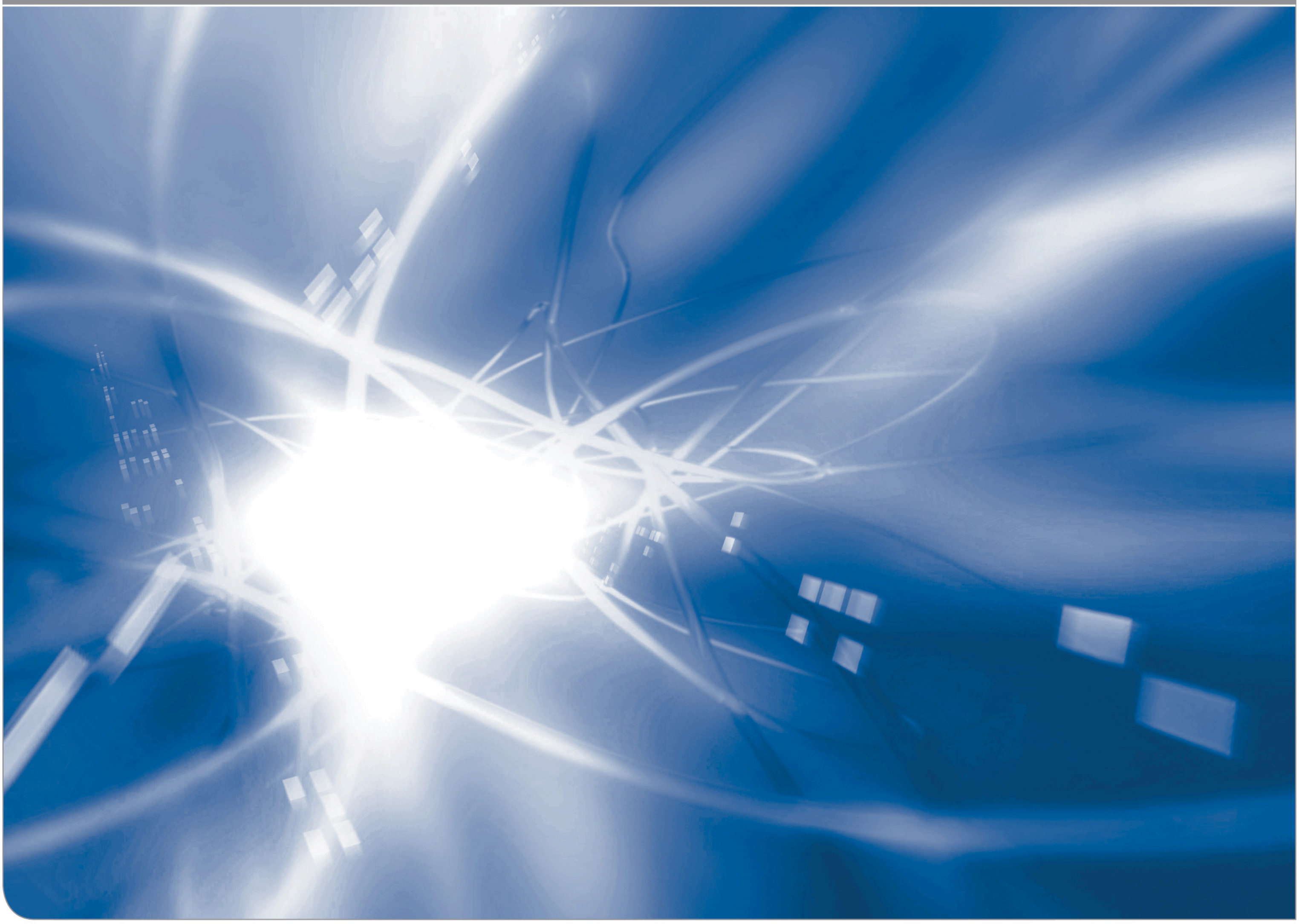
Karlsruhe Institute of Technology

# The TRAJECT Option of the Air-Shower Simulation Program CORSIKA

by M. Doert[1], D. Heck[2]

KIT SCIENTIFIC WORKING PAPERS 1



[1] Fakultät Physik, Technische Universität Dortmund
[2] Institut für Kernphysik, Karlsruher Institut für Technologie (KIT)

**Impressum**

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



2012

ISSN 2194-1629

# Abstract

**The *TRAJECT* Option of the Air-Shower Simulation Program CORSIKA**

This report describes the implementation of the *TRAJECT* option into the Air-Shower Simulation Program CORSIKA. All needed additional input parameters are explained. As an example the arrival directions of the gamma rays coming from the Crab Nebula are simulated for the MAGIC Cherenkov telescope experiment.

# Zusammenfassung

**Die *TRAJECT*-Option des Luftschauer-Simulationsprogramms CORSIKA**

Dieser Bericht beschreibt den Einbau der *TRAJECT*-Option in das Luftschauer-Simulationsprogramm CORSIKA. Alle benötigten zusätzlichen Eingabeparameter werden erklärt. Als Beispiel werden die Ankunftsrichtungen der Gammastrahlung, die vom Krebs-Nebel kommen, für das MAGIC Cherenkov-Teleskop Experiment simuliert.

# Contents

# 1 Introduction

In the standard version of the air-shower simulation program CORSIKA [1] an angular range between minimum and maximum values of the zenith ($\theta$) and azimuth ($\phi$) angle for the direction of the arriving primary particles can be defined. The showers are simulated in a manner covering this range with uniform intensity[1] in $\sin(\theta) \cdot \cos(\theta)$ and $\phi$. For many applications this range is too large and may be restricted e.g. by the *VIEWCONE* option onto a cone with defined opening angle around the fixed direction of $\theta$ and $\phi$.

But to follow a stellar object on its trajectory across the sky this selection of the angles is less suited. Rather one needs a special generation of pairs of zenith and azimuth angles, which move along with the celestial coordinates of the stellar object. Such trajectories also depend on the terrestrial coordinates of the detector and on the time interval of the observation, with which the simulated showers should be compared. To match these specifications, which are primarily required for e.g. Cherenkov telescopes observing $\gamma$-ray emitting sources, the new *TRAJECT* option has been developed.

[1] The zenith angular dependence of the intensity varies in its functional form depending whether the options *VOLUMEDET* or *VOLUMECORR* are selected, see Ref. [2]

# 2 TRAJECT Option

This option allows to produce the simulated shower events along a source trajectory in the sky, in order to match the incident angle distributions of the simulations and data from pointed telescope observations better. While an Earth-bound telescope observes a source, this source moves along a certain trajectory in the sky (defined by zenith and azimuth coordinates). The *TRAJECT* option simulates events along this very trajectory, instead of producing the simulated events from fixed zenith-azimuth positions or within static zenith and azimuth bins. This way, the zenith-azimuth coordinates of the simulated showers are matching the positions where the source was actually observed in the best possible way.

For the calculation of this trajectory, the source's coordinates in the equatorial system, i. e. right ascension and declination, and information about the observation time are required to perform the transformation from equatorial to horizontal coordinates. The needed parameters are the date and start time of the observation and its duration.

To calculate the incident angles for each event, the duration of the observation is divided into single steps and the coordinate conversion is done for each time step by the subroutine *SOURCEPATH*, whereby the number of steps is determined by the number of events to generate.

The keyword

```
TRAFLG   F
```

decides if the trajectory calculation shall be carried out for the simulation run. The keyword

```
SRCPOS    5.57   22.0
```

defines the position of the observed source in equatorial coordinates. Following the keyword

```
TRATM    2000   1   1   21   0   0   3600
```

the time information of the observation which shall be simulated can be set.

The keywords

```
TLAT    28.   45.   42.462  'N'
```

and

```
TLONG    17.   53.   26.525   'W'
```

define the geographic latitude and longitude of the telescope site, while

```
GEODEC    -6.35
```

indicates the geomagnetic declination at the telescope site, e.g. the angle between the geographic and the magnetic North. The keyword

```
TRARAD    0.
```

allows to simulate a broader trajectory, e.g. as an extended source moving in the sky.

# 3 TRAJECT Keywords

In the following the new keywords and their meaning are listed. All these keyword are only availalbe in the *TRAJECT* option.

## 3.1 TRAJECT Selection Parameter

```
TRAFLG    TLOGIC
```

Format = (A6, L), Default = F
TLOGIC: If .true., the zenith and azimuth coordinates of each shower event are determined by the subroutine *SOURCEPATH*.
The determination of the angles by other CORSIKA options (VIEWCONE, VOLUMECORR, or VOLUMEDET) or by the keywords THETAP and PHIP is disregarded.

## 3.2 TRAJECT Source Position Parameters

```
SRCPOS    RA   DEC
```

Format = (A6, 2F), Defaults = 5.57, 22.0
RA: Defines the simulated source's Right Ascension coordinate (in hours).
DEC: Determines the declination coordinate (in degrees).
Limits are: $0. <$ RA $< 24.$; $-90. <$ DEC $< +90.$ .
The default values represent the position of the Crab Nebula.

## 3.3 TRAJECT Telescope Site Parameters

```
TLAT    TLATDGR   TLATMIN   TLATSEC   TLATDIR
```

Format = (A4, 3F, A1), Defaults = 28., 45., 42.462, 'N'
TLATDGR : Latitude of the telescope site (in $^\circ$).
TLATMIN : Latitude of the telescope site (in min).
TLATSEC : Latitude of the telescope site (in sec).
TLATDIR : Direction North = 'N', South = 'S' of the latitude of the telescope site.
Limits are: $0. \leq$ TLATDGR $\leq 90.$; $0. \leq$ TLATMIN $\leq 60.$; $0. \leq$ TLATSEC $\leq 60.$; TLATDIR = 'N' or 'S'.
The default values give the site of the MAGIC telescope.

```
TLONG     TLONGDGR    TLONGMIN    TLONGSEC    TLONGDIR
```

Format = (A5, 3F, A1), Defaults = 17., 53., 26.525, 'W'
TLONGDGR : Longitude of the telescope site (in °).
TLONGMIN : Longitude of the telescope site (in min).
TLONGSEC : Longitude of the telescope site (in sec).
TLONGDIR : Direction East = 'E', West = 'W' of the longitude of the telescope site.
Limits are: 0. $\leq$ TLONGDGR $\leq$ 180.; 0. $\leq$ TLONGMIN $\leq$ 60.; 0. $\leq$ TLONGSEC $\leq$ 60.; TLONGDIR = 'E' or 'W'.
The default values give the site of the MAGIC telescope.

```
GEODEC     GEODECL
```

Format= (A6, F), Default = -6.35
GEODECL: Defines the geomagnetic declination[2], i.e. the directional deviation between the geographic and the magnetic North (in degrees).
Limit is: -45. $\leq$ GEODECL $\leq$ +45. .
The default values give the site of the MAGIC telescope.

## 3.4 TRAJECT Observation Time Parameters

```
TRATM  TYEAR TMONTH TDAY THOUR TMINURE TSECOND  TDURATION
```

Format = (A5, 7I), Defaults = 2000, 1, 1, 21, 0, 0, 3600
TYEAR, TMONTH, TDAY, THOUR, TMINURE, TSECOND: Define the start time of the simulated observation (in year, month, day, hour, min, sec, given in Universal Time).
TDURATION: Determines the duration of the observation (in sec).
Limits are: Only valid values for date and time are admitted; $0 <$ TDURATON.

## 3.5 TRAJECT Broadening Parameter

```
TRARAD     TRAD
```

Format = (A6, F), Defaults = 0.
TRAD: Defines the radius of a spread around the calculated trajectory, (in arcmin).
Limit is: 0. $\leq$ TRAD $\leq$ 3600. .

[2]The sign of the declination is defined positive for eastward declination, negative for westward declination, see also Ref. [3]

# 4 Examples for the Simulated Angular Distribution

The results of the *TRAJECT* option are displayed here, after being processed by the MAGIC detector simulation. In Fig. 1, the zenith vs. azimuth distribution of Monte Carlo files, which have been produced for an exemplary data set, can be seen. The data set contains 149 minutes of observations of the Crab Nebula, covering a zenith angle range from 15° to 47°. The simulated file contains 5000 events. In the upper panel of the Figure, a point source type simulation of the trajectory can be seen. The simulation of a broader trajectory, e.g. to mimic an extended source, is shown in the lower panel for an exemplary source radius of 30 arc minutes.

In case the whole visible sky trajectory from e.g. the Crab Nebula is needed, an exemplary time coordinate set has to be found, which describes the rise of the source at e.g. 50 degrees zenith and the duration till it sets again at the same zenith angle. With this information, the *TRAJECT* option can produce events covering the whole visible sky trajectory of the respective source. The resulting angular distribution of such a simulation for the Crab Nebula can be seen in Fig. 2. To illustrate the compatability of the simulated and the actually observed angles, the pointing positions of randomly chosen Crab Nebula (on source) observations with the MAGIC telescopes [4] have been superimposed.

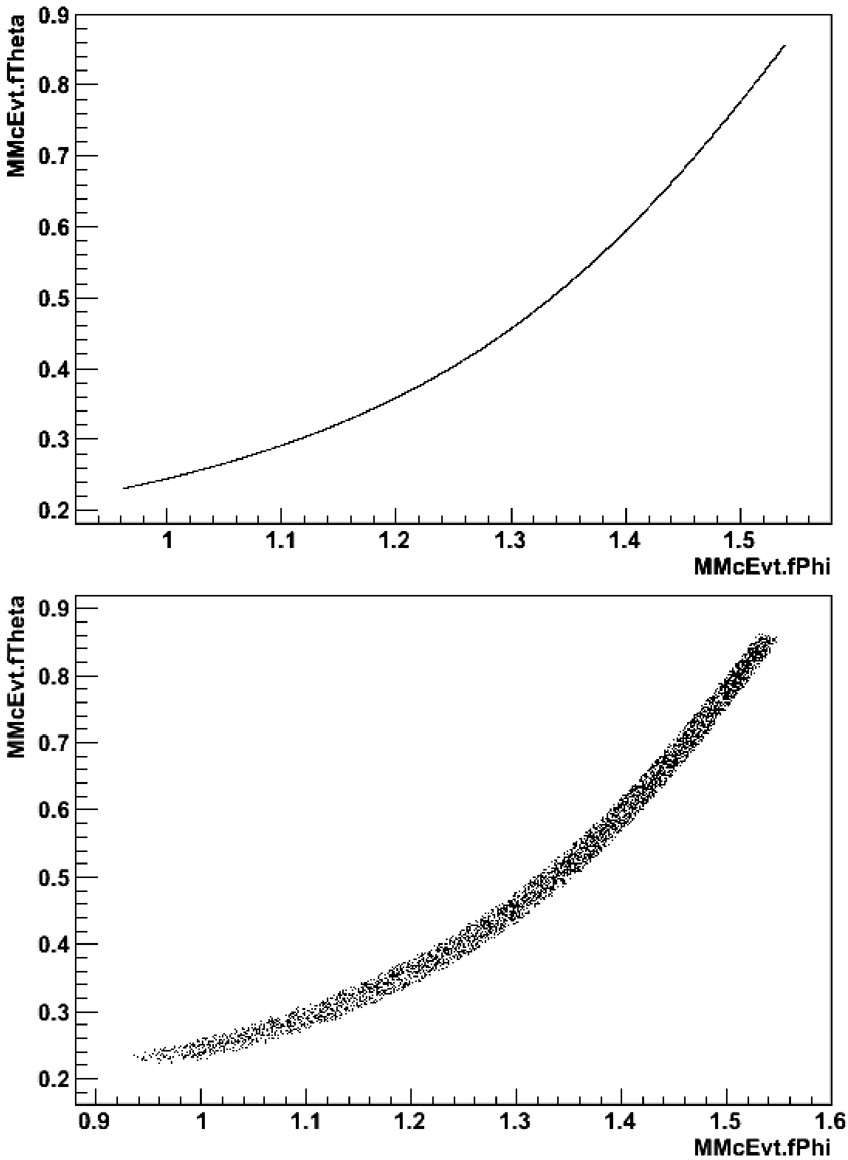



Figure 1: Angular distribution of Monte Carlo files produced with the CORSIKA *TRAJECT* option. The parameters are adjusted to an exemplary data sequence, which contains 140 minutes of observation of the Crab Nebula. 5000 events have been generated. Plotted is the zenith angle (in rad) vs. the azimuth angle (in rad). In the upper panel the simulation of a point source is shown. The bottom panel shows the simulation of a source with radius r $=$ 30 arcmin.

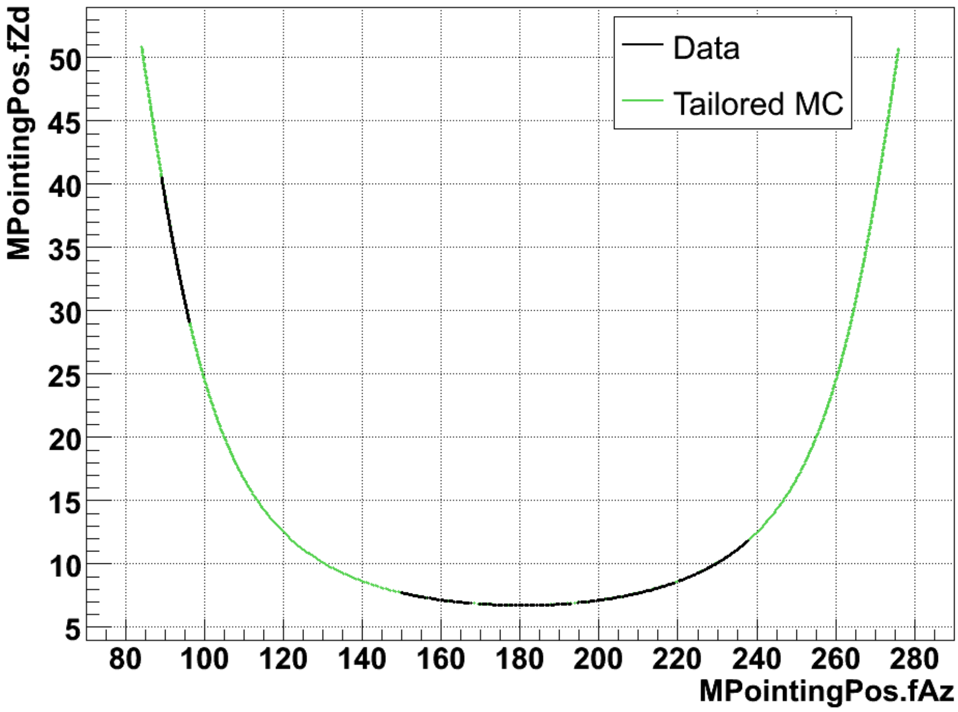



Figure 2: Simulated events for the whole visible trajectory of the Crab Nebula. Plotted is the zenith angle (in deg) vs. the azimuth angle (in deg). The green curve (consisting of unresolved points) shows the distribution of the simulated events. Superimposed in black are data points from randomly chosen telescope observations of the Crab Nebula.

## 4.1 Implementation

In the following section, the implementation of the routine into the CORSIKA code will be described in detail.

For the implementation of this new routine in the CORSIKA program, several additions had to be introduced to the original code of the program. Changes have been made in the routine reading the input file as well as in the main program, and four new routines have been added.

An overview of what has been done can be seen in Fig. 3. In the following the constituent steps of the implementation will be explained.

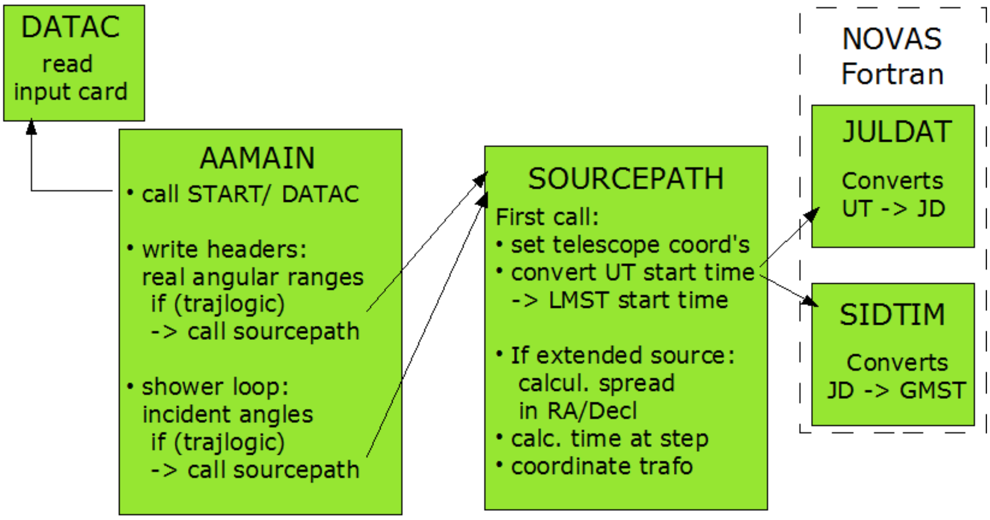



Figure 3: Overview of the implementation of the CORSIKA *TRAJECT* option. Changes have been made in the main program *AAMAIN* and the input file read-in routine *DATAC*. The time conversion routines *JULDAT* and *SIDTIM* have been adapted from the NOVAS library [5]. The subroutine *SOURCEPATH* has been newly implemented. It calls the time conversion, calculates the spreading for extended source simulation and performs the coordinate conversion.

## 4.2 Input Parameter Treatment

As seen before, the *TRAJECT* option needs some additional input information which has to be stated in the input file. Consequentially, these input parameters are introduced to and read in by the CORSIKA program.

First of all the new parameters are declared in every routine (and the main program), where these are used. The assignment of default values and the read-in of the values given in the input file have been extended by the new parameters in the routine *DATAC*.

## 4.3 Validity Check of Input Parameters

After reading the input parameters from the input file they are checked for validity, i.e. if they are within their legal range. This control is performed in the subroutine *TRAJCHECK*. As the parameters of the *TRAJECT* option are used before calling the subroutine *INPRM* which usually accomplishes the consistency checks of all CORSIKA input parameters, this extra routine had to be written and has to be called before the first usage of the *TRAJECT* parameters.

## 4.4 Time Conversion Routines

As the time information is stated as Universal Time in the input file, but for the coordinate transformation local sidereal time is needed, some time conversions had to be made. For these transformations, two routines from the NOVAS [3] library [5] have been added to the CORSIKA program: *JULDAT* and *SIDTIM*.

*JULDAT* receives a UT time, stated by giving year, month, day and hour[4] and converts it to Julian Date.

*SIDTIM* takes a time in Julian Date and converts it to Greenwich Mean Sidereal Time `GMST`.

## 4.5 Calculation of the Trajectory

The core of the new option is formed by the newly written subroutine *SOURCEPATH*.

In there the coordinates of the telescope site are set, the time conversion routines are called, the simulation of the extended source is done and, the most important part, the coordinate transformation from equatorial to horizontal coordinates is carried out for every step along the trajectory. From there, the zenith and azimuth angles describing the source's trajectory in the sky are returned.
The routine is called from the *AAMAIN* program at each step of the event loop separately.
When the subroutine is called for the first time, a general setup is done.

- First the telescope site coordinates are set. As an example the current default values are the coordinates of the MAGIC site [4]:

[3] NOVAS: Naval Observatory Vector Astrometry Subroutines

[4] The hour is given as a floating point variable, which also includes minutes and seconds as the fraction of an hour.

Geographic longitude $\lambda = 17°$ 53' 26.525" (W),
geographic latitude $\phi = 28°$ 45' 42.462" (N),
geomagnetic declination $\delta = -6.35°$.

- Then the observation start time which has been stated in the input file as Universal Time is converted from UT to `GMST`, given in hours, by calling the two time conversion routines. Eventually, the local mean sidereal (start) time `LMST` is calculated using the geographic longitude $\lambda$ which has been converted to hours before:

$$LMST = GMST - \lambda.$$

These values have to be calculated only once. They are saved and used again in all following calls till the end of the loop is reached.
In each call of the subroutine, the following steps are carried out:

- If an extended source shall be simulated, which means the source radius `TRAD` stated in the input file is greater than zero, a spreading in the equatorial coordinates of the source is done within this radius $\rho$ (= `TRAD`). Using the two newly created random numbers $RD1, RD2$ uniformely distributed in the interval $\in (0, 1)$ (endpoints excluded), the modified source coordinates for declination (*DEC*) and right ascension (*RA*) are determined according to

$$\alpha = 2\pi \cdot RD1 \tag{1}$$
$$\epsilon = \rho \cdot \sqrt{RD2} \tag{2}$$
$$DEC = DEC_{source} + \epsilon \cdot \cos\alpha \tag{3}$$
$$RA = RA_{source} + \epsilon \cdot \sin\alpha, \tag{4}$$

  where $\alpha$ is the rotation angle and $\epsilon$ is the radial distance from the actual source position. A schematic illustration can be seen in Fig. 4.
  For a point source, this step is obviously skipped.

- After optionally redefining the source coordinates, the sampling of the trajectory is performed. As mentioned before, this is achieved by moving in time steps, whereas the step size is defined as the fraction of the time duration and the total number of steps. The number of steps is a required argument for the subroutine. In the *AAMAIN* loop over all events, the number of steps is given by the number of events to be produced.
  Now the local mean sidereal time at the current time step is evaluated, using the current event number $N$ (`TN`), the duration of the observation $T$

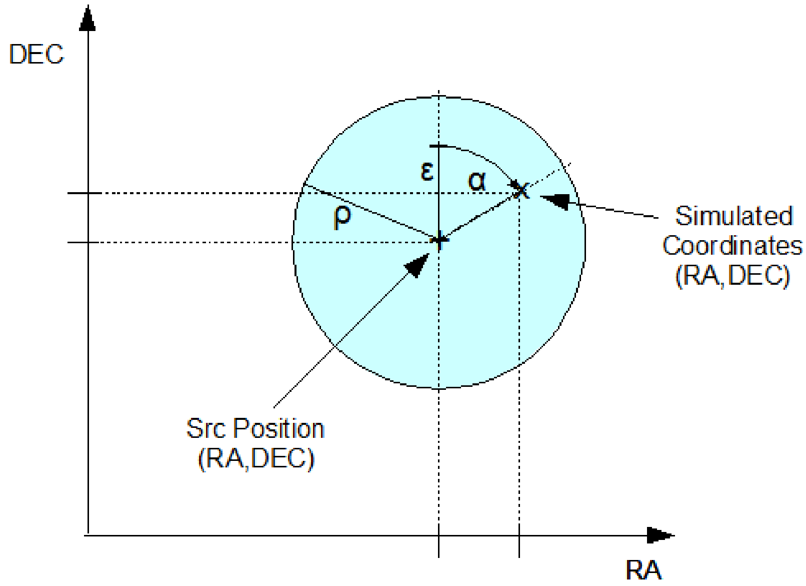



Figure 4: Illustration of the calculation of the spreading in equatorial coordinates. The new coordinates of each event are picked from within a circle in (*RA*,*DEC*) of a given radius $\rho$. The radial distance to the original point is determined by a random fraction of the radius $\epsilon$ and the angular position is defined by a random angle $\alpha$.

(`TDURATION`), the number of steps $S$ (`TSTEPS`) and the formerly calculated start time $LMST_{start}$ (`LMSTSTART`):

$$\mathrm{LMST} = \mathrm{LMST_{start}} + \mathrm{N} \cdot \frac{\mathrm{T}}{\mathrm{S}}. \tag{5}$$

- Knowing the `LMST`, the current hour angle $HA$ of the source can be determined,

$$HA = \mathrm{LMST} - RA, \tag{6}$$

and the actual coordinate transformation from the equatorial to the horizontal coordinate system is carried out according to:

$$\sin(h) = \cos(DEC)\cos(HA)\cos(\phi) + \sin(DEC)\sin(\phi) \tag{7}$$

$$\cos(A) = \frac{\sin(DEC) - \sin(h)\sin(\phi)}{\cos(h)\cos(\phi)}, \tag{8}$$

with the altitude $h$, the azimuth $A$ and the geographic latitude $\phi$.
The resulting coordinates are altitude $h$ and azimuth $A$. To get the coordi-

nates which are needed for the CORSIKA simulation, two more facts have to be paid attention to:

- The zenith angle $\theta$ is given by $\theta = 90° - h$.
- The azimuth angle calculated by this transformation is given in a coordinate system where $A = 0°$ points to the geographic North. In the CORSIKA program, however, the coordinate system is aligned to the magnetic North. Thus, the azimuth coordinate $\phi$ used by CORSIKA has to be corrected for the geomagnetic declination: $\phi = A + \delta$.

• *SOURCEPATH* finally returns the obtained coordinates $\theta$ and $\phi$ to the main program.

## 4.6 Main Program

There are two major changes applied in *AAMAIN*:

**Incident angles in shower loop.** The determination of the primary particle's incident angles within the shower loop has been altered.
While this is generally done by setting the fixed angles or angular ranges given in the input file, now a third possibility is added: If `TRAFLG` is stated as `T`, then the new subroutine *SOURCEPATH* is called instead. In the call, the number of events `NSHOW` is passed to the routine as the number of steps to perform. Subsequently, the returned values are assigned to the respective parameters and CORSIKA moves on to the simulation of the shower.

**Setting the angular ranges.** However, the shower loop is not the only point at which the incident angles have to be calculated. The general run information which is written to the output file by the CORSIKA program also contains the ranges of the incident angles. In the usual case, these are already known from the input file. In the case of the trajectory simulation these ranges are not known a priori and have to be actually calculated. As this information is written to the output file before the actual shower loop is performed, the calculation has to be performed separately.
Thus, the trajectory and the corresponding angles are calculated once already at this point, but with a bigger step size than in the actual shower loop. A step size of one minute has proven to be reasonable.
The minimum and maximum values occupied by $\theta$ and $\phi$ are obtained by iterative comparison within this second loop.
Finally, the obtained ranges are assigned to the respective CORSIKA variables and are written to the output file as general run information parameters.

# 5 Combination with Other CORSIKA Options

In the *TRAJECT* option only the primary angles are affected, therefore this new option may be combined with nearly all other available options[5] without problems. As the trajectory is followed at the sky, only downward going showers are to be respected, so the combination with the *UPWARD* option makes no sense. Do not combine the *INTTEST* option with the *TRAJECT* option, as this does not make any sense.

When combining the *TRAJECT* option with the *VOLUMEDET* or *VOLUME-CORR* option the angles determined by the latter two are disregarded and overridden if the `TRAFLG` (see Sect. 3.1) is activated.

A combination with the *VIEWCONE* option should be possible, but the keyword `TRARAD` fulfils this task much more elegant.

[5]For details on the available options see Ref. [2].

# References

[1] D. Heck et al., *CORSIKA: A Monte Carlo Code to Simulate Extensive Air Showers*, Report **FZKA 6019**, Forschungszentrum Karlsruhe (1998), available from: http://www-ik.fzk.de/corsika/physics_description/corsika_phys.html

[2] D. Heck and T. Pierog, *Extensive Air Shower Simulation with CORSIKA: A User's Guide*, available from: http://www-ik.fzk.de/corsika/userguide/corsika_tech.html

[3] http://www.ngdc.noaa.gov/geomag/

[4] J. Aleksić et al., (MAGIC Coll.), *Astropart. Phys.* **35** (2012) 435; preprint arXiv:1108.1477 [astro-ph] (2011); http://magic.mppmu.mpg.de/

[5] G. H. Kaplan, Software Report: NOVAS, U. S. Naval Observatory, *Bulletin of the American Astronomical Society* **22** (1990) 930; http://adsabs.harvard.edu/abs/1990BAAS...22..930K, Provided by the SAO/NASA Astrophysics Data System

KIT Scientific Working Papers
ISSN 2194-1629