Characterization of Linear Polarization with Cost-effective Techniques Using Quad-Polarization Polarimetry Camera

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This report presents the experimental investigation into the characterization of polarization utilizing a polarimetry camera equipped with quad-polarization filters. The study explores the feasibility of employing cost-effective alternatives for detecting polarization states, particularly in the context of space missions. Through a series of experiments involving a diode laser and optical components, polarization parameters such as the Stokes parameters were determined using data analysis techniques. The results demonstrate the efficacy of the experimental setup in accurately characterizing linear polarization and laying the groundwork for future advancements with more complex polarization states. **Keywords:** Polarimetry, Stokes parameters, Quad-polarization filters

1 Introduction

Polarization is a fundamental property of light that describes the orientation of the electric field vector as light propagates through space. Understanding and characterizing the polarization state of light is crucial in various scientific and industrial applications, particularly in remote sensing and imaging systems deployed in small space missions. The Stokes parameters provide a comprehensive method for describing the polarization state and are especially advantageous in scenarios where both cost and space are limited.

Traditional polarimetry systems, while highly accurate, can be bulky and expensive, making them less suitable for these space-constrained environments. As a result, there is a need for innovative solutions that provide reliable polarization measurements without the high costs and complexity associated with conventional setups.

This project explores the use of a quad-polarizer camera as a cost-effective method for characterizing linear polarization states of light. The quad-polarizer camera is a specialized imaging device equipped with four polarizing filters oriented at $0°$, $45°$, $90°$, and $135°$ relative to a reference axis. This configuration allows for the simultaneous capture of the four linear polarization components in a single snapshot, significantly reducing the need for complex moving parts and additional optical elements.

The objective of this project was to demonstrate that this compact and economical approach is not only effective for characterizing polarization states but also highly suitable for deployment in small space missions. By analyzing the intensity measurements from the camera, the Stokes parameters were calculated, providing a characterization of the polarization state.

The following sections detail the theoretical background, experimental setup, methodology, results, and conclusions of the project, highlighting the potential of this cost-effective polarimetry technique.

2 Theory

The Stokes vector $\mathbf{S}$ is a four-element vector that represents the state of polarization and is defined as follows:

$$
\mathbf{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix}
$$

Each component of the Stokes vector has a specific physical interpretation:

- S_0 represents the total intensity of the light.
- S_1 represents the difference in intensity between horizontally and vertically polarized light.
- S_2 represents the difference in intensity between light polarized at $45°$ and $-45°$ to the horizontal.
- S_3 represents the difference in intensity between right-handed and left-handed circularly polarized light.

In this project, a quad-polarizer camera was utilized to measure the four linear polarization components corresponding to $0°$, $45°$, $90°$, and $135°$. This type of camera allows for simultaneous capture of the different polarization states in a single snapshot, making it a highly efficient and cost-effective solution for polarimetry.

The intensity measurements obtained from the camera at these four angles are directly related to the Stokes parameters by the following equations:

$$
\begin{aligned}
I(0°) &= \frac{1}{2}(S_0 + S_1), \\
I(45°) &= \frac{1}{2}(S_0 + S_2), \\
I(90°) &= \frac{1}{2}(S_0 - S_1), \\
I(135°) &= \frac{1}{2}(S_0 - S_2).
\end{aligned}
$$

These equations allow us to express the Stokes parameters in terms of the measured intensities:

$$
\begin{aligned}
S_0 &= I(0°) + I(90°), \\
S_1 &= I(0°) - I(90°), \\
S_2 &= I(45°) - I(135°), \\
S_3 &= 0.
\end{aligned}
$$

Given that the polarimetry setup in this experiment is limited to linear polarization states, the Stokes parameter S_3 was assumed to be zero. The Stokes parameters S_0, S_1, and S_2 were then used to fully characterize the linear polarization states of the light.

This theoretical framework lays the analysis of the experimental data and validates the use of a quad-polarizer camera as a viable, low-cost solution for polarization measurements in small space missions.

3 Experimental setup

The experimental setup, as illustrated in Figure 1, was designed to characterize the linear polarization states of light using a compact and cost-effective approach. The setup consists of a diode laser as the light source; the laser beam was first collimated using a collimator to ensure a uniform and parallel beam profile.

Following the collimator, the beam passed through a linear polarizer, which served to define the initial polarization state of the light. This allowed for controlled variation of the input polarization state, which was crucial for the subsequent characterization process. In some tests, a quarter-wave plate was introduced after the linear polarizer to convert the linearly polarized light into circularly or elliptically polarized light, enabling the examination of different polarization states.

The light then entered the quad-polarizer camera, positioned at the end of the optical path. The camera is equipped with four polarizing filters oriented at $0°$, $45°$, $90°$, and $135°$ relative to a reference axis. This configuration allowed for the simultaneous capture of the four linear polarization components in a single snapshot, facilitating the rapid and efficient determination of the Stokes parameters..

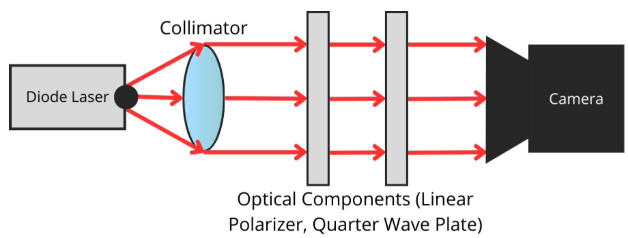

Figure 1: The setup utilized comprised a polarimetry camera (right) equipped with quad-polarization filters and a diode laser (left). The input beam was collimated and then directed through a series of optical components to manipulate the polarization state of the light.

4 Data Analysis

This section provides an overview of the experimental procedures conducted to characterize linear polarization. It outlines the steps involved in data collection, including the manipulation of optical components and the acquisition of polarization data using the polarimetry camera. The subsequent analysis, performed using Python's NumPy and Matplotlib libraries, focuses on calculating the Stokes parameters from the recorded sensor readings, with additional processing to enhance measurement accuracy. The procedures section serves as a guide for replicating the experiments and understanding the methodology employed in the study.

4.1 Data Gathering

The data-gathering process involved carefully adjusting the optical components and recording the polarization states using the quad-polarizer camera. The setup, as detailed in the previous section, allowed for the systematic capture of polarization data under various conditions.

To begin, the linear polarizer was manually rotated to different angles, and unsaturated images were captured at each position using the polarimetry camera. It was crucial to ensure that the captured images were unsaturated to avoid any data loss due to overexposure, which could lead to inaccurate polarization measurements. The quad-polarizer camera simultaneously recorded the four linear polarization components at $0°$, $45°$, $90°$, and $135°$ in each snapshot.

An example of the raw output images from the camera is shown in Figure 2. These images were subsequently processed to extract the intensity values needed for calculating the Stokes parameters. In some cases, a quarter-wave plate was added to the setup to generate elliptical or circular polarization states, allowing for a comprehensive characterization of the polarization behavior.

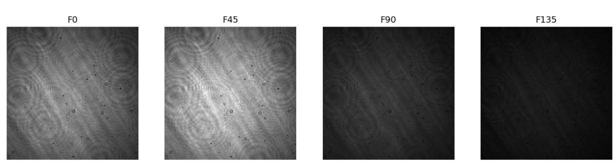

Figure 2: Sample output images from the polarimetry camera for linear polarization. The images correspond to the four polarization angles $0°$, $45°$, $90°$, and $135°$.

4.2 Data Processing and Code

The collected data was processed using Python, specifically with the NumPy and Matplotlib libraries, to determine the Stokes parameters for each polarization state. The following steps outline the data processing methodology:

1. **Background Noise Subtraction:** To enhance the accuracy of the measurements, background noise was subtracted from the recorded intensity values. This step was essential to ensure that the calculated Stokes parameters accurately reflected the polarization state of the light and were not influenced by external factors.

2. **Calculation of Stokes Parameters:** The intensity values corresponding to the four polarization angles were used to calculate the Stokes parameters S_0, S_1, and S_2, as outlined in the theory section. The calculation was performed using simple arithmetic operations in NumPy.

3. **Visualization of Polarization Ellipses:** The calculated Stokes parameters were then used to plot the polarization ellipses. This visualization step was performed using Matplotlib, allowing for a graphical representation of the polarization states. Figure 3 shows the polarization ellipses for linear polarization tests.

The following Python code snippet provides an example of how the Stokes parameters were calculated and visualized:

```
import numpy as np
import matplotlib.pyplot as plt

# Example intensity values
I_0 = ...
I_45 = ...
I_90 = ...
I_135 = ...

# Calculate Stokes parameters
S_0 = I_0 + I_90
S_1 = I_0 - I_90
S_2 = I_45 - I_135
S_3 = 0  # Assuming no circ pol

# Plotting polarization ellipse
theta = np.linspace(0, 2*np.pi, 100)
x = S_0*np.cos(theta) + S_1*np.sin(theta)
y = S_2*np.cos(theta) + S_3*np.sin(theta)

plt.figure()
plt.plot(x, y)
plt.title('Polarization Ellipse')
plt.xlabel('x')
plt.ylabel('y')
plt.grid(True)
plt.show()
```

This approach provided a straightforward yet powerful method to analyze and visualize the polarization states of light, demonstrating the effectiveness of this polarimetry technique for potential use in space applications.

5 Results

The analysis of the collected data provided valuable insights into the polarization characteristics of the investigated light sources. The primary focus of the study was on characterizing linear polarization, and the results demonstrated consistent and meaningful measurements for this polarization state, validating the effectiveness of the experimental setup.

5.1 Linear Polarization

The successful characterization of linear polarization was achieved through the systematic rotation of the linear polarizer and the use of the quad-polarizer camera to capture the corresponding intensity values at different angles. The calculated Stokes parameters for each test scenario closely matched the expected values, confirming the reliability of the setup.

Figure 3 illustrates the polarization ellipse for a test case with linearly polarized light. The results indicated a high degree of linear polarization, with the Stokes parameters S_0, S_1, and S_2 aligning well. This demonstrates that the experimental setup is highly effective in characterizing linear polarization states, providing consistent measurements.

5.2 Exploration of Circular and Elliptical Polarization

Attempts were made to explore circular and elliptical polarization by introducing a quarter-wave plate into the setup. The objective was to extend the study beyond linear polarization and investigate the setup's capability to handle more complex polarization states. However, challenges were encountered, particularly in achieving a stable and well-defined circular polarization state.

Despite these challenges, the experimental setup successfully captured some aspects of elliptical polarization. Figure 4 shows the resulting polarization ellipse when the quarter-wave plate was introduced. Although the results were not as conclusive as those for linear polarization, they provided initial insights into the behavior of the setup under these conditions.

5.3 Summary of Results

Overall, the results demonstrated that the setup is well-suited for characterizing linear polarization, with consistent and meaningful measurements that align with theoretical expectations. While the exploration of circular and elliptical polarization was less successful, the study lays the groundwork for future investigations into more complex polarization states. The findings highlight the potential for further optimization of the setup.

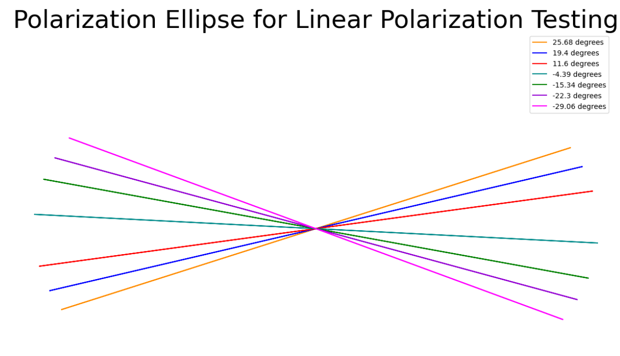

Figure 3: Polarization ellipse for a test case with linearly polarized light. The results show a high degree of linear polarization, with Stokes parameters consistent with predictions. Starting from the top angle, shifts in $10°$ on the linear polarizer were made; hence, obtaining $6° - 15°$ degree shifts between iteration.

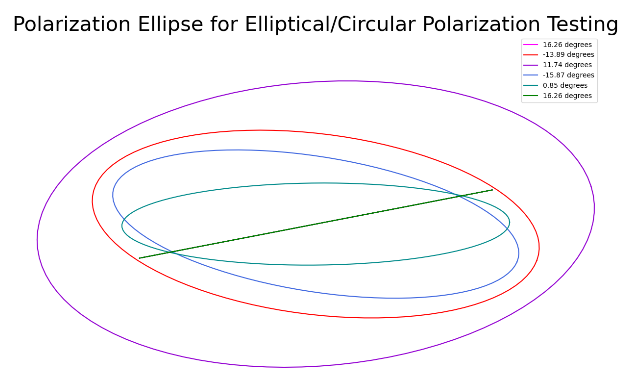

Figure 4: Polarization ellipse for a test case with linear polarizer locked at the $0°$ mark with $10°$ shifts on quarter wave plate (QWP). The results provided initial insights into the behavior of the setup with the quarter-wave plate introduced.

6 Conclusion

The experimental setup and analysis conducted in this study successfully characterized the linear polarization states of light, demonstrating the effectiveness of a cost-effective and compact polarimetry system suitable for small space missions. The use of a quad-polarizer camera allowed for efficient, fast, and accurate measurements of the Stokes parameters, providing a robust foundation for understanding the polarization characteristics of the investigated light sources.

While the primary success was in the characterization of linear polarization, the attempts to explore circular and elliptical polarization revealed challenges, particularly in achieving a stable circular polarization state. These challenges demonstrate the need for further refinement in both the experimental setup and the analysis techniques.

6.1 Proposed Future Work

To build on the findings of this study, several avenues for future work are proposed:

- **Error Reduction Techniques:** Implementing techniques such as flat fielding can help decrease measurement errors and improve the accuracy of polarization characterization. This involves correcting for non-uniformities in the camera sensor's response, leading to more precise data.
- **Exploration of Complex Polarization States:** Future studies should further explore complex polarization states, such as circular and elliptical polarization. This will require not only the use of quarter-wave plates but also a more refined approach to ensure that the retardation introduced by the wave plate is accurately captured.
- **Synchronized Snapshot Capture:** To properly ensure that retardation is captured by the cameras, it is critical that snapshots are captured simultaneously in the quad-polarizer camera. This can be achieved by developing software using the camera's SDK to trigger all polarization channels at the same time. Without this synchronization, any claims about retardation effects would be questionable.

These future directions are crucial for advancing the capabilities of the polarimetry system and ensuring that it can reliably characterize more complex polarization states.

6.2 Acknowledgements

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References

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