Performance of water Tanks and Igloos

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Abstract

Measurements of response of different water Cherenkov tanks, lined with Tyvek reflectors and viewed by a single hemispherical Hamamatsu R5912 photo-multiplier, to muons traversing the tanks are compared with predictions of simulations using MILAGROSIM. Simulations are shown to describe the measurements reasonably well. Results for muon igloos of varying depths from 1m down to 0.15m are presented to aid in the evaluation of how thin we can make them.

1 Introduction

The MILAGRO air shower telescope [1], under construction, has a detector layer at a depth of about 6 meters which consists of light tight boxes(called Igloos) to detect muons present in air showers. Presence of muons in showers will be used for rejection of cosmic ray background. The Igloos are diffuse reflective boxes(lined with Tyvek), each having an area of about 9 m^2 and a depth of 1 meter or less. They are designed to respond to Cherenkov light generated by the passage of a relativistic muon.

Angular resolution of the MILAGRO telescope depends on knowing the location of the position where the axis of the shower hits the ground. For showers whose axis falls outside the MILAGRO pond, shower location is to be achieved by deploying an air shower array around the pond. For showers generated by primaries with energies below a TeV, shower particle density is low and to locate a core needs relatively large area detectors($\sim$ 5 m^2) which are sensitive to shower gammas whose number exceeds that of charged particles by a large factor. A suitable detector element would be to use a water tank which is sensitive to both gammas and electrons.

The MILAGRO collaboration has built prototype Igloos and shower water tanks and measured their response to muons traversing these detectors. This memo summarizes these results and compares them with simulations.

2 Cherenkov Yield from Muons

2.1 Yield per cm

The Cherenkov yield from a singly charge particle traversing a cm of material is given by [2]

$$\frac{dn}{d\lambda dx} = \frac{2\pi\alpha}{\lambda^2} \times sin^2\theta_C \tag{1}$$

We define a yield in which $\sin^2\theta_C$ is removed as(as done in Figure 5 of David Schmidt's memo [3])

$$f(\lambda) = \frac{dn}{d\lambda dx}/sin^2\theta_C \tag{2}$$

This spectral yield of photons, f(λ) is plotted in Figure 1. The integral under the curve gives a total photon production yield as 1088 photons/cm. If the integral of f(λ) is multiplied by $\sin^2\theta_C$ for water(0.437 for β=1.) we get a total yield or photons per cm of water traversed of 475.

2.2 Detected pes per cm

The quantum efficiency for R5912 extends from about 260 nm to 680 nm, and is shown in Figure 2.

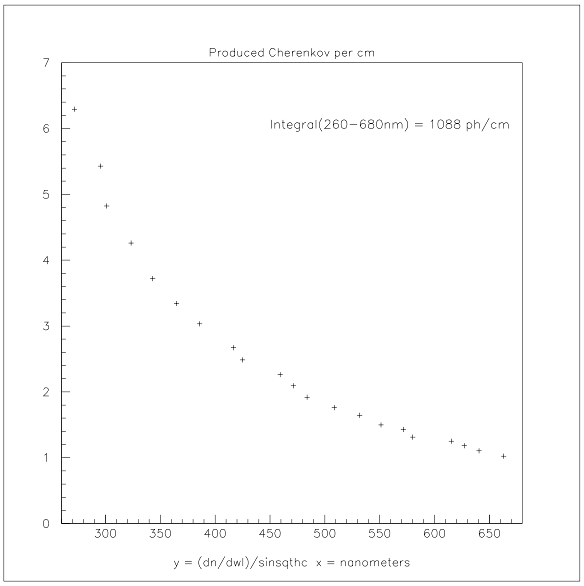

Figure 1: Cherenkov Spectrum

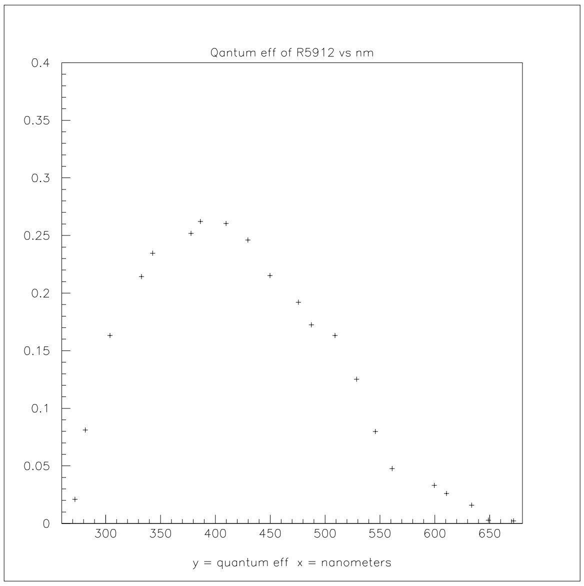

Figure 2: Quantum Efficiency

When the photon spectrum in Figure 1 is multiplied by the quantum efficiency, qe(λ), shown in Figure 2, we get a resulting spectral yield of photo-electrons(pes) as shown in Figure 3. The integral under this curve is found to be 161 pes/cm. If this is multiplied by $\sin^2\theta_C$ then one obtains 70 pes per cm. This compares well with the value of 77 obtained by David Schmidt. Up to the present time, the value that is inputted in MILAGROSIM was 69 pes/cm which was obtained by multiplying 77 by collection efficiency of 0.9. In simulations discussed below we have used 63 pes/cm.

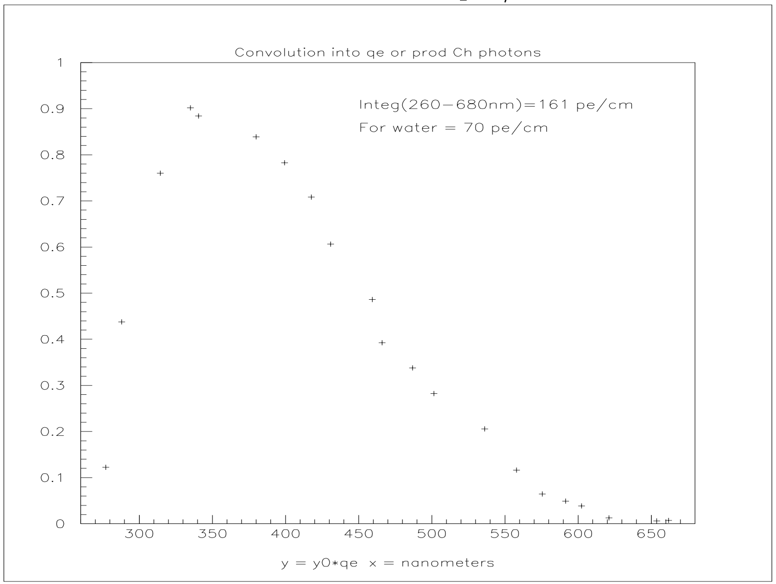

Figure 3:Convolution of dn/d$\lambda/sin^2\theta_c$ with quantum efficiency

2.3 Delta ray contribution

Muon also produces delta rays. Any delta ray with $\beta > 0.75$ will emit Cherenkov light. The number of delta rays which can give rise Cherenkov light per cm of path of water may be written as [4]

$$N_\delta = \frac{0.3 m_e c^2}{\beta_p^2}[(\frac{1}{E_{min}} - \frac{1}{E_{max}}) - \frac{\beta_p^2}{E_{max}} log(\frac{E_{max}}{E_{min}}) + 0.5\frac{E_{max} - E_{min}}{E_p^2}] \tag{3}$$

where β_p is the velocity of the muon, E_p is the energy of the muon, and E_{max} is the maximum energy of delta rays and E_{min} is minimum energy of the delta rays which can emit Cherenkov light. The energy of the delta ray determines its angle of emission. In the simulation, delta rays are generated on an E^{-1} spectrum between E_{min} and E_{max} and then propagated thru water using EGS4. The additional track length introduced by delta rays varies from about 10 % for 300 MeV muons to about 20% for 2 GeV muons. The average energy of muons incident at the surface of the earth can be calculated from the shape of the measured vertical muon spectrum [5] and is about 4 GeV. The average energy at the location of various detectors(e.gg IGLOO in the swimming pool, IGLOO at the bottom of the MILAGRO pond, UCI tanks in the basement) will be lower by an amount which depends on the overburden.

3 Reflectivity and Absorption

Other factors that have to considered in simulating performance of test tanks and igloos are Tyvek reflectivity and transmission of photons in water.

3.1 Reflectivity

We discuss reflectivity first. The reflectivity of Tyvek is a function of wavelength. We get this wavelength dependence from measurements made by Surface Optics corporation [6] and measurements made by David Schmidt [3] which is shown in Figures 4 These measurements were made at an air-Tyvek interface and not for a water-Tyvek interface. In this paper we neglect any differences.

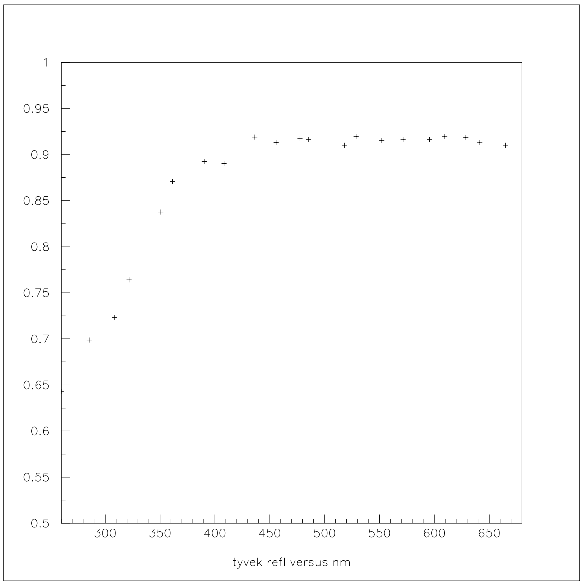

Figure 4. Reflectivity of Tyvek

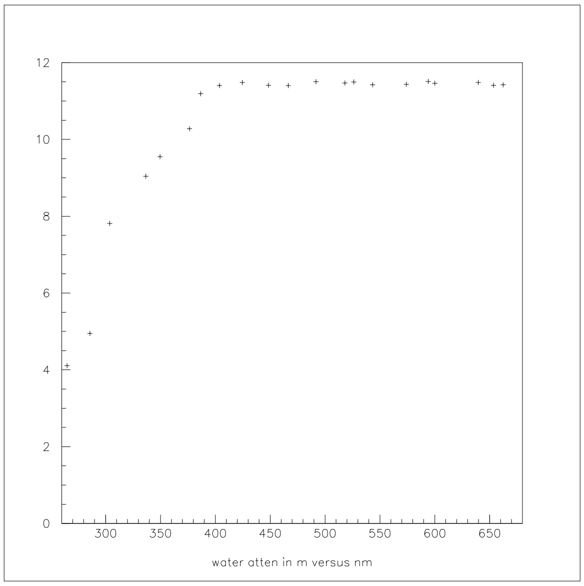

Figure 5: Attenuation Length UCI water

3.2 Absorption

Photons traversing water can undergo both absorption and scattering. Scattering depends on the nature and size distribution of scatterers. Absorption depends on the nature of the scatterers and on the complex part of the refractive index of water(including effects of dissolved impurities). For particulate impurities with sizes larger than the wavelengths of concern here, scattering is mostly forward. Such scattering does not significantly affect the number of photons hitting the tube in a diffusive box. It is, however, important in the kind of measurements of attenuation lengths that are done. Attenuation of Cherenkov photon depends on frequency. As an example we show the measurements of light attenuation done by Michael Schneider on a sample of water used in the test tank at UCI, in Figure 5. For wavelengths larger than 400 nm (where measurements were not available) a constant value of about 11 to 12 m is assumed. It is probably longer than this for larger wavelengths but because of the wavelength dependence of quantum efficiency and the Cherenkov spectrum this is not a bad approximation. As scattering does not remove any photons in a diffuse box, it is the absorption length which we need in simulations. Absorption length should be larger than the measured attenuation length, for instance in the case of perfectly absorbing impurities one gets $\Lambda_{abs} = 2.\Lambda_{atten}$.

A simple program was written which takes the photons per cm produced according to Figure 1 and propagates them thru 2 meters of water and thru two reflections on Tyvek. The spectrum is then folded into the quantum efficiency in figure 2. Two procedures are used: in the first the attenuation and reflection is wavelength dependent and in the second we use 10m and 0.86 reflectivity for water and Tyvek respectively. A comparison of the detected pe spectrum for the two cases, wavelength dependent versus that using constant values is shown in Figure 6. The effect of including wavelength dependence is to shift the peak of the spectrum to slightly higher wavelengths.

The integrals under the curves are found to be essentially the same, for wavelength dependent and wavelength independent calculations. In the results presented below constant values for absorption length and Tyvek reflectivity of were used.

Currently in MILAGROSIM the absorption of light by water is provided as an input which is given a wavelength independent value. Using the wavelength dependence of attenuation length given in Figure 5 we calculate an effective value of 10 meters for the attenuation length. Similarly for Tyvek reflectivity, an average value of 0.86 is taken as input.

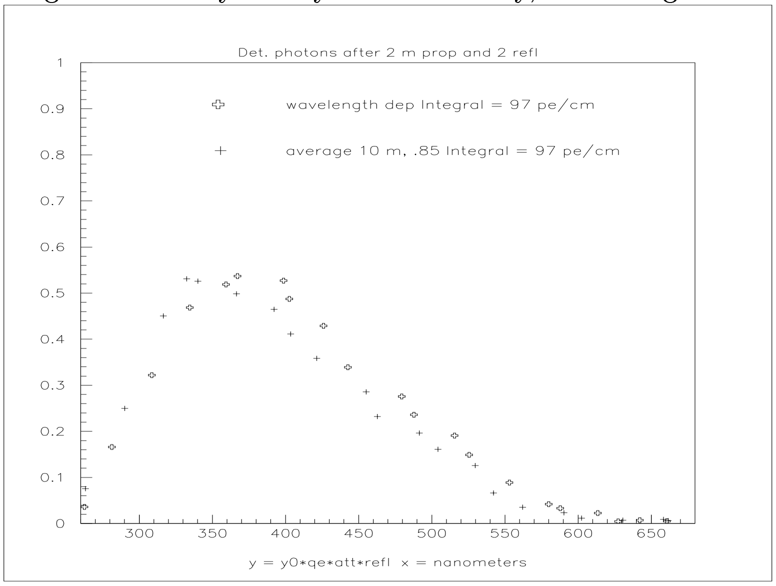

Figure 6: dn/d$\lambda/sin^2\theta_c \times e^{-d/\Lambda} \times Refl$ as a function of wavelength

4 Comparision of Measurements with simulations:

4.1 Jelley estimate of detectable pes

First consider an ideal case of a diffusive box for collecting the light produced by a through going muon by a photo-multiplier of collecting area A_{tube}, ignoring light absorption and including reflectivity. This can be done using a formula which can be found in Jelley's book [7]. For this calculation the following four numbers are needed:

(1) Area of the tube=A_{tube},

(2) Area of the tank surfaces = A_{tank},

(3) The coefficient μ = 1 - <reflectivity> and

(4) The total number of effective pes produced by muon traversal =N, using the value of 63 pes/cm.

The maximum number of pes that can be collected by the PMT, N_{coll} is given by:

$$N_{coll} = N \times (\frac{\rho}{\rho + \mu}) \tag{4}$$

where ρ is given by

$$\rho = \frac{A_{tube}}{A_{tube} + A_{tank}} \tag{5}$$

As an example, for the UCI test tank, we use the numbers:

A_{tube} = 0.063 m^2 (This is 6.28xR^2_{tube})

A_{tank} = 22.34 m^2

μ =1-0.86 = 0.14

ρ = 0.0028

$\frac{\rho}{\rho+\mu}$ = 0.02 N = 6741 pes/m

This gives for N_{coll} = 0.02 N $\sim$ 135 pes. Assuming that on the average a photon will travel through 1.5 m of water, it will suffer an attenuation on the average of exp(-1.5/20) = 0.93, this reduces to about 125 pes. This is not too far from what we are getting in our simulations and is of the same order as obtained by our measurements(Shown in Table II).

4.2 Representative Simulations:

4.2.1 Tank Configurations

Four cases have been simulated using MILAGROSIM for which all are enclosures were lined with Tyvek. The UCI test-tank results were presented by Isabel Leonor [8] at a collaboration meeting, the UCI shower tank measurements were done recently by undergraduate student Maurice Masequesmay under our direction, the IGLOO measurements were done last Scott Hugenberger and by Gaurang Yodh and AGASA measurements [9] are from a preliminary report of that group's Auger test tank. The parameters of the tanks for the four cases are given in the Table I. Location of tubes is given in meters, where (0,0) is the origin.

Table I

DEVICE NAME	SHAPE	HORIZONTAL SIZE meters	DEPTH meters	LOCATION OF PMT X, Y
UC Test tank	Box	±1.2	1.07	0., 0.
UC shower tank	Cylinder	radius =1.2	0.78	0., 0.
IGLOO	Box	±1.42	1.0	0., 0.
AGASA tank	Cylinder	radius =1.8	1.2	1.2, 0.

The location of the muon track was about 0.6 m from the center for the UCI test tank, UCI shower tank and the Igloo and it was in the center for the AGASA configuration, for the cases considered in Table II.

4.2.2 Water attenuation measurements

There are measurements of attenuation for the UCI water, IGLOO water and the AGASA water. For the UCI water the average effective value is $\sim$ 10m, for the IGLOO water it is 4m and for the AGASA water their measurements give about 3 to 4 m averaged over wavelengths and time of observations(the water deteriorated with time).

4.2.3 Overall simulation Results

The simulations were processed thru two versions of MILAGROSIM, for box and cylinder configurations. The results are given in Table II. The program uses 0.86 for Tyvek reflectivity and 63 pes/cm produced by a relativistic charged particle. The simulations were done for 3.5 GeV vertical muons traversing the tank. The table shows the dependence of collected pes as a function of assumed absorption length and also lists the measured values in the column labelled EXP. In this table mean and sigma are obtained from a fit to gaussian of the peak in the pe distributions.

For the UCI test tank and UCI shower tank the simulated values agree with measured values for an average absorption length of about 10 to 20 m. About 100 pes are detected per muon in both these geometries.

The IGLOO results show agreement when 4 m is used for absorption length, with about 46 pes per muon. If the water was better, with 10m absorption length then one would get 71 pes!

The AGASA tank results are also reproduced with 4m absorption length.

DEVICE NAME	Λ METERS	MEAN PES SIMULATION	SIGMA	JELLY'S FORMULA	EXP MEAN, SIGMA
UCI TEST TANK	50	131	16	132	
	30	113	15		
	20	106	15		110, 17
	10	80	15		
UCI Shower tank	50	132	17	129	
	30	129	20		
	20	116	16		102, 13
	10	95	15		
IGLOO	50	105	19	104	
	10	71	12		
	4	46	10		40-50, 15
AGASA	100	99.7±1.7	17.2	100	
	4	24.9±.8	8.6		28, 8

Table II

4.2.4 Pe and time distributions

Next we compare simulated detected pes distributions with those measured for the UCI shower tank. The simulation includes contribution from delta rays which are followed by EGS4. Figures 7, 8 and 9 show the detected pe distributions for a muon track which traverses at a distance of 2 feet from the tube, in the vertical direction.

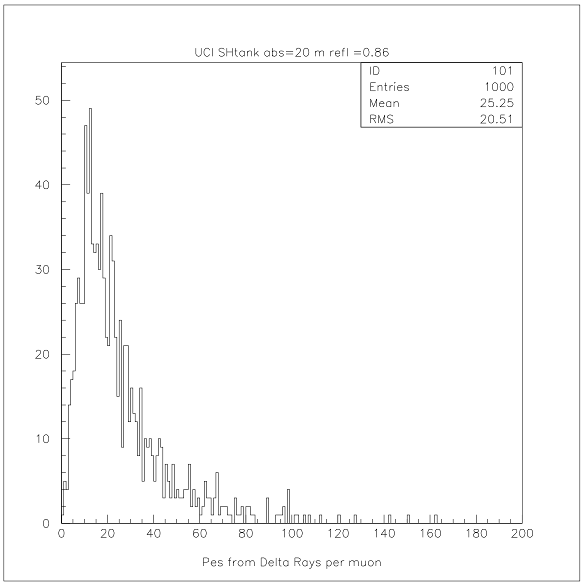

Figure 7. Pes from delta rays

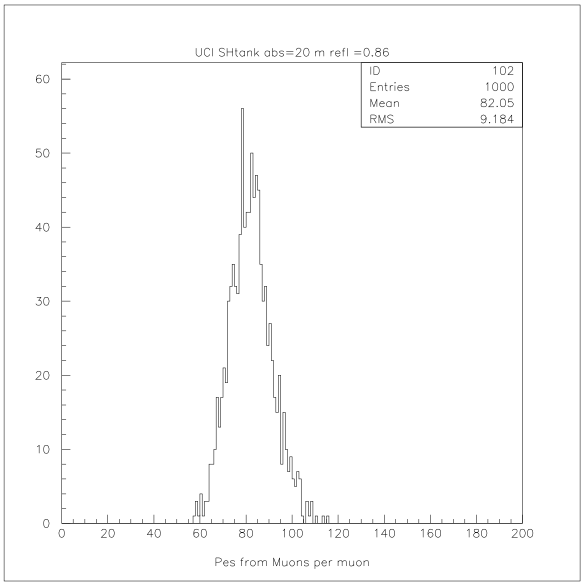

Figure 8. Pes from primary muon

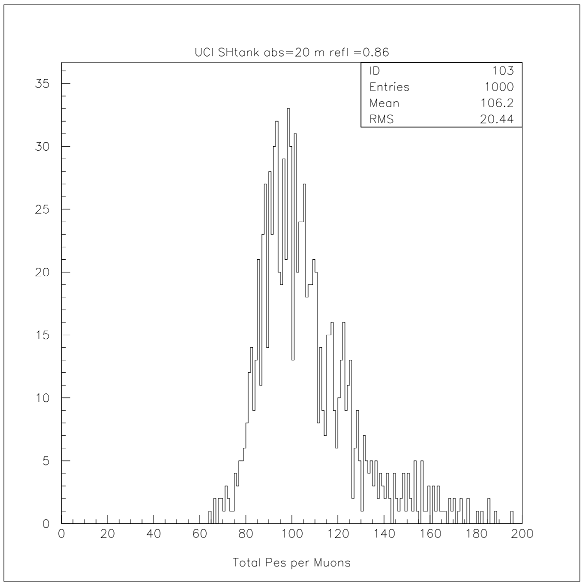

Figure 9. Total pes per muon

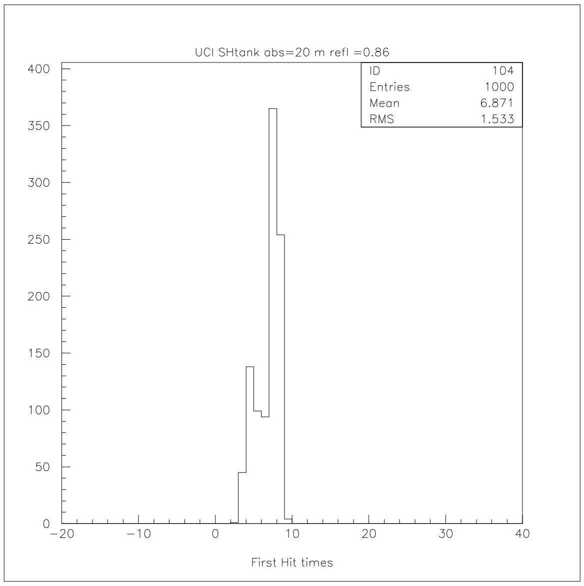

Figure 10. First hit Times

Figure 7 shows the contribution from delta rays, Figure 8 from muons themselves and Figure 9 is the sum. In Figures 7, 8 and 9 the single pe spread was not included. The distribution of times of first hits is shown in Figure 10.

The UCI measurements of the detected pes distribution for the same configuration are shown in Figure 11 and that for the first hit distribution is shown in Figure 12.

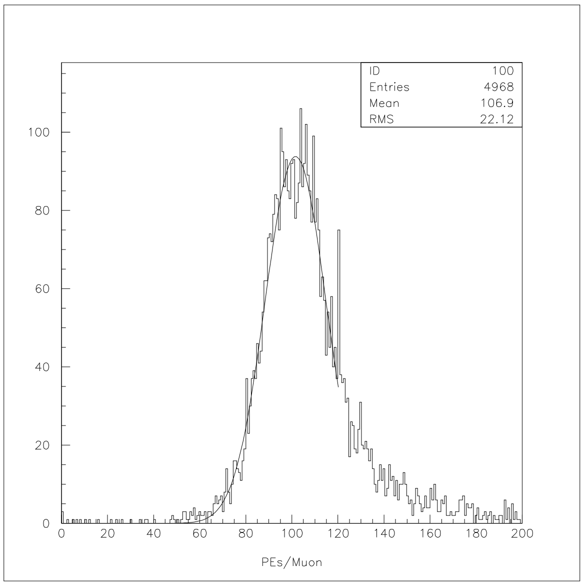

Figure 11. Total pes per muon

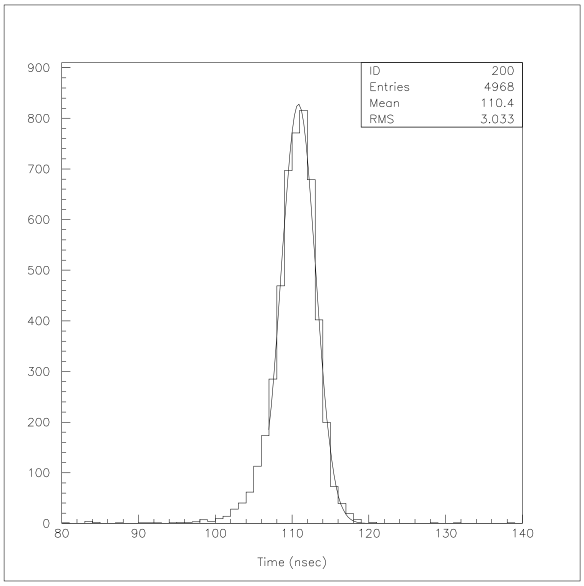

Figure 12. First hit Times

Figures 9 and 11 are quite comparable in both mean and sigma. The widths of the time distributions in Figures 10 and 12 are of similar width, however, it is clear from Figure 10 that the simulation does not have all the experimental time spreads properly included.

In summary, MILAGROSIM does reproduce the measured performance of diffusive tanks which we propose to use for detection of muons and shower core location.

4.3 Effect of varying the depth of IGLOOS

We are currently planning to use IGLOOS with a depth of 1 meter to identify muons. Electromagnetic punch thru depends sensitively on the total number of radiation lengths traversed before reaching the muon layer. It is important, therefore, to maximize this depth without loosing muon identification. Hence in this section a simulation study of response of muon IGLOOS of different thicknesses is presented.

Measurements and simulations for a 1 meter deep IGLOO indicates that some 50 pes are detected for muon traversing at a distance of two feet from the tube and that if a threshold requirement on number of pes of about 20 pes was implemented then we would not loose any muon identification. This is seen in Figures 9 and 11. The muons can impinge over the whole area of the igloo, hence we show simulated distributions of detected pes for the case of uniform illumination by 3.5 GeV muons arriving vertically on the igloo in Figures 13 thru 16.

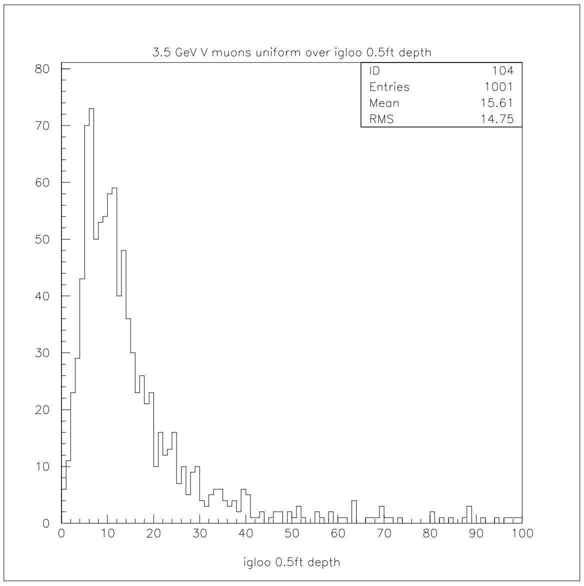

Figure 13. Pes per muon 0.15m depth

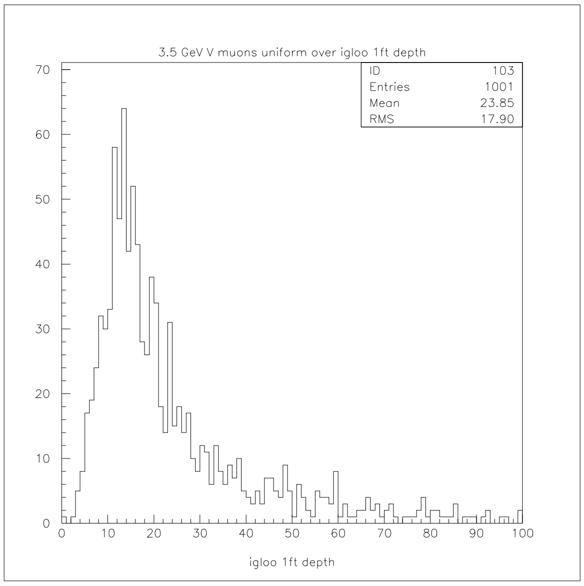

Figure 14. Pes per muon 0.3m depth

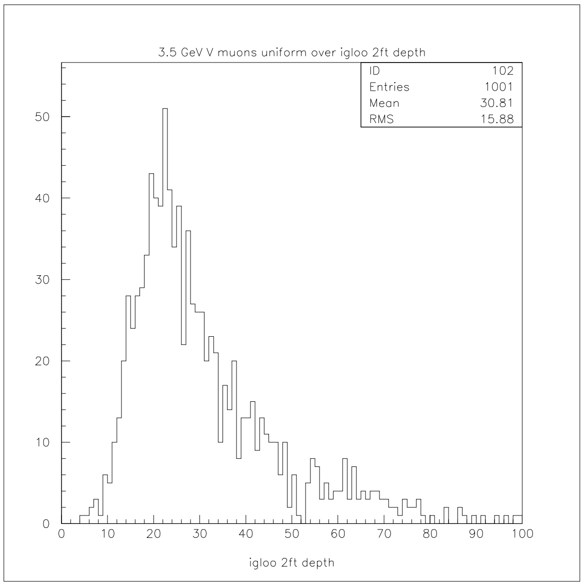

Figure 15. Pes per muon 0.6m depth

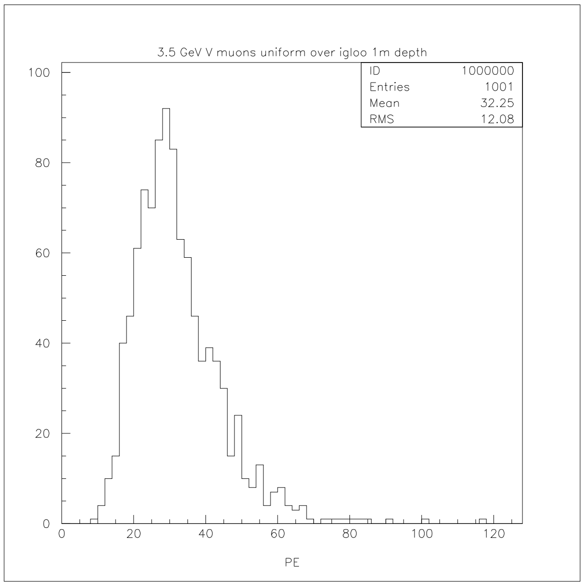

Figure 16. Pes per muon 1.0m depth

One thousand vertical muons($\pm 10^\circ$ were thrown over the IGLOO uniformly distributed over an area of $\sim$ 9 m^2 for each of four depths for an igloo - 0.15m, 0.3m, 0.6m and 1m. An absorption length of 4m was used and Tyvek reflectivity of 0.86. The simulated distributions are shown in Figures 13, 14, 15 and 16 for depths of .15m, 0.3m,0.6m and 1.0m, respectively. To get a clean and fully efficient muon identification a threshold cut of 10 pes has to be made for 1m and 0.6m thicknesses, while for smaller thicknesses the distributions extend to values smaller than 10pes. This suggests that one could use a 2ft thick igloo without loss of muon efficiency.

The value of having good water with absorption length of 10m is shown in Figures 17 and 18, which show the results of similar simulations for 2ft and 1 m igloos. Observe that in this case we can put a threshold cut of 20 pes and still have good efficiency for muons.

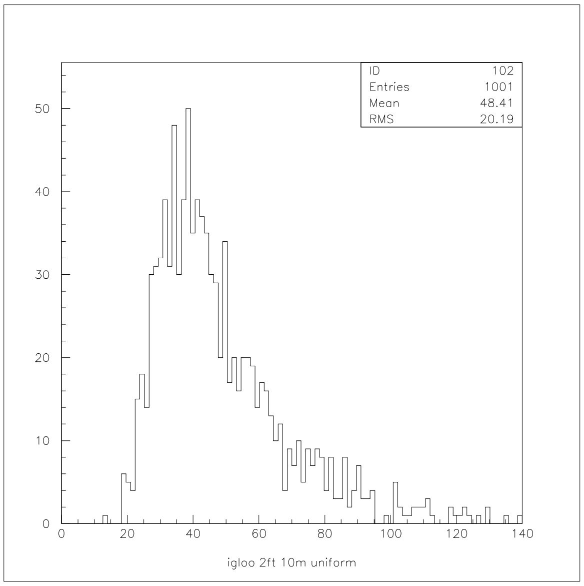

Figure 17. Pes per muon 0.6m d at=10m

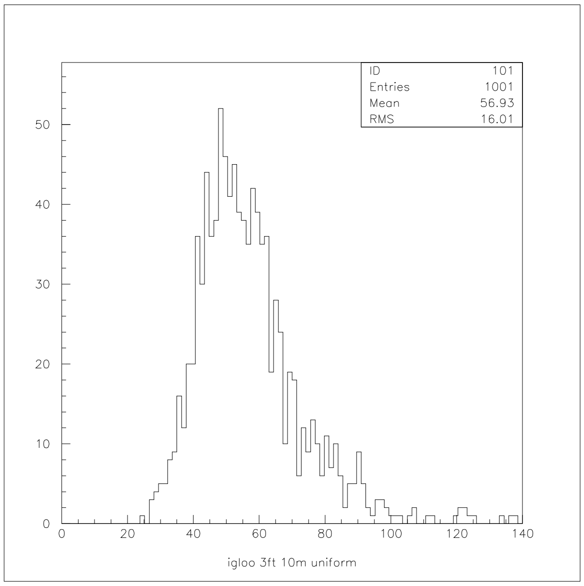

Figure 18. Pes per muon 1.0m d at =10m

4.4 Water and Reflectivity Degradation

In the simulations above, we have used 4m absorption length for the igloo water based upon Michael's measurements and a reflectivity coefficient of 0.86. Typical results of varying Λ and reflectivity individually are summarized below:

1. Varying the absorption length from 10m down to 2m, keeping reflectivity constant changes the number of pes collected from about 45 pes to 25 pes per muon traversing the igloo at 2ft from the tube.
2. Varying the reflectivity from 0.86 down to 0.5, keeping the absorption length at 4m changes the collected pes from 45 down to 20. The decrease is non-linear, slow down to reflectivity of 0.7 and then a more rapid decrease.

It seems that it is more important to keep the reflectivity as high as possible - prevent deposits or growth.

The shower tank was filled with clean water from our test tank and then the water was not changed. We made measurements of the collected pes periodically for about two months and saw no degradation. This will be studied over a longer period when the tank is brought out to Milagro site this month.

5 Conclusions

Reasonable agreement between simulations and measurements of detected pes for through going muons has been shown for four different water Cherenkov tanks. It seems possible to reduce the igloo thickness to 2ft without loss of muon efficiency. We still need to study the nature of punch through from gamma ray showers.

6 Other comments:

Some minor corrections have been made in MILAGROSIM. One is that photons which could hit the back of the tube if the tube was immersed with hemispherical face downward into water, so that there was some water above where the photo-cathode ends on the 'hemisphere', are properly treated. For dealing with cylindrical tanks (for example for possible water tanks for shower core location) appropriate version exists for doing the propagation correctly. MILAGROSIM has the provision for introducing wavelength dependence of both attenuation and reflection but at present they are not installed. Also at present specular reflection is not in although the code exists to put it in.

References

[1] Milagro progress report 1996(unpublished), see also Gaurang B. Yodh, Proc. of the Heidelberg Workshop on TeV Gamma Ray Astrophysics, 1994, edited by H.J.Volk and F.A. Aharonian, Space Science Reviews, **75**,(1996),199.

[2] J.V.Jelley, Cherenkov Radiation and its Applications, (1958), Pergamon Press, England, page 22

[3] David Schmidt, Results of Reflectivity Measurements for the Muon layer, Milagro Memo, Sept 1994(unpublished)

[4] B. Rossi, High Energy Particles,(1952), Prentiss Hall Inc.,USA, page 14ff.

[5] O.C.Alkoffer and P.K.F.Grieder, Physics Data, Fach-inormations-zentrum, Energie Physik Mathematik Gmbh, Karlsruhe, 1984, page 242, (1984) ISSN 0344-8401

[6] Directional reflectance measurements on two special sample materials, by Surface Optics Corporation, January 1995(unpublished)

[7] J.V.Jelley, Cherenkov Radiation and its Applications, (1958), Pergamon Press, England, page 172ff.

[8] Tyvek vs PVC Muon Measurements, by Isabel Leonor, Anthony Shoup and Gaurang Yodh, Milagro Memo, April 1995(unpublished)

[9] N. Sasaki and M. Nagano, private communication, unpublished AGASA report 1996.