INFERENCE OF CLOUD OPTICAL PROPERTIES WITH THE 2FOV RADIOMETER

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OBJECTIVE

One of the long-term objectives of the surface based remote sensing community has been to develop methods to diagnose various optical properties of clouds. For example, Twitty et al. (1975) demonstrated by simulations the possibility of retrieving particle size by measuring the single scattering in the solar aureole. There have been several studies of the feasibility of optical depth and particle size retrieval from measurements of transmitted and scattered solar radiation into Multiple Fields of View (MFOV); for example, see Raschke and Cox (1983), Anikin et al (1991), and Shibara and Asano (1994). Investigation of the applicability of using this approach has continued at the Department of Atmospheric Science at Colorado State University for several years. Theoretical investigation continued using a Monte Carlo modeling approach and various instrument designs were fabricated and deployed to verify the usefulness of the theory. The results of these efforts, while generally consistent with theory, suffered from a problem with non-uniqueness. It was usually possible to find non-unique combinations of optical depth and particle size that could have produced the same measurements. An exception to this dilemma is found the works of Anikin et al (1991), who analyzed spectral transmission measurements into various fields of view using a classic retrieval scheme. Within the last few years, the theoretical efforts at Colorado State University have revealed a particularly simple means to interpret the measurements using the spectral variation of the ratio of transmittances measured in two fields of view. This adaptation appears to have the ability to resolve the effective radius and the optical depth independently. Within the last year, preliminary measurements have been made that have provided initial verification of the two field of view (2FOV) approach.

RESEARCH ACCOMPLISHED

The research accomplished in this area can be divided into theoretical and observational aspects. As noted some activity has taken place in both areas over several years; however, this presentation will concentrate on the research accomplished over the last few years. In the case of the observational aspects, the results have been obtained over the past year.

Theoretical Results

The theoretical aspects are most easily demonstrated beginning with single scattering theory of solar radiation Liou (1980), $I_\lambda(\theta) = I_{0,\lambda}\omega_0 \,\tau/\mu_0 \,\frac{1}{4\pi} P(\theta,\theta_0)\exp\left(-\tau/\mu_0\right)$,

where I the solar radiance observed at an observation zenith angle θ, and a wavelength λ, ω_o is the single particle scattering albedo, τ is the cloud's optical thickness, $I_{0,\lambda}$ is the extraterrestrial solar radiance, θ_0 and μ_0 the solar zenith angle and the cosine of the same, and $P(\theta,\theta_0)$ is the scattering phase function. The above represents only the singly scattered component of the solar radiation, and if the directly transmitted component is included in the measurement, the observed quantity is;

$I_\lambda(\theta) = I_{0,\lambda}\omega_0\tau_0 \frac{1}{4\pi}P(\theta,\theta_0)\exp(-\tau_0) + I_{0,\lambda}\exp(-\tau_0)$, where now $\tau_0=\tau/\mu_0$. If instead of observing the solar radiance at an angle θ, the measurement is made by an instrument with a small finite field of view (fov) $\Delta\theta$, the observed irradiance $E(\Delta\theta)$ given by;

$E(\Delta\theta) = E_0\omega_0\tau_0\exp(-\tau_0)\frac{1}{2}\int_{\Delta\theta} P(\theta,\theta_0)\cos(\theta)\sin(\theta)d\theta + E_0\exp(-\tau_0)$, in which the spectral subscript has been dropped. The observed transmittance is obtained by dividing by the extraterrestrial solar irradiance to obtain; $T(\Delta\theta) = \exp(-\tau_0)\left[1+\omega_0\tau_0\frac{1}{2}\int_{\Delta\theta}P(\theta,\theta_0)\cos(\theta)\sin(\theta)d\theta\right]$.

Thus, the observed transmittance is the actual transmittance plus a contribution due to single scattering. It is the scattering contribution which basically provides the signal for determination of particle size information as demonstrated in Twitty et al. (1975), who simulated particle size retrievals for single scattering in the solar aureole. The above relationship applies exactly only to single scattering, which is valid only at very small optical depths. If we take the natural logarithm of the expression above, we obtain: $\ln(T(\Delta\theta)) = \ln\left\{T_0\left[1+\omega_0\tau_0\frac{1}{2}\int_{\Delta\theta}P(\theta,\theta_0)\cos\theta\sin(\theta)d\theta\right]\right\}$,

in which T_0 is used to denote the direct solar transmittance. Using the standard definition of optical depth, $\tau = -\ln(T)$ yields: $-\tau(\Delta\theta) = -\tau_0 + \ln\left[1+\omega_0\tau_0\frac{1}{2}\int_{\Delta\theta}P(\theta_0,\theta)\cos(\theta)\sin(\theta)d\theta\right]$.

Denoting the term involving the integral of this expression by y, the expression becomes, $\tau(\Delta\theta) = \tau_0 - \ln(1+y)$. Then, if it is assumed that y is small, which is violated for all but the smallest τ, this can be approximated by: $\tau(\Delta\theta) = \tau_0 - y$, or,

$\tau(\Delta\theta) = \tau_0 - \tau_0\left(\omega_0 \frac{1}{2}\int_{\Delta\theta} P(\theta_0,\theta)\cos\theta\sin(\theta)d\theta\right)$. At this point we will adopt a change in notation to make the results compatible with those in Asano and Shiobara (1994), to obtain:

$\tau(\Delta\theta) = \tau_0 k(\Delta\theta)$, where, $k(\Delta\theta) = \left(1 - \frac{\omega_0}{2}\int_{\Delta\theta} P(\theta_0,\theta)\sin(\theta)d\theta\right)$. The cosine factor in the integrand has been set to unity since $\Delta\theta$ is small. Although the approximation above holds only for small values of τ in theory, modeling experiments indicate that it is valid at larger values as well. Fig. 1 compares the approximation above to the full multiple scattering results as calculated by a Monte Carlo model and to the strict single scattering results. Apparently, the reduced optical depth approximation provides a marked improvement relative to the single scattering approximation. Using the relation, $\tau(\Delta\theta) = \tau_0 k(\Delta\theta)$, allows us to express the

Figure 1. Apparent transmittance versus size parameter calculated using multiple scattered Monte Carlo (MC), reduced optical depth (Exp) and single scattering algorithms. Results are simulated for a detector with a 0.75 degree half angle for optical thicknesses of 4.0.

transmittance in a Beer's law form; $T(\Delta\theta) = \exp[-\tau_0 k(\Delta\theta)]$. The results in Fig. 1 indicate the approximate method of reducing the optical depth is a valid over a significant range of the size parameter $x=2\pi r/\lambda$, where r is the particle radius at least for spherical water drops

As shown in Shiabara and Asano (1994), this approximation works very well for the phase function of cirrus clouds presented in Takano and Liou (1989). Results from the reduced optical depth method for the cirrus-cloud phase function are shown in Fig. 2, for the 0.75° field of view. Note that the true and reduced optical depth results are virtually coincident. Similar findings have been reported by Anikin *et al* (1991).

Figure 2. Apparent transmittance calculated with the Monte Carlo (MC) model, the reduced optical depth approximation (Exp) and the single scattering approximation, (SS) for the cirrus cloud phase function and a detector half angle of 0.75 degrees.

Theory also predicts that the measurement of transmittance into small fields of view provides a simple means for diagnosing the true optical thickness from the apparent or measured optical thickness for larger values of the size parameter $(x \geq 150)$. Returning again to the equation of apparent optical thickness, $\tau(\Delta\theta) = \tau_0 k(\Delta\theta)$, it is interesting to examine typical values of $k(\Delta\theta)$. In making many calculations with the Monte Carlo model the value of $k(\Delta\theta) = 1 - \frac{\omega_0}{2} \int_{\Delta\theta} P(\theta, \theta_0) \sin(\theta) d\theta$ was noted. These results indicate that the value of $k(\Delta\theta)$ is roughly 1/2 for larger values of the size parameter. For example, Table 1 shows the values of $k(\Delta\theta)$ as a function of the size parameter, for the fields of view used in the new MFOV for the cirrostratus phase function from Takano and Liou (1989) (shown in the first row) and for mono-dispersed, spherical, liquid water microphysics (shown in the remaining rows). It is seen that over a range of larger values of the size parameter the values of $k(\Delta\theta)$ are in the neighborhood of 1/2, especially for the 2° half angle fov. This implies, based on the formula for single scattering above, that the apparent optical depth $\tau(\Delta\theta)$ is approximately half the true value τ_0 when measured by a detector of 2° half angle. This approximation can be combined with the previous one to derive a particularly simple algorithm for interpreting the results of the measurements into a small fov, assuming the cloud is observed at large values of the size parameter ($x > 150$). For example, Fig. 3 displays the apparent transmittance for three different detector fields of view calculated with a multiple scattering MC model compared to results using the approximation that the apparent optical depth is scaled down by a factor of $k(\Delta\theta)$ equal to 0.5 for the cirrus cloud phase function of Takano and Liou (1989). Similar results are found for spherical particles observed at large size parameters. The results of Fig. 3 indicate that as long as the cloud particles are observed at a large size parameter, the apparent optical depth is approximately half the actual optical depth.

Size Parameter	$\theta_h = 0.75$	$\theta_h = 1.00$	$\theta_h = 2.00$
T & L	.45	.50	.53
142.80	.28	.36	.42
214.20	.39	.42	.46
285.60	.43	.44	.48
357.00	.44	.46	.49
428.40	.46	.47	.50
499.80	.47	.48	.50
571.20	.48	.49	.50
642.60	.49	.49	.51
714.00	.50	.51	.52
785.40	.51	.51	.53
856.80	.52	.52	.54
928.20	.52	.53	.54
999.60	.53	.54	.55

Table 1. Values of $k(\Delta\theta)$ for scattering angles of the MFOV.

Figure 3. Transmittance as a function of optical depth for a cirrus cloud. Calculations are shown for full multiple scattering into various fovs (symbols), the unscattered component (solid line) and the reduced optical depth algorithm (dotted line).

Anikin *et al.* (1991), demonstrated the value of examining the ratios of apparent transmittance measured in different fields of view. The use of ratios is beneficial not only from an analysis standpoint, which is the subject of this section, but also because it permits the device to be used without an absolute radiometric calibration. This assumes that the sensitivity of the instrument is constant over the time required to make to measurements. Of course, using the ratio method does introduce the requirement that the fields of view be known quite accurately. Assuming the validity of the reduced optical depth approximation described above we can write the ratio of transmittance measurements into two fields of view as:
$R_T = \frac{T(\Delta\theta_1)}{T(\Delta\theta_2)} = \frac{\exp[-k(\Delta\theta_1)\tau_0]}{\exp[-k(\Delta\theta_2)\tau_0]}$, or, $R_T = \exp[-(k(\Delta\theta_1) - k(\Delta\theta_2))\tau_0]$, which for brevity we write as $R_T = [\exp(\Delta k)]^{\tau_0}$. For scattering by mono-dispersed droplets this ratio takes a form shown in Fig. 4, which compares the results using the formula for R_T with the MC model for optical thickness from 1 through 4.

Fig. 4 displays the method by which a measure of the particle size and the optical thickness may be separately determined. It is seen that the peak in the ratio of R_T is invariant with optical thickness, but the peak in the curves increases as a function of the optical thickness. It is also seen that the approximation of the transmittance ratios using the reduced optical depth becomes less accurate as the cloud becomes thicker. It is for this reason and because the region of the aureole becomes less apparent that the method is only applicable to relatively thin clouds. The results of Fig. 4 were computed using a mono-dispersed droplet population; however, other results not shown here reveal the peak in the ratio remains relatively invariant (± 20%), when plotted as a function of the effective size parameter $x_{eff} = \frac{2\pi r_{eff}}{\lambda}$, where $r_{eff} = \frac{\int_0^\infty n(r) r^3 dr}{\int_0^\infty n(r) r^2 dr}$. These results suggest a simple means of estimating the effective particle size and the optical thickness from surface observations of transmitted solar radiation through clouds.

Figure 4. Ratios of the transmittance ratios R_T calculated with a Monte Carlo (MC) method and estimated (Exp) by using the reduced optical depth for four optical depths.

Continuing with this approach it has been found that the magnitude of the peak in the approximate expression of the ratio is inversely related to the width or effective variance of the size distribution at least for some distributions. Fig. 5 displays a plot the maximum value of Δk as a function of the effective variance ν_{eff}, where, $\nu_{eff} = \dfrac{\int_0^\infty (r - r_{eff})^2 \pi r^2 n(r) dr}{r^2_{eff} \int_0^\infty \pi r^2 n(r) dr}$. In Fig. 5 the symbols “C.1”, “C.2” etc. refer to various droplet distributions that are generated from a “modified gamma” function as described in Deirmendjian (1969).

Figure 5. The dependence of the maximum value of $\Delta k(\theta)$ as a function of effective variance for various size distributions.

Observational accomplishments

Two instruments have been configured for conducting the initial observations to verify the theory outlined above. The first system comprised a Bomem MB-155 Fourier transform interferometer that was equipped with an aperture wheel for manually selecting the field of view. The manual fov selection could be automated at some point in the future. The detector was a wide-band pyroelectric design that measured the solar spectrum from 0.7 to 10.0 μm at a spectral resolution of 2.0 cm^{-1}. It is noted that the present application does not require high spectral resolution. The solar beam was directed into the interferometer with a mirror operating on a solar tracker that utilized a quadrant detector, although the performance of the tracking mechanism was less than optimal. This limitation caused difficulty in using the desired fov pair although data consistent with the theoretical findings were collected as shown below in Fig. 6. Photo. 1 shows the basic interferometer instrument. The upper portion of Fig. 6 shows plots of modeled R_T transmission ratios (2° / 0.75°) over a limited spectral interval (size parameter) for optical depths recorded by an independent sun photometer with a 2° fov. The optical depths were set to twice the apparent optical depth in accordance with the discussion above. The lower graph shows plots of data collected with the interferometer system under cirrus overcast. Note that the abscissa on the second graph is scaled assuming an effective radius of 30 μm in order to facilitate comparison. The 30μm radius was selected based on the wavenumber corresponding to the peak in the measurements combined with the theoretical peak with size parameter for a (2°/ 0.75°) fov pair. As mentioned above the solar tracker's performance was less than optimal. In order to allow a visual confirmation of the image of the solar disk on the aperture alternate fovs were selected which altered the location of the peak value of R_T somewhat.

Photograph 1. Interferometer used to collect solar transmittances using various fields of view.

Figure 6. Modeled (upper) and measured (lower) ratios of solar transmittances with a two field of view instrument.

Although there were difficulties mainly attributable to the performance of the solar tracking system, these results and other measurements generally confirm the major aspects of the two field of view approach. Note that the simulations do not include the effects of gaseous absorption and thus do not account for the absorption bands present in the measurements.

The second instrument system is one designed specifically to measure the solar transmittance in different fields of view. The instrument consists of a silicon detector that measures the incoming solar radiation entering through a limiting field of view and a spectral bandpass limiting filter. The fields of view and the spectral filters are rotated over the detector under computer control using DC servo motor drives. The system is designed to operate continuously and is small enough to be mounted on a conventional solar tracker. The bandpass of the silicon detector is such that the instrument will detect the effective radius of moderately sized particles (8 to 18 μm) using the current fov pair. This instrument is viewed as a complementary system to the interferometer based system, which is limited to detection of the effective radius of larger particles. The silicon detector based 2fov instrument is undergoing evaluation at the time of the writing of this report. Photo. 2 shows the silicon based 2fov instrument.

Photograph 2. 2fov instrument deployed at Colorado State University.

CONCLUSIONS AND RECOMMENDATIONS

A theory has been presented that indicates the feasibility of inferring the optical depth and effective radius from solar transmission measurements in two fields of view. The theory is based on full multiple scattering calculations using a Monte Carlo algorithm that simulates a backward walk of photons from the active area of the detector, through the field of view and through the cloud and atmosphere. The calculations do not include the effects of gaseous absorption. Two instrument systems are being used to evaluate the theory in separate regions of the solar spectrum. The first system, which is based on a Fourier transform interferometer, has provided preliminary verification of the major aspects of the theory. A second device, which is based on a silicon detector, is currently being tested.

The relatively simple approach to the retrieval of cloud microphysical features belies somewhat the difficulty of the measurement process. The primary difficulty in the measurement process is obtaining accurate solar tracking since the fields of view are quite small. The second difficulty is accurately configuring the instruments' fields of view, since the particular field of view pair determines where the peak in the transmittance ratio will occur. These difficulties are at least partially offset by two considerations: first, the extremely simple manner in with the results may be interpreted, and second, in the fact that the methodology eliminates the need for precise radiometric calibration of the instrument. Finally, it is reiterated that this technique is limited to inference of the properties of clouds with relative small optical depth ($\tau < 5$), approximately.

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REFERENCES

Anikin, P. P., 1991: Determination of the spectral optical thickness and effective partricle size of cirrus clouds. *Isvestiya, Atmos. and Oceanic Phys.,* **27,** 673-680.

Deirmendjian, D., 1969: *Electromagnetic Scattering on Spherical Polydispersions,* American Elsevier Publishing Company Inc., 290 pp.

Liou, K. N., 1980: *An Introduction to Atmospheric Radiation*, Academic Press, 392 pp.

Shibara, M. and, S. Asano, 1994: Estimation of cirrus optical properties from sun photometer measurements. *J. Applied Meteor.,* **33,** 672-681.

Takano, Y., and K. N. Liou, 1989: Solar radiative transfer in cirrus clouds. Part I: Single-scattering and optical properties of hexagonal ice crystals. *J. Atmos. Sci.,* **46,** 3-19.