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Overview of Atmospheric Simulation Efforts in CTA

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Abstract. The Cherenkov Telescope Array (CTA) is an observatory for ground-based gamma-ray astronomy currently under construction, which will observe photons with very high energies (20 GeV – 300 TeV). One of the main contributions to the systematic uncertainties stems from the uncertainty on the atmospheric density profile, of molecules and aerosols. To minimize these systematics a full calibration of the atmospheric properties is important as well as a calibration of the detector response. In the paper we introduce the strategy for atmospheric simulations, use of Monte Carlo simulations and available CTA computing resources. We also describe in more detail realized and planned atmospheric simulations as well as the Czech contribution to this effort.

1 Introduction

The Cherenkov Telescope Array (CTA) is the next-generation instrument for detecting very high energy (VHE) γ-rays (20 GeV – 300 TeV) and it will be the major global observatory for gamma-ray astronomy [1]. These VHE γ-rays originate from non-thermal processes in the universe, both galactic (supernova remnants, pulsars or pulsar-wind nebulae) and extragalactic (active galactic nuclei, starburst galaxies, galaxy clusters or gamma ray bursts). VHE γ-rays cannot be detected directly on the Earth. Instead, when reaching the Earth‘s atmosphere they interact with atmospheric nuclei and electromagnetic showers start to develop. Particles in the shower (mostly electrons and positrons) emit Cherenkov light (mainly in near UV and optical band) which reach the ground level and can be detected by Imaging Atmospheric Cherenkov telescopes (IACTs).

The development of the shower and propagation of the Cherenkov light have great impact on the performance of the observatory (in terms of sensitivity, energy and angular resolution, effective area of arrays, etc., for more details about performance see [2]). The performance is influenced by many things such as atmospheric conditions, geomagnetic field, altitude of the site or night-sky background. All of these effects need to be studied by means of detailed Monte Carlo (MC) simulations. For a general overview of the influence of atmospheric conditions on the performance of an IACT, and the corresponding atmospheric calibration strategy for the CTA, see [3].

2 Monte Carlo Simulations

Detailed MC simulations of the detector response to extensive air showers are widely used within the CTA collaboration. These simulations are used e.g. for characterization of performance of the CTA, almost any science analysis in the CTA (via the generation of instrument response functions), optimization and validation of system parameters during prototyping and the (pre–)construction phase, determination of upgrade scenarios, development of reconstruction algorithms or evaluation of systematic uncertainties.

For these tasks, the CTA MC working group studies the impact of various parameters with large sets of simulated events for different primary particles: protons, electrons and γ-rays in the energy range from 3 GeV to 300 TeV. For example, during the site selection, nine sites (three in the northern and six in the southern hemisphere) with different altitudes, geomagnetic fields, night-sky background and atmospheric conditions were studied with MC simulations in order to determine their scientific performance.

For the simulation of the Cherenkov light emission the CTA collaboration uses the CORSIKA program [4]. CORSIKA was chosen as the basis of the air shower simulations due to its public availability, its rich set of interaction model options and the fact that it is used and tested by a large number of experiments. The simulation of the detector response is usually done by a second program called `sim_telarray`[5], which was originally developed for simulating the HEGRA telescope system. During years the program became much more configurable and flexible.

After simulations of showers and telescope responses these data have to be processed. For this analysis several independent analysis tools can be used: Eventdisplay [6], MARS [7] or FAST[1] [8]. Results of these analyses are then used for CTA‘s needs.

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[1] FAST does not use `sim_telarray` simulations as input, but performs a simplified analytical calculation of the detector response.

2.1 CTA Computing Resources

MC simulations (and other simulations) for the CTA are performed on the CTA Computing Grid (CTACG). CTACG uses the European Grid Infrastructure (EGI) grid [9] through the CTA Virtual Organization since 2008. EGI provides access to resources across Europe using grid computing techniques. The CTA has access to twenty EGI sites in 7 countries and one Advanced Resource Connector (ARC) site in Sweden. Every CTA member can get access to these resources through the CTA Virtual Organization. To access all these resources the CTA is using the DIRAC (Distributed Infrastructure with Remote Agent Control) Interware [10]. DIRAC is a software framework for distributed computing which provides a solution for workload and data management system. More information about DIRAC setup for the CTA can be found in [11].

CTACG available resources are on average 6000 – 8000 (peak) cores while 1000 years of CPU time are spent each year. Available storage is about 2.3 PB of disk and 0.7 PB of tape storage which are distributed among six main sites [12]. It turns out that the storage is usually the main problem of simulations – disks are filling with data very rapidly during CTA mass productions (which are required by the CTA Consortium).

3 Atmospheric Simulations

As mentioned earlier the Earth‘s atmosphere is very important for any IACT – we are using the atmosphere as our calorimeter and therefore it is an integral part of the detector. Atmospheric quality has a great impact on the air-shower development itself, the variation of the Cherenkov angle with altitude, the loss of photons due to scattering and absorption of Cherenkov light out of the camera field-of-view (see [3]).

For these reasons we need to have precise measurements of the atmosphere such as detailed knowledge of the molecular profile, its density and refractive index, ozone absorption and aerosol extinction of Cherenkov light. To get this information CTA plans to use several instruments measuring the atmosphere — Raman LIDARs, the FRAM telescope, All-Sky-Cameras, Ceilometers, sun and moon photometers and radiosondes (see e.g. [13], [14], [15] or [16], for an overview see [3]).

In our study we focused on two main aspects of the atmosphere — molecular density profile and the presence of aerosols — and their effects on the estimated performance of the Northern observatory, i.e. effective area, energy bias and resolution of the array, and angular resolution. We studied several different atmospheric profiles (density, thickness, refractive index, and optical depth profiles), see [17]. Figure 1 shows different extreme density profiles with two reference profiles `Average Winter` and `Average Summer`. Figure 2 shows these profiles in comparison with the average profile `Average Winter`. From Figure 2 we can see what properties different extreme profiles have — e.g. `Extreme14.0_low` (green line) describes an atmospheric profile with density minimum (relative to the `Average Winter`) at an altitude of 14 km. `Extreme16.0_high` (blue) then describes an atmospheric profile with density maximum at an altitude of 16 km (and so on). The results of the simulations, in term of the performance of the observatory in comparison with the profile `Average Winter` – are shown in Figure 3 (energy resolution), Figure 4 (energy bias), Figure 5 (effective area), and Figure 6 (angular resolution). In these figures 'relative' means relative with respect to the profile `Average Winter`. For reconstructions of simulated events we were using the *correct* atmosphere, i.e. the same atmosphere was used for analysis as for the original showers. Note that this is not the usual realistic case when we do not have exact information about the atmosphere (see below). These studies were mainly performed by Federico Di Pierro (INFN Torino) with our participation.

We can see that these atmospheric profiles have relatively small influence on energy resolution of the array, especially in the core energy range (100 GeV $\sim$ 10 TeV) where the error is $\pm 2\%$. In energy bias we do not expect a large effect as we are using the same atmosphere for reconstruction of events as for the data production. The large effects at low energies($<$ 20 GeV) are due to a selection of the events which suffered large fluctuations. Above 20 GeV this is only $\pm 2\%$ effect. Effective area of telescopes is influenced more by these atmospheric conditions — up to 10% in low and high ($\geq$ 10 TeV) energy range, which leads to uncertainties in the flux. At high energy the atmospheres denser in their higher part ($\sim$14 km) produce larger effective areas. The goal angular resolution of the CTA array is around 0.1° at 65 GeV, 0.03° at 1 TeV and 0.02° at 10 TeV, which is satisfied with these profiles. All these analyses where performed with exact profiles, i.e. in case when we have our atmosphere calibrated. But this is not the real case when we have only limited knowledge about the atmosphere. We can also do these analyses without atmospheric calibration, i.e. produce data with extreme profiles and then use the average winter‘s lookup tables (LUT) to reconstruct data. In this case we expect a large effect on the energy bias but only minor effects on the energy resolution (the spread of the reconstructed energies should not increase). Preliminary result of these simulations are shown in Figure 7 (energy resolution), Figure 8 (energy bias) and Figure 9 (angular resolution). We can see that in energy bias there is an energy dependency which could be dangerous for determining energy spectra. The errors are up to $\pm 4\%$ whereas only 2% systematic shift at all energies is allowed. For energy and angular resolutions these effects are rather small as expected.

In the future the analysis needs to be extended also to the southern site and the effect of different kinds of aerosols (dust, clouds) under different conditions (different altitude and thickness) and of the effect of atmospheric calibration uncertainties on reconstructed energy and flux uncertainties.

4 Conclusion

In the paper we described general status of MC simulations within CTA and in more detail our studies of extreme density profiles for La Palma and their effects on the anticipated performance of the observatory. So far we managed to get results with extreme atmospheric profiles with different density, thickness, refractive index, and optical depth profiles for the northern site. We showed that in case we have precise measurements of the atmosphere we can account for these effects and the performance of the observatory is not greatly influenced. Preliminary results without precise atmospheric calibrations showed that there is a large impact on energy bias and therefore it can greatly influence energy spectra.

We are planning to do similar simulations for the southern site as well as to study effects of different aerosols. We also want to perform these studies at different zenith angle. Results without atmospheric calibrations showed that we need to study the effects of the uncertainties of the currently foreseen CTA atmospheric measurements.

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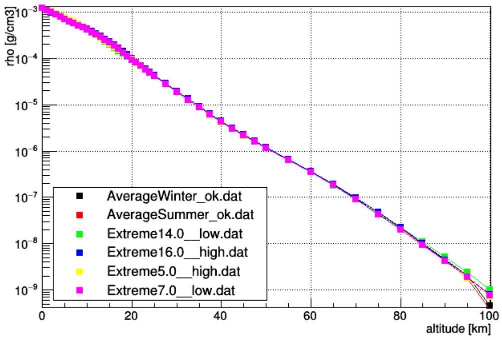

Figure 1. Atmospheric density for different atmospheric profiles (La Palma site). [18]

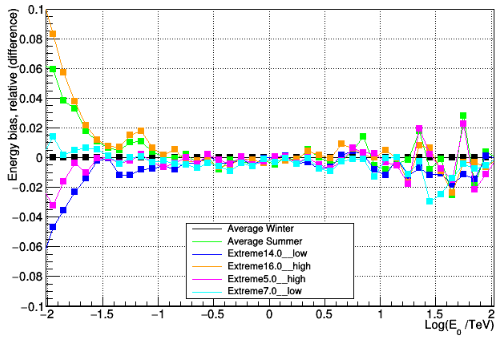

Figure 4. Relative energy bias for different atmospheric profiles (La Palma site). [18]

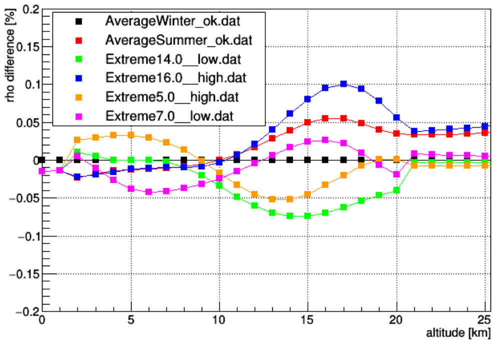

Figure 2. Relative atmospheric density for different atmospheric profiles (La Palma site) with respect to the density profile `Average Winter`. [18]

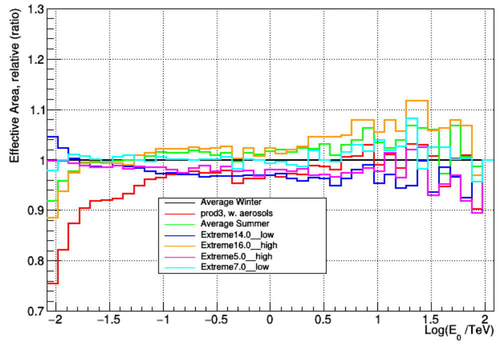

Figure 5. Relative effective area for different atmospheric profiles (La Palma site). [18]

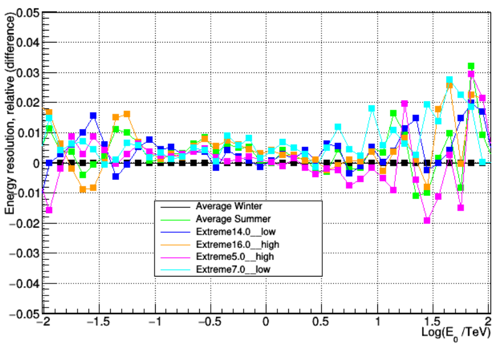

Figure 3. Relative energy resolution for different atmospheric profiles (La Palma site). [18]

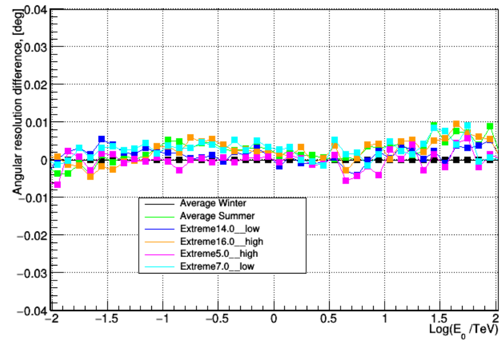

Figure 6. Angular resolution difference for different atmospheric profiles (La Palma site). [18]

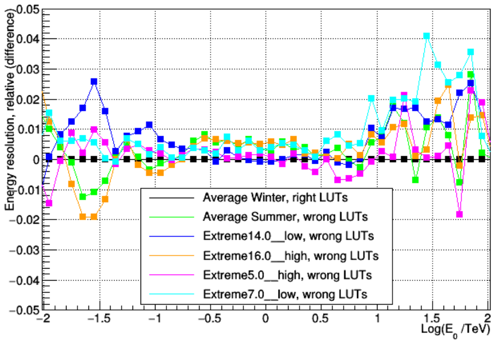

Figure 7. Relative energy resolution for different atmospheric profiles (La Palma site) with wrong LUTs. [18]

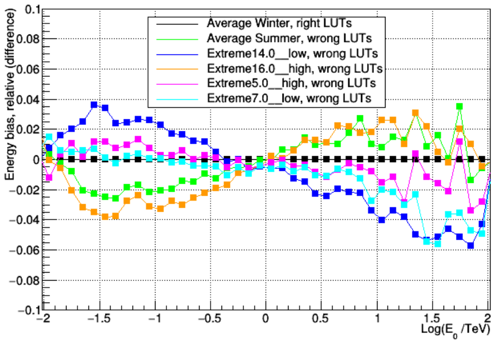

Figure 8. Relative energy bias for different atmospheric profiles (La Palma site) with wrong LUTs. [18]

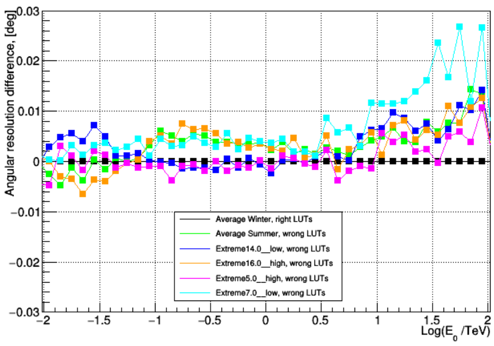

Figure 9. Angular resolution difference for different atmospheric profiles (La Palma site) with wrong LUTs. [18]