Simulation tools for Imaging Atmospheric Cherenkov Telescopes

Federico Di Pierro
INAF - IFSI, Torino
Outline

- Tools for:
  1. Extensive Air Showers simulation
  2. Telescope simulation
General considerations

Any simulation of the IACT technique consists of 2 major steps:

1. the development of extensive air shower (EAS) in the atmosphere and the Cherenkov light emission
   • Done by CORSIKA → D. Heck et al. CORSIKA a Monte Carlo code to simulate extensive air showers, Tech. Rep. FZKA 6019, Forschungszentrum Karlsruhe, 1998

2. the response of the telescope (optics, photon detection, electronics)
   • Done by sim_telarray → K. Bernloher, Astroparticle Physics 30 (2008) 149-158
CORSIKA: simulation of EAS

- **COsmic Ray SImulations for KAscade**
- developed for KASCADE and tested with many EAS experiments
- simulates interactions and decays of nuclei, hadrons, muons, electrons, and photons in the atmosphere up to energies of some $10^{20}$ eV.

It gives *type, energy, location, direction and arrival times of all secondary particles* that are created in an air shower and pass a selected observation level.
CORSIKA hosts several different models for:

- **high energy hadronic** interactions
  - DPMJET, QGSJET (I e II), SIBYLL, EPOS...
- **low energy hadronic** interactions
  - FLUKA, GHEISHA, UrQMD
- **electromagnetic shower** development
  - EGS4 (following individual particles or analytical NKG or thinning)

Hadrons are the diffuse background of IACT's measurements.
Hadron-induced shower development

Development of cosmic-ray air showers

- Primary particle (e.g. iron nucleus)
- First interaction
- Pion decays
- Second interaction

Diagram showing the development of hadron-induced air showers with various particles such as pions, gammas, muons, and electrons involved in the interactions.
Hadron-induced shower development
Shower development: proton

Proton $10^{13}$ eV  
21336 m
Shower development: iron

muons

electrons

hadrons  neutrons

Iron $10^{13}$ eV

24929 m
Shower development: photon

Gamma $10^{13}$ eV

24713 m
Cherenkov light emission: fundamentals

\[ \cos \theta = \frac{1}{\beta n} \]

EAS Cherenkov light cone opening angle, from 10 km to sea level \( \approx 0.8^\circ - 1.4^\circ \)

- depends on atmospheric depth
Cherenkov light emission from EAS

movie: Cherenkov.mp4
Cherenkov light emission from EAS

Gamma (0.3 TeV)  Proton (1 TeV)  Iron (5 TeV)

Height a.s.l. [km]

-200  0  200  -200  0  200  -200  0  200
Cherenkov light emission in CORSIKA: *IACT/ATMO*

- Each charged particles is transported down considering: decay, multiple scattering, bending in the geomagnetic field and ionization loss and, if some options are switched on, cherenkov light emission;

- **Energy thresholds** for particle (when interested in Cherenkov light)
  - $e/\gamma = 20$ MeV (Cherenkov thr.)
  - $\mu/h = 200-300$ MeV (lower than their Cherenkov thr. because they may decay)

- Compilation options specific to Cherenkov simulation:
  - IACT
  - CERENKOV
  - ATMEXT = require tabulated values for the description of the atmosphere (altitude | density | atm. depth | refraction index)
    Different atmosphere models (i.e.: tropical, US standard,...)
  - VIEWCONE = for diffuse emission (background or extended/diffuse gamma sources)
Cherenkov light emission in CORSIKA

- Both **accuracy** and **efficiency** are important

- a track is approximated with segments whose length is chosen in order to avoid systematic effects and keeping a good efficiency (STEPFC parameter)
Cherenkov light emission in CORSIKA

- Both **accuracy** and **efficiency** are important
  - photons are not simulated one by one but in **bunches** (CERSIZ parameter)
  - CERSIZ = the maximal bunch size
Cherenkov light emission in CORSIKA

- Both **accuracy** and **efficiency** are important

- CERWLEN = the index of refraction is made wavelength dependent, a wavelength is given to each bunch (shorter $\lambda$, larger $\theta$)
Cherenkov light emission in CORSIKA: \textit{telescope}

- an array of telescopes \((x_i, y_i, z_i, r_i)\)
- intersection of altitude and azimuth axes, sphere enclosing the dish
- each shower used several times (CSCAT parameter)
- to increase efficiency each sphere is related to a grid at detection level (photon bunches intersection searched only for few spheres)
Telescope simulation: *sim_telarray*

- Developed for HEGRA and HESS (telescope arrays)

- It allow to simulate and set:
  - optical layout
  - photon sensors
  - electronics and output
  - trigger
  - Night Sky Background

- Each telescope can be individually configured

- Fast with respect to CORSIKA
  - CORSIKA output (photon bunches intersecting the spheres) piped out to several “sim_telarray”;
  - can be also used ”offline” if CORSIKA output can be stored on disk
  - efficiency short-cuts (1st cut: number of photons, 2nd: number of pe)
Optics simulation (1)

- **Single mirror** (Davies-Cotton or parabolic)
  - segmented: position, shape and focal length of each tiles
- Realistic (measured) optical qualities can be introduced
  - mirror reflection random angle: due to small-scale surface deviations
  - mirror reflectivity (as a function of wavelength)
  - mis-alignments
- **Dual mirror** (Schwarzschild-Couder)
  - mirrors and focal surface described in terms of even polynomials
- **ray-tracing** (including timing) from stars simulated in the FoV and focused on the camera lid (focus offset for EAS = \((f^{-1} - D^{-1})^{-1} - f\))

Measurement: H.E.S.S. CT4  
Simulation

- off-axis = 2.3°
- shown fields = 0.4°
Optics simulation: an example (confirmed by Zemax)
Optics simulation (2)

- **atmospheric transmission** (Cherenkov photons, also available directly in CORSIKA by CEFFIC options)

- **shadowing** and **light guides** can be included before the photo-sensors simulation
Camera simulation

- For each pixel it is possible to configure:
  - position
  - dimension
  - shape
- The (simplest) trigger of the camera is organized by pixel multiplets
- In front of each pixel can be simulated a light guide (any size/dimension)

Camera for SC, pixel size = 0.2°

Primary: gamma of 30,000 TeV energy at 223 m distance
Light guides simulation

In case of the Davies-Cotton a **Winston cone** stands in front of each PMT:
Quantum efficiency

Q.E. = probability, for a photon hitting the cathode, to produce a photo-electron

![Graph showing the quantum efficiency as a function of wavelength. The graph includes a note: as reported by D. Guerin. Derived from HD measurements, including w.l. dependent collection efficiency into Q.E.]
Single photo-electron response

- **collection efficiency** = probability that a pe actually hits the first dynode and is effectively multiplied rather than elastically scattered

- **afterpulses** = ions in PMT (0(100 ns) after the electron cascade) inducing a signal (for PMT can be high up to ~10 pe)
  - for Cherenkov photons don't matter, whilst matter for NSB
Single photo-electron pulse shapes

- for each pe the pulse shapes are scaled accordingly to random s.p.e. and shifted accordingly to arrival time + random jitter
- all signals from Cherenkov light and NSB are added up

- one pulse to the discriminator (sampling ~ 250 ps)
- it is possible to store the integrated charge or the full waveform

- it is possible to store the integrated charge or the full waveform
Trigger

- **Pixel** trigger = discriminator threshold

- **Camera** (or telescope) trigger = fully flexible, examples: majority (full camera, trigger cells), analog sum, digital sum

- **Array** = n telescopes of the array within a time window (10-100 ns)

- Trigger rate (discr. thr., pixel size, NSB, trigger logic... )
Camera images
Basic ideas of stereo reconstruction