

NAVAL POSTGRADUATE SCHOOL

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THESIS

**DESIGN AND FIRST OPERATIONS OF THE LINEATE
IMAGING NEAR-ULTRAVIOLET SPECTROMETER
(LINUS)**

by

Jean Gray

December 2002

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ULTRAVIOLET SPECTROMETER (LINUS)**

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Submitted in partial fulfillment of the
requirements for the degree of

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from the

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ABSTRACT

Spectral imagery provides a new technology for target detection, defeat of camouflage, concealment and deception, and detection of chemical and biological agents in the atmosphere. The Lineate Imaging Near Ultraviolet Spectrometer (LINUS) is designed to image a narrow passband in the UV portion of the Electromagnetic spectrum. The imaging spectrometer views a 0.5 degree vertical strip, while observing a 20-40 nm wide band currently centered at 300 nm. The 512 x 512 pixel focal plane provides 0.1-1.0 nm spectral resolution, depending on slit width in the dispersive optic instrument. It is designed to scan a 2.5 degree horizontal pattern. The instrument has been calibrated spectrally, and its response to sulfur dioxide has been measured. First observations with the scanning instrument in the laboratory and outdoors at NPS are presented. This work demonstrates LINUS can detect SO₂ down to concentrations less than 100 ppm.

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Finally, I would like to thank my husband, family and friends for all their support during the travel and long hours I worked to complete this thesis. He was very patient when I would tell him I don't know how long I'll be at school for the one week's notice that I'll be out of town for the weekend. Thanks for saving a seat at the restaurant for me. I needed it after the long drive.

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I. INTRODUCTION

A. PROJECT CONTEXT

This thesis deals with the completion and first operations of LINUS. The completion of this thesis marked the passing of several milestones in the development of the Lineate Imaging Near-Ultraviolet Spectrometer (LINUS). LINUS is a third generation imaging spectrometer at the Naval Postgraduate School. There have now been five theses completed during the continuing evolution of LINUS. The first was the Dual-Use Ultra-Violet Imaging Spectrometer (DUUVIS), completed in 1996. The second began in 1997 and is the NPS Ultra-Violet Imaging Spectrometer (NUVIS). While it was an advancement over DUUVIS, it was highly restricted in the wavelengths it could detect. LINUS was conceived as an instrument that could easily be configured to measure a broader spectrum of wavelengths. LINUS also has increased sensitivity.

B. PROJECT OBJECTIVE

The objective of this project is a description of the completed LINUS instrument, its calibration, and the first observation. Prior work on LINUS has been divided into specific systems. To date no comprehensive optical description has been given. This thesis provides an in depth examination of the optical layout, general information on the camera and control systems is also outlined.

Spectral image data from LINUS consists of an intensity measurement across the spectral wavelength and horizontal and vertical spatial dimensions. In order for this data to be useful the values must be converted into meaningful units. This thesis validates the wavelength calibration of the image plane and calibrates LINUS for the detection of SO₂.

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II. OPTICAL DESIGN

A. BACKGROUND

Spectral Imaging is a merger between spectroscopy and traditional imaging. Spectroscopy concentrates on the analysis of wavelength and pays little regard to the spatial features. Imaging is mainly concerned with the spatial features and pays little attention to the spectral features. The merging of these two fields has yielded data that are extremely useful.

Imaging produces a two-dimensional spatial image that measures the differences of light intensity. This method has been used to detect features and patterns. It has been a primary method of intelligence gathering for nearly one hundred years. There are several limitations to this method. Physical attributes are used to classify objects, but it can be defeated with camouflage. Camouflage can be done with several methods. Objects can be covered with nets, painted in colors to change the highlighted areas, or have additional pieces added to change its appearance. Decoys can also be used to confuse imaging systems. Imaging is not an infallible method of information gathering.

Spectroscopy takes advantage of the wavelengths reflected by different objects. As photons enter a material they are reflected, absorbed or pass through. There are four general parameters that describe the capability of a spectrometer: spectral range or band pass, spectral bandwidth, spectral sampling, and signal-to-noise ratio. Spectral range determines the wavelengths that can be detected. Spectral bandwidth controls the resolution of the sensor, the narrower the bandwidth, the narrower the feature the detector can resolve. "Spectral sampling is the distance in wavelength between the spectral band pass profiles for each channel in the spectrometer as a function of wavelength." (Clark, 1.3) Spectral Sampling is also a determining factor for resolution. The final parameter, signal-to-noise ratio is a measure of the spectrometer's ability to measure the spectrum with enough detail to identify the substance. All of these must be taken into account when designing a spectrometer.

One advantage of spectroscopy over traditional imaging is that the wavelength reflected is determined by the atomic make up of the object in question. It is much more difficult to defeat as a reconnaissance technique. Traditional camouflage is rendered useless.

Grating spectroscopy, which is used by LINUS, was originally developed to prove the predictions Quantum Mechanics made about the detailed structure of the hydrogen atom as determined by emitted radiation. (Hecht, 479) This field is governed by the diffraction grating equation:

$$a \sin (\theta_m - \theta_i) = m\lambda \quad (2-1)$$

where a is the distance between slit centers, θ_m is the angle of the principal maxima, θ_i is the incident angle, m is an integer representing the principal maxima, and λ is wavelength..

Spectral imaging combines these two fields in order to produce complex images. These images are combined into a hyperspectral cube that has two spatial and one wavelength dimension. (Figure 2.1) On the sample cube spectral features are clearly visible. On the lower left side of the image the vegetation IR ledge is clearly visible in red. In addition, where the wingtip of the airplane crosses the edge of the image on the center of the right side is also clearly visible. Other structures such as roads and buildings are also seen to exhibit unique patterns.

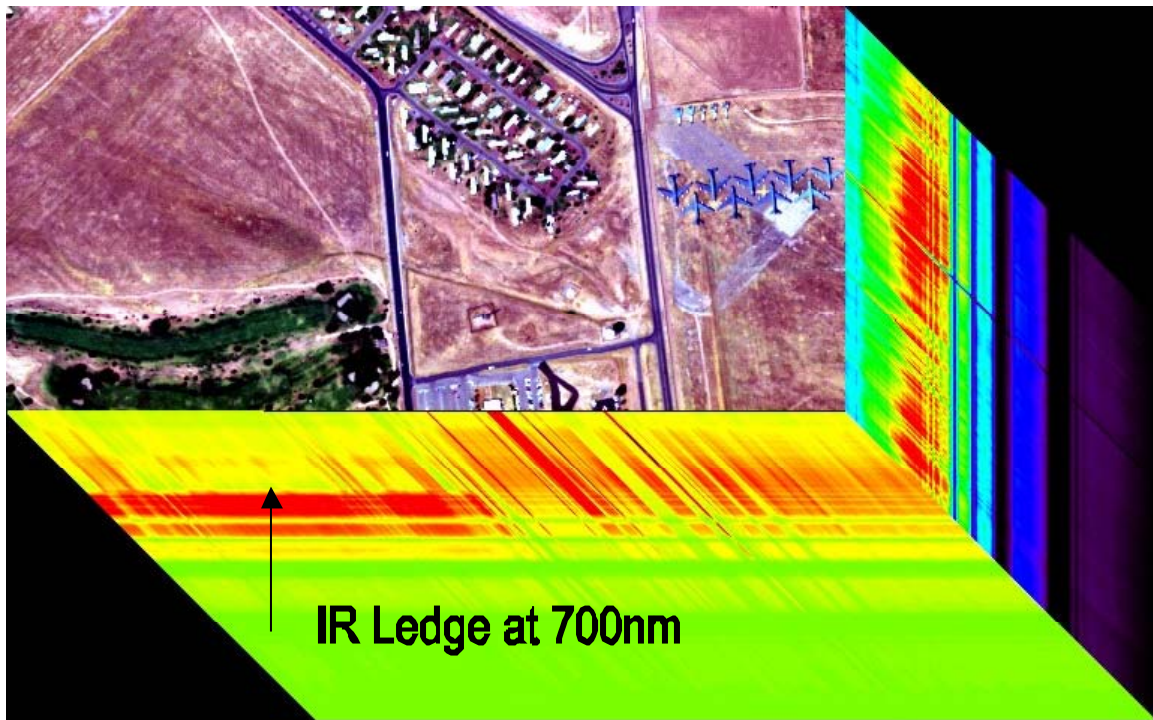


Figure 2.1 Hyperspectral Cube

Sensors using this method have enormous potential in military and civilian applications. Ultra-violet spectral imaging systems have been used to measure volcanic activity. Many hydrocarbons also possess a spectrum that might be observable, leading to greater ability to detect atmospheric pollution and its source. There is also the possibility that this technology could be used to detect biological warfare agents.

B. LINUS

The Lineate Near Ultraviolet Spectrometer (LINUS) is a spectral imaging system that operates in the ultraviolet. It is designed to operate within the atmosphere to detect gases by the scattered ultraviolet spectrum. Currently there are few ultraviolet systems designed for atmospheric use. Most UV systems are designed for use in space either imaging distant stars or planetary objects, such as volcanic discharge from Io. Two of the other systems are the NPS Ultraviolet Imaging Spectrometer (NUVIS) and a correlation spectrometer (COSPEC). NUVIS was a prior system designed at NPS. COSPEC is an older system that has been used commercially. Both of these systems are designed to measure only sulfur dioxide. LINUS is relatively inexpensive, using off the shelf technology. One advantage LINUS has is that it is tunable for a greater wavelength band.

The combination of spectroscopy and imaging yields complex images in three dimensions. The individual images LINUS produces consist of a vertical spatial element and a spectral element. The third dimension is a horizontal element controlled by the sweep of the horizontal field of view by the scanning mirror.

C. OPTICAL SYSTEM

Currently, the optical system is mounted to a standard optical bench 58.5 by 119 cm. The optical system is encased in black Acrylonitril Butadien Styrene. There is a removable lid that allows easy access to the interior. The lid is fastened with quick release Dzus fasteners. The lid is coated with an anti-reflecting felt as is the side of the collection cone. The inside of the lid is lined with foam to prevent light from leaking through the Dzus fasteners. Additionally the chamber containing the scanning mirror is blocked off from the optical chamber with foam baffles. (Figure 2.2) The simplicity of the design and the use of the optical bench make the LINUS instrument quite bulky and

heavy. In its current state it is not a true field instrument. While it can be taken in the field, it is not suitable for transport far from the transport vehicle.

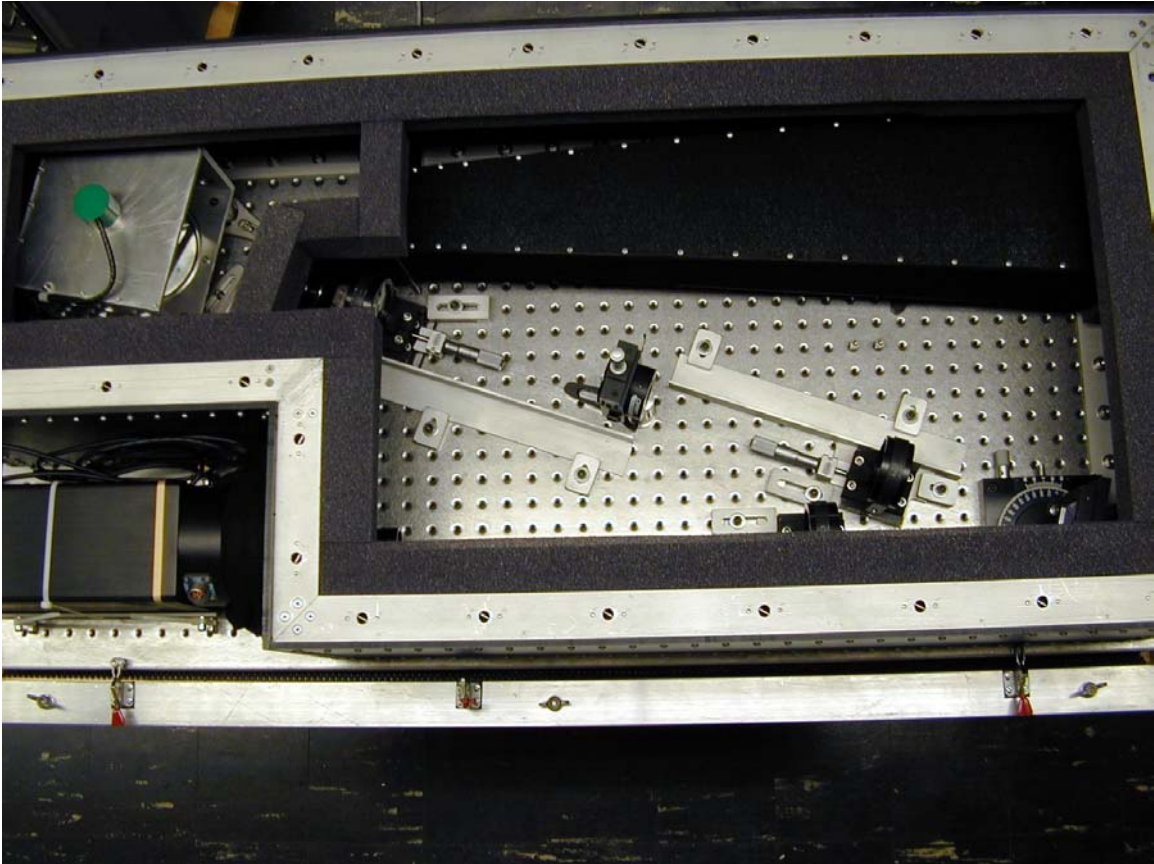


Figure 2.2 Top View of LINUS

The optical system used in LINUS is a simple diffraction grating system. It consists of two reflecting mirrors, a diffraction grating, three objective lenses, adjustable slit and image plane. (Figure 2.3) Light enters LINUS through a collection cone with entrance size of 15.5 cm wide by 9 cm tall, tapering to 7 cm square. From there it is reflected off a scanning planar mirror through a filter. This mirror is precision controlled through a digital encoder. This encoder is a closed loop, DC servo system. The digital encoder is divided into 144,000 step intervals. This allows precise control of the mirror within 0.0025 degrees. It is controlled through a WinView application. For more detailed information on the servo system see Kompatzki's thesis (Kompatzki, 1999). This scanning mirror provides the camera with a 2.5 degree horizontal field of view. By design

the system has a 0.5 degree vertical field of view. The number of increments used to scan the field of view is chosen based on the slit width. (Figure 2.4)

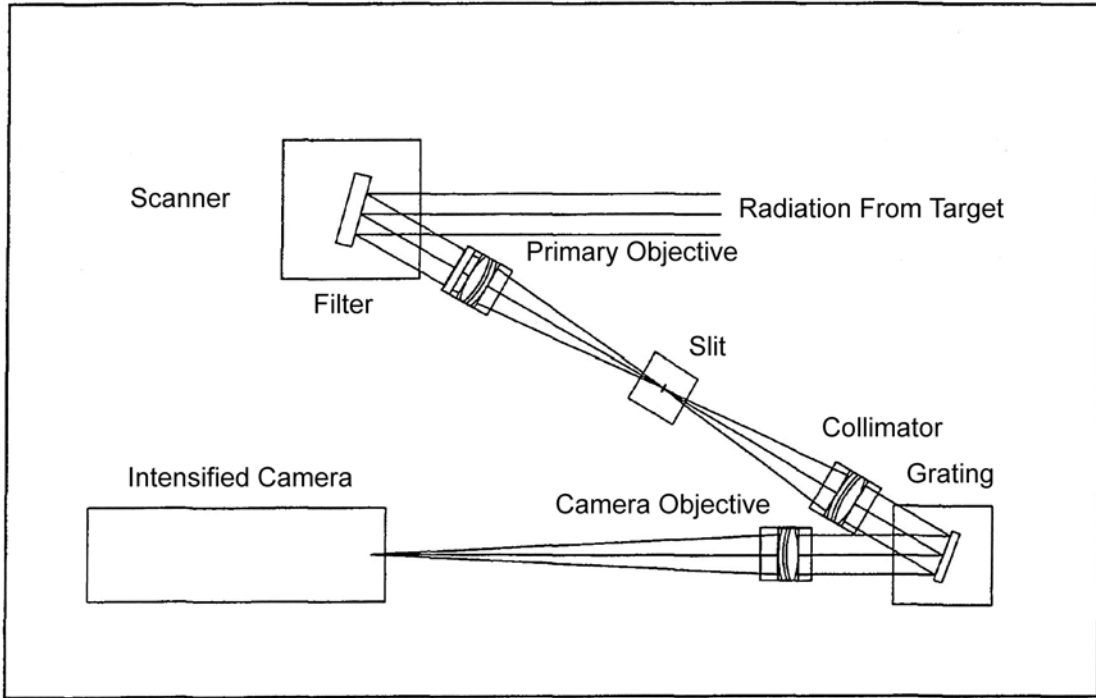


Figure 2.3 Optical Layout

LINUS Pixel Horizontal Displacement at Slit vs Step Size

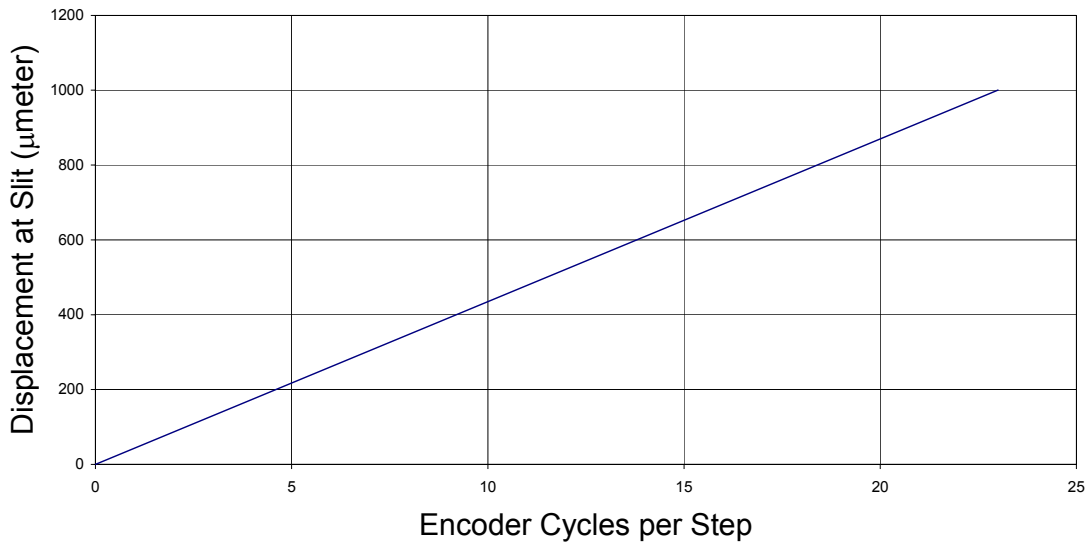
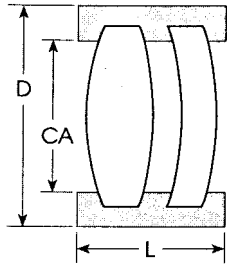


Figure 2.4 Recommended Encoder Step Size



| Doublet Specifications | |
|-------------------------------|--------|
| Outside Diameter (D) | 63.5mm |
| Length (L) | 25.4mm |
| Clear Aperture (CA) | 50.0mm |

Table 2.1 Doublet Specifications

Figure 2.5 Lens specifications

The filtered UV light then passes through the first of the three lenses. All three lenses are manufactured by the CVI Laser Corporation and are doublet lenses. (Figure 2.5, Table 2.1). Each lens is attached to an adjustable micrometer to allow the system to be easily focused for different gases. Focusing data for SO₂ is given at the end of the chapter. The telescope objective and collimating lenses have focal lengths of 250mm, while the camera objective has a focal length of 500mm. The collimated light from the filter is focused by the telescope objective onto the adjustable slit. Slit width is varied depending on the intensity of the ambient light. The slit allows only a thin vertical sampling of the field of view. The slit controls the amount of light that is allowed into the system. The narrower the slit width, the more increments of the mirror are required to image the field of view. Light passes from the slit, traveling 250 mm to the collimating lens. The collimated light travels 17cm and is reflected off the diffraction grating and to the camera objective, 23 cm away. The diffraction grating is 2 inches square and contains 600 lines per millimeter. It is oriented to span wavelengths from 282.4 to 316.9nm. (Kuriger p 39) This wavelength band takes advantage of the strong SO₂ absorption band located between 290 and 310nm. (Figure 2.6) The objective lens is 500mm in front of the camera micro channel plate (MCP).

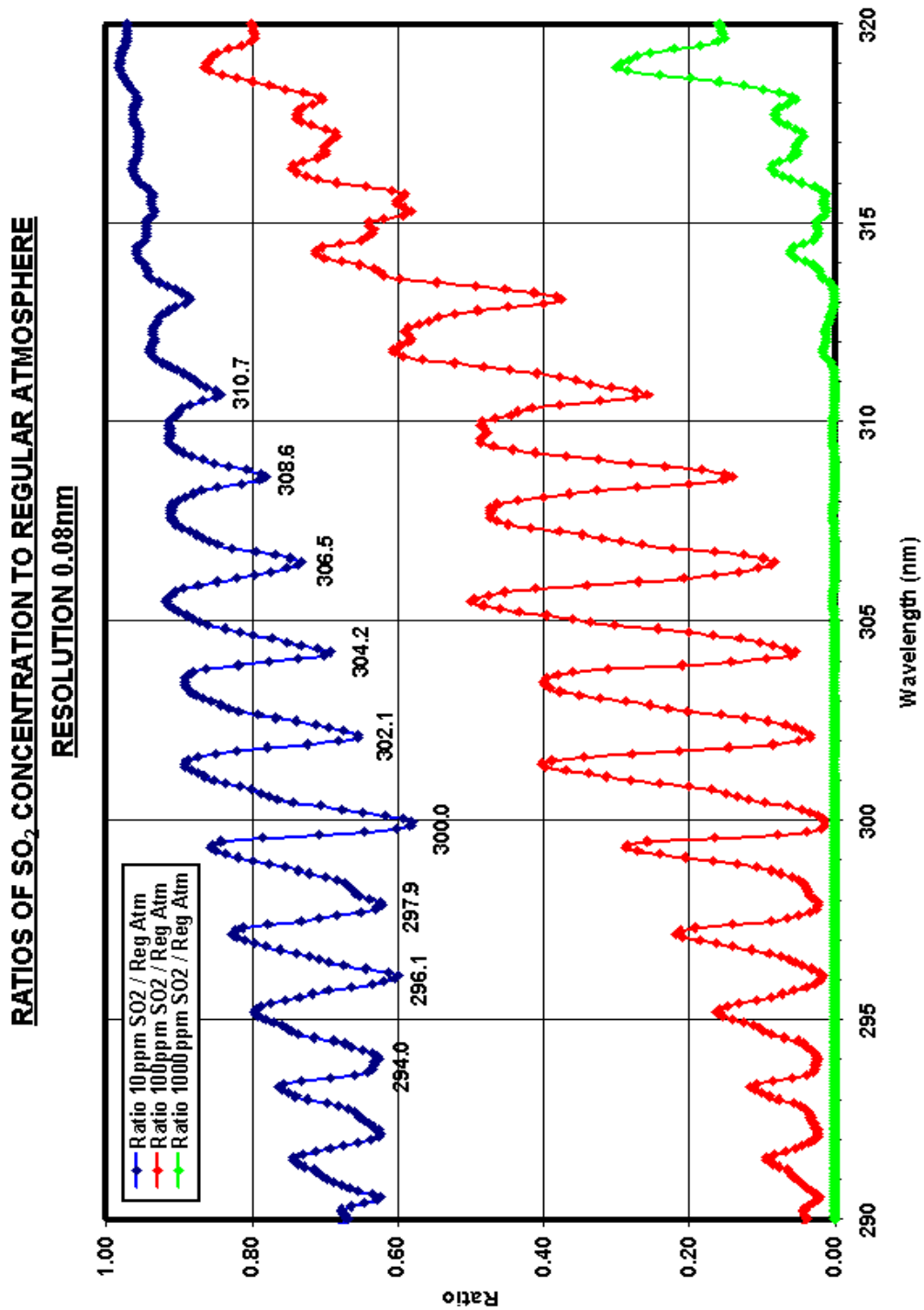


Figure 2.6 MODTRAN Simulation of SO₂ Absorption

D. CAMERA

The camera used in the imaging system is the Princeton Instruments Intensified PentaMAX System. (Figure 2.6) It consists of a camera and an external power

supply/temperature controller. The primary operating system to control the camera is Princeton Instruments Win View. The camera is connected to the computer via a high-speed data serial data link. Settings such as exposure time are controlled through WinView. LINUS utilizes two exposure settings, acquire and focus. In acquire mode, the assigned number of images are acquired for the assigned exposure time and saved to disk. In focus mode, the image is refreshed at the end of each exposure time.



Figure 2.7 Side View of LINUS, Including Camera

The MCP is UV sensitive and records wavelengths from 200 to 550nm. The MCP is coupled to a 512x512 pixel charge-coupling device (CCD) array. The vertical axis records spatial data and the horizontal axis records spectral data. Since the filter prevents some of those wavelengths from entering the optical system it is expected that data will have dark bands on both sides, as there is no signal. A hyper spectral cube is generated by incrementing the scanning mirror. The amount the mirror is incremented is determined by the slit width.

E. SO₂ SETUP

Since LINUS can be calibrated for several wavelengths, the calibration for SO₂ had to be determined. By evaluating the absorption bands of SO₂, it was determined that the 300nm range is the optimum range for detecting SO₂. Therefore the filter used for SO₂ detection is the 300 nm filter. It is a Gaussian filter that has a 50% passband spanning 293-304 nm shown in Figure 2.8 (Omega Optical Company). The filter is modeled using a Gaussian fit of the optical diagram with the equation:

$$f(\lambda) = 15.17 \exp\left(\frac{-(\lambda - 298.43/4.48)^2}{2}\right) \quad (2-1)$$

The optical system was focused at an ambient temperature of approximately 23 degrees Celsius. Each of the lenses and the diffraction grating are adjustable, depending on the sample being measured. To date LINUS has been focused for the detection of SO₂ in the vicinity of 300nm. The settings for the lenses and grating are listed in Table 2.3.

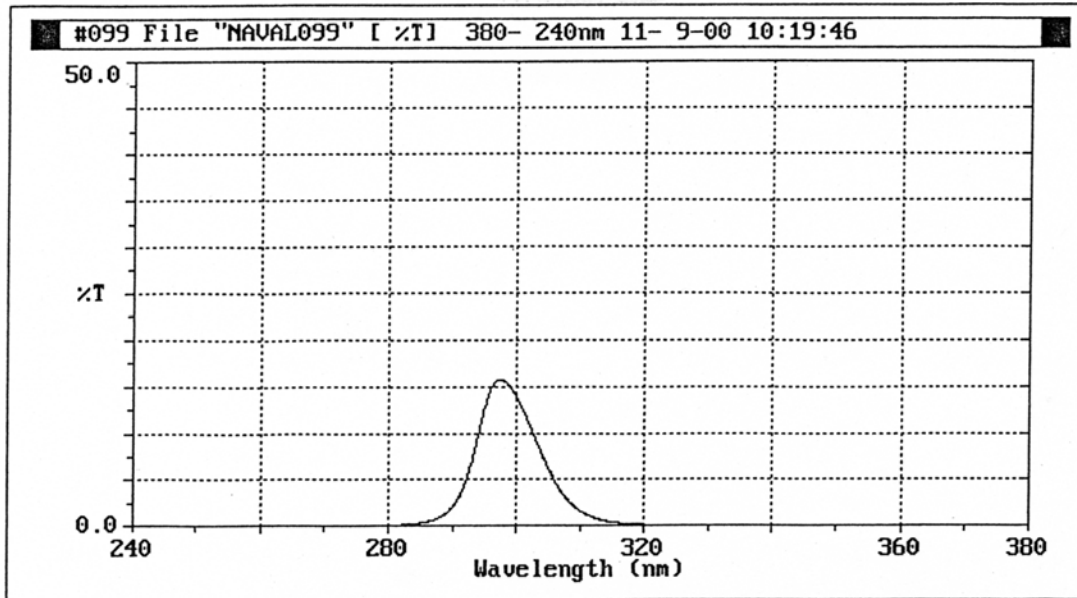


Figure 2.8 Filter Response Function

| | |
|-------------------------|--------|
| Primary Objective (mm) | 10.23 |
| Collimator (mm) | 16.16 |
| Camera Objective (mm) | 15.175 |
| Grating Angle (degrees) | 243 |

Table 2.3 Optical Settings

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III. WAVELENGTH CALIBRATION

A. PURPOSE

The spectral data taken by LINUS is recorded in pixels. For the data to be relevant, it must be converted from pixel number to wavelength. To accomplish this, a source with a known output needs to be measured. In order to determine the calibration we used a platinum (Pt) hollow cathode lamp. (Figure 3.1) The spectrum of the Pt lamp is well studied and has highly defined peaks. The known spectrum for this lamp was obtained from the National Institute of Standards and Technology (NIST) web site. (Sansonetti) This data was then copied into a file format that would be recognized by the IDL programming language.

This work verifies the calibrations conducted by Daniel Kuriger in 2001. Our calibration was conducted prior to taking SO₂ readings in a laboratory setting, thus the optical system was enclosed in its case. Additionally the readings were taken in a partially darkened hallway versus a completely darkened laboratory.



Figure 3.1 Platinum Lamp

B. EXPERIMENTAL SETUP

The Pt lamp was attached to the optical bench and aligned so that it was centered on the aperture. In order to ensure a high enough concentration of light entered, especially at the 0.055 micron slit width, the lamp was placed approximately 10 cm directly in front of the aperture for direct illumination. The lamp was set for maximum intensity.

LINUS has already been focused and the optical system mounted in its permanent position on the optical bench. Specific settings of the optical components are the same as those for the wavelength calibration listed in Table 2.3. For calibration there is no need to scan the horizontal direction. A single image is all that is required. Since this calibration was conducted immediately prior to the SO₂ calibration, the system was fully enclosed. The mirror is aligned to collimate, or the first order image, to ensure the maximum reflection.

C. DATA COLLECTION

Once the equipment was set up, the data acquisition system was set to acquire a single image. The acquisition time was determined through trial and error through the use of focus mode. (Table 3.2) In focus mode the image automatically refreshes without saving at the end of the integration time. Since the Pt spectrum has a maximum in the vicinity of 300nm, the settings for detecting SO₂ were used.

Ideally a method of conducting calibration in the field would be devised. At present, using the Pt lamp is not convenient for fieldwork.

| Slit Width (microns) | Integration Time (sec) |
|----------------------|------------------------|
| 0.055 | 30 |
| 0.11 | 20 |
| 0.2 | 10 |
| 0.55 | 8 |

Table 3.1 Integration Times

The raw data was evaluated to ensure that it had not been saturated. A sample image is shown in Figure 3.2. This image is typical of the Pt spectra observed. The different bands are clearly defined. The horizontal axis is wavelength and the vertical axis is the vertical field of view. The Pt spectrum is confined to the center, horizontally, of the image plane.

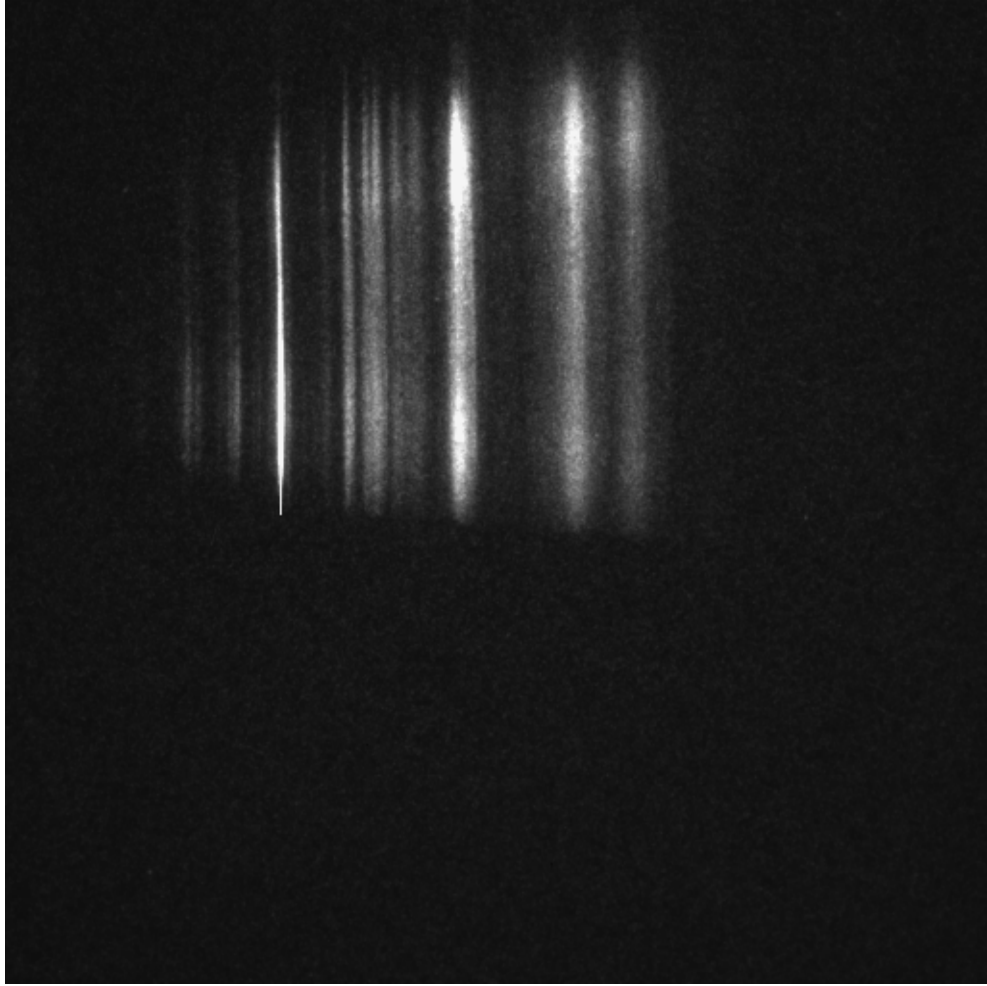


Figure 3.2 Raw Pt Spectrum

D. DATA ANALYSIS

Once collected the data needs to be compared to the known standard. The NIST standards contain only peak intensities. The peaks on the collected data were compared with the peaks of the NIST data. For the purpose of this analysis the four strongest peaks in the vicinity of 300 nm were chosen. That region of the NIST standard was correlated to the data. (Figure 3.3)

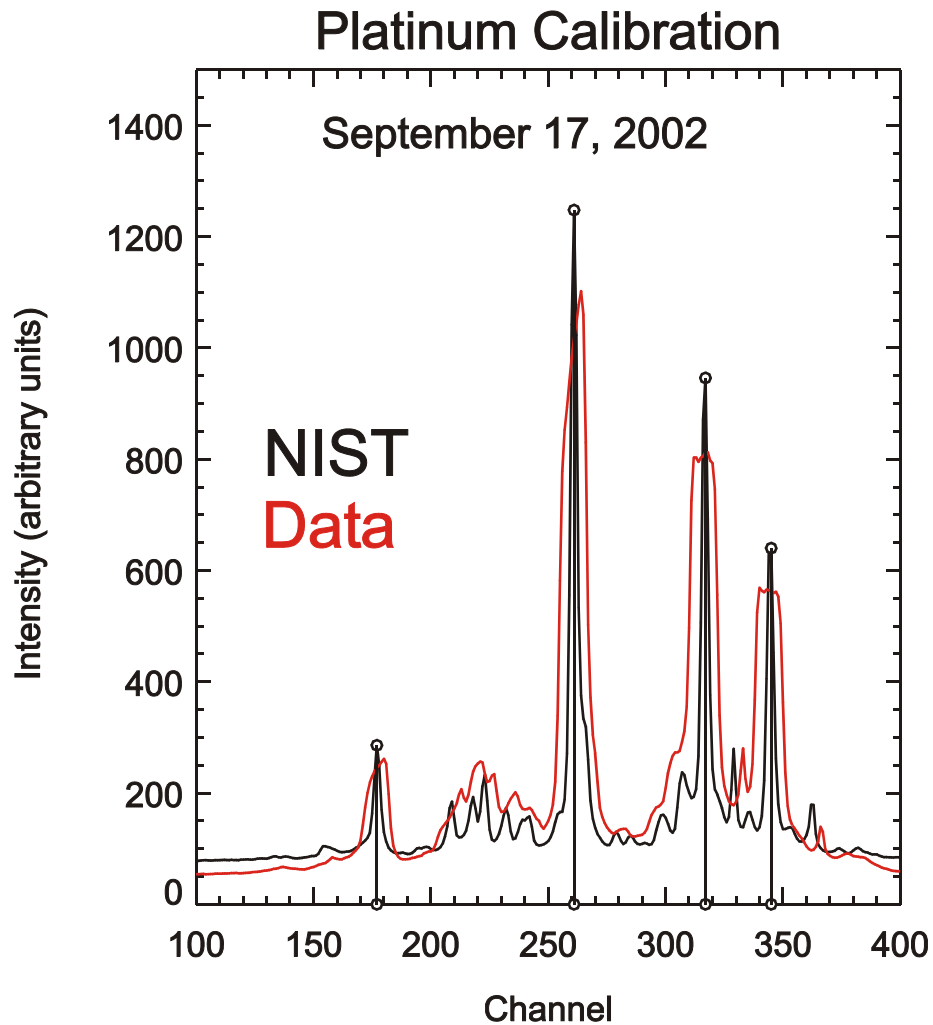


Figure 3.3 NIST/Data Correlation

Once the comparison was completed two different fit methods were used to determine the conversion graph, linear and quadratic. Both fits produced similar results. For data analysis purposes, the linear fit was used. The maximum deviation from the quadratic fit was approximately 0.6 nm at the edges. In the primary data range of channels 150-350 the maximum deviation was less than 0.1 nm. Since LINUS has a spectral resolution of 0.5nm, this deviation is insignificant. An Interactive Data Language (IDL) program was used for the data correlation. The result of the linear fit model is a calibration line shown in Figure 3.4. Values are computed in angstroms to match the NIST data.

Platinum Calibration – September 17, 2002

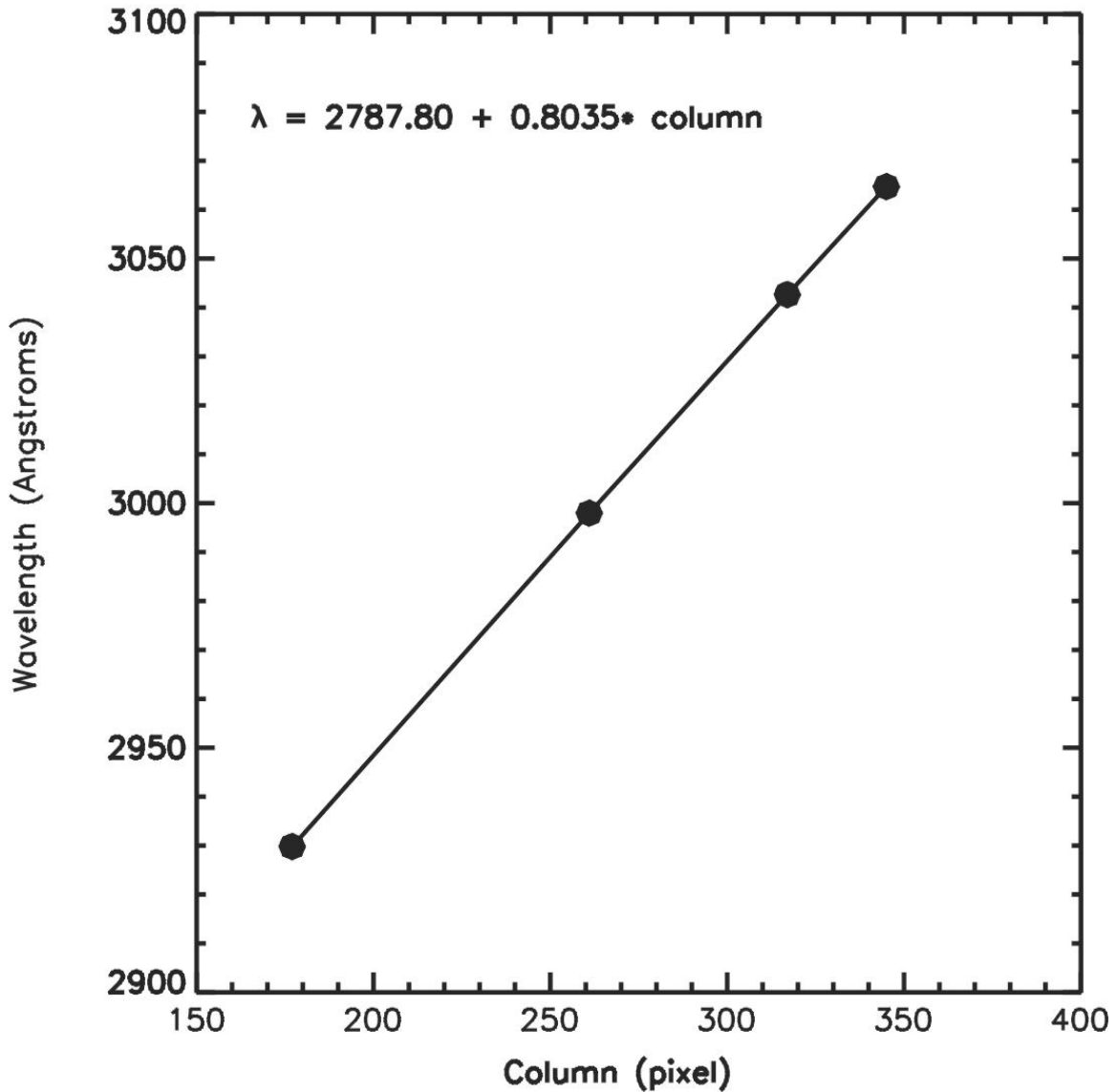


Figure 3.4 Wavelength Calibration Using Linear Fit Model

The quadratic fit yielded a value of:

$$\lambda = 2781.71 + 0.8535 x - 9.684 * 10^{-5} x^2 \quad (3-1)$$

Where x is the column number. A plot of the difference in wavelength between the two fits is shown in Figure 3.5. The data range that we are most concerned with is the vicinity of 300 nm or pixel 260 and in that region the difference between the two fits is negligible.

Platinum Calibration

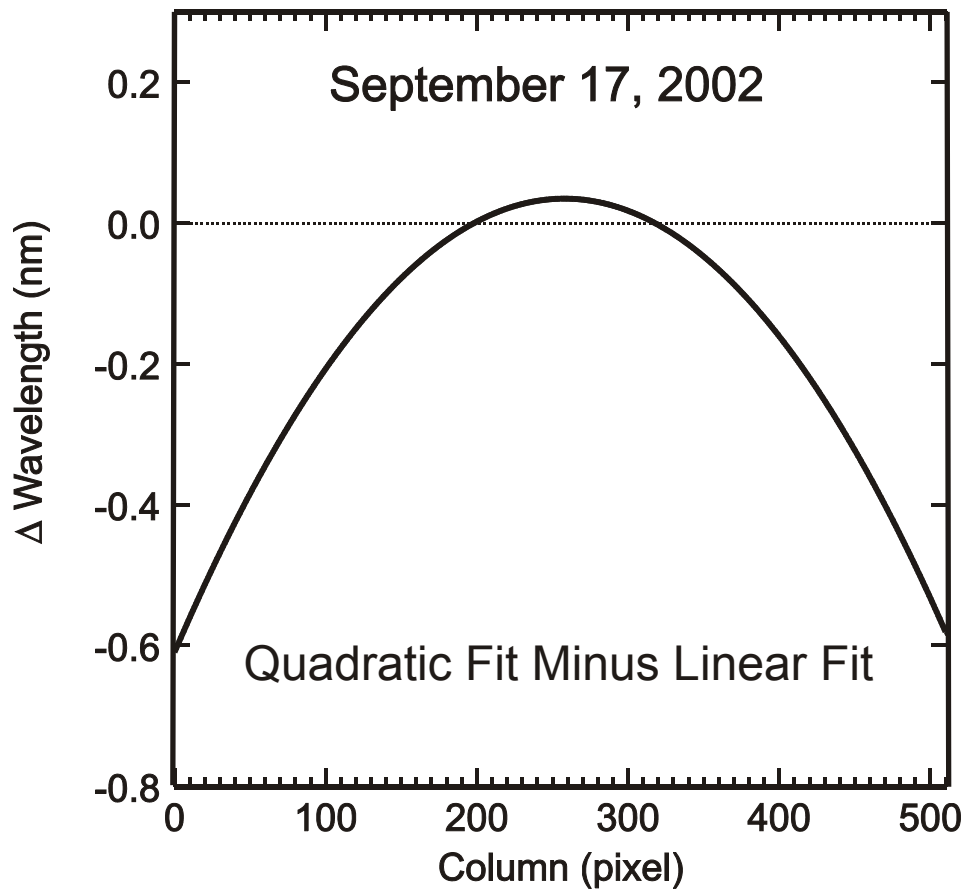


Figure 3.5 Fit Difference

As a final check, the data observed from the Pt lamp was converted to wavelength and compared to the NIST standard. (Figure 3.6)

Platinum Calibration

17 September 2002

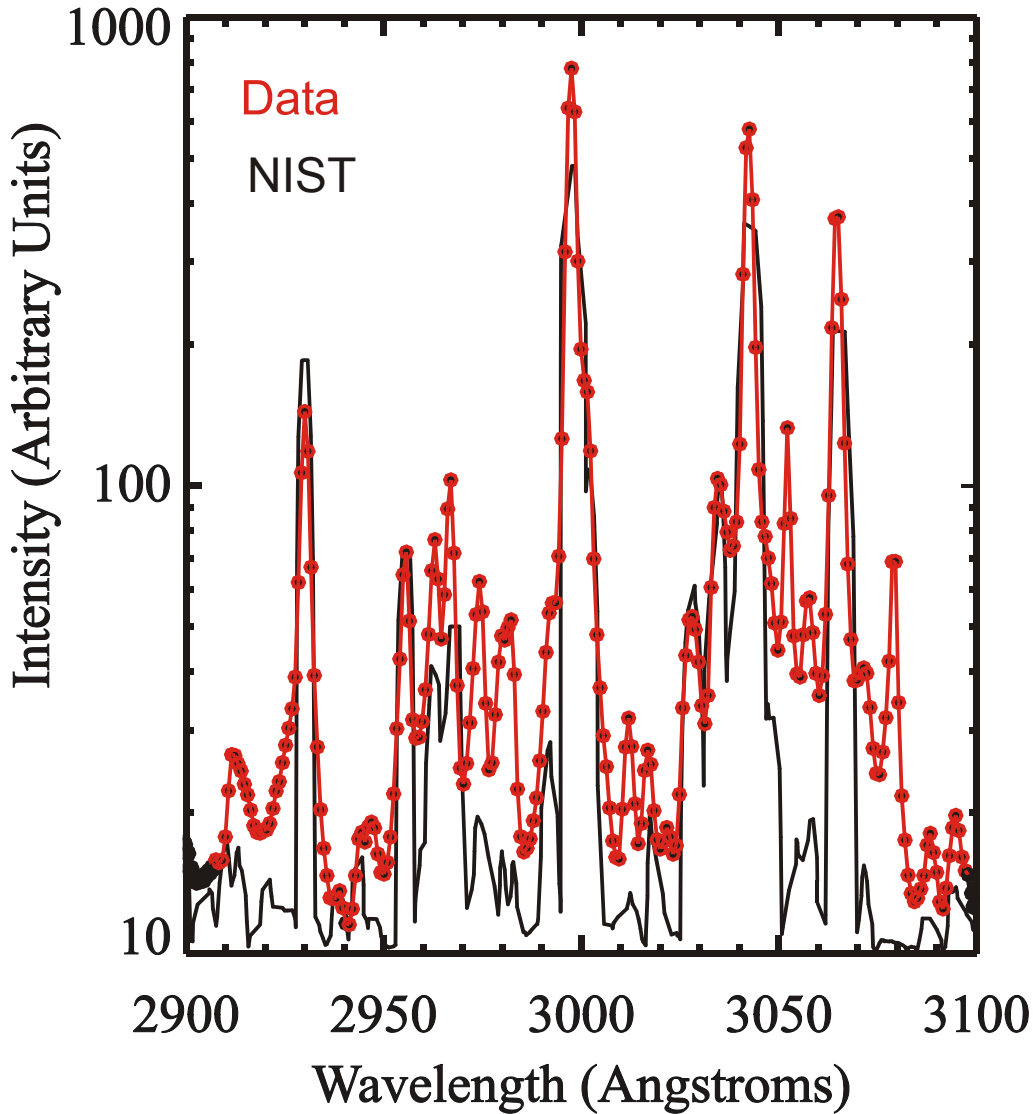


Figure 3.6 NIST/Data Comparison

The above data were obtained with the mirror aligned to collimate. As the mirror sweeps across the field of view, there is a noticeable wavelength shift. Figure 3.7 illustrates the shift of the four strongest wavelengths during a single sweep of the scanning mirror across the image plane.

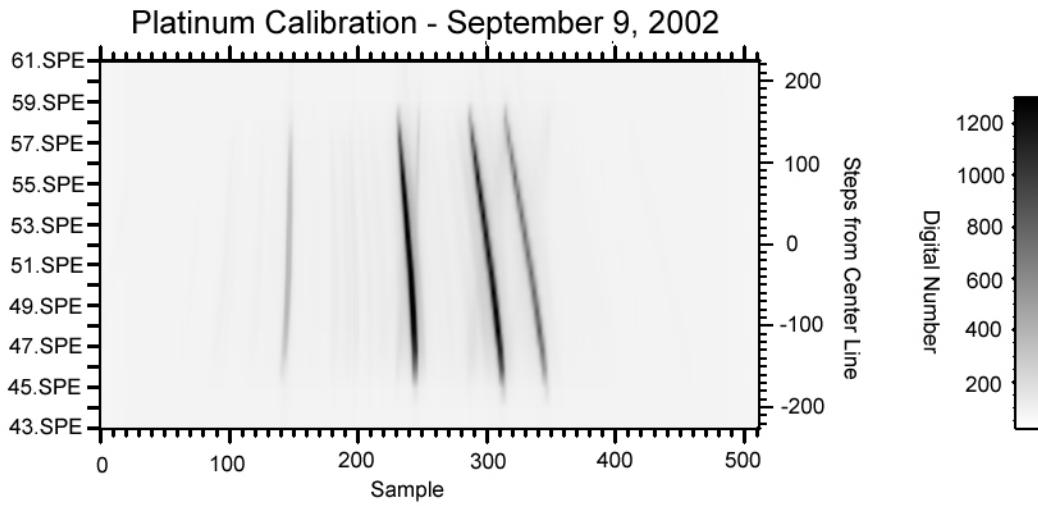


Figure 3.7 Image of Wavelength Shift

The strongest absorption line shifts approximately 10 pixels or 8 nm. The absorption line on the right shifts 23 pixels or 18 nm. As the mirror sweeps the image plane the incident angle is changed slightly. This small change is responsible for the apparent shift in wavelength.

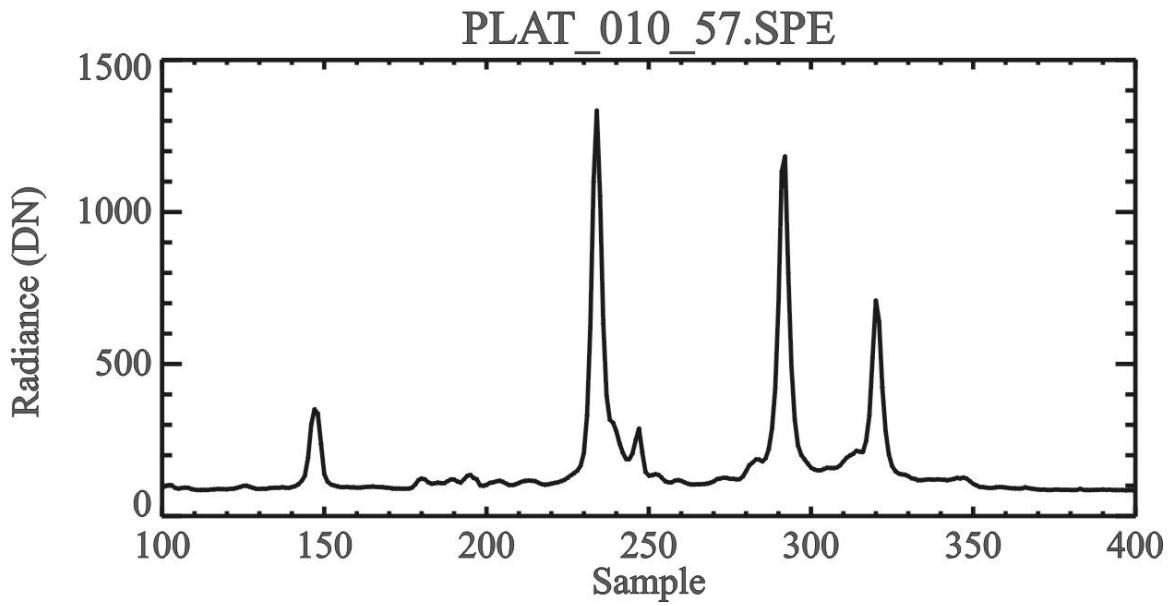
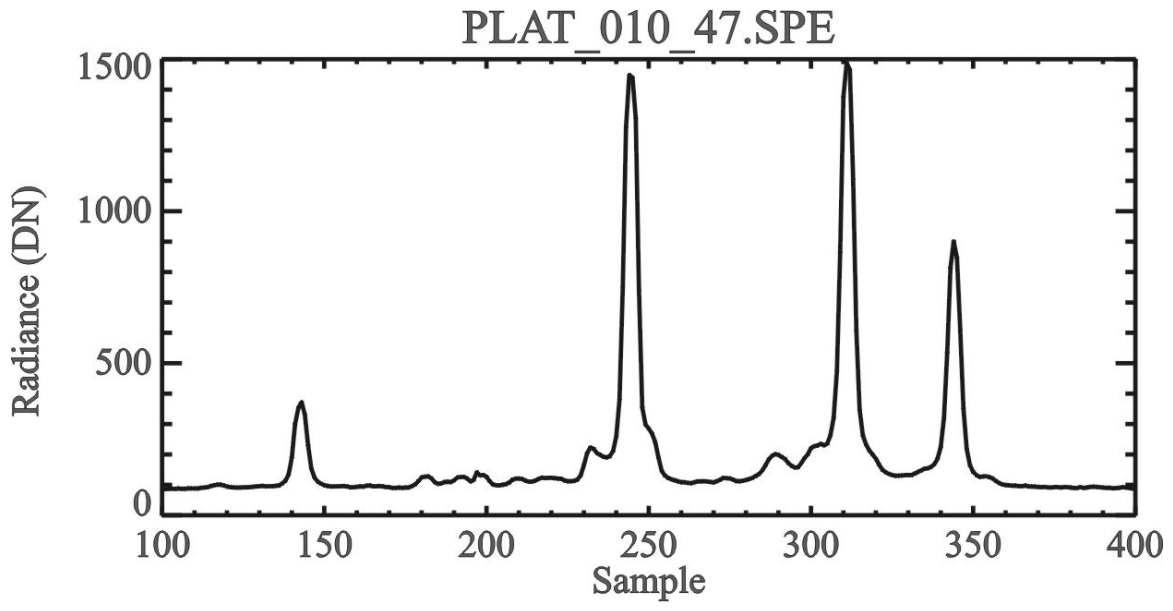


Figure 3.8 Extremes of Wavelength Shift

IV. LABORATORY CALIBRATION OF LINUS

A. PURPOSE

In order for the information gathered in the field to have meaning, LINUS must be calibrated. This is accomplished in the laboratory setting. Images are taken of several different gas concentrations. The data is then analyzed to provide a comparison for field samples. This allows the amount of SO₂ seen in the atmospheric samples to be estimated. Curves of growth for the concentration of SO₂ must be generated. Once these curves are generated, the results can be applied to data taken in the field to determine ambient SO₂ concentrations. This chapter summarizes the laboratory and data analysis procedures used.

B. EXPERIMENTAL OVERVIEW

This experiment concentrated on the SO₂ absorption band between 290 and 310 nm that the instrument is tuned for. SO₂ exhibits a strong absorption band near 300 nm.

C. LABORATORY MEASUREMENT OF SO₂

The procedure used to measure SO₂ concentration is similar to that used by Stephen Marino in the calibration of NUVIS. (Marino, pp 41-61) Since LINUS and NUVIS have different resolutions, there were some modifications to his procedure. They are explained below

1. Gas Test Cell

For this experiment we utilized the small quartz test cell. It is 4 inches (10.16 cm) in diameter, with an 8.77 cm window diameter, and 3.25 cm inner path length. (Figure 4.1) The test cell was purchased from Weiss Scientific Glass Blowing Company. The test cell is encased in aluminum to protect it from damage and was mounted on a wooden block to ensure stability. It was then aligned so that the light passing through it was centered on the aperture.

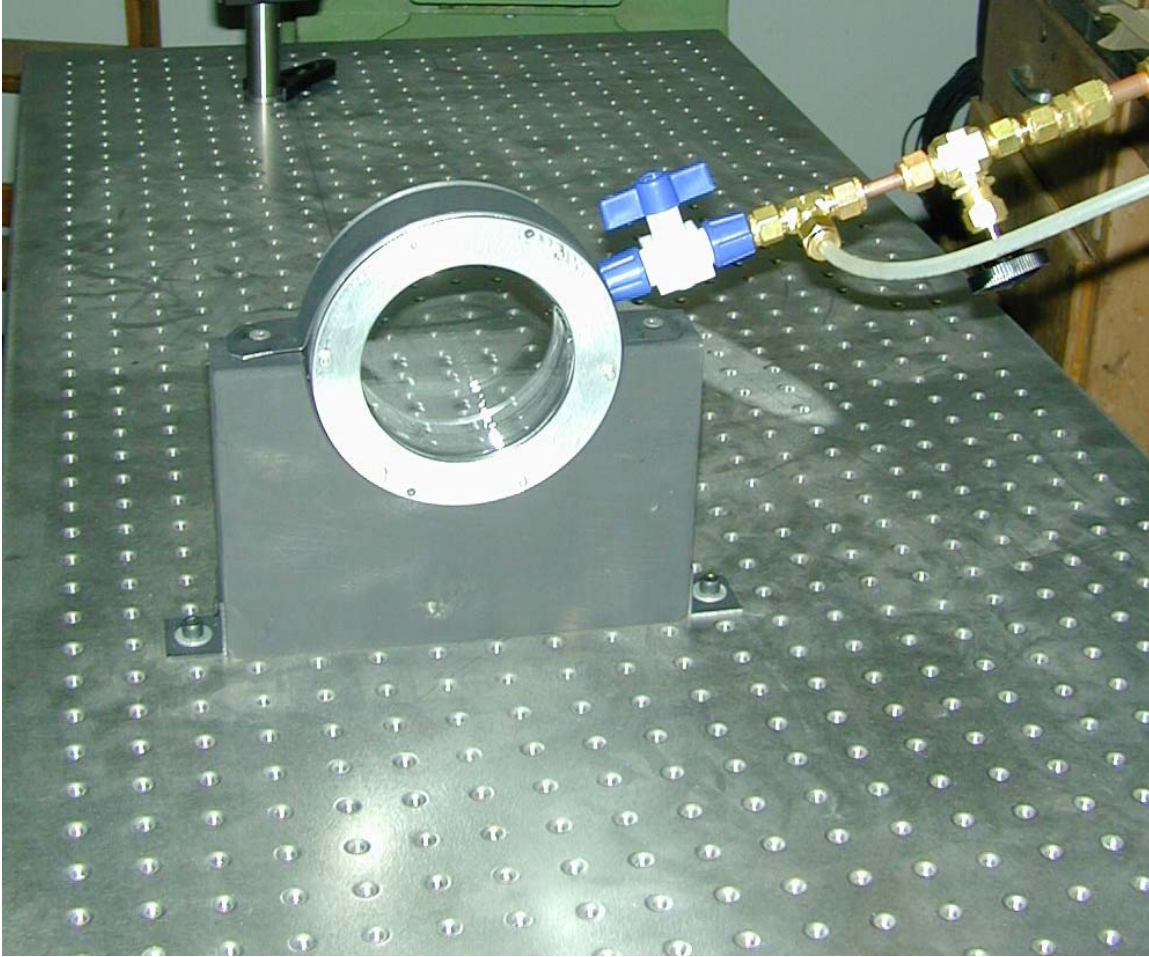


Figure 4.1 SO₂ Test Cell

2. Calibration Source

Initial measurements were made using an EG&G Gamma Scientific deuterium lamp as the illumination source. (Figure 4.2) This lamp has output in the 300 to 375nm range and a maximum output intensity on the order of 10^{-2} ($\mu\text{m}/\text{cm}^2 \text{ nm}$). The output intensity of the lamp varies over time. The lamp has an illumination angle of ten degrees, but a cardboard shield was used to ensure stray light from the lamp did not enter the aperture. The light from the lamp was reflected off an optical mirror and into the test cell. In order to ensure the light entering the test cell was collimated, both the source and the test cell were located 30 in (76.2 cm) from the mirror. (Figure 4.3) Using a cardboard shield over the entrance aperture the lamp and mirror were positioned to ensure the light entering the aperture was centered both horizontally and vertically.

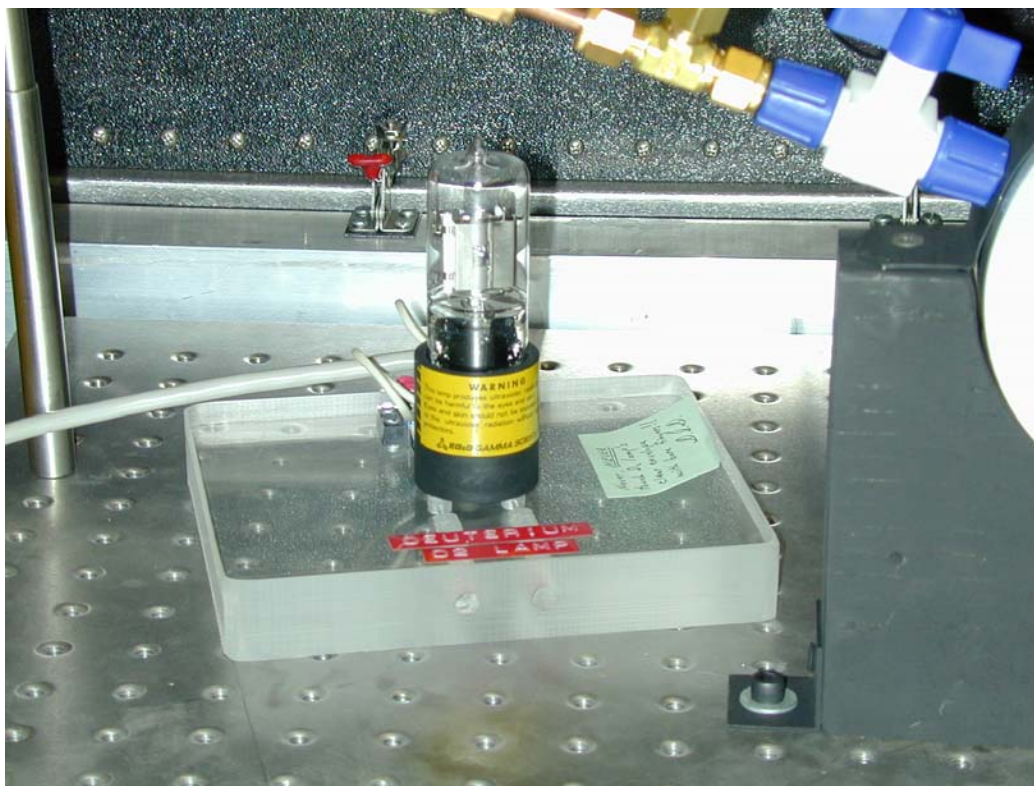


Figure 4.2 Deuterium Lamp

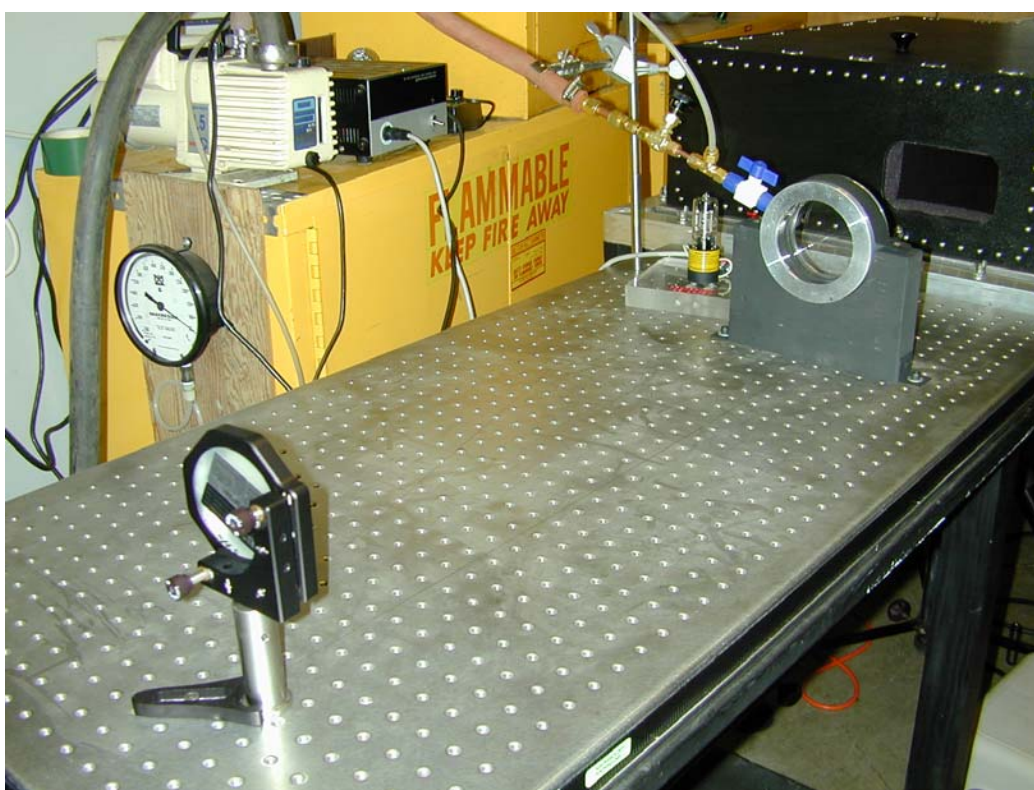


Figure 4.3 Experimental set up

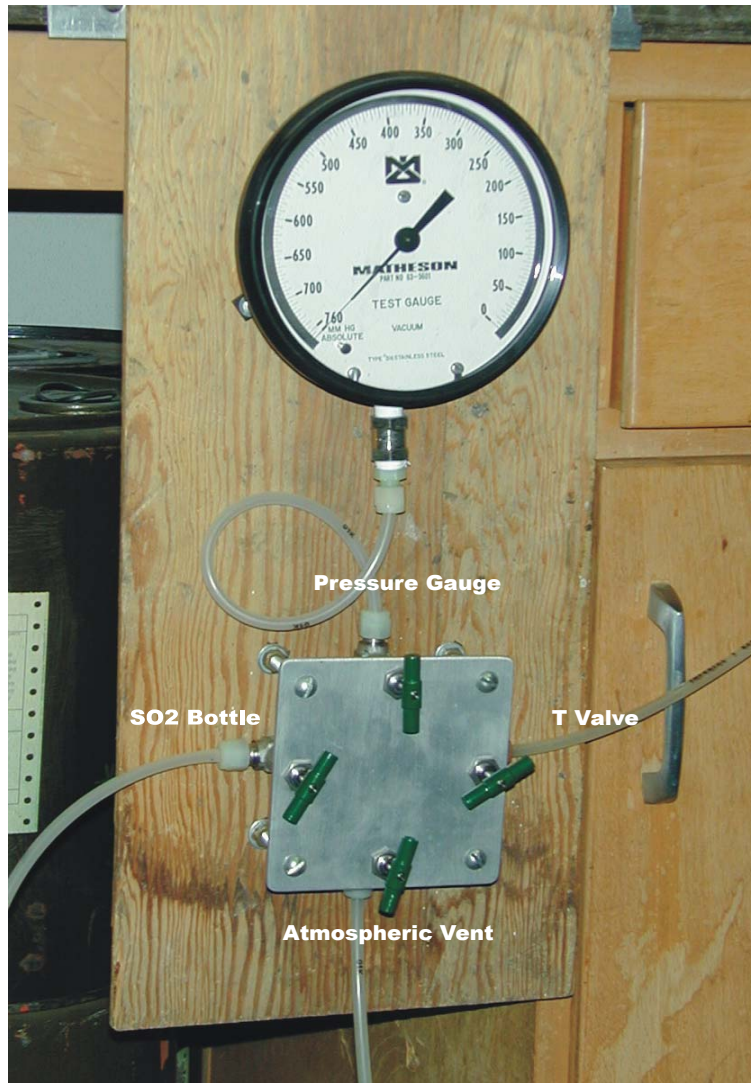


Figure 4.4 Valve Manifold

3. Test Cell Preparation

The test cell had to be connected to several pieces of equipment. The inlet to the test cell is connected to a T-valve assembly. One branch of the T is connected to the vacuum pump. The other branch is connected to a valve manifold. (Figure 4.4) The valve manifold is composed of four branches. One branch is connected to the T-valve. Another is connected to a pressure gauge. A third is connected to the 10% concentration SO₂ bottle and the final is a vent to the atmosphere. The final valve remained unused until testing was complete.

The test cell was evacuated using a mechanical vacuum pump. The exhaust of the pump was vented through a gas exhaust hood. The pressure in the test cell was measured

using the Matheson pressure gauge. The gauge is measured in 5 mmHg increments leading to some imprecision in reading the gas pressure. Once the desired pressure was reached the inlet valve to the test cell was secured to prevent leaks in the T-valve system from causing fluctuations in the test cell pressure. Prior to each concentration being imaged a vacuum image was taken. The deuterium light source produces a varying output over time and for data analysis it is preferable to have a vacuum reading taken as close in time to the sample reading as possible.

4. Data Acquisition

Data was initially acquired a single frame for each pressure. Statistical aberrations in the data obscured the expected output. By taking ten frames at the same this statistical aberration can be average out. The second set of calibration data incorporated this and consisted of ten image sets at each pressure.

The following settings were used for the data acquisition. The MCP was set to 850V and the interior optics aligned for SO₂ detection as described in Chapter II.

Once the cell was prepared and the computer system set up for data acquisition, the overhead lights were extinguished. This was done to reduce the amount of stray light entering the system. The system was first operated in ‘focus mode’ with an evacuated cell in order to determine the optimal integration time for the given slit. (Table 4.1) After the appropriate integration time was chosen, the LINUS control system was placed and in ‘acquisition mode’. For the purpose of calibration there was no scanning of the image plane. The scanning mirror was placed a bore sight to take an image at the center of the field of view.

| Slit Width (microns) | Integration Time (sec) |
|----------------------|------------------------|
| 0.055 | 15 |
| 0.11 | 12 |
| 0.2 | 8 |
| 0.55 | 8 |

Table 4.1 Integration Times

For the calibration the same slit widths that were used in the field were used here. The following SO₂ concentrations (mmHg) were measured: 50, 75, 100, 150, 200, 250, 300, 350, 400, 500, and 600. Pressures below 50 mmHg could not be accurately

measured with the current gauge. As expected the resolution was sharper for the smaller slit widths.

5. Data Analysis

Data from the 0.055 μm and 0.11 μm provided the greatest resolution and are analyzed below. The peaks expected in the SO_2 spectrum were clearly observed. The amount of transmission of the UV light decreased as the concentration of SO_2 was increased. The pressures recorded are the partial pressures and take in to account that the gas was a ten percent SO_2 mixture. Prior to analysis the image of the test cell at vacuum was subtracted from image of the pressurized cell in order to ensure that only the SO_2 spectrum was being measured. The readings for each of the slit widths are combined into a single plot. (Figures 4.5 and 4.6) The partial pressure of 100 mm-Hg corresponds to 4.3×10^3 ppm-m.

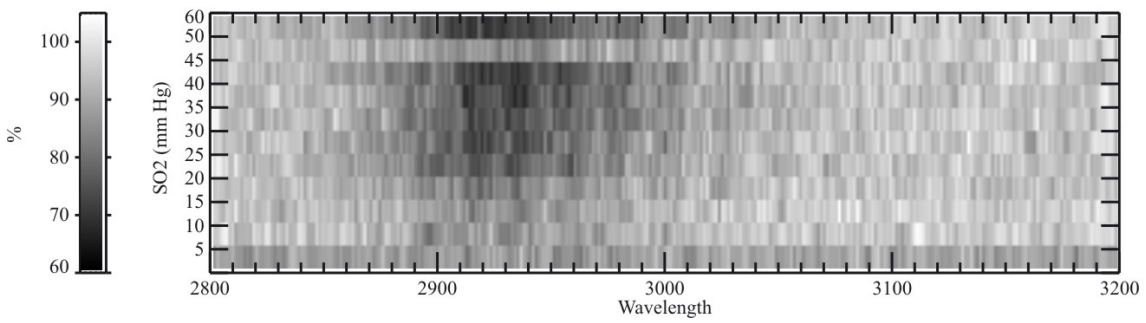
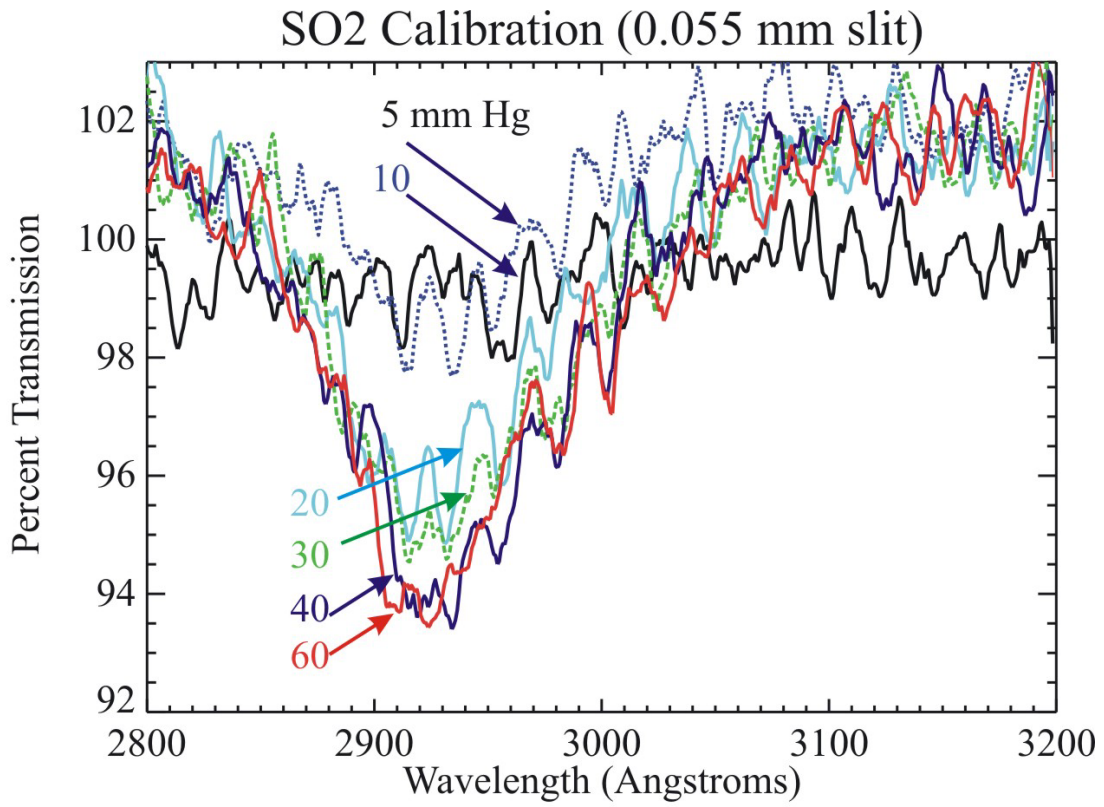


Figure 4.5 0.055 mm Slit SO₂ Concentrations

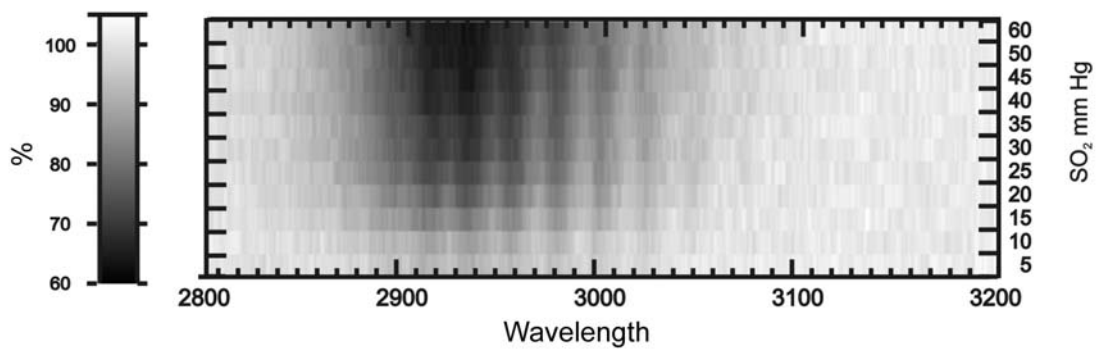
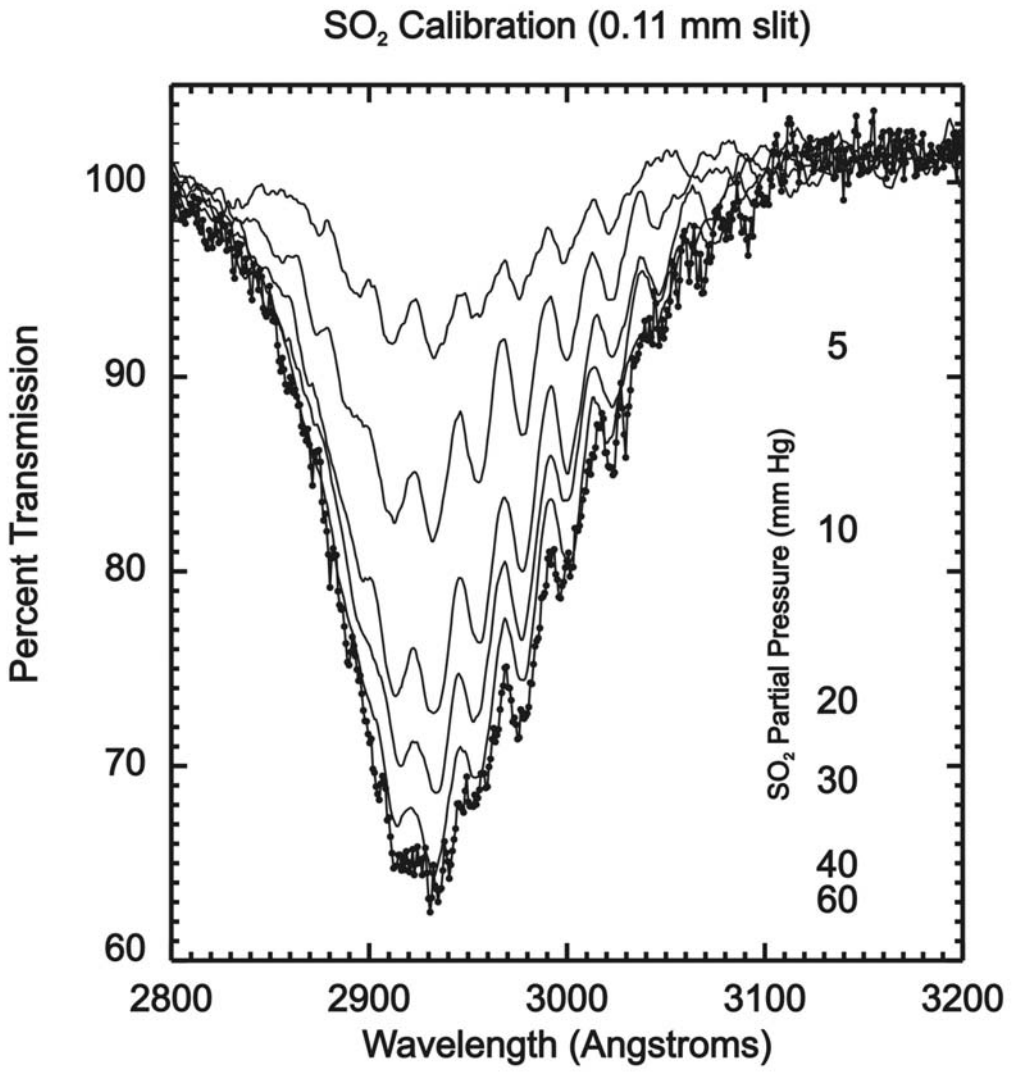


Figure 4.6 0.11 mm Slit SO₂ Concentrations in Arbitrary Units

V. FIRST IMAGING OBSERVATIONS

LINUS has recently undergone a software upgrade from a WinView operating system to a LabView operating system. The LabView system provides a greater degree of automation. Previously, the mirror had to be incremented through manual input after each image was obtained. This could lead to anywhere from 25-45 minutes to obtain one sweep of the field of view. For this reason LINUS was not operating as a spectral imaging system.

With the new software it is now possible to image a system in 5-10 minutes. This new capability was first tested in the lab setting to image a target with vertical lines. The target was illuminated with the broad spectrum deuterium lamp. The results are shown below. Figure 5.1 shows the principle component transform of the 512 images that swept the vertical target. The bright line within the image is the line on the target.

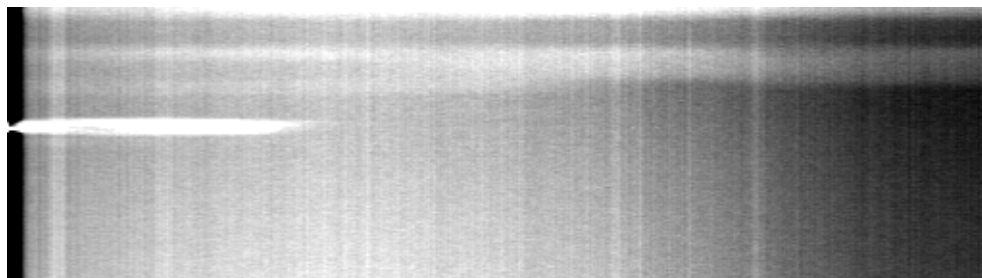


Figure 5.1 Vertical Test Chart

In order to ensure that accurate data is being recorded the wavelengths of coordinates on the line and near the line are compared. The upper line in Figure 5.2 is that data point on the line while the lower line represents an average point on the unlined part of the target. A cross section of the mirror scan across the target (Figure 5.3) shows a sharp peak as the image of the line is taken.

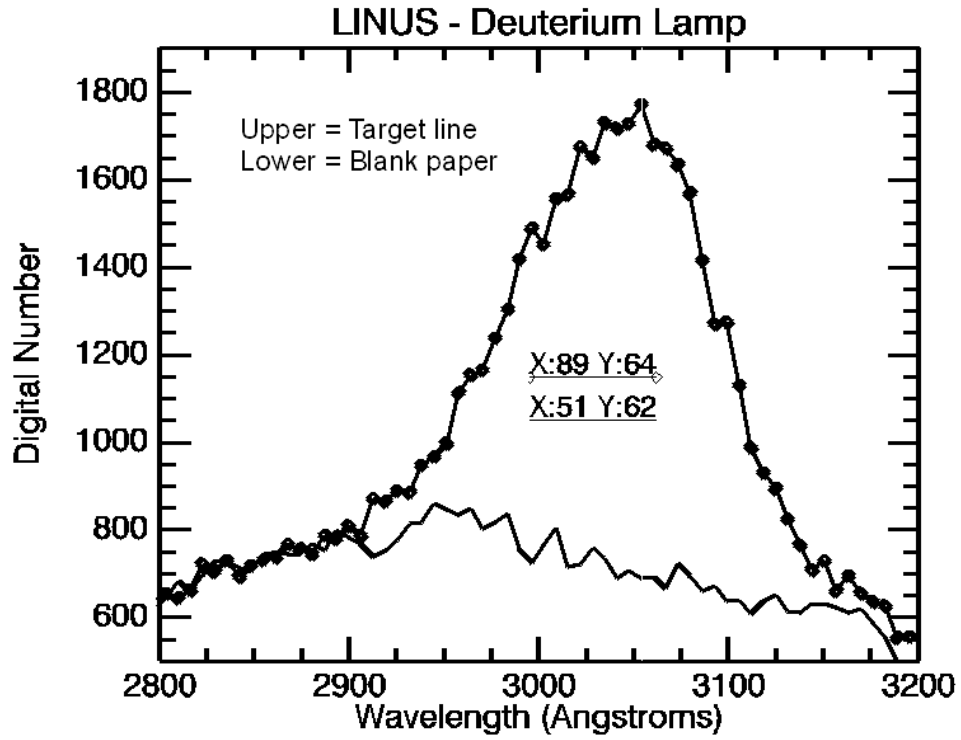


Figure 5.2 Wavelength Comparisons

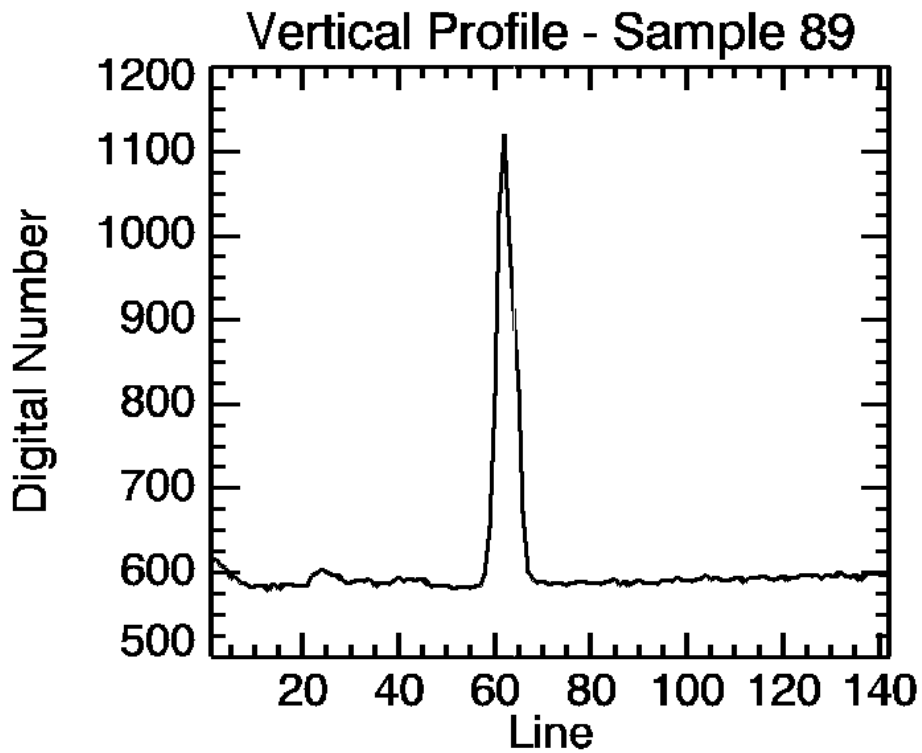


Figure 5.3 Lab Scan Vertical Profile

Once it was determined that LINUS was operating correctly as a spectral imager it was moved outside. The scene imaged outside included a vertical feature, in this case trees. A sweep of the image plane was conducted across a scene this trees. The images were then combined within ENVI and showed the structure of the target trees. Figure 5.4 is a hypercube of the scene. The trees are red and the sky blue in the image axes. In the spectral axis the difference in spectra between the trees and the sky is clearly visible.

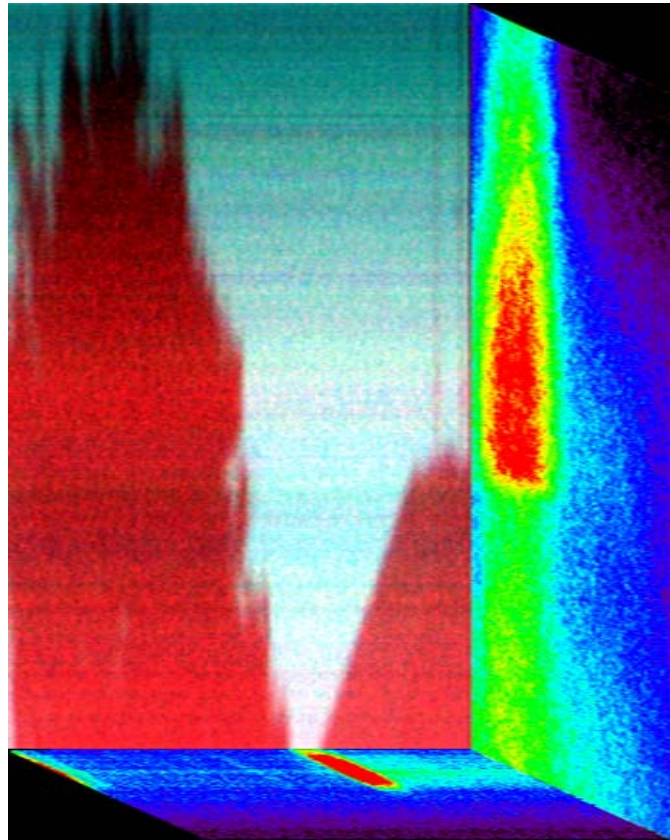


Figure 5.4 LINUS Hypercube (512V x 142H, stretched)

Figure 5.5 illustrates the differences in wavelengths between the different spectral features of the image above. In order to view the hypercube in the orientation where the sky is up and the ground is down the image has been rotated ninety degrees clockwise. The coordinates identified in the figure correspond to those in the original configuration. The zero-zero point is located at the upper left hand corner in the image above with the x-axis going down the left side and the y-axis along the top. The above image shows that LINUS can be successfully employed as a spectral imager.

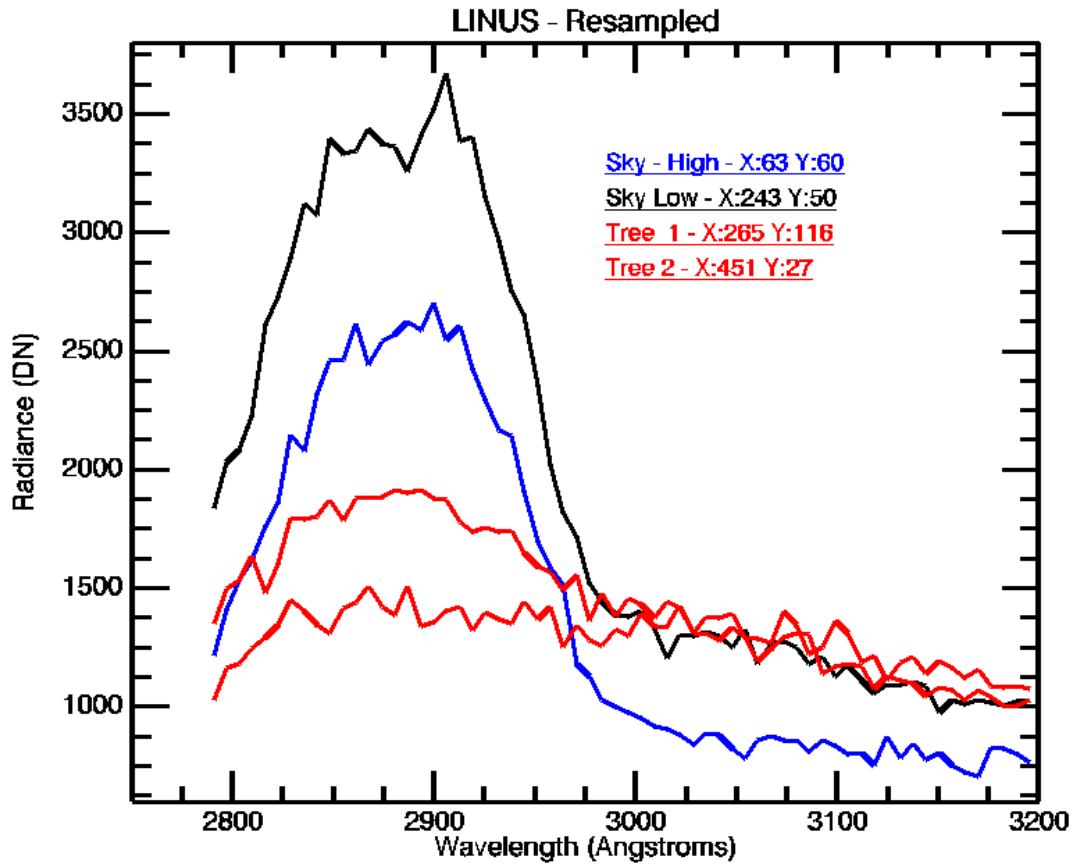


Figure 5.5 Wavelength Differences – Trees Included for Illustrative Purposes Only

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSION

The project was successful in reproducing the wavelength calibration previously conducted. The calibration program is complete and capable of converting pixel number to wavelength on data obtained from LINUS.

The ability to detect SO₂ in a laboratory environment was successfully demonstrated. LINUS is capable of differentiating varying concentrations of gas.

The LINUS system has been successfully used as a spectral imaging system. Images of a known optical target illuminated with a broadband UV source were accurately reproduced. In addition an image of trees illuminated by ambient sunlight was obtained.

B. FUTURE WORK

While wavelength calibration was conducted, it was only conducted for the centerline image. In order to calibrate the data more effectively the calibration test needs to be conducted for the entire field of view.

Now that LINUS is fully operational as a spectral imaging system, it needs to be taken to a field location to conduct further tests on the detection of SO₂. In this vein, the SO₂ data collected in the lab needs to be converted to parts per million in order for the recorded data to have meaning. Additional calibrations should be conducted to ensure the accuracy of the initial results.

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