Multiple Scattering Effects in Space LIDAR

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1. *Introduction*

There are two ways that photons in a laser pulse can return to the lidar receiver. Photons can be backscattered (at 180°) by a cloud particle to return directly to the receiver without further scatter. Photons can also be scattered by the cloud particle into a direction different to the back direction and then return to the receiver after a number of further scatters by other cloud particles. The first scatter can be either in the back or forward hemisphere, from which photons can be scattered into the back 180° direction by further scattering events.

The multiple scattering of photons by cloud particles in the lidar receiver beam has been shown to enhance the received signal at the lidar detector by a significant amount (e.g., Platt, 1981, Kunkel and Weinman, 1976). This has two effects. First, the penetration depth of lidar pulses into clouds is improved. In effect, the observed extinction in the cloud is reduced. Second, the photon path length for multiple scattering in a cloud of high optical depth is longer than the single-scattered path.

2. *Characteristics of multiple scattering in clouds*

Platt (1981), following the early work of Kinkel and Weinman (1976), made extensive calculations on the characteristics of multiple scattering in clouds to a groundbased lidar. Platt showed that for a given wavelength, multiple scattering increased with cloud base range, with cloud optical depth, with range into the cloud, with receiver aperture and with cloud particle size. Platt characterised multiple scattering by a factor η which determined the fractional decrease in effective cloud extinction coefficient. Typically multiple scattering was found to decrease extinction by more than a factor of 2. Calculations of pulse stretching in groundbased lidar showed that the effects were small, and typically from 1 to 10 metres in magnitude.

3. *Multiple scattering effects in space lidar*

The chief difference between space lidar and groundbased lidar is the range to the target cloud. Multiple scattering in the lidar beam increases rapidly with range, thus decreasing η. For a given receiver aperture and cloud optical depth, the multiple scattering factor from space is reduced by at least a factor of 2 over groundbased lidar. Thus, values of η are typically in the region of 0.2 or less for both cirrus and water clouds. However, it is found that pulse stretching in cirrus clouds is still small, whereas in dense water clouds it becomes very large. This is because at space distances, the cloud area defined by the receiver aperture has a radius of about 200 metres, for an aperture of 1 milliradian.

The mean free path (MFP) of a photon travelling in a typical water cloud of extinction coefficient 20 km^{-1} is only 50 m, so that a photon can be scattered many times within the cloud and still escape back to the receiver. In contrast, the MFP in a typical cirrus cloud is ~ 1 to 10 km, so that pulse stretching is still small, even at space lidar ranges.

Monte Carlo calculations done by Platt and Winker (1994, 1995), Winker (1995), Winker and Poole (1995) and Platt (unpublished) illustrate the patterns of multiple scattering from a space lidar. Figure 1 shows the normalised returns from a homogeneous water cloud (Deirmendjian, C1) at a range of 293 km. The single scatter returns show the typical experimental fall-off for an extinction coefficient of 17.25 km^{-1}. The full multiple scattered returns are seen to be orders of magnitude greater, in fact they completely dominate the backscatter. The curves, however, are not exponential, so that η is variable. But the multiple scatter does still increase significantly with receiver aperture. Calculated values of η are shown in Table 1 for two values of receiver aperture. It is interesting that η here decreases with pulse penetration. The values of η for the surface lidar are seen to approach unity because the range is only 2 km.

Figure 2 shows the single and multiple scattered returns for a model cirrus cloud and for a satellite distance of 400 km. The value of η is seen to be ~ 0.2, which is not far different from the values for the boundary layer cloud shown in Table 1.

Figure 3 shows a LITE return for a single profile from a boundary layer cloud. The return from the surface indicates the fundamental resolution of the laser pulse. Figure 4 shows the simulation of returns from a similar boundary layer cloud, with different levels of extinction. The figure shows that for a highly attenuating cloud, the cloud base level is 'washed out', because insufficient single-scattered photons reach the receiver from near cloud base.

4. The LITE multiple scattering experiment

The multiple scattering return is generally sensitive to the receiver detector aperture. A facility was built into the LITE experiment that allowed for several apertures of different receiving angle that could be rotated in turn into the receiver focal plane. These were 1.1 mrad, 3.5 mrad and a centre block that would block off the single scattering but pass the multiple scattered radiation (e.g., Allen and Platt, 1977). Figure 5 shows the results from such an experiment. The curves are a composite of returns from a number of profiles in one dwell time from each aperture as the shuttle crossed an extensive deck of stratocumulus (Platt and Winker, 1995).

5. Pointers for a Space Lidar

(i). Even for quite a narrow receiver aperture (eg., 1.1 mrad), there is substantial multiple scattering in dense boundary layer clouds and other water clouds.

(ii). Multiple scattering has the advantage of improving the transmittance through clouds. At the range of a space lidar extinction is reduced by about a factor of 5.

(iii). Pulse stretching is minimal through cirrus ice clouds.

(iv). Pulse stretching in water clouds varies with the optical depth and this could be utilised to assess the optical depths of highly attenuating water clouds.

(vi). It would be advantageous in a space lidar to have two receiver channels containing different apertures.

6. References

Allen, R. J., and C. M. R. Platt, 1977: Lidar for multiple scattering and depolarisation observations. *Appl. Opt.*, **16,** 3193-3199.

Kunkel, K. E., and J. A. Weinman, 1976: Monte Carlo analysis of multiply scattered lidar returns. *J. Atmos. Sci.*, **33,** 1772-1781.

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Platt, C. M. R., and D. M. Winker, 1994: Vertical distribution, multiple scattering and optical depths of clouds from LITE observations. *SPIE, Lidar Techniques for Remote Sensing,* **2310**, 106-115.

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Winker, D. M., and L. R. Poole, 1995: Monte-Carlo calculations of cloud returns for ground-based and space-based LIDARS. *Appl. Phys. B,* **60,** 355-362.

Table 1 Values of multiple scattering factor $\eta(z_t - z)$ for the cloud of Figure 1 for LITE compared with groundbased lidar at a range of 2 km.

Depth below cloud top or above base	**LITE: 3.5 mrad**	**LITE: 1.1 mrad**	**Groundbased lidar: 2.0 mrad**
(m)	$\eta(z_t - z)$	$\eta(z_t - z)$	$\eta(z - z_b)$
120	0.34	0.36	0.86
240	0.23	0.26	0.89
360	0.19	0.25	0.94
480	0.13	0.23	0.96
600	0.11	0.22	....

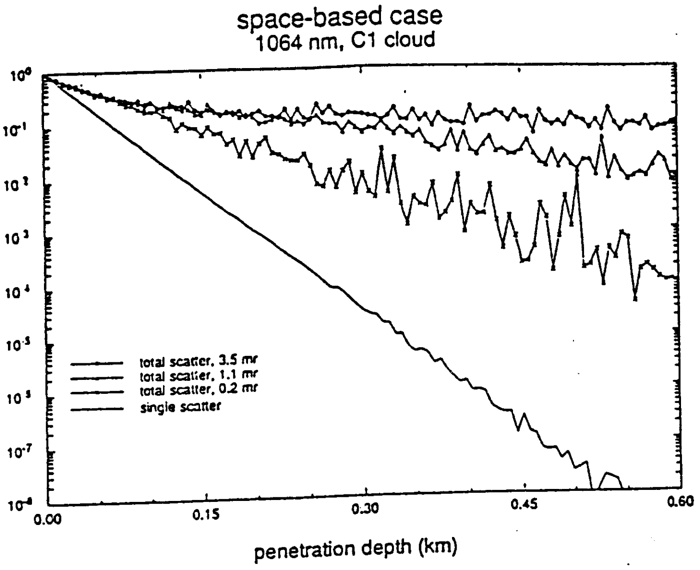


Figure 1.Single and total lidar backscatter returns from a boundary layer cloud.
Range = 293 km.
(Platt and Winker, 1995, or PW).

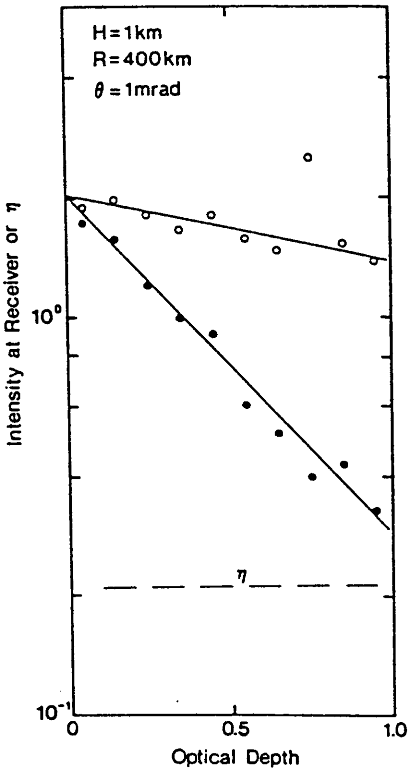


Figure 2. Single and total lidar backscatter returns from a cirrus cloud. Range = 400 km.
(Platt, unpublished).

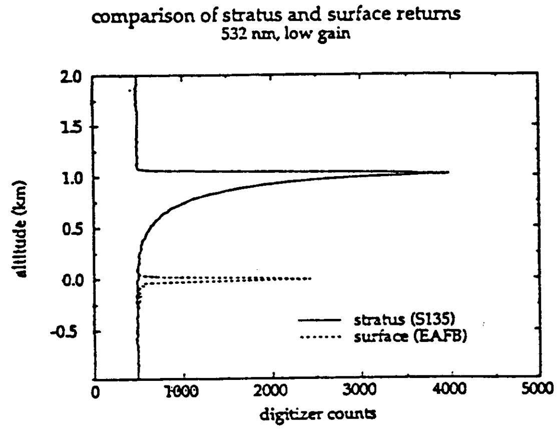


Figure 3. LITE returns from stratus and from the surface. (From PW).

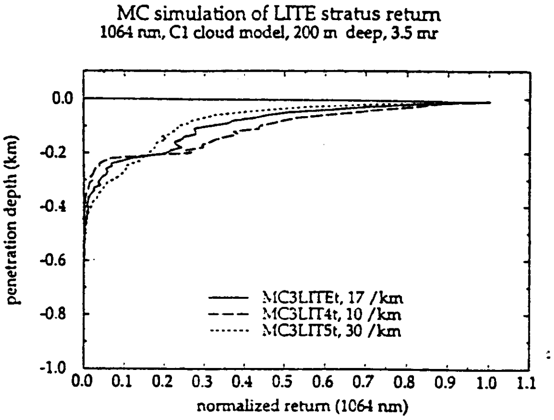


Figure 4. Simulated LITE returns from stratus, depth 200m, for three extinction coefficients. (From PW).

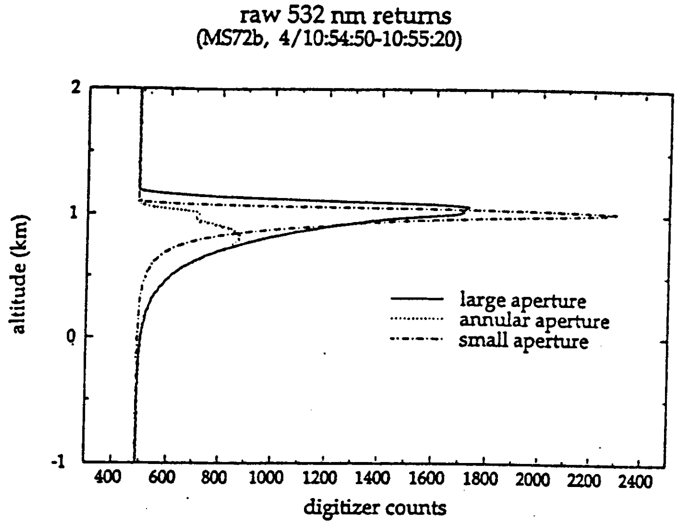


Figure 5. LITE returns at the receiver detector for three different apertures. Large: 3.5 mrad. Small: 1.1 mrad. Blocking: 3.5-1.1 mrad. (Form PW).

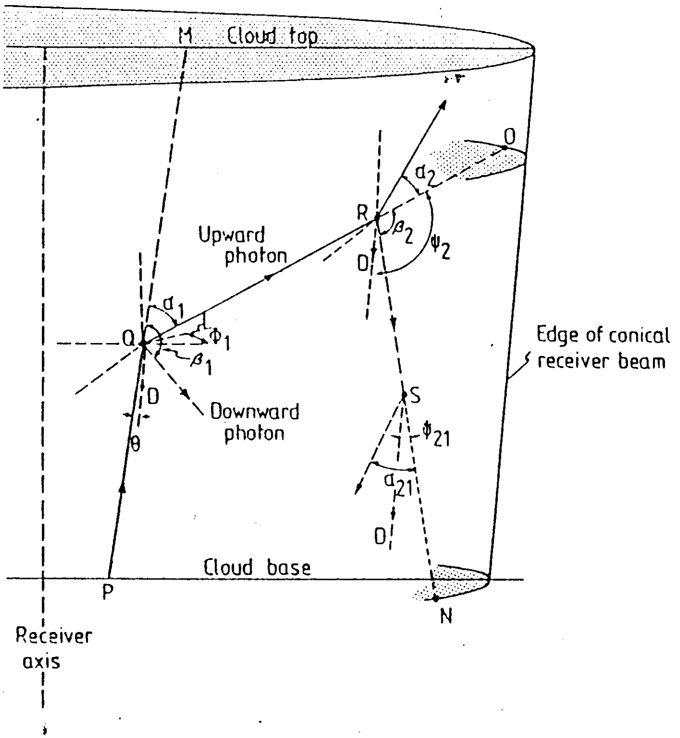


FIG. 3. Schematic of photon scattering from cloud particles within the lidar receiver beam.

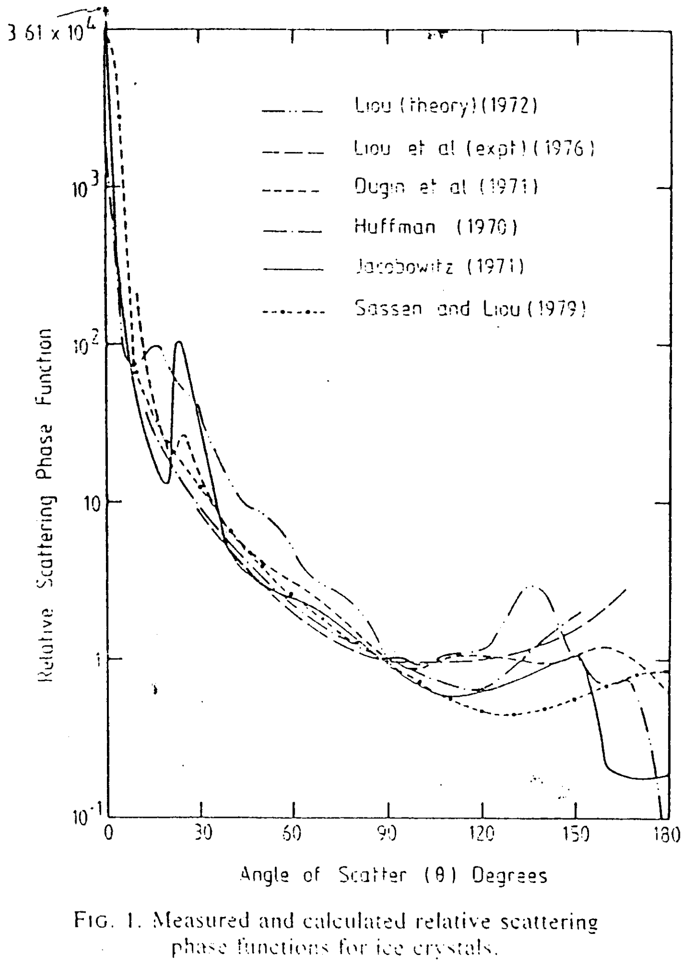
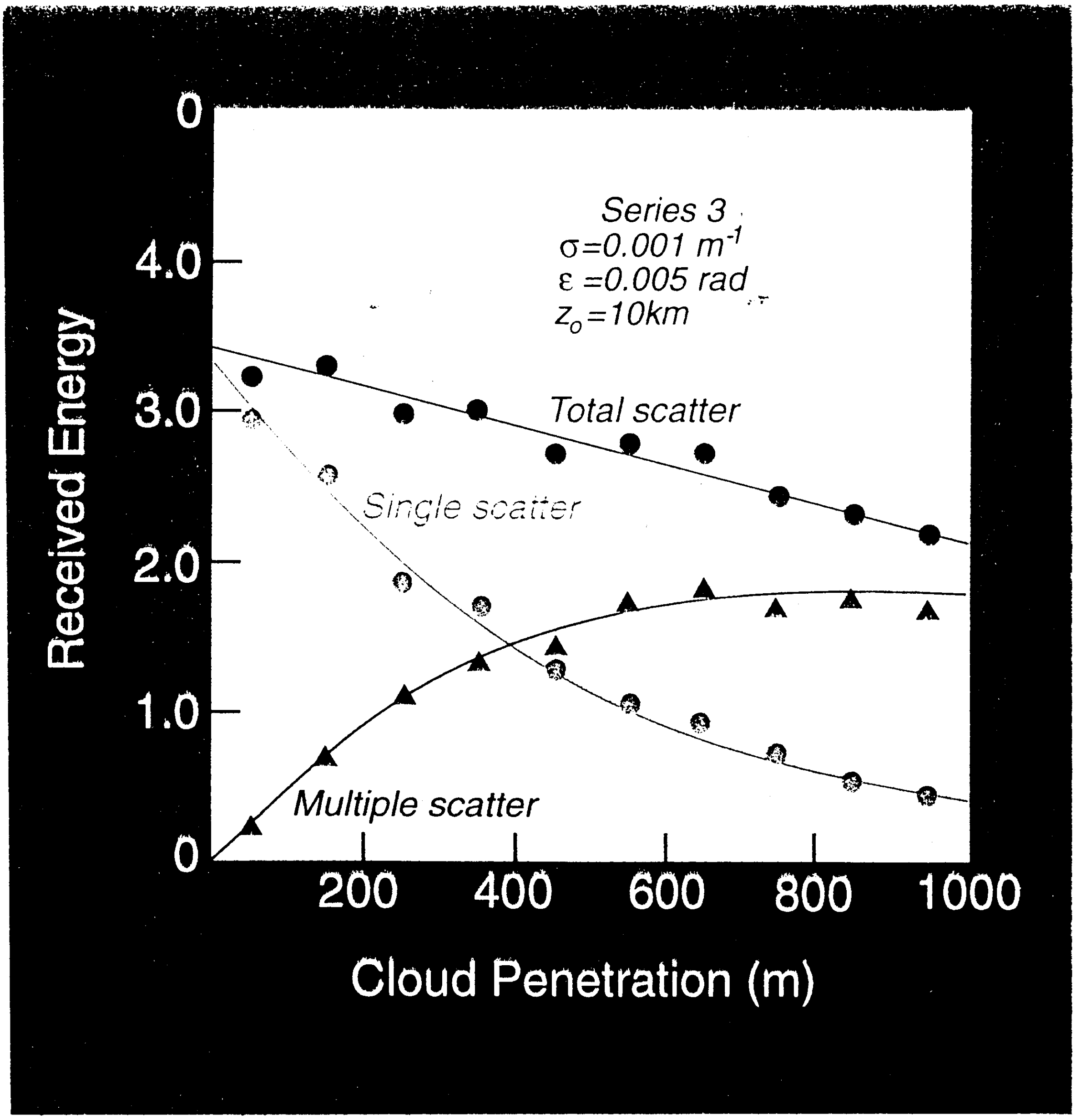


FIG. 1. Measured and calculated relative scattering phase functions for ice crystals.


Series 3
σ=0.001 m-1
ε =0.005 rad
z0=10km
Total scatter
Single scatter
Multiple scatter
Received Energy
0
1.0
2.0
3.0
4.0
0
200
400
600
800
1000
Cloud Penetration (m)

MULTIPLE SCATTERING FACTOR η.

Multiple scattering in clouds causes an increase in effective transmittance τ:

$$\tau = \exp-(\eta\sigma)$$

As $\eta<1$, then transmittance τ is increased by multiple scattering. The factor η is generally variable with cloud penetration. Thus, an effective value is retrieved.
For space lidar, there is evidence that η is perhaps a bit less variable.

η ***decreases with:***

- Range
- Optical depth
- Receiver aperture size.

MULTIPLE SCATTERING LEADS TO UNCERTAINTIES IN RETRIEVAL OF CLOUD OPTICAL DEPTHS.

DETERMINATION OF MULTIPLE SCATTERING COMPONENT.

Multiple scattering can be studied using MULTIPLE APERTURES, as used on lite.

Use of multiple apertures would help to infer the optical depths of clouds more accurately.

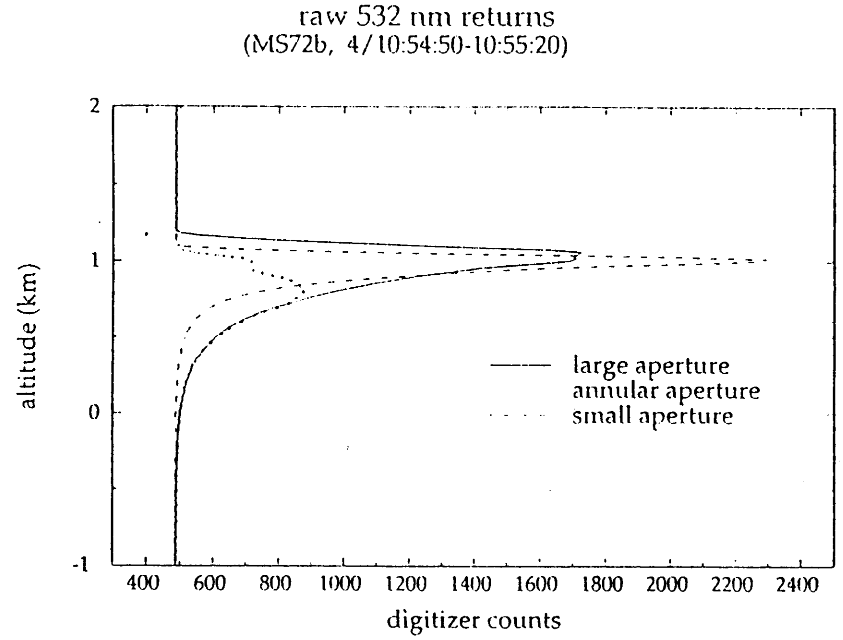


Fig. 8. LITE returns averaged over the dwell times in one cycle of a multiple scattering experiment. Large, small and annular apertures refer to a 3.5 mrad, 1.1 mrad and 3.5-1.1 mrad apertures respectively. Orbit 72.

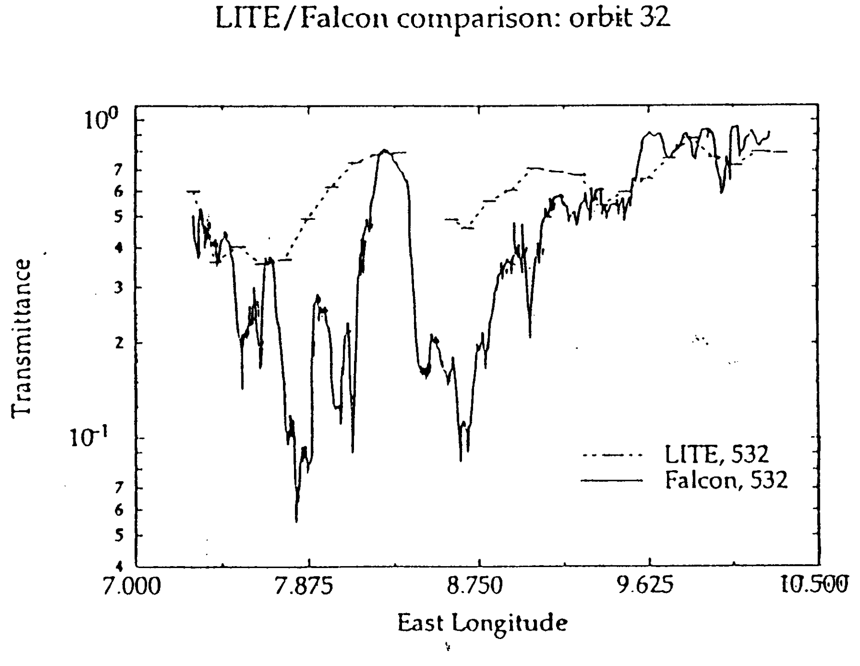


Fig. 9. Transmittances of a cirrus cloud at 532 nm. observed by LITE and by the DLR Falcon aircraft flying along the nadir of the LITE orbit, and at approximately the same time., showing differences attributed to multiple scattering effects.

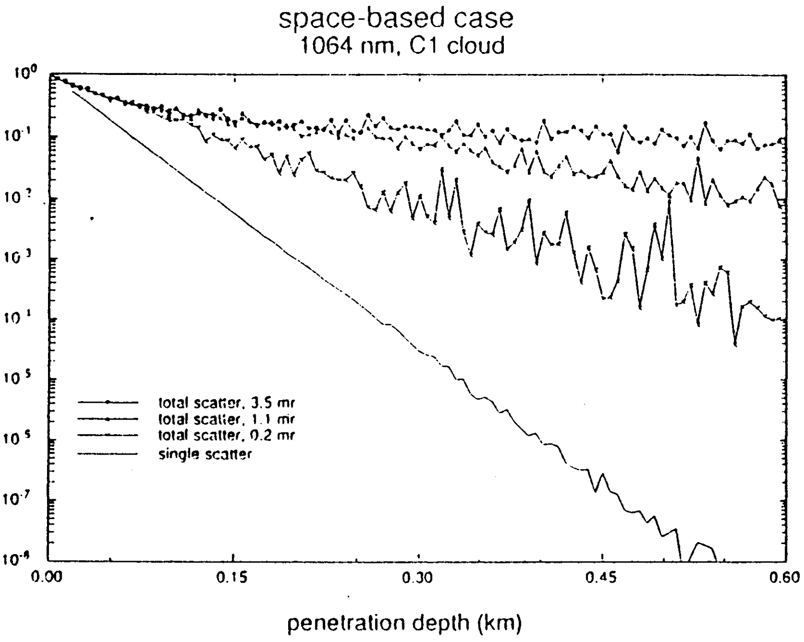


Fig. 1. Monte-Carlo simulation showing normalized returns from a homogeneous C1 cloud at a range of 293 km[5]. Shown are first-order scatter and summation of the first 30 orders for 0.2 mrad, 1.1 mrad and 3.5 mrad receiver fields of view.

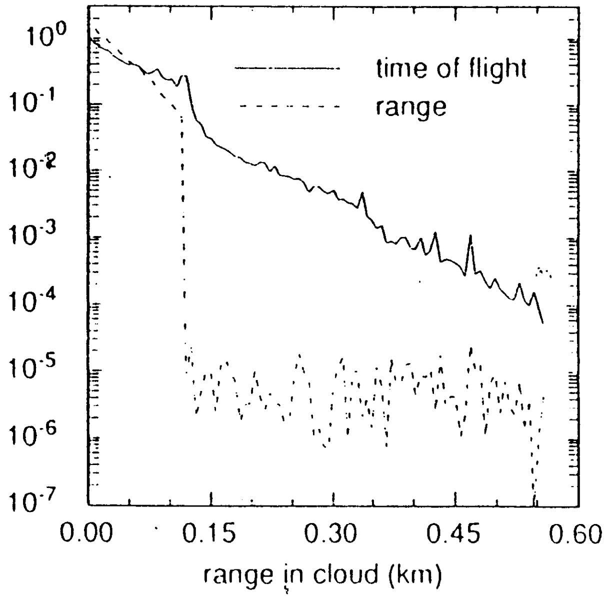


Fig. 2. Pulse-stretching effect of a 120 m thick C1model cloud at a range of 293 km with a receiver field of view of 3.5mrad[5].

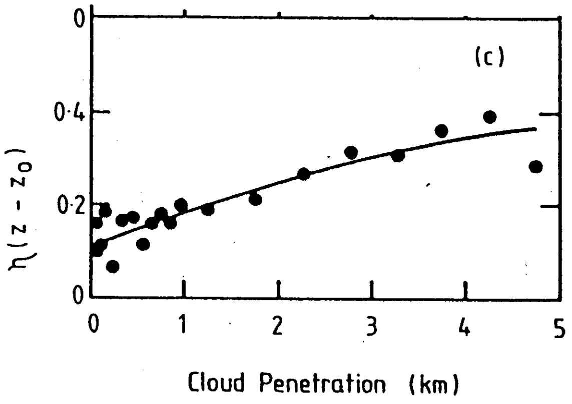
Table 1 Values of multiple scattering factor $\eta(z_t - z)$ for the cloud of Figure 1 for LITE compared with groundbased lidar at a range of 2 km.

Depth below cloud top or above base	LITE: 3.5 mrad	LITE: 1.1 mrad	Groundbased lidar: 2.0 mrad
(m)	$\eta(z_t - z)$	$\eta(z_t - z)$	$\eta(z - z_b)$
120	0.34	0.36	0.86
240	0.23	0.26	0.89
360	0.19	0.25	0.94
480	0.13	0.23	0.96
600	0.11	0.22	....

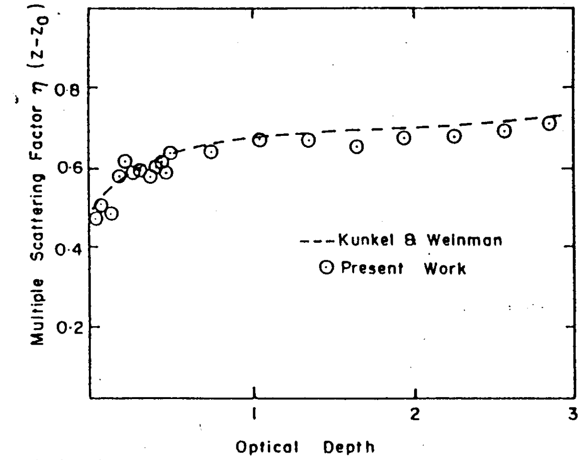
UNSOLVED PROBLEM

MULTIPLE SCATTERING

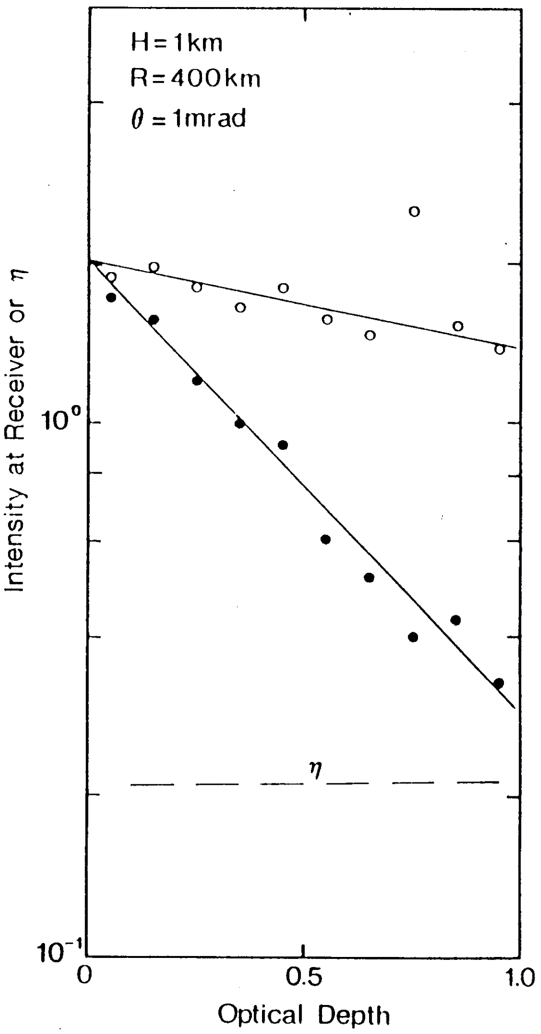
The multiple scattering factor η is very variable, both between clouds at different altitudes and phase functions and between clouds of different optical depth. Furthermore $\eta(z)$ is dependent on cloud penetration and optical depth:

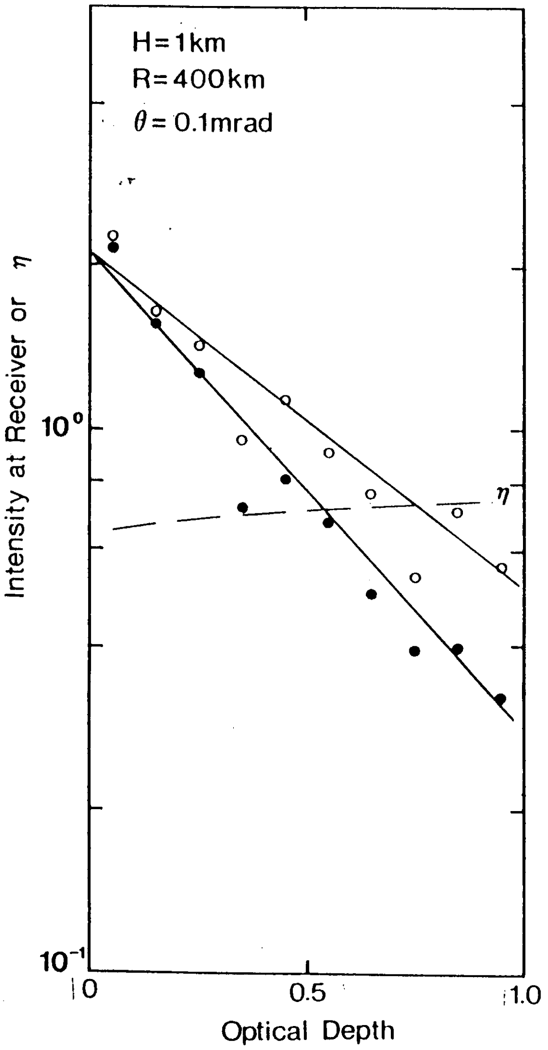


Example of η behaviour. Cirrus cloud phase function, receiver aperture 5 mrad, z_0 = 10 km, $\sigma = 0.001\mathrm{m}^{-1}$.



Example of η behaviour. Stratocumulus cloud phase function. Receiver aperture 5 mrad, z_0 = 1 km, $\sigma = 0.01\ \mathrm{m}^{-1}$.


H=1km
R=400km
θ=1mrad
Intensity at Receiver or η
10⁰
10⁻¹
η
0
0.5
1.0
Optical Depth


H=1km
R=400km
θ=0.1mrad
Intensity at Receiver or η
10⁰
10⁻¹
η
0
0.5
1.0
Optical Depth

(1b)

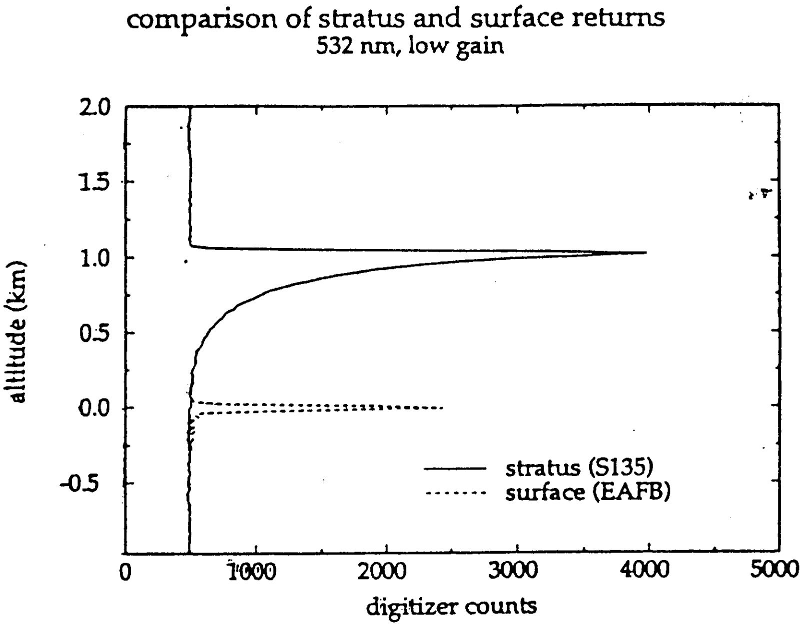


Fig. 5. LITE single profiles. Comparison of a single profile return from a stratus cloud in orbit 135 and a superimposed ground surface return from near Edwards Airforce Base on an ealier orbit.

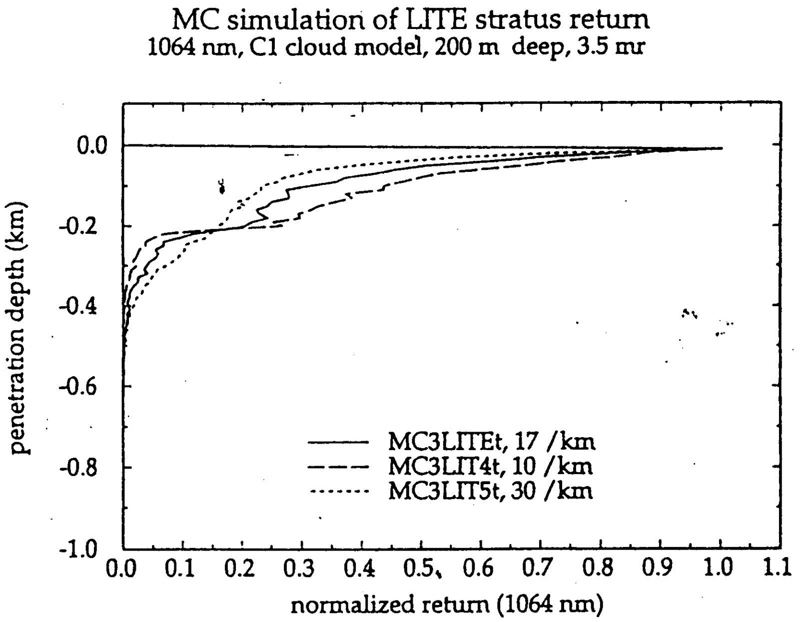


Fig. 6. Monte-Carlo simulated returns from a model homogeneous stratus cloud 200 m deep, showing the effects of increased pulse-stretching as the extinction coefficient of the cloud is increased. The field of view was 3.5 mrad.