

Atmospheric multiple scattering of fluorescence and Cherenkov light from air shower

J. Pękala^a, D. Góra^a, P. Homola^a, M. Risse^{a,b}, B. Wilczyńska^a, H. Wilczyński^a

(a) *Institute of Nuclear Physics PAN, Radzikowskiego 152, 31-342 Kraków, Poland*

(b) *Forschungszentrum Karlsruhe, Institut für Kernphysik, 76021 Karlsruhe, Germany*

Presenter: H. Wilczyński (Henryk.Wilczynski@ifj.edu.pl), pol-wilczynski-H-abs1-he14-poster

Atmospheric scattering of light emitted by an air shower contributes to the direct fluorescence light from the shower, rather than just attenuating it. So far only direct and singly-scattered Cherenkov photons have been taken into account in analyses of the optical image of an air shower. In this paper a Monte Carlo method of evaluating the contribution of scattered light to the optical image is presented. Preliminary results of these simulations are shown.

1. Introduction

Charged particles of an extensive air shower produce a large number of fluorescence and Cherenkov photons on their way through the atmosphere. Fluorescence light coming directly from the shower to the detector provides information needed for determining shower size at different points along the shower track. Scattering of light in the atmosphere results in attenuation of the fluorescence signal, but also contributes to the signal received by the detector. The scattered light (both fluorescence and Cherenkov photons) must be regarded as a background for the direct fluorescence signal, because its intensity relates to history of shower development rather than to current number of particles in the shower.

In most cases, the optical image of a shower consists mainly of direct fluorescence and singly-scattered Cherenkov photons. Direct Cherenkov light makes a significant contribution to the signal in the fluorescence detector only when the shower lands close to the detector site. Scattered light may be relatively strong in all geometrical configurations, especially in the late stages of shower development. Fluorescence and Cherenkov photons produced by the shower may undergo scattering at different angles. A small part of them gets directly to the detector and is recorded together with the direct fluorescence light. Other photons, after traveling some distance in the atmosphere may scatter again, this time in direction of the detector. It is possible that shower photons may reach the detector after a longer series of scatterings. This light is expected to be distributed over larger area of the sky than the direct light from the shower, and due to its longer path it is also respectively delayed [1].

Until now neither scattered fluorescence photons, nor multiple scattering of Cherenkov light have been taken into account in shower reconstruction procedures. The objective of this paper is to find out how much light contributes to the shower signal due to these effects.

2. Method of simulation

Multiple scattering of fluorescence and Cherenkov photons was simulated using the "Hybrid_fadc" program [2]. In the program, calculations are done in steps corresponding to a change of 0.04° in shower position on the sky, as seen by the detector. In each step the program calculates the shower size (using the Gaisser-Hillas parameterization) and the number of emitted photons. Based on these, fluorescence and Cherenkov light (both

direct and singly-scattered) are calculated. The shower is assumed to have no lateral distribution. Calculations are done in 16 wavelength bins covering the range from 276 to 420 nm.

In calculations concerning multiple scattering of fluorescence and Cherenkov photons produced in a given step it is impossible to trace all photons separately, so that some simplifications are inevitable. The total photon number is divided into smaller "packets" (typically 10 thousand packets in each step and each wavelength bin). All following calculations are done for each packet. A packet starts from the shower axis at the point corresponding to a current shower development step, with either isotropic (fluorescence) or exponential (Cherenkov) angular distribution [3]. Assuming that all photons in a packet scatter at one point, the point of first scattering, either by Rayleigh or Mie processes, is randomly chosen. From the two calculated points, the closer one is chosen as the place where the scattering occurs. Knowing the geometry of the event and also the angular distribution of scattering (Rayleigh or Mie respectively), including attenuation factor for the path toward the eye, the signal at the detector due to a portion of the packet is calculated. With the information about the whole path in the atmosphere, the time of arrival is found. In order to trace the rest of the photons in a packet, it is assumed that they continue their flight together. For this smaller packet, a direction is randomly chosen and all calculations, just as for the first scattering, can be repeated several times. These calculations give as output information about each packet: size of signal, arrival direction on the sky and time of arrival to the detector.

3. Preliminary results

With the program described above simulations were made for different shower configurations, namely for all combinations of:

- energy - 10^{18} , 10^{19} , 10^{20} , 10^{21} eV;
- core distance - 3, 7, 15, 25 km;
- ψ angle within the shower-detector plane - 30, 50, 70, 90, 110, 130, 170 degrees for vertical SDP;
- SDP inclination - 30, 45, 60, 70 degrees with $\psi = 90^\circ$.

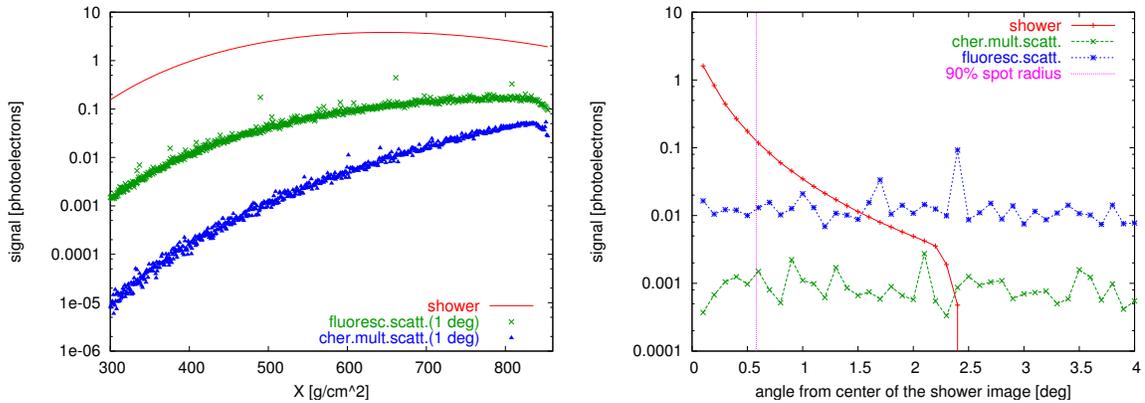


Figure 1. Example of simulation results (vertical 10^{19} eV shower landing 15 km from detector). Shower longitudinal profile and scattered light contribution in 1° -radius circle is shown on the left panel. The "shower" curve includes direct fluorescence, direct and singly scattered Cherenkov photons. On the right panel the distribution of light on the sky (integrated in rings 0.1° wide) in shower maximum is shown. The vertical line marks the radius of the spot containing 90% of the signal.

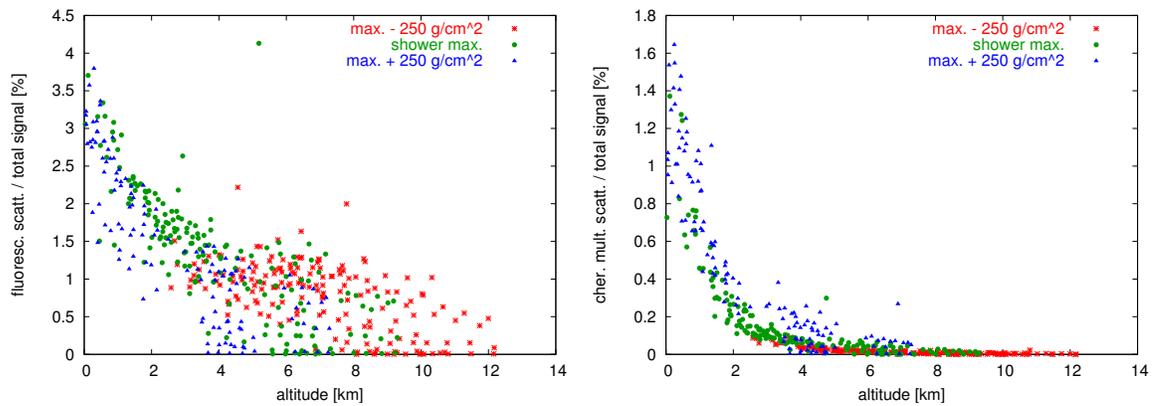


Figure 2. Contribution of scattered fluorescence (left) and multiply scattered Cherenkov (right) to total shower signal plotted versus altitude above ground.

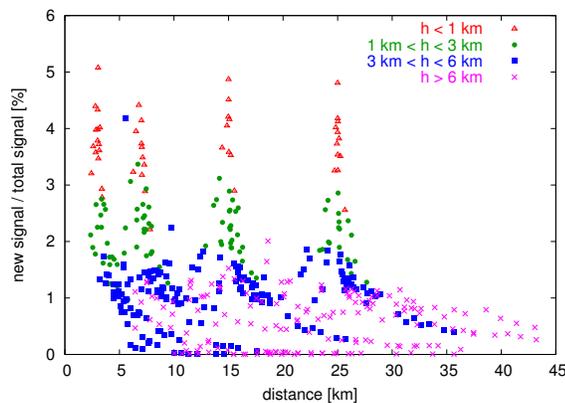


Figure 3. Contribution of scattered light to total shower signal versus the shower-detector distance, in different altitude ranges. The "new signal" includes scattered fluorescence and multiply scattered Cherenkov photons. The points at low altitudes have largest contributions of the scattered light, and are grouped at distances corresponding to chosen core distances of simulated showers.

Example of results from a single simulation run is shown in fig. 1. The signal from multiply scattered light is larger at later stages of shower development, and may finally reach few percent of the total signal from the shower. The contribution of scattered fluorescence light (including single scattering) is at all stages larger than from multiple scattering of Cherenkov light. In order to precisely calculate the contribution from scattered photons, we must know exactly the size of the area on the sky, from which shower light is recorded. When compared to size of shower image, scattered light has very broad distribution, and so the ratio of scattered light contribution to shower signal depends strongly on the light collecting solid angle. To compare contributions of scattered light in various shower geometries, the presented results show contribution of scattered fluorescence and multiply scattered Cherenkov light within a circle containing 90% of light coming directly from the air shower. In analyses of experimental data, the detector characteristics must also be taken into account.

Results from the whole set of simulations performed are presented in figures 2 and 3. Shown are contributions from multiply scattered light for all shower maxima and points 250 g/cm^2 before and after the maximum (if above ground). This contribution appears to be strongly correlated with altitude above ground, rather than with distance from shower to detector. Results from different simulations, representing maxima and points earlier and later in shower development that are at the same altitude, show also comparable contribution of scattered light. This may mean that a simple parameterization, independent of shower age and geometry, is possible. At the lowest altitudes the contribution from multiply scattered light reaches up to 5% of the total signal, therefore it should be taken into account in analysis of experimental data from fluorescence detectors.

In order to investigate the impact of some assumptions made in the simulations, namely atmospheric profile and Cherenkov emission model, on contribution of multiply scattered light, smaller sets of simulations were made. Compared were the US Standard Atmosphere Model [4] (used in all previous simulations) and models of atmosphere in January and July at the southern Pierre Auger Observatory in Malargüe (Argentina). Results of simulations show that changing atmospheric models has little influence on final results. Compared were also results of simulations using different models of angular distribution of Cherenkov emission: simple, one-exponential distribution [3] with more realistic two-exponential one [5]. Also, no significant change of results can be seen.

4. Conclusions

Scattering of fluorescence light and multiple scattering of Cherenkov photons makes a contribution to the signal received by the fluorescence detector, that must be taken into account in analysis of experimental data. The contribution of multiple scattering to the image spot containing 90% of the light received from the shower was presented here. This contribution, which depends on the instantaneous altitude of the shower above the ground, can reach $\sim 5\%$ of the shower signal. Since the multiple-scattering contribution changes with altitude, after this correction the shape of shower profile (and with it depth of shower maximum) may also change. The multiply scattered light has a very broad distribution, and so the exact estimation of its contribution requires information about the solid angle from which light is collected.

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