Fluorescence light curves based on energy deposited derived from CORSIKA

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Abstract

Distributions of energy deposited by a shower in the air through ionization as obtained from CORSIKA are used to derive the flux of light arriving at the fluorescence detector. The longitudinal profile of the light flux is constructed and compared to several real events recorded by the Engineering Array of the Pierre Auger Observatory.

1 Introduction

A reconstruction of an extensive air shower from the fluorescence detector (FD) raw data involves two main tasks: the geometrical reconstruction, i.e. determining the shower trajectory, and evaluation of the energy of the shower, after the geometry fit is done. In the latter task a longitudinal shower profile is determined, starting from the amount of light received by the FD and deriving the number of particles in the shower and hence – the energy of the primary particle.

Traditionally, the "bottom-up" reconstruction scheme is used [1] in which one converts the raw FADC data to the photon flux at the diaphragm $F(t)$. Taking into account the light propagation in the atmosphere, the number of particles in the shower, $N_{ch}(X)$, is determined as a function of atmospheric depth. Finally, using a fit of the Gaisser-Hillas function [2] to this $N_{ch}(X)$

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Preprint 11 February 2003
profile, the total energy of the shower is determined on the basis of an integral of energy deposited by the shower particles, with the assumption that all particles have the same ionization density. In an alternative approach, one starts with a simulation of the shower development in the atmosphere, getting a longitudinal profile of the light induced by the shower along its path. The light is then propagated towards the FD so that the profile of the light flux $F(t)$ arriving at the detector is obtained. The fluorescence yield per particle in a shower is not constant, but depends on the particle energy, more specifically – on its ionization density $dE/dX$ [3–5]. The total fluorescence signal of the shower is thus proportional to the energy deposited by the shower in the air through ionization. Distributions of the energy deposited are now available in the CORSIKA program [6]. Therefore, a possible reconstruction scheme would be to make an initial guess of direction and energy; perform multiple shower simulations with slightly varied primary parameters and for different primary particles; and finally pick the shower parameters which give the best agreement of simulation with measured data (see also [7]). In this paper, we apply the simulations of the shower image obtained using CORSIKA energy deposited distribution, to obtain longitudinal profiles of several events recorded by the Engineering Array (EA).

2 Simulations

The aim of these simulations is to derive the shower image, as recorded by the FD, from properties of the shower itself, properties of the light production process, light propagation in the atmosphere etc. As shown in detail in ref. [8], photons which constitute an instantaneous image of the shower (i.e. those arriving simultaneously to the FD) originate from a range of shower development stages. In [8] the NKG approximation of lateral distribution of particles in the shower was used, with a constant fluorescence yield per particle. Since the fluorescence yield is expected to be proportional to ionization density in the air along a particle track, the energy deposited through ionization by particles of the shower is a better parameter, than density of particles, to study light emission by the shower in the air.

The distribution of the energy deposited by the shower in the air is a convolution of the distribution of particles in the shower and the distribution of ionization density of particles. These distributions can now be simulated with CORSIKA program [9,10]. By these means, an instantaneous image of a shower was simulated [11]. In this paper we apply these simulations to obtain the longitudinal profile of a shower and compare the results with profiles of real showers recorded by the EA.

The simulation procedure is summarized below. As discussed in [8], the simul-
taneous photons i.e. those arriving during a small time window $\Delta t$, originate from surface $S$ shown in Figure 1. During this time window (corresponding to a change of the shower position in the sky by $\Delta \chi = 0.04^\circ$) the shower front moves downward along the shower axis by a small distance $R \Delta \chi$. This means that the small element of surface $S$ in polar coordinates corresponds to a small volume $\Delta V = r \Delta \phi \Delta r R \Delta \chi$, where $\Delta \phi$ and $\Delta r$ are steps in azimuth angle and in radial direction relative to shower axis and $R$ is the distance from the FD to the volume $\Delta V$. The volume $\Delta V$ is located between two CORSIKA observation levels $X_i$ and $X_{i+1}$. The distance between these two levels is divided into $N$ sublevels, each of them labeled by $n$. This situation is illustrated in Figure 1. The value of energy deposit in the volume $\Delta V$ at distance $r$ can easily be constructed by linear interpolation:

$$\rho(X_n, r) = \frac{(N - n)\rho(X_i, r) + n\rho(X_{i+1}, r)}{N}$$  \hspace{1cm} (1)

An additional linear interpolation in radial direction between bins of CORSIKA output was used to find the density $\rho(X_n, r)$ of energy deposit.  

Using the above interpolation, for the values of energy deposit $\rho(X_n, r)$, the number of photons $N_\gamma$ from the volume $\Delta V$ travelling towards the FD (without attenuation) can be calculated based on:

$$N_\gamma = \frac{\rho(X_n, r) dS}{(dE/dX)|_{1.4\text{MeV}}} \sum_{i=1}^{16} \epsilon_i g_i(\rho, T) \frac{\Delta \chi A}{4\pi R_p}$$  \hspace{1cm} (2)

where $i$ counts over 16 wavelength bins [12], $\epsilon_i$ is the fluorescence yield for 1.4 MeV electrons at pressure of 760 mm Hg and temperature of 14°C (see Figure 2A), $dS$ is a projection of surface $r \Delta \phi \Delta r$ into surface perpendicular to direction of the shower axis, $(dE/dX)|_{1.4\text{MeV}}$ is the electron energy loss evaluated at 1.4 MeV, $A$ is the light collecting area of an FD, $R_p$ is the shower impact parameter with respect to the 'eye' and $g_i(\rho, T)$ is a function describing the dependence of the fluorescence yield on density $\rho$ and temperature $T$. Kakimoto et al. [5] provided the analytical form of the $g_i(\rho, T)$ functions. For the 391.4 nm fluorescence line (13th bin in formula (2))

$$g_{13}(\rho, T) = \frac{\rho A_2}{F_1(1 + \rho B_2 \sqrt{T})}$$  \hspace{1cm} (3)

\footnote{The step in radial direction is equal $\Delta r = 1$ m and the binning of two-dimensional CORSIKA histograms of energy deposit is 1 m $\times$ 1 m at distances smaller than 20 m to shower axis, and 10 m $\times$ 10 m at larger distances.}
and for the rest of the fluorescence spectrum

\[ g_i(\rho, T) = \frac{\rho A_1}{2.760 F_1(1 + \rho B_1 \sqrt{T})} \]  

(4)

where \( \rho \) is in units of g/cm\(^3\) and T is in Kelvin. \( F_1, A_1, A_2, B_1 \) and \( B_2 \) are constants and are \( 1.044 \times 10^{-5} \), \( 0.929 \), \( 0.574 \), \( 1850 \), \( 6500 \), respectively. The number 2.760 is the total fluorescence yield outside the 391 nm band. In this way, the spatial distribution of points of origin of the simultaneous photons around the shower axis is obtained as well as distribution of their intensities. These photons are propagated towards the FD, so the attenuation of light on the way is taken into account.

In the region of wavelengths that are relevant to the FD, the main mechanisms of attenuation are Rayleigh scattering (on air molecules) and Mie scattering (on aerosols). The Rayleigh scattering is a relatively stable phenomenon which depends on the density profile of the atmosphere. Mie scattering, on the other hand, is a highly variable phenomenon which depends on aerosol composition and its vertical density profile. The amount of transmitted light \( T \) between a point of slant atmospheric depth \( X_1 \) at altitude \( h_1 \) and point of slant atmospheric depth \( X_2 \) at altitude \( h_2 < h_1 \) due to both Mie and Rayleigh scattering is described by [13]

\[ T = T_{Mie} \times T_R \]  

(5)

\[ T_R = \exp \left[ -\frac{X_1 - X_2}{X_R} \left( \frac{400}{\lambda} \right)^4 \right] \]  

(6)

\[ T_{Mie} = \exp \left[ \frac{h_{Mie}}{L_{Mie}(\lambda) \cos \theta} \left( \exp \left( -\frac{h_1}{h_{Mie}} \right) - \exp \left( -\frac{h_2}{h_{Mie}} \right) \right) \right] \]  

(7)

where \( X_R \) is the Rayleigh mean free path for scattering, \( L_{Mie} \) is the Mie mean free path, which is a strongly variable function of wavelength, see Figure 2B, \( h_{Mie} \approx 1.2 \) km is the aerosol scale height and \( \theta \) is the zenith angle of the light path.

In the Auger Observatory, the horizontal attenuation monitor (HAM) is used to measure the total light attenuation length. Since

\[ \frac{1}{L_{HAM}} = \frac{1}{L_R} + \frac{1}{L_{Mie}} \]  

(8)

the Mie mean free path \( L_{Mie} \) can be easily determined, assuming the (rather well known) Rayleigh scattering length: \( X_R = 2419 \) g/cm\(^2\) corresponding to \( L_R \approx 19.2 \) km at Malargüe.
The shower particles generate a large number of Cherenkov photons in the air. These photons undergo scattering in the atmosphere by Rayleigh and Mie scattering processes and some of them may reach the detector. In consequence, the light received by the FD is composed not only of fluorescence photons, but has a contamination from scattered Cherenkov photons. In our analysis, we assume that the Cherenkov photons in the shower have the same lateral distribution as that of charged particles. Additionally we used the Hybrid HDC [14] procedure for handling Cherenkov light, before a more accurate one is available, to calculate the amount of Cherenkov light at any point of the simultaneous surface. In this paper we show the calculated photon flux in which fluorescence dominates in the received signal (with Cherenkov contribution less than 15 % of the total signal), so possible inaccuracies in the Cherenkov photon distribution are not expected to strongly influence the results.

3 Results

Simulation runs were done for proton and iron showers with geometries and energies as reconstructed in several real events recorded by the FD telescopes of the EA. We’ll discuss in detail three events listed in Table 1. The total number of photons arriving to the telescope aperture from the shower at any stage of its development is calculated and rescaled to 100 ns time bins (the internal Table 1

The primary energies $E_0$, shower zenith angle $\theta$, azimuth angle $\phi$, core position $x_c$, $y_c$ relative to Los Leones and total horizontal attenuation length $L_{HAM}$ are listed for three EA events.

<table>
<thead>
<tr>
<th>Event</th>
<th>$E_0$</th>
<th>$\theta$</th>
<th>$\phi$</th>
<th>$x_c$</th>
<th>$y_c$</th>
<th>$L_{HAM}$</th>
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<tr>
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<td>(deg)</td>
<td>(deg)</td>
<td>(km)</td>
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<td>8.7</td>
<td>342.0</td>
<td>2.875</td>
<td>8.349</td>
<td>16.1</td>
</tr>
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<td>r236e336</td>
<td>9.81</td>
<td>26.4</td>
<td>196.2</td>
<td>2.813</td>
<td>10.751</td>
<td>12.7$^2$</td>
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<tr>
<td>r371e759</td>
<td>14.7</td>
<td>37.7</td>
<td>135.5</td>
<td>-0.258</td>
<td>12.145</td>
<td>11.7</td>
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</table>

$^2$ Default value at Malargüe. The real attenuation length was not measured for this event.
step in the simulation, $\Delta \chi = 0.04^\circ$, typically corresponds to $\Delta t = 3$ to $30$ ns, depending on shower geometry).

Thus a longitudinal shower profile is obtained, which can be compared to the measured photon flux in the real events. In the simulations we use the geometry and energy reconstruction results which are available on the web [15].

The run 229 event 269 (r229e269) will be disscused first. This is an almost vertical shower landing about 8.83 km from the FD (recorded in Los Leones Bay 4). The upper left plot of Figure 3 shows simulated arrival times $t_i$ (in 100 ns bins) versus the viewing angle $\chi$ (in radians). The viewing (elevation) angle $\chi$ is the angle a pixel direction makes with the horizontal line in the shower detector plane (see Figure 1). One can show that

$$ t_i = T_0 + \frac{R_p}{c} \tan(\theta_i/2) \quad (9) $$

where $t_i$ is the arrival time of light from shower segment $i$, $\theta_i = 90^\circ - \chi_i$ is the light emission angle from the shower axis, $R_p$ is the closest point of the shower track to the FD (the impact parameter) and $T_0$ is the time when the plane of shower front on the axis passes the point $R_p$. Simulated points agree very well with observed values of $t_i$ and $\chi_i$ for this event [15], so it can be treated as a test of the simulation geometry.

The upper right panel shows the longitudinal distributions of energy deposit for primary proton and iron showers versus slant atmospheric depth, with different depth of first interaction $X_0$ and depth of shower maximum $X_{\text{max}}$. Ten proton showers and five iron ones were simulated (see Table 2), of which several are shown in Figure 3. The lower left plot in Figure 3 shows simulated photon flux profiles $F_s(t)$ for these proton and iron primaries versus time from Table 2.

<table>
<thead>
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<td>54.90</td>
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<td>742</td>
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the beginning of FD trace in 100 ns bins, using the telescope aperture area
\[ A = \pi \times (1.1)^2 = 3.8 \, \text{m}^2 \] for Bay-4. Open triangles correspond to measured
data, color curves – to simulated showers listed in Table 2, and black line is
the photon flux obtained using constant value of fluorescence yield \( N_\gamma = 4.07 \)
photons/meter and Gaisser-Hillas function [2]. In this plot the default value of
the total (Rayleigh and Mie) horizontal attenuation length \( L_{HAM} = 6.8 \text{ km} \)
at 365 nm was used in the Hybrid-fadc simulation code [14]. The simulations
are about 15-20% lower than the measured values. Fortunately, for this event
there is a measured value of \( L_{HAM} = 16.1 \text{ km} \), so one can easily calculate
\( L_{Mie} = 99.7 \text{ km} \) at 365 nm, and using Figure 2B, for the remaining part of
the fluorescence spectrum.

We note that values of \( L_{Mie} \) are almost ten times larger than values of the core
distance parameter \( R_c = 9.17 \text{ km} \), so it means that contributions of Mie scattering
to the total signal will be negligible. On the other hand, measured values
of \( L_{HAM} \) are about 2 times larger than default values in the Hybrid-fadc
program, so the total signal should increase when we use the measured values of
\( L_{HAM} \) in the simulations, especially for larger atmospheric slant depth, where
light scattering is most important. Indeed, in the lower right plot the calculated
photon flux is always higher than the flux obtained using default values
of \( L_{HAM} \). The difference increases with increasing time from the beginning of
FD trace. This demonstrates the importance of atmospheric monitoring. We
notice that iron profiles fit on average better to the data but early developing
proton showers are similar to the iron curves.

Next we discuss the higher energy event, run 236 event 336 (r236e336), ob-
served from Bay-4. Unfortunately, for this event there is no measured value of
\( L_{HAM} \), so we used average values of \( L_{HAM} = 12.7 \text{ km} \) at 365 nm calculated for
Malargüe. Figure 4 shows the simulated time fit, longitudinal profile of energy
deposited and simulated photon flux at the diaphragm \( F(t) \) for five iron and
ten proton showers with different depth of first interaction and position of
shower maximum, see Table 3. A good agreement within about 10% is seen of

Table 3
The slant depth of first interaction \( X_0 \) and the depth of shower maximum \( X_{max} \) in
g/cm\(^2\) are listed for 10 proton and 5 iron simulation runs of r236e336 event.

<table>
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<td>712</td>
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the simulation profiles (color curves) with measured data (open triangles).

Despite the fluctuations in the raw data itself, one can see a better agreement with the iron simulated profiles than proton. However, two proton profiles (number 2 and 6) corresponding to showers with $X_{\text{max}}$ about 700 g/cm² fit the data just as well. We note that differences between the simulated $F_x(t)$ and the data could be due also to uncertainties in the primary energy assignment and due to an insufficient knowledge on atmospheric properties.

Finally, we discuss the results for run 371 event 759 (r371e759) recorded in Bay 5. In Figure 5 are shown the iron and proton profiles simulated for reconstructed energy $E_0 = 14.7$ EeV (in two middle panels). The two lower panels show the profiles simulated for the same event, assuming a primary energy higher by 30% ($E_0 = 19.1$ EeV). None of the profiles fits the data well. The differences suggest that the shower energy might be in excess of the assumed one. Further studies are under way.

Table 4
The slant depth of first interaction $X_0$ and the depth of shower maximum $X_{\text{max}}$ in g/cm² are listed for 10 proton and 5 iron simulation runs of r371e759 event, for energy 19.1 EeV.

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4 Summary and outlook

A first implementation of a "top down" approach for analysing the FD data has been presented. The simulated distributions of energy deposited by the shower in the air incorporate the variations of particle energies in the shower, and thus account for varying fluorescence yield of the shower particles. In addition, these simulations enable the study of shower profiles for various primary particles, therefore providing an additional constraint useful for identification of the primary.

The simulations presented here are not complete yet. The main improvement which will be made in the near future, is a more precise account of Cherenkov
light generated by the shower. So far the Hybrid_fadc procedure is used to handle Cherenkov photons. A more realistic distribution of Cherenkov photons in the shower can now be simulated with CORSIKA, so it will be implemented in the simulation chain. This is especially important for events in which the Cherenkov contribution is relatively large. Also, multiple scattering of light in the shower is not taken into account. At the moment we assume that the light scattering results in just an attenuation of the signal. However, multiple scattering can also increase the signal by contributing photons which would not get to the detector without being multiply scattered. We believe that the present results motivate further search for a more accurate description of the shower and of the process of its detection.

Acknowledgements. Special thanks to the teams BP² (Brian Fick and Paul Sommers, Bruce Dawson and Luis Prado) for providing the most up to date shower reconstruction parameters. This work was partially supported by the Polish Committee for Scientific Research under grant No. PBZ KBN 054/P03/2001 and by the International Bureau of the BMBF (Germany) under grant No. POL 99/013.

References


Figure 1 Geometry of an EAS as seen by the fluorescence detector. Photons which arrive simultaneously to the eye originate from surface S. See text for more details.
Figure 2 (A) The fluorescence yield (photons/meter) versus 16 wavelength bins for 1.4 MeV electrons at 760 mm Hg and 14° C used in the simulation of the photon flux. (B) The Mie mean free path versus wavelength, corrected according to the Pierre Auger observation level altitude ≈ 1.5 km. This dependence is scaled according to the actually measured value of $L_{Mie}$ at 365 nm.
Figure 3 Display of event r229e269 with primary energy of 2.22 EeV. The upper left part of this figure shows arrival time vs elevation angle. The upper right panel shows simulated longitudinal distributions of energy deposit for primary proton and iron showers at energy $E_0 = 2.22$ EeV as a function of slant depth. The lower left panel shows the calculated fluorescence flux at the telescope aperture versus time for Hybrid fac default values of Mie and Rayleigh scattering lengths. The lower right plot shows the fluorescence signal using the measured value of $L_{HAM}$. 
Figure 4 Display of event r236e336 with primary energy of 9.81 EeV. The upper left part of this figure shows arrival time vs. elevation angle. The upper right panel shows simulated longitudinal distributions of energy deposit for primary proton showers at energy $E_0 = 9.81$ EeV as a function of slant depth. The lower left panel shows the calculated fluorescence flux at telescope aperture versus time for primary iron showers. The lower right shows fluorescence signal using energy deposited for proton showers. The average values of Mie and Rayleigh scattering length for Malargüe were used.
Arrival time in 100ns bins

Viewing angle (rad)

Energy deposit (GeV/(g/cm²))

Slant depth (g/cm²)

Fluorescence/100ns (photons)

Time from the beginning of FD in 100ns bins

Iron showers, \(E_0=14.7\) EeV, \(L_{\text{Mie}}=29.95\) km, \(L_R=19.2\) km.

Proton showers, \(E_0=14.7\) EeV, \(L_{\text{Mie}}=29.95\) km, \(L_R=19.2\) km.

Iron showers, \(E_0=19.1\) EeV, \(L_{\text{Mie}}=29.95\) km, \(L_R=19.2\) km.

Proton showers, \(E_0=19.1\) EeV, \(L_{\text{Mie}}=29.95\) km, \(L_R=19.2\) km.

Figure 5. Display of event r371e759 with primary energy of 14.7 EeV (two middle panels) and 19.1 EeV (two lower panels). The reconstructed profiles at these two energies are compared to the measured profile, as in the previous events.