Capability of Extended Air Shower Arrays for Gamma-Ray Astronomy

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Abstract: Current efforts in ground-based very high energy gamma-ray astronomy use two methods: Atmospheric Cherenkov Telescopes (ACTs) and Extended Air Shower (EAS) Arrays. While ACTs typically have greater sensitivity to gamma-ray point sources and lower energy thresholds, EAS arrays have an enormous advantage in exposure to the sky due to their large fields of view (1-2 sr) and high duty cycle ($>$ 90%). The lower sensitivity of EAS detectors is largely due to the fact that they sample only the particles in the longitudinal tail of the shower that reach the ground level, whereas ACTs are able to observe the shower development high in the atmosphere. An examination of the intrinsic capabilities and limitations of EAS arrays as instruments for gamma-ray astronomy is presented. The angular and energy resolution and effective area of an optimized detector is shown as well as an analysis of gamma/hadron separation. The capabilities of the optimized detector are compared and contrasted to those of the recently proposed HAWC detector.

Introduction

With years of development, the capabilities of atmospheric Cherenkov telescopes (ACTs) throughly studied. Since the detection of the Crab nearly 20 years ago, the use of focal plane imaging and later stereo reconstruction have been developed and optimized. The current generation of ACTs (VERITAS, HESS and Magic) have designs that are well understood and carefully optimized for sensitivity and cost. In contrast, the optimization of EAS detectors has not been so rigorously studied. While the water Cherenkov technology has proven to be the most effective approach as demonstrated by Milagro, other groups use scintillator arrays and RPC for detection of shower particles.

In this paper, we provide an analysis of the intrinsic capabilities and limits of EAS Arrays as instruments for gamma-ray astronomy. This work is based on air shower simulations of gamma-ray showers using CORSIKA[2] and estimation of detector performance based on the HAWC [1] detector simulation. An observation elevation of 4300m a.s.l. is assumed. While higher altitude laboratories are possible, this elevation is roughly the limit above which major subtantial additional costs are incurred for construction and operation. In this paper, we address the angular resolution, energy threshold and resolution and gamma-hadron separation for EAS detectors. Finally, we compare the sensitivity of HAWC with current and future VHE gamma-ray detectors for the detection of point sources.

Intrinsic Energy Threshold

Figure 1 shows the median shower energy at the ground level plotted as a function of primary gamma-ray energy. One can see from this figure that at small zenith zenith angles, 10% of a 1 TeV shower survives to the observation level on average and 20% of the energy of a 10 TeV shower. In this figure, the notion of an ”intrinsic threshold” is introduced at 10 GeV. We will show below that below this energy, reliable reconstruction if difficult. Defining the threshold as a function of energy at the observation level is attractive also, because it is independent of zenith angle and elevation.

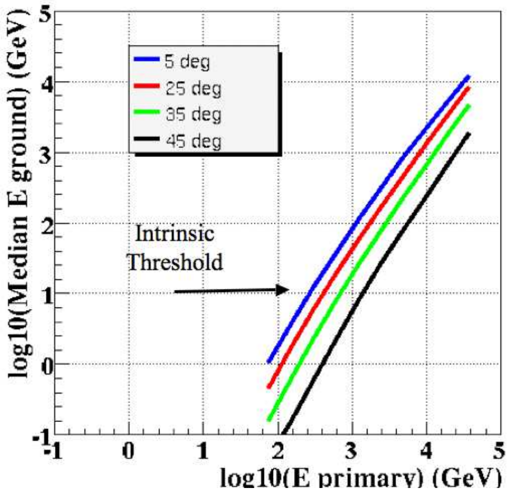

Figure 1: Energy reaching 4300m a.s.l vs primary gamma-ray energy. A range of zenith angles is shown. The 'intrinsic' threshold as defined in the text ranges from 200 GeV to 1 TeV.

Angle and Energy Reconstruction

We have estimated the achievable angular resolution for an EAS array by directly studying gamma-ray cascades with CORSIKA. To do this, we combine the momentum of the particles that reach the observation level in a vector sum. The direction of the resulting vector is compared to the direction of the primary to estimate the angular resolution. We find that the resulting angular resolution is not well characterized as a function of the energy of the primary gamma-ray as longitudinal fluctuation in the shower development lead to large fluctuations in the observed energy at the observation level. For this reason, we choose to characterize the angular resolution as a function of the energy reaching the observation level. Figure 2 shows the angular resolution achievable by an EAS detector.

We find that the optimal angular resolutions (defined as σ for a fit to a Gaussian) for 10 GeV, 100 GeV and 1000 GeV reaching the observation level are $0.55°$, $0.22°$ and $0.10°$ respectively. The angular resolution of the HAWC detector is approximately twice the optimal value, though the angle reconstruction algorithm for HAWC has not yet been optimized, so further improvement is likely. When less than 10 GeV reaches the observation level, the ability to reconstruct events accurately is sufficiently degraded that we choose to identify this energy as an 'intrinsic threshold'.

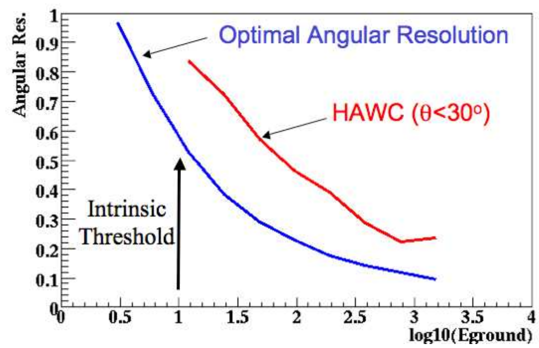

Figure 2: Intrinsic angular resolution of an ideal EAS detector (blue) compared to the angular resolution of the proposed HAWC detector plotted as a function of the energy reaching the observation level. The HAWC angular resolution is computed with a full detector simulation and event reconstruction.

Effective Area

Figure 3 shows the average cascade longitudinal profile as described by approximation B [3]. Note that showers of all energies have the same shape after shower maximum, a power law with slope -1.65. So, in general, if a primary gamma-ray penetrates one radiation length deeper than average, the result will be a 1.65x increase in the energy observable at ground level. This provides the possibility that showers with energies below the nominal energy threshold can be detected by deeply penetrating into the atmosphere before interacting. We can compute the number of radiation lengths (N) that a gamma ray with energy (E), below the nominal threshold energy (E_{thr}), will need to penetrate beyond the average depth in order to be detected.

$$N = \frac{ln(E/E_{thr})}{ln1.65} \quad (1)$$

The probability the a VHE gamma ray will penetrate N radiation lengths before interacting is

$$P = exp(-\frac{9}{7}N) \quad (2)$$

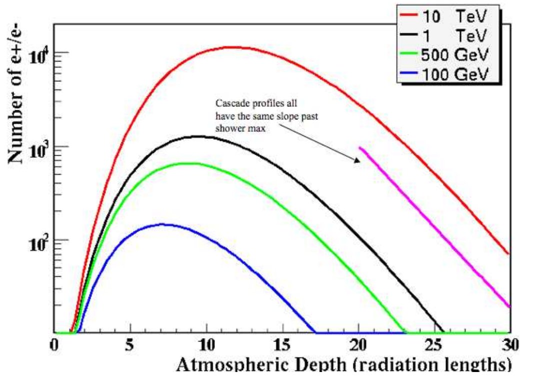

Figure 3: The longitudinal shape of EAS showers of different energies. The slope of the curves is the same for all energies past shower maximum: 1.65x decrease per radiation length.

Combining the two expressions gives

$$P(E) \approx (\frac{E}{E_{thr}})^{2.6}. \quad (3)$$

From this simple computation, we predict that the effective area below the effective threshold should scale like a power-law with index 2.6. Figure 4 demonstrates that this prediction is in excellent agreement with the effective area of the simulated HAWC detector.

The energy resolution for an EAS detector is limited by two factors: the intrinsic longitudinal fluctuations of the shower and the characteristic energy resolution of the EAS shower detector. In practice, we find that the shower fluctuations dominate the energy resolution. As shown in the previous section, the early stages of shower development are of particular importance because the fluctuations in the depth of the initial interaction of the primary gamma ray translate directly into fluctuations in the depth of the shower maximum and the energy reaching the ground level. We have found that the intrinsic energy fluctuations are log-normal where the distribution $log_{10}(\frac{E_{ground}}{E_{primary}})$ is well described by a Gaussian with a width 0.25 times the mean of the distribution. This relation holds for a wide range of shower energies, observation levels and shower angles. For typical values of E_{ground} of 20%, 10% and 5%, we get 1 sigma energy errors of +32%/-24%, +70%/-44% and +300%/-70% respectively. The errors are log-normal, and thus asymmetric.

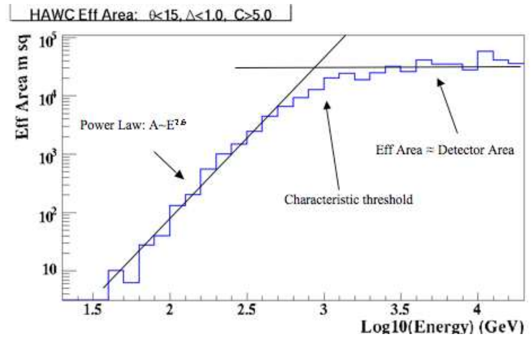

Figure 4: Effective area of the proposed HAWC detector. The blue curve shows the HAWC effective area derived from the detector simulation. The black lines show the effective area can be well described as a power law at low energies and as constant at high energies.

Gamma-Hadron Separation

In general, increasing the size of a detector will increase the collection area and thus the sensitivity. As both signal and background are increased, the relative sensitivity is expected to scale like $(Area)^{0.5}$. In simulations of EAS detectors however, we have found that the effectiveness of the gamma-hadron cuts improves drastically with detector size, because the lateral shower tails are more thoroughly sampled. The background hadron induced showers can be efficiently rejected through the identification of muons, hadrons and secondary EM cores. But, the large transverse momentum of hadronic interactions can spread the shower secondaries over a much larger area than EM showers on the ground level. HAWC will be able to reject $> 98\%$ of the background using cuts that identify large energy deposits separated from the shower core. Simulations of larger versions of the HAWC detector demonstrate that sensitivity as scales like $(Area)^{0.8}$ at least up to 300m x 300m.

HAWC and Future Detectors

The HAWC collaboration has submitted a proposal to the NSF for the construction of a high altitude water Cherenkov EAS gamma-ray observatory. The HAWC instrument is 22,500m^2 with an intrinsic threshold of 800 GeV. The sensitivity of HAWC is shown in figure 5. While HAWC represents a substantial improvement over the current Milagro experiment, with additional funding further improvements are possible over the proposed design. Potential improvements include:

- Increase altitude: Move from 4300m to 4800m - 1.5x lower threshold.
- Increase photocathode density: 3-4 PMTs/cell - 1.5x lower threshold.
- Increase size: Sensitivity $(Area)^{0.8}$ up to 300mx300m, not $(Area)^{0.5}$, due to improved gamma/hadron separation.

Using the HAWC detector as a baseline, we have estimated the sensitivity for 3 different detectors: 1) HAWC, 2) 300m x 300m version of HAWC at a higher elevation with improved PMT density and 3) 1000m x 1000m version of detector (2). We estimate the cost of each detector at $6M, $30M and $300M respectively. The sensitivity of the detectors is shown in figure 5. The sensitivity estimates shown for HAWC include a full simulation of the HAWC detector for gamma-ray signal events and hadronic background events. The simulated events are fully reconstructed with all cut efficiencies included. The stated sensitivities are not theoretical maxima, but conservative estimates for the stated designs. The excellent sensitivity at the highest energies is possible because of the enormous exposure of EAS detectors due to the large FOV and continuous duty cycle.

Conclusion

We have studied the performance of EAS detectors using simulations of gamma-ray cascades. We have found that the effective area and energy resolution of EAS detectors are well described using simple parameterizations due to the simple statistical nature of fluctuations in the depth of the first interaction. We also find that the current and future detectors are far from the potential optimal angular resolution and gamma/hadron separation, so further large improvements are possible.

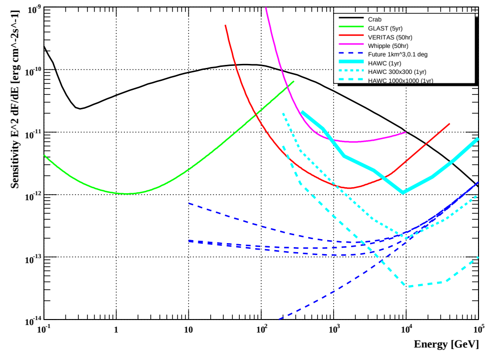

Figure 5: Differential sensitivity per quarter decade. The lines depict the 5 sigma detection flux level with at least 25 gamma rays. Data for GLAST, VERITAS and the $1km^2$ ACT courtesy of S. Fegan. For the $1km^2$ ACT array, the 4 lines refer to 4 different background models.

Even without large sensitivity increases over the current technology, at the highest energies (> 10 TeV), EAS detectors have greater sensitivity than atmospheric Cherenkov telescopes (ACTs) due to their much larger exposure. Furthermore, the wide field and continuous operation capability of EAS detectors makes them ideally suited for surveys, prompt gamma-ray burst observations and detection of diffuse sources. In contrast, the angular and energy resolution of the ACTs is intrinsically better than that of EAS detectors and ACTs also have a lower achievable threshold. The EAS and ACT methods for ground-based VHE astronomy are complementary.

References

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