Characterization of San Antonio de los Cobres for a Cherenkov telescope array in energy range from 20 GeV to 130 GeV

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Abstract: In this work we study the detection of Cherenkov photons produced by particle showers developed in the atmosphere when a charged particle or a gamma ray interacts with the medium in the energy range from 20 GeV to 130 GeV. Extensive air showers are simulated with CORSIKA, using a large aperture telescope to collect the photons that arrive at the Earth's surface. The geographic site chosen for our simulations is San Antonio de los Cobres (SAC), which is currently one of the five candidate sites in the southern Hemisphere for the installation of Cherenkov Telescope Array (CTA). The simulations include seasonal atmospheric profiles (air density, vertical atmospheric depth and air refractive index as a function of altitude), derived from a dedicated analysis of GDAS data (Global Data Assimilation System). The number of photons collected by the telescope is compared with the photons originated by background cosmic rays (from protons to iron). The results are presented and discussed in terms of each energy and the corresponding shower-telescope distance.

Keywords: CTA, GDAS, Cherenkov light, IACT

1 Introduction

The Cherenkov light produced by ultra-relativistic charged particles during the development of an extended air shower can be detected by optical telescopes positioned on the surface of the Earth. Using the light signal collected with the telescopes, a technique to detect and discriminate showers originated by gamma primaries from those originated by hadron primaries has been developed [1]. This technique is currently used to detect gamma rays from astrophysical objects at high energies (GeV to TeV) in observatories like VERITAS [2], MAGIC [3], HESS [4] and soon in CTA [6]. The detection threshold and the capability to discriminate between images produced by gammas and hadrons are dependent on the characteristics of the site where the telescopes are positioned. Sites at high altitudes ($\gtrsim 3500$ m a.s.l.) have a lower energy threshold (~ 10 GeV), a these energies, the detection capability could be negatively impacted by an increase in the background Cherenkov light contamination produced by the hadronic showers. To evaluate this effect, we carried out a full set of hadronic simulations considering San Antonio de los Cobres, Salta Province, Argentina (SAC), because of its high altitude (3600 m a.s.l) and its status as a candidate site for the future installation of CTA [5].

2 Molecular Atmospheric Profiles for SAC

The atmospheric molecular component plays a very important role in the Cherenkov light detection because 1) it is the medium where the particle showers are originated; 2) the Cherenkov light photons are generated and propagate in this medium. Motivated by this, we decided to study the altitude dependence in SAC for the air density, vertical atmospheric depth and refractive index (which depends on the wavelength), considering average seasonal atmospheric profiles (winter, spring, summer and autumn) with data from the Global Data Assimilation System (GDAS) archive information[7]. This was possible because GDAS provides data of the main atmospheric variables every 3 hours at 24 altitude levels, from the surface level up to ~ 27 km a.s.l., with a spatial resolution of 1° in latitude and longitude. For this analysis we used GDAS data from September/2006 to December/2012, considering only data corresponding to night periods (from 21 hs to 6 hs, local time), for the GDAS grid point with coordinates 24° S - 66° W of the latitude and longitude respectively, which is the point closest to SAC (located at ~ 30 km from the CTA proposed site).

By choosing the GDAS grid point closest to SAC we obtained the main atmospheric variables (pressure, temperature, relative humidity and geopotential altitude). Since the highest altitude in GDAS data is $\sim$27 km a.s.l, and we needed to cover the complete atmospheric volume (up to $\sim$100 km a.s.l) for the simulation of extensive air showers with Monte Carlo packages, we extended the atmosphere using data corresponding to the US Standard Atmosphere 1976 [8].

Then we determined the atmospheric density profiles by considering air as an ideal gas composed by a mixture of dry air, CO_2, and water vapour [9]. Subsequently, using the atmospheric density profiles we determined the vertical atmospheric depth profiles (integrating numerically the air density) and the refractive index of air, relative to each wavelength of Cherenkov light in the 200 nm$-$700 nm range [10]. The scheme used to model the atmosphere is similar to the one used by the Pierre Auger Observatory [11], where the applicability of GDAS was also validated with data from radiosondes launched from ground at their site.

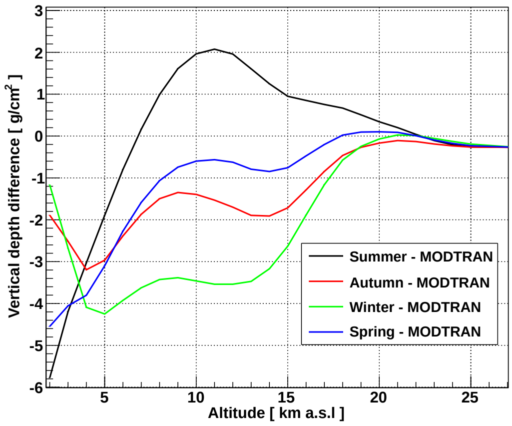

Figure 1: Comparison between our GDAS atmospheric profiles and MODTRAN mid-latitude summer atmosphere provided with CORSIKA. All profiles are quite similar, showing differences no greater than 6 g cm^{-2} for the vertical atmospheric depth.

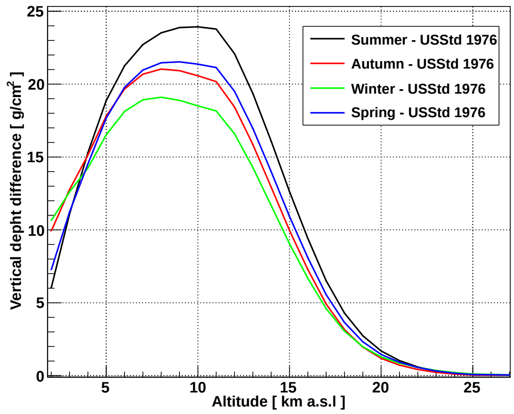

Figure 2: Significant differences are observed between our atmospheric profiles and the US Standard 1976 atmosphere. The differences found for the vertical atmospheric depth are up to ~ 25 g cm^{-2}.

The results obtained in this work for the different four seasonal profiles at SAC have no significant differences between them (less than 5 % and 6 g cm^{-2}, for the refractive index and the atmospheric vertical depth respectively), and are similar to the MODTRAN [12] mid-latitude atmospheres which are supplied within the 'bernlohr' package [13] distributed with CORSIKA [14], these differences are displayed in Figure 1. More significant differences, up to ~ 25 g cm^{-2} and ~ 18 % (atmospheric vertical depth and refractive index respectively) were obtained between our SAC profiles and the US Standard 1976 atmosphere model. In Figure 2 the difference between the seasonal profiles derived from GDAS for the SAC site and the US Standard Atmosphere 1976 are displayed for the vertical atmospheric depth.

3 Monte Carlo Simulations

To determine the sky brightness induced by Cherenkov emission of background hadronic showers, a full set of low energy hadronic simulations was performed. The shower simulations were done using CORSIKA 7.3500 [14], selecting QGSJET-II-04 for high energy hadronic interactions [15] and GEISHA 2002d [16] for low energy hadronic interactions routines. The showers were generated without thinning, using the IACT option in order to simulate the detection of Cherenkov photons arriving at the Earth surface [13, 17]. Since we want to determine the background Cherenkov flux, a square array of 41×41 perfect Cherenkov photon counters of 400 m^2 each was simulated. The detectors were uniformly distributed in a 6 km $\times$ 6 km square grid with 150 m of separation between two adjacent detectors in both directions. Due to the small differences observed between our four GDAS SAC seasonal atmospheric profiles (see Figure 1), we decided to simulate the background flux using the summer profile.

To determine the background flux, the full spectrum of primary nuclei was simulated impinging over one square meter at the top of the atmosphere, in the range $1 \le Z_p \le 26$ (corresponding to $1 \le A_p \le 56$) for 26 different primaries, where Z_p and A_p correspond to the atomic number and atomic weight respectively. The spectrum for each primary was assumed to be a power law of the form $j(E_p) = j_0(E_p/\mathrm{TeV})^{-\gamma}$. The values for j_0 and the spectral index γ of each nuclei were obtained from [18]. To take into account the geomagnetic rigidity cut-off effect, a lower bound of 10 GV was estimated for the SAC site from ref. [19]. Thus, to obtain the total number of particles to simulate for each particle specie we integrated the flux between $(10 \times Z_p) < (E_p/\mathrm{GeV}) < 10^6$, since at this higher energies the flux is so low that it be assumed as an effective upper energy cut-off, considering zenith angles of $0^o \le \theta_p \le 90^o$ and azimuth angles of $-180^o \le \phi_p \le 180^o$. The hadronic background was simulated in detail considering a total flux of 4 hours, corresponding to a total number of $\sim 1.2 \times 10^7$ hadrons per square meter. The Earth's magnetic field was taken into account in these simulations due to the effect it has on the development of showers at low energies, altering the Cherenkov light image collected at the telescope. Additionally, in order to evaluate the photon Cherenkov production produced by photon initiated showers with these atmospheric profiles, a set of monoenergetic ($E_p = 20, 30, 50, 100$ and 130 GeV), monoangular ($\theta_p = 0^o, 30^o$ and 45^o) photon showers were simulated. To determine the possible signal contamination, proton initiated showers were also simulated for the same energies and zenith angles as for photons. For each channel, 100000 showers were simulated, totalizing 3×10^6 additional showers.

4 Cherenkov light at ground level

Using the CORSIKA output files for all the background nuclei primaries, we determine the average number of Cherenkov photons collected by the grid of telescopes as a function of the distance from the impact point, located at the center of the array. Using these values, we determined the average lateral distribution function of the background Cherenkov light intensity. The sampling rate of the camera of the telescopes is mandatory to determine the background photons density over the camera. For this work, a sampling rate of 50 MHz was assumed for the telescope

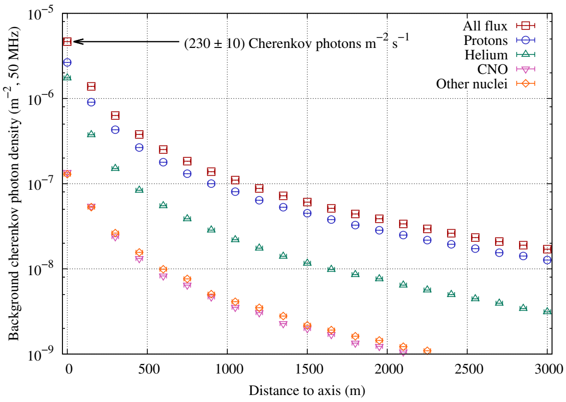

Figure 3: Expected background Cherenkov light produced during the development of extensive air showers initiated by primary hadrons (squares), as a function of the distance to the shower core position. A total flux is expected. By assuming a determined camera sampling rate (50 MHz), the expected density was calculated to be (230 ± 10) photons m^{-2} s^{-1}. We also show the contribution of the main components to this background: primary protons (circles), helium (upward triangles), CNO (downward triangles), and other nuclei (diamonds).

camera, giving a maximum average density of photons of $(4.7 \pm 0.2) \times 10^{-6}$ photons m^{-2}. Generalization to other sampling rates is straightforward. The resulting background density distribution as a function of the distance to the primary impact point is shown in Figure 3, where the total background flux and the contribution for each component are also shown. As expected at this energy the background is dominated by proton and helium contributions.

At the centre of the array, we obtained an integrated flux of background Cherenkov photons of (230 ± 10) photons m^{-2} s^{-1}. However, this flux corresponds to the photons produced by showers impinging 1 m^2 at the top of the atmosphere directly located above the center of the array. Of course, at ground level we need to take into account contribution from all the atmosphere. However, absorption of charged secondary particles and Cherenkov photons in the atmosphere limit the integration distance to a few kilometers from the centre of the array. In the same Figure 3, it can be seen that at 3 km away from the axis, the Cherenkov photon fluence is less than 0.4 % of the fluence at the centre of the simulated array. Then, to calculate the total flux at the centre of the array we numerically integrate the lateral distribution of Cherenkov photons in our array, obtaining a conservative total flux of background Cherenkov photons of $(7.8 \pm 0.2) \times 10^4$ photons m^{-2} s^{-1}. At 50 MHz camera sampling rate, this corresponds to $\sim 1.6 \times 10^{-3}$ Cherenkov photons m^{-2} per time bin due to the stationary hadronic background.

Once we characterized the flux of background photons, we needed to determine the Cherenkov production during showers initiated by photons, and its main contamination signal, protons [17]. As mentioned in the previous section, a full set of CORSIKA simulations of photons and protons was performed. As an example, the average two-dimensional Cherenkov photon density expected at ground level in the SAC site for showers initiated by a vertical photon of 20 GeV and 130 GeV is shown in Figure 4.

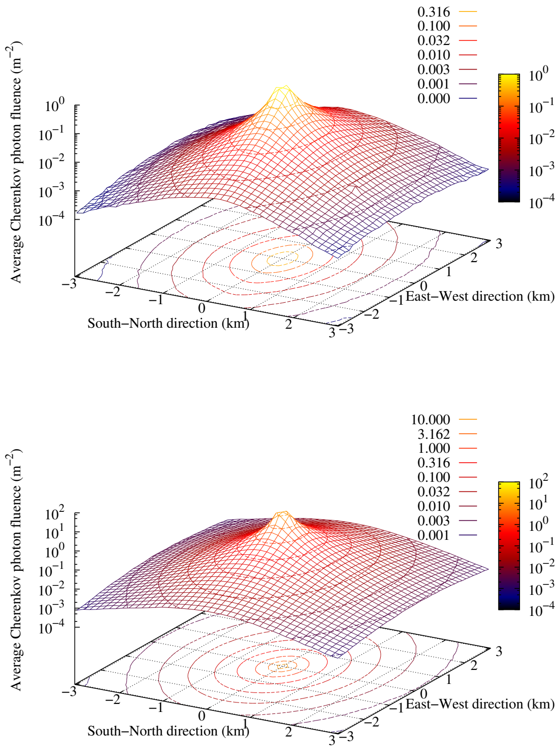

Figure 4: Average Cherenkov photon fluence in San Antonio de los Cobres site originated during the development of EAS by vertical photons of 20 GeV (top) and 130 GeV (bottom). In both cases the East-West asymmetry effect, induced by the interaction of the geomagnetic field with low energy charged particles, is clearly visible.

Finally, Figure 5 shows a comparison for the expected averaged Cherenkov photon fluence at the central detector for showers initiated by photons and protons at three different zenith angles ($\theta_p = 0^o, 30^o$ and 45^o) and for five different primary energies ($E_p = 20, 30, 50, 100$ and 130 GeV).

5 Conclusions

In this work we have characterized the San Antonio de los Cobres site using extended air shower simulations for primaries of gamma and hadrons, using the CORSIKA package with the IACT option, with energies between 20 GeV and 130 GeV.

Seasonal atmospheric profiles for the air density, vertical atmospheric depth and air refractive index were derived from GDAS data for SAC. The atmospheric profiles obtained for SAC showed insignificant differences between them and are similar to the MODTRAN mid-latitude atmosphere.

The Cherenkov light background produced by the hadronic showers was evaluated for a total flux of 4 hours using a square array of Cherenkov telescopes. The average lateral function of the background light of each hadronic primary shows that the total background light is dominated by proton showers, producing a maximum value of ~ 230 photons m^{-2} s^{-1} at distances close to core.

A the energies and zenith angles considered, the

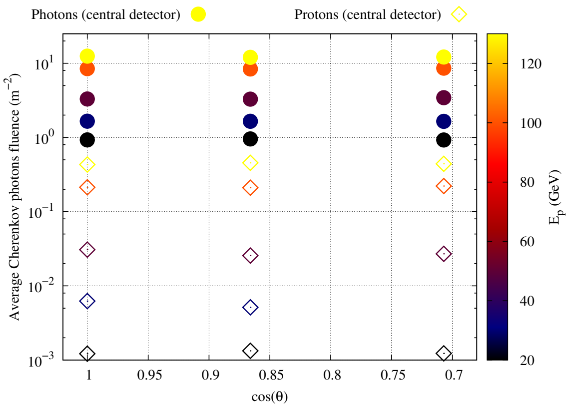

Figure 5: Average expected Cherenkov photon fluence at the SAC site observed at the central detector of the array, for showers initiated by photons (full circles) and protons (empty diamonds).

Cherenkov light produced by photon showers is greater than light originated by proton showers. Particularly, in the centre of the detector array this difference is over ~ 1 order of magnitude at 130 GeV and ~ 3 orders of magnitude at 20 GeV.

The method applied to calculate the Cherenkov light background produced during the development of showers initiated by primary hadrons, is fully general and can be used at different sites. Currently, we are carrying out simulations with large telescope arrays for SAC, properly taken in account the response of each telescope, in order to evaluate the capability to discriminate between showers originated by gamma and hadron primaries.

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