Senior Capstone: Polarization Dispersion for Imaging Spectrometry

David Oluwagbemi
Motion Picture Science
Rochester Institute of Technology
Rochester, New York 14623
Email: ddo7311@rit.edu

***Abstract*—This is a senior capstone exploring an approach to constructing an imaging spectrometer through the use of polarization as opposed to diffraction and refraction, based on interpreting the integrated spectral response of a single layer tuneable filter.**

1. Introduction

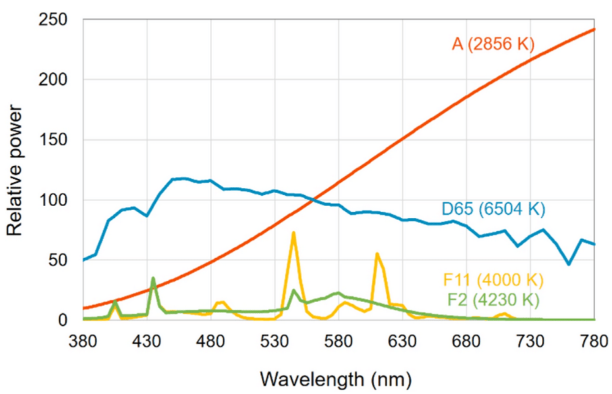


Figure 1: Spectral Power Distributions [1]

1.1. Imaging Spectrometer

A spectrometer is a device used for collecting information about the properties of a phenomenon over a specified range of values. An optical spectrometer focuses on capturing data about the transmission/reflection of light in order to provide the SPD(Spectral Power Distribution) of an observed material. The SPD serves as a graphical tool that displays the relative power of each wavelength's contribution to a light source, also described as hues, the wavelength of visible light corresponds to its color. There are currently two common ways that light sources are split into their component hues. Diffraction involves using a diffraction grating to split the wavelengths. Refraction uses a prism to take advantage of the speed of light as it crosses a medium varying in relation to its frequency. This paper proposes a method that makes use of polarization.

1.2. Polarization

Light is an electromagnetic wave. Fundamentally, this means that all light has electric and magnetic component fields that are perpendicular to each other, oscillating transverse and to the direction of a light rays travel. If one were to visualize a single ray of light as the z-axis of a graph, unpolarized light has multiple fields simultaneously existing 360 degrees around the z-axis within the same ray. Polarizing filters have the ability to "twist" a range of degrees into oscillating in a single direction to be transmitted to the other side of the filter in a falloff much like a cosine function when comparing input vs. output light relative to angle. When light is linearly polarized the phenomena that interact with it become more apparent some substances begin to display optical activity.

1.3. Lyot Filters

A single-layer Lyot filter is an optical setup that consist of a birefringent crystal of a fixed thickness between two polarizers. Lyot filters have tuneable spectral transmission, as the angle of the polarizer around the optical path (z-axis) changes relative to the birefringent material, the center wavelength of transmission through the setup is shifted. Birefringence is a property of anisotropic materials that causes them to split incoming light into two rays with different velocities, known as the ordinary and extraordinary ray, leading to double refraction. Birefringence and optical activity are distinct phenomena, though they may appear similar in certain experimental setups. The key difference lies in their underlying mechanisms. The Lyot filter exploits the birefringent properties of the crystal to achieve wavelength-selective filtering through interference, while optical activity focuses on the chirality of the material, which results in the rotation of the plane of polarization. Although the physical setup of a Lyot filter and an optical activity experiment may be similar—both involving a crystal between two polarizers—their purposes and effects are different, and they are considered separately in the literature. This paper will mainly focus on optical activity for its definition of phenomena. [4]

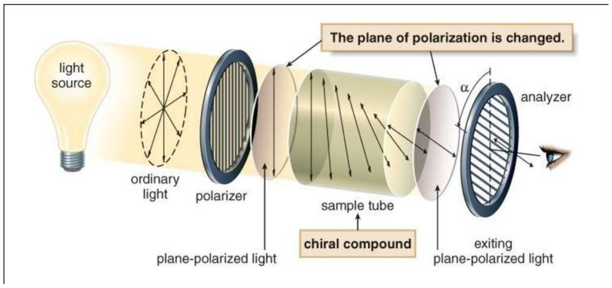


Figure 2: Chirality Setup [6]

1.4. Optical Activity

Optical activity is the ability of a substance to rotate the angle of polarization in light along the direction of propagation. This phenomena occurs in substances that have an asymmetrical atomic structure and therefore cannot be overlaid onto their mirror image due to having an innate handedness, also known as chirality. The rotation of light that passes through an optically active substance is directly proportional to its frequency, the shorter the wavelength the larger the change in angle. Similar to refraction, optical activity disperses light as a function of wavelength, however all wavelengths remain spatially superimposed on the same optical path rather than separated across multiple paths. Optical activity can also be observed in crystals that are optically active due to their crystal structure unlike organic compounds [3].

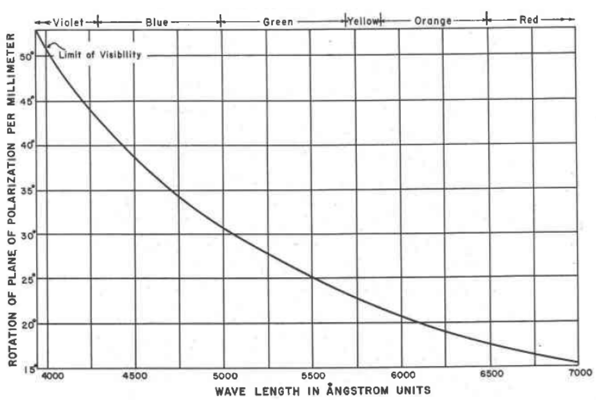


FIG. 2. Rotary dispersion in quartz.

Figure 3: Optical Rotatory Dispersion [2]

1.5. Quartz

Quartz has been chosen to be the most suitable medium for this application. It is a non-soluble, thermal resistant, strong, solid crystal with high transmission across a large range of wavelengths. The rotatory power of quartz is significantly high relative to most substances. High rotatory power allows larger changes in polarization angle over a shorter optical path, which is advantageous for this application in order to allow the spectrometer to be constructed with a smaller setup. Optical activity is graphically represented by ORD (Optical Rotatory Dispersion) Fig.3. By observing ORD's it becomes apparent that organic compounds can rotate some wavelengths clockwise while simultaneously rotating others counter-clockwise, which is difficult to characterize for this project. Quartz exclusively occurs in right-handed or left-handed crystal structures, offering a predictable separation of wavelengths. Additionally, the ability to successively layer left and right-handed quartz allows more dispersion without overlapping wavelengths, similar to the quartz monochromator in Hurlbut and Rosenfield's paper [2]

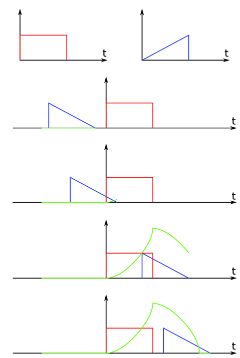


Figure 4: Convolution [8]

1.6. Deconvolution

Deconvolution is a mathematical operation that reverses the resulting convolution of two signals assuming one of them is known Fig.4. For the purposes of this paper, the transmission of a polarization filter along the domain of polarization angle will be shifted to perform a physical convolution and observe the output signal. Knowing the transmission of the polarizer falls off as a function of cosine squared will allow the resulting signal to be deconvolved to produce the original SPD of the light source.

2. Research and Design Objectives

The objective of this capstone project is to explore an approach to reversing the integrated spectral response of a tuneable filter sampled at numerous center wavelengths constructed using a single quartz crystal layer to derive the original spectral power distribution of a measured source, introducing the possibility for a novel method for spectral analysis. This spectrometer aims to address cost-efficiency concerns, potentially providing a more economical solution for researchers and institutions. In addition to cost considerations, the project seeks to explore the limits of accuracy achievable through this method and by establishing a direct relationship between polarization angles and corresponding wavelengths, seeks to observe the result of using polarization as a tuneable filter. A key focus is on studying the convolution of the cosine square intensity falloff formed by a polarization filter with the Spectral Power Distribution (SPD) of observed light across a range of angular degrees. Through these objectives, this project endeavors to promote innovation, affordability, and accuracy in spectral analysis for scientific research.

3. Theory and Methodology

3.1. Hypothesis

Initially, the transmission of the filter at any given position can be interpreted as a convolution between the cosine falloff function of the analyzer (1) and the original SPD.

$$I = I_0 \cos^2 \pi \tag{1}$$

The angle offset of the analyzer can be projected directly onto the wavelength domain based on the thickness of the quartz crystal. The resulting signal is the integrated response at each step/angle of the system. Deconvolution of the signal would be possible assuming a linear translation/shift of the functions center was the only change in the transmission. Knowing the spectral transmission $\tau(\lambda)$, Light source SPD(λ) and center wavelength λ_0 [7]:

$$I(\lambda_0) = \int_{\lambda_{min}}^{\lambda max} SPD(\lambda)\tau(\lambda - \lambda_0)\ d\lambda \tag{2}$$

This condition could not be met using a quartz crystal due to the nonlinear dispersion of optical rotation in quartz Fif.3, approximated as a function by Katzin [5].

$$R = \frac{127.02476}{\lambda^2 - 0.009584310} - \frac{119.77145}{\lambda^2 - 0.009169645} + \frac{3.413 \times 10^4}{\lambda^2 - 1.8163 \times 10^5} \tag{3}$$

Applying the cosine falloff to narrowly dispersed longer wavelengths and widely dispersed shorter wavelengths explains why the actual shape of the filter transmission more closely resembles a skewed cosine function with a that narrows as the center wavelength approaches moves from NIR to UV. Therefore, deconvolution would not be viable as a method unless a theoretical medium with linear dispersion was used. As a result an alternative reversal method based on matrix operations, pseudoinverse, was chosen to optimize the solution for the purposes of this experiment. If the spectral transmission of the filter was known at each step/angle, an inverse matrix transform could be approximated to return the original SPD from the integrated source.

3.2. Methodology

The filter was designed with a single right-handed quartz crystal between two linear polarizers suspended at the center of a gear system with a window for the detector at the center of the system. Measurements were taken at room temperature with a dark surround to minimize error from surrounding visible light and quartz birefringence property changes under thermal expansion. The quartz thickness closest to optimal dispersion for the range of 400nm-700nm obtainable for this experiment was 5.1mm thick. This provided a dispersion of approximately 175° across the spectral range of the device. Using Katzin's approximation it was determined that a change as small as 0.25° was required to change the center wavelength by 1nm. A NEMA 17 stepper motor with 200 steps per revolution is driving the system, with a single step being equivalent to 1.8 degrees. A gear ratio or 7.2:1 was used to achieve the 0.25° target, totaling 1440 steps per revolution for the device, however, only half a revolution is needed to measure the 180° range or 720 steps.

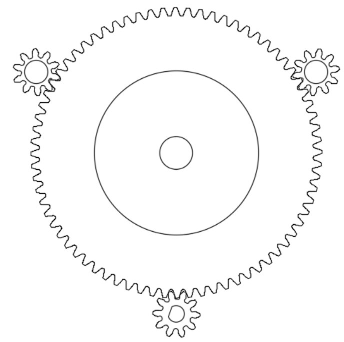
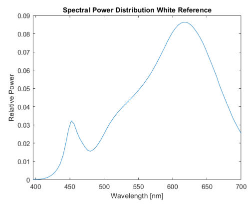


Figure 5: Gear Setup

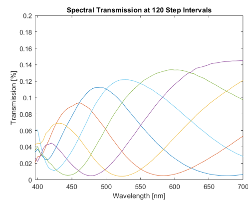
(a) Optical path through the transmissive center, driven by the smaller gear at the bottom of the diagram

Figure 6: Experimental Setup

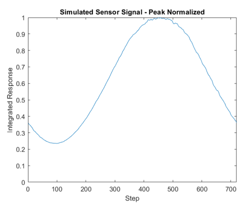
The ground truth transmission data necessary to validate the simulation and create the pseudoinverse was captured using the SpectraScan PR655 Spectroradiometer scripted over serial communication using A Raspberry pi 4B microprocessor in python. The microprocessor was also used to adjust the motor positioning and file management. The automated measurement of 1440 steps took 9 hours to complete predominantly due to the measuring time of the spectroradiometer. The device sensor used for capturing the integrated intensity was the Adafruit TLS2951 HDR Light Sensor and the elapsed time was approximately 10 minutes in order to capture the full revolution. Both measurement times can be reduced by half as only half a revolution is necessary and the full revolution was performed for redundancy.



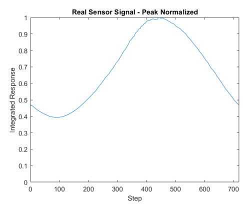
(a) Original SPD Source



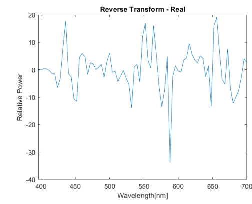
(b) Spectral Transmission



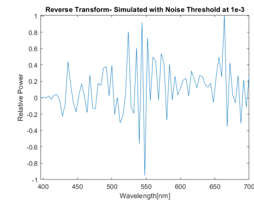
(c) Simulated Response



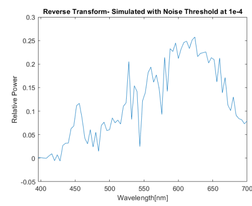
(d) Real Response



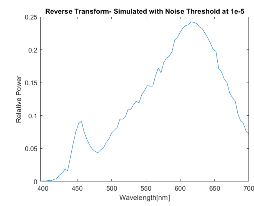
(a) Reversed Real



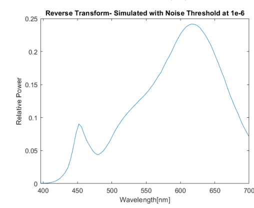
(b) Reversed Sim. 1e-3



(c) Reversed Sim. 1e-4



(d) Reversed Sim. 1e-5



(e) Reversed Sim. 1e-6

Figure 8: Simulation

4. Testing and Analysis

4.1. Preliminary Testing

The experiment was accurately modeled and simulated prior to capture of the ground truth and validated with the measured data. Key differences that can be observed between the simulated and measured transmission functions are the offset real world minimum transmission and the lack of higher peak absorption at low wavelengths in the simulated transmission. The sensor response was also simulated using the measured transmission data. The sensor spectral responsivity could not be characterized due to a lack of a monochromator, however, the known white reference data can be used to scale from the reversed spectra when transformed by the pseudoinverse successfully.

The peak-normalized simulated sensor and real world sensor integrated response look similar, with the knowledge that the real sensor signal is attenuated by the spectral responsivity of the detector. Applying the pseudoinverse to the simulated signal, successfully returns the original SPD, however, the same does not apply to the real world scenario. Upon further characterization, the cause of the transform failing to interpret the sensor signal is noise. When adding noise at successive orders of magnitude to the simulation the reversed signal begins to resemble the real world scenario. By visualizing these changes in Fig.8 the data asserts that a high minimum signal-to-noise ratio of 10,000:1 is required using the approach with this transform. The measurement data taken does not cross this threshold with its current setup.

5. Discussion and Conclusion

The simulation asserts that in ideal high signal conditions the mathematical approach to reversing an integrated signal response using the pseudoinverse of transmission is possible, however, the setup constructed is limited by noise. The experiment was conducted using a single layer dispersion that essentially selectively transmitted a series of wide bandpass filters, however, multiple layers can be implemented to achieve narrow bandpass filters. The implications for the progression of the mathematical reversal would be significantly more robust in a system that has more layers to narrow the bandpass of each step despite having higher absorptance overall.

6. Budget

Budget
Polarization Filters - $10
Z-Cut Quartz Window(Right-Handed) - $300
Adafruit TLS2591 - $6
Stepper Motor - $15
Perfect Diffuser - $20
Total - $351

References

[1] Relative spectral power distributions of the cie standard illuminants... Online, Year not specified. Accessed 20 September 2023.

[2] John L. Rosenfeld C.S.Hurlbut, Jr. Monochromator utilizing the rotary power of quartz, 1952. Accessed 20 December 2023.

[3] William Akers Bassett Elise Ann Skalwold. Quartz: A bull's eye on optical activity, March 20 2015. Accessed 20 December 2023.

[4] Alistair Gorman, David William Fletcher-Holmes, and Andrew Robert Harvey. Generalization of the lyot filter and its application to snapshot spectral imaging. *Optics express*, 18(6):5602–5608, 2010.

[5] Leonard I. Katzin. The rotatory dispersion of quartz, March 20 1964. Accessed 20 December 2023.

[6] Physics Open Lab. Right or left ? optical activity & chirality. Online, August 20 2019. Accessed 20 September 2023.

[7] Elena Nicolescu and Michael Escuti. Compact spectrophotometer using polarization-independent liquid crystal tunable optical filters. *Proceedings of SPIE*, 6661, 09 2007.

[8] Tapani Pihlajamäki. Figure 4.5: The calculation of convolution. two signals (red and blue)... Online, Year not specified. Accessed 20 September 2023.