On the Multiple Scattering Contribution in Backscattered LIDAR Signals for Spaceborne Observations

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ON THE MULTIPLE SCATTERING CONTRIBUTION IN BACKSCATTERED LIDAR SIGNALS FOR SPACEBORNE OBSERVATIONS

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We discuss here some of the problems linked to multiple scattering in the retrieval of the optical thickness of cirrus clouds from spaceborne lidar measurements.

Light scattering is known to be strongly affected by multiple order scattering in dense media. The most important parameters to set a limit between single and multiple scattering is defined by the scattering free path $L = 1/\alpha_S$, where α_S is the scattering coefficient, and the transport mean free path (mfp) L_*. L_* is given by the randomization of the free path L in a diffusive medium as

$$L_* = \frac{L}{(1-g)} \tag{1}$$

where g is the asymmetry factor defined as the first moment of the phase function $P(\theta)$

$$g = \frac{1}{2}\int_{-1}^{1} P(\cos\theta)\cos\theta d(\cos\theta) \tag{2}$$

A medium is defined as diffusive when its geometrical thickness Δz is much larger than the mfp. We will first assume that the backscattering does not introduce any additional angle dependence, so that $P(\theta = \pi)$ is flat over the scattered angles. Usual lidar measurements thus correspond to a two way propagation, and we have $L_* << \Delta z/2$. Using Eq. (1) this corresponds to an optical thickness greater than $\tau_d = 1/2(1-g)$.

For the size distribution of water droplets in cumulus or stratus clouds, $g = 0.85$ gives $\tau_d = 3$. The lower limit defining the single to multiple scattering transition is set by L and corresponds to an optical thickness about 6 times smaller ($\tau_m = 0.5$).

Measurements in clouds of optical thicknesses smaller than 0.5 should thus not be perturbed by multiple scattering. Light scattering by large droplets and especially by crystals is however strongly enhanced in the forward direction, over an angle which corresponds to the diffraction. This is illustrated by the large decrease at small scattering angle in the phase function reported on Fig. 1 for randomly oriented column crystals (Hess and Wiegner, 1994). In this case an additional contribution to the lidar signal is due to the fraction of energy f_L in the forward peak

$$f_L(\theta) = \pi\int_{-\vartheta/2}^{\theta/2} P(\theta')\sin\theta' d\theta' \tag{3}$$

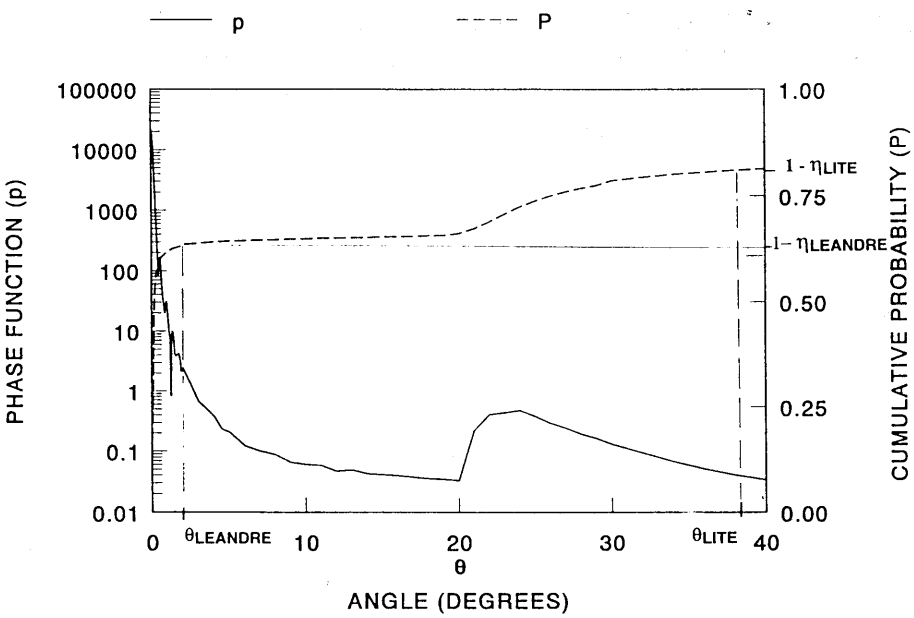

Figure 1 : Calculated forward phase function and cumulative scattering probability for randomly oriented column crystals taken from the COP library (Hess and Wiegner, 1994).

where θ is the analysis angle. This parameter will be used to estimate the perturbation due to forward scattering in the lidar signal at low optical thickness. A relevant parameter is thus defined by the ratio of the field of view angle θ_{fov} and the diffraction angle θ_d. The forward scattering will contribute significantly if it remains in the field of view, or if the field of view is at least larger than a minimal value given by the diffraction angle

$$\theta_{fov0} = \theta_d \frac{\Delta z}{Z} \approx \frac{\lambda \Delta z}{DZ} \tag{4}$$

where Z is the distance between the cloud, composed of particles with diameter D, and the lidar system, operating at a wavelength λ.

Applying Eq. (4) to measurements at λ=0.5 µm in a cloud composed of ice crystals of diameter D = 50 µm over a Δz = 1km thickness, gives a product $Z.\theta_{fov0}$ = 10 m.

This means that for a spaceborne system, for which Z is greater than 200 km, the field of view must be smaller than 0.05 mrd to avoid forward scattering perturbation. This is practically impossible for space lidars operating in the visible as the emitted energy must be high enough to obtain a high signal to noise ratio and as the beam divergence is limited by eye safety constraints. This could be only achieved by lidars operating in the infra-red as for example Doppler lidars.

The forward scattering contribution thus needs to be accounted for in the lidar signal analysis. Outside the cloud, the backscattering is due to molecules and the phase function can be assumed to be constant over the forward scattering angles. Assuming a spaceborne system such as the field of view is larger than the range corrected forward scattering angle ($\theta_{fov} > \theta_{fov0}$), this contribution can be shown to be equivalent to a reduction in optical thickness (Nicolas et al., 1997) by a factor η as proposed by Platt (1973). In a first approximation, η can thus be related to the integral of the scattering phase function f_L as

$$\eta(\theta) = 1\text{-}f_L(\theta) \tag{5}$$

As an example, the phase function and the cumulative probability f_L (given by Eq. (3) for a varying angle θ) are given on Fig. 1. Two plateau regions are clearly evidenced on the cumulative probability f_L which correspond to angles larger than the diffraction peak and than the halo at $\theta = 22°$ due to refraction in hexagonal crystals, respectively. Two angle values $\theta_{LEANDRE}$ (Z = 6 km) and θ_{LITE} (Z = 220 km) are defined on Fig 2, which correspond to the range corrected angles for the backscatter lidar observations using the airborne and spaceborne systems, LEANDRE 1 and LITE respectively. It is shown that the two fields of view for the airborne and spaceborne observations (about 3.5 mrd for both lidar systems) correspond to the two plateau regions and lead to significant differences in the forward scattered energy contribution f_L . We thus obtain two values of the optical thickness reduction factor as given by Eq. (5), which are $\eta_{LEANDRE}$ = 0.38 and η_{LITE} = 0.18, for airborne and spaceborne measurements respectively. It leads to apparent optical thickness values about twice smaller for LITE as compared to LEANDRE measurements. This ratio depends on the assumed crystal shape.

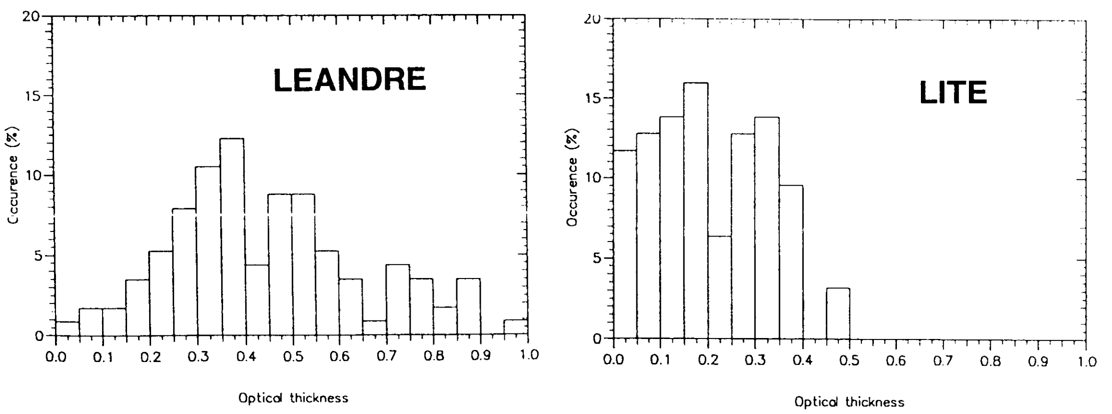

Figure 2 : Distribution of the apparent optical thicknesses as determined from the airborne backscatter lidar LEANDRE1 and LITE for the 1.5 km thick cirrus cloud observed at 9.5 km during orbit 33.

Airborne lidar measurements taken during the orbit 33 of the LITE mission, show that a factor of two is observed on the average apparent optical thickness retrieved from the signal analysis as plotted on Fig. 3 (Pelon et al., 1996), in good agreement with the estimate accounting for the forward scattering contribution.

Conclusion

Forward scattering significantly contributes to the lidar signal in cirrus clouds. This contribution should be accounted for in the determination of their true optical thickness. Comparisons between LEANDRE and LITE measurements, show that the ratio of the apparent optical thicknesses is close to the theoretical value obtained from simple calculations accounting for the forward scattering assuming the observed cirrus cloud is composed of hexagonal crystals.

Aknowledgements

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MULTIPLE SCATTERING EFFECT IN SPACEBORNE LIDAR OBSERVATIONS

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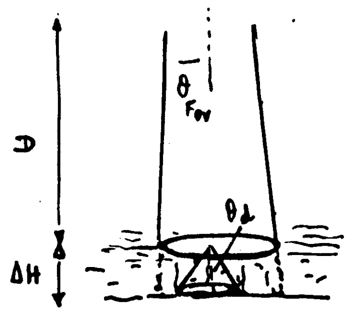
Transport mean free path $l_* = \frac{1}{(1-g)\sigma_e}$



Diffusive medium
$l_* << \Delta H/2$
$\tau >> \frac{1}{2(1-g)} \simeq 3$

NO

Only Diffraction angle from scatterers $\tau < 1$

$\theta_d \simeq \frac{\lambda}{d}$

$\theta_{Fovo} = \theta_d \frac{\Delta H}{D}$

$\theta_{Fov} < \theta_{Fovo}$

YES → single scattering → Ex: HETERODYNE DETECTION → REAL τ MEASURED

NO → importance of scattering at $\theta = 0$ and π (diffraction)

$\eta \simeq 0.5 - R$

(see Nicolas et al. 1996)

Factor ≥ 2 to 3 ref. to real τ values

$d = 20\mu m$ $\lambda = 0.5\mu m$
$\theta_d = 2.5\ 10^{-2}$ rd

$\Delta H = 1$ km; D = 500 km $\theta_{fo} = 0.5\ 10^{-4}$ rd

YES

Diffusion approach

(Analytical vs Monte Carlo)
→ MUSCLE Group.

$\rho = (l_* \cdot \Delta H)^{1/2}$

(see Davis et al. 1996)

importance of scattering at all angles

ex Sc $\tau = 30$
$\Delta H = 300$ m
→ $l_* \simeq 60$ m
$\rho \simeq 130$ m

$\theta_{Fov} > \theta_{Fovm} = \rho / D$

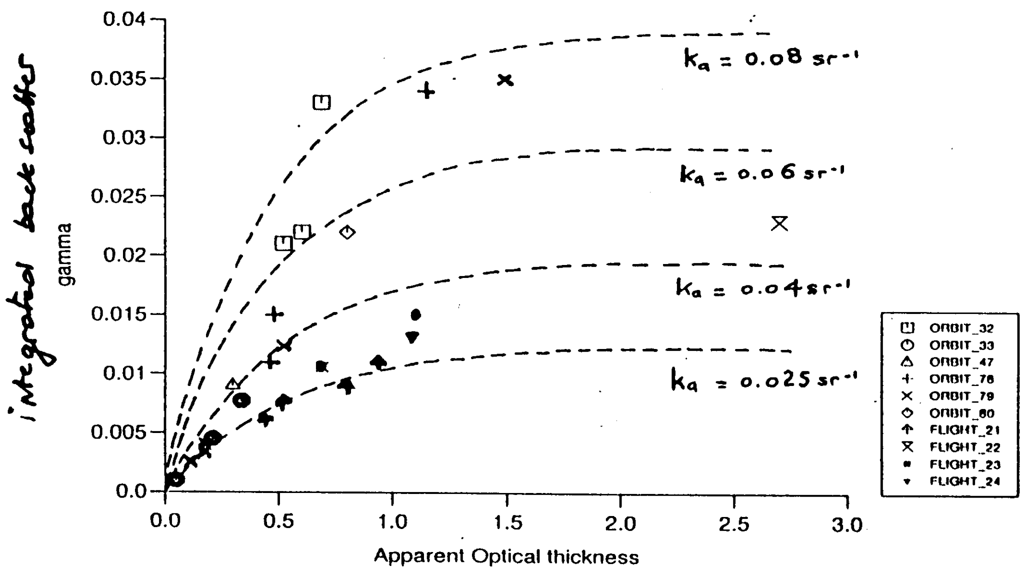
YES → Full multiple scattering signal

NO → partial orders

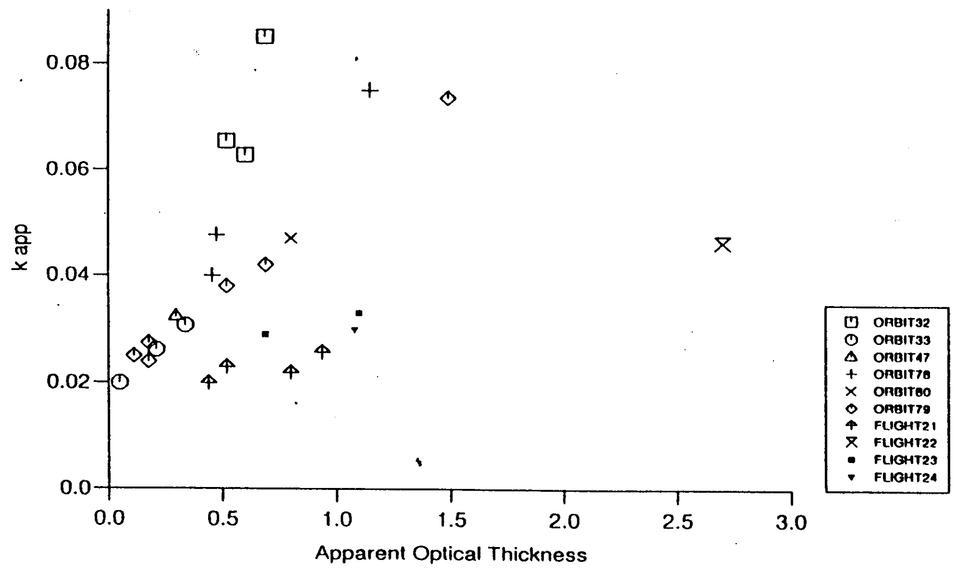
$\left\{ \begin{array}{l} D = 500\text{ km} \\ \theta_{Fovm} \simeq 3\ 10^{-4}\text{ rd} \end{array} \right.$

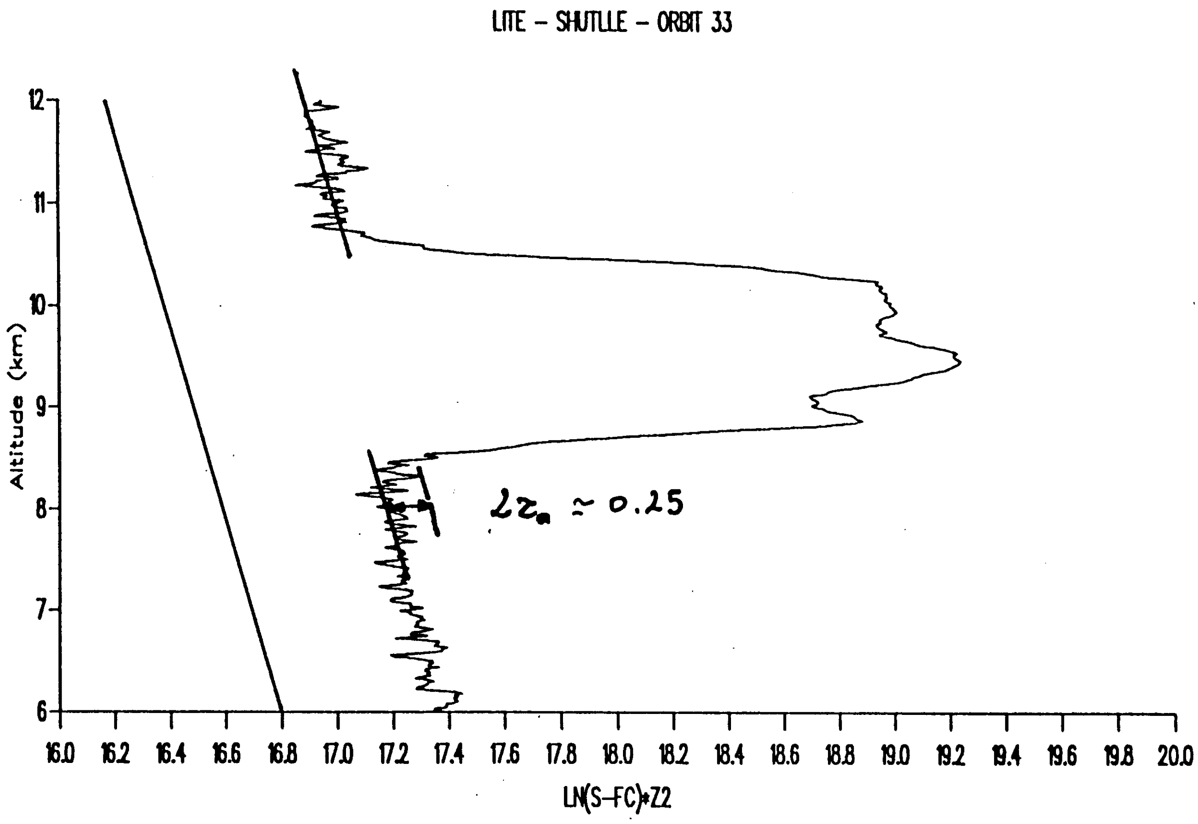
LITE SELECTED PROFILES (AVOIDING SATURATION)
VS AIRCRAFT B. LIDAR (L1)

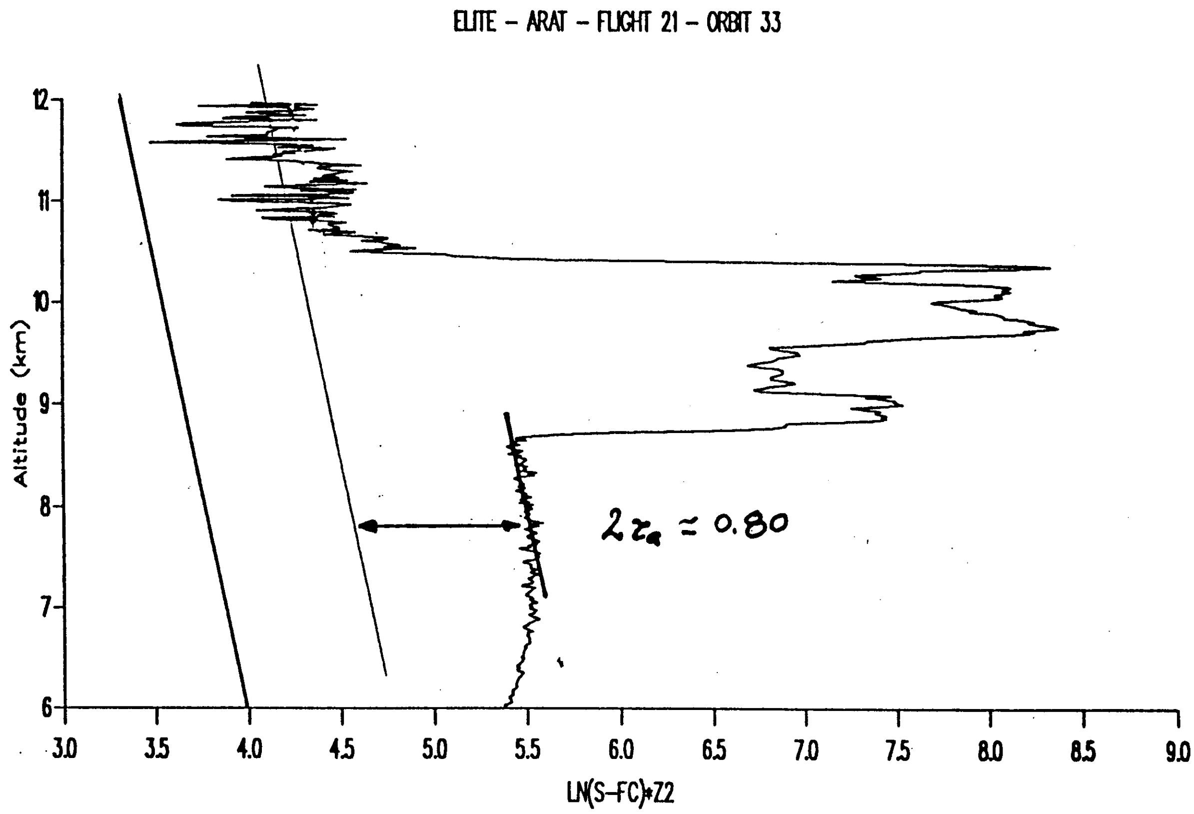
LITE/SHUTTLE - ELITE/ARAT

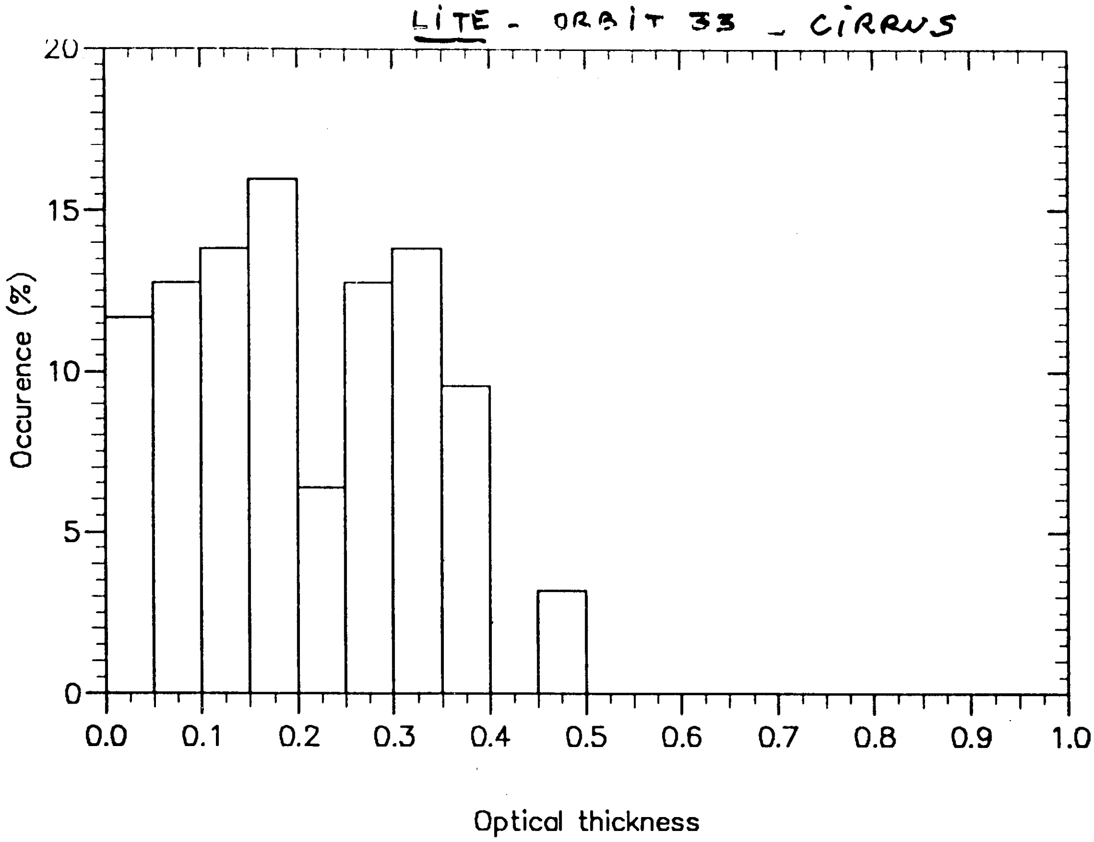


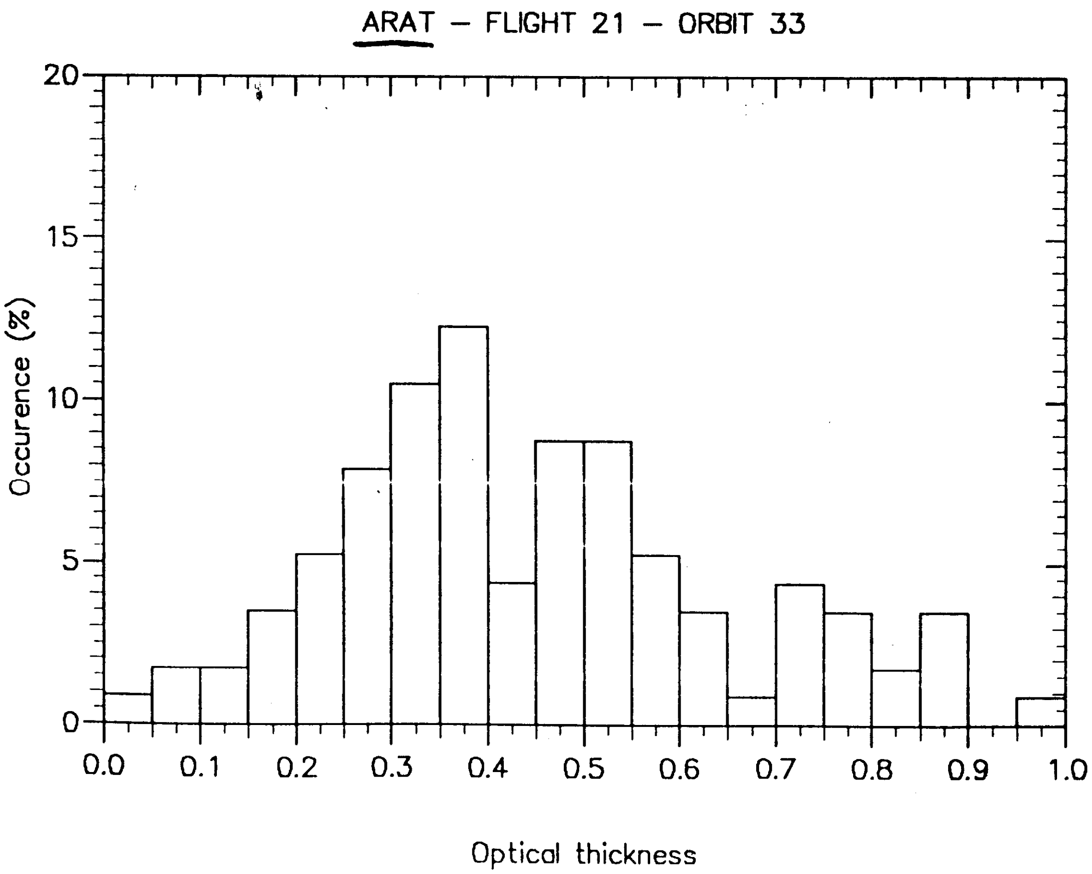
LITE/SHUTTLE - ELITE/ARAT




LITE - SHUTLLE - ORBIT 33
Altitude (km)
LN(S-FC)*Z2
$2z_a \simeq 0.25$


ELITE - ARAT - FLIGHT 21 - ORBIT 33
Altitude (km)
LN(S-FC)*Z2
$2z_a \simeq 0.80$


LITE - ORBIT 33 - CIRRUS
Occurence (%)
20
15
10
5
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Optical thickness


ARAT - FLIGHT 21 - ORBIT 33
Occurence (%)
20
15
10
5
0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Optical thickness