Shower Fluorescence Light Profile Derived from CORSIKA

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Abstract

Simulations of optical image of a shower are implemented into a procedure of shower energy determination. This "top-down" approach starts with shower development and fluorescence light production in the air, to obtain the expected detector response. In this paper, distributions of energy deposited by a shower in the air through ionization, as obtained from CORSIKA, are used to derive the flux of fluorescence light arriving at a detector. The longitudinal profile of the light flux is constructed and compared to real events recorded by fluorescence telescopes of 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 position of the shower axis, and evaluation of the energy of the shower, after the geometry fit is done. In the latter task, a longitudinal shower profile, i.e. the number of shower particles $N_{ch}(X)$ as a function of atmospheric depth, is determined based on the amount of light received at the FD and hence – the energy of the primary particle is inferred.

Traditionally, the "bottom-up" reconstruction scheme is used, 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 longitudinal shower profile is determined. Finally, using a fit of the Gaisser-Hillas function to this $N_{ch}(X)$ 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 average ionization density. In an alternative "top-down" 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 through a realistic atmosphere towards the

pp. 627–630

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 ionization density [6]. The total fluorescence signal of the shower is thus assumed to be proportional to the energy deposited by the shower in the air through ionization. Distributions of the energy deposited are now available from the CORSIKA shower simulation software [5,7]. Therefore, a possible reconstruction scheme would be to make an initial estimate of shower 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. The feasibility of such a procedure is shown here. A similar approach has also been started elsewhere [4].

2. Simulations

The distribution of energy deposited by a 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 the CORSIKA program. On the other hand, photons which arrive simultaneously at the detector, i.e. those which constitute an instantaneous image of the shower, originate from a range of shower development stages. The CORSIKA program provides particle distributions at a set of altitudes in the atmosphere. By using an appropriate interpolation procedure, presented in detail in Ref. [3], one can derive the required 3-dimensional particle distribution.

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 the photon intensities. These photons are propagated towards the FD, so the attenuation of light through Rayleigh scattering (on air molecules), Mie scattering (on aerosols) as well as scattered Cherenkov photons are taken into account in the simulation software (Hybrid_fadc [2]). In this paper, we show the calculated photon flux in which fluorescence dominates the received signal, so possible inaccuracies in the Cherenkov photon distribution are not expected to strongly influence the results.

3. Preliminary results

Simulation runs were done for proton and iron showers with geometries and energies as reconstructed using the traditional bottom-up procedure in two real events recorded by the FD telescopes of the Engineering Array of the Pierre Auger Observatory [1].

The Event1 will be discussed first. Ten proton showers and five iron ones were simulated with different depth of first interaction X_0 and depth of shower maximum X_{max}, of which several are shown in Fig. 1A. This Figure shows simulated photon flux profiles $F_s(t)$ for these proton and iron primaries versus time.

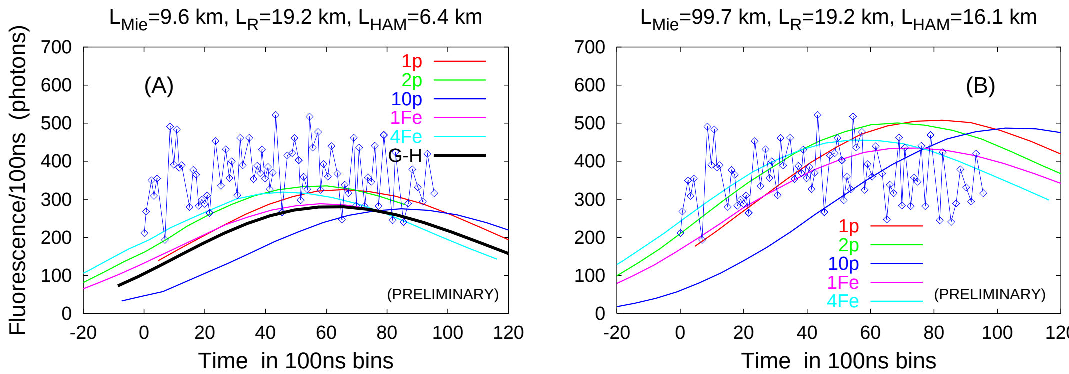

Fig. 1. The calculated fluorescence flux at telescope aperture using energy deposited from CORSIKA. (A) Display of Event1 using Hybrid_fadc default values of Mie and Rayleigh scattering lengths and (B) with a measured value of L_{HAM} from the horizontal attenuation monitor.

The recorded light profile is shown as data points, the color curves represent the simulated showers and the black thick line is the photon flux calculated using a constant value of fluorescence yield $N_\gamma = 4.07$ photons/meter and the Gaisser-Hillas function. In this plot the default value of the total (Rayleigh and Mie) horizontal attenuation length* ($L_{HAM} = 6.4$ km at 365 nm) was used in the simulation code. The simulations are about 15-20 % lower than the measured values. Fortunately, for this event there is a measured value of $L_{HAM} = 16.1$ km [1], so one can easily calculate $L_{Mie} = 99.7$ km at 365 nm. We note that measured value of L_{HAM} is about 2 times larger than the default value in the Hybrid_fadc program, so the total received signal should increase when we use the measured values of L_{HAM} in the simulations, especially for larger atmospheric depth, where light scattering is most important. Indeed, in the plot shown in Fig. 1B the calculated photon fluxes are always higher than the fluxes obtained using the default value of L_{HAM}, shown in Fig. 1A. The difference between new and old fluxes increases with increasing time from the beginning of FD trace, i.e. with atmospheric depth in this case. This demonstrates the importance of atmospheric monitoring.

Next we discuss the Event2. Unfortunately, L_{HAM} was not measured for this event, so we used the average value of $L_{HAM} = 12.7$ km at 365 nm measured at the Auger Observatory. Fig. 2A and 2B show the simulated photon flux at the diaphragm $F_s(t)$ for four iron and ten proton showers with different depth of first interaction and position of shower maximum. An agreement within about 10% is seen of the simulation profiles (color curves) with measured data (diamonds). Despite the fluctuations in the raw data itself, one can see a better agreement

*$1/L_{HAM} = 1/L_R + 1/L_{Mie}$; L_{Mie} and L_R are the Mie and Rayleigh scattering lengths, respectively.

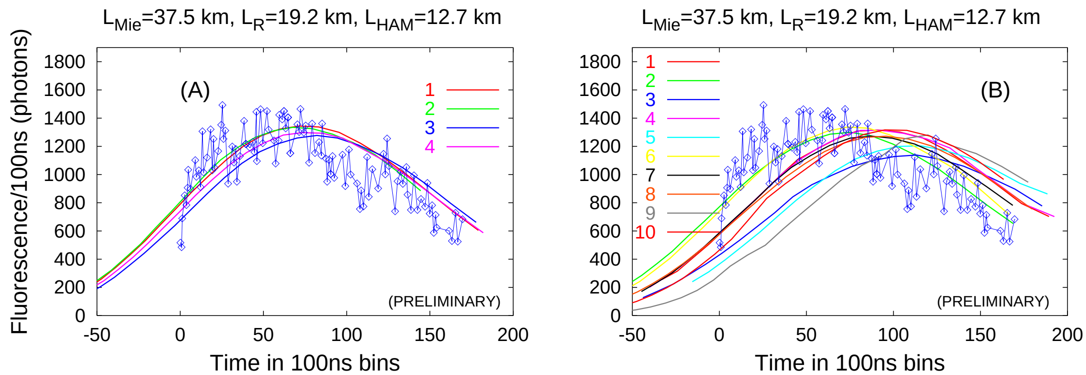

Fig. 2. The calculated fluorescence flux at telescope aperture using energy deposited from CORSIKA. Display of Event2: (A) the fluorescence signal using energy deposited for iron showers and (B) for proton showers.

with the iron simulated profiles than with the proton ones. However, two proton profiles (numbers 2 and 6), corresponding to showers with X_{max} about 700 g/cm^2 fit the data just as well. We note that differences between the simulated $F_s(t)$ and the data could be due to inaccurate assignment of primary energy and/or to an inaccurate L_{HAM}. Measurement of atmospheric attenuation is essential. Then, by varying the energy, one can find its value for which best agreement with data is obtained.

In summary, a first implementation of the "top-down" approach to analyzing the fluorescence detector data based on CORSIKA energy deposits 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 they will provide an additional constraint useful for identification of the primary.

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