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Use of Instrumented Water Tanks for the Improvement of Air Shower Detector Sensitivity

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Abstract

Previous works have shown that water Cherenkov detectors have superior sensitivity to those of scintillation counters as applied to detecting extensive air showers (EAS). This is in large part due to their much higher sensitivity to EAS photons which are more than five times more numerous than EAS electrons. Large area water Cherenkov detectors can be constructed relatively cheaply and operated reliably. A sparse detector array has been designed which uses these types of detectors to substantially increase the area over which the Milagro Gamma Ray Observatory collects EAS information. Improvements to the Milagro detector's performance characteristics and sensitivity derived from this array and preliminary results from a prototype array currently installed near the Milagro detector will be presented.

1 Introduction

The field of Very High Energy (VHE) gamma-ray astronomy has exploded in recent years, mainly pushed by the development of more sensitive telescopes. The emphasis has been to lower energy thresholds, improve angular and energy resolutions and most importantly hadronic cosmic ray background rejection.

Considerable efforts have also been made to develop telescopes which detect VHE extensive air showers (EAS) which have secondaries that survive to ground level, such as Milagro and the Tibet Array. If reasonable sensitivity at VHE energies can be achieved with these detectors, they will offer powerful capabilities, such as full overhead sky coverage both day and night regardless of weather and skylight conditions. This would allow much higher temporal coverage of sources that are already known to be highly variable, such as Active Galactic Nuclei.

The Milagro detector is progressing toward reaching the necessary VHE sensitivity. It is a large (60m x 80m x 8m) water pond instrumented with 723 8" photomultiplier tubes (pmts) in two layers. These pmts detect the Cherenkov light produced by EAS secondaries passing through the optically clear water. Its high altitude (2650m) and sensitivity to both photonic and leptonic EAS components give it an energy threshold such that for zenith traversing sources the peak primary energy will be 1 TeV. After calibrations it will have good angular resolution and hadronic cosmic ray rejection (see McCullough 1999 for more details).

To improve the sensitivity of the current Milagro detector, 172 instrumented, large area ($5m^2$), water Cherenkov detectors (tanks) will be deployed around the pond to effectively extend its active area. As discussed below, this will improve both the energy and angular resolution of Milagro and increase its hadronic cosmic ray rejection, thus improving its overall VHE sensitivity. It can also be used to increase Milagro's efficiency for detecting EAS below 1.0 TeV which have core positions significantly away from the Milagro pond.

2 Water Tank Detector & Array

The criteria for selecting a detector design that will improve the performance of EAS experiments are: low cost and low maintence (a large ground area needs to be covered, typically at a remote high altitude site), high sensitivity to EAS secondary particles, and good timing and particle density resolution. Previous works (Yodh 1996) showed that water Cherenkov detectors have superior sensitivity to those of scintillation counters for detecting EAS secondaries. Thus the tank design proposed here satisfies these design criteria, although the particle density resolution is somewhat poor. On average the pmt signal is about 100 photoelectrons for a through-going vertical muon.

Figure 1 displays a crossectional view of a tank showing the position of the top-mounted, downward-looking 8" pmt and the Tyvek-lined bottom, sides, and floating top. This position of the pmt gives a fairly uniform response across the full tank, although it does degrade the timing resolution somewhat compared to a bottom mounted, upward looking position. Due to its active material, water, the tank is sensitive to both the photonic and leptonic components of EAS as opposed to plastic scintillator based detectors which are mainly sensitive to the leptonic component. The Tyvek lining provides a diffusivly reflective inner surface with $> 90\%$ reflectivity at the important wavelengths determined from convoluting the Cherenkov photon spectrum and pmt quantum efficiency (wavelengths around 350 nm).

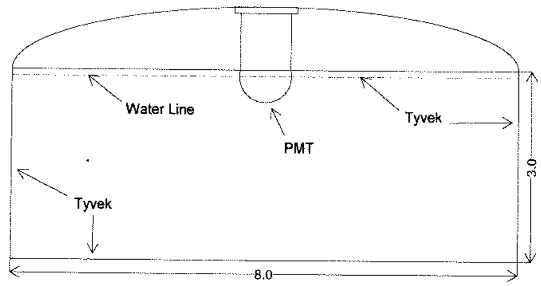

Figure 1: Schematic of example water Cherenkov tank. Key features are top mounted, downward looking pmt and Tyvek lined inner surfaces (units are feet).

The Milagro inspired tank array has 172 tanks placed on a square grid with a spacing of 15 m, giving a full array area of 200m x 200m centered on the Milagro pond.

Monte Carlo generated data was used to determine the performance characteristics of these tanks, and the improvement of the sensitivity of the Milagro detector generated by using these tanks. Corsika was used for generating simulated EAS and the Geant package was used to simulate the tank and Milagro detector responses (see (Westerhoff 1998) for more details).

3 Monte Carlo Estimates of Milagro Performance Improvements

The information acquired with the tanks discussed above can be used in two separate ways. First, it may improve the angular and energy reconstruction resolutions of EAS which trigger the Milagro pond detector by making additional independent shower front timing measurements and by improving the EAS core position resolution for EAS whose cores done not strike the pond. A simple multiplicity trigger condition of 50 pond pmts being hit by an EAS was used as a pond-trigger in simulations. Second, the information can be used to increase the effective area of the Milagro detector by using it in a combined pond-tank trigger.

3.1 Improvements in Pond Triggered Events From simulation, on average about 24 tank pmts are hit per event where a hit is the detection of 1 or more photoelectrons. The occupancy (fraction of the time a given pmt or tank is hit) for pond pmts is about 30% and for tanks is about 10%. The tanks have fewer low pulse height hits than the pond pmts (below 30 pes) but about the same number of large pulseheight hits (above 30 pes).

As seen in Figure 2, our simulations predict that using the tank array in reconstructing EAS core positions can improve the position resolution tremendously for EAS whose core positions are off the pond. This improvement is crucial for EAS energy determination and is also important in EAS angle determination because the pmt hit times must be corrected for EAS shower front curvature about the core position. Current ongoing studies of Monte Carlo generated EAS show that a good core position resolution should improve the hadronic cosmic ray rejection capabilities of Milagro as well.

Figure 2: Plot of median core position error versus core distance from center of Milagro pond using tanks (circles) and not using tanks (crosses).

Improvements in the angular reconstruction resolution of EAS is displayed in Figure 3. The improvement is maximal for low multiplicity (number of pmts in Milagro which detect light) events which are typically low primary energy EAS. It is also maximal for EAS whose cores land far from the pond.

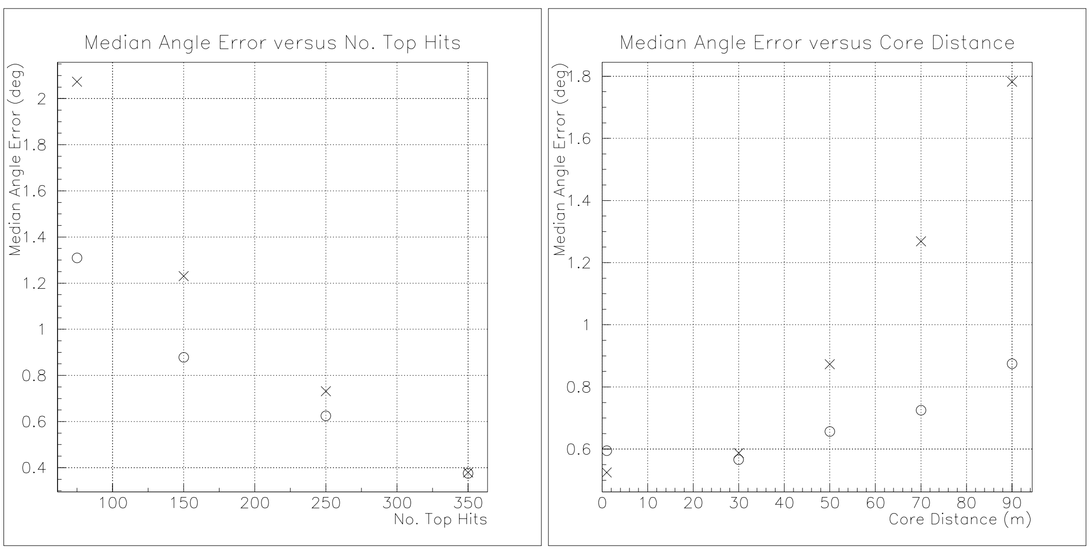

Figure 3: Plots of median angle error versus number of pmt hits in top layer of Milagro pond and versus EAS core distance from center of Milagro pond. Circles are values when tanks are used and crosses are value when tanks are not used.

3.2 Improvements in Trigger Sensitivity Including tank acquired information within the Milagro trigger condition can increase the efficiency for seeing low energy events. This is clearly seen in Figure 4 which displays a plot of the effective area of the Milagro detector for three types of triggers. The pond-only trigger is a requirement that at least 50 pmts be hit by the EAS. The tank+pond trigger is that either the pond trigger be satisfied or that at least 5 tanks be hit by the EAS. The tank-only trigger is that at least 5 tanks be hit and that less than 50 pond pmts be hit by the EAS. The tank-only trigger is included to explicitly show the contribution of the tanks to the effective area.

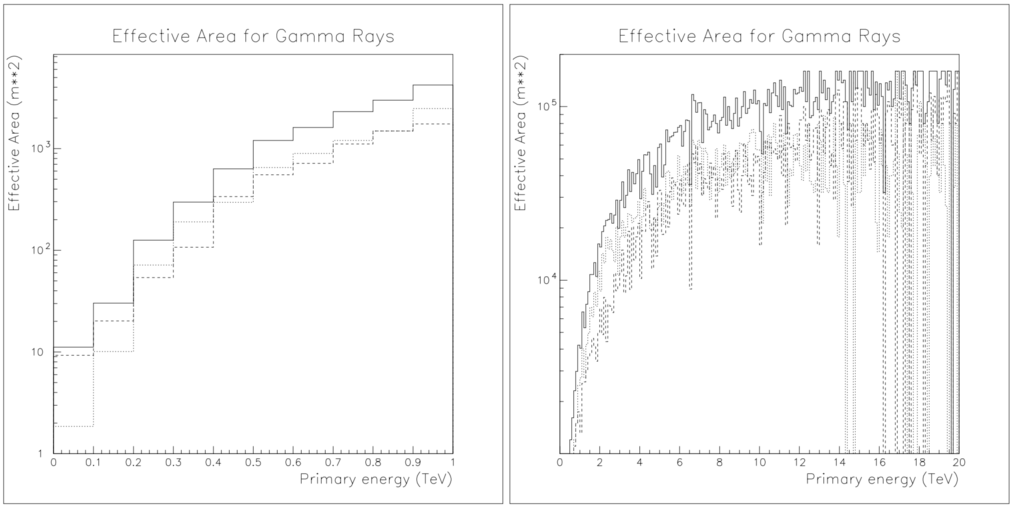

Figure 4: Plot of effective area versus energy. Dashed is pond-only trigger, dotted is tank-only trigger, and solid is pond-tank trigger.

Those events obtained by using the tanks in a trigger condition have an average pond pmt multiplicity of 20 and an angular resolution of about 2.5^o. This resolution is significantly worse than the resolution of pond-triggered events ($< 1.0^o$) but is adequate for doing coincident searches with most BATSE-detected Gamma Ray Bursts and for photon counting analyses where the event angles are not used.

4 Results from a Prototype Array

A prototype tank array has been installed near the Milagro pond to study the response of the water tanks to typical EAS that trigger Milagro. The array consists of 11 tanks built with commercially available polyethylene storage tanks. The installed pmts are of the same type as those in the Milagro pond (Hamamatsu R5912). The tanks are at various distances from the pond which will enable us to study their response as a function of EAS core distance and particle density. The tank hit multiplicity with at pond trigger requirement of approximately 120 hit pond pmts is 2.5. Results from these prototypes will also be presented.

5 Summary

From the above simulation results one can see the predicted large improvement to both the angular and core position resolutions of the Milagro detector using information acquired by a spare array of instrumented Cherenkov water tanks. This improvement is mainly for EAS whose cores do not fall directly on the Milagro pond. Since the sensitivity of an VHE detector is proportional to its angular precision, this improvement will have a large positive effect on Milagro's sensitivity. The greatly improved core position resolution will increase Milagro's sensitivity to various source spectral characteristics.

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