Atmospheric effects on the Cherenkov technique

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Abstract

The impact of several atmospheric parameters on the atmospheric Cherenkov technique has been calculated. These parameters affect the energy calibration, effective areas, and other aspects of imaging and non-imaging Cherenkov experiments. In particular, different density profiles lead to differences of up to 60% in the Cherenkov light density. Seasonal variations are of the order of 15–20%. The quest for improved energy calibration of Cherenkov experiments also shows the need for improved transmission calculations, taking all relevant processes into account and using realistic profiles of absorbers. Shower simulations including scattering processes also reveal the relevance of Rayleigh and Mie scattering. Atmospheric refraction is also taken into account.

1 Introduction

The atmospheric Cherenkov technique has made very significant progress during the last decade. In particular, the imaging atmospheric Cherenkov technique with single telescopes or stereoscopic systems of telescopes has become a mature astrophysical observation technique. Non-imaging techniques, some of which have a long tradition, have also been much improved and are used both for γ-ray source searches as well as for cosmic-ray composition studies. The imaging technique has not only achieved very high levels of hadronic cosmic-ray rejection and a good sensitivity for TeV γ-ray sources but is also becoming an increasingly important and precise spectroscopy method.

As such, much more attention is being paid to various systematic effects now than a decade ago. Apart from instrumental effects, the atmosphere is of most importance in view of energy calibration and effective detection areas. After all, the atmosphere is the target medium for the shower development, the emitter of Cherenkov photons, and the transport medium. Non-imaging Cherenkov techniques trying to disentangle γ-ray from hadron showers or light from heavy nuclei are also affected by atmospheric effects on the lateral shape of the Cherenkov light, e.g. due to shower development and light scattering.

The goal of this paper is the quantitative analysis of the impact of atmospheric parameters like the density profile, light transmission and scattering on imaging and non-imaging Cherenkov techniques. This includes numerical simulations of shower development and Cherenkov light emission, with a modified version of the CORSIKA program (Heck et al. 1998), as well as simulation of the light propagation in the atmosphere. For the latter part, transmission and scattering coefficients have been calculated first with the MODTRAN program (Kneizys et al. 1996) for a set of different model atmospheres. Methods and results are described in more detail also in Bernlöhr (1999).

2 Impact of atmospheric density profiles

The atmospheric Cherenkov technique is sensitive to the density profile in several ways: the development of the air shower, the opening angle $\theta_{\rm c}$ of the Cherenkov cone of each particle as a function of index of refraction n and velocity, and the number of photons emitted by a particle per unit path-length dN/dx.

From the basic equations for $\theta_{\rm c}$ and dN/dx it follows that the amount of Cherenkov light scales with $(n-1)$ (e.g. at shower maximum) and so does the area of the light cone on the ground (the *light pool*). The Cherenkov light density within the light pool would, thus, be expected to be about the same. That is confirmed by shower simulations where the density profile was kept the same (for shower development) but the index of refraction was adapted to different model atmospheres. These model atmospheres are mainly based on Kneizys (1996). An additional antarctic winter profile was constructed from sounding balloon data.

The atmospheric density is to good approximation proportional to $(n - 1)$. Both profiles are, therefore, coupled and consistent simulations result in different altitudes of shower maxima for different atmospheric profiles, i.e. different distances from shower maxima to ground. These different distances finally lead to different Cherenkov light densities within the light pool (see Figure 1). It is important to note that this impact of atmospheric profiles leads to light differences of 60% between tropical and antarctic winter profiles. It is perhaps even more important that differences between average summer and winter profiles are as large as 15–20%. As a consequence, flux calibration in units of a reference source (*Crab*) also should take seasonal effects into account.

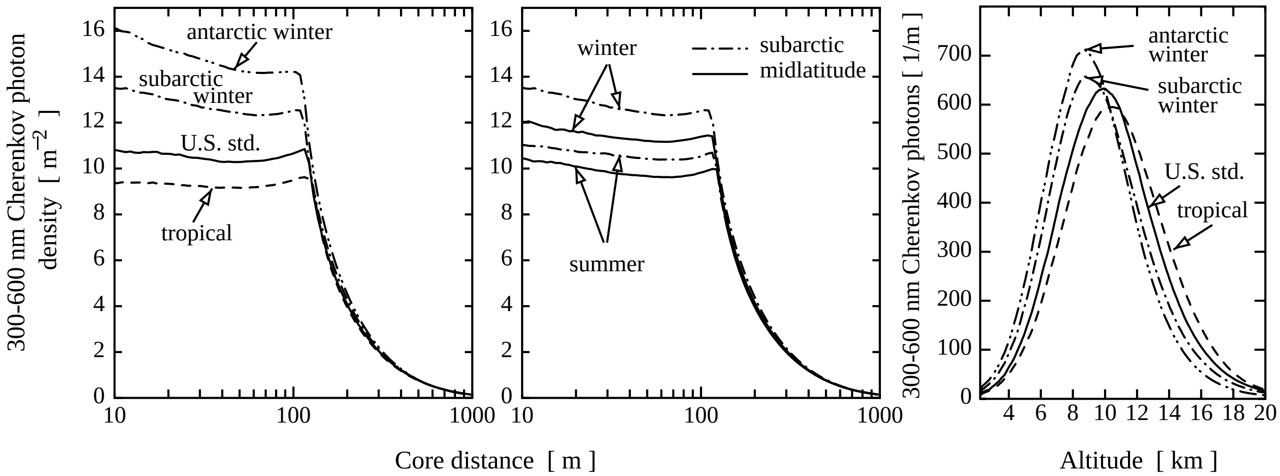

Figure 1: Left and middle: Average lateral distributions of Cherenkov light photons in the wavelength range 300–600 nm for vertical 100 GeV gamma-ray showers in CORSIKA 5.71 simulations with different atmospheric profiles (2000 showers simulated for each profile). Absorption of Cherenkov light is taken into account. Observation altitude is 2200 m above sea level. Left panel: models from tropical to antarctic winter. Middle: Seasonal variations. Right: Longitudinal distribution of Cherenkov light emission.

3 Transmission of Cherenkov light

The atmospheric extinction of light is another source of concern for the energy calibration of atmospheric Cherenkov experiments and to some extent also for the image parameters of telescopes and the lateral distribution of light. There are several sources of extinction: molecular absorption bands (in particular ozone below 340 nm and O_2 below 260 nm), molecular (i.e. Rayleigh) scattering as well as aerosol (Mie) scattering and absorption. Most Cherenkov light in the photomultiplier (PM) sensitivity range is actually lost by molecular scattering. Although some of the light may also be scattered into the line of sight, that is generally not important (see Section 4) and scattering may be treated as an absorption process.

While molecular scattering and O_2 absorption are easily predictable and almost constant at any site, both aerosols and ozone are site-dependent and variable. Aerosols are particularly abundant in the boundary layer of typically 1–2 km thickness above the surrounding terrain where the diurnal variation and the dependence on ground material and wind speed is largest. The main practical problems in calculation of the atmospheric transmission of Cherenkov light are the properties and vertical profile of aerosols. While the total extinction is easily measured with star light, the aerosol extinction profile requires sophisticated LIDAR equipment. Standard backscattering LIDAR measurements, for example, require a number of model assumptions to estimate an extinction profile since the amount of backscattering is not strictly proportional to extinction.

Even in a clean-air, mountain-altitude environment bad assumptions on the aerosol extinction profile may lead to systematic errors in the amount of Cherenkov light of the order of 5% – even when stellar extinction is perfectly reproduced (see Bernlöhr 1999).

Sophisticated models of aerosol and other sources of extinction are available, for example, with the MODTRAN program (Kneizys 1996) – although local conditions may vary. MODTRAN transmission calculations have been used to investigate a number of possible variations. These include variations in the altitude of observer and surrounding areas, in the general type of environment (for example desert or maritime), in the amount of tropospheric ozone or of volcanic dust in the stratosphere. Sample transmissions from various altitudes are shown in Figure 2.

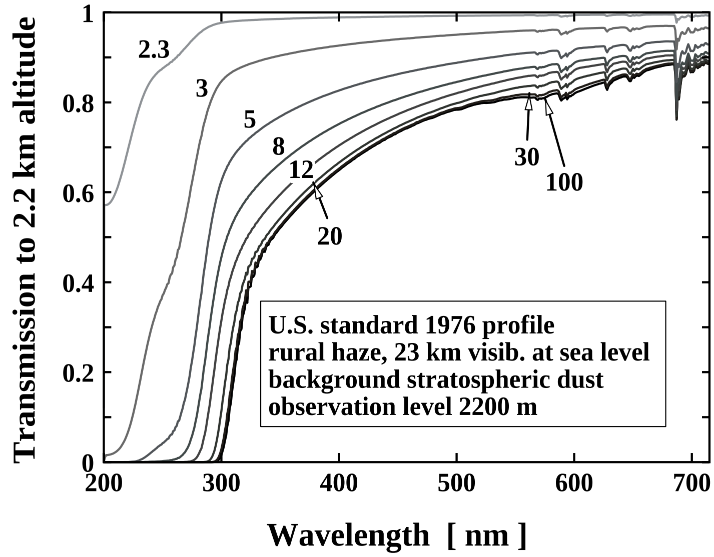

Figure 2: Example of transmission of light from various altitudes (in kilometers) to an observation level at 2.2 km, as calculated with MODTRAN.

Some of the forthcoming Cherenkov installations are planned to be installed at the base of a mountain instead of at the top – for environmental or infrastructure reasons. The MODTRAN calculations, assuming clear skies at both places (e.g. at 1.8 instead of 2.4 km altitude), predict a 4–8% difference in Cherenkov light transmission, depending also on the surroundings. This should be compared to some 15% decrease in Cherenkov light density by purely geometrical reasons (due to 15% larger light pool area).

Other variations studied turned out to be of little significance to most Cherenkov installations. A 1.5–2 fold higher amount of tropospheric ozone as observed on the Canary islands, compared to the tropical model, leads to less than 1% reduction of Cherenkov light detectable by typical photomultipliers with borosilicate windows and bi-alkali cathodes. For UV Cherenkov observations, on the other hand, such a variation would be significant. Another variation with little impact on Cherenkov light turned out to be the level of volcanic dust in the stratosphere, which is insignificant below 14 km altitude. A single, large eruption like Pinatubo in 1991 can, however, extinct the reference star light by 10% for a period of many months.

4 Scattering of light and other effects

In the preceding section, all molecular and aerosol scattering of Cherenkov light is treated as an absorption process. Actually some of this light is scattered into the detector's field of view. Calculation of scattered Cherenkov light requires to know the vertical profile and the *phase function*, i.e. the angular distribution of the scattering process. Both are easy to calculate for molecular (Raleigh) scattering, but in the case of aerosol (Mie) scattering they depend on aerosol properties. Realistic aerosol scattering and absorption coefficients have been calculated with the MODTRAN program. The aerosol phase function of scattering angle γ can be approximated fairly well by a Henyey-Greenstein phase function with asymmetry parameter g:

$$P_{\rm HG}(\gamma) = (1/4\pi)\ (1-g^2)\,/\,(1-2g\cos\gamma+g^2)^{3/2}. \qquad (1)$$

A value of $g = 0.7$, corresponding to a typical tropospheric aerosol phase function in MODTRAN, has been used. CORSIKA was extended for this purpose with ray-tracing code for scattered light.

Figure 3 shows the relevance of both aerosol and Rayleigh scattered light with respect to direct Cherenkov light in the case of 100 TeV proton showers. Actual amounts of scattered light registered by a detector depend on integration times applied. For short integration times only light scattered by rather small angles is relevant. Because aerosol scattering is heavily forward peaked, aerosol scattered light exceeds Rayleigh scattered light by an order of magnitude. For long integration times and distances of more than 3 km from the shower axis, a situation more typical for fluorescence experiments, scattered light eventually exceeds direct Cherenkov light.

In the imaging atmospheric Cherenkov technique with a small field of view and very short integration times, the scattered light is even less significant – typically below 1 per mille of direct light for vertical γ showers and rising like $\sec z$ with increasing zenith angle z.

Two other effects come into play at large zenith angles: the spherical geometry of the atmosphere and refraction. The CORSIKA program is at present using a plane-parallel atmosphere (but see Heck et al. 1999 for a new extension to circumvent this). Analytical calculations of the Cherenkov emission profiles along the shower axis in spherical as well as in planar geometry show that the proper geometry becomes relevant for zenith angles beyond about 70°.

Considering the fact that TeV γ-ray sources can now be located with sub-arcminute accuracy (Pühlhofer et al. 1997), atmospheric refraction of the Cherenkov light becomes relevant at even smaller zenith angles. Numerical ray-tracing (Bernlöhr 1999) reveals that the Cherenkov light of TeV γ-showers has some 50% of the stellar light refraction below 40° zenith angle, some 60% at 60°, and some 80% at 75° – the stellar refraction being proportional to $\tan\theta$ except near the horizon and reaching one arcminute at 45° zenith angle.

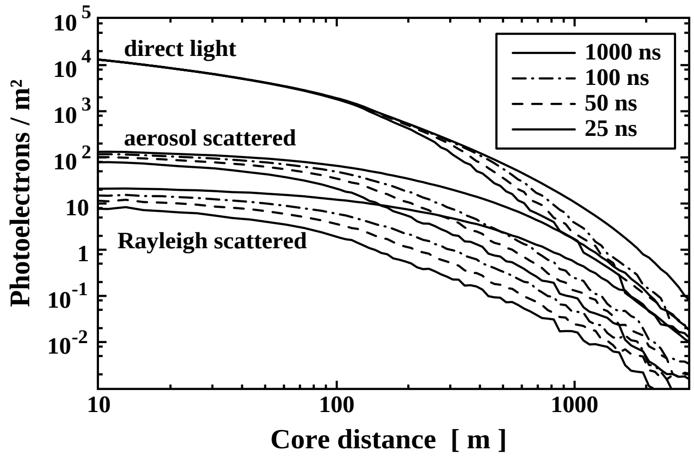

Figure 3: Lateral densities of direct, aerosol scattered, and Rayleigh scattered light in vertical proton showers of 100 TeV energy for different integration times. Mirror reflectivity and PM quantum-efficiency curve (bi-alkali cathode, borosilicate window) are applied for the conversion from photons to photo-electrons. Observation altitude is 2.2 km.

5 Conclusions

Of all atmospheric parameters studied – clouds not considered – the density vertical profile has the most striking impact on the atmospheric Cherenkov technique. Differences of up to 60% between extremely different profiles (tropical/antarctic) are seen. Average seasonal variations for moderate latitudes are of the order of 15–20%. This shows the need that shower simulations are carried out with the appropriate profiles. Seasonal effects should to corrected for when calibrating γ-sources seen during summer (e.g. Mkn 501) with a reference source visible in winter (Crab, northern hemisphere assumed).

Compared to the density profile, the profile of aerosol extinction is of less importance but still significant if energy calibrations of the order of 10% accuracy are aimed at. Monitoring of stellar light extinction is considered essential but perhaps not sufficient. Realistic aerosol profiles should be used in simulations.

Scattered Cherenkov light is generally of little relevance to Cherenkov experiments – in contrast to fluorescence experiments. Small corrections for scattered light might, nevertheless, be needed where the lateral shape is used for composition measurements or γ/hadron separation.

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