Statistical Simulation of Laser Pulse Propagation through Cirrus-Cloudy Atmosphere

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03. Atmospheric aerosol and clouds properties

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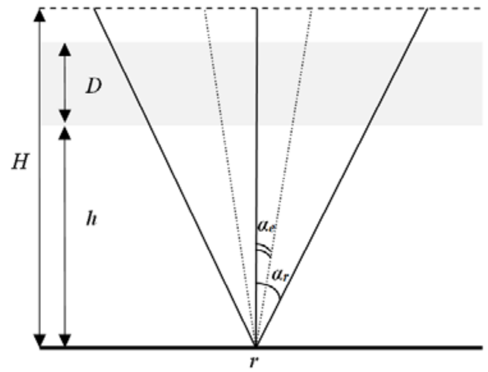
Objective / Statement of the problem

- lidar **multiple** scattering is still a challenging issue for cloud studies
- **multiple** scattering effects play a large role in the sampling of **optically thick** clouds such as cumulus but are, in some ways, just as important when examining **cirrus clouds of various optical depths**
- **high anisotropy** of scattering in the forward direction by ice crystals is the basis of a **significant** effect of multiple scattering for small values of the lidar receiver FOV

problems

objectives

- to develop **Monte-Carlo code** for simulation of echo signals taking into account multiple scattering
- to investigate features unique to considered lidar systems such as multiple scattering effects
- to provide generalized model returns from **cirrus** clouds



The lidar setup and model atmosphere geometry in case of **ground-based** laser sounding

Ground-based obs.

α_e – semi-aperture of emitter
α_r – semi-aperture of receiver
H – height of the atmosphere
D – thickness of cloud layer

Space-borne obs.

the same scheme but the nadir-directed lidar system is located at a height of 800 km

great distance to the sounded targets

a great volume of the atmospheric domain is caught within the lidar FOV and multiple scattering **greatly** affects the lidar return signal

The Monte Carlo model

- to compute multiple scattered monostatic return signals, a numerical algorithm was developed based on a **single local estimator** and Monte Carlo simulation of photon trajectories according to a well-known scheme (Marchuk G.I. et al., 1980)
- **a weighting scheme** was introduced to make the model computationally more efficient
- **a special technique of dependent splitting** of trajectories with respect to the first scattering was implemented

The length of each photon path segment within the cloud is randomly drawn from an exponential distribution such that the probability of the segment length l ($l > 0$) is

$$\boxed{p(l) = \sigma(r(l)) \cdot e^{-\tau(l)}}$$

τ – is the total optical depth along the photon path to each scattering event

Monte Carlo code features:

- the signal is accumulated in time bins according to the total time of flight of the detected photons
- the sum over all scattering events for all transmitted photons represents the lidar signal
- the results of computations are temporal return signals of the lidar (total and for different scattering orders)
- the square root of the variance is estimated for the total return signal

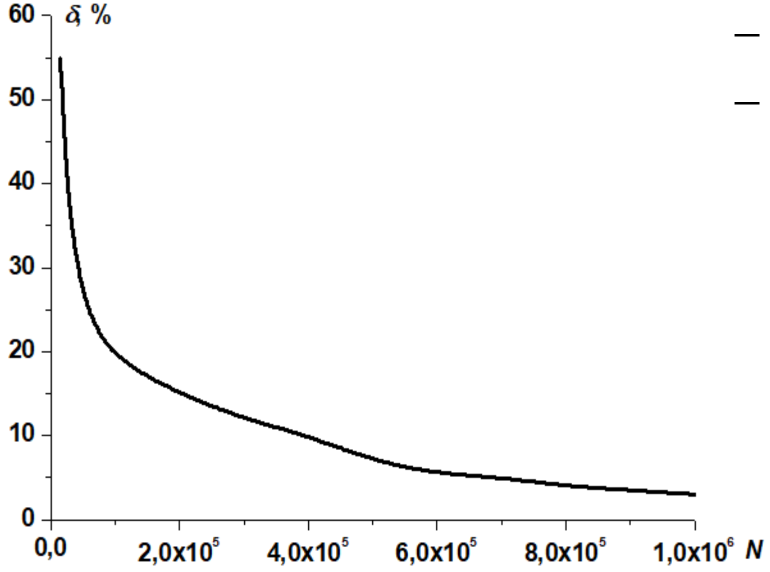
Statistical convergence

simulation outputs were tested to ensure statistical convergence

model of the atmosphere

- ✓ a homogeneous 1 km thick cirrus cloud composed of randomly oriented hexagonal ice crystals (Baum B.A. et al., 2005)
- ✓ cloud extinction coefficient of 0.4 km^{-1}
- ✓ cirrus cloud is located 8 km above the lidar
- ✓ wavelength 0.532 μm
- ✓ a standard atmosphere (Elterman L.)

the relative errors δ, %, as a function of number of photons N per set



– errors δ increase as the number of Rayleigh, aerosol and cloud scatterers

– the processing of significant number of photons is a time consuming operation, but it is required in order to reduce the errors to statistically acceptable level

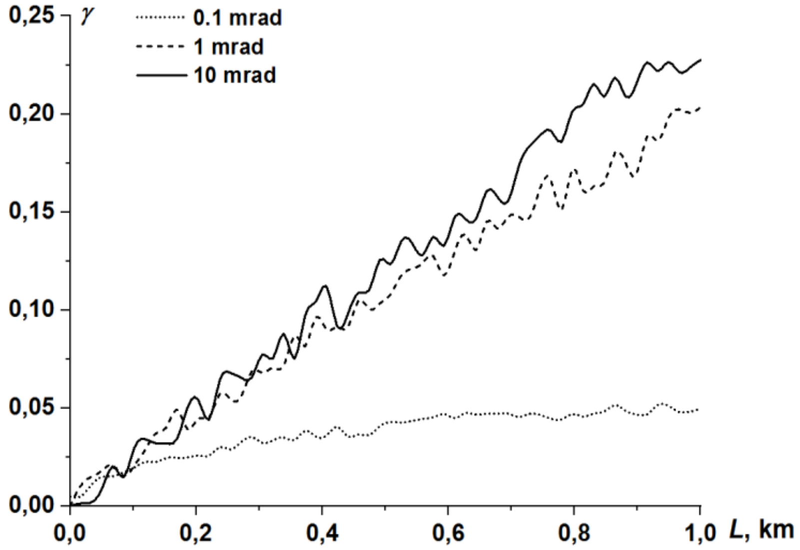
Effects of multiple scattering: ground-based measurements

- the presence of multiple-scattering contributions to the lidar returns biases the interpretation of measurements
- the contribution from higher orders of scattering is highly dependent on receiver field of view (Bruscaglioni P. et al., 1995)

Numerical experiments:

- cirrus-cloudy atmosphere, 1 km thick cirrus layer is located 7 km above the lidar
- no background atmosphere is present
- **ground-based** observations, monostatic lidar system
- cloud optical depth is 0.5
- wavelength is 0.532 μm

Ratio γ of multiple to single scattering for lidar return in cirrus-cloudy atmosphere, calculated for different values of semi-aperture of the receiver (0.1, 1 and 10 mrad) and plotted vs. penetration depth L, km



- the impact of multiple scattering increases the farther into the depth of the cloud
- for semi-aperture equal to 0.1 mrad the contribution of multiple scattering to lidar return remains comparatively small: higher orders contribute about 5% of the total signal
- for semi-apertures equal to 1 and 10 mrad, the sum of the orders greater than one contributes as much as 20 and 23% of the total return to the receiver correspondingly

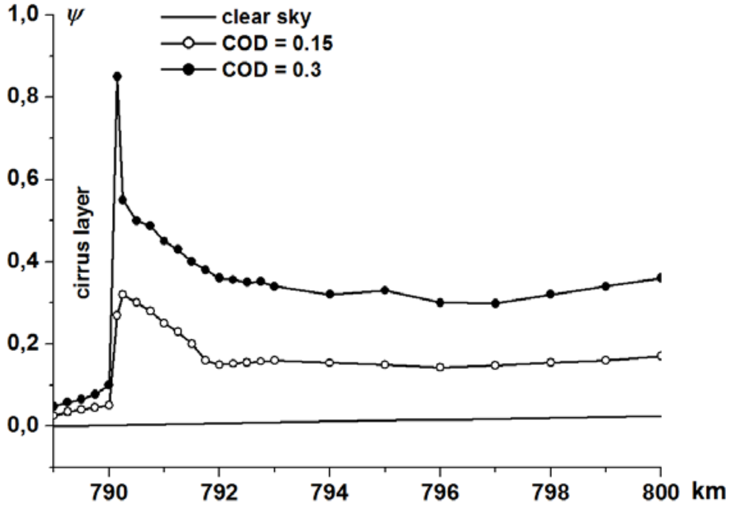
Effects of multiple scattering: space-borne measurements

- multiple scattering plays a much greater role for space-borne than for ground-based lidars due to mainly to the larger diameter of the receiver footprint on a cloud for the space-based systems (Winker D. and Poole L., 1995)

Numerical experiments:

- cirrus-cloudy atmosphere, 1 km thick cirrus layer is located 10 km above the lidar
- molecular atmosphere, wavelength is 0.532 μm
- **space-borne** observations, monostatic lidar system
- cloud optical depths are 0.15 and 0.3
- the receiver FOV is 3 mrad
- nadir-directed lidar located at a height of 800 km

Ratio ψ of multiple scattering to the lidar return in cirrus-cloudy and clear atmospheres



– the ratio ψ curves corresponding to cases of COD 0.15 and 0.3 show a visible similarity

– a characteristic feature is a larger value of the ratio in the lower clear atmosphere than for lidar ranges inside the cloud layer itself