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Atmospheric multiple scattering of a vertically directed laser beam

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ABSTRACT

Vertical laser beams are often used at ground-based cosmic ray observatories employing the fluorescence technique for characterizing the height-dependent properties of the atmosphere, as well as for calibration and telescope alignment studies. The light flux received at a detector from a laser is typically assumed to be only singly scattered out of the beam, with no possibility for the multiple scattering of photons initially scattered in other directions back into the detector's field of view. We present the results of a new simulation for the scattering of light from a vertically-directed laser beam, and derive a parametrization for the multiple scattered signal expected at a detector from such a source as a function of the prevailing atmospheric conditions. The parametrization is then used to estimate the increase in the reconstructed height-dependent aerosol loading when recovered using a laser-based technique.

1. Introduction

The properties of ultra-high energy cosmic rays (UHECRs), including their energy, mass composition, and arrival direction, can be inferred from studies of the cascade of secondary particles they produce when they interact with the Earth's atmosphere (known as an extensive air shower, or EAS). Due to the minute flux of UHECRs at the highest energies, very large ground areas must be instrumented in order to collect sufficient statistics for robust scientific analyses to be performed. The two largest cosmic ray observatories currently in operation, the Pierre Auger Observatory (Auger) [1], covering a ground area of 3000 km^2 in the province of Mendoza, Argentina, and the Telescope Array Experiment (TA) [2], located in central Utah, USA, and covering a ground area of 700 km^2, each combine two techniques for the measurement of the lateral and longitudinal development of air showers in the Earth's atmosphere. In both experiments an array of evenly spaced particle detectors (water-Cherenkov detectors in the case of Auger, and plastic scintillators in the case of TA) sample the lateral distribution of EAS particles at ground level, while telescopes on the periphery of the array allow for reconstruction of the longitudinal shower development by imaging faint isotropic UV fluorescence light from atmospheric nitrogen excited by EAS particles. As the flux of fluorescence photons from a given point on an air shower track is proportional to the energy deposited in the atmosphere, the well-established fluorescence technique allows for a near-calorimetric determination of the shower energy, and therefore of the primary particle that produced it. As the atmosphere is responsible for the transmission of this fluorescence light from its point of emission to the detector, uncertainties in the description of the atmosphere make up a significant part of the systematic uncertainty in the fluorescence technique. The scattering and absorption properties of the atmosphere must be well understood [3].

Atmospheric "test beams" are often used at large ground-based cosmic ray observatories for characterization of the time-varying properties of the atmosphere, as well as for detector calibration and telescope alignment studies. A vertically-directed Nd:YAG laser is installed in the centre of the array at both Auger [4] and TA [5] (and a similar facility has been proposed for the Cherenkov Telescope Array [6]) for this purpose, operating in the middle of the atmospheric fluorescence range at 355 nm, between two major N_2 fluorescence bands at 337 nm and 357 nm. For atmospheric studies in particular, the signal recorded at the fluorescence detectors, located between 20 km and 40 km from the laser facility, is used to probe the height- and time-dependent scattering properties of the atmosphere [7]. In such studies, given the intensity of the laser beam, the atmospheric transmission can be recovered by recognizing that the total amount of light scattered out of the beam is proportional to the intensity of the beam if the atmosphere has been correctly accounted for. In these analyses, laser light is typically assumed to be only singly scattered out the laser beam and towards the detector. This assumption ignores the possibility that some photons will reach the detector after one or more additional scatterings. As multiple scattering (MS) serves to make

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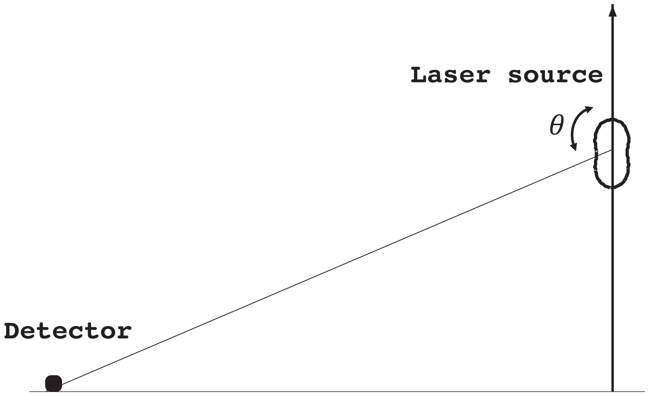

Fig. 1. The angular distribution of emitted light from a laser source is dominated by Rayleigh scattering, having a probability proportional to $1 + \cos^2\theta$ of scattering into a unit of solid angle. In this case the single scattered light component is significantly less than the amount of light scattered in other directions. As this light is available for multiple scattering, we expect a larger multiple scattered fraction from a laser source than we do from one that is isotropic.

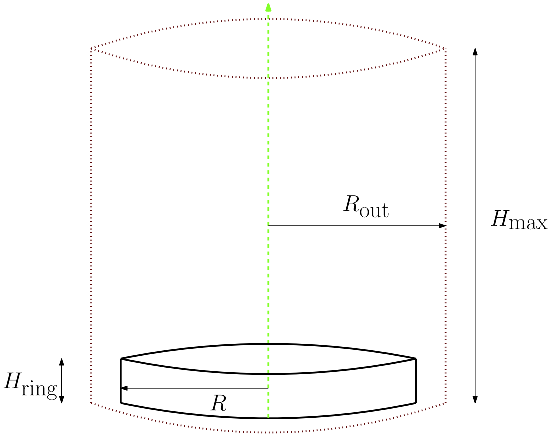

Fig. 2. Side view of the simulation volume. The laser axis is shown in green. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the laser appear slightly brighter than it would under the assumption of single scattering only, this introduces a small systematic underestimation in the extinction properties of the atmosphere. It is therefore important that the effect of the atmosphere on the multiple scattering of a laser beam is well understood.

In this paper we present a new Monte Carlo simulation which has been developed to study the multiple scattered signal received at a detector from a laser source. We derive a parametrization for the multiple scattered fraction which can be applied during the analysis of vertical laser beams to account for the increased light flux due to MS photons. The need for a dedicated simulation applicable to a laser source is motivated in Section 2, and the simulation method is described in Section 3. In Section 4 we discuss some properties of multiple scattered light from a laser source, and in Section 5 we use the results of the simulation to derive a parametrization of the multiple scattered fraction as a function of the atmospheric conditions. In Section 6 our parametrization is compared to an existing parametrization for multiple scattered light from an isotropic shower-like point source. Finally, the effect of multiple scattering on laser-based aerosol loading measurements is estimated in Section 7, before conclusions are drawn in Section 8.

2. Multiple scattering of a vertical laser source

Previous studies of atmospheric multiple scattering have focused on isotropically emitted fluorescence light from air showers [8,9–11], the effect of which is corrected for during shower reconstruction [1]. In the case of a laser beam, the source angular distribution is determined by the combination of the molecular and aerosol scattering angular distributions (known as phase functions). Vertical laser beams used for probing the transmission properties of the atmosphere at both Auger and TA are always viewed by a fluorescence detector at an angle $\geq 90°$ to the beam direction. Since much more light is scattered (per unit solid angle) in the forward and backward directions than towards the detector, and since it is this light that is available for multiple scattering, we expect a larger multiple scattered fraction incident on the detector than we would from an isotropic light source. This is shown graphically in Fig. 1.

The need for a dedicated treatment of the multiple scattering of a laser source can be highlighted quantitatively using a simple geometrical argument. In the case of an isotropic light source, the ratio of the amount of light scattered towards a detector of unit solid angle to the amount scattered in all other directions, is 4π. For a source function determined by the combination of the molecular and aerosol phase functions (see Section 3.1), it can be shown that this ratio is smaller than that of an isotropic source by nearly a factor of two for a laser beam that is viewed at 90° to the beam direction, making some reasonable assumptions about the typical relative abundances of molecules and aerosol particles. That is, given laser and isotropic light sources of equal intensity, the number of detected multiple scattered photons from a laser source could be twice as high.

3. Photon-by-photon simulation of a vertical laser beam

For this work we have developed a new Monte Carlo photon-by-photon multiple scattering simulation of a vertical laser beam called `MSLaserSim`. The simulation exploits the cylindrical symmetry of a vertically moving light source in order to greatly increase the number of collected photons and decrease the simulation time by many orders of magnitude. This technique has been used previously in similar studies of isotropic emitters [8,9].

In this simulation, a light source is located at ground level and emits photons one at a time vertically upwards through a parametrized atmosphere of height $H_{\max} = 30$ km. The height of the simulation volume is chosen such that it extends beyond the maximum altitude observed by a typical fluorescence detector having a field of view extending to 30° in elevation at a maximum laser-detector distance of $\sim$ 50 km. A cylindrical detector ring of height $H_{\text{ring}} = 100$ m and radius R surrounds the light source, and photons propagate through the atmosphere, scattering off of molecules and aerosols, until they either pass through this ring or leave the simulation volume. The radius of the detector ring is varied between 20 km and 40 km, encompassing the typical range of distances at which atmospheric test beams are viewed at large cosmic ray observatories. The simulation volume is slightly larger in radius than the detector ring to allow for the detection of photons that might multiple scatter from behind the detector back into the field of view. Fig. 2 gives a graphical representation of this simulation volume. Information about photons that pass through the detector ring, including their arrival direction, arrival time, number of interactions in the atmosphere, and height of first interaction are recorded. We discuss the atmospheric description and simulation procedure in more detail below.