# Aerosol Characterization Using Stellar Imagery

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## Introduction

The objective of this project is to evaluate the feasibility of using perturbed stellar images (modified by atmospheric scattering and absorption) for characterizing atmospheric solid and liquid aerosols (particles and clouds). The baseline boundary conditions for the study included the potential use of one or more solid-state camera arrays for nighttime, multi-spectral observations.

We begin by describing the rationale for aerosol measurements, including nighttime applications. We then describe a versatile Monte Carlo code that we have used to compute scattering by atmospheric aerosols. Several examples of applications of interest to the Atmospheric Measurement Radiation (ARM) Program will be briefly described. Finally, we present our conclusion: our computations indicate a limited applicability for stellar imagery in aerosol studies, requiring only relatively simple instrumentation.[a]

## Aerosol Scattering and Its Relevance to ARM

A major goal of the ARM Program (DOE 1990) is to improve the understanding and treatment of radiative forcing and feedbacks in global circulation models (GCMs). Focal points of these efforts are the spectral dependence of the radiation budget and the radiative properties of clouds.

Aerosols contribute to these issues both through their direct modification of the radiation balance and through their effects on the formation and dynamics of clouds. The ARM Instrument Development Program (IDP) has recognized the importance of these issues, and several instrument development activities address measurement of direct and diffuse sunlight, solar irradiance attenuation, solar aureole measurements, all-sky imaging, and cloud dynamics. The interpretation of data from these and other instruments will yield some of the atmospheric radiative transport data needed by ARM.

The (daytime) solar intensity and solar aureole have been measured for decades and have been used to extract aerosol information. Frequently, the aerosol size distribution is described by a simple parameterization to allow inversion of the data. Detailed computations of aerosol scattering also date back many years.

Direct combinations of detailed experiments with sophisticated modeling are less common; this program is thus expected to make significant contributions to the state of the art. We have looked in some detail at the solar aureole measurements of Green et al. (1971), who provided absolutely calibrated data. These data can be simulated by our code, thus providing a consistency test. We further use these data to check scaling of stellar and lunar irradiances.

The nighttime aerosol distributions are also important. First, nighttime aerosol data provide continuity of measurement and improve the understanding of aerosol dynamics. Second, the formation and dynamics of clouds continue through the night and are affected by aerosol distributions. Third, stellar measurements allow the simultaneous use of a multitude of sources and, thus, allow better spatial distribution measurements.

Astronomers are very familiar with the effects of "seeing" induced by atmospheric aerosols. In clear sky conditions, the naked eye may not be able to discern an aureole about a star; however, photographs of stars do show noticeable

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aureoles. Quantitative estimates of the effects of haze on stellar images were provided many years ago by van de Hulst (1949). He states that scattering by aerosols dominates images from a 36-inch diameter telescope from at least four minutes of arc through fifteen degrees from the star.

Potential meteorological measurements of stars in the 1990s operate in a somewhat different regime than the photographic imaging performed in the 1940s. We would use solid state detectors with linear intensity response, excellent wavelength response, and digital processing to make quantitative measurements in timescales of order minutes at the receiver plane of a relatively simple optical system.

# The MIE-2 and FLASH Computer Codes

We have chosen to use the FLASH Monte Carlo code to solve the light-scattering problem. This code is a descendant of the program written by Collins et al. (1972). The modern version runs on a Cray and on the Space, Science, and Technology (SST) Division Convex computers and has more than sufficient accuracy for our applications.

The version we have adopted incorporates the curvature of the earth and allows up to fifty aerosol layers and insertion of model clouds if desired. The code is designed to allow computations of twilight situations, where the illuminating source is below the horizon, but still is seen in the atmosphere. FLASH includes measured Rayleigh scattering coefficients as a function of wavelength and temperature, molecular absorption, and a set of Stokes parameters generated through a separate Mie code, which uses a single complex index of refraction at each wavelength. The Mie theory gives accurate solutions to scattering from dielectric spheres and has been well tested against laboratory measurements. Aerosol collections from aircraft show nonspherical particles, particularly near urban areas. However, simulations using assumed spherical particles have been successful in the past. Furthermore, the condensation of water on aerosols leads to the formation of quite spherical scatterers.

Our standard inputs to the code to date include the standard rural aerosol size distributions given by Shettle and Fenn (1979), and the continental, winter, 30 degrees latitude atmospheric density, temperature and humidity profiles from the Air Force Geophysics Laboratory handbook (1985). The vertical aerosol distribution takes the form suggested by Eltermann (1968), with the lowest layer chosen from the surface visibility at a wavelength of 0.55 $\mu$m. Surface reflectivity is assumed to be angularly uniform.

# Some Applications of the Codes to ARM-Relevant Situations

We have, to date, generated 72 sets of angular contours in spectral brightness and percent polarization at four wavelengths (0.4, 0.55, 0.86, and 1.06 $\mu$m), six humidities (relative humidity of 0, 0.5, 0.9, 0.95, 0.98 and 0.99) and three ground-level visibilities (5, 23 and 50 km) with a surface albedo of 0.2.

In addition, we have successfully compared the code output for an aerosol-free atmosphere (Rayleigh scattering and absorption only) to the exact results of Coulson et al. (1970). We have also investigated the use of the almucantar contour of sky brightness towards extraction of the scattering function (the intensities are independent of vertical aerosol distribution for this case). These calculated skies do not represent all the aerosol conditions that would be encountered; however, the tested visibilities likely cover much of both the visibility and humidity ranges that would be expected.

Some general observations on these results are as follows. The direct solar, lunar or stellar transmission is measurable with reasonable instrumentation and shows good sensitivity to higher humidities. We also see a reverse trend of transmission with humidities at two selected wavelengths (0.4 and 0.86 $\mu$m), suggesting the efficacy of a ratio measurement. For the aureole measurements, we see that useful data may be obtained between 0.3 degrees (the extent of the solar [and lunar] discs) and 3 degrees, where the data for various conditions coalesce; better discrimination appears at smaller angles. For polarizations, the major variability occurs at high humidities; polarization differences are generally too small for reasonable instrumentation to measure. Clearly, one gains an advantage from making multiple measurements (e.g., direct intensity, aureole intensity, and polarization at a number of well-chosen wavelengths).

Our computations have allowed us to quantify possible stellar measurements. The low light levels of stars limit our measurement capabilities to direct transmission and integrated aureole data. This leads us to suggest a relatively straightforward optical system with simple solid state detectors; budgets permitting, we would like to consider building a prototype.

Other applications to ARM are suggested. Oak Ridge National Laboratory (ORNL) and Los Alamos National Laboratory (LANL) would like to use LANL modeling support to interpret data obtained by the ORNL pointing shortwave/near-IR radiometer. Taking the actual specifications for the radiometer, we can run a set of representative aerosol scenarios to cover the range of the instruments applicability. We could, if desired, construct a look-up table to relate instrument signals to the most likely aerosol distributions.

Further, we have working versions of the high spectral resolution HITRAN database, as well as LOWTRAN and MODTRAN. These can be used to determine spectral regions of interest. Using these codes in conjunction with the inversion techniques described by Travis Spratlin (ORNL) should lead to definition of an excellent set of wavelengths. Interpretations of daytime data from the ARM/CART all-sky camera(s) could proceed along lines very similar to the above.

With regard to investigations of the "Umkaehr" problem, Lee Harrison (State University of Albany) has suggested obtaining vertical distributions of aerosols at twilight. This is a natural application for the codes; indeed, FLASH was written with precisely this capability. The possibility of obtaining vertical aerosol profiles (even only maximally twice a day), but with reasonably simple instrumentation, should be of interest. Dr. Harrison has also suggested that a study of multiple scattering in clouds would be useful.

Computing the relative importance of multiple scattering compared with single scattering would shed light on the quality of the single-scattering assumption made in some analyses and can define the range of reasonable application of this simplification.

Other computational and science support can be provided to ARM through the Aerosols Group or other mechanisms. The Aerosols Group's 1992 report delineates the desire for many measurements of aerosols: our codes can be applied to modeling some cases of interest. Finally, ARM/CART is now implementing some aerosol measurement capabilities. We have contacted Robert Leifer to initiate discussions on possible collaborations.

# Conclusions

We have brought a new modeling system to the ARM Program, namely, a Monte Carlo code for atmospheric aerosol scattering calculations. A number of applications of the programs are immediately obvious and can be pursued, depending on funding levels. We continue to work with ARM Science Team members to define and pursue problems of interest.

Our first sets of calculations also point to a potential new instrument for ARM/IDP, namely, a simple stellar observation system. The proposed instrument may be as simple as a collection of well-baffled tubes, with spectral filters and reasonable photodiode detectors. The instrument would measure direct irradiance reductions by the atmosphere, as well as the integrated aureole light over a range of angles. While probably not definitive, such an instrument would provide accessible nighttime aerosol data.

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