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Uncertainty and interpretation of aerosol remote sensing due to vertical inhomogeneity

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ABSTRACT

We have built an aerosol retrieval algorithm which combines the Look Up Table (LUT) and least squares fitting methods. The algorithm is based on the multi-angle multi-wavelength polarized reflectance at the Top Of the Atmosphere (TOA) measured by the Research Scanning Polarimeter (RSP). The aerosol state parameters are the aerosol particle effective radius, effective variance, complex index of refraction, and aerosol column number density. Monomodal aerosol size distribution is assumed. The Cost Function (CF) of the least squares fitting is designed in consideration of the RSP instrumental characteristics. The aerosol retrieval algorithm inherently assumes one layer of aerosols within the atmosphere. Synthetic polarized radiance data at the TOA have been created assuming either one or two layers of aerosols using the vector radiative transfer code based on successive order of scattering method. Test cases for one-layer aerosol systems show great performance. Around 90% of the total 1200 test cases have CF values smaller than 50. For these cases, the correlation coefficients of the input and retrieved parameters are generally around or larger than 0.98. The effective variance is slightly worse with the correlation coefficient of 0.76938. On the other hand, test cases for two-layer aerosol systems show that only 50% of the total (also 1200) tested cases have final CFs smaller than 50. Among these successful cases ($CF \leq 50$), the retrieved optical depth can still be interpreted as the total column optical depth, though the correlation coefficient is decreased in comparison with the one-layer aerosol cases. We propose to interpret other retrieved aerosol parameters as the average of corresponding parameters for each layer weighted by its optical depth at 865 nm. The retrieved effective radius and complex refractive index can be explained by this scheme (correlation coefficient around 0.9). The effective variance, however, shows decreased performance with the correlation coefficient of 0.46421. This may be due to the strong nonlinearity dependence of the scattering properties on the effective variance.

1. Introduction

The Earth's climate is affected by the radiative forcing associated with various sources, including total solar irradiance, the absorption of greenhouse gases (GHG), and scattering by cloud and aerosol particles. Among

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these sources the aerosol radiative forcing is one of the leading factors whose magnitude is comparable with that of GHG. The uncertainty of aerosol radiative forcing is far greater than that of the GHG [1]. Part of the reason for this is the lack of global aerosol measurements of sufficient content and quality: the number of required aerosol parameters exceeds the number of observables from the current generation of sensors. Ideally, the aerosol shape and size distribution, composition, spectral index of refraction, and spatial distribution of aerosol concentration throughout the atmosphere should be known to accurately model the aerosol radiative forcing. In order to do meaningful retrievals on a few important aerosol parameters, one normally has to assume prescribed conditions. The number of predetermined conditions and specific ways to implement them depends on the types of satellite platforms and the difference between the numbers of unknown parameters and satellite observables. Each of these assumptions will inevitably cause some uncertainties on the aerosol retrievals. It is very important to quantify these uncertainties through theoretical and experimental analysis in order to understand and properly use the satellite aerosol data products. There are many research efforts devoted to this subject, for instance, Refs. [2–4], and the references within.

There are two types of satellite observation instruments: active and passive. Active systems use active electromagnetic wave sources and measure signals backscattered from targets. The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), one of the most successful missions of this type, is equipped with a backscatter lidar working at two wavelengths (0.532 μm and 1.064 μm). Cloudsat, another active satellite mission, employs a radar system at 94 GHz mainly targeting clouds and precipitation. Active systems have the unique capability of obtaining vertical distribution information of aerosol or cloud particles. Passive systems, on the other hand, measure either the scattered solar light or thermal emission at the TOA. Notable instruments of this type include the MODerate resolution Imaging Spectroradiometer (MODIS), Multi-angle Imaging SpectroRadiometer (MISR), POLarization and Directionality of the Earth's Reflectances (POLDER), and Aerosol Polarimetry Sensor (APS) onboard the Glory satellite.[1]

The four representative passive instruments show a progressive trend of including multi-angle and polarimetry capability to satellite remote sensors. The MODIS measures radiance at the top of the atmosphere at one viewing angle with wide spectral coverage. The MISR instrument observes the radiance at four wavelength bands with added multi-angle viewing capabilities. The POLDER has multispectral bands, polarization capability at three wavelengths, and multi-angle coverages. Last but not least, the APS measures the linearly polarized radiances (Stokes parameters I, Q, U) at wide spectral range at as many as 250 viewing angles. The Research Scanning Polarimetry (RSP) [5] is the airborne version of the APS, which can be used to explore the advantages and potential of the environmental remote sensing combining multispectral, multi-angle, polarimetry measurements. The RSP takes measurements at nine wavelengths of 0.41027, 0.46913, 0.55496, 0.67001, 0.86351, 0.96, 1.59351, 1.88 and 2.26351 μm. The scanning range of the RSP is $\pm 60^{\circ}$ from the nadir, and the instantaneous field of view (IFOV) is 14 mrad.

The radiance acquired by passive sensors at the TOA is the integration of scattered light from the whole column of atmosphere. Normally, it is very difficult to get the vertical distribution of aerosol properties from passive sensors. Due to the limitation of passive sensors, the aerosol vertical distribution is often prescribed as a single layer in aerosol remote sensing algorithms [6–9]. In reality there are often situations where multilayer aerosol distribution is present [10–12]. Fig. 1 shows an example of the aerosol extinction and lidar ratio (ratio between the extinction and backscatter coefficients) vertical profiles measured by the NASA Langley High Spectral Resolution Lidar (HSRL) on August 2, 2007 over the Atlantic ocean to the east of Norfolk, VA, USA. The case shown in Fig. 1 has been described in greater details in [12] (see Fig. 7). The extinction and lidar ratio profiles clearly indicate two layers of aerosols in the atmosphere. The lidar ratio profile, containing information on aerosol type, shows that the two layers of aerosols are of different aerosol types. Indeed, they are a smoke layer originating from forest fires in Montana and Idaho, aloft above urban aerosols near the surface. Questions arise naturally when retrievals that assume a single aerosol layer with vertically uniform optical properties are applied to scenes exhibiting multiple aerosol layers of different types:

> Question I: Can the aerosol retrieval algorithm be used to retrieve aerosol properties for a multi-layer aerosol system? If yes, what is the uncertainty introduced by this underlying assumption?

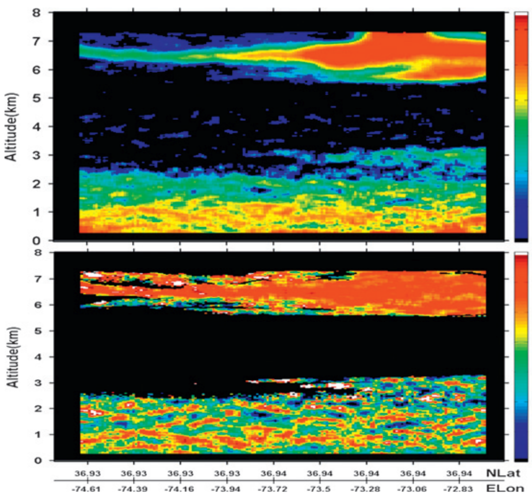

Fig. 1. Layered aerosol distribution taken by the NASA HSRL over the Atlantic ocean at east of Norfolk, VA, USA on August 2, 2007.

[1] The Glory satellite unfortunately failed to reach orbit on March 4, 2011.