DRAFT

This memo is being circulated in draft form in order to solicit comments on the proposal. Our intention is to incorporate those comments and circulate a revised (final) version documenting the collaboration's decision.

January 27, 1995

To: Milagro Collaboration
From: David A. Williams and Richard Schnee
Subj: Scaler Implementation in Milagro

1 Introduction

Since the publication of papers by the Akeno[1] and EAS-TOP[2] collaborations making use of singles' rate data from air shower detectors, a number of collaborators have discussed measuring singles' rates of the Milagro phototubes. Spencer Klein wrote a memo detailing the rationale for instrumenting the photomultipliers in Milagro with scalers.[3] Briefly, a sufficient flux of 10 to 100 GeV particles at the top of the atmosphere produces enough low-energy particles on the ground to be detected as an increase in the singles' rates of the tubes. The scalers provide a mechanism to detect gamma-ray bursts or neutrons from solar flares at energies too low to trigger Milagro. They also provide useful diagnostic information.

Scalers have been installed on the CYGNUS pools to get a head start on Milagro, as described in another recent memo.[4] These scalers have given us some initial data and experience with some of the operational pitfalls.

The purpose of this memo is to discuss the specific implementation of this idea for Milagro. A plan is needed in order to make the best use of the capabilities of the custom front-end electronics. Furthermore, if we are going to have a scaler system up and running at Milagrito, we need to prepare for it. We present some results of simulations, discuss some of the options in hardware and make a specific proposal for how to proceed.

2 Monte Carlo Simulations

2.1 Electronics Issues Addressed

We expect to discriminate the signal from each phototube at two levels, the equivalent of about 0.25 photoelectrons (henceforth called the "low threshold") and the equivalent of 5-10

[1] N. Chiba *et al.*, Astroparticle Phys. **1**, 27 (1992).
[2] M. Aglietta *et al.*, Nuovo Cimento C **15**, 441 (1992); also XXIII ICRC (Calgary), **1**, 61 (1992).
[3] Spencer Klein, "Milagro at 10 GeV," September, 1993.
[4] Richard Schnee and Spencer Klein, "Hardware for CYGNUS Pool Tubes' Singles' Rates," December 14, 1994.

photoelectrons (the "high threshold").[5] For the TDC part of the circuitry, we must generate a $\gtrsim$20 ns fixed width pulse from the low threshold and a $\gtrsim$40 ns fixed width pulse from the high threshold. The scalers will use these pulses, either directly or with some logic. The most detailed system would scale the rates for both thresholds for each individual tube. This system requires 1580 scaler channels in the standard Milagro design. Such a system is probably not a significant burden on the data acquisition, since the scalers need only be read out once a second or so. However, at a marginal cost of ~\$120 per channel for scaler modules, cables, etc., this system does not seem feasible nor appropriate.

The primary purpose of the Monte Carlo simulations was to compare the sensitivities of various configurations that would cut down on the number of scaler channels. Such configurations include cascading tubes together to count their combined rate, ignoring the deeper layers of tubes, and ignoring the data from one of the two thresholds. Therefore we determined the sensitivities of using every tube in each of the top two levels, with both threshold levels, and compared the results to those of various configurations of tubes cascaded together.

We were most interested in cascading tubes together whose front-end electronics will be on the same board, since doing so will avoid the necessity of an external multiplexer. Each board will cover the electronics for 16 tubes, and for trigger purposes, the 16 tubes on each board will be neighbors, most often a 4 by 4 patch. We checked cascading all 16 tubes into one scaler output, cascading two groups of eight of them (arranged in a checkerboard pattern, so that nearest neighbors were not on the same patch) and cascading four groups of four. We also included one configuration of sixteen tubes picked so that none was near another.

Finally, we compared the sensitivity of singles to that of using triggered events. The singles' overall sensitivity and their sensitivity relative to using triggered events help determine their importance to Milagro.

2.2 Details of Simulations

Using the standard Los Alamos EASHOWER program, we threw 100,000 showers from zenith with an E^{-2} spectrum starting at 1 GeV. Using the standard Los Alamos MILAGRO simulation, each shower was thrown 10 times over $\pm$200 meters in x and in y.

The discriminator was taken to fire at the time of the first photoelection hit, and no tube was allowed to drop back below threshold and be hit again by the same shower. Since the time over threshold tends to be much longer than the width of a shower, this approximation cut out very few hits. Hits above the low (high) threshold on tubes in a group cascaded together were counted as distinct if they were separated by 25 (45) nsec, since plans are for the discriminated pulses to be ~20 (40) nsec long, and about 5 nsec is needed for a scaler to distinguish two counts as separate.

Background rates of the CYGNUS pool tubes were used as estimates of the expected backgrounds for Milagro. A rate of 8 kHz was taken for the low threshold for both layers,

[5] Note that the thresholds of the two discriminators will be determined by other electronics issues and **not** by the needs of scalers. The low threshold will be chosen by the requirements of high efficiency for single photoelectrons, good timing, and good noise rejection. The high threshold will be chosen to be immune to prepulsing and to provide good timing and pulse height information for larger pulses.

while 1 kHz was taken for the high threshold, placed at 7.5 pe.

We determined the sensitivity for triggered events assuming a 20-tube trigger; 15- and 25-tube triggers gave results not much different. We assumed a background rate of 1.0 event/bin, as well as an angular resolution such that 70% of source events would be expected in the source bin. To take a worst-case scenario for triggered events, we assumed that no (directional) burst information existed from other experiments, so that the entire overhead sky needed to be searched, for a trials factor of 1000.

2.3 Monte Carlo Results

Figures 1 and 2 show the relative sensitivity of the different methods as a function of energy. Such a plot is particularly useful if we want to imagine an E^{-2} power-law flux that cuts off at some energy. Then we can just add up the standard deviations (plotted for two bins per energy decade) below the cut-off to determine the significance of the total signal expected for the method in question. Although the results are plotted for a given fluence, all results for the singles scale; a fluence ten times as large would result in ten times the number of standard deviations for each cascade configuration.

The number of expected triggered events is small enough that the resulting number of standard deviations is not proportional to the number of events. In order to be able to make useful scaling comparisons, therefore, the results are normalized against the number of events corresponding to a 3σ excess. If 15 events would be a 3σ result, I plot 5 events as 1σ, 10 events as 2σ, etc. Therefore, a number of standard deviations for triggered events should not be trusted if it is far less than or far more than 3σ, except that the result **is** far less than or far more than 3σ (which may be a sufficient answer for our purposes), but the results scale with fluence, and the results for different energy bins may be added together.

Figure 1 shows that any sort of singles system is significantly more sensitive than triggered events only below ~50 GeV. Above ~100 GeV, the triggered events are so much more sensitive than singles' rates that a scaler system is unlikely to add significant information. Therefore, comparisons of the sensitivity of different set-ups for the scalers should focus on energies below ~100 GeV. Figure 2 shows this energy range in greater detail, and Table 1 summarizes the results for various configurations.

At such energies, the most obvious result is that the high threshold does not appear competitive with the low threshold. Below 100 GeV, its signal has only one third the significance of the high threshold's. Doubling the number of channels by scaling both thresholds does slightly worse than doubling the number of channels by decreasing the amount of cascading from 16 to 8 tubes per cascade. Counting the high threshold is not even significantly better than changing from 8 to 4 tubes per cascade on the low threshold.

Results for the calorimetric layer of tubes are even worse. On a tube-for-tube basis, the calorimetric layer is about one fifth as sensitive as the top layer. Scaling the singles' rates of the calorimetric layer for the purpose of detecting bursts of gamma rays does not appear to make sense.

Compared to scaling all tubes individually, none of the cascading schemes does too badly. Cascading together 16 tubes that lie far apart loses only 6% of the signal. Cascading together the 16 tubes on one electronics board, the simplest and cheapest approach, loses 35% of the signal. The other approaches that avoid an external multiplexer, cascading 8 or 4 tubes, lose

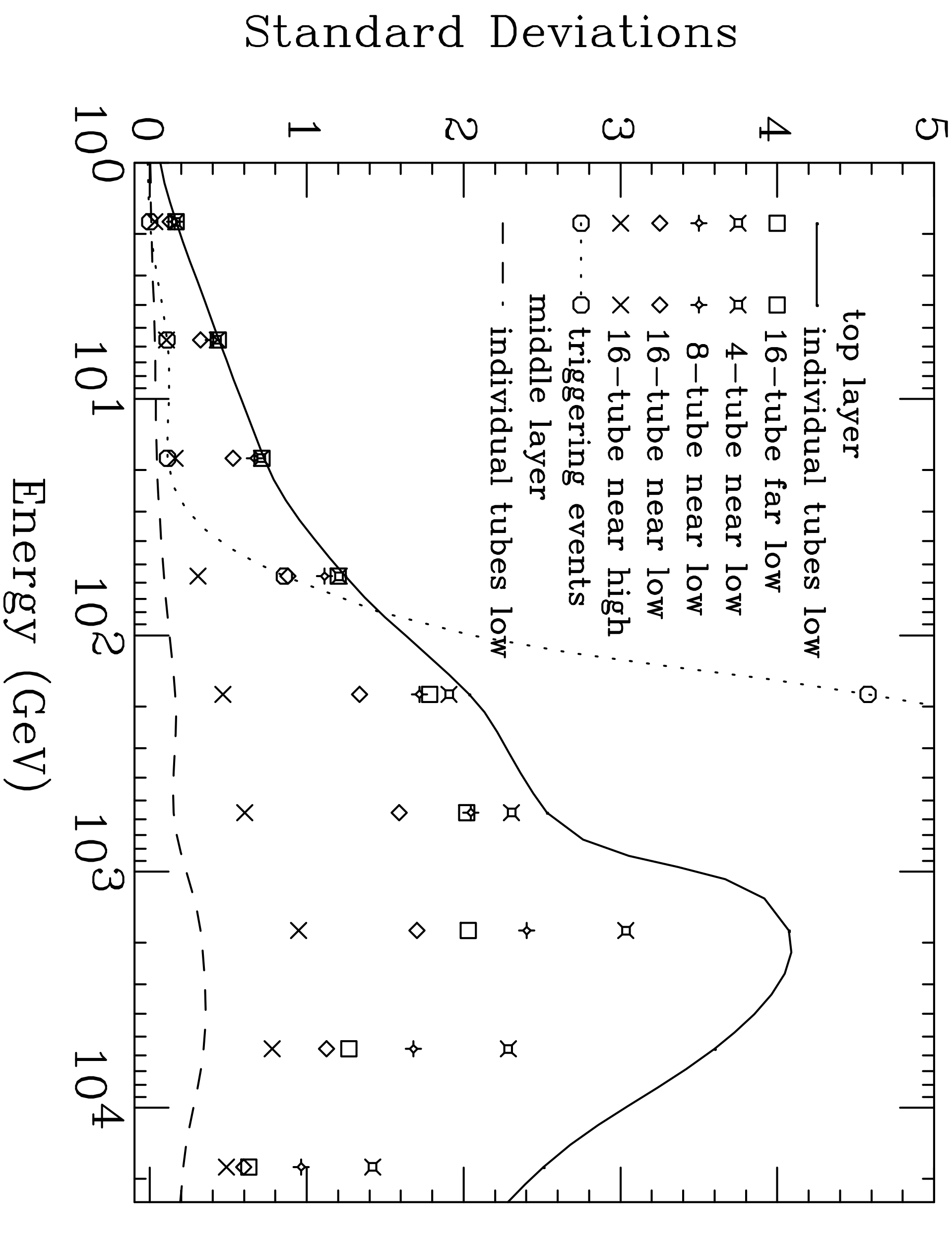

Figure 1: Sensitivity of various configurations to a 1-second gamma-ray burst with fluence $\phi = 10^{-6}$ erg cm^{-2}/ decade.

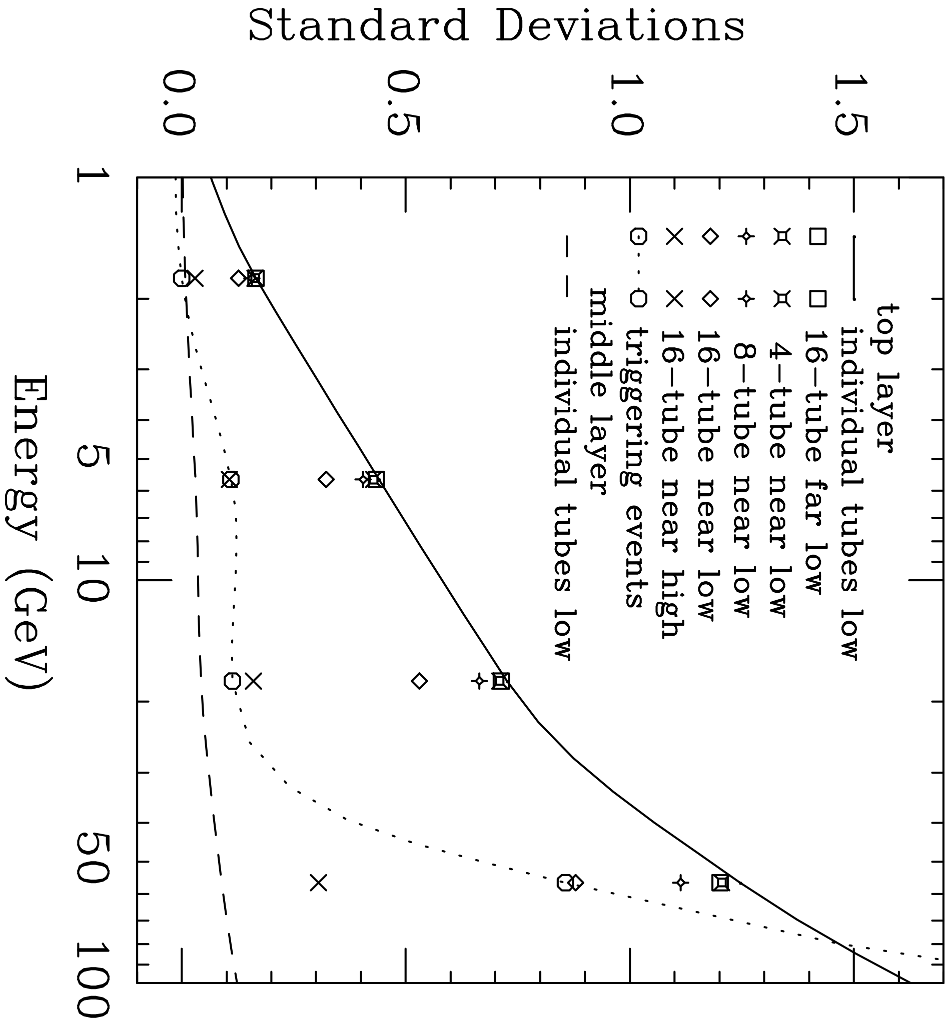

Figure 2: Sensitivity of various configurations to a 1-second gamma-ray burst with fluence $\phi = 10^{-6}$ erg cm^{-2}/ decade.

# of Tubes	Layer	Threshold	σ < 100 GeV	Added σ	Added Channels	Added σ/channel
16	top	low	1.86	1.86	28	0.066
8	top	low	2.34	0.48	28	0.017
4	top	low	2.51	0.17	56	0.003
16	top	high	0.60	0.09	28	0.003
16	middle	low	0.11	0.00	11	0.000
16	top (far)	low	2.51	0.65	...	...

Table 1: Monte Carlo results for various configurations. The 16-tube "far" set-up requires no more channels than the normal 16-tube cascade, but it requires an external multiplexer and more complicated cabling.

only 15% and 5% respectively. The 8-tube cascade provides enough increase in sensitivity be worthwhile, and even the 4-tube cascade is worth considering if the availability of scaler channels allows.

The results also enable us to place an upper limit on the sensitivity of scaling the doubles rates of pairs of tubes. Even if all of the events lost by cascading together 16 tubes were due to particles hitting specific pairs of nearest-neighbor tubes, and the rate due to background cosmic rays were 1 kHz (50% lower than is observed in the CYGNUS pools), the expected significance measured in the doubles rates would not be as large as that in the singles' rates.

3 Hardware Considerations

3.1 Scaler System for Diagnostic Purposes

In addition to providing sensitivity to low-energy signals, the scaler data will be valuable for diagnostic purposes. In this case, we don't care as much about counting the rate from each tube all the time, so long as we can look at each one some of the time. With many tubes cascaded, there is less sensitivity to a problem in one tube. If a problem is large enough to detect, you still don't know which tube has the problem. Thus, the ability to select tubes individually and count their rates would be useful. This capability could easily be implemented on either the front-end modules or an external multiplexer box if built. On the front-end board, a 16-bit mask would determine which of the sixteen tubes are included in an OR'ed output. Setting only 1 bit in the mask would enable a single tube to be examined. With groups of 16 tubes, 51 channels of scalers would be required to monitor all of the tubes in the pond.

3.2 Data Acquisition Format

A number of commercial scaler modules are available, as shown in Table 2. There are two main choices for how to proceed, VME or CAMAC, and in either format, new scaler modules cost about \$100/channel. The scalers need not be in FASTBUS, since the scaler data are not read in with each event. Rather, the scalers are read about once a second. Thus, the scaler data stream can be completely decoupled from the main data acquisition system and even run on a separate computer.

For some time now, we had assumed that Milagro would **not** use CAMAC, and that VME would be the best choice for scalers. A one-crate VME system, using the LeCroy or Joerger modules, would do the job. The best way to read out this system is probably to have the scalers in their own crate, controlled by a MVME-167 running VXWorks, and have the 167 write the data to a disk (which the 167 NSF mounts over Ethernet) on the appropriate CPU.[6] A minimal physics (top layer only, groups of 16 tubes cascaded together) and diagnostic (masked groups of 16 for the whole pond) system requires 80 channels. The more capable system which we propose below requires 130–186 channels. Either would easily fit in one crate.

The second option is to add CAMAC to Milagro. We would build a FASTBUS board to interface to the MBD. We would then be able to read out CAMAC through the MBD and FSCC. Just kidding! We would buy a system such as the Hytec CAMAC Ethernet Crate Controller (ECC 1365) which interfaces to one or more hosts directly over Ethernet. Host software is available from Hytec for the SGI system, as well as VAX and SUN.[7] The controller and host software cost about \$8,500. This approach would enable us to use CAMAC modules, which we have been told we could obtain free from LEEP. They have 256 channels of LeCroy 2551, LeCroy 4434, and Joerger S12 sitting on the shelf right now. There is some question however about how many of these channels work. We can certainly scrounge a CAMAC crate. If we can obtain enough working channels for free, the only hardware cost for this system would be the CAMAC interface.

Having CAMAC capability at Milagro is very likely to be necessary for calibration[8] as well as useful for other control and monitoring functions. Shower data should not be acquired with a hybrid FASTBUS/CAMAC system, but CAMAC could be very useful for mundane tasks like recording the temperature and pressure, reading in the scalers, setting the mask bits, etc.

In either the CAMAC or VME system, there will be quite a bit of work in software to create the appropriate processes to run the system and acquire data.

The decision between VME and CAMAC must be made before the front-end design can be finished, although the differences are minor and can be changed in the final stages of the design. If we are going to use VME, then the appropriate scaler outputs are differential ECL to flat twisted pair cable. If we recycle CAMAC modules, we would want to provide NIM signals to Lemo outputs.

If we adopt a masking scheme to be able to read out individual tubes to monitor their rates, the masking can be done using an output register[9] and cable daisy-chained to the front-end modules. We do not plan to make the front-end modules computer addressable.

[6] Gus Sinnis, private communication.

[7] The U.S. representative for Hytec is Vista Control Systems in Los Alamos, a distinct advantage in terms of support.

[8] Todd Haines, private communication.

[9] For example, CAEN V262 in VME. In CAMAC, there are several possible output registers. Again, we hope to pick one up for free.

Model	Channels	Bits	Format	Cost	Cost/Channel
LeCroy 1151E	16	32	VME	1685	105
Joerger VMESC	16	32	VME	$\lesssim$1795	$\lesssim$112
CAEN V260E	16	24	VME	1806	113
CAEN V560E	16	32	VME	1990	124
Phillips 7132H	32	24	CAMAC	2995	93
Joerger S12	12	24	CAMAC	1495	125
CAEN C257E	16	24	CAMAC	2144	134
LeCroy 2551	12	24	CAMAC	2405	200
LeCroy 4434	32	24	CAMAC	~3340	~104
Struck STR200	32	32	FASTBUS	5520	172

Table 2: Commercial Scaler Modules

The output register would set the bit mask, which would be the same for all modules, under the control of the same process that reads the scalers.

3.3 What to Count

Having summarized the Monte Carlo results, we discuss the hardware considerations for the several ways to trim the channel count:

- Cascade tubes together and count the combined rate.
  For counting single low-energy particles, the tubes are not very strongly correlated, as shown in the Monte Carlo results. There are two ways to cascade tubes together. Cascading can be done directly on the front-end electronics board, or the signals can be brought off that board to an external multiplexer. It is much simpler to do the cascading on the front-end board, which will process signals from 16 tubes. The necessary logic can be easily built into the board, and the number of cables and connectors is reduced. No external multiplexer would need to be built. Furthermore, the circuitry can easily be designed so that jumpers on each board select one of three options:

  - Four OR's of 4 tubes each within the patch of 16.
  - Two OR's of 8 tubes each within the patch of 16.
  - One OR of all 16 tubes in the patch.

  The disadvantage of doing the multiplexing on the front-end board is that for trigger purposes, the 16 tubes on each board will be neighbors, most often a 4 by 4 patch. These tubes are somewhat correlated, and cascading all of them together reduces the sensitivity by about 35%. If the tubes are multiplexed 16-fold in an external box, combining tubes from 16 different 4 by 4 patches, almost no sensitivity (~6%) is lost compared to counting every channel. This means running 790 signals from the front-end to a custom-built multiplexer, thence to the scalers. The cost of the extra cabling and multiplexer is probably about \$3,000 to \$4,000, and the system's reliability is certainly reduced.

- Ignore the deeper layers of tubes.
  The Monte Carlo shows that the hadron layer has much less sensitivity than the surface layer to GRB's. This makes sense if the light is being produced near the surface by low-energy particles and the water has an attenuation length of about 6 m. The light travels roughly an extra attenuation length to get to the deeper tubes, hence the signal is reduced by about 1/3. Furthermore, there are about 1/3 as many tubes in the hadron layer as the surface layer, so there is a additional loss of $1/\sqrt{3}$ simply from statistics. The total reduction of significance of roughly $1/3\sqrt{3} = 0.2$ agrees reasonably well with the Monte Carlo. The muon layer is obscured by a light-tight barrier, so it will have no sensitivity to low-energy electromagnetic particles. For detecting γ-ray bursts, monitoring the rates of the hadron and muon layer tubes is not worth while. It *may*, however, be interesting and possible to monitor the rate of single muons by scaling the high threshold in the muon layer. The rate should be such that a cascade of 16 tubes is adequate for this task.

  The scalers will provide important diagnostic information about the health of the tubes. We are as interested in the health of the muon and hadron tubes as the rest. Whatever diagnostic capabilities we provide on the top layer are probably wanted for the deeper layers. This is also natural from the hardware standpoint; it will be simplest to build only one style of front-end board to use on all three layers. It can have all the needed functionality for any of the layers, and the features required by a particular layer can actually be used.

- Ignore the data from one of the two thresholds.
  The Monte Carlo simulations suggest that for counting low-energy particles, the data from the high threshold does not help substantially, and can be ignored. For counting muons, the high threshold data seems likely to be more interesting. For physics purposes, we should concentrate on scaling the low threshold data in the surface and hadron layers and the high threshold data in the muon layer. Again, it will be simplest to provide for scaling both thresholds on all front-end boards and use the appropriate outputs at each layer.

4 Budget

We summarize the estimated costs of the VME and CAMAC scaler systems in Table 3. At about \$27,000 and \$9,000, respectively, neither system costs an outrageous sum of money. However, there is **no** money for the scaler system in the Milagro budget as it now stands. This is a problem for Milagro, but especially for Milagrito. As with so many of the Milagro systems, to get the most out of Milagrito, we need a lot of the final Milagro hardware up front. This poses some real cash flow problems. Adding any significant additional cost, particularly at the Milagrito phase, is not very appealing. As shown in the table, for the scalers, all of the crate and interface costs must be borne by Milagrito. The only additional

Item	VME System Milagrito	Milagro	Total	CAMAC System Milagrito	Milagro	Total
Crate & Power Supply	\$4,000	—	\$4,000	On hand	—	On hand
Crate Controller						
MVME-167 system	\$5,400	—	\$5,400			
ECC 1365				\$5,000	—	\$5,000
Software	\$1,000	—	\$1,000	\$3,500	—	\$3,500
Scaler Modules						
LeCroy 1151E	\$105 /channel	\$105 /channel	\$105 /channel			
LeCroy 2551				On Hand	On Hand	On Hand
LeCroy 4434				On Hand	—	On Hand
Output Register						
CAEN V262	\$1,150	—	\$1,150			
???				On Hand?	—	On Hand?
Cables	$\lesssim$\$5 /channel	$\lesssim$\$5 /channel	$\lesssim$\$5 /channel	$\lesssim$\$5 /channel	$\lesssim$\$5 /channel	$\lesssim$\$5 /channel
Total	\$11,550 +\$110 /channel	\$0 +\$110 /channel	\$11,550 +\$110 /channel	\$8,500 +\$5 /channel	\$0 +\$5 /channel	\$8,500 +\$5 /channel

Table 3: Budget for Scaler System. The Milagro columns indicate the additional cost to go from the Milagrito system to the full Milagro system. The cost of cables for the CAMAC System assumes that we can get a significant fraction of the Lemo cables free from existing supplies.

cost to complete the system for Milagro is extra channels. This makes the less expensive CAMAC option much more attractive than the VME system financially.

The UCSC group has managed to obtain some funding for the scaler system. We succeeding in obtaining \$4,250 in our current NSF operating budget. This amount is roughly half of what would be needed for the CAMAC system at Milagrito. If we could find a source of another \$4,000–\$5,000 within the collaboration, and we can obtain working modules from LEEP, we would be able to have a singles system for Milagrito without raiding other badly needed resources.

5 The Proposal

For purposes of completing the front-end electronics, the main decisions to be made are exactly what counting options to preserve, and which data acquisition format to use.

The CAMAC option looks preferable to us, primarily because of its lower initial cost. As mentioned above, the data acquisition format influences only the output interface, which can be altered at a late stage of the design.

By incorporating jumpers in the design, we can also preserve nearly all counting options. We propose to to provide six processed signals for scalers on each board:

1. An OR of the low threshold discriminator of 4 tubes.
2. An OR of the low threshold discriminator of a different 4 tubes. By adding a jumper, outputs 1 and 2 become identical, and are an OR of 8 tubes. No two of the eight are nearest neighbors. Hence, they alternate in a checkerboard pattern.
3. An OR of the low threshold discriminator of a different 4 tubes.
4. An OR of the low threshold discriminator of a different 4 tubes. By adding a jumper, outputs 3 and 4 become identical, and are an OR of 8 tubes, complementary to the tubes in groups 1 and 2.
5. An OR of the low threshold discriminator of any arbitrary combination of the 16 tubes. Membership in the OR is controlled by a 16-bit mask, shared in common by all boards in the experiment.
6. An OR of the high threshold discriminator of all 16 tubes.

These outputs will be differential ECL outputs on a 12 pin header, or NIM Lemo outputs, depending on our choice of scaler modules. A third jumper would allow outputs 1–4 to be combined. All four outputs would become identical, and would be an OR of all sixteen tubes.

In addition, we will provide unprocessed low threshold discriminated signals for all 16 channels in differential ECL on a 34 pin header. We propose not to instrument these outputs with scalers. They would allow the scaling of every channel or construction of an external multiplexer at a later date, if desired. They might also prove useful for solar physics. Furthermore, they provide an easy way to access the counting rate in hardware, to diagnose sick tubes.

For the E-M layer, we propose to use OR's of 4 or 8, depending on the availability of scaler channels. This requires 113 or 57 channels, respectively. In the hadron layer, we propose to use OR's of 16, requiring 11 channels. In the muon layer, we propose to instrument the OR of 16 **high** threshold discriminators, again requiring 11 channels. Finally, for all layers, we propose to instrument the masked OR of 16. This takes 51 channels. The total channel count is then 130 or 186, depending on whether we use 4's or 8's in the top layer.

6 Milagrito

For Milagrito, we will have the rough equivalent of a 250–300 tube E-M layer. Assuming 300 tubes, we need 94 or 57 scaler channels to implement the two strategies proposed in the previous section.

In the spirit of Milagrito prototyping, we propose to adopt the more aggressive OR of 4's approach, and to do a bit more. Namely, to instrument output 6, the OR of the high discriminator, and to instrument at least one 16-tube patch with a scaler on every tube's low discriminator. With these data, we can check the background rates, and if we detect bursts, we can check the simulations of the high channel contribution to the sensitivity and of the losses as a result of cascading channels together. The extra 35 needed channels brings the total to 129. This is our preferred scaler system for Milagrito.

The cost of the preferred system is about $9,000 in CAMAC and $26,000 in VME. In CAMAC, the extra channels of the preferred system carry essentially no additional cost. A minimal scaler system for Milagrito in VME, consisting only of an unmasked OR of 16 (for GRB's) and a masked OR of 16 (for diagnostics) would cost about $16,000.

7 Action Items

There are four main questions that need to be answered in order to reach a decision on the implementation of the scaler system:

1. What funds are available for the system, beyond the UCSC contribution? Does anyone else have a little pot of money that could be used for this? Alternatively, if we want to squeeze the rest out of the Milagrito budget, where do we squeeze?

2. Are we scaling the right combinations? Have we considered all of the uses the scalers have and are we preserving enough options? If we get this wrong now, and we keep the proposed 16 channel low-threshold individual output, we have the option later of easily reconfiguring much of the system.

3. Will the Hytec CAMAC system (or some other similar system) do the data acquisition job in a satisfactory manner? We are getting more documentation on the system in order to have a better answer to this question.

4. Can we obtain the CAMAC modules from LEEP and do they work? Even if we can't get all the channels from LEEP, the marginal cost of buying additional channels is similar in CAMAC and VME. If we could get even enough channels from LEEP for Milagrito, it would save us about $10,000 up front.