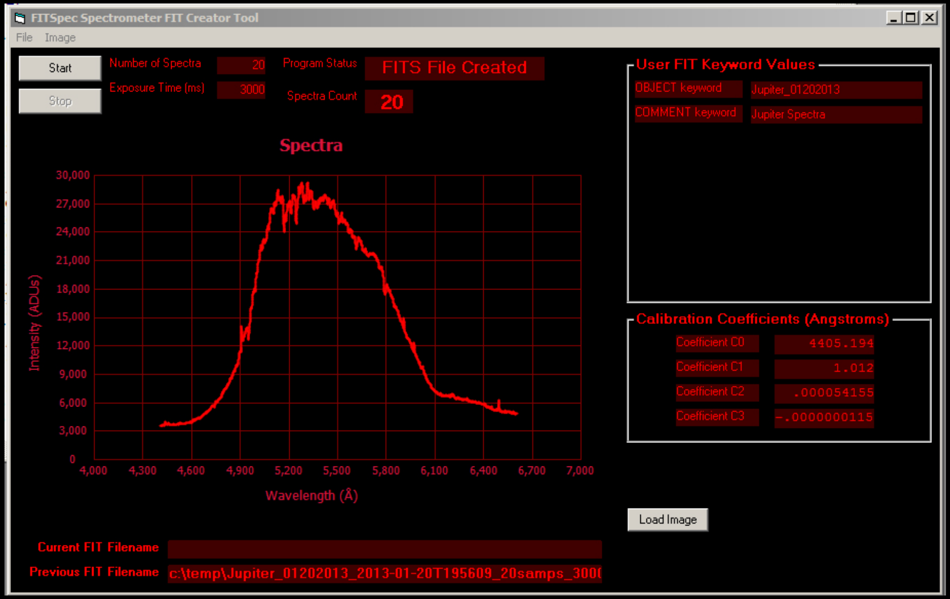


Presented by Jerry Hubbell
Lake of the Woods Observatory (MPC I24)
President, Rappahannock Astronomy Club

ENGINEERING A FIBER-FED SPECTROMETER FOR ASTRONOMICAL USE

Objectives

- Discuss the engineering issues associated with integrating a fiber-fed spectrometer into an astronomical imaging system
- Describe the workings of a modern miniaturized fiber-fed spectrometer
- Describe the fiber-optic cable interface to the astrograph
- Explain the engineering involved in the fiber-head optical interface to the astrograph
- Describe how to engineer a guiding system for the fiber-head
- Discuss the software and procedures to acquire, calibrate, and process the spectral data

Engineering Issues

Several engineering issues must be addressed when coupling a fiber-fed spectrometer to an astrograph.

- First, how do you focus the star on the end of the fiber-optic cable?
- How do you know the light entering the fiber cable is collimated correctly and has the correct focal ratio?
- What is the Numerical Aperture (NA), and what is the proper value for your astrograph?
- How do you feed the light from your astrograph so that you collect data and also guide accurately to keep the light on the end of the fiber?

Engineering Issues

- What is the procedure to focus the light on a 500-micron fiber? A 200-micron fiber?
- What are the design requirements for aligning and sizing the elements in the fiber-optic head?
- How sensitive is the linear CCD used to collect data from the light spread out into a spectrum?
- How does the sensitivity of the CCD affect your science goals and the objects you can effectively observe?
- What is the limiting magnitude for the objects you can observe?
- How do you calibrate the spectrometer?

Engineering Issues

- How do you know that the wavelengths you want to collect are entering the spectrometer?
- How do you know that the guide camera is getting enough light to guide effectively?
- How do you measure and adjust for the linear CCD response curve?
- How do you measure the resolution of the resultant spectra?
- Etc…

Engineering Issues

- As you can see , there are myriad issues when designing, building, and integrating a fiber-fed spectrometer into your astrograph
- Each of these issues can be resolved and addressed in a methodical way

A New Instrument for Amateurs

Professional observatories use fiber-fed spectrometers to acquire high-resolution spectra of stars and other objects. Typically, these instruments are very expensive. Generally, amateurs who get into spectroscopy use a simple transmission grating mounted in a filter holder, such as the Star Analyzer 100 made by Paton Hawksley. However, spectroscopy is a new field for amateur astronomers and is ripe for innovation.

Courtesy Paton Hawksley, Field Tested Software, and Science-Surplus

A New Instrument for Amateurs

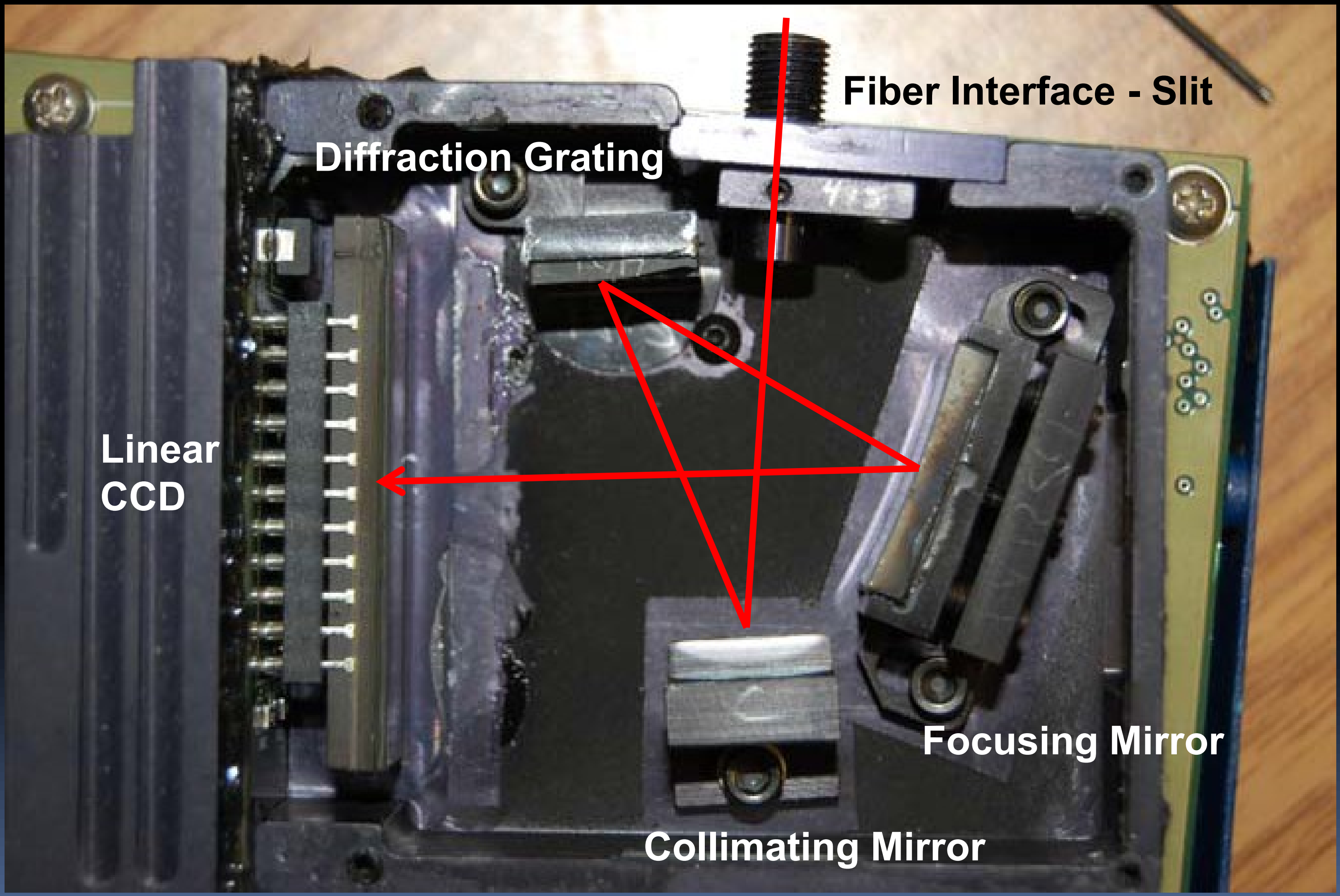
The fiber-fed spectrometer is a different animal altogether.

It consists of several components, all integrated into a very small package. The basic elements include:

- Fiber-optic cable interface
- Imaging Slit
- Collimating mirror
- High-resolution diffraction grating
- Focusing mirror
- Linear CCD chip
- Processing electronics to feed the data from the CCD to the computer

Fiber-Fed Spectrometer Optical Bench

4-inches



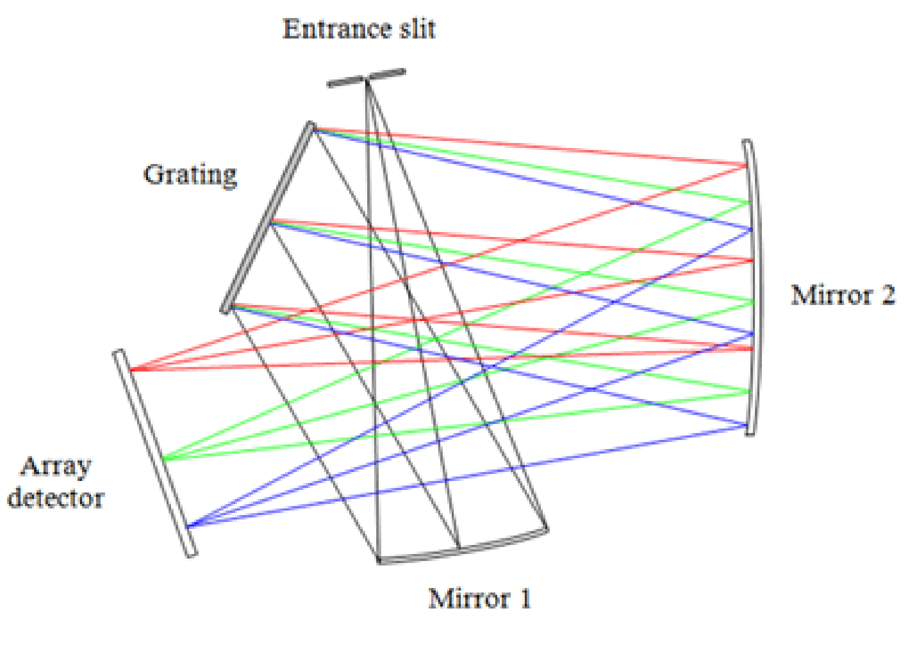
Courtesy Science-Surplus

Fiber-Fed Spectrometer Optical Bench

- The optical bench of the spectrometer is a crossed Czerny-Turner design
- This folded light configuration is very compact and is flexible enough to provide various linear dispersion designs. It expects an entrance light cone of > f/3. This spectrometer is fed by a multimode fiber-optic cable with a Numerical Aperture (NA) of 0.22. The optimal light cone is calculated by:

  Focal Ratio = 1/(2*NA)
  In this case, F/2.27

  (more on this later)



Courtesy BWTek, Inc.

Fiber-Optic Head

- The fiber-optic head is designed to interface the light coming into the astrograph to the fiber-optic connection between itself and the spectrometer slit
- The fiber-optic head performs 3 essential functions:
  1. Brings the light of the desired wavelength band to the end of the fiber-optic cable
  2. Splits the light to feed the fiber-optic cable and the guide camera simultaneously
  3. Brings the light to the proper focus position for both the fiber-optic cable and the guide camera

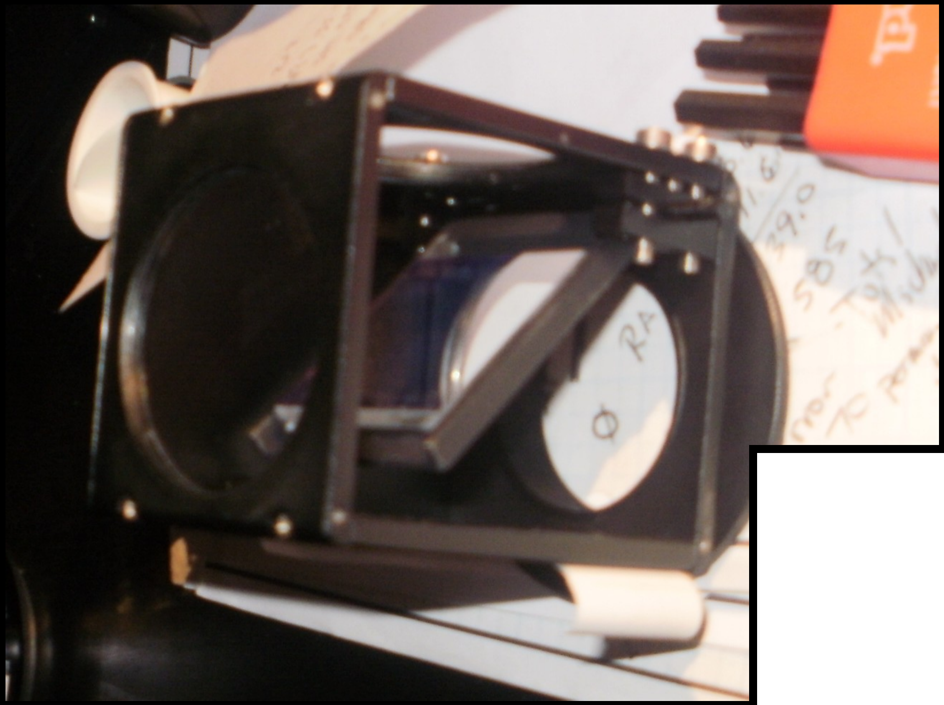
Fiber-Optic Head

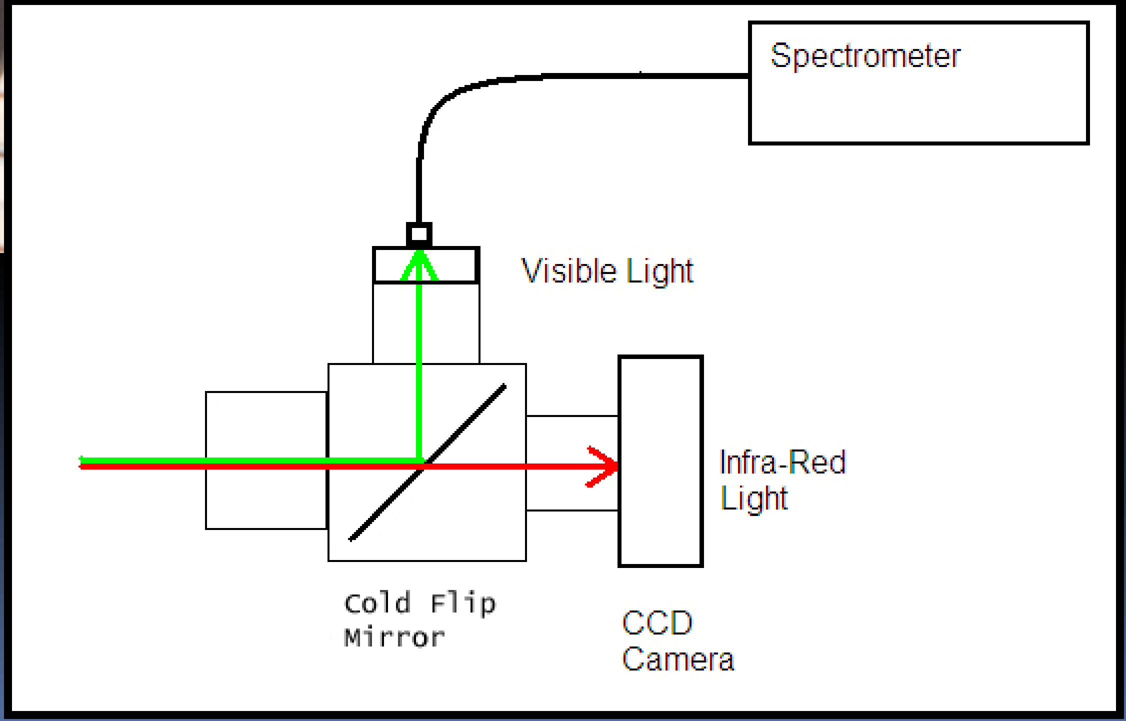
The fiber-optic head also performs two other functions:

- Enables a solid connection to the astrograph focuser to minimize the slop and movement of the fiber-optic cable in relation to the entering light beam
- Provides a solid, precisely aligned and accurate distance setting for the guide camera to bring the fiber and camera into focus simultaneously

Both functions are necessary to maximize the amount of light fed into the fiber-optic cable while providing enough light to the guide camera to track the object under study

Fiber-Optic Head – Cold Mirror





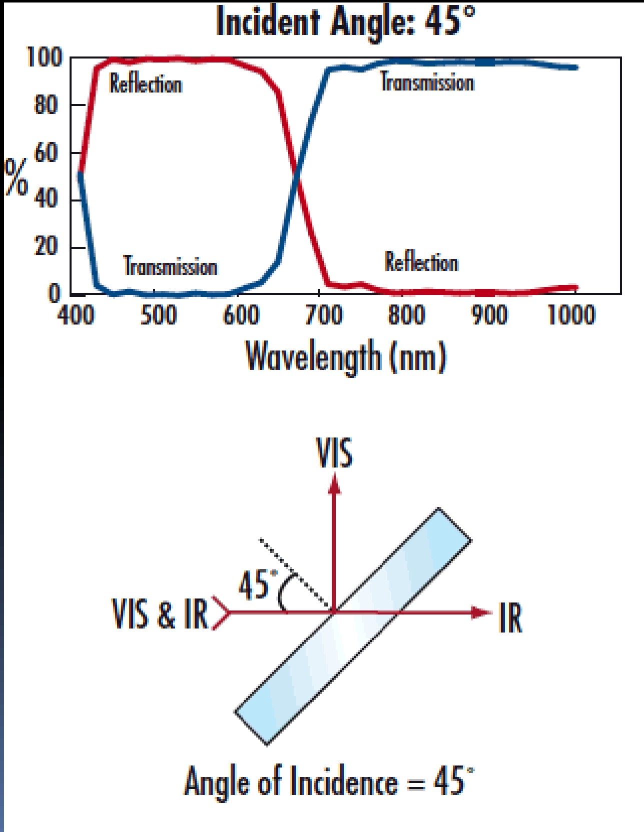
Fiber-Optic Head – Cold Mirror

- The cold mirror splits the light to feed the fiber-optic cable and the CCD guide camera simultaneously
- The component that generally performs this function is a beam-splitter. The cold mirror, on the other hand, splits the light based on the wavelength
- The light is split so that some goes straight through, along the astrograph's optical axis, and the rest is reflected 90 degrees to the optical axis of the astrograph

Courtesy Edmund Optics

Fiber-Optic Head – Cold Mirror

- The cold mirror selected is produced by Edmund Optical and is model 62640 35mm square (45 Deg AOI)
- It reflects light from 4000 Å–6700Å and transmits infrared light (above 6700Å) straight through as shown at the right



Courtesy Edmund Optics

Fiber-Optic Head – Fiber Cable

- As mentioned previously, the light cone coming into the spectrometer is an important consideration for the design of the fiber-optic head
- The design of the spectrometer expects a light cone of >f/3.
- The multimode fiber-optic cable has a Numerical Aperture (NA) of 0.22
- The NA of an optical system is basically a number that characterizes the range of angles over which that system can accept or emit light
- For this astrograph application, the light cone is determined by the focal ratio (FR) of the astrograph and the value of the light cone acceptable to the fiber optic cable

Fiber-Optic Head – FRD

- Focal Ratio Degradation (FRD) is an effect that occurs when the light cone entering a fiber-optic cable is not optimized to its NA
- When the light cone focal ratio (FR) is not optimized, the light transmission rate falls from nearly 100% down to almost 50% or less
- The goal is to maximize the amount of light coming into the spectrometer by minimizing the amount of light lost in the fiber-optic cable
- This is done by using the NA of the fiber to determine the best FR for the fiber and adjusting the light cone FR accordingly

Fiber-Optic Head – FRD

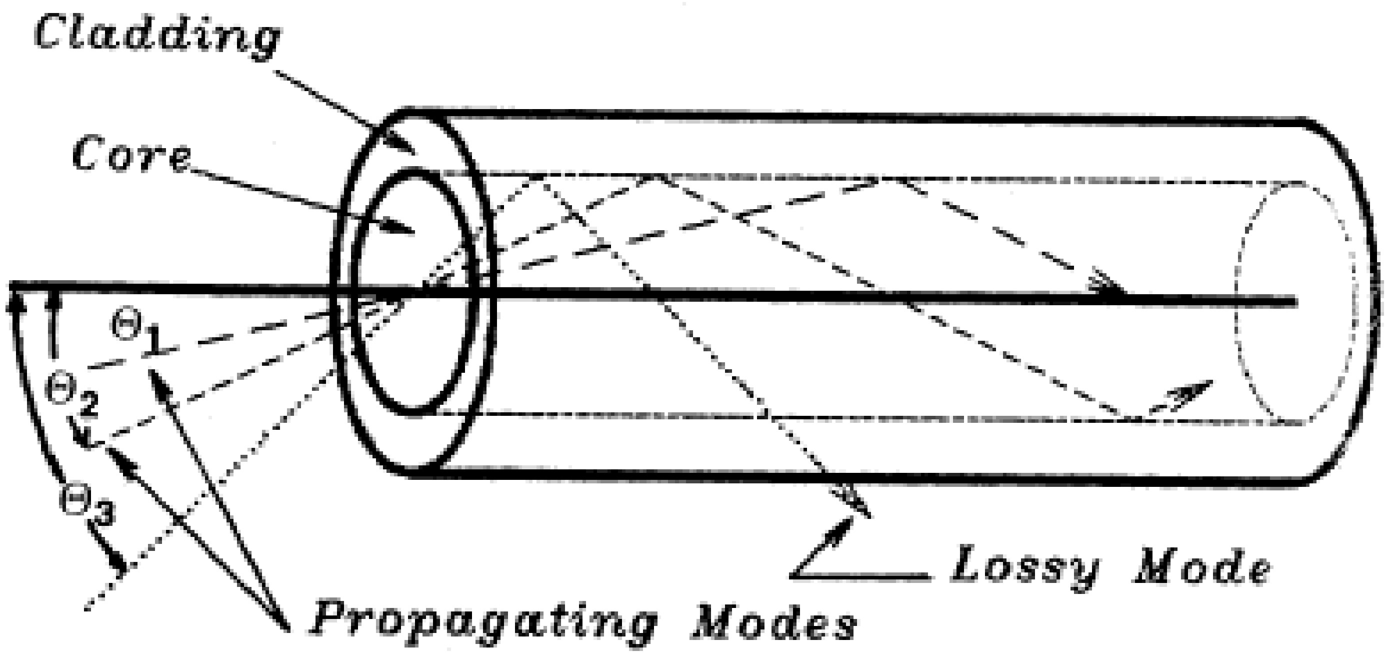


Fig. 1 A typical step index cylindrical fiber is shown with the axis indicated by the solid line. Modes are plane waves incident at a particular angle to the fiber axis. Several incident modes are shown with the dashed lines.

Courtesy SAO/NASA Astrophysics Data System (ADS) "Focal ratio degradation in optical fibers of astronomical interest" Ramsey, L. W. 1998ASPC...3...26R

Fiber-Optic Head – Fiber Cable

To review:

- The multimode fiber-optic cable NA value is 0.22
- The equation that converts the NA value to the optimum light cone f-ratio is: 1/(2*NA)

Therefore:

- For the cable I am using, the optimum f-ratio is f/2.27
- The focal ratios of my astrograph are f/7.5 when using my refractor and f/8.0 for my Ritchey-Chrétien Cassegrain
- The Czerny-Turner design expects > f/3
- What do we do to adapt the astrograph light cone to provide the fiber and spectrometer what they expect?

Fiber-Optic Head – Adjusting FR

In this case, I used 0.5x focal reducer to change the FR from F/8 or F/7.5 down to F/4 or F/3.75, respectively

Fiber-Optic Head – Adjusting FR

- The focal reducer changes the astrograph’s effective focal ratio by a factor of 0.5. This provides the required light cone into the fiber-optic cable to minimize losses caused by FRD
- Adding the focal reducer also shortens the distance from the mirror to the fiber-optic SMA connector so that it is less than the distance from the CCD camera to the mirror
- It is critical to calculate these distances to bring the light to focus at the fiber and on the focal plane of the camera simultaneously
- The result is the CCD camera is imaging at F/8 or F/7.5, and the fiber is imaging at F/4 or F/3.75, respectively

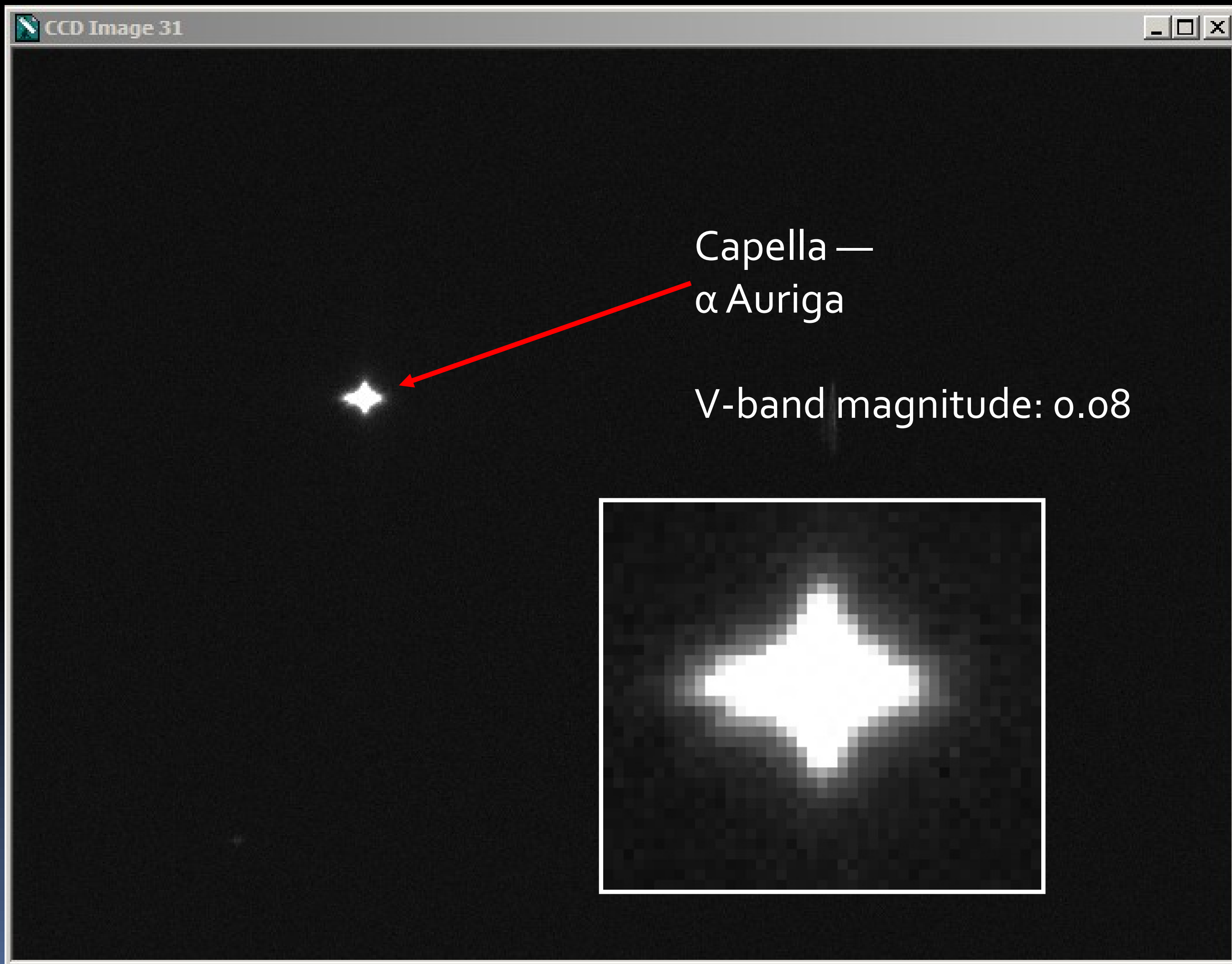
Engineering the Auto-Guider

- The CCD camera receiving the infrared (IR) image of the object under study, typically a star, is the source for real-time data to feed the auto-guiding software
- The auto-guiding software allows you to select a bright object in the frame, and it calculates the center of the object using the centroid calculation
- Once you tell the software to “lock on” to a calculated position, it sends commands to your mount’s auto-guiding port to move the mount in Right Ascension and Declination to keep the object as close to the initial calculated coordinates as possible
- Being able to guide on the IR signal while the visible wavelengths are feeding through fiber-optic cable is a real benefit and simplifies your work

Object Alignment – Focusing

- When initially imaging a bright star, Capella for example, I made the assumption that I had performed the calculations for the distances correctly so that when I focused the star, it would be smaller than the size of the fiber
- Typically when doing deep sky images, for example, a star image with 3–4 arcseconds of seeing, the FWHM of the star image would cover an area 3–4 pixels in diameter
- Because each pixel on my camera is 5.4 microns square, the star would cover an area of about 20 microns in diameter at FWHM
- Because the size of the fiber is 500 microns, it should be fairly easy to keep the star on the fiber end since the fiber is basically 25 times bigger in diameter than a focused star
- In reality, the star focused in the IR and distorted by the cold mirror is probably closer to 200 microns in diameter. This is equivalent to about 45 arcseconds in diameter

Object Alignment – Focusing



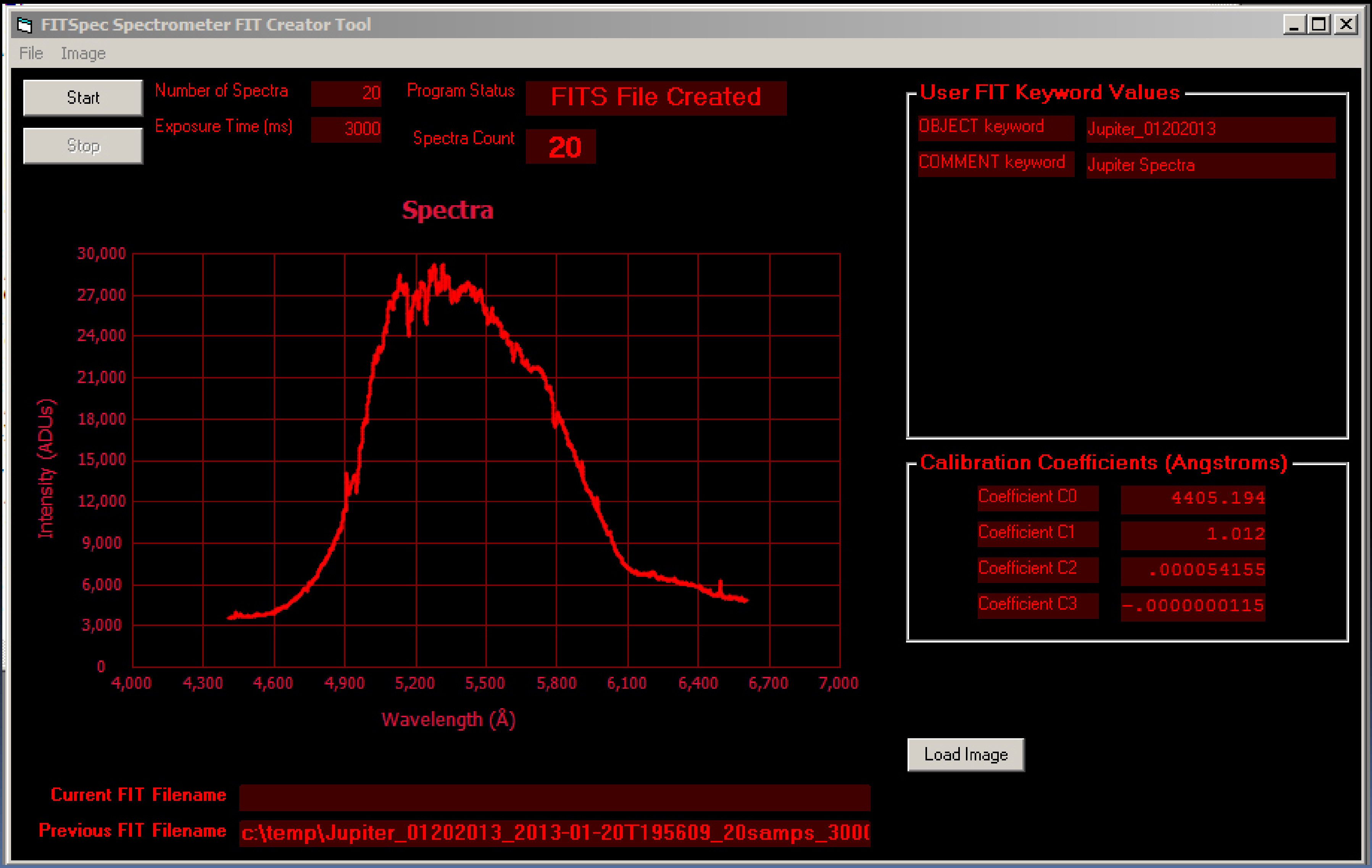
Object Alignment

- Initially, the flip mirror was aligned pretty well to center the object, but there is an offset owing to the refraction of the IR light passing through the 45° angled piece of glass
- Through a trial-and-error process of moving the star image around the CCD and monitoring the real-time output of the spectrometer, I finally located the CCD pixel coordinates that matched the location of the fiber
- The CCD chip is 1391 x 1039, and when used in the Bin x2 mode is 695 x 519
- The pixel location I finally settled on was 200 x 200 ±10 pixels

Auto-Guiding on the Object

- The intent was to start auto-guiding on the star once it was placed in the correct spot to feed light into the fiber-optic cable
- However, because my mount's periodic error (PE) was less than the size of the star image on the CCD, my mount's tracking was good enough to keep the star on the fiber. I always have the option to auto-guide if necessary
- The focusing may have been off some, so depending on the object, auto-guiding may become necessary
- Auto-guiding is absolutely necessary if you want to take a series of exposures with the spectrometer over a 30– to 60–minute period— auto-guiding will compensate for a small declination drift caused by a not quite perfect polar alignment of your mount

Acquiring the Spectral Data



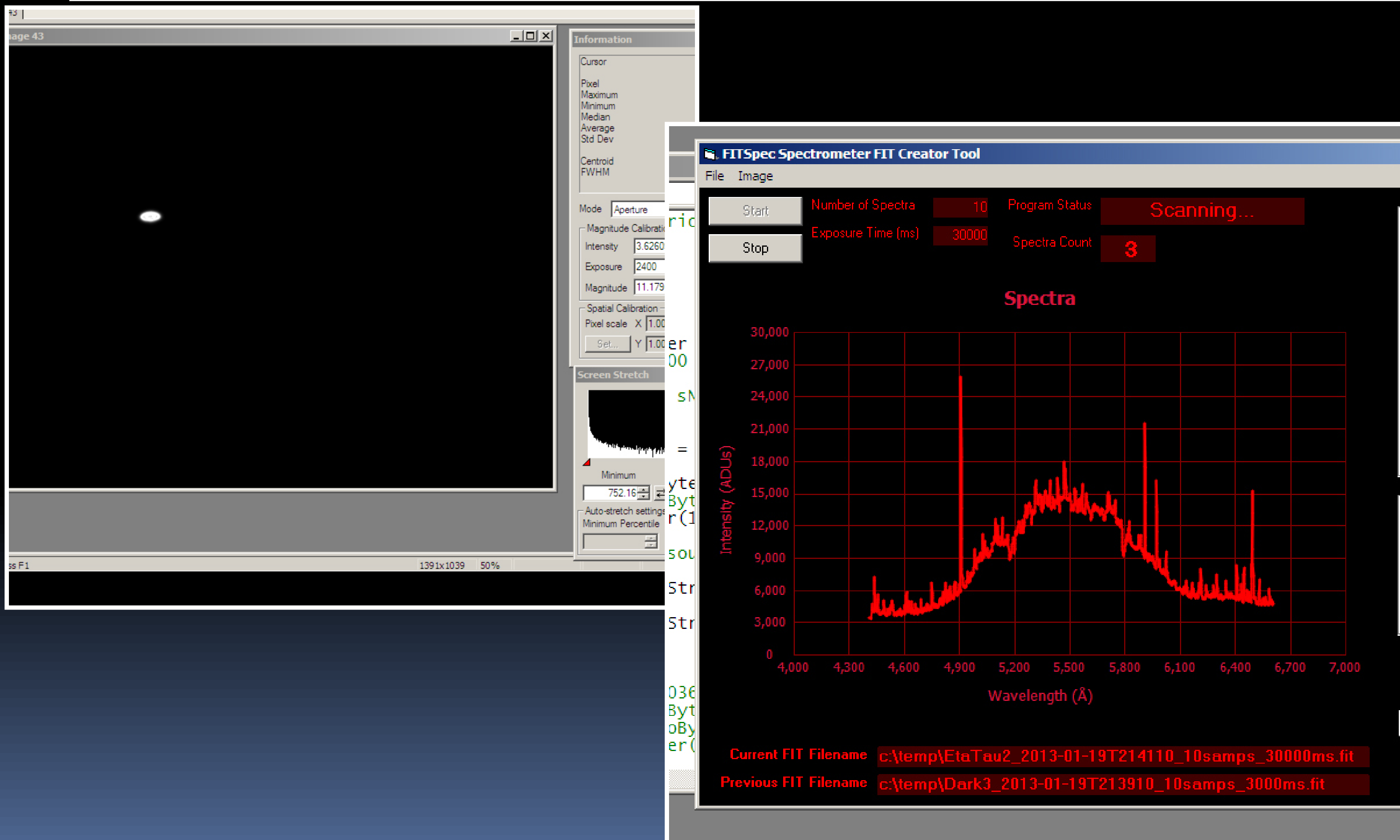
Spectrometer Specifications

- The Science-Surplus Spectrometer is delivered as a DIY kit—the user must align the optical bench to make sure it covers the spectral wavelengths desired
- The Sony ILX511 linear CCD chip is a 2048-pixel chip. The pixel size is 14 microns x 200 microns with a 14-micron pitch. It is sensitive from below 4000Å to above 9000Å. The peak sensitivity is 4500Å
- The spectrometer comes with its own data acquisition software and communicates over a serial connection to the computer. The documentation includes basic operation and alignment of the optical bench, and also the serial command language useful in creating your own software
- I wrote my own software to acquire the data in the way I wanted it formatted so that I could store the data in the FITS file format as an image file

Spectrometer Performance

- The controller on the spectrometer puts certain limits on its operation—the main limit involves the data acquisition parameters
- The spectrometer can only be set to take exposures from 50 milliseconds to 64,000 milliseconds
- Typically spectral data takes a long time to acquire because you are spreading out the light across the CCD, and consequently, the photons are diluted by a factor of 250 to 500. This is equivalent to about 6 or 7 magnitudes in brightness
- What this means is that if we typically can image 12th magnitude stars in 60 seconds with a signal-to-noise ratio (SNR) of 100, then we would only be able to acquire the spectrum (peak value) of a 6th magnitude star. If we want the spectral range of 5000Å to 6000Å to have an SNR of at least 100, then we would be limited to 4th or 5th magnitude stars

Spectrometer Data Acquisition



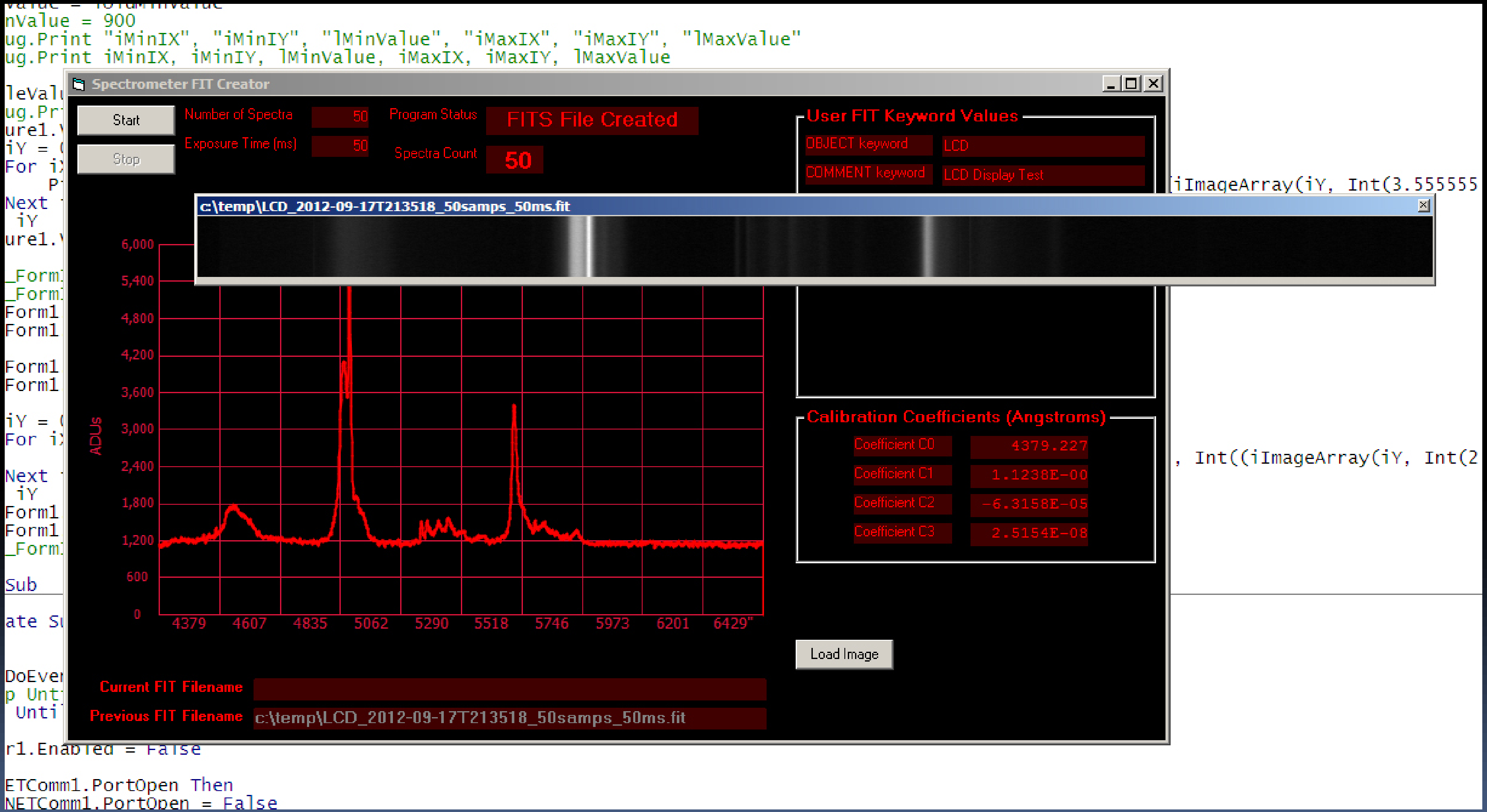
Spectrometer Data Acquisition

- The software I have developed allows me to set the spectrometer's data acquisition parameters (exposure time, number of spectra, filename to store data) and compiles the data into a 3D array stored using the FITS data file format
- The data is presented as a 2D image file, with each row in the image a complete 2,048 element spectrum—the X-axis representing the wavelength of the spectrum
- The Y-axis represents the time axis, with time zero at the top of the image and each row representing a certain exposure time, typically 60 seconds. So 10 rows would represent 10 total data acquisition times
- The data is acquired in 16-bit format, so the amplitude of the spectrum is a value from 0–65,535 counts or ADUs
- The data acquired is the raw values from the linear CCD chip and has several systematic errors that must be removed. Among these are the Thermal Noise, Hot Pixels, and Readout Noise. All these must be removed before calibration is performed

Spectrum Calibration

- The wavelength axis must be calibrated using a reference source
- I have used a fluorescent light source as a calibration source because it has peaks in the Blue, Green, and Red wavelength regions. I have also used the solar spectrum with its associated Balmer Lines as a calibration source
- The procedure is to measure the peak pixel location for a given spectral line, and using at least 3 pixel–wavelength pairs, perform a 2nd or 3rd order polynomial fit to apply to the data
- Once the polynomial is applied to the raw data, then the identification of peaks can begin

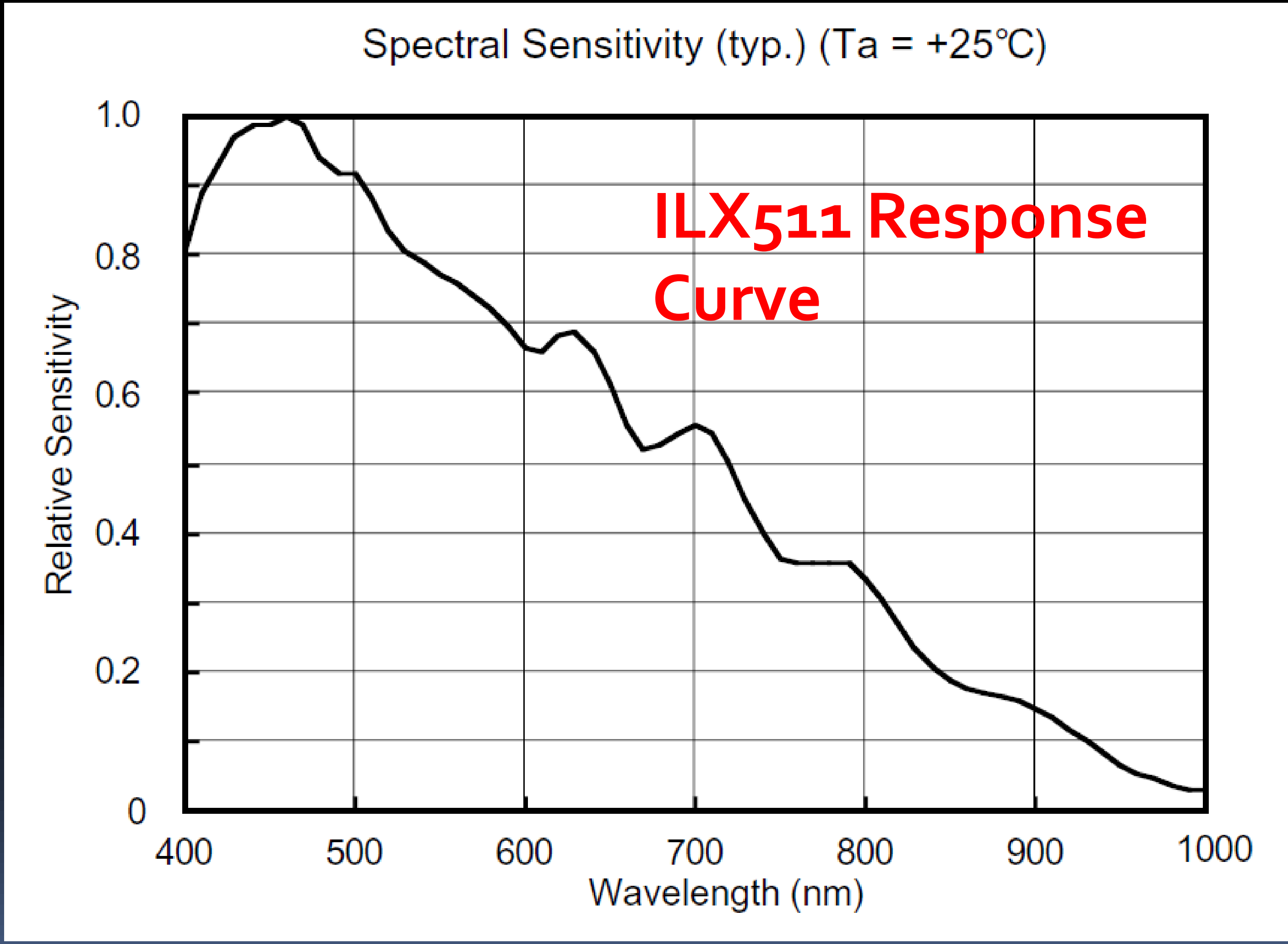
Spectrum Calibration



Calibration and Normalization

- I use another spectrum analysis software—RSpec—for the final processing (Calibration and CCD Response Curve Normalization)
- RSpec was written by Tom Field of Field Tested Software, LLC
- If you recall, Tom gave a talk over the Internet last year in January about spectroscopy
- RSpec has several functions that make it easy to calibrate and normalize your raw spectroscopy data
- CCD Response Curve Normalization is a process where you normalize your raw curve to the response of the CCD. CCD responses are non-linear over the wavelength band, which means that the CCD is more sensitive at some wavelengths and not so sensitive at others

CCD Response Curve

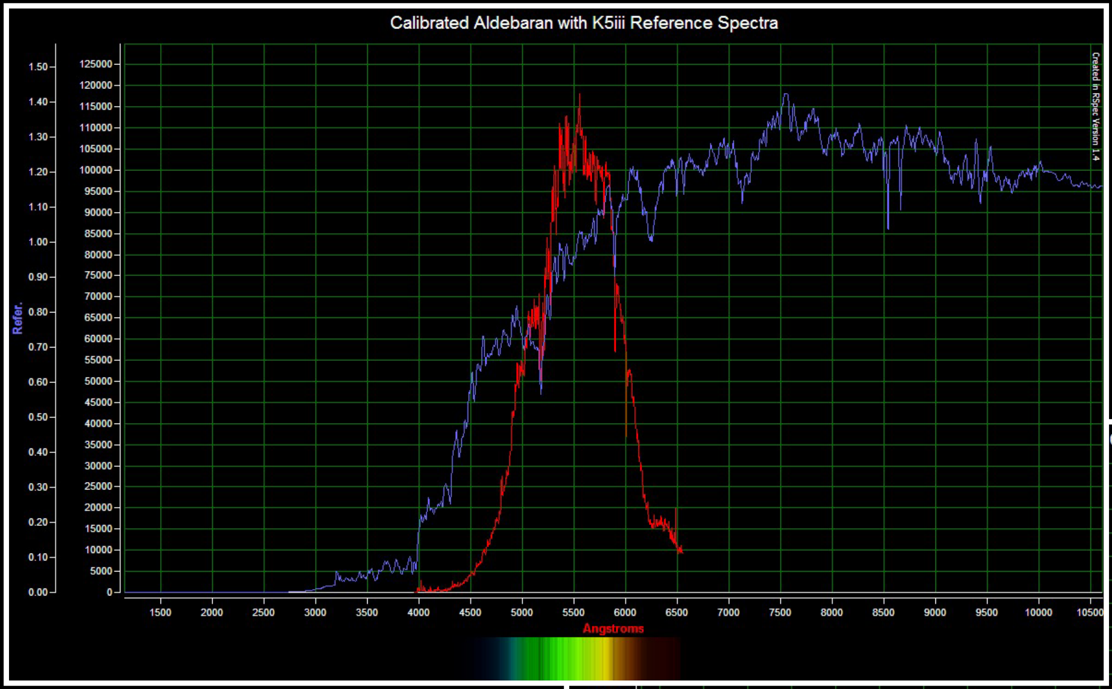


Courtesy Sony - ILX511 Datasheet

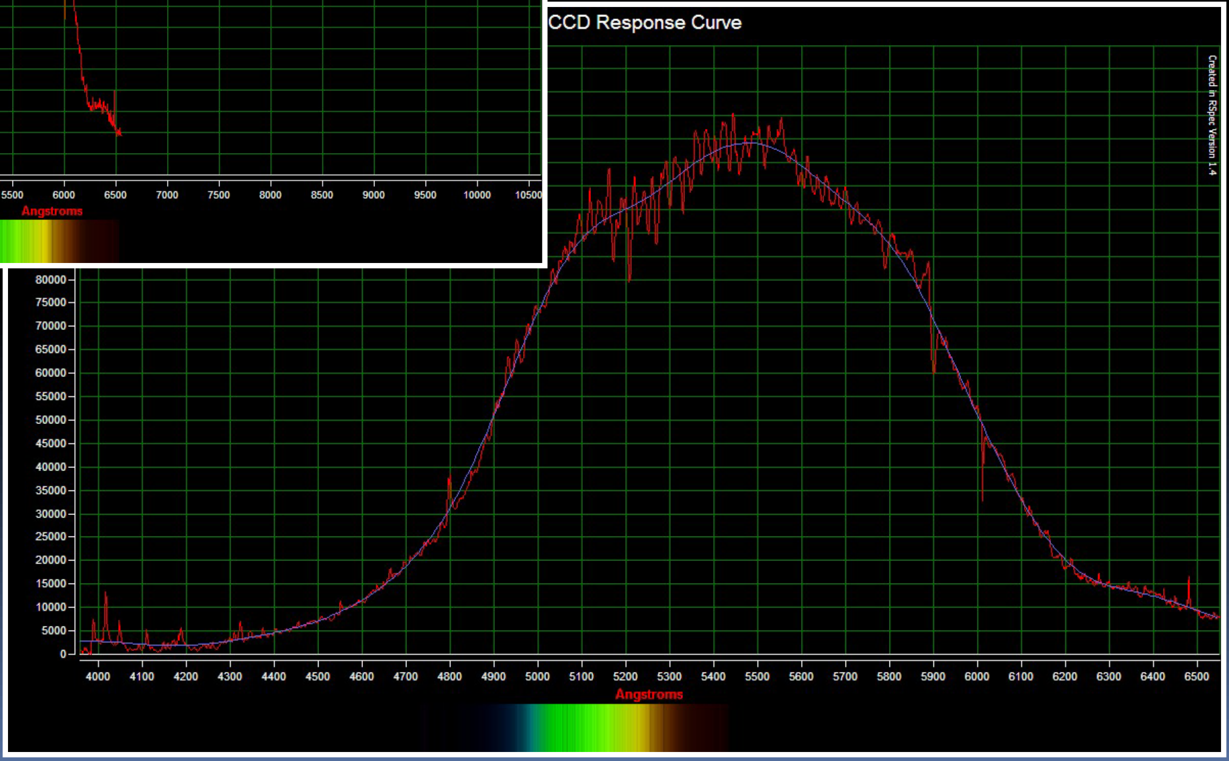
CCD Response Curve Generation

- The procedure to generate a CCD response curve is very straightforward
- All that is necessary is to acquire the spectrum of a given star of a known spectral type
- Then, after doing dark subtraction of the raw data, divide the dark subtracted data by a reference spectrum of the same star spectral type
- What this leaves you with (as a residual) is the CCD response curve that affected the original data

CCD Response Curve Generation



Red Curve / Blue Curve

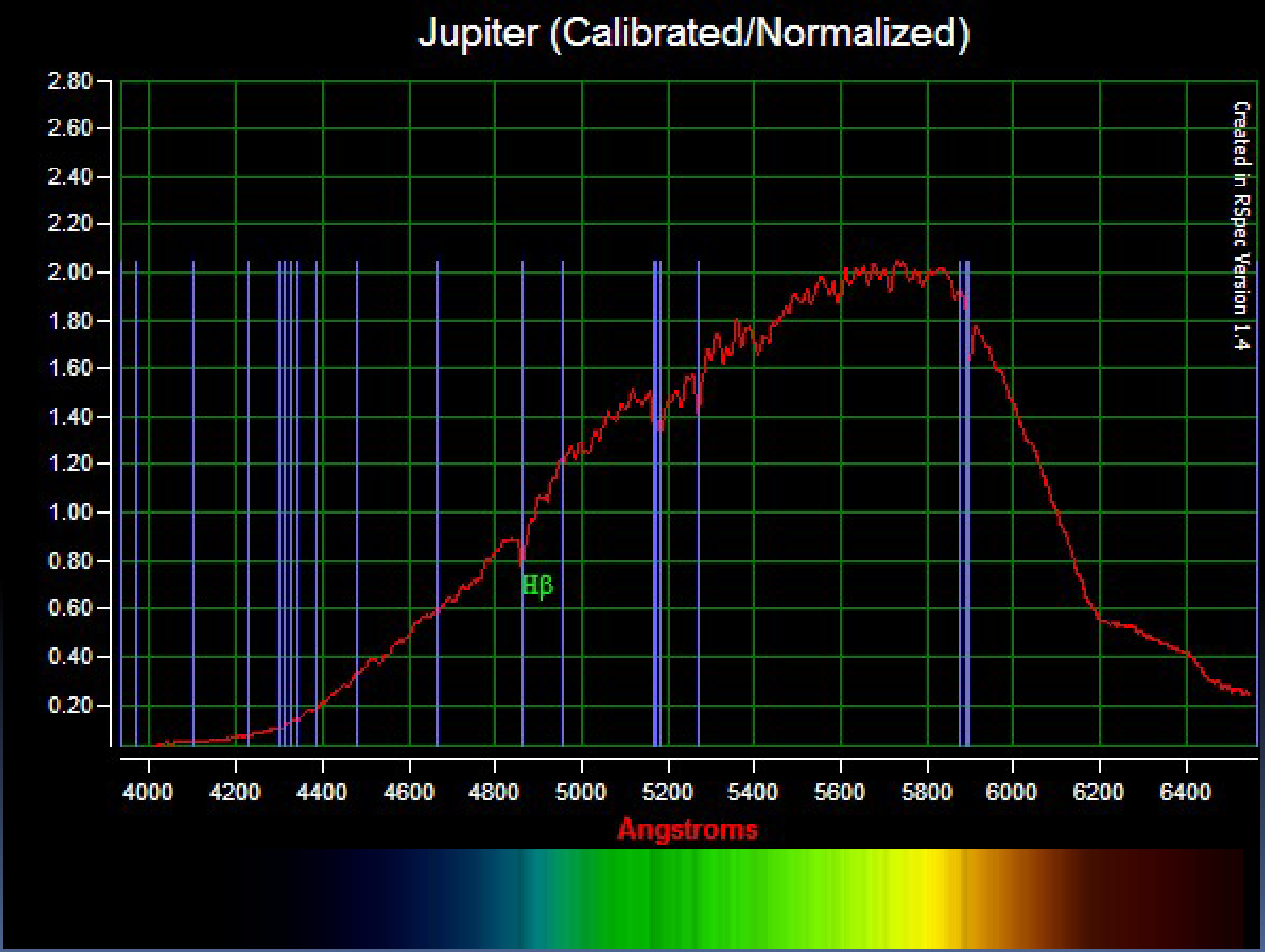


α Tau vs. K5iii

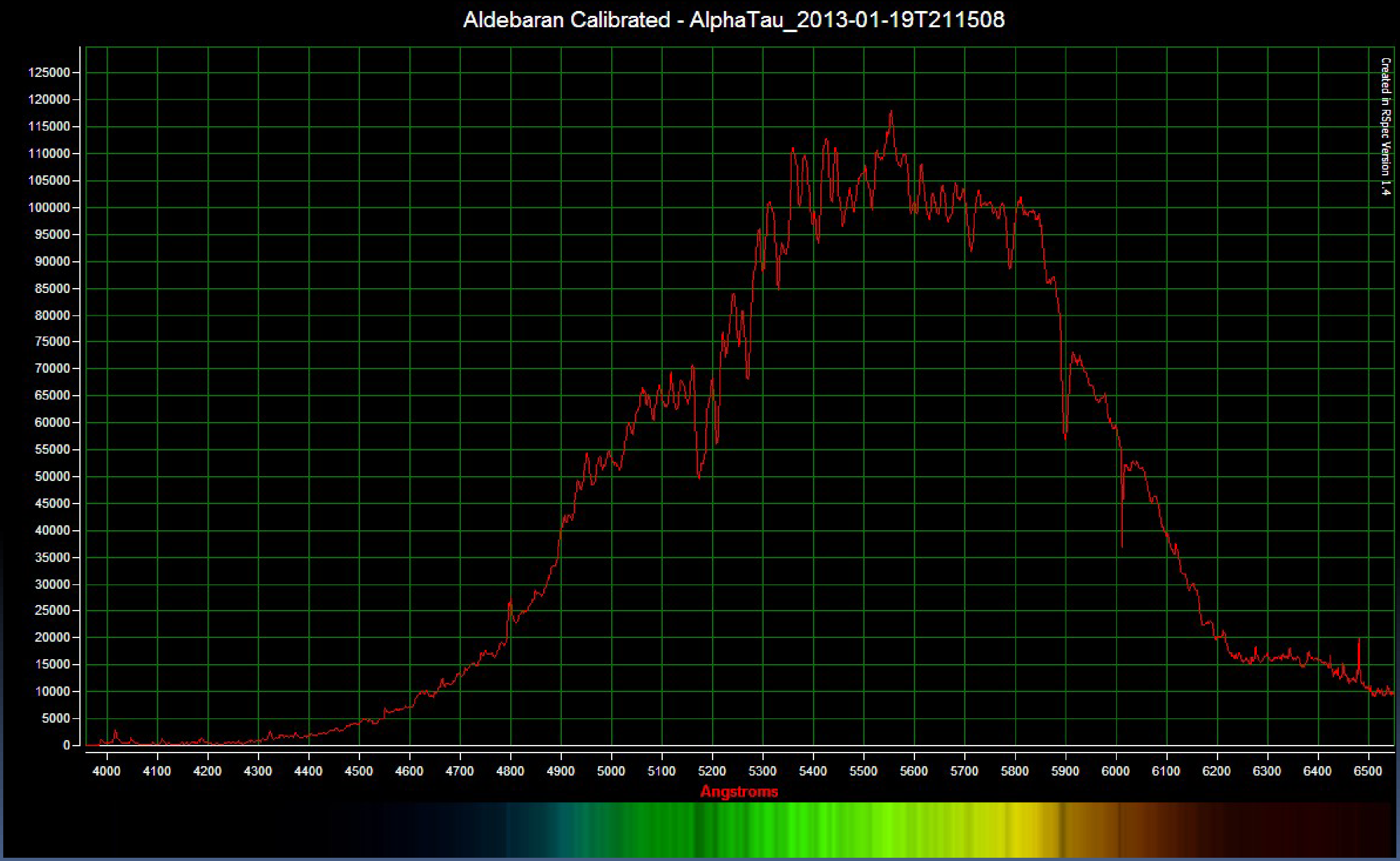
Results

- I started this project in August 2012 and have been working on it off and on since then. A large part of the work was software development done while waiting for various parts to arrive
- I had hoped to have more results to demonstrate thus far, but the time to integrate the system has taken longer than expected
- I have measured the light from the Sun, Moon, Jupiter, and various stars such as Alpha Tau, Eta Tau, Alpha Ari, Alpha Gem, and Alpha And

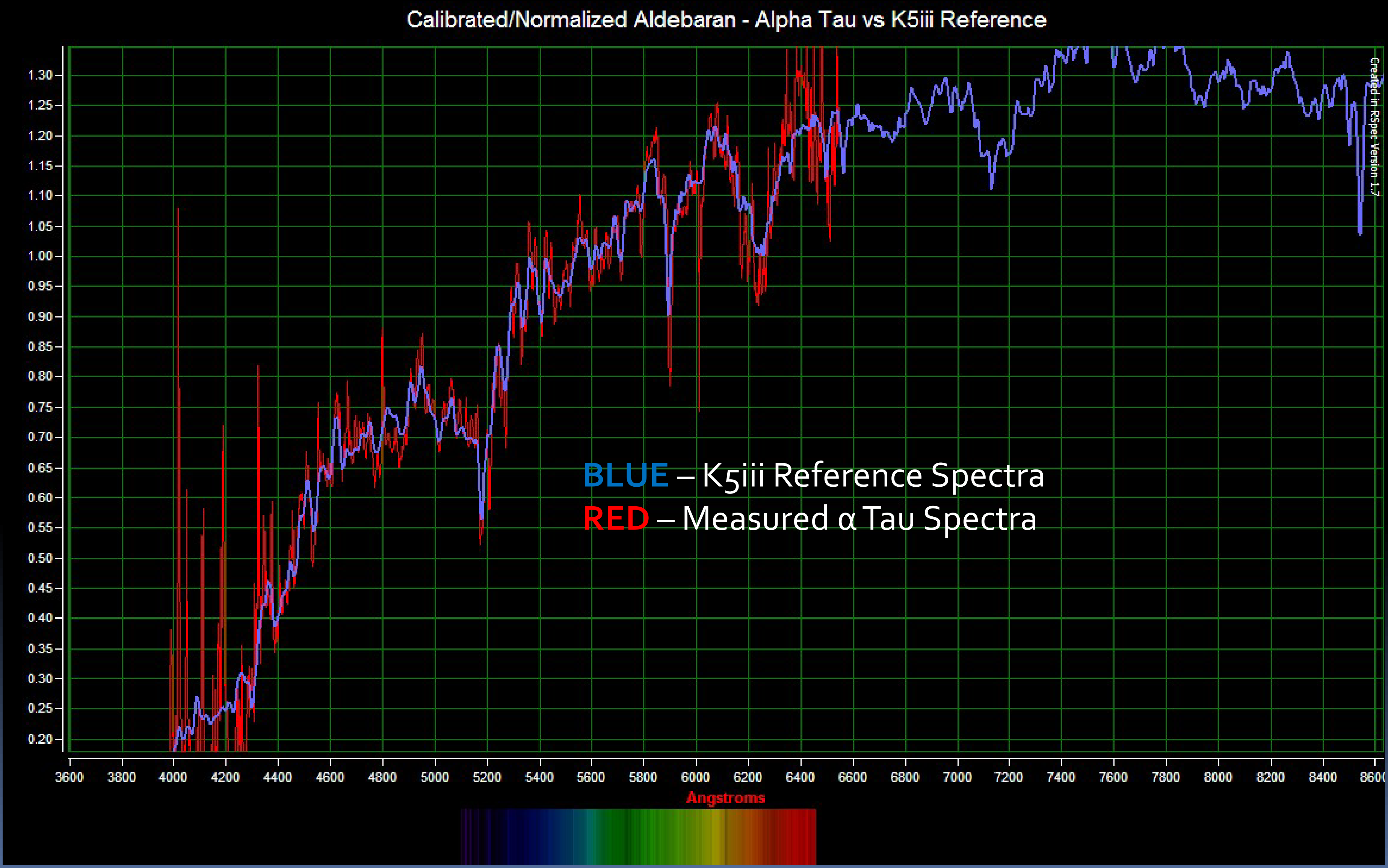
Results – Jupiter



Results – Aldebaran



Results – Aldebaran



Parts List

- Science-Surplus Spectrometer—$200
- Orion Flip Mirror—$170
- Edmund Optical Cold Mirror—$50
- Fiber-Optic Cable Adapter (SMA) —$80
- ATIK 314e CCD Camera—$1,300 (other cameras can be substituted, of course!)
- Time Invested—Probably 250–300 hours

Questions?