A polarimetric algorithm allows scientists to distinguish irregularly shaped dust particles when observed from great distances.

Particles that are suspended in the air, formally known as aerosols, can affect the energy balance of Earth’s atmosphere, thereby changing the climate system. Aerosols also have an important role in the environment and health fields. Dust aerosols, in particular, originate from arid regions, from volcanic eruptions, and also from human activities such as agricultural and industrial practices, and changes in surface water. These particles still have not been assigned a reliable estimate for their influence on climate, partially due to the uncertainties in their optical properties. Surface-based optical remote sensing has been extensively used to characterize aerosol properties, which have been widely employed in the validation of satellite observations. However, for dusts, optical property retrieval remains difficult.

Unlike other particles, such as sulfate, carbon, and nitrate aerosols, which are well approximated by their equivalent spheres, dust particles are generally highly irregular in structure (see Figure 1). Therefore, their optical properties differ significantly. Much effort has been expended to account for the nonsphericity of remotely sensed dust aerosols. Yet no single widely accepted dust light-scattering model exists, owing to difficulties in compensating for the complex microphysical parameters of dust particles (e.g., varying size, shape, and morphology).

Here we present a new approach to retrieving aerosol optical properties based on an atmospheric optical parameter model that avoids conventional parameters like shape. The method has previously proved theoretically capable in the case of nonspherical particles (e.g., for modeled spheroid particles). The algorithm employs several optical measurements, including direct sun irradiance, angular sky radiance, and polarized radiance (i.e., radiance multiplied by degree of polarization) obtained from ground-based polarimetry. To apply the algorithm we first had to find the optimal aerosol SSA (single-scattering albedo). We obtained this variable by fitting measurements with our atmospheric optical parameter model using an iterative radiative transfer calculation. Determining the SSA enabled us to derive the aerosol scattering matrix elements $F_{11}$ (phase function) and $-F_{12}$ (polarized phase function) from correction of angular radiance and polarized radiance measurements, taking into account ground, multiscattering, and molecular influences.

The data used in our study came from 1-year polarimetric measurements of CIMEL automatic sun-sky radiometers located at five African sites (see Figure 2) operated by AERONET (AERosol RObotic NETwork). The results are presented according to four classes with the decrease in particle size quantified by the measured Ångström exponent $\alpha$: class 0.1 with an average $\alpha$ of -0.02, class 0.2 with $\alpha$ of 0.03, class 1 with $\alpha$ of 0.11, and class 2 with $\alpha$ of 0.19. The averaged aerosol optical thickness of 440nm was in the range of 0.78–0.97. The retrieved polarized phase function $-F_{12}/F_{11}$ (normalized by phase function, see Figure 3) shifted upwards entirely with the decrease in particle size. Maximum values of $-F_{12}/F_{11}$ (ranging from 0.14 to 0.21) were observed at the scattering angle of $\sim 100^\circ$.

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Figure 2. Map of the five AERONET sites in Africa used in this study.

Figure 3. Retrieved polarized phase function (normalized by phase function) of total column dust aerosols versus scattering angle (currently only at 870nm wavelength due to instrumental limitations). Retrieval results are presented in four classes and compared with laboratory measurements of mineral dust samples (feldspar and an average of seven laboratory dust samples) and Mie results for spherical particles (based on feldspar size distribution and refractive indices). Spherical particles, on the other hand, gave significantly different functions. Figure 3 compares the Mie results for spherical particles at two wavelengths, in order to show spectral variation of \(-F_{12}/F_{11}\), with the retrieved polarization properties of irregularly shaped particles. The difference between these two kinds of particles is even apparent in the resulting numerical sign of each of the polarized phase functions.

To validate our retrievals, we compared previous laboratory measurements of other types of mineral dust samples. This exercise was somewhat limited by experimental difficulties. For example, the other measurements were not done at the same wavelength as ours, and laboratory samples do not precisely match real dusts in nature. However, this quasi-quantitative comparison still shows strong consistency between our retrievals and laboratory measurements. We arrived at this conclusion because the polarization property of dusts relies to a great degree on particle nonspherical effects. This notion was suggested previously by theoretical and experimental evidence.

The SSA and \(F_{11}\) were also retrieved at four wavelengths, 440, 670, 870, and 1020nm. The spectral SSA shows an increasing trend with the increase in wavelength, while generally decreasing for other types of aerosols. This increase amounts to an average of 0.95 at 0.87\(\mu\)m. Phase function \(F_{11}\) illustrates strong forward scattering and flat backward scattering with a typical value of 0.18 at 120\(^\circ\) (about 30% larger than that of spherical particles).

Thus, the remote sensing of dust optical properties from long-term observations in Africa suggests that shape effect is important in the case of large particles and that polarization is a good tool for revealing the influence of aerosol nonsphericity. At present, our retrieval has been performed at all AERONET sites with polarimetric measurements (mainly in Europe, Africa, and Asia) and has been used to validate space-borne polarization observations. We have also retrieved aerosol microphysical parameters, such as size distribution and refractive indices, but still with a spherical shape assumption.

Our next step will focus on simultaneously developing a methodology, such as using a spheroid model in the microphysical property retrieval, and developing instruments, such as the CIMEL prototype with multiwavelength polarization measurements, in order to improve the remote sensing of dust aerosols.

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