ASTRON 120 Lab 1 Report - Optical Imager

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Abstract

This lab is a compilation of efforts between the group members in Group 6A of the Astronomy 120 course to create a working optical system comprised of an imager, lenses, and various images. Its goal will be to assess the system's sensitivity and precision in capturing images with an optimal signal to noise ratio (SNR). It will assess the properties of an imager, which was made to detect light from an image of Jupiter and a Globular cluster. After the proper assessments are performed on these properties, astronomical measurements will be made, using methods of photometry and astrometry to inspect certain characteristics of the above-mentioned images. This will involve finding an optimal SNR to FWMH (Full-Width at Half-Maximum) ratio. The results of this lab were successful, obtaining a low (and thus favorable ratio, being ¡1 pixel in either direction) of 0.6018 pixels in the x-direction, and 0.8679 pixels in the y-direction.

Nomenclature

- focal length
- field of view (FOV)
- plate scale
- spatial resolution
- detector bias
- dark current
- read noise
- integration time
- photometry
- flux/flux uncertainty
- signal to noise ratio (SNR)
- astrometry
- globular cluster
- full width at half-maximum (FWHM)

1 Introduction

In order to create an effective optical imaging system to capture images with optimal clarity, one must first understand how lenses align with each other, and how their focal lengths interact. This requires a fairly strong foundation in optical physics, particularly in the subject of convex and concave lenses and how they refract light passing through them. For the first section of this lab report (System Build and Testing), we will lay the groundwork for grasping the physics that explain how light can be manipulated to pass through the lenses and focus on a single point inside of an imager/detector (used interchangeably). This involves taking measurements of the distances between separate components of the optical system, to properly direct the light passing through it, as well as measuring metrics such as the plate scale and field of view . Once the correct methods are applied to focus the light, the imager will transmit the image through a cord to a computer, which can then be downloaded for analysis. The analysis in subject will be covered in section 3 of this report (Detector Properties). This section will assess the bias, dark current, and read noise of the image detector. Once these metrics are verified to be well calibrated, the final portion of this report will outline the astronomical measurements, made during the lab work. Using a variety of computational and mathematical methods, this final portion will outline the photometric measurements made on the flux and flux uncertainty of an image of Jupiter's red spot, and the astrometric measurements made on the position and positional uncertainty of a star in an image of a globular cluster.

2 System Build and Testing

This section will highlight the work done on calibrating the lens system - this includes setting up the lenses at the correct distances to optimize the focusing of light into the imager, as well as assessing the plate scale, spatial resolution, and field of view of the imager.

The components of the lens system include:

- Blackfly Monochrome BFS-U3-63S4M-C: 3,072 x 2,048 pixels, pixel size: 2.4 μm (or similar)
- 1x Lens #1: AC254-075-A Ø25.4mm, F=75.0.mm, Visible Achromat
- 1x Lens #2: AC254-100-A Ø25.4mm, F=100.0.mm, Visible Achromat

The materials required to enable the setup of the system include:

- Light source: LED + Power supply
- Pins, Paper cards, tape, rulers
- Posts, post holders, post holder bases
- Optical breadboard
- Object cards
- Gloves

The lenses in this lab were placed on an optical breadboard, along with the Blackfly imager and images of a Ronchi Mask, Jupiter, and a globular cluster. An LED light source was also placed in face of the image to illuminate it. Carefully placed apart from each other and the other components at distances calculated by equations included in this section, the lenses were selected based on having the best ratio of calculated plate scale and field of view compared to other combinations of lenses (50mm + 100mm, 50 + 75mm, etc.). To see a visual of how the setup looked like, please refer to figures 14-16 in the Appendix section of this report.

2.1 Plate Scale

The first activity performed in this lab was to measure the plate scale of our lens setup. Plate scale can be defined as a measure of an optical system's ability to magnify small portions of an image, meaning that a lower plate scale will allow for greater detail on smaller angular sizes. The equation for calculating the plate scale can be defined as follows:

$$\text{Plate Scale} = \frac{\text{PS}}{\text{EFL}} \times \text{Pixel Size}$$

Where the image plane scale is measured in arcseconds/mm, the EFL (Effective Focal Length) in mm, the pixel size in mm^2, and thus the plate scale is measured in arcseconds/pixel.
PS can be found by converting the unit measurement of 1 radian/m, which gives 206,265 arcseconds/mm. The EFL is then calculated using the thin lens equation:

$$\text{EFL} = \frac{1}{F} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

where f_1 is the focal length of the first lens (75*mm*), with f_2 corresponding to the 100*mm* lens, and d is the distance between the lenses ($\approx 55mm$). This combines to give an EFL of $\approx 62.5mm$, which we then assigned to be the distance from the image to the lens closest to it.

Finally, the pixel size was taken from the Blackfly's specifications to be $2.4\mu m$, or $0.0024mm$. Plugging all of these values into the plate scale equation returns a value of 11.55 arcseconds/pixel.

2.2 Field of View

The next activity in this section involved a calculation of the FOV (field of view) of the lens system, as given by this equation:

$$\text{FOV} = 2 \times \arctan\left(\frac{\text{Sensor Dimension}}{2 \times \text{EFL}}\right)$$

Given a sensor dimension of the Blackfly of 7. and an EFL of 62.5mm, the FOV is calculated to be 9.8°. Compared to similar calculations done on alternate two-lens systems with varying focal lengths, we found this ratio of plate scale to FOV to be the best for our needs, given the size of the images used. This meant having a smaller plate scale, and a FOV large enough to fit a whole image, to return the best spatial resolution.

3 Detector Properties

Since detectors are subject to minor performance issues, it is important to measure the signals and noise that can contribute to a lessened quality of resolution.

The metrics measured in this section are bias, dark current, and read noise (all measured in ADU, or Analog Digital Unit). The detector's bias refers to the minimum signal level detected. It's an inherent electronic offset that the detector adds to every pixel before any actual photo signal (light) is recorded. The dark current is similar to bias in the sense that it adds noise to an image, but is a result of thermal activity within the detector, which contributes to the total noise despite the absence of light. Finally, read noise refers to the random electronic noise generated in the process of reading the charge from each pixel of the sensor.

3.1 Bias and Dark Current

Both the bias and dark current are measured similarly - by taking dark frames, which can be done by covering the detector's opening with its shutter or cap. The bias level is measured with short integration/exposure times (used interchangeably in this report), while the dark current is measured with varying integration times. The integration time refers to the amount of time that the detector is exposed to light while taking a single frame. As shown in the figures below, the majority of frames taken revealed a consistent bias level of around 0.278 ADU, with no outliers. To assess the bias level from the frame, the .raw files taken from the imager were first converted into .FITS files using another file containing Python code, provided by Prof. Jessica Lu of the Astronomy Department at UC Berkeley. Using this code, the bias level could then be extracted from the .FITS file, and visualized using histograms to confirm the consistency of its low levels.

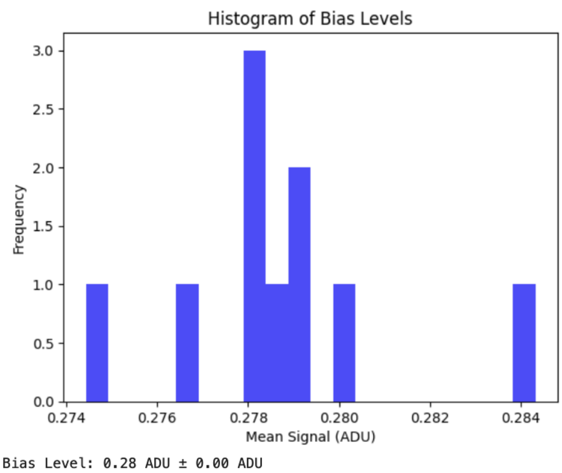

Figure 1: Histogram of Bias Levels

The dark current was then measured using the method described above, also extracted from the .FITS files. This returned an ADU of 1.66 per second, with an uncertainty of 0.02 ADU/second. The ADU scaled virtually linearly with the exposure time when a best-fit line is plotted over a chart of mean signal vs. exposure time.

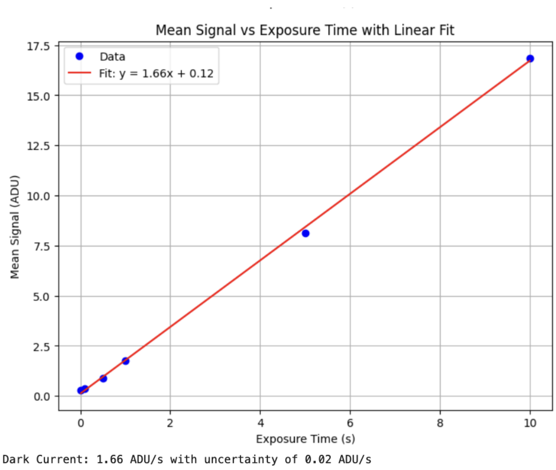

Figure 2: Mean Signal vs Exposure Time w/ Linear Fit

	Exposure Time (s)	Mean Signal (ADU)
0	0.01	0.27
1	0.10	0.36
2	0.50	0.90
3	1.00	1.77
4	5.00	8.15
5	10.00	16.86

Figure 3: Mean Signal vs Exposure Time Table

3.2 Read Noise

The read noise was also measured similarly to the dark current, using varying exposure times, but in the absence of a cover on the detector, so as to measure the noise generated in reading the charge from each pixel as it absorbs light. Plotting the read noise vs exposure time on a graph returned a chart that shows a positive correlation between read noise and exposure time, also showing that read noise was a dominant source of noise compared to the previously measured bias level and dark current.

```
Read Noise (RMS) for 0.005 ms: 7.54 ADU
Read Noise (RMS) for 0.015 ms: 9.07 ADU
Read Noise (RMS) for 0.02 ms: 10.45 ADU
Read Noise (RMS) for 0.025 ms: 11.64 ADU
Read Noise (RMS) for 0.03 ms: 18.05 ADU
Read Noise (RMS) for 0.035 ms: 22.38 ADU
```

Figure 4: Read Noise vs Exposure Time List

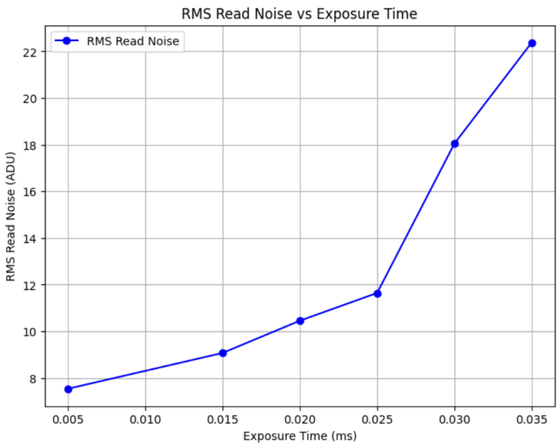

Figure 5: Read Noise vs Exposure Time

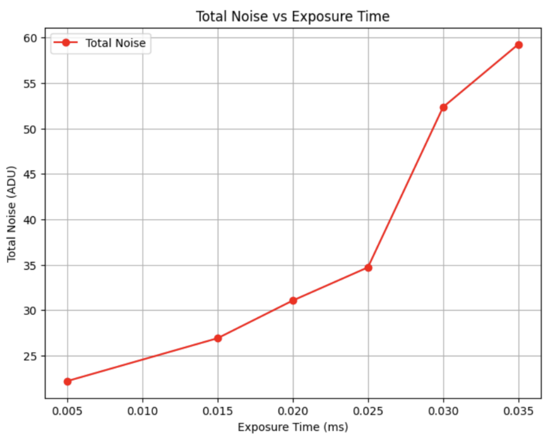

Figure 6: Total Noise vs Exposure Time Chart

4 Astronomical Measurements

Now that the noise levels in the detector have been properly assessed, they can be used to perform more accurate photometric and astrometric measurements on the images used in this lab. As will be seen later on in this section, the background noise (bias, dark current, read noise) can be subtracted from the overall noise in the object frame to return a final, ”cleaned” frame, effectively handling uncertainties in the measurements performed on the final frame.

4.1 Photometry

The main purpose of this subsection will be to measure the flux and flux uncertainty of the ”Great Red Spot” on an image of Jupiter.
The first step in measuring the flux and its uncertainty on an image is to first clean the image from noise, which can be done by following Equation 2, listed in the Appendix of this report. We collected an image of Jupiter using the lens system described in Section 2 of this report, which was again converted from a .raw file to a .FITS. We also collected a flat frame of a blank screen along with a dark frame, normalized to 1, which we used to return a final, cleaned frame of Jupiter, as shown below.

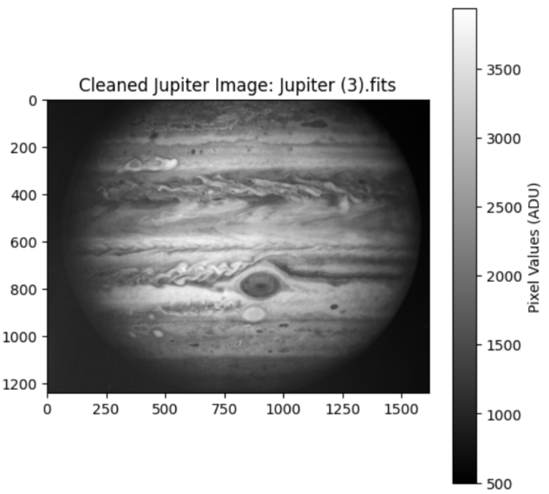

Figure 7: Jupiter Cleaned Image

We then zoomed in on the Great Red Spot using Python to locate the center of the spot on the image, and drew an ellipse around it.

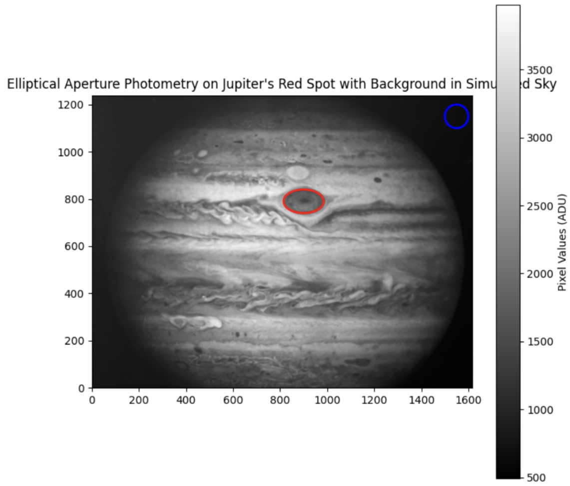

Figure 8: Jupiter Picture, Red Spot Circled

Using the photutils.aperture library to select the space inside the ellipse, (EllipticalAperture function) we plugged this into the aperture_photometry function from the same library, which returned to us the flux data of the spot. We also made use of the CircularAperture function to return a circle of the dark background to the top right of Jupiter for later analysis.

```
Total Flux in Elliptical Aperture (Red Spot): 25214324.47 ADU
Estimated Background Flux (from simulated sky): 691.82 ADU
Net Flux of Red Spot (after background subtraction): 15977265.82 ADU
```

Figure 9: Jupiter Flux Data

With the image now properly rendered, the noise levels assessed, and the photon noise from Jupiter and from the background of its image, we then were able to calculate the signal to noise ratio. To understand how this was calculated, please refer to Equation 1 of the Appendix section - a list of the variables included in the equation show the sub-calculations needed to compute the equation. All of this was done with the use of simple Python operators, using previous data values to substitute into each equation. This returned an SNR of 3114.71.

4.2 Astrometry

Finally, we can repeat the previous photometric methods on an image of a globular cluster to return the position and positional uncertainty of a specific star within the cluster.

Again, images of a globular cluster were captured using the lens system described in this report, and converted from .raw to .FITS. Once again using Equation 2 to clean the image, using a dark and a flat frame, we were able to return a cleaned image of the globular cluster, as shown below. It has already been zoomed in to focus on the desired star to assess for position, with a plus sign marking the centroid of the star.

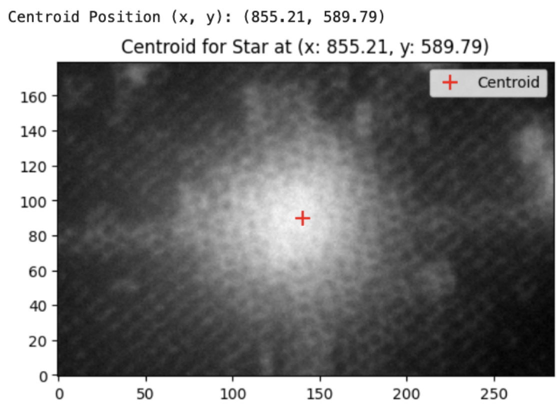

Figure 10: Globular Cluster Centroid Zoomed in (X on centroid)

Using the fitting.LevMarLSQFitter() function from the astropy.modelling module, we were able to fit the space taken up by the star onto a gaussian, which returned to us the FWMH (Full Width at Half Maximum). The FWMH is a measure of the width of a celestial object's image on a detector, defined as the width of the object's image at half of its maximum intensity. It is said that a high SNR/FWMH ratio is optimal for returning the best quality image possible. After running some python code as described below, we obtained an FWHM as shown in the image below.

```
Fitted Centroid (x, y): (848.81, 590.14)
Fitted FWHM (x, y): (258.91, 371.30)
```

Figure 11: Fitted Centroid, Fitted FWHM positions

We then ran some more code, this time using CircularAnnulus from the photoutils.aperture library to encircle the annulus of the star, shown in the image on the next page. This allowed to capture the flux of the star, and then its signal to noise ratio (SNR, of 724.10), following the same set of steps described in the previous section on Photometry - this time with an annulus instead of an ellipse. This returned to us a net flux of 1,868,103.24 ADU. Running some calculations on this flux will show that the star measured was a fairly bright one, at least relative to its neighbors in the globular cluster.

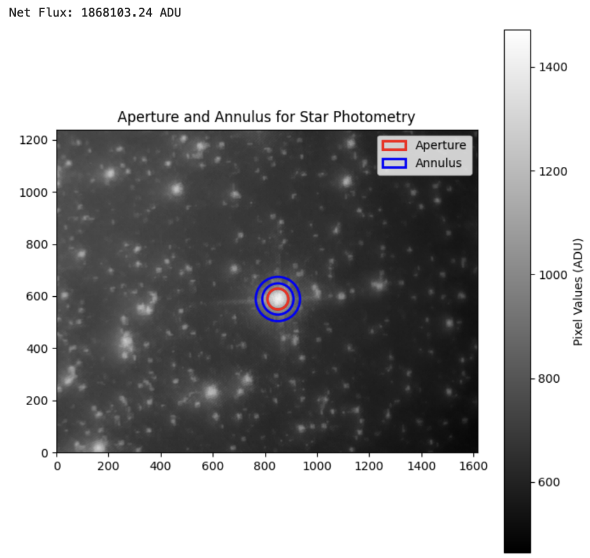

Figure 12: Globular Cluster Aperture and Annulus

Once our flux, signal to noise ratio, and FWMH were obtained, we were then able to plot a graph of the intensity of the star in ADU vs. the distance from the star's centroid in pixels, with a Gaussian overlaid on top. Using this Gaussian, we obtained the value of the FWMH, which turned out to be 185.01 pixels. Dividing the SNR by our obtained FWMH value gave us an astrometric error of 0.6018 pixels in the x-direction, and 0.8679 pixels in the y-direction - both of which are relatively small, thus confirming the success of our lab efforts.

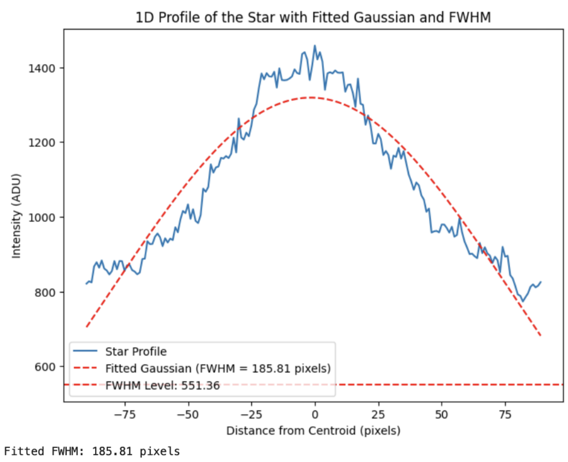

Figure 13: 1D Profile of Star w/ Fitted Gaussian and FWHM

5 Discussion/Conclusions

Throughout the course of this lab, my lab partner and I were facing with a bountiful amount of obstacles and pitfalls, mainly in the extraction of data from the image detector. We hit our first roadblock when taking images to assess the read noise, which we quickly realized to be due to light saturation, because the source of light we used in the images were too bright. Upon advice from Professor Jessica Lu, we switched to a method of using a white screen on a much dimmer phone screen, and thus were able to successfully assess the read noise. We also hit other minor roadblocks in our project, mainly during the astrometric and photometric portions of it, but we were quickly able to bypass those through extensive research online into available astronomy-related Python libraries and functions. Through our persistent and applied efforts, following strictly to the lab guidelines and instructions, we were able to set up our lens system in a way that ensured the highest signal to noise ratio possible by properly measuring the optimal distances between each component in our system. This allowed to perform further analyses on images of Jupiter and of a globular cluster, returning the flux and flux uncertainties of Jupiter's Great Red Spot and of an unknown star in the globular cluster. We finally combined the flux and signal to noise ratio for the cluster to return the SNR to FWMH ratio, which as stated previously, turned out to be at a relatively low (¡1 pixels in either direction) level of 0.6018 pixels in the x-direction, and 0.8679 pixels in the y-direction.

6 Appendix

6.1 Equations

Equation 1

$$\frac{S}{N} = \frac{S\sqrt{T}}{\sqrt{u_r^2 + S + \sum_{i=1}^{n}\left\{(B + D + \frac{R^2}{t}) + \varepsilon_D\left(D + \frac{R^2}{t}\right) + (1+f)^2\varepsilon_B\left(B + D + \frac{R^2}{t}\right) + (1+f)^2\varepsilon_D\left(D + \frac{R^2}{t}\right)\right\}}}$$

Equation 2

$$\text{FINAL FRAME} = \frac{\text{OBJECT FRAME} - \text{DARK FRAME}}{\text{FLAT FRAME} - \text{DARK FRAME}}$$

The variables included in Equation 1 are defined as follows:

- R - read noise
- S - photon noise on the signal, from the object in the image
- B - photon noise on the signal, from the image's background
- D - dark current signal
- T - t_{n_O} (the total integration time accumulated on the object frames)
- f - the ratio of the source signal to the "background" signal per pixel
- ε_B - $\frac{n_O}{n_B}$ (the ratio of the number of object frames to background frames)
- ε_D - $\frac{n_O}{n_D}$ (the ratio of the number of object to dark-current frames)
- u_r - "the average, over n pixels, of any residual" - Lab instructions were unclear, sentence seems to be cut off

6.2 Python Libraries

- matplotlib.pyplot
- numpy
- astropy.io (fits)
- astropy.modelling (models, fitting)
- struct
- glob
- scipy.stats (Poisson)
- scipy.optimize (curve_fit)
- pandas
- photutils.aperture (EllipticalAperture, aperture_photometry, CircularAperture, CircularAnnulus)
- photutils.centroids (centroid_com)
- photutils.detection (find_peaks)

6.3 Images

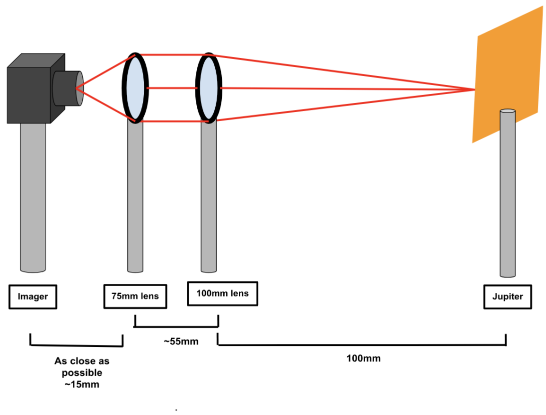

Figure 14: System Design

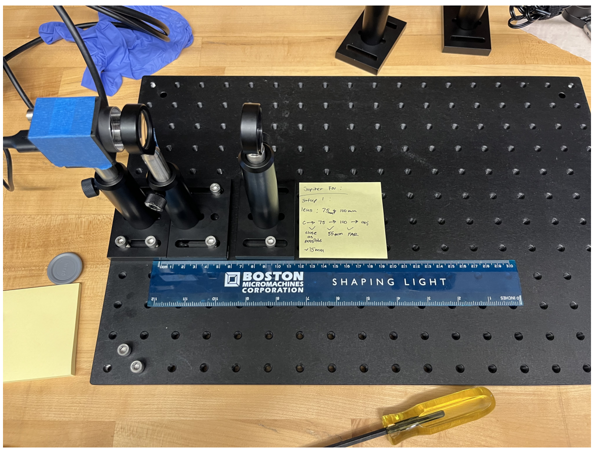

Figure 15: Imager System

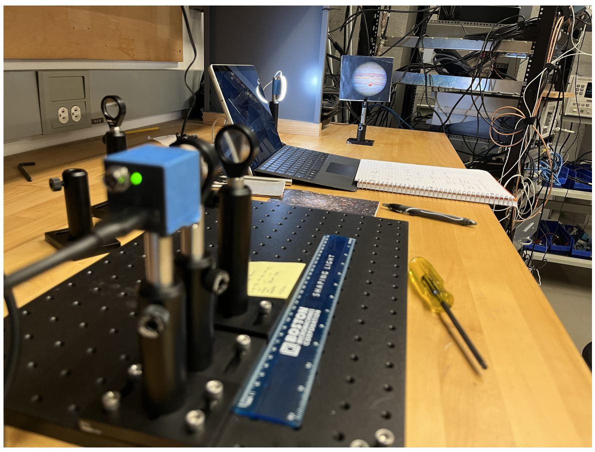

Figure 16: Imager System

7 Acknowledgements

I would like to take the time to thank my lab partner, Levi Galvan, for his persistent efforts in this lab, making major efforts in sourcing the optimal Python libraries and modules to bring our lab results to fruition, along with other strong efforts in various other aspects of this lab. We were able to effectively coordinate our availabilities to spend as much time as possible working on this lab together, to ensure that our efforts were up to par with each other. I would also like to thank professors Jessica Lu and Alan Chew for their excellent advice and guidance throughout this lab, and the Astronomy Department at UC Berkeley for providing us with such an enriching lab experience. Finally, thank you to the reader of this report, I hope that I was able to concisely communicate and portray my lab results to you.