Passive shortwave-infrared polarimetric sensing of cloud thermodynamic phase

Martin Jan Tauc*,† Elizabeth M. Rehbein,‡ Laura M. Eshelman§, Wataru Nakagawa○, and Joseph A. Shaw*
Montana State University, Department of Electrical and Computer Engineering, Bozeman, Montana, United States

Abstract. Cloud thermodynamic phase (CTP) classification is a vital piece of information for determining how clouds affect climate and electromagnetic wave propagation. We describe a passive shortwave infrared (SWIR) three-channel polarimeter for CTP remote sensing. This instrument adds polarimetric sensitivity to the traditional radiance ratio method that capitalizes on the difference in spectral absorption between liquid water and ice. The ground-based polarimeter was used to measure the first three Stokes parameters in three SWIR spectral bands alongside a dual-polarization lidar system for validation. Additionally, we operated the polarimeter in division-of-time and division-of-aperture modes to explore the severity of polarization artifacts that arose from fast-moving clouds. Although temporal smearing of polarization signatures was identified, the impacts were found to be minimal. Using a surface fitting technique, the radiance ratio method was directly compared with a method that combined radiance ratios with the $S_1$ Stokes parameter. We found that the addition of polarimetry improved cloud phase classification ability from $\sim 73\%$ to $95\%$. © 2021 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.JRS.15.024520]

Keywords: cloud thermodynamic phase; atmospheric scattering; polarimetry.

1 Introduction

Clouds are one of the strongest regulators of Earth’s radiation budget and demand diligent study because they are very complex1–5 and are associated with some of the largest uncertainties in climate science.6–8 One of the most fundamental and important cloud properties is the cloud thermodynamic phase (CTP), whether a cloud is composed of spherical water droplets, polyhedral ice crystals, or both. This property is of particular interest because the CTP in and of itself impacts the Earth’s net radiation budget and because it must be known prior to determining other cloud microphysical properties.8–14

Previous researchers have capitalized on liquid water and ice absorbing solar radiation differently at certain wavelengths,15,16 which enables CTP determination with passive remote sensing systems.5,12,17 Recently, our group published a new version of the radiance ratio method in a three-parameter space with ratios defined by

$$R_{1.70,1.64} = \frac{L_{1.70} - L_{1.64}}{L_{1.64}},$$

and

$$R_{1.55,1.64} = \frac{L_{1.55} - L_{1.64}}{L_{1.64}},$$

and

1Present address: Argo AI 1450 Page Mill Road, Palo Alto, California, USA
2Present address: Bridger Photonics, Inc., 2310 University Way, Bozeman, Montana, USA
3Present address: Polaris Sensor Technologies, Inc., 200 West Side Square, Suite 320, Huntsville, Alabama, USA
4Address all correspondence to Joseph A. Shaw, joseph.shaw@montana.edu
where $L_{\text{band}}$ represents radiance in the spectral band centered at the band wavelength in micrometers. That recent paper described simulations that led to our choice of wavelengths and showed experimental results from a spectrometer and dual-polarization lidar to confirm that the new three-parameter formulation of the unpolarized radiance ratio method worked well.

Although the radiance ratio method effectively classifies clouds with large optical depth, recent research showed that polarimetry may be useful on its own for discriminating CTP for clouds with low optical depth. We recently used a visible-wavelength, full-sky polarization imager to experimentally confirm that polarimetry alone at these wavelengths provided effective CTP determination (with validation provided by a dual-polarization lidar). At about the same time, we also developed a shortwave infrared (SWIR) three-channel polarimeter for experimentally studying the value of adding polarization to the three-wavelength radiance ratio method mentioned above.

An early prototype of that instrument, along with preliminary data separately analyzed with the (unpolarized) three-channel radiance ratio method and a simple polarization method, was described in a 2018 conference paper. The first combined use of polarization and the three-channel radiance ratio method was done with a more field-robust version of the SWIR three-channel polarimeter, as described in a 2019 conference paper.

Following that preliminary study, we modified the instrument to allow simultaneous measurements in three polarization states at the 1.55-μm wavelength. This enabled snapshot polarimetry with a division-of-aperture (DOA) approach. This paper discusses the instrument before and after modification with a totally new data set to demonstrate the quantitative value of adding polarization to the three-wavelength radiance ratio method. This combined method uses the $S_1$ Stokes parameter, defined as

$$S_1 = L_\parallel - L_\perp,$$

where $L_\parallel$ and $L_\perp$ are the radiances detected in the planes parallel and perpendicular to the scattering plane, respectively (and the scattering plane contains the Sun, the scattering point, and the observer).

This paper builds on the previous conference papers that described (1) the prototype SWIR three-channel polarimeter with the radiance ratio and polarization methods implemented separately and (2) a more field-ready version of the SWIR three-channel polarimeter with a preliminary combination of the radiance ratio and polarization methods. Here we present more diverse data and reinforce the finding that polarimetry improves CTP classification. We also explore whether fast-moving clouds introduced polarization artifacts into the data by comparing the original polarimeter configuration with a snapshot (DOA) configuration.

## 2 Methodology

The SWIR three-channel polarimeter collected data in two stages: stage 1 took place from January to April 2019 with division-of-time (DOT) polarimetry over the course of 14 days, and stage 2 took place from July to December 2019 with both DOT and DOA polarimetry over the course of 14 days as well. The results from stage 1 showed that there may have been a loss of polarimetric information from fast-moving clouds; therefore, the DOA capability was added in stage 2 to provide temporally simultaneous acquisition of three linear polarization states at one wavelength.

Stage 1 and stage 2 took place during different times of the year, with stage 1 primarily in winter and spring and stage 2 during the summer and fall. Table 1 details the days for each represented experiment and the maximum solar elevation angle for that day. Our experiments were not necessarily during the part of the day when the Sun was at its highest point, but this table illustrates the limitations of the experiment for each day. Actual scattering angles are provided and discussed in Figs. 8 and 9. In the outdoor experiments for remotely sensing CTP, data were compared with a vetted method of CTP classification, a dual-polarization lidar.
The measurements shown here were performed with the instrument oriented such that the horizontal and vertical polarizers were perpendicular and parallel to the scattering plane, respectively (so the $S_1$ Stokes parameter is referenced to the scattering plane). The diagonal polarizer is therefore unnecessary, but it was included in the original design in anticipation of a future imaging version in which each pixel would not be in the scattering plane. In the stage 1 configuration (described below), skipping the diagonal polarization measurement actually would not have saved time, but the stage 2 configuration (described below) was implemented to provide simultaneous measurements at all three polarizations at one wavelength.

### 2.1 Stage 1: DOT Polarimeter

The stage 1 polarimeter, described in detail elsewhere,\textsuperscript{22,23} consisted of three independent optical trains, each with a linear polarizer in front oriented at 0 deg, 45 deg, and 90 deg and followed by a lens and germanium detector. Throughout this paper, these optical trains are referenced by their polarizer orientation (i.e., vertical, horizontal, or diagonal channel). Just prior to the lens, a filter wheel housed three spectral filters centered at 1.55, 1.64, and 1.70 $\mu$m. At each filter wheel position, the polarimeter averaged 100 readings in 1 s and then rotated to the next position in $\sim$2 s. In this form, the DOT polarimeter recorded three measurements at each of three spectral filters, or nine measurements for a full filter wheel rotation, such that the first three (linear) Stokes parameters could be determined at each wavelength. The detector voltage at each filter wheel position was converted to radiance, and the radiance values were used to calculate Stokes parameters directly (with no reduction matrix).

A rendering of the DOT polarimeter is shown in Fig. 1(a), where [from (a) to (b)] the detectors are shown in purple; the lenses are gray; the filter wheel is yellow and houses the spectral filters centered at 1.55, 1.64, and 1.70 $\mu$m as blue, green, and red, respectively; and finally the polarizers are rendered with black and white stripes (denoting the polarizer transmission axis).

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Table 1 The dates and maximum solar elevation angle (measured from the horizon toward zenith) for each day of data collection for stage 1 and stage 2 showed similar elevation angles even though the measurements were done during different times of the year.

<table>
<thead>
<tr>
<th>Date</th>
<th>Maximum solar elevation angle (deg)</th>
<th>Date</th>
<th>Maximum solar elevation angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 January</td>
<td>22.32</td>
<td>8 July</td>
<td>66.77</td>
</tr>
<tr>
<td>10 January</td>
<td>22.46</td>
<td>26 August</td>
<td>54.65</td>
</tr>
<tr>
<td>22 January</td>
<td>24.77</td>
<td>29 August</td>
<td>53.59</td>
</tr>
<tr>
<td>31 January</td>
<td>27.07</td>
<td>5 September</td>
<td>51.04</td>
</tr>
<tr>
<td>12 February</td>
<td>30.77</td>
<td>16 October</td>
<td>35.37</td>
</tr>
<tr>
<td>13 February</td>
<td>31.11</td>
<td>18 October</td>
<td>34.64</td>
</tr>
<tr>
<td>22 February</td>
<td>34.27</td>
<td>24 October</td>
<td>32.51</td>
</tr>
<tr>
<td>21 March</td>
<td>44.70</td>
<td>31 October</td>
<td>30.17</td>
</tr>
<tr>
<td>22 March</td>
<td>45.10</td>
<td>19 November</td>
<td>24.85</td>
</tr>
<tr>
<td>2 April</td>
<td>49.39</td>
<td>26 November</td>
<td>23.38*</td>
</tr>
<tr>
<td>4 April</td>
<td>50.15</td>
<td>2 December</td>
<td>22.38</td>
</tr>
<tr>
<td>18 April</td>
<td>55.27</td>
<td>4 December</td>
<td>22.10</td>
</tr>
<tr>
<td>19 April</td>
<td>55.62</td>
<td>5 December</td>
<td>21.97</td>
</tr>
<tr>
<td>23 April</td>
<td>56.97</td>
<td>6 December</td>
<td>21.85</td>
</tr>
</tbody>
</table>

---

The measurements shown here were performed with the instrument oriented such that the horizontal and vertical polarizers were perpendicular and parallel to the scattering plane, respectively (so the $S_1$ Stokes parameter is referenced to the scattering plane). The diagonal polarizer is therefore unnecessary, but it was included in the original design in anticipation of a future imaging version in which each pixel would not be in the scattering plane. In the stage 1 configuration (described below), skipping the diagonal polarization measurement actually would not have saved time, but the stage 2 configuration (described below) was implemented to provide simultaneous measurements at all three polarizations at one wavelength.
The filter wheel would rotate by 120 deg between the three spectral filters. The polarimeter also had a camera next to the three channels for alignment purposes and to inspect the conditions of the scene. Data from the camera were not used for data processing, but they were helpful for the field of view (FOV) calibration and for insight into the scene in general.

When analyzing the stage 1 data, unexpected trends led us to question if fast-moving clouds were causing polarization artifacts. A changing scene could impact the radiance ratio method as well, but to investigate this possible impact on the DOT polarimetric data, the SWIR three-channel polarimeter was modified to also perform snapshot (or DOA) polarimetry on the 1.55-μm spectral channel.

### 2.2 Stage 2: DOA Addition

In the summer of 2019, the SWIR three-channel polarimeter was disassembled and the filter wheel was modified so that in addition to the spectral filters centered at 1.55, 1.64, and 1.70 μm, three more 1.55-μm spectral filters were included. The disk-shaped filter wheel (with six filter slots) was housed in the filter wheel assembly, which had three openings at 0 deg, 120 deg, and 240 deg. In stage 1, three of the six slots (at 0 deg, 120 deg, and 240 deg filter-wheel positions) were fitted with the three different spectral filters; in stage 2, the three additional 1.55-μm filters were added to the slots at 60 deg, 180 deg, and 300 deg. The three spectral filters [labeled A, B, and C in Fig. 1(b)] enabled the polarimeter to switch between DOA mode and DOT mode each time the filter wheel rotated by 60 deg. In this configuration, when the filter wheel was in its first position, the polarimeter took a measurement for the filters centered at 1.55, 1.64, and 1.70 μm (this was the DOT configuration). Then when the filter rotated by 60 deg into its next position, the polarimeter took a measurement where the three 1.55-μm filters were aligned with the optical trains (this was the DOA configuration). Once the filter wheel moved through all six positions, the DOT configuration provided radiance ratio data as well as the first three Stokes parameters for each of the three spectral bands. It also produced the first three Stokes parameters for the spectral band at 1.55 μm three different times using snapshot polarimetry. After modification, the instrument underwent FOV, spectral, radiometric, and polarimetric calibrations.

#### 2.2.1 Field of view calibration

Calibrating the FOV determined how well the three channels were aligned with respect to each other and identified what part of the sky was measured in reference to the accompanying image.

Fig. 1 (a) The DOT configuration has three separate optical trains that start with a polarizer oriented vertically, horizontally, or diagonally relative to the scattering plane. The next element is a spectral filter that cycles through the 1.55-, 1.64-, and 1.70-μm filters using a filter wheel that rotates in 120-deg increments. Then each optical train has a lens and detector. (b) The DOA addition adds three additional spectral filters centered at 1.55 μm into the three available slots of the filter wheel. In this configuration, the filter wheel rotates in 60 deg steps, and each step alternates between a DOT measurement and a DOA measurement based on which filters are aligned with the optical trains. Black lines indicate the optical path through each train.
To calibrate, the polarimeter was mounted to a pan and tilt mount ∼10 m from a small light source that was considered a point source. Under dark conditions, the polarimeter raster scanned in the horizontal and vertical directions, and the FOV for each channel was estimated based on the relationship between detected power and pointing position as shown in Table 2.

In Fig. 2, the full-angle FOVs are represented as circles on the accompanying image. The most important overlap is between the vertical and horizontal channels because they are used to calculate $S_1$. From this figure and Table 2, it is clear that the two channels had good overlap and thus observed nearly the same portion of the sky, whereas the diagonal channel observed a region slightly overlapping the others.

### 2.2.2 Spectral calibration

To account for the different spectral responses of the individual polarizers, lenses, detectors, and spectral filters, a comprehensive spectral calibration was done using a monochromator, and band-average radiance was determined by viewing a large-aperture integrating sphere. A complete cycle with the stage 1 instrument required three spectral filters to rotate in front of each of three polarizers, for a total of nine unique measurements. This presents the possibility of different radiance measurements in a given spectral channel when viewing a randomly polarized source through the three polarizers, which would contribute a systematic error to the measurement. Table 3 lists the band-average radiance values for the nine measurements and the percent differences for the measurements that theoretically should have been the same in each spectral band.

In the stage 2 instrument, we added three additional 1.55-μm spectral filters in the previously blank filter wheel openings to enable simultaneous measurements at three polarization states at this wavelength. Because of the filter wheel rotation, measurements at this wavelength were obtained with nine different combinations of the three spectral filters (referred to here as $A$, $B$, and $C$) and the three polarizers. This again raises the possibility of systematic errors, which are characterized as band-average radiance differences in Table 4.

#### Table 2

The full-angle FOV of the pan and tilt coordinates for each of the three channels in the polarimeter were all nearly identical.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Pan (deg)</th>
<th>Tilt (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>3.0</td>
<td>2.4</td>
</tr>
<tr>
<td>Horizontal</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Diagonal</td>
<td>3.0</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Fig. 2 A representation of the FOV for the three polarimeter channels mapped onto an example cloud scene (after Fig. 3 but for the rebuilt polarimeter).
2.2.3 Radiometric calibration

The DOT and DOA configurations each had their own radiometric calibration. The calibrations used a halogen light and integrating sphere to produce a disk of light that was spatially uniform in radiance and randomly polarized. The halogen bulb and integrating sphere were separated by a variable attenuator that would modify the total output radiance so that a consistent sweep of radiance values could be mapped to the detected voltage on the polarimeter.

### Table 3

The bandpass radiance for each spectral channel at each polarization state using a randomly polarized radiance source should be identical, but some differences are present. These differences are likely from the inconsistencies in the spectral responses of the detectors, polarizers, and lenses, as well as small misalignments in the optics train.

<table>
<thead>
<tr>
<th>Spectral channel (μm)</th>
<th>Polarization state</th>
<th>Experimental (W m(^{-2}) sr(^{-1}))</th>
<th>Difference relative to the vertical channel (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.55</td>
<td>Vertical (</td>
<td></td>
<td>)</td>
</tr>
<tr>
<td></td>
<td>Horizontal (⊥)</td>
<td>5.28</td>
<td>2.27</td>
</tr>
<tr>
<td></td>
<td>Diagonal (45 deg)</td>
<td>5.34</td>
<td>1.12</td>
</tr>
<tr>
<td>1.64</td>
<td>Vertical (</td>
<td></td>
<td>)</td>
</tr>
<tr>
<td></td>
<td>Horizontal (⊥)</td>
<td>4.86</td>
<td>1.58</td>
</tr>
<tr>
<td></td>
<td>Diagonal (45 deg)</td>
<td>4.89</td>
<td>1.04</td>
</tr>
<tr>
<td>1.70</td>
<td>Vertical (</td>
<td></td>
<td>)</td>
</tr>
<tr>
<td></td>
<td>Horizontal (⊥)</td>
<td>5.98</td>
<td>1.73</td>
</tr>
<tr>
<td></td>
<td>Diagonal (45 deg)</td>
<td>6.05</td>
<td>0.48</td>
</tr>
</tbody>
</table>

### Table 4

The bandpass radiances for each of the three 1.55-μm filters at each of the three polarizers are given along the top row and left column in units W m\(^{-2}\) sr\(^{-1}\). The difference between the filters is given as a percentage and shows that differences between horizontal and vertical channels are 3.53% or less, even though differences are larger in the diagonal channel.

<table>
<thead>
<tr>
<th>Spectral channel (μm)</th>
<th>Polarization state</th>
<th>Experimental (W m(^{-2}) sr(^{-1}))</th>
<th>Difference relative to the vertical channel (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.55</td>
<td>Vertical (</td>
<td></td>
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<tr>
<td>1.64</td>
<td>Vertical (</td>
<td></td>
<td>)</td>
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<td>4.86</td>
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<tr>
<td></td>
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<td>1.04</td>
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<tr>
<td>1.70</td>
<td>Vertical (</td>
<td></td>
<td>)</td>
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</tr>
</tbody>
</table>

2.2.3 Radiometric calibration

The DOT and DOA configurations each had their own radiometric calibration. The calibrations used a halogen light and integrating sphere to produce a disk of light that was spatially uniform in radiance and randomly polarized. The halogen bulb and integrating sphere were separated by a variable attenuator that would modify the total output radiance so that a consistent sweep of radiance values could be mapped to the detected voltage on the polarimeter.
The relationship between detected voltage and radiance was fit with a quadratic function because the detector exhibited a small amount of non-linearity at low radiance levels. The calibration curves for each polarizer orientation and spectral channel were different, but in general they followed the same relationship as shown in Fig. 3.

### 2.2.4 Polarimetric calibration

The last of the calibrations was to ensure that the polarizers were oriented correctly and had acceptable polarization contrast. The setup was similar to the radiometric calibration except for the addition of a wire-grid polarizer on a precision rotation stage between the integrating sphere and the polarimeter. The integrating sphere output a fixed radiance, and the polarizer rotated through 360 deg. The response of each polarization channel is mapped in Fig. 4, which shows that the vertical, horizontal, and diagonal channels were properly oriented within 0.5 deg of their intended orientations. Using Chandrasekhar’s equation for linearly polarized radiation, we calculated the uncertainty in $S_1$ to be $\sim1\%$.

During the polarimetric calibration, the detected radiance originally did not reach zero when the polarizer and analyzer were crossed. This non-zero pedestal was attributed to reflections from scattered light within the setup. Specifically, we discovered one set of reflections from the mirror-like surface of the rotation stage that held the polarizer and another set from the reflective wire-grid polarizers. The latter phenomenon caused the curves to slightly deviate from the expected cosine-squared relationship, but the difference is nearly imperceptible in Fig. 4 and the effect was characterized using Jones calculus.

![Fig. 3](image1.png)

**Fig. 3** An example of one radiometric calibration relationship shows that the data (blue dots) matched the fit (black line) very closely when using a quadratic fitting function.

![Fig. 4](image2.png)

**Fig. 4** Results from the polarimetric calibration show that the polarizers were properly oriented within 0.5 deg of their intended orientations (colors denote test polarizer angle: green for 0 deg, blue for 45 deg, and red for 90 deg).
2.3 Dual-Polarization Lidar Validation

A dual-polarization lidar validated whether the polarimeter was correctly identifying the CTP, based on the widely used lidar cross-polarization method of discriminating between liquid-water and ice clouds.9,25–28 For these measurements, both the dual-polarization lidar and the SWIR three-channel polarimeter were pointed at the zenith.

The time-of-flight nature of the pulsed lidar system determined the height and quantity of layers (as long as clouds were relatively optically thin), and the cross-polarization ratio (i.e., the ratio of cross- and co-polarized returns) from the lidar system identified the cloud as either liquid water or ice. The lidar had a much smaller FOV than the polarimeter, but it was typically within ∼3 deg of the polarimeter’s FOV.

Clouds were discriminated manually by inspecting the co-polarized return and the cross-polarization ratio and then were categorized into various groups depending on the number of cloud layers, whether the cloud(s) were all one CTP, and whether other aerosols such as smoke were potentially affecting the lidar returns. Only time periods in which the dual-polarization lidar consistently identified one CTP (for one or more layers of clouds) for at least 30 s were used in the analysis (this duration was assumed to be sufficient for overlap with the polarimeter).

3 Experiments

Data collection took place in 2019 in two stages that were separated by the addition of DOA capability in July. In both stages, the SWIR three-channel polarimeter was coupled to a rotating mount near the dual-polarization lidar system (see Fig. 5). The rotating mount (Moog S3 QPT-50) had repeatability within 0.25 deg. The zenith-pointing polarimeter rotated in azimuth to bring its reference axis into the solar vertical plane and collected data over the course of ∼15 s per measurement. An initial calibration of the rotating mount determined the azimuth and elevation offset necessary to position the polarimeter into the solar vertical plane. This was done during a clear day, and the polarimeter was carefully oriented so that it pointed directly at the Sun. The camera protruded from the case and typically cast a shadow, but when perfectly oriented into the solar vertical plane, there was no shadow present. Using the azimuth and elevation angle of the stage and the known position of the Sun in the sky, we calculated the offset (to within ∼2 deg) for the rotation stage. The dual-polarization lidar system was operated simultaneously to determine the CTP to validate the data from the polarimeter. The data from the polarimeter were then analyzed to identify if the thermodynamic phases were separable.

Fig. 5 A photograph of the SWIR three-channel polarimeter and the dual-polarization lidar during a typical experiment in Bozeman, Montana, shows that the two were separated by about 1 m and the two instruments were looking near the same part of the sky (after Fig. 4).
4 Analysis

In this section, we show the results of analyzing our data with our recently published three-wavelength radiance ratio method\(^{18}\) alone (Sec. 4.1), with polarization alone (separately for stage 1 and stage 2 instrument versions) (Sec. 4.2), and with the combination of the radiance ratio and polarization methods (Sec. 4.3).

4.1 Radiance Ratio Method

Three independent spectral channels were analyzed in three-parameter space in which each of the axes was one of the three ratios defined in Eqs. (1)–(3). Stage 1 and 2 data are plotted in Fig. 6 where liquid-water clouds are blue squares and circles, and ice clouds are red stars and triangles (remember that the liquid and ice classifications shown here were determined by a dual-polarization lidar). Most of the data are in the lower left portion of Fig. 6 with the exception of some stage 2 ice clouds toward the upper left, which likely represent optically thick ice clouds. The abundance of mixing between CTP was partly due to the slight differences between the instrument in stages 1 and 2. For example, stage 1 ice was decently separated from stage 1 water but poorly separated from stage 2 water. Another reason for the mixing was the large amount of stage 2 ice in the region of the figure that represents very optically thin ice clouds. Liquid-water data, on the other hand, are in a region for clouds with a larger optical depth. Overall, some mixing between CTP was almost certainly because some clouds had a very low optical depth, which produced unclear results with this method. The addition of polarimetric sensitivity was included to help reduce the ambiguity of clouds with low optical depth.

4.2 Polarimetric Method

The addition of polarimetric sensitivity to the radiance ratio method described above gave improved accuracy of CTP classification because polarization signatures helped to discriminate CTP in clouds with low optical depth. The value of the \(S_1\) Stokes parameter (i.e., the difference in parallel and perpendicular polarization relative to the scattering plane) was the primary tool for discriminating between CTP, but the polarization signature from clouds is often very small and requires highly sensitive instruments. During the analysis of stage 1 data, poor discrimination

![Fig. 6 SWIR three-channel polarimeter data showing that liquid-water and ice clouds from stages 1 and 2 have regions of good and poor separation. Some of the mixing between the CTP was likely due to optically thin clouds. Note that stage 1 and 2 water data are difficult to see because they overlap. Recall also that the liquid and ice classifications shown here were determined as ground truth by a dual-polarization lidar.](https://example.com/fig6.png)
between CTP using $S_1$ was potentially due to polarization artifacts from temporal smearing since the polarimeter had to cycle through spectral filters before enough measurements were collected to determine $S_1$, and in that time a cloud may have moved enough to introduce artifacts. Thus to identify whether or not temporal artifacts were a significant limitation in determining CTP from $S_1$, stage 2 of the polarimeter added the ability to take simultaneous measurements (DOA) in the band centered at 1.55 $\mu$m.

This section explores the results of stage 1 and 2 $S_1$ measurements and the impact of polarimetric artifacts. First, stage 1 data were analyzed to find how well CTP was identified using $S_1$; then stage 2 data were analyzed in the same manner; and finally a comparison of DOT and DOA revealed that polarimetric artifacts were not as significant as expected.

### 4.2.1 Stage 1

Stage 1 $S_1$ values were exclusively from the DOT polarimeter. The $S_1$ values are plotted in Fig. 7 as a function of scattering angle, where liquid-water clouds are blue squares and ice clouds are red stars.

The two CTPs in Fig. 7 are best separated in the spectral channel centered at 1.55 $\mu$m. However, the two CTPs still had a bit of overlap at lower scattering angles and at higher wavelengths. Some of this may have been because the clouds had higher optical depth and thus $S_1$ values closer together, but some of it may have been due to the temporal artifacts from fast-moving clouds. To fully test this hypothesis, the stage 2 version of the polarimeter had both DOT and DOA capabilities.

### 4.2.2 Stage 2

The stage 2 DOT data were similar to the data from stage 1, except that there was a constant offset between the two. Figure 8 plots the $S_1$ values for stage 2 data, where liquid-water clouds are blue circles and ice clouds are red triangles.

First, in Fig. 7, the stage 1 $S_1$ threshold that nominally separates the two CTPs was at $\sim -0.03$, whereas in Fig. 8, the stage 2 $S_1$ threshold was $\sim -0.005$, which was closer to zero, as the theory suggested. This offset may have been from some experimental errors, such as the alignment of the polarimeter into the scattering plane. Second, there were many more data in stage 2 than stage 1, so it appears as though there was more overlap between CTP. Part of this overlap was likely from the greater variety of clouds detected, which includes optically thick clouds that have a much weaker polarization signature. As such, the liquid-water data appeared to overlap with ice clouds, which are more likely optically thin.

The snapshot polarimetry (DOA) data in the spectral band centered at 1.55 $\mu$m produced $S_1$ values that were very similar to the DOT stage 2 data plotted in Fig. 8. The comparison of DOA and DOT $S_1$ values is shown in Fig. 9.
To better visualize and understand the difference between the DOT and DOA methods, histograms of the $S_1$ Stokes values were plotted for stage 2 DOT and DOA, and stage 1 data were included for reference. The histograms are shown in Fig. 10, where liquid-water data are blue and ice data are red.

In the stage 2 DOT subplot of Fig. 10, the liquid-water data have a smaller variance. On the other hand, the gap between the two CTP was smaller than in the DOA subplot. As a further means to interpret the subtle differences between the DOT and DOA methods, the means and standard deviations were calculated (assuming Gaussian distributions), and then those values were plotted in Fig. 11.

The left side of Fig. 11 is laid out to match Fig. 10 in that the top plot is for stage 1 $S_1$ values, the middle plot shows stage 2 data from the DOT configuration, and the bottom plot represents the DOA data from stage 2. The plot on the right overlays DOT and DOA data from stage 2 for easy comparison. The most noticeable difference between stage 2 DOT and DOA was the smaller standard deviation and slight shift toward zero of liquid-water data with the DOA configuration. There was almost no noticeable difference in the ice data between DOT and DOA configurations.

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The greater impact on liquid-water data between DOT and DOA configurations in Fig. 11 may primarily be because liquid-water clouds are typically much lower and faster-moving than ice clouds. As such, the cloud region seen by the detectors is smaller and subject to less averaging than a higher cloud with similar inconsistencies. Furthermore, a low cloud with a high

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Fig. 8 The $S_1$ Stokes values for liquid-water and ice clouds from stage 2 are plotted for each spectral channel and show modest separation between the two CTPs (after Fig. 6 but with new data from the rebuilt instrument). Ground-truth liquid and ice classifications provided by dual-polarization lidar.

Fig. 9 The $S_1$ Stokes values in the band centered at 1.55 μm for DOT and DOA polarimetry show liquid-water data as blue circles and ice data as red triangles (ground-truth liquid and ice classifications provided by dual-polarization lidar). The difference between DOT and DOA data was minimal, but the $S_1$ values for liquid water appeared to be slightly better clustered for DOA polarimetry.
velocity will change more during the course of a DOT collection cycle than a typically slow-moving ice cloud.

Nonetheless, despite the small improvement with DOA capabilities, there was still a significant overlap between the two CTPs. One reason may simply be that the polarimeter is not sensitive enough to resolve the very small polarization signatures from sunlight scattering off cloud particles. Another likely culprit for the overlap is the high probability of many optically

Fig. 10 Histograms of the liquid-water and ice data for the stage 1 DOT configuration, stage 2 DOT configuration, and stage 2 DOA configuration showed a minimal difference between DOT and DOA configurations (ground-truth liquid and ice classifications provided by dual-polarization lidar).

Fig. 11 A representation of the distribution of $S_1$ values for the stage 1 DOT configuration, stage 2 DOT configuration, and stage 2 DOA configuration show a minor improvement in the standard deviation of liquid-water data in the DOA configuration (ground-truth liquid and ice classification provided by dual-polarization lidar).
thick clouds in the data set. To identify CTP for both optically thick and thin clouds, the radiance ratio and polarimetric methods were used together in the combined method; because only a small difference was observed between DOT and DOA polarimetry, the combined method only analyzed the DOT data.

4.3 Combined Method

Independently, the radiometric and polarimetric methods had difficulty classifying CTP when a cloud was either optically thin or thick, respectively. However, when combined, the two methods were able to better classify CTP than either method independently. This section compares how well CTP was classified with and without the addition of polarization; all of the analysis was in three-parameter space. We chose to fit a three-dimensional surface to the data to determine the three most useful prediction parameters. This approach demonstrated that the radiance ratio method was improved by the addition of polarimetric data.

In total, the polarimeter produced nine products: three radiance ratios [defined in Eqs. (1)–(3)] and three $S_0$ and $S_1$ Stokes parameters at 1.55, 1.64, and 1.70 μm. MATLAB’s surface fitting tool was used to fit surfaces to each unique set of three parameters for the data identified by the dual-polarization lidar as liquid water and separately for the data identified by the lidar as containing ice. This fitting was repeated for surfaces from the first to fifth orders in the x and y dimensions (for a total of 25 different surfaces). A least-squares solution was used to identify the surfaces that best predicted the measurements classified by the lidar as liquid and ice. Higher order surfaces would over-fit the data and are therefore not recommended in this procedure. (In our analysis, the addition of polarization consistently improved CTP classification, regardless of fit order up to the fifth order and with or without separating the data into fit and test subsets.)

This procedure found that the best classification was achieved with the $S_1$ Stokes parameter (and therefore polarization) as one of the three axes. Data from both stages are plotted in this three-parameter space in Fig. 12. This three-parameter space correctly classified 95% of CTP, whereas the radiance ratio method correctly classified only 73%. Therefore, this analysis indicates that the addition of polarization improved the CTP classification.

![Fig. 12](https://www.spiedigitallibrary.org/journals/Journal-of-Applied-Remote-Sensing/024520-13-Apr-Jun-2021-%F0%9F%84%95Vol.15(2)/Downloaded From: https://www.spiedigitallibrary.org/journals/Journal-of-Applied-Remote-Sensing on 01 Aug 2022 Terms of Use: https://www.spiedigitallibrary.org/terms-of-use)
5 Conclusion

Classification of CTP is particularly important for improving our understanding of the climate. This paper discusses a passive polarimeter with three spectral channels that could improve the methods by which CTP is detected. Alone, the radiance ratio and polarimetry methods are valid under limited conditions. The combined methods, however, produce increased classification accuracy, suggesting that polarization is a powerful addition to the well-established method of using radiance ratios for CTP classification.

Although polarization improved the number of correct classifications, there was still a region of ambiguity between CTP. Despite our theory that the ambiguity was caused by polarization artifacts from fast moving clouds, the differences between DOT and DOA polarimetry were minimal. The other likely reasons for the ambiguity stem from the low sensitivity of the polarimeter and thus its inability to completely resolve the trace polarization signals. Even though our calculations determined an uncertainty in \( S_1 \) of only 1%, the differences in theory and experimental measurements suggest that this value may in fact be higher. Because real clouds are often very complex, the models used to simulate polarization signatures may not be broad enough to adequately model them. Furthermore, the microphysical properties of clouds can be very complex and can influence the measurements of the SWIR three-channel polarimeter in ways that have not been fully considered.

In the text, we tabulated many uncertainty values that will be useful in future studies of the sensitivity of CTP retrieval to random and systematic errors. Future passive polarimeters for CTP classification may benefit from more sensitive detectors and quicker acquisition times that approach DOA polarimetry. Moreover, a spectropolarimeter\(^{31,32}\) would provide a more detailed spectral map of clouds along with the \( S_1 \) Stokes parameter. There is a balance between cost and accuracy when applying this technology to CTP classification, and the work presented here has shown the utility and relatively high accuracy of classification of a low-cost three spectral channel polarimeter.

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References


**Martin Jan Tauc** received his BS degree in mathematics and physics from the University of Oregon and his MS and PhD in electrical engineering from Montana State University. He is currently employed as a hardware engineer at Argo AI working with LiDAR for autonomous vehicles.
Elizabeth M. Rehbein received her BS degree in physics from Montana State University. She is currently employed at Bridger Photonics working in data processing to facilitate methane detection for the oil and gas industry using LiDAR solutions.

Laura M. Eshelman received her BA degree in physics in 2013 from Gustavus Adolphus College and her PhD in electrical engineering in 2018 from Montana State University. She currently works at Polaris Sensor Technologies, Inc. developing a polarized sensor for GPS-denied navigation.

Wataru Nakagawa received his BS degree in physics from Stanford University and his MS degree and PhD in electrical and computer engineering (applied physics) from the University of California, San Diego, La Jolla, California, USA. He is currently an associate professor in the Department of Electrical and Computer Engineering at Montana State University, Bozeman, Montana, USA. His research interests include near-field optical effects in photonic structures and interdisciplinary applications of nanostructured optical devices.

Joseph A. Shaw received his BS degree in electrical engineering from the University of Alaska, his MS degree in electrical engineering from the University of Utah, and his MS degree and PhD in optical sciences from the University of Arizona. He is director of the Optical Technology Center and a distinguished professor at Montana State University, Bozeman, Montana, USA, where he develops optical remote sensing systems for environmental science. He is a fellow of OSA and SPIE and was the 2019 recipient of the G. G. Stokes Award from SPIE.