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Air Shower Simulation with CORSIKA in the Presence of Atmospheric Electric Fields

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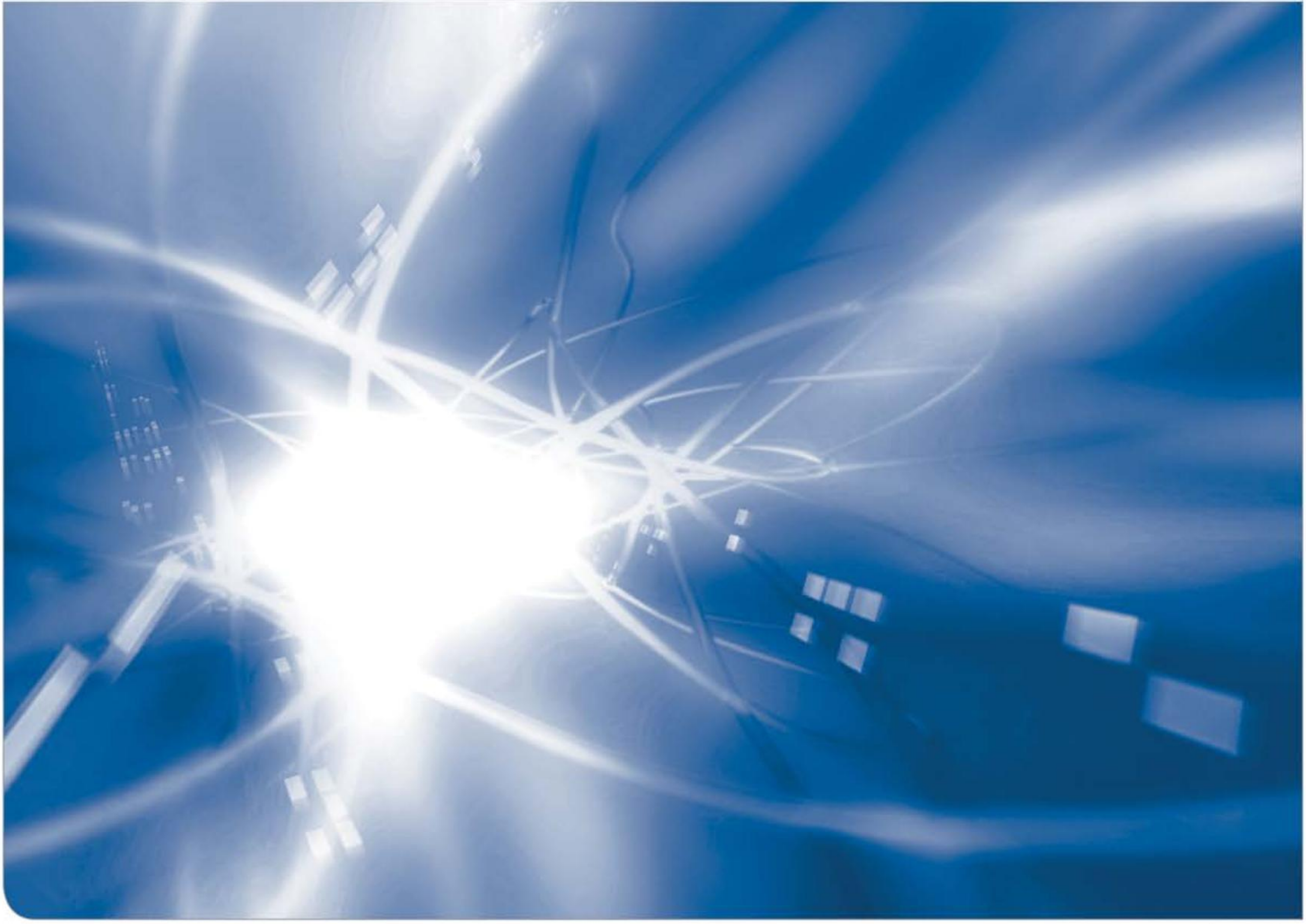

KIT – University of the State of Baden-Wuerttemberg and National Research Center of the Helmholtz Association

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Impressum

Karlsruher Institut für Technologie (KIT)
www.kit.edu

2012

ISSN 2194-1629

Abstract

Air Shower Simulation with CORSIKA in the Presence of Atmospheric Electric Fields

This report describes the modifications of the air shower simulation program CORSIKA to take into account the influence of atmospheric electric fields on charged shower particles. Atmospheric electric fields are observed in thunderstorms. Only in the transport of the electrons rsp. positrons the effects are large enough to be considered.

Zusammenfassung

Luftschauer-Simulation mit CORSIKA in der Gegenwart von atmosphärischen elektrischen Feldern

Dieser Bericht beschreibt die Modifikationen des Luftschauer-Simulationsprogramms CORSIKA um den Einfluß atmosphärischer elektrischer Felder auf geladene Schauerteilchen zu berücksichtigen. Solche elektrischen Felder werden in Gewittern beobachtet. Nur beim Transport von Elektronen bzw. Positronen sind die Effekte groß genug um sie in Betracht zu ziehen.

Contents

1 Introduction

Atmospheric electric fields can influence the development of cosmic air showers. In the standard version of the Extensive Air Shower (EAS) simulation code CORSIKA [1] the effects of atmospheric electric fields are not included. Especially in thunderstorms, where electric fields with strengths of the order up to 1 kV/cm may appear, the movement of the electromagnetic particles becomes affected. To study this influence the EFIELD option has been added to the EAS simulation program CORSIKA. Depending on the movement of the electromagnetic particles relative to the direction of the electric field two effects have to be considered: In case the electrons (rsp. positrons) move parallel to the electric field strength they suffer an acceleration (i.e. they gain or loose energy), while in the case of electric fields perpendicular to the electron movement the electron traces become curved by the particle deflections.

In most cosmic ray experiments these effects are too small to be detected by the ground detectors, but the influences on the emission of radio pulses from the atmospheric shower will not be negligible [2]. So an important application of the new EFIELD option is to simulate the modifications of radio pulses from cosmic showers in the presence of thunderstorms [3]. These simulation results might afterwards be compared with measurements of experiments like LOPES [4] or AERA [5].

A possible influence of atmospheric electric fields on the number of gamma rays and electrons (rsp. positrons) from vertical showers arriving at the Pierre Auger Observatory [6] and on the bending of the muon arrival directions in highly inclined showers is discussed in Ref. [7].

This report describes how an electric field is considered in the CORSIKA programming. In Sect. 2 the normal treatment of the eletron (resp. positron) transport in the subroutine $ELECTR$ is explained. The necessary modifications of this subroutine for the EFIELD option are discussed in Sect. 3. Sect. 4 describes how the user can specify the electric field strength as function of the space coordinates by programming the subroutine $elfield$.c.

2 Transport of Electrons/Positrons in CORSIKA

Within CORSIKA the transport of electron rsp. positron particles is treated in the subroutine $ELECTR$ of the taylor-made version of the **E**lectron **G**amma **S**hower code EGS4 [8] which is adapted to the barometric atmosphere with a density decreasing exponentially with increasing altitude.

The mean free path to the next interaction is determined by the (energy dependent) total cross section for electrons/positrons which is the sum of all cross sections for Bremsstrahlung, annihilation, Molière multiple scattering, and Møller (e^- e^-) rsp. Bhabha (e^+ e^-) scattering. This total cross section SIG0 is interpolated from tables established with the PEGS4 program. These tables are contained within the `EGSDAT6_xx` file which is read in by the subroutine $HATCH$ during the initialization phase of CORSIKA. The individual range STEP of the electrons/positrons to the next interaction is calculated as

$$\mathrm{STEP} = -log(\mathrm{RNDM})/\mathrm{SIG0} \tag{1}$$

where RNDM is a random number.

This step length may be reduced by limitations imposed from the energy loss in collisions as determined by the (restricted) Bethe-Bloch stopping power with Sternheimer treatment of the density effect and from the energy loss in 'soft Bremsstrahlung' processes. To save computing time the explicite generation of Bremsstrahlung photons below the photon threshold is not simulated, rather the energy loss of the charged particle is subsumed into the tables of the continuous energy loss. The interested reader may find further details in the EGS4 manual [8].

The step size resulting from these limitations is corrected for the altitude dependent barometric density. A further range limitation is applied by the deflection in the Earth's magnetic field in a manner which ensures the bending angle of the particle path to be smaller than 0.2 rad. The treatment of the deflection of electrons/positrons in a magnetic field is described in the EGS4 manual (see p. 127 of Ref. [8]).

Before undergoing an interaction it is checked that the particle is transported completely over the original distance of Eq. (1) to the next interaction point and eventual step size reductions e.g. by multiple scattering or magnetic field bending limitations are compensated for by performing additional transport steps.

3 Modifications of the Subroutine ELECTR

To take into account the influence of an electric field on the transport of electromagnetic particles the CORSIKA subroutine $ELECTR$ has to be extended. This extension follows the programming of the procedure `emf_macros.mortran` which is contained within the `egs4unix_3.2` package available from Ref. [9]. This macro has been developed by A.F. Bielajew [10], and his derivation of the formulas which form the basis of the programming is used as guidance for the following.

An electric field $\vec{\mathcal{E}}$ acting on a charge q causes a force $\vec{\mathcal{F}}$ on this charge which finally results in a change of its momentum $\vec{p}$ with time t. This is given by the relation

$$\vec{\mathcal{F}} = \frac{d\vec{p}}{dt} = q\vec{\mathcal{E}} \, . \tag{2}$$

The relativistic electron momentum $\vec{p}$ is expressed by the electron rest mass $m_\circ$, the velocity $\vec{\beta}$ in units of the speed of light c, and the usual relativistic factor $\gamma = 1/\sqrt{1-\beta^2}$ to

$$\vec{p} = m_\circ c \gamma \vec{\beta} \, .$$

As one is interested in the momentum change as function of the electron movement path one uses the differential path length ds which is related to the time t by

$$ds = (ds/dt)dt = (c\beta)dt \, .$$

Therefore Eq. (2) may be rewritten to

$$\frac{d(\gamma\vec{\beta})}{ds} = \frac{q}{m_\circ c^2 \beta}\vec{\mathcal{E}} \, . \tag{3}$$

The differential operator on the left hand side of Eq. (3) may be expressed as $d(\gamma\vec{\beta}) = \gamma^3\vec{\beta}(\vec{\beta}\cdot d\vec{\beta}) + \gamma d\vec{\beta}$. So the left hand side of Eq. (3) may be rewritten as

$$\frac{d(\gamma\vec{\beta})}{ds} = \gamma(\gamma^2\vec{\beta}\vec{\beta} + 1)\frac{d\vec{\beta}}{ds} \, . \tag{4}$$

Replacing γ^2 by $1/(1-\beta^2)$ simplifies the bracket on the right hand side of Eq. (4). Thus Eq. (3) can be rewritten to

$$\frac{d\vec{\beta}}{ds} = \frac{q}{m_\circ c^2 \beta\gamma}(\vec{\mathcal{E}} - \vec{\beta}(\vec{\mathcal{E}}\cdot\vec{\beta})) \, . \tag{5}$$

For a constant electric field independent of the position the general solution of the equation of motion Eq.(5) leads for the position coordinate $x_\parallel$ parallel with the electric field to an expression with terms in $\cosh$ and $\sinh$ of the argument $q\mathcal{E}x_\perp/(m_\circ c^2\gamma\beta_\perp)$ where $x_\perp$ and $\beta_\perp$ are the components perpendicular to the electric field. If the field strength is not too strong one can expand the hyperbolic functions in power series retaining the linear term in the field strength, which results in

$$x_\| \approx \frac{\beta_\| x_\perp}{\beta_\perp} + \frac{q\mathcal{E}x_\perp^2}{2m_\circ c^2\gamma\beta_\perp^2} \; .$$

The values of β and γ are the initial values at the begin of the deflection step. The position coordinates perpendicular to the electric field are not affected by the electrical field.

The program modifications in the subroutine $ELECTR$ which are applied in the EFIELD option are collected in several blocks of statements. The components of the electric field vector at the starting point of the transport step are gained by a call to the subroutine $elfield$.c, which is described in Sect. 4 below. Additional program statements check whether the step size to the next interaction point eventually has to be shortened to prevent that the deflection in the electric field exceeds 0.02 rad (about 1.14°). A second criterion for the reduction of the step size demands that the energy change (increase or decrease) by the electric field should not exceed 2% of the energy at the begin of the step.

For this eventually reduced step size the transport parameters like deflection in the magnetic field, distance to the next layer boundary of the 4-layer atmosphere model, correction of the local step length according the varying density of the atmosphere etc. are calculated as usual.

A second call of the subroutine $elfield$.c gives the components of the electric field vector at the end of the transport step. Further program statements are added to calculate the modified direction of the particle movement at the end point of the transport step caused by the deflection within the electric field. The appropriate program statements which perform the changes in the direction of the particle movement work in analogy with the particle deflection in the magnetic field (see p. 127 of Ref. [8]) considering the average electric field strength between the start and the end point of the step. As both kinds of deflection - by magnetic and by electric fields - are kept small by the limitation of the step size, these two contributions are treated independently and are superimposed, neglecting higher order terms which might come in if both fields are strong, or if the transport step is very large. At the end of the transport step the change (gain or loss) of the particle energy by an electric field component parallel to the particle movement direction is applied. By the step size limitation it is guaranteed that these changements in the energy during the step are small enough to neglect higher order effects e.g. in the transport time needed for the considered step.

4 How to Specify the Electric Field

The subroutine $elfield$.c defines the functional dependence of the electric field strength on the space coordinates. It has to be written in the C-language. The subroutine example which is delivered with the CORSIKA program package forms a template which gives a zero electric field. This template offers the user a basis for his own modelling of an arbitrary electric field. For the modification of this subroutine an ordinary text editor is sufficient. The $./coconut$ configuration and installation tool automatically compiles the $elfield$.c subroutine and links it with the compiled CORSIKA program if the EFIELD option has been selected in the configuration step.

In calling the $elfield$.c subroutine from the $ELECTR$ subroutine (see Sect. 3 above) the input variables x, y, and z are transmitted giving the position (in cm) at which the field components have to be calculated. The variables x and y refer to the intersection of the shower axis with the lowest observation level (also in combination with the CURVED option), while the zero point of the z-coordinate is defined at sea level. For the definition of the coordinate system see Fig. 1 of Ref. [11]. The output variables $\mathrm{U_x}$, $\mathrm{U_y}$, and $\mathrm{U_z}$ give the components of the electric field strength vector (in V/cm). Any functional form of the field strength dependence on the space coordinates may be defined by the user. All variables transferred to and from the $elfield$.c subroutine are defined as double precision variables.

Normally the electric field is caused by weather conditions, thunderstorms etc., so the electric field does not extend into the stratosphere. Such an extension would eventually generate unrealistic effects, as in those altitudes the energy loss by ionization or radiation of the electromagnetic particles is rather low because of the low atmospheric density, while with a constant electric field up to the border of the atmosphere (which is defined in the CORSIKA program at an altitude of 112.8 km) the energy gain may overcompensate the radiative energy loss. This would lead to unrealistic avalanche processes in the early stages of the shower development.

Defining an electrical field configuration the user is responsible that no electrical potential difference should remain between the top of the atmosphere (entrance of the primary particle into the atmosphere) and the ground level.

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ISSN 2194-1629

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