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PHOTO-POLARIMETRIC SENSITIVITIES TO LAYERING AND MIXING OF ABSORBING AEROSOLS

OLGA V. KALASHNIKOVA,[a*] MICHAEL J. GARAY,[ab] ANTHONY B. DAVIS,[a] DAVID J. DINER,[a] AND JOHN V. MARTONCHIK [a]

ABSTRACT. We investigate to what extent multi-angle polarimetric measurements are sensitive to vertical mixing/layering of absorbing aerosols, adopting calibration uncertainty of 1.5% in intensity and 0.5% in the degree of linear polarization of Multiangle Spectro-Polarimetric Imager (MSPI). Employing both deterministic and Monte Carlo radiative transfer codes with polarization, we conduct modeling experiments to determine how the measured Stokes vector elements are affected at UV and short visible wavelengths by the vertical distribution, mixing and layering of smoke and dust aerosols for variety of microphysical parameters. We find that multi-angular polarimetry holds the potential to infer dust-layer heights and thicknesses at blue visible channel due to its lesser sensitivity to changes in dust coarse mode optical properties, but higher sensitivity to the dust vertical profiles. Our studies quantify requirements for obtaining simultaneous information on aerosol layer height and absorption under MSPI measurement uncertainties.

1. Introduction

Radiative heating by absorbing smoke and dust mixtures, which are frequent and important components of the atmosphere, alter atmospheric dynamics and thermodynamics and must be taken into account to adequately predict the overall impact of aerosol on clouds, weather, and climate. Polarimetric measurements have been advocated in recent years as an additional tool to better understand and retrieve the aerosol properties needed for improved predictions of aerosol radiative forcing on climate. Recent polarimetric sensitivity studies have demonstrated that the degree of linear polarization ($DOLP$) is strongly influenced by the parameters of the aerosol size distribution, the aerosol refractive index, particle shape, the aerosol optical depth (AOD), and vertical layering [1, 2]. In this study, we introduce a formal approach to assessing the sensitivity of both intensity and polarization signals to absorbing aerosol layering. The approach takes explicit account of measurement uncertainties. In this work, we are concerned only with measurement sensitivity rather than the larger question of retrievability. If ignored, this height sensitivity can introduce biases in aerosol property retrievals at short (ultraviolet or blue) wavelengths; if properly exploited, it may enable simultaneous extraction of aerosol profiles and single scattering albedo (SSA).

2. Approach

To explore the sensitivity of absorbing aerosol types to vertical layering and mixing, we employ plane-parallel (1-D) vector radiative transfer codes to calculate the angular distribution of the polarized radiation reflected from layers of aerosol embedded in a Rayleigh scattering atmosphere. Differences in the calculated top-of-atmosphere radiances are considered in terms of realistic instrument uncertainties. We focus on two commonly occurring absorbing aerosol types: spherical particles consistent with biomass burning aerosols and non-spherical particles consistent with transported coarse-mode dust. In general, these types of particles are often found layered or mixed in the real atmosphere. Both smoke and dust absorb solar radiation at visible wavelengths, and contribute to atmospheric heating; however, their microphysical and optical properties differ significantly. We derive the smoke microphysical models from recently reported smoke aerosol properties. The phase matrix for spherical smoke particles was calculated using a Mie code. We derive the dust microphysical model by applying a size distribution representative of dust inferred from AERONET retrievals [O. Dubovik, personal communication] and wavelength-dependent dust refractive indices [I. Sokolik, personal communication]. To calculate the dust scattering matrix, we use the AERONET numerical model described by [6]. For deterministic calculations, we use a successive-orders-of-scattering (SOS) model for the coupled atmosphere-ocean system [7] with a depolarizing Lambertian surface having a constant albedo. The atmospheric profile is specified with a finite sequence of discrete (finitely thick, optically uniform) layers, stacked top-to-bottom each with a given optical depth, scattering phase matrix, and SSA. The elements of the phase matrix are expressed as expansions in generalized spherical (Wigner-d) functions. At present, the Rayleigh depolarization factor is not included in the SOS code. For comparison to the SOS code, we also use a recently developed Monte Carlo (MC) model that accounts for aerosol loadings in a spatially continuous manner, and includes the Rayleigh depolarization factor.

3. Measurement uncertainty assessment

The central concern of this work is the assessment of the effects of absorbing aerosol layers under measurement uncertainties achievable for the next generation of multi-angle, polarimetric imaging instruments. As guidelines, the on-orbit performance of the Multiangle Imaging Spectro-Radiometer (MISR) [4] instrument for intensity measurements and polarization sensitivities of Multiangle Spectro-Polarimetric Imager (MSPI) [5] instruments were considered. The performance of other instruments, such as APS and POLDER, can be accommodated by adjusting the relevant parameters described below. The relative channel-to-channel uncertainty in the intensity calibration, σ_I, for the MISR instrument is $\approx 1.5\%$ of I [3]. Therefore, we assume relative uncertainty in intensity of $0.015I$, which implies that the standard deviation of the intensity, σ_I, is given by:

$$\sigma_I = \delta_I \times I = 0.015I \tag{1}$$

Instrument uncertainties in the measurement of polarization are often expressed as σ_{DOLP}, the standard deviation of the $DOLP = \sqrt{Q^2 + U^2}/I$. A representative estimate of the polarization standard deviation, σ_{DOLP} = 0.005, was chosen for this study. To obtain the standard deviation in Q (the only component of $I_{\rm pol} = \sqrt{Q^2 + U^2}$ in the principal plane), we note that $Q = qI$ and applying the propagation of errors, we obtain:

$$\sigma_Q = \sqrt{(I\sigma_q)^2 + (Q\delta_I)^2} \tag{2}$$

where $\sigma_q = \sigma_{DOLP} = 0.005$ and $\delta_I = 0.015$. To quantify the observational differences between the two types of independent observations, e.g, between the situations of the aerosol in the boundary layer vs. an elevated aerosol layer, we introduce "z-score" or "standard score" statistics, that is given by:

$$z_i(f) = \frac{\left|f_i - f_i^{(\mathrm{ref})}\right|}{\sqrt{\sigma_i^2(f) + \sigma_i^2(f^{(\mathrm{ref})})}} \tag{3}$$

where f and $f^{(\mathrm{ref})}$ are measurements at different observational situations, i denotes the viewing angle, and σ's represent uncertainties in the observations. The values of z have a simple statistical interpretation in that they express the (absolute) difference between two measurements as a function of the standard deviation of the measurements.

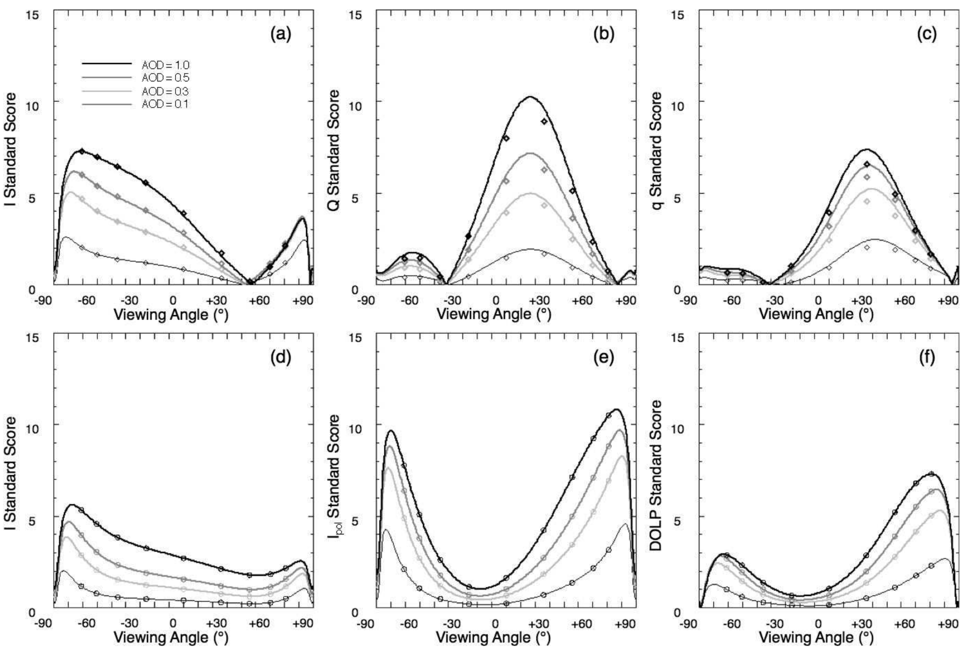

Figure 1. Top row, standard scores for smoke mixed from 2 to 4 km and 0 to 2 km in the principal plane with a black surface. Solar zenith angle = $60°$. Open symbols indicate MC results including Rayleigh depolarization factor. **(a)** I Standard Score, **(b)** Q Standard Score, **(c)** q Standard Score. Bottom row, same as above for realistic viewing geometry, surface albedo = 0.1, solar zenith angle = $30.39°$, relative azimuth angle = $49°$. Open symbols indicate nominal MISR viewing directions. **(d)** I Standard Score, **(e)** I_{pol} Standard Score, **(f)** $DOLP$ Standard Score.

4. Results

Instead of working with intensities directly, measurements of intensity will be expressed as bidirectional reflectance factors (BRFs), where the $BRF = \pi I/\mu_0 F_0$ and $pBRF = \pi I_{\rm pol}/\mu_0 F_0$. The $I_{\rm pol}$ uncertainties for off principal plane observations are calculated by substituting $I_{\rm pol}$ for Q and σ_{DOLP} for σ_q in Eq. (2).

Figure 1 shows the example of smoke height sensitivity in terms of different aerosol optical depths (AOD). The plots show differences in observed multi-angle signals between smoke in the boundary layer (0–2 km) vs. elevated smoke above the boundary layer (2–4 km) for BRF (panels a,d), $pBRF$ (panels b,d) and q and $DOLP$ (panels c,f) for a black surface in the principal plane (panels a–c) and a Lambertian surface with albedo of 0.1 (panels d–f) at 0.44 μm. These differences are divided by the associated measurement uncertainty, according to Eq. (3), to obtain the "standard score," which could also be interpreted as "instrument observability score." We adopt value of 3 as a limit of instrument observability because it implies less than a 0.1% probability that the measurements come from the same underlying distribution. The intensity standard score in this example indicates that intensity observations are starting to be sensitive (in at least 3 cameras) to the smoke vertical layering for $AOD > 0.3$ over the black surface in the principal plane, and $AOD > 1.0$ for the realistic viewing geometry and the desert-like surface.

Using the intensity and polarization standard scores as a guidelines, we established that multiangle polarimetric measurements with realistic imaging instrument uncertainties have the potential to better characterize dust vertical distributions at blue channel, where $I_{\rm pol}$ is not sensitive to changes in dust optical properties but is sensitive to the dust vertical profile for dust $AOD > 0.3$. We also found that smoke vertical distribution and layering with dust, if ignored, can introduce biases in radiometric or polarimetric aerosol property retrievals from UV to green band measurements.

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[a] Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA, US

[b] Raytheon Company
Pasadena, CA, US

* To whom correspondence should be addressed | Email: Olga.Kalashnikova@jpl.nasa.gov

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