

Digital all-sky polarization imaging of the total solar eclipse on 21 August 2017 in Rexburg, Idaho, USA

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All-sky polarization images were measured from sunrise to sunset and during a cloud-free totality on 21 August 2017 in Rexburg, Idaho using two digital three-camera all-sky polarimeters and a time-sequential liquid-crystal-based all-sky polarimeter. Twenty-five polarimetric images were recorded during totality, revealing a highly dynamic evolution of the distribution of skylight polarization, with the degree of linear polarization becoming nearly zenith-symmetric by the end of totality. The surrounding environment was characterized with an infrared cloud imager that confirmed the complete absence of clouds during totality, an AERONET solar radiometer that measured aerosol properties, a portable weather station, and a hand-held spectrometer with satellite images that measured surface reflectance at and near the observation site. These observations confirm that previously observed totality patterns are general and not unique to those specific eclipses. The high temporal image resolution revealed a transition of a neutral point from the zenith in totality to the normal Babinet point just above the Sun after third contact, providing the first indication that the transition between totality and normal daytime polarization patterns occurs over a time period of approximately 13 s. © 2020 Optical Society of America

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1. INTRODUCTION

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. During an eclipse, the moon casts a complete shadow called the umbra (total eclipse), surrounded by a partial shadow called the penumbra (partial eclipse). Molecular scattering in the daytime sky produces a band of maximum polarization positioned 90° from the Sun, with a polarization vector oriented orthogonal to the scattering plane defined by the incident and scattered rays [1,2]. In the band of maximum polarization, the degree of linear polarization (DoLP) is nominally high but significantly less than the theoretical upper limit of 100% because of multiple scattering from aerosols [2–6], clouds [7–10], and the underlying surface [2,4–6,11]. During a total solar eclipse, the unobscured portion of the Sun continues to produce the same polarization pattern throughout the partial eclipse phase, just with decreased sky brightness [12,13]. However, in the sudden absence of the Sun

at second contact, the totality sky color, intensity, and polarization quickly change, leaving the sky brightness similar to twilight conditions with solar zenith angles between 95° and 97° [12–20]. 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 shifts to the blue, while the sky near the horizon reddens from the distant scattering [12,15,19]. In totality, skylight arises from scattering at altitudes primarily above 8 km, and aerosols have minimal impact on sky brightness and color [14]. The lack of scattered light in the lower troposphere during totality also results in extended visibility range (we were able to briefly view distant mountains during totality that were obscured by aerosol scattering before and after totality [21]).

Early measurements by G. Shaw with a scanning polarimeter at the 1973 African solar eclipse suggested that the DoLP pattern at totality was nominally symmetric about the zenith [12]. Können's subsequent model suggested that it should be completely symmetric about the zenith [22] because instead

of the Sun, the light source during totality becomes multiply scattered light from outside the umbra, which extends all around the horizon. More recent measurements with all-sky imagers revealed the existence of neutral points and polarization patterns that are not as symmetric as originally believed and evolve throughout totality [13,20,23–25] (neutral points are discontinuities in the polarization pattern, where the DoLP is zero and the angle of polarization (AoP) shifts by 90° because of multiple scattering [26]). Können's model predicted a polarization pattern that was completely symmetric about the zenith, while G. Shaw's measurements exhibited a slightly asymmetric pattern, which he suggested arose from skylight being more polarized over the nearby lake (in the solar hemisphere) than over the bright desert (in the antisolar hemisphere) because the dark surface reflected less multiply scattered light back into the sky. Können, on the other hand, suggested the asymmetry arose from using a scanning polarimeter during the dynamic conditions of totality. The zenith-symmetric hypothesis was shown to be not quite accurate, however, by all-sky polarization images recorded using a film-based rotating-polarizer instrument during a 1999 eclipse in Hungary [13,23] and a 2006 eclipse in Turkey [20]. The all-sky images exhibited evolving polarization patterns that were not as symmetric about the zenith as predicted previously. In fact, the DoLP images exhibited a high degree of circular symmetry only near the end of totality in 1999 (for a morning eclipse with the shadow approaching from the antisolar direction) [13,23] and at the beginning of totality in 2006 (for an afternoon eclipse with the shadow approaching from the solar direction) [20]. Throughout totality, neutral points were observed near the zenith and in the antisolar hemisphere. For both eclipses, maximum polarization was observed in the solar hemisphere with minimum polarization in the antisolar hemisphere, which agrees with the scanning measurements from the 1973 Kenya eclipse [12].

In this paper, building on prior film-based all-sky imaging of solar eclipse polarization by others [13,20,23], we present the first digital-camera all-sky eclipse images of DoLP and AoP from the 21 August 2017 "Great American Eclipse," along with characterization of the surrounding environmental conditions. This is the most complete set yet of all-sky polarization images during a solar eclipse, with the highest number of images, the highest digital dynamic range (14-bit digital images versus 8-bit film scans), the most uniform distribution of images at nearly constant time intervals throughout the eclipse (and at longer intervals of 5 min before and after the eclipse), and the most complete characterization of the surrounding environment to enable quantitative testing of future models. This was also the first time a division-of-aperture imager [27] was used to record all polarization states simultaneously during a solar eclipse instead of at different times with a rotating-polarizer (division-of-time) polarization imager. The all-sky polarization images were recorded continuously from sunrise to sunset, including through partial and total eclipse in mid-morning, revealing neutral regions with minimum (but not exactly zero) DoLP that shifted position in the sky throughout totality, as also observed earlier by Sipőcz *et al.* [20] in red, green, and blue (RGB) images at eight different points of time during totality.

Our all-sky images were recorded using two three-digital-camera all-sky polarimeters [28] and one division-of-time

liquid-crystal-based all-sky polarimeter [29]. We recorded 25 polarimetric images in totality. At and near the observation site we also operated an infrared cloud imager (ICI) (fisheye-lens variation of previously reported instruments [30,31]) to measure cloud distributions, a hand-held spectrometer to measure surface reflectance, and an AERONET solar radiometer [32] to characterize the atmospheric aerosols. Surface reflectance was also retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite instrument to compare with the local spectrometer data. These ancillary data provide characterization of the surrounding environmental conditions that was not available for previous eclipse polarization measurements.

This paper expands on preliminary data shown in earlier conference papers [24,25] with more fully calibrated, processed, and interpreted data and complements the corona polarization study reported in this same issue [33]. In the balance of this paper, we describe the all-sky polarimeters (Section 2), the 2017 solar eclipse parameters (Section 3), the surrounding environmental observations (Section 4), and our eclipse polarization observations (Section 5). A discussion of the results in Section 6 is followed by conclusions in Section 7.

2. ALL-SKY POLARIMETERS

We measured skylight polarization from sunrise to sunset with three all-sky polarization imagers in Rexburg, Idaho on 21 August 2017. The liquid-crystal-based polarimeter operated in this experiment with 10-nm bands centered at 450, 530, and 670 nm [29]. To our knowledge, this instrument was the first all-sky polarization imager based on liquid crystal variable retarders (LCVRs), enabling full four-Stokes-parameter imaging (similar instruments reported later include [34,35]), whereas other digital all-sky polarization imagers recorded the three linear Stokes parameters using a rotating filter wheel with a fisheye lens [36–39], building on ideas demonstrated earlier with a multiaperture film camera viewing a reflective dome [40] and narrow-angle images obtained with film cameras [41,42]. Our LCVR all-sky polarimeter has been used previously to study skylight polarization variation with aerosols [5,6], clouds [7,8], and surface reflectance [11]. In this imager, two LCVRs are used behind a fisheye lens and collimating optics to electronically vary the retardance to capture four sequential images rapidly so that a full DoLP and AoP image pair can be obtained in less than a few tenths of a second at each wavelength for daytime conditions.

The LCVR polarimeter, with its narrow spectral bands, was expected to be challenged by the low-light conditions of totality, so to provide fast spectral and polarimetric low-light images, we developed two visible-wavelength three-camera all-sky polarimeters based on digital single-lens-reflex (DSLR) cameras, each fitted with a Sigma 8-mm circular fisheye lens ($f/3.5$) with a precision-cut Meadowlark polarizer attached to the back of the lens (Meadowlark Optics PC-100X100-VIS-0 and PC-100X100-VIS-60) [28]. Each fisheye lens had a polarizer whose transmission axis was aligned to 0° , 60° , or 120° relative to a reference axis defined perpendicular to the top-to-bottom axis of the camera. Polarizer alignment was validated with a crossed-polarizer test using a reference polarizer



Fig. 1. All-sky polarimeters operating during the 21 August 2017 solar eclipse. The white case on the left with a sun occulter is the LCVR polarimeter. The Nikon (left) and Sony (right) three-camera polarimeters are on the table to the right.

in a precision rotation stage and an integrating sphere source. The polarizers had an extinction ratio greater than 1000 for wavelengths between 425 and 700 nm and greater than 500 for wavelengths between 400 and 425 nm. One system used three Nikon D700 DSLR cameras, the other, three mirrorless Sony $\alpha 7s$ cameras with an expanded International Standards Organization (ISO) range relative to the Nikon cameras. The relative spectral response functions were measured for the RGB channels of both camera systems using a monochromator and power meter [28]. The maximum and half-bandwidths of the spectral sensitivity curves were $R = 595 \pm 35$ nm, $G = 525 \pm 45$ nm, and $B = 455 \pm 35$ nm for the Nikon system and $R = 600 \pm 35$ nm, $G = 530 \pm 50$ nm, and $B = 440 \pm 45$ nm for the Sony system [28]. The cameras were triggered simultaneously and controlled remotely by a laptop computer, with a backup manual remote trigger. During totality, the Nikon polarimeter's exposure time was bracketed between 1/250, 1/100, 1/80, and 1/60 s with an ISO value of 4000, while the Sony polarimeter's exposure time was set to 1/100 s with ISO values bracketed between 4000, 5000, and 8000.

We performed radiometric and polarimetric calibrations on each polarimeter. The cameras were initially manually aligned better than approximately 2° , and the image alignment was further refined in rotation and translation using the Sun and

a bright star near the zenith that remained visible throughout totality to a final uncertainty less than 1 pixel ($\sim 0.06^\circ$). The polarimetric calibrations were performed using an external rotating polarizer and an integrating sphere viewed at multiple angles to fully capture the imager's system matrix over the entire fisheye field of view [29]. Maximum error for the Stokes S_1 and S_2 parameters was estimated to be worst-case $\pm 1.1\%$ and $\pm 4\%$ with 100% linear input and considering variation over the full fisheye field of view for the LCVR all-sky polarimeter and Nikon all-sky polarimeter, respectively, using the methods in Ref. [29]. Radiometric calibrations were performed on each spectral channel through a linear fit relating camera digital number to integrating sphere radiance (averaged over the relative spectral response function).

Figure 1 shows a photograph of the all-sky polarimeters at the eclipse measurement campaign. During the span of totality (2 min and 17 s), the LCVR, Nikon, and Sony all-sky polarimeters captured one, nine, and fifteen image sets, respectively. Initial exposure and ISO settings were found by recording polarization images at twilight and comparing results to previous measurements and models. 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).

3. 2017 SOLAR ECLIPSE PARAMETERS

We conducted our experiment at the BYU-Idaho astronomical observatory, located west of Rexburg, Idaho. The observation site was 8.8 km from the center line of totality, and the duration of totality was approximately 2 min and 17 s. The path of totality and umbra at mid-totality (17:34:14 UTC = 11:34:14 MDT) are shown in Fig. 2. The geographical coordinates of our measurement site and parameters of the solar eclipse are listed in Table 1.



Fig. 2. Path of totality and umbra at mid-totality (17:34:14 UTC) for our observation site near Rexburg, Idaho. The green line indicates the edges of the umbra and the red line indicates the center line of totality. NASA background image.

Table 1. Parameters of the Total Solar Eclipse on 21 August 2017 near Our Observation Site

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
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

4. ENVIRONMENTAL OBSERVATIONS

To characterize the environmental conditions at and near the observation site, we operated an all-sky thermal ICI [30,31] to characterize cloud type and spatial distribution and an AERONET solar radiometer to document the aerosol properties [32]. Figure 3 shows all-sky thermal images from our fisheye ICI, which revealed thin cirrus clouds at sunrise that diminished before totality, leaving the sky cloud free through sunset. At first and fourth contact, the 500-nm aerosol optical depth was 0.17 and 0.19, respectively (more complete aerosol property retrievals can be obtained from the AERONET website [32]). Nearly ideal atmospheric conditions were present during totality, with the sky completely free of clouds and with less wildfire smoke relative to days just before the eclipse (the average 500-nm aerosol optical depth was 0.14, 0.27, and 0.41 on 21, 20, and 19 August, respectively).

At the observatory site, we operated a mobile weather station that showed results similar to those provided by the BYU-Idaho Physics Department. The temperature decreased from 20.8°C to 17.5°C (while humidity increased) from first to second contact and the temperature increased from 17.5°C to 22.7°C from third to fourth contact. The band-integrated solar irradiance

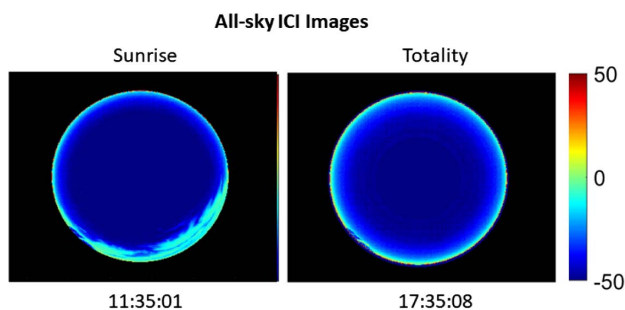


Fig. 3. All-sky ICI images of brightness temperature [°C] with north up and west to the right (as would be seen lying on the ground, looking into the sky) on the morning of 21 August 2017 at 11:35:01 UTC (left, ~1 h before sunrise) and in totality at 17:35:08 UTC (right, 15 s before third contact). Thin cirrus clouds can be seen in the south-southwest at sunrise, but the sky was cloud-free during totality.

decreased from 574.1 to 0.021 W/m² from first to second contact and increased from 0.028 to 818 W/m² from third to fourth contact. During totality we could see planets, stars, and the solar corona, and birds around us began behaving as if it were nighttime.

Samples of surface reflectance spectra were measured with a hand-held ASD spectrometer and supplemented with MODIS surface reflectance data. At 469, 555, and 645 nm, the surface reflectances retrieved from MODIS (for a 75-km radius around the observation site) were 0.06, 0.09, and 0.10 (on a normalized scale from 0 to 1), respectively, in close agreement with the ASD data taken near the observation site.

5. ECLIPSE OBSERVATIONS

Daytime skylight polarization without an eclipse has a distinct pattern that rotates through the sky in time, based on the position of the Sun, as observed in Fig. 4 and Visualization 1. In the polarized all-sky images, north is at the top and west is to the right, as would be seen for an observer lying on the ground, looking up into the sky, and AoP is referenced to the principal plane containing the Sun and zenith [43]. Neutral points of zero polarization can be observed in the DoLP images, corresponding to a 90° change in the AoP image along the solar principal plane. The daytime neutral points are isolated in the center panel of Fig. 5, which shows Nikon DoLP and AoP images from 13:45:24 UTC on 21 August (eclipse morning). The rising Sun was just above the eastern horizon ($az = 84.35^\circ$, $el = 11.49^\circ$, left side), so the band of maximum polarization crossed the sky near the zenith. The center panel displays DoLP with a 0.1 threshold to highlight the Babinet point above the Sun and the Arago point above the antisolar point [26]. At these points, the DoLP is zero and the AoP has a 90° discontinuity.

During totality, the Nikon and Sony all-sky polarimeters recorded nine and fifteen measurements, respectively, while the LCVR all-sky polarimeter was able to record only one measurement. The LCVR all-sky polarimeter was limited by narrow 10-nm filter bandwidths, and the Nikon system recorded fewer successful images than the Sony system as a result of one of the bracketed exposure settings for the Nikon cameras being underexposed. Figure 6 shows all-sky images (sum of the 0°, 60°, and 120° polarized images) and RGB-averaged radiance images (Stokes parameter S_0 calibrated to mW cm⁻² sr⁻¹) at the beginning, middle, and end of totality. The brightness and polarization of skylight was observed to change dramatically during totality as the umbra moved from the northwest horizon to the southeast horizon. The eastern sky was brightest at the start of totality, and the western sky was brightest at the end of totality. At mid-totality, the skylight distribution was nearly symmetrical about the zenith and twilight-like conditions were observed near the horizon, wrapping 360° around us. The images shown in Fig. 6 were recorded using the Nikon all-sky polarimeter with ISO = 4000, $f\# = 3.5$, and exposure time = 1/80 s. Similar results were observed with the Sony system.

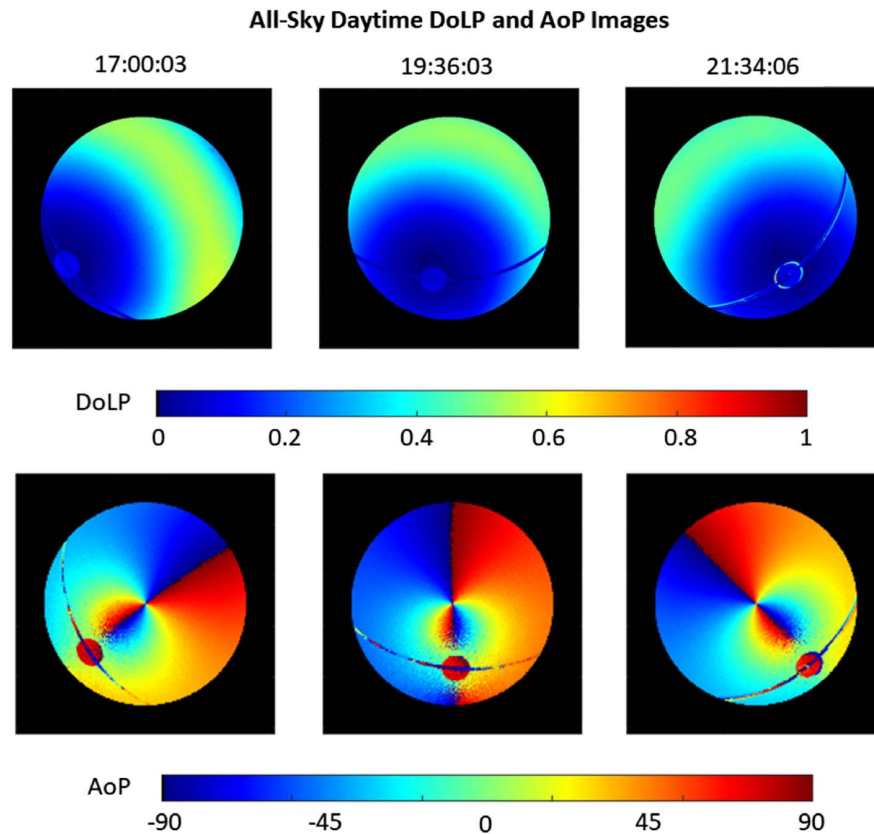


Fig. 4. All-sky DoLP and AoP images from the 450-nm channel of the LCVR polarimeter, recorded from morning to evening on 21 August 2017. The measurement times (UTC) are listed above each pair of DoLP and AoP images. The AoP is referenced to the solar principal plane [43], and the images are displayed with north at the top and west to the right. The spatial and temporal distribution of the DoLP and AoP from sunrise to sunset on 21 August 2017 can be viewed in [Visualization 1](#).

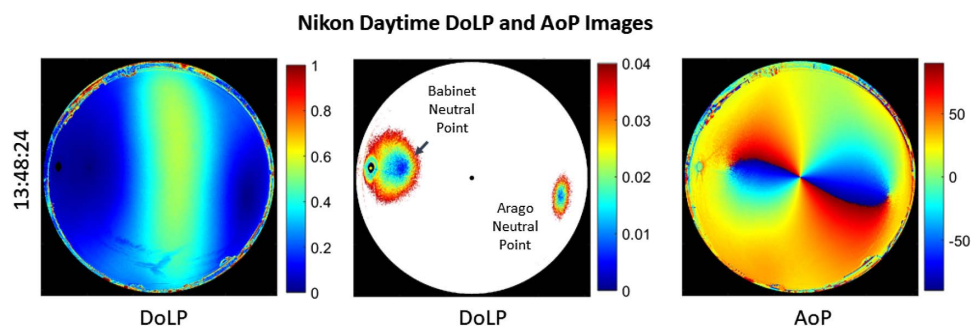


Fig. 5. All-sky DoLP and AoP images from the Nikon blue channel at 13:45:24 UTC on the morning of 21 August 2017 (eclipse day) illustrate the zero-DoLP neutral point measurement capability of the three-camera Nikon all-sky polarization imager. The small, farthest-left circle (especially visible in the center panel) is the Sun.

A. Temporal and Spatial Polarization Distribution

Immediately before and after totality, the maximum sky polarization was in a band located approximately 90° from the Sun, even though the source was only a tiny piece of the Sun. The maximum DoLP observed 90° from the Sun before totality (57%) was greater than the DoLP observed in totality (35%), and the maximum band of polarization shifted from the usual Sun-centered circle to a nominally zenith-centered circle (with the most symmetric pattern occurring near the end of totality).

The spatial sky polarization pattern varied temporally throughout totality, as shown in Figs. 7 and 8. Along the solar principal plane in these figures, neutral points [26] with minimum DoLP (not quite zero) were observed, one at the zenith and one near the antisolar horizon, starting at the beginning of totality. The consistent measurement of zero DoLP at daytime neutral points (Fig. 5) removes concern about instrumental polarization in the fisheye lenses, possibly causing the totality neutral point DoLP to be small but nonzero.

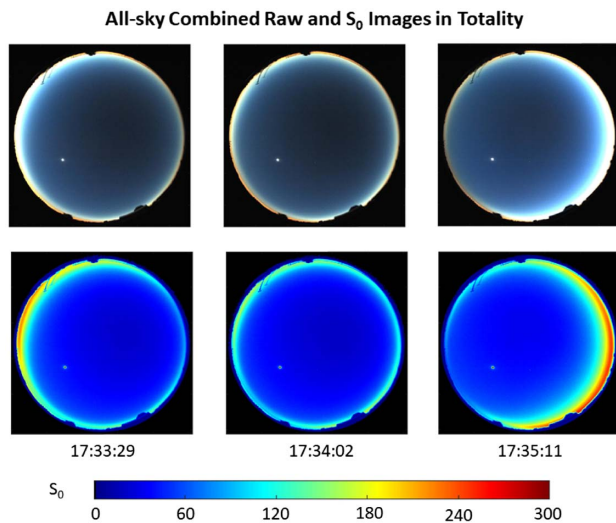


Fig. 6. Combined raw (sum of the 0° , 60° , and 120° images) and RGB-averaged radiance (S_0) images measured on 21 August 2017 in totality, from second to third contact with the Nikon all-sky polarimeter. Measurement times (UTC) are listed below each column. The brightest region of the sky shifted from the east at the beginning of totality to the west at the end of totality (as the umbra moved from the northwest horizon to the southeast horizon). Near mid-totality, the skylight distribution was symmetrical about the zenith. The images are aligned with north at the top and west to the right, and S_0 images are calibrated to radiance units of $\text{mW}/(\text{cm}^2 \text{sr})$.

From second to third contact, the near-zenith neutral point moved slightly closer to the zenith, while the near-horizon neutral point moved outward, disappearing by the end of totality. The changes in the AoP along the solar principal plane indicate the presence of neutral points, although with minimum DoLP that was not quite zero (~ 0.04), similar to observations at the 1999 and 2006 eclipses [13,20,23]. Figure 9 highlights the neutral point locations with DoLP images displayed with 0.1 threshold. In this figure, it becomes apparent that the near-horizon neutral point was located slightly to the southern side of the solar principal plane (plane containing the Sun and the zenith), as was observed also in the earlier eclipses. Note that the antisolar near-horizon neutral point possibly could be explained as an Arago point for a virtual Sun formed by the bright eastern horizon in early totality.

We generally observed minimum polarization from the zenith to the antisolar horizon and maximum polarization near the horizon in the plane running perpendicular to the solar principal plane through the zenith. This could possibly be a residual effect from the normal sunlit band of maximum polarization, arising at least partly from Rayleigh scattering just outside the umbra. These patterns were observed in images from all three of our all-sky polarization imaging systems. We also note that 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.

The high temporal density of images also allowed us to resolve details of the transition out of totality, which revealed that the zenith totality neutral point shifted rapidly (but not instantaneously) to become the normal Babinet point, just above the

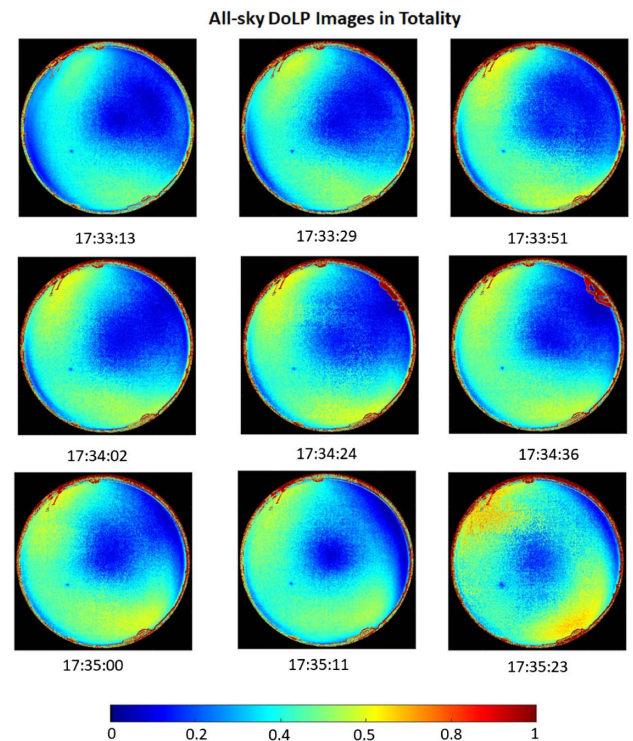


Fig. 7. All-sky DoLP images recorded during totality from second to third contact on 21 August 2017 by the Nikon system at the measurement times (UTC) listed below each image (second contact was at 17:33:06 UTC, and third contact was at 17:35:23 UTC). The images are aligned with north at the top and west to the right. The spatial and temporal distribution of the DoLP in totality on 21 August 2017 can be viewed in Visualization 2, and a version scaled to a maximum of 0.25 can be viewed in Visualization 3.

Sun. Figure 10 shows DoLP images with normal threshold (top) and 0.1 threshold (bottom) from several seconds before and after third contact. The left panel shows the zenith neutral point surrounded by a zenith-symmetric circle of low DoLP at 17:35:11 UTC, 6 s before third contact. The center panel shows the zenith neutral point beginning to shift slightly sunward at 17:35:28 UTC, 5 s after third contact. Finally, in the right frame, the zenith neutral point has shifted entirely sunward to the normal Babinet point position by 17:35:36, 13 s after third contact (the left and middle images were recorded by the Sony system, and the right image was recorded by the Nikon system). The top full-scale DoLP images show the overall DoLP pattern smoothly transitioning from the totality pattern to the daytime pattern. This is the first time such detail has been observed, which suggests that the zenith and near-horizon neutral points are, by conservation of discontinuity index, of order $+1/2$ [26], with the zenith point transitioning from and to the Babinet point and the near-horizon point likely transitioning from and to the Arago point (which was well below the horizon by this late-morning time). Therefore, the transition between normal daytime and totality polarization patterns appears to occur less suddenly than previously believed, taking approximately 13 s in this observation.

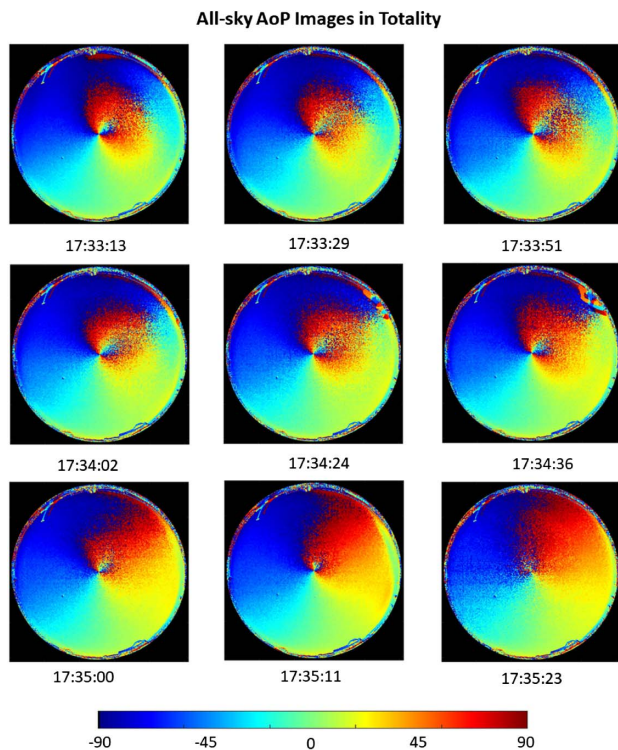


Fig. 8. All-sky AoP images recorded with the Nikon system during totality from second to third contact on 21 August 2017. The AoP is referenced to the solar principal plane, and the measurement times (UTC) are listed below each image. The images are aligned with north at the top and west to the right. The spatial and temporal distribution of the AoP in totality on 21 August 2017 can be viewed in Visualization 4.

B. Spectral Dependence

In Fig. 11, S_0 , AoP, and DoLP images show the spectral polarization patterns recorded in the RGB channels near mid-totality at 17:34:02 UTC with the Nikon all-sky polarimeter. The sky was brightest in the blue channel throughout totality, and the DoLP was symmetric about the solar principal plane in both the blue and green channels, except the neutral point near the horizon (which was also the minimum observed DoLP value), which we showed in the previous section was located slightly to the south side of the principal plane. 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, which casts uncertainty on the spectral variation discussed here.

For comparison with the historically significant measurements from the 1973 African eclipse, principal plane slices through the all-sky DoLP images are shown in Fig. 12. These slices are similar to the scans recorded at the 1973 Kenya eclipse [12] and were extracted from the fisheye images to highlight the shift of the near-zenith and near-horizon neutral points for each wavelength between second and third contact. Although the red-channel DoLP is weak and noisy in Fig. 11 near mid-totality, in Fig. 12 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

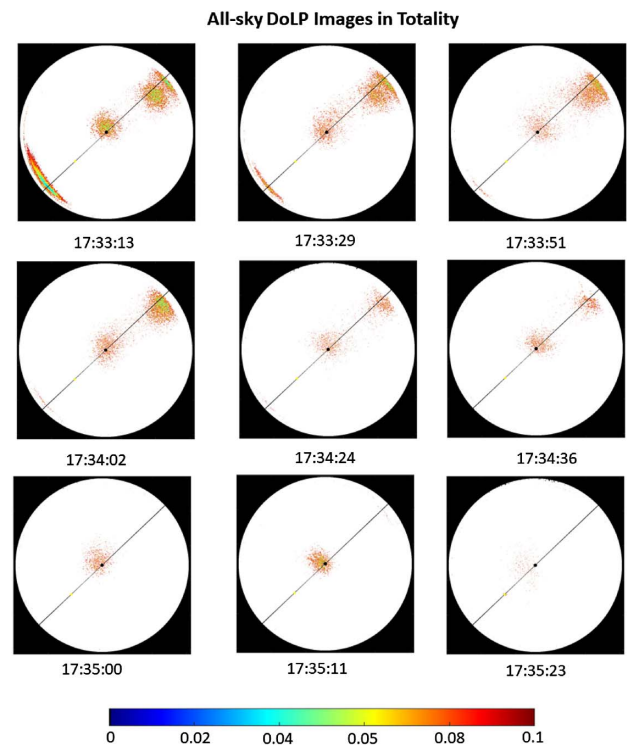


Fig. 9. All-sky DoLP images thresholded at 0.1 show the temporal evolution of totality neutral points at the zenith and near the antisolar horizon.

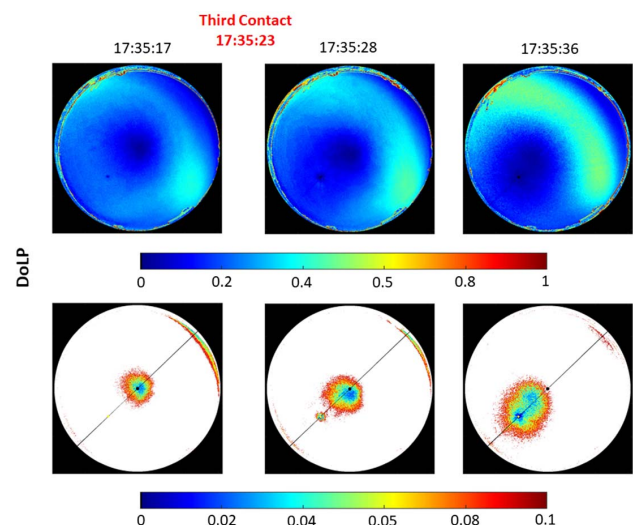


Fig. 10. All-sky DoLP images from the blue channel scaled with maximum = 1 (top) and maximum = 0.1 (bottom) show that the zenith neutral point at 17:35:11 UTC (left, third contact -6 s) shifted slightly sunward by 17:35:28 UTC (center, third contact $+5$ s) and further sunward by 17:35:36 (right, third contact $+13$ s) to become the Babinet point. The first and second images were recorded by the Sony system and the third image was recorded by the Nikon system.

zenith angles of -60° to 20° . Near the end of totality, the red channel DoLP became nominally symmetric about the zenith, similar to the blue and green channels.

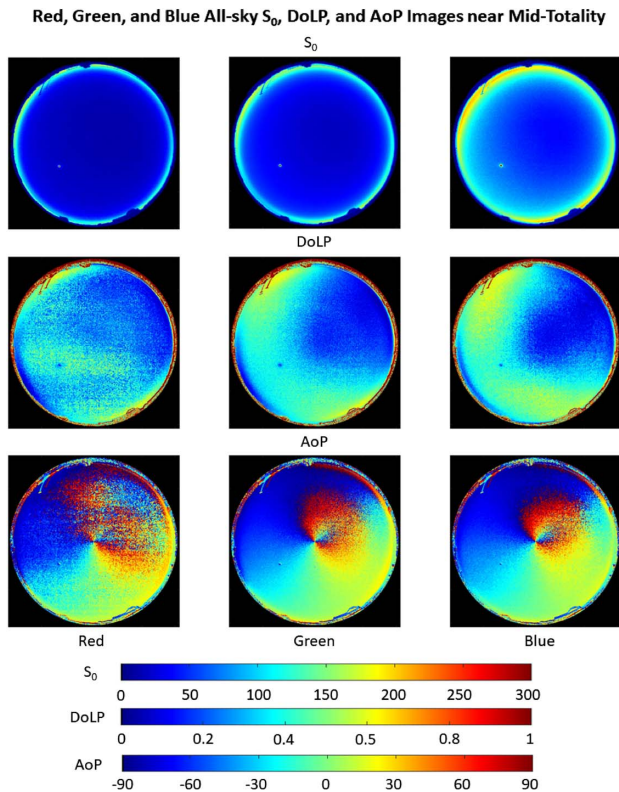


Fig. 11. All-sky S_0 , AoP, and DoLP images recorded near mid-totality at 17:34:02 UTC for the RGB channels. The AoP is shown referenced to the solar principal plane, and S_0 images are calibrated to radiance units of mW/(cm² sr). The images were recorded by the Nikon system using ISO = 4000, F/# = 3.8, and exposure time = 1/80 s.

In all cases shown in Fig. 12, the 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 (i.e., to larger zenith angles). For every measurement during totality, the maximum polarization in the solar principal plane was found in the solar hemisphere direction. Interestingly, the minimum and maximum DoLP values both were observed to increase from second to third contact.

Prior to the 1973 Kenya eclipse, observers had focused on measuring polarization 90° from the Sun. However, our study, along with results presented for the 1973 [12], 1999 [13,23], and 2006 [20] eclipses, show that the maximum polarization during totality is found predominantly in the solar hemisphere and not 90° from the Sun. For our observations before totality, the DoLP observed 90° from the Sun in the RGB channels was greater than 50%. At the beginning of totality, the DoLP observed 90° from the Sun was at most 18% in the red channel and 8%–13% in the green and blue channels. Near the end of totality, the DoLP observed 90° from the Sun in the RGB channels was approximately 35%. These results illustrate the highly dynamic situation with sky polarization during totality.

6. DISCUSSION

From second to third contact, we recorded nine RGB polarimetric images with the three-camera Nikon all-sky polarimeter, fifteen RGB polarimetric images with the three-camera Sony all-sky polarimeter, and a single 450-nm polarimetric image with the LCVR all-sky polarimeter. The narrow filter bandwidth prevented the LCVR system from taking multiple images during totality. For the one polarimetric measurement, it took over 1 min to capture the four Stokes images needed to reconstruct the Stokes vector and retrieve the DoLP and AoP. The unique contributions reported in this paper include the following advancements:

- the first use of digital cameras to record 14-bit images with direct radiometric and polarimetric calibration (previous pioneering all-sky eclipse polarization images were 8-bit scans of photographic slides [13,20,23]);
- the first simultaneous imaging of three polarization states during an eclipse, which resolves lingering questions about how much of the observed patterns arose from time-sequential measurements by scanning polarimeters [12] or a single camera operated as a division-of-time polarimeter [13,20,23];
- the most temporally uniform and largest number of images during totality and the first with temporal symmetry around mid-totality (compared with three images before mid-totality in 1999 [13] and six images before mid-totality and two after mid-totality in 2006 [20]);
- the first record of clear-sky polarization from sunrise to sunset on the eclipse day;
- the first eclipse polarization images accompanied by simultaneous and quantitative documentation of clouds, aerosols, and surface reflectance, all of which must be known for accurate polarized radiative transfer modeling;
- the first documentation of the transition of a totality neutral point into a post-totality neutral point;
- the first measurement of the time for the totality eclipse polarization pattern to transition to a daytime-like partial-eclipse polarization pattern.

Our results corroborate the previous pioneering all-sky eclipse polarization measurements made by a Hungarian group at an August 1999 solar eclipse in Hungary [13,23] and at a March 2006 solar eclipse in Turkey [20]. Using a film camera and fisheye lens with a rotating polarizer, they were able to take a series of three images (three before mid-totality) during the 1999 eclipse and eight images (six before totality, two after mid-totality) during the 2006 eclipse. Totality was 2 min and 22 s for the 1999 Kecel, Hungarian solar eclipse, 3 min and 45 s for the 2006 Side, Turkey solar eclipse, and 2 min and 17 s for the 2017 Rexburg, Idaho solar eclipse. Our images confirm that the earlier observations constitute a general eclipse polarization pattern that is not unique to one specific eclipse. Furthermore, our images provide an independent validation of the results from the 1999 eclipse, which followed the same geometry as the 2017 eclipse, as detailed below.

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.

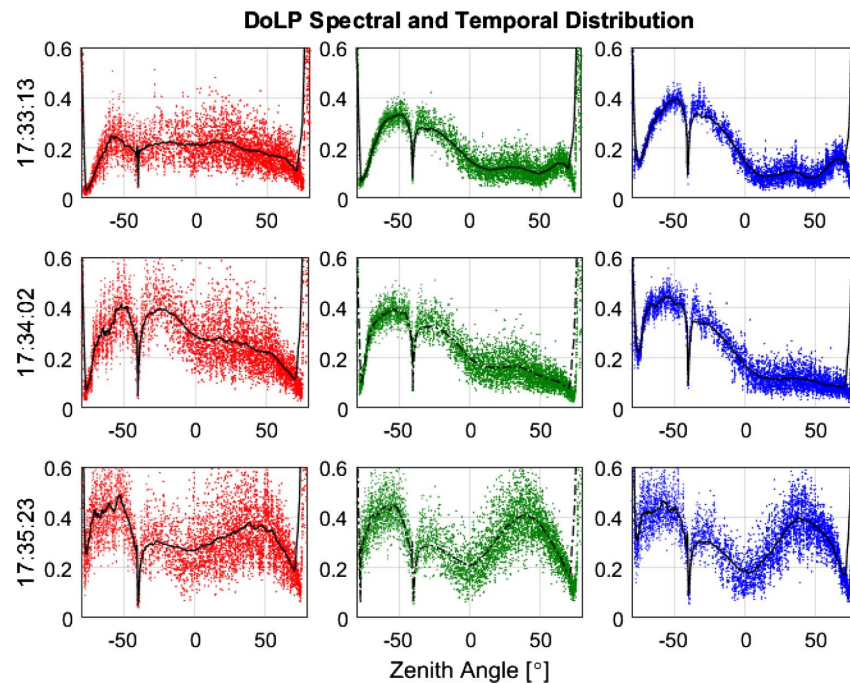


Fig. 12. Principal-plane slices extracted from the red (left), green (center), and blue (right) fisheye DoLP images at the beginning of totality (17:33:13 UTC, top), near mid-totality (17:34:02 UTC, middle), and at the end of totality (17:35:23 UTC, bottom). The Sun was located at -40.6° zenith angle.

In all cases, a rapid 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 antisolar hemisphere, neutral points were observed near the antisolar principal plane and horizon. As the umbra crossed the solar hemisphere, 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 antisolar 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 is general and not unique for each eclipse.

From the results observed with the all-sky polarimeters, G. Shaw's mid-totality results from the 1973 African solar eclipse [12] indicate that neutral points in the antisolar 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 [13,23] and 2017 solar eclipses, where neutral points were observed in the antisolar hemisphere from the beginning of totality through mid-totality. At the time of G. Shaw's study, the complex and dynamic nature of the totality polarization pattern was unknown. Given what we know now about the dynamic

lighting conditions, we recommend using a fisheye digital imaging system, like the ones we developed for this eclipse, to ensure that eclipse sky polarization can be measured accurately and quickly throughout the sky as a function of time.

As summarized in Table 2, results from past experiments using point-source polarimeters [44–48], scanning polarimeters [12], and all-sky imagers [13,20,23–25] suggest that skylight polarization measured during totality varied with environmental parameters, similar to normal daytime sky polarization. For all measurements, the AoP was generally observed to be independent of wavelength, except for a recent suggestion for the sky near the corona [49]; however, the location of the observed neutral points depended on wavelength. 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 antisolar 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. Without a more complete model, we do not know what to expect for spectral polarization variation during totality, but Rayleigh scattering theory predicts that daytime (noneclipsed) skylight DoLP with low aerosol content tends higher at longer visible wavelengths, since more multiple scattering occurs for shorter wavelengths. The actual spectrum varies strongly with aerosols and surface reflectance [5,6]. Therefore, the spectral discrepancies in the 1999, 2006, and 2017 measurements could be the result of different aerosol and surface conditions. For example, the 1999 eclipse measurements [13,23] were made under terrestrial surface conditions of the Hungarian Great

Table 2. Summary of Mid-Eclipse Sky Polarization Measurements^{a, b}

Observer	Year	Solar Zenith Angle [°]	Obs. Point Zenith Angle [°]	Measurement Type	Wavelength	DoLP [%]
de Bary <i>et al.</i> [47]	1961	78	12	point sensor (ground-based)	Green	0
Moore <i>et al.</i> [48]	1965	49	41	point sensor (airborne)	475 nm	0.5
Miller <i>et al.</i> [17]	1965	25	65	point sensor (airborne)	601 nm	4.5
					558 nm	31
					578 nm	35
					610 nm	28
					630 nm	26
Rao <i>et al.</i> [45]	1966	20	70	point sensor (airborne)	475 nm	19
Dandekar and Turtle [44]	1970	44	46	point sensor (ground-based)	475 nm	21
					600 nm	<0.5
Gerharz [46]	1970		38–53	imager (ground-based)	535 nm	<2.5
Shaw [12]	1973	53	37	scanning (ground-based)	400	4
Pomozi <i>et al.</i> [13], Horvath <i>et al.</i> [23]	1999	32	full sky	all-sky imager (ground-based)	450 nm	~2 – 12
					550 nm	~9 – 22
					650 nm	~10 – 30
Sipöcz <i>et al.</i> [20]	2006	46	full sky	all-sky imager (ground-based)	450 nm	~1 – 8
					550 nm	~2 – 16
					650 nm	~3 – 20
Eshelman <i>et al.</i> (this work)	2017	51	full sky	all-sky imager (ground-based)	455 nm	~8 – 43
					525 nm	~8 – 38
					595 nm	~13 – 38

^aSingle-point sensor observations were taken 90° from the Sun in the solar principal plane.

^bAll-sky polarization results represent the range of polarization observed in the solar principal plane near mid-eclipse.

Plain, while the 2006 measurements [20] were made at the shore of the Mediterranean Sea. If Rayleigh scattering dominated (i.e., low aerosol content) with a spectrally flat surface reflectance, the DoLP would likely peak in the red channel for noneclipsed daytime measurements [5,6]. However, for the 2017 solar eclipse, the surface reflectance was higher in the red channel than for the green and blue channels, which would normally correspond to a higher DoLP in the blue channel because a higher surface reflectance creates more multiply scattered light that reduces the DoLP [2,4–6,11]. This underscores the importance of future observers' measuring and reporting environmental conditions and highlights the importance of a model to understand the spectral dependence of polarization during totality.

Modeling the skylight during an eclipse is complex. Skylight polarization depends on a variety of factors such as the scattering geometry, aerosols, clouds, and the underlying surface reflectance. At the time Können developed his model [22], there was only one scanning data set available [12]. Können noted that all-sky polarization measurements were needed to compare measured results with quantitative models. He also had to neglect the initial polarization state of light scattered from outside the umbra into the umbra because measurements were not available. Building on the pioneering all-sky images from the 1999 and 2006 eclipses [13,20,23], our data set described here contributes to both of these needs, providing well-calibrated

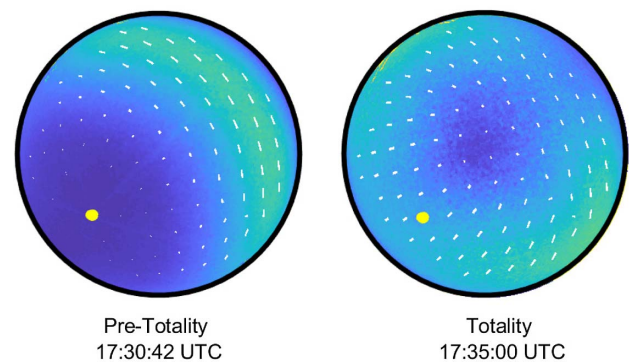


Fig. 13. Nikon DoLP images with AoP vectors before totality (17:30:42 UTC) and during totality (17:35:00 UTC). The length of the vectors represents the DoLP, and the orientation of the vectors represent the AoP. As the umbra moves, the distribution of the contributing parallel and perpendicular polarization changes, shifting the location of the observed neutral points.

measurements before, during, and after totality, along with well-characterized environmental parameters. These data should be used to more completely explain eclipse polarization using polarized multiple-scattering radiative transfer codes.

In the absence of such modeling, a qualitative understanding of how neutral points arise in the otherwise quasi-zenith-symmetric totality polarization pattern can begin by considering

the AoP and DoLP patterns created outside the umbra by primarily single Rayleigh scattering. Following a similar approach to [13], we show the AoP and DoLP patterns in Fig. 13 before totality (left) and during totality (right), with vector line lengths denoting DoLP and orientations denoting AoP. Outside the umbra, the usual clear-sky polarization pattern has maximum DoLP approximately 90° from the Sun, with the AoP oriented perpendicular to the scattering plane. 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 antisolar 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 combines with equal magnitudes and orthogonal polarizations to form a neutral point. Because there really are not simply two sources in this multiple-scattering problem, the neutral point does not exhibit exactly zero polarization.

Consideration of higher-order scattering at greater viewing angles should explain the multiple neutral points in the observed AoP images, although such modeling remains to be done. As the umbra moves, the position of the neutral points also move, driven by the changing higher-order scattering of light with different initial polarization states. We expect that this is why the neutral point exists near the horizon and changes as the umbra moves, though a detailed explanation will require a high-order polarized scattering model.

7. 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 nine times using our Nikon all-sky polarimeter system and fifteen times with our Sony system. At second contact, the polarization pattern changed quickly 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. Our images recorded immediately before and after third contact revealed for the first time that the zenith totality neutral point transitioned quickly (but not instantaneously) to become the Babinet point during partial totality and during daytime following the entire eclipse. This also constitutes the first measurement of the time required for the sky polarization pattern to transition from the totality pattern to the daytime-like pattern of polarization that persisted through partial totality and beyond (~ 13 s in our measurements).

For the first time, all-sky polarimeter systems based on three simultaneously operating digital cameras were used to record three linear polarization states simultaneously to remove any lingering uncertainty about the previous pioneering division-of-time polarimetric images and scans. The three-camera all-sky polarimeters were robust, easy to use, cost-efficient, and provided the largest number of all-sky polarization measurements

during a solar eclipse to date. These imagers recorded polarimetric images evenly distributed in time throughout totality (and continuously from sunrise to sunset on the eclipse day), producing the most temporally uniform all-sky polarization data set to date, accompanied by the cloud, aerosol, and surface reflectance measurements that will be required for model development and validation.

Our results provided valuable corroboration of the spatial, temporal, and neutral-point conclusions from the pioneering all-sky images recorded at the 1999 and 2006 eclipses. 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 is general and not unique for each eclipse.

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Disclosures. LME: Polaris Sensor Technologies (E).

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