.  In tomography, only 30% measurable structure from ground-based data. With utilization of GPS Radio technology coupled with the UV Photometry-Collocated (GROUP-C) experiment, LITES and TIP are designed to provide the needed 70% of global tomographic structure data[3].

In this project, the 135.6 nm wavelength in the nighttime sky was the focus for $O^+$ detection in both LITES, limb (across the earth just below the surface) and TIP, nadir (downward) look angles; however, there exists a limited-angle problem which occurs where instrumentation look-angles are limited as well as the inevitability of atmospheric noise and plasma bubbles formed in the layer caused by a displacement of ions within a change in the electromagnetic field.. The limited angle problem was demonstrated to show the information loss in ionospheric tomography for LITES and in the future can possibly be remedied to allow more degrees of freedom in measurements and thus provide a continuous distribution of intensities in their respective amplitudes.

Analyzing the results of a full-angle model in the sinogram and backprojection can test if the transform is working correctly. Through forward-modeling, if the electron density of a particular region of the ionosphere is known; thus, a prediction can be made about what will be observed by the spectrometer. However, the mathematical solutions of the measured data are non-unique which implies that the bounds are over or under constrained and at some cases both at the same time. The simple least-squares inversion techniques (algebraic reconstruction) typically yield unacceptable results in the presence of this noise. However, there is another possible solution through FBP (Filtered Back Projection) which is what was attempted in this project.

<u>Procedure:</u>

First, a density plot was generated using raw data from AURIC (Atmospheric Ultraviolet Radiance Integrated Code) for the measured electron densities in the 135.6 nm spectrum, nighttime F-layer from an estimated observation height of 410 km.

A 2D image of electron densities as a function of altitude and latitude was created. For the forward transform, the program used a Radon transform to make collective, 1D projections of the function.

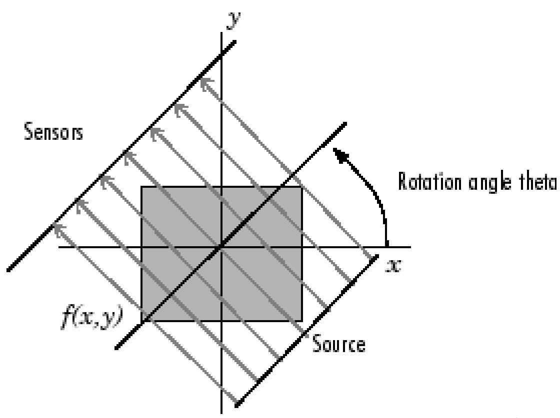
A sinogram is the forward (Radon) transform which is a series of parallel beams of an object of interest at a collection of angles for every angle theta along a projection line. All points on this line satisfy the Radon Transform[6]:

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

The backprojection (inverse Radon transform), shows how well the resolution/information appears in an image given a number of angles in the forward transform. The program used an FBP filter (Reconstruction with the Filtered Back Projection) applied to the Fourier transformed projections to try to curtail information loss in the transform. More specifically, it used the Fourier Slice Theorem which is a method of inverse Radon transformation by making slices through its origin parallel to the projection line, resulting in a projection at an angle in polar coordinates as a rotation basis of the inverse vector space. First it is assumed that the Fourier Transform is equal to the Fourier slice[4]:

$$\hat{F}_1 \hat{P}_1 = \hat{S}_1 \hat{F}_2$$

... where F1 is the 1D Fourier Transform operator acts with the P1 projection operator (a projection of 2D function onto a 1D line). F2 is the 2D Fourier Transform operator which acts with the S1 slice operator that takes a slice through the origin of the function and reconstructs it to the original image[3].



Fourier Slice Theorem Image Source: Rice University[5]

Fourier Slice Theorem in Cartesian coordinates:

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

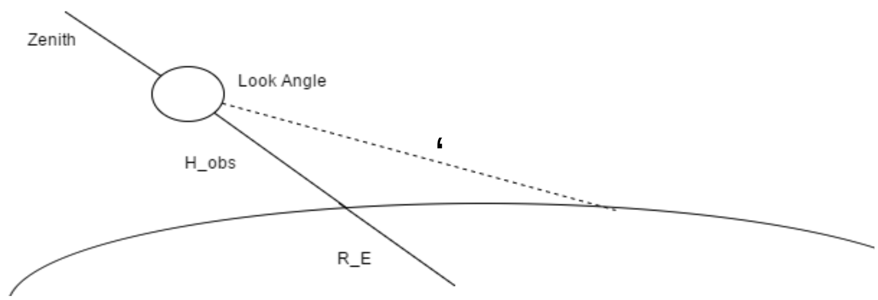
Fourier Slice Theorem in Polar coordinates:

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

Next, to get an idea of the information loss from the sinogram to the backprojection, two “plumes” of varied size were inserted into the image by zeroing out a column of the electron densities and given a 0-180 degree look angle, giving a full set of angles. A plot of the sinogram and backprojection was generated for the full angle to test if the program was working correctly.

Next, the angles from 0-180 were replaced with the limb tangent point altitude data from LITES which gave the range of angles in flight by applying a trigonometric equation taken from the Earth's radius (6,371 km), observation height (410 km), and zenith tangent point altitudes (120-360 km) as follows:

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




*LITES Limb Angles from Zenith Altitudes*

Following the full-angle projections, the nadir (TIP) look angles in the range of 73-83 degrees were added to the sinogram by assuming TIP pointing in the Earthward direction:

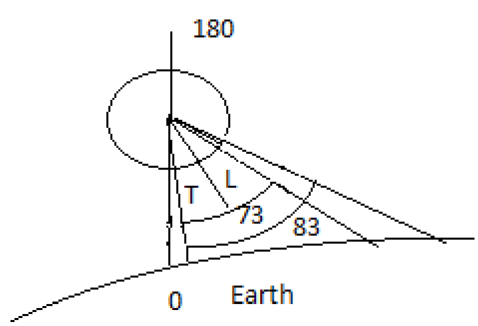



*Diagram for TIP viewing Earthward*

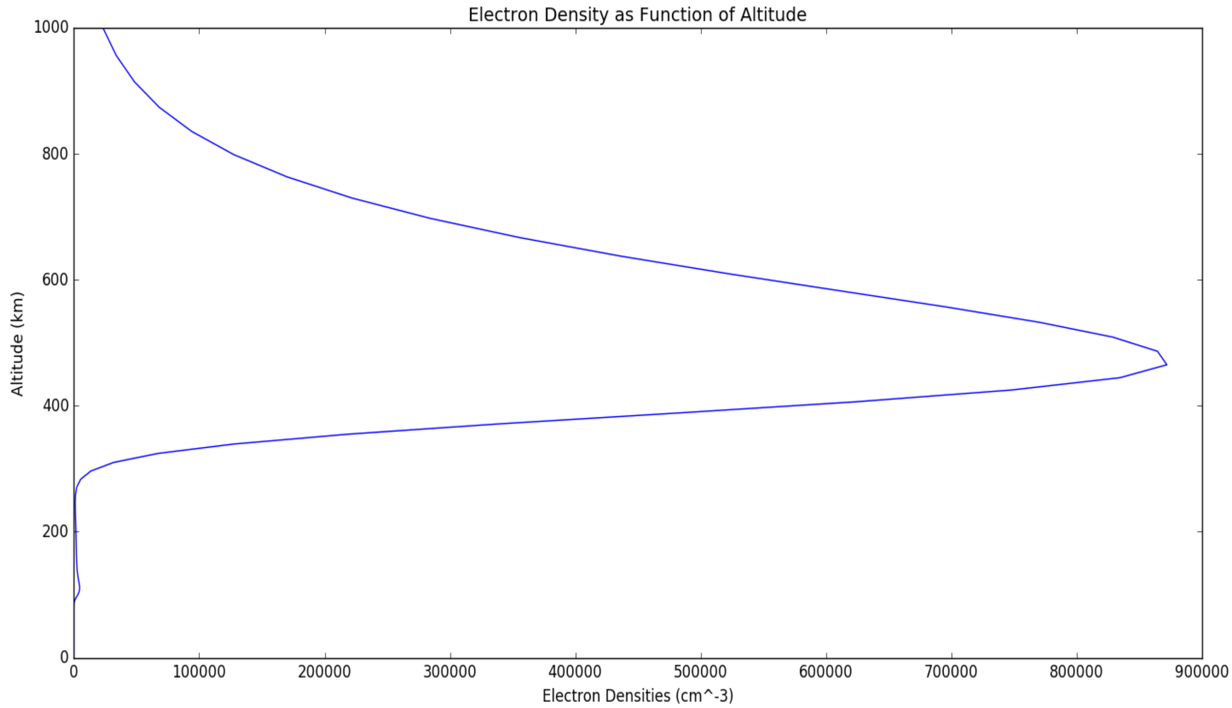
The sinogram and backprojections plots were generated for LITES and both LITES and TIP.
For the LITES analysis, the plume widths were varied and observation heights (360-405 km) and other reasonable zenith altitudes were attempted to get an idea of what might work in creating a successful backprojection.

The plume widths in the backprojection for both LITES and TIP angles were measured by taking a slice of an altitude row at 400 km in an edge plot. A Canny Detection edge plot uses kernel convolution noise, producing low-level edge detection. The noise in the backprojection from information loss was controlled by a sigma factor which reduces noise by applying a Gaussian blur. The edges were more well-defined as a result. Next, the canny edge detection plot used a sobel filter and hysteresis thresholding method which applies an inverse tangent function to configure the directions of the edge. Setting high-threshold levels picked out the most sharp edges. Low-threshold levels were applied to follow the edges until it determined what is and is not a prominent edge in the image.

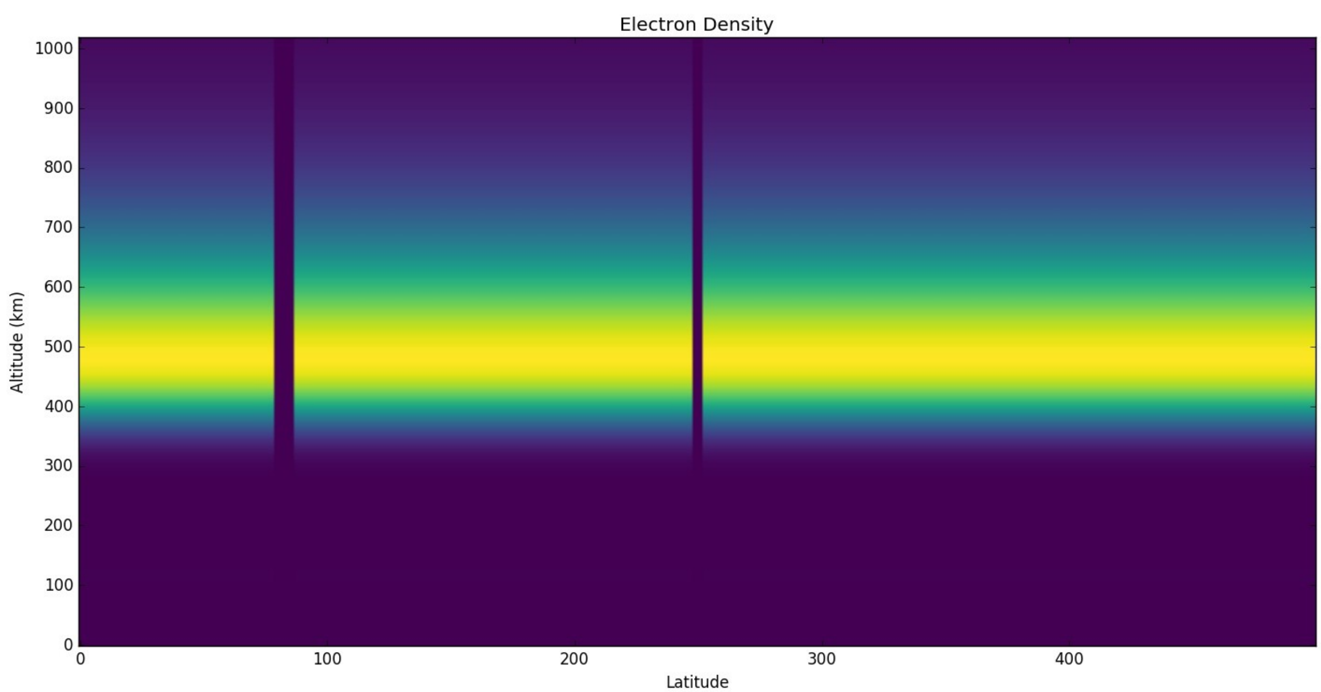
Results and Analysis:

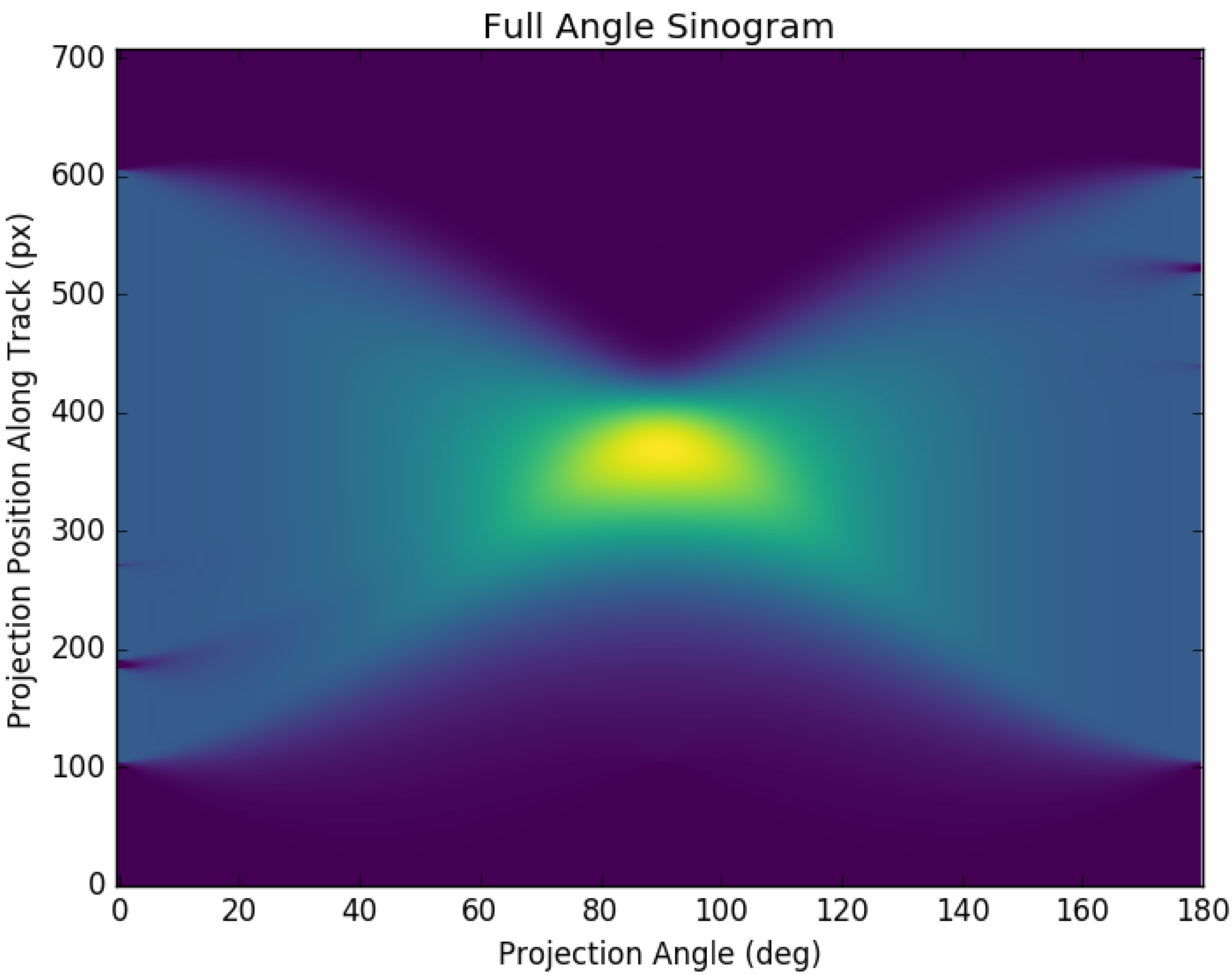
The scale height of the density band was measured at approximately 566 km by use of the Chapman function which assumes a constant density gradient, giving the scale height per peak value. The measured width of the band was 240 km. The plume widths were measured in the original image at 4.0 and 16.0 km. The backprojection plume widths were measured at 2.0 and 16.0 km. The wider the plumes were made, the more accurate the measurement. Unfortunately, the limited angle case for LITES still remains an issue. TIP measured the densities reasonably well with some minimal information loss (as expected). In short, it appears that the program works well, but the instrument limitations and little available information in the atmosphere at the limited angles were the main issues.

A minor issue in the program was the slant in the intensity band in the backprojection. This was due to the program used being made for full angle backprojections only. There is a weighted average for the pixels in which the program did not use in order to normalize the angles of the pixels being mapped back to the original image. This could, in the future, be remedied by manipulating the original source code for the program and calculating a weighted average for the pixel normalization. There was also a washed-over appearance to the backprojection intensity which was another normalization not made by the program. Normalization attempts were made to remedy this, but were unsuccessful.

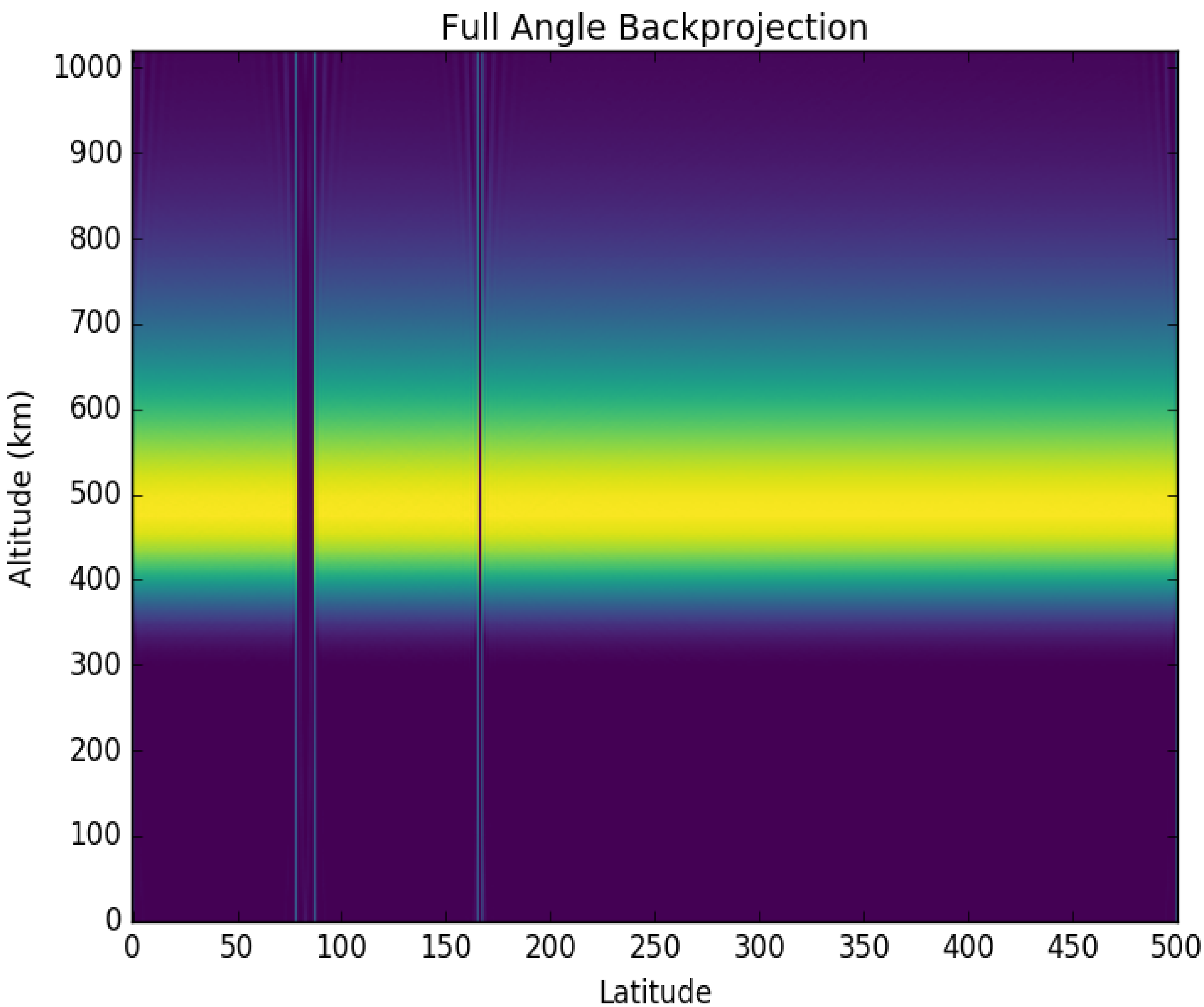


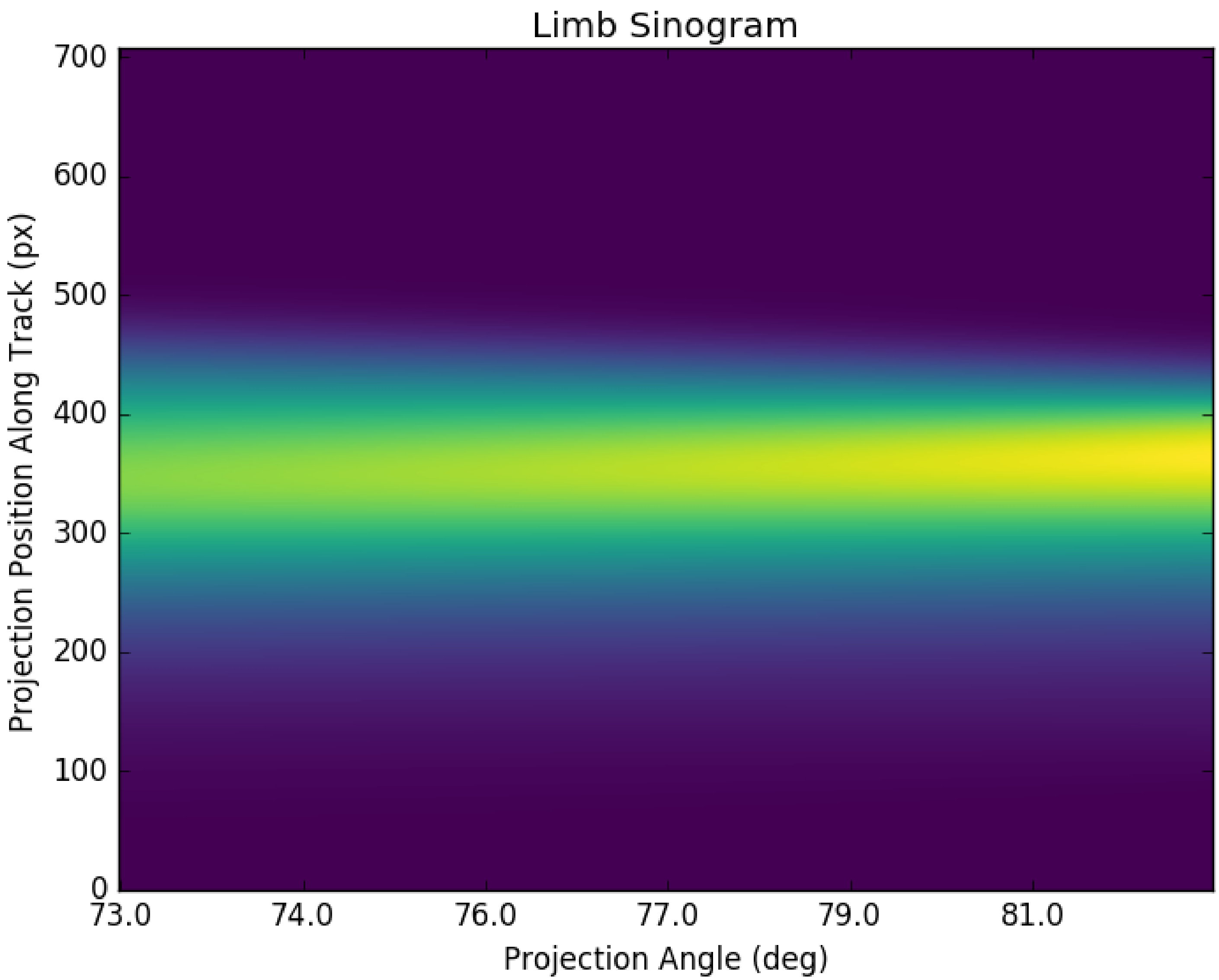

*Original Electron Density 2D Plot. Plumes measured at 4.0 and 16.0 km*



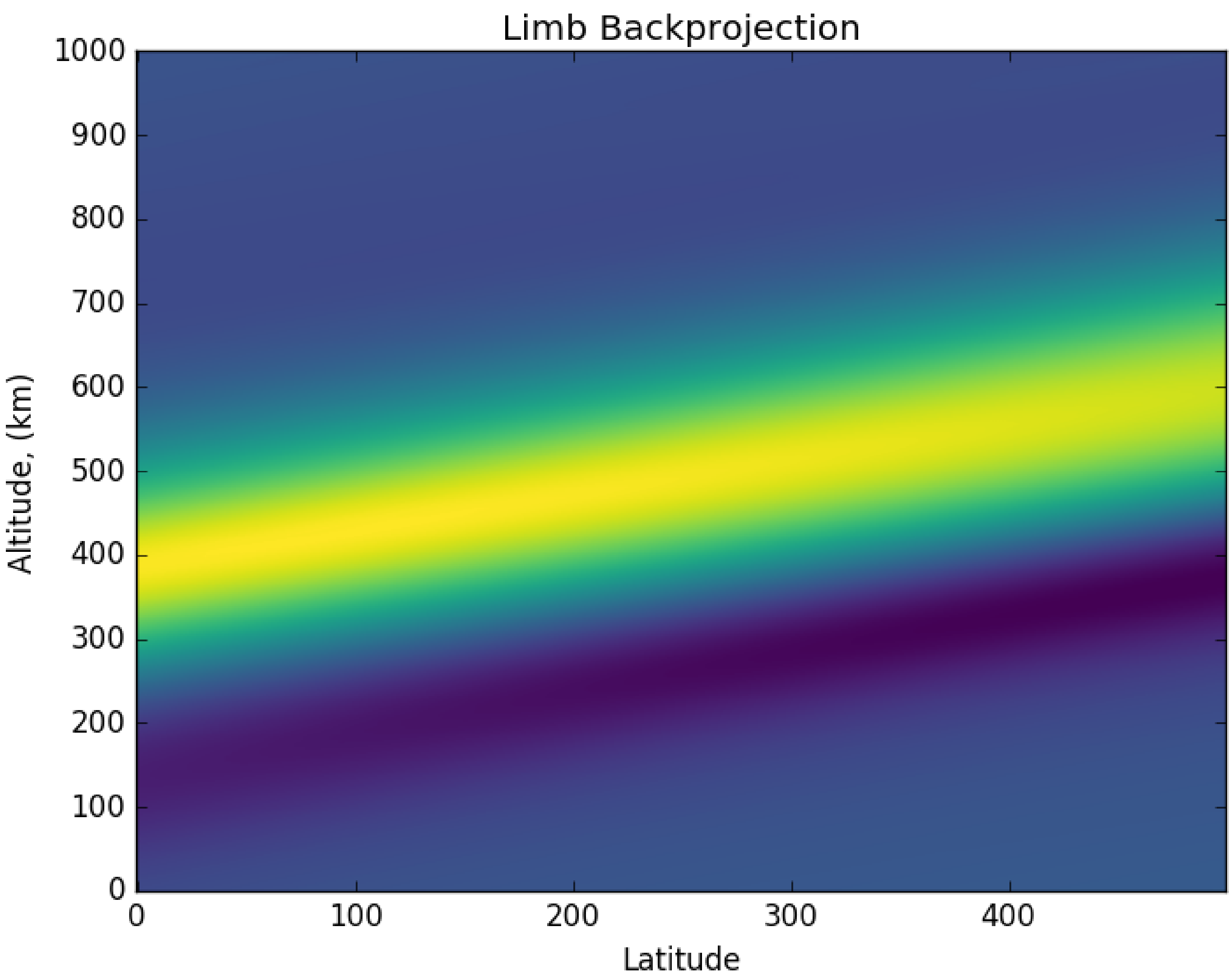


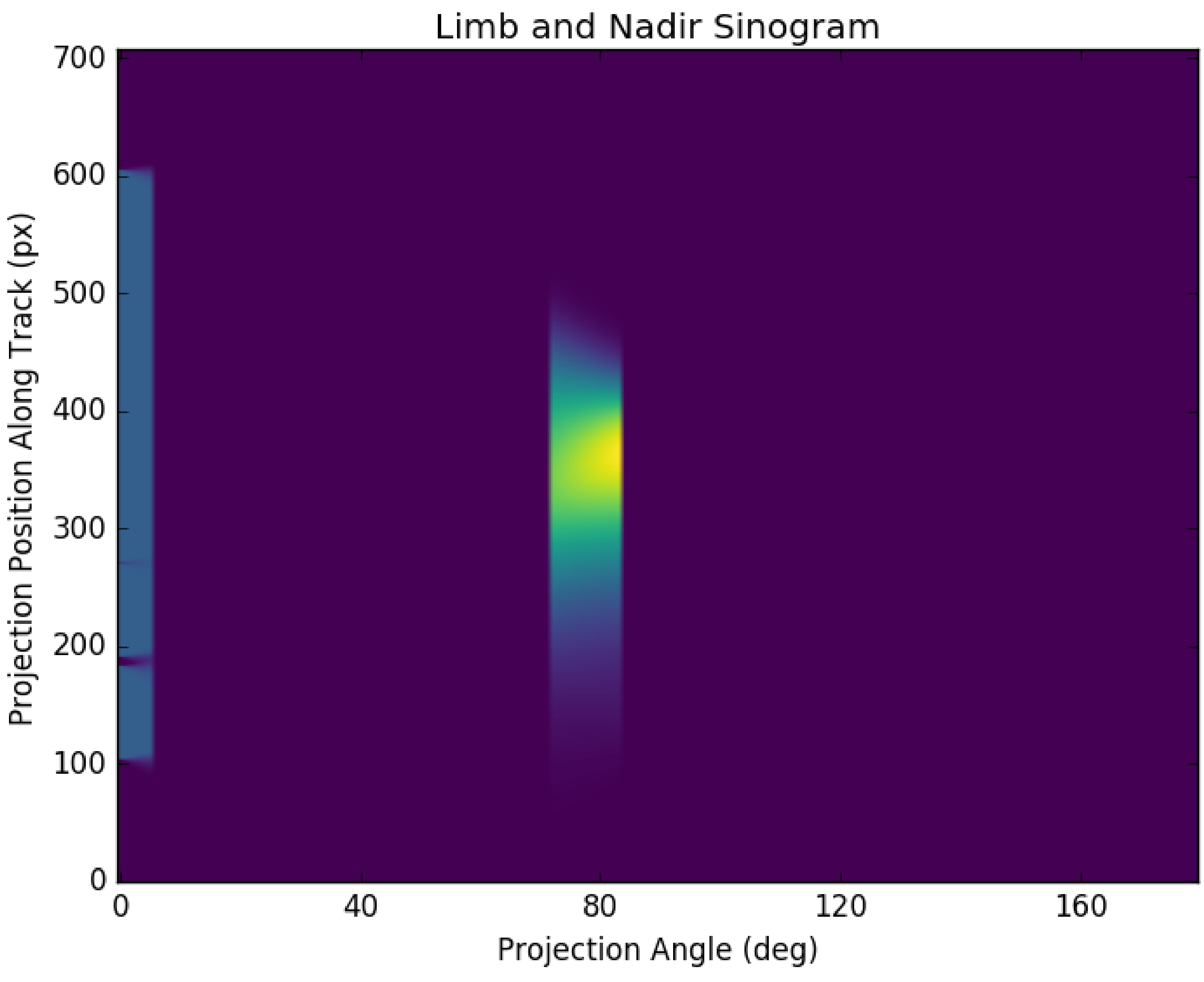

*0-700 position for a 500 px image at 45 deg rotation*

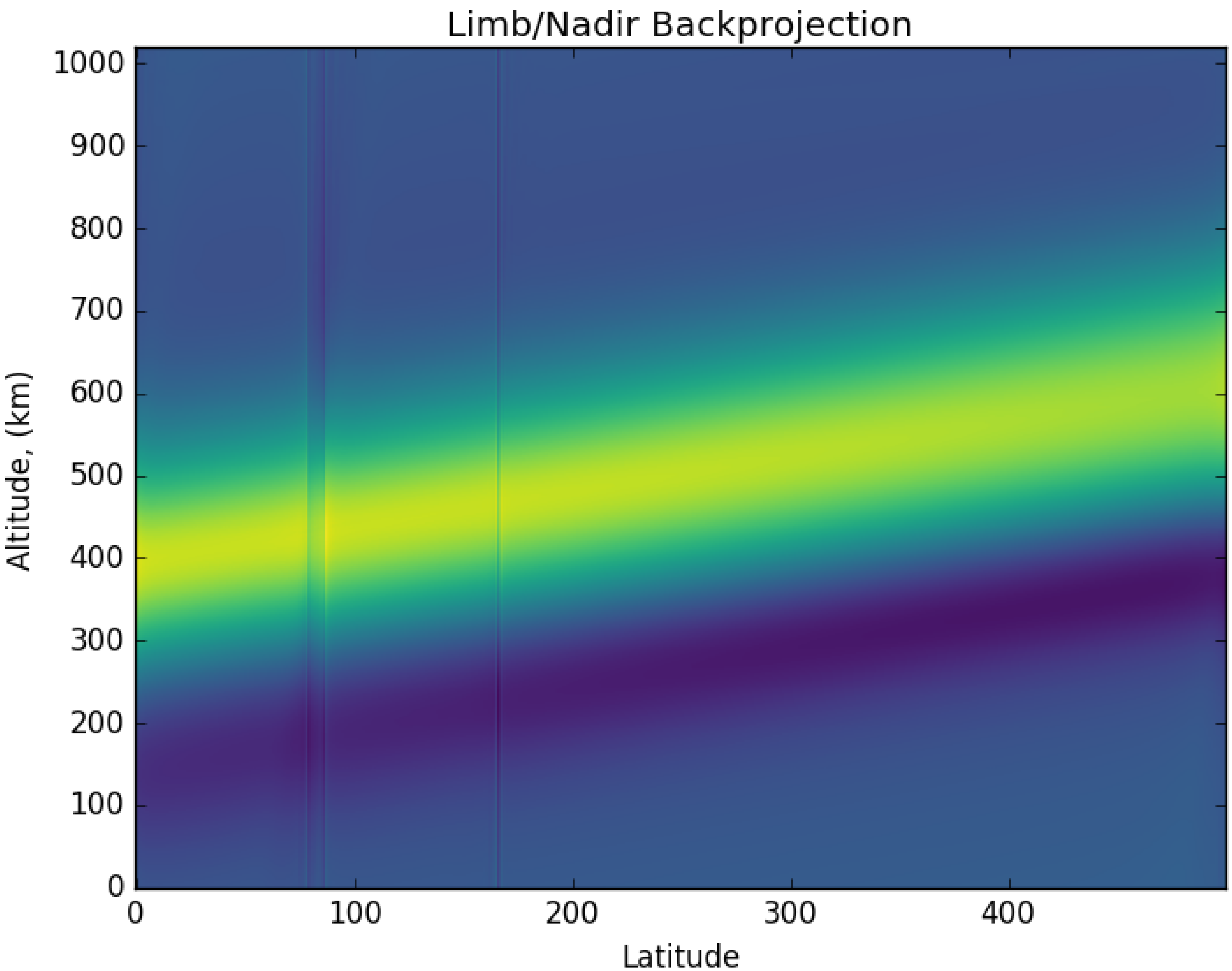

Full Angle Backprojection
Altitude (km)
Latitude
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400
450
500

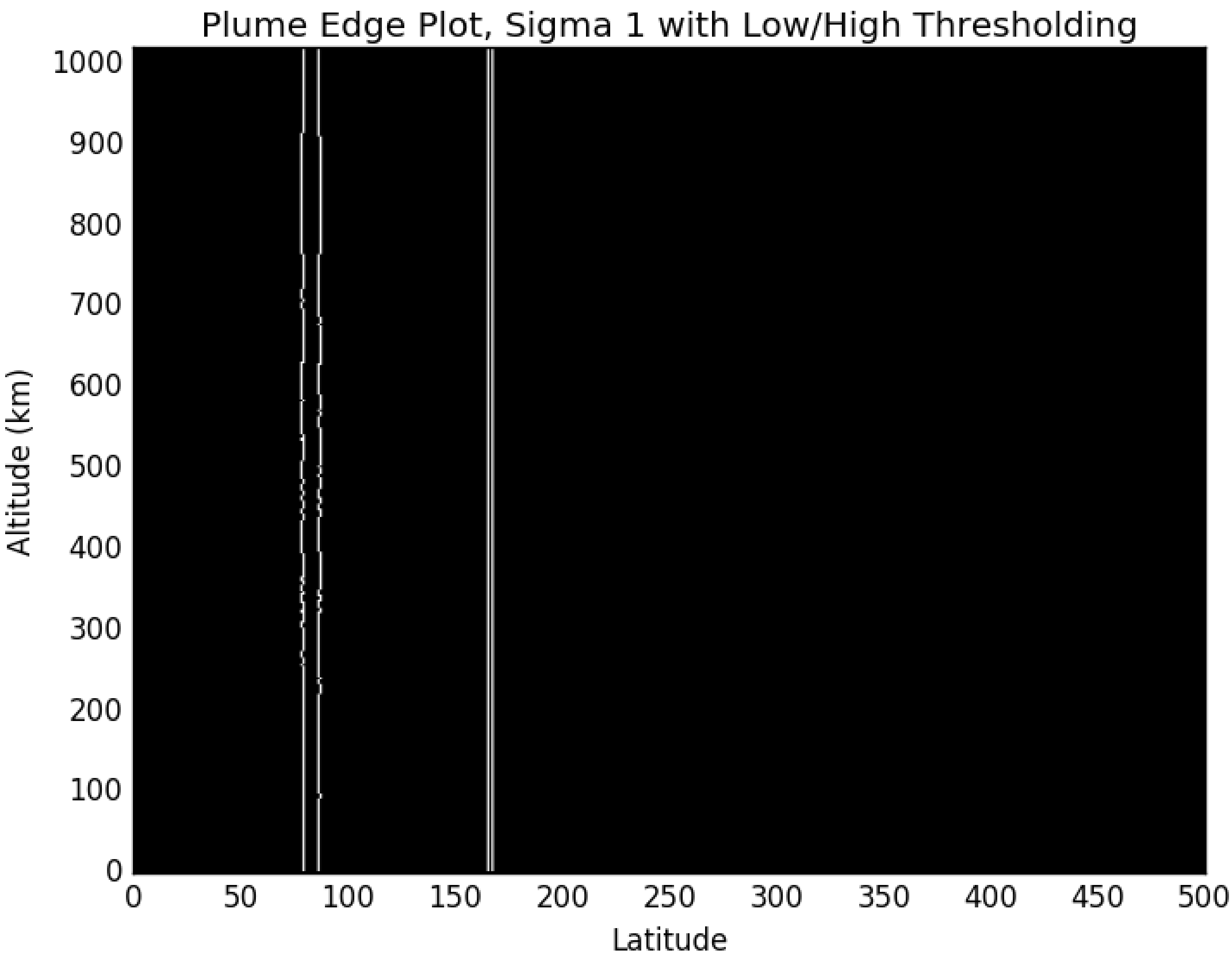


Limb Sinogram
Projection Position Along Track (px)
0
100
200
300
400
500
600
700
73.0
74.0
76.0
77.0
79.0
81.0
Projection Angle (deg)


Limb Backprojection
Altitude, (km)
Latitude
1000
900
800
700
600
500
400
300
200
100
0
0
100
200
300
400


Limb and Nadir Sinogram
Projection Position Along Track (px)
Projection Angle (deg)
0
100
200
300
400
500
600
700
0
40
80
120
160


Limb/Nadir Backprojection
Altitude, (km)
0
100
200
300
400
500
600
700
800
900
1000
Latitude
0
100
200
300
400


Plume Edge Plot, Sigma 1 with Low/High Thresholding
Altitude (km)
Latitude
0
100
200
300
400
500
600
700
800
900
1000
0
50
100
150
200
250
300
350
400
450
500

Bibliography:

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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 Source: “Image Projections and the Radon Transform”. Rice University. www.clear.rice.edu/elec431/projects96/DSP/bpanalysis.html.