

Development of Spectrometer Software for Ti:Sapphire Laser

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Abstract

The College of Saint Benedict and Saint John's University Physics Department has worked with and built spectrometers aimed at measuring laser outputs. Kaitlyn McKenzie ('23) sought to build a low cost spectrometer in pursuit of measuring the output spectrum of a mode - locked Ti:Sapphire laser. In her project she built a physical model that utilized a diffraction grating and USB camera to capture wavelengths. In my project, I push her project further by replacing the diffraction grating with a lower density grating and building a software package with the intention of capturing and displaying the spectral data. The development and testing of this software package comprised most of the work on this project. This program evaluates the USB camera input as a matrix of pixels composed of input intensities ($0 - 255$). It then culminates this data into usable information for the user by representing the input intensity as a function of the laser wavelength.

1 Introduction

Spectrometers are instruments built to analyze input light. This process yields many useful applications across chemistry, physics and biology. Light behaves predictably when traversing through mediums or reflecting off of materials. As a result, information regarding the material and light can be deduced from the information a spectrometer provides. In McKenzie's physical model, she utilizes a Littrow configuration. [1]

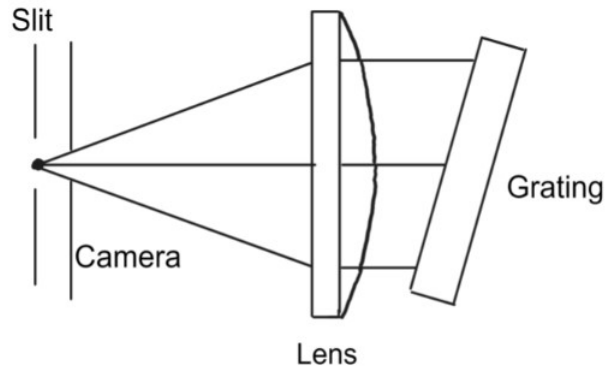


Figure 1: Physical set up inside of the spectrometer. Input light is diffracted off of the grating, which then is focused upon a USB camera.

Input light is diffracted differently based upon its wavelength according to:

$$d \sin(\theta) = n\lambda \quad (1)$$

Of course, white light and often many sources of light have a bandwidth of input light colors [2]. Due to this, a spectrometer can be built with a camera and a diffraction grating. The camera captures the first order diffracted light reflected off of the grating. This order would correspond to the β_1 angle in figure 2. To adjust the observational wavelengths, one must adjust the grating such that the first order light strikes the camera in the center.

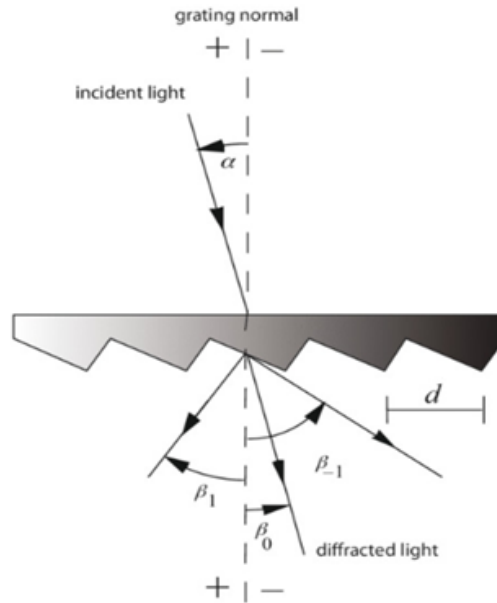


Figure 2: Diffraction grating geometry. Input light is reflected at an angle based upon the wavelength.

The camera captures the amount of incident light that is hitting each pixel and relays that information to some user as shown in figure 3. In order to capture the bandwidth of interest for the Ti:Sapphire laser (750 – 850nm), a grating with a lower groove density was employed.

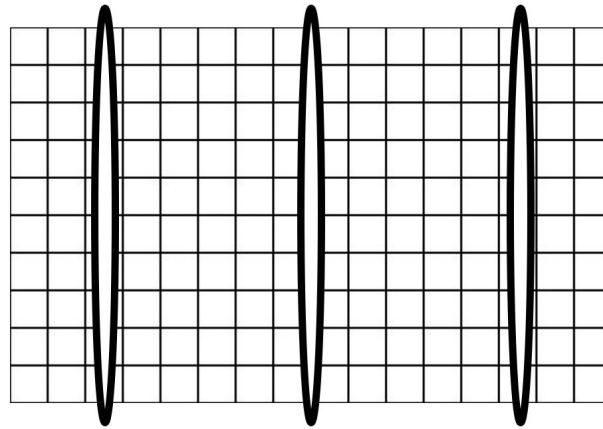


Figure 3: Pixel representation of USB camera with intensity bands along columns. The column at which the light hits the camera can represent the wavelength of input light.

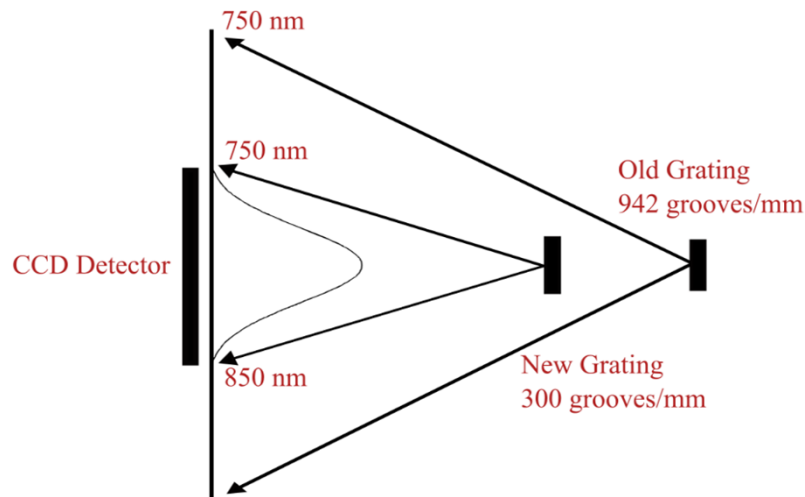


Figure 4: This diagram shows a comparison of the old diffraction grating and new diffraction grating. The old diffraction grating had 942 grooves per millimeter while the new diffraction grating has 300 grooves per millimeter. The reduction in groove density allows for the bandwidth of interest (750 nm – 850 nm) to be fully on the camera detector.

A program was made to digest input data from the camera to a spectrometer output. The input was treated as a two-dimensional array of float values representing the intensity of light on each pixel of the camera. Then, from this information, the middle rows representing the

horizontal lines on the camera were acquired. This data was then summed which represented the x wavelength axis of a spectrometer. A one-dimensional array of summed intensity values was then plotted as a function of pixel location.

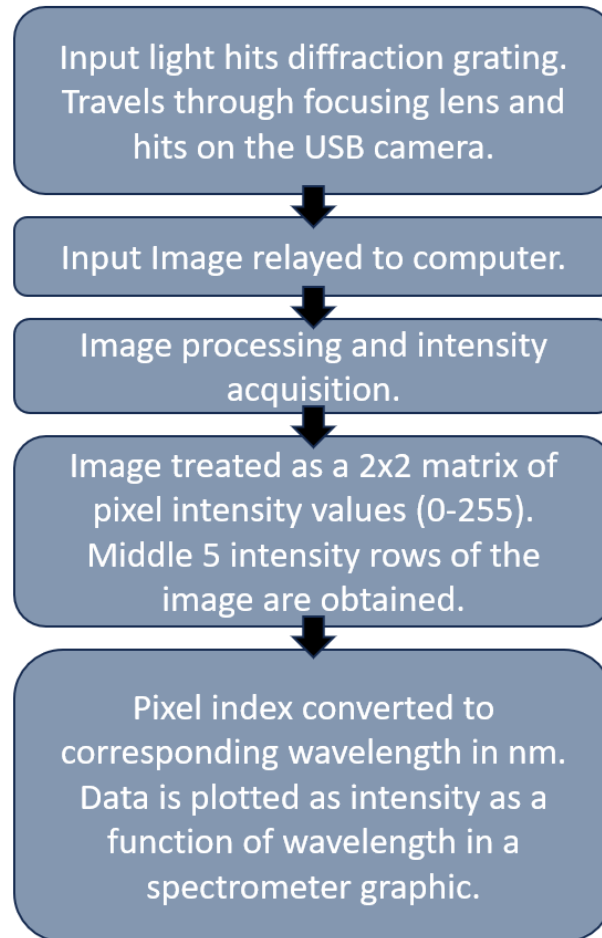


Figure 5: Flow diagram of spectrometer software from input of USB data to output.

Calibration took place subsequent to program construction. In this process, different reliable and coherent light sources were used to identify which pixel corresponded to an input wavelength. In turn, the program was configured such that the input light was converted straight to intensity as a function of wavelength. Figure 5 outlines the steps in the software

from the light hitting the USB camera to the spectral output. This project focused on building usable and robust software for a previously constructed spectrometer. The software is aimed to allow students to monitor the spectral information for the Ti:Sapphire laser and understand how the spectral output changes between its continuous wave operation and its mode-locked pulsing operation.

2 Design and Testing

The primary design efforts went into the software aimed at converting the input into a tangible interface for a user. LabVIEW was used as the chosen software programming environment. LabVIEW is a software mechanism that allows a user to build programs with given functions and packages. These programs can be implemented in subsequent programs through virtual instruments (VI's). LabVIEW uses the VI as a way to package a set of instructions into a module. A VI would be analogous to a function in traditional programming languages. The goal of this program was to integrate it into an existing interface built by Greg Taft. His existing package works with the Ocean Optics spectrometer that the CSBSJU Physics Department already owns. It functions with inputs given from the commercial spectrometer. In order to implement it with the project spectrometer, a sub VI was made to convert the primitive data output from the USB camera to data the program could handle. The first task of the program was to initialize and capture an input image (figure 6). This was done using an existing package in LabVIEW called "Imaq" and their vision acquisition function. This initializes and grabs an image from a camera that the software has access to. After this, the software has the capacity to take photos on some camera registered in "Imaq". It also offers error handling functions that might occur.

Examples of errors encountered might be invalid camera name and invalid image format.

The error functions then throw a message to the user indicating the problem.

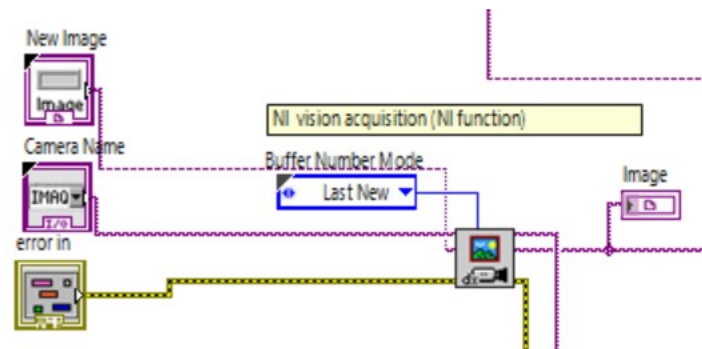


Figure 6: Initialization of camera function and acquisition of an image. This step allows the program to access the computer's built-in camera or an input camera through a USB port.

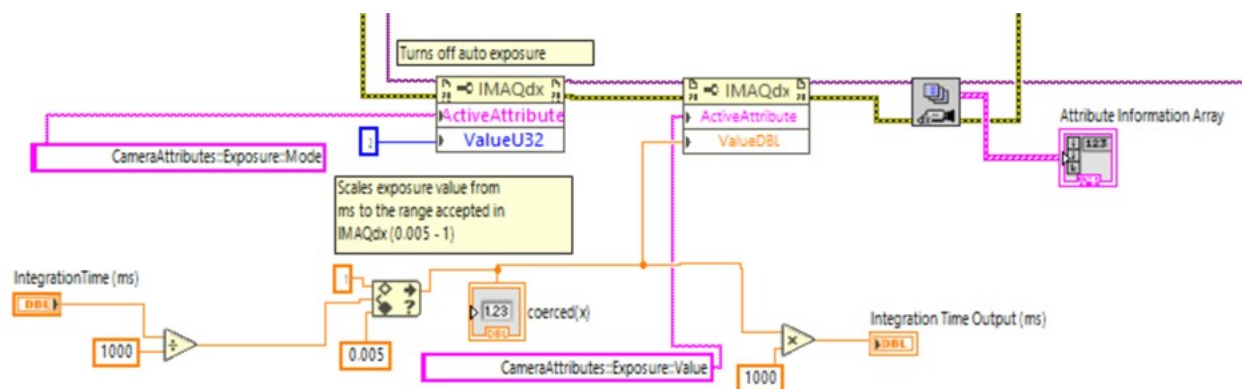


Figure 7: Exposure / shutter speed change. This section of the program takes in the integration time from the user and converts it into a exposure value that is coerced within the LabVIEW accepted range. This value represents the amount of light the aperture of the camera accepts upon image acquisition. The more light let in results in a higher sensitivity used with low intensity light sources.

In the developmental phase and during initial testing, a paramount consideration revolved around integrating a camera functionality with the ability to manipulate exposure values. The rationale behind this imperative feature stemmed from the potential of direct laser light to induce over stimulation or saturation within the camera system, where individual

pixels could reach their maximum intensity thresholds. By implementing the capability to adjust exposure values (figure 7), the system aimed to mitigate these challenges, facilitating a more precise and controlled incidence of the laser beam without encountering issues of pixel saturation.

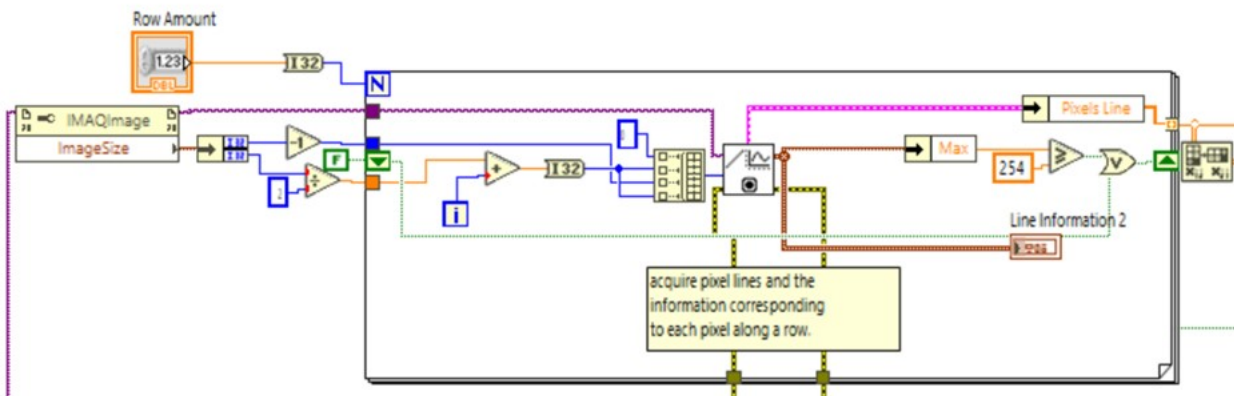


Figure 8: Adjustment of row acquisition. This section allows the user to change the amount of rows that will be added up for the intensity as a function of wavelength. It utilizes several default National Instruments (NI) functions that extract various information about the pixel intensities. It then displays this information for the user to examine.

In the pursuit of acquiring vital information pertaining to intensity values, a dedicated row acquisition section, as depicted in Figure 8, was implemented. This pivotal component facilitated the program in extracting pertinent data concerning the middle pixel rows and their associated intensity values. To further refine the resolution, a process of summation was employed to aggregate these intensity values. This strategic approach aimed to augment resolution by endowing the program with adaptability and resilience, empowering it to effectively navigate and accommodate the variability inherent in imperfect light sources. Following this procedure, the pixel intensity values undergo scaling using the values obtained during calibration, as illustrated in Figure 9.

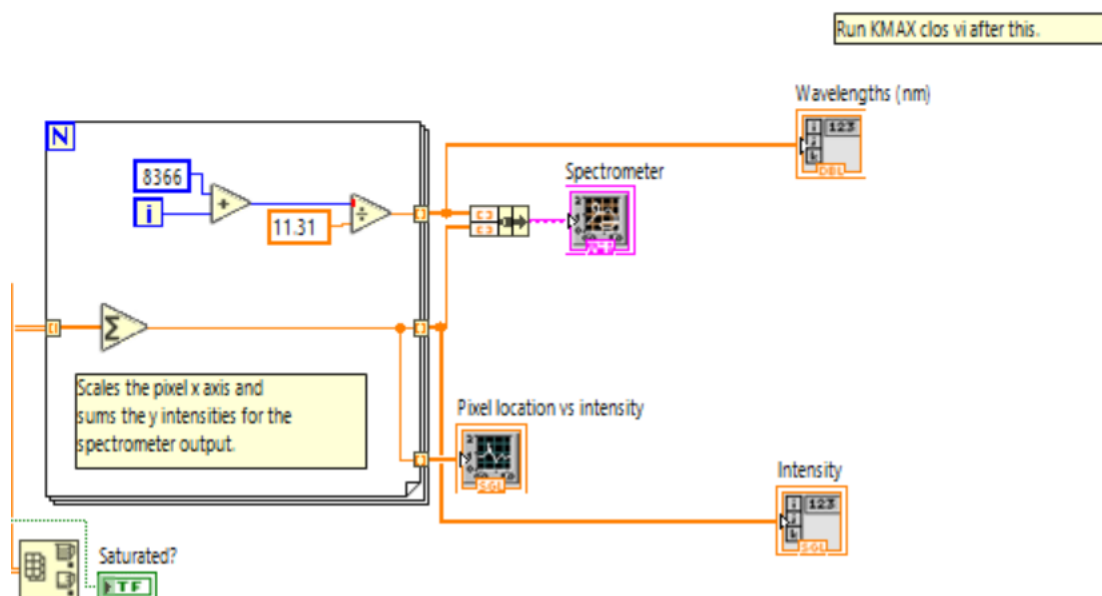


Figure 9: Scaling of intensity values. This section scales the pixel values using proper adjustment parameters derived from calibration.

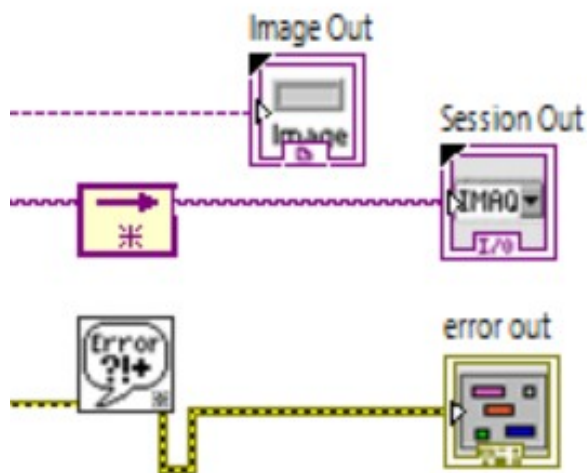


Figure 10: Error handling functions. This aborts the program upon error conditions.

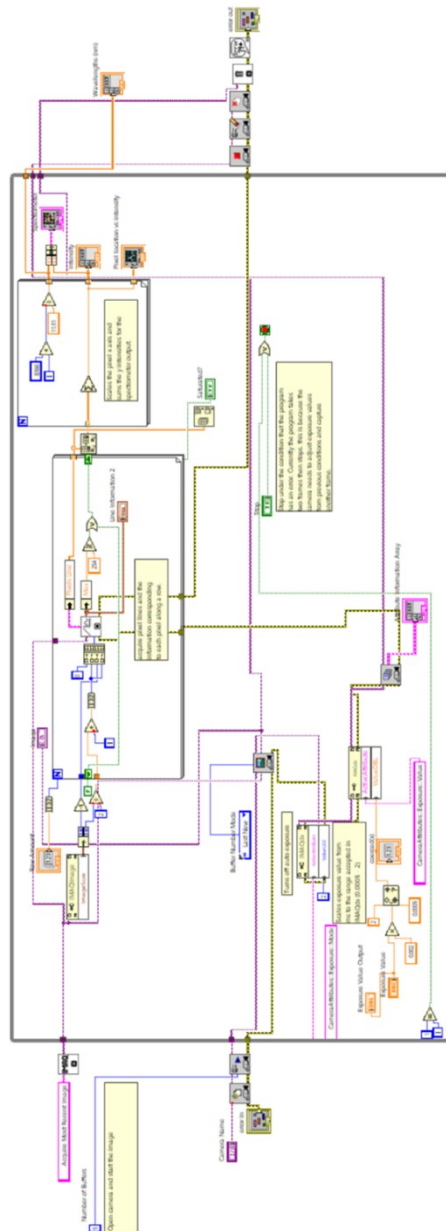


Figure 11: LabVIEW spectrometer block diagram. This VI was used as a sub – VI for the final interface. This takes in an input image -> extracts the 2 - dimensional array representing the intensities of each pixel -> converts pixel index into wavelength -> plots the intensities as a function of wavelength.

Testing the spectrometer software involved a systematic approach aimed at ensuring its

accuracy and reliability in wavelength measurement. One fundamental aspect of this testing process was the utilization of known wavelengths as reference points. By inputting light sources with precisely known wavelengths into the spectrometer, it was possible to evaluate how accurately the software could identify and quantify these wavelengths. In the calibration process, it was opted to utilize a range of diode lasers sourced from the undergraduate research office. These lasers were carefully selected to span the desired wavelength range of 750 to 850 nm, ensuring comprehensive coverage for use purposes. Specifically, the testing included wavelengths of 847.2 nm, 832.6 nm, 780 nm, and 750 nm in the selection. Given their diode nature, it's important to note that these lasers inherently carried uncertainties as specified by the manufacturer. However, despite these inherent uncertainties, the approach to capturing output intensities resulted in readings with relatively low uncertainty. This was largely due to the capabilities of the program, allowing it to accurately discern which pixel registered the most significant intensity reading, thus minimizing any potential measurement discrepancies. Upon inputting light with known wavelengths, the software generated output intensities corresponding to each wavelength detected. These output intensities were then carefully analyzed to ascertain their correlation with the expected values. Any discrepancies between the known wavelengths and the wavelengths identified by the software were meticulously examined to pinpoint potential sources of error. To calibrate the spectrometer software and establish a conversion factor from pixel location on a USB camera row to wavelength, a series of systematic experiments were conducted. The output intensities obtained from the known wavelengths were plotted against their corresponding pixel locations on the USB camera row. This allowed for the visualization of the relationship between pixel location and wavelength. By analyzing the plotted data, a proper slope and conversion factor could be determined, enabling accurate conversion of pixel location to wavelength.

This calibration process was crucial for ensuring the precise measurement of wavelengths in subsequent experiments and real-world applications. Overall, the testing of the spectrometer software involved a comprehensive evaluation of its ability to accurately identify wavelengths using known references. Through meticulous analysis and calibration, the software could be optimized to deliver reliable measurements essential for various scientific and industrial purposes.

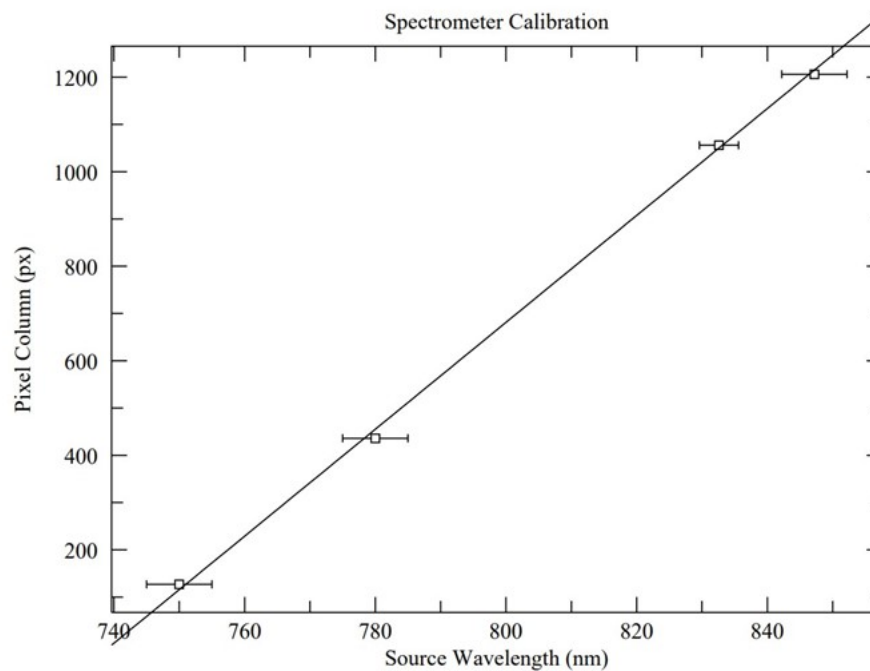


Figure 12: Calibration data for finding conversion factor. Pixel column plotted as a function of known wavelength. This allowed for a conversion factor to be implemented into the program.

3 Data and Results

Following calibration, the software underwent testing with the Ocean Optics commercial spectrometer, a crucial step in ensuring accuracy and reliability. This testing procedure

utilized the Titanium-doped Sapphire (Ti:S) laser in two distinct modes: continuous wave and pulsed operation. In pulsed operation, the Ti:S laser emitted light across a spectrum spanning approximately 780 to 810 nm. This specific bandwidth is frequently employed in various undergraduate laboratory experiments and research endeavors due to its versatility and relevance in optical studies. Conversely, the continuous wave operation of the Ti:S laser was a very narrow peak centered around 790 nm. Unlike its pulsed counterpart, continuous wave operation did not involve the accumulation of wavelengths into pulses of light using prisms. Instead, it emitted a singular wavelength, providing a consistent and stable source of light for transmission and analysis. This mode is particularly useful for applications where a single, precise wavelength is required. By testing the software against these different operational modes and spectral ranges of the Ti:S laser, one could ensure its effectiveness and compatibility with diverse experimental setups and research needs. Figures 13 and 14 illustrate the completed interface displaying the spectra for the user.

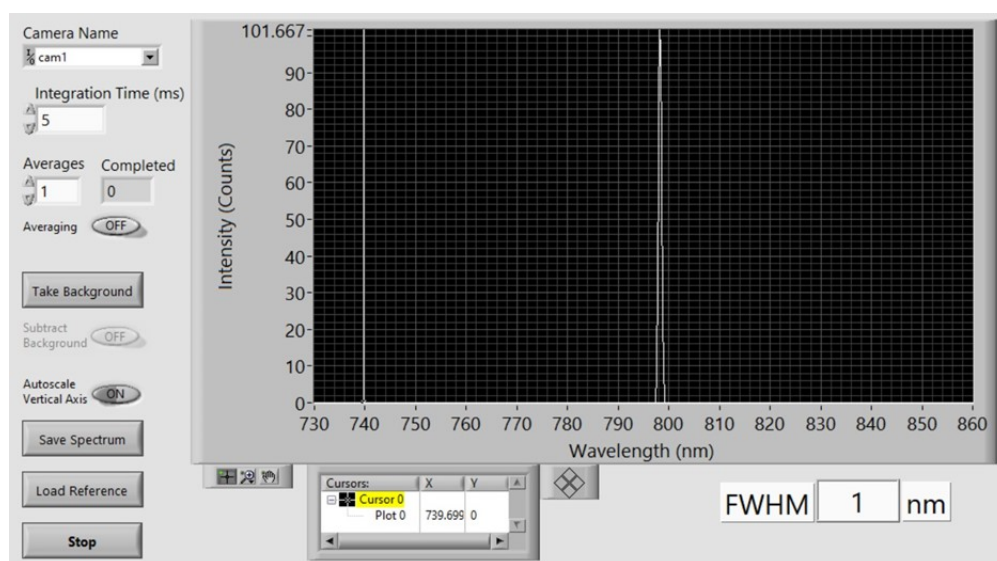


Figure 13: “KMAX” spectrometer software Ti:S CW operation.

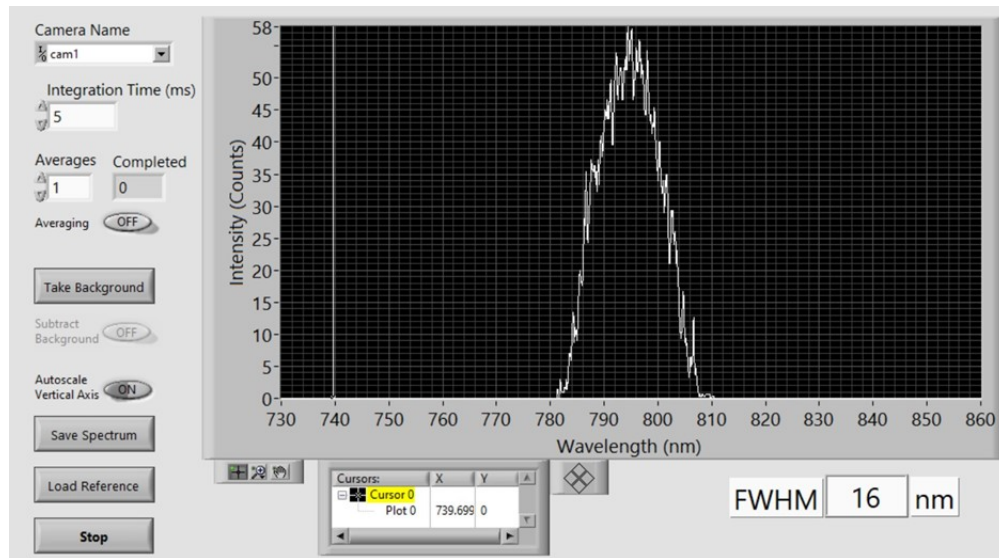


Figure 14: “KMAX” spectrometer Ti:S pulsed operation.

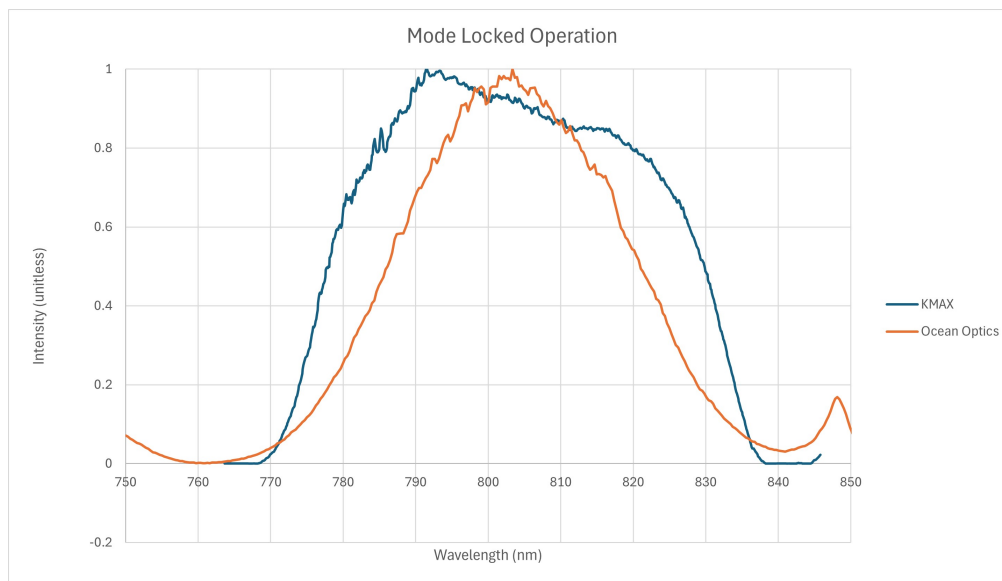


Figure 15: Mode locked comparison between Ocean Optics spectrum and KMAX. Both outputs were normalized by dividing each data point by the maximum output. This allowed for easier comparison.

In mode locked operation, the KMAX software has a slightly larger bandwidth. Wave-

lengths appear to be relatively equally intense throughout the bandwidth. This error likely came from a slight misalignment in the slit. As light enters the misaligned slit, it hits the camera with a slight angle and slightly misrepresents the intensity of the wavelength. The slit can be adjusted to avoid this problem.

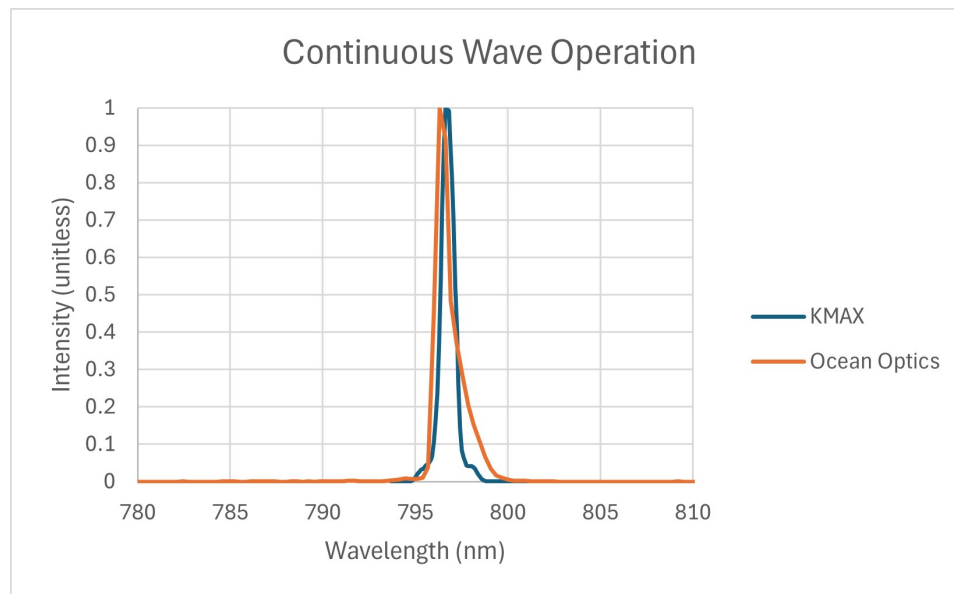


Figure 16: Continuous wave operation comparison between Ocean Optics and KMAX. Outputs from both were normalized in the same way as in figure 15.

The "KMAX" software replicated the Ocean Optics within roughly 0.3 nm. The extra noise sensed in the Ocean Optics software is filtered out with the a lower sensitivity in "KMAX" acquisition. Both pieces of software allow for integration time adjustment. This indicates how often the software will acquire an image. In the case of KMAX, it converts integration time into an exposure value. This value is associated with how frequently the camera grabs an image. If the camera is saturated with light, the exposure should be lower and conversely higher if there is low incident light.

4 Future Work

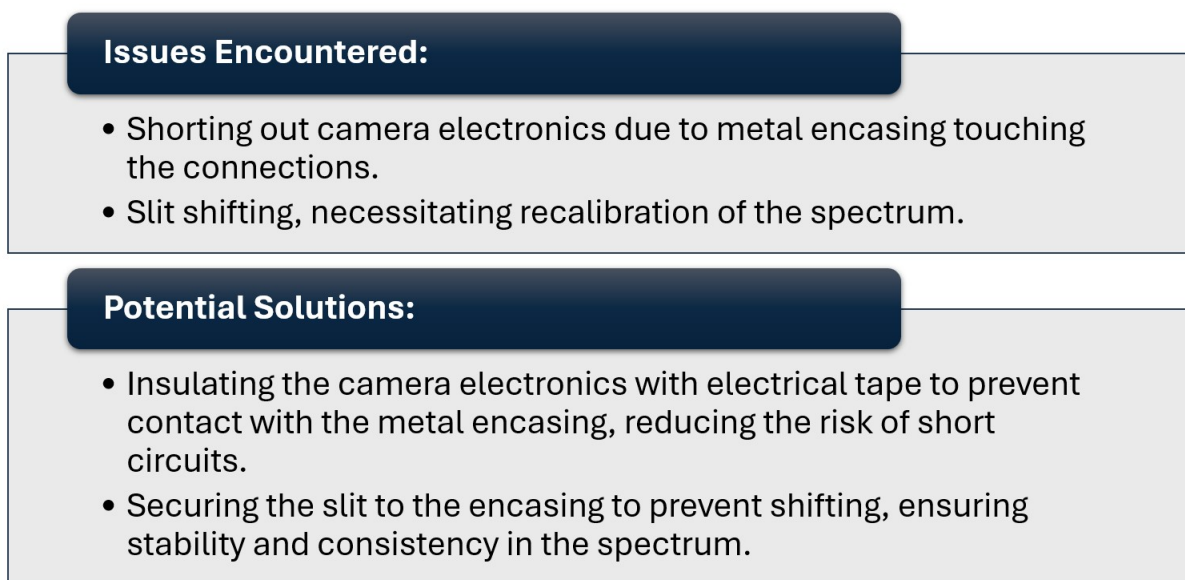


Figure 17: Future work graphic that outlines struggles and potential solutions for others to employ.

As undergraduate students move forward with utilizing the software, it's essential for them to maintain a solid grasp of several key elements, namely the calibration process, techniques for comprehending the spectrum, and the fundamental framework of the software. First and foremost, a thorough understanding of the calibration process is paramount. This involves familiarity with the various steps undertaken to ensure the accuracy and reliability of the software's measurements. Students should be well-versed in how different parameters, such as wavelength and intensity, are calibrated using reference standards and procedures. Moreover, they should appreciate the significance of calibration in minimizing errors and uncertainties in their experimental results. Additionally, students should possess proficiency in techniques for interpreting and understanding the spectrum. This entails the ability to analyze spectral data generated by the software and extract meaningful insights from it.

Understanding concepts such as peak identification, spectral resolution, and signal-to-noise ratio is crucial for effectively interpreting spectral information and drawing valid conclusions from experimental data. Furthermore, students should have a solid grasp of the basic framework of the software. This includes familiarity with its user interface, navigation tools, and data analysis functionalities. By understanding how to navigate the software efficiently and leverage its capabilities effectively, students can optimize their workflow and maximize their productivity in conducting experiments and analyzing results. Overall, by keeping these key aspects in mind - the calibration process, techniques for understanding the spectrum, and the basic framework of the software - undergraduate students can enhance their proficiency and confidence in using the software for their research endeavors. This foundational knowledge will not only enable them to conduct experiments more effectively but also contribute to their overall growth and development as researchers in their respective fields.

5 Conclusion

The KMAX software project introduced an innovative method for capturing wavelengths using a USB camera, seamlessly integrating it with pre-existing software. This integration served as a vital interface between users and the Ti:S laser, enhancing usability and functionality. The project encompassed several key stages, including the development of a column acquisition function, calibration, and rigorous testing procedures. These sequential steps were essential in ensuring the effectiveness and reliability of the software. Firstly, the column acquisition function was meticulously designed and implemented to enable efficient and accurate data capture from the USB camera. This function played a pivotal role in facilitating the seamless interaction between the camera and the software, enabling users to

acquire precise wavelength information with ease. Subsequently, calibration procedures were conducted to fine-tune and optimize the performance of the software. Calibration ensured that the software accurately interpreted and processed data captured by the USB camera, minimizing errors and discrepancies in wavelength acquisition. Finally, rigorous testing was carried out to validate the functionality and robustness of the software under various conditions and scenarios. This comprehensive testing phase helped identify and rectify any potential issues or bugs, ensuring that the software met the highest standards of performance and reliability. Overall, the implementation of the KMAX software project provides users with a sophisticated and user-friendly interface for interfacing with the Ti:S laser. Additionally, this proved the ability for undergraduates to build and test lab equipment inexpensively.

References

- [1] Kaitlyn McKenzie. “Senior Physics Thesis”. In: *College of Saint Benedict and Saint John’s University* 1.3 (2023), pp. 1–20.
- [2] Frank Pedrotti. *Introduction to Optics*. Addison-Wesley, 2007.