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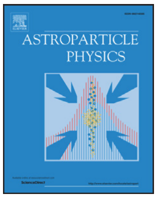

Computing the electric field from extensive air showers using a realistic description of the atmosphere

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ABSTRACT

The composition of ultra-high energy cosmic rays is still poorly known and constitutes a very important topic in the field of high-energy astrophysics. Detection of ultra-high energy cosmic rays is carried out via the extensive air showers they create after interacting with the atmosphere constituents. The secondary electrons and positrons within the showers emit a detectable electric field in the kHz-GHz range. It is possible to use this radio signal for the estimation of the atmospheric depth of maximal development of the showers $X_{\max}$, with a good accuracy and a duty cycle close to 100%. This value of $X_{\max}$ is strongly correlated to the nature of the primary cosmic ray that initiated the shower. We show in this paper the importance of using a realistic atmospheric model in order to correct for systematic errors that can prevent a correct and unbiased estimation of $X_{\max}$.

1. Introduction

Recently a lot of efforts have been put into determining the mass composition of cosmic rays using the radio signal [1–3]. Several methods exist by now with different approaches but the goal is the same: reconstructing the atmospheric depth of the shower maximum, $X_{\max}$, where the number of particles is maximum. This atmospheric depth is highly correlated to the mass of the primary cosmic ray. To be competitive, the uncertainty on its estimation should be close to or better than that achieved with the fluorescence technique ($\sim 20\,\text{g/cm}^2$, see [4]). The composition of the highest-energy cosmic rays (above 1 EeV) is still poorly known, since it is difficult to measure composition using a surface detector that only samples the shower at ground level. Besides, the fluorescence light technique, more apt for composition measurements, has a duty cycle of the order of 14% [5], making it difficult to provide $X_{\max}$ measurements for a large number of showers at the highest energies. The radio technique, consisting in the measurement of the electric field induced by the extensive air showers created by cosmic rays, could be an excellent alternative to obtain the $X_{\max}$ with an almost 100% duty cycle. Extracting the $X_{\max}$ using the radio signal relies on an atmospheric model. The electric field emission is highly beamed towards the direction of propagation of the shower and the shape of its distribution at the ground level depends on the distance between the point of maximum emission and the shower core. This property can be exploited to reconstruct $X_{\max}$ from the radio signal. However, to make this method accurate, one needs to know the atmospheric depth corresponding to a given distance with precision. The electric field measured by the antennas strongly depends on the characteristics of the atmosphere in which secondary shower particles evolve: air density, air refractive index at radio frequencies, temperature, pressure and humidity. For a long time, simulation codes computing this electric field assumed a standard atmosphere. Nowadays, with high precision measurements on large radio arrays running continuously such as AERA [6], it has become important to refine this atmospheric model. Indeed, it is clear that the atmospheric characteristics vary significantly with time (day/night effect and seasonal variations) and these variations are responsible for systematic uncertainties that can prevent an accurate estimation of the $X_{\max}$. Ideally, we need to know the atmospheric state at the time a shower is detected. This is possible using the Global Data Assimilation System [7] (GDAS) data. In this paper, we show how we use these data together with a standard atmospheric model for the highest altitudes to compute an accurate air density model as a function of altitude at the time of the detection of the event. The knowl-

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edge of the air density and humidity ratio also allows to compute the realistic air refractive index which is needed for the amplitude and time structure of the signal. Several descriptions of the atmosphere are in use in different simulation codes such as SELFAS [8], ZHAireS [9] and CoREAS [10]. We show that the choice of the atmospheric model induces uncertainties in the atmospheric depths up to some tens of g/cm^2 which is comparable to the uncertainty on the $X_{\max}$ obtained with the fluorescence data. The paper is organized as follows. In Section 2, we briefly present the geometrical description of the shape of the Earth and its atmosphere and the atmospheric depths computations. In Section 3 we describe the GDAS data and its use to build a realistic atmospheric model that we will use to calculate the atmospheric depths and the air refractive index. We compare the results with those obtained assuming the basic US Standard model [11]. In Section 4 we quantify the influence of the air refractive index and air density profiles calculated with the GDAS data on the produced electric fields. Then, in Section 5 we study the case of a simulated shower which develops in the atmospheric conditions of a sample day. We show that using the US Standard model on the $X_{\max}$ estimation leads to biased results, unless we use the same atmospheric conditions than those of the day and time of the detected (here simulated) event. In this paper, we will note **V** the shower axis and **B** the geomagnetic field.

2. Geometry of the atmosphere

Usually, the shape of the atmosphere is taken as flat or spherical. The spherical shape is taken into account when dealing with inclined showers, typically for zenith angles $\theta \geq 60°$. In Fig. 1, we present both descriptions. The atmospheric depth at distance ℓ from observer O and corresponding to an elementary path $\mathrm{d}\ell$ is given by $\mathrm{d}X_{\mathrm{slant}} = \rho(z(\ell))\,\mathrm{d}\ell$, where ρ is the air density and z the altitude above sea level. In the flat approximation $\mathrm{d}z = \mathrm{d}\ell \cos\theta$ where θ is the zenith angle — between the vertical at O and (OM) — so that $\mathrm{d}X_{\mathrm{slant}} = \rho(z)\,\mathrm{d}z/\cos\theta = \mathrm{d}X_{\mathrm{v}}/\cos\theta$, where $\mathrm{d}X_{\mathrm{v}}$ is the vertical elementary atmospheric depth. After integration we obtain:

$$X_{\mathrm{slant}}(\ell) = X_{\mathrm{v}}(z(\ell))/\cos\theta. \tag{1}$$

$X_{\mathrm{v}}(z)$ represents the vertical atmospheric depth; it is known as the Linsley's parameterization when considering the US Standard model and provides the integrated atmospheric depth traversed vertically from “infinity” (i.e. where ρ is negligible, before entering the atmosphere) to altitude z. The flat approximation is thus correct for vertical showers but considering the accuracy that radio methods intend to achieve, a comparison to a spherical description is necessary for inclined showers. The expression of the atmospheric depth in Eq. (1) does not apply when $\theta \neq 0$ because the atmospheric layers are curved. Moreover at a position M, the zenith angle θ' is not the same than the angle θ at O (see Fig. 1 right). We consider an observer O at the altitude h. The radius of the Earth is denoted R. A point M on the shower axis is located at an altitude z (above the sea level). The zenith angle at M depends on its position along the shower axis: it is θ for $M = O$ (corresponding to an observer located at an altitude h). A simple geometrical calculation gives:

$$\ell = \sqrt{(R+z)^2 - (R+h)^2 \sin^2\theta} - (R+h)\cos\theta$$

$$z = \sqrt{\ell^2 + (R+h)^2 + 2\ell(R+h)\cos\theta} - R$$

$$\cos\theta' = \sqrt{1 - \left(\frac{R+h}{R+z}\right)^2 \sin^2\theta}$$

The atmospheric slant depth is calculated numerically by integrating the atmosphere density along the shower axis:

$$X_{\mathrm{slant}}(\ell) = \int_{\ell}^{\infty} \rho(z(\ell'))\,\mathrm{d}\ell' \tag{2}$$

Where $\rho(z(\ell'))$ is the air density at a given altitude z corresponding to a particle-to-observer distance ℓ' along the shower axis. A comparison is made between the two descriptions in Fig. 2: we choose an observer O at sea level and a shower with a zenith angle θ. The atmospheric depth crossed by the shower from outer space up to a distance ℓ to the observer along the axis is computed either with the flat approximation or the spherical description. Both descriptions give equal results for a vertical shower ($\theta = 0°$). Using the flat approximation leads to errors of the order of 10 g/cm^2 for zenith angles larger than 60°. In the seek of accuracy, we should be very cautious with the flat approximation, even for not too inclined showers. In SELFAS, we always use the spherical description, independently of the zenith angle.

Apart from the atmospheric depths, we also checked the effect on the electric field computations. We found that one really needs to consider the spherical shape only for inclined showers ($\theta \geq 60°$).

3. Physico-chemical aspects of the atmosphere

The variations of the meteorological conditions are studied for the CODALEMA experiment. In the following sections, only data for the location of Nançay, France, are presented.

3.1. The GDAS data

The characteristics of the atmosphere that are needed for computing the electric field emitted by air showers are the air refractive index (η) and density (ρ) at any altitude z. These parameters depend on relative humidity (R_h), temperature (T) and total pressure (P) that vary on a daily basis.

As an illustration, we present in Fig. 3 the relative humidity as a function of the altitude from the GDAS data on March 18, 2014. We see that at a given altitude, the variations are very important according to the time of the day and consecutively, the same holds for the air density and index values.

In Fig. 4, we show the same plot but for the temperature (top) and pressure (bottom). For temperature, above an altitude of $3-4$ km the variations are negligible as a function of time. The pressure is not varying significantly over time at fixed altitude and can also be taken as constant with time. However the latter quantities can vary more importantly over longer timescales. In this example of a single day, we can conclude that the precise knowledge of the pressure, temperature and relative humidity is mandatory in order to accurately compute the air index and density profiles. The values displayed in Figs. 3 and 4 were obtained from the GDAS which provides a database of measurements of physicochemical characteristics of the atmosphere.

Each GDAS file contains a week of data and one must extract the ones corresponding to the desired location. The files contain measurements for every 3 hours at the surface and 23 geopotential heights up to an altitude of $z_{\max}^{\mathrm{GDAS}} = 26$ km above sea level.

The results of the simulation of the EAS-induced electric field depend on the air index and density models of the atmosphere in which the shower develops. The adopted approach to provide SELFAS with realistic air profiles along with a proper geometrical description of the atmospheric layers from the GDAS data is explained in the next sections. Detailed comparisons between the US Standard model and the GDAS profiles, as well as the consequences on the $X_{\max}$ reconstruction will be presented. Among all the available parameters provided by the GDAS, we use the pressure P in hPa, the geopotential height Z_g in gpm[1], the temperature T in K and the relative humidity R_h in %. As the GDAS provides

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[1] geopotential meters