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Monte-Carlo calculations of cloud returns for ground-based and space-based LIDARS

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Abstract. A Monte-Carlo model is described which has been developed for calculation of multiply scattered LIDAR returns. Results are shown for the common problem selected by the MUSCLE (MUltiple SCattering LIDAR Experiments) group for intercomparison, which represents a typical ground-based cloud-sensing scenario. This is contrasted with returns from the same cloud sensed by a space-based LIDAR, where multiple-scattering effects are much greater. The magnitude of multiple-scattering effects is seen to be largely determined by the optical depth across the receiver field of view at the cloud.

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It is generally recognized that multiple scattering can make significant contributions to LIDAR returns from clouds and other dense media. The primary effect of the multiple scattering is to make the extinction coefficient of the medium appear to be less than it really is. This effect can be minimized by using narrow transmitted beams and a small receiver Field Of View (FOV), and can often be reduced to a level where it is less important than other unknowns. For a LIDAR in Earth orbit this is not possible. The range from the LIDAR to the atmosphere is large and even narrow fields of view yield quite large footprints in the atmosphere. Secondly, eyesafety of persons on the ground is a concern and relatively large laser beam divergences are required in order to have high laser pulse energy and still meet requirements for maximum exposure thresholds. Our interest in LIDAR multiple scattering has been stimulated by involvement in a NASA program to put a LIDAR system in orbit on the Space Shuttle, the LIDAR In-space Technology Experiment (LITE) [1].

Monte Carlo techniques have been applied in a wide variety of ways to the study of radiative transfer. This paper describes a relatively simple and direct Monte Carlo procedure for the simulation of multiply-scattered LIDAR returns by modeling as directly as possible the physical scattering process. The basic procedure consists of constructing random photon trajectories, following the photons through multiple scatterings in the cloud, and computing the received signals. The statistics of the trajectories are determined by probability distributions derived from the scattering and absorption properties of the cloud particles. This direct simulation approach has several advantages. It allows great flexibility in the problems which can be studied. It can be applied to any medium for which the scattering phase function and other basic optical properties are known. Complex sensing geometries can be modeled which are difficult or impossible to handle analytically. Virtually any desired parameter describing the scattered radiation can be derived. Once a basic model is developed it can easily be adapted to other problems. The disadvantage ot the method is that it is computationally intensive. Because it is a statistical technique, a large number of photon trajectories must be computed to reduce the variance in the results. A variety of variance reduction techniques of increasing sophistication have been developed [2, 3]. These techniques along with the availability of fast desktop computers make Monte Carlo a practical and convenient approach. While the model described here has been developed primarily for investigating multiple scattering effects on space-based LIDARS, it is quite general and can be used to study a wide variety of LIDAR problems. The model has been applied to the common problem decided on by participants in the MUSCLE (MUltiple SCattering LIDAR Experiments) workshop series, and comparisons with the results of other MUSCLE groups are reported in the joint paper in this issue [4]. In the remainder of this paper we describe the Monte Carlo method used, then applications to the MUSCLE common problem and to several real-world problems.

1 Method

The model was originally developed for simulations of oceanographic LIDARS [5] and has recently been modified for application to the problem of homogeneous clouds. The approach which has been taken is to model as directly as possible the physical scattering process, and is essentially the procedure describe by Kunkel and Weinman [6]. Results obtained are being used as a benchmark against which to compare the performance of more sophisticated techniques with greater computational efficiency.

The cloud optical properties which must be specified are the extinction coefficient σ, single-scatter albedo ω, and the single-scatter phase function $P(\theta)$. The transmitted beam is assumed to have a Gaussian profile, and the angle at which each photon leaves the transmitter is a random value drawn from the appropriate probability distribution. 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 is

$$p(l) = \sigma e^{\sigma l}.$$

Inhomogeneous clouds may be treated in a similar manner if the appropriate probability density function can be constructed. At the end of each path segment, the photon is scattered in a random direction, with a probability density function determined by $P(\theta)$. Photons which leave the bottom or top edges of the cloud are dropped. Photon trajectories within the cloud are followed until they have traveled to a distance beyond the angular field of the receiver where the probability of being scattering back into the field is low: usually to a distance corresponding to an optical depth of 2.

The solid angle subtended by the LIDAR receiver from the cloud is generally small and the fraction of photon trajectories which terminate at the receiver is extremely low. It is impractical to calculate the number of individual photon trajectories required to accurately estimate the signal. To improve computational efficiency, the single photon is replaced with a packet containing a large number of photons and this packet is assigned a weight of unity. Each time a new scattering angle is computed, the probability of scattering directly back to the receiver is computed analytically:

$$p = P(\theta_r)\, e^{-\tau_r} \Delta\Omega \,/\, 4\pi ,$$

where θ_r is the required scattering angle, τ_r is the optical depth between the scattering site and the receiver, and $\Delta\Omega$ is the solid angle subtended by the receiver. At each scattering site within the receiver FOV, this fractional weight is removed from the photon packet and added to the detector signal. 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 procedure described here is very generic and a variety of statistical weighting techniques are available which could be used to improve the computational efficiency [4, 7, 8]. Due to the characteristics of the multiple scattering process, a technique may prove useful for one problem but have no benefits for another. Weighting techniques must also be properly normalized or bias errors are introduced. While inefficient, the procedure described here is a good starting point in developing more sophisticated algorithms.

2 Applications

A common problem for analysis has been chosen by the MUSCLE participants in order to assess the performance of the various approaches being used to compute LIDAR multiple scattering effects. The problem was designed to represent a typical scenario for ground-based LIDAR sensing of water clouds. The lidar is specified to operate at a wavelength of 1.064 μm, with a beam divergence of 0.1 mrad and a receiver FOV of either 1 mrad or 10 mrad. The LIDAR is located 1 km from the base of a homogeneous cloud. The phase function of the cloud is defined by the Deirmendjian C1 size distribution [9]. The extinction coefficient of the cloud is 17.25 km^{-1} with

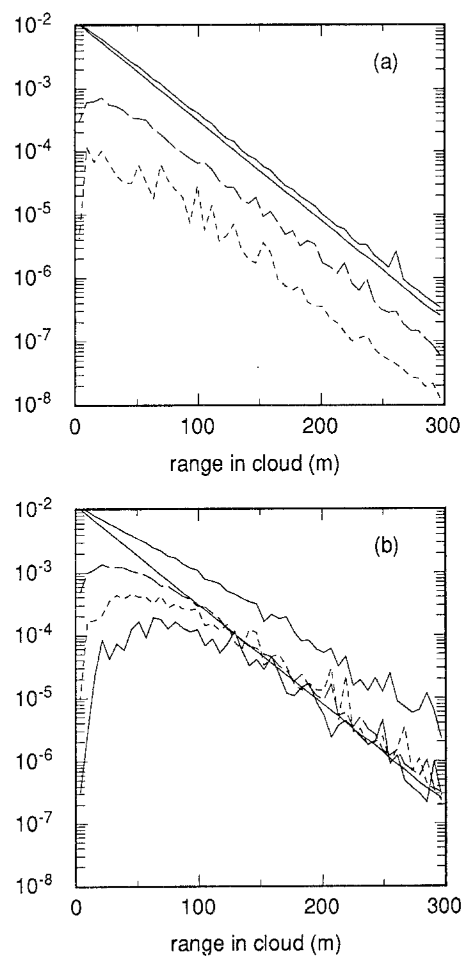

Fig. 1a, b. Solutions to the MUSCLE common problem. **a** 1 mrad FOV. *Curves* from *top to bottom* are: total signal, single-scatter signal, second order, third order. **b** 10 mrad FOV. *Curves* from *top to bottom* are: total signal, single scatter-signal, second order, third order, fourth order a single-scatter albedo of unity. Complete specifications are given in Bissonnette et al. [4].

The results shown in Fig. 1 were obtained by computing 2 million photon trajectories for each FOV. Comparisons with other MUSCLE participants are given in the joint paper [4]. Thirty orders of scattering were considered for these calculations. It was found that the first 4 orders were sufficient to describe the 1 mrad case while 10 orders were required for the 10 mrad case. The 10 mrad case exhibits much higher multiple scattering because the probability for a scattered photon to be rescattered within the receiver FOV is primarily determined by the optical depth across the radial width of the receiver footprint in the cloud. (There is also some dependence on the phase function. A phase function which is sharply peaked in the forward direction will tend to keep the scattered photons within the FOV relative to a more isotropic phase function). As will be seen in the next example, multiple scattering increases with the diameter of the receiver footprint, whether this is due to an increase in the angular field or an increase in the range to the cloud.

The remaining three figures show multiple scattering returns from the same homogeneous C1 cloud defined above, but for a space-based LIDAR. For each example, 200 000 photon trajectories were constructed and 30 orders of scattering were computed. Figure 2 illustrates the buildup of higher order scattering as the pulse penetrates the cloud. The LIDAR is located 293 km above the cloud top and the FOV in this case is 3.5 mrad. This corresponds to the sensing geometry of LITE for nighttime measurements. Due to the very large size of the receiver footprint, scattered photons have a high probability of scattering many times within the receiver FOV before being scattered out. The behavior of the double-scatter signal is much the same as in the 10 mrad ground-based case, but the higher orders are greatly enhanced. Twenty to 30 orders of scattering must be considered for a penetration depth of 600 m.

Figure 3 compares the single-scatter return with the total return at three different fields of view. The diameter of the receiver footprint for 0.2 mrad FOV is about one mean free path ($1/\sigma$). As the FOV increases, more scattering events per trajectory occur within the FOV and contribute to the signal, and the variance of the result decreases somewhat. The contributions of the higher order scattering are so strong that the total return drops only 1 order of magnitude through the cloud for the largest FOV, even though the optical depth is 10. Beyond the first few meters of penetration, the return signal is dominated by higher-order scattering. Thus, no retrieval algorithm for parameters such as extinction coefficient will be successful without taking multiple scattering into account. The detected signal is seen to be dependent on the receiver FOV. This indicates the possibility of combining measurements at different fields of view to derive information about the cloud particles.

When accumulating photon statistics during the model calculations, returns may be binned either by time of flight or by the range at which the final scattering occurred. Figure 4 shows the return for a C1 cloud 120 m

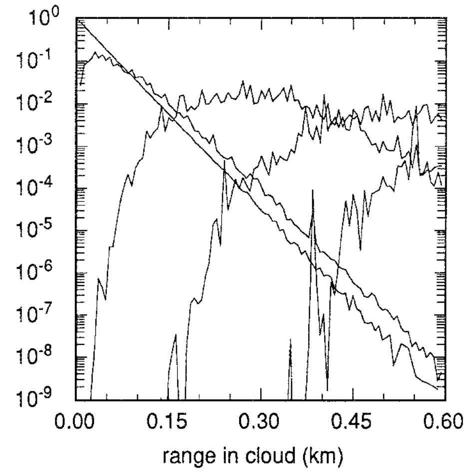

Fig. 2. Relative scattering from a homogeneous C1 cloud for a space-based LIDAR with 3.5 mrad FOV at a range of 293 km. Shown are first, second, tenth, twentieth and thirtieth scattering orders

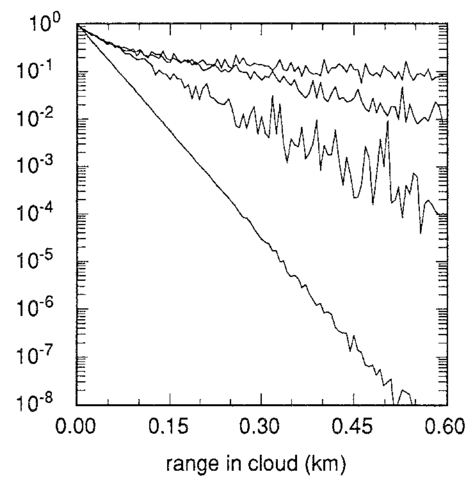

Fig. 3. Normalized returns from a homogeneous C1 cloud at a range of 293 km. Shown are first-order scatter and summation of the first thirty orders for 0.2 mrad, 1.1 mrad, and 3.5 mrad receiver FOV

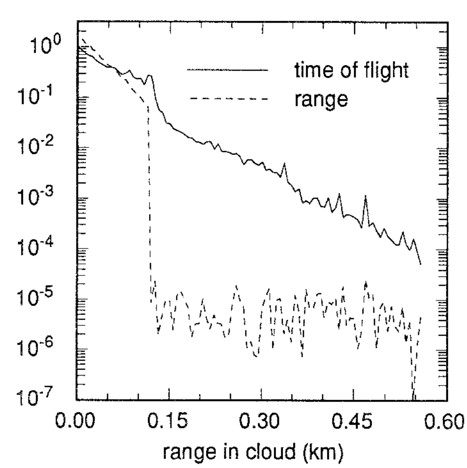

Fig. 4. Pulse-stretching effect of a 120 m thick C1 cloud at a range of 293 km with a receiver FOV of 3.5 mrad

deep binned both ways. On the far side of the cloud is a Rayleigh atmosphere, providing a non-zero signal. When binned by time of flight the lower edge of the cloud appears to be diffuse. When binned by range, it is seen that the lower edge of the cloud is in fact sharply defined, and it is the increased path length of the multiply-scattered photons which produces the appearance of a diffuse edge. While the profile binned by time of flight does not drop to clear-air levels until far beyond the cloud base, it does show a significant decrease at the base. This result suggests that the pulse stretching produced by multiple scattering will not prohibit a determination of the true cloud base. Because of the large receiver footprint, light which is forward scattered in the cloud is not necessarily lost from the beam, and, in some cases, multiple scattering may allow LIDAR measurements of cloud thickness to be performed on deeper clouds than would otherwise be possible.

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