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Simulations of detector arrays and the impact of atmospheric parameters

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Abstract: In Monte-Carlo simulations of gamma-ray or cosmic-ray detector arrays on the ground (here mainly arrays of imaging atmospheric Cherenkov telescopes), the atmosphere enters in several ways: in the development of the particle showers, in the emission of light by shower particles, and in the propagation of Cherenkov light (or fluorescence light or of particles) down to ground level. Relevant parameters and their typical impact on energy scale and so on are discussed here.

Keywords: Monte Carlo simulations, air showers, Cherenkov telescopes, gamma rays, cosmic rays

1 Introduction

Ground-based gamma-ray and cosmic-ray detectors make use of the atmosphere as a part of their instruments. Incoming energetic particles (neglecting neutrinos or exotic particles for the purpose of this paper) will interact with the atmosphere, produce secondary particles and initiate a particle cascade or extensive air shower. The level of inclusion of the atmosphere into the instrument differs between different detection techniques. Particle detector arrays are affected by the development of extensive air showers. Beyond the atmospheric overburden on ground, the atmospheric profile will also matter, due to the competition between interactions and decays of secondary unstable particles produced in interactions. Since most of the development of air showers happens at altitudes of up to a few ten kilometers of altitude, the change of atmospheric composition beyond about 80 km altitude has, fortunately, no significant impact onto the air shower development and detection.

For atmospheric Cherenkov detectors as well as for air fluorescence detectors, the atmosphere enters at two additional levels. The first is the emission process and the second is the propagation of the emitted light down to the photo-detectors. The Cherenkov and fluorescence processes depend in different ways on changes in density profiles. For the fluorescence technique, there is a competition between fluorescence light emission and collisional de-excitation, after the nitrogen molecules get excited by the charged particles in the air shower. The higher efficiency of light emission is balanced basically by lower excitation in lower density air. As a consequence, the fluorescence process depends relatively weakly on the air density profile, except for the shower development itself. The Cherenkov emission process is more strongly impacted by the density profile. Higher density, resulting in an almost proportionally enhanced refractivity (index of refraction minus one, $n-1$), results in enhanced emission as well as lowering the minimum particle velocity necessary for emission. It also increases the Cherenkov emission angle and spreading out the light on the ground over a larger area.

Both the Cherenkov and fluorescence techniques are affected by the light propagation, by absorption as well as by scattering. The absorption processes are not just affected by the main composition components but also affected by trace gases, like ozone or water vapour. At that stage the detailed composition profile thus enters the game. Scattering includes Rayleigh scattering - thus directly linked to the density profile - and Mie scattering on aerosols (also resulting in light absorption). As a consequence, these detection techniques are affected by the aerosol density, chemical composition, size distributions – and all of these depend on altitude and change with time.

Simulations of air showers and detector response usually need some simplifications, in order to run in an efficient way. This paper will also try to point out some often-used simplifications which should be applied with care.

Since this paper is focusing on the impact of atmospheric parameters, a number of other site-related topics will be omitted, including the impact of the night-sky background (NSB) on Cherenkov or fluorescence detectors and the impact of the geomagnetic field.

2 Shower development and density profile

Ground-level measurements of the pressure and gravity can tell the total atmospheric overburden as the most important atmospheric parameter for particle detector arrays. This will not be enough for a detailed simulation of the shower development, in particular for the electron/muon ratio. This is due to the competition between interaction and decay for particles like kaons and charged pions. Different atmospheric density profiles can therefore result in differences in the longitudinal shower development, even when this is expressed as a function of atmospheric depth traversed (in g/cm^2, counted from the top of the atmosphere). Even without such differences, different atmospheric profiles can result in different lateral distributions of particles on the ground because the relation between atmospheric depth and altitude is changed. Simulations will typically be set up to match an average (or seasonal average) of the density profile at the detector site. These profiles may be pure model profiles, e.g. from MODTRAN [1] or NRLMSISE-00 [2] or from radiosonde data complemented by models or other data beyond the altitude range covered by the radiosondes. For latitudes up to about 30 degrees the MODTRAN tropical model is generally a good description and seasonal variations typically small (see Figure 1, resulting changes in Cherenkov light density below 5 percent) while local and

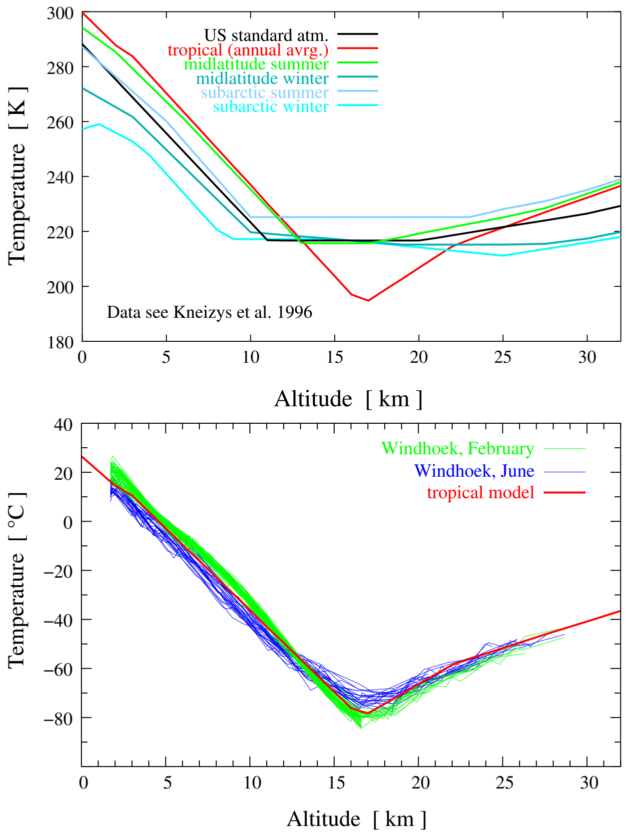

Figure 1: Examples of atmospheric profiles (here: temperature profiles). Top: MODTRAN [1] model profiles. Bottom: Seasonal extreme profiles from radiosonde data taken near Windhoek, Namibia, compared with the tropical model.

seasonal variations at higher latitudes are larger (resulting in changes of 10 percent or more).

Since simulations are carried out for average profiles and not for instantaneous profiles, even if these were available, corrections for the impact of slightly different profiles may improve the resulting accuracy, .e.g based on ground-level measurements like pressure and temperature or derived from weather models like the altitude of some pressure levels. Frequent simplifications in simulation programs include piece-wise exponential or linear density profiles as a function of altitude, and in most cases also an altitude-independent composition. The former can sometimes result in artifacts and needs some care while the latter is not considered a problem since the first interaction is typically well below 80 km where the composition starts to change.

3 The Cherenkov emission process

The atmospheric Cherenkov technique is affected to a large extent by the atmospheric profiles through the longitudinal shower development (see Figure 2). The next obvious impact of atmospheric parameters on the Cherenkov light emission is by the index of refraction n, through the Cherenkov cone opening angle $\cos\theta = 1/(n\beta)$ with $\beta = v/c$ standing for the velocity v of the emitting particle. The index of refraction also enters into the amount of Cherenkov light emitted per unit path length and unit wavelength being proportional to $\sin\theta$. The refractivity $n-1$ is to good approximation proportional to the air density, but for improved

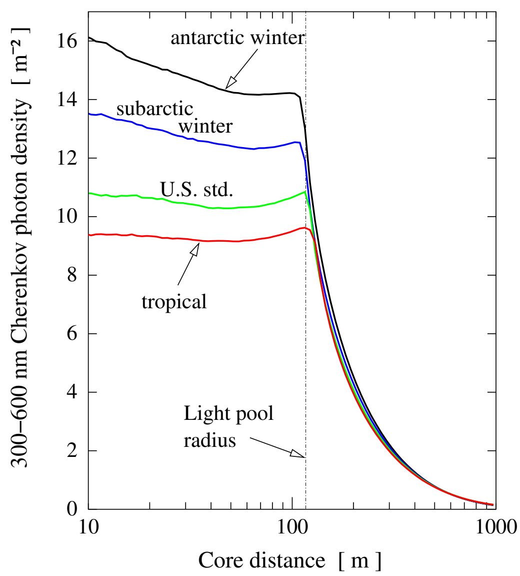

Figure 2: Comparison of average Cherenkov light density on the ground for vertical 100 GeV gamma-ray showers at an observation level of 2200 m, for different atmospheric profiles from Figure 1 (top).

accuracy additional corrections are needed for composition (in particular the water vapour partial pressure) and for wavelength. The impact of both of these is illustrated in Figure 3.

The most important simplification in simulations is perhaps to neglect the wavelength dependence of the index of refraction. The CORSIKA program [3], for example, uses by default a fixed index of refraction corresponding to a wavelength of 400 nanometers but provides the option to include the wavelength dependence [4], although at a significant cost in terms of efficiency. This is related to the reduction of photons tracked down to the telescopes, in CORSIKA by means of grouping them into *photon bunches*, to a level just low enough that they would usually not result in more than one photo-electron in the detector simulation. With wavelength-independent index of refraction, this ‘low enough’ is related to the inverse of the average photon detection efficiency over the whole wavelength range while in the wavelength-dependent case it is related to the inverse of the peak photon detection efficiency.

4 Dependence on site altitude

Observation of air showers with imaging atmospheric Cherenkov telescopes (IACTs) depends quite significantly on the observation altitude – even though this dependence is much weaker than the altitude dependence for particle detector arrays. The primary altitude dependence for IACTs is due to their distance from the shower maximum (see Figure 4). At higher altitudes, the telescopes are closer to the emission region and the emitted light thus less diluted at the observation level, resulting in a larger density of photons over a smaller area on the ground. At high altitudes, the energy threshold of IACTs will thus be lower.

At the same time, IACTs at high altitude will see larger fluctuations in the shower images because of random particles penetrating down to or close to ground level. As a result, it becomes increasingly difficult to distinguish between

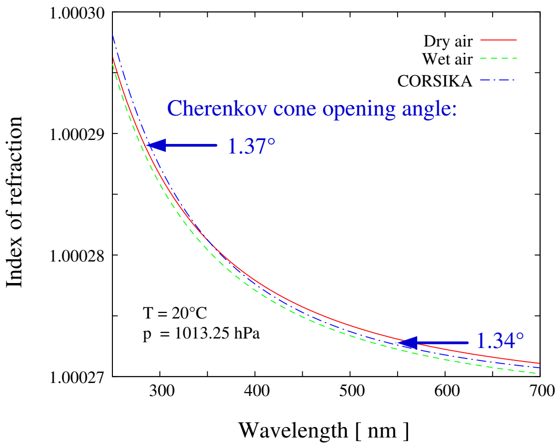

Figure 3: The index of refraction in dry and wet air at normal conditions as a function of the wavelength. In addition to the accurate calculations [5] the simplified wavelength dependence [4] available in the CORSIKA air shower simulation package [3] is also shown.

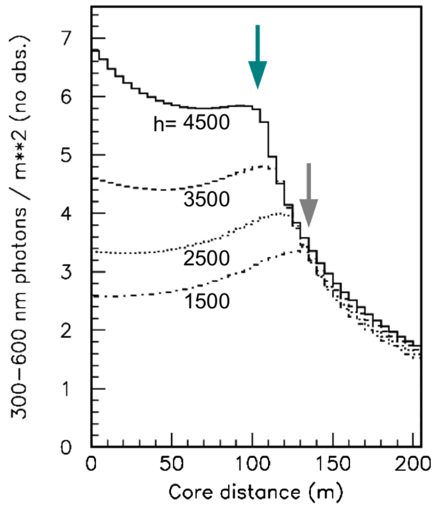

Figure 4: The dependence of the lateral density of Cherenkov photons on the ground from vertical showers initiated by 30 GeV gamma rays, as a function of core distance for different observation altitudes *h*. No field-of-view restrictions and no extinction of Cherenkov light are applied here. In general, the larger photon density in the so-called light pool (see arrows) at high altitude is because the light is spread out over a smaller area than at lower altitudes. The resulting photon density at large core distances (not shown here) will be smaller at higher altitude. The peak in photon density at small core distances, only visible for high altitudes, is mainly due to particles penetrating down to observation level.

gamma- (or electron-) initiated electromagnetic showers and the usually more irregular hadron showers initiated by protons or nuclei (poor gamma-hadron discrimination).

Also the instrument field-of-view (FoV) may be too small to image all of the Cherenkov light, in particular at a large impact parameter (distance to the shower axis). The necessary FoV (and thus telescope cost) to completely catch a shower image is increasing with altitude. For a fixed FoV of telescopes in an IACT array, showers are generally seen in fewer telescopes at a high-altitude site, resulting in a poorer angular and energy reconstruction and, again, in poor gamma-hadron discrimination.

As a consequence of these effects, high-altitude sites are generally only preferable for observations close to the energy threshold of the instrument. For energies well above threshold, an IACT array at a lower altitude will result in better angular and energy resolution, in a larger effective detection area and, in particular, in a better rejection of the cosmic-ray background.

5 Extinction and scattering of Cherenkov light or fluorescence light

A significant part of the Cherenkov light or fluorescence light produced by air showers is lost on the way to the ground. As long as light scattered into the detector FoV within the signal readout period is of little relevance, this loss is just the extinction. The extinction includes absorption by a number of molecules as well as Rayleigh scattering and Mie scattering on aerosols. Among the absorbing molecules, ozone and normal oxygen are most prominent. For ozone, the main absorption bands are the Hartly bands in the 200-300 nm range and the Huggins bands up to 340 nm; the Chappuis bands near 600 nm being much weaker. Oxygen absorption is most relevant in the Herzberg continuum below 242 nm and in the Herzberg band around 260 nm. In addition, there is some absorption on water vapour (see [6]).

For typical Cherenkov detector, using photomultiplier tubes with borosilicate windows, the impact of the highly variable tropospheric ozone profile on the signal from air showers is only at the level of one or two percent. For detectors with higher UV response, it can be really significant, in particular when muon rings are used for calibration purposes. Calibration of Cherenkov detectors with significant photon detection efficiency below 280 nm will therefore require much more intense atmospheric monitoring than with typical current devices. For the detection of fluorescence light, most of which is emitted in the 300-400 nm range, tropospheric ozone is not an issue. The stratospheric ozone layer, on the other hand, is not relevant since at this altitude the shower development has usually not even started.

The molecular Rayleigh scattering can be accurately calculated from the density profile and included in the simulations. The main uncertainty in the extinction of Cherenkov or fluorescence light is generally the Mie scattering on aerosols. Even under fairly good observation conditions, the aerosol optical depth can easily vary by 0.1, resulting in 10 percent more or less light in the detector. The vertical profile of these aerosols is best monitored with Lidars, if possible without interfering too much with observations then best along the line of sight of the telescopes. The total extinction is more reliably obtained from star light, and is an important cross-check to the atmospheric transmission tables required in the simulation of the light yield from the air showers. Since aerosols (including hydrosols) can change with temperature, day-time measurements (e.g. based on scattered sun light) can be biased – simulations are better based on measurements during night time.

Both direct and scattered Cherenkov light are well known to have a significant impact on the fluorescence technique, due to the much higher intensity of the Cherenkov light

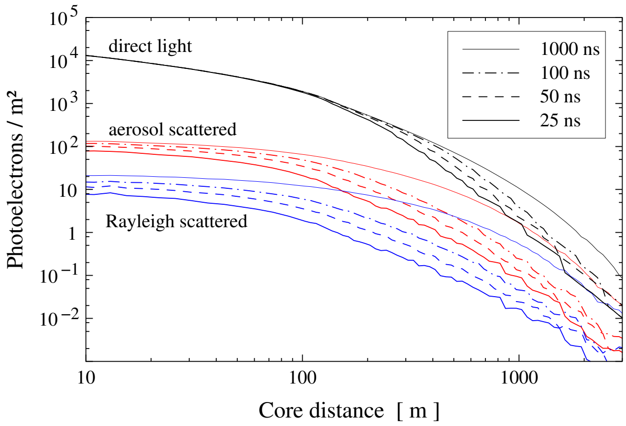

Figure 5: The relevance of scattered Cherenkov light with respect to the non-scattered direct Cherenkov light for different integration times, for vertical proton showers of 100 TeV. Mirror reflectivity and PMT quantum efficiency have been applied but no FoV restriction or image cleaning. The aerosol scattering phase function follows a Henyey-Greenstein function with asymmetry parameter g=0.7 [6].

in the forward direction, in comparison to the weak and isotropic fluorescence light. Scattered Cherenkov light has little impact though on the IACT technique, due to observations being restricted to within a few hundred meters from the shower axis, and also due to the short integration times [6]. Most of the scattered Cherenkov light within the camera FoV of an IACT would arrive well outside the few nanoseconds integration time of the signal – only light scattered under very small angles and/or close to the detector would have any chance of arriving within some 10 ns of the direct light. For Rayleigh-scattered light this is of the order of 10^{-3} of the direct signal, for Mie-scattered light perhaps as much as a percent (see Figure 5). In addition, most of the scattered light arriving within the integration time would generally be rejected by the image cleaning used to suppress NSB noise.

Only in situations where the aerosol scattering phase function is dominated by very large particles, with a size of about the wavelength or more and resulting in enhanced forward scattering, might the scattered Cherenkov light contribution exceed the level of a few percent of the the direct Cherenkov light. Most likely, the aerosol optical depth in such untypical conditions would exceed levels where the IACT data is rejected from further analysis anyway. More relevant are changes to the scattering phase function for the fluorescence technique where in situations of enhanced forward scattering even scattered fluorescence light may be significant (see [7, 8, 9]).

A tricky problem to the Cherenkov and fluorescence techniques are aerosol layers (or thin clouds) intersecting the shower. Stratospheric aerosols from volcano eruptions in distant locations are generally no problem since most of the shower development is below such aerosol layers. Aerosol layers in the lower troposphere (such as the boundary layer), i.e. after the end of the shower, are also not a major problem if properly monitored. They will affect all light in the same way and can be easily corrected for, even from the trigger rate of the instrument itself [10], although they will increase the energy threshold of the instrument. The layers intersecting the shower however will change the image shapes (for IACTs) or longitudinal profile (for fluorescence telescopes). This will not only affect the energy calibration and detection area but also the gamma-hadron discrimination to the extent that the gamma-ray efficiency is very poorly known. Although it can in principle be corrected for, if very well monitored and simulations include these layers, the required effort in correcting such data will generally be considered too high – unless affecting observations of extreme interest – and the affected data will most likely be discarded.

6 Conclusions

Knowledge of the atmospheric density profile is important for proper simulation of any type of ground-based air shower instrument, for particle detector arrays as well as for Cherenkov or fluorescence detectors. For the latter two the profile enters also in the light emission processes. It is particularly relevant for the Cherenkov emission where the related index of refraction determines the minimum velocity for Cherenkov emission, the number of photons emitted per unit path length and also the Cherenkov cone opening angle. Most simulations assume a wavelength-independent index of refraction but the wavelength dependence can be turned on, at the expense of the simulation efficiency.

The extinction of Cherenkov and fluorescence light depends in addition to Rayleigh scattering and absorption on O_2 also on aerosols and on trace gases like ozone and water vapour. The tropospheric ozone absorption is of particular concern for Cherenkov detectors with extended UV response using muon rings for calibration. Hardly any simulations make use of measured ozone profiles. Except for this ozone part, the atmospheric transmission tables used in the simulations – in particular the total aerosol optical depth – can be best checked with star light extinction. For further improving the accuracy of the simulations, the aerosol profile along the line of sight should be monitored. Nevertheless tricky are aerosol layers intersecting the shower development, requiring dedicated and well adapted simulations for correcting their effect.

Scattered light, in particular scattered Cherenkov light, is highly relevant to the fluorescence technique but only has a small effect for IACTs. For IACT simulations, it is generally ignored.

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