Photopolarimetry and Aerosols

B. Cairns, B. E. Carlson, A. A. Lacis, and L. D. Travis
National Aeronautics and Space Administration
Goddard Institute for Space Studies
New York, New York

Introduction

Evidence that tropospheric aerosols can cause a direct radiative forcing comparable in magnitude, though opposite in sign, to the expected climate forcing by greenhouse gases (Hansen and Lacis 1990; Penner et al. 1994), makes a compelling case for improved efforts to obtain accurate information about the distribution of tropospheric aerosols and their radiative impact. The only method, by which we would expect to obtain a global picture of the magnitude and variability of aerosol properties, is from satellite measurements. As discussed by Wang and Gordon (1994), the retrieval of aerosol optical thickness, using satellite reflectance measurements requires an aerosol model, namely the specification of the aerosol scattering phase function and single-scattering albedo. Most often, the scattering properties are modeled using Mie theory, which is valid only for spherical particle shape, because shape information is unavailable. However, as shown by Mishchenko et al. (1994), even moderate nonsphericity results in substantial errors in the retrieved aerosol optical thickness, if the data is analyzed using Mie theory. Further, even for spherical particles, it is essential to determine whether the aerosols are absorbing (e.g., biomass burning) or not absorbing (e.g., sulfate), to correctly determine the aerosol forcing. Moreover, erroneous assumptions about shape can lead to significant errors in the inference of absorption. Therefore, it is important for the effective use of satellite reflectance measurements, to have a reliable global climatology of aerosol single scatter properties and the ability to cross-check satellite retrievals of aerosol properties against other, more accurate measurements.

The only current remote sensing method that can retrieve both a plausible particle size distribution, surface albedo, and an average complex refractive index is the combined measurement of the solar direct beam and the diffuse sky radiance (Wang and Gordon 1993; Nakajima et al. 1996). This type of measurement is made on a routine basis by a worldwide network (AERONET) of instruments (Holben et al. 1997). However, there are problems with these retrievals in that uncertainty in the calibration of the sky radiometer used for these measurements can cause serious biases. By contrast, polarization is a relative measurement and so the accuracy with which it can be measured is limited only by the care with which the instrument used in its measurement is designed and characterized. Indeed, there are a significant number of instruments in the AERONET network that measure polarized sky radiances, though there has thus far been little attempt at analysis of these measurements.

Although it has long been appreciated that both the surface albedo and aerosol microphysical properties and loading have a significant effect on polarization (Coulson 1988; Herman et al. 1971), ground-based polarimetric sky radiance measurements have provided few quantitative results. Notable exceptions are the surface albedo retrievals by Ivanov et al. (1971) and vertical profiles of stratospheric aerosols made by Steinhorst (1977). Factors that may have been responsible for the limited interest in polarimetry, as a remote sensing tool, are the relative complexity and computational intensity of the analysis models. However, effective methods for handling single and multiple scattering of polarized light in the atmosphere have been developed (de Haan et al. 1987) which, combined with the rapid increase in computer speed and memory of typical workstations, have brought detailed polarization analysis well within the reach of relatively modest computational resources.

Measurements and Analysis

We have acquired a considerable amount of highly accurate polarimetric data over the past three years. Initial measurements used the engineering spare of the Galileo PPR with two bands at 410 nm and 678 nm. More recently, we have acquired data in nine bands at 410, 470, 555, 670, 863, 961, 1590, 1880, and 2250 nm, using the research scanning polarimeter (RSP). The polarimetric accuracy of these measurements is better than 0.2%, when the signal to noise ratio (SNR) is adequate. The SNR is usually adequate in all bands, except the 2250-nm band, where the diffuse transmittance is roughly 10^{-5} for a typical aerosol load.

An iterative inversion method, similar to those presented by Wang and Gordon (1993), and by Nakajima et al. (1996), has been used to estimate aerosol models from measurements of sky radiance and polarization (Cairns et al. 1997). The fact that polarization is included in the model, with appropriate weighting for its accuracy, allows the estimation of both optical depth and surface albedo as part of the inversion process. Because the method uses a Newton-Raphson iteration, explicitly calculates the functional variation of the radiance and polarization distribution with aerosol model, the uncertainties in the retrieval process are estimated as part of the method. This uncertainty estimate, since it is a good approximation to the joint covariance matrix of all the parameters in the aerosol model, gives a realistic estimate of how well constrained the retrieved aerosol model is. We find that the simple one-dimensional error analyses, usually presented as estimates of the uncertainties in retrieval methods, are unreliable. They provide no reliable bounds on the true uncertainties in aerosol retrieval.

All that is required for the implementation of the iterative algorithm is a vector radiative transfer code that is fast enough so that the algorithm can be iterated to convergence. Usually, only five to ten iterations are required to reduce the root mean square (rms) difference between the modeled and measured polarization and intensity to the level of instrumental uncertainties.

As an example of the type of information that can be derived from polarimetry, we show in Figure 1 the upward looking measurements of the sky polarization and radiance in the 410, 470, 555, 670, and 865 nm bands. The observations are shown with their error bars (0.3% for polarization and 5% for radiance). A simple look-up table of atmospheric models, with different aerosol effective radii, refractive indices, optical depths, and different surface albedoes was searched to find a best fit to the data. The model found from this look-up table was then used as the starting point for a Newton-Raphson iterative search for the aerosol model that best fits the observations. This model fit is shown with a dashed line and is almost indistinguishable from the observations (0.3% rms deviation).

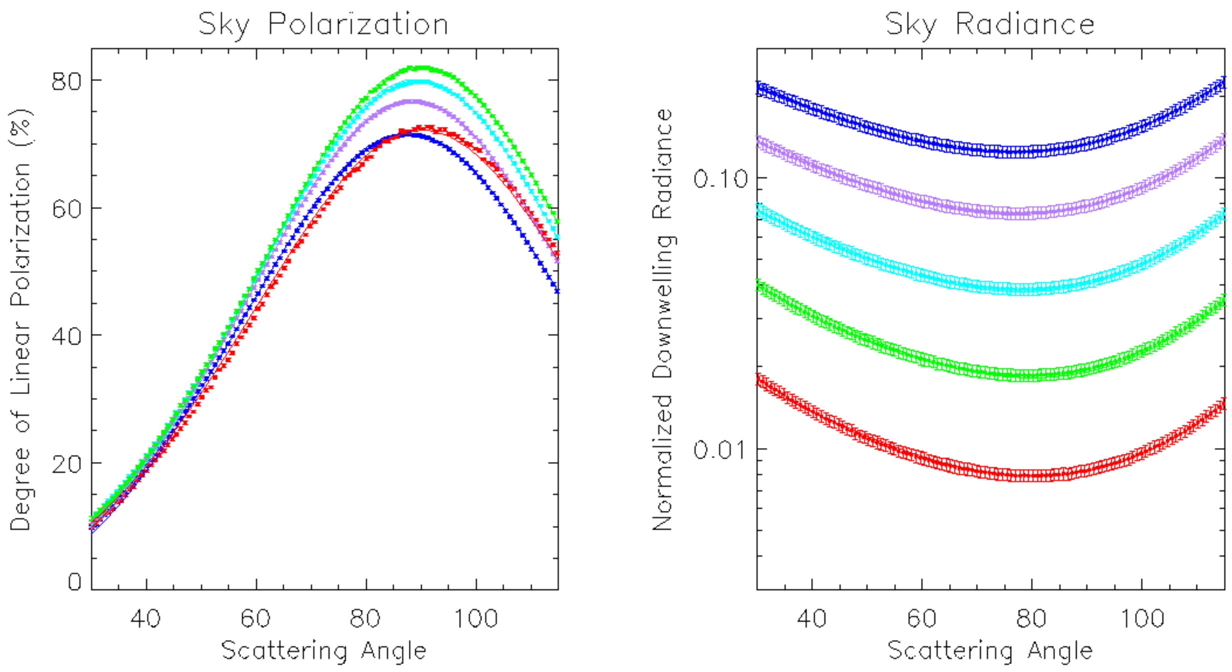

Figure 1. Upward looking sky radiance measurements taken on a mountaintop.

The intensity measurements were not used in the estimation of the aerosol model and can therefore be regarded as a partially independent check of the radiometric calibration. The rms relative deviation between the measured and modeled intensity is 3%, which is the expected radiometric calibration uncertainty for this instrument. The aerosol model that was found to be the best fit to the polarization data had an effective radius of 0.12 µm, a refractive index of 1.38, and an optical depth of 0.01. These measurements were made at 990 m (3250 feet) above sea level, near Santa Barbara, California, well above the marine boundary layer. As an example of the method when the data is not almost pure Rayleigh scattering, we show a similar figure for measurements at sea level (Figure 2). These measurements were taken on a day when there were forest fires in Southern California, so the aerosol loading is partially smoke, although this was not apparent visually.

The aerosol model that was found to be the best fit to the polarization data had an effective radius of 0.2 µm, a refractive index of 1.5, and an optical depth of 0.125. This refractive index is consistent with polarimetric nephelometer measurements of smoke aerosols (Veretennikov et al. 1980). No attempt has been made, so far, to fit the data to a multi-model aerosol distribution, though this is feasible and has been demonstrated on simulated data sets.

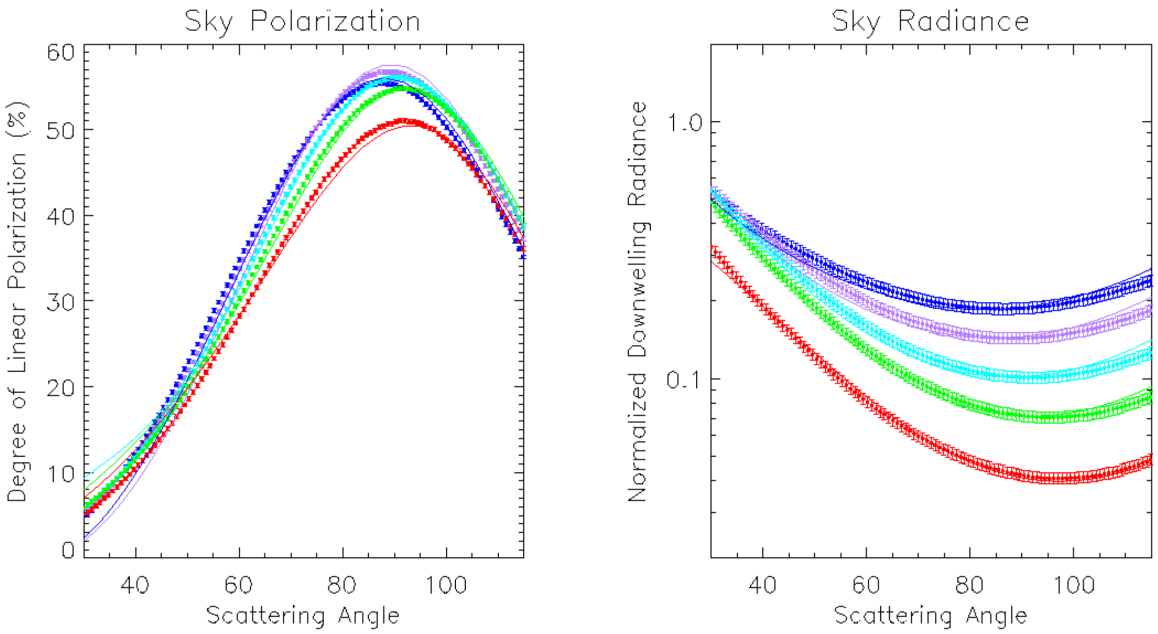

Figure 2. Upward looking sky radiance measurements taken at sea level with smoke aerosols present.

Conclusions

We have developed a simple iterative algorithm that can be used to invert sky radiance and polarization measurements in order to retrieve an aerosol microphysical model. The iterative method we use indicates that intensity and polarimetric measurements provide information that is, if not orthogonal, at least complementary. This information can be optimally combined, based on the known uncertainties in the intensity and polarimetric calibration. The ease with which good polarimetric calibration can be provided means that polarimetric measurements provide much stronger constraints on aerosol retrievals than intensity measurements. However, the optimal combination of intensity and polarization measurements yields a final retrieval that has the best possible accuracy and reliable error bounds.

References

Cairns, B., B. E. Carlson, A. A. Lacis, and E. E. Russell, 1997: An analysis of ground-based polarimetric sky radiance measurements. *Proc. SPIE*, **3121**, 382-393.

Coulson, K. L., 1988: *Polarization of intensity and light in the atmosphere.* Deepak Publishing, Hampton, Virginia.

de Haan, J. F., P. B. Bosma, and J. W. Hovenier, 1987: The adding method for multiple scattering calculations of polarized light. *Astronom. Astrophys.*, **183**, 371.

Hansen, J. E., and A. A. Lacis, 1990: Sun and dust vs. greenhouse gases; an assessment of their relative roles in global climate change. *Nature*, **346**, 713-719.

Herman, B. M., S. R. Browning, and R. J. Curran, 1971: The effects of atmospheric aerosols on scattered sunlight. *J. Atmos. Sci.*, **28**, 419-428.

Holben, B. N., T. F. Eck, I. Slutsker, D. Tanre, J. P. Buis, A. Setzer, E. Vermote, J. A. Reagan, Y. J. Kaufman, T. Nakajima, F. Levenu, I. Jankowiak, and A. Smirnov, 1997: Automatic sun and sky scanning radiometer system for network aerosol monitoring. *Remote Sens. Env.* Submitted.

Ivanov, A. I., G. Sh. Livshitz, and E. L. Tem, 1971: Seasonal variation of albedo of a region by skylight polarization measurements. In *Scattering and Absorption of Light in the Atmosphere.* Nauka, Kazakh SSR, 56-58 (in Russian).

Mishchenko, M. I., L. D. Travis, A. A. Lacis, and B. E Carlson, 1994: Satellite remote sensing of nonspherical tropospheric particles. *Proc. SPIE*, **2311**, 150-161.

Nakajima, T., G. Tonna, R. Rao, P. Boi, Y. J. Kaufman, and B. N. Holben, 1996: Use of sky brightness measurements from ground for remote sensing of particulate polydispersions. *Appl. Opt.*, **35**, 2672-2686.

Penner, J. E., R. J. Charlson, J. M. Hales, N. S. Laulainen, R. Leifer, T. Novakov, J. Ogren, L. F. Radke, S. E. Schwartz, and L. Travis, 1994: Quantifying and minimizing uncertainty of climate forcing by anthropogenic aerosols. *BAMS*, **75**, 375-400.

Steinhorst, G., 1977: Stratospheric aerosol concentrations determined by an iterative method from twilight polarization measurements. *Contrib. to Atm. Phys.*, **50**, 508-523.

Veretennikov, V. V., V. S. Kozlov, I. E. Naats, and V. Ya. Fadeyev, 1980: On the determination of the optical constants and microstructure of smoke aerosols from optical polarization measurements. *Izv. Atmos. Oceanic Phys.*, **16**, 177-181.

Wang, M., and H. R. Gordon, 1993: Retrieval of the columnar aerosol phase function and single-scattering albedo from sky radiance over the ocean: simulations. *Appl. Opt.*, **32**, 4598-4609.