Cloud Liquid Water and Particle Size Detection Using a Raman Lidar

D. N. Whiteman
National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland

S. H. Melfi
University of Maryland
Baltimore, Maryland

Introduction

Due to the great radiative capacity of clouds and the difficulty associated with modeling them, cloud research is a central part of the Atmospheric Radiation Measurement (ARM) Program. Accurate in situ and remote measurements of cloud properties are needed to help validate model predictions. The remote techniques that are currently in use for determining cloud liquid water and particle size generally rely on complex inversion techniques to derive the desired quantities. We report here on progress toward developing a technique for remotely determining cloud liquid water and average particle size using Raman Lidar. This technique has the advantage of using the Raman scattered signal from liquid water in clouds, which can provide a direct quantification of the amount of liquid water in the cloud.

Background

Raman Lidar systems have been used for many years to measure various atmospheric parameters including water vapor and aerosols. The measurement of water vapor is typically made by centering a bandpass filter at the v_1 transition of 3657 cm^{-1}. However, the Raman spectrum from liquid water spans a range of approximately 2800 cm^{-1} to 3800 cm^{-1} and thus overlaps the region of the spectrum that is used for the water vapor measurements. This means that if any liquid water is present in the volume that is being sensed by a Raman Lidar the signal measured in the water vapor channel will be increased due to Raman scattering from the liquid.

This effect has been observed in clouds using the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center Scanning Raman Lidar (SRL) (Melfi et al. 1997). Here, we present work in three areas related to developing a useful Raman Lidar technique for cloud liquid water and particle size measurements: 1) development of the theory allowing liquid water content and average particle radius to be simultaneously determined using a Raman Lidar; 2) analysis of earlier Raman Lidar measurements where the liquid and vapor signals are co-mingled; and 3) measuring the liquid and vapor components of the water spectrum using separate optical channels, which simplifies the analysis.

Theory

Raman Scattering from Spheres

Laboratory measurements of Raman spectra from single optically levitated microspheres have been performed (Schweiger 1990). The Raman spectrum of these spheres possesses many resonances, the number of which can exceed the number of resonances in the corresponding Mie spectrum. However, the intensity of Raman scattering when averaged over a broad distribution of sizes is proportional to the total volume of the particles (Schweiger 1991). In the case of non-precipitating water droplets in clouds, which are nearly perfect spheres, the Raman intensity is thus proportional to the mass of liquid water in the cloud. Thus, after calibration, a measurement of Raman scattering from liquid water in a cloud yields the liquid water content of a cloud volume directly.

Solution Technique for Average Radius and Number Density

Assuming a gamma function for the droplet size distribution in a cloud, a size distribution, which has been shown to fit single-maximum particle size distributions found in real clouds, may be expressed

$$n(a) = \frac{27}{2}\frac{N}{\bar{a}^3}\, a^2 \exp\!\left(-3\frac{a}{\bar{a}}\right)$$

where N is the total number of drops cm^{-3}, n (a) da is the total number of drops cm^{-3} and $\bar{a}$ is the average radius. Using this distribution and the definition of liquid water content of

$$w_L\ (gm^{-3}) = 10^6 \left(\frac{4\pi}{3}\right)\rho_w \int_0^\infty a^3 n(a)\, da$$

where p_w is the density of water in g cm^{-3}, two simultaneous equations

$$\bar{a}^3 N \simeq 1.07\,10^{-7}\,\frac{w_L}{\rho_w} \qquad (1)$$

and

$$\beta_{ray}\ (\text{Aerosol Backscatter Ratio} - 1) = \frac{27}{2}\frac{N}{\bar{a}^3}\int_0^\infty a^2 \exp\!\left(-3\frac{a}{\bar{a}}\right)\frac{d\sigma}{d\Omega}(\pi, a)\, da \qquad (2)$$

are derived. The solution of these equations yields average droplet radius and number density. The equations may be recast into a single equation for $\bar{a}$, which simplifies the numerical solution:

$$\beta_{ray}\ (\text{Aerosol Backscatter Ratio} - 1) = \frac{1.44\,10^{-6}}{a^{-6}}\,\frac{w_L}{\rho_w}\int_0^\infty a^2 \exp\!\left(-3\frac{a}{\bar{a}}\right)\frac{d\sigma}{d\Omega}(\pi, a)\, da \qquad (3)$$

In these equations, β_{ray} is the Rayleigh backscatter coefficient calculated from the atmospheric density, Aerosol Backscatter Ratio is defined as the ratio (Rayleigh scattering +Mie scattering)/(Rayleigh scattering) and is derived from the lidar data (Whiteman et al. 1992), $\frac{d\sigma}{d\Omega}(\pi, a)$ is the Mie backscatter cross section as a function of particle size.

After solving for $\bar{a}$, the number density is obtained through Eq. (1). the lidar must be calibrated to provide cloud liquid water content w_L as input to these equations. Note that all the quantities required from the Raman Lidar as input to these equations are ratios of two different lidar signals. In the ratio, any multiple scattering influence should tend to cancel and thus the influence due to multiple scattering on the measurements should be small.

Analysis

Stability of Solution

To test the robustness of the retrieval technique outlined above, the stability of the solution of Eq. (3) was tested for several test cases. One of those is shown here. Using typical values of cloud backscatter coefficient (km^{-1} sr^{-1}) and liquid water content ($g\ m^{-3}$) of 1 and 0.1, respectively, the solution for average particle radius was found to be about 4.7 µm. Figure 1 shows the difference between the right and left-hand sides of Eq. (3) as a function of average radius. The solution at 4.7 µm is a stable minimum.

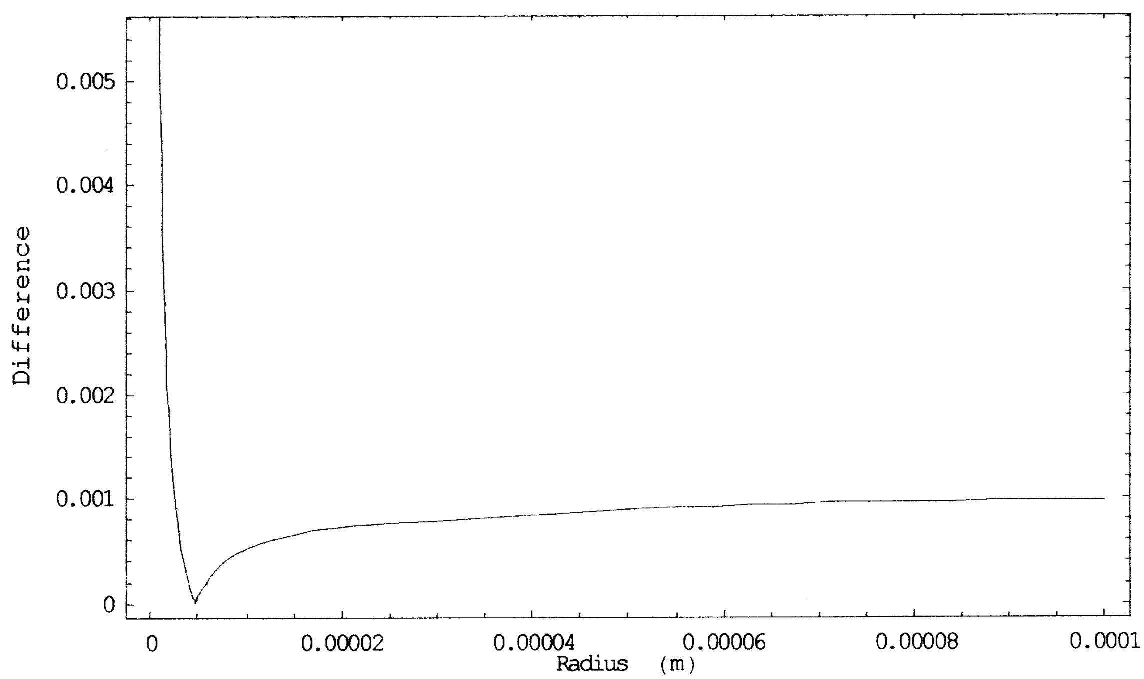

Figure 1. Function space for the solution of average radius given cloud backscatter coefficient and liquid water content. The retrievals using Eq. (3) are well-behaved.

Analysis of Earlier SRL Data

As a preliminary test of the cloud retrieval routines outlined above, SRL data from the Second Convection and Moisture Experiment held at Wallops Flight Facility in 1995 were analyzed. In these data, strong enhancements of the water vapor signal were measured in clouds, which were due to Raman scattering from the liquid droplets in the cloud. These strong enhancements are shown in Figure 2 as the red curve labeled "MRLidar." This is the lidar water vapor mixing ratio signal that shows mixing ratios in excess of saturation ("SatMR") between the altitudes of approximately 0.4 km and 0.9 km. The assumption was made that the portion of this signal in excess of saturation was due to liquid water scattering and thus was proportional to the liquid water content of the cloud. This was converted to units of liquid water content by assuming that the maximum liquid water content of the cloud was I g m^{-3} for this cloud of optical depth 2.8. We chose this approach as a way to test our retrieval technique and not as an absolute calibration of the lidar. The strong elastic return from the cloud is shown in green, the retrieved average radius is shown in purple and the corresponding number density is in blue.

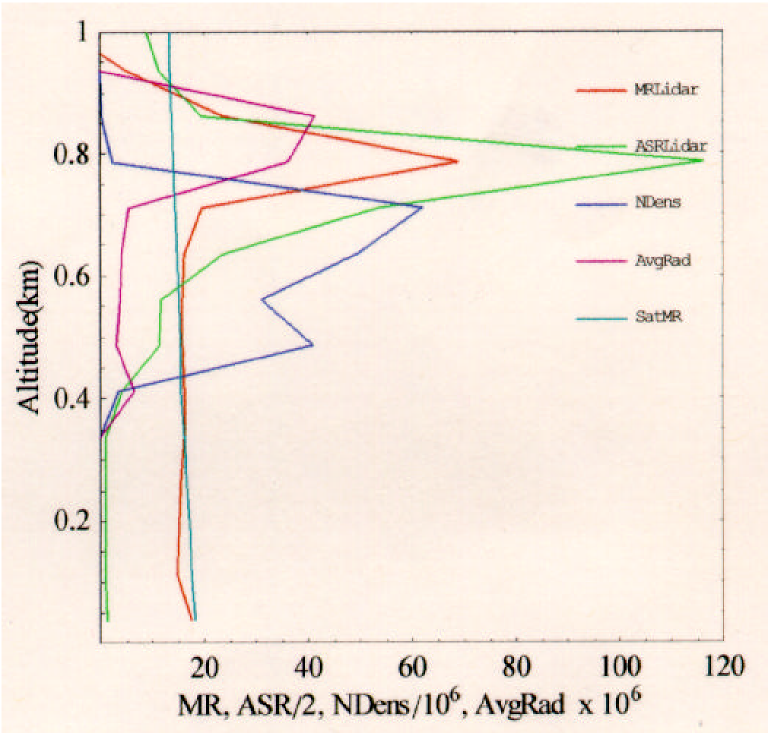

Figure 2. Lidar-derived water vapor mixing ratio and cloud backscatter ratio, saturation mixing ratio from radiosonde and retrievals of cloud liquid water and average particle radius based on data from Wallop Flight Facility on September 9, 1995. The portion of the water vapor signal that is in excess of saturation is taken to be proportional to the liquid water content. Average particle radius is retrieved by assuming a maximum liquid water content in the cloud of 1 gm^{-3}. Average particle radius varies from approximately 3 µm to 40 µm.

Between 0.4 km and 0.7 km, the retrieved radii are in the range of approximately 3 µm to 6 µm with the number densities typically between 4-6 x 10^7 m^{-3}. Above 0.7 km, the retrieved radii rise to approximately 40 µm while the number densities are in the range of approximately 1-2 x 10^6 m^{-3}. This relationship of the average radius tending to increase while the number density decreases is a commonly observed behavior in clouds (Rogers et al. 1989).

Separate Measurements of Cloud Liquid Water and Water Vapor

In order to eliminate some of the assumptions used in the analysis shown in Figure 2, work is in progress, which allows water vapor and liquid water to be separately measured in the cloud environment. On August 20, 1998, preliminary measurements were made demonstrating this capability and are shown in Figure 3. The uncalibrated curves shown in the figure are to illustrate relationships between the different components of the cloud volume that is being sampled. The curves are proportional to the quantities that they are measuring. The liquid water mixing ratio curve is shown in red, the water vapor mixing ratio curve is shown in green and the aerosol scattering ratio curve is shown in blue. The cloud extends between the altitudes of approximately 0.7 km and 2.2 km. The liquid water mixing ratio increases from cloud base to a peak just below 2 km. The variations in the liquid water curve are strongly correlated with the variation in the aerosol scattering ratio curve but whereas the

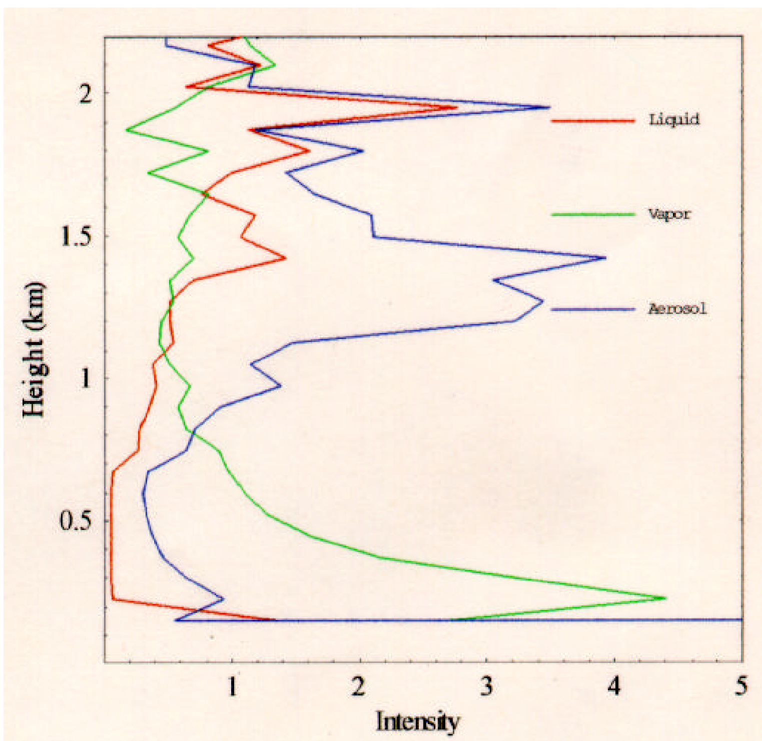

Figure 3. Raman Lidar measurements of water vapor, liquid water, and aerosol backscatter in a cloud from Andros Island, Bahamas on August 14, 1998. These measurements provide separate detection of the liquid and vapor components of the cloud. Thus no assumptions about the saturation level in the vapor signal will be required to perform the analysis.

aerosol scattering ratio is generally decreasing above 1.5 km, the liquid water mixing ratio is generally increasing. These data show the same relationship as illustrated in Figure 2 but the measurements here have been made separately for water vapor and liquid water.

Summary

The Raman Lidar has been used to simultaneously observe Raman scattering due to liquid water and water vapor along with Mie scattering due to the cloud droplets. A retrieval technique has been developed allowing liquid water content, average particle radius, and particle number density to be calculated. The technique was shown to provide stable solutions for both average particle radius and number density. Average particle radius and number density were calculated using an assumption about the maximum liquid water content of the cloud. Once the lidar is absolutely calibrated, the simultaneous measurement of liquid water, water vapor, and Mie scattering will allow studies such as the relationship of water vapor to cloud particle growth to be performed.

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