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False Degree of Linear Polarization using Imaging Polarimeters in Low Light Conditions

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PREFACE

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False Degree of Linear Polarization using Imaging Polarimeters in Low Light Conditions

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Abstract

Polarization improves target detection in images by improving the visibility of the target against its local background and reducing clutter detections [1]. However, in both indoor and outdoor testing, we observed regions in camera (visible and near-infrared) images where the Degree of Linear Polarization (DoLP) is unexpectedly high. We call this "false DoLP". Testing and modeling shows that DoLP increases as the intensity decreases. This can lead to false alarms, as the dark areas appear polarized. We will present images and data that illustrate the issue from indoor and outdoor testing. We will present a hypothesis to explain the data collected.

1. **Background**

Motivation: Polarization aids in contrast enhancement, clutter reduction, and provides shape and texture information. The motivation for this work is to quantify the benefits and limitations of using inexpensive, low size, weight, power, and cost cameras for this application. We used a visible near infrared polarization camera to explore and quantify the benefits and limitations of using polarization. During this process, we found a limitation, false DoLP that can introduce clutter into the polarization image. Figure 1 shows an image of an outdoor test with a Spectralon panel and a blackbody. We noticed polarization where we did not expect to see polarization. The technical background section explains why we do not expect to see polarization on a highly diffuse object using a viewing angle normal to the surface.

Technical background: John Schott presents a fundamental treatment of polarization in his book *Fundamentals of Remote Sensing*.[3] He presents a simplified explanation in section 4.3 that we repeat here for convenience of the reader. Four linear polarizers measure the incoming light, vertical (E_V), horizontal (E_H), 45 (E_{+45}) degrees and -45 (E_{-45}) degrees where E is scalar irradiance in W/m^2. The un-normalized Stokes parameters can then be calculated as:

$$S_0 = E_H + E_V$$
$$S_1 = E_H - E_V$$
$$S_2 = E_{+45} - E_{-45}$$

Where S_0 is the incident irradiance, S_1 is related to horizontal polarization, and S_2 is related to the 45-degree polarization. S_0 is often referred to as the thermal image when using imaging polarimeters.

We define the Degree of Linear Polarization as:

$$DoLP = \frac{\sqrt{S_1^2 + S_2^2}}{S_0}$$

We can think of DoLP as the percentage of the incoming light that is linearly polarized.

Highly diffuse materials such as Spectralon have multiple, random scattering centers that results in highly random polarization, i.e., polarization filters will pass the same intensity regardless of orientation. This results in S_1 and S_2 with mean values of zero. As a result, DoLP is minimized. The Fresnel equations show that the "s" and "p" polarization reflectances are equal at zero incidence angle [1]. "p" polarized light has an electric field polarized parallel to the plane of incidence, while the "s" polarized light is perpendicular to this plane. Thus, a viewing angle perpendicular to a surface should produce low DoLP provided the source is uniformly polarized.

2. **Outdoor, Indoor and Laboratory Tests**

Outdoors: We set up an outdoor test shown in Figure 1 with a variety of objects that we wanted to characterize. We noticed regions of unexpected brightness in the polarization image. We looked at the intensity and DoLP in two regions of interest, 1) the 5% Spectralon panel and 2) the face of the blackbody. We acquired data at one light level.

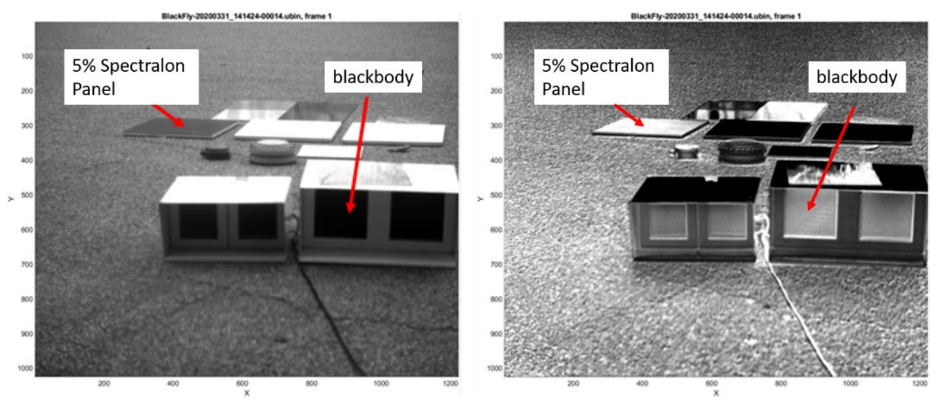

Figure 1 Outdoor Blackfly-S images showing intensity on the left and DoLP on the right.

We can see that there is high DoLP in both the Spectralon panel and the face of the blackbody. As stated previously, we do not expect high DoLP because the diffuse nature of the Spectralon panel should have low DoLP. In addition, the very low incidence angle on the blackbody should also produce low DoLP.

Indoors: We then set up a test indoors using the same Spectralon panel and blackbody. Figure 2 shows the intensity and polarization images from one frame. We acquired data at 11 distinct light levels. Both the dark Spectralon and the front face of the blackbody are very similar materials in the visible region, as both are diffuse reflectors with low reflectivity. Furthermore, both surfaces are oriented in a manner that is close to normal to the camera. With a highly diffuse surface, we expect little or no polarization as explained in the background section. Likewise, we expect little or no polarization from a surface with an incidence angle that is approaching zero as explained in the background section.

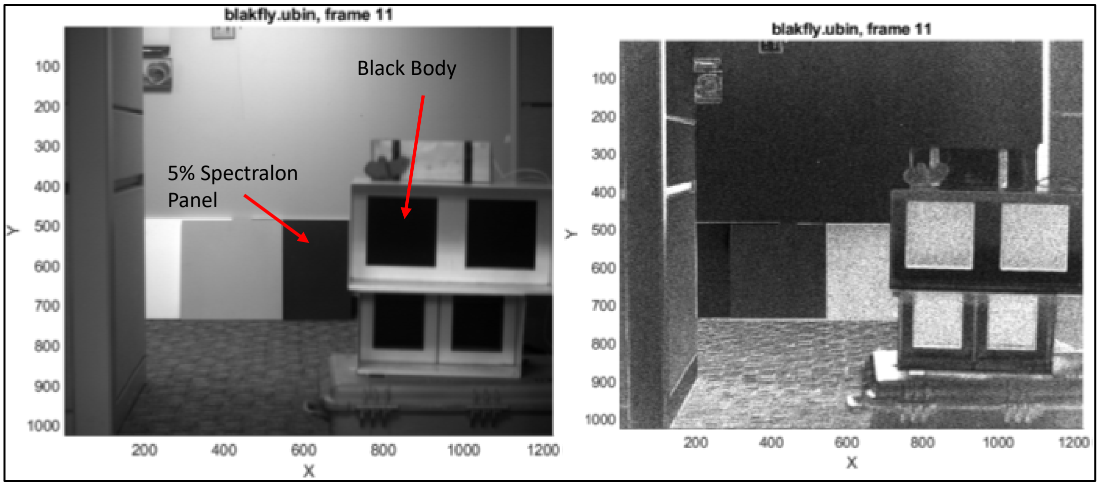

Figure 2. Indoor Blackfly S images showing intensity on the left and DoLP on the right

Figure 3 shows that, as the light level decreases the measured DoLP increases. For example, when S0 = 145 counts, the DoLP measured 31.5%.

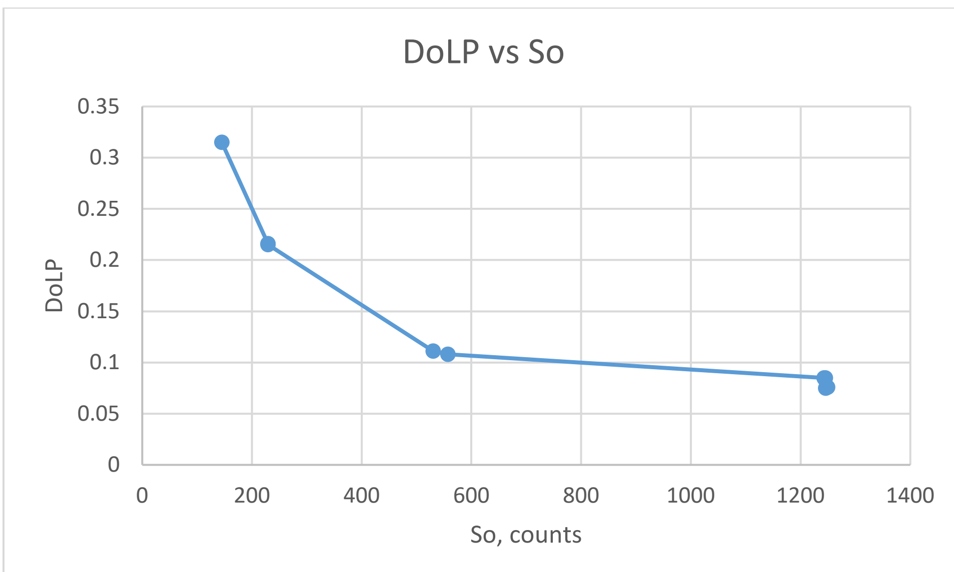

Figure 3. DoLP vs S_0 for the 5% Spectralon panel at various light levels showing that, as light level decreases, DoLP increases.

3. **Modeling**

We performed a modelling analysis to attempt to explain this phenomenon. We present our hypothesis in Appendix A. While the modelling shows increasing DoLP as intensity decreases, we do not have a specific connection between the measured characteristics of the imager in the camera and the measured DoLP results. Nonethless, we believe the observed high DoLP values associated with low light levels are a result of shot noise.

4. **Summary**

We have shown that false polarization regions can occur in visible near infrared imaging polarimeters. We can think of false polarization as additional clutter in the DoLP image. This includes both diffuse and specular surfaces. In addition, surfaces with an incidence angle near zero degrees display false polarization when the signal level is small. Modeling shows that, as the signal decreases, shot noise dominates and drives the DoLP to higher values. Future work will investigate practical methods to mitigate false DoLP in an operational scenario.

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[1] Pantuso, F., Bright, C., Harr, R., Polcha, M., & LaPointe, A. (2018). "IR Polarization for Natural Clutter Suppression." In *2018 IEEE Research and Applications of Photonics In Defense Conference (RAPID)* (pp. 1-2). IEEE.

[2] James R. Janesick. "Scientific Charge-Coupled Devices", SPIE press

[3] John Schott. "Fundamentals of Remote Sensing", SPIE press

Appendix A

We performed an analysis to explain why DoLP increases as signal level decreases. The noise of a CCD/CMOS focal plane array has three regions: read noise, shot noise, and pixel non-uniformity noise [2]. A photon transfer curve plots the noise (as expressed by the standard deviation) vs. the mean response of a digital camera on a log-log scale. A photon transfer curve allows one to identify and distinguish noise components in a camera's output. When examining the mean DoLP vs S_0 relationship, these noise components will dominate at different levels of S_0. At high light levels, fixed pattern noise from pixel non-uniformity will dominate. At lower light levels, Poisson noise, also called shot noise will dominate. At some point, as the light level decreases further, the read noise will dominate.

We created a numerical model in MATLAB to obtain the relationship between S_0 and DoLP for the shot noise region and the non-uniformity noise region. The model assumes a polarimeter's pixels are interleaved, E_{+45}, E_{-45}, E_H, and E_V, and receive or produce independent noise. Figure 4 depicts the variation of DoLP versus intensity using this noise model. We assume Gaussian noise for the pixel non-uniformity, Poisson noise for the shot noise, and chi-square noise for the read noise. The specific values and crossover points on the DoLP curve depend on noise level assumptions, which we did not measure experimentally. Better non-uniformity correction will lower the noise level DoLP at high intensity. Frame averaging will lower shot noise that will lower the DoLP noise in that region.

In a pixel non-uniformity region, noise standard deviation is linearly related to signal level [2] (page 102). We created 40 images using different mean values with linearly related standard deviation. The images are de-interleaved to simulate the output of four polarization filters. We compute S_0 and DoLP from the de-interleaved outputs. We calculate and plot the mean DoLP and the mean S_0 for each image. The result is the flat line indicated in red in Figure 4.

In a shot-noise region, noise is uncertainty in the amount of charge collected. This is a Poisson process where noise is proportional to the square root of the number of incident photons. For the numerical modeling, we use MATLAB's "poissrnd" function to generate the images then compute S_0 and DoLP as above. The result is the curved blue line in Figure 4.

In a read-noise region, noise is a function of the specific imager used. Janesick [2] explains read noise as noise that represents the random noise measured under totally dark conditions. This noise is ultimately limited by on-chip amplifier noise but can represent any other noise sources that are independent of the signal level (e.g., shot noise generated dark current). We measured the DoLP under total darkness and used that value as the limiting DoLP shown in green in Figure 4. We did not use the read noise of the camera. When read noise dominates, the DoLP is constant at the DoLP noise limit since the signal is below the read noise. The image intensity is no longer a function of the signal level. The sensors output is the read noise. Thus, the DoLP will be constant in this region when expressed as a function of the light's intensity.

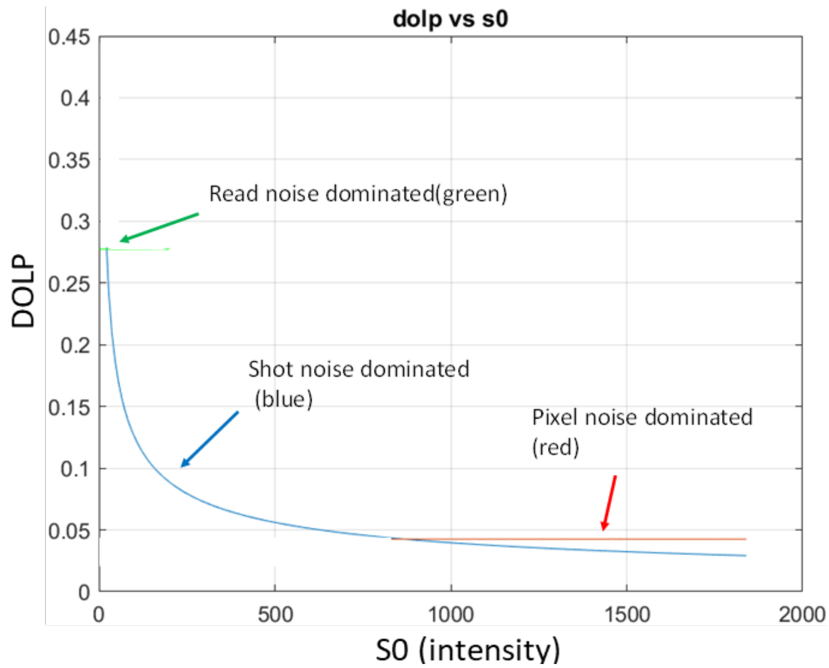

Figure 4. DoLP vs. S_0 in three noise regions. At high intensity, the DoLP (due to pixel non-uniformity) is constant (red). As intensity decreases, the DoLP increases due to shot noise (blue). At some point, read noise dominates (green).

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