Multiple Scattering from Cirrus Clouds
: A Fast Approach to Retrieve Optical Characteristics of the Atmosphere from LIDAR Returns

W. Renger

(DLR, Institut fuer Physik der Atmosphaere)

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Wolfgang Renger, DLR, Institut fuer Physik der Atmophaere
D-82234 Oberpfaffenhofen

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Multiple scattering in the atmosphere is less import when using lasers for remote sensing applications in contrast to the transfer of natural radiation in the atmosphere. This is due to the small divergence of the pulsed laser beam and the corresponding narrow field of view of the receiving telescopes. Still, multiple scattering should not be neglected especially for high optical depths. Therefore multiple scattering effects are essential in the case of lidar slant visibility measurements, but the multiply scattered component of the lidar return signal has been widely considered as negligible for an optical depth of less than some 0.1. Consequently, the standard lidar inversion methods for atmospheric haze and optically thin clouds assume single scattering only .

Despite of this, during the International Cirrus Experiment (ICE) with the ALEX lidar it was shown that neglecting multiple scattering leads to meaningless results even for small optical depths of some 0.01. Ruppersberg introduced a multiple scattering term in a mathematically correct way into the lidar equation. In this work the multiple scattering term of the lidar equation is approximated by the second order scattering. With this approach an inversion procedure is constructed.

The restriction of multiple scattering effects to double scattering is supported by several studies e.g. made by Eloranta and Weinman. Phase functions of ice crystals in cirrus clouds show even steeper forward scattering peaks compared to those of water droplet clouds The major part of the radiation which is forward scattered by cirrus particles remains within the telescope's field of view for long distances. At maximum this second order component is reaching the optical thickness of the cloud.

For the inversion scheme regarding double scattering as the major contribution to multiple scattering following assumptions were made:

1. the phase function is sufficiently represented by a simple exponential law, determined by the value of the phase function at the scattering angle zero and it's steepness following from the Babinet theorem.

2. The angular response of the phase function is flat at 180 °

The validity of these assumptions has been investigated by comparing the approximation with an exact algorithm for calculating multiple scattering by use of Monte-Carlo-simulation.

Consider a LIDAR-system which emits P_i photons in a short pulse at time $t = 0$. Propagating through the atmosphere, a certain amount of them is scattered and absorbed by molecules, and by aerosol and cloud particles. At time t corresponding to a range $r = ct/2$ a small number of photons

$$(1) \qquad \Delta P(r) = \Delta P^{(1)}(r) + \Delta P^{(m)}(r)$$

is received by the lidar system. The component $\Delta P^{(1)}(r)$ is the number of singly scattered photons in a range interval $\Delta r = c\Delta t/2$, whereas the other component $\Delta P^{(m)}(r)$ is the number of multiply scattered photons

With the definition of the multiple scattering factor

$$(2) \qquad Q_{ms}(r) = \frac{\Delta P^{(m)}(r)}{\Delta P^{(1)}(r)}$$

we get

$$(3) \qquad \Delta P(r) = \Delta P^{(1)}(r)(1 + Q_{ms})$$

The single scattering component is calculated from the classical single scattering lidar equation. Using the classical LIDAR-equation and introducing a system constant K

$$(4) \qquad K = \frac{r_0^2}{\eta P_i A}$$

where r_0 is a fixed minimum distance (overlap=1), P_i the number of emitted photons, η the overall efficiency an A the effective area of the receiving aperture one yields:

$$(5) \qquad \sigma_e(r) \cdot \Delta r = K \cdot (\sigma_e / \beta)(r) \cdot \frac{\Delta D(r)}{\tau_r^2 \cdot (1 + Q_{ms}(r))}$$

where the transmittance is:

$$(6) \quad \tau(r) = \exp(-\int_0^r \sigma_e(r')dr'$$

and the extinction coefficient σ_e is assumed to be equal to the scattering coefficient (no absorption).

Introducing now the following simple approximation for the phase function for small scattering angles (forward scattering)

$$(7) \qquad \beta'(\vartheta_p, r_p) \approx \beta_\lambda^{'}(0, r_p) \exp(-\frac{\vartheta_p}{\vartheta_w(\lambda, r_p)})$$

where $\beta_\lambda^{'}(0, r_p)$ is the value of the phase function for scattering angle 0° and ϑ_w is the scattering angle where the phase function has dropped down to 1/e. With this assumption an integration over the phasefunction and a following backscattering process can analytically be made. The approximated double scattering contribution for each gate interval at distance r_i can be calculated by:

$$(8)\, Q_{ms}^{(2)}(r_i) \approx \Delta r \sigma_e(r_i) + \Delta r \sum_{j=1}^{i-1} \sigma_e(r_j) \left[1 - (1 + \frac{i-1/2}{i-j} \frac{\alpha}{\vartheta_w(\lambda, r_j)}) \exp(-\frac{i-1/2}{i-j} \frac{\alpha}{\vartheta_w(\lambda, r_j)}) \right]$$

To test this approach a model atmosphere with different cirrus layers has been used. From these data Lidar profiles were constructed taking into account any order of multiple scattering. These Lidar profiles were inverted using the approximation and Monte-Carlo simulations. The phase functions for cirrus clouds were taken from Hess et al and Strauss.

The comparison shows good agreement as far as the optical depth of the cirrus cloud is below 1. Also for the Deirmendjan C1 cloud with moderate optical depths this approach gives better results than the single scattering inversion

It should be emphasised that there is a far field effect after having penetrated a cirrus cloud which has an effect on measurements taking place beyond the cloud, which is slowly decreasing with increasing distance from the cloud. This is of particular interest for sounding of Polar Stratospheric Clouds, stratospheric ozone measurements and stratospheric temperature soundings based on measuring the Rayleigh scattering coefficient. Even sounding of the sodium layer may be effected. Common to many of these Lidar measurements is the technique to prevent an overload of the detector chain by the narrow signal up to an altitude of 10 to 15 km by use of electro-optical or mechanical shutters. Therefore in these applications in general there is lack of information about thin or moderate cirrus clouds which were passed at altitudes, where the signal was blocked off.

For demonstration purposes this inversion scheme was applied on Lidar profiles simultaneously measured by the NASA-Shuttle Lidar LITE and the airborne DLR Lidar ALEX. Also these results are in good agreement.

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The influence of multiple scattering from ice clouds on lidar returns and the application of a double scattering scheme to retrieve optical characteristics.

Gerhard H. Ruppersberg, Martin Kerscher *
Masoud Noormohammadian**, Ulrich G. Oppel**,
Wolfgang Renger

Institut fuer Physik der Atmosphaere
Deutsche Forschungsanstalt fuer Luft- und Raumfahrt (DLR)
82230 Oberpfaffenhofen

*Sektion Physik
Ludwig--Maximilians-Universitaet Muenchen
Theresienstrasse 37
80333 Muenchen

** Mathematisches Institut
Ludwig-Maximilians-Universitaet Muenchen
Theresienstrasse 39
80333 Muenchen

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Definition of the multiple scattering factor

$$Q_{ms}(r) = \frac{\Delta P^{(m)}(r)}{\Delta P^{(1)}(r)}$$ for a given range intend

$$\Delta P(r) = \Delta P^{(1)}(r)\,(1 + Q_{ms}(r))$$

LIDAR EQ.

$$\Delta P(r) = P_i\, \Delta r\, A \frac{\beta(r)\,\tau^2(r)}{r^2}\,(1 + Q_{ms}(r))$$

1. STEP

SIMPLE ATMOSPHERE CONTAINING
1 CLOUD LAYER 500 m thick (6.6 km – 7.1 km)
with varying opt. depth and phase function

2. STEP
Monte Carlo Simulation of a LIDAR Profile

3. STEP
Calculation of the multiple scattering factor Q_{ms}, assuming different phase functions by M.C. simulation and by the simple Approximation.

4. Inversion to extinction profile and optical depth and comparison

BASIC IDEAS (LIMITATIONS)

1. Phase function with an extremely strong forward peak (Cirrus clouds).

2. Approximation of the phase function by an exponential function

3. Flat response of the backscatter coeff. (phase function at $\vartheta = 180°$ for some mvad)

4. Analytical integration with respect to the scattering angle

5. Limitation to double scattering

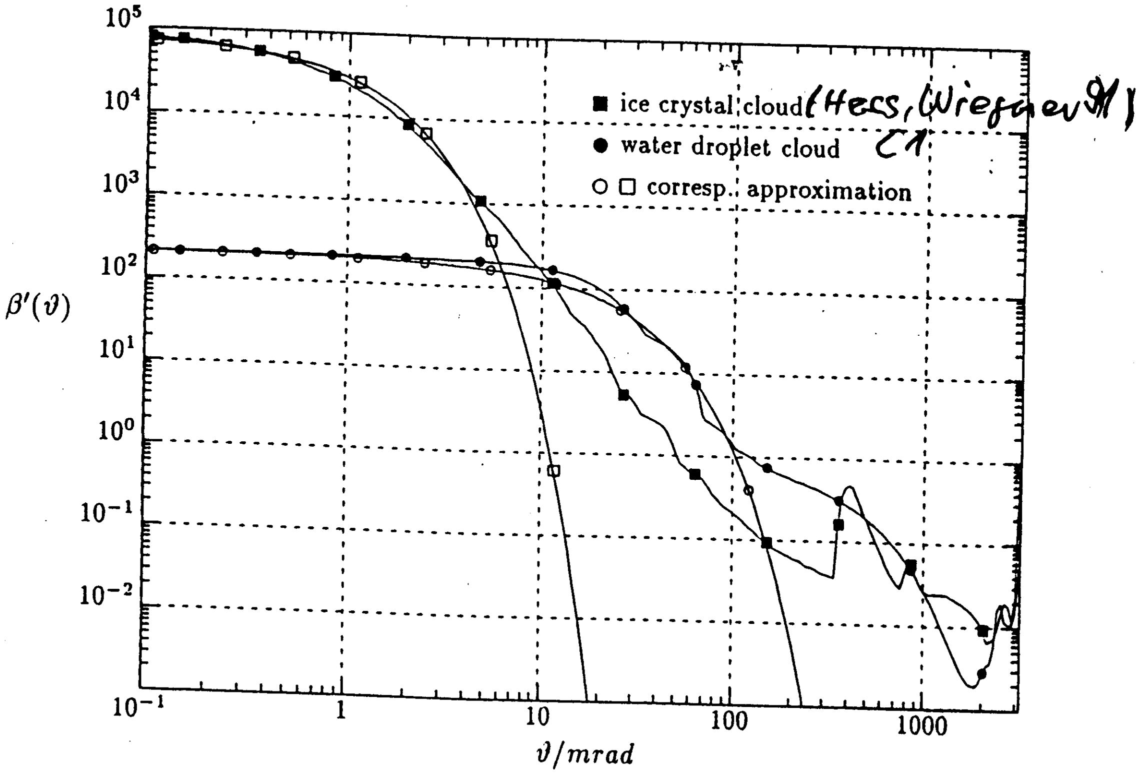

Figure 1: Phase functions for the clouds at the height of 6.6 to 7.1 km with temperature in the range $-(25\cdots30)^oC$. Filled squares: ice crystal cloud according to No. 1.1 of Table 1. Filled circles: water droplet cloud according to No. 3.1 of Table 2. Open symbols: approximations according to Equations (19) and (20).

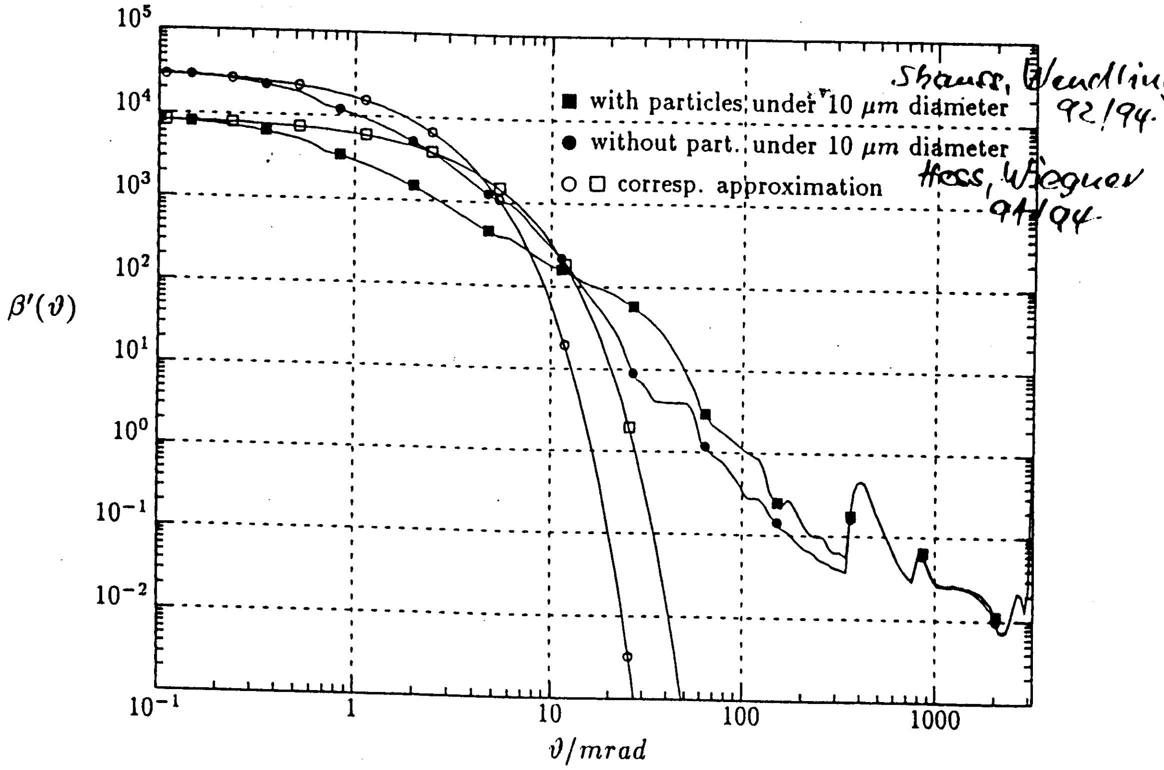

Figure 2: Phase functions for the clouds at the height of 10.0 to 10.5 km with temperature in the range $-(55 \cdots 60)°C$. Filled circles: ice crystal cloud without particles under 10 μm diameter according to No. 1.8 of Table 1. Filled squares: ice crystal cloud with particles under 10 μm diameter according to No. 2.2 of Table 2. Open symbols: approximations according to Equations (19) and (20).

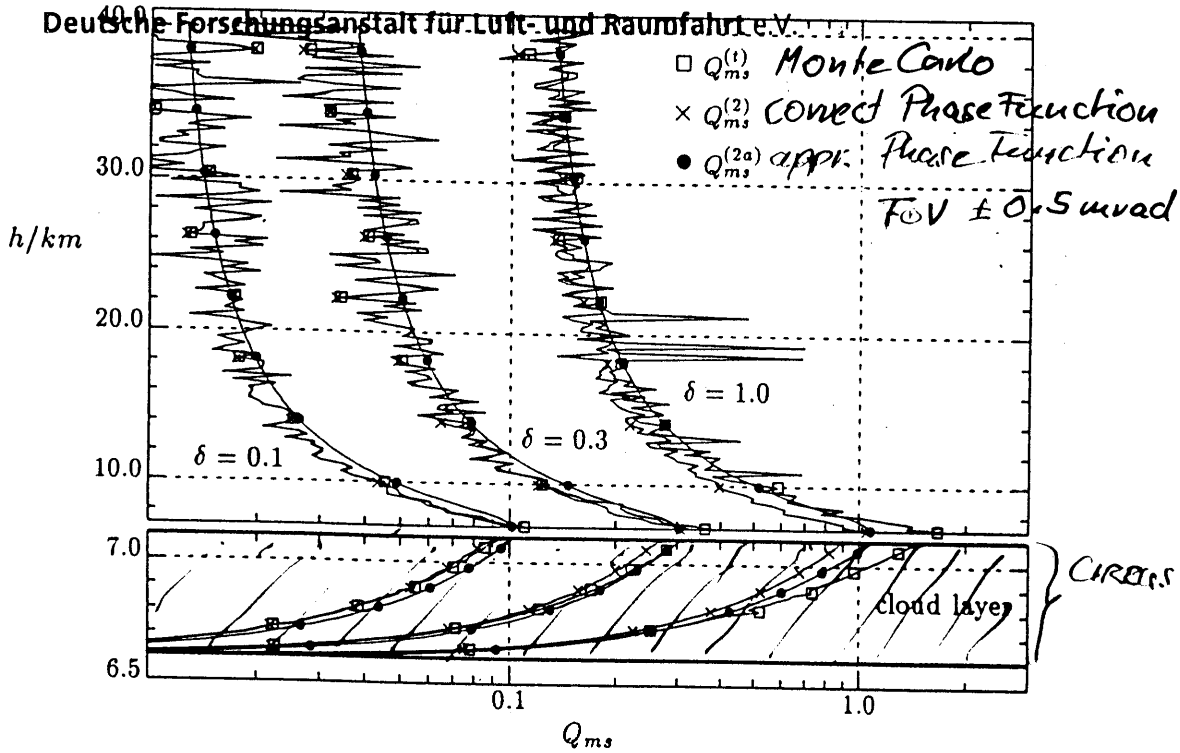

Figure 4: Q_{ms}–approximations as a function of the height h for ice crystal clouds at the height of 7 km with optical depths 0.1, 0.3 and 1.0 (left, middle and right group of curves) using lidar systems with a receiver FOV angle $\alpha = \pm 0.5$ $mrad$. Open Square: total multiple scattering factor $Q_{ms}^{(t)}(h)$ calculated with the Monte Carlo program. Crosses: double scattering factor $Q_{ms}^{(2)}(h)$ with respect to Equation (11). Filled circles: approximated double scattering factor $Q_{ms}^{(2a)}(h)$ with respect to Equation (23).

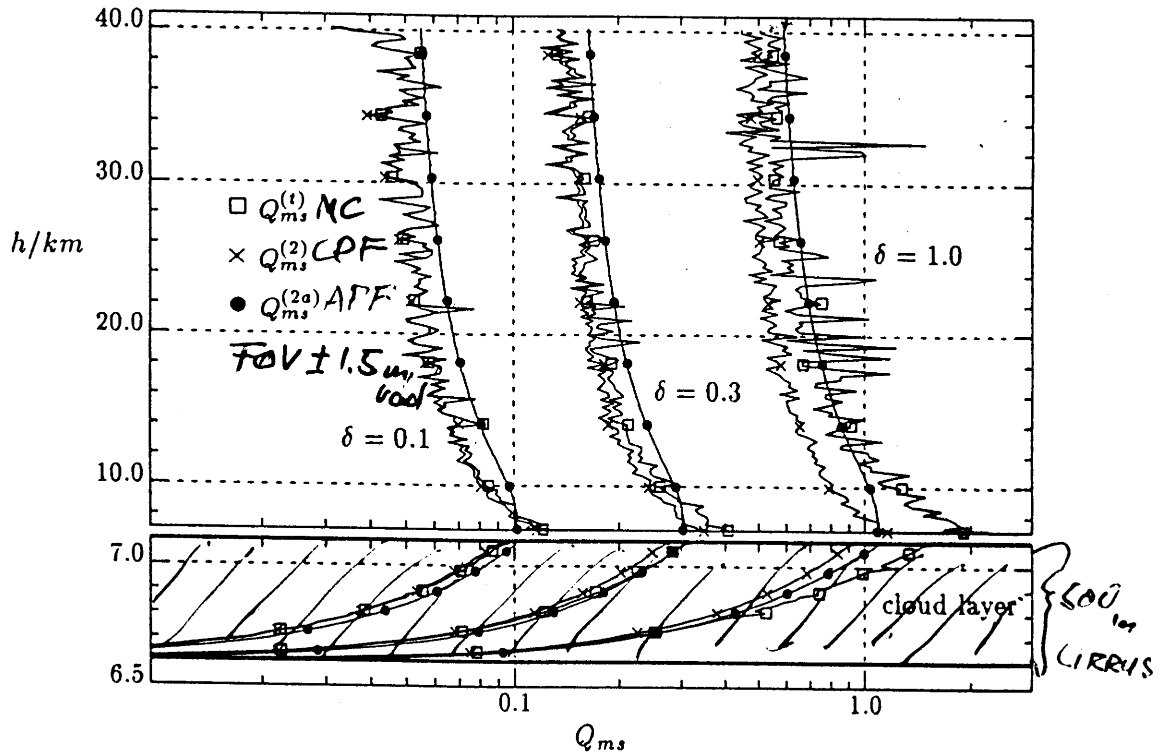

Figure 5: Same as Figure 4, showing the Q_{ms}-approximations as a function of the height h for ice crystal clouds at the height of 7 km using lidar systems with a receiver FOV angle $\alpha = \pm 1.5$ $mrad$.

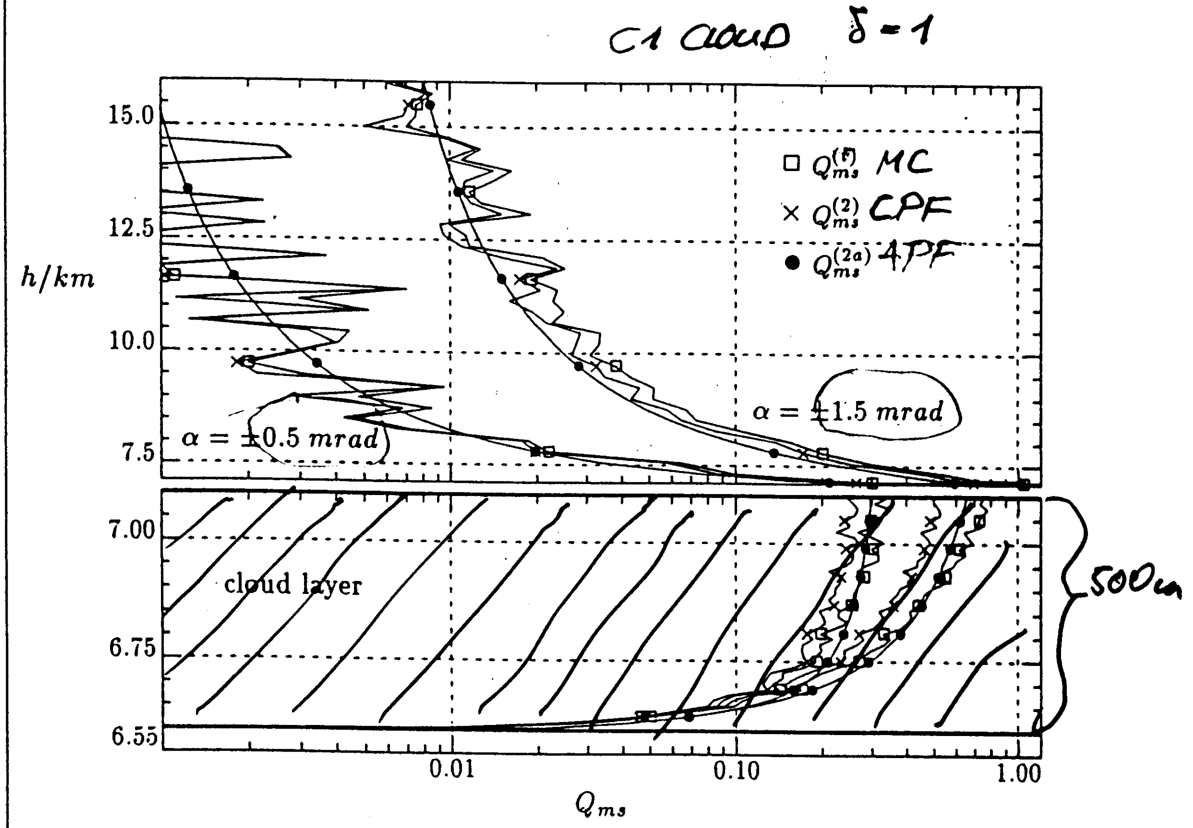

Figure 6: Same as Figure 4, showing the Q_{ms}-approximations as a function of the height h for water droplet clouds at the height of 7 km with the optical depth 1.0 using lidar systems with a receiver FOV angle $\alpha = \pm 0.5\ mrad$ (left group of curves) and $\alpha = \pm 1.5\ mrad$ (right group of curves).

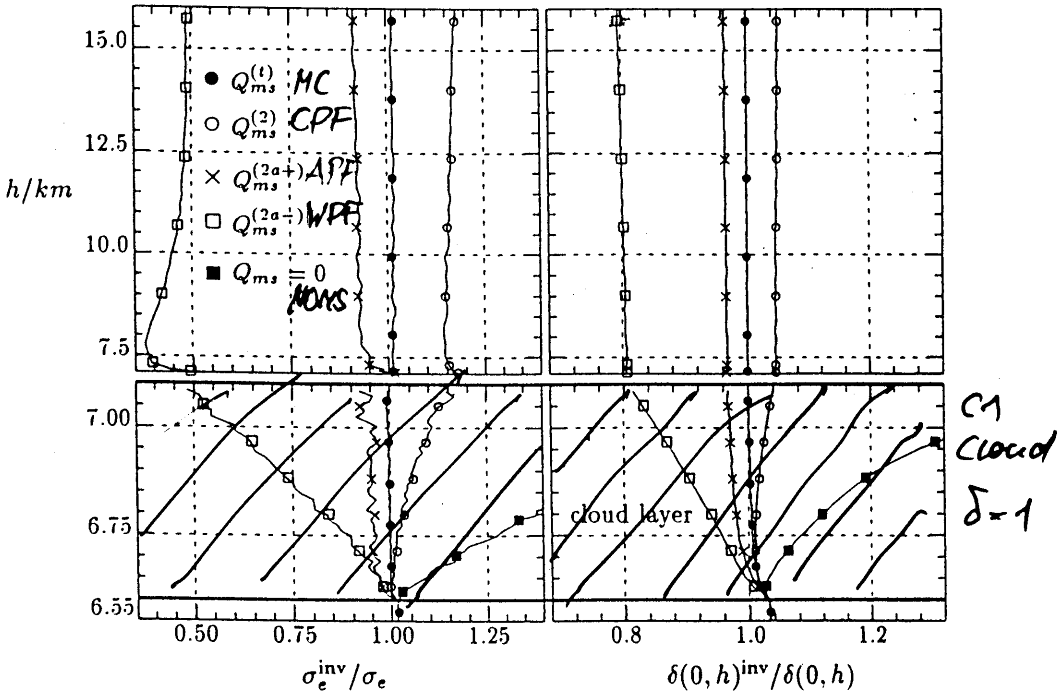

Figure 9: Same as Figure 7 with a water droplet cloud at the height of 7 *km* but an optical depth 1.0 was used.

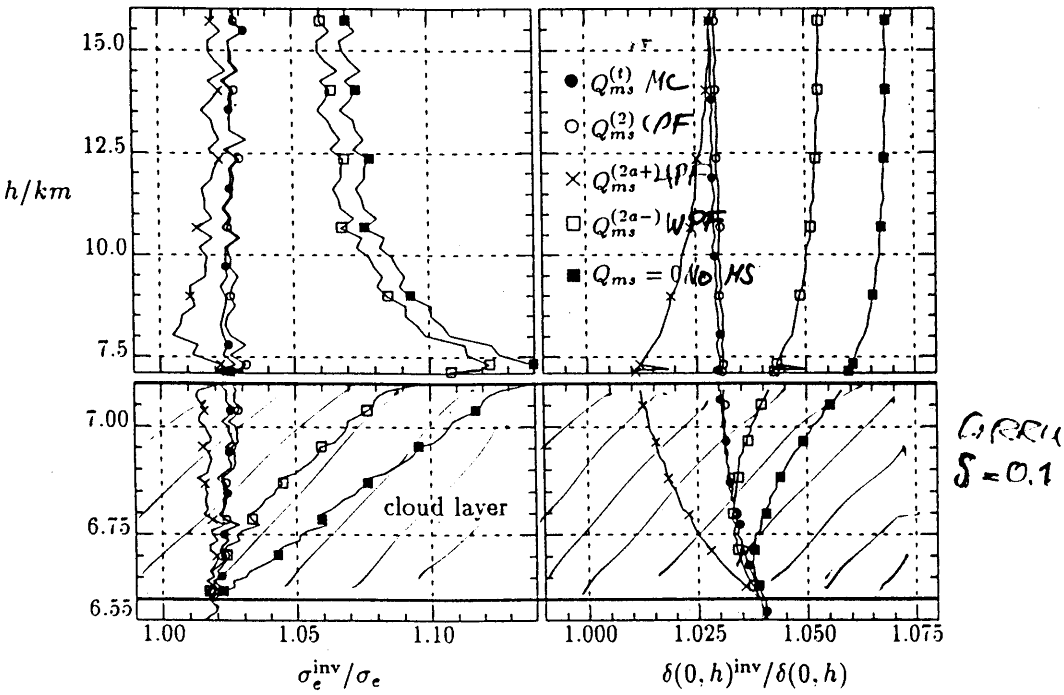

Figure 10: Same as Figure 7, except that the inverted signals were simulated using a ice crystal cloud with phase function No. 1.1 of Table 1 at the height of 7 *km* with an optical depth 0.1.

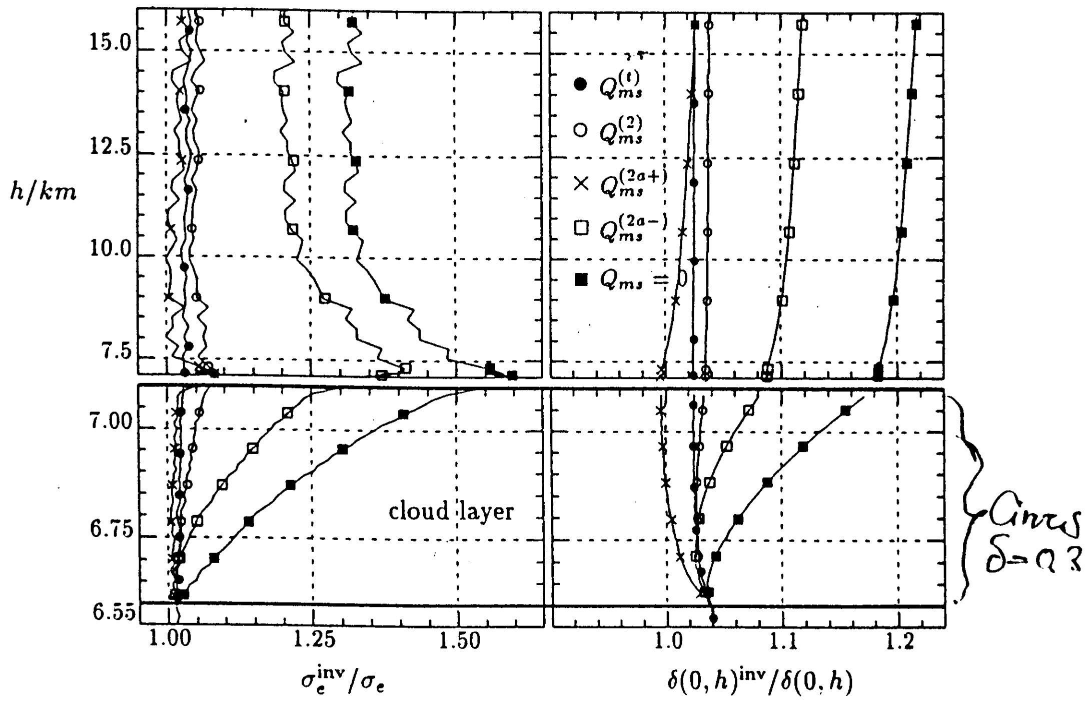

Figure 11: Same as Figure 7, except that the inverted signals were simulated using a ice crystal cloud with phase function No. 1.1 of Table 1 at the height of 7 km with an optical depth 0.3.

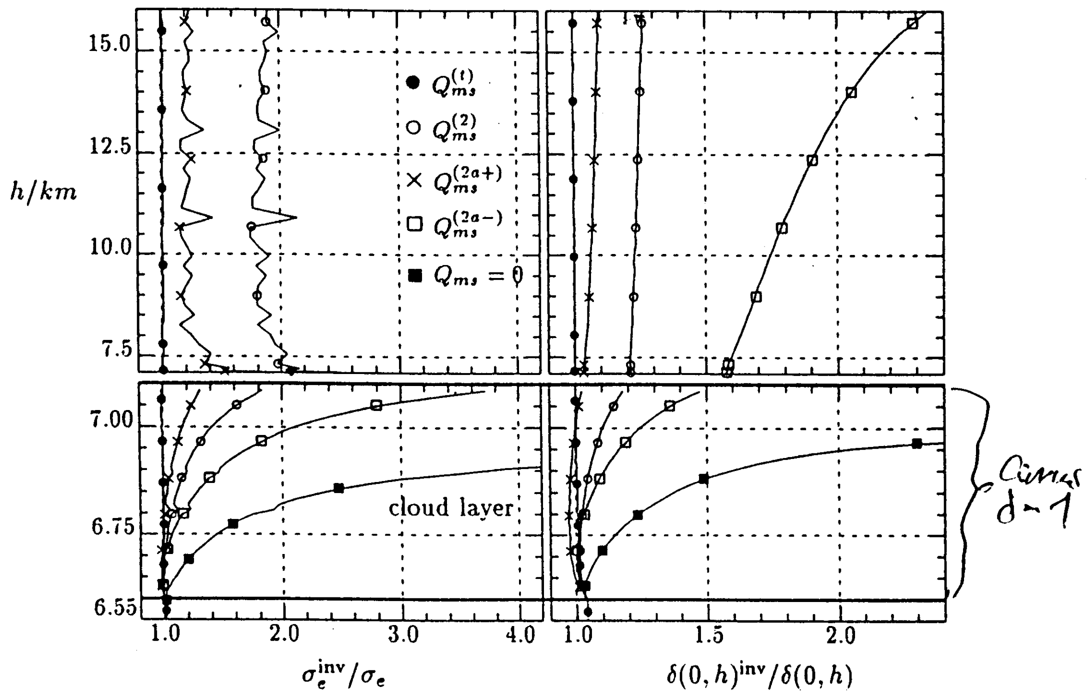

Figure 12: Same as Figure 7, except that the inverted signals were simulated using a ice crystal cloud with phase function No. 1.1 of Table 1 at the height of 7 km with an optical depth 1.0.