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Polarization Measurements Using a COTS Digital Camera

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ABSTRACT

This paper presents a methodology to obtain polarization profiles using a COTS (commercial-off-the-shelf) digital camera. It contains calibration techniques to insure robust and accurate determination of the Stokes parameters and the system polarization state. It calculates the Stokes parameters for each scene pixel along with the degree of polarization, azimuth and ellipticity angles for each of the RGB channels. A detailed calculation shows that the quasi-monochromatic approximation for the wavelength dependence of the quarter wave plate can be extended to include the broad band RGB channels. A simple and inexpensive camera calibration converts RGB values to optical density and then to relative intensity values. An analysis is presented for the wavelength dependent response of the tuned zero-order quartz quarter-wave retarder, the broad band RGB channels and the fourth Stokes parameter. The noise characteristics of the digital camera are analyzed along with a detailed calibration of the imagery for target characterization applications. An extensive validation process using white light compares known polarization states with the empirical results from the COTS camera. A RGB pseudo-coloring scheme, related to the Poincaré sphere, is introduced for the visualization of polarization parameters of daylight scenes.

Keywords: polarization, polarimetry, visual polarization, digital imaging, image acquisition/recording, image processing

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INTRODUCTION

Our entry into the polarization scene began over a decade ago. At that time, polarization measurements were acquired using spot measurements from a luminance meter and a typical SLR 35 mm camera[1-2]. During the previous four years, we have studied the problems associated with using a COTS (commercial-off-the-shelf) digital camera to determine polarization parameters in a daylight scene[3-5]. Although a number of registration problems have yet to be completely resolved, we will show that it is possible to make polarization measurements using a typically "quasi-monochromatic" methodology with a COTS digital camera. This paper describes a methodology for measuring the four Stokes parameters in each of the approximately 100 nm RGB channels using a COTS digital camera. A calibration scheme converts RGB pixel values to relative intensities and the spatial, thermal and electrical noise characteristics of the CCD detector are examined. An equation compensates for the phase difference between the incident wave and the tuned frequency of a quartz zero-order quarter-wave retarder. An extensive validation process using white light compares known polarization states with the empirical results from the COTS camera. An RGB pseudo-coloring scheme, related to the Poincaré sphere, is introduced for the visualization of polarization parameters of daylight scenes.

STOKES PARAMETER FORMALSIM

The human visual system cannot easily detect polarized light. Some observers can determine, through sighting Haidinger's brush[6], that skylight is polarized. However, the human visual system is incapable of determining the complete polarization state of a light beam. Three

independent parameters must be determined for each scene pixel to completely characterize a polarization image[7]. The Stokes' parameter representation is one methodology for measuring the polarization state of an image[8]. This method involves four intensity measurements for each scene pixel using four distinct optical configurations. Each measurement corresponds to the intensity of the beam after it passes through each of four different filter system arrangements. The four Stokes parameters, sometimes called S_0, S_1, S_2 and S_3, are derived from these four measured intensities and form a four-element column vector in four-dimensional mathematical space. The Stokes parameters are applicable to a beam of light that is completely polarized, partially polarized or unpolarized; the beam may be monochromatic or polychromatic. The Stokes parameters for completely polarized light propagating along the +z-axis are

$$S_0 = E_{0X}^2 + E_{0Y}^2 \quad S_1 = E_{0X}^2 - E_{0Y}^2 \quad S_2 = 2\,E_{0X}\,E_{0Y}\cos\delta \quad S_3 = 2\,E_{0X}\,E_{0Y}\sin\delta \tag{1}$$

Normalized parameters are obtained by dividing S_0, S_1, S_2 and S_3 by S_0. For partially polarized light the degree of polarization P is given by[9]

$$\mathbf{P} = \frac{I_{Polarized}}{I_{Total}} = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0} \tag{2}$$

where $I_{Polarized}$ is the intensity of the polarized component and I_{Total} is the total intensity. When the Stokes parameters are normalized, the degree of polarization P becomes the radius of a sphere with center coincident to the typical Poincaré sphere (see Figure 1) of unit radius (P = 1). The inside of the Poincaré sphere can be used to represent the polarized portion of partially polarized light (P < 1). The polarization forms on the surface of the inside spheres (P < 1) are

exactly the same as the polarization forms on the surface of the sphere of unit radius. From the geometry of Figure 1 and Eq. (2) it can be shown that for normalized Stokes parameters and for any degree of polarization

$$S_1 = P \cos 2\psi \cos 2\chi \qquad S_2 = P \sin 2\psi \cos 2\chi \qquad S_3 = P \sin 2\chi \tag{3}$$

In fact, Eq. (3) represents the spherical coordinates of any point on the surface or inside of the Poincaré sphere where $(x, y, z) = (S_1, S_2, S_3)$.

The polarization form associated with elliptical polarization, as shown in Fig. 2, is given by the following expression

$$\left(\frac{E_y}{E_{0y}}\right)^2 + \left(\frac{E_x}{E_{0x}}\right)^2 - 2\left(\frac{E_y E_x}{E_{0y} E_{0x}}\right)\cos\delta = \sin^2\delta \tag{4}$$

The polarization azimuth angle, ψ, and the ellipticity angle, χ, are also defined in Fig. 2. Using Eqs. (2) and (3), ψ and χ can be determined from

$$\sin 2\chi = \frac{S_3}{\sqrt{S_1^2 + S_2^2 + S_3^2}} \qquad \text{and} \qquad \tan 2\psi = \frac{S_2}{S_1} \tag{5}$$

The parameter χ varies from +45° to -45°; it is positive for right-handed polarization forms and negative for left-handed polarization forms. The parameter ψ varies from 0° to 180°; it is 0° for horizontal polarization forms and 90° for vertical polarization forms.

CAMERA CALIBRATION

COTS digital cameras are effective "black boxes" with little or no support from the manufactures with regard to their calibrated response functions for the various RGB channels. They do not provide schematics for electronic or digital circuits to implement noise and color correction algorithms. The COTS camera manufacturer has different goals and objectives for camera performance than does the scientist or engineer who calculates the Stokes parameters from calibrated digital imagery. The calibration process is particularly important for extracting a linear intensity relationship from RGB grey level image data. An accurate calibration in terms of the intensity values insures that linear, spatial averaging over multiple pixels improves signal to noise characteristics and reduces random noise in the polarization imagery.

Dark Frames and Flat-Field Frames

COTS digital cameras typically use rectangular arrays of photoreceptors in a sensor configuration called charge coupled devices (CCDs)[10]. Each CCD image consists of individual detector elements or pixels, which accumulate photoelectric charges that integrate over time. The detection and amplification stages introduce noise into the imagery which consists of thermal or "dark currents" and electronic noise. An analysis of imagery taken with a lens cap over the camera lens, a dark image frame, is used to quantify the effects of these types of noise phenomena. The characteristics of a dark image frame are different for each kind of digital camera and for each of its RGB channels. Ideally, the non-zero values obtained from a dark frame need to be subtracted out of the non-dark image frames. An analysis of the dark image

frame of an Epson 850Z digital camera showed absolutely no non-zero values for any of its channels. For this camera, thermal noise is subtracted out prior to the determination of the RGB values. Typically, non-zero values obtained from a dark frame change with exposure time and zoom setting. A comprehensive study of this phenomenon is essential for accurate scientific work.

Flat frames are CCD images created by exposing the CCD to a uniform field of light. They can be used to calibrate variations in photosite sensitivity for the entire CCD chip. These images are a photosite map of the CCD's sensitivity to light. If large variations in sensitivity occur consistently at a particular photosite, they can be corrected with a computer program.

Spectral Response of the RGB Channels

A study was conducted to determine the spectral response of the RGB channels of the relatively inexpensive Epson 850Z digital camera. Twelve different narrow band (10 nm) color filters (diameter = 2 inches) ranging from 440 nm to 660 nm were positioned sequentially in front of the camera. A collimated beam of white light was transmitted through the filters and into the camera producing a uniformly colored circular image. Since adjacent pixels have slightly different sensitivities, average RGB values were calculated using a 10 X 10 pixel area from each digital image. This procedure was followed for each of the color filters used in the study. Figure 3 gives an example of the average RGB values obtained from each of the three channels when in the fixed white balance (W/B) mode of the Epson 850Z.

As shown in Figure 3, the red channel response has a sharp cut-off at approximately 600 nm. The red channel continues to respond to wavelengths up to approximately 540 nm; however, a small response is observed for wavelengths less than 480 nm for this channel. Figure 3 shows that the green channel responds to all wavelengths between 440 nm and 660 nm with a peak response at 540 nm. The green channel is most sensitive to wavelengths between 520 nm and 560 nm. The blue channel response has a sharp cut-off at approximately 480 nm. The blue channel continues to respond to wavelengths up to approximately 520 nm; however, a small response is observed for wavelengths greater than 600 nm for this channel.

RGB to Optical Density to Relative Intensity

The digital camera converts each 8-bit RGB channel value into an integer between 0 and 255. These RGB pixel values are not intensity values that can be used to immediately calculate the Stokes parameters. To determine the mathematical nature of the conversion of RGB pixel values to light intensity, a Macbeth Color Checker[11] was photographed with different neutral density filters in front of the lens of the digital camera. Neutral density filters have known optical densities, which reduce the transmission through them according to

$$I_T = I_0 \, 10^{-D} \tag{5}$$

where D = optical density, I_0 = incident intensity and I_T = transmitted intensity. The achromatic gray level portions of the Macbeth Color Checker (colors #19 - #24) have a broadband spectral response with reflectance values corresponding to known optical densities. Figure 4 shows the average green channel pixel values for different product combinations of Macbeth reflectance

and neutral density filter transmission. A MatLab[12] algorithm calculated the average pixel response over a 10 X 10 pixel area. The best polynomial curve fit through the points was determined to be a hyperbola of the form

$$A x^2 + B xy + C y^2 + D x + E y + F = 0 \quad (6)$$

where x and y correspond to optical densities and RGB values, respectively. The coefficients in Eq. (19) are different for each color channel of the digital camera. Using the fixed white balance option of the Epson 850Z, the coefficients obtained for the green channel are:

$$A = C = 0.19926,\ B = 35.67852,\ D = 127.49000,\ E = -55.65087 \text{ and } F = -520.1110 \quad (7)$$

MEASURING THE STOKES PARAMETERS

The Stokes parameters can be measured using a linear polarizer and a retarder. If light is first transmitted through a linear retarder with its fast axis oriented at an angle Ω with respect to the x-axis and then transmitted through a linear polarizer with its transmission axis oriented at an angle θ with respect to the x-axis, the intensity of the transmitted light can be expressed as

$$I(\Omega,\theta,\varepsilon) = 0.5\ \{S_0 + [\cos 2\theta - \sin 2\Omega \sin 2(\Omega - \theta)\ (1 - \cos \varepsilon)]\ S_1$$
$$+ [\sin 2\Omega \cos 2(\Omega - \theta) - \cos 2\Omega \sin 2(\Omega - \theta) \cos \varepsilon\ ]\ S_2 - \sin 2(\Omega - \theta) \sin \varepsilon\ S_3\} \quad (8)$$

where ε is the phase difference produced by the retarder and is a function of the retarder thickness. $I(\Omega,\theta,\varepsilon)$ denotes an intensity measurement corresponding to a particular set of values for Ω, θ and ε. Equation 9 compensates for the difference in phase shifts between the incident light and a retarder phase shift of 90° where λ is the wavelength of the incident light and λ_T the tuned wavelength of the retarder, both in nanometers[11].

$$\varepsilon = \frac{\pi}{2}\left(\frac{\lambda_T - 50.876}{\lambda - 50.876}\right) \tag{9}$$

Figure 5 shows the phase difference for a quartz retarder as a function of the input wavelength for specific tuned wavelengths. The slope $d\varepsilon/d\lambda$ in Figure 5 has its smallest values for a quartz retarder tuned to the blue end of the spectrum and for input wavelengths in the red end of the visible spectrum (the red channel of a COTS digital camera).

The Stokes parameters can be determined experimentally from the following four measurements, as shown in Figure 6:

$$I_1 = I(0, 0, 0) \quad I_2 = I(0, 90, 0) \quad I_3 = I(0, 45, 0) \quad I_4 = I(0, 45, \varepsilon) \tag{10}$$

In this arrangement, a retarder is inserted into the optical path for only the fourth measurement. The four measurements described in Eq. (10) are not the only four measurements that will lead to a determination of the Stokes parameter. In a previous work[13], we describe a simple two-element variable filter system where neither the polarizer nor the retarder needs to be removed for any measurement.

Figure 7 shows an experimental setup to acquire this four-image sequence. It shows a digital camera, a linear polarizer, a hinged retarder and a hinged filter mounted on a tripod. The retarder and filter are hinged so that they can be moved quickly, precisely and reproducibly into and out of the optical path perpendicular to the optical axis. Substituting Eq. (10) into Eq. (8) confers that

$S_0 = I(0, 0, 0) + I(0, 90, 0) = I_1 + I_2$

$S_1 = I(0, 0, 0) - I(0, 90, 0) = I_1 - I_2$;

$S_2 = 2\, I(0, 45, 0) - S_0 = 2\, I_3 - S_0$

$$S_3 = \frac{2I_4 - S_0 - S_2 \cos\varepsilon}{\sin\varepsilon} \qquad (11)$$

The following sample calculations determine the degree of polarization, P, the polarization azimuth angle, ψ, and the polarization ellipticity angle, χ, for a single pixel in the green channel of the Epson 850Z digital camera. Assume the following data: (1) the tuned wavelength for the retarder is 436 nm, (2) the input wavelength is 550 nm and (3) the RGB pixel values corresponding to I_1, I_2, I_3 and I_4 are 125, 123, 137 and 127 respectively. Using Eq. (9) gives ε = 1.212 radians. Using Eqs. (6) and (7) to convert RGB green channel values to optical density yields 0.951, 0.963, 0.878 and 0.929. The corresponding relative intensities, using Eq. (5), are: $I_1 = 0.112$, $I_2 = 0.109$, $I_3 = 0.132$ and $I_4 = 0.118$. Calculations of the Stokes parameters from Eq. (11) yields $(S_0, S_1, S_2, S_3) = (0.221, 0.003, 0.044, -0.001)$. The normalized Stokes parameters are $(S_0^*, S_1^*, S_2^*, S_3^*) = (1.000, 0.014, 0.200, -0.003)$. From Eqs. (2) and (3): $(P, \psi, \chi) = (0.200, 43$ deg., -0.4 deg.).

BROADBAND RELATED ERRORS

The phase difference of a retarder is wavelength dependent, as Eq. (9) illustrates. Hence, the fourth Stokes parameter, expressed in Eq. (11), is also wavelength dependent. Since Eq. (9) can only accommodate one input wavelength and the bandwidth of an RGB channel is approximately 100 nm, errors are introduced into polarization parameters dependent on S3; namely, P and χ (Eqs. 2 and 5).

Although ε and λ are not related linearly throughout the visible spectrum, they are nearly so within the approximate 100 nm bandwidth of an RGB channel (see Figure 5). Therefore, to a good approximation, the wavelength corresponding to the average value of ε for a given RGB channel is the one corresponding to the midpoint of the channel. Alternately, the average value of ε, using a quartz quarter-wave retarder, can be obtained from

$$\varepsilon_{avg} = \frac{1}{\lambda_B - \lambda_A} \int_{\lambda_A}^{\lambda_B} \frac{\pi}{2} \frac{\lambda_T - 50.876}{\lambda - 50.876} d\lambda \tag{12}$$

where λ_A and λ_B are the beginning and ending wavelengths of an RGB channel. Integration of Eq. (12) gives

$$\varepsilon_{avg} = \left(\frac{\pi}{2}\right) \frac{\lambda_T - 50.876}{\lambda_B - \lambda_A} \left[\ln(\lambda_B - 50.876) - \ln(\lambda_A - 50.876)\right] \tag{13}$$

The input wavelength that corresponds to ε_{avg}, λ_C, is obtained by substituting ε_{avg} for ε in Eq. (9) and solving for λ. Interestingly, the value obtained for λ_C is independent of the tuned wavelength λ_T. For λ_A = 400 nm and λ_B = 500 nm (the blue channel) λ_C = 447.9 nm; for λ_A =

500 nm and λ_B = 600 nm (the green channel) λ_C = 548.3 nm; for λ_A = 600 nm and λ_B = 700 nm (the red channel) λ_C = 648.6 nm. In other words, the wavelength corresponding to ε_{avg} for a given RGB channel is the midpoint wavelength.

The fourth Stokes parameter, as expressed in Eq. (11), is the only Stokes parameter that is wavelength dependent. Therefore, it is responsible for any errors resulting from extending quasi-monochromatic theory to include wider bandwidths. The source of bandwidth errors originates with I_4 in Eq. (11). Solving Eq. (11) for I_4 gives

$$I_4 = 0.5\,(S_0 + \cos\varepsilon\, S_2 + \sin\varepsilon\, S_3) \tag{14}$$

Suppose light consisting of a flat spectral response for each RGB channel and having the same Stokes parameters for each wavelength is transmitted though a quartz quarter-wave retarder. The average value of I_4 is obtained from

$$I_{4avg} = \frac{0.5}{\varepsilon_B - \varepsilon_A}\int_{\varepsilon_A}^{\varepsilon_B}(S_0 + \cos\varepsilon + \sin\varepsilon\, S_3)\, d\varepsilon \tag{15}$$

where ε_A and ε_B are the phase differences corresponding to the beginning and ending wavelengths of an RGB channel. Integration of Eq. (15) gives

$$I_{4avg} = \frac{0.5}{\varepsilon_B - \varepsilon_A}\left[(\varepsilon_B - \varepsilon_A)\, S_0 + (\sin\varepsilon_B - \sin\varepsilon_A)\, S_2 - (\cos\varepsilon_B - \cos\varepsilon_A)\, S_3\right] \tag{16}$$

Table 1 provides three examples of the errors introduced in the fourth Stokes parameter by transmitting a broadband polarized light beam through the fourth filter of Figure 6. The best case and worst case scenario are given for each example. The first two rows refer to Example 1,

rows three and four refer to Example 2 and rows five and six refer to Example 3. Example 1 relates to right circular polarization with (S_0, S_1, S_2, S_3) = (1,0,0,1) and (P, χ) = (1, 45 deg.). Example 2 relates to elliptical polarization with (S_0, S_1, S_2, S_3) = (1,-0.250, 0.433, 0.866) and (P, χ) = (1, 30 deg.). Example (3) relates to linear polarization with (S_0, S_1, S_2, S_3) = (1,-0.500, 0.866, 0.000) and (P, χ) = (1, 0 deg.). The best case scenario uses a ¼ wave retarder tuned to 400 nm and corrected to the center frequency of the red channel. The worst case scenario uses a similar tuned wavelength of 700 nm corrected to the center frequency of the blue channel. In Example 1, the best case scenario produces an error in the value of P that is less than 0.5% and an error in the value of χ that is less than 0.1 degrees; the worst case scenario produces a 7.8% error in the P-value and an error in the value of χ that is less than 0.1 degrees. In Example 2, the best case scenario produces an error in the value of P that is less than 0.01% and an error in the value of χ that is less than 0.1 degrees; the worst case scenario produces a 6.3% error in the P-value and a 1.1 degree error in the value of χ. In Example 3, the best case scenario produces an error in the value of P that is less than 0.01% and a 0.2 degree error in the value of χ; the worst case scenario produces an error in the value of P that is less than 0.01% and a 0.3 degree error in the value of χ.

EXPERIMENTAL VALIDATION

The approximate bandwidth of white light is between 400 nm and 700 nm. Several COTS digital cameras were examined and found to have RGB channels with approximate half-widths of 50 nm. The typical spectral response of these channels is approximately as follows: red channel: 600-700 nm, green channel: 500-600 nm and blue channel: 400 and 500 nm. Each

wavelength in a white light beam may have a different set of Stokes parameters and therefore a different polarization form for each narrow band region of the spectrum. Although there may be mechanisms that produce abrupt changes or discontinuities in the Stokes parameters at a specific wavelength, many processes produce uniform or slowly varying changes in the polarization parameters within a white light beam. For example, the normalized Stokes parameters for monochromatic light transmitted through a linear polarizer and retarder (shown in Figure 8) are given by

$$S_0 = 1$$

$$S_1 = \cos 2(\beta - \alpha) \cos 2\beta + \sin 2(\beta - \alpha) \sin 2\beta \cos \sigma$$

$$S_2 = \cos 2(\beta - \alpha) \sin 2\beta - \sin 2(\beta - \alpha) \cos 2\beta \cos \sigma$$

$$S_3 = \sin 2(\beta - \alpha) \sin \sigma \qquad (17)$$

where σ is the phase difference produced by the retarder. For a quartz retarder[11]

$$\sigma = \frac{\pi}{2}\left(\frac{\lambda_T - 50.876}{\lambda - 50.876}\right) \qquad (18)$$

Column A of Figure 9 contains the superimposed polarization forms associated with the minimum, maximum and average wavelengths within the RGB channels for white light transmitted through the apparatus in Figure 8. These theoretical values are compared with the experimental data in Column B to validate the results from the Epson 850Z camera. The imagery was recorded using the filter system of Figure 6 and the apparatus in Figure 7. The quartz retarder was a zero-order, quarter-wave plate tuned to 546 nm. Images were acquired for

different elliptically polarized states generated with the apparatus of Figure 8 for each of the RGB channels. A MatLab script converted RGB values to intensity for each pixel. The average Stokes parameters were calculated over a 10 X 10 pixel region to improve spatial signal to noise characteristics.

Column B compares the theoretical polarization forms, using the mean wavelength in a RGB channel, to empirical values obtained from the Epson 850Z. The graphical comparisons in column B show good agreement between the elliptical polarization states for "quasi-monochromatic" and broadband white light.

VISUALIZING POLARIZATION PARAMETERS IN A DAYLIGHT SCENE

The Stokes parameters can easily be encoded in a daylight scene by assigning RGB values to the normalized values of S_1, S_2 and S_3 at each pixel site in the scene as follows:

$$R = \text{int}[127.5\ (1 - S_1)],\ G = \text{int}[127.5\ (1 - S_2)] \text{ and } B = \text{int}[127.5\ (1 - S_3)] \quad (19)$$

This pseudo-color scheme closely relates to the Poincaré sphere representation of polarized light where each Stokes vector maps into unique RGB values for $0*P*1$. The surface of the sphere consists of totally polarized light with P = 1(Figure 10a). Unpolarized light ($S_1 = S_2 = S_3 = 0$) corresponds to middle gray (R = G = B = 127) at the center of the sphere while the inside of the sphere relates to partially polarized light ($0<P<1$) (Figure 10b). In this color scheme, unpolarized or weakly polarized light is middle gray or highly unsaturated in the primary colors. The azimuth and ellipticity polarization angles are essential parameters in obtaining a complete

polarization profile. One method of displaying these calculated parameters is to assign a different color to each specific angle. The equator of the Poincaré sphere plays a very special role in our pseudo-coloring scheme (Figure 10c). It corresponds to linearly polarized light (S_3 = 0) and is also used to encode the polarization azimuth and ellipticity angles in a daylight scene, as given in Eq. (20). Substituting χ for ψ in Eq. (20) produces a color-mapping scheme for the χ-images as given in Eq. (21).

$$R = \text{int}[127.5\,(1 - \cos 2\psi)],\ G = \text{int}[127.5\,(1 - \sin 2\psi)] \text{ and } B = 127 \qquad (20)$$

$$R = \text{int}[127.5\,(1 - \cos 2\chi)],\ G = \text{int}[127.5\,(1 - \sin 2\chi)] \text{ and } B = 127 \qquad (21)$$

Since black (0,0,0), white (255,255,255) and yellow (255,255,0) are excluded from the encoding scheme of Eqs. (20-21), they are used for special conditions. Black is used when $S_0 = 0$, white for indeterminate values such as dividing by zero and for P = 0; yellow is used in the ψ-images whenever $\chi = \pm 45°$ (circular polarization). The normalized Stokes parameters for circular polarized light are $(S_0, S_1, S_2, S_3) = (1,0,0,\pm1)$. Since the ψ-value is related to the ratio S_2/S_1 (Eq. 5), ψ is indeterminate for circular polarization. Polarization states that are nearly circular are ill-conditioned with respect to ψ. Referring to Eq. (5), if $\sin 2\chi$ is greater than one or less than -1 (due to measurement errors), then χ is undefined. The undefined χ-values are circumvented by assuming $\chi = 45°$ when $\sin 2\chi > 1$ and $\chi = -45°$ when $\sin 2\chi < -1$.

The degree of polarization, P, varies between 0 and 1. The simplest method of encoding this parameter in a daylight scene is to use the equation [pixel value] = 255 P. The black areas (pixel

value = 0) in the resulting monochrome image will correspond to no polarization and the white areas (pixel value = 255) will correspond to light that is 100 percent polarized.

Figure 11 gives an example of the use of the visualization process described above. The polarization parameters P, ψ and χ are displayed for a vehicle in daylight at 12:00 on April 26, 2000 in Warren, MI. The altitude of the sun was 55 degrees and the azimuth (south = 0) of the sun was 319 degrees. The interpretation of these polarization parameters as a function of the relative position of the sun have been analyzed and compared to laboratory data. These findings will be presented in a future paper.

CONCLUSIONS:

This paper develops a systematic methodology to measure the four Stokes parameters for each pixel in an RGB image where the scene is illuminated by broad band radiation in the visual part of the electromagnetic spectrum. A calibration procedure maps the COTS digital camera RGB eight bit grey levels into their corresponding relative intensity values. The calibration process produces linear intensity values that allow for linear averaging over a selected number of pixel regions of the image. This process reduces random errors in the polarization images. This capability is very important because of the inherent ill-conditioning in many polarization states. The fourth Stokes parameter measurement requires a retarder element, which is wavelength dependent and normally limited to narrow band incident light. Detailed calculations show that the quasi-monochromatic approximation can be extended to include the spectral response of the broad band RGB channels. We provide equations to compensate for the phase differences

between the tuned frequency of the retarder and an arbitrary input wavelength. Excellent agreement is achieved between the theoretical and experimental data for known elliptical polarization states.

The Stokes parameters are encoded into a polarization image by assigning RBG color coordinates to their normalized values. This color encoding scheme closely relates to the Poincarè sphere representation of polarized light where each Stokes vector maps into unique RGB values for $0 \leq P \leq 1$. We then use this visualization technique to represent the degree of polarization, azimuth and ellipticity angles associated with natural daylight scene imagery.

Future work will examine the following issues arising from this research. Interpretation of the physical phenomena associated with polarization imagery including daylight illumination conditions and material characteristics within the scene. We will analyze the effects of spatial and temporal registration errors upon the fidelity of P, ψ and χ polarization images.

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13. G.R. Gerhart and R.M. Matchko, "Method of determining polarization profiles for polychromatic sources," United States Patent Office, Washington D.C., Patent Number 5,734,473, Col. 4, (1998).

Table Caption

Table 1. Three examples of the errors introduced in the measurement of the fourth Stokes parameter by transmitting a broadband polarized light beam through the fourth filter of Figure 6. The first two rows refer to Example 1, rows three and four refer to Example 2 and rows five and six refer to Example 3. The best case and worst case scenario are given for each example. The best case scenario uses a tuned wavelength of 400 nm and the red channel. The worst case scenario uses a tuned wavelength of 700 nm and the blue channel.

Figure Captions

Figure 1. The Poincare sphere.

Figure 2. The polarization ellipse.

Figure 3. The channel spectral response of an Epson 850Z digital camera.

Figure 4. Conversion from RGB to optical density for the green channel of an Epson 850 Z. A Matlab algorithm calculated the average pixel response from a 10 X 10 pixel area.

Figure 5. The relationship between the phase difference of a zero-order quartz quarter wave retarder and the wavelength transmitted through it for four different tuned wavelengths: 650, 550 and 450 nm.

Figure 6. The four-filter system used to determine the Stokes parameters. P is the transmission axis of a linear polarizer and R is the fast axis of a zero order quartz quarter-wave retarder.

Figure 7. An experimental camera setup to acquire the four-image sequence for obtaining the Stokes parameters associated with each pixel in the scene.

Figure 8. Apparatus for producing known polarization forms. Light of wavelength λ is transmitted through a linear polarizer with its transmission axis at an angle α relative to the x-axis and transmitted through a zero-order quarter-wave retarder with its fast axis at an angle β to the x-axis.

Figure 9. Column A: Polarization forms generated with the apparatus of Figure 8 and corresponding to the minimum, maximum and midpoint wavelengths within each color channel. Column B: A comparison between the known polarization forms, produced by using a midpoint wavelength for each RGB channel, to those actually obtained from the Epson 850Z.

Figure 10. (a) The surface of the colorized Poincaré sphere. (b) The colorized Poincaré sphere of unit radius. On the surface of the sphere, $P = 1$. At the center, $P = 0$. Inside the sphere $P < 1$. (c) The Equatorial plane of the colorized Poincaré sphere.

Figure 11. An example of the use of the encoding methodology to colorize the polarization parameters. The degree of polarization P, the polarization azimuth angle ψ and the ellipticity χ are shown for 12:00. Viewing is toward the north.

Input Stokes Parameters				Quartz Retarder Parameters					Output Polarization Parameters			
S_0^*	S_1^*	S_2^*	S_3^*	λ_T (nm)	λ_A (nm)	ε_A (rad)	λ_B (nm)	ε_B (rad)	I_{4avg}	S_3	P	χ (deg)
1.000	0.000	0.000	1.000	400	600	0.999	700	0.845	0.898	1.004	1.004	45.0
1.000	0.000	0.000	1.000	700	400	2.921	500	2.270	0.755	0.922	0.922	45.0
1.000	-0.250	0.433	0.866	400	600	0.999	700	0.845	0.975	0.866	1.000	30.0
1.000	-0.250	0.433	0.866	700	400	2.921	500	2.270	0.539	0.793	0.937	28.9
1.000	-0.500	0.866	0.000	400	600	0.999	700	0.845	0.761	-0.006	1.000	-0.2
1.000	-0.500	0.866	0.000	700	400	2.921	500	2.270	0.136	-0.011	1.000	-0.3

Table 1

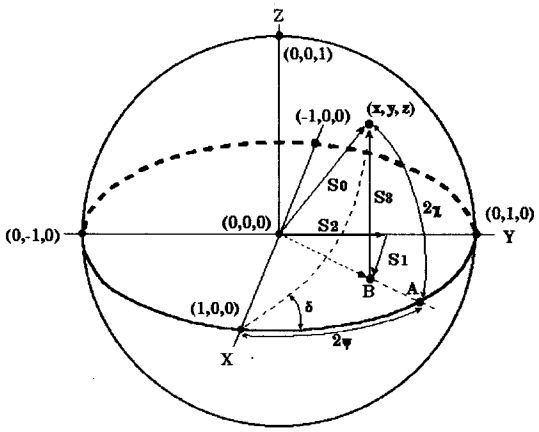


Figure 1

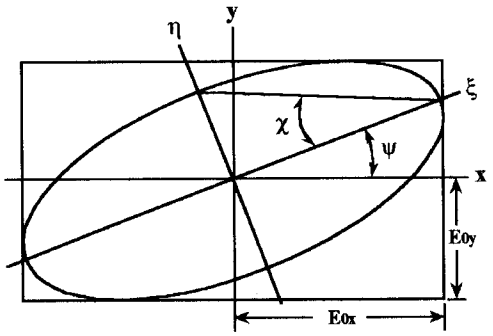


Figure 2

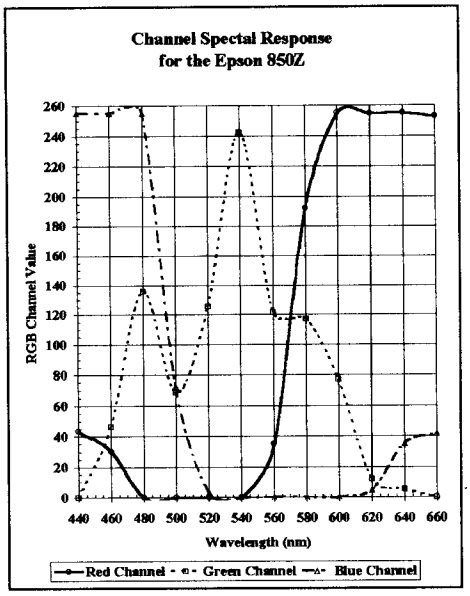

Channel Spectal Response
for the Epson 850Z
RGB Channel Value
260
240
220
200
180
160
140
120
100
80
60
40
20
0
440 460 480 500 520 540 560 580 600 620 640 660
Wavelength (nm)
Red Channel
Green Channel
Blue Channel

Figure 3

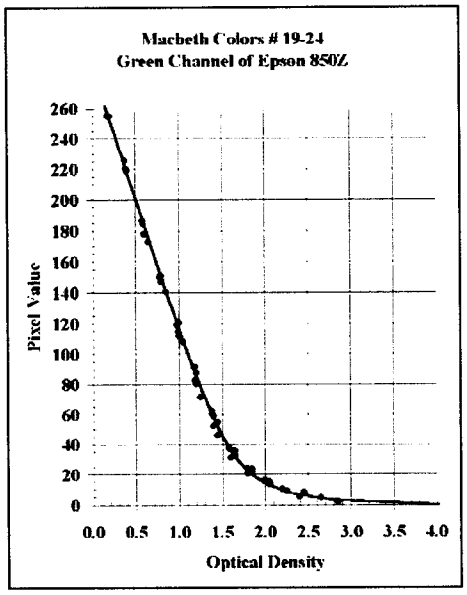

Macbeth Colors # 19-24
Green Channel of Epson 850Z
Pixel Value
260
240
220
200
180
160
140
120
100
80
60
40
20
0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0
Optical Density

Figure 4

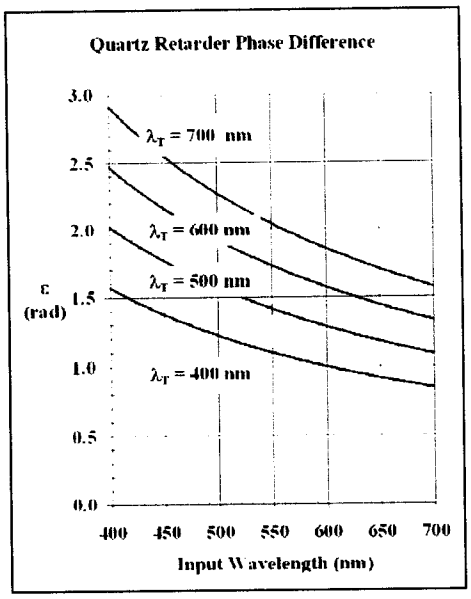

Quartz Retarder Phase Difference
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ε
(rad)
λT = 700 nm
λT = 600 nm
λT = 500 nm
λT = 400 nm
400
450
500
550
600
650
700
Input Wavelength (nm)

Figure 5

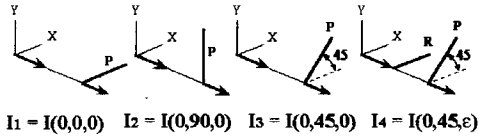


Figure 6

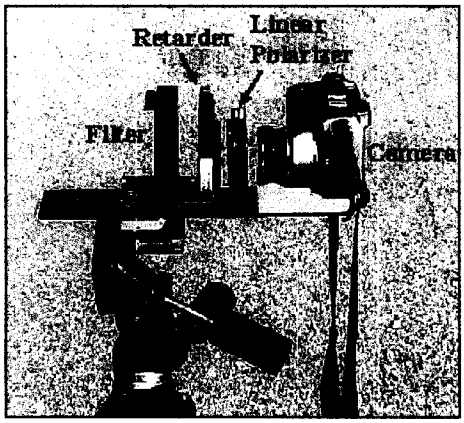


Figure 7

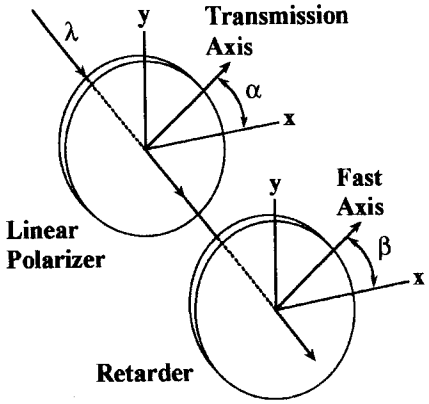

λ
y
Transmission
Axis
α
x
y
Fast
Axis
β
x
Linear
Polarizer
Retarder

Figure 8

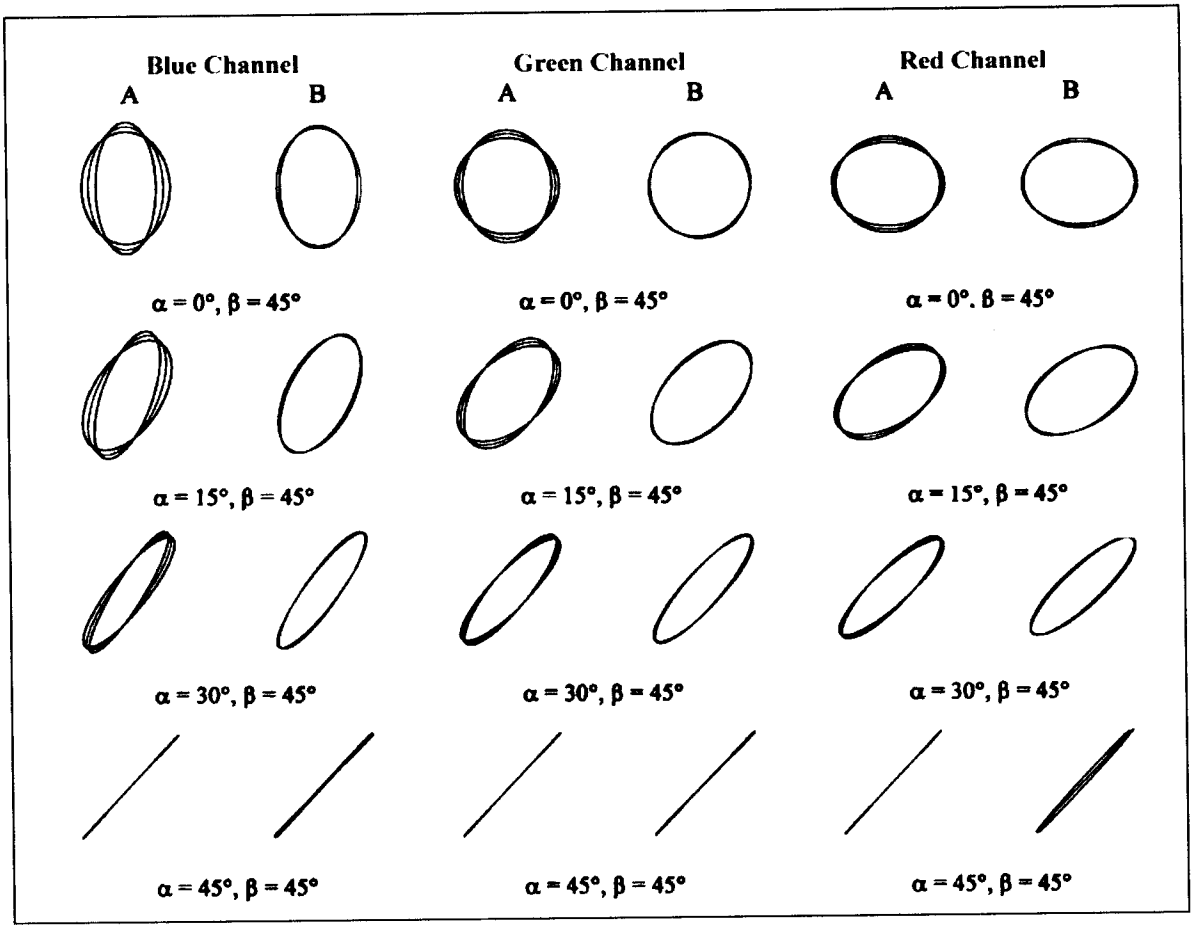
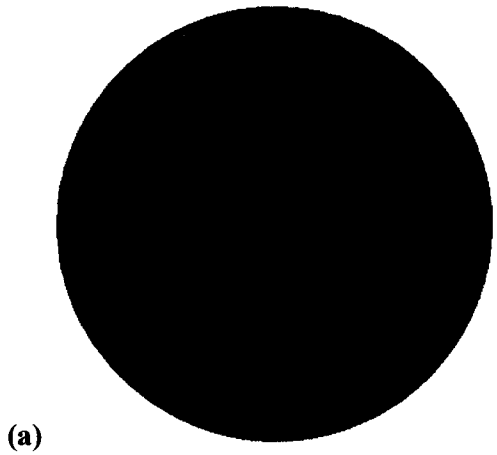
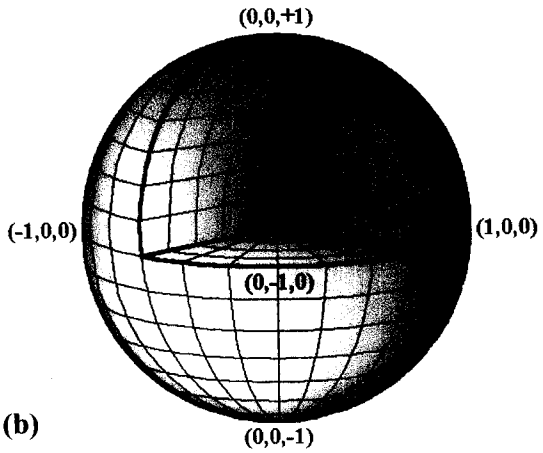

Blue Channel
Green Channel
Red Channel
A
B
A
B
A
B
α = 0°, β = 45°
α = 0°, β = 45°
α = 0°. β = 45°
α = 15°, β = 45°
α = 15°, β = 45°
α = 15°, β = 45°
α = 30°, β = 45°
α = 30°, β = 45°
α = 30°, β = 45°
α = 45°, β = 45°
α = 45°, β = 45°
α = 45°, β = 45°

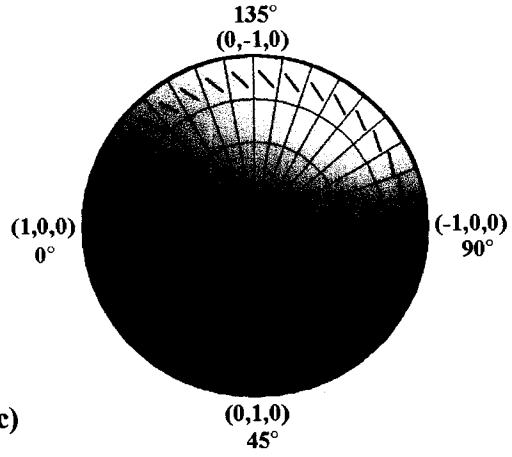
Figure 9



(a)

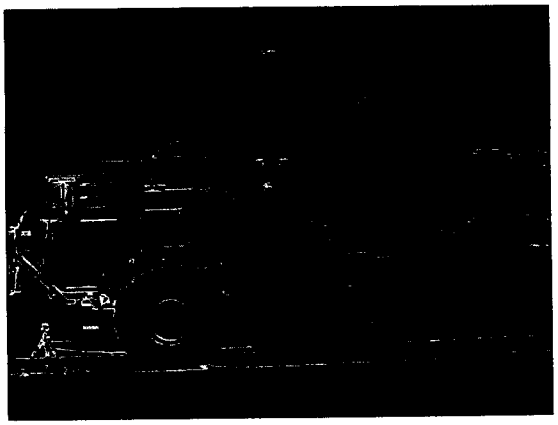


(b)

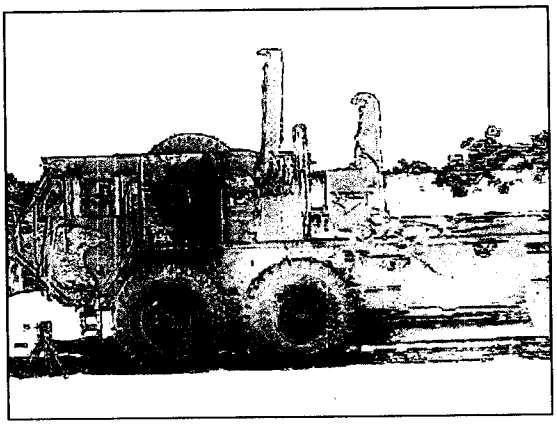


(c)

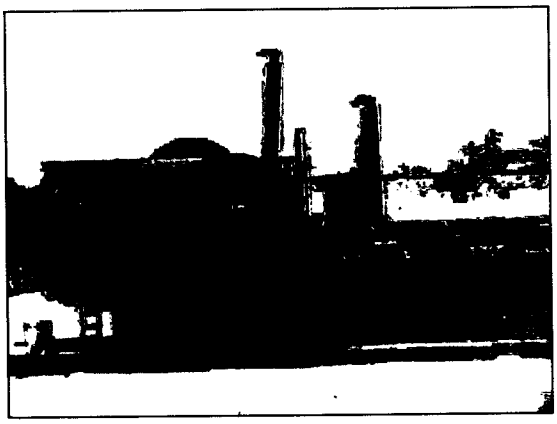
Figure 10



(a) P at 12:00



(b) ψ at 12:00



(c) χ at 12:00

Figure 11