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Contribution of atmospheric scattering of light to shower signal in a fluorescence detector

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Abstract: The light emitted by an extensive air shower undergoes scattering on molecules and aerosols in the atmosphere. The scattering effect not only attenuates the light, but also contributes to the signal recorded by a detector. Hence, this effect directly influences the determination of shower energy. In routine analyses so far only contributions from direct and singly-scattered Cherenkov photons have been accounted for. Monte Carlo simulations were used in this work to study single and multiple scattering of fluorescence photons as well as multiple scattering of Cherenkov photons, for various shower geometries and varying distributions of aerosols in the air. The resulting contribution of scattered photons to the signal recorded in a fluorescence detector was obtained. A parameterization of this additional contribution is provided that can be used in shower reconstruction in the fluorescence technique of cosmic ray detection.

Introduction

The effect of scattering of light in the air results in attenuation of light emitted by an air shower before it arrives to a detector. However, it may also contribute to the signal received by the detector when light scatters several times before finally getting to the detector. Since the intensity of the scattered light does not relate directly to current number of particles in a shower, the scattered light is a background for a "useful" unscattered fluorescence light.

In routine air shower analyses so far, only the background due to direct and singly scattered Cherenkov light is subtracted from the signal recorded by a fluorescence detector. A contribution to the signal coming neither from multiply scattered Cherenkov photons, nor from scattered (singly and multiply) fluorescence light, is subtracted. Failure to account for this additional background signal results in overestimation of shower energy in the fluorescence method of shower detection.

The aim of this work is to quantify the contribution from scattered fluorescence and multiply scattered Cherenkov photons to the shower signal recorded by a fluorescence detector and to provide means to amend the existing shower reconstruction procedure so that a correction for the multiple scattering contribution can be applied.

Simulation set

Simulations of scattering, and tracing of scattered photons were done using the `Hybrid_fadc` program [2]. The original program was modified [6], so that multiple scattering of both fluorescence and Cherenkov photons can be simulated separately. Wavelength-dependent Rayleigh scattering on molecules and Mie scattering on aerosols are simulated.

An extensive set of simulations was made. Simulation runs were performed for various shower energies, different shower-detector distances and different shower inclinations. Also, a variable distribution of aerosols in the atmosphere, with different aerosol concentration at the ground and different scale height of the distribution were tested. In addition, a possible dependence of the scattering effect on the molecular atmosphere distribution (i.e.

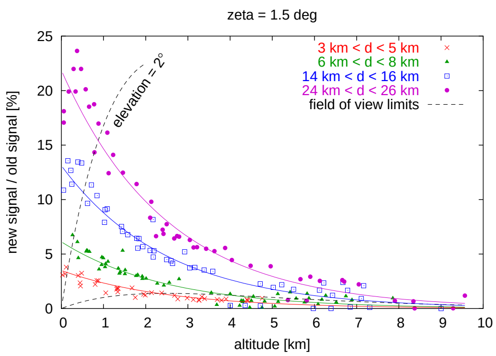

Figure 1: Contribution of scattered light to shower signal versus altitude above ground for selected shower-detector distances. The solid lines are fits of Eq.1. The dashed lines show limits of a detector field of view (elevation 2°–30°).

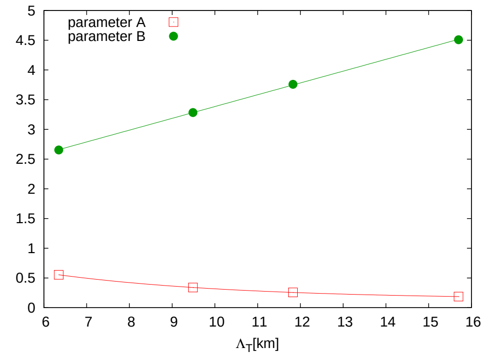

Figure 2: Dependence of the A and B parameters on the total horizontal attenuation length (see the text for details).

variable vertical distribution of air mass) and on location of a detector at different altitudes above sea level were checked.

Two distributions of Cherenkov photon emission from a shower were also used: a simple exponential distribution [1] and a more realistic two-exponent one [5].

Contributions to the signal in a detector were recorded, coming from direct fluorescence and direct and singly scattered Cherenkov light, which are accounted for in routine shower reconstruction algorithms. These are collectively called in this paper the "old signal". In addition, the newly analysed contributions from multiply scattered Cherenkov and scattered (singly and multiply) fluorescence photons, called here the "new signal", were recorded.

Contribution of scattering

The results of simulations are quantified in terms of variable M = "new signal"/"old signal", i.e. in percentage of the total shower signal used in shower reconstruction so far. It was shown in [6] that the contribution of scattered fluorescence light and multiply scattered Cherenkov light to the shower "image spot" falls with altitude of shower front above the ground. The "image spot" is the solid angle within which 90% of the signal is received.

It is important to note that pixellization of the field of view of a fluorescence detector must be taken into account. The angular size of the image spot depends on the shower-detector distance and for distant showers has a radius of about half of a degree. On the other hand, the radius of a detector pixel size is usually larger than 0.5°. Since the angular distribution of the scattered light is much wider than that of the direct fluorescence [6], the relative contribution of the scattered component depends on the solid angle, from which signal is collected in the detector. For example, in fluorescence telescopes of the Pierre Auger Observatory the signal is collected from a solid angle with a radius larger than 1° [3]. Therefore, for distant showers this solid angle is larger than the image spot of the shower, and in consequence the contribution from multiple scattering is increased.

The scattering contribution to shower signal can be well parameterized by

$$M = A\zeta d \exp(-h/B) \qquad (1)$$

where ζ is the radius of the signal collection angle in the detector, d – the shower-detector distance, h is the altitude of the shower front above the ground; A and B are parameters of the fit. As shown in Fig.1, Eq.1 very well describes the contribution from scattering. For low altitudes this contribution can exceed 20% for distant showers. If the detector field of view is limited at low elevations, the distant showers are not observed at very low altitudes. For example, only the region to the right

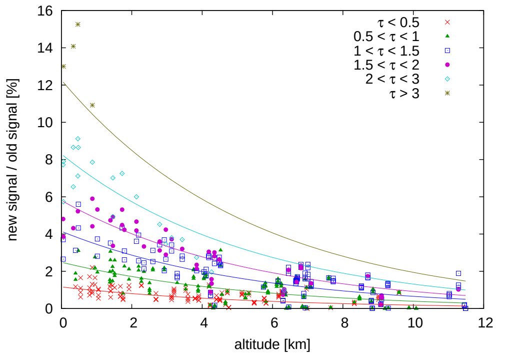

Figure 3: Contribution of multiple scattering for all values of the total horizontal attenuation length, in groups of the optical depth τ along the shower-detector line of sight. The lines are fits of Eq.2 with mean values of the respective τ intervals.

from "elevation=2°" dashed curve in Fig.1 can be observed in the Auger fluorescence detectors.

The A and B parameters of Eq.1 depend on distribution of aerosols. We show this dependence as a function of the total horizontal attenuation length Λ_T (for the wavelength of 361 nm) which can be easily measured experimentally. Fig.2 shows the dependence of A and B on Λ_T:
$A = a_1 \exp(-\Lambda_T/a_2) + a_3$, with $a_1 = 1.77 \pm 0.03\%$, $a_2 = 4.37 \pm 0.06$km, $a_3 = 0.14 \pm 0.01\%$; $B = b_1\Lambda_T + b_2$, with $b_1 = 0.198 \pm 0.004$, $b_2 = 1.40 \pm 0.03$km.

Alternatively, the scattering contribution can be expressed as a function of the optical depth τ of the shower-detector line of sight:

$$M = F\zeta\tau \exp(-h/G) \tag{2}$$

with $F = 3.32 \pm 0.01\%$, $G = 5.43 \pm 0.03$km.

The contribution of the multiple scattering to the shower signal was found to be rather insensitive to details of vertical air mass distribution. Simulations were performed using the US Standard Atmosphere Model, as well as seasonal atmospheric profiles for the southern site of the Auger Observatory. The differences between them are important for determination of depth of shower maximum. However, local differences of air density among these models appear to be rather insignificant for the scattering effect. Similarly, variation of the detector altitude above sea level by a few hundred meters does not affect the scattering contribution. We note that the air density depends on altitude above sea level, while the distribution of aerosols – on altitude above ground, so that the Rayleigh and Mie scattering effects might contribute differently. Nevertheless, the total scattering contribution to shower signal does not appear to be noticeably sensitive to the detector altitude.

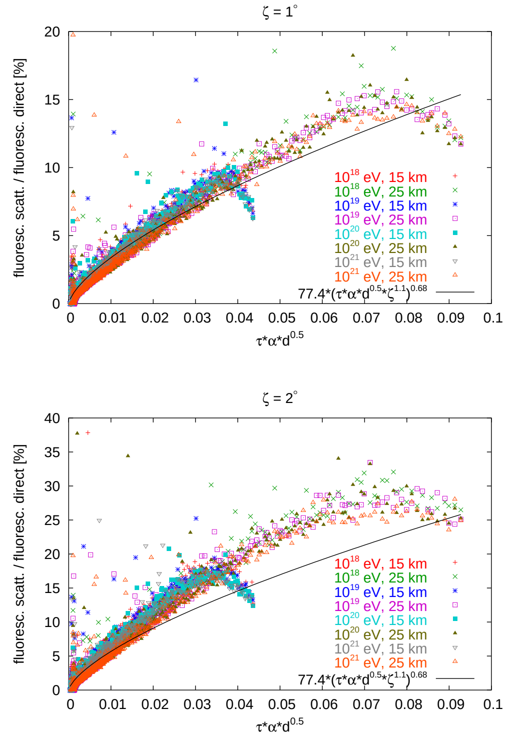

Figure 4: Comparison of fluorescence light scattering with results of [7] for $\zeta = 1°$ and $\zeta = 2°$. The data points are results of this work, the lines represent the fit given in [7].

Similarly, different distributions of Cherenkov emission from the shower, proposed in [1, 5] result in similar scattering contributions to the shower signal.

Comparison with other results

Some studies of the scattering contribution can be found in the literature. In Ref.[7] scattering of flu-

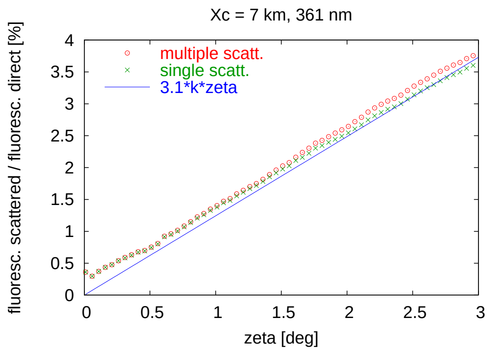

Figure 5: Comparison of Rayleigh scattering of fluorescence light with results of [4]. The data points are results of this work, the line represents the fit given in [4]

orescence light was studied assuming a uniform fluorescence light intensity along the shower track. To make the comparison, scattering of fluorescence light only was extracted from our simulations. The comparison shown in Fig.4 demonstrates a reasonable agreement in the range of small scattering contributions.

Another study was made in Ref.[4] of Rayleigh scattering only of fluorescence photons in a constant-density atmosphere. Since the air density in a real atmosphere falls approximately exponentially with altitude, positions of shower front low above the horizon were selected from our simulations, to study light propagation in a near-constant air density. A comparison of the Rayleigh scattering only of fluorescence light with the results of [4] is shown in Fig.5. One can conclude therefore that a comparison of results of [7] and [4] with corresponding subsets of our results shows a satisfactory agreement.

Conclusion

A comprehensive study of multiple scattering contribution to shower signal as recorded by a fluorescence detector was made. This contribution is parameterized as a function of the signal collection angle ζ in the detector, the shower-detector distance, the shower front altitude above ground and the total horizontal attenuation length (Eq.1), or as a function of ζ, optical depth and altitude (Eq.2). The scattering contribution varies along the shower track, and may exceed 10% for distant showers low above the horizon. Failure to account for the multiple scattering effect may result in a *systematic* overestimation of the shower energy by a few percent.

Since the contribution to the signal received by a detector varies along the shower track, it may change the shape of the shower longitudinal profile, and in consequence, the reconstructed depth of shower maximum is affected. This change, however, is generally small, a few g/cm^2.

The parameterization of the scattering contribution presented in this paper can be readily implemented into existing algorithms of shower reconstruction in the fluorescence detection technique.

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