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A Third Generation Water Cherenkov Observatory

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Abstract: The construction of the High Altitude Water Cherenkov (HAWC) gamma ray observatory will be completed in 2014. By September of 2013, HAWC will start continuous operations with the first third of the 300-detector array. As the commissioning of the instrument is approaching planning for a third generation Water Cherenkov Observatory can be done. Several ideas to improve the sensitivity, the gamma/hadron discrimination at lower energies and the energy and angular resolution of a continuously operated, large field of view detector array will be discussed. A path to optimize an instrument for the Southern Hemisphere is presented.

Keywords: Gamma Ray, HAWC, Water Cherenkov.

1 General Requirement

The HAWC Collaboration is building a high energy gamma ray observatory at a latitude of 19 degrees north and 4,100 m altitude asl on the Sierra Negra mountain in the State of Puebla, central Mexico [1]. The array consist of 300 water Cherenkov detectors (WCD) instrumented to detect the incoming gamma/cosmic ray through the Cherenkov light emitted by the air shower particles as they traverse the large water containers. The first 30 detectors went into operation in December 2012. One third of the array was constructed by May of this year and will enter continuous scientific operation in the fall of 2013. The full observatory is expected to enter operations late in 2014.

The aim of this presentation is to generate a discussion of the desirability of establishing a similar observatory in the Southern Hemisphere and present some improvements that could be implemented over the HAWC design. These are presented as a Gedanken experiment with little hard facts. Detailed simulations and optimizations need to be done by groups willing to explore such a possibility. The focus is on gamma rays although such an instrument would also simultaneously observe the much more abundant cosmic rays.

Such a continuously operating instrument with a wide field of view and continuously operating would survey the Southern skies and in particular the center of the Galaxy and would complement HAWC, the lower energy gamma ray satellite-based observatories like FERMI, SWIFT as well as other future observatories such as the planned CTA-South air Cherenkov telescopes.

2 HAWC design

The HAWC observatory consists of individual metallic tanks of 7.3 m diameter and 5 m height with a light- and water-tight plastic membrane, the bladder, containing the highly purified water and 4 hemispherical photomultipliers (PMT) anchored to the bottom and looking up to detect the Cherenkov light of the impinging particles. The large area PMTs have sensitivity to single photo electrons and sub-nanosecond timing resolution. HAWC will cover a 22,000 m2 site with 12,000 m^2 of active surface.

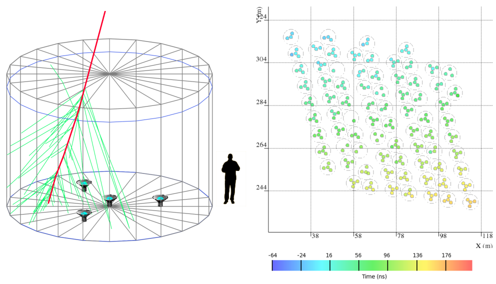

Figure 1: Left a HAWC WCD, right one event of HAWC100, the arrival time is indicated by the colours

Consisting of 300 individual water Cherenkov detectors (WCD) it detects the particles from atmospheric showers by their production of Cherenkov light as they enter the 200,000 litre water containers. It can detect showers in the hundred GeV to hundreds of TeVs over a large field of view over the detector and with very high duty cycle. Figure1 shows a schematic diagram of a HAWC WCD and a measured event from HAWC during the construction phase having 80 WCD.

The direction of the primary particle can be reconstructed from the arrival time of the shower front over the different detectors of the array, their energy is estimated from the number of fired PMTs and their integrated signals. In order to discriminate between primary gamma or cosmic ray, producing an electromagnetic or a hadronic air shower, the topology of the event is used. Electromagnetic showers are smooth with a monotonically decreasing energy density of the shower particles as function of the distance from the shower centre. Hadronic interactions on the other hand produce large angle high momentum particles that produce energy clumps and a larger muon component from the decay in flight of pions and kaons. The performance of the HAWC observatory is discussed in [2].

3 A third generation observatory

The HAWC detector performance is based on the arrival time and amplitude of the signals at the 4 PMTs of each WCD. Some of the several possible improvements to the HAWC design will be discussed below. A detailed cost/performance analysis would need to be done to evaluate what a realistic next generation observatory would look like and estimate its overall capabilities.

3.1 Area and Layout

The sensitivity of a HAWC-like array grows, to first order linearly with the area of the array. An array 2 to 4 times larger than HAWC would array will probably be affordable under current funding scenarios. For an even larger array the geometry should be optimized. Namely it should have a more compact central core to improve the detection at the lower energies and get more sparse at larger distances to increase the sensitivity at energy beyond 100 TeV.

3.2 Altitude

By siting the Southern observatory at a higher altitude than the 4,100 m of the HAWC array one would be closer to the shower maximum thereby increasing the lower energy response and improving the sensitivity, the angular and energy resolution and the gamma/hadron discrimination. Places like ALMA in the Atacama Desert of northern Chile have suitable sites at 5,000 m asl. Even higher elevations could be found in Bolivia, but they might be too cold for a WCD.

3.3 Detection of the air shower particles

The detection of the electromagnetic shower particles in a WCD is done trough the Cherenkov light emitted as the particles enter the water tank of the individual detectors. The amount of emitted Cherenkov light can be increased by placing a 1 radiation length layer of lead above the water tanks as a converter.

In a HAWC-like WCD the shape and direction of the incoming shower front is determined by the arrival time of the Cherenkov light to the PMTs in the different WCD detectors. The direction of the incoming primary gamma ray is obtained from the normal to the fitted shower front shape. Although the PMTs have sub-nanosecond time resolution, the fact that each one of them sees a large fraction of the total water volume gives an inherent uncertainty on the position of the point that emits the first detected Cherenkov light that translates in a timing uncertainty. The ARGO experiment [3] has shown that it is possible to cover large areas of ground based shower detectors with thin gas detectors having 100 ps time resolution. The segmentation in ARGO into 56 x 46 cm2 pads results in a 1.8 ns time resolution. A finer granularity would be desirable to measure the arrival of the shower front and its width with a 0.5 ns resolution. Figure 2 shows the measurement of a shower plane as seen by the ARGO detector.

The energy of the primary gamma ray is inferred from the signal produced by the PMTs from the detected Cherenkov light at the shower front. The EM shower deposits its energy in the top 1.5m water layer. In HAWC the PMTs are placed at the bottom of the tank, 4.5 m from the surface in order to detect also the much larger signals from a through going muon and to improve the gamma/hadron discrimination at the cost of reducing the light seen from EM showers. In a new detector that divides the water volume into two regions these functions can be separated optimizing their measurement. A 2 m upper bladder with white reflecting walls, seen by several PMTs would integrate a much larger fraction of the total Cherenkov light from the EM component. A lower 3m deep bladder would detect the through going muon component. In order to shield this volume better, the spaces between tanks could be filled with dirt, effectively burying the tanks. Figure 3 shows such a segmented WCD.

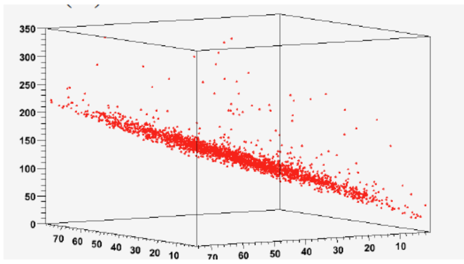

Figure 2: Shower plane measured by the ARGO experiment

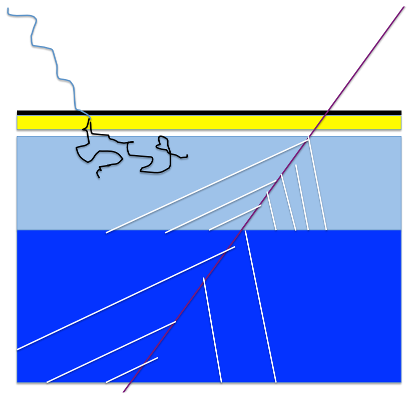

Figure 3: Multi-layered gamma observatory having a timing array and a EM layer and muon layer

The separation of the measurement of the EM component on the upper 2m of the water volume and the muon and hadron signal starting 2m below the surface will improve the gamma/hadron separation by having a better measurement of possible muons into the shower core.

3.4 Determination of the shower maximum and improvement of the pointing accuracy

The inherent fluctuations in the shower development given by the variations in atmospheric depth at which the primary gamma ray interacts thereby initiating the EM cascade effectively degrades the energy resolution in the case where the shower depth is not measured as is the case n HAWC. The current HAWC detector provides no information that could determine the depth of the shower maximum for each event, but in a new instrument this could be done. Already the shape and with of the shower front determined by the timing array contains information to restrict the range of the estimate of the depth of the shower maximum. More detailed information could be obtained, at least during night time, by deploying an array of non imaging Cherenkov counters sampling the atmospheric Cherenkov light produced during the development of each shower. Arrays such as AROBIC and HiSCORE [4] have demonstrated their performance. In this case to complement the timing and WCD arrays, the non focusing air Cherenkov array should be much more compact than HISCORE. The combination of the timing and air Cherenkov observations have the capability substantially improving the angular resolution and therefore the imaging of the gamma ray sources.

3.5 Electronics, trigger and data acquisition

In the HAWC WCDs, the centrally located high quantum efficiency PMTs have the highest single rates of approximately 50 kHz for signals above one quarter of a single photoelectron. The PMT signals are digitized with a dual threshold time over threshold (ToT) by multi-hit TDCs. The triggers are then performed by a central computer farm in software and stored on disk.

A next generation observatory, with possibly several layers of detectors: a timing array, an array detecting the EM component of the showers, a muon-hadron array and non imaging air Cherenkov detectors would have count rates that can easily be pre-processed and digitized with distributed electronics near the individual detectors. Local groups of detectors can provide level zero triggers which could be processed at higher DAQ level producing more global triggers.

4 Conclusions

It is argued that a it would be desirable to have a wide field of view, continuously operating gamma ray observatory to survey the skies of the Southern Hemisphere complementing the HAWC water Cherenkov array being built at 19 degrees northern latitude at 4,100 m asl in the mountains of central Mexico.

There are several directions to improve over the HAWC layout: increasing the sensitive area, placing it at a higher altitude and separating the detection functions into different layers of the array. These could result in a finely segmented timing array to define the shower front, a layer of water Cherenkov detectors to measure the EM component of the air showers followed by a deeper layer of water Cherenkov detectors measuring the muon and hadron component. Information about the development of the air shower can be obtained during clear nights with an array of non-focusing Cherenkov counters. Information on the depth of the shower maximum improves the energy resolution and the measurement of the arrival times of the air Cherenkov light improves the angular reconstruction of the direction of the primary gamma ray.

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