Retrieving Properties of Thin Clouds from Solar Aureole Measurements

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Retrieving Properties of Thin Clouds from Solar Aureole Measurements

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ABSTRACT

This paper describes a newly designed Sun and Aureole Measurement (SAM) aureolegraph and the first results obtained with this instrument. SAM measurements of solar aureoles produced by cirrus and cumulus clouds were taken at the Atmospheric Radiation Measurement Program (ARM) Central Facility in Oklahoma during field experiments conducted in June 2007 and compared with simultaneous measurements from a variety of other ground-based instruments. A theoretical relationship between the slope of the aureole profile and the size distribution of spherical cloud particles is based on approximating scattering as due solely to diffraction, which in turn is approximated using a rectangle function. When the particle size distribution is expressed as a power-law function of radius, the aureole radiance as a function of angle from the center of the solar disk also follows a power law, with the sum of the two powers being \( \frac{5}{2} \). This result also holds if diffraction is modeled with an Airy function. The diffraction approximation is applied to SAM measurements with optical depths \( \lesssim 2 \) to derive the effective radii of cloud particles and particle size distributions between \( \lesssim 2.5 \) and \( \lesssim 25 \) \( \mu m \). The SAM results yielded information on cloud properties complementary to that obtained with ARM Central Facility instrumentation. A network of automated SAM units [similar to the Aerosol Robotic Network (AERONET) system] would provide a practical means to gain fundamental new information on the global statistical properties of thin (optical depth \( \lesssim 10 \)) clouds, thereby providing unique information on the effects of such clouds upon the earth’s energy budget.

1. Introduction

An understanding of global, three-dimensional clouds, including particle phase and size distributions of cloud particles, is essential for understanding man-made radiative forcing in the atmosphere (see Forster et al. 2007). This paper describes a new ground-based instrument to provide such measurements for clouds with optical depths ranging from 0 to \( \sim 10 \). A network of such sensors could be used to gain information on the global statistical properties of these optically thin clouds, their role in the earth’s energy budget, and their effect on the global climate. Furthermore, such ground-based sensors could be used to calibrate satellite-based cloud sensors, thereby enabling more accurate, global coverage.

According to Forster et al. (2007) in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change, radiative forcing (RF) is the concept used for the quantitative comparisons of the strength of different human and natural agents in causing climate change. RF is defined as the change in net irradiance (solar plus longwave) in W m\(^{-2}\) at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at unperturbed values. The AR4 describes two areas where human activity affects cloud RF. The first area is aerosol-induced cloudiness, in which human activity causes a change in the
Aerosol-induced cloudiness is sometimes referred to as the first indirect effect (Ramaswamy et al. 2001). According to the AR4, estimates from general circulation models (GCMs) indicate that aerosol-induced cloudiness will generally reflect more solar radiation back to space but also trap more infrared radiation. There is a consensus that the net effect of such man-made increases in cloudiness is to cool the atmosphere, with net global mean cooling ranging from −0.22 to −1.85 W m$^{-2}$. For comparison, the RF associated with net human CO$_2$ emissions as of 2005 is stated in Forster et al. (2007, Fig. 2 and Table 2.1) to be +1.66 ± 0.17 W m$^{-2}$. The large uncertainty in the magnitude of aerosol-induced cloudiness suggests a clear need to improve our understanding of it and its connection with RF.

Aircraft contrails and cirrus clouds also reflect solar radiation and absorb infrared radiation. It is thought that the absorption of infrared radiation dominates, leading to a net (small) positive RF. In this case, there are actually two effects: the effect of the linear contrails themselves and the effect of cirrus cloud cover that develops in response to contrail formation. Their net RF is estimated to be in the range of +0.01 to +0.08 W m$^{-2}$, with a mean value of ~0.03 W m$^{-2}$ (Forster et al. 2007; Sausen et al. 2005; Stordal et al. 2005). The AR4 states that the cloud albedo effect and cirrus effects resulting from contrails on radiative forcing are highly uncertain, with no general consensus having emerged as of 2007.

Although optically thin clouds play an important role in determining the earth’s energy budget and the global climate, the specifics of the role remain poorly understood. Despite existing instrumentation, field campaigns, analyses, and use in GCM studies, the determination of the macrophysical, microphysical, and optical properties of clouds is among the largest uncertainties in estimating the impact of clouds on the radiative fields in GCMs (Turner et al. 2007). Moreover, one of the key uncertainties in climate model simulations is the feedback of upper-tropospheric clouds (i.e., cirrus) on the earth’s radiation budget (Comstock et al. 2007).

A global database describing the areal coverage, optical depths, and physical properties of optically thin clouds would provide crucial information for addressing this issue. Case studies, such as those undertaken at the Atmospheric Radiation Measurement Program (ARM) Central Facility (CF) in Oklahoma and described by Turner et al. (2007) and Comstock et al. (2007), have provided some of this information. Generally, however, these studies have left substantial gaps in our knowledge of cloud properties. Satellite measurements from the Moderate Resolution Imaging Spectroradiometer (MODIS) and Polarization and Directionality of the Earth’s Reflectances (POLDER; see Breon and Doutrizaux-Boucher 2005) have also contributed information on cloud optical depths and particle size distributions. However, there are difficulties in interpretation, particularly over inhomoogeneous land areas and from inhomogeneities in the clouds themselves within the instrument fields of view, as well as difficulties in the calibration of the satellite sensors and algorithms relative to cloud microphysical properties (Rosenfeld and Feingold 2003).

Existing and planned satellite sensors retrieve a variety of cloud parameters, as indicated in Table 1. Generally, such satellite retrievals provide useful information on the areal coverage of clouds at large spatial resolution. Furthermore, the accuracy of such measurements for thin clouds (optical depth $\approx$ 10) and the microphysical properties of such clouds need further investigation and refinement. On the other hand, ground-based sensor networks such as the Aerosol Robotic Network (AERONET) and Micro Pulse Lidar Network (MPLNET) provide cloud and aerosol information for very low optical depth situations (optical depth $\approx$ 1). AERONET is primarily focused on measuring aerosol optical depth, and data processing is terminated when it is determined that clouds are in the field of view. Micropulse lidars (MPLs) in MPLNET are useful for determining the macrophysical

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**Table 1. Cloud measurements as obtained by a number of satellite and ground-based (grnd locs) systems compared with SAM.**

<table>
<thead>
<tr>
<th>System</th>
<th>Optical depth</th>
<th>Areal coverage</th>
<th>Spatial resolution</th>
<th>Particle size</th>
<th>Physical depth</th>
<th>Cloud-top alt</th>
<th>Layers</th>
</tr>
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<tbody>
<tr>
<td>ISCCP</td>
<td>No</td>
<td>Global</td>
<td>280 km</td>
<td>Yes (coarse)</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>HIRS</td>
<td>0–6 and &gt;6</td>
<td>Global</td>
<td>20 km</td>
<td>No</td>
<td>Coarse</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>MODIS</td>
<td>0–70</td>
<td>Global</td>
<td>1 km</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>NPOESS</td>
<td>0.1–64</td>
<td>Global</td>
<td>6–25 km</td>
<td>Yes</td>
<td>Coarse</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>AERONET</td>
<td>0–1</td>
<td>Grnd locs</td>
<td>1.5 km</td>
<td>Aerosols</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>MPLNET</td>
<td>No</td>
<td>Grnd locs</td>
<td>1 m</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>SAM</td>
<td>0–10</td>
<td>Grnd locs</td>
<td>0.1 km</td>
<td>Clouds</td>
<td>No</td>
<td>No</td>
<td>No</td>
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characteristics of cloud layers (tops and bases) at very high spatial resolution and thus make useful adjuncts to independent cloud optical depth measurements. The Sun and Aureole Measurement (SAM) instrument is a new ground-based aureolegraph, designed to measure cloud optical depths in the 0–10 range at high spatial resolution (≈0.1 km, depending upon cloud advection speed). The upper limit of 10 is a consequence of the need to detect the solar disk and depends upon cloud type through the particle size distribution. SAM aureole measurements can also be used directly to determine cloud particle size distributions in the 2.5- to 25-μm region.

This paper describes the implementation of SAM\(^1\) and reports the first results obtained with this instrument. The SAM system, described in sections 2 and 3, is designed to be compact, self-contained, portable, and largely or fully automated. Some inaugural measurements with SAM are presented in section 4. These results were obtained in support of the U.S. Department of Energy (DOE) Cloud and Land Surface Interaction Campaign (CLASIC) and Cumulus Humilis Aerosol Plume Study (CHAPS) field experiments at the ARM facility during June 2007 (Berg et al. 2009). The results include ≥5-h-long data sequences in which the cloud optical depths, aureole profiles, particle size distributions, and effective particle radii are determined with ≥12-s time resolution. Section 5 presents a general framework for deriving cloud particle size distributions and effective particle radii from SAM data. A theoretical relationship between the size distribution of spherical particles and the slope of the aureole profile is derived starting with the single scattering approximation and based on approximating scattering as due solely to diffraction which, in turn, is approximated using a rectangle function. When the particle size distribution is expressed in the form of a power law in radius (see, e.g., Heymsfield and Platt 1984), the aureole radiance profile as a function of angle from the center of the solar disk also has a power-law form, with the sum of the two powers being 5. Moreover, this latter result also holds if diffraction is modeled using an Airy function. We limit application of this approximation to situations in which the optical depth is less than 2, based on simulations of the effects of multiple scattering on aureole shape.

2. The SAM aureolegraph

Radiation from the sun or another celestial object, when scattered by the particles comprising an optically thin cloud, is seen as an aureole of light surrounding that object when viewed by a ground observer. The radiance \( L_A \) of the scattered radiation as a function of the angular distance \( \theta \) from the center of the celestial object can provide unique information about the distribution of sizes, shapes, and spatial orientations of the cloud particles that is not available via other passive remote sensing techniques (Mims 2003). Min and Duan (2005), expanding on their earlier work (Min et al. 2004) using a multifilter rotating shadowband radiometer to retrieve cloud optical depths, derived a technique for retrieving effective particle radii using information in the aureole. However, rather than attempting to derive aureole radiance profiles from shadowband measurements, they base their retrieval technique on matching shadowband measurements to simulations of instrument measurements based on radiative transfer model calculations for specified particle size distributions. SAM retrieves aureole radiance profiles directly as described later.

SAM uses a pair of calibrated cameras, each with a filter that currently has a bandpass centered at 670 nm and a spectral width of 10 nm. Figure 1 shows a schematic diagram for SAM, which is similar in function to, but simpler than, a solar coronagraph (Lyot 1939). The aureolegraph tube is about 15 cm in diameter with a length of 46 cm.

\(^1\) Patent applied for.
The solar disk camera SD mounted on the outside of the aureolegraph tube directly views the sun (to the left in the figure). SD is a PixeLINK model PL-A741 complementary metal–oxide–semiconductor (CMOS) monochrome camera with a 2/3-in format, 1280 × 1024 pixel focal plane array. SD is fitted with a Pentax 25-mm focal-length C-mount lens that yields a pixel scale of 0.0144° per pixel. In addition to the spectral filter, SD is fitted with a neutral density filter to keep the image of the solar disk on scale in at least one of the images acquired over the range of integration times used. The images acquired by SD are saved as 8-bit images using a FireWire (IEEE 1394–DCAM) interface. The read noise is <1.5 digital number (DN) with the longest integration times used, and it is negligible in the 8-bit images acquired with the shorter integration times typically used, yielding a dynamic range with respect to read noise of >170.

The sun and surrounding aureole are imaged by objective lens O onto reflective imaging surface IS, in which a hole has been placed so that the image of the solar disk passes through IS and is absorbed in beam dump BD. Aureolegraph camera A views IS using mirror M. In this way, A directly measures the aureole radiance profile $L_A(\theta)$ to within $\pm 0.5^\circ$ of the center of the solar disk, with minimal interference from the bright solar disk itself.

Objective lens O is a fused silica- and Ar-coated plano-convex singlet with a focal length of 300 mm and a diameter of 38 mm. IS is covered with a non-Lambertian, high-gain reflective tape to yield the brightest possible image of the aureole. The aperture to BD is a 6-mm hole in the screen with an apparent diameter of 1°. The aureolegraph has a total field of view of $\pm 8.5^\circ$, which is limited by the size of IS. Aureolegraph camera A is a PixeLINK model PL-A741-R CMOS monochrome camera. Aureolegraph camera A is functionally identical to the model used for SD but is constructed with its focal plane rotated 90° to the camera’s long axis and uses M to view IS. Both SD and A display no appreciable blooming or charge leakage from saturated pixels. Like SD, A is fitted with a Pentax 25-mm focal-length C-mount lens that yields a pixel scale of 0.0148° per pixel when viewing IS.

SD and A are radiometrically calibrated using a reference source traceable to the National Institute of Standards and Technology (NIST). The linearity of each camera’s response is also assessed in the laboratory over the full dynamic range of an image using the same source. Each camera’s actual integration times are measured for all six of the nominal integration times used during data acquisition, which range from 0.16 to 990 ms (indicated). This procedure ensures that the relative radiometric accuracy of the calibrated images over the full dynamic range is good to better than 1.3%. The estimated absolute radiometric accuracy of the aureolegraph images is about $\pm 15\%$. To improve the accuracy of SD images further, it is deployed adjacent to an AERONET site for several hours to observe the sun under low optical depth conditions. This fine tuning (cross calibration) reduces this camera’s absolute radiometric uncertainty to about $\pm 3\%$.

A data collection event consists of taking repeated sequences of images with both cameras. In a typical sequence, each camera acquires an image in turn using six different integration times at a rate of one image per second. The image exposures have been selected so that a large dynamic range of radiances can be covered. The temporal frequency of SAM measurements is adjustable up to a maximum rate of $\sim 5$ sequences per minute.

The SAM optical system is mounted on a tracker to keep the instrument pointed at the sun. The tracker deployed for the field experiments described herein tracked the position of the solar disk using an ephemeris and was periodically adjusted manually. A newer version of the solar tracker, brought into service in 2008, features an active tracking system that uses images of the solar disk from SD to provide feedback such that the solar disk remains centered to within 0.01°. When the solar disk is not visible or is partially obscured (conditions where the acquired data would normally not be used), the internal ephemeris continues tracking the calculated solar disk position with an uncertainty growing slower than 0.5° h$^{-1}$ until the solar disk is reacquired. Any residual tracking errors in data acquired when the solar disk is visible are corrected during data processing when aureole profiles are generated. The portable version of SAM is illustrated in Fig. 2.

3. Collection and processing of SAM data

The reduction and processing of SAM data consist of a number of automated steps or transformations to select, calibrate, and combine the data from its two cameras (Fig. 3). From each sequence of SD images, the unsaturated image with the longest integration time is selected for calibration. This image provides the best signal-to-noise ratio and dynamic range among the SD images. After dark images, which are acquired at the beginning and end of each observation session, are subtracted from this raw image, a calibration algorithm is applied to convert the raw data number values into units of spectral radiance ($W \, m^{-2} \, sr^{-1} \, nm^{-1}$).

Next, each sequence of A images is processed. Each raw image in the A image sequence has the dark image corresponding to that integration time subtracted from it and is then calibrated into units of spectral radiance,
using a procedure similar to that employed for the SD images. Starting with the A image with the longest integration time, all of its pixels with values at or near saturation are replaced with the corresponding unsaturated pixels of the A image with the second longest integration time. The pixels in the A image with the second longest integration time that are at or near saturation are then replaced with the corresponding unsaturated pixels of the A image with the third longest integration time. This process is continued until an A image with no saturated pixels is obtained. The resulting stacked image has a significantly larger dynamic range than any single A image of the solar aureole.

The radiance averaged over the solar disk is compared with a fiducial exoatmospheric value to determine the total optical depth \( \tau_c \) of the atmospheric column between the instrument and the sun. Note that this method of determining \( \tau_c \) ceases to be directly applicable when \( \tau_c \) is so large that the solar disk is not distinguishable from the aureole. Therefore, the largest value of \( \tau_c \) that can be directly analyzed with SAM depends upon the forward scattering properties of the particles, which in turn depend primarily upon particle size and wavelength. This value is \( \tau_c \approx 10 \) for typical water clouds and is smaller for cirrus.\(^2\)

The value of \( \tau_c \) is multiplied by the cosine of the solar zenith angle to obtain the total vertical optical depth \( \tau_v \) from the top of the atmosphere to the observer. An estimate of the Rayleigh scattering contribution to \( \tau_v \), based on an atmospheric pressure of 1 atm and the given solar elevation angle, is then subtracted from the measured value to give the particulate (cloud and/or aerosol) vertical optical depth \( \tau \) (see section 5).

Aureole profiles are generated from azimuthal (horizontal) and altitudinal (vertical) traces through the center of the sun in the merged image. A mean radial aureole profile, averaged over all directions outward from the center of the sun, is also extracted, along with the standard deviation of the fluctuations about this profile.

4. SAM data collections on 12 and 23 June 2007

Optical depths and aureole profiles as functions of time for two SAM datasets obtained during the June 2007 DOE CLASIC and CHAPS field experiments are presented here. Both datasets were obtained at the ARM CF (Stokes and Schwartz 1994) near Lamont, Oklahoma, and were concurrent with datasets obtained with other instruments that are permanently located at the site. These include the ARM CF total sky imager (TSI; Long et al. 2001), MPL (Campbell et al. 2002), and Cimel sun photometer (CSPHOT; Holben et al. 1998), the latter being associated with the AERONET network. In comparing data from these instruments (see Figs. 4, 6), one needs to keep in mind the differences in their locations and lines of sight. MPL, for example, points near zenith, whereas SAM tracks the moving sun. As a result, the two instruments typically are viewing parts of cloud layers that can be separated by tens of degrees. CSPHOT, like SAM, tracks the sun, but the two units were separated by some tens of meters so that their lines of sight intersected

\(^2\) However, when the solar disk is not discernable, SAM measurements of the diffuse radiance can be combined with model calculations to retrieve \( \tau_c \).
the cloud layer(s) at points that are separated by corresponding distance(s). Because the locations of the sun and zenith are readily apparent in TSI images, these images are helpful in interpreting the measurements from the various instruments, especially with broken or highly structured cloud layers.

a. Data from 12 June 2007

The first SAM dataset described here was recorded on 12 June 2007. An overview of the SAM data, as well as data obtained with ARM CF instruments, is shown in Fig. 4. SAM data were recorded and analyzed every ~12 s over the 5.2-h interval shown, resulting in ~1500 measurements of cloud particle size distributions. Figure 4a presents the measured values of the mean aureole profile $L_A(\theta)$, color-coded for radiance (see scale). The bright band at the bottom is the solar disk; its radiance correlates with $\tau$. Aureole radiance measurements extend to ~8°. There are several reasons for the occasional gaps in the aureole radiances and products derived using them. Some of these gaps correspond to times when the operator was making instrument adjustments (newer versions of SAM are fully automated). In other cases, further processing of aureole measurements was halted when $\tau$ exceeded 2 by zeroing the data, because multiple scattering effects could be expected to reduce the validity of the diffraction approximation retrieval of particle size. Multiple scattering effects are discussed in section 5e, but the value of 2 was somewhat arbitrarily selected. Figure 4b shows the reconstructed particle size distribution derived using the diffraction approximation (see section 5); the color scale encodes the differential particle column density.

Figures 4c–e show the measured optical depth, power-law slope of the particle size distribution, and effective radius of the particles (see section 5). Note the distinct change in the character of the aureole and particle density profiles at about 1800 UTC. As the backscatter data from the MPL show on close inspection (Fig. 4f), cloudiness during the first half of the observational time interval was dominated by optically thin cirrus at an altitude of ~10–12 km, but the cirrus diminished around 1800 UTC. The MPL data also show two instances, at about 1700 and 1900 UTC, of the presence of altostratus at an altitude of ~9 km. During the latter part of the day, boundary layer cumulus at ~2 km are evident in the MPL plot and are responsible for spikes in the SAM plots of $\tau$. The TSI images at the bottom of the figure confirmed the MPL data; variegated cirrus dominated the sky before 1800 UTC and small, boundary layer cumulus appeared thereafter.

Figure 5 displays a more detailed plot of $\tau$ versus time, as measured with SAM, along with corresponding ARM CSPHOT measurements over the same time interval. SAM data points, collected every ~12 s, appear continuous in this plot. The isolated orange and light-blue data points are optical depth measurements taken with CSPHOT and processed to levels 1.0 and 1.5, respectively. Overall, we find that the values obtained with SAM and CSPHOT are in good agreement, but the optical depth

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3 Level 1.0 data represent real-time measurements that have not been cloud screened and may not have had a final calibration applied. Level 1.5 data are similar to level 1.0 but have been automatically cloud cleared. Currently, manually inspected, quality assured, level 2.0 data from CSPHOT are not available for CLASIC through the AERONET Web site.
FIG. 4. (a)–(e) Illustrative results from the SAM data collections on 12 Jun compared with other data products from the ARM CF: (f) MPL, (g) TSI, and (c) CSPHOT (orange and light-blue data points). Color-coded images of (a) the aureole profile as a function of time, with individual profiles recorded every 12 s, and (b) the particle size distribution as a function of time. Other images show the (c) optical depth, (d) fitted power-law slope of the particle size distribution, and (e) effective radius of the particles as functions of time. See text for an explanation of how these various cloud parameters were derived.
range of CSPHOT is limited to $\tau \leq 1$. The rather abrupt change in the variations of $\tau$ with time at ~1800 UTC corresponds to the departure of the cirrus deck, followed by the passage of isolated cumulus clouds after ~1900 UTC.

b. Data from 23 June 2007

The second SAM dataset was recorded on 23 June 2007, and the results analogous to Figs. 4 and 5 are presented in Figs. 6 and 7. As seen in the TSI images (see Fig. 6g), a combination of thin cirrus and cumulus clouds dominated the sky during most of the day. MPL data (Fig. 6f) indicated that the cumulus clouds were located at the top of the atmospheric boundary layer. Sonde measurements at 1728 UTC showed a wind speed of ~4–5 m s$^{-1}$ at the top of the boundary layer; because the SAM optical depth measurements in Fig. 7 were taken every ~12 s, this corresponds to a horizontal spatial resolution of ~50–60 m. These data illustrate how SAM datasets may prove useful for exploring cloud-edge and intercloud effects.

c. Aureole profiles and associated size distributions

As Figs. 4 and 6 show, there is detailed information about the aureole profile (Figs. 4a, 6a), and derived results for the particle size distribution (Figs. 4b,d,e, 6b,d,e) available every ~12 s over a ~5- to 6-h interval. To illustrate what the solar aureole profiles look like, Fig. 8 shows the SAM profile at 15,186 UTC 12 June 2007, when SAM data collection was Initiated and when optically thin cirrus was apparent. Figure 9 shows the retrieved cirrus cloud particle size distribution at that time, derived from the SAM data by use of the diffraction approximation (see section 5). The steep slope of the aureole profile is characteristic of cirrus with its abundance of large particles. The effective particle radius, calculated as the ratio of the third to the second moment of the size distribution over the range from ~2.5 to ~25 $\mu$m, is 10.7 $\mu$m.

Figure 10 shows a second example of an aureole profile, taken from the SAM observations at 20.378 UTC 23 June 2007, a time when boundary layer cumulus and aerosols dominated the sky. The aureole profile is shallower than that shown in Fig. 8, which is repeated as the light-gray curve in Fig. 10. The corresponding particle size distribution, derived using the diffraction approximation (see section 5), is shown in Fig. 11. The smaller particles in the boundary layer cumulus and aerosols produce a shallower aureole profile and have a correspondingly steeper particle size distribution. In the next section, the diffraction approximation used to extract the slopes of the cloud particle size distributions and effective particle radii from the aureole profiles is derived. A simple, approximate relationship between the slopes of the particle size distribution and associated aureole follows from this derivation.

Thus, for each SAM aureole that is recorded, a mean profile and an associated approximate particle size distribution are derived using the diffraction approximation (see section 5). Running particle size distributions for the entire data collections of 12 and 23 June 2007 are shown as color images in Figs. 4b and 6b. A simple measure of the particle size distribution is its best-fit power-law slope. Plots summarizing these slopes for the two data collections on 12 and 23 June 2007 are shown in Figs. 4d and 6d and expanded in Fig. 12. The steepness of the slope of the particle size distribution is a measure of the relative prevalence of large particles, with shallower slopes indicating increased abundances of large particles. Around 1800 UTC 12 June, the slope of the particle size distribution shows an abrupt decrease (Fig. 12), corresponding to the departure of cirrus cloudiness with its large particles and the subsequent dominance of aerosols and boundary layer cumulus with smaller particles. The variability of the slopes on 23 June (Fig. 6) is associated with the patchiness of the boundary layer cumulus deck on that day.

d. Uncertainties in the measured parameters

Uncertainties in the recovered particle size distributions stem from three sources: (i) statistical uncertainties in the measured aureole profiles, (ii) systematic errors in measuring the aureole profiles, and (iii) the inversion process used to derive particle size distributions. As mentioned earlier, the statistical uncertainties in the measured aureole profiles are estimated empirically by computing the rms deviations from the mean in the aureole radiance over each annulus for which the aureole is measured. The results are shown as error bars on
the aureole profiles shown in Figs. 8 and 10. In general, the fractional uncertainties are less than 10% over the important angular range of 0.4°–8° from the center of the solar disk.

Systematic uncertainties in the measured aureole profiles are more difficult to estimate. Great care was taken to correct the aureole images, using images of flat external fields to remove any nonuniformities in the camera
detector chips as well as any nonuniform scattering response of the imaging screen onto which the aureole is projected. Measurements were collected on clear days with and without an external occluding sphere to establish the spurious scattering properties of the instrument and its optical train. This latter effect, which is subtracted from the measured aureole, is characterized by a pattern whose intensity falls sharply with angular distance from the center of the instrumental field of view. Even without subtraction, these spurious scattering effects are appreciable only for $\tau_c \leq 0.3$ and do not contribute significantly to the aureole beyond $\sim 1^\circ$.

Uncertainties introduced during the process of inverting aureole profiles to particle size distributions (via the diffraction approximation; see section 5e) are discussed extensively in sections 5d and 5e. In advance of this discussion, we report that the recovered power-law slopes are accurate to within an estimated uncertainty of $\sim 0.1$, provided, of course, that the underlying size distribution is in fact a power law.

The SAM measurements are demonstrably stable and repeatable. For example, an examination of the slopes of the power-law size distribution with time (see Fig. 12) shows that on 12 June 2007 there are long stretches (many minutes) when the slope varies only very slowly with time and shows rms fluctuations about the local mean of typically $\pm 0.1$. By contrast, the mean slope slowly varies in a systematic way with the onset of different cloud conditions from $2.2$ to $4.6$. This speaks

FIG. 7. As in Fig. 5, but on 23 Jun.

FIG. 8. SAM radial mean aureole radiance profile at 15.186 UTC 12 Jun 2007, when cirrus dominated the sky. The spacing of the data points is $\Delta \theta = 0.015^\circ$. The displayed error bars are the measured rms fluctuations about the mean value in each annular radius of the aureole. The dashed portion of the curve is an interpolation that spans an annular gap in the data between the two cameras (see Fig. 1 and section 3). The data points and error bars are sufficiently dense beyond $\theta \simeq 0.5^\circ$, so that they blend into what appears to be a thick curve.

FIG. 9. Cloud particle size distribution, derived from SAM data by use of the diffraction approximation (see section 5), at 15.186 UTC 12 Jun 2007, when thin cirrus dominated the sky. The aureole profile used to derive this size distribution is the one shown in Fig. 8. The best-fit power-law slope is $-3.07$ and is indicated in the inset box along with other SAM-determined cloud parameters: an optical depth of 0.78 and an effective particle radius of 10.7 $\mu$m.

FIG. 10. SAM mean aureole radiance profile at 20.378 UTC 23 Jun 2007, when boundary layer cumulus and aerosols dominated the sky. The spacing of the data points and the determination of the error bars are as in Fig. 8. The aureole profile from Fig. 8 is superposed as the light gray curve for comparison. The remaining specifications are as in Fig. 8.
Finally, determination of the accuracy of the particle size retrievals suffers from a lack of “truth” data. As noted by Dowling and Radke (1990), accurate measurements of cirrus microphysical properties were not available until the advent of accurately instrumented aircraft, and even then the reported size distributions were biased in favor of large particles because of the inability to measure particles in the 1–100-$\mu$m range (the range where SAM operates). We can say that our results (i) are consistent with particle size distributions that have appeared in the literature and (ii) make qualitative sense for the types of clouds that are in the instrument’s field of view. Correlations with measurements of in situ particle samplers in future SAM field experiments should make valuable contributions to resolving this issue.

5. Derivation of cloud particle size distributions and effective radii from SAM data

a. The diffraction approximation

As noted in section 2, SAM measurements consist of solar disk and aureole radiance $L_A(\theta)$ as a function of angular distance $\theta$ from the center of the solar disk. The aureole radiance is related to the single scattering phase function $P(\theta)$. In our usage, $P(\theta)$ is normalized such that an isotropic scatterer would have $P_{\text{iso}}(\theta) = 1$ [i.e., the integral of $P(\theta)$ over all directions yields a value of $4\pi$].

Unless stated otherwise, throughout this section the line-of-sight optical depth from the sun to the observer is assumed to be the result of scattering within a single optically thin, uniform, plane-parallel cloud layer in combination with atmospheric Rayleigh scattering along the line of sight (so that, in particular, the contribution to the line-of-sight optical depth resulting from atmospheric aerosols or additional cloud decks is negligible). In this case, $\tau$ and $\tau_c$, as defined in section 3, are simply related by $\tau_c = \tau/\mu_s$, where $\mu_s$ is the cosine of the solar zenith angle and $\tau_c$ is directly measured by the SAM SD camera. With these approximations and assuming single scattering, $P(\theta)$ and $L_A(\theta)$, which is measured by the SAM A camera, are related by (see, e.g., Liou 2002, p. 302)

$$L_A(\theta) = \sigma \frac{P(\theta)}{4\pi} \tau_c e^{-\tau} F_\odot \approx P(\theta),$$

where $F_\odot$ is the irradiance of the sun and $\sigma$ is the single scattering albedo (the ratio of the scattering cross section to the extinction cross section). In practice, the proportionality of $P(\theta)$ and $L_A(\theta)$ is a good approximation for clouds with $\tau_c \approx 3$ (see section 5e).

Consider forward scattering ($\theta \leq 10^\circ$) from cloud particles whose characteristic sizes $a$ are large compared to the electromagnetic wavelength $\lambda$. Diffraction plays a major role in such cases. In the diffraction approximation, the solar aureole is assumed to be dominated by diffraction from particles with $a \gg \lambda$. In this approximation, the particles are taken to be spheres of radius $a$. The treatment of the scattering process is further simplified to produce an analytic relationship between the forward scattering pattern and the particle size distribution. The
simplification consists of replacing the forward scattering pattern with a rectangle function as illustrated in Fig. 13. The differential contribution to \(P(\theta)\) resulting from particles with radii between \(a\) and \(a + da\) is then given by

\[
dP(\theta \leq \frac{\lambda}{2a}) \approx n(a) \frac{\sigma(a)}{\Delta \Omega_a} da, \tag{2}
\]

where \(n(a)\) is the particle size probability distribution, \(\sigma\) is the scattering cross section, and \(\Delta \Omega_a\) is the solid angle of the diffraction pattern. Integrate Eq. (2) over particle size to find \(P(\theta)\):

\[
P(\theta) \approx \int_0^{\theta} n(a) \frac{\sigma(a)}{\Delta \Omega_a} da, \tag{3}
\]

where from simple diffraction theory \(a(\theta) = \lambda/2\theta\).

Take \(\sigma\) to be twice the geometric cross section, which is asymptotically correct in the limit of large particles:

\[
\sigma(a) = 2\pi a^2, \quad \Delta \Omega_a \approx \frac{\pi \lambda^2}{4a^4}. \tag{4}
\]

Substitute these relations into Eq. (3) to obtain

\[
P(\theta) \approx \frac{1}{\lambda^2} \int_0^{\theta} n(a)a^4 da. \tag{5}
\]

Differentiate this expression with respect to \(\theta\) and solve for \(n(a)\):

\[
n(a) \approx \frac{dP}{d\theta} \frac{\lambda^2}{a^4(da/d\theta)}. \tag{6}
\]

Substitute \(\theta = \lambda/2a\) and \(da/d\theta = -\lambda/2\theta^2\) into Eq. (6) to obtain

\[
n(a) \approx \frac{dP}{d\theta} \frac{\theta^6}{\lambda^3}. \tag{7}
\]

Thus, given \(dP/d\theta \propto dL_A/d\theta\) as a function of \(\theta\) based on SAM measurements, \(n(a)\) can be determined from Eqs. (1) and (7) to within a multiplicative constant.

b. Column density and normalization

Again, in the diffraction approximation define a composite cross section \(\sigma_c\) as the average over the size distribution:

\[
\sigma_c = \frac{\int_0^{\infty} 2\pi a^2 n(a) da}{\int_0^{\infty} n(a) da}. \tag{8}
\]

Because \(\tau_c\), which is directly measured from the SAM profile, is simply the product of \(\sigma_c\) and the column number density \(N_p\) of scattering particles along the line of sight from the sun to the observer, the absolute units for \(n(a)\) can be determined from

\[
\int_0^{\infty} n(a) da = N_p = \frac{\tau_c}{\sigma_c}. \tag{9}
\]

In practice, one numerically integrates over the range of particle sizes contributing to the aureole measurements (2.5 \(\mu\)m \(\leq a \leq 25\) \(\mu\)m) and neglects the contribution to \(\tau_c\) from particles of larger and smaller sizes. The effects of smaller and larger particles are difficult to estimate but are expected to be small. In the case of the smaller particles, the use of twice the geometric cross section becomes a significant overestimate as the particle size decreases and the Rayleigh scattering regime is entered. In the case of the larger particles, concentrations tend to fall very rapidly with particle size. For example, when Heymsfield and Platt (1984) parameterized particle size distributions for ice clouds, they used power-law distributions. The power-law slopes that they found ranged from \(-2.21\) to \(-3.85\) for particles smaller than \(10^3 \mu\)m and tended to be steeper for larger particles. In the case of the shallower slopes (for which large particles are more important), an alternative procedure might be to extrapolate the SAM size-distribution profile to larger sizes for the purpose of determining the normalization. Quantification of the errors associated with these approximations requires comparing SAM data collections with in situ particle measurements.

c. Power-law distributions

When \(n(a)\) is represented by a power-law distribution \(n(a) \propto a^{-\alpha}\) and truncation issues are ignored for present purposes,
\[ \frac{dP(\theta)}{d\theta} \propto n(a)\theta^{-6} \propto a^{-\alpha}\theta^{-6} \propto \theta^{\alpha-6}, \quad (10) \]

or, after integration,

\[ P(\theta) \propto \theta^{\alpha-5}. \quad (11) \]

That is, the sum of the exponents of the power-law functions representing the particle size distribution and the aureole profile is \(-5\).

The correspondence of power-law distributions also holds if diffraction is modeled with an Airy function. Equation (9.168) in Jackson (1975) provides the following expression for the angular distribution of the intensity \(I_a(\theta)\) (W sr\(^{-1}\)) of radiation of wavelength \(\lambda\) (\(\mu\text{m}\)) diffracted by a circular aperture of radius \(a\) (\(\mu\text{m}\)) at angle \(\theta\) (rad) relative to the direction of the incident radiation:

\[ I_a(\theta) = I_i \left( \frac{2\pi a}{\lambda} \right)^2 \left[ J_1 \left( \frac{2\pi a \sin \theta}{\lambda} \right) \right]^2, \quad (12) \]

where \(J_1\) is the first-order Bessel function and \(I_i = \pi a^2 F_0\) is the power (W) incident normally on the aperture. According to Babinet’s principle of complementary screens (see, e.g., section 9.11 of Jackson 1975), the intensity scattered from a circular disc is the same as that from a circular aperture. Furthermore, similar to the Kirchhoff domain of diffraction, scattering by an object large compared to the wavelength can be approximated by diffraction from a screen that is the projected area of the object normal to the incident direction (see, e.g., section 9.13 of Jackson 1975). Consequently, diffraction from a spherical particle can be well approximated by diffraction from a circular aperture. The intensity \(I_a(\theta)\) diffracted by a sphere written in terms of scattering phase function \(P_d(\theta)\) is

\[ I_a(\theta) = \frac{F_0\sigma_s P_d(\theta)}{4\pi}. \quad (13) \]

Taking \(\sigma_s = \pi a^2\), equating (approximately) \(I_a(\theta)\) and \(I_s(\theta)\) in Eqs. (12) and (13), and solving for \(P_d(\theta)\) yields

\[ P_d(\theta) \approx \left( \frac{\pi a}{\lambda} \right)^2 \left[ \frac{2J_1 \left( \frac{2\pi a \sin \theta}{\lambda} \right)}{2\pi a \sin \theta} \right]^2. \quad (14) \]

The composite phase function \(P_c(\theta)\) for a power-law distribution of particles, each represented by this individual phase function, is the normalized average, weighted by the product of the cross section and the particle density. Applying the small angle approximation \((\sin \theta \approx \theta)\), changing the integration variable to \(x = 2\pi a\theta/\lambda\), and simplifying yields

\[ P_c(\theta) \propto \lambda^{3-\alpha}\theta^{\alpha-5} \int_0^\infty x^{2-\alpha} [J_1(x)]^2 \, dx. \quad (15) \]

Note that the integral in this equation is simply a constant. Because for a thin cloud layer the shape of the aureole is proportional to the composite phase function, it turns out again that the sum of the power-law slopes of the particle size distribution and the aureole is \(-5\).

\(d\). Robustness of the diffraction approximation

Numerical experiments were performed to test the robustness of the diffraction approximation. Consider a collection of spherical water droplets represented by a power-law size distribution. Single scattering phase functions were calculated for individual particles of radii 1, 2, 3, \ldots, 300 \(\mu\text{m}\) using the Mie scattering algorithm of Bohren and Huffman (1983). Figure 14 shows composite phase functions for power-law size distributions of these particles, with power-law slopes ranging from \(-5\) to \(-2\).

Note the increasing height of the forward scattering peak as the slope increases from \(-5\) to \(-2\), corresponding to the increased proportion of large particles in the ensemble. Scattering to the side (e.g., at 100°) is seen to decrease with flattening power-law slope of the size distribution, as required by the normalization of the phase functions. Note also the change in character of the phase function between \(\sim0.8°\) and \(\sim8°\), which coincides with the angular measurement region of SAM. The curves

\[ \text{FIG. 14. Composite phase functions for power-law distributions of spherical water droplets. The results were obtained with the Mie scattering algorithm of Bohren and Huffman (1983). The slopes of the input power-law size distributions are indicated by the color coding, where Re is the effective radius (micrometers) for each size distribution.} \]
for ensembles with fewer large particles (steeper power-law slopes) are convex upward, whereas for those with more large particles (shallower slopes) they are concave upward. In the future, it may be possible to derive additional information by quantifying the curvature. In any case, it is clear that, for optically thin clouds, both the overall slope and the shape of the forward scattering part of the phase function (and therefore of the small angle portion of the aureole) are diagnostic of the proportion of large particles to small ones.

As a test of the practical utility of the diffraction approximation for power-law distributions of spherical particles, the prediction of the relationship between the slopes of the size distribution and phase function in Eqs. (11) or (15) was checked. The composite phase functions in Fig. 14 are reasonably straight (on log–log plots) from very small scattering angles up to $3^\circ$–4°. At larger angles, departures from straight-line behavior limit applicability of the theory. Straight lines were fitted to the composite phase functions using a least squares procedure (Press et al. 1986) weighted by the spacing of the scattering angles on a logarithmic scale to avoid a bias associated with the increased density of points at large scattering angles. Figure 15 shows the resulting phase function slopes calculated between the angles of 0.8° and 3° and between 0.8° and 4° as functions of the slope of the size distribution. The dashed line in the figure shows the theoretical prediction from Eq. (11) or Eq. (15). We find that the correspondence between the fitted phase function slopes and the theoretical prediction is reasonably close ($\leq 0.3$) for size-distribution slopes between −2.5 and −4.5, which is where most of the size-distribution slopes inferred from SAM measurements are found to lie (see Fig. 12).

Figure 16 shows the effective radius for a power-law distribution of spherical particles with radii between 1 and 300 μm. The fractional change in the effective radius with size-distribution slope provides a measure of the sensitivity of the effective radius to changes in the power-law slope of the size distribution. For example, the effective radius for a size distribution with power-law slope of −3.5 is 17.3 μm, and the error in the effective radius for an error of 0.1 in the power-law slope is 4.2 μm. Consequently, although the relationship between the power-law slopes of the aureole and particle size distribution holds qualitatively, its use quantitatively to estimate effective radius may lead to significant errors.

e. Multiple scattering effects

The broadening of aureole radiance profiles by multiple scattering effects was also investigated using numerical Monte Carlo simulations of aureoles seen through a uniform, plane-parallel cloud composed of water droplets with the sun at zenith. Using the composite phase functions described earlier, $\tau_c$ was varied from 0.1 to 3. Figure 17 shows the resulting radiance profiles using the composite phase function for the illustrative case of a power-law size-distribution slope of −3.5. Close inspection of this figure shows that, in the forward scattering region ($\theta \approx 10^\circ$), the aureole radiance reaches a maximum for $\tau_c$ in the range from ~1 to ~3. More importantly, the radiance profile flattens only gradually with increasing $\tau_c$, at least for values of $\tau_c$ up to 3. As shown in Eq. (1), the shape of the radiance profile is the same as that of the composite phase function profile in the limit of small $\tau_c$. The near independence of the
radiance profile on $\tau_c$ in Fig. 17 and similar results (not shown) obtained for other values of the power-law size-distribution slope between $-4.0$ and $-2.5$ suggest that the radiance profile is a good proxy for the phase function profile in the forward scattering region, even when $\tau_c$ is not small [and thus when Eq. (9) for the absolute normalization of the size distribution cannot be applied].

The power-law slopes of the simulated aureole radiance profiles in Fig. 17 were measured using the same procedure used for the phase functions. Figure 18 shows the dependence of the measured power-law slope of the radiance profile on $\tau_c$. The slope of the power-law distribution of droplet radii was taken to be $-3.5$. For $\tau_c$ equal to 0.1, the measured aureole slope is $-1.51$, only slightly different from the theoretical prediction of the diffraction approximation of $-1.50$. As $\tau_c$ increases to quite substantial values, the measured aureole slope decreases only slightly, which is consistent with a modest flattening of the aureole profile from multiple scattering. This helps further quantify that the aureole profile is a good proxy for the phase function profile, even when $\tau_c$ is not small.

**f. Effects of an underling aerosol layer**

The SAM measurements reported here were collected in the relatively clean environment at the DOE ARM site in northern Oklahoma. It is reasonable to ask what might happen in a polluted environment. Because the size distribution derived using the diffraction approximation is proportional to the gradient of the aureole profile and aureoles produced by small aerosol particles are relatively flat, one expects an aerosol layer to have little impact. To quantify the effect, the two aureole radiance profiles shown in Figs. 8 and 10 were modified to simulate the effects of an underlying aerosol layer, which was modeled using a Junge size distribution of water droplets:

$$n(a) \propto a^{-\nu - 1},$$ (16)

where the exponent $\nu$ was taken as 3.3. Note that including even smaller particles, for example, by using a modified gamma function distribution, would only serve to lessen the effect of aerosols for a given optical depth, because the effect of these particles is to decrease the slope of the aureole. The aerosol phase function $P_{aer}(\theta)$ was calculated using Mie theory for water drops with radii $a$ from 0.1 to 10 $\mu$m. The aerosol loading was specified through the aerosol optical depth $\tau_{aer}$, which was taken to be 0.1.

Equation (1) was adapted to model the radiance scattered by the aerosol layer $L_{aer}(\theta)$, ignoring the diffusely scattered radiance from the overlying cloud layer:

$$L_{aer}(\theta) = \sigma_{aer} \frac{P_{aer}(\theta)}{4\pi \mu_s} n_{aer} e^{-\tau_{aer}/\mu_s} F_\odot.$$ (17)

The SAM-measured aureole radiance profile $L_{SAM}(\theta)$ was reduced by the transmittance of the aerosol layer, $T_{aer} = e^{-\tau_{aer}/\mu_s}$, and combined with the modeled aerosol radiance reduced by the SAM-measured transmittance of the cloud layer, $T_{SAM} = e^{-\tau_{SAM}/\mu_s}$, to model the aureole radiance from the two layers:
The aureole profile measured at 20.378 UTC 23 June 2007 is compared in Fig. 19 with the profile that has been artificially augmented with the underlying aerosol layer. Note how little the aerosol scattering affects the aureole profile, despite the fact that the optical depth of the aerosol layer ($\tau_{\text{aer}} = 0.1$) exceeds half that of the cloud layer ($\tau_{\text{SAM}} = 0.175$). It should come as no surprise then that the size distributions calculated via the diffraction approximation for the two profiles in Fig. 19 are also very similar, as shown in Fig. 20.

The effective radii calculated for the measured and augmented profiles are 7.7 and 6.8 $\mu$m, respectively. Similarly, the power-law slopes of the two size distributions are $-3.48$ and $-3.75$, respectively. The addition of the underlying aerosol layer has slightly skewed the cloud particle size distribution to smaller particles in accordance with one’s expectation.

The same numerical experiment was performed using the measured profile at 15.186 UTC 12 June 2007. The effective radii of the measured and augmented aureole profiles are 10.8 and 10.5 $\mu$m, respectively. Similarly, the power-law slopes of the two size distributions are $-2.77$ and $-2.84$, respectively. The effects of the aerosol layer are considerably reduced in this case, because its optical depth ($\tau_{\text{aer}} = 0.1$) is considerably less than that of the cloud layer ($\tau_{\text{SAM}} = 0.78$).

g. Measuring aerosol phase functions

The diffraction approximation provides some insight into the range of particle sizes for which SAM aureole measurements provide information. Recalling that $a \sim \lambda/2\theta$, the angular half width of the sun sets the upper limit at $77 \mu$m. Practical considerations (e.g., pointing errors and internal instrumental scattering) reduce this value. At the other end, extending the aureole angular measurements beyond the current limit of $\sim 8^\circ$ may help to extend the retrievals to smaller particles. Pushing the diffraction approximation somewhat beyond its limits, a factor of 6 increase in the aureole angular extent to $\sim 50^\circ$ would correspond to radius measurements of $\sim 0.4 \mu$m. Such an increase would also facilitate identifying the presence of hexagonal particles in cirrus from their halos.

Measurement of a significant part of the $0^\circ$–$180^\circ$ aerosol phase function should be possible using radiometric imaging in place of mechanically scanning photometry. Figure 21 compares the phase function for the aerosol model discussed in section 5f with those for Rayleigh scattering and a marine stratus layer. For scattering angles beyond about $\sim 50^\circ$, Rayleigh scattering (with a nominal optical depth of $\sim 0.043$ at a wavelength of 670 nm) competes with aerosol scattering, complicating measurements in this region. On the other hand, with imaging instruments
there are many measurements over most of the range of scattering angles that can be averaged to improve the signal-to-noise ratio.

6. Results and conclusions

SAM is a newly designed and implemented aureolegraph that is distinguished by its compactness, portability, and capacity for partially or completely unattended operation. We have demonstrated that SAM measurements can be carried out and interpreted in terms of cloud particle phase and size distributions for optically thin clouds. Typical SAM data collections measure optical depth and particle size distribution at a rate of up to \(~5 \text{ min}^{-1}\) over a period of \(~5 \text{ h} \text{ or more.}\)

In June 2007, SAM was deployed at the ARM site in Oklahoma. Measurements were made and analyzed, and results were compared with standard ARM sensors in the field. Measurements and analyses were presented for two days (12 and 23 June 2007) of this deployment. The aureole radiance profile from 15.186 UTC 12 June shows a shape and inferred particle size distribution that is consistent with the large ice particles associated with cirrus. Concurrent ARM micropulse lidar data indicate a thin cirrus layer near 9-km altitude, thus verifying the interpretation of the SAM measurements. The aureole profile from 20.368 UTC 23 June, on the other hand, shows a shape characteristic of smaller particles, as would be expected for clouds composed of water droplets. In this case, concurrent micropulse lidar data indicate boundary layer cumulus at an altitude of \(~1 \text{ km, which is again consistent with the SAM interpretation.\)

Concurrent observations with the ARM TSI on both dates provide further confirmation of the cloud types identified with SAM. Optical depths derived from SAM and CSPHOT compare well; however, there were times on both days when thin cirrus was present (with optical depths \(\leq 1\)), which the AERONET automatic algorithm failed to identify as corrupted by clouds.

A theoretical relationship between the size distribution of spherical particles and the slope of the aureole profile was derived based on approximating scattering as due solely to diffraction, which in turn was approximated using a rectangle function. When the size distribution was represented as a power-law distribution of spherical particles, the aureole profile was shown also to have a power-law form, with the sum of the powers of the two being \(~5.\) This latter result continued to hold when diffraction was modeled using an Airy function.

The lack of sensitivity of the current (two camera) version of SAM to small particles means that the contribution of these particles to retrieved size distributions is not directly measured. As suggested by the curves in Fig. 21, small particles are important for their contribution to scattering at angles from \(~45^\circ\) to \(~135^\circ.\) We have started work on adding a third camera to extend the angular range of SAM aureole measurements to \(~50^\circ\) to furnish additional information to improve this situation as well as to provide a capability to detect hexagonal ice crystals in cirrus from the presence of halos. We have also started work on adding a visible near-IR sun spectrometer to SAM as an alternative way of furnishing information on small particles from the variation of the solar transmittance with wavelength.

We are in the process of developing improved methods for extracting the particle size distributions from SAM measurements. We speculate that some existing algorithms, such as those developed for aerosol size-distribution retrievals, may find utility in the analysis of SAM data. We welcome inquiries from scientists who may be interested in collaborating with us on the use of SAM data.

In summary, we have shown that SAM can be used to derive cloud optical depth and cloud particle size distribution at short (\(\leq 12 \text{ s}\)) time intervals for a single layer of uniform, optically thin cloud. Comparison with other ground-based sensors routinely operating at the ARM site demonstrates consistency with SAM. However, SAM has demonstrated the capability to observe very thin clouds and retrieve their microphysical properties. Such thin clouds can significantly affect radiative forcing and thus need to be taken into account in radiative forcing calculations. We think that a network of automated SAM sensors could be used to gain information on the global statistical properties of optically thin clouds and their role in the earth’s energy budget and the global climate. Furthermore, such a network could be used for the calibration of satellite cloud sensors to aid in the construction and interpretation of global cloud models.

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REFERENCES


