ALL-SKY IMAGING OF VISIBLE-WAVELENGTH ATMOSPHERIC POLARIZATION AT MAUNA LOA, HAWAII

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I. INTRODUCTION

An all-sky imaging polarimeter has been designed and built to study cloud and aerosol effects on visible-wavelength polarized skylight [1,2]. Capable of imaging both the sky dome with a fisheye lens and localized targets with a telephoto lens, this imager has been used to study polarization signatures from the atmosphere as well as from smooth and rough plates. Figure 1 shows a layout and a photograph of the imager, which is calibrated for both polarization and radiance.

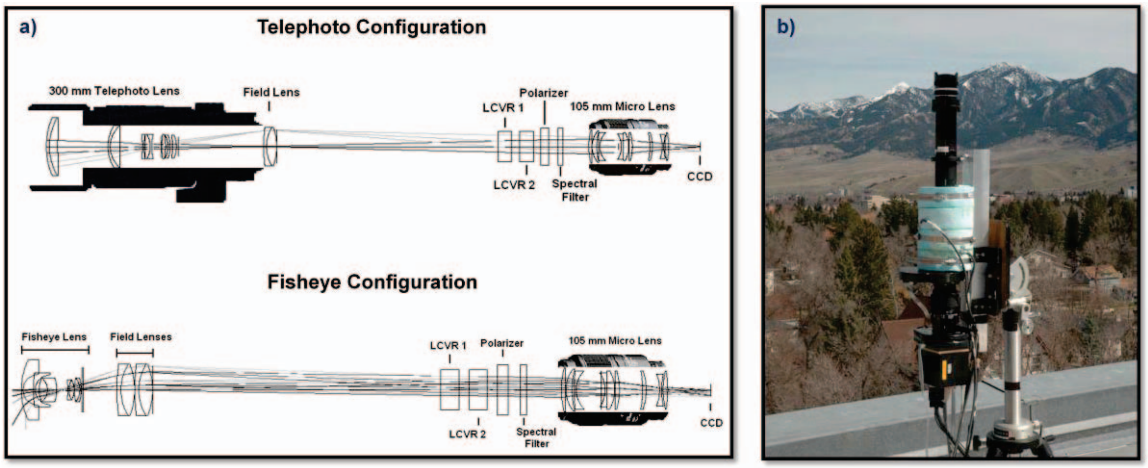

Figure 1: a) Instrument in telephoto (top) and fisheye (bottom) configuration and b) image of the fisheye mode.

II. PROBLEM STATEMENT

The main goals of this research are to quantify the effects of clouds, aerosols, and surface albedo on polarization signatures. This is critical for the generation and validation of polarized radiative transfer models and for prediction of polarization signatures of objects of interest. Recent research also has shown the added benefit of polarization for improving aerosol retrievals from sky radiance measurements [3].

III. METHODS

The instrument is a division-of-time polarimeter [4]; one polarization image set comprises four images taken sequentially at different polarization states, repeated for five visible and near-infrared wave bands. The resulting images contain a full four-element Stokes vector at each pixel. The measurements are rapid in polarization space and slower in wavelength space. At each wavelength (selected by a rotating filter wheel), two liquid-crystal variable retarders are used to modify the polarization state of the imager for rapid polarization imaging of dynamic scenes that contain moving objects or clouds. Stokes parameters are retrieved from the polarized images using a system-matrix inversion technique [*4*]. From the Stokes parameter data, images are generated of parameters such as the degree of (linear) polarization (DoLP) or Angle of Polarization (AoP).

In our current research, the changing features of the DoLP from the effects of different aerosol and cloud conditions are the main focus. Rayleigh scattering theory dictates that molecular scattering will follow a $1/\lambda^4$ wavelength scaling, with maximum DoLP at angles 90° from the sun [*5*]. This yields a maximum DoLP arc that moves from the zenith at sunrise to the horizon at midday and then back to the zenith in the afternoon. Figure 2 shows intensity-normalized Stokes-parameter images on the left used to produce the DoLP image shown on the right. Our standard processing routines use the S_3 circular polarization images to identify instrument calibration problems since nearly every measurement situation we encounter has no mechanism for generating circular polarization.

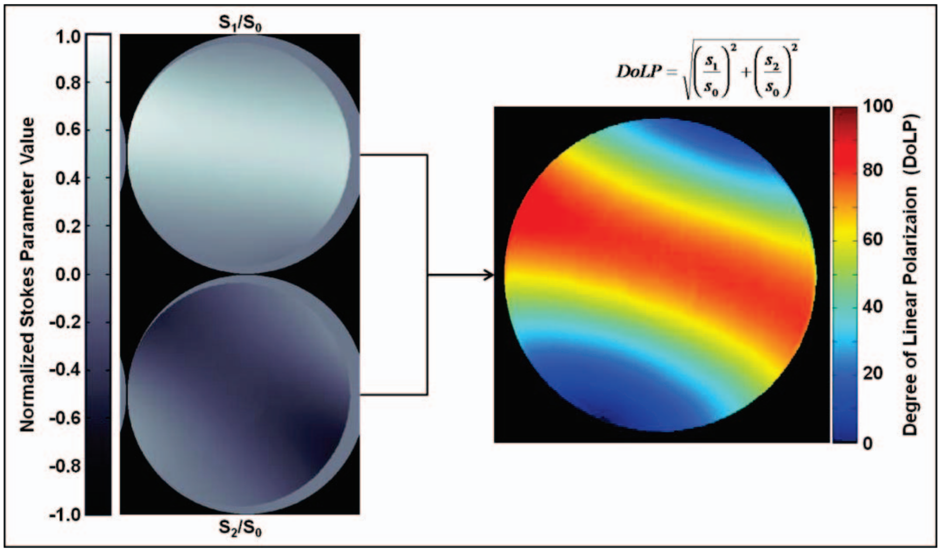

Figure 2: Intensity-normalized Stokes images (left) used to form DoLP image (right).

The actual polarization seen in the real atmosphere differs from pure Rayleigh scattering predictions primarily through reduced DoLP. Scattering by clouds and aerosols and reflection from the ground increases the amount of unpolarized light, which decreases the maximum atmospheric DoLP. To begin quantifying the complicated relationships among these variables, the polarimeter has been deployed at Montana State University in Bozeman, MT, and at the NOAA Mauna Loa Observatory (MLO) on the island of Hawaii. In Bozeman deployments, the polarization data were complemented with data from a suite of supporting instruments that include a co-located weather station, scanning solar radiometer, infrared cloud imager, and cloud lidar. The MLO deployment in the summer of 2008 provided critical clear-sky data used to both validate the calibration of the instrument and to confirm sky polarization measurements made by K. Coulson in the late 1970s and early 1980s [*6*,*7*].

IV. RESULTS

Early results from Bozeman deployments showed that clouds in a clear portion of a partly cloudy sky have significantly reduced maximum DoLP values relative to truly clear sky conditions [*1*,*2*]. Furthermore, several hours before clouds become visible in a previously clear sky, cloud precursor signals are seen as fluctuations in the polarization signature [*2*], From the deployment at Mauna Loa, we found that clouds located below the imager affect the DoLP in a different manner. Clouds above the instrument naturally occlude portions of the sky that contain polarized scattered light and also scatter unpolarized light, thereby decreasing the net DoLP of scattered skylight. When clouds are present beneath the imager, as was the case on top of Mauna Loa in Hawaii, it was found that the high cloud albedo led to large amounts of mostly unpolarized upwelling radiance that greatly reduced the DoLP below the Rayleigh scattering level. As an example, Fig. 3 shows DoLP images for two days at Mauna Loa, along with corresponding GOES radiance images of the same area. Note the decreased DoLP magnitude resulting from the increased cloudiness on 3 June relative to 23 May 2008. Figure 4 further highlights this difference with a plot of the DoLP maximum profile along the principal plane through the sun, zenith and observer (origin) for the two days in question.

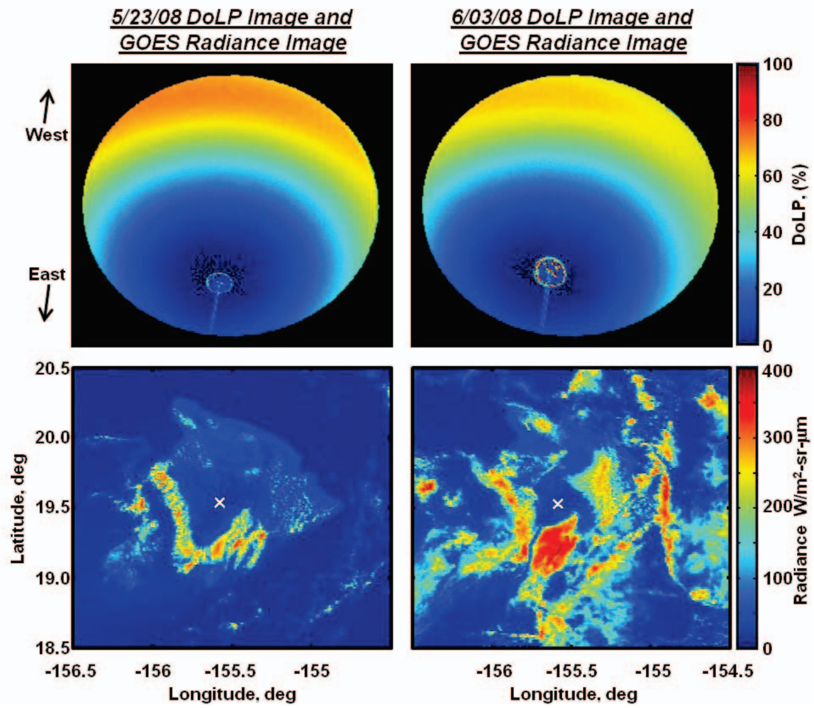

Figure 3: Upward-viewing all-sky DoLP images (top) and corresponding down-looking GOES images of Hawaii (bottom) from 23 May (left) and 3 June 2008 (right). Increased cloudiness on 3 June 2008 (right) leads to reduced DoLP. 'X' indicates the approximate instrument location at the Mauna Loa Observatory.

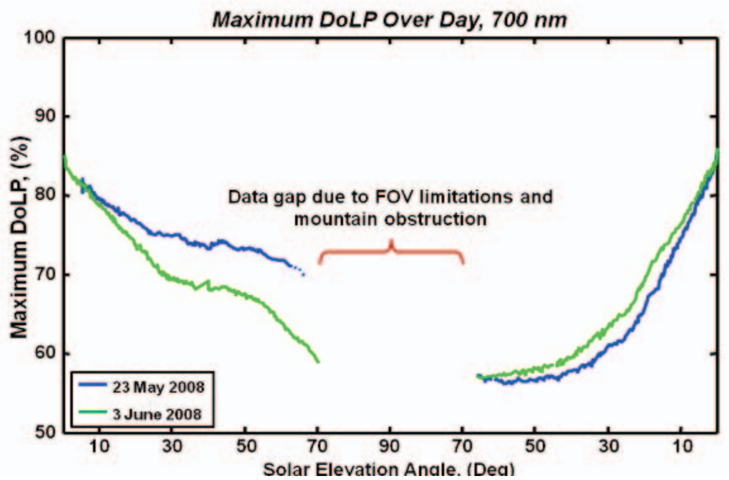

Figure 4: Maximum DoLP principal plane profile at 700-nm wavelength for two days with differing cloud conditions. There was more cloudiness on 23 May 2008 (blue line) relative to 3 June 2008 (green line).

V. SUMMARY AND FUTURE WORK

Episodic deployment of an all-sky polarization imager has generated data that are leading to increased understanding of the interaction of surface albedo, aerosols, and clouds in modifying the polarization of skylight at visible and near-infrared wavelengths. The instrument recently has been modified to operate in an unattended outdoor mode, and has been gathering continuous daytime data since June 2009. Future work is focusing on gathering data in a wide variety of conditions to generate a model for quantitative prediction of sky polarization and resulting ground-object polarization signatures. Future work is also addressing the retrieval of atmospheric aerosol properties of from the angular and spectral variation of polarized sky radiance.

VI. References

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