

A STUDY OF ATMOSPHERIC POLARIZATION IN UNIQUE SCATTERING
CONDITIONS AT TWILIGHT, DURING A SOLAR ECLIPSE, AND FOR CLOUD
PHASE RETRIEVALS USING ALL-SKY POLARIZATION IMAGING

by

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of the requirements for the degree

of

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Electrical Engineering

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DEDICATION

To my parents,

You have taught me to live in each moment,
laugh often, and love unconditionally.

Without you,
I would not be where I am today,
or who I am today.

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ABSTRACT

Polarization is a fundamental property of light that can be detected with polarization-sensitive instruments for many remote sensing applications. To quantitatively interpret the remote sensing data, an understanding how naturally occurring polarization depends on wavelength and environmental parameters is needed. The most obvious source of naturally occurring polarization is atmospheric scattering. For a clear-sky environment, Rayleigh scattering dominates, resulting from scattering by atmospheric gas molecules that are much smaller than the optical wavelength, and a distinct all-sky polarization pattern exists. A band of maximum degree of linear polarization can be observed 90° from the sun with polarization vectors orientated perpendicular to the scattering plane (i.e. the plane containing the incident and scattered light). However, aerosols, clouds, and underlying surface reflectance can alter the observed sky polarization. Military, environmental, and navigational applications exploit the sky polarization pattern to detect objects, retrieve aerosol and cloud properties, and to find compass headings based on the sky polarization pattern. Sky polarization is also being used to calibrate the polarization response of large telescopes. It is important to understand how partially polarized skylight can vary with environmental factors, as well as with wavelength and solar position, so that polarization measurements can be interpreted correctly. The direction of polarization when aligned to a specific reference frame can provide additional information beyond the basic polarization pattern. This dissertation expands the current knowledge of skylight polarization by validating radiative transfer simulations in the shortwave infrared, by reporting the first-ever retrievals of cloud thermodynamic phase from all-sky polarization images using the Stokes S_I parameter referenced in the scattering plane, and by quantifying how partially polarized skylight varied under unique scattering conditions during the 2017 solar eclipse. In order to accurately predict cloud thermodynamic phase and to analyze the temporal distribution of skylight during a total solar eclipse, a physics-based understanding of the Stokes parameters and angle of polarization (AoP) with respect to the instrument, scattering, and solar principal planes was also developed. Through each experiment, two underlying threads were observed. First, in order to accurately interpret results, environmental parameters needed to be characterized. Second, when rotated into a specific reference frame, the Stokes parameters and AoP can be utilized differently and provide unique insights when analyzing all-sky polarization data.

CHAPTER ONE

INTRODUCTION

Motivation

Light propagates as a transverse electromagnetic wave that can be detected by humans in the visible spectrum between approximately 380 nm and 740 nm. Not directly observable by humans is polarization, which represents the orientation of the electric field vector of light in a plane normal to the propagation direction. With a polarization-sensitive instrument, polarization can be observed in the natural environment through reflection, emission, and scattering processes. Rainbows and glories [1-3], halos [4, 5], sun glints [6], skylight [7-9], and the reflection of light from smooth surfaces exhibit unique polarization characteristics [10-16]. Military sensing and surveillance applications exploit scattered, reflected, or emitted polarization to detect objects on the ground, in the air, and in space because polarization provides an added dimension beyond intensity and color [17-20]. Environmental remote sensing applications use ground-based, airborne, and spaceborne polarimeters to retrieve aerosol [21-23] and cloud properties [24-27], which are important parameters needed in current weather and climate models. Polarimeters are also being designed to detect the presence of liquid droplets on extrasolar terrestrial planets [28]. Based on observing insects and birds who use polarization for navigation [29-34], polarization imagers are now being designed as navigational systems that use the angle of polarization as a polarized light compass [35-39]. This is critical for when GPS is degraded or denied. All-sky polarimetry is also now

being used as a calibration source to determine polarization cross-talk properties of large telescopes [40]. For a day-to-day example, polarized sunglasses are used to remove glare from light reflecting from smooth surfaces.

In applications such as these, it is important to understand how partially polarized skylight can vary with environmental factors, such as aerosols, clouds, underlying surface reflectance, and scattering geometry, so that polarization measurements can be interpreted correctly. Therefore, in previous work at Montana State University, a physics-based understanding of how polarized skylight depends on atmospheric and surface parameters was developed [41-46]. This work concentrated primarily on understanding the visible-to-near-infrared (Vis-to-NIR) degree of linear polarization (DoLP) in wavelengths bands centered from 450 nm to 780 nm during daytime (the DoLP is a quantity that measures the fraction of intensity attributable to linearly polarized light). In this dissertation, the relationships between skylight polarization and surrounding environmental parameters in the shortwave infrared (SWIR) were validated using a SWIR imaging polarimeter from 1500 to 1800 μm . A physics-based understanding of the Stokes parameters and angle of polarization (AoP) with respect to the instrument, scattering, and solar principal planes was also developed to accurately predict cloud thermodynamic phase. In addition, AoP and DoLP fisheye images from the 2017 total solar eclipse are presented to show how partially polarized skylight varies for a day-to-night range of brightness under unique scattering conditions.

Literature Review

Visible-to-Shortwave-Infrared-Skylight Polarization

Other than polarization that can be detected by resolving sunspots or the solar limb, the spatially integrated sunlight is randomly polarized. At visible and shortwave infrared wavelengths for Earth-based observers, polarization in nature arises primarily from the scattering of sunlight in the atmosphere and from reflection at smooth surfaces. For a clear-sky environment, Rayleigh scattering dominates for particles much smaller than the optical wavelength (e.g., the molecules of gases such as nitrogen and oxygen that make up the atmosphere). A single Rayleigh scattering event produces 100% linearly polarized light at angles 90° from the sun, with a polarization vector oriented orthogonal to the scattering plane defined by incident and scattered light [8, 9]. The degree of linear polarization for Rayleigh scattering varies according to

$$\text{DoLP} = \text{DoLP}_{\max} \left(\frac{1 - \cos^2 \theta}{1 + \cos^2 \theta} \right), \quad (1)$$

where θ is the scattering angle defined by incident and scattered rays and $\text{DoLP}_{\max}$ is the maximum degree of polarization (which is 1 for the theoretical Rayleigh scattering case). Due to molecular anisotropy, the maximum DoLP in the real atmosphere is less than 1 [9, 47], and the location of the maximum DoLP varies spectrally between scattering angles of 86° and 106° , as observed in Figure 1. As the sun appears to move through the sky, the band of maximum polarization also changes position in the sky, always remaining oriented approximately 90° from the sun's location [11]. In the rare conditions of a pure Rayleigh scattering atmosphere, the skylight degree of polarization generally

increases with wavelength since scattered irradiance is inversely proportional to the fourth power of the wavelength, thus reducing multiple scattering at longer wavelengths.

The maximum degree of polarization can be reduced by multiple scattering from atmospheric aerosols [45-49], clouds [25-27, 42, 50], and underlying surface reflectance [11, 43]. By using a measurement-driven successive orders of scattering (SOS) radiative transfer model [51], validated with an all-sky polarimeter [45], Pust and Shaw found skylight polarization to vary from the VIS-NIR spectrum for real environments [44]. In this spectral range they found skylight polarization to have a strong dependence on the aerosol optical depth and surface reflectance. The individual quantitative contribution of aerosol content and surface reflectance on skylight polarization was further studied in the VIS-to-SWIR spectrum by Eshelman and Shaw [52] using the same radiative transfer model, modified to include spectral extrapolations of aerosol optical depth out to 2.5 μm and hand-held surface reflectance measurements. Through simulations with the SOS radiative transfer model, skylight polarization in the VIS-to-NIR was found to have a strong dependence on the aerosol optical depth while skylight polarization in the SWIR varied primarily with the aerosol volume size distribution. In fact, at SWIR wavelengths, the DoLP in a cloud-free atmosphere was found to actually increase when the air became smoky. The simulations showed that for wavelengths where the aerosol optical depth was greater than the Rayleigh optical depth (typically wavelengths $\geq 1 \mu\text{m}$), the predicted DoLP generally decreased with wavelength, but only after rising to a level that was much higher for a smoky atmosphere than for clean air (the rate of decrease depended on the aerosol size distribution).

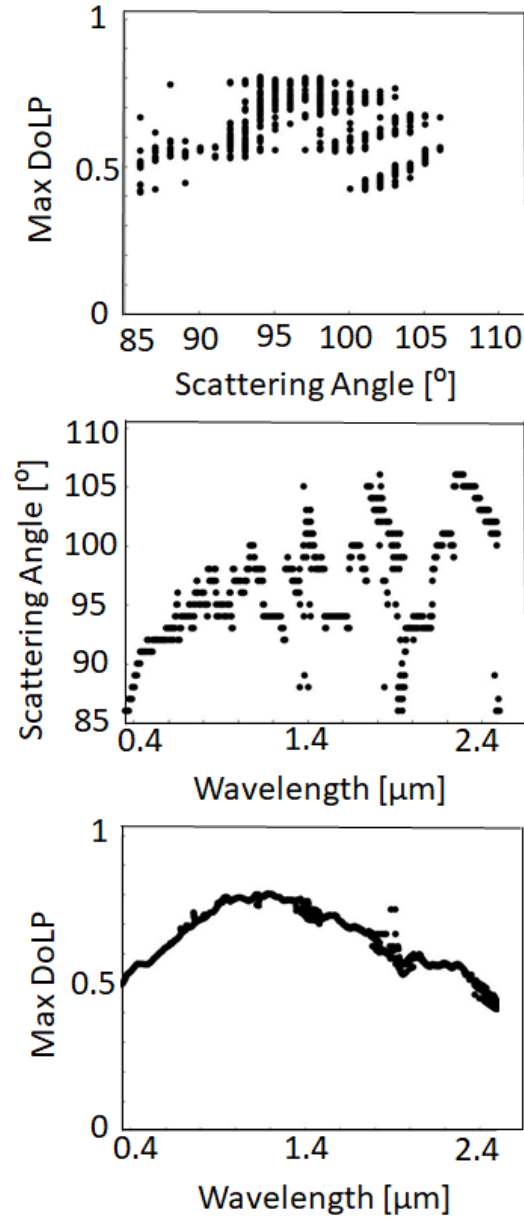


Figure 1. Radiative transfer simulations showing the relationship between scattering angle, wavelength, and maximum DoLP for a moderately-hazy environment on 18 August 2014 with zero surface reflectance. The input aerosol parameters (optical depth, volume size distribution, and index of refraction) were retrieved from AERONET. The solar azimuth and zenith angles were 118° and 49° , respectively. The maximum DoLP varied with wavelength and scattering angle (compared to the prediction that maximum DoLP occurs at a 90° scattering angle). Due to molecular anisotropy [9, 47], the maximum DoLP in the real atmosphere is less than 1, and the location of the maximum DoLP varies spectrally between scattering angles of 86° and 106° .

Starting from this understanding of how clear-sky polarization varies with aerosol parameters and underlying surface reflectance in the VIS-SWIR spectrum during daytime conditions, the objective of this study was to extend this understanding deeper by studying skylight polarization at twilight and during a total solar eclipse, by measuring the SWIR skylight DoLP to validate the previous simulations [52, 53], and by studying the polarization of clouds, which are more complex and difficult to study than clear-sky.

Skylight Polarization at Twilight and during a Total Solar Eclipse

Twilight is an interesting time to measure skylight polarization because of the rapid change from direct to indirect illumination that occurs when the sun transitions from above to below the horizon. With the sun below the horizon, twilight polarization arises from light multiply scattered by high-altitude aerosols [54]. Cronin et al. [55] measured skylight polarization as the solar elevation angle increased from -7.7° to -1.7° using a polarized spectrometer and found sky polarization to be greatest in the red spectrum. At elevation angles less than -6.5° , skylight polarization in the visible spectrum was observed to become noisy in the spectral ranges of 350 nm to 450 nm and 650 nm to 750 nm, respectively. Skylight polarization was not measured at solar elevation angles less than -7.7° due to sensitivity limitations with their spectrometer. Cronin et al. also measured skylight polarization using a wide-angle polarimeter as the solar elevation angle increased from -15.4° to 1.9° . Their measurements were spectrally integrated and the observed polarization became noisy and unrecognizable at elevation angles less than -13° [55].

A solar eclipse is an even more extreme multiple-scattering situation. During totality, a ring of skylight near the horizon (which arises as single and multiply scattered sunlight from outside the shadow region) is the main source of light and the band of maximum polarization, originally located approximately 90° from the sun, shifts to being nominally symmetric about the zenith [56]. Glenn Shaw from the University of Alaska – Fairbanks was the first to quantify and explain this shift by using several scanning polarimeters and radiometers during the 1973 solar eclipse in Kenya, Africa. He also found that the zenith sky brightness at totality was similar to twilight conditions with a solar elevation angle between -5° and -7° [56]. G. Shaw used a simple model to qualitatively predict his eclipse sky brightness measurements [57], which were in good agreement with contemporary and later studies [58, 59].

In 1987, Können published a model for eclipse sky polarization, which helped to further explain Shaw's 1973 eclipse polarization measurements [60]. Können's model predicted a polarization pattern that was completely symmetric about the zenith, while Shaw's measurements exhibited a slightly asymmetric pattern centered on the zenith. Shaw suggested that the skylight was more polarized over the nearby lake because the dark surface of the lake reflected less sunlight back up into the sky to be multiply scattered, whereas the sky over the bright desert on the other side was less polarized because of this multiple scattering process. Können, on the other hand, suggested the asymmetry arose from using a scanning polarimeter during the dynamic conditions of the eclipse. All-sky polarization images recorded during a 1999 eclipse in Hungary [61, 62] and a 2006 eclipse in Turkey [63] exhibited full-sky polarization patterns similar to the

previous scanning measurements [56], which showed skylight polarization to be generally symmetric about the zenith. These measurements were made using a film-based, rotating-polarizer polarimeter. A symmetric pattern was observed near the end of totality in 1999 (for a morning eclipse with the shadow approaching from the anti-solar direction) [61, 62] and at the beginning of totality in 2006 (for an afternoon eclipse with the shadow approaching from the solar direction) [63]. In addition, a temporal distribution of neutral points near the zenith and anti-solar hemisphere was observed. For both eclipses, maximum polarization was observed in the solar-hemisphere with minimum polarization in the anti-solar hemisphere, which is in agreement with the scanning measurement recorded by G. Shaw in 1973 [56]. The all-sky results were the first to show a temporal distribution of skylight polarization measured from second contact (start of totality) to third contact (end of totality); however, their measurements did not include quantitative details about the aerosol properties, cloud distributions, or ground reflectance near the measurement sites. In order to have a complete understanding of the results of sky polarization measurements, better polarization images with more supporting data about environmental parameters are needed.

Cloud Thermodynamic Phase Detection

Clouds cover approximately 60 percent of Earth's surface and they play a significant role in the climate system, as they can regulate surface precipitation, shade the Earth's surface, and increase the greenhouse effect; however, they are one of the biggest sources of uncertainty in weather and climate models [64-66]. Through absorption and scattering, clouds also strongly attenuate optical beams propagating through the

atmosphere for communication or sensing purposes [67-72]. The absorption and scattering of clouds, as well as their net warming or cooling effect, depends on their physical properties, such as height, optical thickness, size, shape, and thermodynamic phase (if they contain ice crystals or liquid particles). Retrievals of cloud properties from satellite, airborne, and ground-based measurements also require cloud phase to be determined [73-75], so there is great interest in new or improved methods of remotely sensing cloud thermodynamic phase.

Cloud thermodynamic phase has been measured previously using both active and passive instruments. Active cloud lidar [76-79] and mm-wave radar systems [80, 81] with polarization sensitivity can distinguish between ice and water clouds. For example, the polarization state of light scattered from polyhedral ice crystals is altered so that there is a significant fraction of cross-polarized light (i.e., light oriented perpendicular to the transmitted light polarization state), whereas light undergoing single scattering by liquid water droplets retains its transmitted polarization state (i.e., the cross-polarized signal is effectively zero).

Cloud phase also can be retrieved from passive measurements of radiance emitted or scattered by clouds at wavelengths with a different imaginary refractive index (i.e. absorption) for liquid and ice. These methods use one or more channel with absorption that is higher for ice than for liquid and one channel with nearly equal absorption for both ice and liquid. For example, this has been done with thermal infrared channels at 8.5, 11, and 12 μm [82], 3.7, 11, and 12 μm [83], and with a continuous spectrum between 11 and 19 μm [84]. Another method added a visible channel at 0.65 μm and shortwave infrared

(SWIR) channels at 1.63 and 1.90 μm , along with thermal IR channels at 8.5, 11, and 12 μm [85]. A SWIR method used channels at 1.64 and 1.70 μm [26, 86, 87] and a near-infrared method relied on spectra in the wavelength range of 850-1050 nm, in which ice absorption was found to be higher than water absorption for certain parts and lower in other parts [88].

Recently, Knobelspiesse et al. [25] showed that the direction of linear polarization (expressed by the sign of the Stokes S_I polarization vector) should be useful for determining cloud thermodynamic phase with a passive ground-based polarimeter. Knobelspiesse et al. found that a positive S_I value indicates a liquid cloud, while a negative S_I value indicates an ice cloud. They provided initial validation of simulation results using zenith-pointing, polarization-sensitive Cimel radiometers from the NASA Aerosol Robotic Network (AERONET). Their simulations suggested that the optimal measurement for cloud thermodynamic phase was not at the zenith, but in a direction in the solar principal plane approximately 55° from the sun. Previous work at MSU looked into detecting clouds using the AoP [42]; however, in the band of maximum polarization, clouds were hard to distinguish and a clear connection between cloud phases was not studied.

Dissertation Outline

This dissertation contributes to the understanding of how skylight polarization changes as a function of wavelength, how skylight polarization varies with angle and wavelength during the multiple-scattering situation of a solar eclipse, and how all-sky polarization imaging can be used to remotely sense cloud thermodynamic phase.

Whereas previous research on sky polarization at MSU emphasized the measurement and use of the DoLP, the AoP reference plane became a significant aspect of the work presented in this dissertation. For accurate prediction of cloud thermodynamic phase, the AoP (and the related Stokes S_1 and S_2 parameters) needed to be rotated from the instrument plane to the scattering plane that is unique for every pixel in the all-sky image and for every solar position. Similarly, to visualize the sky polarization during eclipse totality in a manner that facilitated comparison with other observations, the instrument-plane AoP had to be referenced to the scattering or solar principal plane. Therefore, chapter two discusses the visualization of all-sky polarization images. The definition of the Stokes parameters are given and the DoLP and AoP quantities are derived using the Stokes parameters S_1 and S_2 , which represent the linear states of polarization. The instrument, scattering, and solar principal planes are defined and then the calculation methods of rotating the AoP between each plane of reference are shown.

In chapter three, the polarimeters used to measure skylight polarization in this dissertation are presented. A SWIR imaging polarimeter was used to validate SWIR simulations of skylight polarization for a smoke-free and smoky environment. A visible-

wavelength, LCVR-based all-sky polarimeter [41] was redesigned for better system performance and for extended twilight and nighttime measurements after being continuously deployed for daytime studies since 2009 [89]. This all-sky polarization imager was used as a primary instrument in my studies and in this chapter, upgrades to this instrument are discussed. Chapter three also outlines the design and calibration of a visible three-camera all-sky polarimeter that was designed for recording all-sky polarization images during the total solar eclipse on 21 August 2017.

In chapter four, shortwave infrared validation measurements for clear and smoke-filled atmospheres are presented. This work addresses the need to study how skylight polarization changes in the SWIR, as detectors are now being designed with higher pixel densities and improved noise-equivalent degree of linear polarization. This gives SWIR polarimeters a potential advantage over VIS and long-wave infrared (LWIR) polarimeters in areas pertaining to enhanced long range visibility, haze penetration, forest fire prevention, and low-light night imaging [90-94]. The measurements presented in this chapter provided the first experimental validation of earlier simulations [52, 53], which showed that the skylight DoLP actually increased in the SWIR when the sky transitioned from clean to smoky conditions.

In chapter five, 2017 solar eclipse measurements and twilight polarization measurements taken with the visible LCVR-based and three-camera all-sky polarimeters are presented. This work demonstrates the change between the DoLP and AoP during daytime conditions, during a solar eclipse, and when the sun is below the horizon. Studying how skylight polarization changed at twilight was important in preparing for the

solar eclipse and in analyzing the solar eclipse results. The measured AoP during totality exhibited similar patterns as the measured AoP at twilight. The twilight and eclipse measurements also required similar exposure and camera ISO settings. A sequence of all-sky polarization images recorded throughout the eclipse totality are shown and discussed in this chapter. These images exhibit variations, including neutral regions with minimum DoLP that shift position in the sky throughout totality. A simple qualitative model to help support the interpretation of our results and a detailed description of the supporting instruments deployed is also given in this chapter.

Chapter six summarizes cloud thermodynamic phase measurements using visible-wavelength all-sky polarization imagers, with which we were able to detect the cloud phase for ice, liquid, and multi-layered clouds. These measurements were validated at the zenith using a dual-polarization lidar [77]. Analysis in this chapter describes and interprets measured Stokes S_0 , S_1 , S_2 , and derived DoLP and AoP quantities in the instrument and scattering planes of reference. A comparison of results with respect to scattering angle, the lidar cross-polarization ratio, and wavelength are also given.

Chapter seven concludes by describing the significance of the work presented in the chapters of this dissertation and how this work can be continued and expanded in the future.

CHAPTER TWO

VISUALIZATION OF STOKES ALL-SKY POLARIZATION IMAGES

Stokes Parameters

Polarized light can be described by the Stokes vector $\vec{S}$, containing the parameters S_0 , S_1 , S_2 , and S_3 (also referred to as I , Q , U , V). The Stokes parameters can be defined by

$$S_0 = I_{0^\circ} + I_{90^\circ}, \quad (1)$$

$$S_1 = I_{0^\circ} - I_{90^\circ}, \quad (2)$$

$$S_2 = I_{45^\circ} - I_{135^\circ}, \quad (3)$$

$$S_3 = I_R - I_L, \quad (4)$$

where I represents the observed irradiance, the angles denote the direction of the transmission axis of a linear polarizer with respect to a common reference plane (all with zero phase difference), and the subscripts R and L represent right- and left-handed circular polarization states. By definition, all Stokes parameters have units of irradiance (W m^{-2}), although a full radiometric calibration is not always necessary and Stokes parameters are often determined from relative intensity measurements. In terms of what our polarimeter measures, the Stokes parameter S_0 represents the total radiance ($\text{W m}^{-2} \text{sr}^{-1}$), with the Stokes parameters S_1 , S_2 , and S_3 representing the difference between 0° and 90° polarization, the difference between linear $+45^\circ$ and -45° polarization, and the difference between right- and left- hand circularly polarized light, respectively [95, 96]. In Earth's atmosphere for nearly all conditions, the amount of circularly polarized light is negligible [11].

Mueller Matrices

The Mueller matrix is a mathematical tool for describing how partially polarized light is altered by propagation along a path or through an optical element or system. It represents the diattenuation, retardance, and depolarization properties of a system [96, 97]. A Mueller matrix can be used to relate the output Stokes vector with the input Stokes vector. Equation 5 shows the use of a standard Mueller matrix to transform an input Stokes vector from an original input polarization state to a potentially different output polarization state:

$$\begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix}_{output} = \begin{bmatrix} m_{00} & m_{01} & m_{02} & m_{03} \\ m_{10} & m_{11} & m_{12} & m_{13} \\ m_{20} & m_{21} & m_{22} & m_{23} \\ m_{30} & m_{31} & m_{32} & m_{33} \end{bmatrix} \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix}_{input} . \quad (5)$$

For lossless free-space propagation, the diagonal elements m_{00} , m_{11} , m_{22} , and m_{33} are equal to 1, with the other elements equal to 0. By normalizing all the elements by m_{00} , the unpolarized system transmittance can be factored out of the equation. The elements m_{01} , m_{02} , and m_{03} are related to the diattenuation in a material which describes the change of the transmitted irradiance as a function of the incident polarization state. This property causes materials to allow one polarization component to pass, while absorbing the orthogonal component [95-97]. The elements m_{10} , m_{20} , and m_{30} are related to polarizance, which describes the degree of polarization of the exiting light for unpolarized incident light [96]. Finally, all elements including and to the right of m_{11} , m_{21} , and m_{31} describe the retardance of the system or propagation path. A calibration Mueller matrix was created for each visible all-sky polarimeter. This was used to reconstruct the Stokes vector of the

incident light from the instrument-influenced measured Stokes vector, following the methods presented by Pust and Shaw [41].

Derived Quantities (DoLP, AoP)

The Stokes parameters can be used to derive the Degree of Linear Polarization, DoLP and the Angle of Polarization, AoP. The DoLP,

$$\text{DoLP} = \frac{\sqrt{S_1^2 + S_2^2}}{S_0}, \quad 0 \leq \text{DoLP} \leq 1, \quad (6)$$

is a quantity that measures the fraction of intensity attributable to linearly polarized light. When the DoLP equals 1, the light is completely linearly polarized. A DoLP value of 0 indicates randomly polarized light. The AoP,

$$\text{AoP} = \chi = \frac{1}{2} \cdot \tan^{-1} \left(\frac{S_2}{S_1} \right), \quad 0 \leq \chi \leq \pi, \quad (7)$$

indicates the angle between the plane of polarization and the plane of reference. The relationships between the AoP and the signs of the Stokes parameters S_1 and S_2 are listed in Table 1 and shown in Figure 2. The AoP is measured counterclockwise from the reference axis in Figure 2.

$S_3 = 0$	$S_1 > 0$	$S_1 = 0$	$S_1 < 0$
$S_2 > 0$	$\tan(2\chi) > 0$ $\cos(2\chi) > 0$ $0 < \chi < \pi/4$	$\tan(2\chi)$ doesn't exist $\cos(2\chi) = 0$ $\chi = \pi/4$	$\tan(2\chi) < 0$ $\cos(2\chi) < 0$ $\pi/4 < \chi < \pi/2$
$S_2 = 0$	$\tan(2\chi) = 0$ $\cos(2\chi) > 0$ $\chi = 0$	$\tan(2\chi)$ doesn't exist $\cos(2\chi) = 0$ χ uncertain	$\tan(2\chi) = 0$ $\cos(2\chi) < 0$ $\chi = \pi/2$
$S_2 < 0$	$\tan(2\chi) < 0$ $\cos(2\chi) > 0$ $3\pi/4 < \chi < \pi$	$\tan(2\chi)$ doesn't exist $\cos(2\chi) = 0$ $\chi = 3\pi/4$	$\tan(2\chi) > 0$ $\cos(2\chi) < 0$ $\pi/2 < \chi < 3\pi/4$

Table 1. The relationships between the AoP (χ) and the Stokes S_1 and S_2 parameters. The sign of S_1 varies with χ according to $\cos(2\chi)$.

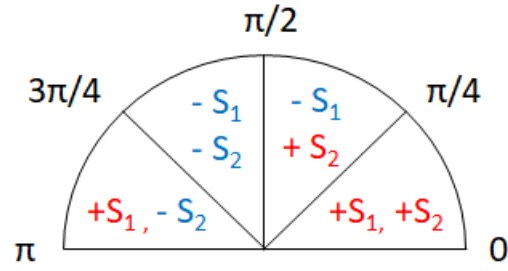


Figure 2. The relationships between the AoP (χ) and the Stokes S_1 and S_2 parameters.

Polarization Angle Reference Planes

In a single-Rayleigh-scattering environment, the skylight AoP and DoLP have a distinct pattern that rotates through the sky in time, based on the position of the sun. A maximum band of polarization occurs approximately 90° from the sun, with the direction of polarization oriented perpendicular to the scattering plane defined by the incident and scattered light. For each pixel, the measured linear Stokes parameters, S_1 and S_2 , and the derived AoP can be referenced to the instrument, scattering, and solar principal planes (to be defined later), while the Stokes S_0 and derived DoLP are independent of reference frame.

Instrument Plane Reference

In the instrument plane of reference, the recorded angle-dependent Stokes parameters, S_1 and S_2 , and the derived AoP are referenced with respect to the axis of the instrument's internal polarizer, with the AoP measured counterclockwise from the reference axis. An example showing how the fixed-instrument AoP changes with solar position is given in Figure 3. Each all-sky image is oriented with north at the top and west to the right, as would be seen by an observer lying on the ground, looking up into the sky. The three all-sky images are for three different solar positions: the left-hand image is for morning (sun in the southeast), the center image is for midday (sun to the south), and the right-hand image is for afternoon (sun in the southwest). Displaying these measurements with respect to the instrument plane causes the AoP patterns to change with solar position

(these patterns would remain constant with solar position if they were shown relative to the continually evolving scattering plane, to be discussed next).

While this measurement coordinate system does not provide a uniform AoP pattern, it can be beneficial for navigational applications. When referenced to the instrument plane, the orientation of the polarimeter can be found from the position of the sun in the measured AoP image, thereby providing a way to retrieve compass-based heading positions from the AoP image if you know the position of the sun.

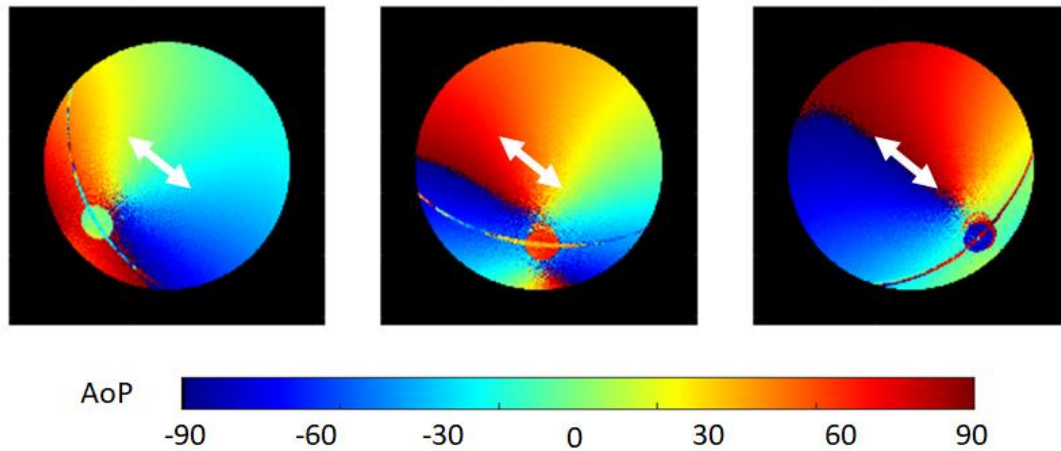


Figure 3. AoP images referenced to the instrument plane with solar azimuth and zenith angles corresponding to 123° , 183° , and 230° , and 45° , 32° , 42° , respectively. Measurements were recorded in Rexburg, Idaho on 21 August 2017 at 17:00:03 (Left), 19:36:20 (Middle), and 21:34:06 (Right) UTC. The AoP was referenced to the axis of the internal polarizer (white arrow) and measured counterclockwise. The top of the image represents north and the right side of the image represents west.

Scattering Plane Reference

To compare measured results in the entire AoP image with Rayleigh scattering theory, a transformation of the coordinate system is needed to align the reference plane to each pixel's unique scattering plane. The scattering plane, denoted by the gray plane SOV in Figure 4, contains the direction of incident sunlight and scattered light in the viewing direction for the observer position. The scattering plane is unique for each pixel in the all-sky image. Once rotated into the scattering plane, the AoP and angle-dependent Stokes parameters have a uniform distribution throughout the sky and this pattern rotates with the solar position, as observed in Figure 5, where the AoP is approximately 90° for each pixel in the all-sky image. Not expressing these angle-dependent polarization parameters relative to the scattering plane would present errors in the analysis of cloud thermodynamic phase and in the retrieval of aerosol parameters, both applications that rely on knowing the Stokes parameters referenced to the scattering plane.

Note also in Figure 5 that neutral points are observed near the sun and are represented by a 90° change in AoP. Neutral points, locations with zero polarization, arise from multiple scattering creating polarization oriented parallel to the scattering plane, which offsets the polarization oriented perpendicular to the scattering plane (which arises from first-order scattering). In Figure 5, neutral points exist just below and just above the sun.

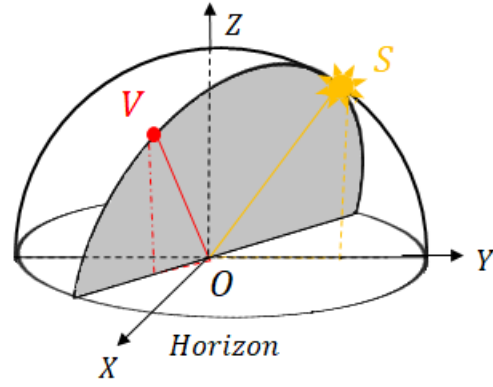


Figure 4. Scattering plane illustration. The solar scattering plane contains the directions of incident light and scattered light in the viewing direction of the observer denoted by the gray plane SOV.

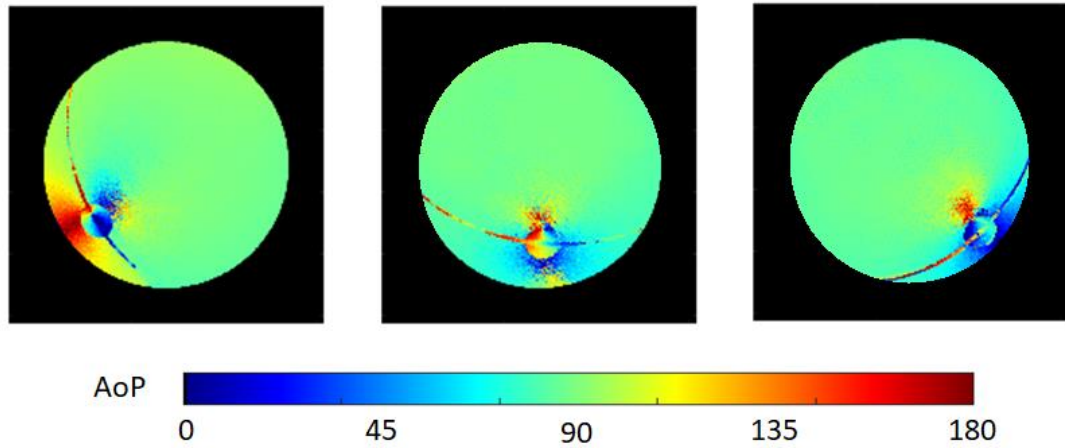


Figure 5. AoP images referenced to the scattering plane with solar azimuth and zenith angles corresponding to 123° , 183° , and 230° , and 45° , 32° , 42° , respectively (from the same images as in Figure 3). Measurements were recorded in Rexburg, Idaho on 21 August 2017 at 17:00:03 (Left), 19:36:20 (Middle), and 21:34:06 (Right) UTC. In this reference frame, the AoP distribution is uniform and rotates with the position of the sun. Neutral point locations are indicated by 90° changes in the AoP. The top of the image represents north and the right side of the image represents west.

Instrument $\rightarrow$ Scattering Plane Calculation. The method presented by Schutgens et al. [98] was applied to transform the AoP measured in the instrument plane to an AoP referenced to the scattering plane at each pixel. Once the AoP was rotated, the normalized Stokes S_1 and S_2 parameters in the new reference frame (RF) could be calculated using Equations 8 and 9,

$$\left(\frac{S_1}{S_0}\right)_{RF} = \text{DoLP}_{\text{ins}} * \cos(2 * \text{AoP}_{\text{RF}}) , \quad (8)$$

$$\left(\frac{S_2}{S_0}\right)_{RF} = \text{DoLP}_{\text{ins}} * \sin(2 * \text{AoP}_{\text{RF}}) , \quad (9)$$

where DoLP_{ins} represents the DoLP in the instrument plane of reference. The calculations in this method were based on the single-scattering Rayleigh model, in which the AoP is perpendicular to the scattering plane that contains the source, the scattered light from the viewing direction, and the observation point. In Figure 6, the incident and scattered light is described by the zenith and azimuth angles, (θ_i, ϕ_i) and (θ, ϕ) , respectively. The azimuth angle for each view angle (pixel) of the polarimeter is referenced to north and is defined with respect to a right-hand coordinate reference, using the positive zenith direction as the axis of rotation. In practice, we related each pixel of the fisheye image to its corresponding zenith and azimuth angles by performing a spatial calibration, as described in Chapter 3.

Rotation of the AoP originally referenced to the instrument plane into a scattering-plane reference required calculation of the cross product

$$\vec{n}_s = \vec{v}_p \times \vec{s}_i \quad (10)$$

of the incident light vector that points in the direction of the source ($\vec{s}_i$) and the scattered light vectors that point in the viewing direction,

$$\vec{v}_p = (\cos \emptyset \sin \theta, \sin \emptyset \sin \theta, \cos \theta). \quad (11)$$

This defines the scattering plane unique to each pixel in the image. The angle of polarization can be found using Equation 12,

$$\text{AoP}_{sp} = \theta_{sp} = \arccosine \left(\frac{\vec{v}_p \cdot \vec{n}_s}{|\vec{v}_p| |\vec{n}_s|} \right), \quad (12)$$

where $\vec{v}_p$ is again the light entering the system and $\vec{n}_s$ is the vector normal to the scattering plane. Figure 7 shows the angle between these two vectors.

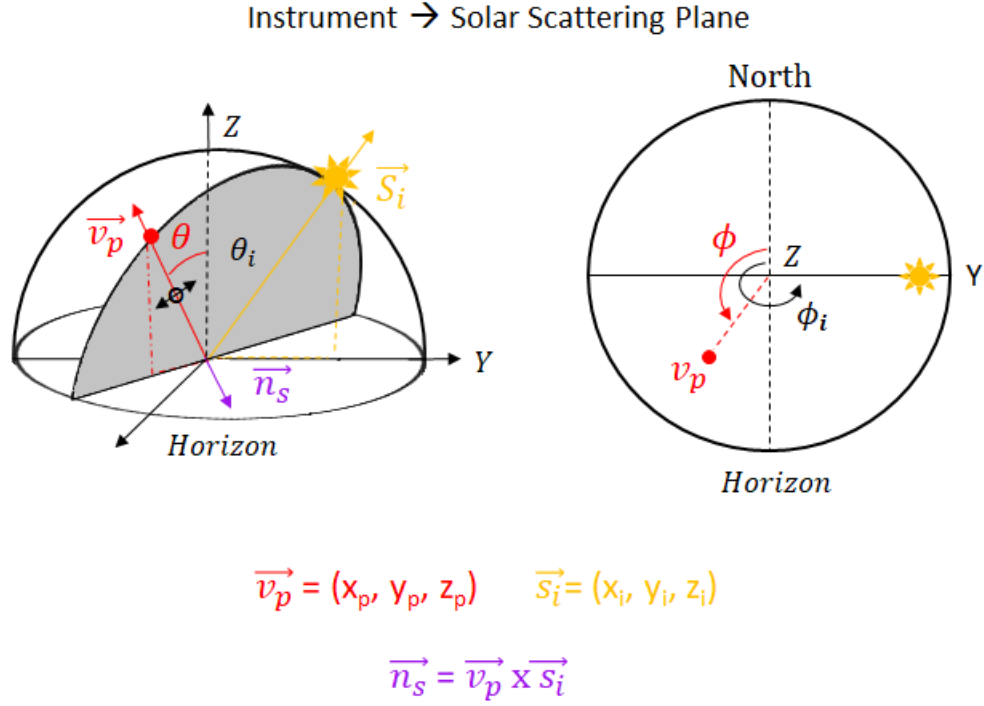


Figure 6. Solar scattering plane with reference notation. The solar scattering plane contains the directions of incident light ($\vec{S}_i$) and scattered light ($\vec{v}_p$) in the observer's viewing direction. The incident and scattered light is described by the zenith and azimuth angles, (θ_i, ϕ_i) and (θ, ϕ) , respectively. The scattered light has a polarization vector orthogonal to the light ray. The scattering plane normal vector is $\vec{n}_s$.

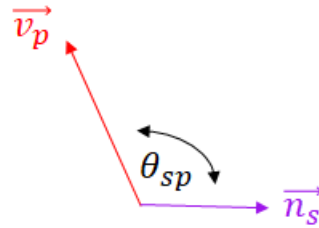


Figure 7. The angle between the light entering the system ($\vec{v}_p$) and the vector normal to the scattering plane ($\vec{n}_s$) is the angle of polarization referenced to the scattering plane. This is found by taking the arccosine of the dot product of the two vectors, $\vec{v}_p$ and $\vec{n}_s$ as shown in Eq. (12).

Principal Plane Reference

AoP measurements are also commonly aligned to the solar principal plane when analyzing multiple-scattering processes [48, 98, 99] and in retrieving compass-based headings for navigational applications [36-38]. For this reference frame, the scattered light $\vec{v}_p$ is referenced to the solar principal plane, which contains the incident light and local zenith, denoted by the gray plane SOZ in Figure 8. This results in each instrument-frame AoP value being aligned to the solar principal plane, which creates a common reference coordinate system for all pixels. This results in a similar AoP pattern that rotates with the solar position, as shown in Figure 9.

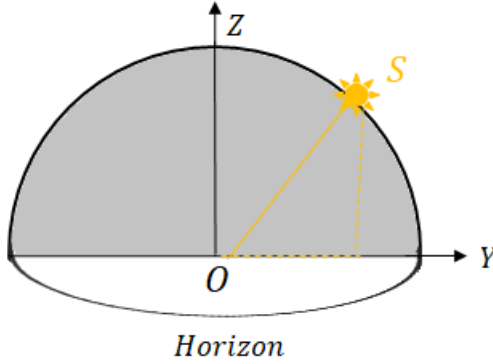


Figure 8. Solar principal plane illustration. The solar principal plane contains the incident light and local zenith denoted by the gray plane SOZ.

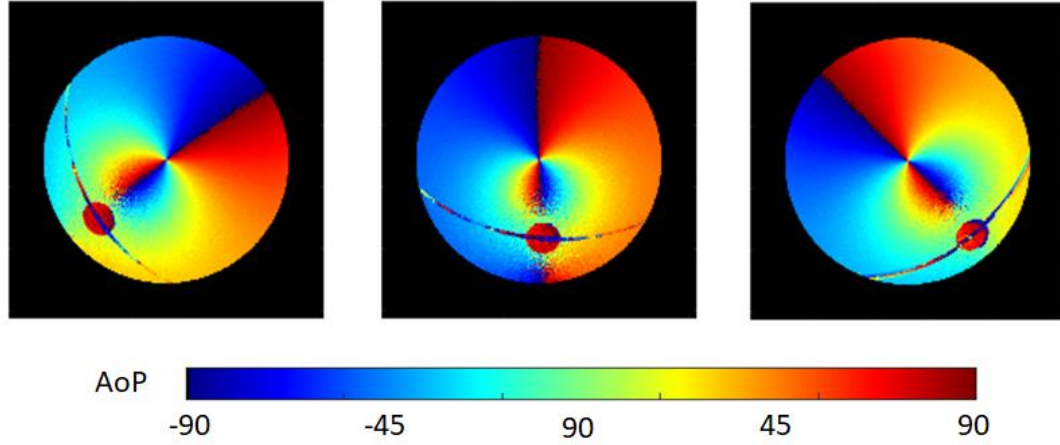


Figure 9. AoP images referenced to the solar principal plane with solar azimuth and zenith angles corresponding to 123° , 183° , and 230° , and 45° , 32° , 42° , respectively (from the same images as in Figure 3). Measurements were recorded in Rexburg, Idaho on 21 August 2017 at 17:00:03 (Left), 19:36:20 (Middle), and 21:34:06 (Right) UTC. In this reference frame, the AoP is measured clockwise from the solar principal plane (matching the approach used in [61-63]). The top of the image represents north and the right side of the image represents west.

Instrument $\rightarrow$ Solar Principal Plane Calculation. The method presented by Li et al. [100] was used to transform the Stokes S_1 and S_2 parameters from the instrument plane to the solar principal plane by using a rotation Mueller matrix (Eq. 13). The AoP in the solar principal plane was then derived from the realigned Stokes parameters. The reference coordinate system was transformed by rotating each pixel from the instrument plane by a counterclockwise rotation angle α (Figure 10).

$$\begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix}_{\text{principal-plane}} = L[\alpha] \cdot \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(2\alpha) & \sin(2\alpha) & 0 \\ 0 & -\sin(2\alpha) & \cos(2\alpha) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix}_{\text{instrument}} \quad (13)$$

Instrument $\rightarrow$ Solar Principal Plane

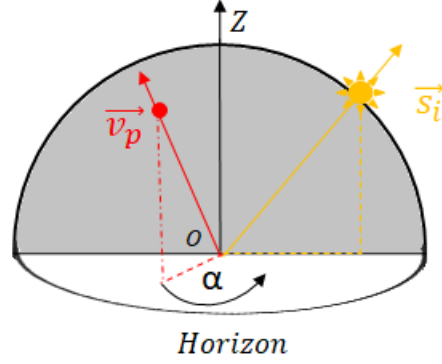


Figure 10. Reference coordinate system with the solar principal frame represented by the gray plane. The reference coordinate system can be transformed by rotating each Stokes pixel referenced in the instrument plane by a counterclockwise rotation angle α , which represents the azimuth angle measured from the solar principal plane to the rotated pixel.

Fisheye Lens Operation

When quantifying skylight polarization using all-sky polarimeters, the Stokes parameters are measured for each pixel at the focal plane and then converted to a Cartesian vector. The magnitude of this vector is the degree of polarization and the x and y components represent the direction of polarization. The amount of rotation the light vector experiences is determined by the zenith angle of the observed pixel. For light incident from the horizon, the rotation of the light direction vector is 90° , while light incident from the zenith is not rotated. Thus, the recorded AoP image is a projected version of the incoming AoP. By mathematically reversing the bending process of the lens, the initial AoP can be calculated. A mapping between the pixel locations on the image plane and the zenith angle of the incident light is needed to accurately describe the measured Stokes parameters and to rotate the Stokes parameters between different reference frames [41].

All-Sky Polarization Images

In Figure 11, all-sky polarization Stokes S_1 , S_2 , AoP, and DoLP images can be viewed, referenced to the instrument plane (left column), scattering plane (middle column), and principal plane (right column). The images were recorded with the LCVR polarimeter in Rexburg, Idaho (latitude: 43°49'46.13" N; longitude: 111°53'6.14" W) on 21 August 2017. The all-sky images are oriented with north at the top and west to the right. The DoLP magnitude did not change in the different reference frames (row 4); however, noticeable differences between the S_1 , S_2 and AoP images were observed, specifically in the measurement time series presented in Figure 12. A clear-sky was observed through the measurement series; therefore, the skylight polarization was always polarized perpendicular to the scattering plane. As the solar geometry changed, the S_1 , S_2 , and AoP images referenced in the instrument, scattering, and solar principal planes changed.

For measurements referenced to the instrument plane (Figure 12, rows 1-3), the S_1 , S_2 , and AoP images varied based on the position of the sun with respect to the orientation of the imager's reference polarizer. Referencing the polarization angles in the scattering plane created uniform S_1 , S_2 , and AoP images (Figure 12, rows 4-6) that rotated with the solar position. The direction of polarization was observed to be perpendicular to the solar principal plane (in all pixels except in a small region near the sun where the signal could be saturated or otherwise affected by strong multiple scattering and related neutral points). In the principal plane reference, the magnitudes of the S_1 , S_2 , and AoP (Figure 12, rows 7-9) were observed to be dependent on the solar position.

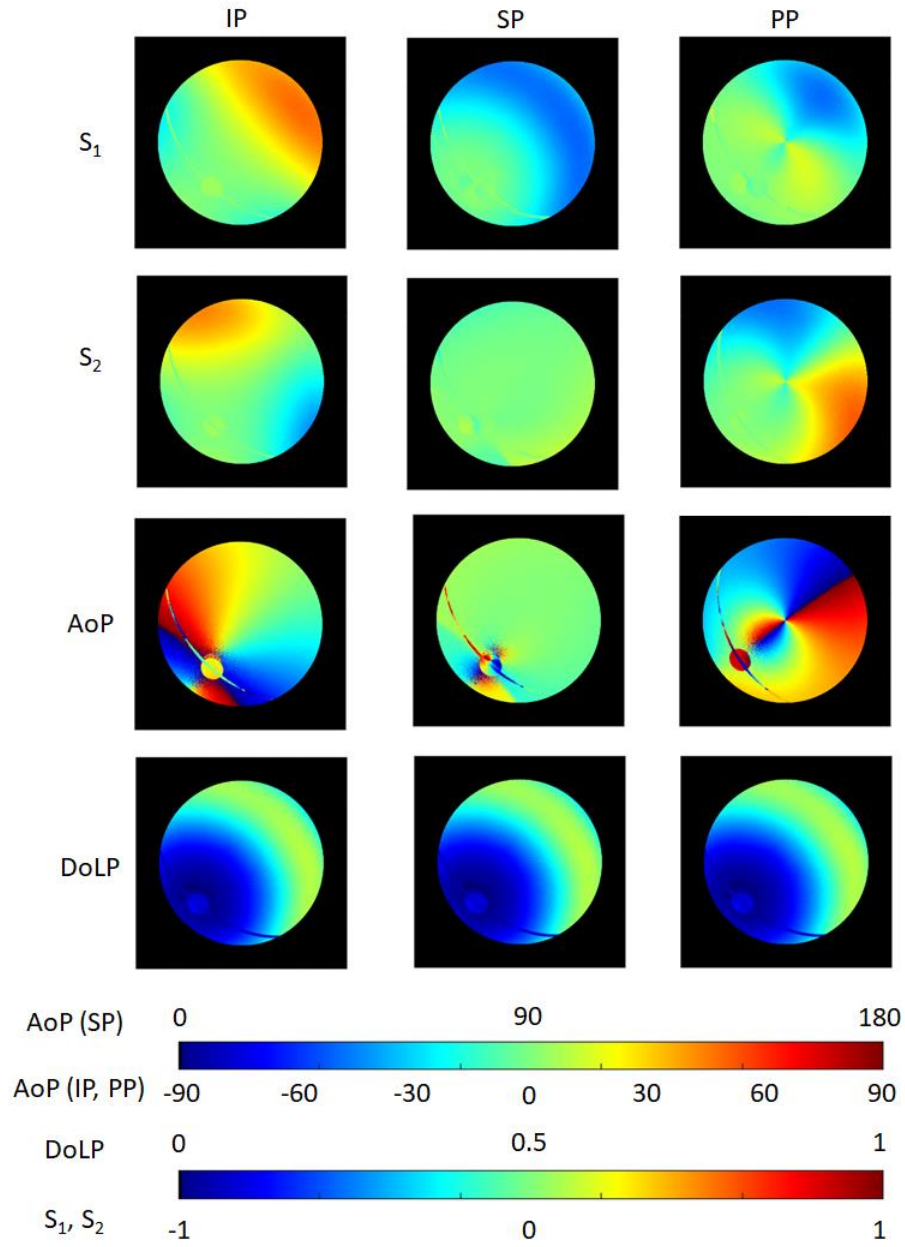


Figure 11. Measured all-sky 450 nm S_1 , S_2 , AoP, and DoLP images referenced to the instrument plane (IP), scattering plane (SP), and principal plane (PP). The images were recorded with the LCVR all-sky polarimeter at 17:00:03 UTC on 21 August 2017 in Rexburg, Idaho. The solar azimuth angle and zenith angle were 123.1° and 45.0° , respectively. The top of the image represents north and the right side of the image represents west.

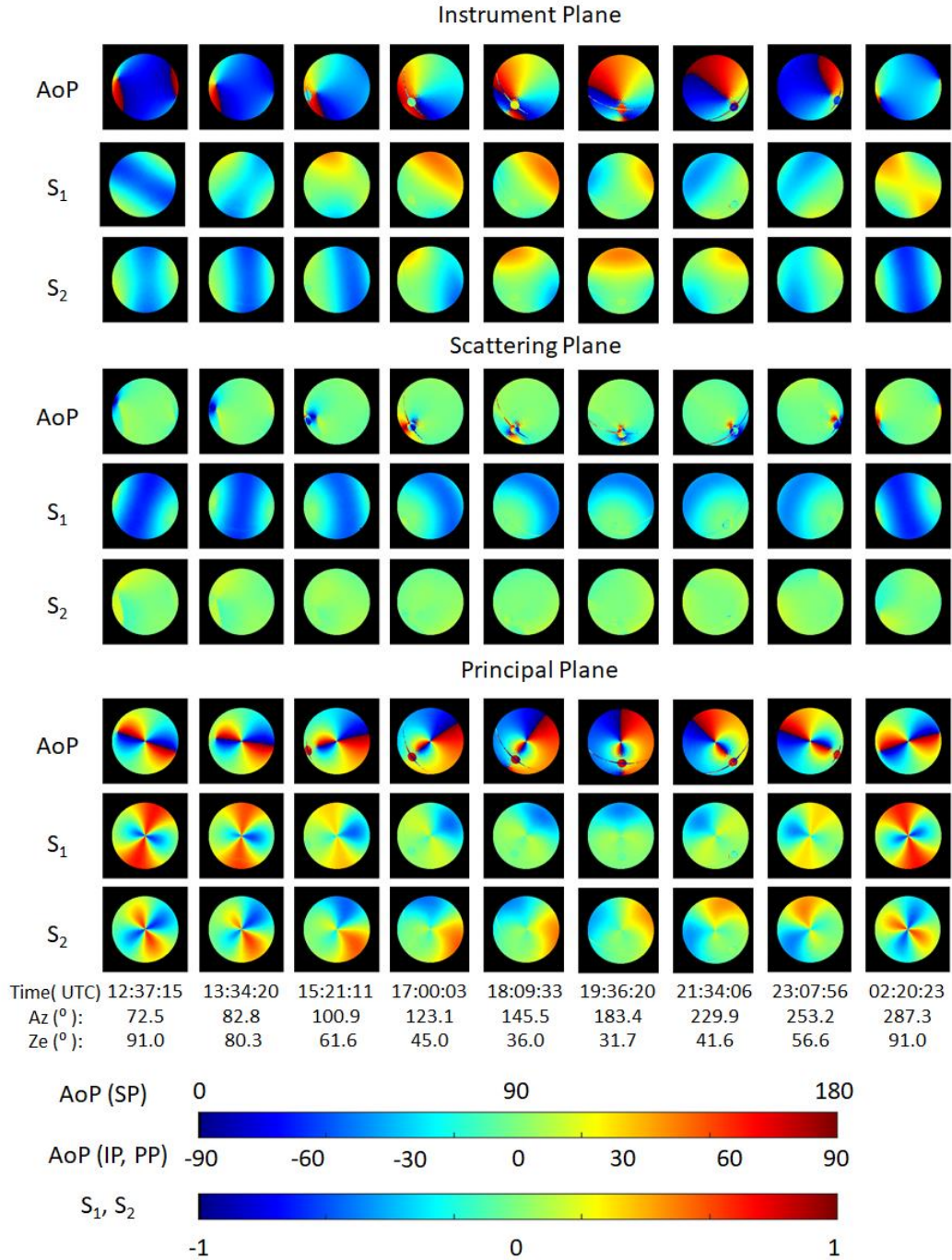


Figure 12. Time series of measured AoP, S_1 , and S_2 images recorded with the LCVR all-sky polarimeter (450 nm) referenced to the instrument plane (top panels), scattering plane (middle panels), and principal plane (bottom panels). The measurements were recorded in Rexburg, Idaho on 21 August 2017. Each column represents a separate measurement with the corresponding time and solar azimuth and zenith angles positioned below the column. The top of the image represents north and the right side of the image represents west.

Neutral Points

A neutral point in an all-sky image represents a point where the measured DoLP is equal to zero. At a neutral point, the DoLP gradually increases with angular distance. The neutral points arise from multiple scattering in the atmosphere, which creates a polarization component oriented parallel to the scattering plane, offsetting the single-scattered polarization oriented perpendicular to the scattering plane. Neutral points arise when the intensities of the perpendicular and parallel light are equal. At a neutral point, the AoP switches 90° along the solar principal. For measurements referenced to the principal plane, the switch of AoP at the zenith is a result of the coordinate reference frame and is not from a neutral point. Neutral points vary with solar position, wavelength, and relate to the amount of atmospheric turbidity and the type of particles present in the atmosphere [54, 101].

The main neutral points are called Arago, Babinet, and Brewster, after the scientists who first described or studied them. In 1809 Dominique Francois Jean Arago discovered partially linear polarization and observed a neutral point in the anti-solar direction [7]. In 1840, Jacques Babinet [102] discovered a second neutral point situated above the sun and in 1842, David Brewster predicted a third point below the sun at the same angular distance the Babinet point lies above the sun [103]. Brewster confirmed his prediction experimentally in 1846 [104]. Horvath et al. measured a 4th neutral point approximately opposite the Arago point along the anti-solar principal direction [105]. The fourth neutral point can only be observed from the sky by an air- or space-borne observer, looking down.

Measurements of the AoP from 21 August 2017 are shown in Figure 13 to illustrate the neutral point locations in the instrument-plane, scattering-plane, and principal-plane references. Examples are shown for daytime (left) and twilight (right). The Brewster (Br) neutral point can be observed for solar zenith angles less than 90° , where the Arago (A) neutral point can be observed for solar zenith angles greater than 90° (i.e., at twilight, with the sun below the horizon). As the solar zenith angle increases from 90° , the Babinet neutral point decreases in altitude, the Brewster neutral point vanishes, and the Arago point becomes observable.

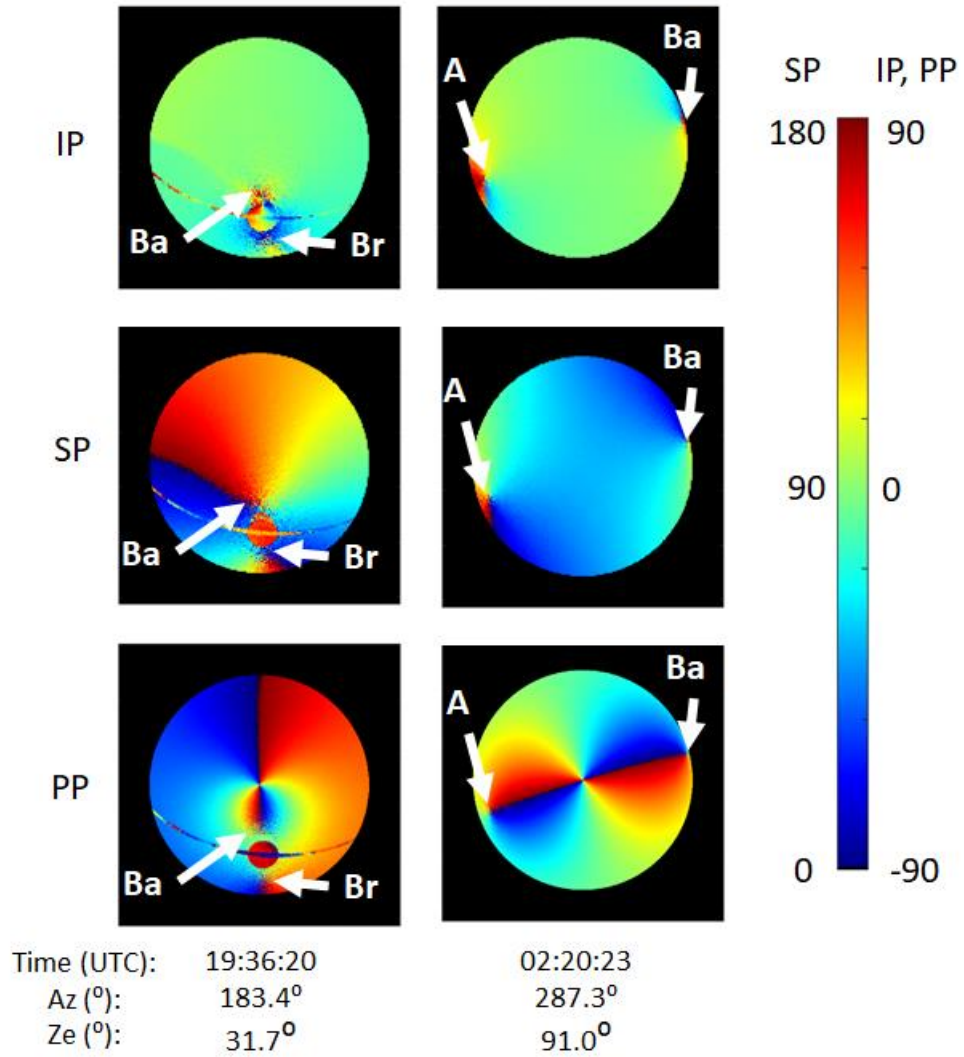


Figure 13. Angle of polarization referenced in the instrument plane (IP), scattering plane (SP), and principal plane (PP), respectively. The images on the left and right correspond to measurements made in Rexburg, Idaho on 21 August 2017. The Babinet (Ba) neutral point can be observed in both images. The Brewster (Br) neutral point can be observed for zenith angles less than 90°, where the Arago (A) neutral point can be observed for zenith angles greater than 90°. The top of the image represents north and the right side of the image represents west.

Summary

To accurately predict cloud thermodynamic phase in this dissertation, the AoP (and the related Stokes S_1 and S_2 parameters) needed to be rotated from the instrument plane to the scattering plane that is unique for every pixel in the all-sky image and for every solar position. Similarly, to visualize the sky polarization during the solar eclipse in a manner that facilitated comparison with other observations, the instrument-plane AoP had to be referenced to the solar principal plane. A detailed explanation on how to rotate the AoP between different reference frames was provided in this chapter.

In Figures 11 and 12, the S_1 , S_2 , and AoP images, referenced to the instrument, scattering, and principal planes, were observed to change as the sun moved from sunrise to sunset. Both the instrument and principal plane S_1 , S_2 , and AoP images were dependent on the solar scattering geometry. The instrument plane AoP was dependent on the solar position and the orientation of the imager's internal polarizer. As the solar position changed, the AoP referenced in the principal plane was aligned perpendicular to the scattering plane; however off-axis, the S_1 , S_2 , and AoP images varied. This off-axis variation was dependent on the solar scattering geometry. The S_1 , S_2 , and AoP values referenced in the scattering plane had a uniform distribution that rotated with the solar position.

By exploiting the direction of linear polarization in the measured AoP, which is dependent on the Stokes S_1 and S_2 parameters, azimuth sensing can be used to build GPS-independent navigational systems [36-38]. The navigational systems rely on knowing the direction of polarization in order to obtain heading coordinates; therefore, measurements

referenced to either the instrument or principal planes benefit these applications. For example, the AoP image referenced to the instrument plane can be used to determine the location of the polarimeter with respect to the solar principal plane. In the left image of Figure 3, the measured AoP value of zero (along the solar principal plane), indicates that the polarimeter was perpendicular to the solar principal plane (since the AoP pattern in clear-sky is perpendicular to the scattering plane).

The Stokes S_1 parameter, when defined in the scattering plane, can be used to determine cloud thermodynamic phase [25-27] and if referenced to the almucantar plane, the retrieval of aerosol parameters (aerosol particle size, shape, and the real part of the complex refractive index) can be inferred from the Stokes S_1 and S_2 parameters, which could help in identifying aerosol types. The almucantar plane contains a solar zenith angle with varying azimuth angles at a set zenith angle.

CHAPTER THREE

POLARIMETERS

In this dissertation project I have worked directly with three types of polarimeters operating in the visible and shortwave infrared. The shortwave infrared polarimeter and the visible LCVR-based polarimeter are division-of-time polarimeters [17], meaning that they take a series of measurements sequentially in time using different analyzers (i.e. rotating polarizers or electronically varied liquid crystal retardance) to retrieve a Stokes image in which each pixel contains a Stokes vector for that part of the observed scene. The time-sequential nature of the measurements obtained by these instruments can lead to significant polarization artifacts when the light fluctuates during a measurement sequence. This creates problems when trying to measure skylight polarization during dynamic lighting conditions in low-light conditions, such as twilight or a solar eclipse. Therefore, we developed two different visible three-camera all-sky polarimeters so that polarimetric images could be recorded over a dynamic range of lighting conditions. These three-camera polarimeters record three images simultaneously and are considered a division-of-aperture polarimeter. The detectors in this system must be spatially registered so that the field of view of the detector elements on each focal plane are well aligned. In this chapter I describe each of these polarimeter systems, their operating modes, and required calibrations, to facilitate reader understanding of later chapters.

SWIR Imaging Polarimeter

Figure 14. SWIR rotating-polarizer imaging polarimeter.

In my M. S. Thesis [53], a successive-orders-of-scattering radiative transfer model was used to study skylight polarization in the shortwave infrared. In this dissertation, the SWIR imaging polarimeter shown in Figure 14 was used to validate those models in a single band from 1.5 to 1.8 μm . This passive polarimeter was developed at Polaris Sensor Technologies (Huntsville, Alabama) and captures radiance images in units of $\text{W}/(\text{m}^2 \text{ sr})$ at 0° , 45° , 90° , and 135° polarizer angles sequentially in time through a polarizer rotating continuously at a spin rate up to 120 revolutions per second. Once a measurement is completed, a non-uniformity correction is applied to the measured images and a post-processing algorithm computes a Stokes vector representing

the polarization state for each pixel in the image. The focal plane array in this polarimeter is liquid-nitrogen cooled and its field of view is 9.1° by 7.3° .

Visible LCVR-Based All-sky Polarimeter

Throughout my work at Montana State University, the visible LCVR-based all-sky polarimeter, locally referred to as “Polly,” was a primary tool used in studies of cloud thermodynamic phase, skylight polarization during the 2017 solar eclipse, and the effects of wildfire smoke on skylight polarization. This instrument was developed before my arrival at Montana State University [41] and uses a fisheye lens to image the sky with a field of view of approximately 160° . It is a ground-based imager that operates in 10-nm-wide wavelength bands centered at 450 nm, 490 nm, 530 nm, 670 nm, and 780 nm. This LCVR all-sky polarimeter has been an extremely valuable instrument that has been used to quantitatively relate skylight polarization to environmental parameters such as aerosols [45, 46], clouds [27, 42], and surface reflectance [43].

In this polarimetric imager, two liquid crystal variable retarders (LCVRs) are used to electronically vary the retardance seen by incoming light. Four sequential images are rapidly-acquired so that a full Stokes image can be measured in less than a few tenths of a second, at each wavelength. The LCVRs allowed rapid acquisition that enabled reliable measurements in partly cloudy skies by avoiding polarization artifacts from inter-frame cloud motion. This polarimeter relies on a full radiometric and polarimetric calibration. The polarimetric calibration was performed using an external rotating polarizer and an integrating sphere viewed at numerous angles to fully capture the imager’s system matrix

over the entire fisheye field of view. Maximum error for the Stokes S_1 and S_2 parameters was estimated as $\pm 1.1\%$ with 100% linear input [41]. The LCVR polarimeter and a diagram explaining its internal components are shown in Figure 15 (in this photo, the polarimeter was temporarily deployed without a weatherproof housing).

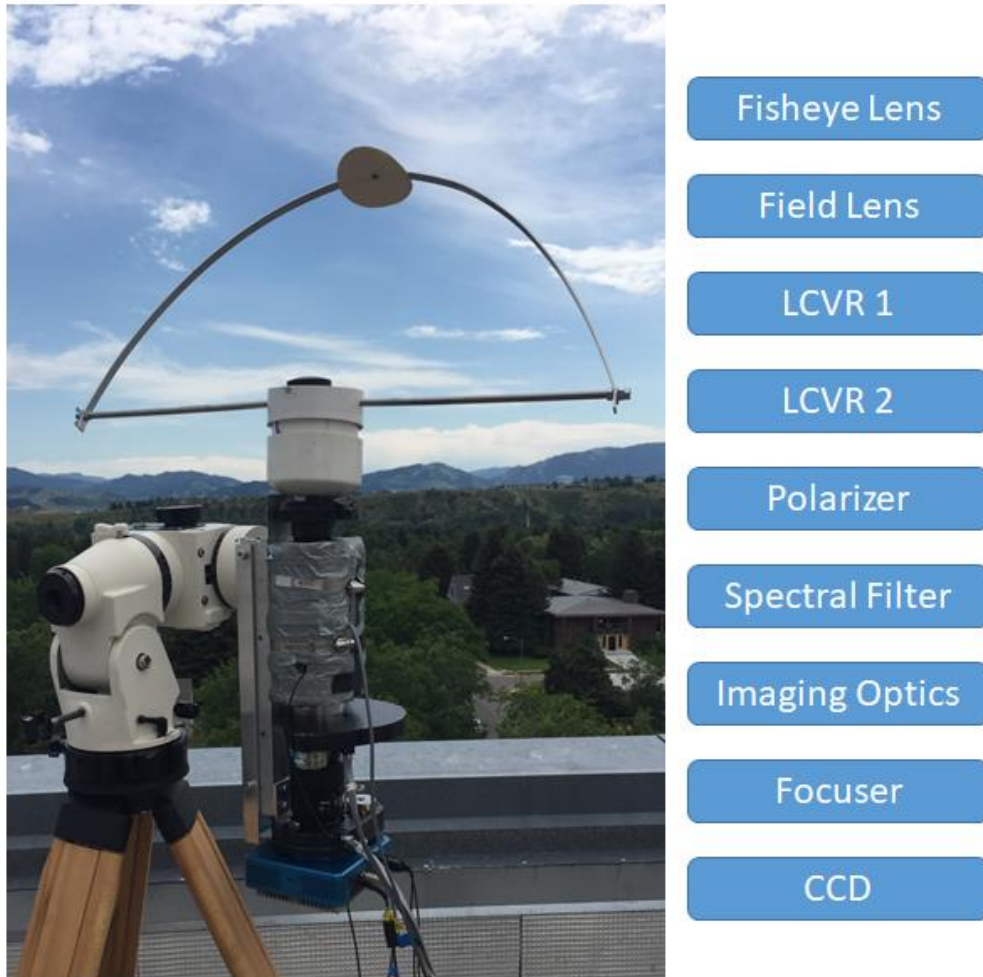


Figure 15: A photograph of the visible LCVR-based all-sky polarimeter taking cloud thermodynamic phase measurements on 30 June 2016 and a schematic representation of the internal components of the optics train.

Polarimeter Redesign

This all-sky polarimeter system had been operating continuously since 2009 [89] and in 2013 (at the start of my career at Montana State University), it needed repairs and upgrades to continue operation and to improve efficiency, reliability, and accuracy. System upgrades included replacing the original camera, focus wheel, filter wheel, and LCVR controller, performing a new fisheye radiometric and polarimetric calibration, and designing and building a new weatherproof, temperature-controlled case. The upgrades to this polarimeter, that are outlined in the following sections improved the overall sensitivity, data quality, and stability of the collected images and gave us the ability to take measurements during darker conditions, namely during twilight. After the changes were implemented, a full calibration was performed with the fisheye lens.

LCVR Improvements. Prior to the 2016 upgrades, if electrical power was removed from the LCVRs, the polarimeter calibration was lost. To fix this issue, a new dual-channel LCVR controller replaced the two original single-channel LCVR controllers, reducing the need to perform a full calibration every time power was removed from the system. With this improvement, the polarimeter could be moved between measurement sites and the calibration was found to be stable as long as the optical train was not changed.

Camera Replacement. A new Apogee Alta F astronomical-grade 4-megapixel camera with cooling capabilities down to -20°C replaced the previous DALSA 1-megapixel camera. This change was implemented as a result of fluctuations exhibited by the previous camera, which made maintaining calibration difficult. The Apogee camera quantum efficiency is twice that of the DALSA camera and it has significantly less spatial noise, as can be observed in the DoLP images in Figure 16.

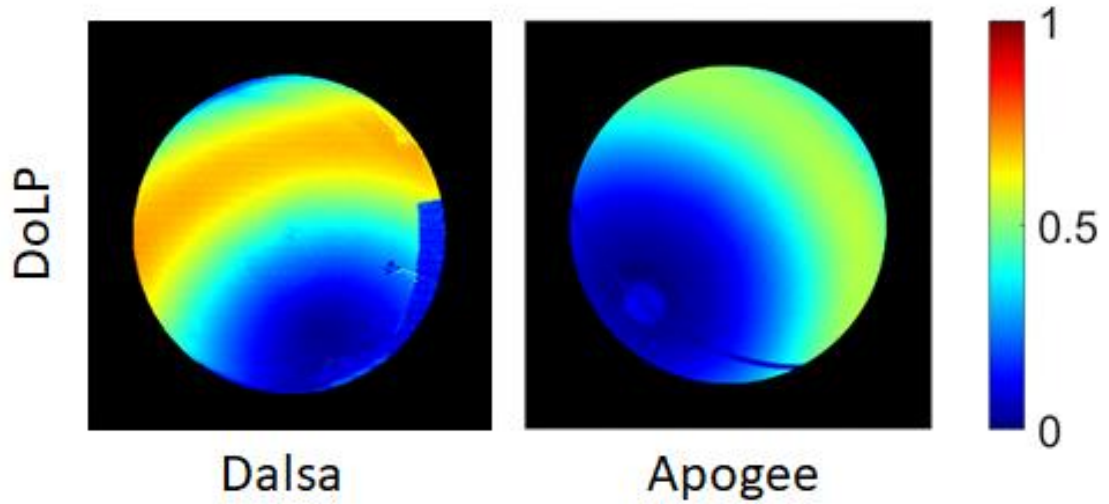


Figure 16. LCVR-based all-sky DoLP images recorded by the DALSA (Left) and Apogee (Right) cameras on 18 October 2005 and 21 August 2017, respectively. The solar azimuth and zenith angles were $(199^{\circ}, 123^{\circ})$ and $(33^{\circ}, 45^{\circ})$, respectively. The DALSA DoLP image was shown in ref. [41], Figure 7. The top of the images are aligned to north, with the right side of the image aligned to west.

Spectral Filter Replacement. To expand the spectral capabilities of this instrument from the visible to the near infrared, a 780-nm filter replaced the 700-nm filter. With this change, “red edge” effects and near-infrared polarization could be measured, the latter being especially useful for aerosol studies. This instrument can now measure skylight polarization in 10-nm-wide wavelength bands centered at 450 nm, 490 nm, 530 nm, 670 nm, and 780 nm. With the addition of the 780-nm channel, a second polarizer was added to the system because the original polarizer only performed properly to wavelengths up to 700 nm. Unfortunately, the use of this reflective polarizer caused reflections to appear as ghost images in the final optical image. To fix this issue, the second polarizer was tilted in the optical train to “steer” the ghost reflections into the black casing. Figure 17 displays images before and after the second polarizer was tilted in the optical train.

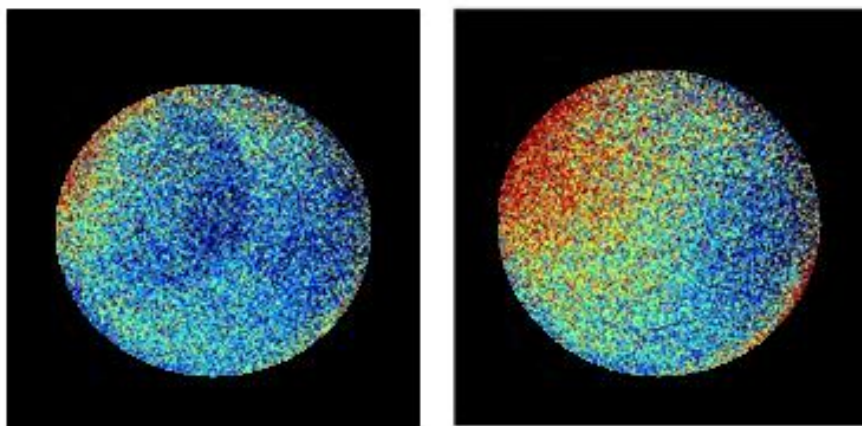


Figure 17. (Left) An example of reflection artifacts from the new reflective polarizer installed in the all-sky polarimeter’s optical train to allow for “red edge” effect detection and (Right) the resulting image once the new polarizer was tilted with respect to the optical axis.

Filter Wheel and Focuser Replacement. The internal filter wheel and focuser were replaced in 2013. A new mount had to be created to correctly position the focuser and camera with respect to the imaging lens and the aluminum rail holding the polarimeter's optical components (Figure 18). The designed mount was initially created as a 3D print. The final mount was machined as an aluminum piece for strength and durability. Figure 18 shows the 3D printed mount (blue).

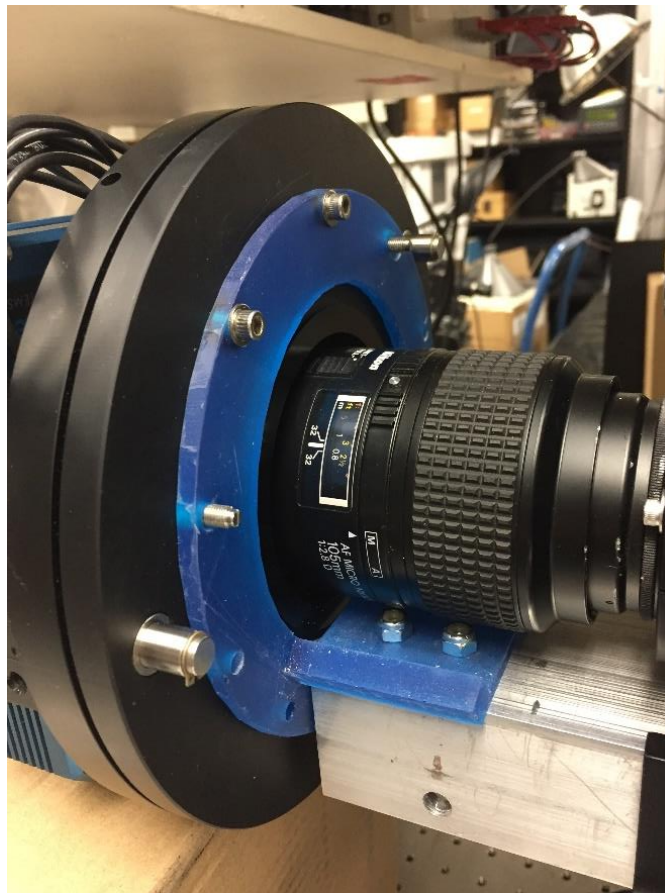


Figure 18. 3D printed mount (blue) connecting the focuser and camera to the imaging lens and aluminum optical rail.

Sun Occulter – Case Redesign

To easily access the all-sky polarimeter and to run the all-sky polarimeter continually, the polarimeter's original tube housing was replaced with a new rectangular housing structure. This new housing included a removable panel on one side for easy access and new heating and cooling units to regulate the housing internal temperature. The original cable chain, which limited the azimuthal direction of the sun occulter, was replaced by an internal slip ring so the sun occulter could move 360°. Chad Whiteley worked on getting the new housing structure operational by upgrading the heating and cooling units and by updating the occulter code to work without the cable chain assembly. To test the new heating and cooling units, he studied the polarimeter case temperature under a variety of conditions; some tests were done inside of a solar simulator, and many others were conducted outdoors. The heaters were found to maintain the set temperature of 25°C within the housing structure sufficiently well in cold weather; however, the coolers struggled to maintain the set temperature when the outside temperature was above approximately 30°C. This can be observed in Figure 19 when the internal temperature of the housing containing the all-sky polarimeter rose above the set point temperature during a measurement in June of 2017. For the LCVRs to be operational and maintain calibration, the LCVR heaters needed to be maintained at an internal temperature of ~40°C, which became difficult if the internal temperature of the housing dropped below 25°C; therefore, as long as the heaters could maintain the set temperature, the cooling problems were not critical. Extra insulation improved the cooling efficiency, but an extra cooling element still needs to be added to the system to

solve the issue completely. Martin Tauc helped with designing the case structure and with brainstorming about reoccurring problems. The previous and new housing can be viewed in Figure 20.

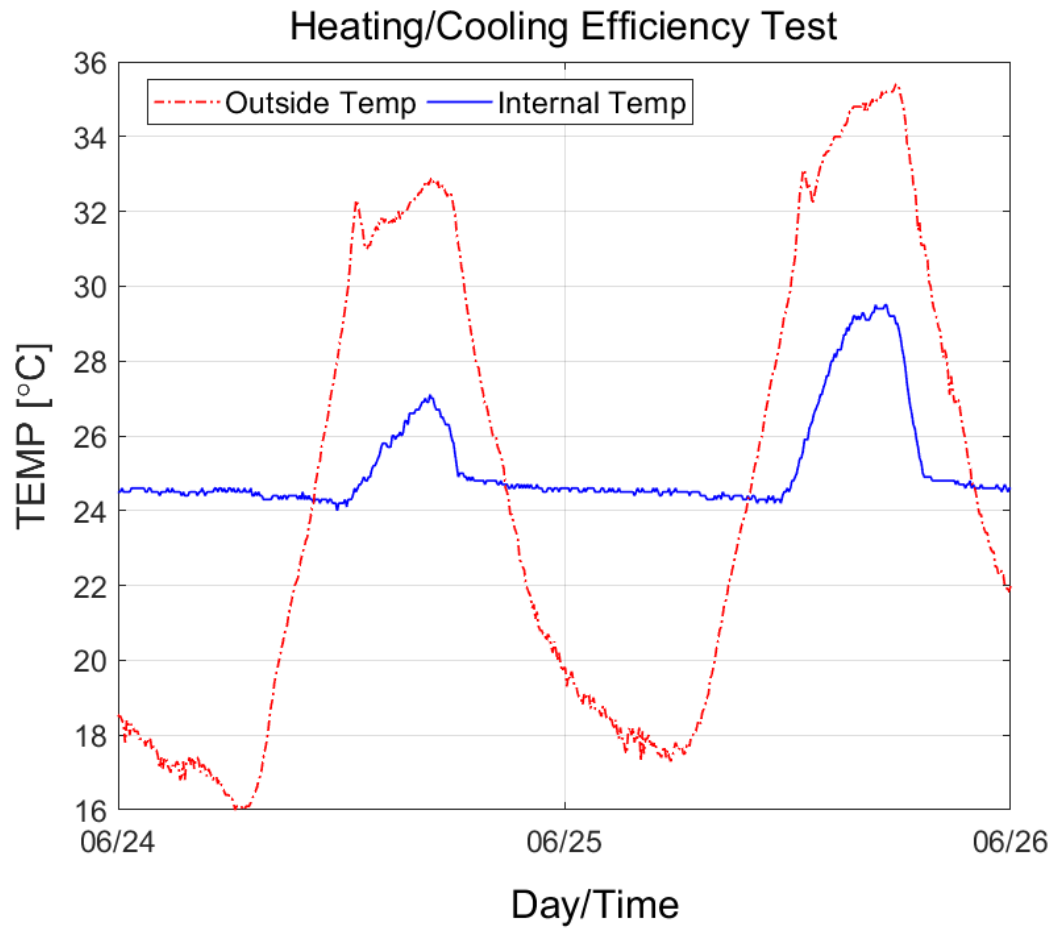


Figure 19. Internal temperature of the housing containing the all-sky polarimeter and the outside temperature were measured in a two-day test in late June 2017.



Figure 20. (Left) Old LCVR all-sky polarimeter housing and (Right) new all-sky polarimeter housing.

Visible Three-Camera All-sky Polarimeters

Two separate all-sky polarimeter systems were built using three Nikon D700 cameras and three Sony $\alpha 7s$ cameras, respectively. Both operate with standard red, green, and blue wavelength bands. Each camera is fitted with a fisheye lens and a linear polarizer to enable recording of polarized all-sky images. Neither the Nikon nor Sony system has yet been housed in a manner that would allow extended, unattended operation.

The visible three-camera Nikon all-sky polarimeter was initially designed to take measurements during the 2017 solar eclipse; however, it has also been used to detect cloud thermodynamic phase and it will be used to study sky polarization at night. This system is portable, robust, and easy to use. It is sensitive in low-light conditions and by

using three DSLR cameras with polarization filters aligned to 0° , 60° , and 120° , simultaneous spectral and polarimetric image acquisition can be achieved.

An alternative system was also created using three mirrorless Sony $\alpha 7s$ cameras. This system has an extended ISO sensitivity range beyond the performance of the Nikon cameras. Unless otherwise stated, the measurements presented in the following sections were made with the Nikon cameras. Camera characterization and calibration measurements are provided in this chapter for the Nikon system only.

Three-Camera All-Sky Polarimeter Design

Three cameras, each equipped with 180° field-of-view circular fisheye lenses (SIGMA 8 mm, F3.5, EX DG, Nikon F mount) and each containing a fixed linear polarizer orientated at 0° , 60° , or 120° , establish the visible three-camera all-sky polarimeters. The polarizer angles were selected to achieve good signal-to-noise ratio for all linear polarization elements in the recovered 3-element Stokes vector. The DoLP and AoP at each pixel of the all-sky images were calculated from the linear Stokes parameters,

$$S_0 = \frac{2}{3}(I_{0^\circ} + I_{60^\circ} + I_{120^\circ}), \quad (14)$$

$$S_1 = \frac{2}{3}[(I_{0^\circ} - I_{60^\circ}) + (I_{0^\circ} - I_{120^\circ})], \quad (15)$$

$$S_2 = \frac{2}{\sqrt{3}}(I_{0^\circ} - I_{60^\circ}), \quad (16)$$

corresponding to the polarizers oriented at 0° , 60° , and 120° relative to the camera axis (the polarizers were mounted at the back of the fisheye lens in each camera). The

orientation of the reference axis is aligned perpendicular to the top and bottom axis of the camera.

Details for each camera are given in Table 2. Besides having good day-to-night sensitivity, these polarimetric systems could be controlled remotely by a computer as well as a manual trigger, allowing us to simultaneously trigger each camera with or without the computer. Bryan Stanley and Martin Tauc helped with designing the control software. The camera systems can be seen in Figure 21. For the Sony camera, we used an adapter (VELLO LAE-SE-NF, version 4) to couple the Nikon-mount fisheye lens to the E-mount on the Sony cameras.

Camera Comparison	Nikon D700	Sony a7S
Camera Type	DSLR	Mirrorless
Image Sensor Type	CMOS	CMOS
Sensor Size (mm)	36.0 x 23.9	35.8 x 23.9
Effective Pixels (Megapixels)	12.1	12.2
Total Pixels (Megapixels)	12.9	12.4
Bit Depth	12 or 14 Bit	14 Bit
Max Resolution	4256 × 2832	4240 × 2832
ISO Sensitivity	200 - 6400	50 - 409600
Shutter Speed Sensitivity (seconds)	1/8000 – 30	1/8000 - 30
Storage Media	Compact Flash	SD
GPS	Yes	No
Time with Seconds	Yes	No
Exposure Bracketing	Yes	Yes
Remote Control	Yes	Yes
Operating Temperature Range (°F)	32 to 104	32 to 104
Lens Mount	F	E

Table 2. Nikon D700 and Sony α 7s camera specifications.



Figure 21. (Left) Nikon D700 three-camera all-sky polarization imaging system recording a cloud phase measurement. (Right) Sony $\alpha 7s$ 3-camera all-sky polarization imaging system during a twilight test conducted to prepare for the 21 August 2017 solar eclipse. (Right) Photo provided courtesy of Joseph A. Shaw.

Camera Characterization

To quantitatively interpret the images recorded in the red, green, and blue channels (so that we could compare our measurements with radiative transfer simulations and perform a radiometric calibration), the relative spectral response (RSR) of the Sony $\alpha 7s$ and Nikon D700 cameras was measured using a tunable monochromator light source. RSR measurements were made with a polarizer inserted between the camera and fisheye lens. For each image, the brightness of each channel was expressed in digital number (DN), proportional to the image irradiance. For each wavelength in the monochromator sweep, we averaged pixels within the center region of the monochromator window and divided this average value by the power in the monochromator output beam (measured with an optical power meter). This process resulted in a relative response curve (sampled at 5-nm intervals) that accounted for the spectral variation in the lamp output. Each set of measurements was normalized to its peak value. Figure 22 shows the RSR function for

the RGB channels, each normalized to its maximum value. Images were recorded at 1/8000 s exposure time for both cameras, at ISO 50 for the Sony α 7s and ISO 100 for the Nikon D700 (the lens aperture was wide open at f/3.5 for all measurements).

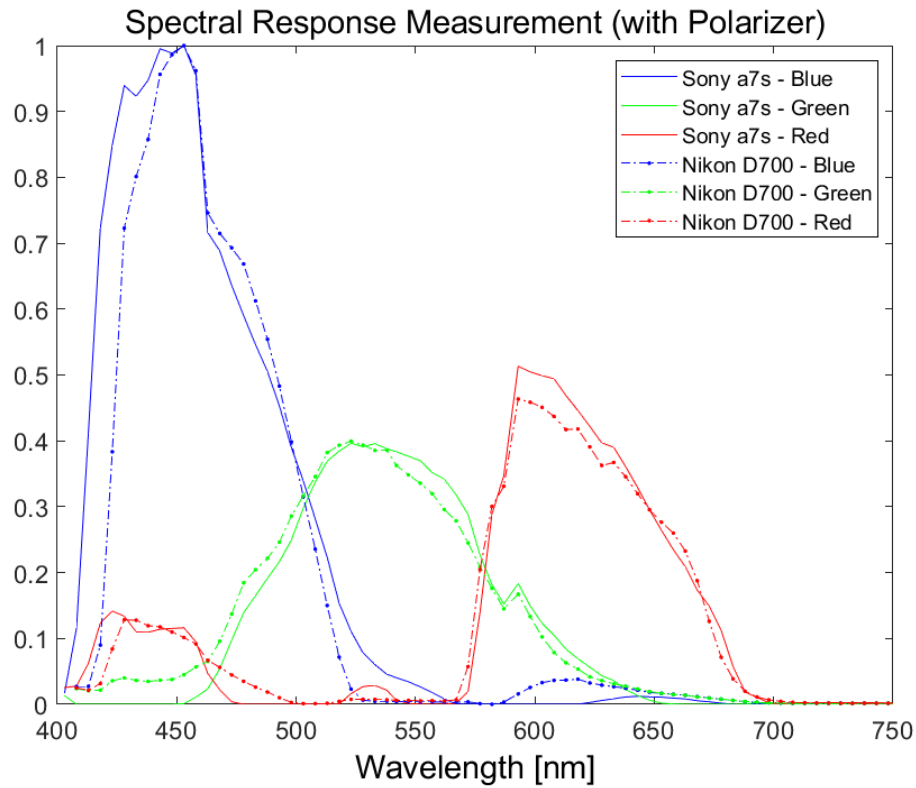


Figure 22. Relative spectral response of the Sony α 7s and the Nikon D700. Images were recorded at an ISO setting of 50 and 100 for the Sony and Nikon cameras, respectively. The exposure time for both cameras was set to 1/8000 seconds. The monochromator was swept in 5-nm intervals.

For all conditions, the blue channel had about two times higher sensitivity than the red and green channels. There was also spectral channel crosstalk: the red channel exhibited a small sensitivity in the blue spectrum and the blue channel exhibited a similar small sensitivity in the red spectrum. The difference between the Nikon and Sony RSR functions can be viewed in Figure 23. The maximum red, green, and blue peaks in the

RSR measurements (Figure 22) corresponded to approximately 450 nm, 530 nm, and 600 nm, respectively. RSR measurements were taken by Taiga Hashimoto with help from Seth Laurie.

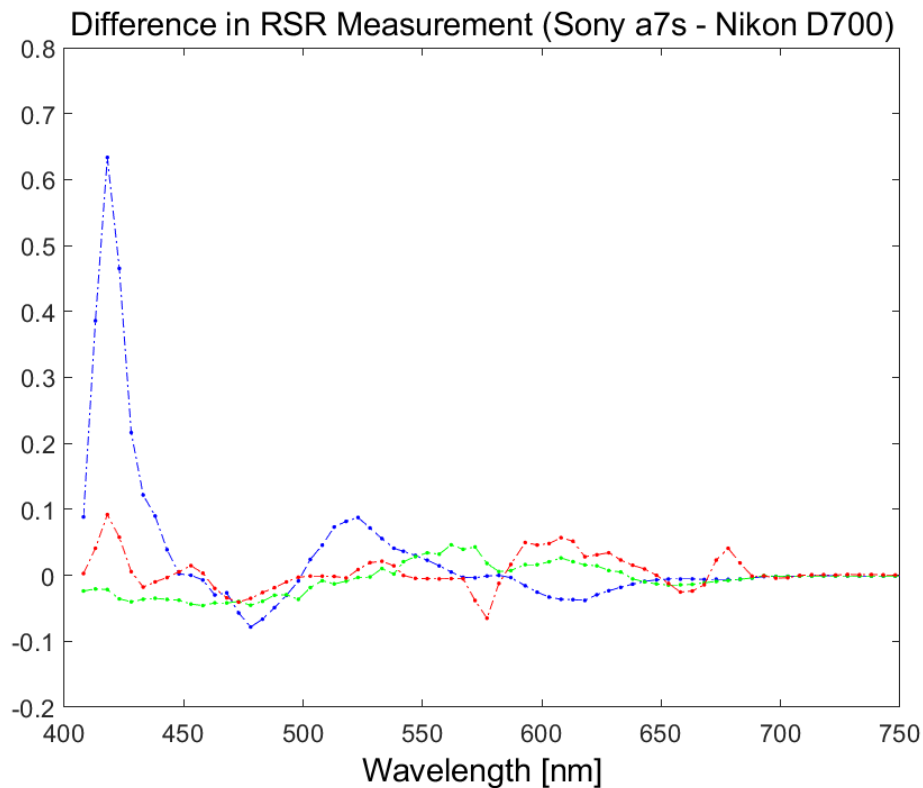


Figure 23. Relative spectral response (RSR) difference between the Sony α 7s and the Nikon D700. Beyond 450 nm, the two cameras had a maximum difference of approximately 0.1 between their measured RSRs.

Pixel-Angle Relationship

In addition to determining the RSR of each camera, we mapped the pixel – angle relationship for each system to enable calibration of the polarization effects of the fisheye lens. A fisheye lens bends incident light from a full 180° field-of-view onto a flat image

plane, meaning that light incident on the horizon is rotated 90°, while light incident at the zenith is not. The amount of rotation can be determined by the zenith angle of the incident light. A mapping between the angle and the corresponding location on the image plane (expressed in pixels) can be found by taking an image of a physical checkerboard pattern. The pixel – angle relationship for the Nikon camera is given in Figure 24. The angle relates to the measured distance from the camera to the center of the reference checkerboard and the measured distance from the center of the checkerboard to a corresponding square. The pixel parameter in Figure 24, relates to the number of pixels in the recorded image which correspond to the measured distance from the center of the checkerboard to a corresponding square.

The radial pixels from the center of the lens have an equidistant projection related to the pixel-angle map. A projection map relates distance in the image to a zenith angle and can be described by Equation 17,

$$D = P_d \times \theta, \quad (17)$$

where D is the distance from the center of the image (in pixels), θ is the zenith angle of the incident light for an upward-viewing fisheye lens, and P_d is a factor that relates the two. This projection must be known in order to rotate pixels between reference frames and to properly compare all-sky images to polarized radiative transfer models. Figure 25 represents the equidistant projection map for the Nikon cameras.

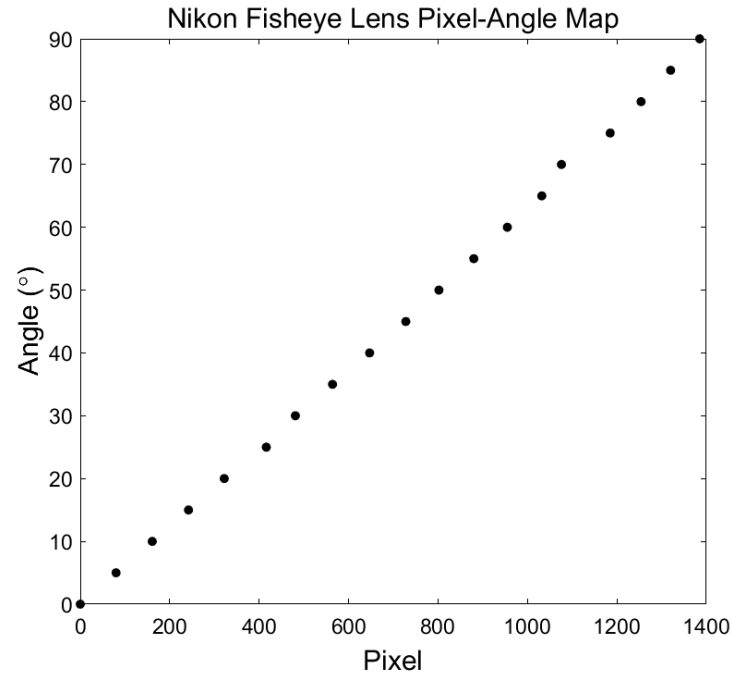


Figure 24. Pixel-angle map (from the center point of the lens) for a Sigma 8-mm, f/3.5 fisheye lens coupled with a linear polarizer to a Nikon D700 camera.

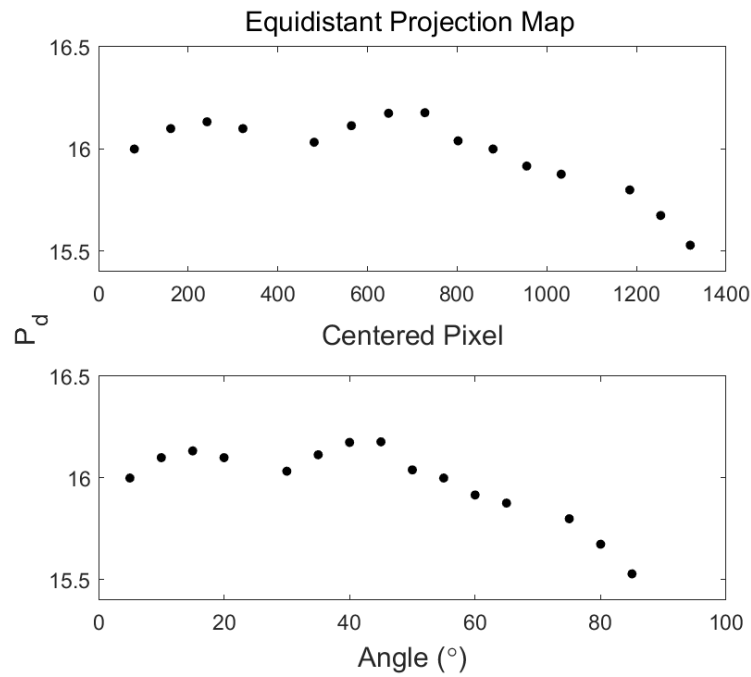


Figure 25. Equidistant map from the center point of the lens (Top) and angle (Bottom) for a Sigma 8-mm, f/3.5 fisheye lens coupled with a linear polarizer to a Nikon D700 camera.

Radiometric Calibration

Dark Noise. For each measurement, dark noise was subtracted from the measured image. For the Nikon cameras, dark noise was found to depend on both the ISO and exposure settings, as observed in Figure 26. Generally, a low dark noise corresponded to low ISO settings. As the exposure time increased, the dark noise became slightly lower. The dark noise for each measurement was adjusted based on the ISO and exposure time. The measured values were converted to double-precision format scaled from 0 to 1, which is why decimal values are observed for digital number.

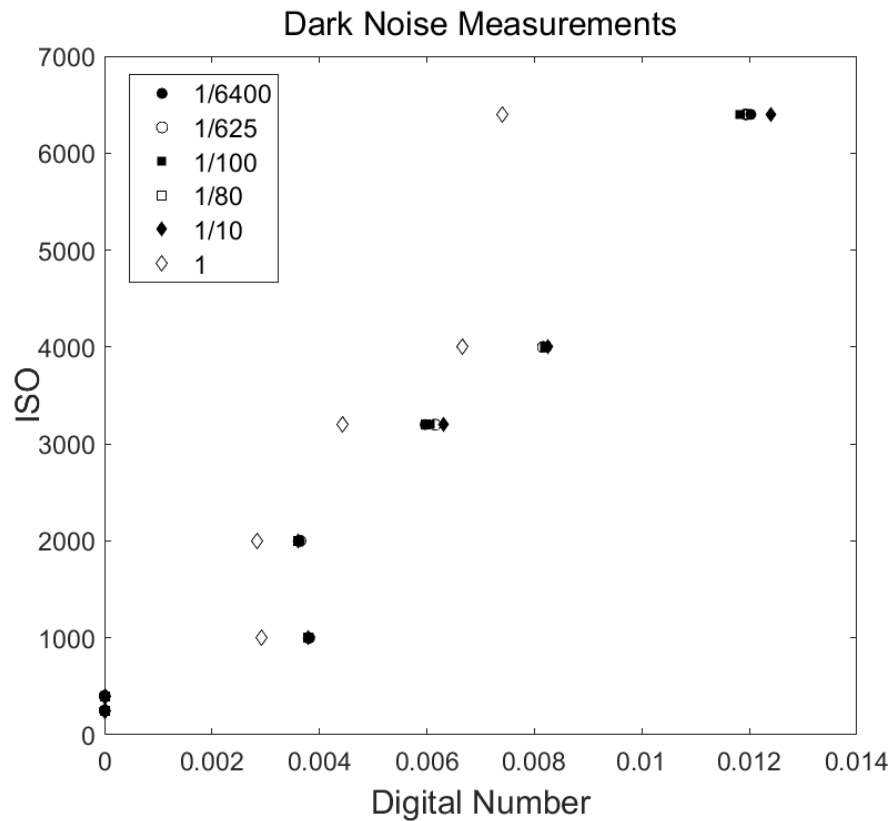


Figure 26. Dark noise measurements from the 0° Nikon camera (the angle corresponds to the internal reference polarizer orientation). Similar measurements were observed with the 60° and 120° cameras. The legend corresponds to the exposure time in seconds.

Digital Number Relationship to Radiance (Linear Radiance Calibration). A linear equation relating digital number (DN) to radiance was experimentally determined for each camera using a calibrated integrating sphere as a uniform and unpolarized source. This calibration was applied to all measurements after subtracting the dark noise. To create the linear calibration curve relating radiance and DN, the variable attenuator (VA) of the integrating sphere was adjusted from closed to open in equally spaced intervals. This corresponded to a change in the output current of the integrating sphere's calibrated optical detector. For each adjustment, the detected output current was then converted to a band-integrated radiance using Equation 18,

$$L_{VA} = \frac{\text{amps}}{\text{amps_factor}} \cdot L_{VA=0}, \quad (18)$$

where L_{VA} is the measured band-integrated radiance corresponding to a specific variable attenuator position, and “amps” is the detector current measured at that specific position. The “amps_factor” relates to the detector current measured when the integrating sphere was calibrated at the factory and the VA was fully open ($VA = 0$). $L_{VA=0}$ is the band-integrated radiance found when relating the spectral distribution of the camera to the radiance of the calibrated sphere. $L_{VA=0}$ was found by multiplying the RSR of the camera by the spectral radiance curve of the integrating sphere (Figure 27). The band-integrated radiance ($L_{VA=0}$) in units of ($\text{mW cm}^{-2} \text{sr}^{-1}$) was then found for each red, green, and blue channel to be 1.08, 0.76, and 0.62, respectively (for the wide-open variable aperture on the integrating sphere) by using the “trapz” function in Matlab to estimate the numerical spectral integral for each channel. Once found, the parameters $L_{VA=0}$ and “amps_factor” are assumed to not change within approximately 100 hours of calibration. The

“amps_factor” and spectral output can be found in the integrating sphere’s calibration report.

As the variable attenuator was changed for each measurement, an image of the integrating sphere’s output was recorded and the band-integrated radiance (L_{VA}) for that specific VA position was calculated with the center pixels in the measured image averaged (~ 400 pixels). Figure 28 shows a series of images as the position of the variable attenuator was changed. A linear fit between the calculated band-integrated radiances and corresponding measured digital numbers (DNs), at different variable attenuator positions was then found for each spectral channel of each camera. An example linear fit for the blue channel of the 0° -polarizer camera is shown in Figure 29. The y-axis corresponds to the calculated band-integrated radiance in units of $\text{mW}/(\text{cm}^2 \text{ sr})$ and the x-axis corresponds to the averaged DNs recorded in each measurement. Calibration coefficients (gain and offset) for all cameras and filters are given in Table 3. By using the slope (gain) and intercept (offset) from the linear fits, the measured DN was then converted to band-integrated radiance. Figure 30 shows the averaged DNs of each measurement and the calculated band-integrated radiance in units of $\text{mW}/(\text{cm}^2 \text{ sr})$ for each camera and filter as the variable attenuator was adjusted. Each camera was aligned so that the fisheye lens was centered with respect to the integrating sphere’s port.

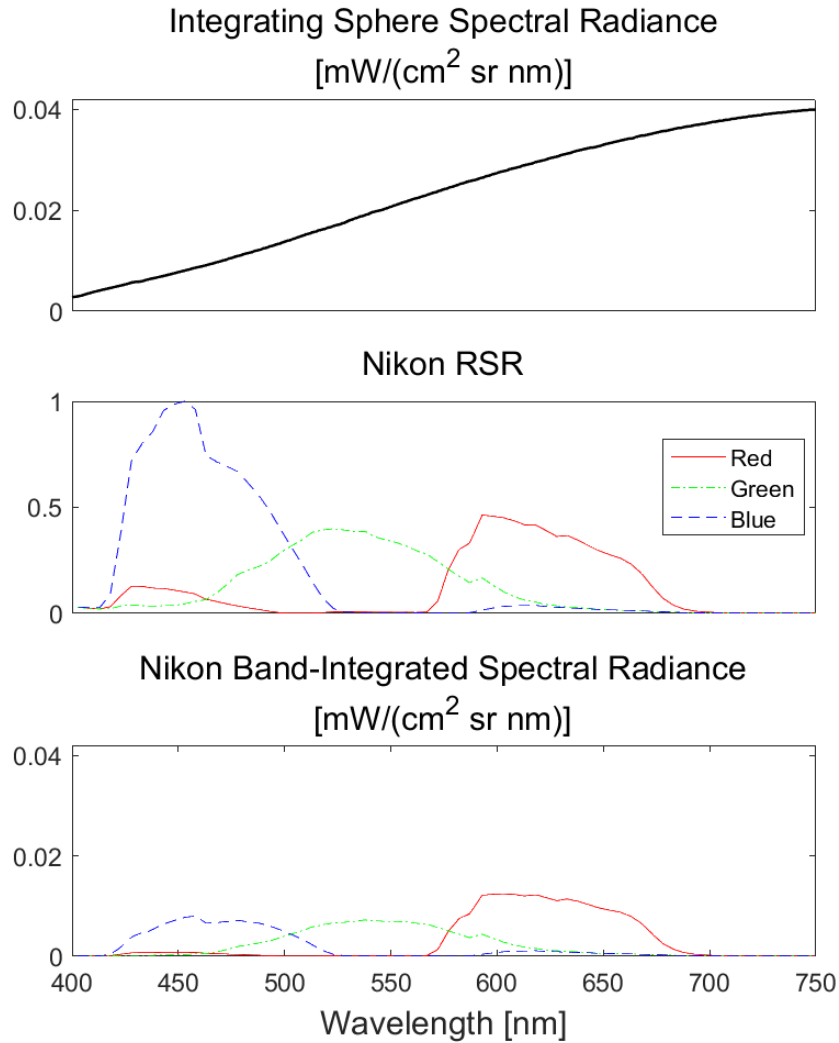


Figure 27. The spectral radiance from the integrating sphere (Top) was multiplied by the Nikon RSR curves for each channel (Middle) to find the spectral band-integrated radiance for the red, green, and blue channels of the Nikon camera in units of $\text{mW}/(\text{cm}^2 \text{ sr nm})$ (Bottom). The band-integrated radiance ($L_{VA=0}$) in units of $\text{mW}/(\text{cm}^2 \text{ sr})$ was then found for each red, green, and blue channel to be 1.08, 0.76, and 0.62, respectively, by using the “trapz” function in Matlab to estimate the numerical spectral integral. The variable attenuator of the integrating sphere was fully opened at this measurement.

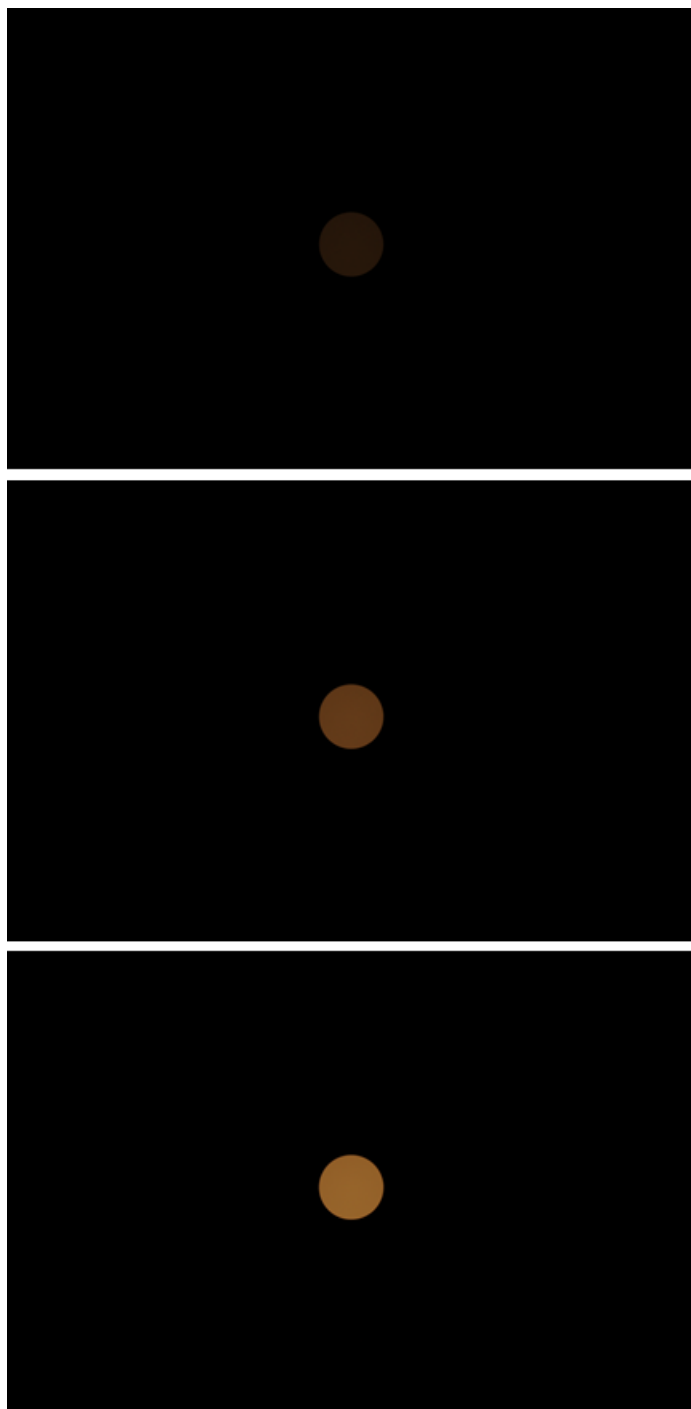


Figure 28. Nikon images as the variable attenuator adjusted the integrating sphere's output current. To create a linear calibration, the center digital numbers (~ 400 pixels) were averaged and plotted against the band-integrated radiance in units of $\text{mW}/(\text{cm}^2 \text{ sr})$, calculated using Equation 18.

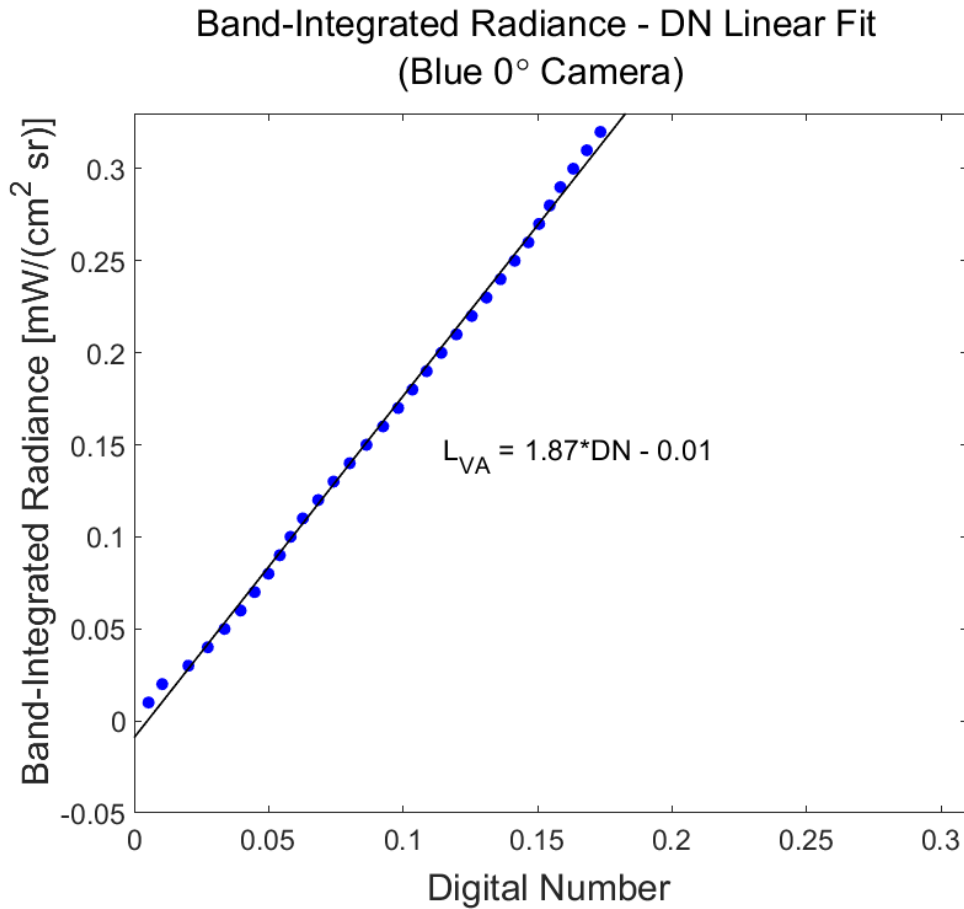


Figure 29. Radiometric linear calibration curve for the blue channel, 0° camera. A linear fit was applied to find the gain and offset coefficients, which were then used to relate the measured DN to band-integrated radiance (L). This process was done for each camera and each filter. The calibration coefficients can be found in Table 3.

	Gain			Offset		
	Red	Green	Blue	Red	Green	Blue
0° Camera	0.8442	0.9398	1.8698	-0.0139	-0.0019	-0.0101
60° Camera	0.8407	0.9191	1.7966	-0.0171	-0.0036	-0.0120
120° Camera	0.7787	0.8206	1.5726	-0.0253	-0.0061	-0.0101

Table 3. Nikon all-sky polarimeter radiometric calibration coefficients for each camera and filter.

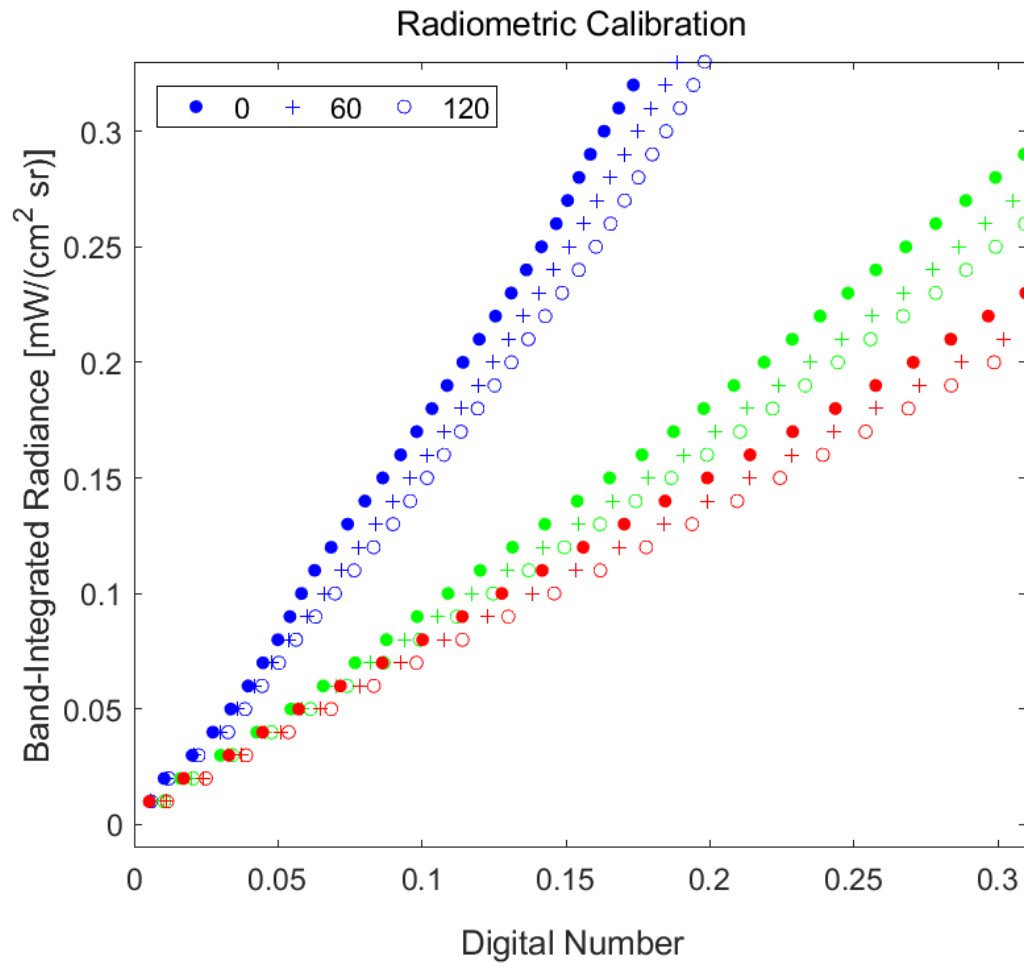


Figure 30. Linear radiometric calibration data for the red, green, and blue channels of the cameras and fisheye lenses with 0°, 60°, and 120° polarizers.

Polarimetric Calibration

Polarizer Alignment. At the back of each fisheye lens in the three-camera all-sky polarimeters, a high-quality 2.54-cm square linear polarizer was mounted with its transmission axis orientated at 0° , 60° , or 120° relative to a reference axis (the 0° polarizer was referenced perpendicular to the top-to-bottom axis of the camera). The polarizers were models: PC-100X100-VIS-0 and PC-100X100-VIS-60, from Meadowlark Optics and were precision cut at the factory to achieve the specified orientation. On the back side of the fisheye lens, there were four set screws used to hold the retaining plate surrounding the polarizers in place. A 10-cm-diameter rotating analyzing polarizer (Meadowlark Optics model: PC-109MM-VIS), placed between the camera being measured and the integrating sphere, was used to verify the position of each polarizer. In Figure 31, the polarization orientations for each camera correspond to maximum radiance values at 180° (0°), 60° , and 120° , respectively, verifying the polarizers within each camera were correctly aligned. The measured values in Figure 31 correspond to the radiance of the averaged center pixels in each measurement.

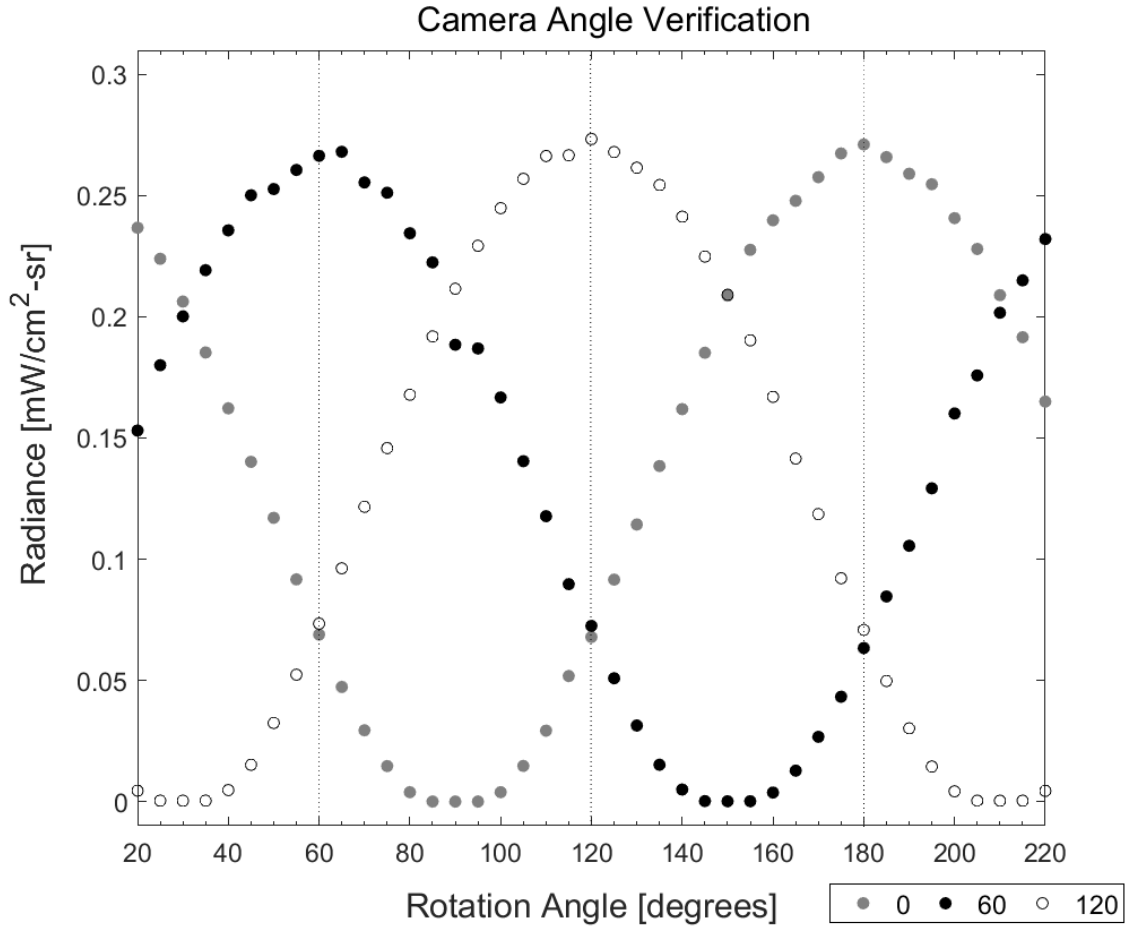


Figure 31. Verification of the polarization orientation aligned in each camera.

Fisheye Calibration Methodology. A polarimetric calibration of the fisheye lens (for each pixel) was completed in piecewise angle steps following the methods presented in [41], which describes the calibration process for the LCVR polarimeter. For the fisheye calibration, the integrating sphere and analyzing polarizer were placed on an optical breadboard that could be rotated about a fixed-axis as shown in Figure 32. To build the calibrated piecewise image, the integrating sphere and analyzing polarizer were rotated about the center of the fisheye lens, while the polarimeter was physically rotated

0°, 45°, 90°, and 135° between each measurement. Unlike this single-camera polarimeter, the three-camera all-sky polarimeters each contained three separate cameras; therefore, the calibration process involved calibrating each individual camera separately to build the fisheye system matrix. A system matrix corresponding to each measurement location was created by recording images with each camera as the analyzing polarizer was rotated 0°, 60° and 120°, respectively. In Table 4, the camera and rotation angles are given for each cell of the individual system matrix. The measurements recorded with each camera correspond to a specific row in the raw system matrix.

0° Camera, 0° Rot. Angle	0° Camera, 60° Rot. Angle	0° Camera, 120° Rot. Angle
60° Camera, 0° Rot. Angle	60° Camera, 60° Rot. Angle	60° Camera, 120° Rot. Angle
120° Camera, 0° Rot. Angle	120° Camera, 60° Rot. Angle	120° Camera, 120° Rot. Angle

Table 4. System matrix configuration. Each camera was used to build a separate row of the system matrix as the analyzing polarimeter was rotated 0°, 60°, 120°, respectively. The matrix cells describe the camera and rotation angle of the analyzing polarizer. A full fisheye system matrix was created by piecing together each individual system matrix and interpolating between the data points.

It was important to align each camera with respect to the same position so that the overall field of view was consistent between each measurement. In post-processing, calibrated slices were created over the entire fisheye field of view. An interpolation was then applied between the slices to build the system Mueller matrix of the polarimeter, which is shown in Figure 33. The Stokes vectors corresponding to 0°, 60°, and 120° are given in Table 5. Since we only had three linear polarizers, our system matrix was a 3×3 linear Mueller matrix, which did not include circular polarization. The maximum linear error of the Nikon system was observed to be $\pm 4\%$. The maximum error of the LCVR

system was $\pm 1.1\%$ [41]. The larger error associated with the Nikon all-sky polarimeter most likely comes from the alignment during calibration.

Stokes Parameters at Specific Polarization Angles		
0°	60°	120°
1	1	1
1	-0.5	-0.5
0	0.866	-0.866

Table 5. Stokes parameters corresponding to 0° , 60° , and 120° polarizers.

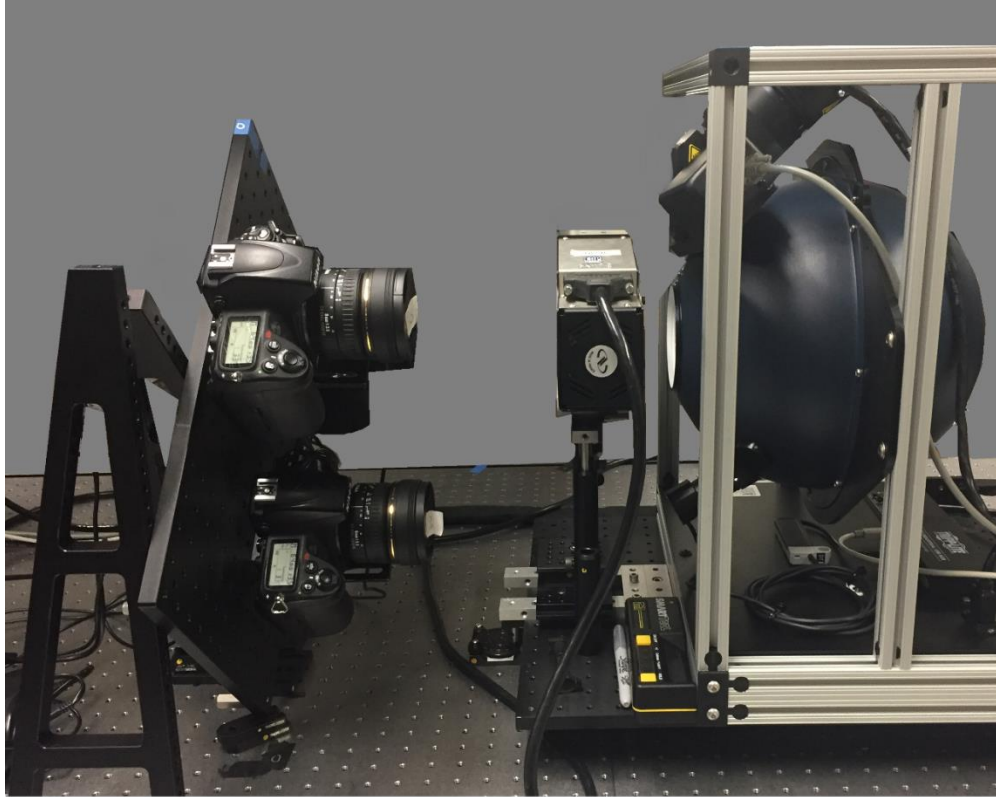


Figure 32. Polarimetric calibration setup. The three-camera Nikon all-sky polarimeter is on the left, with the integrating sphere on the right. The analyzing polarizer is located between the integrating sphere and the camera system.

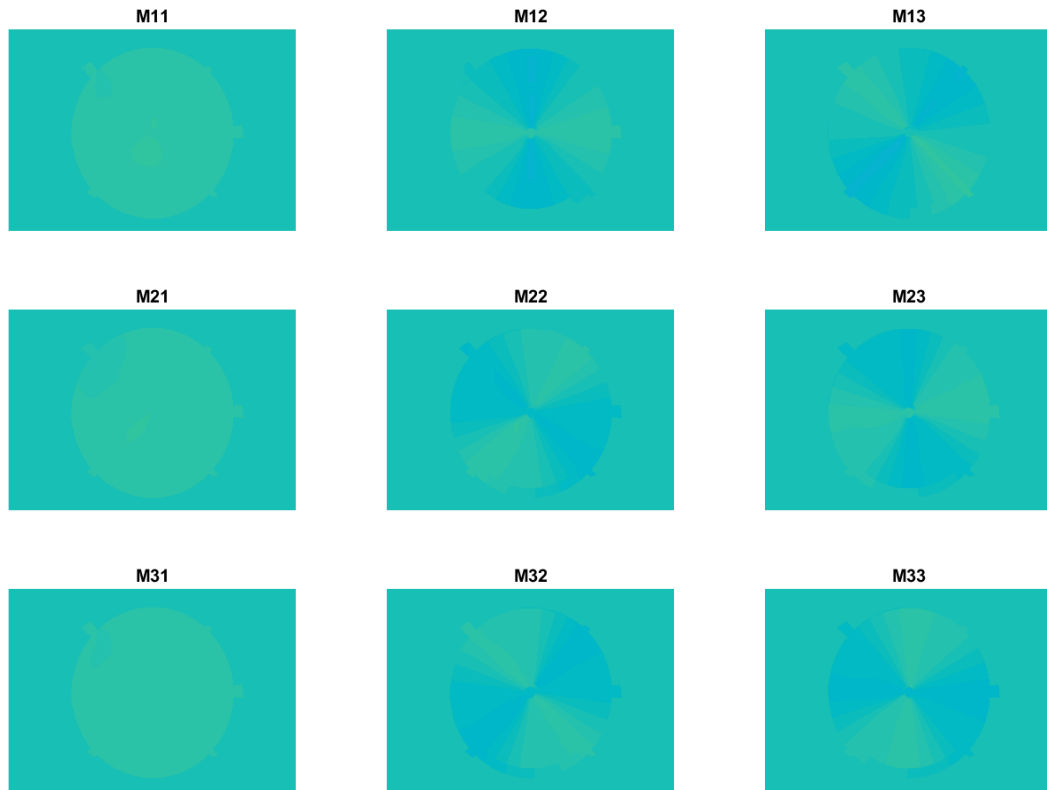


Figure 33. System Mueller matrix for the visible three-camera all-sky polarimeter (each pixel of these images represents the corresponding element of a Mueller matrix unique to that pixel).

Image Alignment

For each measurement, the all-sky systems were leveled so that the focal plane of each camera was approximately perpendicular to the zenith plane. The pixel-to-tilt-angle error associated with the zenith alignment was found to be 10 pixels with an angle uncertainty of 0.01° . The detectors in this system were also spatially registered so that the field of view of the detector elements on each focal plane were well aligned. The images were aligned with respect to two points in the far-field using the Matlab functions “imtranslate” and “imrotate.” In Figure 34, misaligned and aligned examples are shown for the 2017 solar eclipse in Rexburg, Idaho. The DoLP in the aligned image corresponds

to a minimum point at the sun, while the DoLP in the misaligned image has a distribution of skylight polarization at the sun. The misalignment is noticeable in the comparison images I_{00} , I_{60} , and I_{120} .

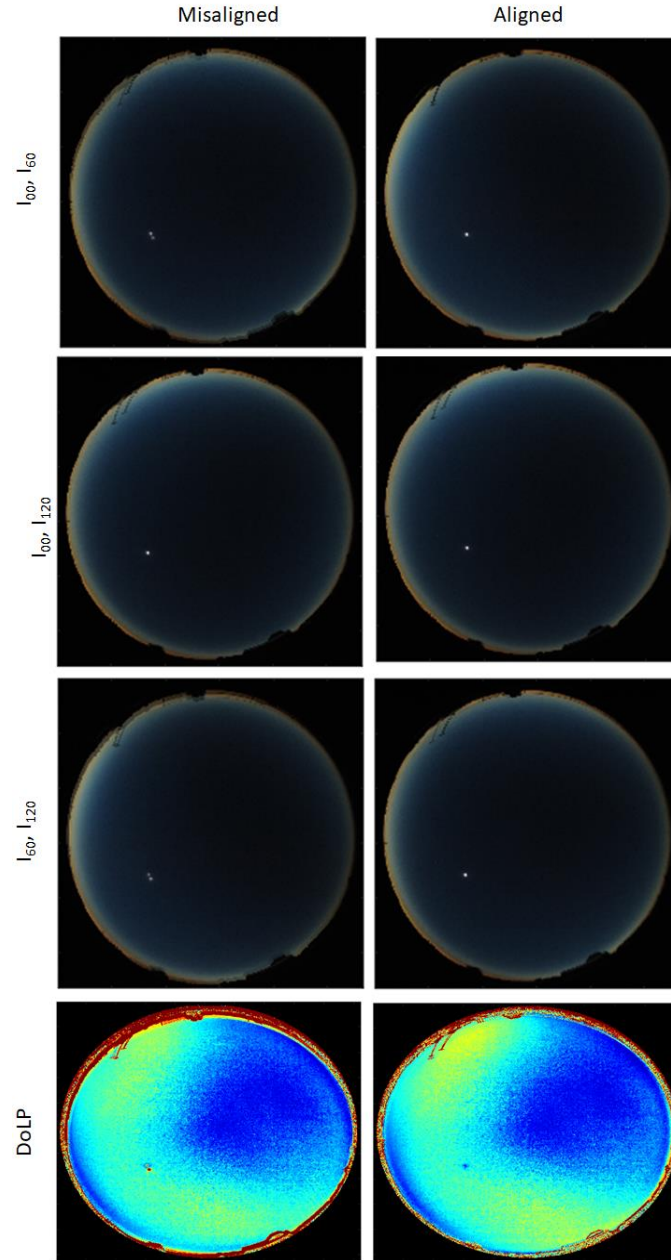


Figure 34. Examples of spatially aligning the images taken with the three cameras. Misalignment images are shown on the left with aligned images on the right. I_{00} , I_{60} represents aligning the image with the 0° reference to the image with the 60° reference.

CHAPTER FOUR

THE VIS-SWIR SPECTRUM OF SKYLIGHT POLARIZATION

Contribution of Authors and Co-Authors

Manuscript Sections in Chapter 4

Author: Laura M. Eshelman

Contributions: Modeled skylight polarization in the SWIR with aerosol and surface parameters from a clear and smoky day, performed validation measurements with a SWIR imaging polarimeter, performed data analysis, generated figures, and wrote the manuscript that has now been published in *Applied Optics*.

Co-Author: Joseph A. Shaw

Contributions: Obtained funding, managed project, guided research project overall, provided important insight and overview in the analysis of the measurements, aided in the preparation of the manuscript and figures.

Manuscript Information

Laura M. Eshelman and Joseph A. Shaw

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Visible-to-Shortwave Infrared Validation Measurements

As part of my dissertation, I used a SWIR rotating imaging polarimeter to validate the successive-orders-of-scattering radiative transfer simulations presented in my M. S. Thesis. The skylight DoLP was previously shown to vary primarily with aerosol optical depth and underlying surface reflectance for visible-to-near-infrared (VNIR) wavelengths [45, 44] and in my M. S. Thesis, I extended this study to $2.5\text{ }\mu\text{m}$ [53]. The modeled DoLP depended heavily on the aerosol size distribution at SWIR wavelengths and on the aerosol optical depth at VNIR wavelengths. Once the aerosol optical depth became greater than the Rayleigh optical depth, the predicted polarization deviated significantly from Rayleigh scattering theory. The SWIR polarization spectrum generally decreased at wavelengths beyond $1\text{ }\mu\text{m}$ at a rate dependent on the aerosol size distribution.

In this chapter, validation measurements of SWIR skylight polarization in a $1.5 - 1.8\text{ }\mu\text{m}$ band are shown. These measurements were made on clean and smoky days. In both simulations and measurements, the SWIR skylight polarization was greater in the smoky atmosphere than in the clean atmosphere. This work provides critical information regarding the nature of how skylight polarization changes from the VIS-to-SWIR and helped in analyzing the solar eclipse and cloud phase measurements. The remaining sections of this chapter contain direct excerpts taken from our paper published in *Applied Optics* [52].

Model Overview

We modeled the VIS-SWIR skylight polarization spectrum using Lenoble's SOS radiative transfer model [51] embedded within a Matlab code [46]. The model was modified to include spectral extrapolations of aerosol properties retrieved from an AERONET (Aerosol Robotic Network) ground-based solar radiometer [106,107] and surface reflectance spectra from a handheld spectrometer. Our measurements were taken in Bozeman, Montana, USA (45.67 °N, -111.05 °W; elevation 1507 m).

To retrieve the VIS-SWIR skylight polarization, the model computed a Stokes vector $\vec{S}$ containing the four Stokes parameters S_0 , S_1 , S_2 , and S_3 , where S_0 is the total radiance, S_1 is the difference between the 0° and 90° linearly polarized components, S_2 is the difference between the +45° and -45° linearly polarized components, and S_3 is the difference between right- and left-hand circularly polarized components (in our calculations, 0° represented a linear polarizer orientated orthogonal to the scattering plane defined by the incident and scattered rays). The Stokes parameters were used to calculate the degree of linear polarization.

Our modeled results showed that spectral patterns of skylight polarization existed from the VIS to the SWIR and that SWIR polarization was greater for smoky air than for clean air. The latter was a surprising result and in this chapter we describe the use of a SWIR imaging polarimeter (described in Chapter 3.1) to measure skylight polarization in a single band from 1.5 to 1.8 μm to validate our modeling efforts. We measured clean-sky polarization on 28 April 2015 at 16:18 (UTC) and a sky containing thick wildfire smoke on 20 August 2015 at 19:57 (UTC) in Bozeman, Montana.

Aerosol Characterization. For comparing measured and modeled results, the maximum DoLP for each day was calculated using the AERONET-retrieved aerosol optical depth, size distribution, and refractive index as inputs to the SOS model. The aerosol optical depths, volume size distributions, and indices of refraction from 28 April 2015 and 20 August 2015 are shown in Figures 35-37, respectively. Thick wildfire smoke was observed on 20 August 2015, resulting in the large AOD shown in Figure 35.

Surface Reflectance Characterization. The surface was modeled with a green grass reflectance spectrum measured with a hand-held spectrometer (Figure 38). The adequacy of this simple approach is indicated by the excellent agreement between this spectrum and the average reflectance measured in the MODIS 1.628 - 1.652 μm band, also plotted on Figure 38 for 28 April, 29 April, 1 August, 19 August, and 20 August (all dates in the year 2015). The MODIS surface reflectance measurements were spatially averaged over a radius of 50 km from our measurement site.

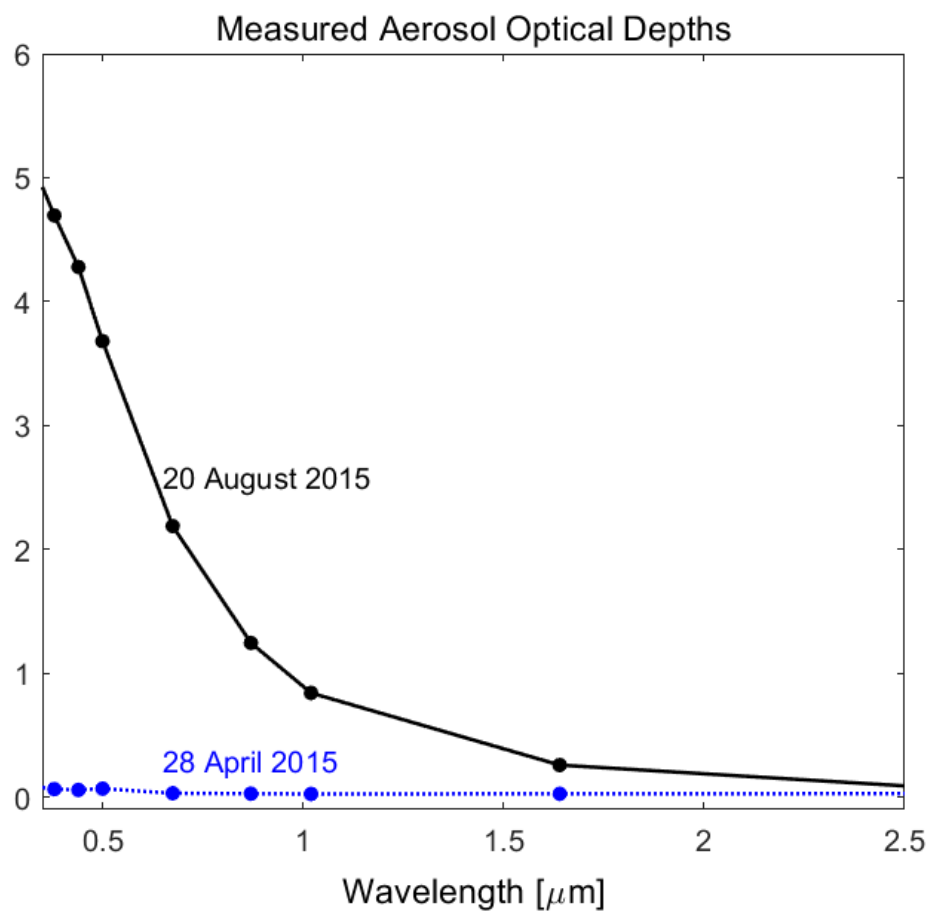


Figure 35. Interpolated and extrapolated AERONET aerosol optical depths (AOD) for a clean atmosphere on 28 April 2015 and a smoky atmosphere on 20 August 2015.

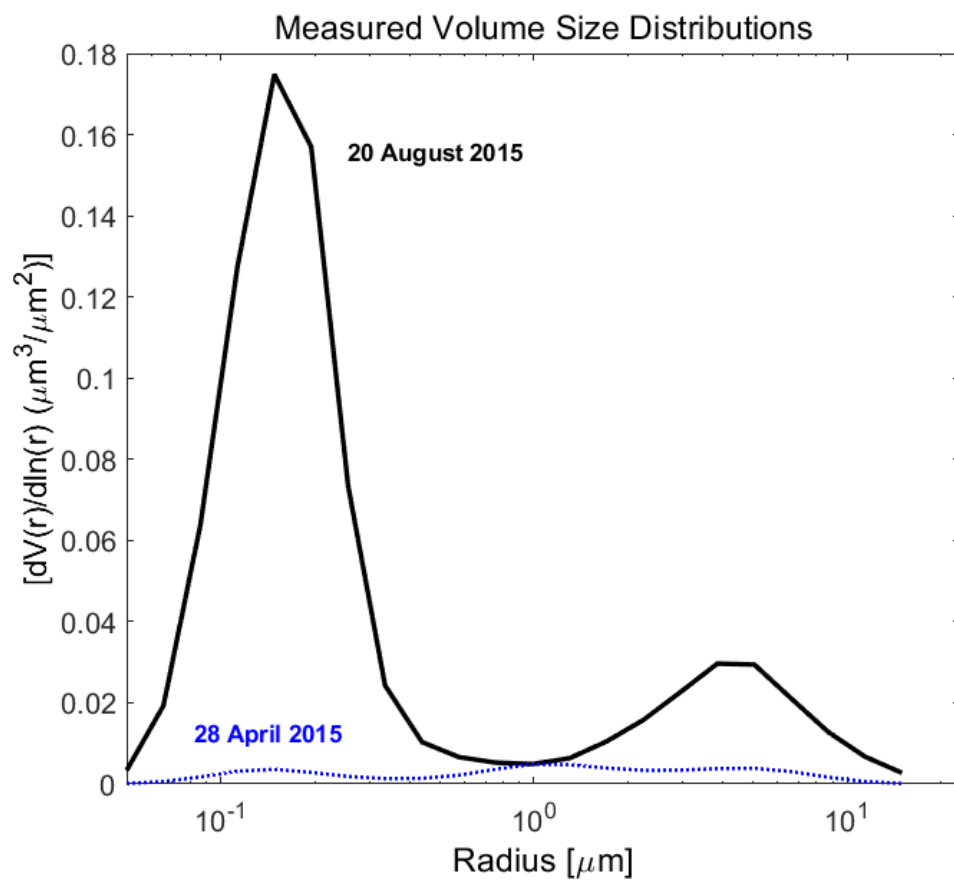


Figure 36. AERONET-retrieved aerosol volume size distributions ($dV(r)/d\ln(r)$ $[\mu\text{m}^3/\mu\text{m}^2]$) for a clean atmosphere on 28 April 2015 and a smoky atmosphere on 20 August 2015.

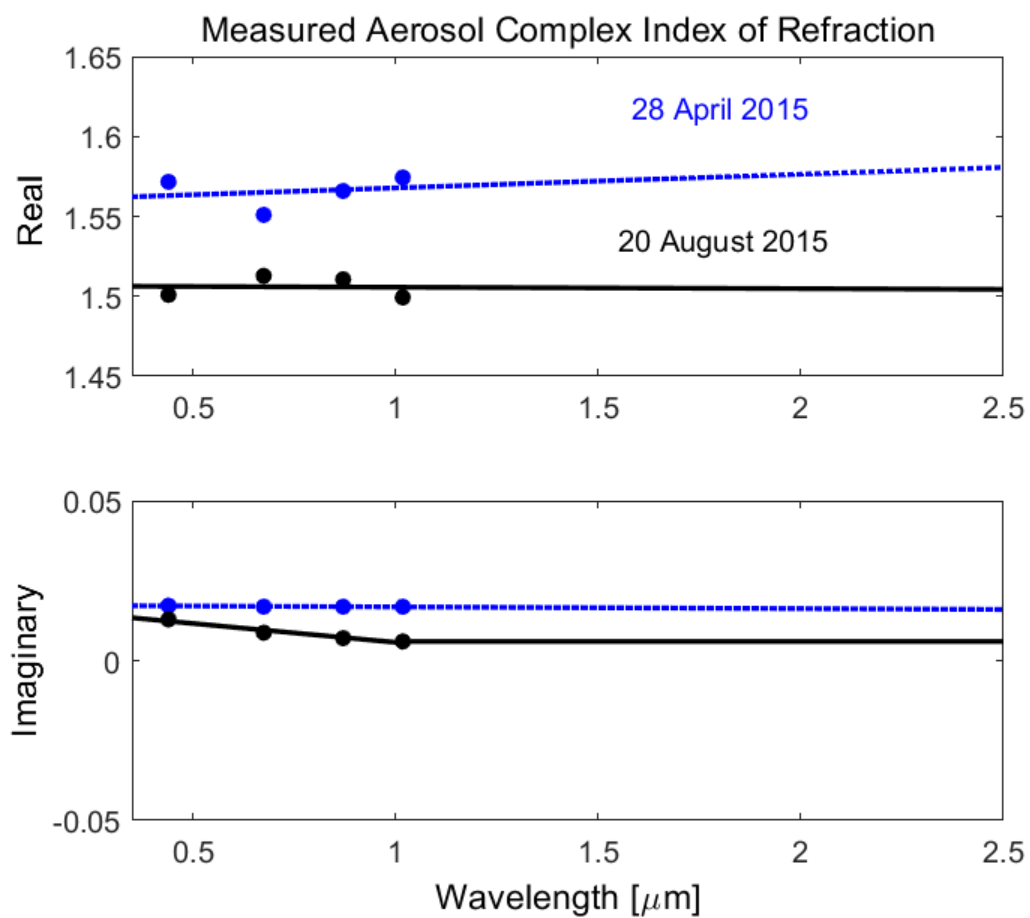


Figure 37. Interpolated AERONET complex indices of refraction for a clean atmosphere on 28 April 2015 and a smoky atmosphere on 20 August 2015.

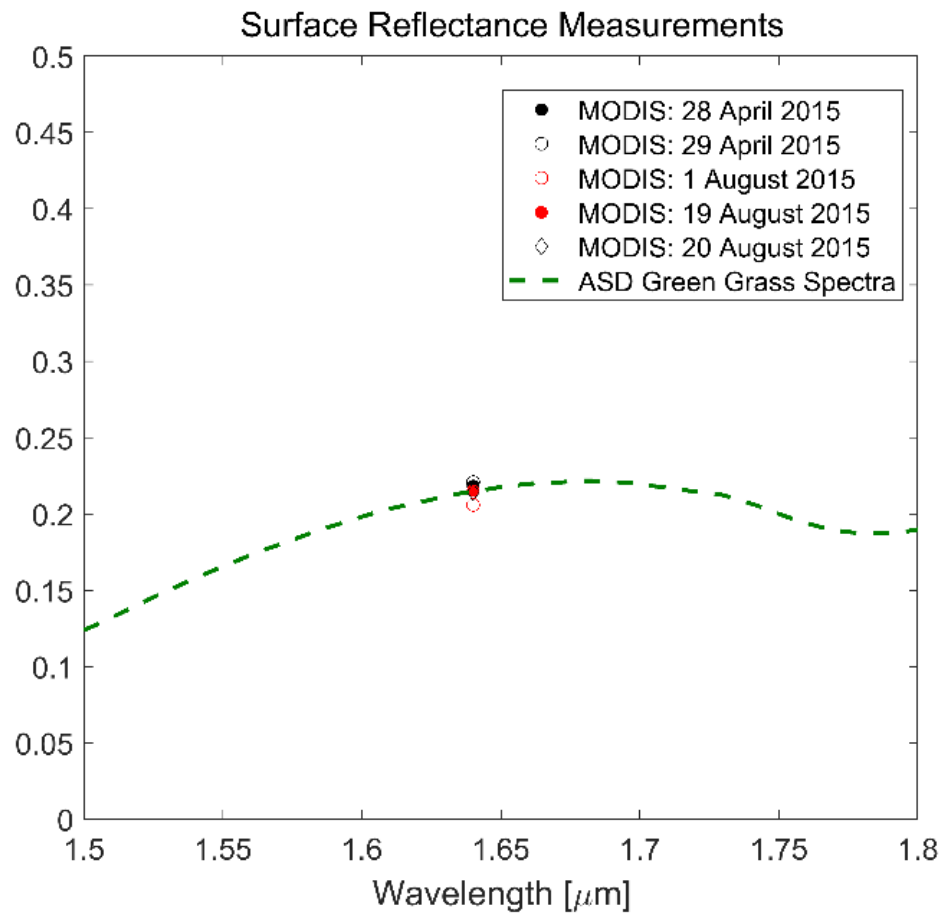


Figure 38. Measured green grass spectra and MODIS-retrieved surface reflectance in the 1.628 - 1.652 μm band and spatially averaged over a circle of 50-km radius centered on our observation site.

Measured Skylight Polarization with Simulated Fisheye Models

The field of view of the SWIR polarimeter was 9.1° wide by 7.3° high. The instrument could not be pointed at elevation angles larger than approximately 30° because of the liquid-nitrogen-cooled focal plane array. This meant that we could not make measurements exactly at the point of maximum DoLP. Therefore, to align our measurement locations with the simulated results, we used an image of a grid pattern to map the angles of each pixel in the SWIR polarimetric images. The reference horizon was taken as the roofline in the reference images. To aid visualization and interpretation of our measured and simulated results, we also created simulated fisheye all-sky images of the polarization across the entire sky, averaged over the $1.5 - 1.8 \mu\text{m}$ SWIR polarimeter band. The top of each fisheye image represents north and the right side represents east.

Clear-Sky Measurement. On 28 April 2015 we measured skylight polarization on a mostly clear day with a few small clouds near the horizon. A reference image of our measurement is given in Figure 39, where the instrument was looking Northeast with the sun behind and to the right of the imager. The solar azimuth and elevation angles were 114° and 41° , respectively. The maximum band of polarization was centered at an azimuth angle of 294° , approximately 49° above the horizon. In the simulation, the clean-air maximum DoLP varied between 17% and 27% across the validation measurement band of $1.5 - 1.8 \mu\text{m}$. The simulated band-averaged DoLP in a $1.5 - 1.8 \mu\text{m}$ rectangular bandpass was 21% (Figure 40).



Figure 39. Reference image of our measurement on 28 April 2015. The solar azimuth and elevation angles were 114° and 41° , respectively.

The top image of Figure 41 is the actual SWIR DoLP measurement, which shows the skylight DoLP decreasing top-down from 13% to 8%. The polarimeter's field of view covered elevation angles from 9.1° to 1.8° with respect to the horizon, and in between these angles the DoLP was modeled to be approximately 8%. The modeled data averaged over $1.5 - 1.8 \mu\text{m}$ are represented in the bottom fisheye image of Figure 40. The red arrow indicates the viewing direction of the polarimeter.

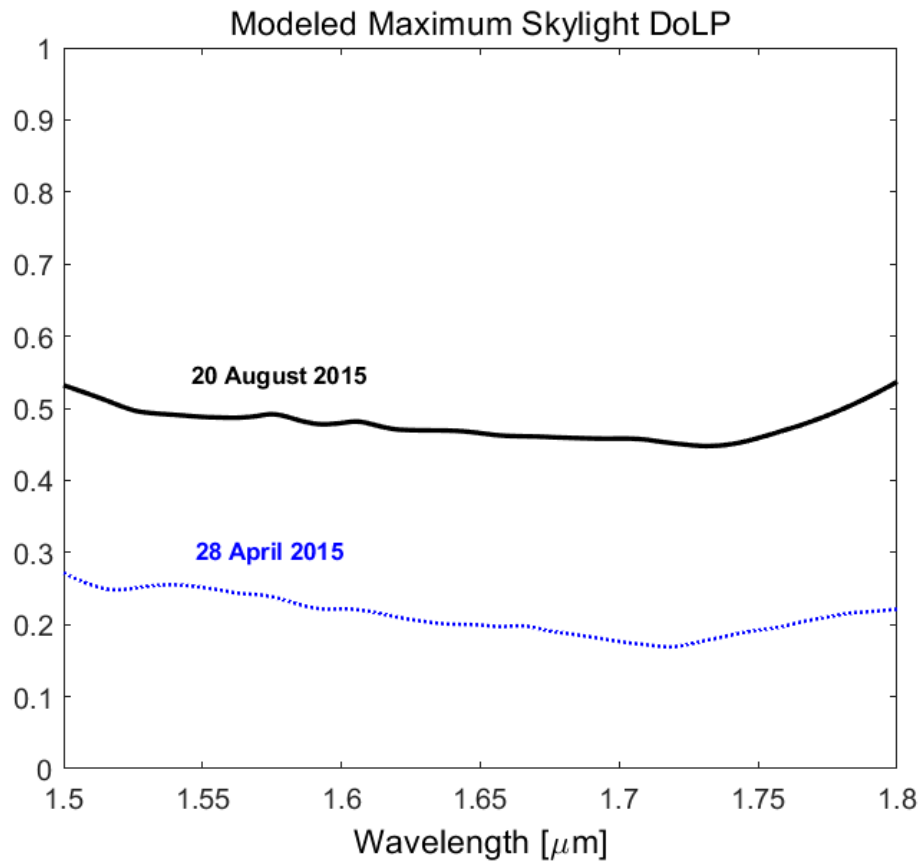


Figure 40. SOS modeled maximum skylight polarization across the 1.5 - 1.8 μm validation band for a clean-sky on 28 April 2015 and a sky containing thick wildfire smoke on 20 August 2015.

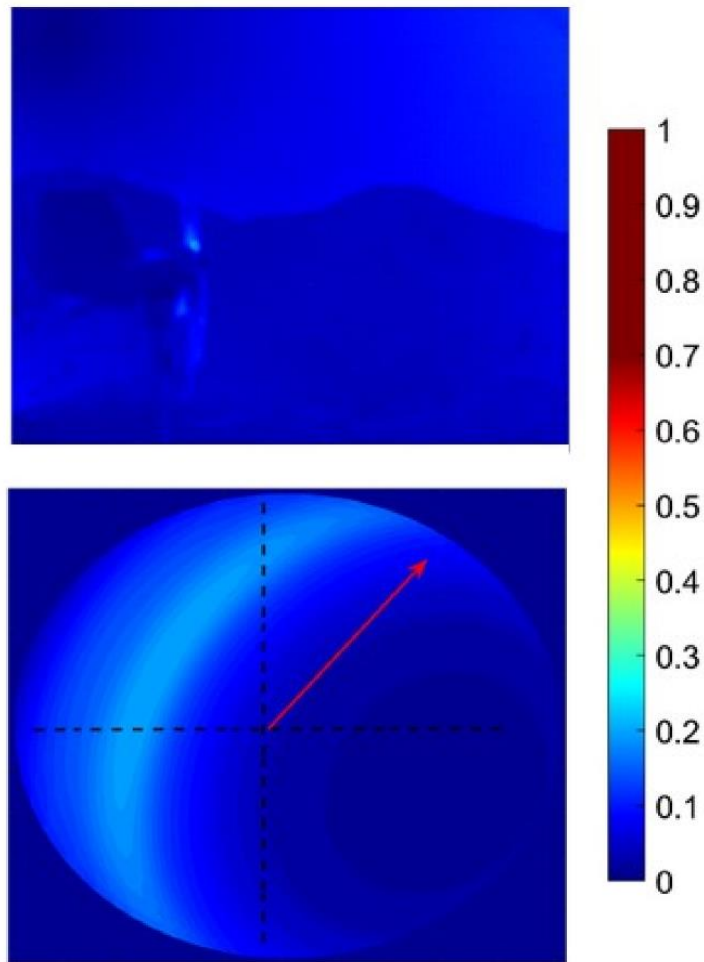


Figure 41. (Top) Measured DoLP on 28 April 2015. Skylight polarization was measured to decrease top-down from 13% to 8%. (Bottom) Fisheye modeled maximum DoLP dependence averaged over 1.5 to 1.8 μm . The red arrow indicates the polarimeter pointing direction, where the modeled maximum polarization was 8%.

Smoky Sky Measurement. A sky filled with thick wildfire smoke was measured on 20 August 2015. A reference image of our measurement is shown in Figure 42. The polarimeter was directed Northwest with the sun to the left of the imager. The solar azimuth and elevation angles were 193° and 56° , respectively. The maximum band of polarization was centered at an azimuth angle of 13° , approximately 34° from the horizon. Across the spectral band of $1.5 - 1.8 \mu\text{m}$ where our SWIR validation measurements were made, the maximum DoLP for the smoky atmosphere simulations varied between 45% and 54%, with a band-average value of 48% (Figure 40).



Figure 42. Reference image of our measurement on 20 August 2015. The solar azimuth and elevation angles were 193° and 56° , respectively.

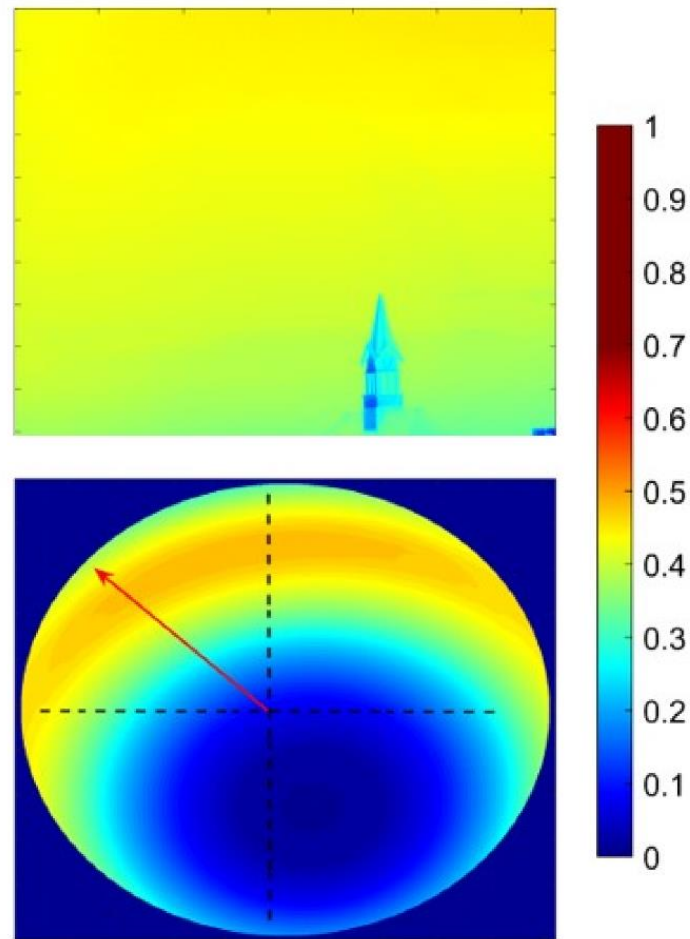


Figure 43. (Top) Measured DoLP on 20 August 2015. Skylight DoLP was measured to decrease top-down from 45% to 36%. (Bottom) Simulated all-sky fisheye DoLP image averaged over 1.5 - 1.8 μm . Across the band of maximum polarization, the modeled DoLP ranged from 45% to 54%, with a band-average value of 48%. The red arrow indicates the portion of sky the polarimeter was viewing, in which the modeled polarization was 46-44%.

In the top image of Figure 43, the skylight DoLP was observed to decrease top-down from 45% to 36%, approximately 22° to 15° above the horizon. The modeled DoLP was 46-44% between these angles. A simulated all-sky fisheye DoLP image averaged over the 1.5 - 1.8 μm band is shown in the bottom of Figure 43. The red arrow indicates the viewing direction of the polarimeter. For both clean and smoky situations, our measurements and simulations agreed to within the measurement and modeling uncertainties, indicating that as the aerosol optical depth becomes greater than the Rayleigh optical depth, changes in the SWIR skylight polarization are driven primarily by the aerosol volume size distribution and scattering cross-sections. Because of this, the smoky atmosphere was found to have higher DoLP than a clean atmosphere in both simulation and measurement.

Conclusions

This chapter presented measurements that validated modeling results shown in my M.S. thesis, which provided insight into how aerosol and surface parameters separately and together control skylight polarization in the VIS to SWIR spectral range (0.35 to 2.5 μm). Once the aerosol optical depth became greater than the Rayleigh optical depth, the degree of linear polarization in the SWIR spectrum was found to depend strongly on the aerosol size distribution, whereas the VIS polarization depended most strongly on the aerosol optical depth. Most of the particles on the smoke-filled day were found within the accumulation mode of the volume distribution plot (Figure 36), indicating that these smaller and more polarizing particles had a much smaller scattering cross section than the predominantly larger particles found on the clear day. The surface reflectance spectrum

influenced skylight polarization in the same manner from the VIS through the SWIR, with a higher surface reflectance decreasing the sky polarization. Measurements of skylight polarization made on a clean day and a smoky day were used to verify that the degree of linear polarization in the SWIR spectrum was indeed higher for smoky air than for clean air. These simulations and measurements are essential to the work done at Montana State University and provide new and unexpected insights into how smoke affects sky polarization at SWIR wavelengths.

Smoke alters skylight polarization in the shortwave infrared completely opposite of how one would expect and this has impacts on various other studies. For example, in our cloud phase study, we have observed the spectral dependence of S_I to flip if the atmosphere contains smoke. By simulating SWIR polarization, we have been able to develop a physics-based understanding of skylight polarization in the shortwave infrared. This is needed in order to accurately understand measurements that were taken in a variety of environmental conditions.

CHAPTER FIVE

SOLAR ECLIPSE MEASUREMENTS

A total solar eclipse is an extraordinary event where the moon passes between the sun and the Earth, completely blocking the sun for a short period of time. The moon casts a complete shadow called the umbra, surrounded by a partial shadow called the penumbra. Observers within the umbra observe a total eclipse, while observers within the penumbra observe a partial eclipse. Measuring skylight polarization during an eclipse is interesting because the residual skylight during totality is a combination of multiple scattering within the umbra and single scattering from outside the umbra near the horizon. The usual daytime sky polarization pattern, on the other hand, arises from single scattering and is only modestly modified by multiple scattering.

In the visible spectrum on a cloud-free, non-eclipsed day, a single Rayleigh scattering event theoretically can produce 100% linearly polarized light at angles 90° from the sun, with a polarization vector oriented orthogonal to the scattering plane defined by the incident and scattered rays. The actual degree of polarization is, however, reduced by multiple scattering from atmospheric aerosols [45-49], clouds [25-27, 42, 50], and the underlying surface [11, 43, 44]. Throughout a partial eclipse, atmospheric scattering of light from the unobscured portion of the sun remains the main source of sky polarization as the sky brightness decreases linearly with the percent obscuration (up to $\sim 98\%$). When totality (obscuration 100%) is reached, the sky distribution of color, intensity, and polarization changes quickly and dramatically, leaving the sky brightness similar to

twilight conditions with a solar elevation angle between -5° and -7° , corresponding to solar zenith angles between 95° and 97° (solar zenith angle = $90^\circ - \text{solar elevation angle}$) [56, 58, 108-110]. The brightest skylight during totality occurs in a ring near the horizon, where light is scattered from outside the umbral region. At the zenith, the color of the sky generally shifts to the blue, while the sky near the horizon reddens from the distant scattering. Multiple scattering at totality creates a cylindrical band of maximum polarization positioned symmetrically about the zenith [56, 61-63] and leads to a distribution of neutral points within the umbra [61-63].

On 21 August 2017 we measured skylight polarization during a total solar eclipse in Rexburg, Idaho, using three all-sky polarimetric imagers. All-sky polarization images were recorded using the Nikon and Sony all-sky polarimeters and the LCVR-based all-sky polarimeter. Skylight polarization was measured from sunrise to sunset in blue, green, and red spectral channels by the three-camera systems, and in 10-nm bandwidths centered at 450 nm, 530 nm, and 670 nm by the LCVR system. Immediately before and after totality the maximum sky polarization occurred in its usual pattern, with a band of maximum polarization positioned approximately 90° from the sun. However, during totality skylight polarization became nominally symmetric about the zenith. With the Nikon and Sony systems, this was observed clearly in the blue and green channels and less obviously in the red channel, which had a greatly diminished signal because of weaker scattering.

At and near the observation site we also operated an infrared cloud imager to measure cloud distributions, a hand-held spectrometer to measure surface reflectance, and an AERONET solar radiometer [111] to characterize the atmospheric aerosols. Surface

reflectance was also retrieved from the MODIS satellite instrument to compare with the ASD spectra. This ancillary data set provided a substantial characterization of the conditions in the surrounding atmosphere and on the underlying surfaces. Through the transition phase from partial eclipse to totality, changes in sky brightness and distribution, temperature, and animal behavior were observed. As the percent obscuration increased, the surrounding skylight was observed to decrease as if someone was turning the sun off with a dimming switch. At totality, twilight conditions were observed 360° around us and a decrease in temperature was observed from the start of partial eclipse to totality. Also, as the sky transitioned from light to dark, planets and stars were observed, as was the sun's corona during totality. This chapter describes measurements of all-sky polarization as the sky brightness and polarization distribution changed from daylight to partial eclipse to totality and back. We address the question of how skylight polarization in totality changes based on the position of the umbra. Our 2017 solar eclipse research group is shown in Figure 44.



Figure 44. 2017 solar eclipse research group. Pictured left to right: Joseph Shaw, Glenn Shaw, Martin Tauc, Laura Eshelman, Preston Hooser, Taiga Hashimoto, William Weiss, and Kendra Gillis. Photo provided courtesy of Joseph A. Shaw.

Twilight Measurements

During the total solar eclipse, the sky brightness was expected to change by three to four orders of magnitude (like the transition from daytime to twilight) and it was expected to be similar to twilight conditions with a solar zenith angle between 95° and 97° . To prepare to record well-exposed images during the eclipse, in the months prior to the eclipse we experimentally found correct exposure and ISO settings for each camera as the sky transitioned from day to twilight. Using the model presented by [59], the sky brightness during a solar eclipse from first contact (start of partial eclipse) to fourth

contact (end of partial eclipse) can be predicted if the observed solar irradiance from the day before the eclipse is known. We were able to predict exposure and ISO settings by comparing our twilight measurements, at a known solar irradiance, with the solar eclipse model. Figures 45 and 46 show S_0 , DoLP, and AoP images measured with the visible LCVR-based all-sky polarimeter at 450 nm and 530 nm, respectively, with solar zenith angles ranging between 95° and 97° in Bozeman, Montana on 19 June 2016. In the S_0 image the sky was observed to be brighter in the 450 nm channel, where the DoLP was found to be larger in the 530 nm channel, matching the results in [55]. As the solar zenith angle increased, the DoLP in both channels became smaller and the band of maximum polarization became narrower as the Babinet and Arago neutral points appeared in the AoP image (referenced to the solar principal plane). The neutral points can be observed in the DoLP image as a minimum polarization point (normally zero). In Figures 45 and 46, the neutral points were observed near the horizons in the solar principal plane. The neutral points arise from multiple scattering in the atmosphere creating a polarization component oriented parallel to the scattering plane, which offsets the single-scattered polarization oriented perpendicular to the scattering plane. Neutral points arise when the intensities of the perpendicular and parallel light are equal. At a neutral point, the AoP switches 90° along its solar principal. The switch of AoP at the zenith is a result of the coordinate reference frame and does not represent a neutral point since the DoLP is not zero (or minimal). DoLP and AoP principal plane slices from Figures 45 and 46 are shown in Figures 47 and 48, respectively. In Figure 47, the minimal DoLP values observed near zenith angles of -70° and 70° indicate neutral points that have both a

temporal and spectral dependence. For shorter wavelengths, the neutral points were observed to have greater DoLP values, at positions closer to a zenith angle of zero. The change in AoP (Figure 48) from a constant -90° or 90° (besides at the zenith) is another indication of neutral points.

For comparison with the LCVR-based all-sky polarization measurements at twilight, S_0 , DoLP, and AoP images measured with the three-camera Nikon all-sky polarimeter on 21 August 2017 in Rexburg, Idaho are shown in Figures 49-50 for the red, green, and blue channels, respectively, with solar zenith angles ranging between 95° and 99° . Similar patterns were observed, with the sky brightest in the blue and the DoLP greatest in the red. The neutral points were easier to observe with the three-camera polarimeter, presumably because of the wider filter bandwidths. With both polarimeters, the neutral point positions were observed to depend on wavelength and sun position. As the solar elevation angle decreased, the neutral points shifted toward the zenith (Figure 47). The red channel was observed to start to diminish and become noisy around a solar zenith angle of 97° , which also was found in previous measurements [39, 54, 55].

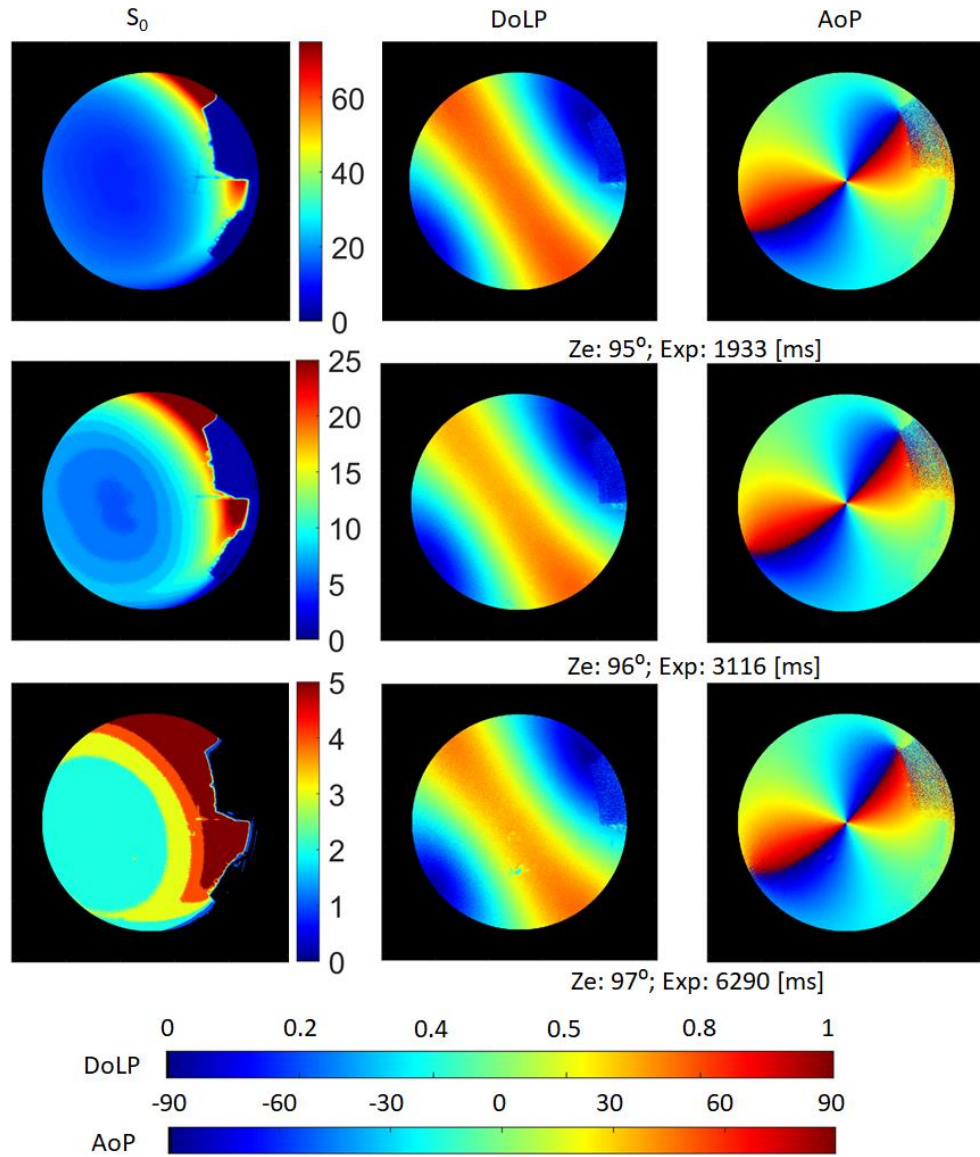


Figure 45. Twilight S_0 , DoLP, and AoP images measured with the LCVR polarimeter (with the sun occulter turned off) at 450 nm on UTC date 20 June 2016 in Bozeman, Montana with solar zenith angles ranging between 95° and 97°, corresponding to UTC times 03:41:46, 03:46:31, and 03:54:01, respectively. S_0 images correspond to radiance with units of $\mu\text{W}/(\text{cm}^2 \text{ sr})$ in a 10-nm-wide spectral band.

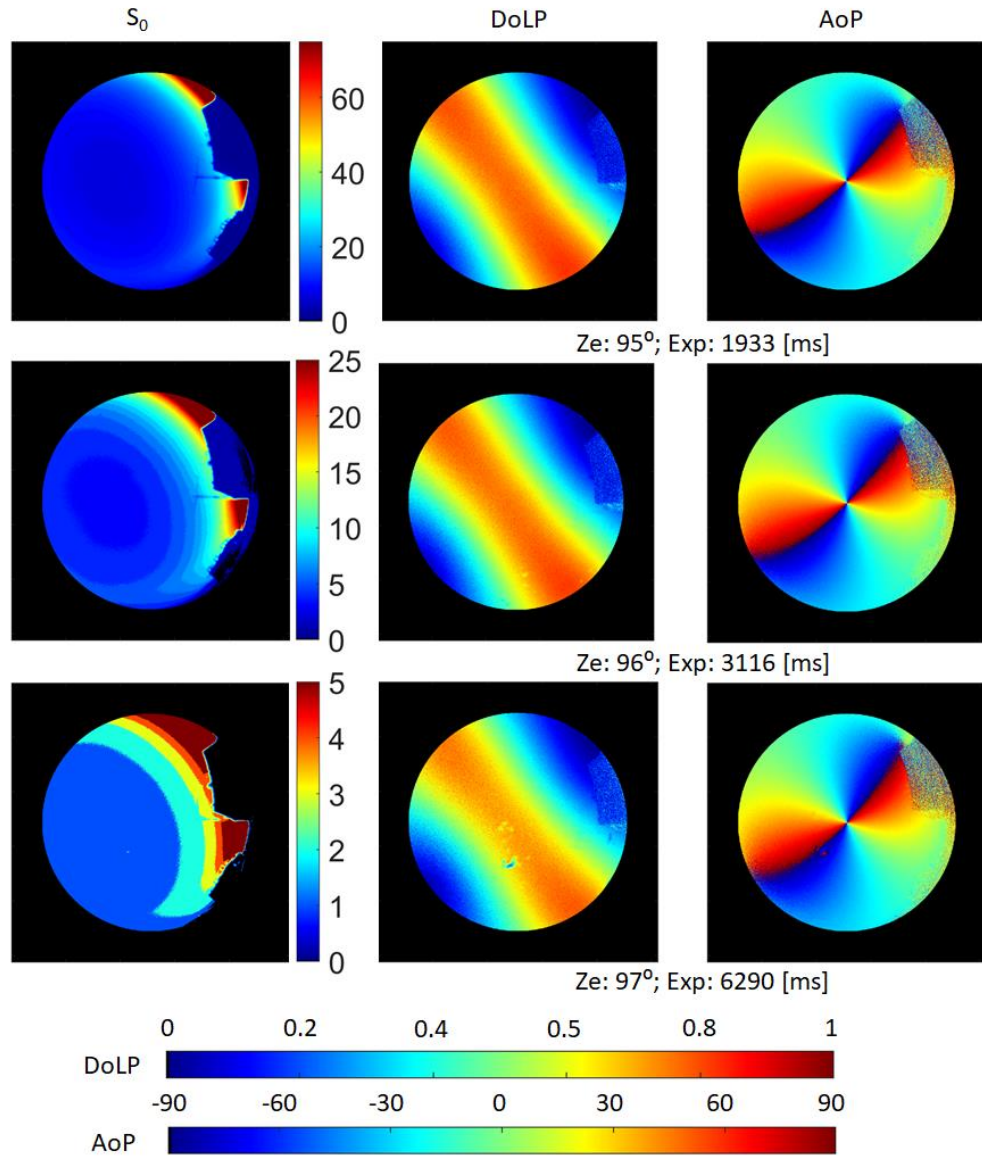


Figure 46. Twilight S_0 , DoLP, and AoP images measured with the LCVR polarimeter (with the sun occulter turned off) at 530 nm on UTC date 20 June 2016 in Bozeman, Montana with solar zenith angles ranging between 95° and 97° corresponding to UTC times 03:41:46, 03:46:31, and 03:54:01, respectively. S_0 images correspond to radiance with units of $\mu\text{W}/(\text{cm}^2 \text{ sr})$ in a 10-nm-wide spectral band.

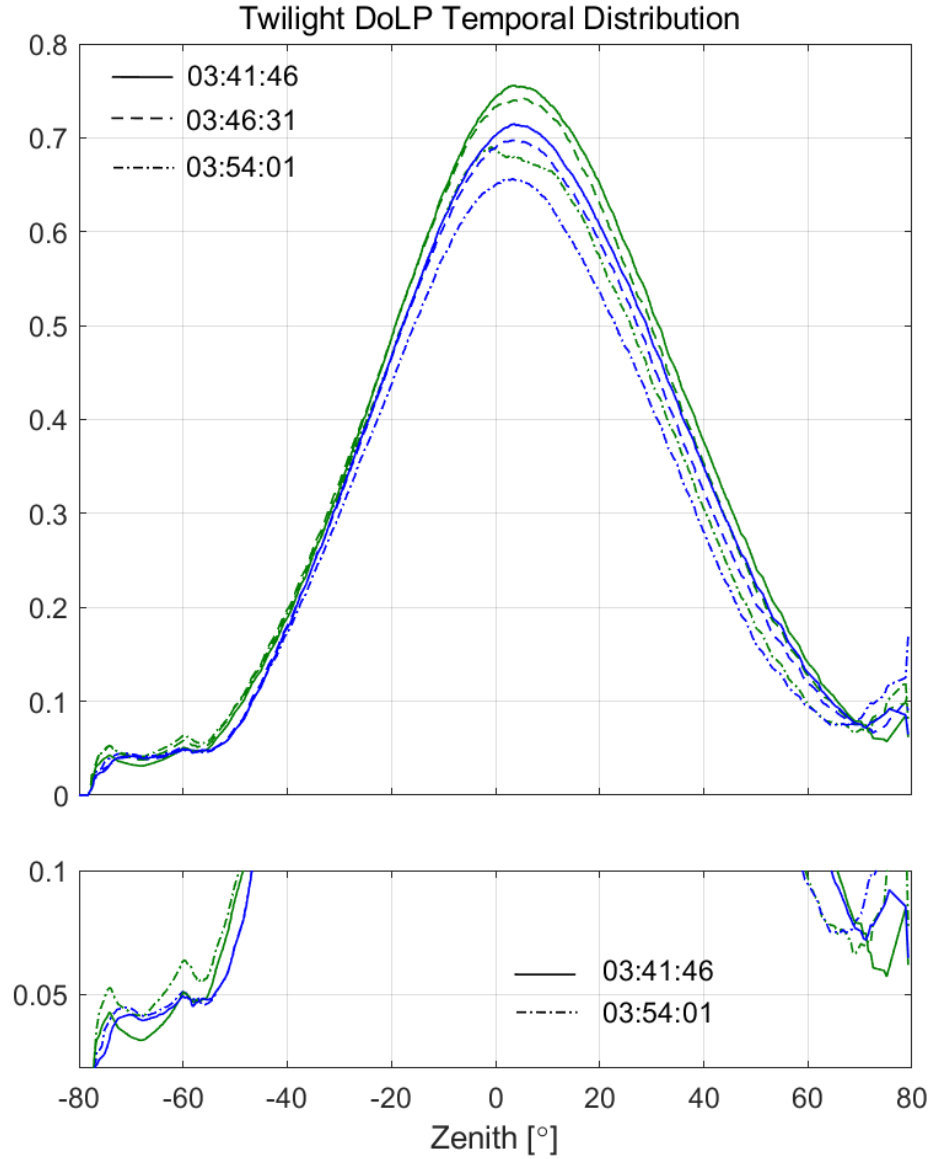


Figure 47. Principal-plane DoLP slices extracted from the blue and green images in Figures 40 and 41, respectively, corresponding to measurement times recorded at 03:41:46 UTC, 03:46:31 UTC, and 03:54:01 UTC in Bozeman, Montana on UTC date 20 June 2016. The bottom image is a zoomed-in version of the near-horizon region of the top image for 03:41:46 UTC and 03:54:01 UTC.

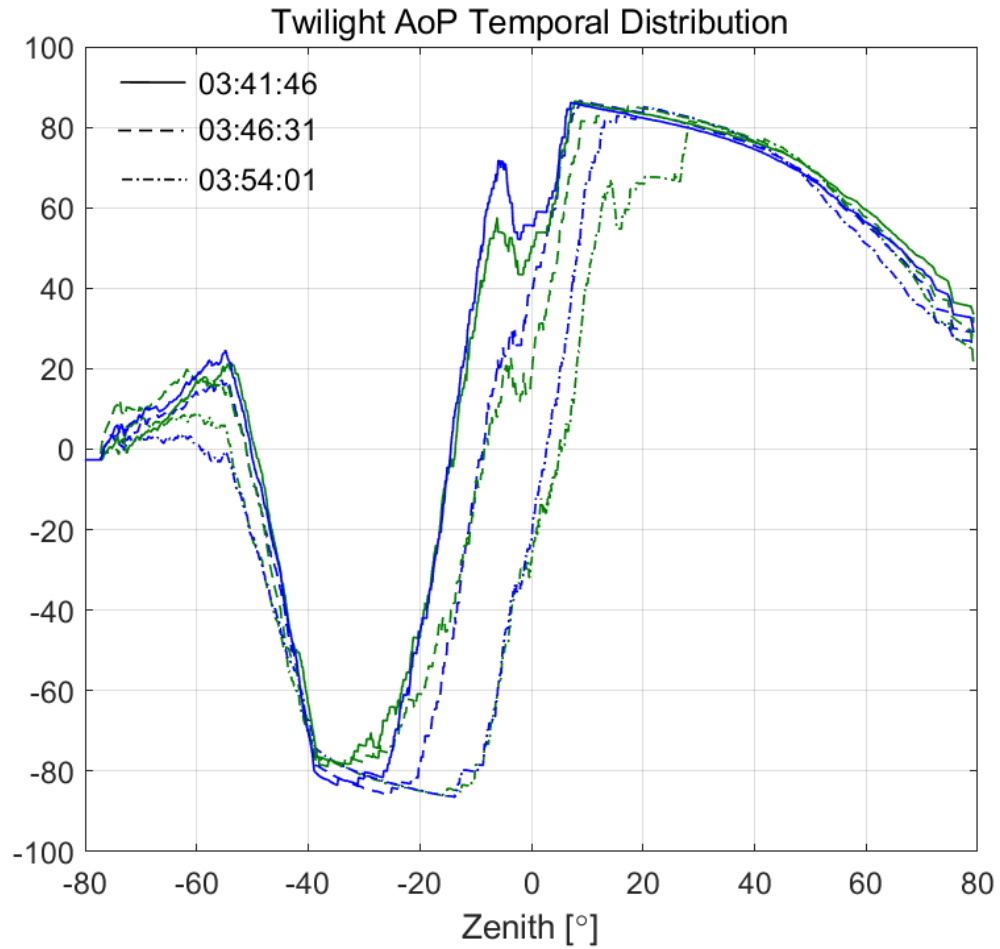


Figure 48. Principal-plane AoP slices extracted from the blue and green images in Figures 40 and 41, respectively, corresponding to measurement times recorded at 03:41:46 UTC, 03:46:31 UTC, and 03:54:01 UTC in Bozeman, Montana on UTC date 20 June 2016. The AoP is shown referenced to the solar principal plane.

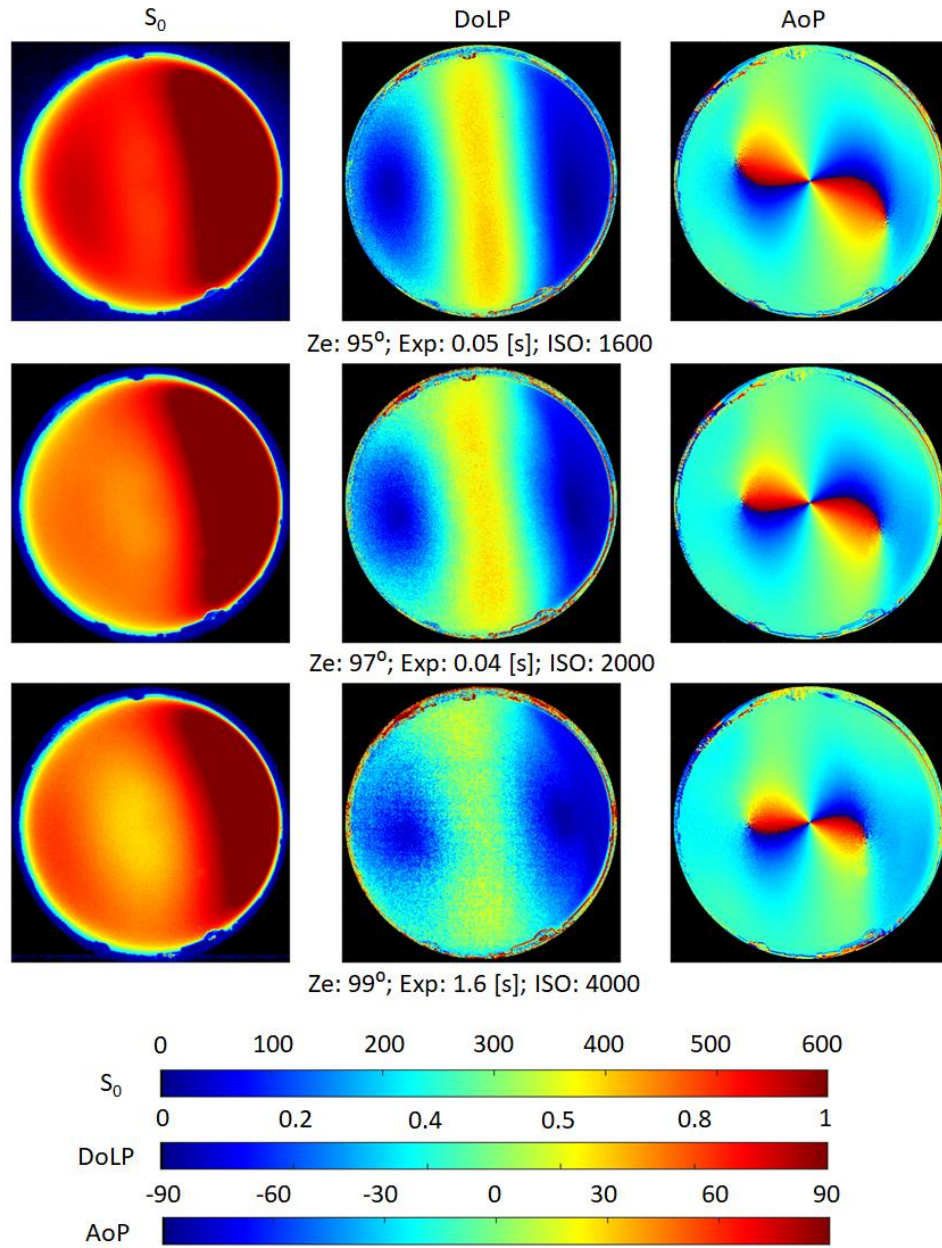


Figure 49. Twilight S_0 , DoLP, and AoP blue channel images measured with the Nikon all-sky polarimeter on UTC date 22 August 2017 in Rexburg, Idaho with solar zenith angles ranging between 95° and 99° , corresponding to measurement times of 02:43:10 UTC, 02:55:49 UTC, and 03:08:08 UTC, respectively. S_0 images correspond to radiance with units of $\text{mW}/(\text{cm}^2 \text{ sr})$ in the blue spectral band shown in Figure 22.

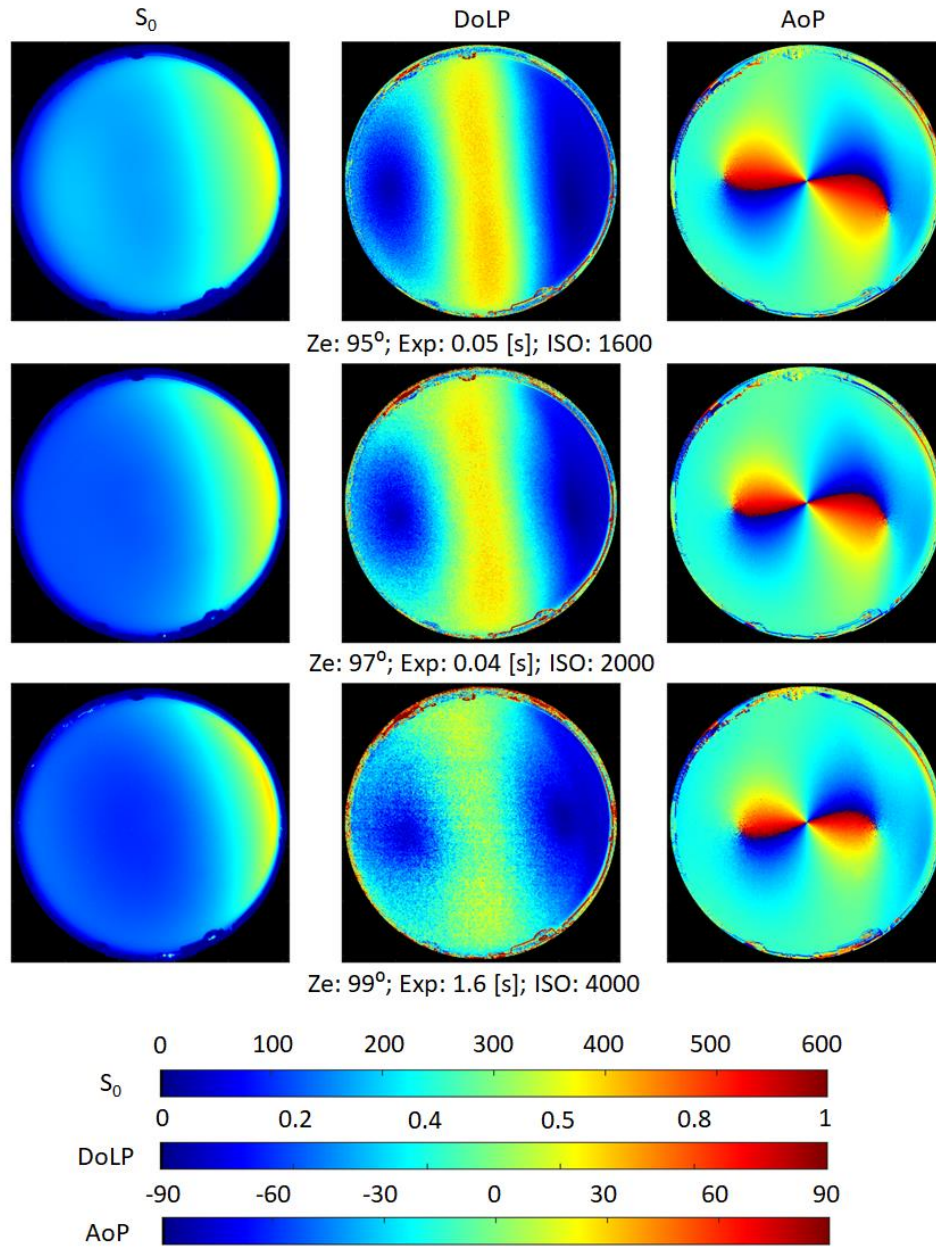


Figure 50. Twilight S_0 , DoLP, and AoP green channel images measured with the Nikon all-sky polarimeter on UTC date 22 August 2017 in Rexburg, Idaho with solar zenith angles ranging between 95° and 99°, corresponding to measurement times of 02:43:10 UTC, 02:55:49 UTC, and 03:08:08 UTC, respectively. S_0 images correspond to radiance with units of mW/(cm² sr) in the green spectral band shown in Figure 22.

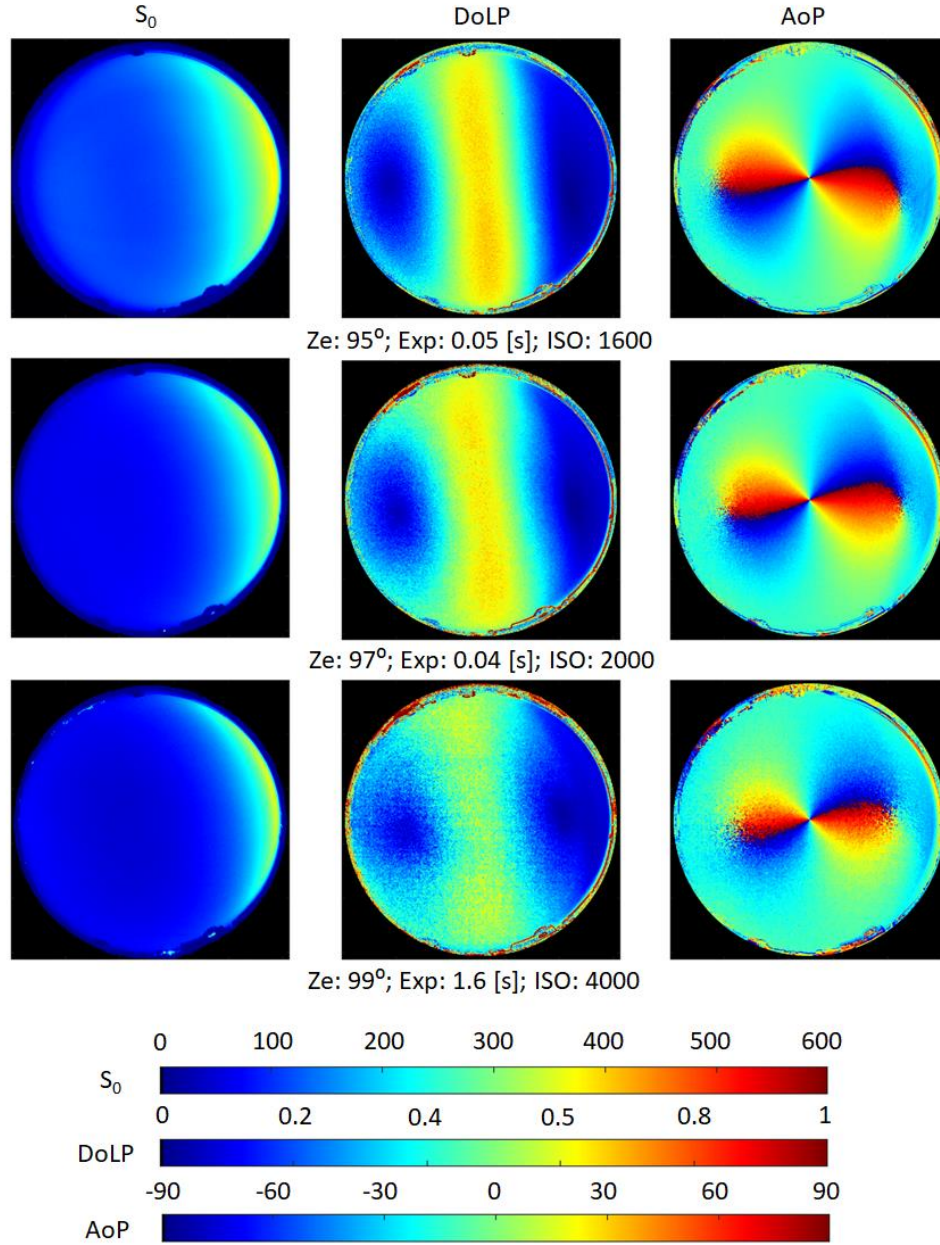


Figure 51. Twilight S_0 , DoLP, and AoP red channel images measured with the Nikon all-sky polarimeter on UTC date 22 August 2017 in Rexburg, Idaho with solar zenith angles ranging between 95° and 99° , corresponding to measurement times of 02:43:10 UTC, 02:55:49 UTC, and 03:08:08 UTC, respectively. S_0 images correspond to radiance with units of $\text{mW}/(\text{cm}^2 \text{ sr})$ in the red spectral band shown in Figure 22.

For the 2017 solar eclipse, totality was expected to last approximately 2 minutes and 17 seconds in Rexburg, Idaho. Therefore, we needed a polarimeter that was capable of acquiring fast spectral and polarimetric images. Narrow 10-nm filter passbands limited the ability of the LCVR-based all-sky polarimeter to take images quickly. For example, in Figures 45 and 46, it took approximately 15-50 seconds (for elevation angles ranging between -5° to -7°) to measure the four images required to build a Stokes vector. Therefore, we developed the two visible three-camera all-sky polarimeters, with polarization filters aligned to 0° , 60° , and 120° , so that fast spectral and polarimetric images could be acquired in low-light twilight and eclipse conditions. Over solar zenith angles of 95° to 99° (in Figures 49-51), the Nikon all-sky polarimeter was able to take well-exposed images using exposure times of 0.05, 0.04, and 1.6 seconds at ISO settings of 1600, 2000, and 4000, respectively.

Eclipse Parameters

We captured all-sky polarization measurements on 21 August 2017 from sunrise to sunset at the BYU Idaho observatory just outside of Rexburg, Idaho. The observation site was 8.8 km from the center line of totality and the duration of totality was approximately 2 minutes and 17 seconds. The path of totality and umbra at mid-totality (17:34:14 UTC = 11:34:14 MDT) are shown in Figure 52. The geographical coordinates of our measurement site and parameters of the solar eclipse are given in Table 6.

Moon/sun size ratio	1.029
Eclipse obscuration	100.0%
Duration of Totality	2 m 17 s
Solar elevation angle at mid-totality	49.4°
Solar azimuth angle at mid-totality	133.0°
Velocity of the umbra	0.839 km/s (1877 mph)
Path width	106 km
Major axis of the elliptical umbra	~130 km
Minor axis of the elliptical umbra	~90 km
Start of partial eclipse (first contact)	16:15:35 (UTC)
Start of total eclipse (second contact)	17:33:06 (UTC)
Maximum eclipse (mid-totality)	17:34:14 (UTC)
End of total eclipse (third contact)	17:35:23 (UTC)
End of partial eclipse (fourth contact)	18:58:11 (UTC)
Latitude of observation site	43°49'46.13" N
Longitude of observation site	111°53'6.14" W
Distance from center line of totality	8.8 km (3.6 miles)

Table 6. Parameters of the Total Solar Eclipse on 21 August 2017 for our observation site near Rexburg, ID.

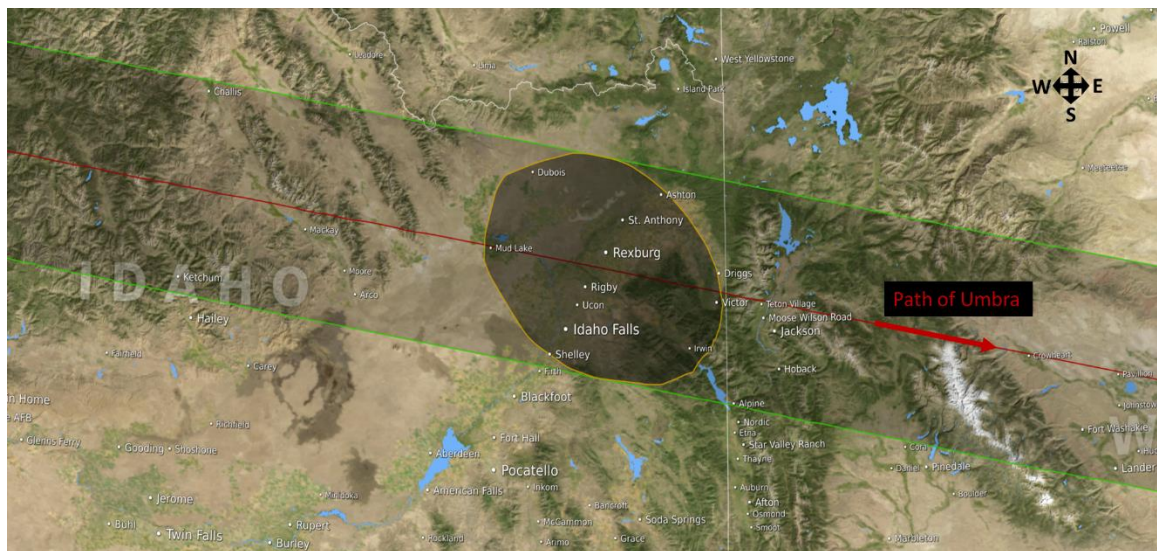


Figure 52. The path of totality and umbra at mid-totality near Rexburg, Idaho (17:34:14 UTC). NASA image.

Nearly ideal atmospheric conditions were present at the time of totality, with the sky free of clouds and with less wildfire smoke relative to the days prior to the eclipse (the average 500-nm aerosol optical depth was 0.14 on 21 August, compared to 0.41 on 19 August and 0.27 on 20 August). Thin cirrus clouds were observed at sunrise, but they diminished before totality and the sky remained quite clear through sunset.

Supporting Instruments

At and near the observation site on 21 August 2017, an infrared cloud imager, a weather station, an ASD hand-held spectrometer, and an AERONET solar radiometer collected data. MODIS surface reflectance was also used to compare with the ASD measurements. These instruments provided us with a good characterization of the conditions of the surrounding atmosphere and underlying surfaces needed to model and analyze our data. Weather station data, including solar irradiance, temperature, wind speed and direction, relative humidity, and barometric pressure measured at Romney Hall on the BYU Idaho campus are shown in Figure 53. Aerosol optical depth measurements taken with the Rexburg AERONET solar radiometer are given in Figure 54 with surface reflectance measurements near the observation site displayed in Figure 55 (Figure 56 shows the locations of each surface reflectance measurement). Figure 57 shows the MODIS-retrieved surface reflectance in comparison with the ASD measurements and Figure 58 shows the radial distributions used to retrieve the surface reflectance from the MODIS datasets. The retrieved MODIS data in the visible spectrum approximately matched the ASD measurements taken of the lava rocks south-east of the observation site

and the alfalfa field near the observation site. As the sky brightness dimmed from first contact to second contact, the solar radiometer algorithm interpreted the reduced sunlight as if more aerosols were present in the atmosphere, resulting in higher aerosol optical depths which corresponded to the solar irradiance decreasing from 570 to approximately 0 W/m² in Figure 53. At totality, the temperature and wind speed were observed to decrease while the relative humidity increased. A portable weather station measured similar temperature and relative humidity at the observation site. In the morning, clouds were observed around the horizon, and at the time of totality no clouds were present, which is confirmed in the infrared cloud images shown in Figures 59 and 60.

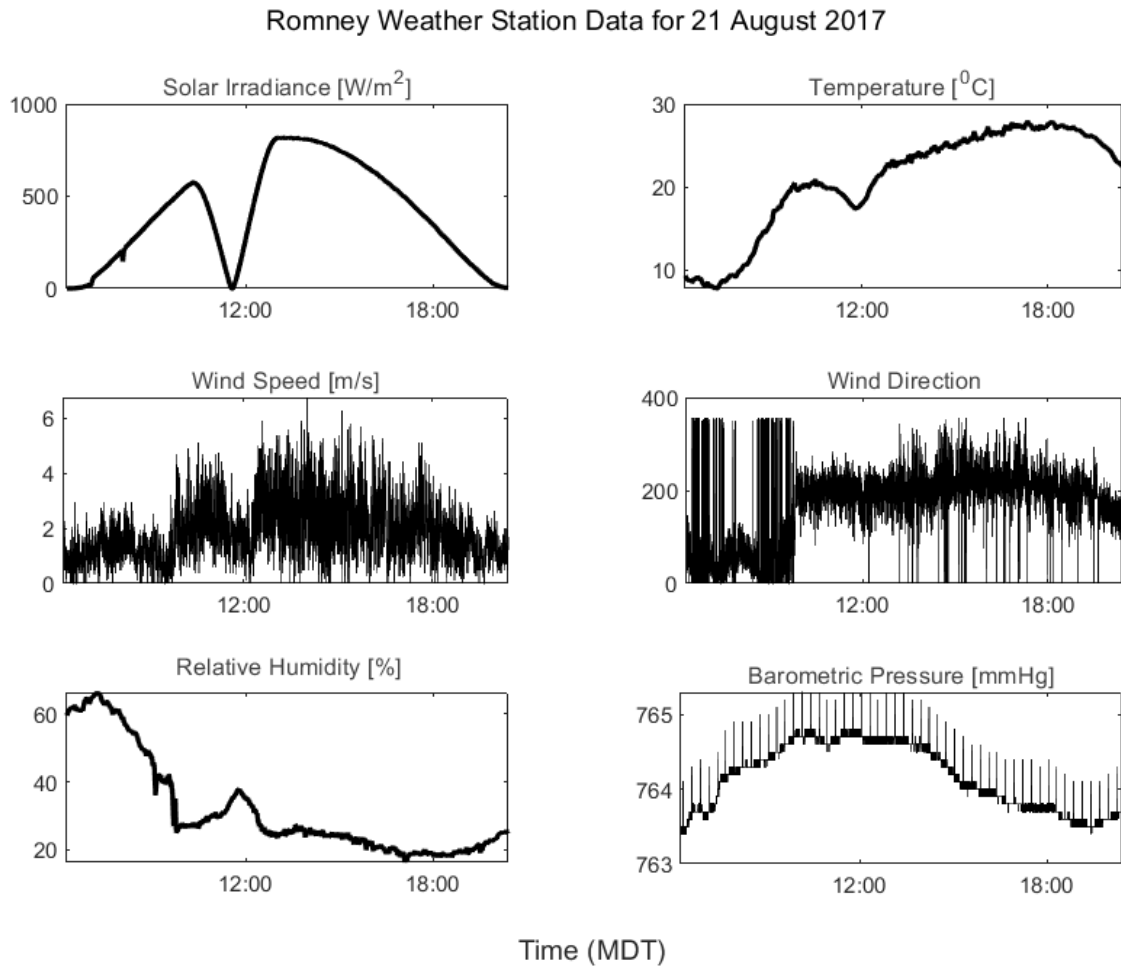


Figure 53. Weather station data taken on the BYU Idaho campus in Rexburg, Idaho on 21 August 2017. Data provided to us by Professor Steve Turcotte at BYU Idaho.

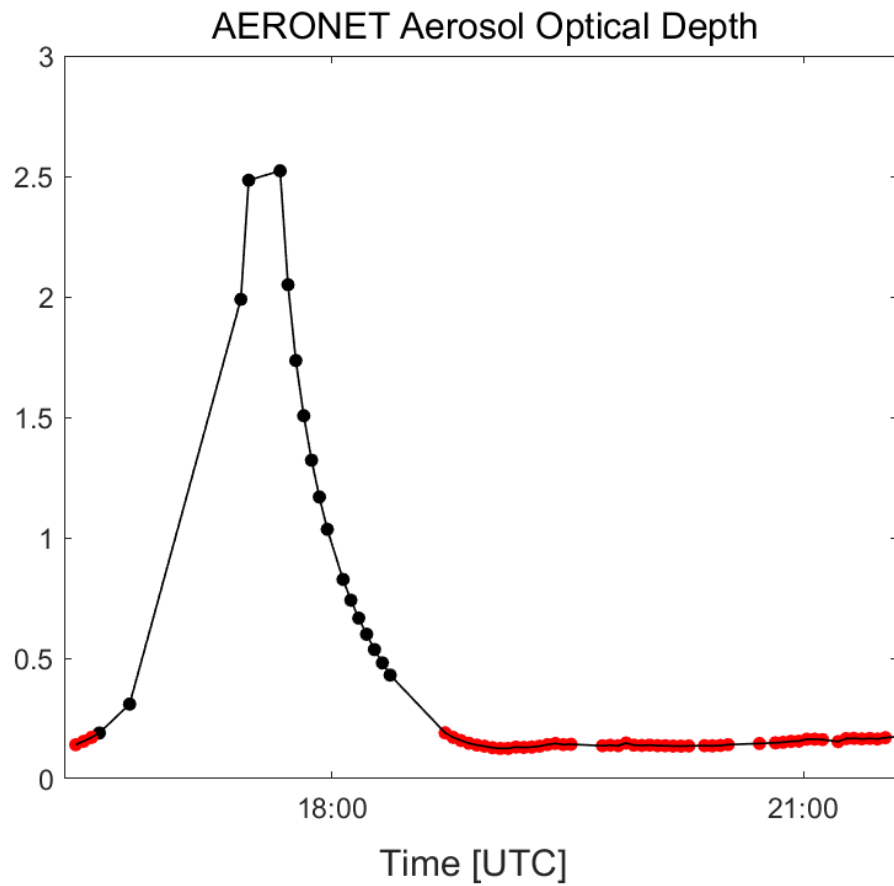


Figure 54. AERONET aerosol optical depth measurement (500 nm) taken on the BYU Idaho campus in Rexburg, Idaho [106] on 21 August 2017. The black and red circles correspond to the processed level-1 and level-2 data, respectively.

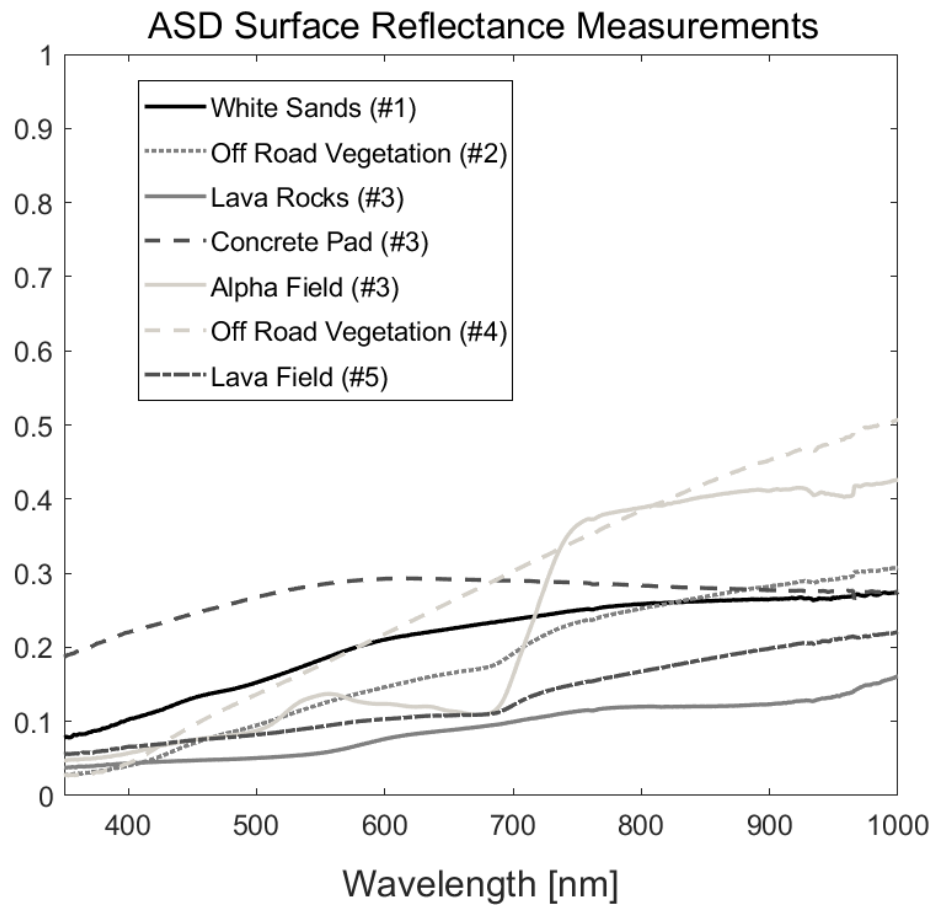


Figure 55. ASD measured surface reflectance taken near the observation site and in the umbral path. Measurements were made on 7 September 2017 by Martin Tauc. The numbers in the reflectance plot label correspond to the measurement locations marked on the Google image in Figure 56.

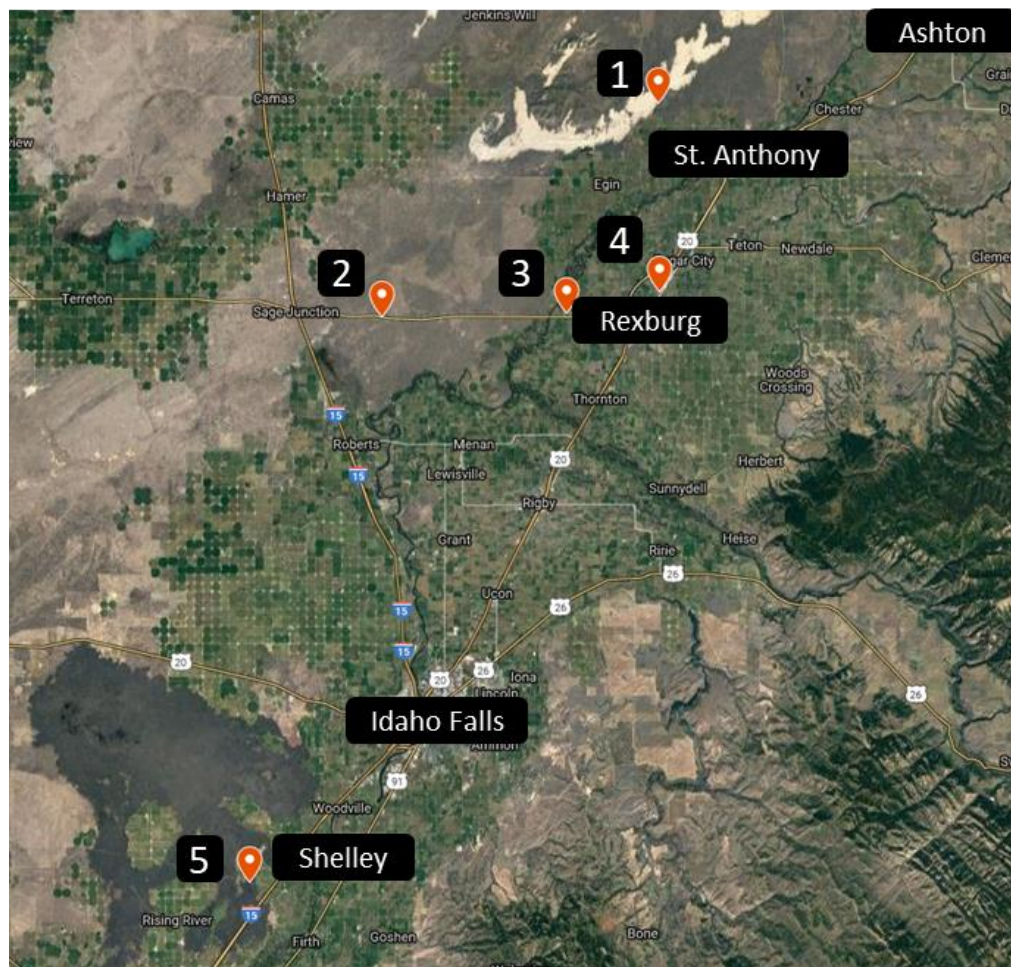


Figure 56. Google image with pins corresponding to the location of each surface reflectance measurement in Figure 55.

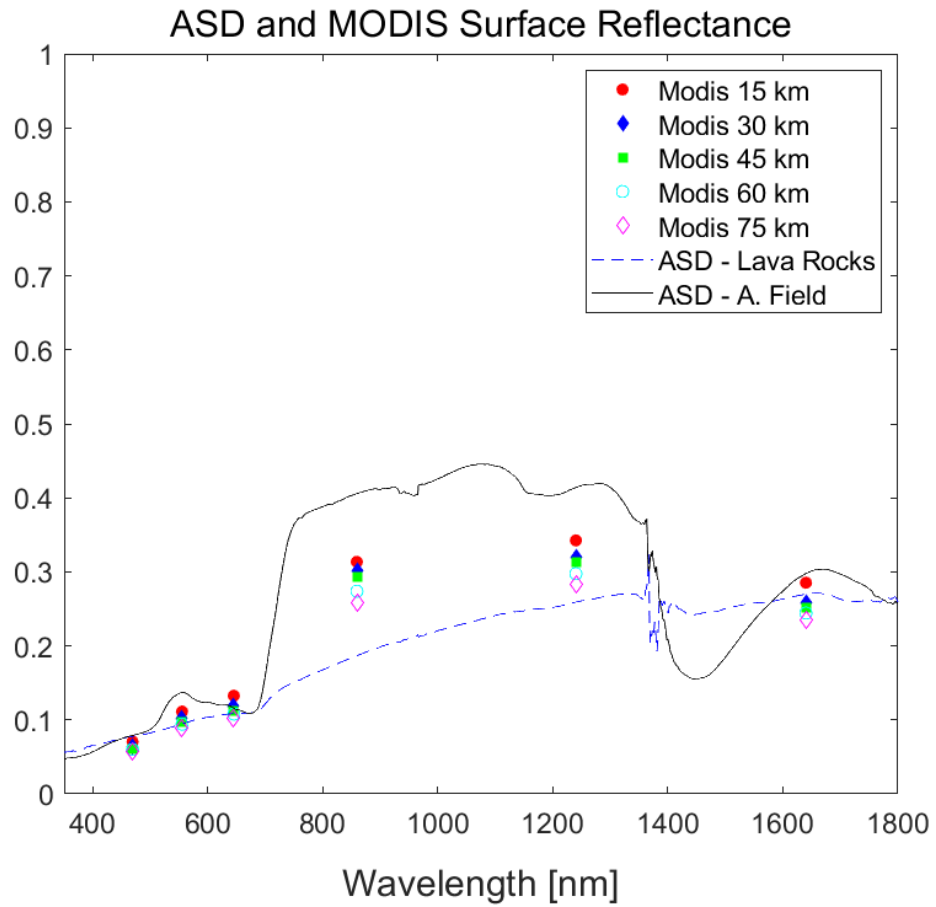


Figure 57. MODIS retrieved surface reflectance in radial distances of 15, 30, 45, 60, and 75 km with ASD measurements of lava rocks south-east of the observation site and an alfalfa field next to the observation site.

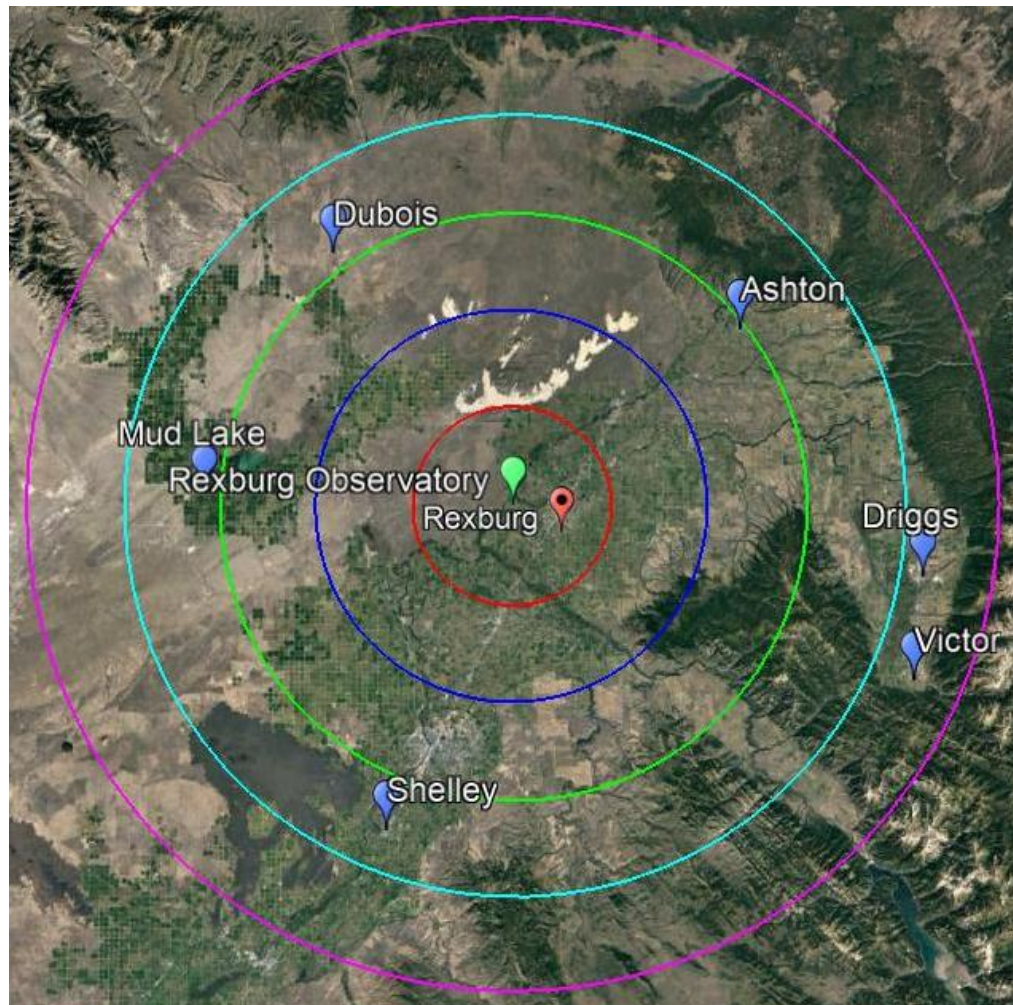


Figure 58. Radial distributions used to retrieve surface reflectance from the MODIS datasets. The blue pins correspond to the umbral diameter at mid-eclipse. The green pin corresponds to the BYU Idaho observatory measurement site and the red pin corresponds to the city of Rexburg, Idaho. Musaddeque Syed helped with downloading and processing the MODIS datasets.

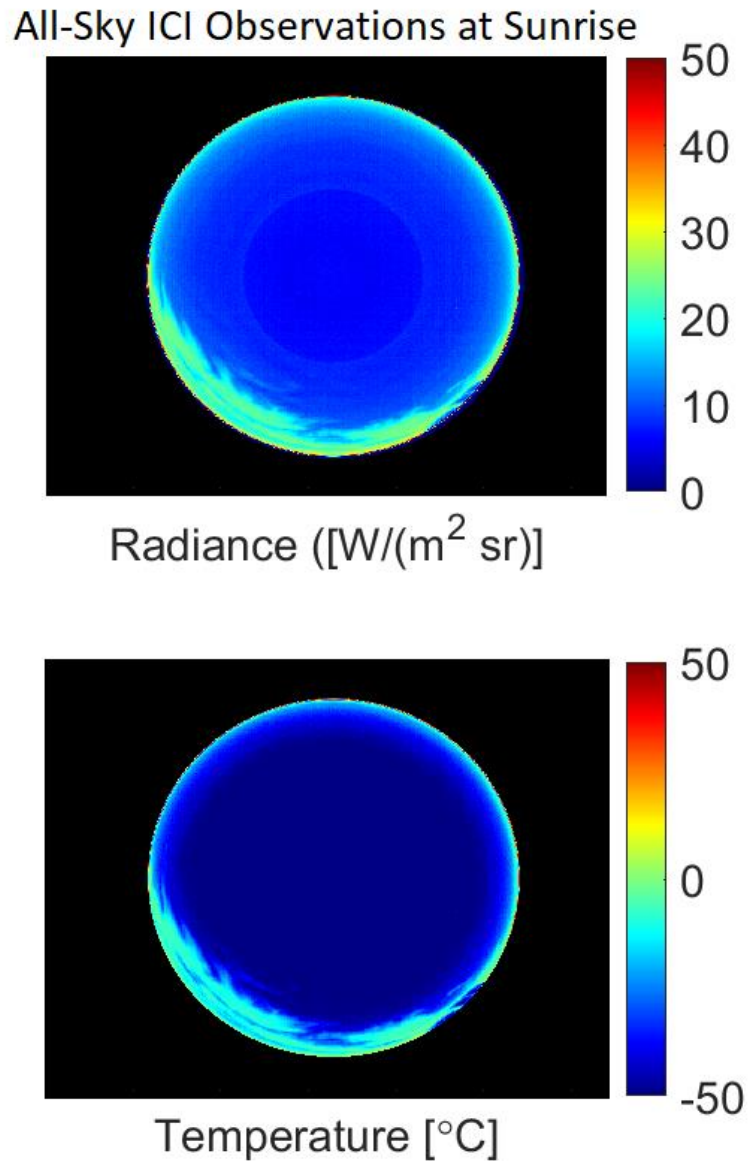


Figure 59. All-sky Infrared Cloud Imager (ICI) measurement taken the morning of 21 August 2017 at 11:35:01 UTC. Thin clouds can be seen near the lower-left horizon (south-southwest). The top and bottom images correspond to the measured radiance and temperature distributions, respectively. Images are aligned with north on top and east to the right. Data provided by Preston Hooser.

All-Sky ICI Observations at Totality

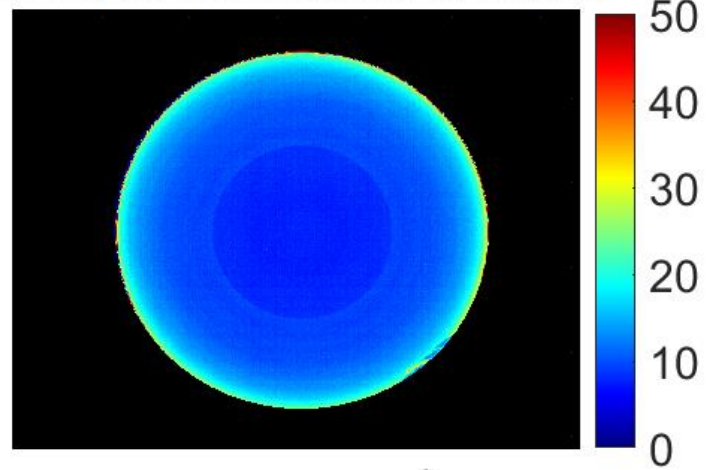
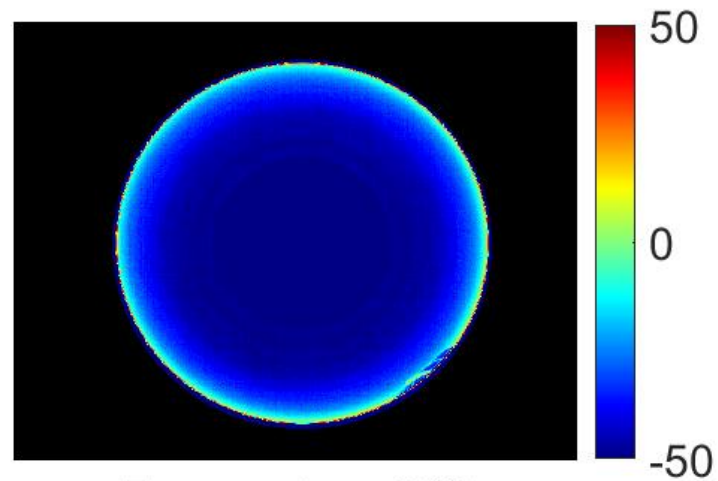
Radiance ($[\text{W}/(\text{m}^2 \text{ sr})]$)Temperature [$^{\circ}\text{C}$]

Figure 60. All-sky Infrared Cloud Imager (ICI) measurement taken from totality at 17:35:08 UTC. The top and bottom image correspond to the measured radiance and temperature distributions, respectively. No clouds can be seen within the images, which are aligned with north on top and east to the right. Data provided by Preston Hooser.

Eclipse Polarization Measurements

We were able to take multiple images through totality with our three-camera Nikon and Sony all-sky polarimeters. The LCVR-based all-sky polarimeter was able to take one measurement during totality (the four polarization images were acquired between 17:33:06 UTC and 17:35:05 UTC). The observations and results described in the remaining sections correspond to measurements taken with the Nikon all-sky polarimeter unless otherwise stated (very similar results were obtained with the Sony system). The camera systems were controlled remotely using a laptop computer, with a manual remote trigger for backup, which allowed us to simultaneously trigger the cameras. During totality, the Nikon polarimeter's exposure time was bracketed between 1/250, 1/100, 1/80, and 1/60 seconds with an ISO value of 4000, while the Sony polarimeter's exposure time was set to 1/100 seconds with ISO values bracketed between 4000, 5000, and 8000. The f-number of each system was set to 3.5. During the span of totality (2 minutes and 17 seconds), the Nikon and Sony all-sky polarimeters captured 11 and 15 image sets, respectively. Initial exposure and ISO settings were found from taking DoLP measurements at twilight and comparing results to previous measurements and models. Figure 61 is a photograph of the three all-sky polarization imagers deployed during the eclipse experiment.



Figure 61. All-sky polarimeters used to measure skylight polarization on 21 August 2017. The LCVR-based all-sky polarimeter is on the left with the two three-camera all-sky polarimeters on the right. The Sony camera system is the closest to the right. Photo provided courtesy of Joseph A. Shaw.

Eclipse Observations

The eclipsed sun and sky can be viewed in Figure 62, which shows the skylight distribution near the beginning and end of totality. The brightness and polarization of skylight was observed to change dramatically during totality, as the umbra moved from second to third contact. Figure 63 shows a sequence of combined raw images (sum of the 0° , 60° , and 120° images), along with the corresponding RGB-averaged S_0 , and DoLP images recorded with the Nikon all-sky polarimeter before, during, and after totality. Immediately before and after totality, the maximum band of polarization was approximately 90° from the sun, even though the source was only a tiny piece of the sun. The DoLP observed after totality was greater than the DoLP observed before totality and, in totality, the maximum band of polarization shifted to be nominally symmetric about the zenith (with the most symmetric pattern occurring near the end of totality). Figures 64 and 65 also show the distribution of skylight polarization as the umbra moved from second to third contact, measured with the Nikon and Sony systems, respectively. During totality the spatial skylight polarization pattern was observed to vary temporally. Along the solar principal plane, minimum DoLP values were observed at the beginning of totality (these minima occurred at what has been referred to as type-2 neutral points [61] because the DoLP is a minimum, but not zero). Initially, one minimum DoLP value was observed near the zenith and another minimum value was observed near the horizon. In the images presented in Figure 64, a black circle was placed at the zenith. From second to third contact, the neutral point near the zenith was observed to move in towards the zenith, while the neutral point near the horizon was observed to move outward,

disappearing by the end of totality. A similar polarization pattern was measured during totality by the LCVR-based polarimeter, as shown in the 450-nm S_0 , AoP, and DoLP images in Figure 66. Because the automatic exposure algorithm used in this all-sky polarimeter did not converge rapidly at the onset of totality and because this division-of-time polarimeter required approximately 119 seconds to record the needed four polarization images for reconstructing the Stokes images, there was only one Stokes image recorded by this instrument during totality.



Figure 62. Eclipsed sky at totality with the BYU Idaho observatory in the background at the beginning of totality (Top) and at the end of totality (Bottom), showing how the brighter horizon shifted from the east (top) to the west (bottom). Picture taken nominally looking south with the sun in the southeast using a Nikon D800 camera and 20-mm lens (ISO 2000, with exposures of 1/80 s at f/4.5 for the top image and 1/60 s at f/4 for the bottom image). Photo provided courtesy of Joseph A. Shaw.

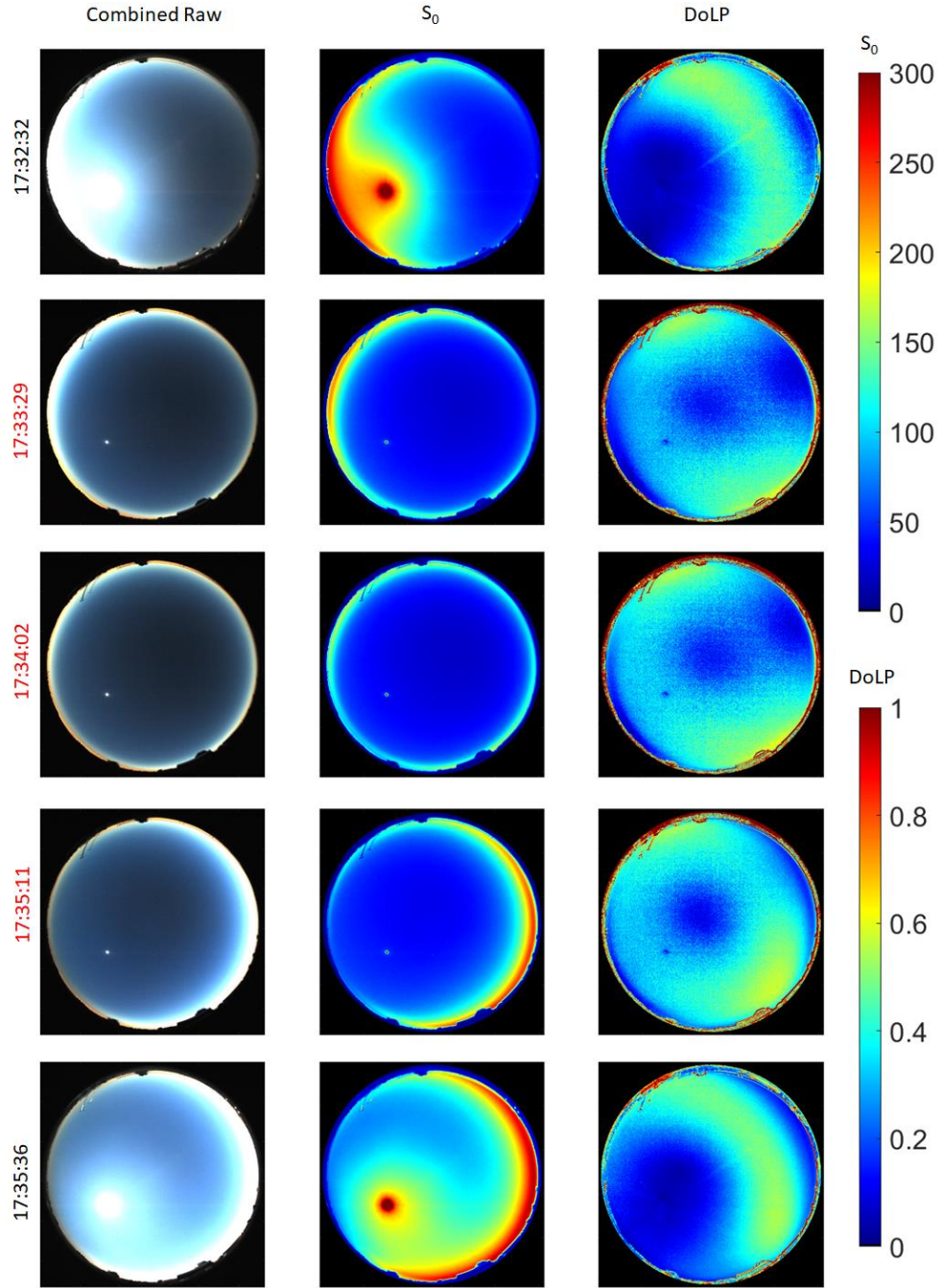


Figure 63. Time series of the combined raw images from the 0°, 60° and 120° cameras, along with the corresponding RGB-averaged S_0 , and DoLP images from the Nikon all-sky polarimeter before, during, and after totality (totality times marked in red). S_0 images correspond to radiance with units of mW/(cm² sr).

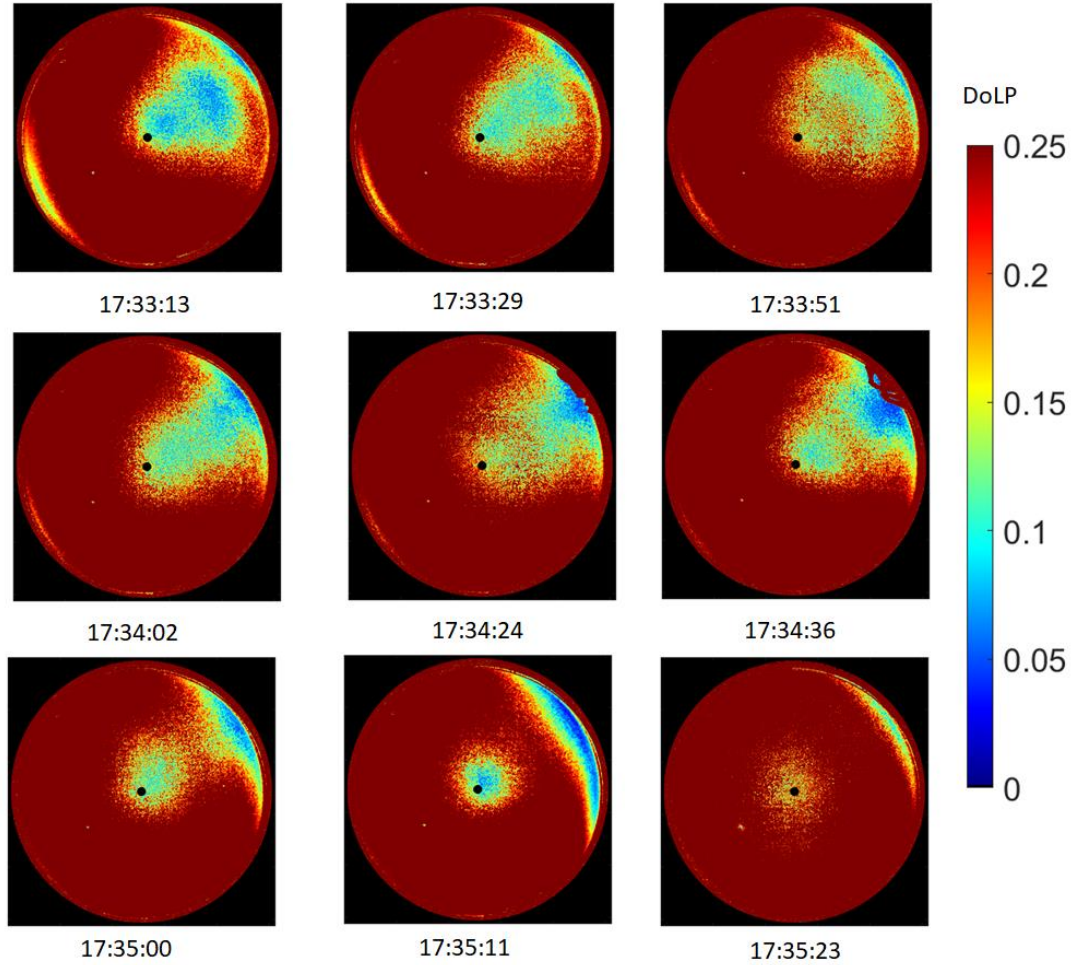


Figure 64. Temporal variation of all-sky DoLP in the blue channel during totality from second contact to third contact, measured with the three-camera Nikon all-sky polarimeter (ISO 4000, $f/3.5$) at the UTC time marked below each all-sky image. The exposure time was $1/60$ s for the image recorded at 17:13:13 UTC, $1/80$ s for the images recorded at 17:33:29 UTC, 17:34:02 UTC, 17:34:36 UTC, and 17:35:11 UTC, respectively, $1/100$ s for images recorded at 17:33:51 UTC, 17:34:24 UTC, and 17:35:00 UTC, respectively, and $1/250$ s for the image recorded at 17:35:23 UTC.

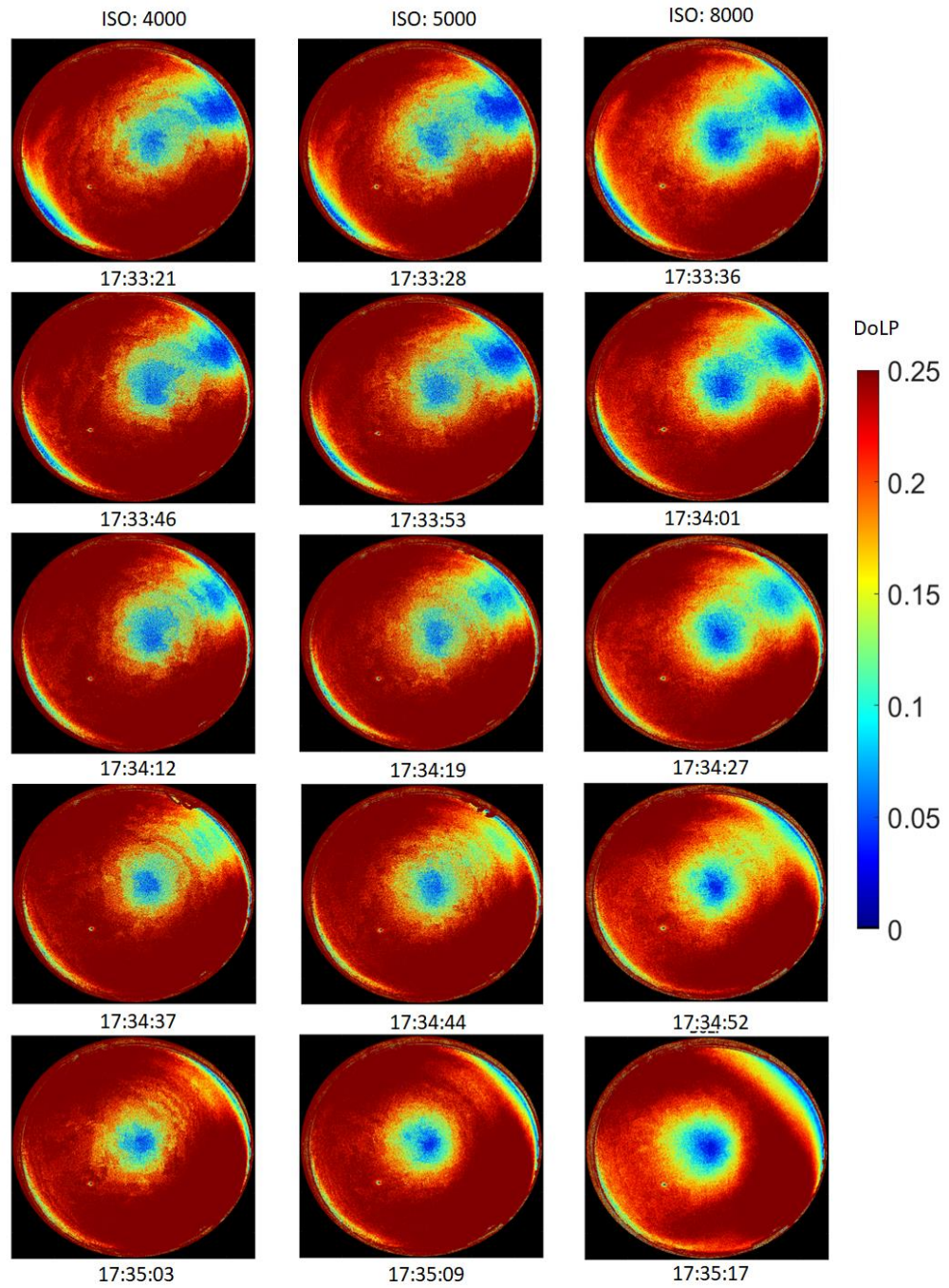


Figure 65. Temporal variation of all-sky DoLP during totality from second contact to third contact, measured with the three-camera Sony all-sky polarimeter with 0.01-s exposure at f/3.5 and the ISO value listed above each column. Below each all-sky image is the UTC time.

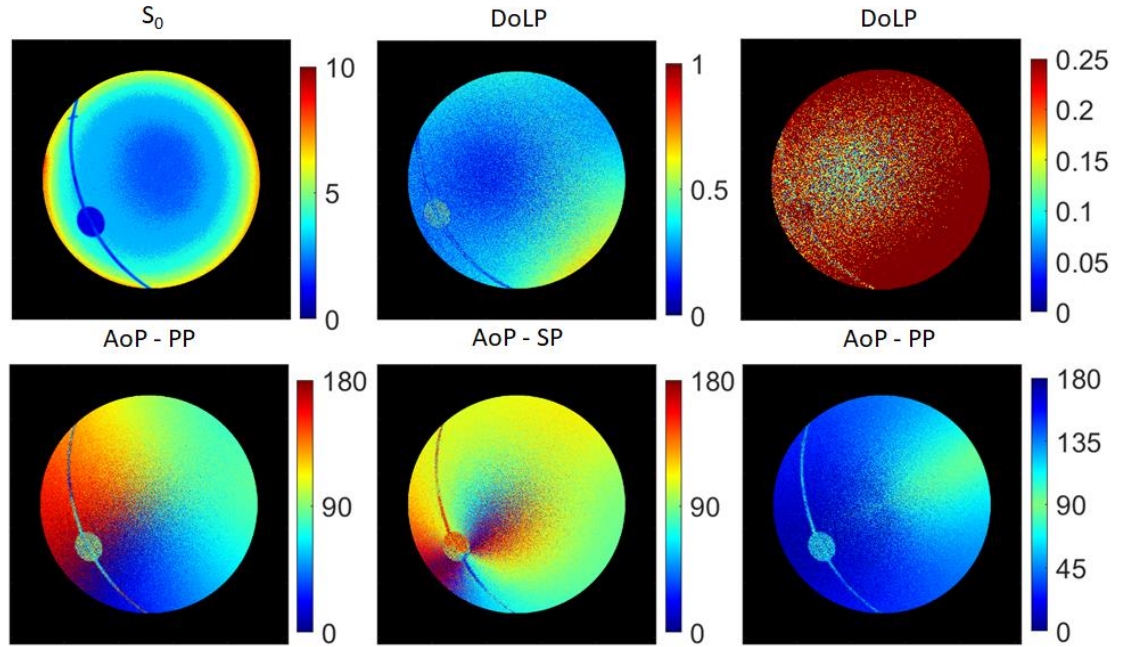


Figure 66. S_0 , AoP, and DoLP 450 nm all-sky images recorded with the LCVR polarimeter at 17:35:05 UTC with 526-ms exposure at $f/4$. The AoP images are shown referenced to the instrument plane (PP), scattering plane (SP), and the principal plane (PP). The scale in the top-left DoLP image matches the scale used in Figures 64 and 65. S_0 images correspond to radiance with units of $\text{mW}/(\text{cm}^2 \text{ sr})$.

Spectral Dependence

In Figure 67, S_0 , AoP, and DoLP images show the spectral polarization patterns observed in the red, green, and blue channels near mid-totality at 17:34:02 UTC. The brightness of skylight was observed to be greatest in the blue spectrum. The DoLP was observed to be symmetric about the solar principal plane in both the blue and green channels, including neutral points near the horizon (which corresponded to observed minimum DoLP values). At the neutral point, a 90° switch in AoP was observed. The red S_0 image had significantly less light and the polarization patterns were not as well defined as in the green and blue images.

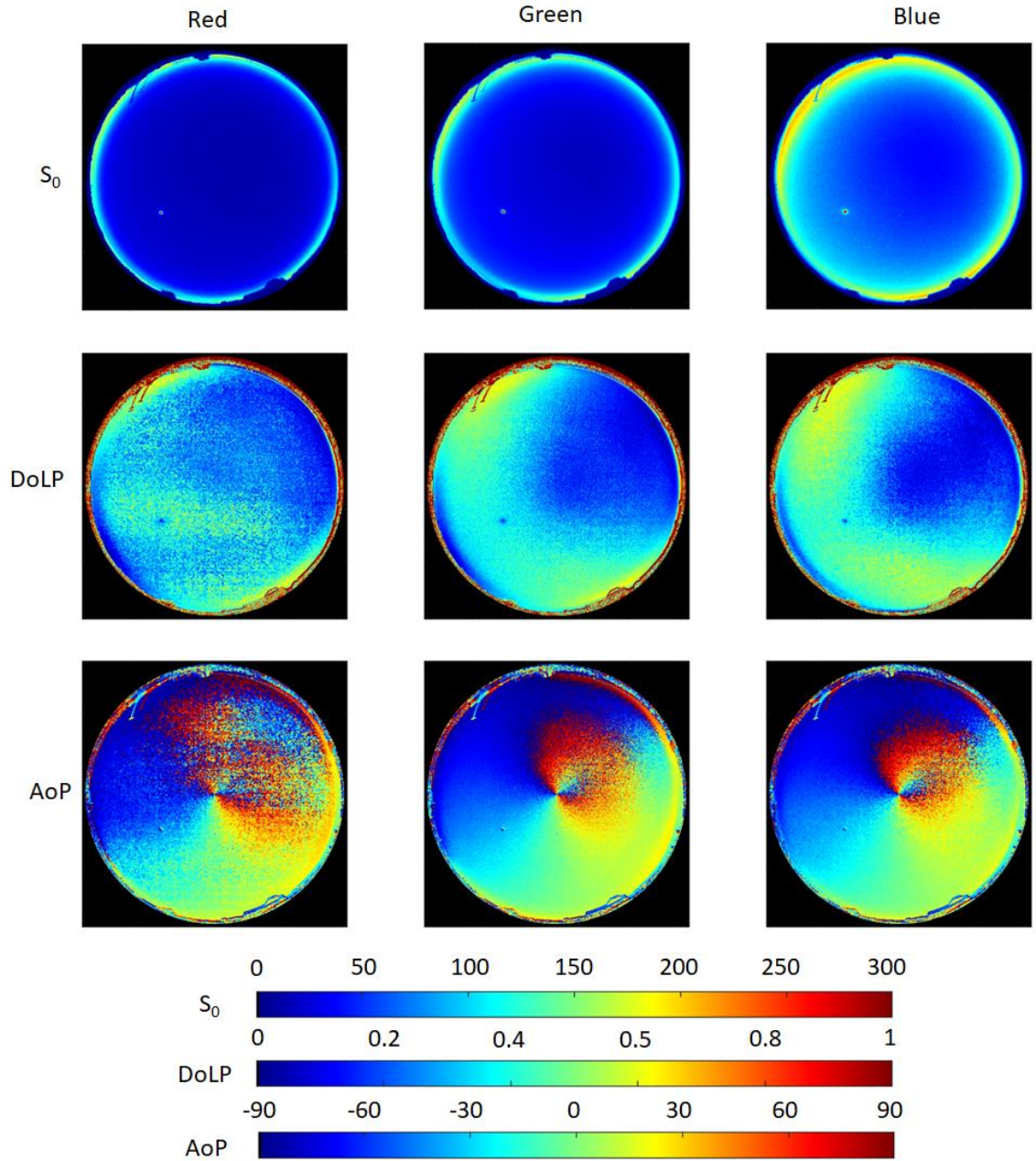


Figure 67. S_0 , AoP, and DoLP RGB images measured with the Nikon all-sky polarimeter near mid-totality at 17:34:02 UTC for the red, green, and blue channels. The AoP is referenced to the principal plane and S_0 images correspond to radiance with units of $\text{mW}/(\text{cm}^2 \text{ sr})$.

In Figures 68-72 I explore the temporally variable asymmetry in the polarization patterns observed from second to third contact. These images show that the sky polarization pattern became mostly symmetric about the zenith near the end of totality. Minimum polarization was observed from the zenith to the anti-solar horizon, with maximum polarization occurring near the horizon in the plane running perpendicular to the solar principal plane through the zenith (Figure 72). This effect was observed with both the Sony and Nikon polarimeters and in the one polarimetric measurement taken with the LCVR polarimeter. The Sony and Nikon systems were deployed with one rotated 180° relative to the other, so the similarity of the results from these independent systems rules out systematic errors as an explanation for the observed polarization asymmetry. Figures 69-72 show slices through the all-sky DoLP and AoP images to illustrate the polarization symmetry as it varied throughout totality. As shown in Figure 68, these slices were taken along the solar principal plane and over an almucantar slice taken at a constant zenith angle of 70° through all azimuth angles. The circular mask in Figure 68 (top image) is an almucantar slice through all azimuth angles at a constant zenith angle of 51° . The principal plane slices were extracted from the measured fisheye images to quantitatively evaluate skylight polarization in the principal plane, specifically the distribution of the neutral points located at the zenith and near the horizon for each wavelength, as the umbra moved from second to third contact. The almucantar slice was created to capture the maximum polarization observed perpendicular to the solar principal plane. Comparisons were then made between our results and previous measurements that used point-source, scanning, and all-sky polarimeters.

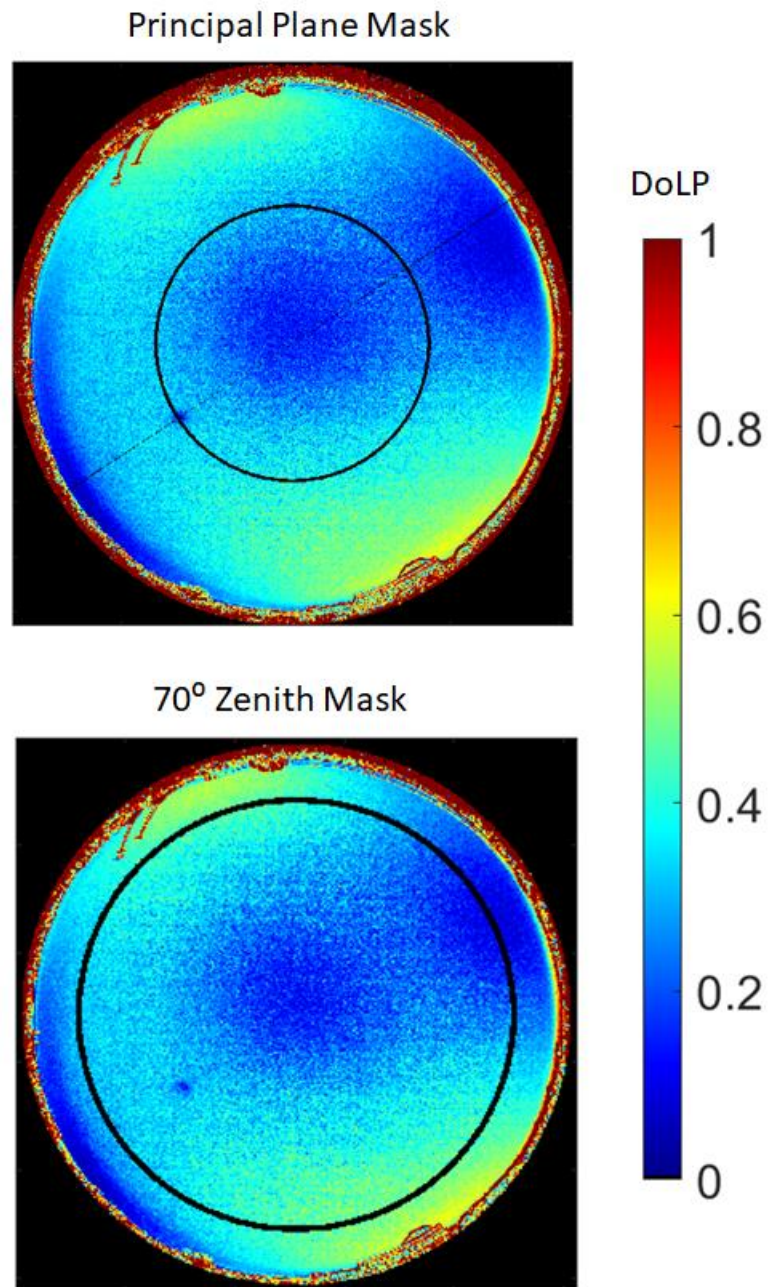


Figure 68. Masks showing the locations of the principal plane (Top) as well as the almucantar slice taken at a constant zenith angle of 70° through all azimuth angles (Bottom).

The spectral and temporal variation from second to third contact can be observed in the slices through the principal plane in Figure 69. The red channel DoLP was observed to be weak and noisy in Figure 67 near mid-totality; however, in Figure 69 at 17:34:02 UTC, the polarization in the red channel was greater than the observed polarization in the blue and green channels between zenith angles of -40° and 70° . At the beginning of totality, the distribution of sky polarization in the red channel was approximately constant in magnitude over zenith angles of -60° to 20° . Near the end of totality, the red channel DoLP became nominally symmetric about totality, similar to the blue and green channels. In all cases shown in Figure 69, the observed DoLP at the zenith was greatest in the red channel and lowest in the blue channel. Between each measurement time, the maximum DoLP in the blue and green channels was observed to shift towards the horizon (larger zenith angles).

In totality (similar to twilight), high altitude aerosols scatter light to the observer and the sky brightness was observed to shift toward the blue spectrum (Figure 67) because of the λ^{-4} dependence of Rayleigh scattering. On the other hand, the DoLP tends in the opposite direction for Rayleigh scattering, with polarization occurring in the red part of the spectrum compared to the blue, which is observed in Figure 69. Generally, the maximum polarization occurs in the red channel; however, at the beginning of totality (17:33:33 UTC), maximum polarization is observed in the blue channel. The symmetric distribution of skylight polarization around the horizon could explain the observed polarization trend at the beginning of totality.

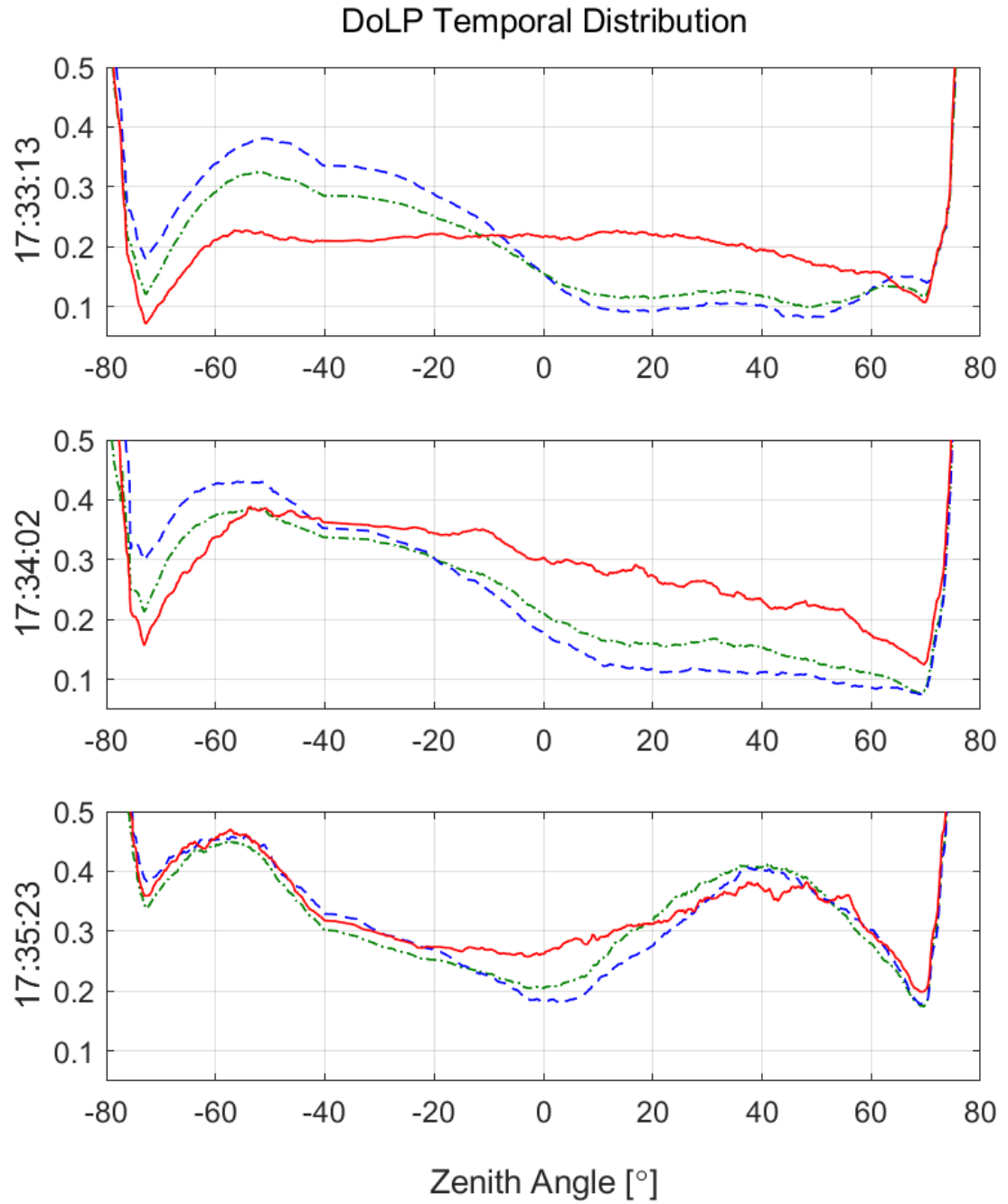


Figure 69. Principal-plane (solid line) slices extracted from the red, green, and blue fisheye DoLP images at the beginning of totality (17:33:13 UTC), near mid-totality (17:34:02 UTC), and at the end of totality (17:35:23 UTC).

Figures 70-71 show the green and blue DoLP and AoP slices at the start of totality, mid-totality, end of totality, and post-totality in the principal planes and almucantar slices, respectively. For every measurement during totality, the maximum polarization in the solar principal plane was found in the solar-hemisphere direction. The maximum polarization observed during totality in the solar hemisphere for the green and blue channels was 44% and 45%, respectively. At the zenith, maximum and minimum observed polarization occurred in the red and blue channels (Figure 69), respectively. Interestingly, the minimum and maximum DoLP values both were observed to increase from second to third contact.

Before totality, the maximum observed polarization ($\sim 90^\circ$ from the sun) in the green and blue channels was 57% and 54%, respectively. Near the end of totality, the maximum observed polarization ($\sim 90^\circ$ from the sun) in the green and blue channels was approximately 35%. At the beginning of totality, the maximum observed polarization ($\sim 90^\circ$ from the sun) was between 8-13% in the green and blue channels. These results demonstrate that maximum skylight polarization is dependent on the solar geometry and changes as the umbra moves from second to third contact. Previous researchers using point-source polarimeters only recorded measurements 90° from the sun. This study, along with results presented in 1973 [56] and 1999 [61, 62] and 2006 [63], show that in totality, maximum polarization is found predominately in the solar-hemisphere and not 90° from the sun.

At the beginning of totality, the locations of the minimum values of polarization that were observed near the horizon and at the zenith were found to depend on wavelength. The presence of neutral points can be confirmed using the AoP slices shown in Figure 71. The changes in the AoP along the solar principal plane indicate the presence of neutral points (classified as type 2 by Horvath et al. since the minimum polarization is not zero [61]). There are two neutral points and throughout totality one shifted toward the zenith while the other shifted toward the horizon. Between mid-totality and the end of totality, the minimum polarization (neutral) points observed in the DoLP slices near the horizon are considered a type-3 neutral point [61] since their AoP has the same orientation as Rayleigh single scattering (i.e., the orientation of the AoP at the horizon is perpendicular to the solar principal plane).

Almucantar slices taken at a constant zenith angle of 70° through all azimuth angles at the beginning of totality (17:33:13 UTC), near mid-totality (17:34:02 UTC), and at the end of totality (17:35:23 UTC) are shown in Figure 72. Azimuth angles of 0° and 90° correspond to north and east, respectively. Skylight polarization perpendicular to the solar principal plane was observed to shift from second contact to third contact. The skylight polarization on the horizon was observed to be minimum approximately 180° from the sun and maximum approximately 90° from the sun (in azimuth). Maximum polarization at the end of totality was observed to be 61% and 65% for the blue and green channels, respectively. These values were greater than the values measured in the principal plane, in totality and out of totality.

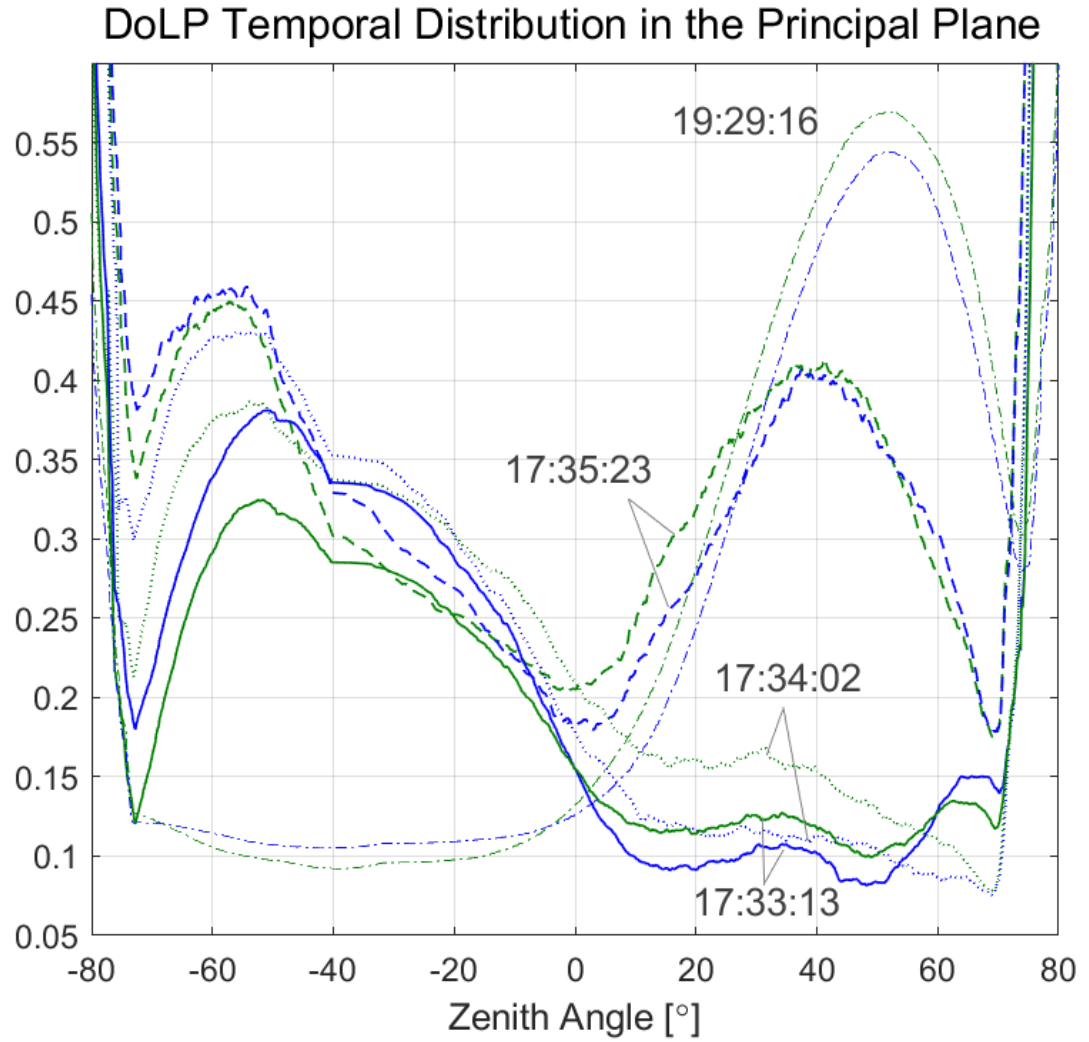


Figure 70. Principal-plane DoLP slices extracted from the green and blue images at the beginning of totality (17:33:13 UTC), near mid-totality (17:34:02 UTC), at the end of totality (17:35:23 UTC), and after totality (19:29:16 UTC).

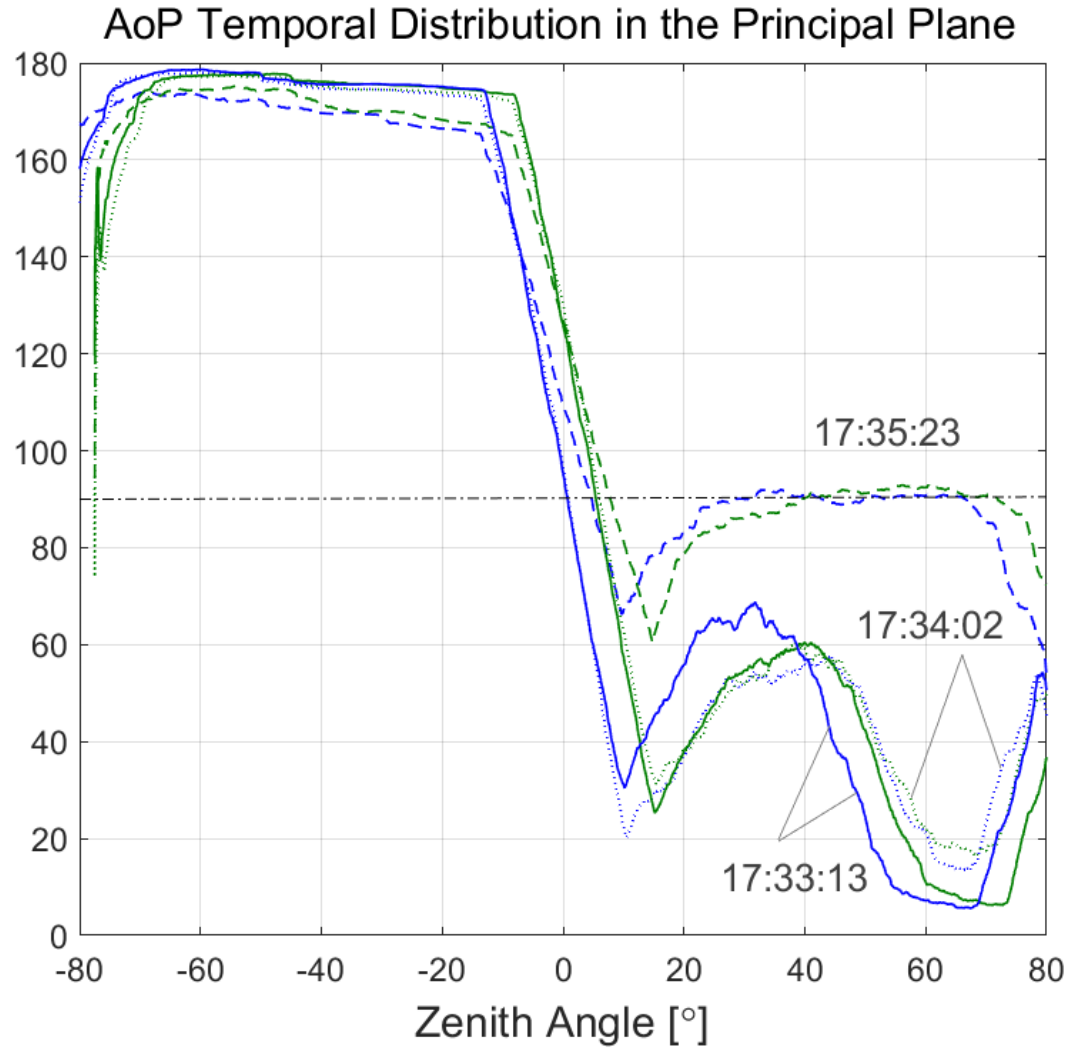


Figure 71. Principal-plane AoP slices extracted from the green and blue images (with AoP referenced to the solar principal plane) at the beginning of totality (17:33:13 UTC), near mid-totality (17:34:02 UTC), at the end of totality (17:35:23 UTC), and after totality (192616 UTC).

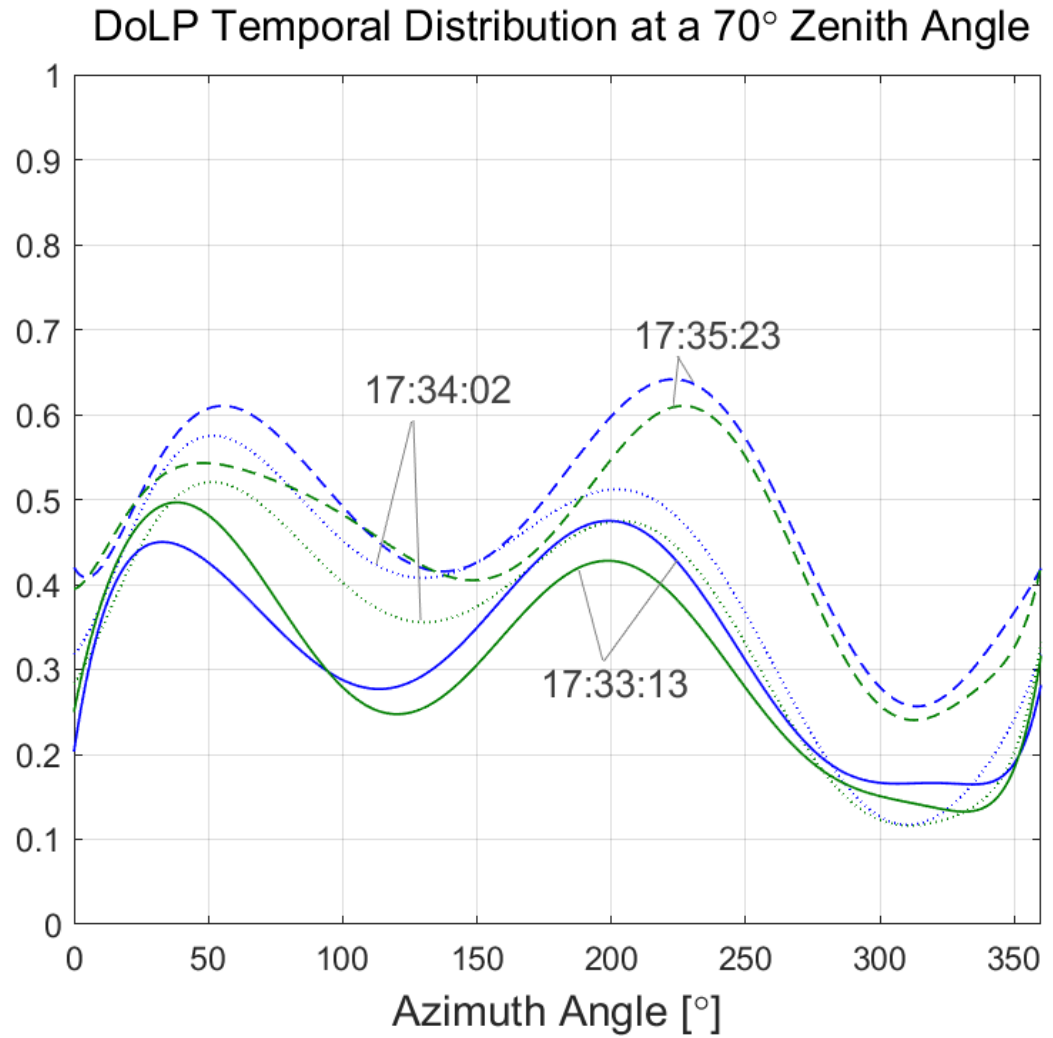


Figure 72. Almucantar slices taken at a constant zenith angle of 70° through all azimuth angles at the beginning of totality (17:33:13 UTC), near mid-totality (17:34:02 UTC), and at the end of totality (17:35:23 UTC). Azimuth angles of 0° and 90° correspond to north and east, respectively.

Qualitative Explanation of Eclipse Polarization

To qualitatively understand how the neutral points arise in the otherwise zenith-symmetric totality polarization pattern, a simple model can be constructed by considering the AoP and DoLP patterns created outside the umbra by primarily single Rayleigh scattering. Outside the umbra, the usual daytime polarization pattern for a clear sky has maximum DoLP approximately 90° from the sun, with the AoP oriented perpendicular to the scattering plane. The observed AoP and DoLP patterns before totality (left) and during totality (right) are shown together in Figure 73A, in which DoLP is encoded as the length of the lines and the AoP is encoded as the orientation of the lines. Single-scattering dominates outside the umbral region and during totality this light is scattered toward the observer (in the umbra). The light scattered into the umbra from the solar hemisphere (outside the umbra) is generally weakly polarized parallel to the scattering plane and the light scattered into the umbra from the anti-solar hemisphere (outside the umbra) is generally strongly polarized perpendicular to the scattering plane. Therefore, at some point within the umbra, multiply scattered light from these two sources combine with equal magnitudes and orthogonal polarizations to form a neutral point (Figure 73B). Because there really are not simply two sources in this multiple-scattering problem, the neutral point does not exhibit exactly zero polarization.

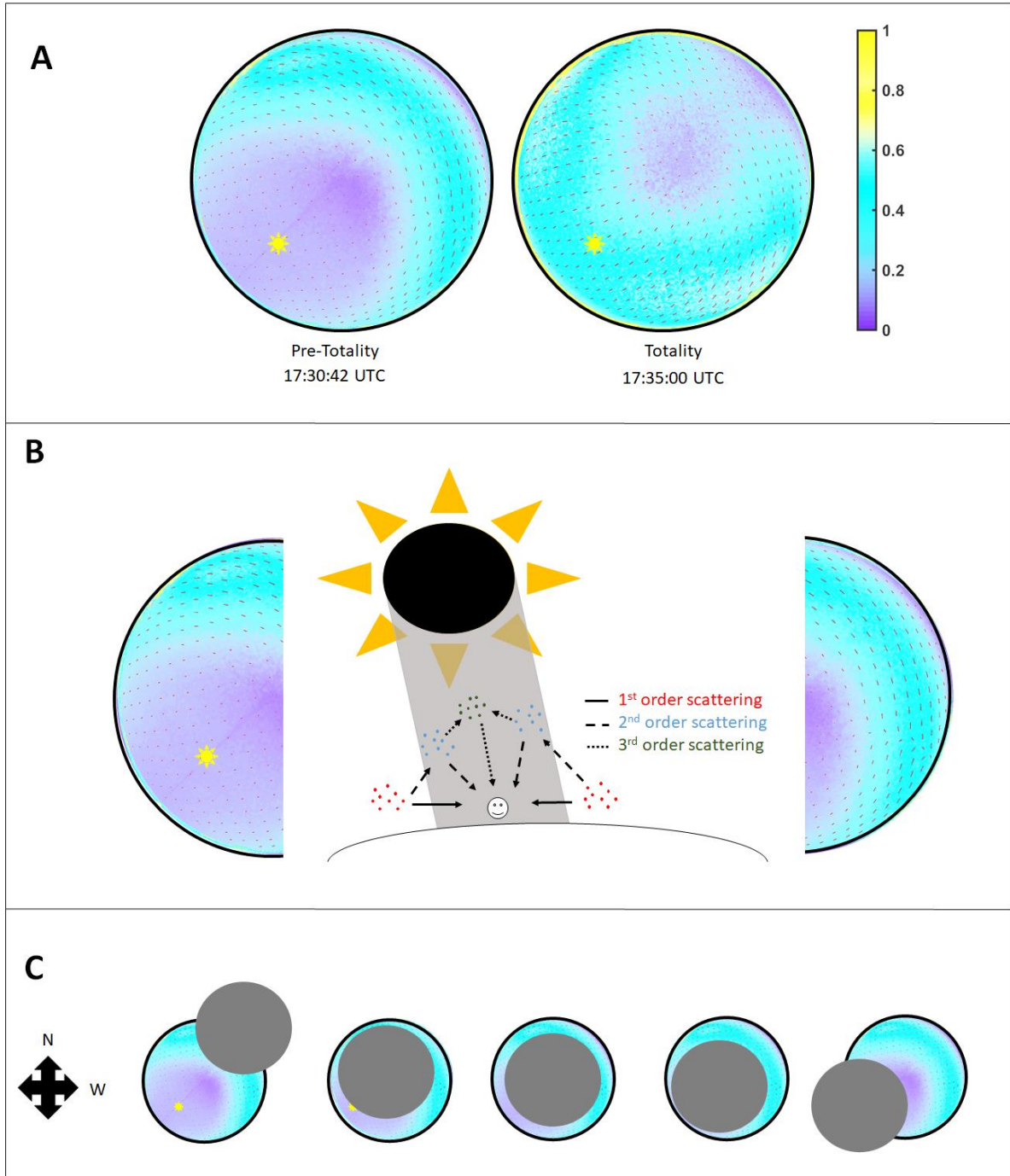


Figure 73. Nikon DoLP images with AoP vectors before (17:30:42 UTC) and during totality (17:35:00 UTC). The length of the vectors represent the DoLP magnitude (A). Illustration of the eclipse scattering contribution and geometry (B). As the umbra moves (C), the distribution of the contributing parallel and perpendicular polarization changes, shifting the location of the observed neutral points. The umbra is represented by the gray outline.

Moving beyond a single-scattering model, second- and higher-order scattering at greater viewing angles can explain the multiple neutral points in the observed AoP images. For example, single-scattered light from outside the umbra, along the horizon, can re-scatter at the zenith above the observer. In third-order scattering, single-scattered light from outside the umbral region can scatter at a point on the horizon which then can scatter at another point above the observer. This light is then directed to the observer and contains a mixture of AoP vectors, creating an additional neutral point near the horizon. As the umbra moves (Figure 73C), the position of the neutral points also move, driven by the changing higher-order scattering as the combination of polarization states coming from the horizon change. This is the reason why the neutral point exists near the horizon and changes as the umbra moves.

Discussion

From second to third contact we were able to take a series of 11 red, green, and blue polarimetric images (9 well exposed) with the three-camera Nikon all-sky polarimeter, 15 red, green, and blue polarimetric images with the three-camera Sony all-sky polarimeter, and a single 450-nm polarimetric image with the LCVR-based all-sky polarimeter. The narrow filter bandwidth limited the LCVR-based all-sky polarimeter from taking multiple images. For the one polarimetric measurement, it took over a minute to capture the four Stokes images needed to measure the DoLP and AoP. Given the time restraint and dynamic conditions of totality, the three-camera polarimetric systems (with linear polarizers orientated at 0° , 60° , and 120° , respectively) have provided the best quality and number of images to date. They offer the advantage of fast polarimetric and

spectral image acquisition, they are robust, they can measure skylight polarization in the entire sky-dome, and each camera can be triggered simultaneously using a laptop (or manual remote triggers). In addition, the camera exposure times and ISO settings can be bracketed to ensure well-exposed images. They have the disadvantage of using three separate cameras and lenses to record simultaneous polarization images, but careful calibration minimizes any negative impact.

Previous all-sky eclipse polarization measurements were made by a Hungarian group at an August 1999 solar eclipse in Hungary [61, 62] and at a March 2006 solar eclipse in Turkey [63]. Using a film camera and fisheye lens with a rotating polarizer, they were able to take a series of 3 images (2 before mid-totality, 1 after mid-totality) during the 1999 eclipse and 8 images (6 before totality, 2 after mid-totality) during the 2006 eclipse. Totality was 2 minutes and 22 seconds for the 1999 Kecel, Hungarian solar eclipse, 3 minutes and 45 seconds for the 2006 Side, Turkey solar eclipse, and 2 minutes and 17 seconds for the 2017 Rexburg, Idaho solar eclipse. Our three-camera all-sky polarimeters were able to take the greatest number of polarimetric images in the shortest amount of time since they weren't limited by a rotating polarization filter wheel or narrow filter bandwidths. They also took polarimetric images evenly distributed in time throughout totality, allowing us to collect the best all-sky polarization data set to date. Our 2017 eclipse measurements were the only study yet to be accompanied by cloud, aerosol, and surface measurements.

At totality for both the 1999 and 2017 eclipses, the sun was positioned in the southeast and the umbra moved northwest to southeast. In 2006, the sun was positioned

southwest during totality and the umbra moved from southwest to the northeast. In all cases, a sudden change in the DoLP and AoP pattern at the beginning and end of totality was observed (from the usual daytime polarization pattern to one that was nominally symmetric about the zenith). As the umbra crossed the anti-solar position, neutral points were observed near the anti-solar principal plane and horizon. As the umbra crossed the solar position, a symmetric DoLP pattern was observed around the zenith. The AoP was observed to be asymmetric, with polarization parallel to the scattering plane in the solar principal plane and perpendicular to the scattering plane in the anti-solar principal plane. As the umbra moved across the observation point, the geometry of light scattering changed due to the varying illumination conditions of the eclipsed sky. This resulted in complex temporal changes of the celestial polarization patterns observed during totality. The all-sky polarimetric images we recorded follow a similar trend as those in previous measurements, which suggests that the overall temporal pattern of sky polarization during a solar eclipse are general and not specific for each eclipse.

From the results observed with the all-sky polarimeters, G. Shaw's mid-totality results from the 1973 African solar eclipse [56] indicate that neutral points in the anti-solar half of the scan were most likely observed, as a result of the solar scattering geometry. In 1973, the sun was northwest of the observation site during totality and the umbra moved from the southeast to the northwest. This is the exact geometry observed in the 1999 [61, 62] and 2017 solar eclipses, where neutral points were observed in the anti-solar hemisphere at the beginning of totality through mid-totality. At the time of G. Shaw's study, the complex nature of single- and multi-scattering in regards to the

polarization observed during a solar eclipse was unknown. Given the dynamic lighting conditions, we recommend using a fisheye imaging system, like the ones we developed in this eclipse, to ensure that skylight polarization can be measured accurately throughout the sky.

Table 7 summarizes results from past experiments that used point-source polarimeters and imagers and it shows that skylight polarization measured during totality can vary depending on environmental parameters (similar to normal daytime conditions). The spectral discrepancies between the measurements suggest environmental parameters were different, rather than one measurement was right and the other was wrong. For all measurements, the AoP was generally observed to be independent of wavelength; however, the location of the observed neutral points was wavelength dependent. For the all-sky polarimetric eclipse measurements made in 1999 and 2006, the measured red channel DoLP was greatest. In contrast, at the beginning of totality in 2017, we observed greater DoLP in the blue and green channels in the solar principal plane and greater DoLP in the red channel in the anti-solar principal plane. At the end of totality, we observed greater DoLP in the red and blue channels overall; however, the DoLP observed at the zenith was greater in the red channel. Rayleigh scattering theory predicts longer wavelengths to have the greatest DoLP, since more multiple scattering occurs for shorter wavelengths, but the actual spectrum varies strongly with aerosols and surface reflectance. Therefore, the different spectral discrepancies in the 1999 [61, 62], 2006 [63], and 2017 measurements are likely the result of different aerosol and surface conditions. For example, the 1999 [61, 62] and 2006 [63] measurements were made near

oceans, which tend to have surface reflectance that is spectrally even and low. If Rayleigh scattering dominated (i.e., low aerosol content), one would expect the DoLP in the red channel to be the greatest. However, for the 2017 solar eclipse the surface reflectance was higher in the red channel than for the green and blue channels (Figure 57). This would normally correspond to a higher DoLP in the blue channel because a higher surface reflectance reflects more light into the atmosphere, which re-scatters and causes a depolarization effect [11, 43, 44].

Modeling the skylight during an eclipse is complex. Skylight polarization in general is dependent on a variety of factors such as the scattering geometry, aerosols, clouds, and the underlying surface reflectance. At the time Können developed his model [60], there was only one scanning data set available. Können suggested that in order to compare measured results with quantitative models, all-sky polarization measurements describing the entire sky were needed. Now that such data sets are available, new models should be developed to more completely understand the complex polarization patterns of skylight polarization during a total solar eclipse.

Conclusions

All-sky polarization images were measured from sunrise to sunset using three all-sky polarimeters on 21 August 2017. During totality, we measured skylight polarization 11 times using our Nikon all-sky polarimeter system and 15 times with our Sony system. At second contact, the polarization pattern suddenly changed from the usual daytime pattern with maximum polarization 90° from the sun to one that was nominally

symmetric about the zenith. We observed a temporally varying asymmetry in the pattern of skylight polarization during totality, which was a result of the dynamic changes in skylight scattering as the umbra moved from second to third contact. The three-camera all-sky polarimeters are robust, easy to use, cost efficient, and have provided the largest number of all-sky polarization measurements during a solar eclipse to date. These instruments also have provided the first-ever set of all-sky images with all polarization states being imaged simultaneously.

Observer	Year	Solar Zenith Angle [°]	Obs. Point Zenith Angle [°]	Measurement Type	Wavelength	DoLP [%]
E. de Bary et al.[112]	1961	78	12	Point source Ground-based	Green	0
J. G. Moore and C. R. N. Rao [113]	1965	49	41	Point source Air-borne	475 nm	0.5
					601 nm	4.5
R. E. Miller and W. G. Fastie [114]	1965	25	65	Point source Air-borne	558 nm	31
					578 nm	35
					610 nm	28
					630 nm	26
C. R. N Rao et al. [115]	1966	20	70	Point source Air-borne	475 nm	19
					601 nm	21
B. S. Dandekar and J. P. Turtle [116]	1970	44	46	Point source Ground-based	475 nm	4
					600 nm	<0.5
R. Gerharz [117]	1970		38-53	Imager Ground-based	535 nm	<2.5
G. E. Shaw [56]	1973	53	37	Scanning Ground-based	400	4
I. Pomozi et al. [61], G. Horvath et al. [62]	1999	32	Full sky	All-sky imager Ground-based	450 nm	~2-12
					550 nm	~9-22
					650 nm	~10-30
B. Sipöcz et al. [63]	2006	46	Full sky	All-sky imager Ground-based	450 nm	~1-8
					550 nm	~2-16
					650 nm	~3-20
Eshelman et al.	2017	51	Full sky	All-sky imager Ground-based	B	~8-43
					G	~8-39
					R	~13-38

Table 7. Summary of mid-eclipse sky polarization measurements. Point source observations were taken 90° from the sun in the solar principal plane. All-sky polarization results represent the range of polarization observed in the solar principal plane near mid-eclipse.

CHAPTER SIX

ALL-SKY POLARIZATION IMAGING OF CLOUD THERMODYNAMIC PHASE

Contribution of Authors and Co-Authors

Partial Manuscript in Chapter 6

Author: Laura M. Eshelman

Contributions: Detected all-sky thermodynamic phase by measuring the Stokes S_1 parameter with the visible LCVR-based all-sky polarimeter, made dual-polarization lidar measurements to verify the measured cloud phase at the zenith, generated figures, and drafted the manuscript that has been submitted to the peer-reviewed journal *Optics Express*.

Co-Author: Martin Jan Tauc

Contributions: Processed cloud optical depth measurements from the lidar dual-polarization measurements.

Co-Author: Joseph A. Shaw

Contributions: Obtained funding, managed project overall, provided important insight and perspective in the analysis of the measurements, aided in the preparation of the manuscript and figures.

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All-Sky Polarization Imaging of Cloud Thermodynamic Phase

This chapter describes a study that used measurements from the LCVR-based all-sky polarimeter for determining cloud thermodynamic phase. This work is currently in the review process for the journal *Optics Express*. Sections in the first half of this chapter (Pgs. 138-160) contain direct excerpts from the paper in review. Work completed later with the three-camera Nikon all-sky polarimeter is not included in the journal paper that is currently undergoing peer review.

Background Summary

Knowing the cloud thermodynamic phase (if a cloud is composed of ice crystals or liquid droplets) is crucial for many cloud remote sensing measurements and can help in simulating and interpreting cloud radiation measurements to better understand the role of clouds in climate, weather, and optical propagation. Knobelspiesse et al. [25] showed that for simulated zenith observations, the algebraic sign of the S_I Stokes parameter (related to the difference between perpendicular and parallel linear polarization in the scattering plane) can be used to detect cloud thermodynamic phase when observed with a ground-based passive polarimeter. The solar scattering plane contains the directions of incident sunlight and scattered light. A positive or slightly negative S_I value indicates a liquid cloud with linear polarization parallel to the scattering plane, while a more negative S_I value indicates an ice cloud with linear polarization perpendicular to the scattering plane. They provided initial validation of simulation results using zenith-pointing, polarization-sensitive Cimel radiometers from the NASA Aerosol Robotic Network (AERONET).

The objective of this chapter was to detect cloud thermodynamic phase using a ground-based, all-sky imaging polarimeter following the same method. The Knobelspiesse et al. simulations suggested that the optimal measurement for cloud thermodynamic phase was not at the zenith, but in a direction in the solar principal plane approximately 55° from the sun. With our calibrated visible LCVR-based all-sky polarimeter operating in 10-nm-wide wavelength bands centered at 450 nm, 490 nm, 530 nm, 670 nm, and 780 nm, we were able to verify this. We were also able to verify this method using our visible three-camera Nikon all-sky polarimeter using the RGB channels. We detected ice, liquid, and multi-layered ice and liquid clouds using the measured S_1 Stokes parameter and we independently verified our results using dual-polarization lidar measurements at the zenith. Since we used all-sky polarization images from a multi-month campaign and did not focus solely on principal-plane measurements at the zenith, we found similarities and differences from what was described in their paper and we also observed similarities and differences between our two instruments. These will be addressed further in the results and discussion sections.

Dual-Polarization Lidar Overview

A dual-polarization lidar [77] was used to validate zenith cloud thermodynamic phase measurements taken with the all-sky polarimeter. This lidar uses a liquid crystal variable retarder in the receiver to alternate between co-polarized and cross-polarized polarization states of the backscattered signal from alternate laser pulses at a rate of 30 pulses/s. The laser source is linearly polarized and the two received signals are either parallel (co-polarized) or orthogonal (cross-polarized) to the laser signal. The cross-

polarization ratio (δ) was measured as a ratio of the cross-polarized and co-polarized signals. This ratio identifies the presence of ice crystals in the clouds since light scattered from polyhedral ice crystals has a significant fraction of cross-polarized light, while light singly scattered from water droplets does not [76].

Visible LCVR-Based All-Sky Polarimeter Measurements

The visible LCVR-based all-sky polarimeter and dual-polarization lidar were operated together at times when ice, liquid, and multi-layered clouds were present throughout a multi-month period in Bozeman, Montana. Example images showing S_0 , S_1 , DoLP, and AoP measured at 530 nm are displayed in Figures 74 and 76 with corresponding lidar cross-polarization ratios given in Figures 75 and 77, respectively. In Figure 74, examples of an ice cloud from 25 October 2016, a liquid cloud from 28 August 2018, multi-layered clouds from 5 July 2016, and clear sky from 15 February 2017 are shown. The solar zenith angles for these measurements were 65.9° , 41.4° , 23.1° , and 58.4° , respectively. In Figure 76, examples of liquid clouds from 20 September 2018 and 22 August 2018 and ice clouds from 28 September 2018 and 7 November 2016 are shown. The solar zenith angles for these measurements were 67° , 62° , 72° , and 50° , respectively. The images are shown with the top of the image representing north and the right side of the image representing west, and with angles measured relative to the scattering plane.

Stokes S_0 and DoLP images were used to determine the presence of clouds. Cloudy pixels were identified by higher radiance values in the S_0 images or lower values

in the DoLP images relative to the background sky because of multiple scattering within the cloud [42, 50]. However, because the AoP for ice clouds is aligned perpendicular to the scattering plane, the same as the clear sky, polarization angle alone is not a reliable indicator of clouds or cloud phase. The S_I images, however, look significantly different for the different cloud types. Most importantly, in agreement with the theoretical predictions, the ice cloud in Figure 74 produced negative S_I values (average value = -0.056), while the liquid cloud produced positive values (average value = 0.003). The multi-layered cloud in Figure 74 showed positive S_I values for the liquid clouds and negative S_I values for the ice clouds seen through the gaps in the liquid clouds (average ice value = -0.016; average liquid value 0.001). In this figure, the ice clouds are identified by the negative S_I values (corresponding to an AoP perpendicular to the scattering plane), while the liquid clouds are identified by the positive S_I values (corresponding to an AoP parallel to the scattering plane). The background skylight in all cases was polarized perpendicular to the scattering plane. In the examples presented, notice that cloud phase can be observed in the entire image, not just at the zenith.

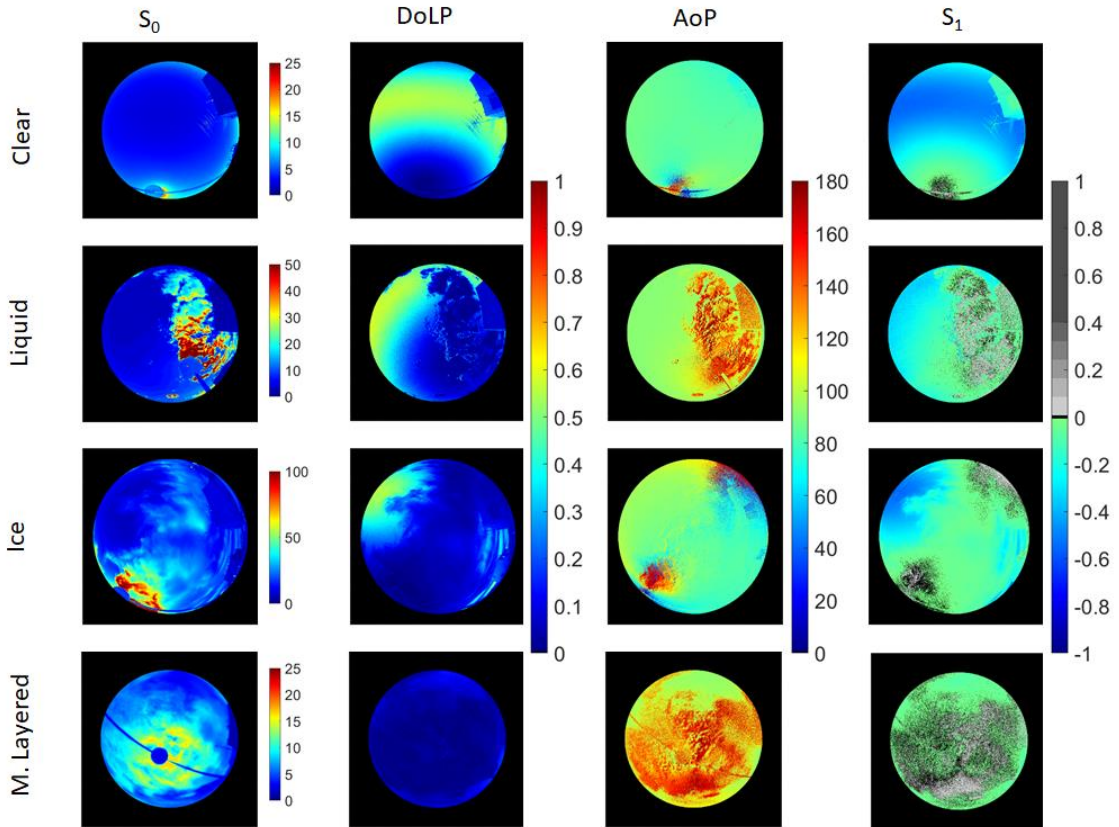


Figure 74. Visible LCVR-based all-sky polarimeter S_0 , S_1 , DoLP and AoP images referenced to the scattering plane. The measured S_1 values for the entire sky-dome indicate the presence of ice clouds on 25 October 2016, a liquid cloud on 28 August 2018, and multi-layered (ice and liquid) clouds on 5 July 2016. The solar zenith angles for these measurements were 65.9° , 41.4° , 23.1° , and 58.4° , respectively. Generally, negative values of S_1 indicate ice and positive values of S_1 indicate liquid cloud phase. A clear-sky on 15 February 2017 is representative of a Rayleigh atmosphere where positive values of S_1 indicate linear polarization parallel to the scattering plane and negative values of S_1 indicate linear polarization perpendicular to the scattering plane. For the all-sky images, the top of the image represents north and the right side of the image represents west. Measurements were recorded in Bozeman, Montana.

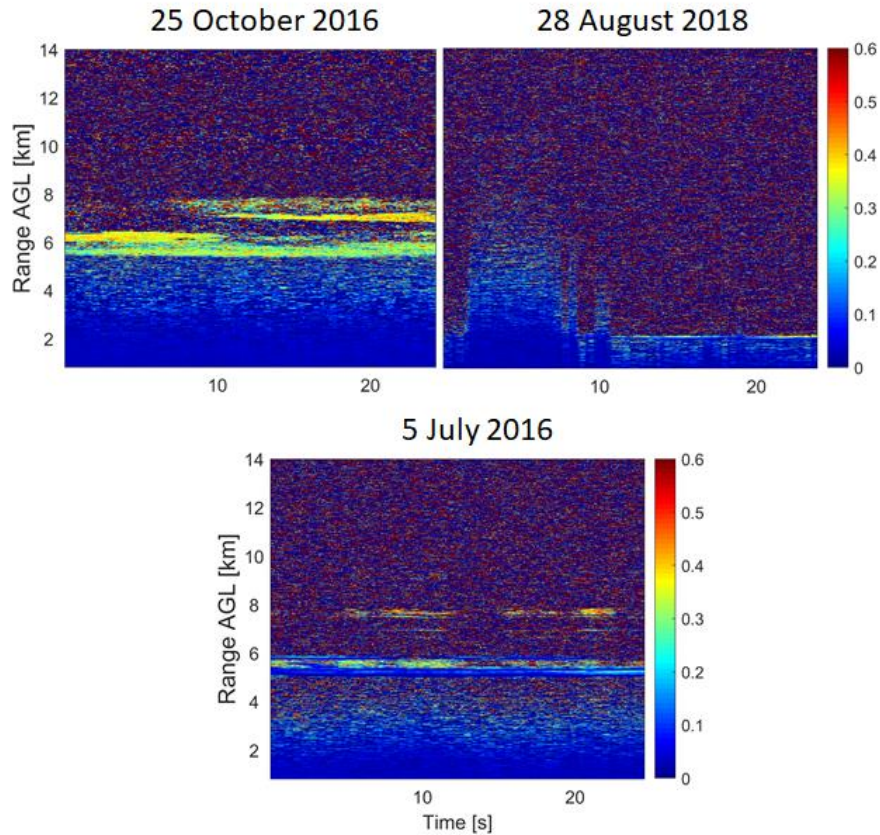


Figure 75. Dual-polarization lidar cross-polarization ratio measurements for 25 October 2016 (ice), 28 August 2018 (liquid), and 5 July 2016 (multi-layered). Measurements were taken at the zenith with the lidar running simultaneously with the visible LCVR-based all-sky polarimeter. The range on the y-axis represents the height of the clouds in the sky with respect to ground level (AGL). The color bar scaling represents the cross-polarization ratio. A cross-polarization ratio above 0.08 represents ice, while a cross-polarization below 0.08 represents liquid. Ideally, the cross-polarization ratio should be approximately zero for liquid; however, multiple scattering within the cloud layers can cause the cross-polarization to be greater than zero.

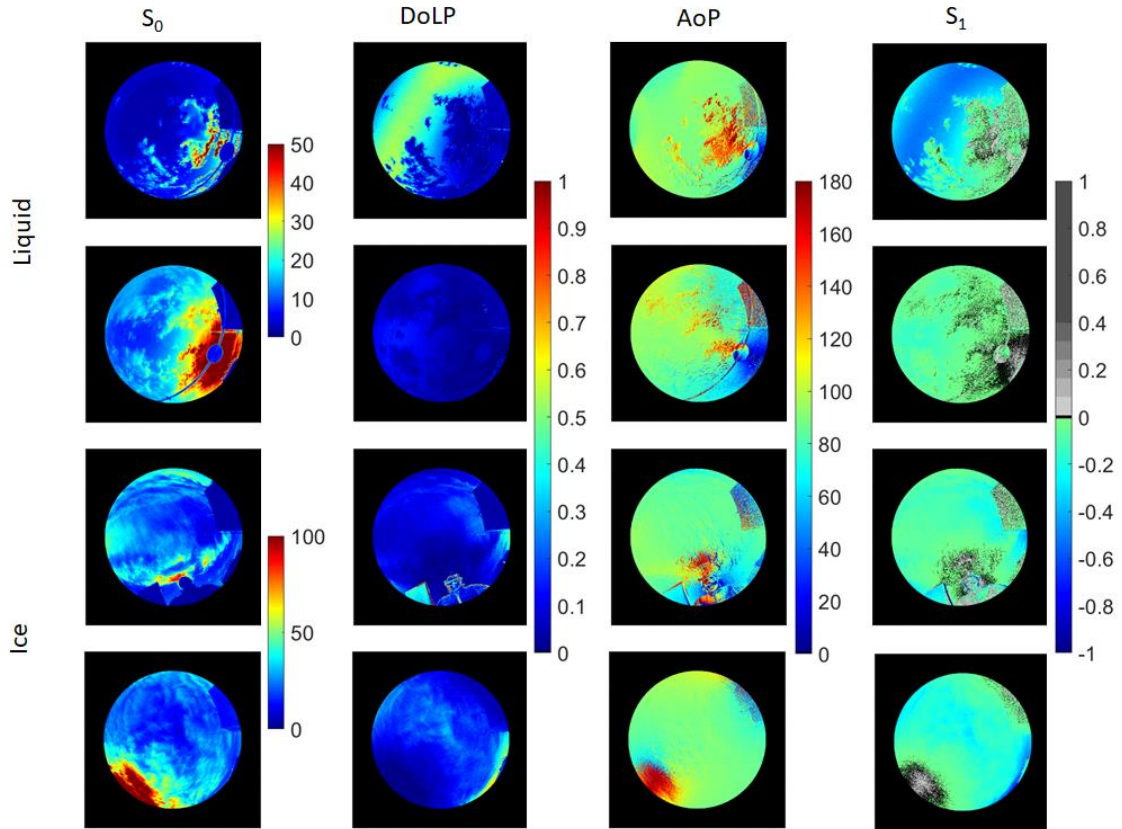


Figure 76. Visible LCVR-based all-sky polarimeter S_0 , S_1 , DoLP and AoP images referenced to the scattering plane. The measured S_1 values for the entire sky-dome indicate the presence of liquid clouds and ice clouds. Liquid clouds were observed on 20 September 2018 (First Row) and 22 August 2018 (Second Row) and ice clouds were observed on 28 September 2018 (Third Row) and 7 November 2016 (Fourth Row). The solar zenith angles for these measurements were 67° , 62° , 72° , and 50° , respectively. Generally, negative values of S_1 indicate ice and positive values of S_1 indicate liquid cloud phase. For the all-sky images, the top of the image represents north and the right side of the image represents west. Measurements were recorded in Bozeman, Montana.

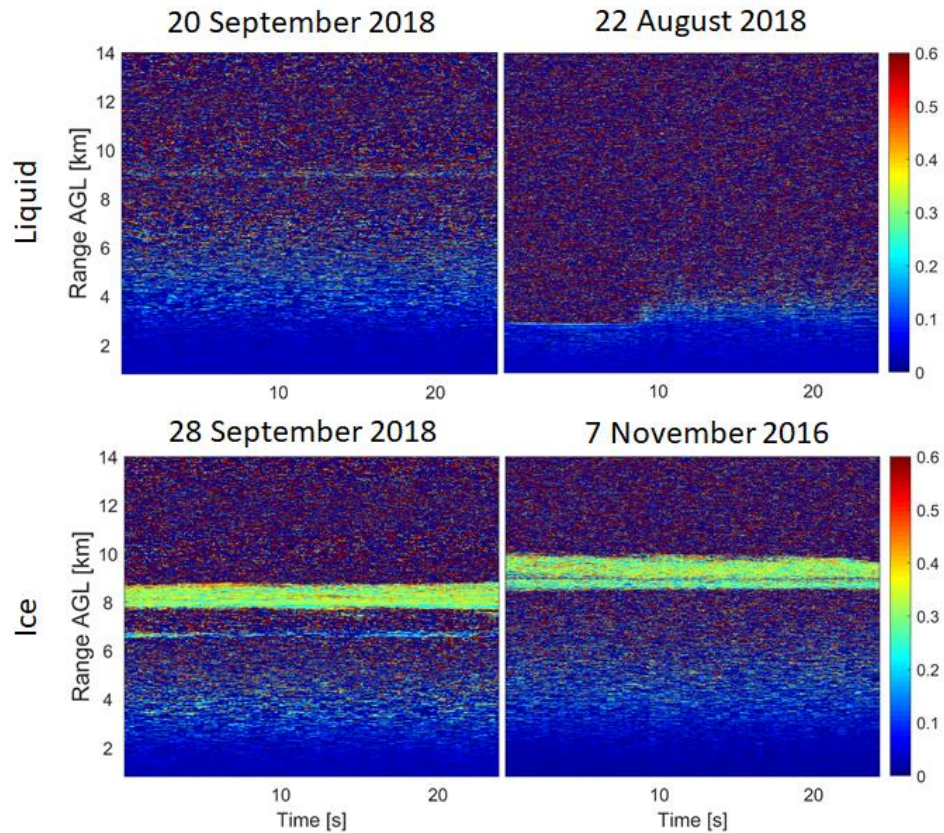


Figure 77. Dual-polarization lidar cross-polarization ratio measurements from 20 September 2018 (liquid), 22 August 2018 (liquid), 28 September 2018 (ice), and 7 November 2016 (ice). Measurements were taken at the zenith with the lidar running simultaneously with the visible LCVR-based all-sky polarimeter. The range on the y-axis represents the height of the clouds in the sky with respect to ground level (AGL). The color bar scaling represents the cross-polarization ratio. A cross-polarization ratio above 0.08 represents ice, while a cross-polarization below 0.08 represents liquid. Ideally, the cross-polarization ratio should be approximately zero for liquid; however, multiple scattering within the cloud layers can cause the cross-polarization to be greater than zero.

Zenith Measurements

A summary of 27 different zenith measurements at each all-sky polarimeter wavelength, validated with the dual-polarization lidar, are shown in Figure 78, with corresponding data listed in Table 8. The listed S_I parameters were calculated by masking a region of clouds near the zenith (in a cone of 5° radius) and by averaging the masked S_I values for the cloud pixels. A mask of the cloud pixels was created by normalizing the S_0 image and selecting values greater than the background skylight. In Table 8, the zenith angles correspond to the scattering angles in the solar principal plane, similar to the simulations presented in Knobelspiesse et al. [25] (the scattering angle is defined as the angle between the solar illumination direction and the scattered direction). The zenith angles in parentheses correspond to cloud pixels measured off-axis (i.e. not at the zenith) with the same cloud-identification procedure applied. A positive or slightly negative S_I value theoretically indicates a liquid cloud, while a more negative value indicates an ice cloud. Accordingly, we measured negative S_I values for ice clouds (verified at the zenith with the lidar) and both negative and positive values for verified liquid clouds. We detected cloud phase for multiple days with solar zenith angles ranging from 23° to 72° . Lidar validation measurements are presented in Figure 79. A lidar cross-polarization ratio less than 0.08 indicates liquid, while a cross-polarization ratio greater than 0.08 indicates ice (the cross-polarization ratio for liquid phase should be approximately zero; however, multiple scattering can lead to cross-polarization ratios above zero). Notice that in Figure 79 there is a clear separation between the verified liquid and ice S_I values.

Solar Geometry				Polarimeter (S_I)					Lidar	AERONET
	Date	Time	Ze	450 nm	490 nm	530 nm	670 nm	780 nm	δ	AOD
2016										
1	0123	2101	68	-0.202					0.47	0.20
2	0304	1953	52	-0.156	-0.143	-0.119	-0.075	-0.053	0.40	0.19
3	0304	2024	53	-0.139	-0.132	-0.104	-0.058	-0.038	0.40	0.08
4	0401	2056	45	-0.008	0.003	0.010	0.023	0.025	0.03	0.03
5	0401	2115	47	-0.027	-0.016	-0.006	0.016	0.021	0.02	0.07
6	0401	2150	51 (46)	0.003	0.007	0.014	0.025	0.023	0.02	0.07
7	0401	2234	57 (50)	-0.040	-0.026	-0.014	-0.004	-0.003	0.02	0.02
8	0630	1811	27	-0.002	-0.001	0.001	0.002	0.005	0.03	0.36
9	0705	1941	23	-0.011	-0.014	-0.016	-0.017	-0.009	0.39	0.66
10	0705	1941	23	0.001	0.004	0.001	0.004	0.006	0.02	0.66
11	0706	2016	25	0.000	-0.001	-7.2e-5	-0.003	-0.005	0.06	0.07
12	0902	1838	39 (73)	-0.067	-0.041	-0.034	-0.005	0.009	0.03	0.21
13	1018	2158	67	-0.125	-0.062	-0.049	-0.039	-0.025	0.40	0.01
14	1021	1607	70	-0.096	-0.077	-0.064	-0.027	-0.016	0.03	0.36
15	1025	1649	66	-0.086	-0.065	-0.056	-0.033	-0.017	0.41	0.04
16	1107	1629	72	-0.227	-0.209	-0.181	-0.107	-0.071	0.34	0.17
2018										
17	0731	1455	63	-0.078	-0.074	-0.072	-0.078	-0.075	0.31	0.16
18	0803	1721	39 (73)	-0.112	-0.115	-0.127	-0.180	-0.203	0.11	0.47
19	0816	1525	59	-0.178	-0.174	-0.173	-0.193	-0.191	0.18	0.24
20	0822	2232	62	-0.062	-0.053	-0.034	-0.038	-0.033	0.04	0.47
21	0828	2059	41 (24)	0.002	-0.001	0.003	0.005	0.006	0.05	0.08
22	0830	2019	39	-0.004	-0.006	-0.005	-0.005	-0.011	0.03	0.20
23	0919	1918	44	-0.065	-0.057	-0.049	-0.033	-0.034	0.04	0.27
24	0920	1543	65	-0.003	-0.002	0.001	0.015	0.010	0.03	0.12
25	0920	2307	67 (20)	-0.020	-0.020	-0.018	-0.013	-0.009	0.02	0.10
26	0926	1735	52	-0.165	-0.137	-0.137	-0.075	-0.073	0.33	0.08
27	0928	2012	50	-0.064	-0.050	-0.044	-0.022	-0.009	0.32	0.07

Table 8. All-sky polarimeter (zenith S_I), dual-polarization lidar, and AERONET data. For each day, the time of measurement (UTC) as well as the solar zenith (Ze) angles were recorded (time notation: MMDD). Scattering angles in the principal plane (i.e. zenith measurement) correspond to the solar zenith angles. Angles in parentheses represent the zenith angle of cloud pixels measured off-axis. For each wavelength, the mean cloud phase retrieved from the polarimeter's Stokes S_I image was recorded. Cloud phase measurements were validated using a dual-polarization lidar. The cross-polarization ratio (δ) indicates liquid ($\delta < 0.08$) or ice ($\delta > 0.09$) phase. The AERONET aerosol optical depth (AOD) corresponds to level 1.0 processed data at 500 nm. Missing values in the polarimetric measurements represent a time when the corresponding wavelengths were not selected. The measurement site latitude and longitude coordinates were 45.67 and -111.05, respectively.

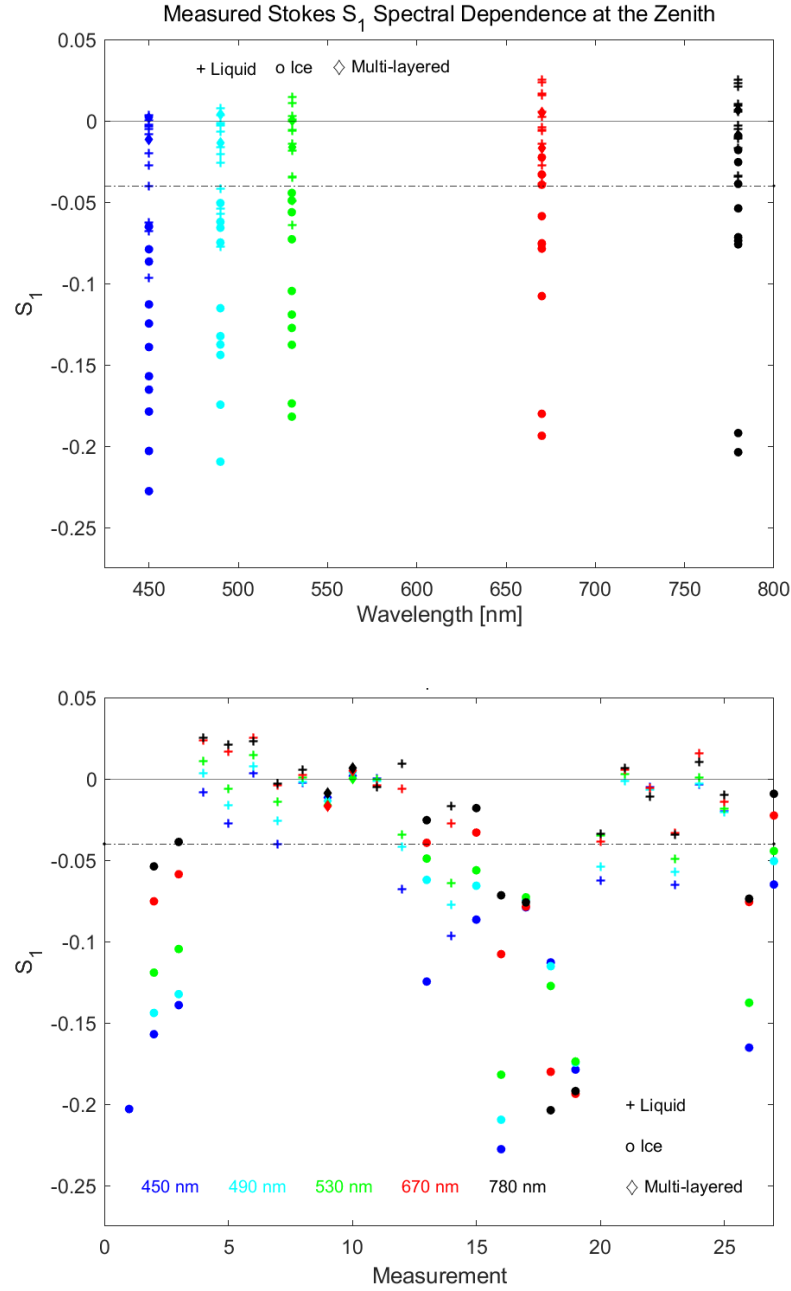


Figure 78. Multi-wavelength all-sky polarimeter measurements validated with a dual-polarization lidar at the zenith. Liquid clouds are represented by the plus (+) symbols, ice clouds are represented by the unfilled circles (o), multi-phase clouds are represented by diamonds (◇). The 450, 490, 530, 670, and 780 nm measurements are represented by blue, cyan, green, red, and black colors, respectively. Ice clouds were generally found to have S_1 values less than -0.04 (dashed line) and liquid clouds tended to be both positive and slightly negative (at scattering angles larger than 60°).

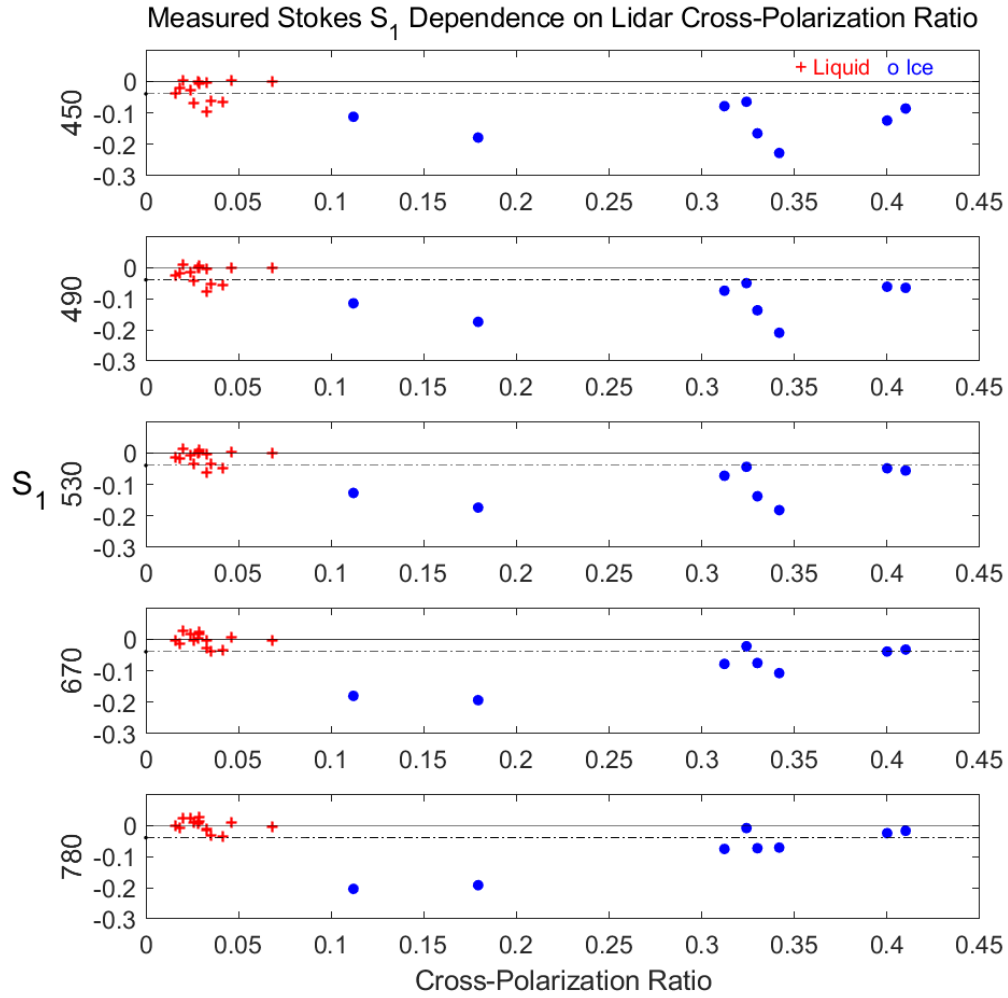


Figure 79. The observed relationship between the Stokes S_1 parameter in the scattering plane and the lidar's measured cross-polarization ratio at the zenith for each wavelength. Liquid clouds are represented by the red plus (+) symbols, ice clouds are represented by the blue, filled circles (o).

In our observations shown in Figure 78, clouds were generally more polarizing at shorter wavelengths for ice clouds and at longer wavelengths for liquid clouds, in agreement with the Knobelspiesse predictions. From Figure 78, we determined a threshold of $S_I = -0.04$ to distinguish between zenith-validated liquid and ice clouds. An S_I value greater than -0.04 indicates liquid phase, while a S_I value less than -0.04 indicates ice phase.

Polarimetric cloud phase determination was also observed to depend on scattering angle, especially for liquid clouds. The simulations of Knobelspiesse et al. [25] showed that ice clouds could be detectable between scattering angles of approximately 10° and 150° , while liquid clouds could only be reliably detected between scattering angles of 10° and 70° (using the baseline that ice clouds are negative and liquid clouds are positive). For liquid clouds, measured S_I values were greatest between scattering angles of 10° and 60° , as observed in Figure 80, which shows the S_I scattering angle dependence with wavelength (for measurements validated at the zenith). Our optimal scattering angle was observed to be closer to 45° , not 55° as predicted by Knobelspiesse. For scattering angles greater than 60° , the classification of liquid phase was observed to vary with wavelength. For clouds determined to be liquid with zenith lidar observations, S_I measurements at 670 and 780 nm were greater than -0.04 , while measurements at 450, 490, and 530 nm were less than -0.04 . A diagonal threshold could also be used to enhance the detection of cloud phase at shorter wavelengths. In general, ice clouds could be determined reliably for scattering angles from 0° to beyond 70° . The scattering angle dependence for the measured pixels in the entire field of view will be discussed further in the All-Sky Measurement section.

In Figure 78, measurements 11, 18, and 19 were observed to have reverse wavelength dependence relative to the other measurements. Measurement 11 corresponds to verified liquid S_I values, where measurements 18 and 19 correspond to verified ice S_I values. These measurements were made on 6 July 2016, 3 August 2018, and 16 August 2018, respectively. The liquid S_I values in measurement 11 could suggest a minimum scattering angle needed to reliably detect liquid phase based on spectral measurements. In this case, the scattering angle was 25° and S_I values were greatest at shorter wavelengths. In measurements 18 and 19 (made at scattering angles of 73° and 59° , respectively), the aerosol optical depth at 500-nm wavelength was 0.47 and 0.24, respectively, indicating the atmosphere was quite smoky. It seems likely that this spectral reversal arose because the smoke layer was selectively depolarizing the shorter-wavelength light scattered from the cloud above; however, an alternate idea to consider is that the smoke aerosols could have enhanced the long-wavelength polarization, as we recently observed at SWIR wavelengths for thick wildfire smoke [52, 53], although in those previous observations the smoke only enhanced the polarization for wavelengths longer than $1\ \mu\text{m}$. The S_I dependence on aerosol optical depth can be observed in Figure 81.

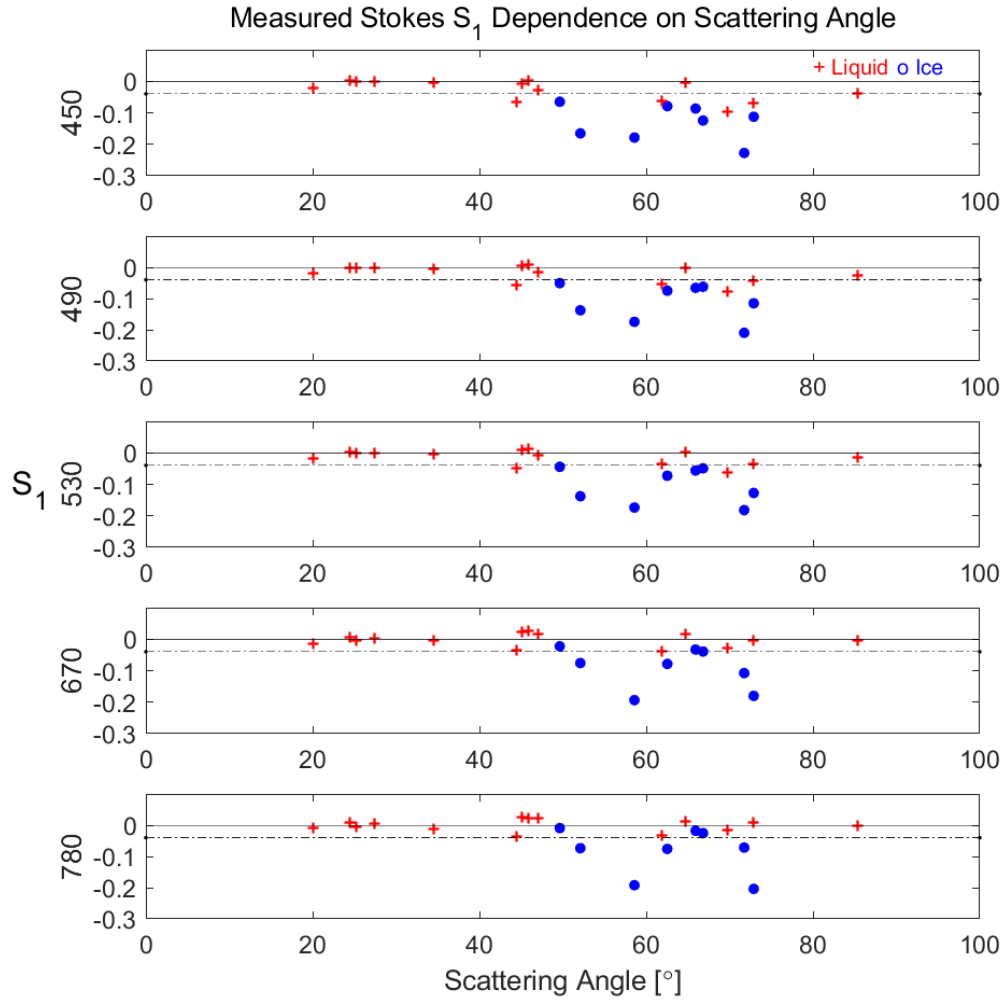


Figure 80. The observed relationship between the Stokes S_1 parameter in the scattering plane at the zenith and the corresponding scattering angle for each wavelength.

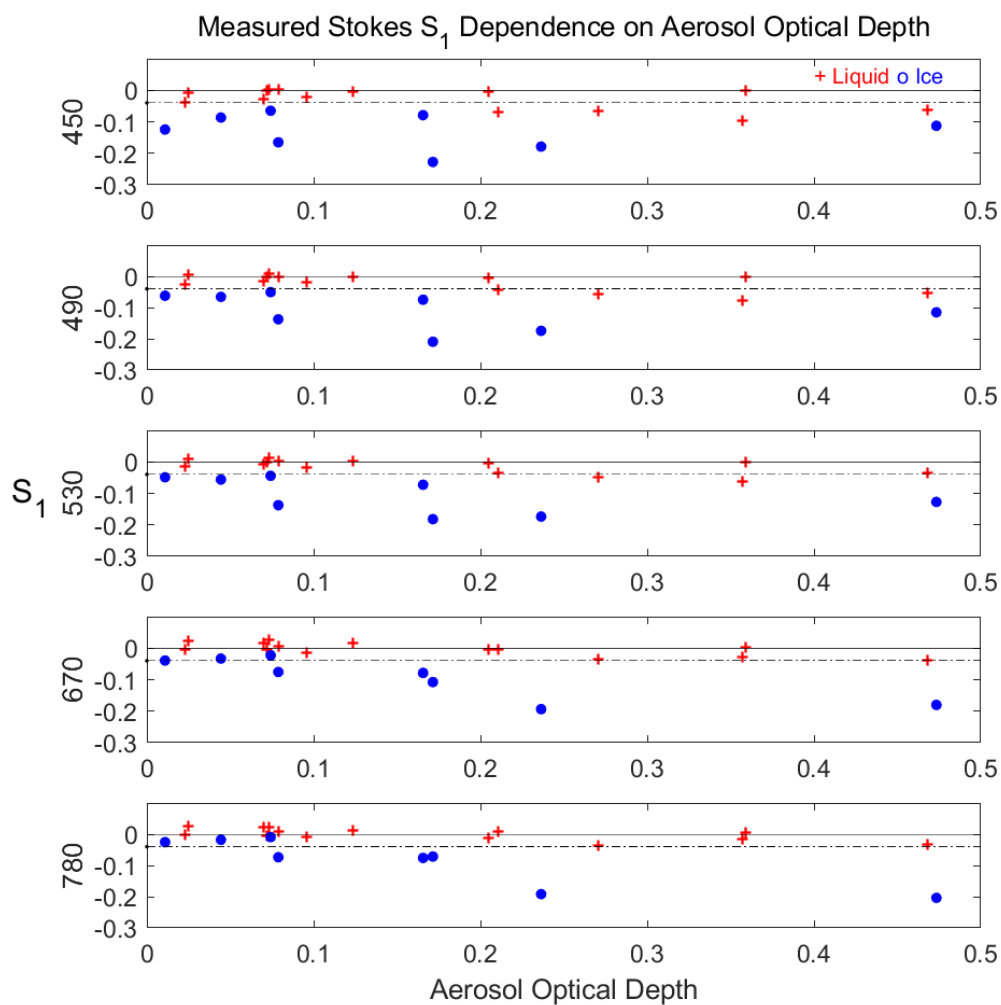


Figure 81. The observed relationship between the Stokes S_1 parameter in the scattering plane and the AOD retrieved from AERONET for each wavelength. An observed switch in the spectral dependence was observed for ice clouds at AOD values greater than 0.2. Below an AOD value of 0.2, the S_1 value was greatest at shorter wavelengths. Above an AOD value of 0.2, the S_1 value was greatest at longer wavelengths.

All-Sky Measurements

In Figure 82, all-sky images show the relationship between S_I (referenced to the scattering plane) and scattering angle for the five polarimeter wavelengths in the entire sky-dome for a zenith-verified liquid example on 1 April 2016. This multi-wavelength example shows liquid clouds having greater S_I values and more of the cloud being detected in the image at longer wavelengths. Scattering angles of 10° and 70° are shown on the images with black lines to indicate the approximate angular range in which liquid phase can be reliably identified. All-sky polarimeter S_I images at 530 nm from 1 April 2016 and 31 July 2018 are also shown in Figure 83 with scattering angles of 10° and 70° . Figures 82 and 83 show the significance of measuring cloud phase with respect to scattering angle when detecting liquid phase. Ice phase can be detected in the entire image of an all-sky Stokes S_I image, where liquid phase detection is mainly bound between scattering angles of 10° and 70° and depends on wavelength.

A mask of the cloud pixels in Figure 84 was created by normalizing the S_0 image and masking out values greater than the background skylight (if using a RGB camera system, cloud masking could be done using methods presented by [118]). We did not use a red/blue ratio to find clouds with the visible LCVR-based all-sky imager because there is a multi-second delay between image sets at different wavelengths (this system provides rapid calculation of a polarimetric image sequence, but with a larger delay between spectral channels). The masked regions were then applied to the S_I image, scattering angle image, and zenith angle image (Figure 84) to visualize the measured S_I dependence with scattering angle (Figure 85) and zenith angle (Figure 86) in the entire all-sky image. Ice clouds were

generally found to have S_I values less than -0.04 (dashed line), where liquid clouds tended to be both positive and slightly negative. At scattering and zenith angles greater than 60° and 25° , respectively, liquid clouds were found to have S_I values less than -0.04.

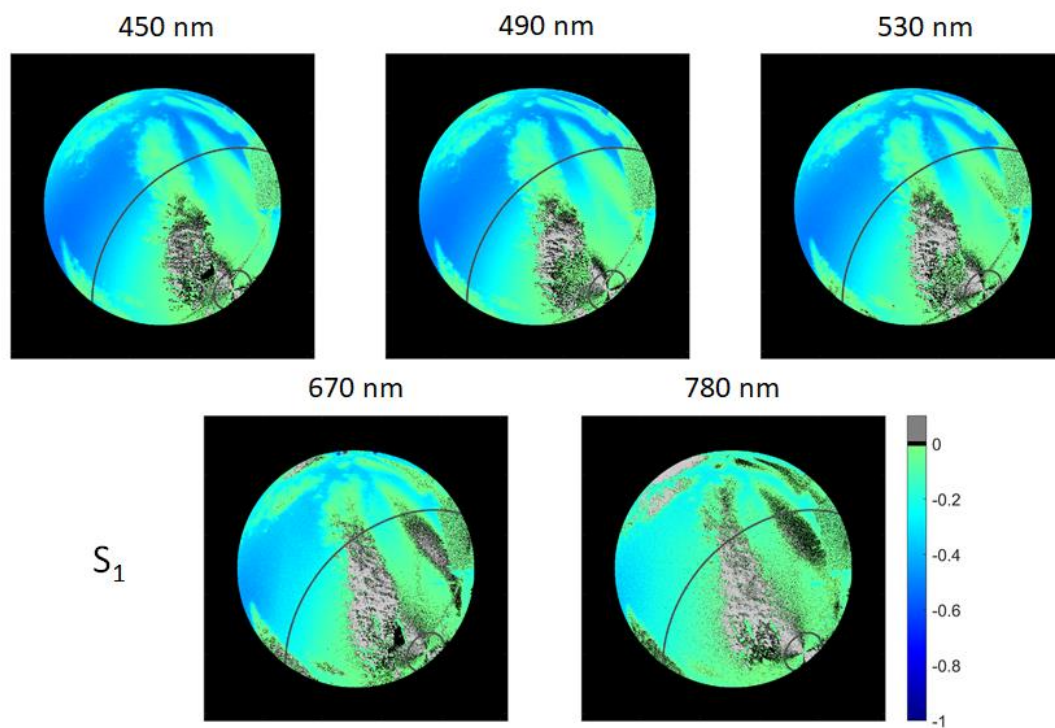


Figure 82. The observed variation with wavelength of the Stokes S_I parameter expressed relative to the scattering plane for a liquid cloud on 1 April 2016 for a solar zenith angle of 51° . Scattering angles of 10° and 70° are shown on the images with black lines.

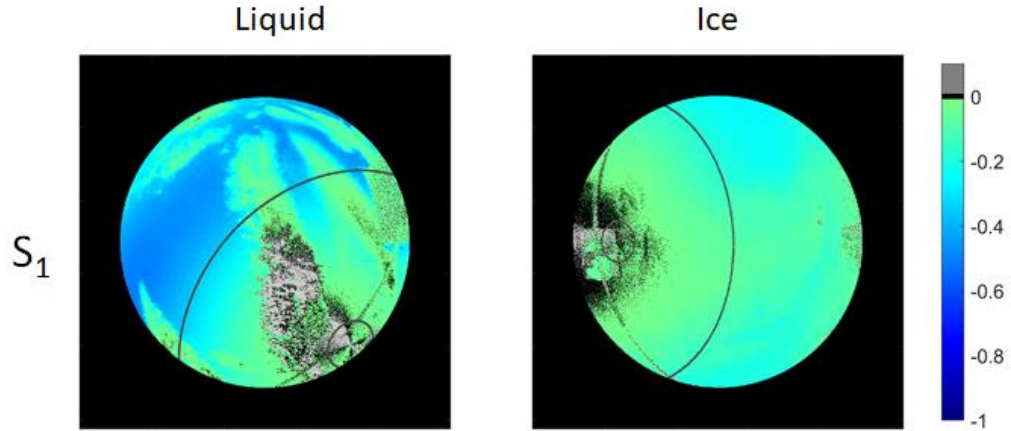


Figure 83. All-sky polarimeter S_1 images at 530 nm from 1 April 2016 and 31 July 2018 showing liquid and ice clouds for solar zenith angles of 51° and 63° , respectively. Scattering angles of 10° and 70° are shown on the images with black lines.

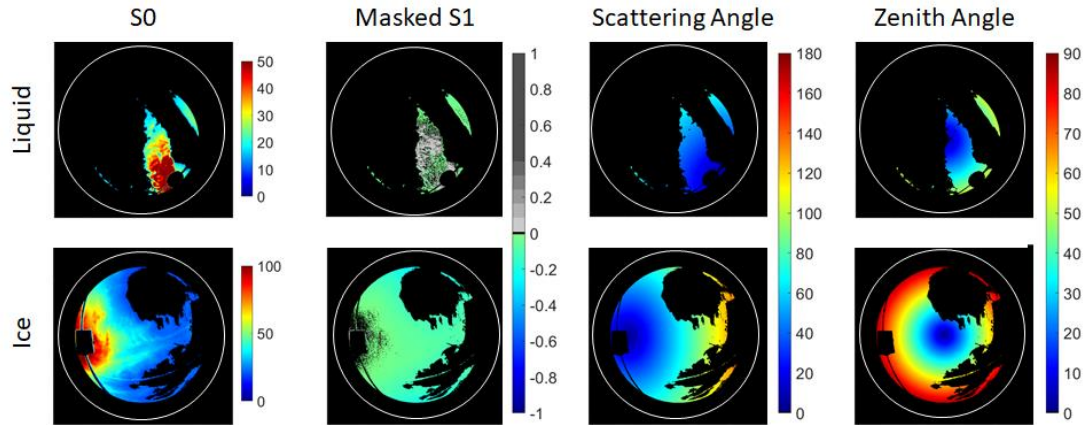


Figure 84. Example of cloud pixel masking using the S_0 image to detect the presence of clouds, with corresponding masked cloud pixels in the S_1 , scattering angle, and zenith angle images.

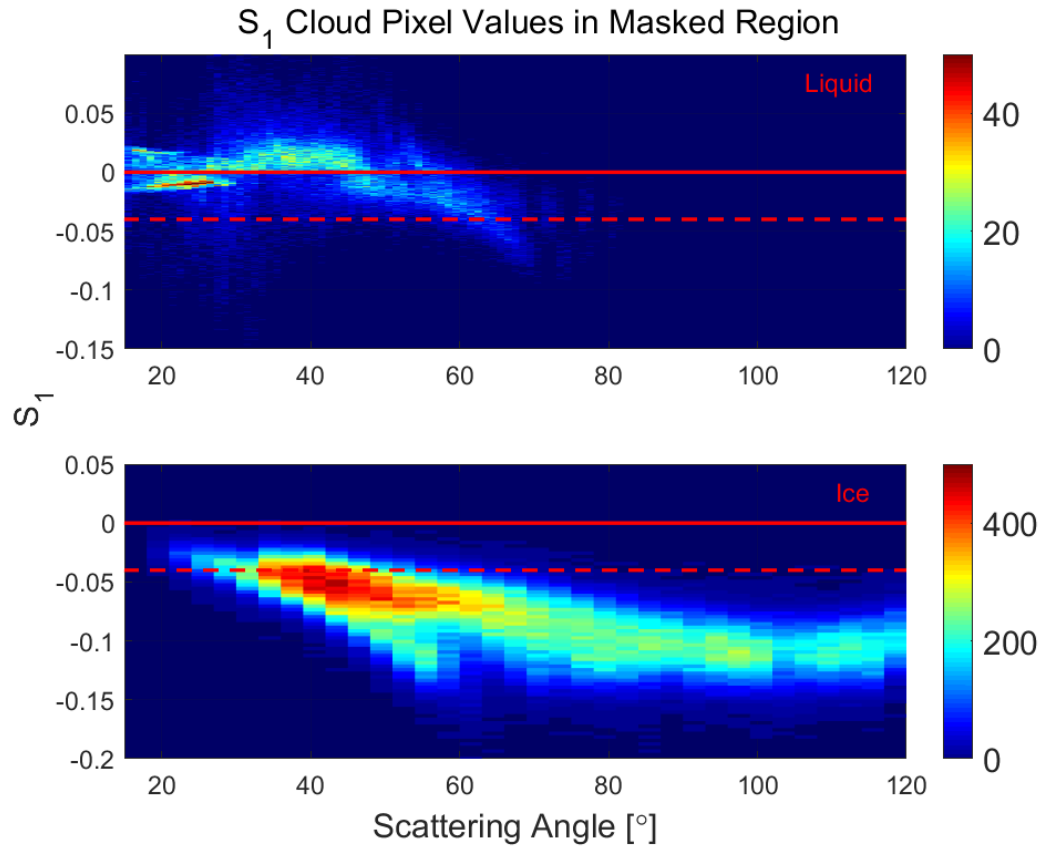


Figure 85. The relationship between the measured cloud S_1 values (referenced to the scattering plane) and scattering angle for liquid clouds on 1 April 2016 (top) and ice clouds on 31 July 2018 (bottom) at 530 nm. Ice clouds were generally found to have S_1 values less than -0.04 (dashed line), where liquid clouds tended to be both positive and slightly negative. At scattering angles greater than 60°, liquid clouds were found to have S_1 values less than -0.04, thus overlapping with the range of S_1 values that would otherwise indicate ice clouds. The solar zenith angles were 51° and 63°, respectively.

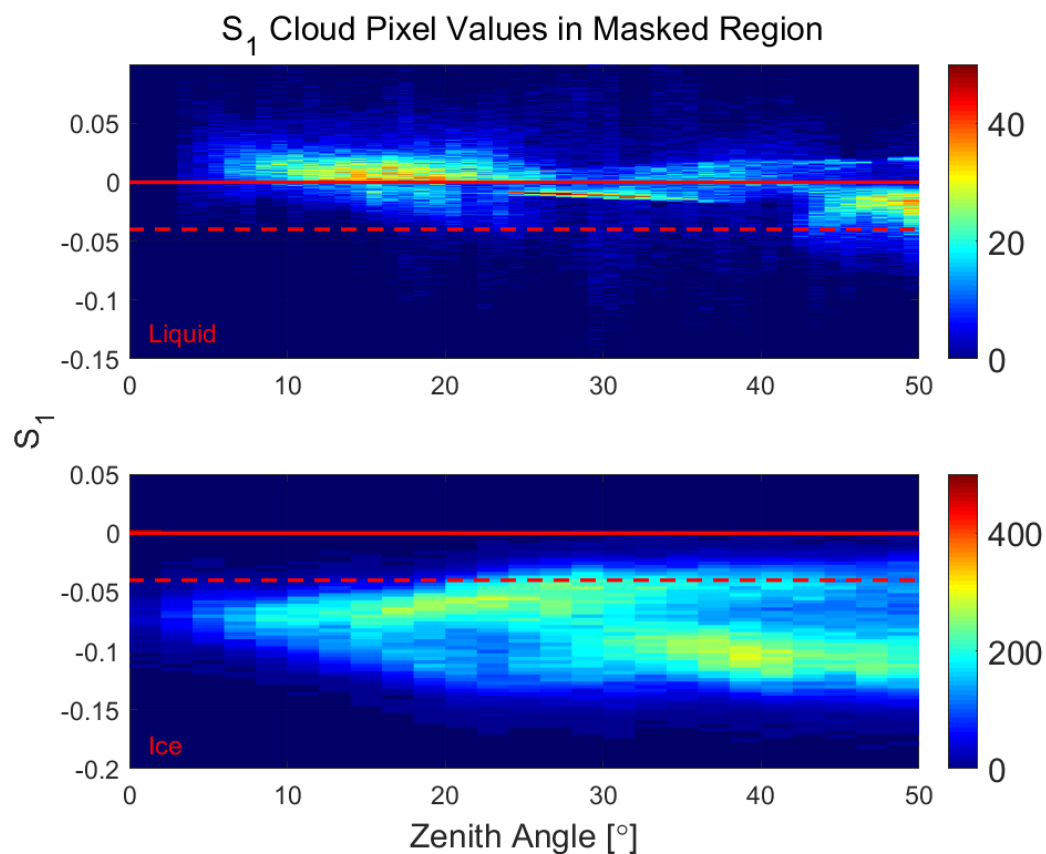


Figure 81. The relationship between the measured cloud S_1 values (referenced to the scattering plane) and zenith angle for liquid clouds on 1 April 2016 (top) and ice clouds (bottom) on 31 July 2018 at 530 nm. Ice clouds were generally found to have S_1 values less than -0.04 (dashed line), where liquid clouds tended to be both positive and slightly negative. Liquid clouds tended to be more positive for zenith angles less than 25°. Ice clouds were negative for all zenith angles. The solar zenith angles were 51° and 63°, respectively.

Discussion

Careful observation guidelines must be considered when measuring cloud phase in the entire sky dome. First, the sun-cloud-observer geometry significantly affects the measured S_I image. If the polarimeter's reference frame is not aligned to the scattering plane, the determination of cloud phase cannot be made accurately, as illustrated in Figure 87. With S_I expressed in the polarimeter's reference plane (IP), cloud phase is ambiguous and depends on the scattering geometry. However, expressing S_I relative to the scattering plane (SP) for each pixel allows us to reliably detect liquid phase over the scattering angles of 10° to 70° (for Figure 87, the lidar's cross-polarization ratio was approximately 0.02 at a cloud height of 3.5 km, indicating liquid-phase clouds). In other words, for a fisheye image it is necessary to rotate the polarimeter's frame of reference into the scattering plane reference, as described in chapter 2, to determine cloud phase in the entire image, not just the principal plane. For measurements with a point-source polarimeter, the instrument could be deployed on an azimuthal mount so that the polarimeter's reference frame was always aligned with respect to the solar scattering plane (i.e. the reference polarizer would be parallel to the scattering plane). With the instrument aligned in this fashion, the polarimetric reference plane at each point would be the solar scattering plane unique to that position.

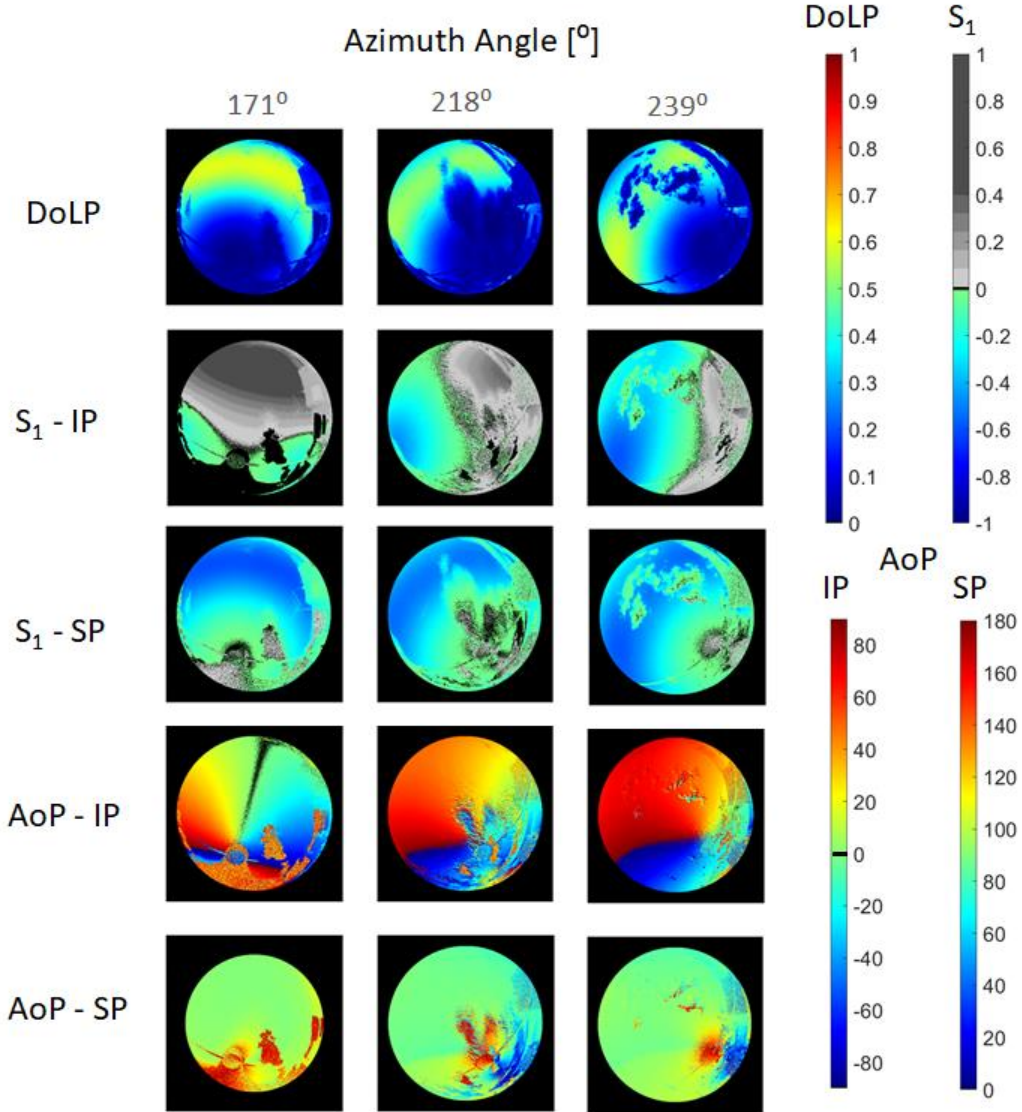


Figure 87. DoLP, S_1 , and AoP images in the instrument plane (IP) and scattering plane (SP) from 1 April 2016 with solar azimuth angles of 171°, 218°, and 239° and zenith angles of 41°, 47°, and 57°, respectively. This figure demonstrates the importance of aligning the polarimeter's reference frame to the scattering plane. In the polarimeter's reference frame, both phases are detected depending on the scattering geometry whereas in the scattering plane, liquid phase is detected over the scattering angles of 10° and 70° (the lidar's cross-polarization ratio was approximately 0.02 at a cloud height of 3.5 km (AGL), indicating liquid phase).

The spectral distribution of S_I values in Figure 79 suggests that it might be possible to use an RGB polarimeter [119] for fast spectral and polarimetric acquisition, possibly employing a red/blue ratio to identify clouds. Using the threshold of -0.04 for measurements made with the narrow-band LCVR polarimeter, ice phase was correctly identified 80% of the time for the 670 nm and 780 nm channels and 100% of the time for the 450 nm, 690 nm, and 530 nm wavelength channels. Liquid phase was correctly identified 100% of the time for the 670 nm and 780 nm channels and 70%, 77%, and 85% for the 450 nm, 690 nm, and 530 nm channels, respectively. Figure 88 shows that it may be possible to enhance the cloud phase identification by using two wavelengths, such as red and blue, because ice clouds tend to have larger S_I magnitudes at shorter wavelengths (blue), where liquid clouds tend to have larger S_I magnitudes at longer wavelengths (red). A common threshold of approximately -0.04 could be used or possibly separate thresholds could be found for the red and blue channels to identify cloud phase. However, these initial data suggest this classification may not always work for multi-layered clouds or for measurements at scattering angles greater than approximately 60°.

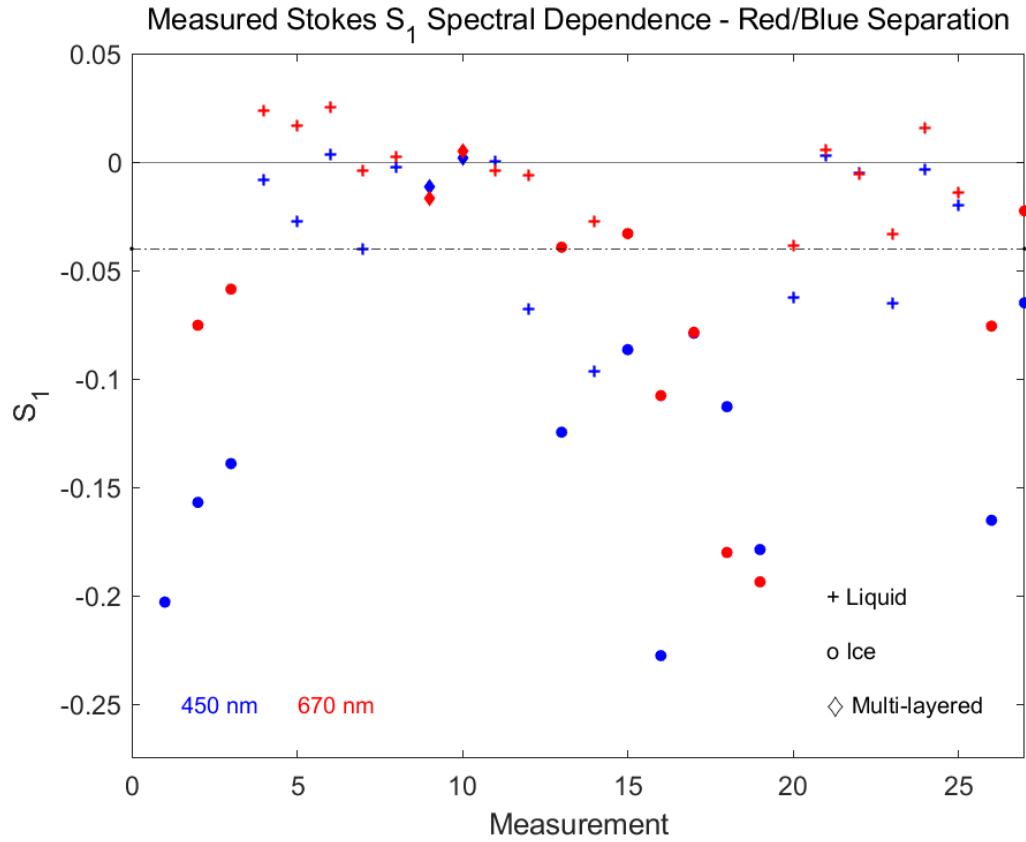


Figure 88. Red/blue wavelength validated all-sky polarimeter measurements with a dual-polarization lidar at the zenith. Liquid clouds are represented by the plus (+) symbols, ice clouds are represented by the unfilled circles (o), multi-phase clouds are represented by diamonds (♦). The 450 and 670 nm measurements are represented by blue and red colors, respectively.

Three-Camera All-Sky Polarimeter Measurements

To supplement the results observed with the LCVR-based all-sky polarimeter, the visible three-camera all-sky polarimeter was used to detect cloud thermodynamic phase for multiple days ranging from July 2018 to September 2018 in Bozeman, Montana. RGB images were analyzed and with this polarimeter a red/blue ratio [118] was applied to mask cloud pixels in the S_I image. The cloud pixels were calculated by masking a region of clouds near the zenith (in a cone of 5° radius). By using three DSLR cameras with polarization filters aligned to 0° , 60° , and 120° , simultaneous spectral and polarimetric acquisition could be achieved. Two limitations exist with this system. The first is that it currently is not housed in a weather proof case. For each measurement, the system needs to be set up; however, this is not a huge issue since the system is compact, portable, and is controlled with a laptop. The second limitation is that currently there is no sun occulter on the system. A manual occulter was tested, but with three cameras this blocked a large piece of the field of view. Operating without an occulter leads to minor ghost artifacts that sometimes can be observed in the solar principal plane, above and below the sun, in the Stokes S_I and AoP images. These artifacts were not observed in the LCVR-polarimeter images because on that instrument a sun occulter was always used.

Example I_0 , AoP, and S_I images measured in the blue channel are displayed in Figures 89, 91, and 93 for verified ice, liquid, and multi-layered clouds (containing both ice and liquid phase), respectively. Corresponding lidar cross-polarization ratio measurements are given in Figures 90, 92, and 94, respectively. These all-sky polarization

images are aligned with north at the top and west to the right and the Stokes parameters and AoP images presented in this section are referenced relative to the scattering plane.

Results obtained with the Nikon system were similar to those obtained with the LCVR system. In general, liquid clouds were observed to rotate the AoP by 90° from the polarization orientation found in ice clouds and the clear sky. Ice clouds were observed to not deviate significantly from clear-sky AoP. In the Stokes S_I images, ice clouds produced negative S_I values, while the liquid clouds produced positive values. The background skylight in all cases was observed to be polarized perpendicular to the scattering plane. In Figure 89, the detection of ice phase was generally independent of scattering angle; however, ghost effects from the sun resulted in positive S_I values above and below the sun in the solar principal plane, limiting the detection of ice clouds in this region. In Figure 91, the liquid clouds were sometimes dependent on scattering angle, similar to the results observed with the visible LCVR-based all-sky polarimeter; however, in most cases, the liquid phase could be determined in the entire all-sky image. In Figure 93, both liquid and ice phase could be observed and were not dependent on scattering angle. Ghost effects were observed in all cases and could have been removed by using a sun occulter; however, this would limit the all-sky field of view. With this system, off-zenith measurements beyond a scattering angle of approximately 50° gave the most reliable results.

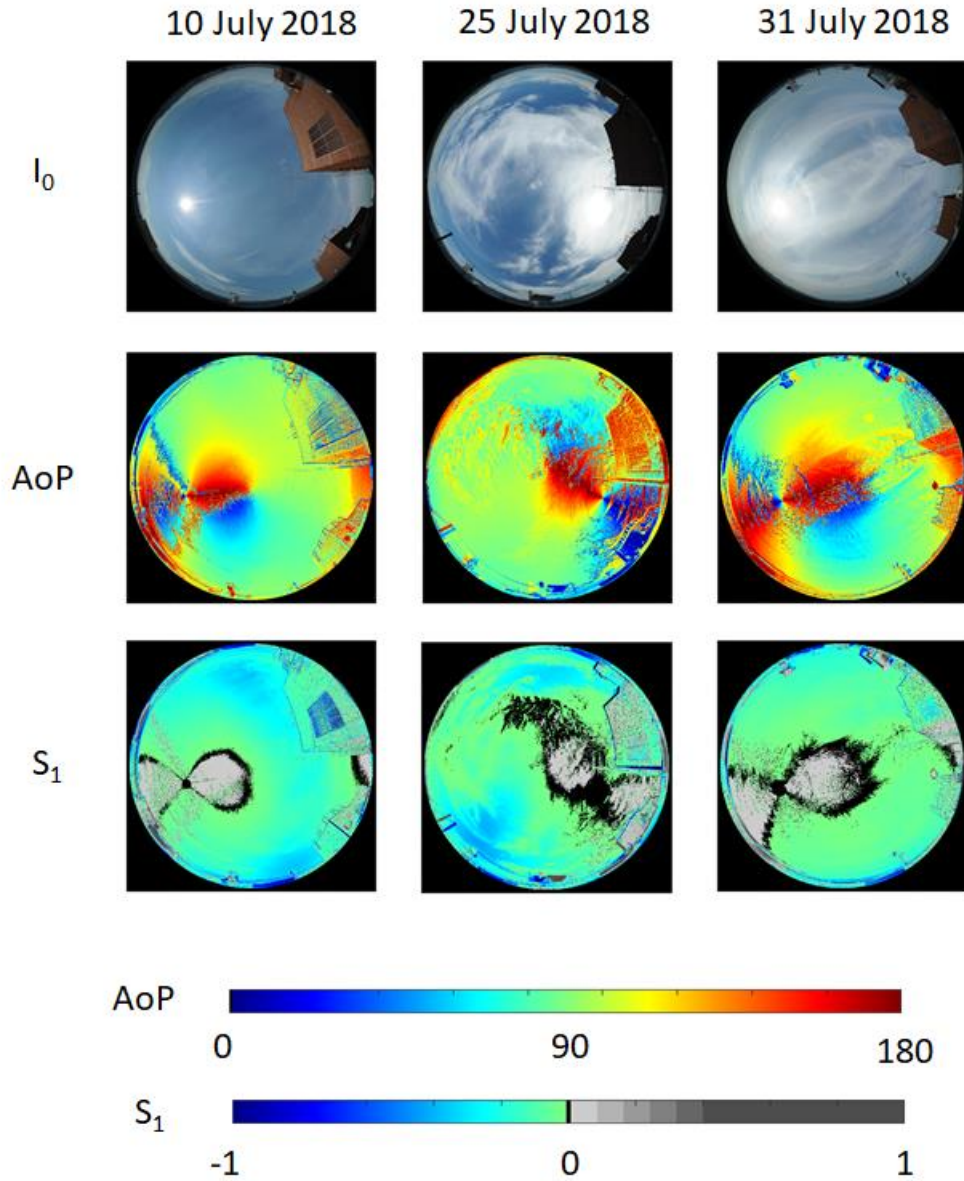


Figure 89. Three-camera Nikon all-sky polarimeter I_0 , AoP , and S_1 images referenced to the scattering plane. Ice clouds were observed on 10 July 2018 (Left), 25 July 2018 (Middle), and 31 July 2018 (Right). The solar zenith and azimuth angles were 49°, 43°, 47°, and 99°, 247°, 110°, respectively. Negative values of S_1 indicate ice. For the all-sky images, the top of the image represents north and the right side of the image represents west. Measurements were recorded in Bozeman, Montana. Notice in the I_0 image at the upper right that a 22° halo adds additional evidence of ice.

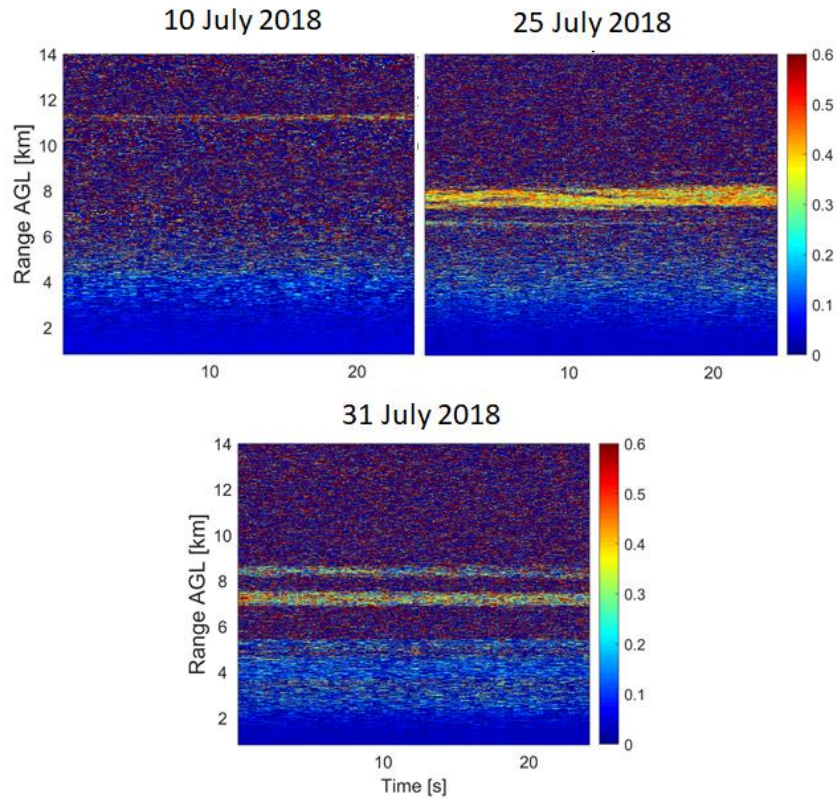


Figure 90. Dual-polarization lidar cross-polarization ratio measurements from 10 July 2018, 25 July 2018, and 31 July 2018 showing ice phase. Measurements were taken at the zenith with the lidar running simultaneously with the three-camera Nikon all-sky polarimeter. The range on the y-axis represents the height of the clouds in the sky with respect to ground level (AGL). The color bar scaling represents the cross-polarization ratio. A cross-polarization ratio above 0.08 represents ice, while a cross-polarization below 0.08 represents liquid. Ideally, the cross-polarization ratio should be approximately zero for liquid; however, multiple scattering within the cloud layers can cause the cross-polarization to be greater than zero.

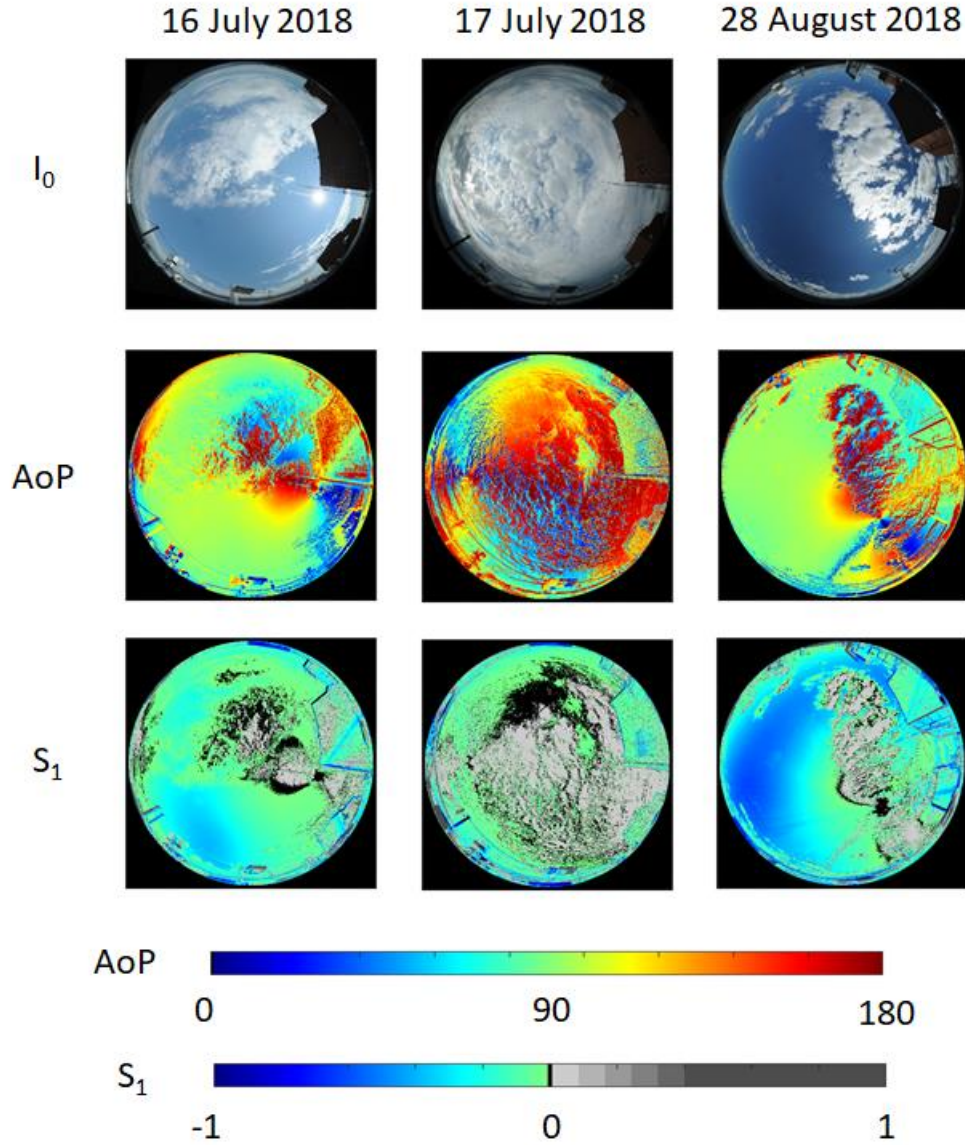


Figure 91. Three-camera Nikon all-sky polarimeter I_0 , AoP, and S_1 images referenced to the scattering plane. Liquid clouds were observed on 16 July 2018 (Left), 17 July 2018 (Middle), and 28 August 2018 (Right). The solar zenith and azimuth angles were 50° , 60° , 42° , and 260° , 90° , 217° respectively. Positive values of S_1 indicate liquid. For the all-sky images, the top of the image represents north and the right side of the image represents west. Measurements were recorded in Bozeman, Montana.

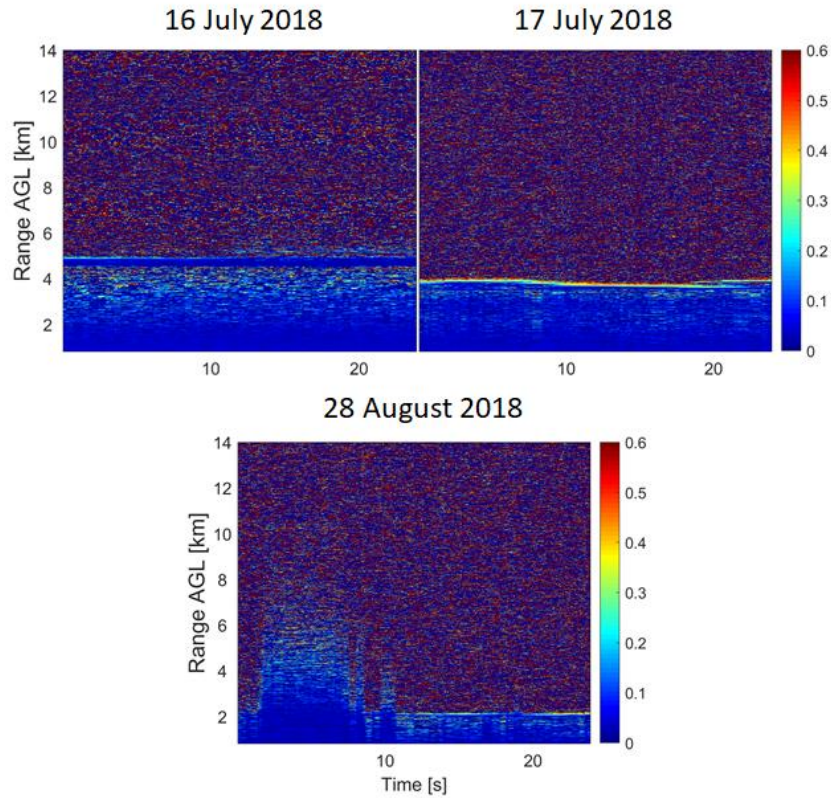


Figure 92. Dual-polarization lidar cross-polarization ratio measurements from 16 July 2018, 17 July 2018, and 28 August 2018 showing liquid phase. Measurements were taken at the zenith with the lidar running simultaneously with the three-camera Nikon all-sky polarimeter. The range on the y-axis represents the height of the clouds in the sky with respect to ground level (AGL). The color bar scaling represents the cross-polarization ratio. A cross-polarization ratio above 0.08 represents ice, while a cross-polarization below 0.08 represents liquid. Ideally, the cross-polarization ratio should be approximately zero for liquid; however, multiple scattering within the cloud layers can cause the cross-polarization to be greater than zero.

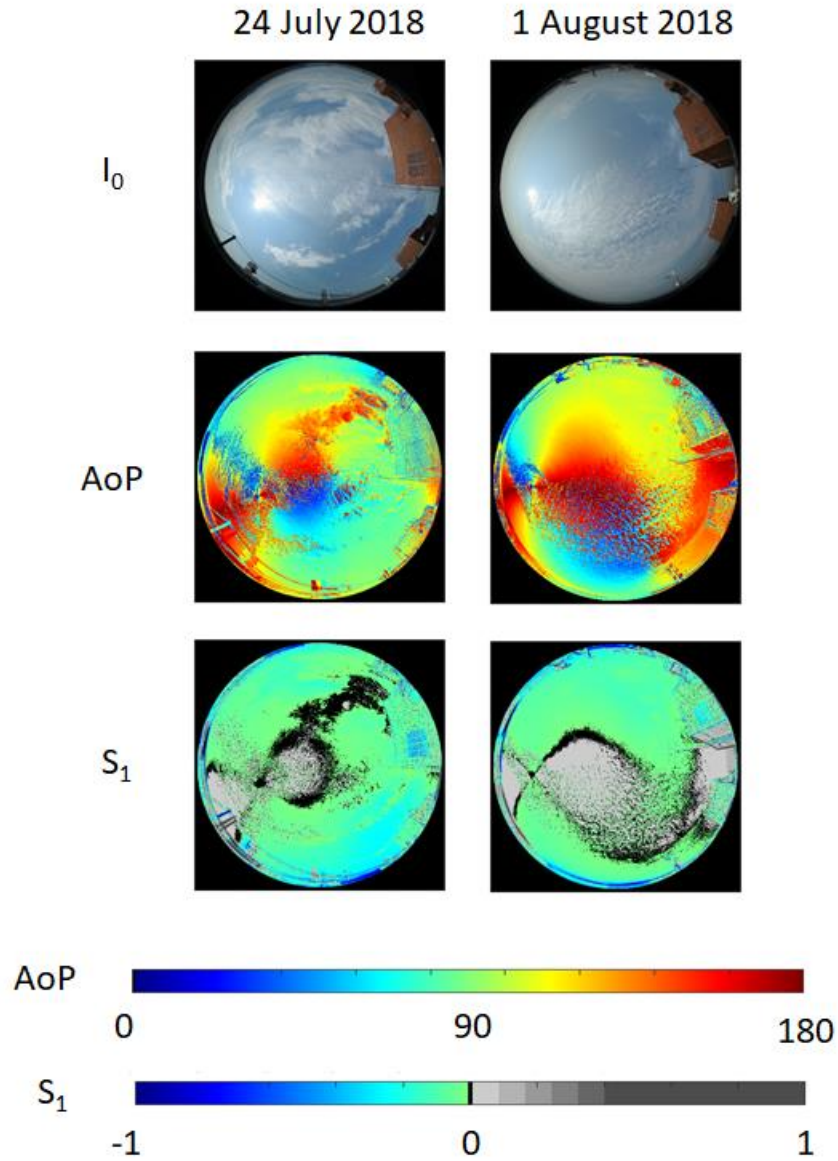


Figure 93. Three-camera Nikon all-sky polarimeter I_0 , AoP, and S_1 images referenced to the scattering plane. Multi-layered clouds containing both liquid and ice phase were observed on 24 July 2018 (left) and 1 August 2018 (right). The solar zenith and azimuth angles were 46° , 58° , and 108° , 97° , respectively. Positive values of S_1 indicate liquid and negative values indicate ice. For the all-sky images, the top of the image represents north and the right side of the image represents west. Measurements were recorded in Bozeman, Montana.

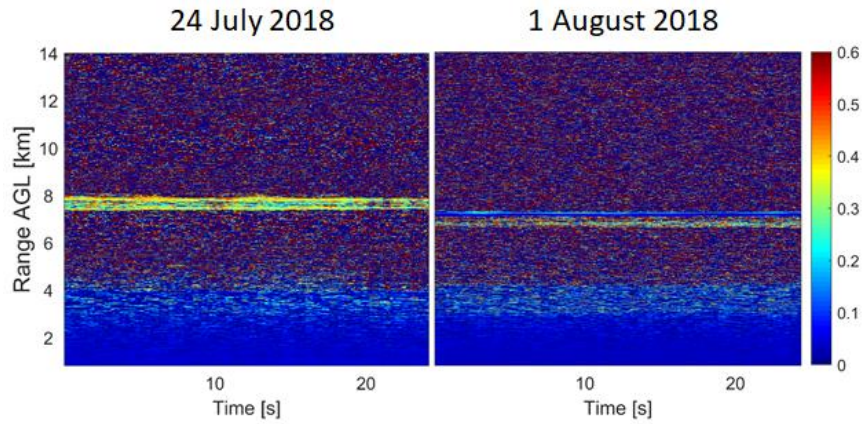


Figure 94. Dual-polarization lidar cross-polarization ratio measurements from 24 July 2018 and 1 August 2018 showing liquid and ice phase. Measurements were taken at the zenith with the lidar running simultaneously with the visible three-camera all-sky polarimeter. The range on the y-axis represents the height of the clouds in the sky with respect to ground level (AGL). The color bar scaling represents the cross-polarization ratio. A cross-polarization ratio above 0.08 represents ice, while a cross-polarization below 0.08 represents liquid. Ideally, the cross-polarization ratio should be approximately zero for liquid; however, multiple scattering within the cloud layers can cause the cross-polarization to be greater than zero.

Zenith Measurements

A summary of 35 different three-camera Nikon all-sky polarimeter measurements (for each wavelength) validated with the dual-polarization lidar at the zenith are shown in Figure 95 with corresponding data given in Table 9. The listed S_I parameters were calculated by masking a region of clouds near the zenith (radial cone of 5°) and by averaging the masked S_I cloud pixels. A mask of the cloud pixels was created using a red/blue ratio, similar to the method presented in [118]. In Table 9, the zenith angles correspond to the scattering angles in the solar principal plane (similar to the simulations presented by Knobelspiesse et al.). We measured negative S_I values for ice clouds (verified at the zenith with the lidar) and both negative and positive values for verified liquid clouds. We detected cloud phase for multiple days with solar zenith angles ranging from 27° to 111° . Lidar validation measurements are presented in Figure 96.

In contrast to the LCVR polarimeter measurements, the Stokes S_I parameters for liquid phase were generally positive, except for four cases where the scattering angles were greater than 79° . For liquid clouds, the measured S_I values were greatest between scattering angles of 40° and 50° , as observed in Figure 97, which shows the S_I scattering angle dependence with wavelength for measurements made at the zenith. Between scattering angles of 60° and 80° , the Stokes S_I values for liquid phase turn negative. For ice clouds, as the scattering angle increases, the Stokes S_I values become more negative, agreeing with the results found using the LCVR all-sky polarimeter.

In our observations in Figure 95, clouds were generally more polarizing at longer wavelengths for ice clouds, which is opposite of the general trend observed with the measurements made with the visible LCVR-based all-sky polarimeter. However, this is in agreement with the LCVR-based polarimeter observations made when the 500-nm AOD was greater than ~ 0.2 , which was the case for the wavelength-reversed data in Figure 95. A large AOD at the Bozeman AERONET site typically signifies smoke in the atmosphere. Liquid clouds were observed to be more polarizing at longer wavelengths when the AOD was less than ~ 0.2 agreeing with the measurements presented with the visible LCVR-based all-sky polarimeter. In this study, when the AOD was greater than ~ 0.2 , liquid clouds were observed to be less polarizing at longer wavelengths, although this trend was observed to reverse as the scattering angle increased past a scattering angle of 79° . Liquid clouds were more polarizing at longer wavelengths when the AOD was greater than ~ 0.2 and less polarizing at longer wavelengths when the AOD was less than ~ 0.2 . These results generally agree with the observed measurements made with the visible LCVR-based all-sky polarimeter and stress the importance of knowing the aerosol conditions and the scattering angle at which each measurement is made. Maximum error for the Nikon Stokes S_1 and S_2 parameters was estimated as $\pm 4\%$ with 100% linear input.

Solar Geometry				Polarimeter (S_I)				Lidar	AERONET
	Date	Time	Ze	R	G	B	Av	δ	AOD
2018									
1	0710	1552	50	-0.022	-0.021	-0.003	-0.013	0.40	0.19
2	0712	1303	79	-0.177	-0.250	-0.269	-0.240	0.03	0.06
3	0716	2306	50	0.014	0.005	0.002	0.007	0.03	0.11
4	0717	1456	60	0.020	0.019	0.021	0.021	0.02	0.20
5	0717	2251	48	0.049	0.041	0.036	0.042	0.04	0.13
6	0718	2209	41	0.023	0.022	0.025	0.024	0.04	0.14
7	0721	2125	35	0.020	0.019	0.022	0.021	0.02	0.19
8	0724	1624	46	-0.003	-0.009	-0.007	-0.006	0.35	0.26
9	0724	1624	46	0.002	-0.001	0.001	0.001	0.05	0.26
10	0724	1641	43	0.009	0.007	0.011	0.009	0.03	0.21
11	0724	2001	27	0.024	0.025	0.028	0.027	0.06	0.21
12	0725	1542	53	-0.168	-0.190	-0.151	-0.167	0.18	0.09
13	0725	2218	43	-0.070	-0.058	-0.048	-0.060	0.42	0.18
14	0727	2202	41	0.011	0.006	-0.003	0.004	0.04	1.58
15	0728	0549	111	-0.124	-0.144	-0.162	-0.142	0.05	0.09
16	0731	1534	56	-0.024	-0.017	-0.008	-0.016	0.32	0.27
17	0731	1751	34	-0.058	-0.033	-0.024	-0.037	0.31	1.17
18	0731	1854	29	-0.010	-0.010	-0.005	-0.008	0.30	0.38
19	0731	2050	32	-0.055	-0.053	-0.054	-0.055	0.40	0.22
20	0801	1509	60	0.008	0.008	0.004	0.007	0.03	0.36
21	0801	1509	60	-0.076	-0.061	-0.041	-0.057	0.37	0.36
22	0803	1714	40	-0.080	-0.031	-0.016	-0.038	0.26	0.53
23	0812	1630	49	0.038	0.045	0.049	0.046	0.04	0.65
24	0813	0256	94	-0.277	-0.272	-0.203	-0.240	0.07	0.55
25	0813	0308	96	-0.145	-0.108	-0.074	-0.100	0.05	0.55
26	0816	1521	61	-0.091	-0.070	-0.057	-0.071	0.22	0.24
27	0816	2138	42	0.004	0.008	0.017	0.011	0.04	0.62
28	0816	2138	42	-0.035	-0.019	-0.004	-0.017	0.35	0.62
29	0824	1350	78	-0.144	-0.090	-0.070	-0.097	0.32	0.49
30	0825	1449	68	-0.083	-0.072	-0.078	-0.077	0.19	0.33
31	0828	2101	42	0.031	0.022	0.019	0.024	0.04	0.08
32	0830	2006	38	0.025	0.023	0.023	0.024	0.02	0.20
33	0830	2006	38	-0.035	-0.049	-0.042	-0.042	0.40	0.20
34	0906	1458	69	-0.114	-0.094	-0.061	-0.086	0.32	0.17
35	0906	1548	60	-0.105	-0.067	-0.045	-0.068	0.34	0.18

Table 9. Three-camera Nikon polarimeter (zenith S_I), dual-polarization lidar, and AERONET data. For each day, the time of measurement (UTC) as well as the solar zenith (Ze) angles were recorded (time notation: MMDD). Scattering angles in the principal plane (i.e. zenith measurement) correspond to the solar zenith angles. For each wavelength, the mean cloud phase retrieved from the polarimeter's Stokes S_1 image was recorded. Cloud phase measurements were validated using a dual-polarization lidar. The cross-polarization ratio (δ) indicates liquid ($\delta < 0.08$) or ice ($\delta > 0.09$) phase. The AERONET aerosol optical depth (AOD) corresponds to level 1.0 processed data at 500 nm. Measurements were recorded in Bozeman, Montana.

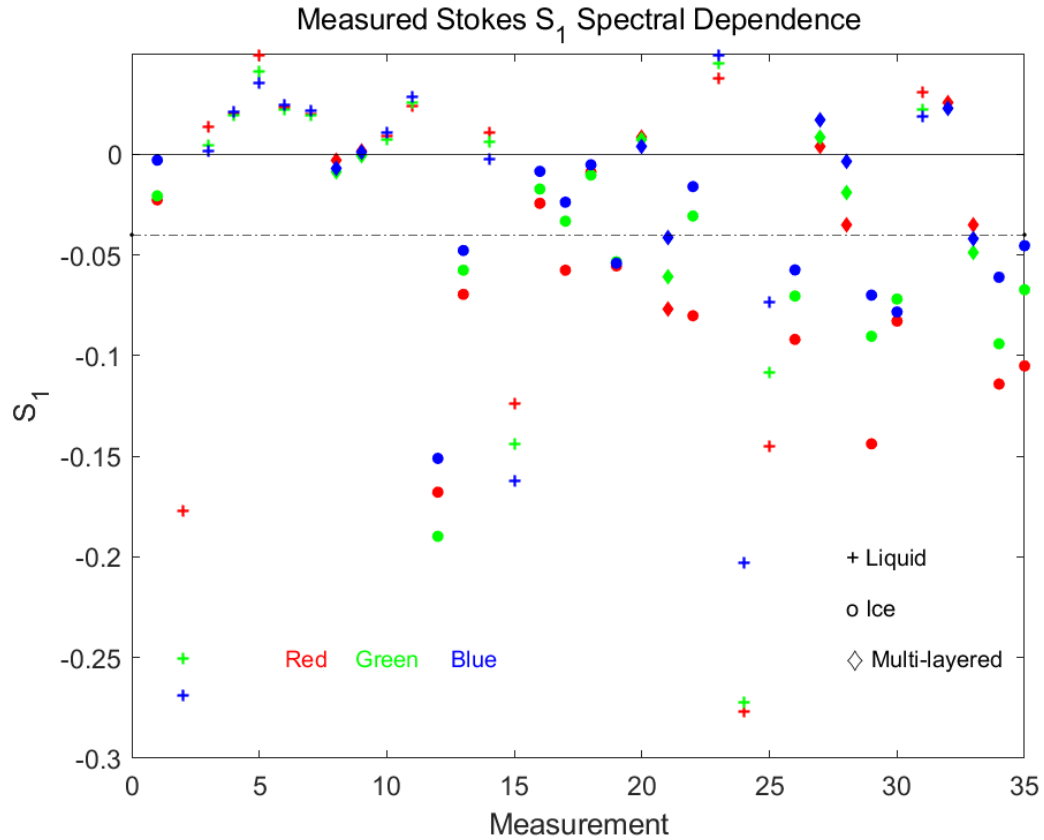


Figure 95. Multi-wavelength measurements from the Nikon polarimeter validated with a dual-polarization lidar at the zenith. Liquid clouds are represented by the plus (+) symbols, ice clouds are represented by the unfilled circles (o), and multi-phase clouds are represented by diamonds (◊). Ice clouds were found to have negative S_1 values where liquid clouds were found to have positive S_1 values.

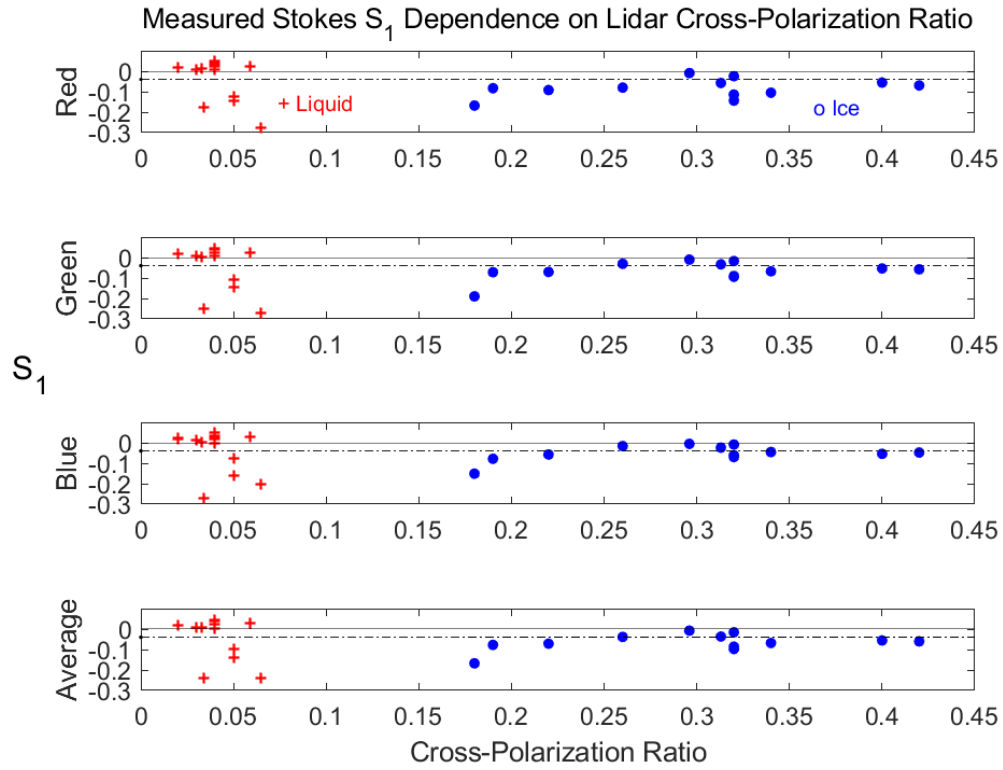


Figure 96. The observed relationship between the Stokes S_I parameter in the scattering plane and the lidar's cross-polarization ratio at the zenith for each wavelength. Liquid clouds are represented by the red plus (+) symbols, ice clouds are represented by the blue, filled circles (o). The Stokes S_I measurements were made with the three-camera Nikon polarimeter. Negative verified liquid S_I values correspond to measurements recorded at scatter angles greater than 79° .

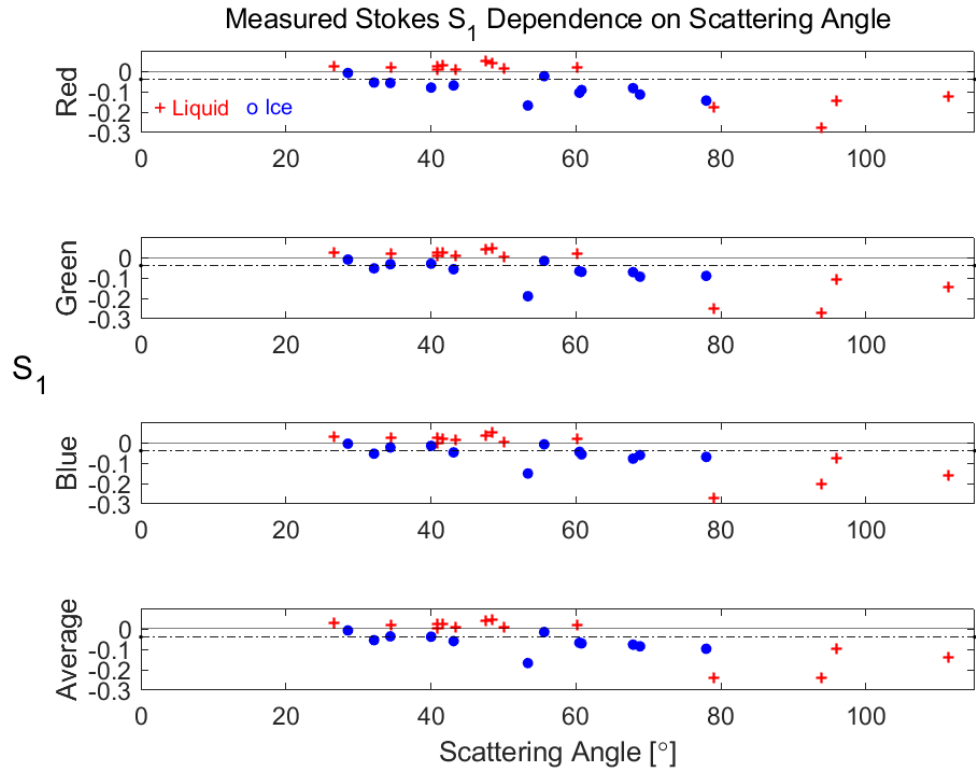


Figure 97. The observed relationship between the Stokes S_1 parameter in the scattering plane at the zenith and the corresponding scattering angle for each wavelength. The Stokes S_1 measurements were made with the three-camera Nikon polarimeter.

Discussion

Our measurements with both the LCVR and Nikon all-sky polarimeters are in good agreement with the Knobelspiesse predictions when the 500-nm AOD is less than ~ 0.2 [25]. Generally, the measured Stokes S_1 values are negative for ice clouds and positive for liquid clouds (the threshold was set to -0.04 for the LCVR all-sky polarimeter). The difference of filter bandwidth between each system could explain the differences observed between each measurement system in regards to the threshold; however, both polarimeters measured similar trends. For example, the measured S_1 values for liquid phase were predominately smaller in magnitude than the measured values for ice phase. The simulations presented by Knobelspiesse were shown to work better for clouds with smaller optical depths. Ice clouds generally have lower optical depths and therefore should have larger S_1 magnitudes. Using the threshold of -0.04 for measurements made with the narrow-band LCVR polarimeter, ice phase was correctly identified 80% of the time for the 670 nm and 780 nm channels and 100% of the time for the 450 nm, 690 nm, and 530 nm wavelength channels. Liquid phase was correctly identified 100% of the time for the 670 nm and 780 nm channels and 70%, 77%, and 85% for the 450 nm, 690 nm, and 530 nm channels, respectively. Using the threshold of zero for measurements made with the Nikon polarimeter, ice phase was correctly identified 100% of the time for all channels and liquid phase was correctly identified 77% for the red and green channels and 72% for the blue channel.

Measurements observed with both all-sky polarimeters depended on scattering angle. In agreement with the Knobelspiesse et al. simulations, the measured S_1 values for

liquid clouds tended to become more negative (below the threshold of -0.04 for the LCVR-based all-sky polarimeter) at scattering angles greater than 60° and the measured S_I values for ice clouds increased in magnitude as the scattering angle increased. Liquid phase was observed to generate the largest-magnitude S_I between scattering angles of 40° and 50° for each system. For both phases, a reversal in wavelength dependence was observed as the AOD became greater than ~ 0.2 , which could be a result of the smoke aerosols selectively depolarizing the light. For scattering angles greater than 60° , a wavelength reversal for liquid clouds was also observed (in general agreement with the Knobelspiesse et al. simulations).

The measurements presented in this chapter demonstrate the significance of knowing the surrounding environmental conditions, as well as the solar scattering geometry. If using point-source polarimeters, the direction at which the instrument is pointed, as well as the orientation of the internal polarizer, are critical in detecting cloud thermodynamic phase. Measurements should be rotated into the scattering plane to ensure correct analysis. In the simulations presented by Knobelspiesse et al, S_I values varied depending on solar geometry and cloud characteristics. To fully compare our results to the simulations presented by Knobelspiesse et al, we would have to use their model and incorporate the environmental conditions and solar and observational geometries from our measured days.

Our main objective was to verify that the ground-based all-sky polarimeter systems reliably determined cloud thermodynamic phase, as validated at the zenith with a dual-polarization lidar. The results of this study strongly suggest this method could be used to

determine cloud thermodynamic phase from all-sky polarimetric images, although further validation and study is warranted. This study was limited to days in which the all-sky polarimeter was running at the same time as our dual-polarization lidar. Sixty-two measurements of cloud phase were presented overall in this chapter. An expanded study could make use of a more continuously operated all-sky polarimeter and dual-polarization lidar to more completely explore the potential of this method being applied throughout an annual cycle. Such a study would also benefit from the use of a scanning lidar system to measure the off-zenith cross-polarization ratio. Cloud-base heights along with temperature profiles also can be used to help verify cloud phase. Knobelspiesse et al. showed that a cloud was more polarizing with a smaller cloud optical thickness, full validation of which would require high-quality cloud optical depth retrievals [120, 121].

Finally, to more completely compare our results to the simulations presented by Knobelspiesse et al, we would have to use their model and incorporate the environmental conditions and solar and observational geometries from our measured days. This work is crucial for many cloud remote sensing applications and can help in simulating and interpreting cloud radiation measurements to better understand the role of clouds in climate, weather, and optical propagation.

CHAPTER SEVEN

CONCLUSIONS

This dissertation contributes to the understanding of how skylight polarization changes as a function of wavelength, how skylight polarization varies with the distribution of multiple-scattered light during a solar eclipse, and how all-sky polarization imaging can be used to remotely sense cloud thermodynamic phase. The AoP reference plane became a significant aspect of the work presented. For accurate predictions of cloud thermodynamic phase, the AoP (and the related Stokes S_1 and S_2 parameters) needed to be rotated from the instrument plane to the scattering plane that is unique for every pixel in the all-sky image and for every solar position. Similarly, to visualize the sky polarization during eclipse totality, in a manner that simplified comparison with other observations, the instrument-plane AoP had to be rotated to the principal-plane reference. When referenced to the scattering plane or solar principal plane, the reference coordinate system is consistent. This is advantageous when measuring cloud and aerosol parameters, obtaining a heading from an AoP compass map, and when analyzing multiple-scattering processes.

A novel all-sky polarimeter system based on three simultaneously operating digital cameras has been presented. This system can detect cloud thermodynamic phase and rapidly record linear Stokes images of skylight polarization in low-light situations such as the solar eclipse. Two separate all-sky polarimeters were built using three Nikon D700 and Sony $\alpha 7s$ cameras, respectively. Both operate with standard red, green, and

blue wavelength bands and each of the three cameras was fitted with a fisheye lens and precision linear polarizers. These systems are portable, robust, cost-efficient, easy to use, and sensitive in low-light conditions. By using three DSLR cameras with polarization filters aligned to 0° , 60° , and 120° , respectively, simultaneous spectral and polarimetric image acquisition can be achieved in red, green, and blue spectral bands. During the 2017 solar eclipse, we recorded 24 well-exposed polarimetric all-sky images, creating the largest polarimetric solar eclipse dataset to date. A temporal variation of skylight was observed as the umbra moved from second to third contact. Our results were in agreement with previous measurements, but added to them by providing the first-ever radiometrically and polarimetrically calibrated digital all-sky images of sky polarization through an entire eclipse totality and stressed the importance of characterizing the surrounding environmental conditions as skylight polarization varied based on the surrounding aerosols, surface reflectance, and solar geometry in each measurement. This work advanced the knowledge of how skylight polarization varies under different lighting conditions and presents a new polarimeter design that can be used to capture all-sky images at three different polarization states simultaneously in both day and night. The speed of the three-camera system is not limited by narrow filter bands or a rotating polarizer. This system has the potential be useful in characterizing the Stokes parameters, DoLP, and AoP at night, which could significantly contribute to studies of climate and navigation, as well as other remote sensing measurements.

The SWIR validation measurements presented in this dissertation provide the first experimental measurements showing that skylight DoLP in the SWIR is greater for

smoky air than for clean air. Previous measurements have incorrectly analyzed skylight polarization under the assumption that skylight polarization in the SWIR follows similar patterns as skylight polarization in the visible spectrum. Incorrectly interpreting skylight polarization in applications that rely on long-range visibility, haze penetration, and object detection in low-light conditions could create critical consequences.

By measuring the Stokes S_I parameter in cloudy pixels, liquid, ice, and multi-layered clouds were detected using two separate visible-wavelength all-sky polarimeters. This work presents a new approach to measuring cloud thermodynamic phase using a ground-based all-sky polarimeter. This study was limited to days in which the all-sky polarimeter was running at the same time as our dual-polarization lidar. Nevertheless, sixty-two measurements of cloud phase were presented overall in Chapter 6. Our measurements with both the LCVR and Nikon all-sky polarimeters are in good agreement with the Knobelspiesse predictions [25]. Generally, the measured Stokes S_I values are negative for ice clouds and positive for liquid clouds (the threshold was set to -0.04 for the LCVR all-sky polarimeter). For both phases, a reversal in wavelength dependence (from higher polarization for blue light to higher polarization for red light) was observed as the AOD became greater than ~ 0.2 , which could be a result of the smoke aerosols selectively depolarizing the short-wavelength light. For scattering angles greater than 60° , a wavelength reversal for liquid clouds was also observed, which is in agreement with the scattering phase matrix calculations presented by Knobelspiesse et al. The measurements presented in Chapter 6 demonstrate once again the significance of knowing the surrounding environmental conditions, as well as the solar scattering geometry. Our main

objective was to verify that the ground-based all-sky polarimeter systems reliably determined cloud thermodynamic phase, as validated at the zenith with a dual-polarization lidar. The results of this study strongly suggest this method could be used as a new method for determining cloud thermodynamic phase, which is a vital parameter in climate and cloud studies and which constitutes the first step of most cloud-parameter retrievals. The optimal detection of cloud phase was found between scattering angles of 10° and 60° and when the AOD was less than ~ 0.2 .

Overall, the research reported in this dissertation has expanded the current knowledge of skylight polarization by validating radiative transfer simulations in the shortwave infrared, by reporting the first ever retrievals of cloud thermodynamic phase from all-sky polarization images using the Stokes S_I parameter referenced in the scattering plane, and by quantifying how partially polarized skylight varies under unique scattering conditions during the 2017 solar eclipse in Rexburg, Idaho. A physics-based understanding of the Stokes parameters and angle of polarization with respect to the instrument, scattering, and solar principal planes was developed to accurately predict cloud thermodynamic phase and to analyze the temporal distribution of skylight polarization in dynamic lighting conditions. This is a new capability at MSU and will be important in future polarization studies by enabling quantitative uses of the AoP in different reference frames, each of which has value in different applications.

REFERENCES CITED

1. J. A. Adam, "The mathematical physics of rainbows and glories," *Phys. Rep.* 356(4), 229–365 (2002).
2. D. Deirmendjian, "Scattering and Polarization Properties of Water Clouds and Hazes in the Visible and Infrared," *Appl. Opt.* 3, 187-196 (1964).
3. G. P. Können and J. H. de Boer, "Polarized rainbow," *Appl. Opt.* 18, 1961-1965 (1979).
4. G. P. Können, "Polarization and intensity distributions of refraction halos," *J. Opt. Soc. Am.* 73, 1629-1640 (1983).
5. G. P. Können and J. Tinbergen, "Polarimetry of a 22° halo," *Appl. Opt.* 30, 3382-3400 (1991).
6. J. A. Shaw and M. Vollmer, "Blue sun glints on water viewed through a polarizer," *Appl. Opt.* 56(19), G36-G41 (2017).
7. M. J. A. Barrall, *Oeuvres de francois Arago I-V*. Paris: Gide, (1858).
8. J. Tyndall, "On the blue color of the sky, the polarization of skylight, and polarization of light by cloudy matter generally," *Proc. R. Soc. Lond.* 17, 223-233 (1868).
9. L. Rayleigh, "On the transmission of light through an atmosphere containing small particles in suspension, and on the origin of the blue sky," *Phil. Mag.* 47, 375-384 (1899).
10. J. A. Shaw, *Optics in the Air: Observing Optical Phenomena through Airplane Windows* (2017).
11. K. L. Coulson, *Polarization and intensity of light in the atmosphere* (1988).
12. O. Sandus, "A review of emission polarization," *Appl. Opt.* 4(12), 1634-1642 (1965).
13. J. A. Shaw, "Degree of linear polarization in spectral radiances from water-viewing infrared radiometers," *Appl. Opt.* 38(15), 3157-3165 (1999).
14. J. A. Shaw, "Infrared polarization in the natural Earth environment," *Proc. SPIE* 4819, 129-138 (2002).

15. J. A. Shaw and C. Marston, "Polarized infrared emissivity for a rough water surface," *Opt. Express* 7(11), 375-380 (2000).
16. J. A. Shaw, "Polarimetric measurements of long-wave infrared spectral radiance from water," *Appl. Opt.* 40(33), 5985-5990 (2001).
17. S. J. Tyo, D. L. Goldstein, D. B. Chenault, and J. A. Shaw, "Review of passive imaging polarimetry for remote sensing applications," *Appl. Opt.* 45, 5453-5469 (2006).
18. F. Goudail, P. Terrier, Y. Takakura, L. Bigué, F. Galland, and V. DeVlaminck, "Target detection with a liquid-crystal-based passive Stokes polarimeter," *Appl. Opt.* 43, 274-282 (2004).
19. D. A. Lavigne, M. Breton, G. Fournier, J. M. Charette, V. Rivet, and A. Bernier, "Target discrimination of man-made objects using passive polarimetric signatures acquired in the visible and infrared spectral bands," *Proc. SPIE* 8160, 816007 (2011).
20. S. Lin, K. M. Yemelyanov, E. N. Pugh, and N. Engheta, "Polarization enhanced visual surveillance techniques," *IEEE International Conference on Networking, Sensing and Control* 1, 216-221 (2004).
21. Z. Li, P. Goloub, C. Devaux, X. Gu, J. Deuzé, Y. Qiao, and F. Zhao, "Retrieval of aerosol optical and physical properties from ground-based spectral, multi-angular, and polarized sun-photometer measurements," *Remote Sensing of Environment* 101 (4), 519-533 (2006).
22. J. Deuzé, F. Bréon, C. Devaux, P. Goloub, M. Herman, B. Lafrance, F. Maignan, A. Marchand, F. Nadal, G. Perry, and et al., "Remote sensing of aerosols over land surfaces from POLDER-ADEOS-1 polarized measurements," *Journal of Geophysical Research: Atmospheres*, 106, 4913– 4926 (2001).
23. G. van Harten, J. de Boer, J. H. H. Rietjens, F. Snik, A. Di Noia, O. P. Hasekamp, J. Vonk, H. Volten, J. M. Smit, J. S. Henzing, and C. U. Keller, "Atmospheric aerosol characterization with a ground-based SPEX spectropolarimetric instrument," *Atmos. Meas. Tech.* 7, 4341-4351 (2014).
24. G. van Harten, D. J. Diner, B. J. S. Daugherty, B. E. Rheingans, M. A. Bull, F. C. Seidel, R. A. Chipman, B. Cairns, A. P. Wasilewski, and K. D. Knobelspiesse, "Calibration and validation of Airborne Multiangle SpectroPolarimetric Imager (AirMSPI) polarization measurements," *Appl. Opt.* 57, 4499-4513 (2018).

25. K. Knobelspiesse, B. van Dienenhoven, A. Marshak, S. Dunagan, B. Holben, and I. Slutsker, "Cloud thermodynamic phase detection with polarimetrically sensitive passive sky radiometers," *Atmos. Meas. Tech.* 8, 1537-1554 (2015).
26. M. J. Tauc, C. L. Baumbauer, B. Moon, A. M. Abel, D. W. Riesland, L. M. Eshelman, W. Nakagawa, J. A. Shaw, "Cloud thermodynamic phase detection with a 3-channel shortwave infrared polarimeter", *Proc. SPIE 10655 Polarization: Measurement Analysis and Remote Sensing XIII*, pp. 1065500 (2018).
27. L. M. Eshelman, M. J. Tauc, and J. A. Shaw, "Cloud thermodynamic phase detection using an all-sky imaging polarimeter, *Appl. Optics* (submitted 2018).
28. J. Bailey, "Rainbows, Polarization, and the Search for Habitable Planets," *Astrobiology* 7, (2007).
29. B. Greiner, T. W. Cronin, W.A. Ribi, and et al., "Anatomical and physiological evidence for polarisation vision in the nocturnal bee *Megalopta genalis*," *J. Comp. Physiol A* 193, (2007).
30. E. Warrant and M. Dacke, "Visual Orientation and Navigation in Nocturnal Insects," *Brain Behav. Evol.* 75, 156-173 (2010).
31. K. P. Able, "Skylight Polarization Patterns and the Orientation of Migratory Birds," *Journal of Experimental Biology* 141, 241-256 (1989).
32. J. B. Phillips and F. R. Moore, "Calibration of the sun compass by sunset polarized light patterns in a migratory bird," *Behav. Ecol. Sociobiol.* 31, 189 (1992).
33. I. Pomozi, G. Horvath, and R. Wehner, "How the clear-sky angle of polarization pattern continues underneath clouds: full-sky measurements and implications for animal orientation," *J. Exp. Biol.* 204, 2933-2942 (2001).
34. S. B. Karman, S. Z. M. Diah, and I. C. Gebeshuber, "Bio-Inspired polarized skylight-based navigation sensor: a review," *Sensors* 12(11), 14232-14261 (2012).
35. D. Lambrinos, M. Maris, H. Kobayashi, T. Labhart, R. Pfeifer, and R. Wehner, "An autonomous agent navigating with a polarized light compass," *Adapt. Behav.* 6, 131-161 (1997).
36. T. Ma, X. Hu, L. Zhang, J. Lian, X. He, Y. Wang, and Z. Xian, "An Evaluation of Skylight Polarization Patterns for Navigation," *Sensors* 15, 5895-5973 (2015).

37. H. Zhao, W. Xu, Y. Zhang, X. Li, H. Zhang, J. Xuan, and B. Jia, "Polarization patterns under different sky conditions and a navigation method based on the symmetry of the AOP map of skylight," *Opt. Express* 26, 28589-28603 (2018).
38. T. Aycock, A. Lompadó, T. Wolz, and D. Chenault, "Passive optical sensing of atmospheric polarization for GPS denied operations," *Proc. SPIE* 9838, 98380Y (2016).
39. A. Barta, A. Farkas, D. Száz, Á. Egri, P. Barta, J. Kovács, B. Csák, I. Jankovics, G. Szabó, and G. Horváth, "Polarization transition between sunlit and moonlit skies with possible implications for animal orientation and Viking navigation: anomalous celestial twilight polarization at partial moon," *Appl. Opt.* 53, 5193-5204 (2014).
40. D. M. Harrington, J. R. Kuhn, A. L. Ariste, "Daytime sky polarization calibration limitations," *Proc. SPIE* 9912, 99126S (2016).
41. N. J. Pust and J. A. Shaw, "Dual-field imaging polarimeter using liquid crystal variable retarders," *Appl. Opt.* 45, 5470-5478 (2006).
42. N. J. Pust and J. A. Shaw, "Digital all-sky polarization imaging of partly cloudy skies," *Appl. Opt.* 47, H190-H198 (2008).
43. A. R. Dahlberg, N. J. Pust, and J. A. Shaw, "Effects of surface reflectance on skylight polarization measurements at the Mauna Loa Observatory," *Opt. Express* 19, 16008-16021 (2011).
44. N. J. Pust, and J. A. Shaw, "Wavelength dependence of the degree of polarization in cloud-free skies: simulations of real environments," *Optics Express* 20(14), 15559-15568 (2012).
45. N. J. Pust, A. R. Dahlberg, M. J. Thomas, and J. A. Shaw, "Comparison of full-sky polarization and radiance observations to radiative transfer simulations which employ AERONET products," *Opt. Express* 19, 18602-18613 (2011).
46. J. A. Shaw, N. J. Pust, E. Forbes, "Effects of wildfire smoke on atmospheric polarization," *Proc. SPIE* 9099, Polarization: Measurement, Analysis, and Remote Sensing XI, 909907 (2014).
47. D. R. Bates, "Rayleigh scattering by air," *Planet. Space Sci.* 32, 785-790 (1984).
48. E. Boesche, P. Stamnes, T. Ruhtz, R. Preusker, and J. Fischer, "Effect of aerosol microphysical properties on polarization of skylight: sensitivity study and measurements," *Appl. Opt.* 45, 8790-8805 (2006).

49. A. Kreuter, C. Emde, and M. Blumthaler, "Measuring the influence of aerosols and albedo on sky polarization," *Atmospheric Research* 98, 363-367, (2010).
50. G. Horváth, A. Barta, J. Gál, B. Suhai, and O. Haiman, "Ground-based full-sky imaging polarimetry of rapidly changing skies and its use for polarimetric cloud detection," *Appl. Opt.* 41, 543-559 (2002).
51. J. Lenoble, M. Herman, J. L. Deuzé, B. Lafrance, R. and Santer, D. Tanré, "A successive order of scattering code for solving the vector equation of transfer in the earth's atmosphere with aerosols," *Journal of Quantitative Spectroscopy and Radiative Transfer* 107, 479-507 (2007).
52. L. M. Eshelman and J. A. Shaw, "The VIS–SWIR spectrum of skylight polarization," *Appl. Opt.* 57, 7974-7986 (2018).
53. L. M. Dahl, "The visible-to-short-wave-infrared spectrum of skylight polarization," Master's Professional Paper, <https://scholarworks.montana.edu/xmlui/handle/1/9205>, (2015).
54. K. L. Coulson, "Characteristics of skylight at the zenith during twilight as indicators of atmospheric turbidity, 1: Degree of polarization," *Appl. Opt.* 19(20), 3469-3480 (1980).
55. W. T. Cronin, J. E. Warrant, and B. Greiner, "Celestial polarization patterns during twilight," *Appl. Opt.* 45(22), 5582-5589 (2006).
56. G. E. Shaw, "Sky brightness and polarization during the 1973 African eclipse," *Appl. Opt.* 14, 388-394 (1975).
57. Shaw, G. E., "Sky radiance during a total solar eclipse: a theoretical model," *Appl. Opt.* 17(2), 272-276 (1978).
58. S. M. Silverman and E. G. Mullen, "Sky brightness during eclipses: a review," *Appl. Opt.* 14(12), 2838-2843 (1975).
59. K. P. Möllmann, and M. Vollmer, "Measurements and predictions of the illuminance during a solar eclipse," *Eur. J. Physics* 27(6), 1219-1314 (2006).
60. G. P. Können, "Skylight polarization during a total eclipse: a quantitative model," *J. Opt. Soc. Am.* 4(3), 601-608 (1987).
61. I. Pomozi, J. Gal, G. Horvath, and R. Wehner, "Fine structure of the celestial polarization pattern and its temporal change during the total solar eclipse of 11 August 1999," *Rem. Sens. Env.* 76, 181-201 (2000).

62. G. Horvath, I. Pomozi, and J. Gal, "Neutral points of skylight polarization observed during the total eclipse on 11 August 1999," *Appl. Opt.* 42(3), 465-475 (2003).
63. B. Sipocz, R. Hegedus, G. Kriska, and G. Horvath, "Spatiotemporal change of sky polarization during the total solar eclipse on 29 March 2006 in Turkey: polarization patterns of the eclipsed sky observed by full-sky imaging polarimetry," *Appl. Opt.* 47(34), H1-H10 (2008).
64. V. Ramanathan, R. D. Cess, E. F. Harrison, P. Minnis, B. R. Barkstrom, E. Ahmad, and D. Hartmann, "Cloud-Radiative Forcing and Climate: Results from the Earth Radiation Budget Experiment," *Science* 243, 57 (1989).
65. O. Boucher and et al., In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge Univ. Press, (2013).
66. W. B. Rossow, and R. A. Schiffer, "Advances in Understanding Clouds from ISCCP," *Bulletin of the American Meteorological Society* 80, 2261-2287 (1999).
67. A. Deepak, U. O. Farrukh, and A. Zardecki, "Significance of higher-order multiple scattering for laser beam propagation through hazes, fogs, and clouds," *Appl. Opt.* 21(3), 439-447 (1982).
68. S. Jaruwatanadilok, A. Ishimaru, and Y. Kuga, "Optical imaging through clouds and fog," *IEEE Trans. Geosci. Rem. Sens.* 41(8), 1834-1843 (2003).
69. S. Arnon and N. S. Kopeika, "Adaptive optical transmitter and receiver for space communication through thin clouds," *Appl. Opt.* 36(9), 1987-1993 (1997).
70. F. Courvoisier, V. Boutou, J. Kasparian, E. Salmon, G. Mejean, J. Yu, and J-P. Wolf, "Ultraintense light filaments transmitted through clouds," *Appl. Phys. Lett.* 83(2), 213-215 (2003).
71. S. Arnon, D. Sadot, and N. S. Kopeika, "Analysis of optical pulse distortion through clouds for satellite to earth adaptive optical communication," *J. Modern Optics* 41(8), 1591-1605 (1994).
72. S. Piazzolla and S. Slobin "Statistics of link blockage due to cloud cover for free-space optical communications using NCDC surface weather observation data," *Proc. SPIE* 4635, 138-149 (2002).
73. J. R. Key and J. M. Intrieri, "Cloud Particle Phase Determination with the AVHRR," *J. Appl. Meteor.* 39, 1797-1804 (2000).

74. S. Platnick, M. D. King, S. A. Ackerman, W. P. Menzel, B. A. Baum, J. C. Riedi, and R. A. Frey, "The MODIS cloud products: algorithms and examples from Terra," *IEEE Transactions on Geoscience and Remote Sensing* 41, 459-473 (2003).
75. J. C. Chiu, A. Marshak, C. H. Huang, T. Várnai, R. J. Hogan, D. M. Giles, B. N. Holben, E. J. O'Connor, Y. Knyazikhin, and W. J. Wiscombe, "Cloud droplet size and liquid water path retrievals from zenith radiance measurements: examples from the Atmospheric Radiation Measurement Program and the Aerosol Robotic Network," *Atmos. Chem. Phys.* 12, 10313-10329 (2012).
76. K. Sassen, "The Polarization Lidar Technique for Cloud Research: A Review and Current Assessment," *Bulletin of the American Meteorological Society* 72, 1848-1866 (1991).
77. N. L. Seldomridge, J. A. Shaw, and K. S. Repasky, "Dual-polarization lidar using a liquid crystal variable retarder," *OPTICE* 45, 106202-106210 (2006).
78. R. A. Stillwell, R. R. Neely III, J. P. Thayer, M. D. Shupe, and D. D. Turner, "Improved cloud-phase determination of low-level liquid and mixed-phase clouds by enhanced polarimetric lidar," *Atmos. Meas. Tech.*, 11, 835–859, (2018).
79. A. Lacour, H. Chepfer, M. D. Shupe, N. B. Miller, V. Noel, J. Kay, D. D. Turner, and R. Guzman, "Greenland Clouds Observed in CALIPSO-GOCCP: Comparison with Ground-Based Summit Observations," *Journal of Climate* 30, 6065-6083, (2017).
80. S. M. Sekelsky, and R. E. McIntosh, "Cloud observations with a polarimetric 33 GHz and 95 GHz radar," *Meteorology and Atmospheric Physics* 59, 123-140 (1996).
81. M. S. Norgren, G. deBoer, and M. D. Shupe, "Observed aerosol suppression of cloud ice in low-level Arctic mixed-phase clouds," *Atmos. Chem. Phys.* 18, 13345–13361, (2018).
82. K. I. Strabala, S. A. Ackerman, and W. P. Menzel, "Cloud properties inferred from 8–12- μ m data," *J. Appl. Meteor.* 33, 212–229 (1994).
83. J. R. Key and J. M. Intrieri, "Cloud particle phase determination with the AVHRR," *J. Appl. Meteor.* 39, 1797–1804 (2000).
84. D. D. Turner, S. A. Ackerman, B. A. Baum, H. E. Revercomb, and P. Yang, "Cloud Phase Determination Using Ground-Based AERI Observations at SHEBA," *Journal of Applied Meteorology* 42, 701-715 (2003).

85. B. A. Baum, P. F. Soulen, K. I. Strabala, M. D. King, S. A. Ackerman, W. P. Menzel, and P. Yang, "Remote sensing of cloud properties using MODIS airborne simulator imagery during SUCCESS. 2. Cloud thermodynamic phase," *J. Geophys. Res.*, 105(D9), 11781–11792 (2000).
86. W. H. Knap, P. Stammes, and R. B. A. Koelemeijer, "Cloud thermodynamic-phase determination from near-infrared spectra of reflected sunlight," *J. Atmos. Sci.* 59, 83–96 (2002).
87. P. Pilewskie and S. Twomey, "Cloud phase discrimination by reflectance measurements near 1.6 and 2.2 μm ," *J. Atmos. Sci.* 44, 3419–3421 (1987).
88. J. S. Daniel, S. Solomon, R. W. Portmann, A. O. Langford, C. S. Eubank, E. G. Dutton, and W. Madson, "Cloud liquid water and ice measurements from spectrally resolved near-infrared observations: A new technique," *J. Geophys. Res.* 107(D21), 4599, doi: 10.1029/2001JD000688 (2002).
89. J. A. Shaw, N. J. Pust, B. Staal, J. Johnson, and A. R. Dahlberg, "Continuous outdoor operation of an all-sky polarization imager," *Proc. SPIE* 7672, 76720A (2010).
90. M. A. Miller, R. V. Blumer, and J. D. Howe, "Active and passive SWIR imaging polarimetry," *Proc. SPIE* 4481, 87-99 (2002).
91. R. G. Driggers, V. Hodgkin, and R. Vollmerhausen, "What good is SWIR? Passive day comparison of VIS, NIR, and SWIR," *Proc. SPIE* 8706, 87060L (2013).
92. M. P. Hansen and D. S. Malchow, "Overview of SWIR detectors, cameras, and applications," *Proc. SPIE* 6939, 69390I (2008).
93. B. Stark, M. McGee and Y. Chen, "Short wave infrared (SWIR) imaging systems using small Unmanned Aerial Systems (sUAS)," 2015 International Conference on Unmanned Aircraft Systems (ICUAS), 495-501 (2015).
94. D. Lindsay, J. W. Bangs, J. Vampola, F. Jaworski, L. Mears, R. Wyles, J. Asbrock, E. Norton, M. Reddy, K. Rybnicek, A. Levy, N. R. Malone, "Large format high operability low cost infrared focal plane array performance and capabilities," *Proc. SPIE* 8154, Infrared Remote Sensing and Instrumentation XIX, 81540S (2011).
95. E. Collett, *Field Guide to Polarization*, *SPIE Press*, Bellingham, WA (2005).
96. R. Chipman, W. T. Lam, and G. Yound, *Polarized Light and Optical Systems* (2019).

97. S. Lu and R. A. Chipman, "Interpretation of Mueller matrices based on polar decomposition," *J. Opt. Soc. Am. A* 13, 1106-1113 (1996).
98. N. A. J. Schutgens, L. G. Tilstra, P. Stammes, and F. M. Bréon, "On the relationship between stokes parameters q and u of atmospheric ultraviolet/visible/near-infrared radiation," *J Geophys Res: Atmos* 109, (2004).
99. O. Dubovik and M. D. King, "A flexible inversion algorithm for retrieval of aerosol optical properties from Sun and sky radiance measurements," *J. Geophys. Res.* 105(D16), 20673–20696, (2000).
100. L. Li, Z. Li, K. Li, L. Blarel and M. Wendisch, "A method to calculate Stokes parameters and angle of polarization of skylight from polarized CIMEL sun/sky radiometers," *J Quant Spectrosc Radiat Transfer* 149, 334-346 (2014).
101. J. Gál, G. Horváth, V. B. Meyer-Rochow, R. Wehner, "Polarization patterns of the summer sky and its neutral points measured by full-sky imaging polarimetry in Finnish Lapland north of the Arctic Circle," *Proc. R. Soc. Lond. A* 457, 1385-1399 (2001).
102. J. Babinet, "Sur un nouveau point neutre dans l'atmosphère," *C. R. Acad. Sci. Paris* 11, 618-620 (1840).
103. D. Brewster, "On the existence of a neutral point and two secondary neutral points," *Rep. Brit. Assoc. Adv. Sci.* 2, 13-25 (1842).
104. D. Brewster, "On the polarization of the atmosphere," *Philos. Mag. J. Sci.* 31, 444-454 (1847).
105. G. Horváth, B. Bernáth, B. Suhai, and A. Barta, "First observation of the fourth neutral polarization point in the atmosphere," *J. Opt. Soc. Am. A* 19, 2085-2099 (2002).
106. B. N. Holben, T. F. Eck, I. Slutsker, D. Tanré, J. P. Buis, A. Setzer, E. Vermote, J. A. Reagan, Y. J. Kaufman, T. Nakajima, F. Lavenue, I. Jankowiak, and A. Smirnov, "AERONET—A Federated Instrument Network and Data Archive for Aerosol Characterization," *Remote Sensing of Environment* 66, 1-16 (1998).
107. Bozeman AERONET Site, <http://www.aeronet.gsfc.nasa.gov/>;
https://aeronet.gsfc.nasa.gov/cgi-bin/type_one_station_opera_v2_new?site=Bozeman&nachal=2&level=3&place_code=10.

108. K. J. Voss and Y. Liu, "Polarized radiance distribution measurements of skylight. I. System description and characterization," *Appl. Opt.* 36, 6083-6094 (1997).
109. Sharp, W. E., Lloyd, J. W. F., and Silverman, S. M., "Zenith Skylight Intensity and Color during the Total Solar Eclipse of 20 July 1963," *Appl. Opt.* 5, 787-792 (1966).
110. Gedzelman, S. D., "Sky color near the horizon during a total solar eclipse," *Appl. Opt.* 14, 2831-2837 (1975).
111. Rexburg AERONET Site, https://aeronet.gsfc.nasa.gov/cgi-bin/type_one_station_opera_v2_new?site=Rexburg_Idaho&nachal=2&level=3&place_code=10.
112. E. de Bary, K. Bullrich, and D. Lorenz, "Messungen der Himmelsstrahlung und deren Polarisationsgrad während der Sonnenfinsternis am 15.2.1961 in Viareggio (Italian)," *Geofis. Pura Appl.* 48, 193-198 (1961).
113. J. G. Moore and C. R. N. Rao, "Polarization of the daytime sky during the total solar eclipse of 30 May 1965," *Ann. Geophys.* 22, 147-150 (1966).
114. R. E. Miller and W. G. Fastie, "Skylight intensity, polarization and airglow measurements during the total solar eclipse of 30 May 1965," *J. Atmos. Terr. Phys.* 34, 1541-1546 (1972).
115. C. R. N. Rao, T. Takashima, and J. G. Moore, "Polarimetry of the daytime sky during solar eclipses," *J. Atmos. Terr. Phys.* 34, 573-576 (1972).
116. B. S. Dandekar and J. P. Turtle, "Day sky brightness and polarization during the total solar eclipse of 7 March 1970," *Appl. Opt.* 10, 1220-1224 (1971).
117. R. Gerharz, "Appearance of the atmospheric scatter field during a solar eclipse," *J. Geophys.* 42, 163-167 (1976).
118. M. S. Ghonima, B. Urquhart, C. W. Chow, J. E. Shields, A. Cazorla, and J. Kleissl, "A method for cloud detection and opacity classification based on ground based sky imagery," *Atmos. Meas. Tech. Discuss.* 5, 4535-4569 (2012).
119. L. M. Eshelman, M. J. Tauc, T. Hashimoto, P. Hooser, K. Gillis, W. Weiss, B. Stanley, G. E. Shaw, and J. A. Shaw, "All-sky polarization measurements of the total solar eclipse on 21 August 2017," *Proc. SPIE 10655, Polarization: Measurement, Analysis, and Remote Sensing XIII*, 106550L (2018).

120. M. D. Shupe, "A ground-based multisensor cloud phase classifier," *Geophys. Res. Lett.* 34, L22809, (2007).
121. E. W. Eloranta, High spectral resolution lidar. *Lidar: Range-Resolved Optical Remote Sensing of the Atmosphere*, Springer-Verlag, (2005).