Calibration method for equivalent extinction ratio of polarized pixel in integrated micropolarizer array camera

Bin Feng, Zelin Shi, Haizheng Liu, Yaohong Zhao, Jianting Liu

Abstract

Equivalent extinction ratio and polarization orientation are two significant parameters representing the performance of a polarized pixel in an integrated micropolarizer array camera. With manufacturing and integrating errors of the micropolarizer array, equivalent extinction ratios are nonuniform and polarization orientations of polarized pixels deviate from their nominal values. Measuring the equivalent extinction ratio and the polarization orientation of each polarized pixel by rotating a polarizer at a tiny step is extremely time-consuming and even inaccurate. Therefore, this paper proposes a calibration method for the equivalent extinction ratio and the polarization orientation of each polarized pixel. Its principle is derived by theorizing the relationship between an orientation of a linearly polarized incident light and its digital output of a polarized pixel. In experiment, this derived principle is applied to an integrated micropolarizer array camera. Experimental result proves that calibrated equivalent extinction ratios generally vary from 4.5 to 10, with a mean of 7.939 and a standard variation of 1.053.

Keywords: Equivalent extinction ratio; polarization orientation; micropolarizer array; polarization imaging

1. INTRODUCTION

Polarization imaging can obtain information relating to a dielectric constant, refraction index, reflectivity, surface roughness and a surface normal direction [1]. It is widely used in those fields such as industrial inspection, environmental monitoring, medical diagnosis, marine detection, atmospheric remote sensing, biomimetic navigation, astronomical observation, microscope imaging and military safety [2,3].

An integrated micropolarizer array imager has those merits such as a high transmission efficiency, high extinction ratio and real time [4-6]. It outperforms some conventional polarization imagers such as division of time systems, division of amplitude systems, and division of aperture systems [7]. Recently, an integrated micropolarizer array camera is expected to mount on an airborne platform.

However, the manufacturing and integrating errors of an micropolarizer array affect its performance [8,9]. In the development of an integrated micropolarizer array camera, some manufacturing errors cannot be unavoidable. An integrated micropolarizer array camera is formed by bonding a micropolarizer array on a focal plane array (FPA) of a conventional camera. Each micropolarizer has slight variations in physical structures such as grating period, cycle and thickness. Similarly, each pixel of a camera has different response properties. If a micropolarizer array is directly bonded to the FPA by glue, the coated glue may be nonuniform on the FPA and even fill the grating grooves. All those factors jointly cause equivalent extinction ratios to be nonuniform and cause a polarization orientation of each polarized pixel deviating from its nominal value. In order to achieve a high performance, this paper proposes a calibration method for an equivalent extinction ratio and a polarization orientation of each polarized pixel in an integrated micropolarizer array camera.

2. DERIVED PRINCIPLE

For a linearly polarized light with an intensity of I, the output of each polarized pixel can be expressed as,
\[ D_{(k,z)} = \eta_k^H I \cdot \cos^2 (\psi_z - \theta_k) + \eta_k^L I \cdot \sin^2 (\psi_z - \theta_k) + b_k \]  \hspace{1cm} (1)

where \( k \) denotes a sequence number of a polarized pixel, \( \eta_k^H \) and \( \eta_k^L \) respectively represent the major and minor responsivities as the polarization orientation of a linearly polarized light rotates, \( \theta_k \) denotes the polarization orientation relative to a reference orientation, \( \psi_z \) denotes the orientation of a linearly polarized light relative to the reference orientation, and \( b_k \) denotes the offset of an integrated micropolarizer array camera.

\[ \cos^2 (\psi_z - \theta_k) = \frac{1 + \cos[2(\psi_z - \theta_k)]}{2} \]  \hspace{1cm} (2)

\[ \sin^2 (\psi_z - \theta_k) = \frac{1 - \cos[2(\psi_z - \theta_k)]}{2} \]  \hspace{1cm} (3)

The Equation (1) can be rewritten as,

\[ D_{(k,z)} = \frac{1}{2} I [(\eta_k^H + \eta_k^L) + (\eta_k^H - \eta_k^L) \cos[2(\psi_z - \theta_k)])] + b_k \]  \hspace{1cm} (4)

Let,

\[ \eta_k^+ = \frac{1}{2}(\eta_k^H + \eta_k^L) \]  \hspace{1cm} (5)

\[ \eta_k^- = \frac{1}{2}(\eta_k^H - \eta_k^L) \]  \hspace{1cm} (6)

\[ Y_{(k,z)} = D_{(k,z)} - b_k \]  \hspace{1cm} (7)

The Equation (4) can be rewritten as,

\[ Y_{(k,z)} = I(\eta_k^+ + \eta_k^- \cos 2\psi_z \cos 2\theta_k + \eta_k^- \sin 2\psi_z \sin 2\theta_k) \]  \hspace{1cm} (8)

For a given polarized pixel, the parameters of \( \eta_k^+ \), \( \eta_k^- \) and \( \theta_k \) are invariable. However, if the orientation \( \psi_z \) of a linearly polarized light is changed by rotating a high extinction ratio polarizer, the polarized pixel of the polarization camera will output different \( Y_{(k,z)} \). The following equation holds,
An integrating sphere

A high extinction ratio polarizer controlled by a motorized precision rotator

An optical lens

An integrated micropolarizer-array imager

Figure 2. Optical diagram of our experimental setup.

By rotating the polarizer, we can obtain the linearly polarized light with different orientations. We set the horizontal orientation as a reference. By respectively rotating the polarizer by 0 degree, 45 degrees, 90 degrees and 135 degrees, we obtain four outputs of each polarized pixel. By means of the Equation (11)-(13), we can obtain the equivalent extinction ratio and the polarization orientation of the $k$-th polarized pixel. By repeating across the entire array, we can calibrate equivalent extinction ratios and polarization orientations of all the polarized pixels.

Figure 3 shows that equivalent extinction ratios generally vary from 4.5 to 10, with a mean of 7.939 and a standard variation of 1.053. For the micropolarizer array before integration, its mean of equivalent extinction ratio is greater than 35. A segment between the micropolarizer array and the FPA degrades the extinction ratio. The central region and bottom region have a higher equivalent extinction ratios than the other regions. In our integrated micropolarizer array...
camera, the micropolarizer array and the detector is integrated by glue. The glue is nonuniformly coated, which seriously causes the nonuniformity of equivalent extinction ratios.

Figure 4(a) shows that the most of differences between the calibrated and the nominal polarization orientations are within the range of -1 degree to 1 degree. Figure 4(b) shows the histogram of four polarization orientations. The expected distribution is that each nominal polarization orientation accounts for about 1/4 of total polarized pixels. Because we focus more on the relative orientation, the mean of calibrated orientation values of polarized pixels with a nominal of 0 degree is taken as a reference value. This reference value is used to subtract all the calibrated polarization orientation values. Therefore, in Table 1, the mean of calibrated polarization orientations of 0 degree is zero. Table 1 proves that the calibrated polarization orientations are closer to their nominal values for 0 degree and 90 degree polarized pixels. 0 degree polarized pixels with a nominal value of 0 degree is close to nominal value but has a largest scatter. The polarized pixels with a nominal value of 90 degrees has a least scatter.

![Figure 3(a). Distribution of calibrated equivalent extinction ratios of polarized pixels.](image1)

![Figure 3(b). Histogram of calibrated equivalent extinction ratios of polarized pixels.](image2)

![Figure 4(a). Differences between calibrated and nominal polarization orientations of polarized pixels.](image3)

![Figure 4(b). Histogram of calibrated polarization orientations.](image4)

<table>
<thead>
<tr>
<th>Nominal values of polarization orientation</th>
<th>0 degree</th>
<th>45 degrees</th>
<th>90 degrees</th>
<th>135 degrees</th>
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<tbody>
<tr>
<td>Mean (degree)</td>
<td>0</td>
<td>46.76</td>
<td>90.0095</td>
<td>136.46</td>
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<tr>
<td>Standard variation</td>
<td>0.7069</td>
<td>0.5243</td>
<td>0.3782</td>
<td>0.7025</td>
</tr>
</tbody>
</table>

Table 1 The mean and standard variation of calibrated polarization orientations.
4. CONCLUSIONS

It is extremely time-consuming and even inaccurate to measure a polarization orientation and an equivalent extinction ratio of each polarized pixel by rotating a polarizer at a tiny step. By means of the proposed method, we can calibrate the equivalent extinction ratio and the polarization orientation of each polarized pixel for an integrated micropolarizer array camera. Based on the calibrated polarization property of each polarized pixel, an accurate nonuniformity correction approach for an integrated micropolarizer array camera deserves further research.

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REFERENCES