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On the prospects of Ultra-High Energy Cosmic Rays detection by high altitude antennas

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ABSTRACT

Radio emission from Ultra-High Energy Cosmic Rays (UHECR) showers detected after specular reflection off the Antarctic ice surface has been recently demonstrated by the ANITA balloon-borne experiment. An antenna observing a large area of ice or water from a mountaintop, a balloon or a satellite may be competitive with more conventional techniques. We present an estimate of the exposure of a high altitude antenna, which provides insight on the prospects of this technique for UHECR detection. We find that a satellite antenna may reach a significantly larger exposure than existing UHECR observatories, but an experimental characterization of the radio reflected signal is required to establish the potential of this approach. A balloon-borne or a mountaintop antenna are found not to be competitive under any circumstances.

1. Introduction

The detection of Extensive Air Showers (EAS) by instruments placed at high altitude above ground was proposed as early as 1972 by Chudakov [1]. Cherenkov photons, emitted in a narrow cone of $\approx 1^\circ$ half-angle along the EAS axis, may be diffused after hitting ground (e.g. by snow or water). A Cherenkov detector overlooking the Earth surface from a mountain or a balloon may provide a huge detection aperture at low cost. Several experiments have explored this concept [2]. Also, the detection of UV fluorescence light from Ultra-High Energy Cosmic Rays (UHECR) by a satellite instrument is at the core of the JEM-EUSO proposal [3].

ANITA [4], a balloon-borne experiment searching for high energy neutrinos through the coherent radio emission from the neutrino-induced shower in the Antarctic ice, has recently presented evidence of radio detection of EAS [5]. The characteristics of the events – polarization and dependence on the geomagnetic field – suggest that the detected radio signal comes from specular reflection off the ice of the EAS highly-beamed geomagnetic radio emission [6]. A full understanding of the detected signals is still lacking. When a data-driven modeling of the measurements is used [5], the sample of events is found to have a mean energy of $1.5 \cdot 10^{19}$ eV, and a mean angle of observation relative to the true shower axis of 1.5°. Based on these observations, which suggest that UHECR may be detected with a reasonable aperture by a balloon-borne antenna, a forthcoming ANITA-III flight will include a dedicated trigger for UHECR candidates. The proposed EVA mission [7] – a more sensitive balloon-borne antenna – estimates that several hundreds of events will be detected above 10^{19} eV when extrapolating ANITA results to a 50 day flight. Recently, a satellite experiment – the Synoptic Wideband Orbiting Radio Detector (SWORD) – based on the same principle has been proposed [8].

Since radio signals are minimally attenuated by the atmosphere, a high altitude antenna may detect showers landing at very large distances, potentially providing a large exposure for UHECR. It is thus relevant to evaluate whether this novel technique can play a role in the next generation of UHECR experiments. In this paper, we have derived the exposure of a high altitude antenna under very general assumptions. While a more accurate estimate requires a detailed knowledge of the radio emission and of the detector system, this study already provides insight on the prospects of this technique for UHECR detection.

2. Geometric exposure of a high altitude antenna

An analytical estimate of the geometric aperture of a high altitude antenna can be derived under certain approximations. Consider an antenna with an azimuthal field of view of 360° placed at an altitude h above a spherical Earth. To be detected,

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the specular reflection of the EAS axis is required to be within an angle θ_d of the direction $\vec{P}$ from the shower impact point to the antenna (see Fig. 1). The antenna is assumed to have 100% detection efficiency, independent of the shower energy or the distance to the EAS impact point. The geometric aperture is defined as:

$$A = \int_S \int_{\Delta\Omega} \cos\theta^* d\Omega dS, \quad (1)$$

where θ^* is the angle of the EAS axis with respect to the local zenith at the shower impact point, $\Delta\Omega$ is the detection solid angle of radius θ_d, and S is the area of the spherical cap visible to the antenna.

The calculation gives:

$$A = 2\pi^2 \sin^2\theta_d \frac{[h(2R_E+h)]^{\frac{3}{2}} - h^2(3R_E+h)}{3(R_E+h)}, \quad (2)$$

where R_E is the radius of the Earth.

In deriving Eq. (2), we assumed that the radio emission originates from the shower's impact point at ground. A more realistic estimate may be obtained by taking the position of the maximum development of the shower in the atmosphere as the origin of the radio emission. Since an analytical expression for the geometrical aperture cannot be derived in this case, a Monte Carlo simulation was performed. A uniform distribution of the shower's impact point was generated over the Earth spherical surface. The shower direction was then generated according to an isotropic distribution. We assumed that the radio emission originated at a depth of 850 g/cm^2 (the average shower maximum of a $6 \cdot 10^{19}$ eV proton [9]), and the corresponding point of emission along the shower axis was obtained assuming the US Standard Atmosphere model [10]. The radio emission was parameterized as a cone of half-angle θ_d around the shower direction, starting at the point of emission. The shower was considered to be detected when the antenna was within the radio emission cone reflected by the spherical Earth surface. The time-integrated apertures (i.e. the exposures) derived with this simulation are given in Fig. 2 as a function of the detection angle θ_d for an antenna located on a mountaintop, in a balloon, and in a satellite ($h = 4$, 40, and 800 km, respectively). The exposures are calculated for one year of data taking, assuming 13% duty cycle (50 days flight/year) for the balloon-borne antenna, and 100% duty cycle for the other altitudes. The exposure for a satellite antenna estimated from Eq. (2) is also given in Fig. 2. When the altitude of the antenna is much higher than the point of radio emission, the analytical calculation gives a reasonable estimate, and we included it for reference.

The actual exposure of an experiment depends on the frequency response of its antenna, since the angular distribution of the EAS radio emission is expected to be frequency dependent. The frequency bands of the ANITA, EVA and SWORD experiments are f = 200–1200 MHz, 150–600 MHz and 30–300 MHz, respectively. In the following, we will compare two different parameterizations of the beam pattern of the EAS radio emission, $F(f, \theta_d)$. The first parameterization comes from SWORD [8], and is based on the synchrotron radiation formula and ANITA data. The corresponding beam patterns for frequencies $f = 30$ and 200 MHz are shown in Fig. 3 (black lines). We obtained a second parameterization with the CoREAS [11] simulation package, which is widely used to study radio emission from EAS. Showers of energy 10^{18} eV and $5 \cdot 10^{19}$ eV with zenith angle of 75° [12] were analyzed (a large zenith angle was chosen because most of the aperture comes from distant reflections). The beam pattern was obtained from the electric field at ground assuming the emission point to be at the maximum of the shower development. We found the beam pattern to change minimally with the shower energy. The CoREAS beam patterns are also given in Fig. 3 (blue lines). The two parameterizations are substantially different, with the SWORD model predicting a much larger beam. Also, the CoREAS beam presents a Cherenkov-like ring pattern which is absent in the SWORD beam model.

Since the beam pattern becomes narrower for higher frequencies, the maximum aperture is obtained for the lowest frequency of the detection band. Let's first consider the SWORD beam pattern. For f = 150–200 MHz of the ANITA and EVA experiments, the beam emission drops at $\theta_d \approx 5°$. The yearly exposure of a balloon-borne antenna for $\theta_d = 5°$ is ≈ 1100 km^{2}sr yr (Fig. 2), which can be taken

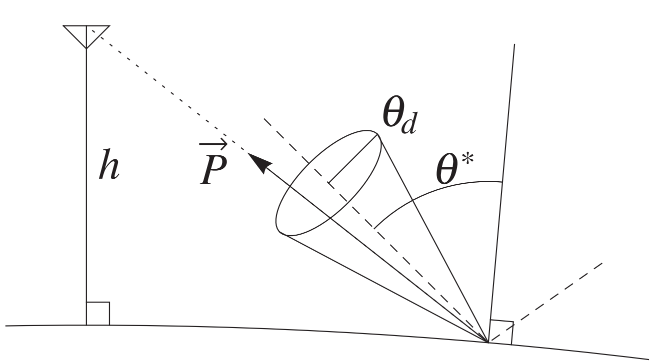

Fig. 1. Geometry of cosmic ray detection by a high altitude antenna.

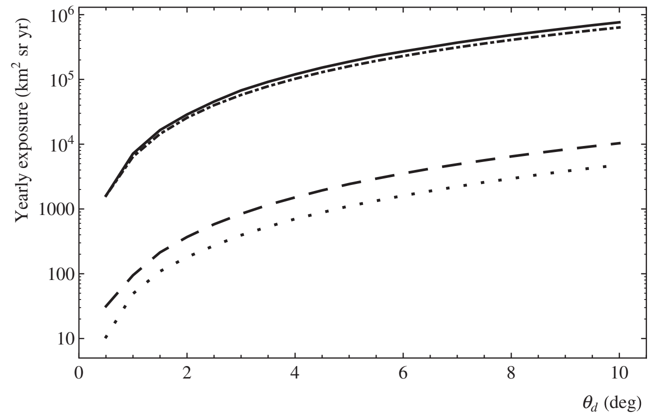

Fig. 2. Yearly exposures as a function of detection angle for a mountaintop (dashed line), a balloon-borne (dotted line) and a satellite antenna (solid line). The dash-dot line represents the exposure for a satellite antenna as estimated by an analytical calculation.

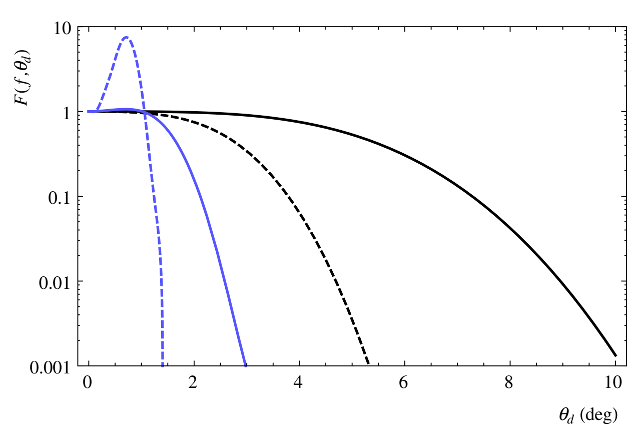

Fig. 3. Beam pattern of the cosmic ray radio emission at 30 MHz (solid line) and 200 MHz (dashed line) taken from SWORD (black) and from CoREAS simulations (blue). The curves are normalized to one at $\theta_d = 0°$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)