



Robust calibration method for polarization cameras integrated with chromatic retarders

HUIHUI LI,¹  SUBIAO BIAN,^{2,3,*} AND ORIOL ARTEAGA^{3,4} 

¹*School of Marine Engineering, Jimei University, Xiamen 361021, China*

²*College of Metrology Measurement and Instrument, China Jiliang University, Hangzhou 310018, China*

³*Dep. Física Aplicada, PLAT Group, IN2UB, Universitat de Barcelona, Barcelona 08028, Spain*

⁴*oarteaga@ub.edu*

**subiaobianbian@ub.edu*

Abstract: Polarization cameras provide a compact and efficient solution for real-time polarization imaging but suffer from chromatic calibration errors when used in combination with wavelength-dependent optical components such as linear retarders. In this work, we introduce an analytical calibration method specifically designed for polarization cameras integrating chromatic retarders, which can be used both in monochromatic and color sensors. This method algebraically accounts for spectral averaging and depolarization effects arising from wavelength-dependent retardance, enabling robust and accurate polarization calibration across different spectral channels. The approach is experimentally validated using a commercial color polarization camera (FLIR Blackfly S) with integrated RGB Bayer filters and micro-polarizers, along with broadband illumination sources. Experimental results demonstrate that the effective spectral parameters, such as the effective wavelength and spectral bandwidth obtained by our calibration method, are close to theoretical predictions.

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1. Introduction

Polarization imaging technology has garnered increasing interest in recent years due to its ability to capture information that is inaccessible to conventional intensity-based imaging systems [1,2]. To extract polarization information, various system architectures have been developed, including division-of-time, division-of-amplitude, division-of-aperture, and, notably, division-of-focal-plane (DoFP) approaches [3]. Among these, DoFP systems stand out for their compact design and capability to perform real-time polarization imaging by integrating micro-polarizer arrays directly onto the sensor. DoFP cameras enable the simultaneous acquisition of polarization states with micro-scale spatial variations in a single exposure, which has enabled advanced applications in biomedical diagnostics, remote sensing, industrial inspection, and target detection.

Polarization imaging has been progressively advancing toward high-information-content systems by integrating multispectral imaging technology [4,5]. This enables the acquisition of wavelength-resolved polarization images, a capability that has already been successfully commercialized through color polarization cameras [6]. Color polarization cameras integrate a Bayer color filter array with a micro-polarizer array on a single sensor chip, allowing simultaneous acquisition of spectral, and polarization information. The resulting data enables richer scene interpretation, such as material classification, spectral-polarimetric target recognition, and improved visibility under scattering environments. Moreover, polarization cameras have evolved into powerful tools for quantitatively evaluating material properties such as surface stress, optical anisotropy, and microstructural variations [7]. When integrated with additional optical components—such as linear retarders, circular retarders, and polarizing beam splitters—these systems are capable of measuring the complete Stokes vector and performing full Mueller matrix imaging [1,8,9].

Various factors can affect the quality of polarization images, including lens aberrations, pixel crosstalk, and the mosaic sampling structure of the sensor, all of which can introduce spatial and spectral inconsistencies that distort the measured polarization state. Among these, spectral-domain polarization imaging is particularly susceptible to errors caused by the averaging of polarization signals over finite bandwidths, especially when broadband light sources are used [10]. This spectral averaging can manifest as an effective depolarization, which is influenced by several factors, including the spectral distribution of the illumination, the transmission characteristics of the wavelength filters that can be present in the camera, and the dispersive behavior of optical elements. These effects become particularly pronounced when the optical components employed in the system exhibit strong wavelength dependence, thereby introducing significant chromatic aberrations. A common approach to mitigate such issues is to incorporate narrowband filters or to avoid using highly dispersive optical elements; however, these strategies do not fundamentally eliminate the averaging effect. Therefore, to achieve accurate polarization measurements, it is essential to explicitly account for and correct the spectral averaging and associated depolarization effects introduced by chromatic components [11].

In this work, we present an analytical calibration framework specifically designed for polarization cameras operating over broadband spectra. While the method is demonstrated using color polarization cameras as a representative case, it is equally applicable to monochromatic sensors. The proposed method models the spectral averaging effects using a Gaussian formalism and derives closed-form expressions that account for both the micro-polarizer array and the additional wavelength-dependent retarder. By requiring only two known polarized illumination states, the method enables efficient and accurate estimation of key parameters such as the effective retardance and a depolarization parameter. Since the calibration relies entirely on analytical derivation, it avoids the complexity of numerical regression or iterative fitting. Experimental validation shows good agreement between calibrated parameters and theoretical spectral characteristics, confirming the method's accuracy and practical value for multispectral polarization imaging. Furthermore, the approach is readily extendable to a wide range of multispectral or spectropolarimetric imaging systems.

2. Theory

For most LED light sources, the spectral emission profile can be accurately approximated using a Gaussian function, characterized by a symmetric intensity distribution centered at a specific wavelength [12]. Even thermal light sources like Planckian spectra, whose emission spectra typically have broader and asymmetric features, can still be reasonably approximated by Gaussian distributions when restricted to narrow wavelength intervals around their emission peaks.

Mathematically, the Gaussian representation of the spectral intensity of a typical source is given by:

$$L_{\text{light}}(\lambda) \propto \exp\left[-\frac{(\lambda - \lambda_o)^2}{2\sigma_o^2}\right] \quad (1)$$

where, λ_o and σ_o represent the central wavelength and spectral bandwidth (standard deviation) of the light source, respectively. Similarly, optical filters—commonly employed to selectively extract specific wavelength ranges—are often designed to exhibit bell-shaped transmission characteristics. These filter transmission profiles can thus be effectively represented by a Gaussian function as well [13], expressed as:

$$T_{\text{filter}}(\lambda) \propto \exp\left[-\frac{(\lambda - \lambda_e)^2}{2\sigma_e^2}\right] \quad (2)$$

where, λ_e and σ_e denotes the central wavelength and spectral bandwidth of the filter, respectively. When a Gaussian-modeled light source and filter are used in combination, their effective spectral

response—represented by the product of the source's emission profile and the filter's transmission profile—is also closely approximated by a Gaussian distribution:

$$w(\lambda) = L_{\text{light}}(\lambda) T_{\text{filter}}(\lambda) \propto \exp\left[-\frac{(\lambda - \lambda_{\text{eff}})^2}{2\sigma_{\text{eff}}^2}\right] \quad (3)$$

The effective parameters are defined as:

$$\sigma_{\text{eff}}^2 = \left(\frac{1}{\sigma_o^2} + \frac{1}{\sigma_e^2}\right)^{-1}, \quad \lambda_{\text{eff}} = \sigma_{\text{eff}}^2 \left(\frac{\lambda_o}{\sigma_o^2} + \frac{\lambda_e}{\sigma_e^2}\right). \quad (4)$$

2.1. Spectral effects of the micro-polarizer array

In a conventional DoFP polarization sensor, each unit cell comprises four adjacent pixels, each equipped with a micro-polarizer oriented at distinct angles—commonly 0° , 45° , 90° , and 135° . This spatial arrangement allows simultaneous estimation of the Stokes vector at each pixel, thus characterizing the polarization state of incident light. Over a finite spectral bandwidth, the measured intensity array detected by the sensor can be mathematically represented as:

$$\mathbf{I} = \left(\int w(\lambda) \mathbf{M}_P d\lambda \right) \mathbf{S}_{\text{in}} \quad (5)$$

where, $\mathbf{S}_{\text{in}} = [S_0, S_1, S_2, S_3]^T$ is the incident Stokes vector, and $\mathbf{M}_P$ denotes the first-row Mueller matrix corresponding to the micro-polarizer array. The function $w(\lambda)$ represents the normalized effective spectral response of the combined system, satisfying $\int w(\lambda) d\lambda = 1$. It inherently incorporates both the intensity distribution of the illumination source and the wavelength-dependent efficiency of the optical filter. For an ideal micro-polarizer array exhibiting uniform polarization response across all wavelengths, the integration and spectral weighting $w(\lambda)$ in Eq. (5) can generally be neglected. However, practical micro-polarizers, particularly in multispectral or infrared imaging applications, typically exhibit some chromatic behavior—i.e., wavelength-dependent polarization efficiency, extinction ratio, and transmission.

Within narrow spectral bands, such as individual RGB color channels, these variations often manifest as smooth and monotonic trends that can be effectively approximated by linear functions. Under such spectral constraints, Eq. (5) can be simplified to:

$$\mathbf{I} = \langle \mathbf{M}_P \rangle \mathbf{S}_{\text{in}}, \quad (6a)$$

$$\langle \mathbf{M}_P \rangle = \int w(\lambda) \mathbf{M}_P(\lambda) d\lambda = \frac{1}{2} \begin{bmatrix} 1 & u & 0 & 0 \\ 1 & 0 & u & 0 \\ 1 & -u & 0 & 0 \\ 1 & 0 & -u & 0 \end{bmatrix}, \quad (6b)$$

where, $\langle \cdot \rangle$ denotes spectral averaging over the considered wavelength range. The depolarization factor of the polarizer array u , varying between 0 and 1, quantifies the polarization efficiency of the micro-polarizer array, with $u = 1$ representing ideal polarization selectivity and values $u < 1$ indicating partial depolarization or reduced polarization efficiency [14]. The value of u can be directly determined experimentally by illuminating the system with a known polarization state, such as horizontally polarized light (0°), described by the input Stokes vector $\mathbf{S}_{\text{in}} = [1, 1, 0, 0]^T$.

In this case, the measured intensity vector is denoted as $\mathbf{I}^0$:

$$\mathbf{I}^0 = \frac{1}{2} \begin{pmatrix} 1+u \\ 1 \\ 1-u \\ 1 \end{pmatrix}, \quad u = \mathbf{I}_0^0 - \mathbf{I}_2^0, \quad (7)$$

where, $\mathbf{I}_i$ denotes the i^{th} element of the measured intensity vector. Additionally, accurate alignment of the polarization axis can be confirmed by observing symmetry conditions, specifically that $\mathbf{I}_0^0$ and $\mathbf{I}_2^0$ are symmetric about unity, and $\mathbf{I}_1^0$ and $\mathbf{I}_3^0$ both equal one.

2.2. Spectral effects of the retarder

In practical polarization imaging systems, cameras are often integrated with additional optical components to fully characterize the polarization state, particularly when measuring circular or elliptical polarization. Among these components, the retarder is frequently employed due to its ability to introduce a controlled phase retardance δ between two orthogonal polarization components (commonly referred to as p - and s -polarizations). This makes retarders indispensable in advanced Stokes vector and Mueller matrix imaging systems that utilize polarization cameras [8,9].

When a retarder is integrated into a multiple-spectral polarization imaging system, Eq. (6a) must be modified accordingly as follows:

$$\mathbf{I} = \langle \mathbf{M}_P \rangle \int w(\lambda) \mathbf{M}_R(\theta, \delta) d\lambda \mathbf{S}_{\text{in}} \quad (8)$$

Natural retarders exhibit wavelength-dependent retardance δ and a uniform azimuth angle θ . Thus, Eq. (8) needs to be further expressed as,

$$\mathbf{I} = \langle \mathbf{M}_P \rangle \langle \mathbf{M}_R(\theta, \delta) \rangle \mathbf{S}_{\text{in}} \quad (9a)$$

where,

$$\begin{aligned} \langle \mathbf{M}_R(\theta, \delta) \rangle &= \int w(\lambda) \mathbf{M}_R d\lambda \\ &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C_{2\theta} & S_{2\theta} & 0 \\ 0 & -S_{2\theta} & C_{2\theta} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \langle C_\delta \rangle & -\langle S_\delta \rangle \\ 0 & 0 & \langle S_\delta \rangle & \langle C_\delta \rangle \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C_{2\theta} & -S_{2\theta} & 0 \\ 0 & S_{2\theta} & C_{2\theta} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \end{aligned} \quad (9b)$$

where, the short notation $S_X \equiv \sin(X)$ and $C_X \equiv \cos(X)$ has been used. To approximate the spectral average of the wavelength-dependent retardance functions of $\delta(\lambda)$, we perform a first-order Taylor expansion around the filter center wavelength where $\delta(\lambda) \approx \delta(\lambda_e) + \delta'(\lambda_e)(\lambda - \lambda_e)$. Substituting this into $\cos(\delta(\lambda))$ and $\sin(\delta(\lambda))$ and applying trigonometric addition identities, the integrals become weighted combinations of Cosine and Sine functions modulated by a Gaussian profile.

The resulting expressions are

$$\begin{aligned}\langle C_\delta \rangle &= \int w(\lambda) C_\delta(\lambda) d\lambda \\ &\approx \exp\left(-\frac{1}{2}[\delta'(\lambda_e)]^2 \sigma_{\text{eff}}^2\right) \cos\left[\delta(\lambda_e) - \delta'(\lambda_e)(\lambda_e - \lambda_{\text{eff}})\right] \equiv \nu C_\delta\end{aligned}\quad (10a)$$

$$\begin{aligned}\langle S_\delta \rangle &= \int w(\lambda) S_\delta(\lambda) d\lambda \\ &\approx \exp\left(-\frac{1}{2}[\delta'(\lambda_e)]^2 \sigma_{\text{eff}}^2\right) \sin\left[\delta(\lambda_e) - \delta'(\lambda_e)(\lambda_e - \lambda_{\text{eff}})\right] \equiv \nu S_\delta\end{aligned}\quad (10b)$$

In Eq. (10), $\delta(\lambda_e)$ is the retardance provided from the retarder at the wavelength λ_e , and $\delta'(\lambda_e)$ is the first derivative. λ_e can be found according to the real quantum efficiency of the channel filter. Unknown parameters are λ_{eff} and σ_{eff} related to the light source of the application scenario. The defined depolarization factor of retarder ν (ranging from 0 to 1) is influenced by $\delta'(\lambda_e)$, σ_{eff} , and the final δ is related to the information of $\delta(\lambda_e)$, $\delta'(\lambda_e)$, λ_e , λ_{eff} , which demonstrates that the system parameters is highly dependent on the spectral of ambient light. In the case of an achromatic retarder or a spectrally narrow light source, both σ_{eff} and $\delta'(\lambda_e)$ approach zero, resulting in a depolarization factor ν that is close to 1. Under such conditions, the depolarization effect becomes negligible, and it is unnecessary to account for it in calibration. However, for highly chromatic retarders, the first-order approximation may introduce significant numerical errors, potentially limiting the applicability of the analytical model.

With consideration of Eq. (10), Eq. (8) can be finally expanded as,

$$\mathbf{I} = \frac{1}{2} \begin{bmatrix} (S_0 + uS_1 (C_{2\theta}^2 + \nu C_\delta S_{2\theta}^2) - uS_2 C_{2\theta} S_{2\theta} (1 - \nu C_\delta) - uvS_3 S_{2\theta} S_\delta) \\ (S_0 - uS_1 C_{2\theta} S_{2\theta} (1 - \nu C_\delta) + uS_2 (\nu C_\delta C_{2\theta}^2 + S_{2\theta}^2) - uvS_3 C_{2\theta} S_\delta) \\ (S_0 - uS_1 (C_{2\theta}^2 + \nu C_\delta S_{2\theta}^2) + uS_2 C_{2\theta} S_{2\theta} (1 - \nu C_\delta) + uvS_3 S_{2\theta} S_\delta) \\ (S_0 + uS_1 C_{2\theta} S_{2\theta} (1 - \nu C_\delta) - uS_2 (\nu C_\delta C_{2\theta}^2 + S_{2\theta}^2) + uvS_3 C_{2\theta} S_\delta) \end{bmatrix} \quad (11)$$

where, ν is the depolarization factor of the retarder over the bandwidth. Equation (11) exhibits symmetry, reflecting the orthogonality of polarization states (0° and 90° , 45° and 135°), ensuring their combined intensities equal the total intensity S_0 .

To retrieve the retarder unknown parameters (δ , ν , θ), the system is illuminated with at least two known polarization states (typically 45° linear polarization light, $\mathbf{I}^{45}$, and left circular polarization, $\mathbf{I}^l$), yielding simplified expressions,

$$\mathbf{I}^{45} = \frac{1}{2} \begin{pmatrix} 1 + C_{2\theta} S_{2\theta} (uvC_\delta - u) \\ 1 + uvC_\delta C_{2\theta}^2 + uS_{2\theta}^2 \\ 1 - C_{2\theta} S_{2\theta} (uvC_\delta - u) \\ 1 - uvC_\delta C_{2\theta}^2 - uS_{2\theta}^2 \end{pmatrix}, \mathbf{I}^l = \frac{1}{2} \begin{pmatrix} 1 - uvS_{2\theta} S_\delta \\ 1 - uvC_{2\theta} S_\delta \\ 1 + uvS_{2\theta} S_\delta \\ 1 + uvC_{2\theta} S_\delta \end{pmatrix} \quad (12)$$

Using the resulting measured intensities $\mathbf{I}^l$, the closed-form expression of azimuth angle can be directly calculated as,

$$\theta = \frac{1}{2} \arctan\left(\frac{\mathbf{I}_0^l - \mathbf{I}_2^l}{\mathbf{I}_1^l - \mathbf{I}_3^l}\right) \quad (13)$$

Once θ is determined, the quantities uvS_δ and uvC_δ can be directly extracted from $\mathbf{I}^l$ and $\mathbf{I}^{45}$, respectively. With these values, the effective retardance δ and depolarization factor ν can be unambiguously calculated, completing the analytical calibration process.

In many practical cases, such as when the retarder azimuth angle θ is known (e.g., fixed to 0° for alignment), the complexity of calculations can be further reduced. For a high-efficiency polarizer array ($u = 1$), Eq. (14) provides a highly simplified two-shot calibration approach, enabling direct estimation of δ and v with high reliability and minimal computation.

$$\mathbf{I}^{45} = \frac{1}{2} \begin{pmatrix} 1 \\ 1 + vC_\delta \\ 1 \\ 1 - vC_\delta \end{pmatrix}, \mathbf{I}^l = \frac{1}{2} \begin{pmatrix} 1 \\ 1 - vS_\delta \\ 1 \\ 1 + vS_\delta \end{pmatrix} \quad (14)$$

v and δ can be easily determined that,

$$\delta = \arctan\left(\frac{\mathbf{I}_3^l - \mathbf{I}_1^l}{\mathbf{I}_1^{45} - \mathbf{I}_3^{45}}\right) \quad (15a)$$

$$v = \sqrt{(\mathbf{I}_3^l - \mathbf{I}_1^l)^2 + (\mathbf{I}_1^{45} - \mathbf{I}_3^{45})^2} \quad (15b)$$

3. Experimental validation

To experimentally demonstrate the validity and effectiveness of the proposed chromatic calibration method, we employed a commercial color polarization camera (FLIR Blackfly S) featuring a Sony IMX250MYR CMOS sensor. This sensor provides a resolution of 2448×2048 pixels with an 8-bit depth per image. Each super-pixel of the sensor integrates both a Bayer color filter array and a polarization filter array, as depicted in Fig. 1(a). Specifically, the color filter array is based on the standard RGB Bayer pattern, while the polarization filter array consists of micro-polarizers oriented at 0° , 45° , 90° , and 135° . The spectral quantum efficiencies of the RGB filters depicted in Fig. 1(b) [15], are closely approximated by Gaussian functions. The corresponding central wavelengths and spectral bandwidths are summarized in Table 1.

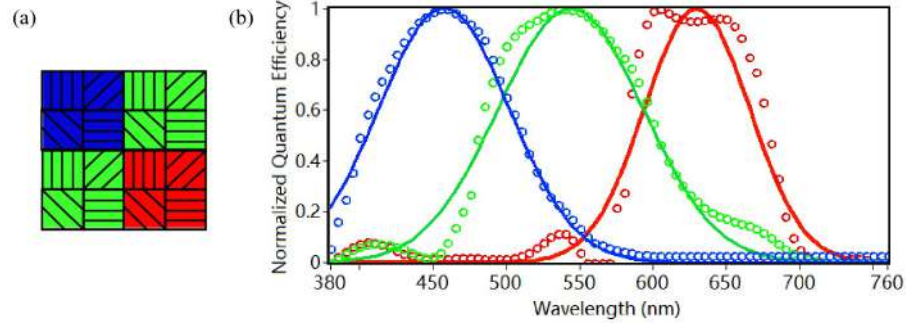
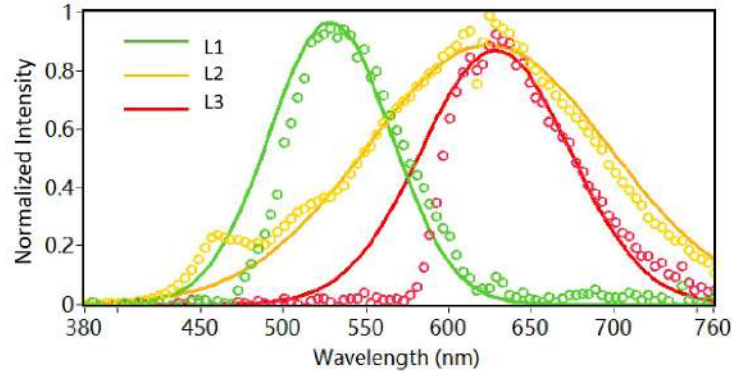


Fig. 1. Color polarization camera sensor. (a) Pixel layout of a super-pixel with the color and polarization filter array. (b) Normalized quantum efficiency of RGB filter and fitted by Gaussian distribution.

Furthermore, three distinct broadband illumination sources, designated as L1, L2, and L3, each covering different spectral regions shown in Fig. 2 are selected to assess the spectral response of the polarization camera. The spectral distributions of these sources were also modeled effectively using Gaussian functions, with their fitted central wavelengths λ_o and bandwidths σ_o presented in Table 2.

Table 1. Central wavelength and bandwidth of the quantum efficiency of the RGB Bayer filter

Color Channel	Blue	Green	Red
λ_e (nm)	455.5	543.8	629.9
σ_e (nm)	43.4	49.5	35.9

**Fig. 2.** Normalized light source spectrum from 380 nm–760 nm.**Table 2. Central wavelength and bandwidth of the light source**

Light source	L1	L2	L3
λ_o (nm)	528.5	623.7	628.2
σ_o (nm)	36.7	73.1	44.8

3.1. Determination of the depolarization factor of polarizer array

The depolarization factor of micro-polarizer array u was measured using the procedure outlined in Section 2.1. A high-quality Glan-Taylor Calcite Polarizer (Thorlabs GT10), capable of generating highly polarized and spectrally broadband illumination, was placed in front of the camera, as shown in Fig. 3. The depolarization factor u was computed from the spatial average of the camera's entire field of view. To achieve precise horizontal alignment of the polarizer with respect to the camera, the second and fourth elements of the measured Stokes vector were adjusted to be identical, ensuring the first element was maximized relative to the third according to Eq. (7). The measured values of u across the red, green, and blue channels under each illumination source are presented in Table 3. All three color channels exhibited excellent polarization fidelity, although the red channel displayed slightly lower values with higher measurement uncertainty.

Table 3. Depolarization factor and standard error in space of RGB channel in micro-polarization array illustrated in different light source

Light Source	$u(\text{Red})$	$u(\text{Green})$	$u(\text{Blue})$
L1	0.989 ± 0.006	0.997 ± 0.001	0.991 ± 0.002
L2	0.992 ± 0.003	0.997 ± 0.002	0.996 ± 0.002
L3	0.991 ± 0.003	0.996 ± 0.003	0.993 ± 0.002

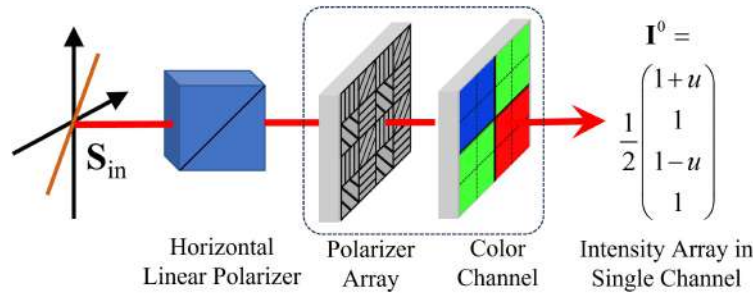


Fig. 3. Color polarization camera configured with a horizontal linear polarizer.

3.2. Determination of the depolarization factor of retarder

A nominal full-wave polymer film retarder (Edmund Optics: WP560), providing strong chromatic dispersion, was integrated between the objective lens and the polarization camera. This configuration was set to introduce pronounced spectral averaging effects of the retardance, thereby amplifying the resultant depolarization phenomena and providing a more rigorous test for the calibration framework. The wavelength-dependent retardance of the WP560 retarder was accurately characterized using a home-built Mueller matrix ellipsometer based on Fresnel rhomb compensators [16], operating in transmission mode across the spectral range of 380–770 nm, as shown in Fig. 4(a). For visualization clarity, the measured retardance values are presented after subtracting 360° , such that the nominal full-wave retardance (360°) near 560 nm is normalized to 0° . This adjustment facilitates better comparison of dispersion trends over the spectral range. To simplify system integration and ensure consistent optical alignment, the azimuthal orientation of the retarder was fixed at 0° , which aligns with standard practices in micro-polarization array configurations used in polarization cameras.

According to the procedure outlined in Section 2.2. The effective retardance δ and the depolarization factor ν of the integrated retarder were characterized by illuminating the camera with two distinct polarization states: 45° linear polarization and left circular polarization, as illustrated schematically in Fig. 4(b). The measured intensity distributions within each color channel were used to calculate δ and ν via Eq. (15). These experimentally derived values for each illumination scenario and color channel are summarized in Tables 4 and 5, respectively where the standard error represent the spatial variations.

Table 4. The effective retardance (δ) and spatial standard error in RGB color channels configured with the illumination of three light sources (L1, L2, L3)

Light Source	$\delta(\text{Red})$	$\delta(\text{Green})$	$\delta(\text{Blue})$
L1	$-53.82^\circ \pm 1.31^\circ$	$-5.22^\circ \pm 1.74^\circ$	$74.27^\circ \pm 2.90^\circ$
L2	$-54.48^\circ \pm 1.36^\circ$	$-11.91^\circ \pm 1.16^\circ$	$65.82^\circ \pm 3.07^\circ$
L3	$-57.35^\circ \pm 1.20^\circ$	$-16.33^\circ \pm 2.20^\circ$	$46.24^\circ \pm 5.20^\circ$

It is observed that the spectral distribution of the illumination sources has a significant impact on both the effective retardance and the depolarization factor of the retarder. In particular, the variation of effective retardance is more pronounced in the blue and green channels, reflecting the stronger light sources dependence in these spectral regions. Meanwhile, Their depolarization factor is substantially lower compared to that in red channel. These can be attributed to the enhanced dispersion of the retarder material in the blue and green spectral bands. The results

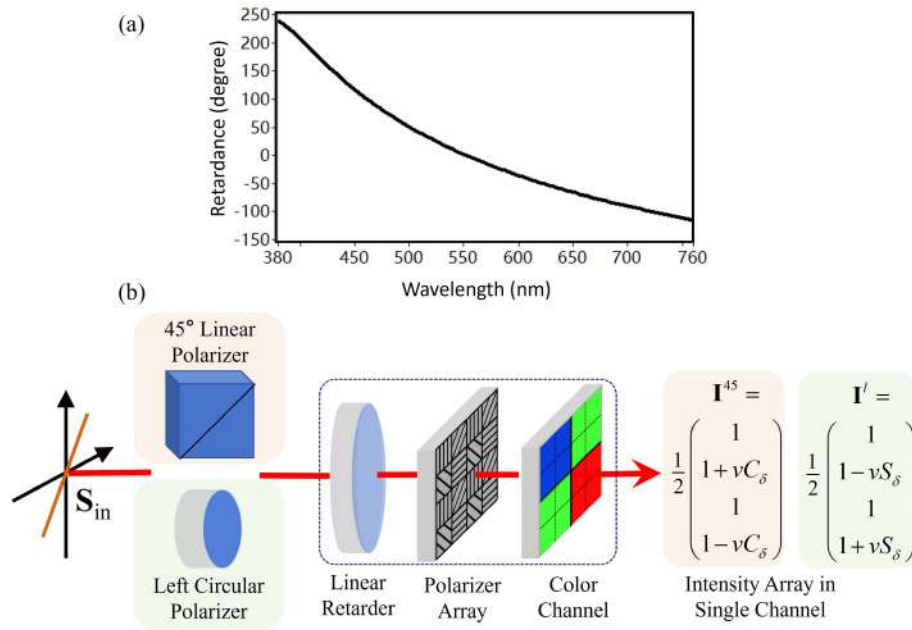


Fig. 4. Color polarization camera configured with a retarder. (a) Measured retardance of the full waveplate thin film. (b) Calibration using a 45° linear polarizer and a left circular polarizer.

Table 5. The depolarization factor (ν) and spatial standard error of retarder in each color channel with the illumination of three light sources (L1, L2, L3)

Light Source	$\nu(\text{Red})$	$\nu(\text{Green})$	$\nu(\text{Blue})$
L1	0.73 ± 0.01	0.65 ± 0.01	0.48 ± 0.02
L2	0.69 ± 0.02	0.65 ± 0.02	0.42 ± 0.02
L3	0.76 ± 0.02	0.66 ± 0.03	0.53 ± 0.01

highlight the spectral characteristics influence chromatic depolarization effects, especially under the condition of changing illuminations.

With the experimentally obtained effective retardance (δ) and depolarization factor (ν) under illumination by light source L2, the effective bandwidth (σ_{eff}) and effective central wavelength (λ_{eff}) of the combined spectral response (light source and RGB filter) were further calculated using Eq. (10). These experimental values were then compared to their theoretical counterparts in Table 6. The results reveal that the experimentally derived spectral parameters for each color channel are close to those predicted from the known spectral profiles of the illumination and filter functions.

The observed discrepancies of λ_{eff} and σ_{eff} may originate from two main sources. First, the Gaussian approximation used to model both the light source and the filter transmission spectra may not fully capture the true spectral shape, particularly in the presence of asymmetries or non-negligible side lobes. Second, the first-order Taylor expansion adopted to approximate the wavelength-dependent retardance of the waveplate is centered at the nominal central wavelength (λ_c) of the filter, which exist unavoidable error. Meanwhile, the first-order approximation is not sufficiently accurate with rapid retardance variation, higher-order terms or numerical integration may be considered for enhanced accuracy. Despite these limitations, the agreement between

Table 6. The simulated and experimental effective wavelength ($\lambda_{\text{eff}}^{\text{sim}}$, $\lambda_{\text{eff}}^{\text{exp}}$) and bandwidth ($\sigma_{\text{eff}}^{\text{sim}}$, $\sigma_{\text{eff}}^{\text{exp}}$) of the combination of the light source (L2) and RGB filter

Color Channel	Red	Green	Blue
$\sigma_{\text{eff}}^{\text{sim}}$ (nm)	32.23	40.12	37.33
$\lambda_{\text{eff}}^{\text{sim}}$ (nm)	628.63	568.94	499.35
$\sigma_{\text{eff}}^{\text{exp}}$ (nm)	31.61 ± 3.21	22.63 ± 2.12	21.19 ± 6.22
$\lambda_{\text{eff}}^{\text{exp}}$ (nm)	629.90 ± 4.42	543.94 ± 3.43	455.18 ± 10.55

theoretical and experimental results validates the accuracy and robustness of the proposed chromatic calibration method.

3.3. Demonstration example

The proposed calibration method was demonstrated using a custom-design full-Stokes polarization camera configured with a homogeneous dispersive retarder, whose configuration is the same as shown in Fig. 4. This camera utilizes wavelength-dependent retardation effects in different color channel to reconstruct the complete Stokes vector with the premise of assuming weak chromatic incident light over the wavelengths. It is worth noting that in this context, the chromatic behavior is not a limitation, but rather a functional characteristic. The details about this full Stokes polarization camera can be found in our previous work [8]. For the experiment, a stone sculpture was used, with a polarizing film placed in front to generate pure linearly polarized light. A small plastic film segment placed over the polarizing film introduced an additional birefringence effect, resulting in ellipticity of polarized light. Under illumination from the designated light source (L2), the reflected light from the stone sculpture was captured by the full polarization camera, as depicted in Fig. 5(a).

A comparative analysis of measured Stokes imaging between our calibration method and the conventional settings (which exclude depolarization factors (u and v) and assume the retardance corresponding to the filter center) is presented in Fig. 5(b), illustrating the degree of polarization (DoP), ellipticity, angle of linear polarization (AoLP), and one of contour lines. Overall, the global structure of the polarization image remains largely consistent after calibration. However, a detailed examination reveals notable improvements introduced by the proposed method. Before calibration (BC), the DoP measured at the pixel corresponding to the polarizing film was significantly underestimated, with values around 0.6—substantially lower than the theoretical expectation of unity. After calibration (AC), the DoP at this location increased markedly to approximately 1, aligning well with the expected value for a perfectly linearly polarized input. While the ellipticity at the polarizing film remained largely unchanged, slight deviations were observed in some regions of the image, indicating localized correction effects. Moreover, the AoLP exhibited a shift of approximately 5° , suggesting that spectral depolarization effects can impact the angular accuracy of polarization measurements. These results validate the necessity of incorporating depolarization factor calibration, particularly for applications requiring precise polarization state reconstruction under broadband or spectrally varying illumination conditions.

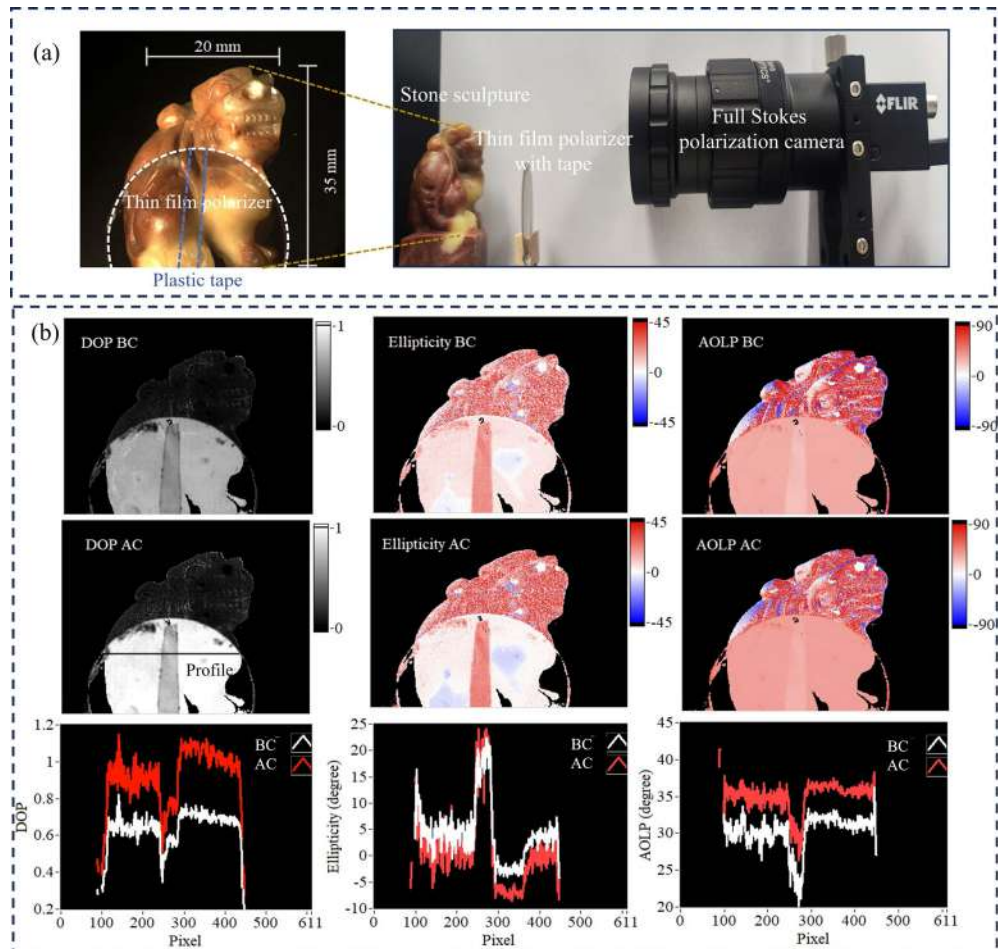


Fig. 5. Full Stokes imaging before calibration (BC) and after calibration (AC). (a) Stone sculpture and a home-made full Stokes camera. (b) Measured degree of polarization (DoP) ranging from 0 to 1, ellipticity ranging from -45° to 45° and angle of linear polarization (AoLP) ranging from -90° to 90° .

4. Conclusion

In this study, we proposed and experimentally demonstrated an analytical calibration method designed to accurately characterize and compensate for chromatic polarization errors in color polarization cameras equipped with wavelength-dependent optical components. Our method leverages algebraic modeling of spectral averaging and depolarization effects, enabling precise calibration using intensity measurements from only two well-defined polarization states. The experimental validation with a commercial polarization camera and broadband illumination sources shows that our calibrated effective spectral parameters—such as effective wavelengths and spectral bandwidths—align closely with theoretical expectations, underscoring the method's robustness and accuracy.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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