# Estimations of Cloud Particle's Effective Radii from Ground-Based Measurements of Solar Radiation Transmission by Semi-Transparent Clouds

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## Introduction

Effective radius of cloud particles (i.e., the ratio of third to second moment of size distribution) is an important parameter, which enables to estimate optical characteristics of clouds and, comparing with optical depth, the liquid (crystal) water path.

At first sight, the transparency measurements in visible and near-lR spectral regions are not suited for the determination of microphysical parameters of semi-transparent clouds since the weak dependence of the spectral extinction upon the particle size for particles much greater than the wavelength. But in reality, some portion of the scattered light comes always into the photometer due to its finite Field of View (FOV) and finite angular size of the Sun. Near forward scattering is more sensitive to the cloud particle's size spectra. Thus, on the one hand, the input of the scattered light into measured signal impedes determination of the true optical depth of cloud, but on the other hand, it may help to evaluate the characteristics of size spectra. The technique of retrieving must take into account the effects of multiple scattering and finite Sun.

## Relation Between Measured Optical Depth and Size Spectrum

The results of measurements (Anikin 1994) indicate that the near linear relation exists between measured values $\tau_{exp}$ of the optical depth of semi-transparent clouds for different FOVs and different wavelengths in UV, visible and IR spectral regions. This relation is valid for optical depths up to several units (solar zenith angles <60°). Numerical simulations (Anikin et al. 1992) and theoretical analysis (Zege et al. 1994) confirm this relationship and show that the measured optical depths are also proportional to the actual value of cloud optical depth $\tau$. The account of the molecular and aerosol scattering does not change this result. So we can write:

$$\tau(\lambda) - \tau_{exp}(\alpha,\lambda) = k(\alpha,\lambda)\tau \tag{1}$$

where $\lambda$ is wavelength and $\alpha$-FOV of photometer ( the effect of finite Sun will be discussed below). It must be noted that in the single scattering approximation coefficient k depends upon $\tau$ too and tends to zero with the growth of the cloud optical depth. The negligible dependence of k upon $\tau$ when only the concentration of cloud particles is varying is caused by changing of the input of multiple scattered light. Nevertheless it can be shown (Anikin et al. 1996) that $k(\alpha, \tau)$ may be expressed in terms of single scattering in following form:

$$k(\alpha,\lambda) = 2\pi\int_0^{\alpha-} f(\phi)\sin\phi\, d\phi \tag{2}$$

where $f(\phi)$ is a phase function of cloud particles, normalized to the single scattering albedo. Cross sectional size distribution S(r) (r- radius of particle) of cloud particles is connected with cloud optical depth by equation:

$$\tau(\lambda) = \int Q_{ext}(\lambda,r)S(r)dr \tag{3}$$

where $Q_{ext}$ is extinction effectivity factor. Analogous equation can be written for directed scattering coefficients $\tau(\lambda)f(\phi,\lambda)$:

$$\tau(\lambda)f(\phi,\lambda) = \int Q_{\phi}(\lambda,\phi,r)S(r)dr \tag{4}$$

with angular scattering effectivity factor $Q_{\phi}$. It follows from Eqs. (1) - (4) that S(r) is related to $\tau_{exp}$ by integral equation:

$$\tau_{exp}(\lambda,\alpha) = \int Q(\lambda,\alpha,r)S(r)dr \tag{5}$$

with kernel function Q

$$Q(\lambda,\alpha,r) = Q_{ext}(\lambda,r) - 2\pi\int_0^{\alpha-} Q_{\phi}(\lambda,\phi,r)\sin\phi\, d\phi \tag{6}$$

In case of liquid droplets, kernel function is given by Mie theory.

## Finite Sun Effect

The analysis of the significance of the finite angular size β of the Sun (β ~ 32') showed that for cloud transparency measurements with FOVs more than $1^o$ it is negligible. If FOV α is much less than b, then effective FOV γ is equal to β. In intermediate situations, the effective FOV is a function of two arguments - geometrical FOV α and Mie parameter x = 2πr/λ. In the general case, the upper limit of integral in Equation 6 must be substituted to γ/2. The results of calculations of k(γ,x) for several values of x as a function of α are compared with k(α,x) in Figure 1.

## Description of Instruments and Measurements

Spectral measurements of the transmission of solar radiation by semi-transparent clouds were carried out during cloud-radiation experiments at Zvenigorod Scientific Station of the Institute of Atmospheric Physics, Russian Academy of Sciences. Complex of spectrometers provided synchronous measurements with FOV of 15 minutes at five (six) spectral regions from 0.3 to 12 mcm with spectral resolution Δλ = 1 nm for λ = 0.3 - 2.2 mcm and 40 nm for λ = 2.2 -12 mcm. The solar beam was directed to spectrometers by mirrors controlled by tracking unit. For more details see Anikin et al. (1981).

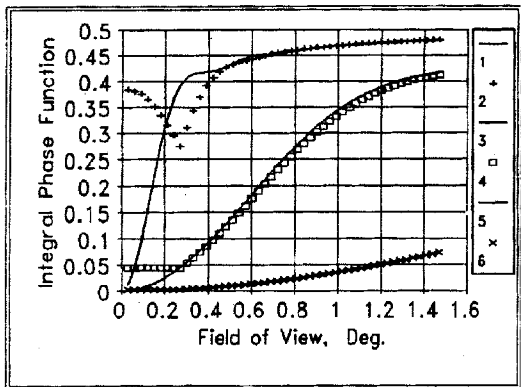

**Figure 1**. Finite sun effect 1, 3, 5 - k(α, x); 2, 4, 6 -k(γ, x) for x = 600 (1, 2); 130 (3, 4); 30 (5, 6).

During the Atmospheric Radiation Measurement Program Enhanced Shortwave Experiment (ARESE) intensive observation period (IOP) in September and October 1995, the measurements were made with Multiple Field of View (MFOV) photometer at wavelength λ ~ 0.53 mcm. The Fields of View are 1.9°, 3.2°, 5.3°, 6.7°, 8.3°. MFOV was mounted at solar tracking system.

## Retrieval of Cloud Particle's Effective

The iterative algorithm of Twitty (1975) was applied to Equation (5). The method was tested on model size distributions with effective radii from 1.5 mcm to 20 mcm. An agreement within 20 per cents occurred between true and retrieved effective radii in spite of the insufficient number of measured parameters (five or six).

Spectral measurements at Zvenigorod and MFOV data of ARESE were inverted to size distributions and effective radii were evaluated. Due to the weather conditions during ARESE mostly cirrus were observed. Examples of size spectra obtained are given in Figure 2. Effective radii of the Cirrus cloud particles were found to be more than 30 mcm at both sites. It must be mentioned that in case of cirrus clouds size distributions and effective radii correspond to the spherical particles with the same spectral or angular dependencies of measured optical depth. The technique enables us to also estimate the true value of optical depth which for cirrus clouds is approximately two times greater in visible region than measured.

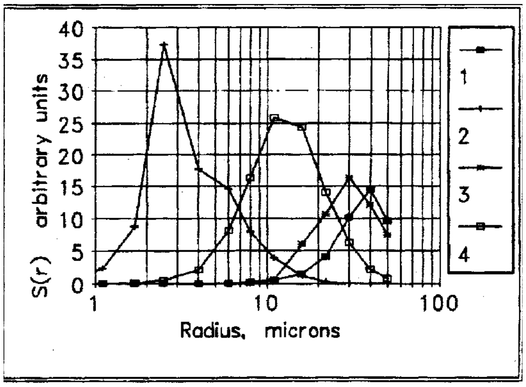

**Figure 2**. Cloud particle's size distributions retrieved from spectral measurements at Zvenigorod (1, 2) and from MFOV data (3 - 10/07/95; 4-09/29/95). Cloud types Ci (1, 3); Ac (2); Sc (4). Effective radii are 40 mcm (1); 6 mcm (2); 35 mcm (3) and 18 mcm (4).

## Summary

The simple technique of retrieving both effective radii and actual optical depth from ground-based synchronous measurements of solar radiation transmission with photometers of different FOVs or for a set of different wavelengths was developed. The method takes into account dependence on the particle size of the scattered into FOV solar light. The estimates of cloud particle's effective radii were made from measurement data gained at Zvenigorod (Moscow Region, Russia) and during ARESE IOP (Lamont, OK).

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