ASTR 304 -- Advanced Experimental Techniques
Spring 2019 (McLeod)
Spectrometer Project Final Report

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Introduction

Students in the Wellesley College Astronomy Department have not had an opportunity to take and analyze spectra for more than 20 years, as there has not been room in the curriculum for doing so. However, the Department is purchasing a new telescope to replace the 24” Sawyer research telescope, and we view this as an opportunity to bring the capability for spectroscopy back to the Whitin Observatory. The new instrument will be a Planewave CDK700, which has a 0.7m primary mirror and an effective f/6.5 beam, and whose dual Nasmyth ports will allow us to simultaneously mount our imaging CCD on one side and a spectrograph on the other side.

In this course, we aimed to design and build a spectrometer for our new telescope. We aimed to design a low-cost system that could be mounted in place of the eyepiece at the second Naysmith port and cover the range ~ 400-700nm in one shot with a resolution of R~1000.
Our final design is a fiber-fed spectrometer with an effective “slit” width that projects to 4.5” on the sky. We will achieve full spectral coverage with a 600 line/mm grating at R~500 (“low resolution”, or 1.2nm @600nm). Our design allows us to swap in a 1200 line/mm grating to achieve R~1000 (“moderate resolution”, or 0.6nm @600nm) at the expense of spectral coverage. In the future it might also be possible to replace the fibers with smaller-core ones to increase the resolution over the full range.

Using our spectrometer, we hope that Wellesley students will be able to observe objects both inside and outside our Solar System. Among the projects we might like to tackle:

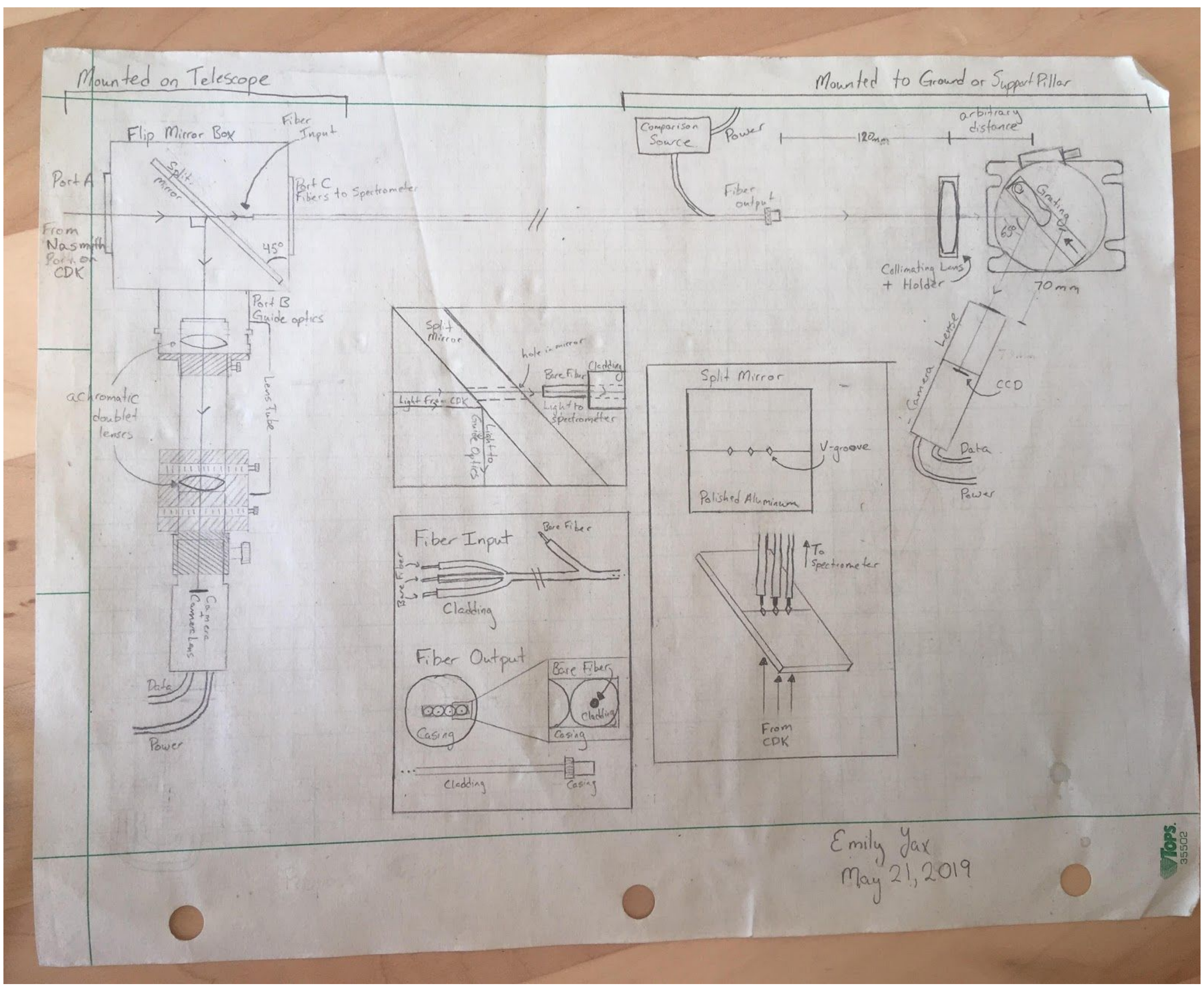
- Spectral types of OBAFGKM stars like Annie Jump Cannon, Wellesley Class of 1884 (ASTR 107, Introductory Astronomy) -- desired spectral coverage 400-700nm, low resolution is fine (and better than AJC had!)
- Atmospheric composition and rotation of the planets in our Solar System (ASTR 223, Planetary Atmospheres and Climates) -- R~500 will put ~20 resolution elements across the methane bands; R~1000 will yield Jupiter’s rotation rate if we can centroid lines to ~1/4th of their FWHM
- Rotation curves for nearby bright galaxies (ASTR 210, Cosmology) -- v=200 km/s corresponds to 0.4nm @600nm so the R~1000 mode could make this possible if we can centroid lines to better than their FWHM
- Emission line ratios from bright nebulae (ASTR 206, Astronomical Techniques) -- the R~500 mode would allow simultaneous measurement of the H and [OIII] lines, while the higher R~1000 mode would allow us to split the [SII] lines for density determinations
- Redshifts for the brightest quasars e.g. 3C273, V~13 (ASTR 206 or 210) -- easily done with even the R~500 mode

In the sections below we describe our design for the spectrometer, the guide system, and the analysis software. Our design was inspired by the one used by Kannapan, Fabricant, and Hughes (2002 PASP 114, 577) who built a fiber-fed system for a 16” telescope at Harvard.

Design

System schematic

The sketch below shows an overview of our preliminary design. In order to decrease the strain placed on the spectrograph when the telescope is moved due to differential gravitational forces, we will not mount the bulk of our optics on the telescope itself, but on the ground or the pier for the telescope instead, and use optical fibers to transmit light from the telescope to the spectrometer. This allows us more freedom to make the spectrometer whatever size is necessary, as we would not be constrained by its own weight, the weight of the CCD, or the size of the layout needed, as well as giving future observers the option to quickly and easily switch out the grating. This option is based on this paper by [Kannappan et al](), who built a fiber optic telescope for Harvard's Knowles telescope in the early 2000s. Kannappan noted several advantages to this design, including easy access to the optical components, for cleaning or for instructional purposes.



Guide system

Optical Design

To acquire and track a target object for observation, our setup requires the use of a guide camera system. The guide camera provides a 4.2’ x 2.4’ FOV centered around the spectrograph fiber assembly entrance.

Figure 2 provides a schematic of the guide camera assembly. The guide camera system connects through a Meade flip mirror system (1). Light enters the assembly through Port A (13) which will be connected to a Naysmith port of the CDK. Some of this light will hit the optical fibers which protrude through the center of the mirror. The optical fiber cable then extends out of Port C (14). The light hitting the mirror which does not fall on the optical fiber array is reflected out of Port B (2) and into the guide camera optics.

The light enters the 1” lens tube (5) which is placed so that the male end of the tube is 3.5 cm away from the mirror. This puts the first achromatic doublet lens (4a), which sits 2.3 cm from the male end of the lens tube, 5.8 cm away from the focal plane of the mirror, which is near its focal length of 60mm (we focused by testing on an 8” Meade telescope, described below). The diameter of the beam of light as it reaches the first lens is approximately 9.23 mm across, which is significantly less than the diameter of the lens itself, around 25.4 mm across. The calculations for the size of the beam’s diameter are shown below in Figure 1. The lens tube is placed so that it does not need to be moved in the 2” to 1” adapter; instead adjustments to the focus of the first lens (4a) should be made with the threaded 2” rings on Port B. The lens tube is stabilized using 1 mm thick strip of rubber (7) that must be placed opposite the set screw of the 2” to 1” adapter (3).

Inside the 1” diameter tube are the two achromatic doublet lenses. These lenses are plano-convex, meaning one side of the lens is flat while the other side is convex. Light collected by the CDK arrives at the flip mirror focused, since it has been placed at the CDK’s focal point. The light is then diverging when it comes off of the mirror and goes into the lens tube assembly. The light enters the flat side of the first lens and comes out of the convex side of the lens as collimated light. The collimated light then enters the convex side of the second lens so that when it leaves the flat side of the second lens it is converging, where it will focus ~6 cm away, onto the CMOS camera detector (12). Because the light is collimated when it reaches the second lens, the distance between the two lenses does not change the image. The 1” lens tube must then be adapted to fit onto the 1.25” CMOS camera port, which is accomplished by attaching a 1” to 1.25” adapter (11) onto the other end of the lens tube. The distance of the second lens to the CMOS must match the focal length of the lens. The second lens (4b) sits 4.7 cm away from the end of the 1” end of the 1” to 1.25” adapter (11). This placement allows the CMOS to be moved in either direction in the 1.25” holder (11) to sit at the focal plane of the second lens (4b).

The connection was not perfect, however, so a connector had to be fashioned out of PVC pipe (9), a thin rubber strip (10), two hose clamps (8), and electrical tape. The 1.25” adapter (10) is placed onto the end of the 1” lens tube (5) with electrical tape securing the two ends together to ensure that no outside light is entering the system. A 2 ⅜” long section of PVC pipe with 1 ⅝” internal diameter was cut and then a ¼” section was removed for adjustability. Two 1mm rubber strips (7,10) were cut for the ends of the lens tube and eyepiece adapter to shim the spacing and secure the connection between the tubes and the PVC. Two hose clamps were tightened around each end of the PVC tube to secure the two tubes together. The ZWO ASI guide camera (12) is placed into the 1” to 1.25” adapter (10) at the focal distance of the second lens, about halfway into the 1.25” adapter to allow room to adjust and focus the camera. The guide camera can then be connected via USB to a computer so that the target can be properly guided down the ends of the fibers.

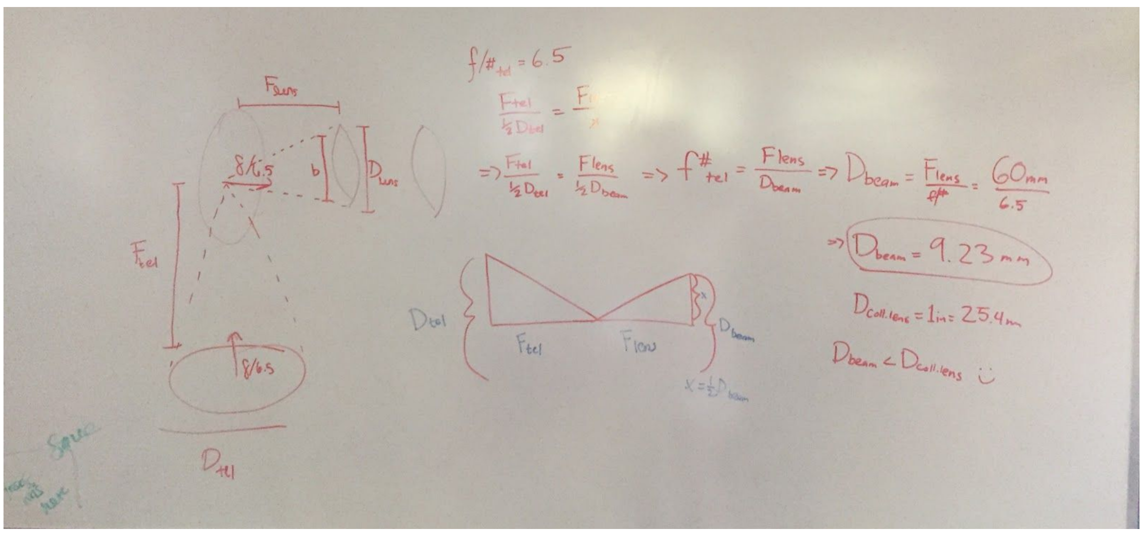


Figure 1: Shows calculation of beam diameter using similar triangles method. Concluded that beam size of light is less than diameter of lens.

Guide camera

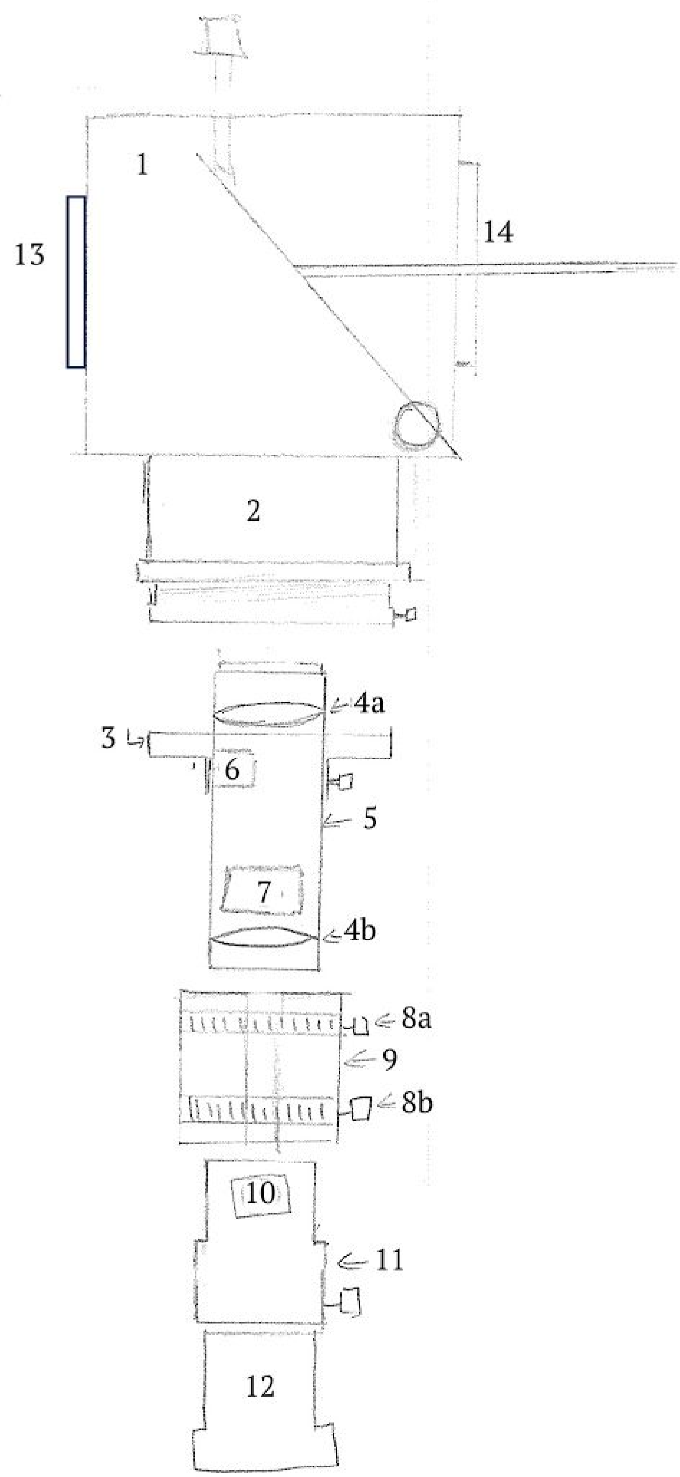
The Guide Camera being used is "ZWO ASI290MM Mini Monochrome Astronomy Camera." Information about the camera can be found at:
https://www.highpointscientific.com/zwo-asi290mm-mini-monochrome-astronomy-camera-asi290mini

- Pixel Scale: 2.9 x 2.9 µm, or 0.13 arcseconds at the focal plane of the CDK
- FOV: 4.2’ x 2.4’ (1936 x 1096 pix)
- Read Noise: 3.1 e-
- Quantum Efficiency: ~60%

Meade Test

The design setup was tested on one of the Meade telescopes to ensure that the lenses were placed at the proper distance and that an image could be formed using our setup. We focused the telescope onto a flag approximately 30 arcseconds across. A link to a video of the flag waving in the wind can be found below. The guide camera system was then connected to the eyepiece of the telescope and minor adjustments of each component were performed until they were at the proper focal distance and a clear image could be formed. The guide camera was then connected to the adapter and plugged into a PC computer to test the positioning of the individual components and to see if a clear image could be obtained using the entire setup. We tested the design on the finial of the flagpole and after minor adjustments, achieved a clear image. A test of a nighttime target later this week will complete the quality assessment of the guide optics system.

Link to movie of daytime Meade test--waving flag.



Guide Assembly Schematic

1. Meade Flip Mirror Box
2. Port B with 2 1/16” threaded opening and set screw
3. 2” to 1” adapter with set screw
4. (a,b) 1” achromatic doublet lens
5. 10cm long 1” lens tube
6. 1mm thick rubber to shim lens tube into adapter (3)
7. 1mm thick rubber to shim lens tube into connector assembly
8. (a,b) 1 ½” hose clamp
9. 2 ⅝” PVC
10. 1mm thick rubber to shim eyepiece adapter into connector assembly
11. 1” to 1 ¼” Meade eyepiece adapter
12. ZWO ASI Guide Camera
13. Port A connected to Naysmith mount on CDK
14. Port C

Figure 2: Guide optics assembly schematic that shows each component of the system.

Guide Assembly Photos

Figure 3: Guide assembly attachment with lens tube, 1” to 1.25” adapter, and PVC connection. Meade flip mirror system and guide camera not shown.

Figure 4: Guide camera assembly with Meade flip mirror system attached. Guide camera not shown.

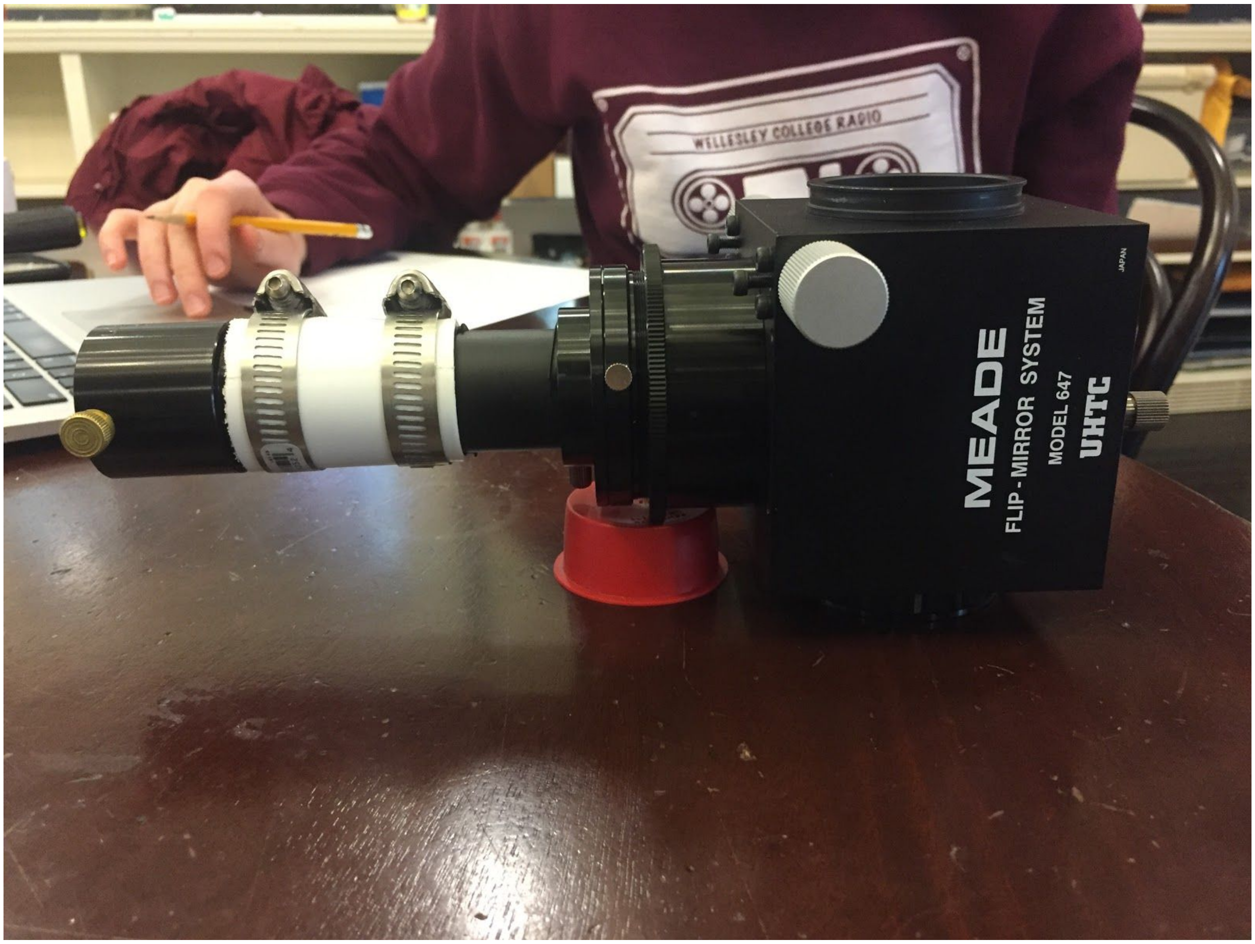


Figure 5: Guide camera system with Meade flip mirror system (side view). Guide camera not shown. Featuring Robin Siddall.

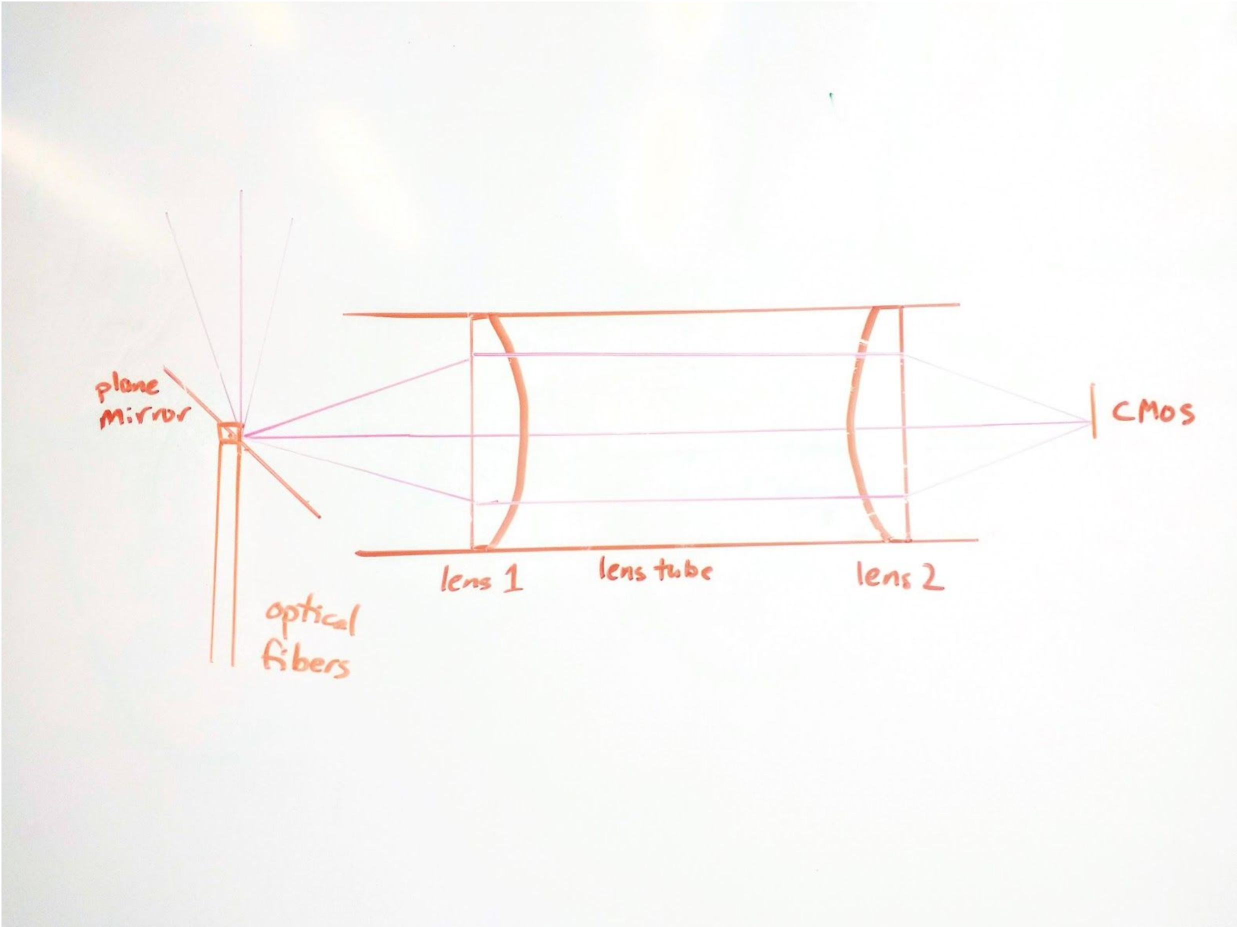


Figure 6: Lens tube Optical Assembly

Fiber train

Spectrometer

We designed our spreadsheet based on a Low Resolution Spectrometer spreadsheet created by Dr. Dan Fabricant. By inputting the basic info about the telescope, input beam, CCD, desired angle, central wavelength, etc., the spreadsheet produces the exact dimensions needed for the spectrometer.

In our case, we had the following input parameters. f/ in refers the light coming from the telescope, and f/ out refers to the light entering the spectrometer after it has been focal ratio degraded by the fibers. We made the decision to use a 600 grooves/mm grating, and an ATIK 414EX CCD with ~1400 pixels, each 6.45 microns across. We were able to play with the collimated beam diameter and the camera-collimator angle to get our desired result. We also chose to look for first order spectra with a central wavelength of 5000 Angstrom in the visible spectrum.

1	**Fundamentals:**						
2	telescope parameters	700.00	mm	f/ in	6.500		
3	camera-collimator angle	65.00	degrees	f/out	5.000		
4	collimated beam diameter	18.50	mm				
5	grating grooves/mm	600.00					
6	ccd specs	6.45	microns	1392.000	pixels horiz	1040.000	pixels vert
7	camera focal length	50.00	mm	1.969	inches		
8	slit width	4.5	arcsec	100.000	microns		
9	order	1.00					
10	central wavelength	5500.00	angstroms				
11	desired blaze wavelength	5000.00	angstroms				

From this input data, we received the following outputs:

12									
13	**Calculated Quantities:**								
14	scale	22.06	microns/arcsec						
15	collimator focal length	120.25	mm		Gm * lambda	0.330			
16	angle of incidence	43.78	degrees		deg/rad	57.296			
17	angle of diffraction	21.22	degrees		(pos = opp sides grat norm)				
18	anamorphic magnification	1.29							
19	grating length	25.62	mm						
20	blaze angle (central wave)	11.28	degrees		Gm * lambda	0.300			
21	blaze angle (desired)	10.35	degrees		23.074	diff ang			
22	reduction factor	2.41							
23	scale at CCD	0.70	arcsec/pix						
24	spatial sampling	1.42	pixels/arcsec						
25	spectral sampling	5.0	pixels/slitwidth						
26	dispersion	1.98	angstrom/pixel						
27	spectral coverage	2756.87	angstroms						
28	spectral limits	4145.35	to	6902.222	angstroms				
29	slit length	16.31	arcmin						
30									
31	resolution	9.888	angstroms						
32	resolving power	556.225							
33									
34	**Camera Parameters**								
35	CCD Width	10.18	degrees		8.978	mm	CCD Height	6.708	mm
36	CCD diagonal	12.73	degrees		11.21	mm		7.641175502	degrees
37	diffracted beam diameter	23.89	mm						
38	mono f/ (spectral)	2.09							
39	camera-grating distance	70.000	mm		2.756	inches			
40	approximate camera aperature	35.624	mm		1.403	inches			
41	camera-coll beam clear	110.416	mm						
42	camera f/	1.404							
43									

The yellow quantity, camera-grating distance is a variable input quantity that we were able to play around with to get the rest of our desired values. The key calculated quantities are highlighted in green. These include the grating length, the scale at the CCD, the spectral coverage, the resolution, the camera aperture, the camera-collimator beam clear, and the camera f/.

The grating length dictated the size of the grating we needed to purchase for the spectrometer. We chose to go oversized on the grating, to 50mm square.

The spectral coverage gives us roughly the 4000-7000 Angstrom range, covering the visible spectrum like we wanted. If we wanted to go above/below that range we still could by tilting the grating further in one direction or the other.

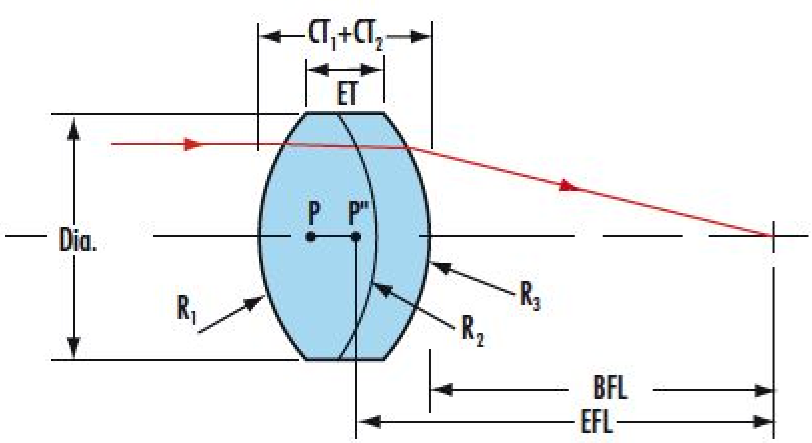
The resolution is around 550. Our original goal was to build a 1000 resolution spectrometer, but with the project's constraints we are happy to settle there, as it will still allow us to achieve most of our scientific goals.

The camera aperture, camera-collimator beam clear, and camera f/# were all quantities that we had to adjust our other parameters to accomodate for. We chose the camera lens ahead of time to be a 35mm diameter, 50mm focal length, f/1.4 Nikon lens. Therefore, the 50mm was an input in the top half of the spreadsheet, and we had to nudge the camera-grating distance, beam size, and camera-grating angle around to get the 35mm and 1.4 that we needed. The camera-collimator beam clear was also important, because if it was less than zero then the camera lens would actually be in the path of the beam leaving the collimator, blocking light from entering the grating.

Once we were happy with all of the parameters and knew that we had a spectrometer that, on paper, would work, we created layout sketches and set about ordering parts and assembling.

Collimator

The collimator is a 40mm diameter, 120mm focal length VIS-NIR coated achromatic lens from Edmund Optics.



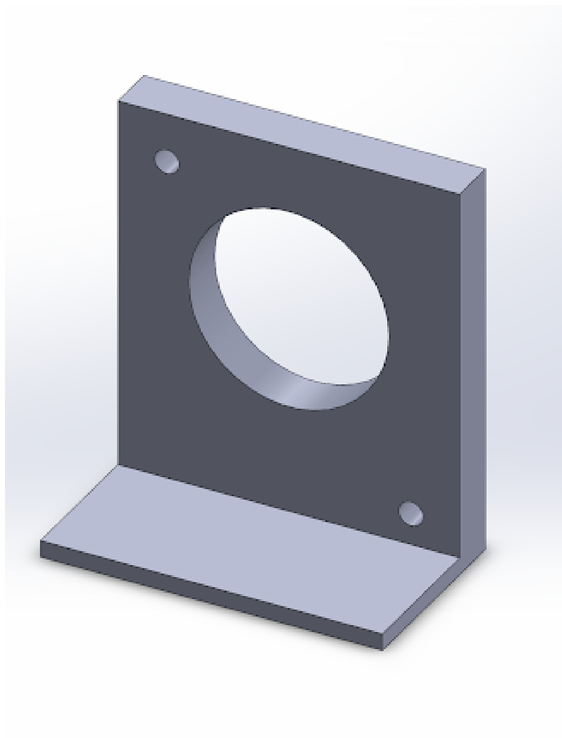
The VIS-NIR coating reduces the reflection of light in those wavelength ranges.

Light will enter the flat side of the lens on an angle, and exit the lens through the curved side collimated.

The collimator will be mounted in a custom enclosure that we will 3D print. The enclosure is made up of three pieces: the main lens holder, and two sandwich pieces that will hold the lens inside. The three pieces will be connected via 5 mm througholes.

Main Lens Holder:

3D mockup w/ main depth 10mm, base depth 40:



2D render with dimensions:

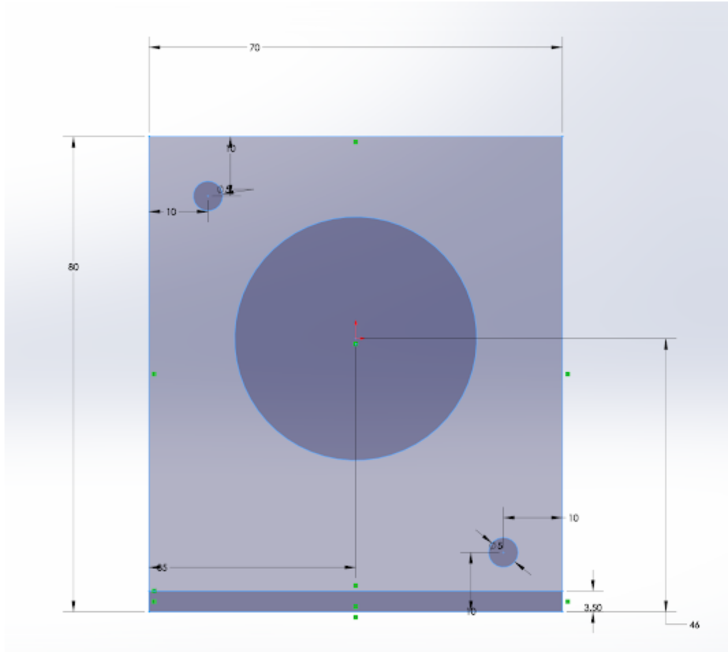
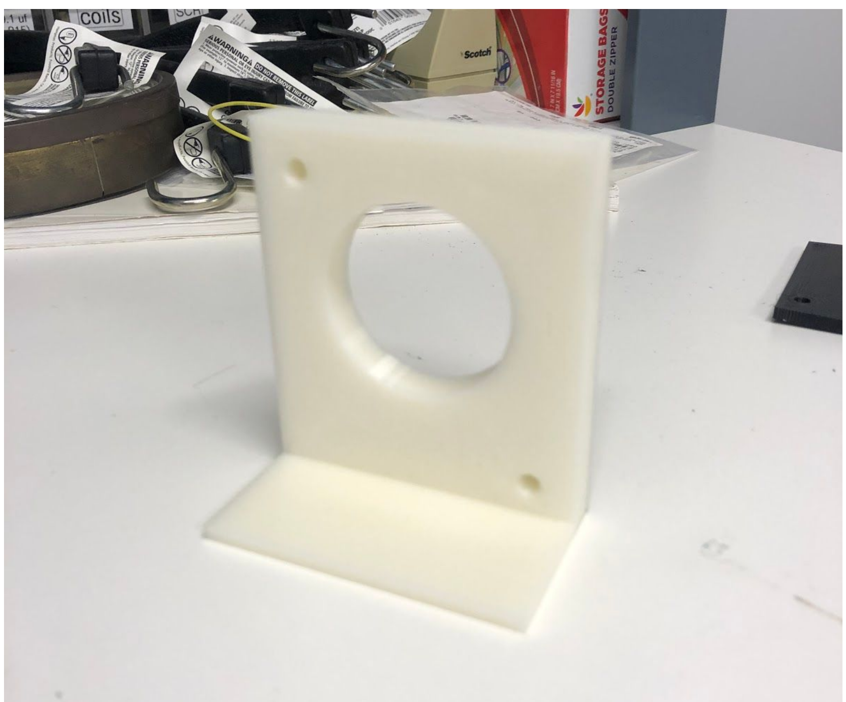
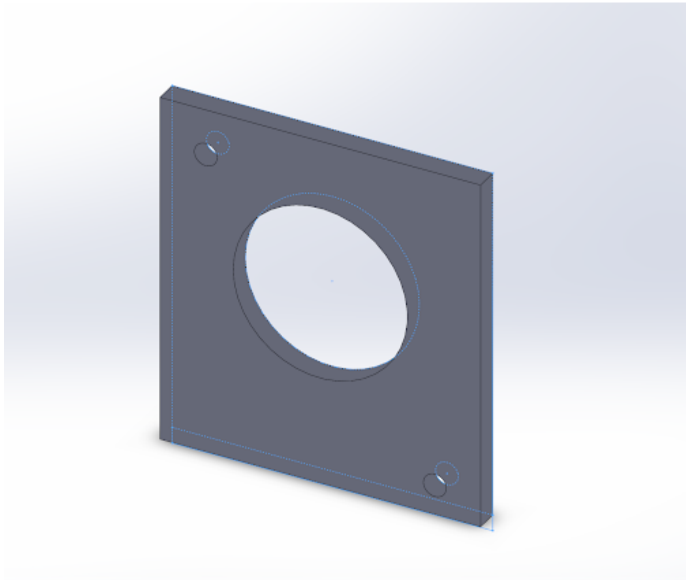


Image of the actual piece:



Outer ‘sandwich’ pieces:

3D render (depth: 5mm):



2D render:

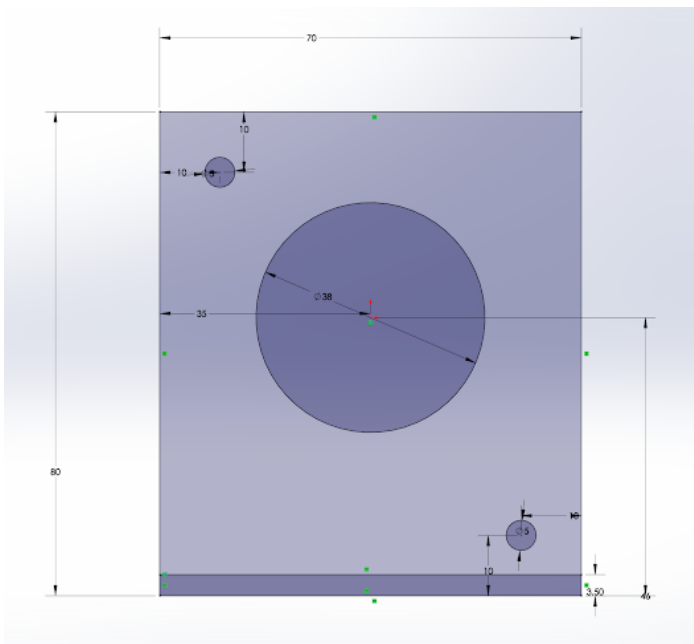
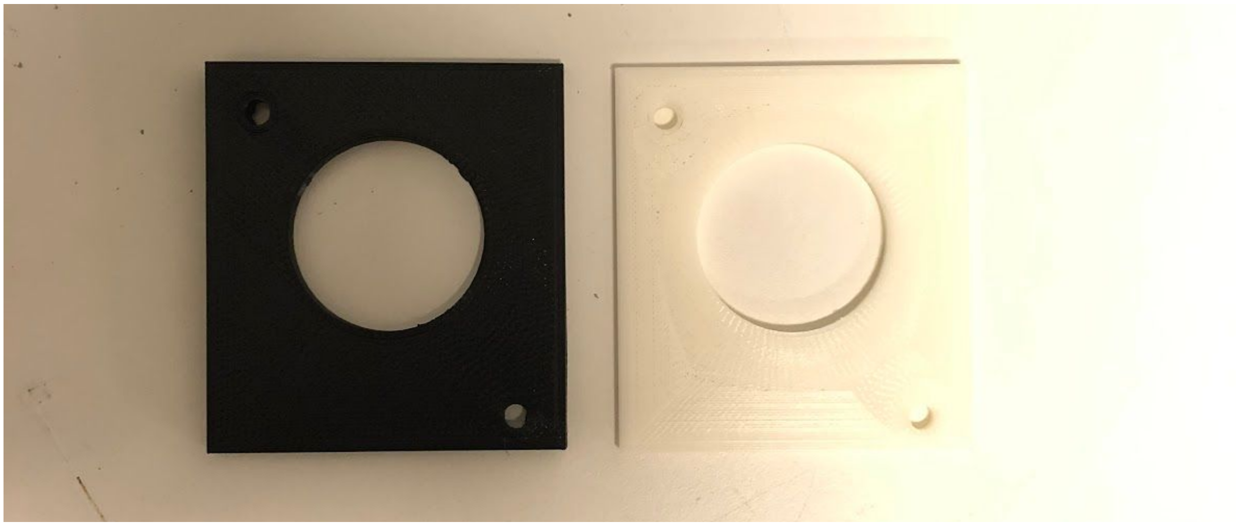
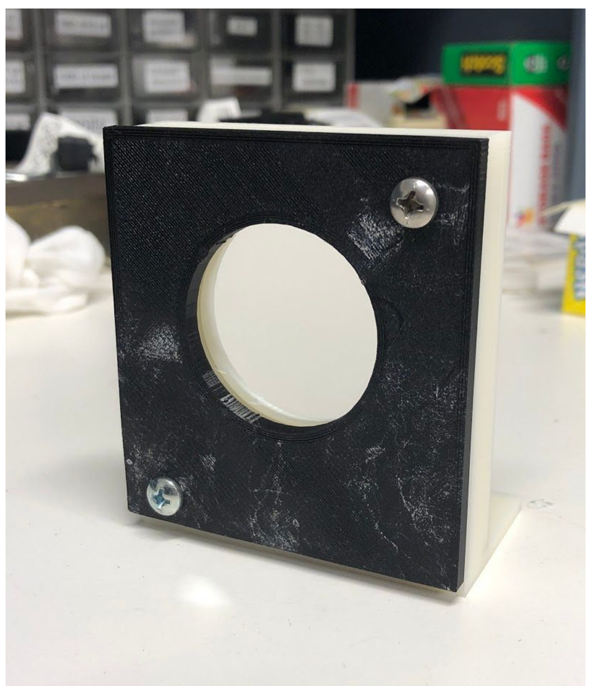


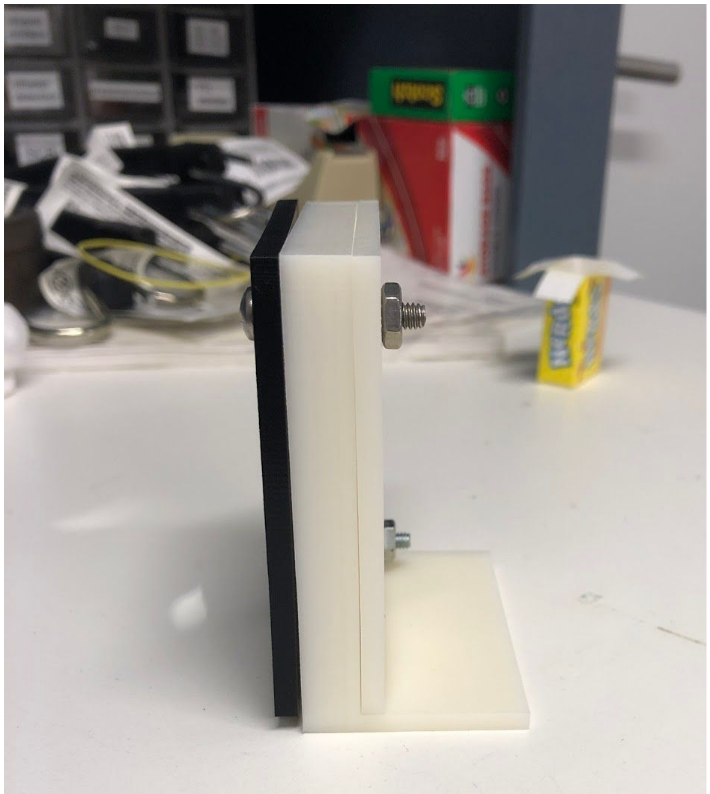
Image of the actual piece:

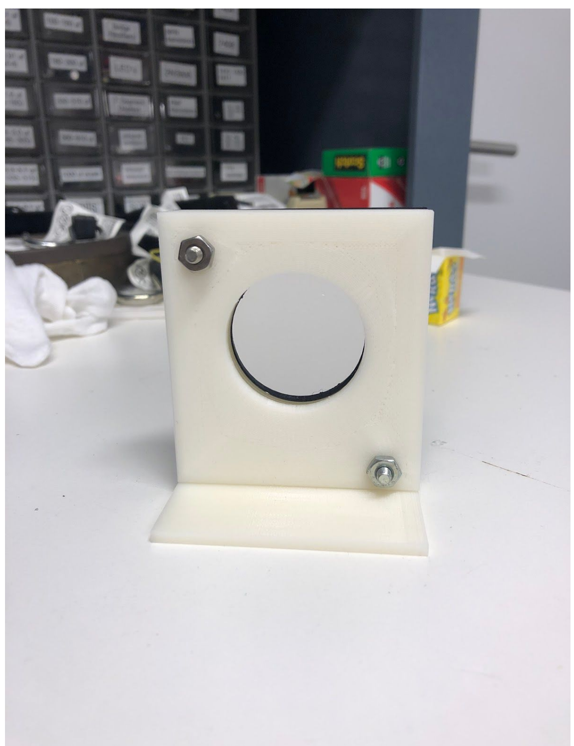


Connected pieces:

The connections are made through the througholes with two 8-32 1” screws and two 8-32 hex nuts



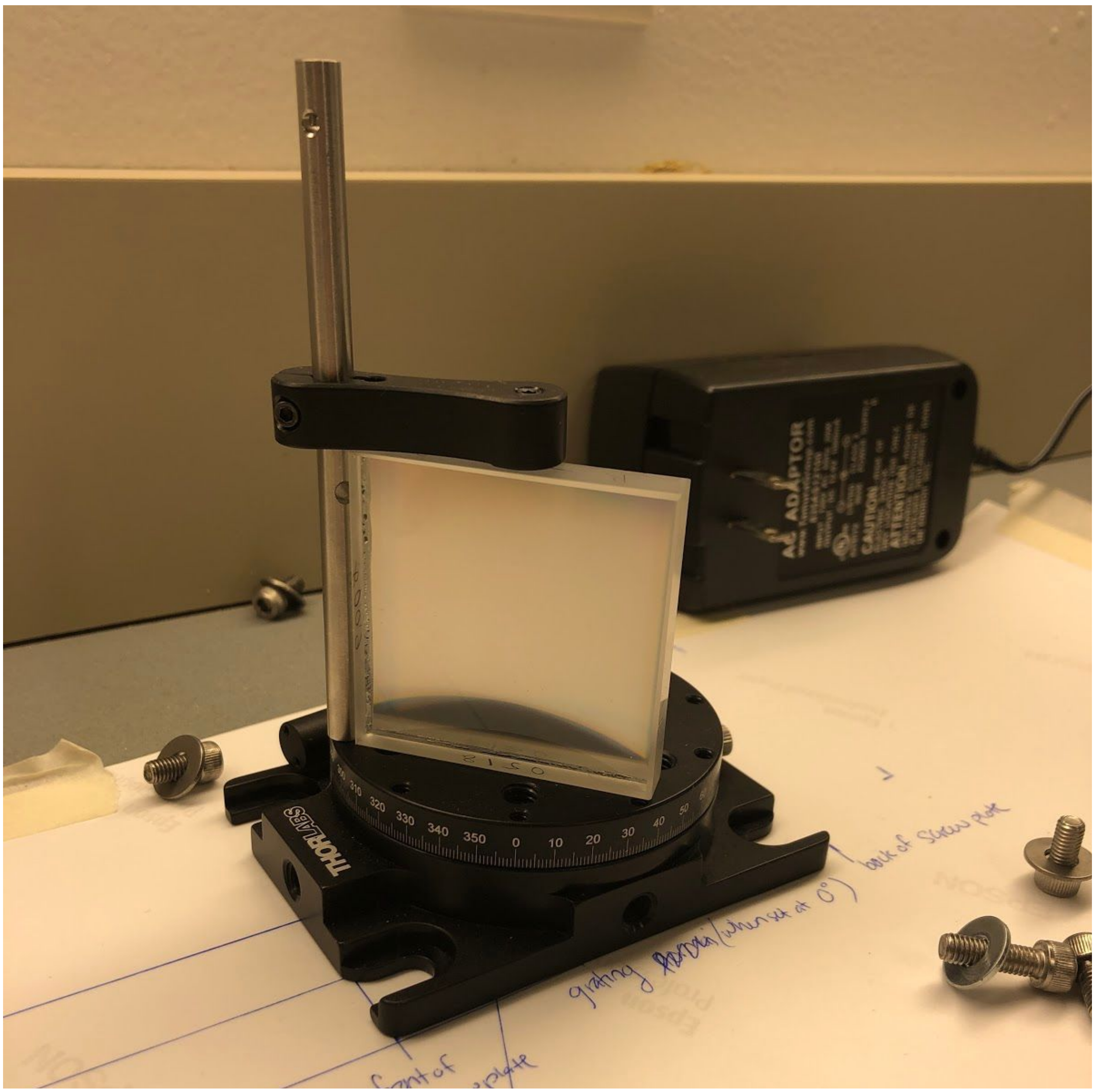




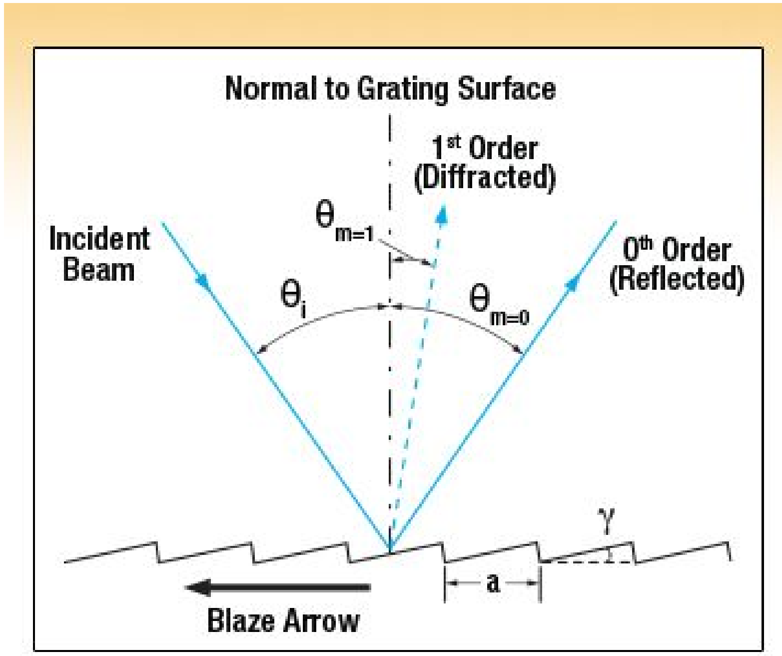
Grating

We chose a 50mmx50mm 600 lines/mm diffraction grating from ThorLabs. The 600 lines/mm will double the resolution compared to a 300 lines/mm, but does not cause a reduction in the spectral coverage that a 1200 lines/mm grating would create. We could go up to the 1200 lines/mm grating if we wanted to in the future, and make the necessary adjustments to the incident angle on the grating to get the wavelength regions we want.

The grating is held in place with a ThorLabs rotating stage and clamp arm for precision angling and stability. (see image below)



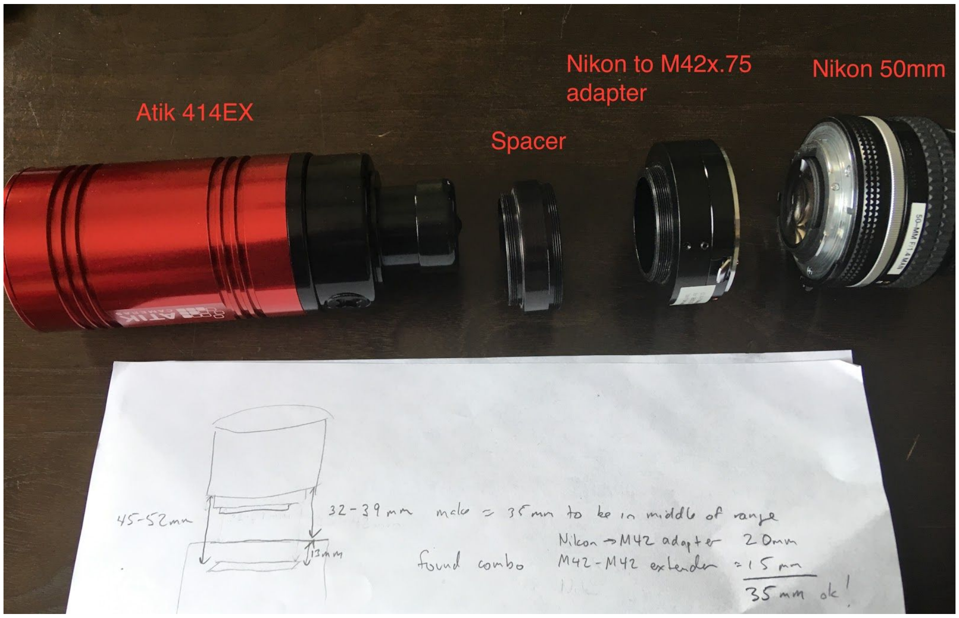
The arrow on the grating points from red to blue dispersion. This is a diagram from [Thorlabs] explaining the correct way to orient a diffraction grating.



Camera lens and CCD

Our design calls for a 50mm camera lens, for which we used an f/1.4 Nikon lens that we had on hand from previous astrophotography projects. To record the spectrum we purchased an ATIK 414EX CCD which is a cooled monochrome system with 1392x1040 pix each 6.45μm on a side.

The ATIK 414EX camera comes equipped with M42x0.75 female threads for attaching to a lens or telescope (it also has a M42x0.75 M -1.25" M adapter that we did not use). The Nikon 50mm camera lens that feeds it can focus over a range of distances 45-52mm from the Nikon connection on the back end of the lens, and the CCD's back focal distance is 13mm. Thus we needed connectors and spacers summing to 32-39mm. We accomplished this with two parts found in the Observatory basement: A Nikon F to M42 M42x0.75 M adapter (20mm) and an M42x0.75 spacer (15mm when installed). The resulting 35mm offset is right in the middle of the desired range.



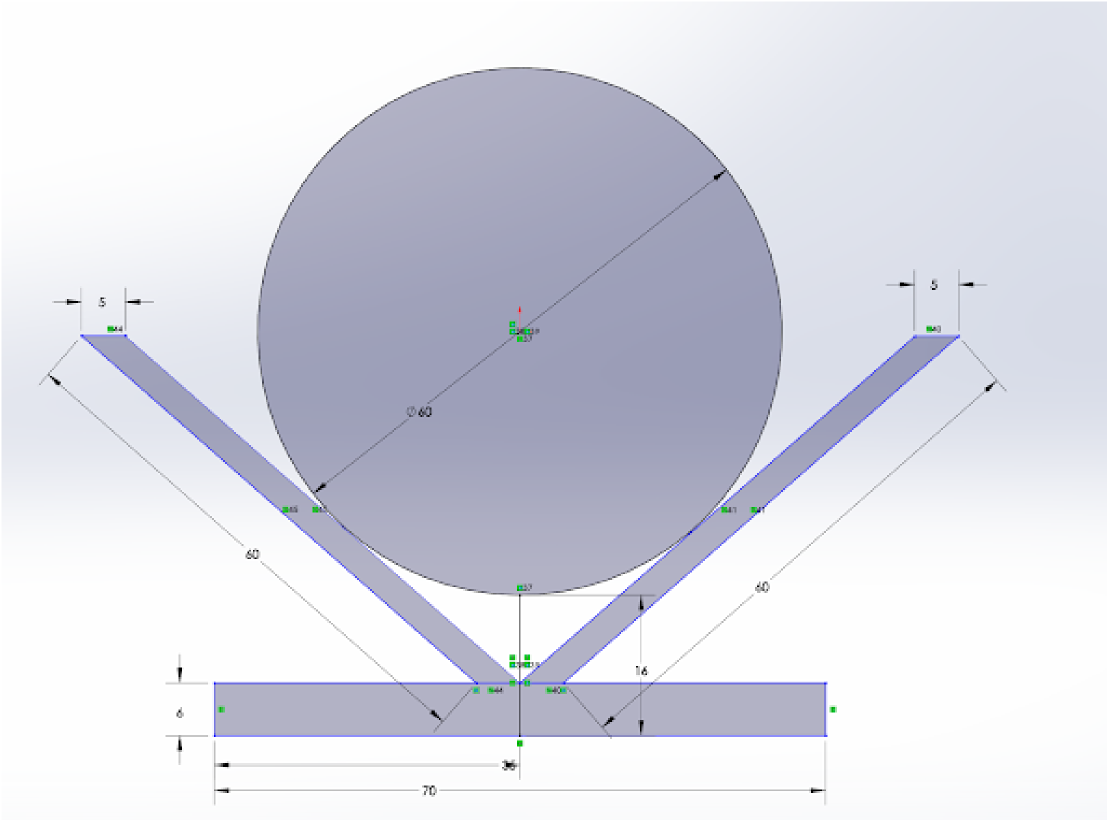
The camera is rotated to ensure that the long side of the CCD is along the dispersion direction.

The camera lens/CCD combination is held in place by two 3D printed v-shaped supports that keeps the piece level and holds the CCD chip at the height of the incoming light. Each has slightly different dimensions to account for their differing circumferences.

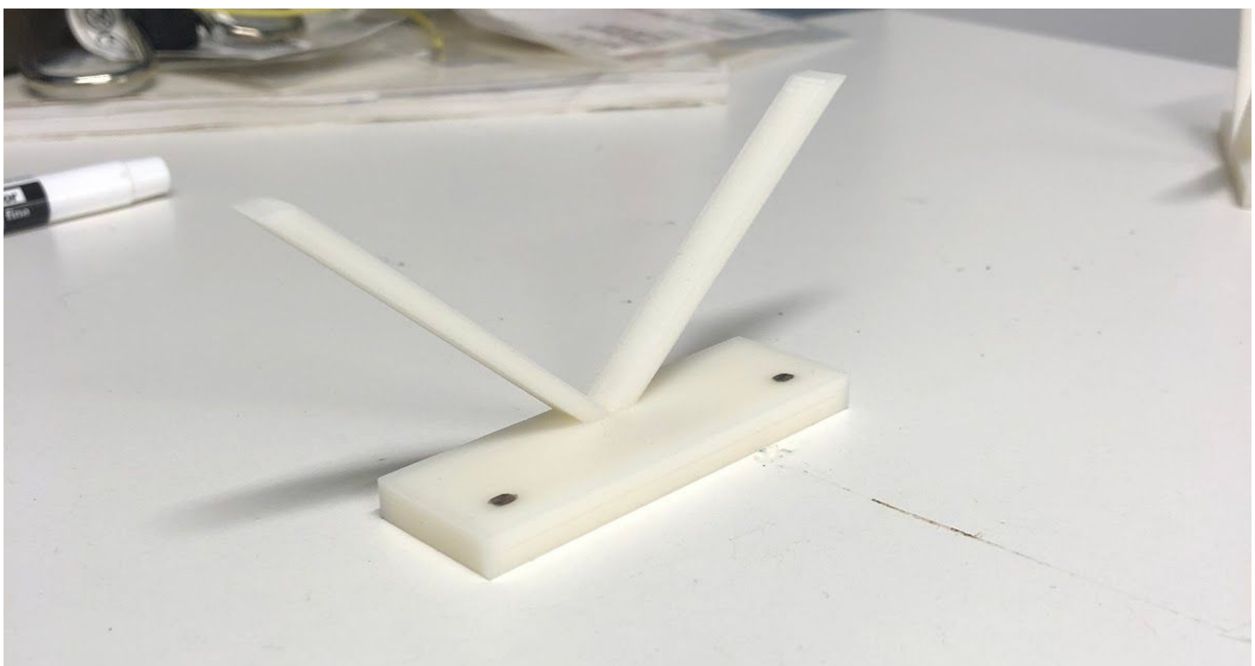
Camera Lens Holder:

Above: 3D render of the V-support that holds the Camera Lens. The arm depth is 7 mm and the base depth is 22 mm.

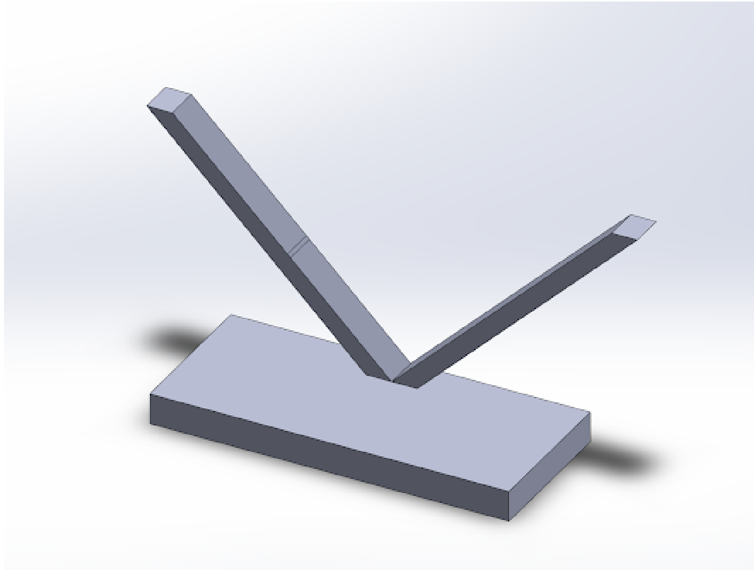
Below: Dimensioned 2D image of the Camera Lens support



Real Piece:

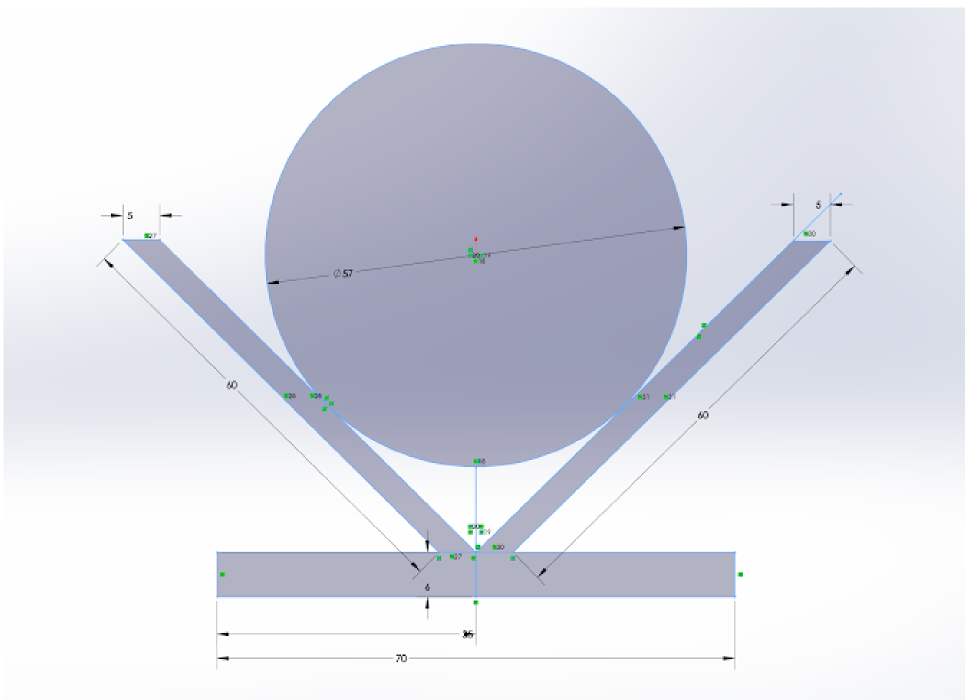


CCD Holder:

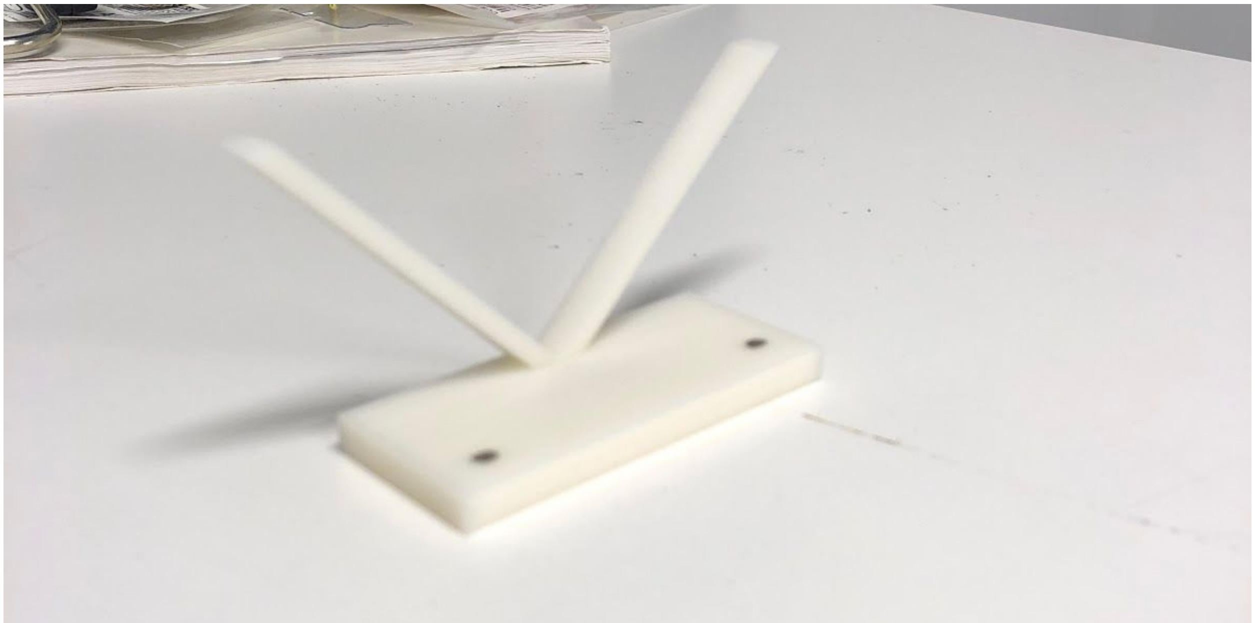


Above: The V-support for the CCD rendered in 3D. The arms have a depth of 7 mm and the base has a width of 30 mm. The base on this piece is larger so that the two can be differentiated between.

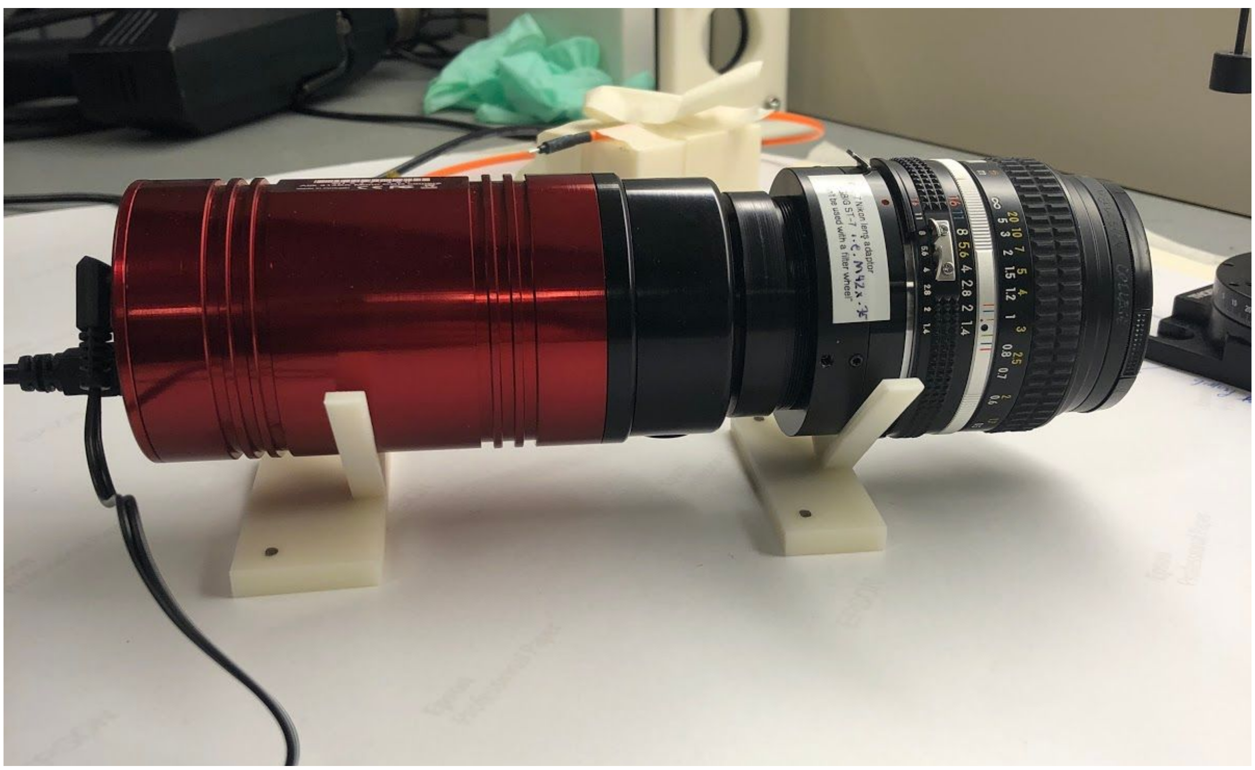
Below: The 2D drawing of the same piece, with dimensions.



Real Piece:

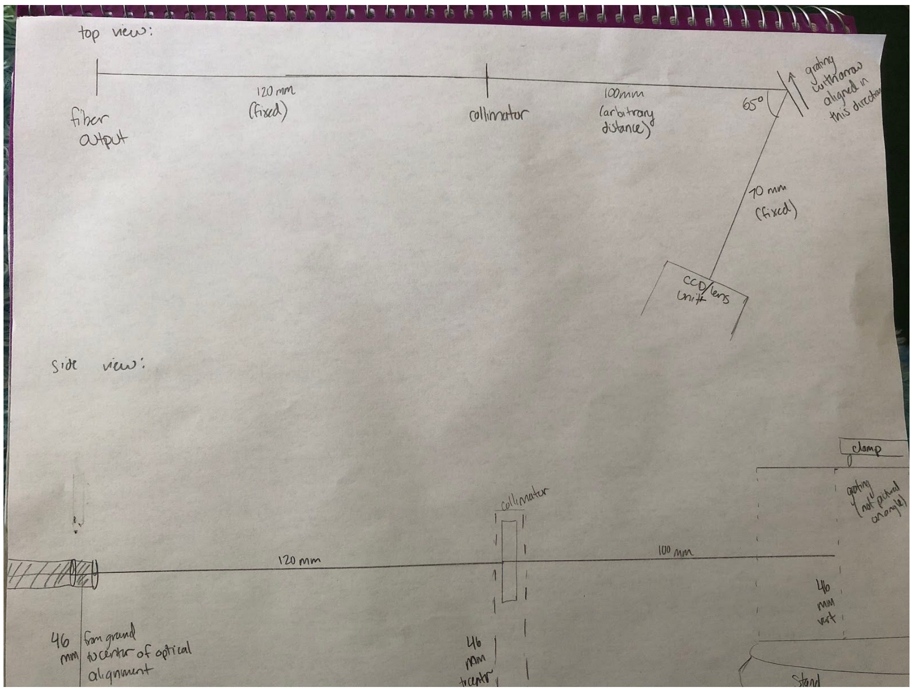


In Use:

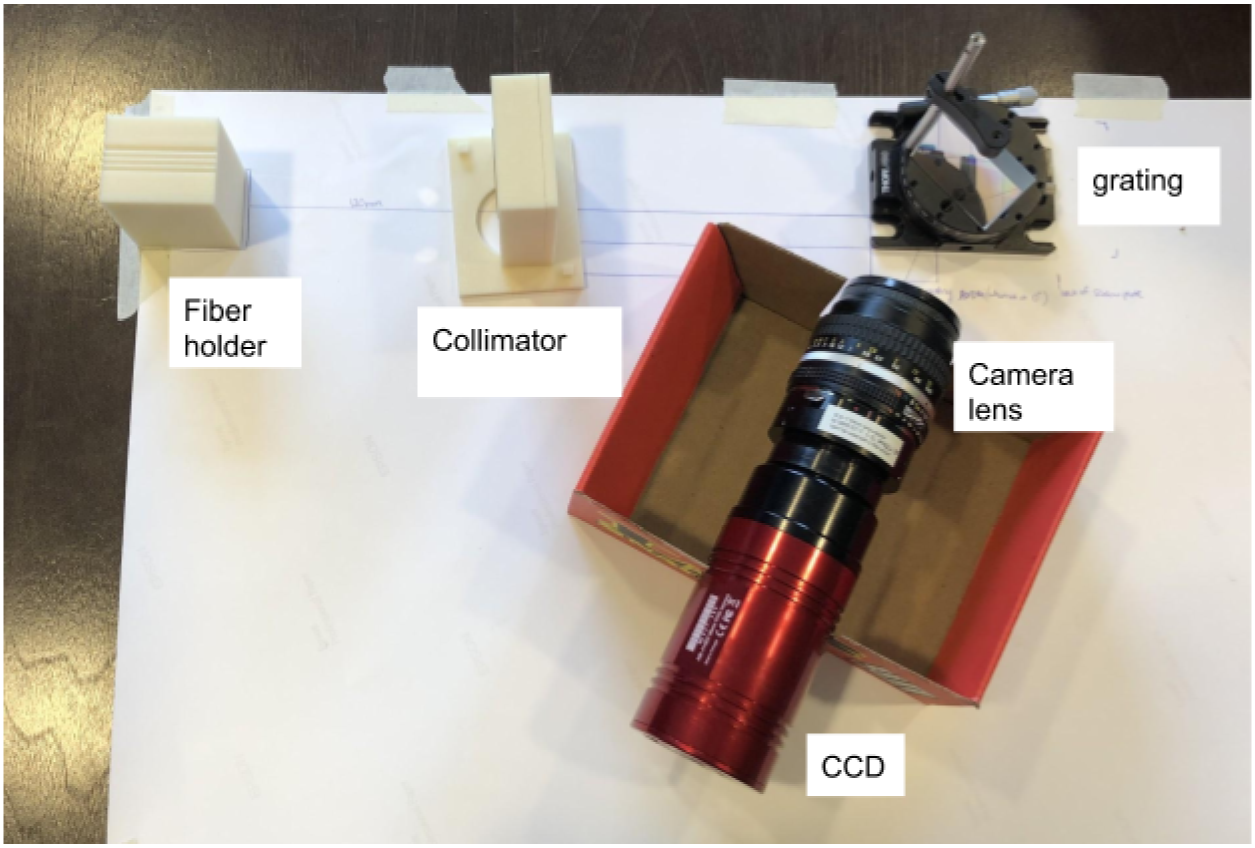


Spectrometer Layout

Sketch of planned optical layout:

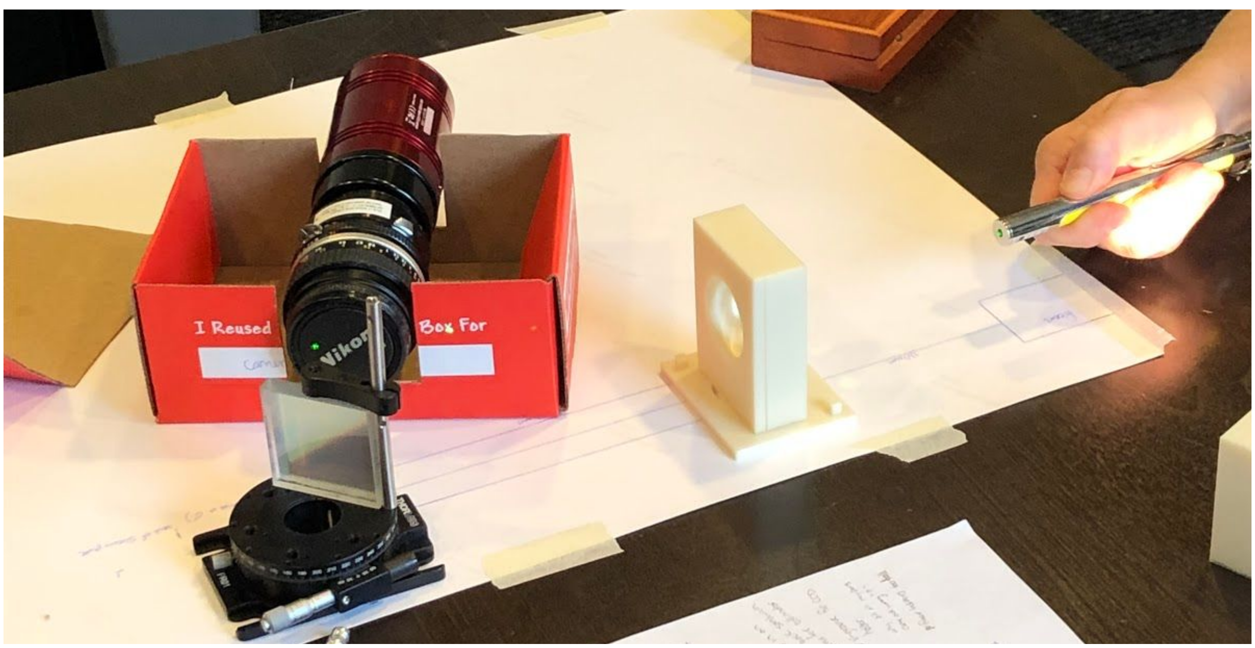


Initial optical layout using first print of parts: (May 6)

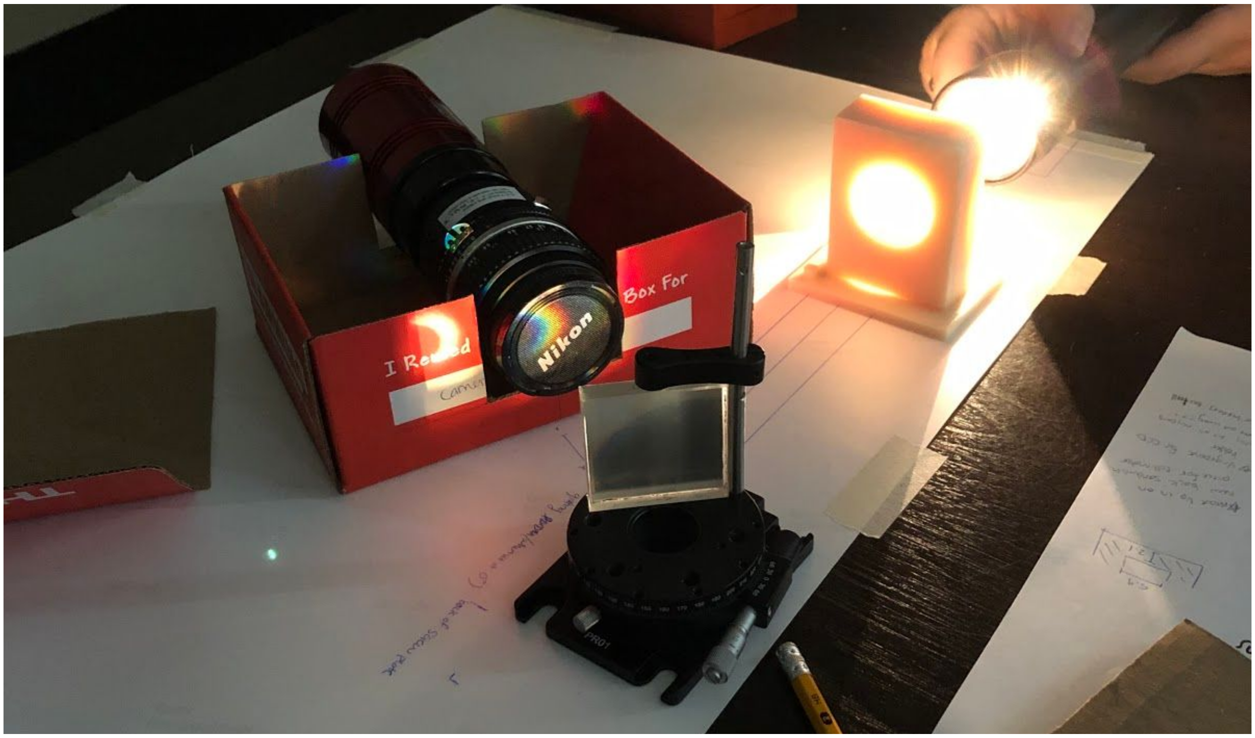


Initial running of light through the collimator and grating and onto the camera lens (May 6):

1) Using a laser beam:

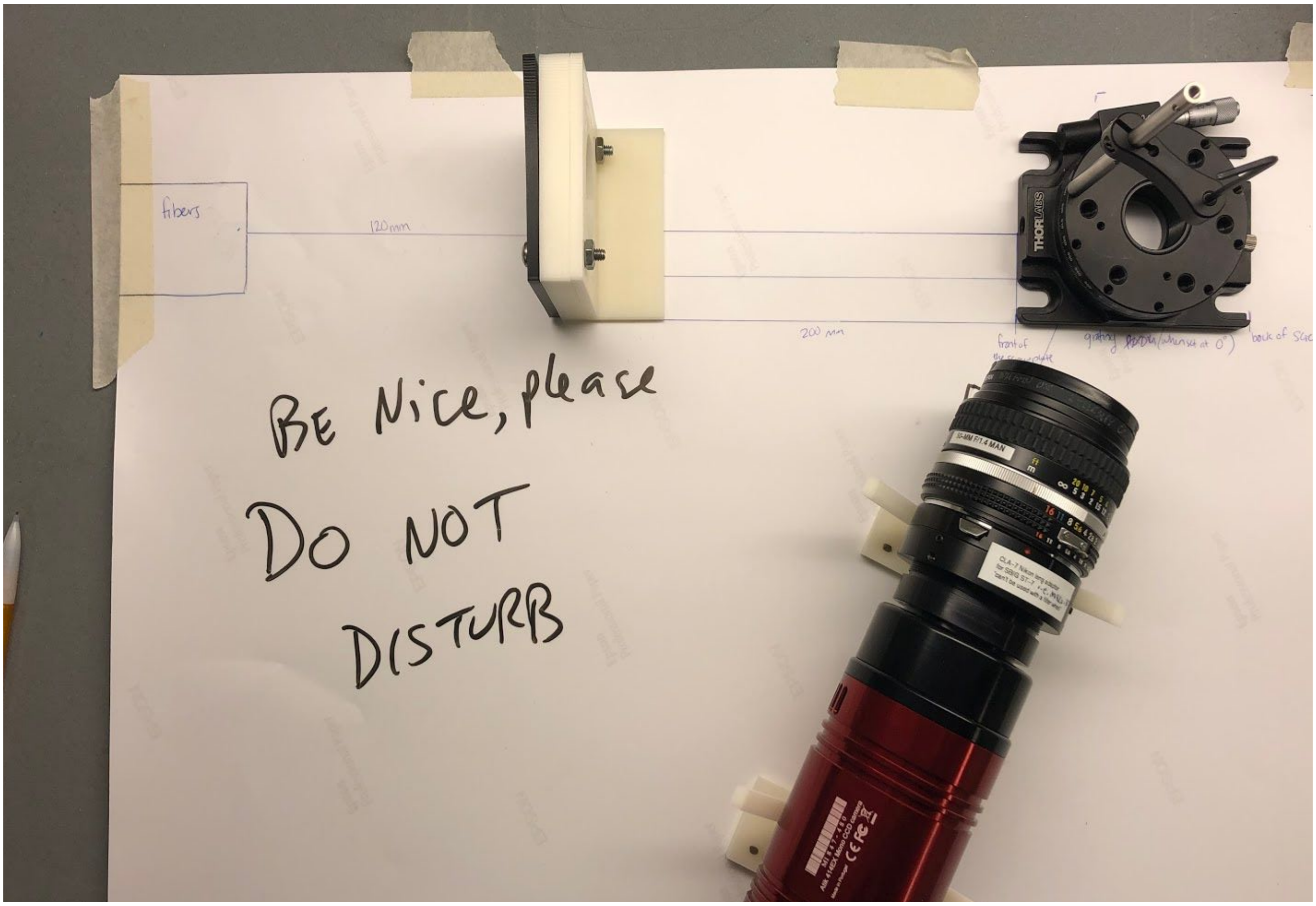


2) Using a flashlight to get a spectrum:



On May 6th we were also able to do an initial test of putting light through a fiber and onto the CCD, but the room was too bright to get any kind of real spectral image.

Updated optical layout using second print of parts: (May 17th)



Comparison lamps

We intend to repurpose the comparison lamp box from the 10C spectrometer. There is an Hg and an Ne lamp inside of that box. We plan to run a fiber between one of these lamps and our new spectrometer to create a comparison source. This would put the lamp's spectrum onto the images with our target's spectrum, which can then be used to calibrate the wavelength of the unknown spectrum.

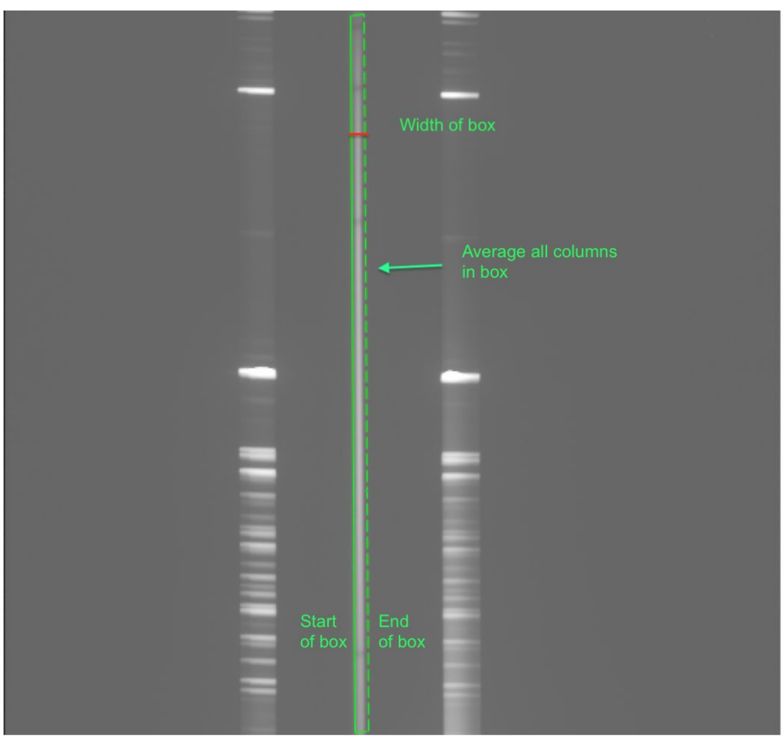
Analysis software

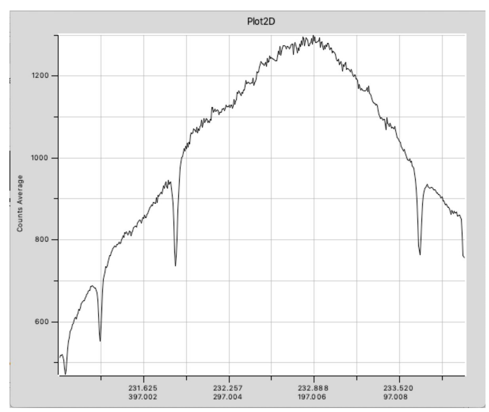
We wrote software that converts 2D fits images taken with the spectrometer into 1D spectra, that may then be analyzed. We aimed for our code to be usable for professors and their research assistants and for students in the observation techniques (ASTR 206) class. The students might have little or no formal coding experience. For this reason, we avoided using pyRAF or other complex software analysis routines, instead focussing on making the software accessible and usable while maintaining the essential functionalities.

Our final product takes two forms, which can be used independently and do the same thing. One product is a Jupyter notebook, which has the advantage of greater legibility and a more approachable interface for novice coders. However, installing Anaconda or Canopy is not easy and the program runs inconsistently on different machines. Therefore, we decided to provide a second product, which is all the same code that's in the Jupyter notebook in a single python file. This can be run from command line or any python environment, provided the necessary packages are installed. On that note, we also installed all the necessary packages and Python 3.7 on the Wellesley observatory computer and tested the python file version of our code and it worked without issues. The control room computer should also have Anaconda installed to allow any student to run the jupyter notebook.

Tools

After some early flirtations with RSpec and pyds9, we settled on a set of simpler packages: numpy, scipy, astropy, specutils, and matplotlib. We used matplotlib to display our plots throughout the code. Astropy displays the FITS images with its fits package and numpy slices the images to produce the plots. For our test images, the spectra ran vertically in the 2D fits image, therefore we allow users to select the pixel columns that correspond to the target's spectrum, creating a box around the spectrum. We then wrote a function that averages the intensity of each row of pixels in the selected columns to mitigate noise and obtain a clearer 1D spectrum. Averaging the columns in the user-selected box, then allows the user to plot the brightness along the spectrum vs. the y-axis pixels in a 1D spectrum.





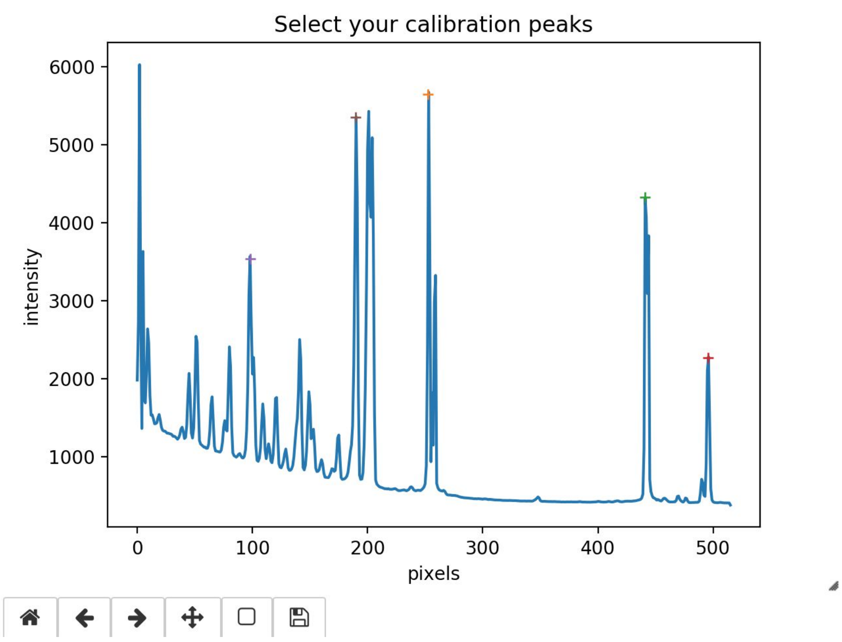
Example of a box drawn around the target's spectrum in DS9 and the resulting spectrum from averaging the intensity of the columns in the box

We also provided a way to extract the sky spectrum using the same slicing method as was used along the target's spectrum. The user may then subtract this background from the target spectra.

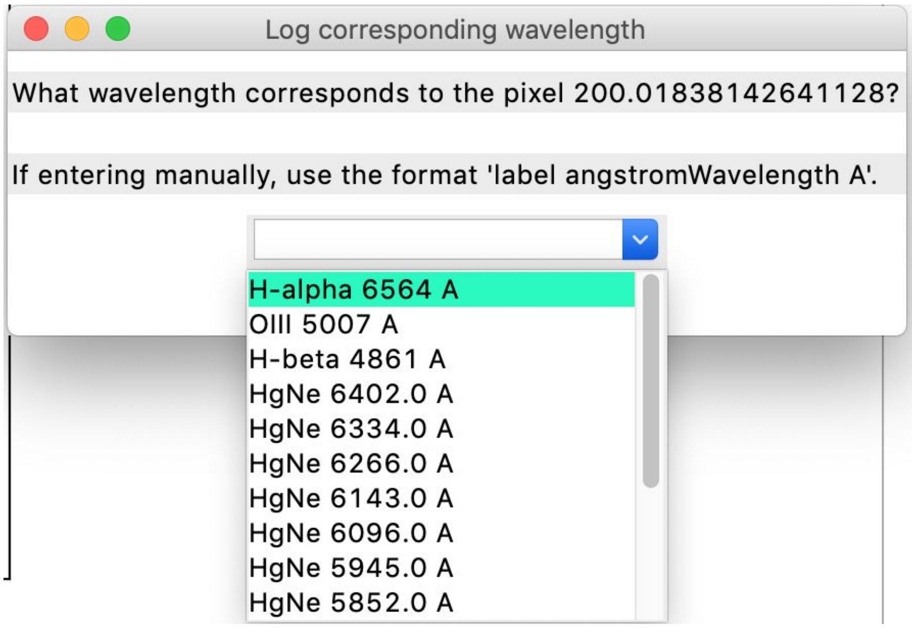
Wavelength Solution

Our code relies on a semi-manual wavelength solution the first time the user runs it. However, we tried to make this as easy as possible by providing a mercury-neon lamp comparison source along with the solved and labeled plot of the same from the old 10C spectrometer. Our wavelength solution code pulls up a plot of the comparison source (users can modify where on the image the code looks for this). The user then clicks directly on the plot. Which prompts a pop-up window where the user can either manually enter the wavelength value at that pixel x-value (in the case that the wavelength solution uses neither the HgNe source nor a H-alpha/OIII/H-beta source) or choose the wavelength value from a drop-down value. One bug we couldn't figure out was a Windows-Mac issue: on Windows, we were able to have the "Add Wavelength" button on the pop-up automatically close the dialog when pressed, but this caused the program to stop working on Mac computers, so we commented that line of code out. It can be uncommented on a Windows machine for a more efficient user experience.

Once the user has selected its solution data points, our code does a quadratic fit and outputs coefficients for an equation that can translate the x-axis pixel values into wavelength values.



Example of plot to select calibration points. Click at the top of the peaks for which you know the wavelength. These will be marked with a cross once you select which wavelength that peak is.

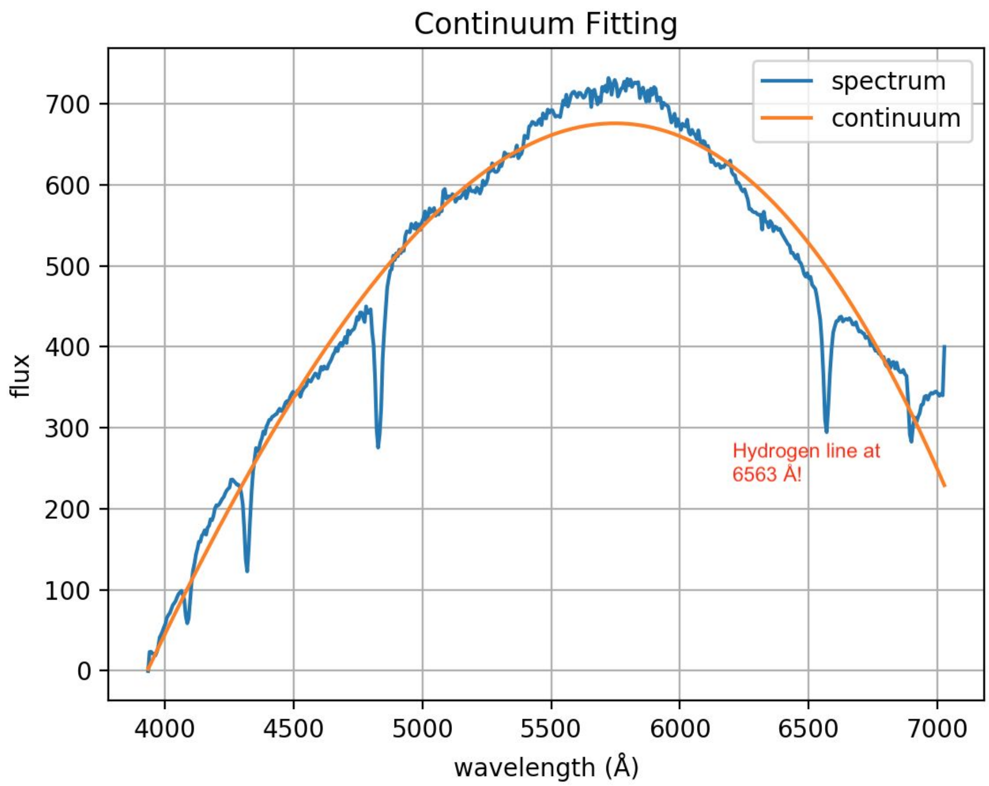


Example of popup window that opens once the user selects a peak on the calibration plot. The user then may select which wavelength that peak is either through a dropdown menu of HgNe calibration spectrum peaks, night sky peaks, or by manually entering the wavelength.

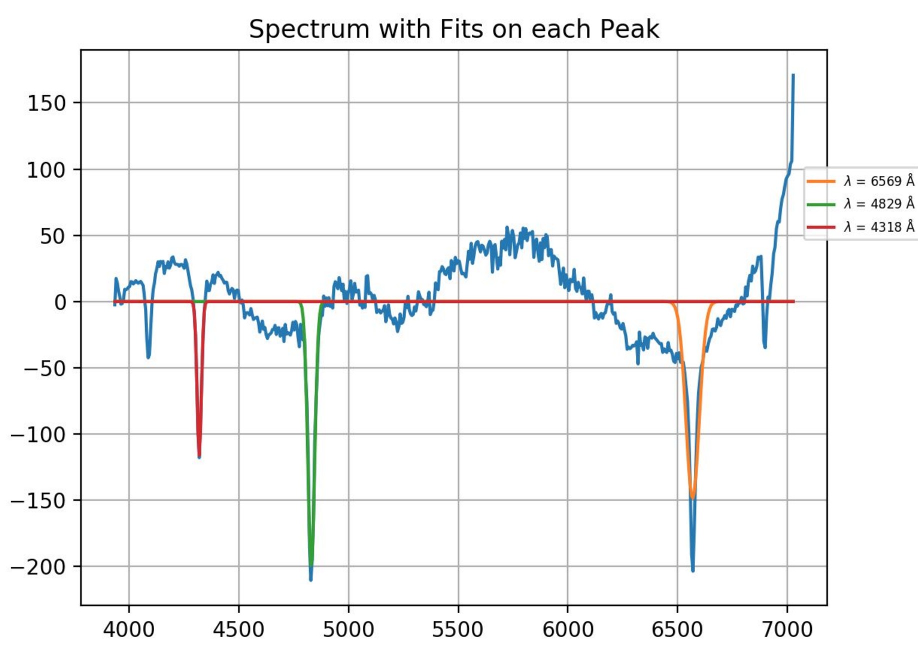
Building and Analyzing the 1D Spectra

Once the user has a wavelength solved x-axis and general intensity y-axis, they may build their spectrum as a Spectrum1D class, which allows them to analyze their spectrum using the various tools provided in the specutils package. We employed some of these tools for a basic analysis in our code.

First, the user may fit a continuum spectrum to the data and then subtract it to recover a flat spectrum centered around 0. This then allows the user to use a line finding tool and a gaussian fitting tool to identify and extract properties from the emission and absorption peaks in the spectrum. With these two simple tools, the user may learn the central wavelength, FWHM, and other characteristics of the peaks. We have then left it open for the user to choose which of the many specutils tools they would like to use to continue to analyze their spectra.



Wavelength calibrated spectrum with a fit continuum.



Continuum subtracted spectrum with gaussian fits on each absorption line.

Bugs

As mentioned earlier, the wavelength calibration pop-up cannot close automatically on Macs, so that line of code is commented out in our published code.

It appears that the Python script (.py) does not always function properly on Mac OS command line.

When running the program in Jupyter, the plots usually aren't interactive the first time you run the cells. To fix this, just start from the first cell again and run each one until you get to one that has a plot. It should be interactive on the second try.

The wavelength calibration fitting sometimes produces a warning when run. It appears the covariance parameters of the least squares fit cannot be estimated if there is too small of a data sample size. This means that selecting more calibration points may get rid of this warning. The continuum fitting also gives a warning based on the model used in the continuum fit. We used the general specutils fit_generic_continuum, but the user may choose to alter the continuum fitting routine using a different continuum model.

Where to find it

Our code (both Jupyter and .py) can be found on Claire Cannatti's Github at github.com/clairec1997/SpectralAnalysisPython on your internet browser. The repository also includes sample FITS images for testing the code setup and a reference image of HgNe wavelengths, as well as other reference images. Select download zip, which will download a folder with all of the repository's contents. Finally launch either anaconda or canopy to navigate to the jupyter notebook Spectral Analysis.ipynb.

To run this code, put it in the same folder as the images you want to analyze or else modify the image names to include the appropriate path to your images.

Rejected Paths

We tried to use pyds9 but decided against it because the package doesn't work on Windows computers, and we can't rely on ASTR 206 students to all have Mac or Linux machines, or to be able to install and use Ubuntu, which is a command-line interface and intimidating for novice programmers.

TBD

- Parts to be designed and built
  - Enclosure (or at least its bottom)
  - Fiber mount at collimator end
  - Pickoff mirror / beam sampler and holder
  - Fiber holders both ends
- Leftover questions
  - Do we need an order blocking filter? Where? Do the fibers or beam sampler transmission affect this?
  - Do we want to remove the UV filter from the camera lens (left on for now to help keep the lens clean)
- Note all of Lindsey's notes, spreadsheets, 3D plans etc are in this drive

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Appendix I -- complete parts list

Guide Optics				
Item, Quantity	*Dimensions*	*Features*	*Cost*	*Purpose*
1” Tube, x1	10cm long 1” diameter	External and Internal Threading	$45.90 from ThorLabs SM1L40	Houses 2 achromatic doublet lenses
Achromatic 1” doublet lenses, x2	1” diameter	54.3mm focal length	$78.80 each from Thorlabs AC254-060-A	Refocuses light reflected off of split mirror onto guide camera CCD
Additional retaining rings, x3	For 1” tube	1” threaded rings	$4.50 each from Thorlabs SM1RR	Holds lenses inside tube in place
CMOS Guide Camera- ZWO ASI290MM Mini Monochrome Astronomy Camera	1936 x 1096pix 2.9 µm pix 36 mm x 61 mm	Connects and powers via USB-C	$299 from High Point Scientific	Provides image to guide target object into optical fibers
Camera Adapter- 2 Inch Male – SCT Male Adapter	2”	Attaches to 2” eyepiece slot and presents a M attachment end	$26 from Optical Structures Incorporated LA1060	Connects guide camera and fiber assembly box to CDK Naysmith port.
PVC, 2 small rubber rectangle, tape, and hose clamps	2 ⅜” long PVC with 1 ⅝” internal diameter and ¼” section removed for adjustability (refer to schematic); 1mm thick rubber; black electrical tape; 1.5” adjustable hose clamps	Allows adjustability through hose clamps	< $10	Mate 1” tube to 1” end of 1” to 1.25” adapter. Tape to secure tubes underneath adapter and block light

Meade Flip Mirror Box (Ports A,B,C described below)	3” x 3 $\frac{1}{16}$ ” x 3 $\frac{5}{16}$ ” box	Flip mirror system with three connecting ports - (a)one to CDK adapter, (b)one to guide camera with 1” long threading system, and (c)one for optical fibers	Found in basement Retails $119, no longer available from Meade	Guides light from CDK to flip mirror and through guide camera attachment
Port A (see schematic)	2 ⅛” outer diameter and 1 ⅞” inner diameter on threaded ring; 1 $\frac{9}{16}$ ” inner diameter into box	Dust cap, threaded female ring	See Meade Flip Mirror Box	Connects telescope to flip mirror system
Port B (see schematic)	2 $\frac{1}{16}$ ” inner diameter of first threading set to 1 ¼” inner diameter of 2” to 1” adapter. Height from base of port to first ring 1”	Set screw on both threading sets	See Meade Flip Mirror Box	Connect guide camera attachment system to flip mirror system
Port C (see schematic)	1 ¾” inner diameter, 2” outer diameter	Raised 1 ¾” ring	See Meade Flip Mirror Box	Connects fiber system to flip mirror
1” to 1.25” eyepiece adapter	1” diameter on one end and 1.25” diameter on other end with set screw on 1.25” end	Set screw provides stability and adjustability for connection	Found in basement Retails $24.99	Connects 1.25” port on Meade flip mirror system to 1” lens tube
Spectrometer				
Collimator Lens x1	40mm diameter,	Coated for	$143 from	Collimate light coming

	120mm focal length,	VIS+NIR range of wavelengths. f/# = 3.00	Edmund Optics 49381	out of the fibers
600 l/mm Diffraction Grating x1	50x50x9.5mm	500nm blaze	$198 from Thorlabs GR50-0605	Disperse the light into a spectrum
Rotating Stage + Clamping Arm + Clamping Arm Extension		Holds Optics up to 3.61" (91.7 mm) Tall	Stage: $341, Arm + extension: $30, from Thorlabs PR01, PM4, PM4SP	Hold the diffraction grating in place and allow for precise changes in the angle of incidence.
ATIK 414EX Monochrome CCD	1392x1040 pix 6.45μm pix BFD=13mm	Cooled, USB2.0, 12V DC 1A M42x0.75 F threads	$1489 from High Point Scientific ATK-ATK0136	Take images of spectra created by the optical setup.
Power supply Tamura 835AS12100	12 V, >= 1 A Center +, 2.1mm	Rated to -10C	Found in basement, current retail price around $9 on Amazon.	Power ATIK camera
Camera Lens- Nikon	35mm aperture, F=50 mm, f/1.4		Found in basement, current retail price around $325 here	Focus light from the diffraction grating onto the CCD
Nikon adapter	~20mm thick	Nikon F and M42x0.75 M	Found in basement, current retail around $29	Connect Nikon lens to M42x0.75 spacer
M42x0.75 spacer	~15mm thick when connected	M42x0.75 threads M and F	Found in basement, current retail around $13	Spacer from Nikon lens connector to CCD
3D Printed Stands (Two prints)	1st print: 28.03 sq. inches 2nd print: 100 grams	Initial print printed wrong dimensions, reprint corrected this. Two v-shaped stands	1. $253 on We-Lab printers 2. $10 on Knapp printers	Holds collimator, camera lens, and CCD in place

		for the camera lens/CCD, 3 pieces to sandwich the collimator in place.Each piece has room to drill down into and secure it to the base.		

Fibers

Total cost

Guide Optics: $45.90 + $78.80 + $4.50 + $299 + $26 + $10 + found in basement ($0)= $464.20
Spectrometer: 143 + 198 +341 +30 +1489 + 253 + 10 = $2464

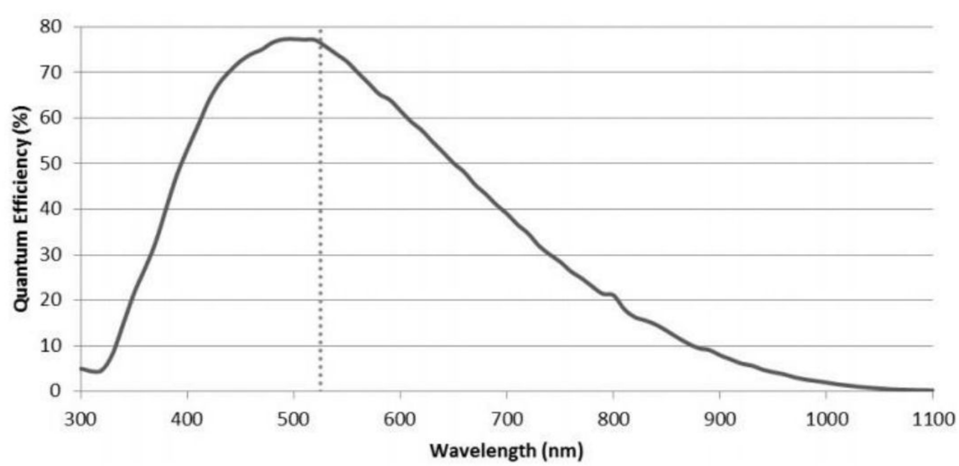
Appendix II --technical spec sheets

CMOS guide camera

ZWO ASI174MM Mini Mono Camera Specifications

- Sensor: Sony 1/2.8″ CMOS IMX290/IMX291
- Peak QE ~ 80%
- RN ~ 3.5e
- Resolution: 2.1 MP (1936 x 1096)
- Pixel Size: 2.9 μm
- Minimum Exposure: 32 μs
- Maximum Exposure: 300 s
- ROI: Supported
- ST4 Guider Port: Yes
- Focus Distance to Center: 8.5 mm
- Shutter Type: Rolling
- Protect Window: AR coated
- Operating System Compatibility: Mac, Windows, Linux
- Interface: USB 2.0
- Bit Rate: 12bit output (12bit ADC)
- Adapter: 1.25" M28.5x0.6
- Dimensions: 36 mm x 61 mm
- Weight: 60 g (3.1 oz.) without lens
- Working Temperature: -5ºC - 45ºC
- Storage Temperature: -20ºC - 60ºC
- Working Relative Humidity: 20% - 80%
- Storage Relative Humidity: 20% - 95%

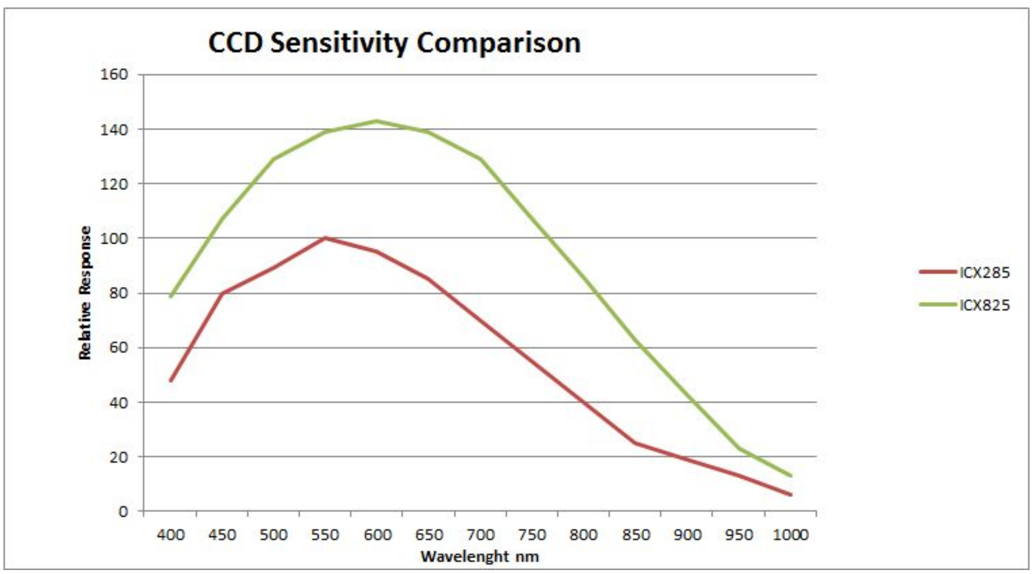
ASI174 Mono Sensor



CCD camera

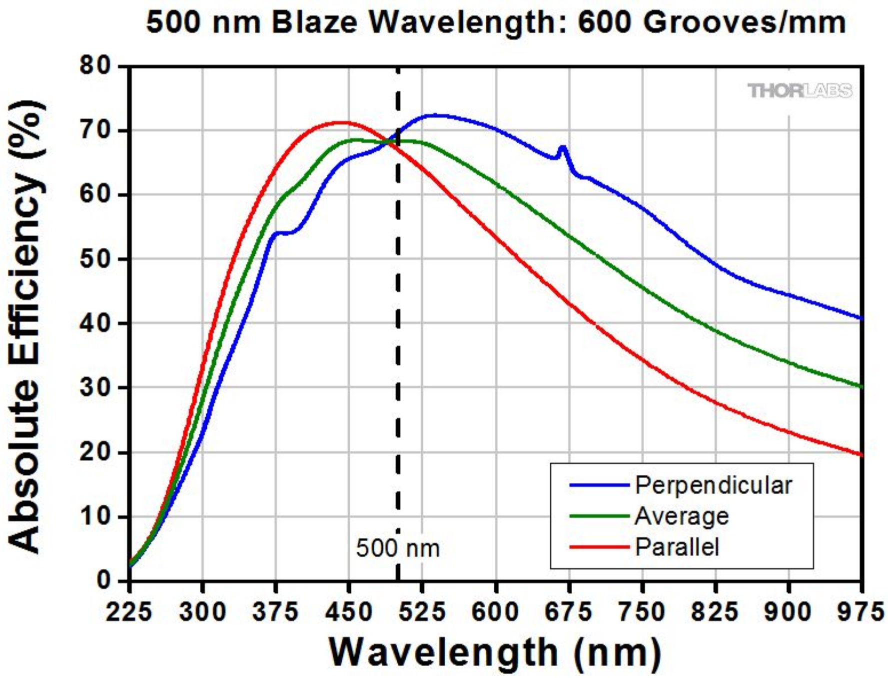
Atik 414EX monochrome cooled CCD

- Peak QE 71%
- Sensor Type: CCD - Sony ICX825
- Horizontal Resolution: 1391 pixels
- Vertical Resolution: 1039 pixels
- Pixel Size: 6.45 µm x 6.45 µm
- ADC: 16 bit
- Readout Noise: 4e- typical value
- Gain Factor: 0.28e-/ ADU
- Full Well: ~18,000e-
- Dark Current: ~0.001 electrons/second at -10°C
- Interface: Mini-USB 2.0 High Speed
- Power: 12v DC 1A
- Maximum Exposure Length: Unlimited
- Minimum Exposure Length: 1/1000 s
- Cooling: Thermoelectric set point with max ΔT=>-30°C
- Weight: approx. 400 gr
- Backfocus: 13mm ±0.5



Grating

- Thorlabs GR50-0605   600 g/mm
    - 50mm x 50mm x 9.5mm
    - blazed 8º37' for 500nm



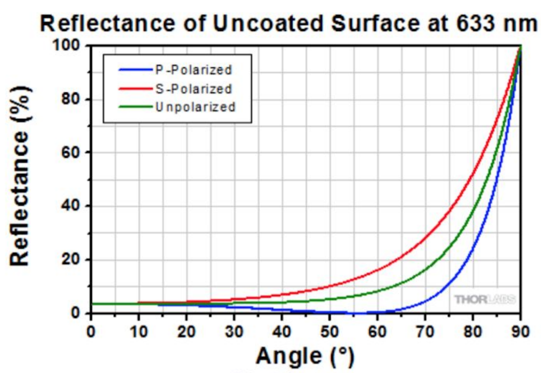
Beam sampler

Beam sampler will reflect 1-10%. Curves below indicate for unpolarized light at 45° will reflect about 5%, mostly from the uncoated surface. The AR coated surface will transmit most of that inside of 350-700nm. At >800nm though the second (coated) surface will block more…

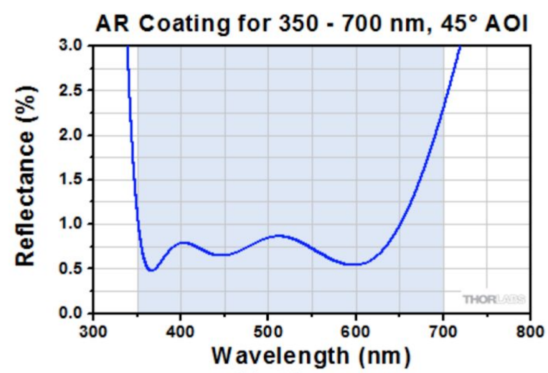
"These laser-quality beamsplitters are typically used for monitoring applications where optical losses and wavefront distortions of the transmitted beam need to be kept to a minimum. The back surface is wedged to eliminate internal fringes and AR coated to minimize ghosting."

D=0.5"
https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=913&pn=BSF05-A
D=1"
https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=913&pn=BSF10-A

Beam Samplers with AR Coating for 350 - 700 nm



Click to Enlarge
Click Here for Data
The sampled beam is reflected from the uncoated surface of the beam sampler. The plot above shows the percent of the incident beam reflected by the uncoated surface of the optic over a range of incident angles. The mirrors are optimized for use at a 45° AOI.



Click to Enlarge
Click Here for Data
The back surface of each beam sampler with an item # ending in -A is AR coated for 350 - 700 nm, minimizing back reflections of the transmitted beam at this surface.

Appendix III -- camera software setup on Vera (Obs Control Rm)

Guide Camera

1. Downloaded drivers from https://astronomy-imaging-camera.com/software-drivers
2. Open/run download
3. Go to C:\Program Files (x86)\ASCOM\Platform 6\Tools\DriverConnect64, run ASCOM.DriverConnect.exe. Select "Camera" under drop down, then click "choose" then click "ASI Camera (1)"
4. Open MaxIm --> Connect Camera --> Setup Camera --> Select "ASCOM," then click "Advanced..." --> Select "ASI Camera (1)" --> ok, ok. connect

CCD

1. Download "Core Software" from https://www.atik-cameras.com/downloads/. Run application
2. When the popup window "select additional components" pops up, leave default "Core Software" checked, and scroll all the way down and also check "ASCOM Drivers"
3. Go to C:\Program Files (x86)\ASCOM\Platform 6\Tools\DriverConnect64, run ASCOM.DriverConnect.exe. Select "Camera" under drop down, then click "choose" then click "ATIK Camera"
4. Open MaxIm --> Connect Camera --> Setup Camera --> Select "ASCOM," then click "Advanced..." --> Select "AtikCamera" --> ok, ok. connect