miniHAWC: A First Step Towards HAWC

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Abstract

In this memo I investigate the performance of a high-altitude water Cherenkov detector for all-sky VHE astrophysics. The major difference between this instrument and HAWC is its size. This instrument would re-use all of the existing Milagro PMTs and electronics and therefore keep costs to a minimum. After describing the detector and simulation I demonstrate its sensitivity to the Crab Nebula and to gamma-ray bursts. This detector, miniHAWC, would be about 8 times more sensitive than Milagro to a Crab-like source, and able to see GRBs at cosmological distances.

Detector Design

The miniHAWC instrument design is constrained by the total number of available PMTs from Milagro and the existing electronics and data acquisition system (which can not operate at a trigger rate in excess of 2000 Hz). The number of PMTs (including outriggers is 898. To keep the geometry symmetric I envision a square array, and to maximize the background rejection capabilities, demand that the top and bottom layer be of equal size. This leaves 449 PMTs per layer for a 21 *x* 21 grid of PMTs. This gives us 16 spare PMTs.

The PMT spacing is set to 4 meters (as opposed to 2.7 meters in Milagro) to expand the physical area of the detector and compensate for the absence of outrigger tanks. To maintain sensitivity to all particles that enter the pond the top layer of PMTs is placed 2 meters below the water surface (as opposed to 1.3 meters for Milagro). The bottom layer should be at the same depth as Milagro (6 meters) but due to a slight bug in the geometrical implementation (ugeom.F of GEANT3) the depth of the simulated bottom layer is 6.7 meters. In the near future I will run with a true 6meter water depth to see if this is important. My educated guess is that this will not make a noticeable difference in the background rejection capabilities of the instrument, and if it does than we simply build the pond a little deeper.

The last major change from the Milagro design is the addition of curtains between the PMTs. The curtains begin at the surface of the water and extend down to ½ the depth of the pond. The curtains are modeled as a material that absorbs 95% of the incident light. The reflections are treated as purely diffuse. Figure 1 shows a schematic blow-up of the design.

The detector was placed at an altitude of 4572m above sea level. While this is about 270m higher than the Tibetan plateau near Yangbajing, it is the same altitude as the HAWC simulations. To facilitate direct comparisons I left the altitude at this level. For comparison I will run a simulation in the future at 4300m asl. (4572m is the altitude of the Sierra Negra site in Mexico).

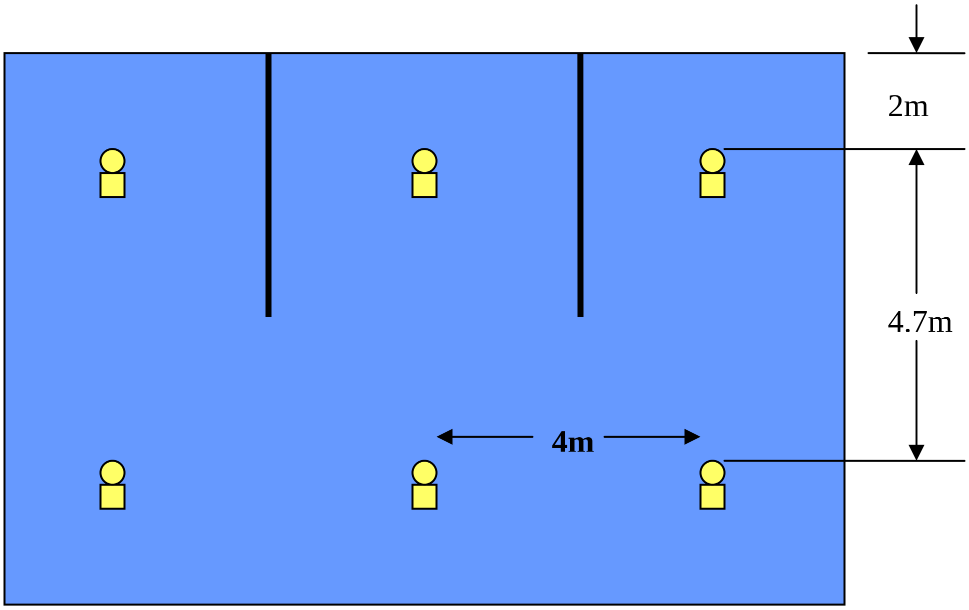

Figure 1 Schematic view of 3 cells of miniHAWC. The complete detector is a 21x21 grid of such cells.

Monte Carlo Simulation

To allow scaling from Milagro I used the same simulation that was used to run the bulk of the Milagro simulations. CORSIKA 6.003 was used to generate the extensive air showers and propagate them to the observation level. GEANT 3.2 was then used to track the particles through the detector and simulate the detector response. Again to facilitate comparison with Milagro I used a layer of air between the water and the cover. Though I think the curtains act to minimize the effect of reflections from the surface. Note that we have found several bugs in the simulation of Milagro (notably the quantum efficiency of the PMTs is about 20% too high), but I still think it is safer to use this simulation and scale from actual observations with Milagro, than to try and dead reckon both the background rate and the signal rate with the simulation.

For both gamma rays and protons the simulations were run from 0-45 degrees in zenith angle (0-360 in azimuth), thrown with a radial distribution (N(r)~r) (the events are then re-weighted to give equal area distribution for all plots and figures below), thrown to a core distance of 1 km. The energy distribution for both gamma rays and protons was from 50 GeV to 10 TeV and for gamma rays the spectral index was -2.4, while for protons the spectrum was -2.7. In the analysis below the gamma rays are re-weighted to have the spectrum of the source under study (the Crab spectrum was taken as -2.49).

The Event Trigger and Reconstruction

The trigger was a simple multiplicity trigger, requiring 40 or more PMTs to be hit in the top layer. Since miniHAWC is of comparable size as Milagro, has similar number of PMTs in the top layer, and the PMTs will have similar singles rates, this trigger should be straightforward to implement. At present the only unresolved question here is large angle muons, which required Milagro to use a risetime trigger below ~55 PMTs. But the curtains should lower the trigger rate from single muons, and if need be we can always implement the risetime trigger in miniHAWC as well.

The reconstruction algorithms are the same as those currently used by Milagro. The core reconstruction is the Gaussian core locator, but uses only the top layer (as there are no outriggers) and the angular reconstruction uses both the top and bottom layers. The curvature/sampling corrections and the PMT weights are as derived for Milagro. I expect that with the addition of the curtains we can make substantial improvements in the angular reconstruction for miniHAWC, but have not yet had the time to do this work.

Simulation Results

1. Effective Area

In Figure 2 (3) I show the effective area vs. energy for gamma rays (protons). There are two lines in both figures. The red line shows the triggered area and the blue line shows the area for events that are successfully reconstructed. For gamma rays the definition of a successful reconstruction is that 20 or more PMTs are used in the angular reconstruction and the event was fit within 1.2 degrees of its true direction. For proton events the only requirement is that 20 or more PMTs are used in the fit.

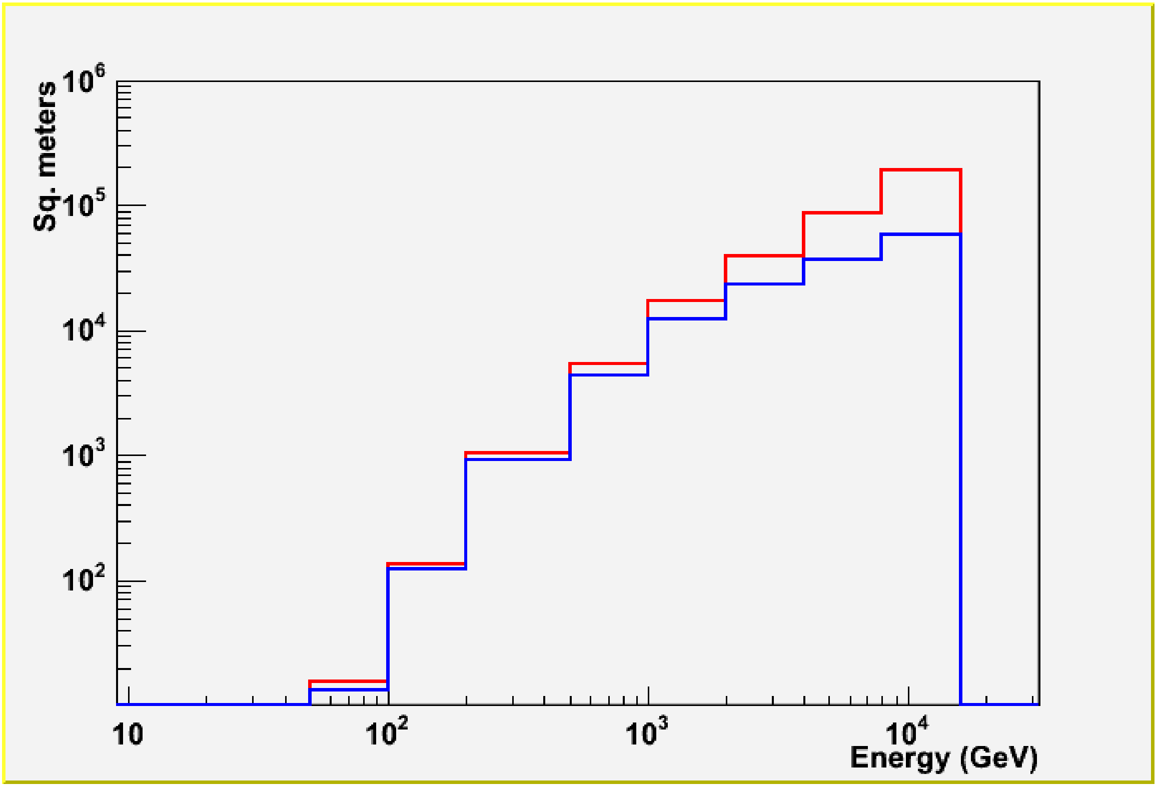

Figure 2 Effective area for gamma ray primaries. Red (blue) histogram is for triggered (fit) events. See text for definition of fit event.

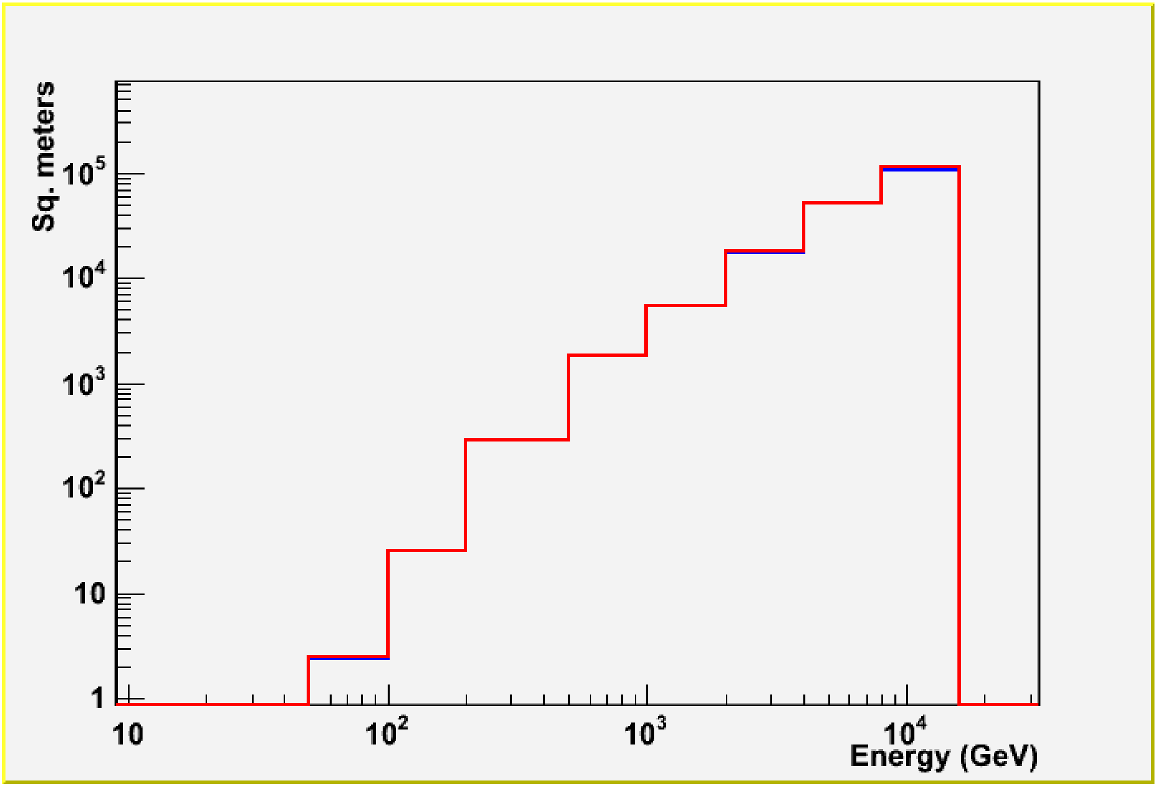

Figure 3 Effective area for proton primaries. Blue (fit) and red (triggered) histograms are identical.

Note that the y-axis scale is different in the two figures. For comparison, where miniHAWC has 100 m^2 of effective area at 100 GeV, Milagro has roughly $10m^2$ of effective area. This is about as expected from simple scaling arguments (approximation B gives 5*x* for altitude and the pond is ~2*x* larger than Milagro) though the curtains should in principle give a lower effective area. In fact the curtains do reduce the effective area for gamma rays somewhat, but the reduction in the proton area is much more dramatic, making the curtains a good gamma/hadron discriminator.

2. Core Reconstruction

Figure 4 shows the range of core distances for triggered events in miniHAWC, the blue curve is for gamma ray primaries and the red line for proton primaries. Note that few proton events trigger the detector beyond a core distance of 300 meters. This is not the case for Milagro and is most likely due to the curtains. Figure 5 shows the core error for gamma ray primaries that were successfully fit.

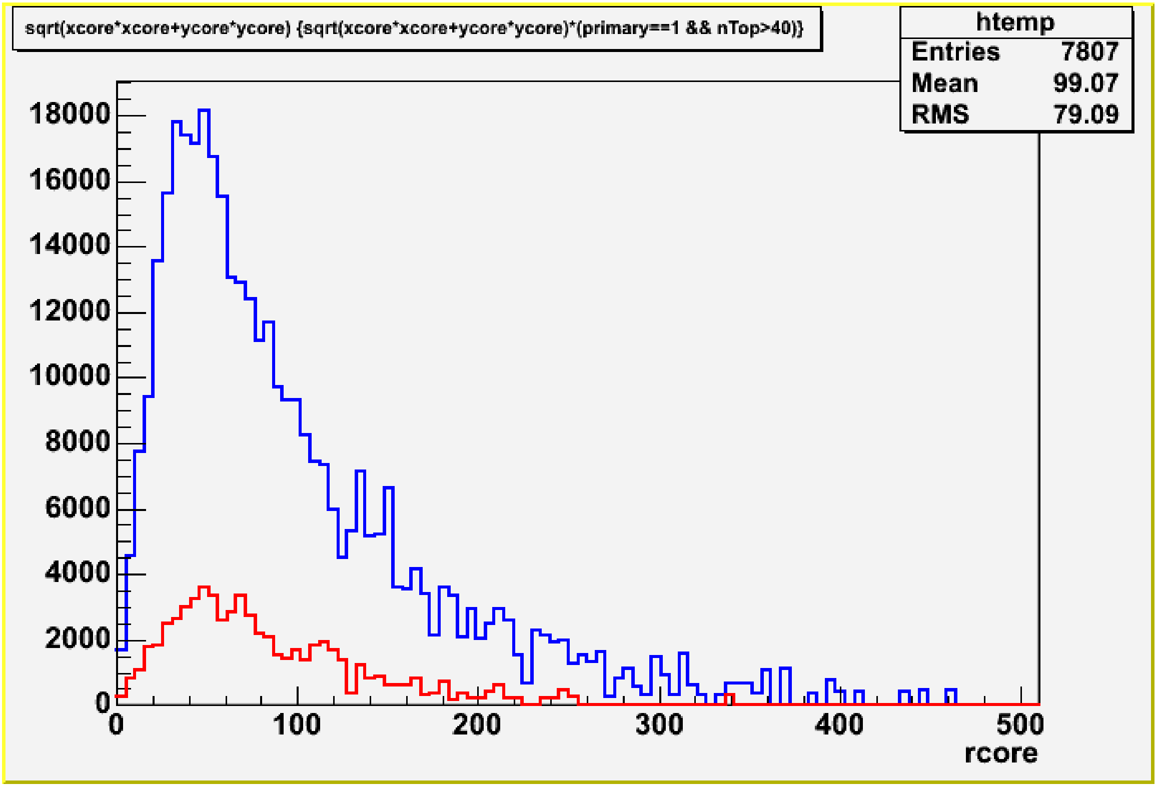

Figure 4 Core distance distribution for triggered events. Blue curve is for gamma ray primaries and the red curve for proton primaries.

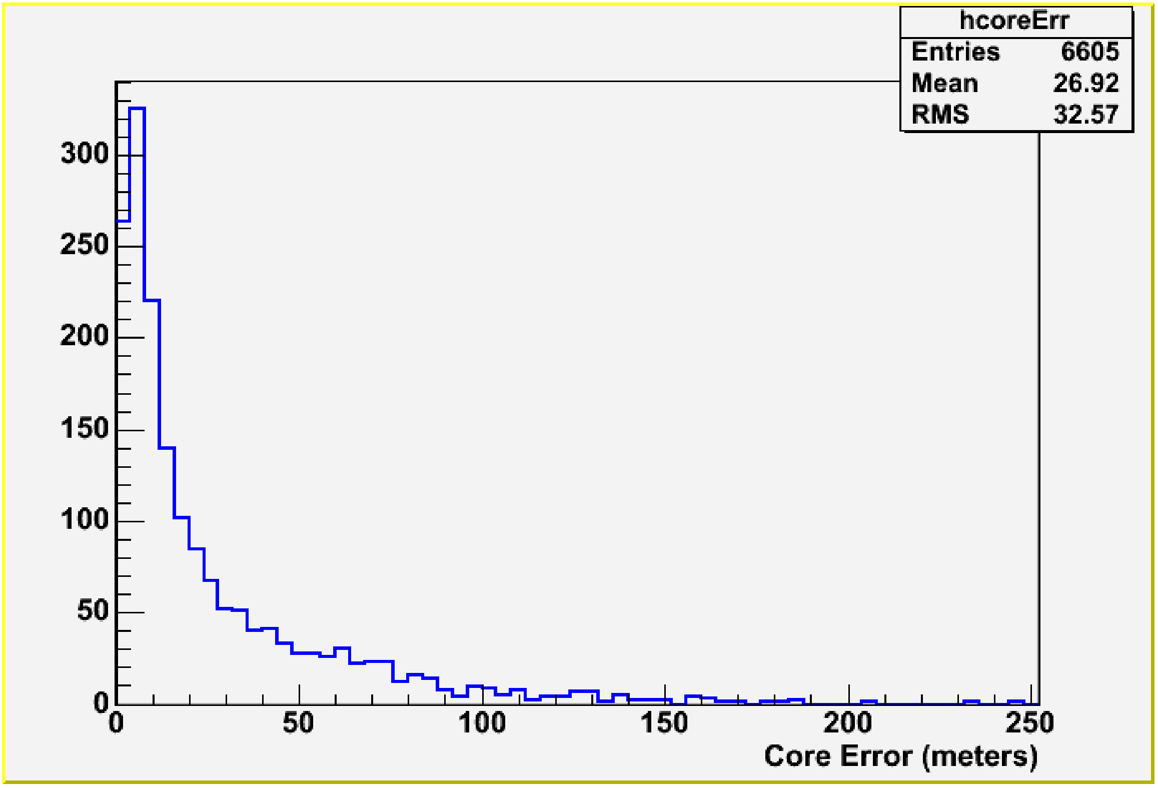

Figure 5 Core error for fit gamma ray primary events.

3. Angular Reconstruction

Figure 6 shows the space angle difference between the true event direction and the fit event direction. With a peak at 0.5 degrees this is similar to that seen in Milagro with the outriggers. This would imply that one should use an analysis bin of 0.7 degrees, as is now used for Milagro with the outriggers. In the sensitivity calculations below I use an analysis bin of 1.2 degrees as was originally used in Milagro. Again this is to compare directly with the old reconstruction of Milagro.

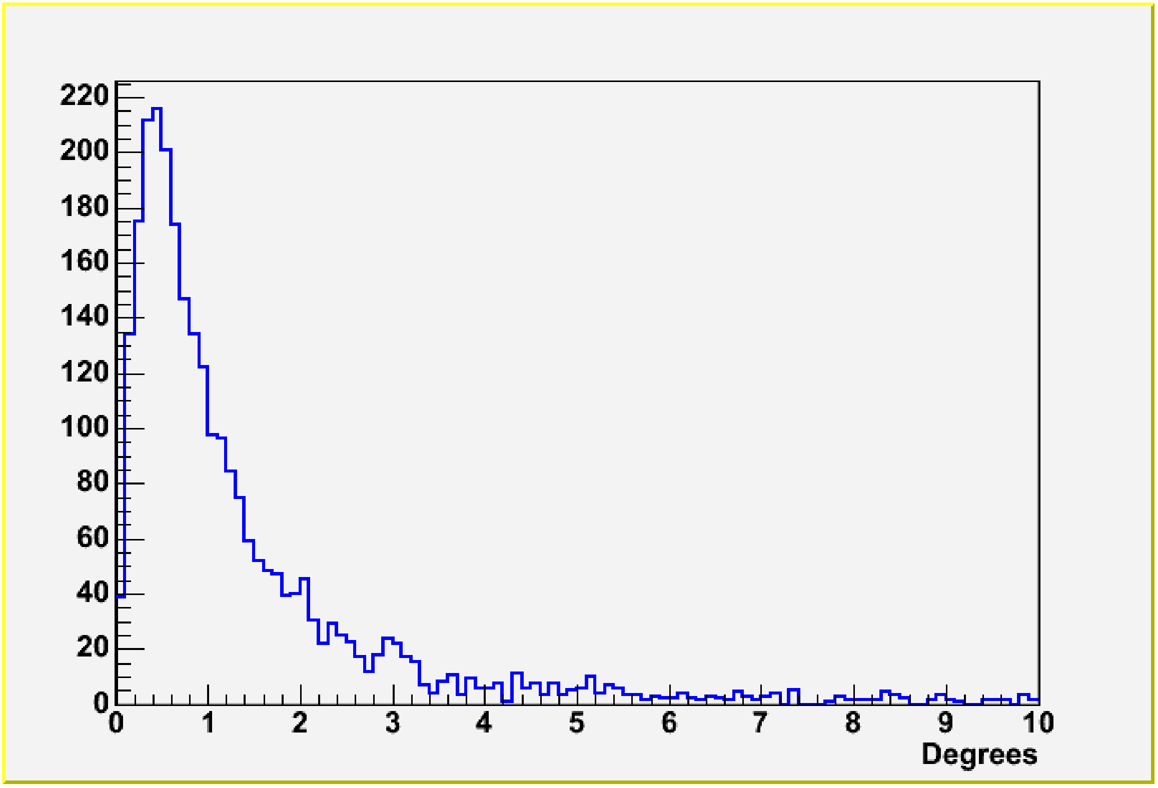

Figure 6 Space angle difference between it and true event direction for gamma ray events with 20 or more PMTs used in the fit.

4. Background Rejection

As with HAWC I find that the standard compactness criteria does not work as well at higher altitude. I therefore use the same cut as derived for HAWC, a modified version of the compactness parameter defined as nTop/cxPE. nTop is the number of PMTs hit in the top layer and cxPE is the number of PEs in the "hottest" PMT in the bottom layer where the PMTs within 10 meters of the fit core are excluded from the search for the maximum. Figure 7 shows the distributions for gamma rays (blue) and protons (red). Figure 8 shows the Q factor as a function of the cut level (events with nTop/cxPE<cutLevel are excluded) and Figure 9 shows the gamma ray (blue) and proton (red) efficiencies as a function of the cut level. A Q-factor of 1.8 is achievable that retains 80% of the gamma ray events. While this Q factor is only marginally greater than that observed in Milagro it retains many more gamma rays (50% for Milagro) and has a much smaller energy dependence as we will see below.

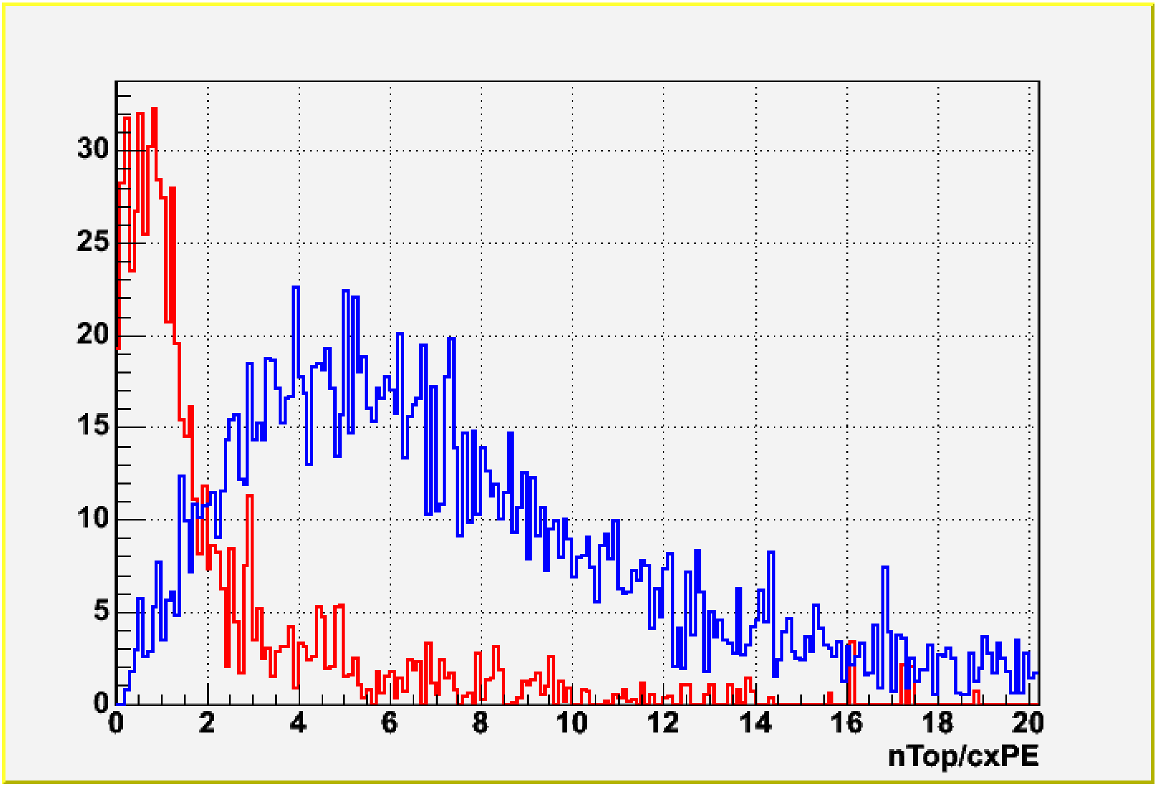

Figure 7 nTop/cxPE for gamma ray (blue) and proton (red) primary events. Protons are included if they have 20 or more PMTs used int he fit and gamma rays are included if they have 20 or more PMTs in the fit AND they are reconstructed within 1.2 degrees of their true direction.

Figure 8 Q-factor as a function of the cut level. Events with nTop/cxPE less than the cut level are excluded.

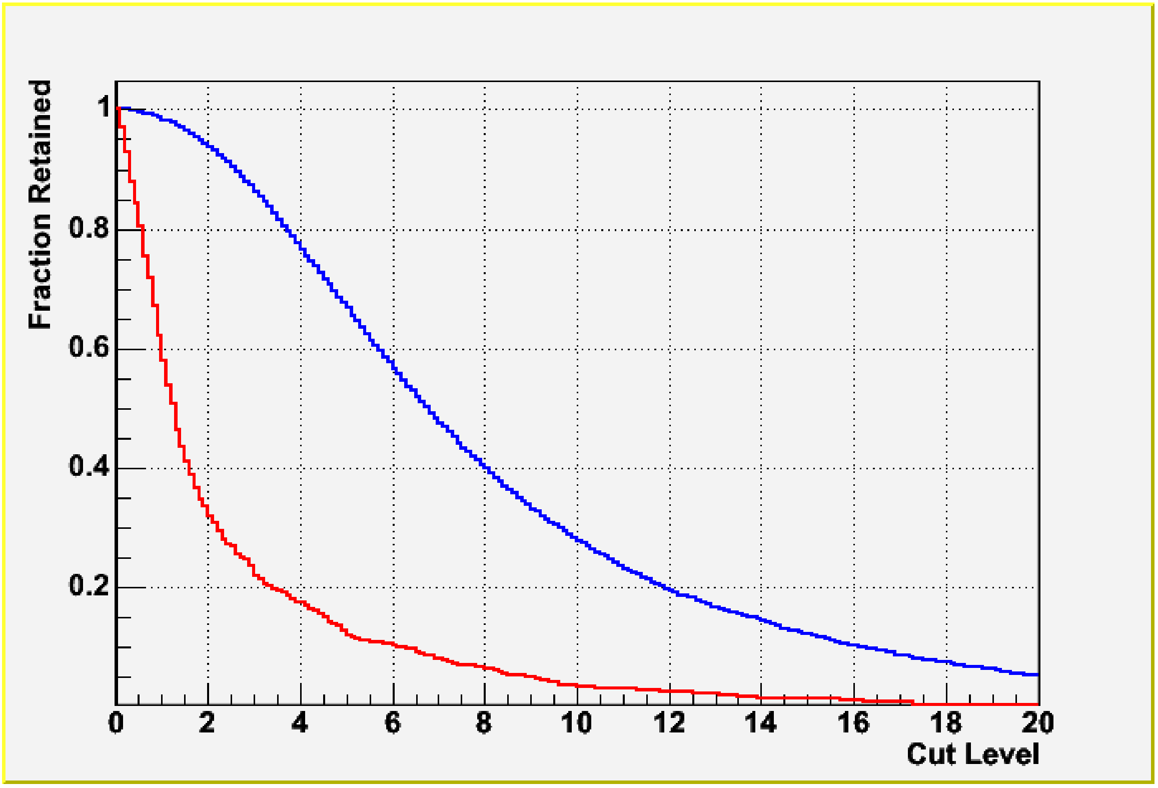

Figure 9 Gamma ray (blue) and proton (red) efficiencies as a function of cut level.

Sensitivity Calculations

1. The Crab Nebula

The Crab Nebula is modeled as a source with the spectrum of $dN/dE=3.2\times10^{-11}\ E^{-2.49}\ cm^{-2}sec^{-1}$, where E is given in units of TeV. While this is not the correct spectrum for higher energies (most relevant for Milagro) it is correct below 1 TeV and useful for its simplicity. For a detector with a lower energy response than Milagro it is a conservative spectrum as it steepens at higher energies.

To predict the sensitivity of miniHAWC the simulation is compared to the Milagro simulation and then the Milagro simulation is normalized by our observation. The Milagro baseline reconstruction code and trigger are used (as was published in the Crab paper). Therefore we predict 4 sigma in a year of Milagro observation and the miniHAWC results should be scaled from this. To perform the scaling I use the "Sensi" program from Andy S. which simulates a complete transit of the sources for one day. Since the range of zenith angles thrown with the simulation only covers 0-45 degrees a source transit is defined between these limits. The declination of the Crab is used (22 degrees) and it is assumed that the detector is at the same latitude as Milagro (36 degrees). I then find the number of gamma ray events per day and the number of proton events per day for a source transit. Then for each detector I scale nGammas/sqrt(nProtons) and multiply by the Milagro result (4 sigma in a year) to find the expected signal from the Crab for miniHAWC. I do this for both raw and cut events where the cut events have the background rejection criteria applied. For miniHAWC this is the parameter nTop/cxPE as defined above and for Milagro this is the compactness parameter as described in the Crab paper. Table 1 gives the results of the above analysis.

Note that while the gamma ray events should be correctly normalized the proton events are not as the true cosmic ray rate was not used in the simulation. To find the true number of background events per day one must scale from the Milagro results as published in the Crab paper. For the raw data Milagro obtained about 20,000 events per day from the Crab region (a 1.2 degree bin around the Crab) and for the cur data about 2300 events/day.

Table 1 Sensitivity analysis for the Crab Nebula. The table entries are the number of events per day. While the gamma ray events are correctly normalized the proton events are not.

Detector	Raw γ's	Raw p's	Raw Q	Cut γ's	Cut p's	Cut Q
Milagro	37	85	4	17.8	8.5	6.1
miniHAWC	220	67	27	173	11	52

There are two things of interest in Table 1. First is the fact that miniHAWC is about 8.5 times more sensitive than Milagro to a Crab-like spectrum (52/6.1). Secondly the event rate in miniHAWC is actually lower than that observed in Milagro. This means that all of the Milagro electronics can be used to build miniHAWC. It should also be noted that the trigger requirement for Milagro was set to 50 PMTs whereas we actually ran with a 60 PMT threshold before the VME trigger was installed. This has the net affect of raising the apparent sensitivity of Milagro (and therefore lowering the apparent sensitivity of miniHAWC), i.e. the numbers given in the table are conservative. By simply decreasing the bin size used in the miniHAWC analysis the sensitivity can be improved by 10%. While the VME trigger does not affect the sensitivity to the Crab (only to gamma-ray bursts) the outriggers do improve the Milagro result. For Milagro with the outriggers and Tony's reconstruction (and a 60 PMT trigger) the raw "Q" is 6.6 and the cut "Q" is 10. This is consistent with our expectations that the outriggers and Tony's reconstruction should improve our sensitivity by 50%. However, since we have not been able to demonstrate this improvement over a long period of time I felt it safer to extrapolate from the results presented in the Crab paper.

2. Gamma-Ray Bursts

One of the prime motivations for Milagro and HAWC is the observation of VHE counterparts to gamma-ray bursts. Both Brenda and Julie have presented plots indicating Milagro's sensitivity to GRBs. Because there can be absorption both at the source and in transit from the source to the earth, both of which are uncertain, deriving an absolute sensitivity to GRBs is problematic. However, we can compare sensitivity between experiments based on simple models. In the simplest model we assume that the emission spectrum from the GRB has no cutoff and the only absorption is due to the intergalactic IR fields. For distant GRBs this is probably a valid approximation, but it is probably too simplistic for nearby GRBs. But it allows a comparison of sensitivity between Milagro and miniHAWC. In what follows I assume the IR model as given by Knieske 2004. This model is valid to larger redshift ranges than the Stecker parameterizations. Brenda has fit the data given in the paper to the following function (which is valid between z~0.2 and z~1, beyond z=1 the opacity given by this parameterization is too large) $\tau = (z^{1.33})(E/90.)^{1.5}$, where E is the gamma-ray energy in GeV.

I present the results in two different ways. In the first method I find the results for a full source transit (for a source passing through zenith). As this is an average response over our fov it does not represent the correct result for any single GRB, but gives a good idea of the relative sensitivity between experiments. The input spectrum is $E^{-2.4}$. Tables 2 and 3 give the results for miniHAWC and Milagro, respectively. For Milagro I used the VME trigger, with Tony's reconstruction and a 1.2 degree radius bin. No gamma/hadron cut is applied to the Milagro data, as this would degrade our sensitivity. For miniHAWC, I again use Tony's reconstruction and a 1.2 degree bin, but the trigger criteria is the simple 40 PMT multiplicity trigger. For miniHAWC both raw results and cut results (after application of the above described gamma/hadron cut) are given. The meanings of the table entries are the same as for Table 1 above. One can see that at nearby redshifts miniHAWC is about a factor of 9 more sensitive than Milagro and has the same relative sensitivity to a GRB at a redshift of 2 as Milagro has to a GRB at a redshift of 0.2 (modulo the $1/r^2$). So if a GRB is luminous enough, the IR absorption will not prevent miniHAWC from detecting it. An interesting observation is that at any redshift the cut data yields a higher sensitivity than the raw data. This shows, that unlike Milagro, the gamma/hadron rejection in miniHAWC does not have an strong energy dependence and works well for low-energy gamma rays.

Brenda has supplied me with Figures 10 and 11. In these plots we show the sensitivity of Milagro (Figure 10) and miniHAWC (Figure 11) as a function of source redshift for several different zenith angles. (The miniHAWC numbers are given for the cut data.) The y-axis sensitivity is the source luminosity required for the detector to detect the GRB at the 5-sigma level. Unlike the above calculation this plot does include the $1/r^2$ effect on the luminosity at earth. However, the basic result is the same as above, miniHAWC is about 10 times more sensitive than Milagro to GRBs and can see to much greater redshifts. The triangles on the plot are the measured value of luminosity (in the MeV band) vs. redshift from well localized GRBs.

Table 2 miniHAWC relative sensitivity as a function of redshift. Numbers are for an $E^{-2.4}$ spectrum and a 1.2 degree bin size. All numbers are relative.

Redshift	Raw g’s	Raw p’s	Q-Raw	Cut g’s	Cut p’s	Q-cut
0.0	288	80	32	224	18.6	52
0.2	66	80	7.4	45	18.6	10.4
0.4	37	80	4.1	25	18.6	5.8
0.6	25	80	2.8	17	18.6	3.9
0.8	19	80	2.1	12	18.6	2.9
1.0	15	80	1.7	10	18.6	2.3
1.2	13	80	1.4	8	18.6	1.9
1.4	11	80	1.2	7	18.6	1.6
2.0	7.8	80	0.9	5	18.6	1.2

Table 3 Milagro relative sensitivity as a function of redshift. "Q" should be compared to the numbers in Table 2 for miniHAWC.

Redshift	Raw g’s	Raw p’s	Q-Raw
0.0	96	114	9.0
0.2	12.7	114	1.18
0.4	7.9	114	0.74
0.6	6.1	114	0.57
0.8	5.2	114	0.49
1.0	4.7	114	0.44
1.2	4.3	114	0.40
1.4	4.0	114	0.37
2.0	3.5	114	0.33

Conclusions

I have shown that the Milagro PMTs and electronics can be re-used to build a detector with about a factor of 8 greater sensitivity than Milagro. This detector would be able to detect the crab Nebula at the 5-sigma level in about 8 days (or 34 sigma in one year). This would allow us to detect a 3-Crab flare in about 3.5 hours (~1 source day). The same improvement in sensitivity is seen with respect to gamma ray bursts.

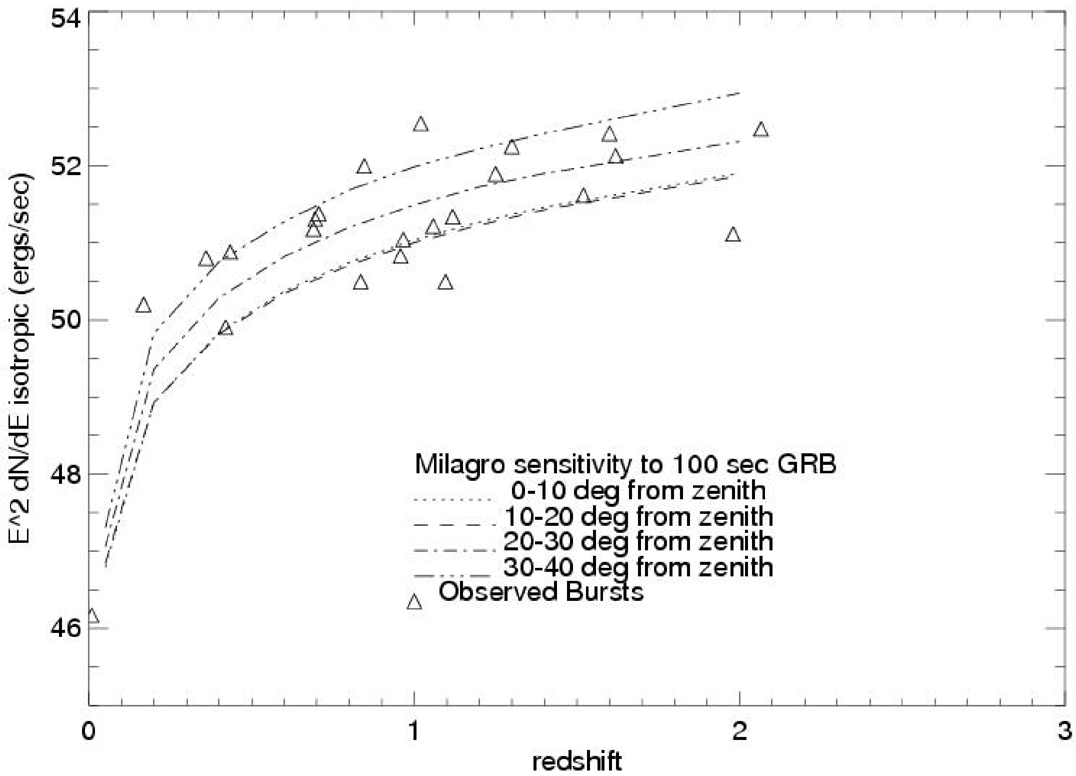

Figure 10 Milagro sensitivity to GRBs as a function of redshift.

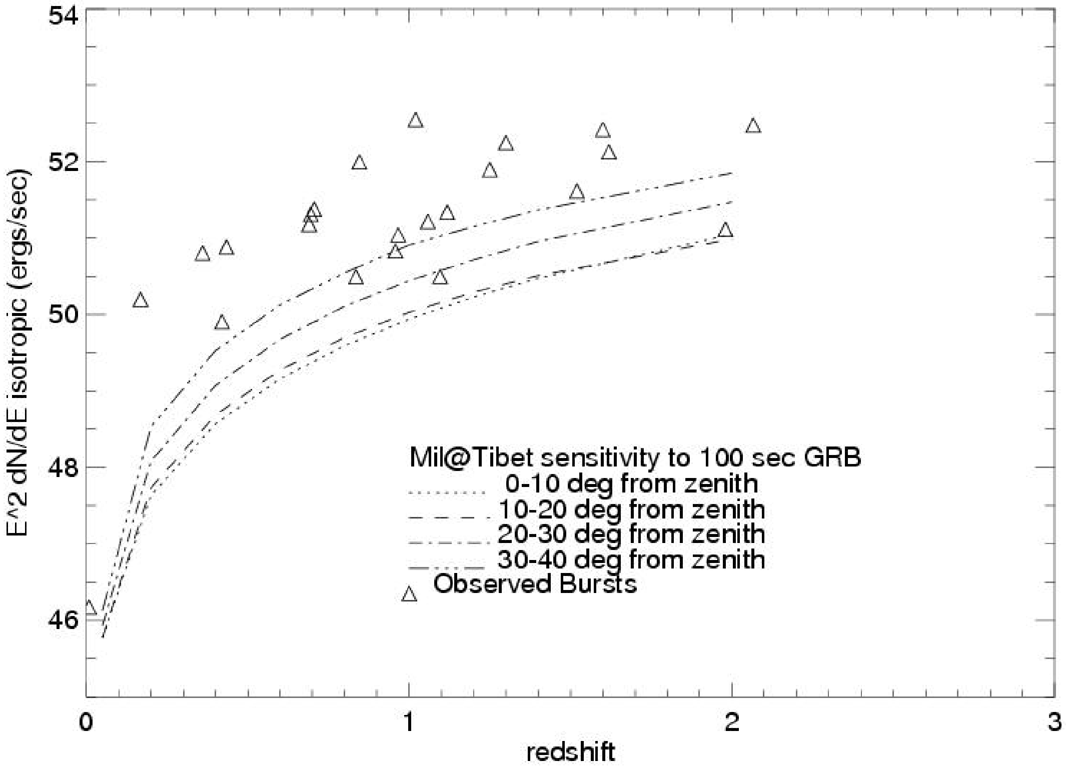

Figure 11 miniHAWC sensitivity to GRBs as a function of redshift.

References

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Knieske, T.M., Bretz, T., Mannheim, K., and Hartmann, D.H., A&A, **Vol 413**, pp 807-815 (2004).