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RETRIEVAL OF CLOUD DROPLET SIZE DISTRIBUTION PARAMETERS FROM POLARIZED REFLECTANCE MEASUREMENTS

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ABSTRACT. We present an algorithm for retrieval of cloud droplet size distribution parameters (effective radius and variance) from the Research Scanning Polarimeter (RSP) measurements. The RSP is an airborne prototype for the Aerosol Polarimetery Sensor (APS), which is due to be launched as part of the NASA Glory Project. This instrument measures both polarized and total reflectances in 9 spectral channels with center wavelengths ranging from 410 to 2250 nm. For cloud droplet size retrievals we utilize the polarized reflectances in the scattering angle range between 140 and 170 degrees where they exhibit rainbow. The shape of the rainbow is determined mainly by single-scattering properties of the cloud particles, that simplifies the inversions and reduces retrieval uncertainties. The retrieval algorithm was tested using realistically simulated cloud radiation fields. Our retrievals of cloud droplet sizes from actual RSP measurements made during two recent field campaigns were compared with the correlative in situ observations.

1. Introduction

Accurate characterization of optical and microphysical properties of clouds and their interaction with solar radiation is essential for climate modeling and prediction. Currently operational methods for remote sensing of cloud droplet size in the solar spectral domain are based on the multispectral measurements and do not include polarization [1]. These retrievals are affected by uncertainties due to 3D nature of radiation fields not accounted for in the 1D radiative transfer models used in the retrieval algorithms [2, 3], as well as to gaseous and aerosol absorptions [4, 5]. On the other hand, retrievals of cloud droplet size from polarized reflectance measurements in the rainbow region (cf. [6, 7]) are free of these uncertainties, since the shape of the rainbow is dominated by single scattering of light by cloud particles. The retrievals of droplet effective radius and variance described in this paper are just as accurate over land, or ocean (no surface albedo issues), and are valid independent of the optical depth down to unity (i.e. work for common low-water-path clouds). They can also be combined with lidar-derived extinctions at the cloud top in order to compute the number concentration of cloud droplets [8].

2. RSP Measurements

The Research Scanning Polarimeter (RSP) is an airborne prototype for the Aerosol Polarimetery Sensor (APS), which is due to be launched as part of the NASA Glory Project [9]. This instrument measures I, Q, and U components of the Stokes vector in 9 spectral channels with center wavelengths of 410, 470, 555, 670, 865, 960, 1590, 1880 and 2250 nm. The total and polarized reflectances

$$R = \frac{\pi I}{\mu_s I_0}, \quad \text{and} \quad R_p = -\frac{\pi Q}{\mu_s I_0} \tag{1}$$

are then derived from these Stokes parameters. Here I_0 is the extraterrestrial solar irradiance, and μ_s is the cosine of the solar zenith angle. The Stokes parameter Q in Eq. (1) is defined with respect to the scattering plane containing both solar and view directions (parameter U in this plane is negligibly small). The RSP is a push-broom sensor scanning along the aircraft track within $\pm 60^o$ from nadir and making samples at 0.8^o intervals. The scans (containing around 150 instantaneous measurements each) are aggregated into "virtual" scans, each consisting of all reflectances (at a variety of scattering angles) from a single point on the ground or at the cloud top. This aggregation can be done using either the aircraft attitude data, or the own RSP measurements of brightness contrast. Besides cloud properties, RSP (and eventually APS) measurements can be used for accurate retrievals of aerosol optical depth, size, and refractive index, as well as for characterization of the ground surface and chlorophyll concentrations in the ocean.

3. Retrieval Algorithm

For cloud droplet size retrievals we utilize the scattering angle dependences of the polarized reflectances in 410, 865, and 2250 nm spectral channels. Our technique is focused on the sharply defined structure (rainbow) in the polarized reflectances of clouds within the scattering angle range between 135^o and 165^o. To analyze the shape of the polarized rainbow, we first perform a rotation from the measurement coordinate frame to that of the scattering plane; then, we fit the polarized reflectance computed according to Eq. (1) by a family of functions based on single scattering domination assumption:

$$R_p(\gamma) = a \cdot P_{12}^{(Mie)}(\gamma, r_{\text{eff}}, v_{\text{eff}}) + b \cdot \cos^2 \gamma + c, \tag{2}$$

where γ is the scattering angle, r_{eff} and v_{eff} are respectively the effective radius and variance of the cloud droplet size distribution [10], which is assumed to have a Gamma distribution form. The phase matrix elements $P_{12}^{(Mie)}$ are computed using Mie theory for a grid of effective radius and variance values, while a, b, and c are empirical fitting parameters accounting for contributions to the polarized reflectance from cloud multiple scattering, molecular atmosphere, aerosols, and ground surface. Our fitting technique consists of 2 steps: first, we count minima and maxima in the observed rainbow signature and match these numbers with those from the corresponding lookup tables (give or take 1); after that we directly look for the best fit among the plausible subset of forward models selected on the first step. After the best fit cloud size model is selected we perform a refinement procedure in its neighborhood on a denser grid in r_{eff} and v_{eff}.

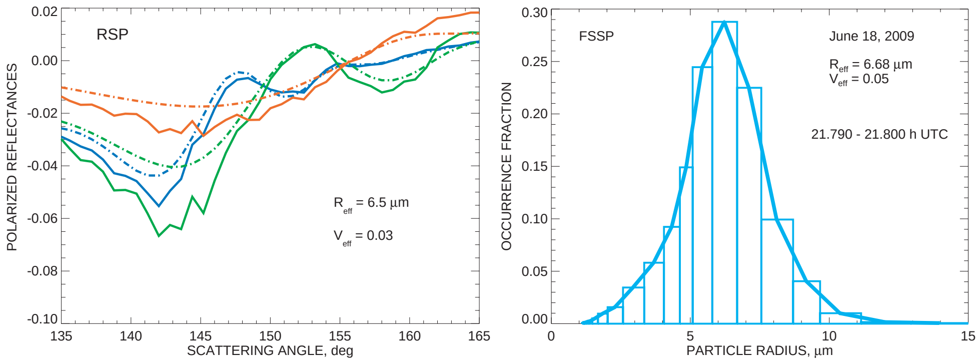

Figure 1. Cloud droplet size retrievals from RACORO field campaign. Left: polarized reflectances from a small cumulus cloud vs. scattering angle (blue – 410 nm, green – 865 nm, red – 2250 nm); solid – RSP-measured, dashed – best fit for the retrieved $r_{\rm eff}$ and $v_{\rm eff}$. Right: in situ (FSSP-measured) droplet size distribution from a nearby cloud.

To justify our retrieval method, we demonstrated on simulated data that the parameterization (2) adequately separates the cloud single scattering contribution from all the others, providing high accuracy retrievals. We used the modified vector doubling/adding code [11] for forward modeling of reflectances for plane-parallel atmospheres. In addition to this, the radiative transfer model MYSTIC (Monte Carlo code for the phYSically correct Tracing of photons In Cloudy atmospheres [12]) was used for computation of 3D radiation fields and simulation of RSP measurements. This radiative transfer model was applied to a realistic cloud field obtained from large-eddy simulations (LES [13]) of shallow, maritime convection based on idealizations of measurements obtained during the Rain in Cumulus over the Ocean project (RICO).

4. Analysis of field campaign datasets

We present the results of application of the described algorithm to the datasets from two recent field campaigns: the Coastal Stratocumulus Imposed Perturbation Experiment (CSTRIPE, 2003) and the Routine AVP CLOWD (Clouds with Low Optical Water Depths) Optical Radiative Observations (RACORO, 2009). The latter campaign was coordinated by the Atmospheric Radiation Measurement (ARM) Aerial Vehicles Program (AVP). Our retrievals showed good agreement with the correlative near-cloud-top *in situ* measurements of cloud droplet sizes performed during these field campaigns. For example, Fig. 1 compares RSP-derived droplet size from a small cumulus cloud (RACORO, June 18, 2009) with an *in situ* size distribution measurement by Forward Scattering Spectrometer Probe (FSSP, on-board a different aircraft) made in a nearby cloud. (Such comparison is justified since both RSP and FSSP datasets show little cloud-to-cloud variabiliy in droplet size.)

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