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Telescope Array Aperture: Mono, Stereo and Hybrid

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Abstract: We have developed detector simulators for the Telescope Array fluorescence telescopes (TA FDs) and the surface particle detector array (SD). In this paper, we present an efficient method for an evaluation of the TA FD aperture with a Monte-Carlo technique. The basic assumption in this method is that each TA-FD station is comprised of 12 telescopes of identical characteristics. With this method it is possible to calculate the trigger efficiencies of a whole station for a given shower event by building up individual telescope triggering functions with an appropriate superposition scheme. We use this method to calculate the FD aperture for various detector configurations, as mono, stereo, and hybrid observation modes. We also discuss expected results and astrophysical significance from the TA first year observation.

Introduction

The detector constructions for the TA experiment completed in March 2007 [1], and test observations have been started in May with the telescopes of the two FD stations [2] and an engineering SD sub-array [3]. The TA detector simulators [4] have also been developed by implementing real detector parameters. The main purpose of TA is to determine the energy spectrum of ultra high energy cosmic rays, and a precise evaluation of the detector aperture is quite important in this experiment. However, it is not straightforward to calculate an FD aperture because of a complex structure of the detector fiducial volume compared in cases of SD arrays. In this paper, we discuss a method to calculate the TA FD aperture with a Monte-Carlo technique for various detector configurations, for monocular and stereo observations, including vetoed telescopes, and also hybrid observations with SD.

Detector Simulator

In the TA detector simulator, the detector components as PMTs or mirrors are defined by *classes*: an object-oriented design is used. The observatory itself is also represented by a class of an aggregation of many objects of class *instances*. For example, an FD station has twelve instances of the *telescope class*, and each telescope object is comprised of instances of the *PMT class* and the *mirror class*, and so on. The parameters of detector components as PMT quantum efficiencies or mirror reflectances are given as *attributes* of the corresponding classes. Fluorescence photon injections into PMTs are calculated by ray-tracings. The night-sky background photons are also considered in simulations by using real observational data obtained at the site. The signal finding procedures are same with those implemented in the FD electronics [5, 6, 7].

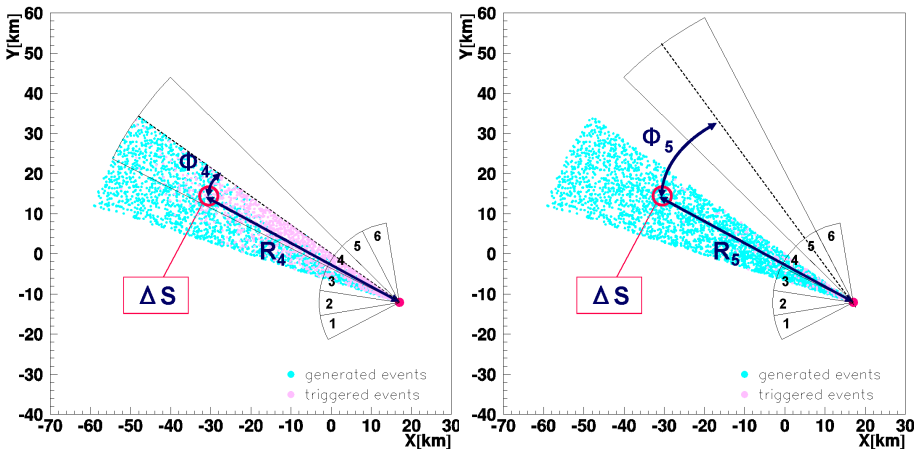

Figure 1: Simulation coordinates. Showers located in the region ΔS are represented by (R^4, Φ^4) seen from the telescope #4, and also they can be denoted as (R^5, Φ^5) for the telescope #5.

Trigger Functions and Aperture

In order to evaluate the TA aperture, we first define *trigger functions*, which give detection probabilities for showers with core positions in a region represented by the coordinates (R, Φ), the distance and the angular distance about a station (a similar approach was also reported in ref. [8]). The observation area in a field of view (FOV) of an FD station is split in azimuthal direction into six slices, and each of them has $\pm 9^\circ$ width, the FOV of a single telescope (Figure 1). Then we generate air shower events of core locations (R^k, Φ^k) in the FOV of the k-th telescope, and examine triggering criteria for each of the telescopes. In this case, the single telescope detection probability is written as (here we omit the radial coordinate R for simplicity),

$$\begin{aligned}\epsilon^k(\Phi) &= f_0^k(\Phi^k) \\ &\quad + \overline{f_0^k} f_1(\Phi^{k\pm1}) \\ &\quad + \overline{f_0^k f_1^k} f_2(\Phi^{k\pm2}) \\ &\quad + \cdots \end{aligned} \tag{1}$$

where f_0^k is the probability that the showers are triggered by the nearest telescope (k), $f_i^k(\Phi^{k\pm i})$ gives the probability that showers are triggered by the nearest k but not triggered by the $2^{\rm nd}\cdots(i\pm1)^{\rm th}$ nearest telescopes, and $\overline{f_i^k} \equiv 1 - f_i(\Phi^{k\pm i})$. The reason we need the functions not only f_0 but also $f_1, f_2, \cdots$ is that showers can be detected by multiple cameras and thus the the functions f_0^k are not independent each other. Therefore the trigger function of an FD station cannot not be represented by just a superposition of the function f_0 (as $\epsilon'(\Phi) = \sum_i \left[\Pi_{j=1}^{i-1}\overline{f_0^j} f_0^i\right]$). The trigger functions for other sliced regions $\epsilon^k(\Phi)$ can be evaluated by combining the functions f_i and $\overline{f_i}$ properly and changing the number of terms in the sum of the equation (1). By using these functions, we can calculate the trigger function of an FD station for showers at (R, Φ) as (by restoring the coordinate R),

$$\epsilon(R, \Phi) = \sum_{k=1}^{N} \epsilon^k(R, \Phi) \tag{2}$$

An advantage of this method is that the region in which shower events are generated can be limited within an FOV of a single telescope, $-9^\circ \le \Phi^k \le 9^\circ$. Since the detection range of the TA FDs is large ($\sim 60\,{\rm km}$), it is much time consuming to simulate air showers in the whole observation area of the stations. Another advantage is that once the functions f_0, f_i are defined, the FD trigger functions can be easily calculated for various detector configurations, as for monocular and stereo observations, including vetoed telescopes, and also for hybrid observations. The trigger functions of the three

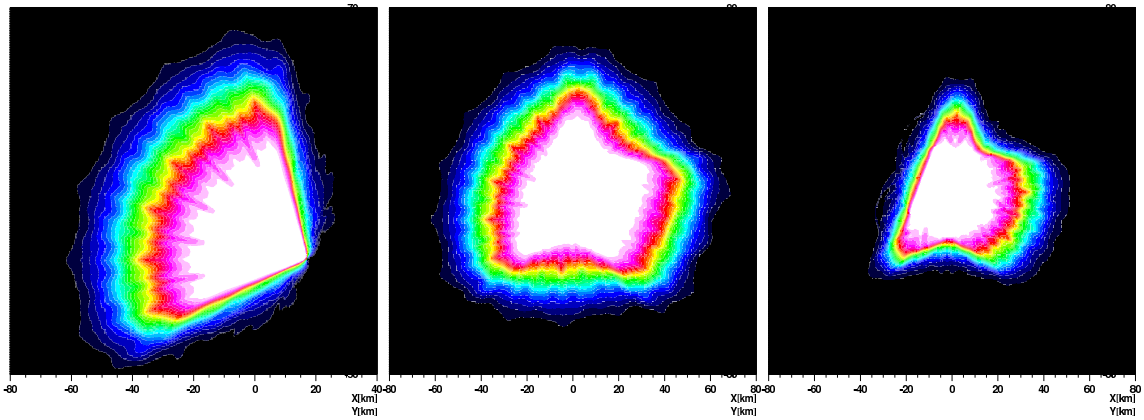

Figure 2: TA FD trigger functions at 10^{20}eV for observation modes of mono station, mono/3 stations (OR sum of the three mono trigger functions), and stereo/3 stations (OR sum of the stereo trigger functions of ${}_3\mathrm{C}_2$ combinations).

Particle	Proton					
Direction	$0 < \theta < 60^\circ, 0 < \phi < 360^\circ$					
$\log E_{[\mathrm{eV}]}$	18	18.5	19	19.5	20	20.5
$R_{\max}$ [km]	40	50	60	70	80	90
Φ	$\pm 9^\circ$					
#Events	9k	11k	14k	16k	18k	20k

Table 1: Simulation parameters for calculations of $f_i(R, \Phi)$

FD stations for mono/stereo observation modes are shown in Figure 2.

The FD aperture are calculated by using the trigger functions as

$$A(E) = \int \epsilon(R, \Phi; E) \cos\theta \, \mathrm{d}\Omega \mathrm{d}S \qquad (3)$$

The hybrid aperture is evaluated by replacing the FD trigger function ϵ by $\epsilon_{\mathrm{FD}} \times \epsilon_{\mathrm{SD}}$. For simplicity, we define the SD trigger efficiency as 1 (0) for showers inside (outside) the array comprised of 576 detectors[1]. The results are shown in Figure 3. Note that the aperture calculated here are for "ideal" cases: to determine cosmic ray energy spectrum using real observational data, the aperture must be defined by considering various observational conditions, as variation of PMT gains, night-sky background photons, or atmospheric corrections.

Expected Event Rate

It is worthy to estimate shower event rate in TA observations by assuming cosmic ray energy spectra. Here we use the AGASA [9] and the HiRes [10] spectra, and the observation time is assumed as 50 hours in a month. The results of the two spectrum cases for the three observation modes (mono, stereo and hybrid) are shown in Figure 4. For example, the expected number of events of cosmic rays with energies greater than 10^{20} [eV] in one-year monocular observation of the three FD stations are 11 and 0.6 in the cases of the AGASA and the HiRes spectra. Therefore, with a good energy resolution ($\sim 10\%$) of the TA detectors, it is possible to obtain a conclusive result for the GZK cut-off problem in cosmic ray physics in the first few years observation.

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1. In the final design of the TA SD array, the number of surface detectors is 512 [1, 3].

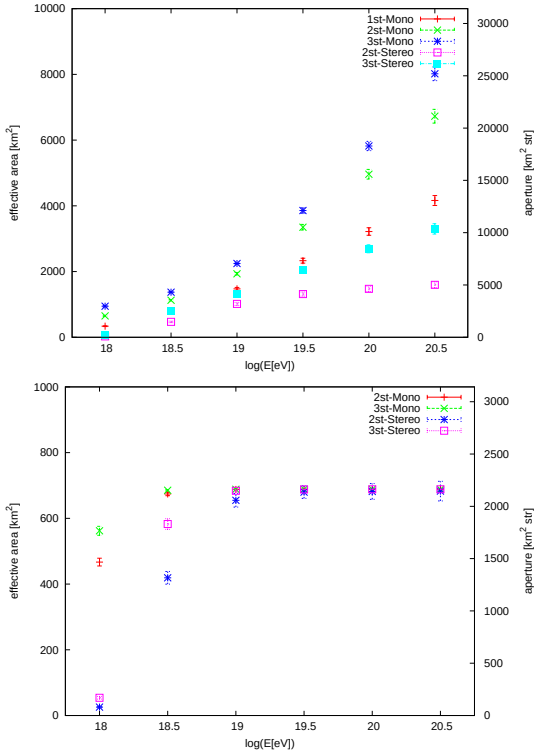

Figure 3: TA aperture of FD (upper) and Hybrid (lower) observations

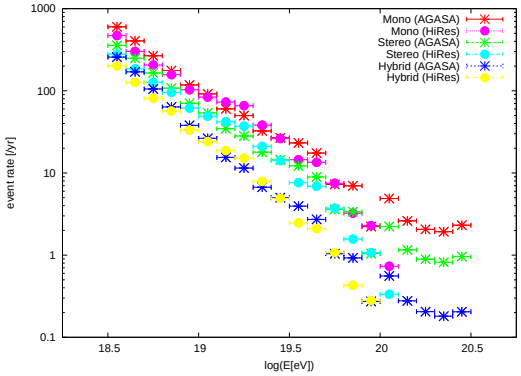

Figure 4: TA event rates expected from the AGASA spectrum (crosses) and the HiRes spectrum (circles) for the three observation modes.

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