Physics Goals and Triggering DUMAND II

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Abstract

We discuss the options for on-line triggering for DUMAND II, beginning with the physics which is desired to be saved and estimating some efficiencies and noise rates for proposed triggers. By triggering we mean the algorithms employed for first level filtering. The suggested triggers utilize total energy deposition, and string 2 and 3 fold neighbor coincidences to efficiently capture relativistic events such as muons and cascades. This will also capture some types of exotica. Another type of trigger is needed to capture slowly moving particles, and yet another for possible supernova detection. Both the latter triggers rely upon monitoring of optical module count rates above various thresholds. It appears that all the physics goals can be met with a trigger processing scheme involving one layer of programmable processors, communicating with one data harvesting computer to achieve the necessary 3 order of magnitude front end rejection in incoming raw data rate.

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1 Introduction: Where's the Physics?

The data stream coming to the shore station must be searched as it arrives for the physics data we want to save. We cannot save everything, and all not immediately recorded will be lost. Thus we must think carefully about how best to save both the expected physics (muons and neutrino interactions), try to find a few "long shots", and also to make ourselves available for fortuitous discovery. In the following I will first list the physics we have considered as worthy and possible for exploring with DUMAND II. This is to be differentiated from the phenomena sensed by the detector: different physics may have the same requirements for triggering.

1.1 High Energy Neutrino Astronomy

The main goal is, of course, the detection of high energy muon neutrinos, made manifest as single muons. The muons produce conical light wave fronts that are detectable out to about $24m$ from the track [1]. The triggering problem addressed herein thus naturally involves use of the strong spatial and temporal clustering of the photodetector signals. High energy muons ($> 1TeV$) will give more light than lower energies, and be easier to detect, so that if we design for minimum ionizing muons we will be conservative[2]. Stopping muons are also worthwhile saving, since their rate relates to the neutrino spectral index, but produce more feeble signals. Just how efficient a trigger is at picking these out, and whether they can be fitted, needs computer simulations, now being carried out by Vic (and others I hope).

1.2 Neutrinos from Fermilab

In order to detect the $20GeV$ neutrino beam from the Main Ring Injector proposed for Fermilab, we must be sensitive to low energy muons, the lower the better. Given the muon range of roughly $5m/GeV$ one can conclude without benefit of Monte Carlo that given the $40m$ string spacing and $10m$ module spacing on the strings, that detection by a half dozen modules will require a range of at least $40m$, or energy threshold of at least $8GeV$. Note that knowing the direction and time for such events should help substantially in beating down the background.

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[1] Detection probability of 1/2 for a muon at impact parameter of $23.5m$, face on direction of photon arrival, see Figure 9. The probability is still 30% at $50m$.

[2] See the Monte Carlo study report of A. Okada, ICRR-209-90-2, for details. He shows, in Figure 3(b) therein, that the effective area grows slowly to $1TeV$ muon energy, and then grows more nearly linearly (just as dE/dx).

1.3 Cosmic Ray Muons

Downgoing muons from interactions of cosmic rays in the atmosphere overhead are interesting for various studies, ranging from direct production to muon astronomy. (The latter only being viable if high energy muons are indeed anomalously produced by the "gamma rays" seen at around $10^{15} eV$.) Obviously, if we make a trigger that is not direction sensistive, we will collect muons of all origins with the same trigger. The downgoing atmospheric muons constitute the highest expected rate of events in the array, about $3/minute$, in contrast to upcoming (and side going) muons from atmospheric neutrino interactions, which will occur at only about $10/day$.

1.4 Multiple Muons

Multiple downgoing muons are useful for studies of cosmic ray composition. Since these events will produce more light per PMT and more struck PMTs, with similar timing structure, one would expect also that whatever trigger is selected for single muons will work as well or better for multiple muons. Significant efforts are yet needed to understand how well we can extract the science, but triggering appears to be easy.

1.5 ν_es and Hadronic Cascades

When a neutrino interacts in or near the array, the light produced by the cascade of particles from the nuclear vertex may also be detectable. In the case of a charged current electron neutrino interaction, we may detect the electromagnetic cascade. While the rate of such events will be less than for through going muons, they are well worth studying. Not much work has yet been done with the Monte Carlo programs on this subject however, so the energy threshold is still uncertain, but as can be seen in Figure 16, it is significant. In terms of the signal in the detector, the cascade will be a few meters long with brightness in proportion to total energy. Most of the light will travel at the Cherenkov angle to the cascade direction, but there is some in every direction. In terms of timing, the light looks somewhat like a point source, but directionally peaked in amplitude, see Figure 17.

There is, of course, also an intermediate class of events: those with showers and muons. This class would be subsumed by the above, and comes presumably free. How well such events can be fit and distinguished from either of those classes remains to be explored in simulations.

1.6 Anomalous Interactions

We should not forget some of the exotica claimed from old underground cosmic ray experiments, because our size may reveal what has only been hinted at previously. A good example is the large electromagnetic cascades seen in the Kolar Gold Fields. Such events contained of the order of a TeV of electromagnetic energy (which makes one think of electron neutrino interactions), but with the peculiar characteristic of a large ($30°$) opening angle between sub-cascades. Such a phenomena, if confirmed, could be the opening to preonic structure, for example, and thus is well worth making sure we can save (though fitting is not likely to be easy).

In general, any interaction involving particles moving near the speed of light in vacuum will result in something that looks like either a line source (muon) or a point source (cascade), or both. So, it seems that the triggers that catch the physics above will do for any other wonders we have not yet thought about, but which involve simultaneous relativistic particles. The main effort for triggering considerations is to push downwards on the energy threshold.

1.7 Slow Massive Particles

There remain two other classes of phenomena which we have considered, which are not caught by the above, and they are both worthy of some fair amount of effort: massive slow particles and supernovae.

By massive slow particles I mean anything slow compared to a muon, but fast compared to a fish or even the speed of sound. The likely velocities are in the range from the speed of light down to meteoritic velocities, or $1.0 \geq \beta \geq 10^{-4}$, with array crossing times between $1\mu sec$ and $10msec$. One example of such an object would be a "nuclearite", as espoused by Glashow and DeRujula to solve the dark matter problem, which would be composed of a heavy quark bag which leaves an ionized glowing trail [3]. Another example would be a magnetic monopole of the variety proposed by Rubakov, which gobbles nucleons along it's path, reradiating them as pions and such, again making much light. The latter would

[3] See Vic Stenger's note about this HDC-3-87, 1987

be less bright than the former, but would have temporally tight photon emissions. Both can be characterized as causing large light levels in PMTs distributed along their path. They may not produce tight time coicidences between modules, of the type caught by the primary muon trigger, so they form a class needing special discussion.

Such particles have been sought by existing underground detectors, and many limits published, without even a hint of a signal. However, DUMAND, being 50 times larger in area than IMB (as a benchmark), can make substantial progress with a few years of live time, moving the limits down an order magnitude or more.

1.8 Supernova Neutrinos

The final class so far identified, is due to the interactions produced by a supernova within our galaxy. On the basis of observations in Kamiokande and IMB from SN1987A we have a good idea of how many events to expect: a collapse at $5kpc$ should give roughly 1 interaction per ton of water, spread over a time of less than $10 seconds$, or about 2×10^6 events in the detector volume. Sadly they are all of energy far below (by $100\times$) our individual detection threshold, so we have no chance with the fast coincidence techniques of detecting the individual interactions. The total energy deposition is about $20TeV$, which while emminently detectable in one few nanosecond event, is not at all obviously detectable spread over $10 seconds$. For comparison, the total K^{40} decay energy deposited in the detector volume in the same time is about $2.6 \times 10^{16} eV$, more than $1000\times$ greater. This would seem to make the detection hopeless, except for local (at one PMT) coherence in time.

While the K^{40} events are all around $1MeV$, the mean of the supernova events is about $10MeV$, and the tip of the spectrum extends to $50MeV$ or more. One can think of each PMT as comprising a poor man's detector, which has some chance to collect a multi-PE signal from a fortuitously aimed event throughout a fairly large volume. If, for example, we have a 1 in 100 chance of getting a multi-PE hit from throughout a volume of radius $10m$, then we could have 8000 multi-PE hits in $10sec$. If the background rate above the as yet unspecified multi-PE threshold is, say, 1% of the K^{40} rate, then the increase in the multi-PE rate due to the supernova could be 20σ.

However, this handwaving argument has quite a few "ifs" in it, and should only be taken as motivation to work on the problem. For present purposes, however, what I want to indicate is simply that (as far as I can see), the only hope we have of detecting a supernova with DUMAND II is via the rate of multi-PE events. Perhaps our best strategy will not be to trigger on superova-like events, but only to record those which are supernova like, with the intention of *a posteriori* correllation with other detectors with better low energy sensitivity.

One might object that it is not worth spending much effort on supernova detection because there are other detectors that can do far better. As we saw from the case of SN1987A, there certainly is much room for confirmatory detections. Moreover, if we are lucky and have a collapse within a kpc, then DUMAND II data could be very important in examining the time distribution, because of our high rate handling capability, where a detector such as IMB will be completely jammed by full buffers.

1.9 Types of Phenomena

Summing up, it seems that all the physics possibilities we have identified so far can be placed into 4 categories in terms of the phenomena to be sought by the triggering system:

- muon like (line source moving at c)
- point source like (localized in time and space)
- slowly moving ($\beta > 10^{-4}$) singles rate increase traversing array
- uniformly distributed multi-PE rate increase (up to $10 sec$)

Perhaps we need to associate some priorities with these categories. Clearly the first two dominate our physics goals with DUMAND II. The latter are long shots, but of great physics value if found. Note that while trigger efficiency is important for the first two it is not for the latter.

2 What kind of Triggers?

The design goal for the on-line triggering equipment at the shore station is to tag, on the fly, the physics we want to save for further processing. The total data rate to shore is vastly too much to save entirely: $\sim 2 \times 10^8 bits/sec$ [4] or $\sim one\ 8mmtape/2min$! We must select the interesting physics and discard the rest; anything not saved immediately will be lost forever. (Certainly we will want to save a random sample of the unselected incoming data). Naturally we will save as much as possible, but we cannot reasonably save more than a tiny fraction of the data stream. Restricting the data saved to one $8mm$ tape per day implies saving $\leq 10^{-3}$ of the incoming data at the shore station. Anyway, if we cannot keep up with processing on-line it is hard to imagine how we could later catch up, unless we only wanted to go back and search the archives for some event at a particular time. (In fact we probably can comfortably save all the physics data selected by the on-line analysis on disk, with tape serving only as backup, in case of disk crash, and as archive to permit the recovery of subtleties that may escape the on-line filter.)

We are thus in the uncomfortable position, typical of modern counting experiments, where the decisions made about the front end electronics will determine what phenomena we can observe. As we shall see below, that is no problem for the major goal of the project, neutrino astronomy employing high energy muons as the neutrino pointers, but we wish to be careful to attempt to allow for serendipitous discovery too.

The first level triggers must meet two criteria:

- *efficiency in extracting the physics, and*
- *suppression of background to a rate manageable by the next level.*

By triggering efficiency we mean the probability of collecting events which might later be successfully fitted. The definition is thus a bit sloppy, because fittability is not easily defined, even for throughgoing muons. 1% loss is a desireable goal (99% efficiency), however as typical of such experiments, realistically we expect to live with data losses of order of 10%. If we are to do such measurements as neutrino oscillation studies with the atmospheric neutrinos, then we must work at knowing our effective area well, including the effect of triggering efficiency, which will depend upon angle.

For suppression of random background light induced triggering, the goal must be to keep the rate of triggering below that which will saturate the data harvesting computer. We do not yet know what that rate is precisely, but we shall assume

[4] 216 modules, with 60,000 counts per second, at 16 bits per count

herein that we want to keep it to $< 10^3 triggers/sec$ for computer processing. If we take a trigger as comprising $2\mu sec$ of data (assuming that SN triggers and slow particle triggers contribute little to the total trigger rate), then $1000 triggers/sec$ would harvest 1/500 of the data stream. This is already close to the amount of data that we can afford to store, so we can contemplate saving everything passing the first level trigger[5]. Hence, once the first level processor has thrown away the obviously random data, we can make rather loose criteria on saving events therafter, and the fitting computer should have plenty of time to run everyone's fitter, on-line.

Note that if we have a first level hardware trigger rate of $10^3/sec$, the software filtering at the second level and beyond will have to get another rejection factor of 10^8 for upcoming muon tracks in order to make the random noise background to neutrino events negligibly small ($< 10\%$ of atmospheric neutrinos). (This is distinct from the fitter requirement of not reconstructing downgoing muons wrongly as upcoming, which is about a factor of 2×10^{-3}).

2.1 Optical Noise

A few words are in order about the assumptions relative to the incoherent firing of the optical modules. We learned in the SPS experiment that the background rate in the ocean would give us typically 30,000 counts per second from the Hamamatsu PMTs. We expect that with improved module efficiency, that may be nearer 60,000 counts per second in DUMAND II. The individual K^{40} decays generate so few photons (about 40) that the probability of a PMT getting 2 or more PEs from a given decay is $< 1\%$ of the overall PE rate. The probability that 2 neighbor modules see the same K^{40} decay is totally negligible. Thus higher pulse heights than one PE will come from within the PMT, due to the sloppiness of the electron multiplication, or due to internal effects such as ion feedback.

Bioluminescence will occur sometimes, we believe. Our measurements are very limited, and not in a real equilibrium situation, but we think that random bioluminescent events may occur perhaps 1% of the time (as creature flashes). It could be that a cloud of luminescing material will drift into the array once in a while, and we assume that we will simply be off the air for that period,

[5]With simple zero suppression, 1000 events per second would be reduced to $\sim 10^6 bits/sec$ or one 8mm tape every 5 hours. Another factor of ten would then make for a comfortable recording rate.

which we expect to be infrequent. For the situation of a local flash of light (which flashes we know last for durations of typically one second) we will simply gate off the temporarily blinded PMT. In order not to overflow the buffer at the SBC digitizer, this will have to be done at the optical module. One of the jobs of the shore station circuitry will be to keep constant track of the status of every module in the array. We anticipate that the effect of such local flashes will be restricted to one module, and will not generate excess coincidences due to correllated increases in random rate, and even if they do occur, they will be almost all at the one PE level.

2.2 Simple Coincidence?

All triggering schemes make selections in four-space (and maybe more, if we include charge, for example). The simplest trigger, beloved of all experimentalists, is the time coincidence: requiring some threshold number of signals within a predetermined time window. This works very well for an experiment such as IMB, in which the major trigger is simply the observation of more than 10 photomulitplier (PMT) hits from anywhere in the detector within 100 ns. This will not work in DUMAND, as long realized, because of the substantial noise rate due to K^{40} in seawater (expected count rate of $R_m = 60,000/sec/module$[6]) and the large size of the array ($\tau =\sim 1\mu sec$ across). In calculating random coincidence rates (we do assume that the PMT noise rates are not correllated), the important quantity is the expected number of hits in time τ, M, which we can write as:

$$M = R_m \times N_m \times \tau \approx 13,$$

where N_m is the total number of optical detectors, 216 in DUMAND II.

Thus 13 PMT coincidences will occur all the time, and even 25 PMT coincidences will occur at a rate of $\sim 10^3/sec$. The distribution of the number of module hits for through going muons is illustrated in Figure 1. The mean number of PMTs hit by a throughgoing muon is about 13, so such a simple coincidence is close to being useful (13 noise hits plus 13 correllated muon induced hits). However, it seems that the trigger described next is somewhat better.

I have run a Monte Carlo calculation for cascades of elementary particles, with a 1/E spectrum extending from $1GeV$ to $10TeV$, and the result is shown

[6]Note that we have taken the practice of employing $100,000 counts/sec$ as the safe design value for noise calculations.

in Figure 10 (fittable events are taken as those with more than 5 non-noise hits). One sees a rapidly falling distribution, which points to the importance of seeking efficiency for small numbers of hits. The question of whether the smaller of these events can be fitted is not addressed herein.

2.3 An Energy Trigger TE

A slightly more sophisticated trigger, which we designate TE, could employ the total number of photoelectrons (PE) in the array. Since the K^{40} noise will be almost entirely single PE uncorrelated (in time or space) noise, the summed PE rate will be close to the random PMT count rate. The mean number of PEs per through going muon event is about 23, as illustrated in Figure 2. The reason for this is, of course, that the muon is likely to pass close to one or more modules and produce large pulse heights in a few of them. The random rate for events the size of typical muon events would be, assuming Poisson statistics,

$$R_k = P(\geq (M+k) \mid M)/\tau \approx 0.33/sec,$$

for $k = 12$, $M = 13$ and $\tau = 1\mu sec$.

Since 85% of the muons penetrating the array have more than $12PE$, a trigger threshold of 25 that would include most muons would have a random triggering rate of about 1000/sec. I am not very sure of this calculation, however, since I have assumed that the distribution of photoelectrons in the whole array obeys Poisson statistics.

The results of the calculation for cascades is shown in Figure 11, where once again the distribution falls rapidly with increasing numer of photoelectrons. In order to say something quantitative about the efficiency of the TE trigger for catching such events we need to use a model spectrum. An unrealistically flat spectrum was employed in the calculation (for computational ease in generating the effective volume versus energy show in Figure 16).

Implementation of such a trigger can be carried out with the specialized processors which Wisconsin plans for the trigger processor card (at least one per string). The string level trigger processors would calculate a string sum for each rollover period ($1\mu sec$), and this would be passed to the next level processor for making the sum of strings. In order to not have the rate dominated by single large hits from one module, (as normally occur in PMTs due to ions) it will probably be necessary to require a minimum number of modules as well.

While some of the specialized triggers discussed below can dip into the noise a bit better, the energy trigger has the nice property of making minimal demands upon our preconception of the event topology. It should collect any deposition of energy by relativistic particles. The energy threshold for a spherically radiating source in the poorest place for light collection, in the center of a six unit cell (wedge $10m$ high), would correspond to a mere 6 GeV.

We should note that in the conversion from pulse width to PE for each module, we can use a lookup table in the trigger processor. As Ralph Becker-Szendy has suggested, this need not be linear: we may find that the sum of squares, or some other power, is a better trigger. This is because the signals explored so far do tend to produce large pulse heights in a few modules. In any case, by building such conversion into the lookup table generation we can optimize the trigger experimentally.

2.4 Plane Wave, Local Coincidence $T3$

Considering possible triggers for DUMAND II, at the time of writing the proposal, Vic Stenger proposed triggers which involved coincidences on (any of) three strings. The sub-triggers within the strings would require coincidences of adjacent modules. Vic's combinations were 4-3-2, 3-3-2, 5-2-0, and 4-3-0. The individual modules were only required to have $\geq 1PE$, and no there was PE sum requirement. In June '89 it was realized that since each of the combinations above involves a triple hit on a string, we might be able to make a trigger at the string level without the extra complication of a second layer, if we could keep the random coincidence rate within bounds.

One can easily see that a plane wave will have exactly the same time difference between pairs in the 3 neighbor hits. The light wave from a muon is conical however, so subtracting the differences will not yield zero, but should be small. It is necessary to employ a Monte Carlo simulation in order to explore this question quantitatively (see description in Appendix A).

In Figure 3 we show the distribution of time differences between neighbor modules as a function of zenith angle of the muon track. The time differences are unique for vertical tracks, and most widely distributed for horizontal tracks, the overall shape being banana like. (The scattered points are due to random noise.) The time difference of neighbor coincidence pairs are plotted against each other in Figure 4, where one sees that the hits are confined below the diagonal. The difference of differences is illustrated in Figure 5, again versus zenith angle of the track, and in the projection of this scatter plot in Figure 6, except that the latter contains only the smallest value per muon. We see that a cut of $15ns$ will keep about 85% of the muons, but there is a systematic tendancy for the large time difference events to be near horizontal. The concern about introducing a systematic bias in the trigger will be addressed below, but this example emphasizes the importance of having multiple triggers in operation simultaneously.

Figures 12 through 15 present plots that are the same as Figures 3 through 6, except they are for cascades of particles. The main conclusion to draw from here is that the $T3$ works very well for cascades, as shown in Figure 15, where one sees a totally negligible number of events beyond $15ns$.

As shown in Appendix 3, the expected rate of simple triple coincidences is about a thousand per second, and scaling with the cube of the module noise rate. With the $15ns$ cut the difference of differences trigger, hereafter called $T3$, the predicted rate falls to a comfortable $50/sec$.

2.5 Neighbor Pairs with High Pulse Heights $T2$

Another possibility is to use neighbor pair coincidences, but with a requirement of some minimum pulse height, which we shall designate $T2$. We realize that employing amplitude in the trigger is not generally desirable, both because it is more technically difficult, but more importantly because pulse height is poorly resolved. Nevertheless, we know that some of the muon trajectories will produce a large pulse height in some modules, for example, those trajectories that are near horizontal and pass near one module, possibly not producing a $T3$.

Some other physics phenomena may do the same, producing a large pulse height in only 2 PMTs on one string, and perhaps enough hits on other strings to make the event distinguishable from background. In a way, $T2$ can be thought of as just a local verion of the array wide TE.

We can test the efficiency of such a trigger with the Monte Carlo, but the problem is that we do not yet know the relationship between noise rate and amplitude for the real optical modules, in the real ocean, and cannot thus make reliable calculations of trigger random rates. If we assume that the Philips PMT is capable of a reduction of the noise by a factor of 50, and the Hamamatsu PMT capable of a factor of 10 similarly, then the $67k/sec$ reduces to a more tolerable $34/sec$, if we require $\geq 2PE$ in each module [7].

As we shall see below, this trigger is rather effective at extracting some events not otherwise caught, though it mostly does overlap with $T3$.

2.6 Nuclearites

Now let us discuss the case of the fast lantern, which I shall call a nuclearite generically. Such particles will raise the noise rate in the PMTs within several tens of m along the track. If the rate goes high enough it will trip the PMT into shutdown mode, as for bioluminescence. The latter takes some time to happen, being governed by the rate limiting circuit at the PMT, but probably only $10\mu sec$[8]. The fast data transmission circuit has a factor of ten or so dynamic range in terms of rate for all the PMTs, but the local digitizer will soon become saturated if we do not limit the PMT rates.

Hence we just cannot track the progress of a nuclearite through the array by watching the singles rates in the PMTs, as they arrive via the fast digitizer circuit. Since the larger end of traversal times we expect is only $10ms$, the particle will have gone by the time the fast rate limiters recover. Nor can we track the progress by the rate measurements sent ashore on the Command and Control link, because we cannot sample the rate and send it to shore many times in a second. Thus it seems that we can only observe the progress of the nuclearite by the noting times of the last pulses before the rate limiter kicks in. Moreover the relatively slow integral rate information recovered from the C^2 link can be used for total amplitude as well as fitting the trajectory spatially.

The trigger processor circuit on shore will know when a module has gone into hibernation mode by finding a *start* without a *stop* pulse. We do not know how often bioluminescence will produce such pulses, but the TTR4 data suggested

[7] Note that herein I have treated PEs as integers, while in fact the PMT output pulse charge is smeared (by fluctuations in the electron multiplier circuit) to an effectively continuous function. For this reason we need both the noise rate versus output charge, under appropriate random light illumination, and we need the distribution of in time pulses for various light levels (producing $1, 2, 3, ...PE$). The former is needed for the random noise calculations, the latter for efficiency assessment.

[8] The PMT rate limiter parameters have not been settled yet, but I am proposing that the optical modules will shut off their fast data output if they receive more than 100 hits in $10\mu sec$, and that they will stay in that state until their microprocessor measures a rate back to normal, but no less than 1 second. These times may not turn out to be the final values, but they cannot be far wrong.

that it might be 1% of the time. If this were so, and the duration of the pulse were typically one second, then we could expect that there would be about 2 PMTs shutdown in the array at any given moment. It would not be too much data then to record the exact starting time of the pulses with no *stop*. Thus, one of the tasks of the data harvesting computer, can be to keep a watch for unusual fluctuations in such a rate, and if found to look for a progression of the hits through the array. The rate information measured at the PMT and sent to shore on the Command and Control link can then be employed to refine the fit, and measure the total light output of the track.

No one has yet studied the question of threshold and efficiency for such a particle (any volunteers?). My guess would be that we are about as efficient as for muons in catching tracks that have enough light to drive the nearest PMTs into rate limitation. The energy threshold must be something like an equivalent of 100 times the light from a muon, eg. with an equivalent dE/dx of $> 200MeV/cm$, for a $\beta \approx 10^{-2}$ particle, and scaling upwards with decreasing β. It seems that such particles might be missed by this trigger near the upper velocity range, but they probably would be caught by the TE trigger if they cause enough light to exceed the array threshold in one rollover cycle. I do not see this as a big problem if there is some loss in this region, since the expectation for heavies would be to be at least gravitationally bound to the galaxy, and travelling in the range of $\beta \approx 10^{-2:-4}$.

Until we have more in ocean experience I have no way to calculate the rate of random triggers for such a beast. While this is a matter we will have to explore after the array is in operation, it is hard to imagine that the false event rate would be large (if it is we are in trouble for other physics with dead time from biolumineсsence!).

2.7 Monopoles

The other possibility is that the slow massive particle is visible only in bursts of light along it's path, as in the case of a monopole promoting nucleon decays along its trajectory via the Rubakov process. These remnants of the nucleon may give coincidences between at least neighbor modules. An unknown quantity in this affair is the crossection for such interactions, and the limits are usually presented with this as a parameter. The interaction length may be equivalent to a strong interaction, and thus we might see one or more decays per meter. For this case then we would have many trials for local coincidences. The light is surely more feeble than the nuclearite case, so we cannot count on picking them up by overall rate. Hence it seems that we must pick them out by $T2$ coincidence trails. Since we wil trigger on $T2$ the data will go to the next level processor, which can then keep a watch for a series of $T2$'s marching through the array.

Again, we will have to employ experience to assess the false event rate. Someone who wants a nice project could, however, begin the process of calculating the range of sensitivity of DUMAND II in velocity and cross section space.

2.8 Supernova Trigger

As stated in section 1, I really am not at all convinced we have a chance for detecting supernovae, but feel it well worth some fair amount of effort. At this time the only chance I see is for us to record a statistically significant increase in the rate of individaul module signals with a threshold $> 1PE$. As for assessing either of the important questions of efficiency and threshold of catching the signal (which would translate into how much of the galaxy we can "see"), or false trigger rate. The former needs some Monte Carlo simulations, and the latter needs the PMT noise rate versus amplitude distributions.

However, for planning the trigger we can say that it is desireable to implement the capability for each trigger card to keep a second by second tally of the number of hits per module above some individually programmable threshold (this is in addition to the total rate of triggers).

3 Rate and Efficiency of Triggers

The triggering efficiency for through going muons has been studied with the simple Monte Carlo. It would be nice to have a universal definition of fittability, but (particularly in the presence of noise) this does not seem possible. I could fit the events, but that would only test the trigger relative to my fitter, and everyone's fitter is slightly different. The following table presents some of the results for an isotropic flux of single, minimum ionizing, through going muons. Figure 7 shows the effective area for each trigger versus zenith angle, for what I define as fittable muons, $\geq 6hits$. Figure 8 shows the same plot for a definition of $\geq 12hits$ on $\geq 3strings$, demonstrating that the efficiency of the triggers does not relatively change much, though the effective area goes down a fair amount.

	$T2$	$T3$	TE	SUM
Efficiency	60.3%	63.9%	79.5%	90.8%
Excl. Eff.	3.4%	4.3%	14.6%	-
Eff. Area	$22,414m^2$	$23,750m^2$	$29,567m^2$	$33,738m^2$
Noise Rate	$137/sec$	$54/sec$	750	$942/sec$

One might be tempted to conclude that the $T3$ trigger is fairly useless. That is not the case, though in the table it has been subsumed by the TE triggers, because it, alone among the triggers depends only upon the geometry of the coincidence and not upon pulse heights. Of the triggers, I only feel comfortable about the rate predictions for $T3$, having had to make shaky assumptions about pulse heights for calculating the others. Also, note that though the array total area, averaged over all arrival angles now totals nearly $34,000m^2$, and nearly $50,000m^2$ over the lower hemisphere, this does not mean that we can fit all of those events in practice. This gives the people writing fitting routines something for which to aim!

The effective volume of the array is illutrated in Figure 16. By effective volume I mean the fraction of generated events which produced more than 5 hits and which generated one or more triggers, times the test volume in which they were generated ($2 \times 10^7 m^3$). Note that the effective volume reached the test volume at $10TeV$, so that further calculation may reveal the effective volume continuing to rise. This is a bit amusing since the contained volume is only about $2 \times 10^6 m^3$, so almost all the events are being seen from afar! Are they fittable?

4 Conclusion

We have discussed various possible triggers for the DUMAND II array, and find that 3 easily implemented triggers ($T3$, $T2$, and TE) will work for the main goal of recording muons. The $T3$ trigger requires small second time differences between trios of modules ($15ns$). The $T2$ trigger tags neighbor near coincidences with unusual pulse heights ($90ns$, $\geq 4PE$). The TE trigger seeks large numbers of PEs from anywhere in the array ($1\mu sec$, $\geq (13+12)PE$).

More simulation work is needed on cascades and low energy muons, but the proposed triggers probably work about as efficiently as we shall achieve at plucking such events out of the data stream. More work is needed in studying fitting of such low energy events. And more effort is needed in characterizing the signals and noise from the PMTs.

These triggers also seem to have a good chance to extract non-standard types of events involving relativistic particles of all types. Triggers for slow, bright particles, and for supernova detection, require special consideration, and a different type of hardware implementation. Our best approach seems to be through the implementation of means to record the times of PMT saturation, PMT noise rates each second (both single and multi-PE), and by searching for patterns in $T2$ coincidences.

While it is not clear if we have a chance to detect supernova neutrinos, the best opportunity appears to be via the monitoring the rates of pulse heights more than one PE and seeking few second increases distributed throughout the array.

Summarizing what is needed of the trigger card:

- search for single string triggers $T2$ and $T3$
- tally total PEs for each rollover and forward to next level
- tally totals of all pulses, and pulses exceeding a predetermined threshold, by module for each second
- note PMT start pulses without stops, and pass along start time, updating PMT status word to be read with scaler rates each second

Summarizing what is needed at the next level for data filtering and preliminary fitting:

- collect and filter single string triggers, seek $1000\times$ reduction
- make PE totals for TE, and test for trigger every rollover cycle
- watch for array wide increases in single PE and multi-Pe rates

- watch for ripple of PMT shutoff times

This document should be looked upon as a starting point for more detailed considerations. Of more immediate concern, for making progress on the system design, it seems that we will be able to create the triggers we need with the system as presently conceived, and that we are at least not far from optimum triggering.

Acknowledgements

The work reported herein draws upon the efforts of many people. I want particularly to acknowledge Ralph Becker-Szendy, Art Roberts and Vic Stenger for their many conversations on this matter, as well as many of the other collaborators, and particularly those at the Seattle Workshop.

Appendix A Monte Carlo assumptions

The Monte Carlo program used in the studies reported herein was written not to be all encompassing, but to be reasonably fast and simple so that I could try out different trigger configurations without huge computer time. The basic muon generating routine generates tracks perpendicular to a disk centered on the array. The orientation is made uniformly random, and the tracks are taken as infinitely long. The angles and distances relative to each module are calculated, and the mean number of PE expected in each module is generated. Then the actual number of PEs are Poisson fluctuated about that number. No effects of amplitude smearing are used, and no conversion to digitized units is introduced (not needed for present purposes).

The function employed for calculating the number of PEs is

$n_{PE}(d) = n_0(d + d_0)^{-\alpha} e^{-\beta d} F(\psi)/d,$

where $n_0 = 277.6$, $d_o = 17.86m$, $\alpha = 0.437$, $\beta = 0.02085/m$, and the slant distance d is in m, perpendicular to the track. This function is illustrated in Figure 9, where on sees that the minimum ionizing muon represented by this function will produce a mean of $1PE$ at a slant distance of $28m$. The function is for head on illumination, and the angular distribution must be inserted. I use

$F(\psi) = A_0(0.525cos(\psi) + 0.475)$

for the Hamamatsu PMT, and

$F(\psi) = A_0(0.546cos(\psi) + 0.606)$,

for $cos(\psi)$ between -0.9 and 0.75, 0.0 for $Cos(\psi) < -0.9$, and A_0 otherwise, for the Philips PMT. The types of PMTs are taken to be alternating on the strings, and all PMTs taken to be face downwards. I believe that these are exactly the same functions as used by Vic Stenger, and documented in his notes about his Monte Carlo program. (The attentuation function is a result of a calculation I did years ago, updated in May 1988 for new input data. See HDC-81-10 for details.)

The cascade simulation is simplified, employing the point source approximation presented by Art Roberts in the 1978 DUMAND Workshop, 1, 103 (1978). Events are generated throughout a cylindrical volume, extending either side of the reference disk, as decribed above. For the preliminary calculations presented herein I used a disk of radius $150m$, and the cylinder was $305m$ long. It is evident (see Figure 16) that above 10 GeV we have significant contribution from events outside the array.

Noise is inserted at a rate of 60,000 hits per second in each module, in a time window of $1\mu sec$ centered on the event mean time.

Appendix B Calculation of Minimum Number of Hits

An interesting question is: what is the actual limitation on the smallest size of coincidences caused by muon-like events in the array which can be extracted from noise? Forget for the moment whether such events can be fitted. The idea is that there is some space in which these events are as tight as possible, and in which the random coincidences will be minimal. This is a sort of phase space approach.

Imagine that we continuously plot all events on a direction plot, with a number of cells equal to the best resolution we can achieve. This might be $N_D = 10^4$ for one degree resolution. Imagine also that we divide each direction into as many impact points as we have temporal resolution to support, again say $N_P = 10^4$ (about $2m^2$ grid). A through going muon would illuminate typically $l = 20$ modules, though hitting a mean of about $k = 12$ (though this is what we shall solve for soon).

For this trial track (with chosen direction and impact point) we can thus predict the relative time of arrival of photons at all modules to within the variation of geometry and the time resolution of the system. Suppose then that we ask the question every $2ns$ as to whether or not there is a coincidence of module signals amongst the 20 candidate modules along the trial track. The rate of random coincidences will then be given by the number of trials per second times the probablility of a coincidence of that level:

$R_k = (N_D N_P/\tau_m) m^k/k!$,

where the latter term is approximately the Poisson probability of getting k coincidences when m are expected, when $m << 1$. The expected number $m = l R_m \tau_m = 0.0024$ for the stated conditions. So while the number of trials is vast, the probability drops fast with increasing k, such that for a value of $k = 8$ the rate is a negligible once in 23 years! The value of $2ns$ may be overly optimistic, but even so, if it were as bad as $8ns$ we find a rate of only once per 1.4 years for $k = 9$.

I thus conclude that we could do identify physics events solely on the basis of phase space, with a negligible background from random coincidences if the coincidence threshold is as low as 8 or 9 modules. Moreover, this is conservative since the question we have asked has to do with the topology expected of muons, and we can apply pulse height criteria on top of the space-time fit. Without further consideration we can also state that we should be able to employ muon fits down to the level of about 7 hits (with expected random rate of $4 \times 10^5/year$), if we accept an increase in the background due to cosmic ray muons.

It seems to me that this is telling us that we could in principle accept triggers down to the level of about 12 noise hits plus 6 real muon hits, and that an ideal fitter could extract the signals from noise. Based upon the previous discussion of the gross coincidence rate in a coarse time window of $1\mu sec$, we see that a simple trigger will not come close to this ideal goal. On the other hand, the $T3$ does get events down at this level, so this tells us it is being fairly efficient at getting out the maximum amount of physics.

Appendix C Random Rate of 2 and 3 Fold Neighbor Triggers

First consider the rate of neighbor coincidences. The coincidence time window, in order to accept all trajectories, must be at least the flight time of photons in water travelling from one module to the next. If the module spacing is $D_m = 10m$, the speed of light c, and the index of refraction in seawater $n_w = 1.35 \approx 4/3$, then:

$\tau_2 \;=\; \times n_w \times D_m/c \approx 45ns.$

If the number of modules per string is $N_m = 24$, the number of strings $N_s = 9$, the individual module noise rate $R_m = 60,000/sec$ [9], then the total array rate of random pair coincidences will be:

$R_2 = (N_m - 1) \times (N_s) \times 2 \times R_m^2 \times \tau_2 \approx 67,000/sec.$

The random rate for three neighbor concidences is just the triple coincidence rate times the number of combinations:

$R_3 = (N_m - 2) \times (N_s) \times 3 \times R_m^3 \times \tau_3^2,$

where $\tau_3 =$ the coincidence window for triple neighbor coincidences, This is equal to the flight time for a photons in water to traverse the distance between the farthest modules, $20m$, or about $90ns$. The random rate for triples anywhere in the array is then about,

$R_3 = 1040/sec,$

which is still not tolerable, particularly since this could become $5,000/sec$, if the module noise rate turns out to be $100,000/sec$.

It was for this reason that the difference of differences trigger was developed. The question to be addressed here is what is the expected noise rate with this cut. We approach this in two steps. First consider the requirement of as close a neighbor pair coincidence as possible.

We get a factor of six right away by requiring the window to be half and the reduced combinatorics: every time there is a hit in a potential center member of a triple we ask the question of whether there was a neighbor coincidence in a time + or − τ_2 about that event. We can do better, however, since if the signal is early on one side, it must be late on the other, so we can gain another factor of two. You can picture the hits about the center module time as uniformaly populating a square region in a scatter plot of one neighbor's time difference versus the other, as seen in Figure 4 for muons, and Figure 13 for cascades. The requirement of one being early while the other is late cuts the square on the diagonal. The further requirement of the time difference being less than some value (which we determioned from the Monte Carlo to be about 15 ns without losing many events), then we are further restricting the area of the plane to a parallelogram of base $\Delta = 15ns$ and height $2\tau_2$, but less a triangular region of area $\Delta^2/2$. The resulting rate is then given by:

$R_3' = (N_m - 2) \times N_s \times R_m^3 \times \Delta \times (2\tau_2 - \Delta/2) \approx 50/sec,$

[9] We take all modules to be equal in noise rate. With some trouble one may show that for a large number of modules it works well enough to take the mean noise rate for such coincidence calculations. This has been experimentally verified in the IMB detector in 1983.

for a net gain of a factor of 20 over the simple triple coincidence R_3.

Figure 1: Number of muon caused hits in fittable events

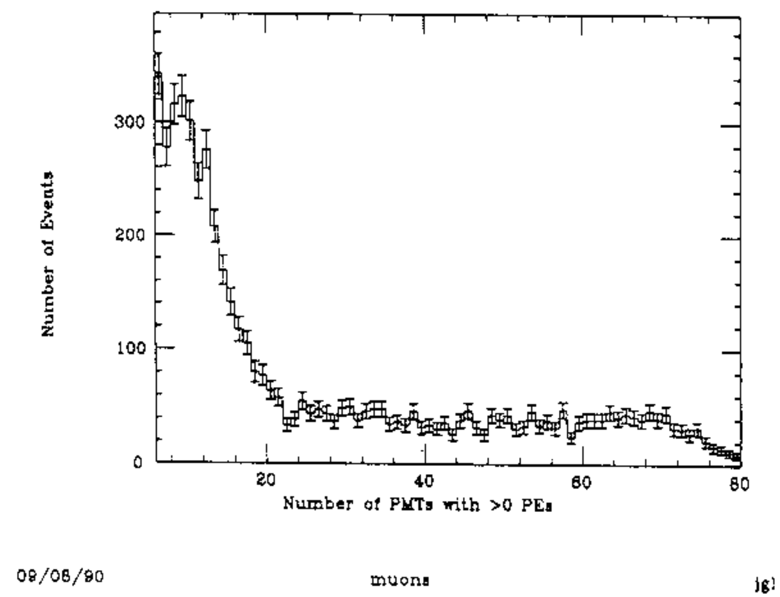


Figure 2: Muon caused PEs in fittable events.

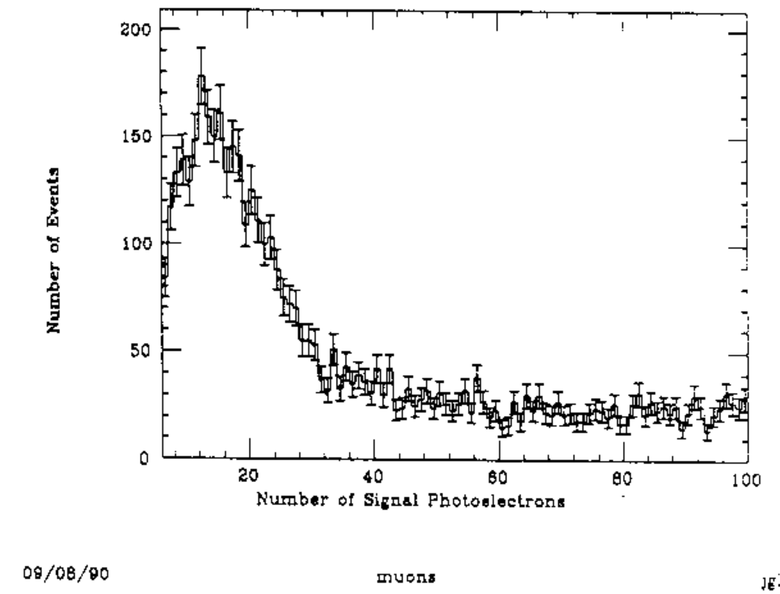


Figure 3: Pair time differences versus zenith angle.

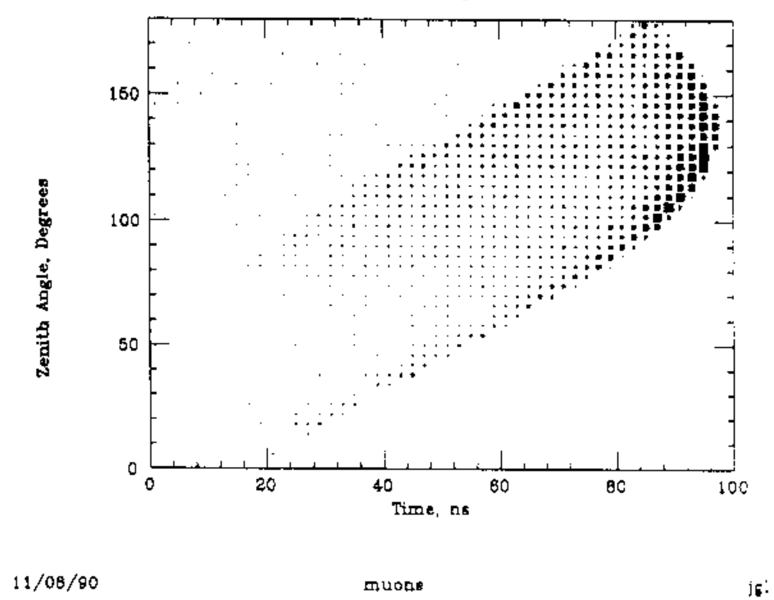


Figure 4: Neighbor pair time differences.

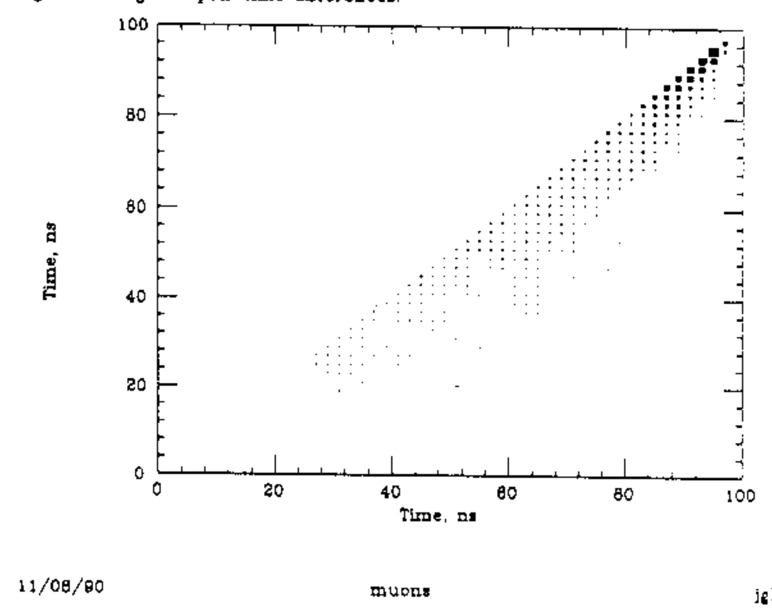
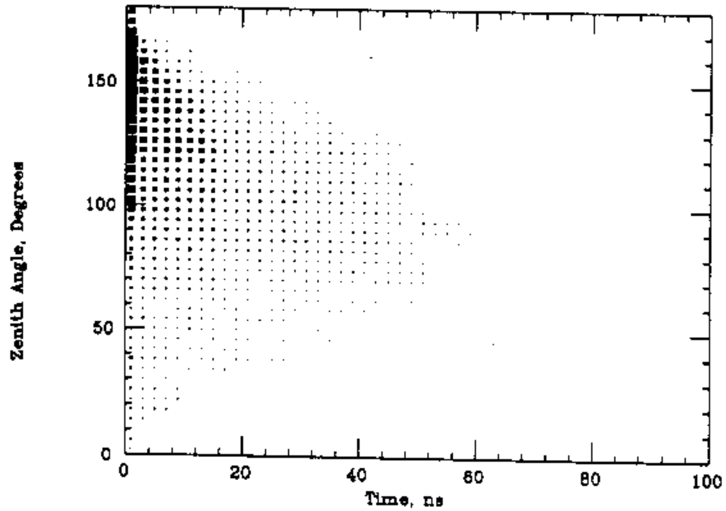
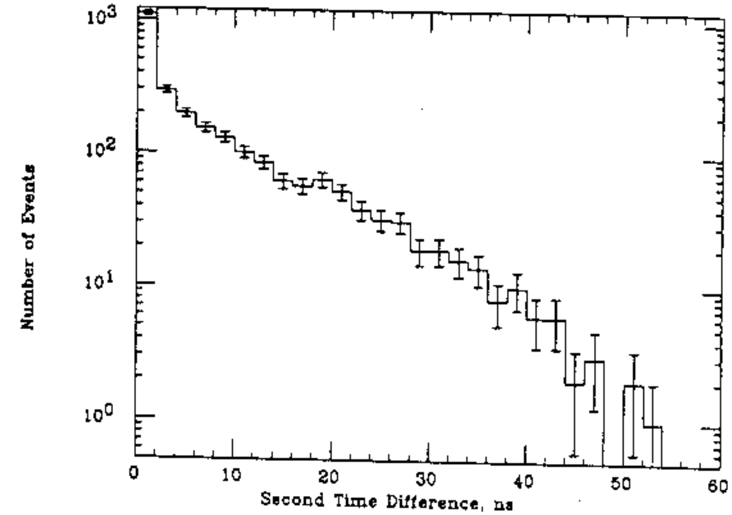


Figure 5: Second time difference versus zenith angle.



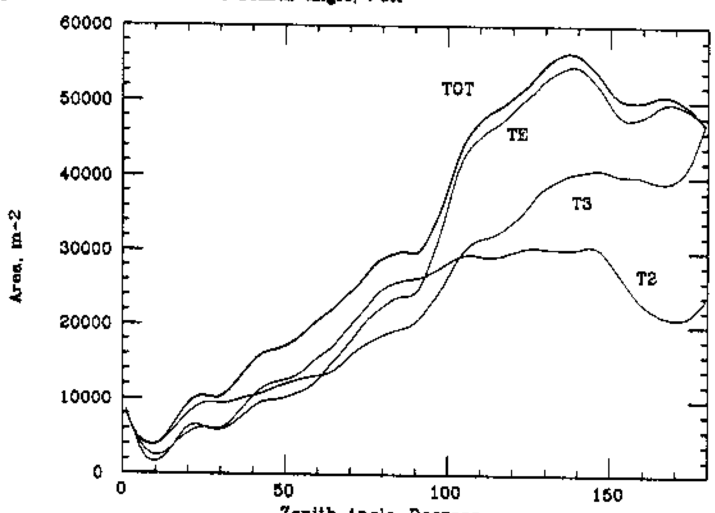
11/08/90 muons jgl

Figure 6: Smallest second time difference per event.



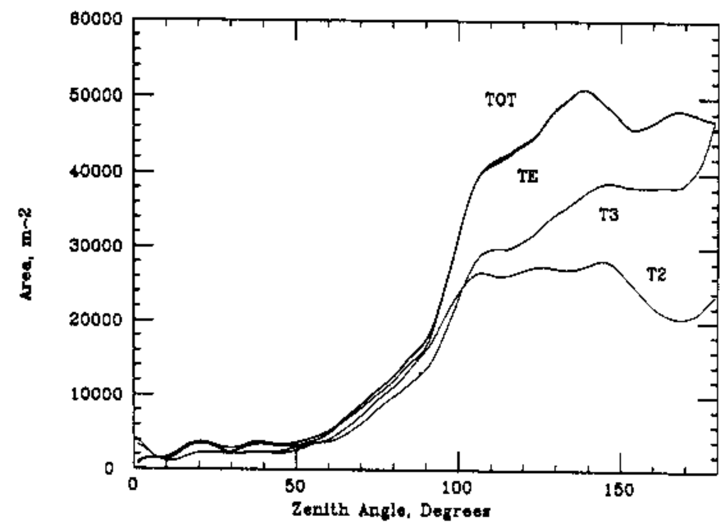
09/08/90 muons jgl

Figure 7: Effective area vs zenith angle, >5H



09/08/90 muons jgl

Figure 8: Effective area vs zenith angle, >11H, >2S.



11/08/90 muons jgl

Figure 9: Photoelectrons versus slant distance.

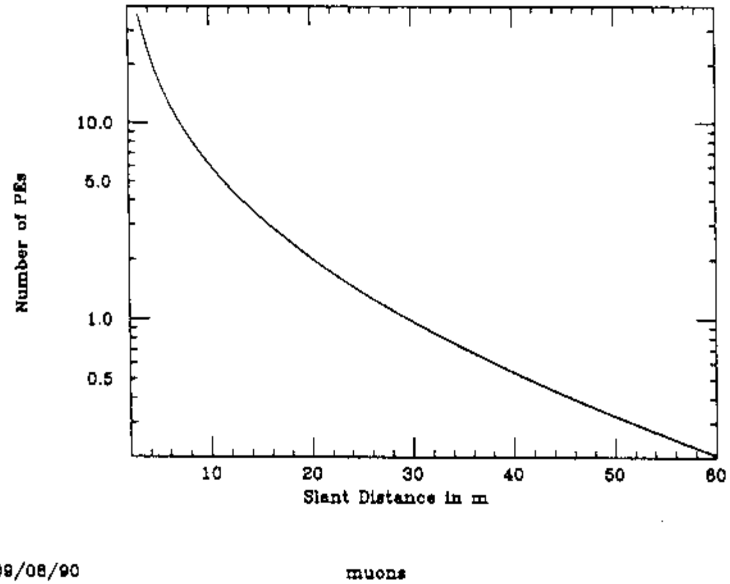


Figure 10: Number of cascade caused hits in fittable eve

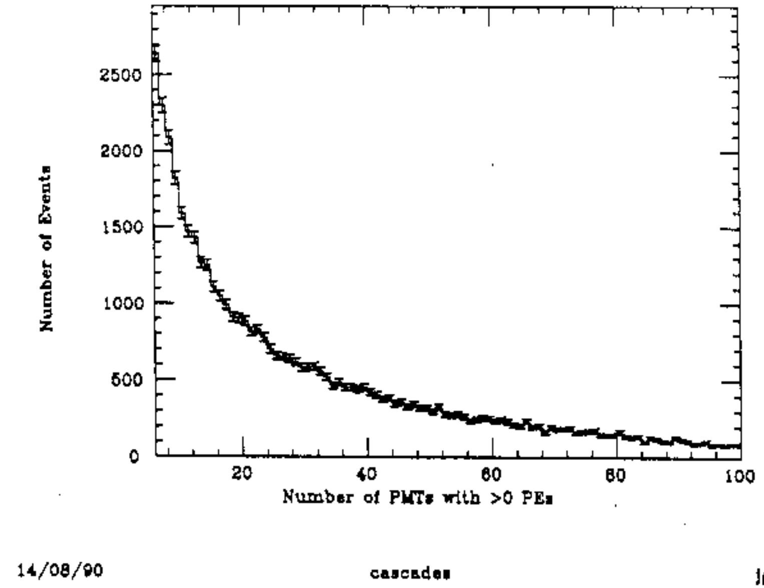


Figure 11: Cascade caused PEs in fittable events.

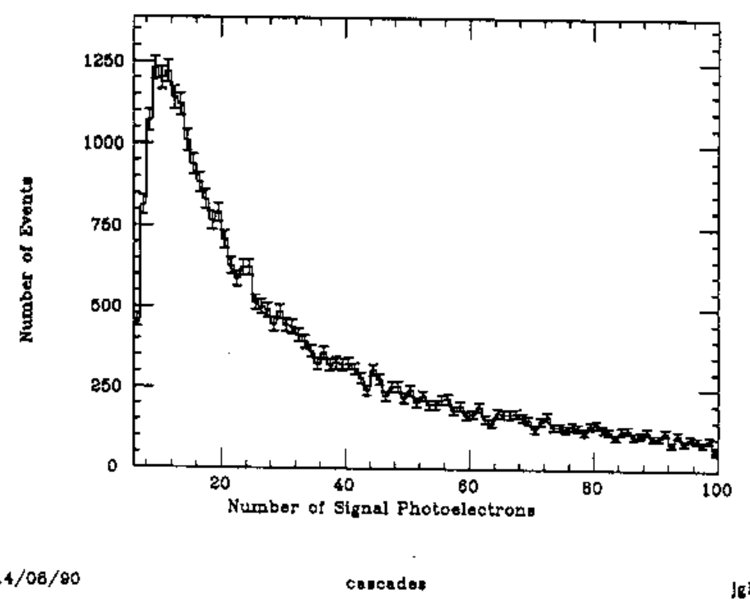


Figure 12: Pair time diffs versus zenith angle.

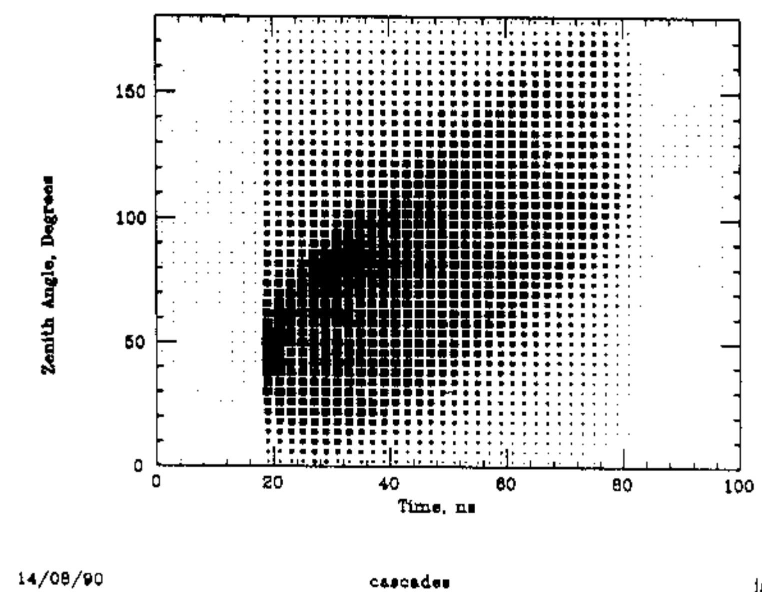
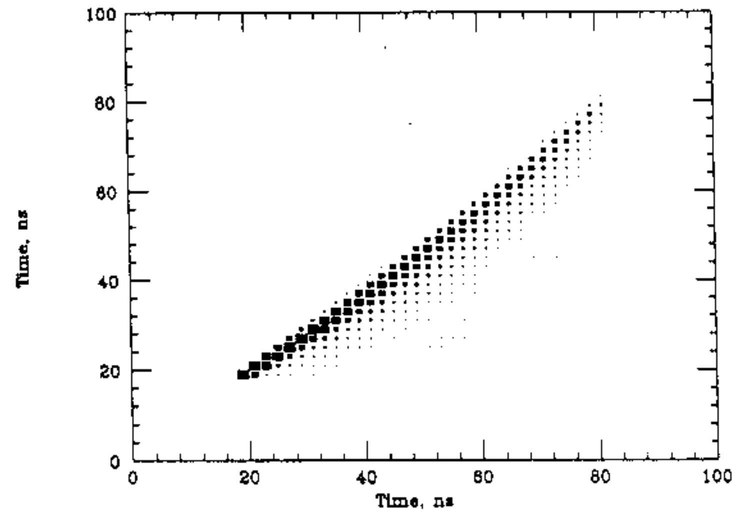
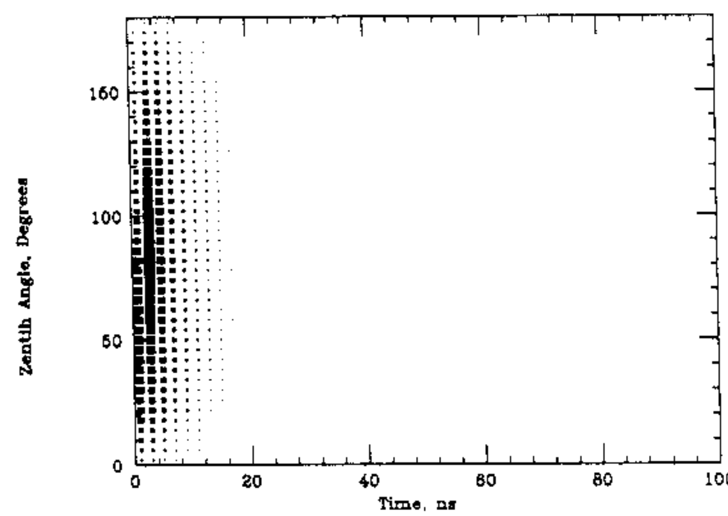


Figure 13: Neighbor pair time differences.



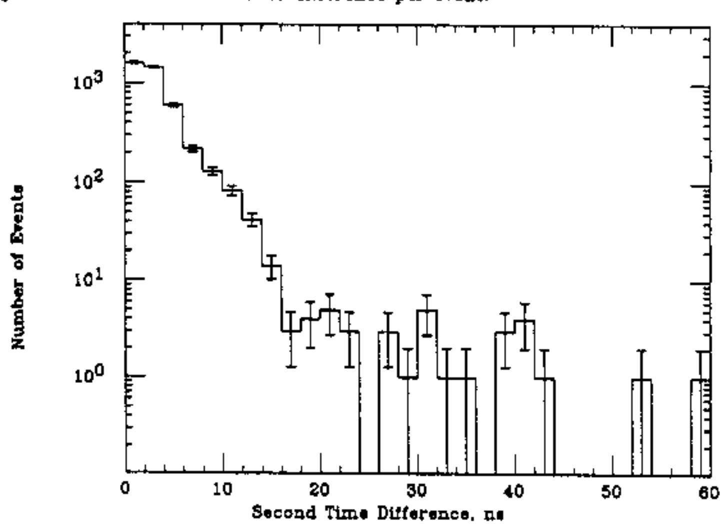
14/08/90 cascades jgl

Figure 14: Second time difference versus zentih angle



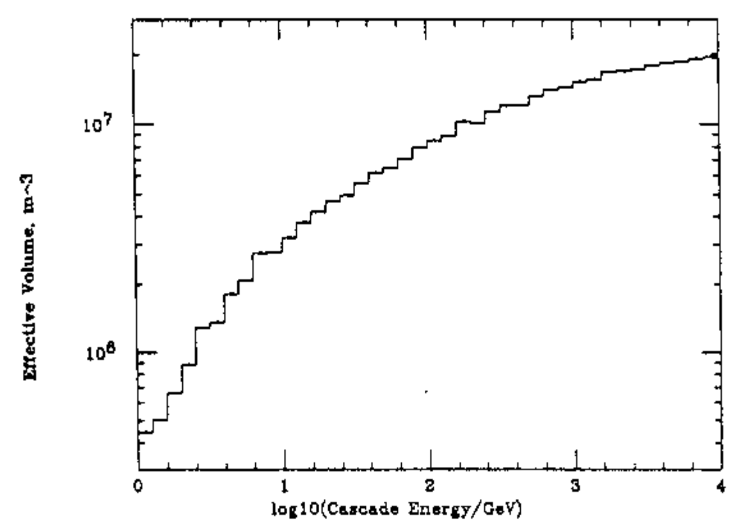
14/08/90 cascades jgl

Figure 15: Smallest second time difference per event.



14/08/90 cascades jgl

Figure 16: Effective volume versus cascade energy.



14/08/90 cascades jgl

Figure 17: PEs vs angle, 10 Gev cascade at 20m face on.

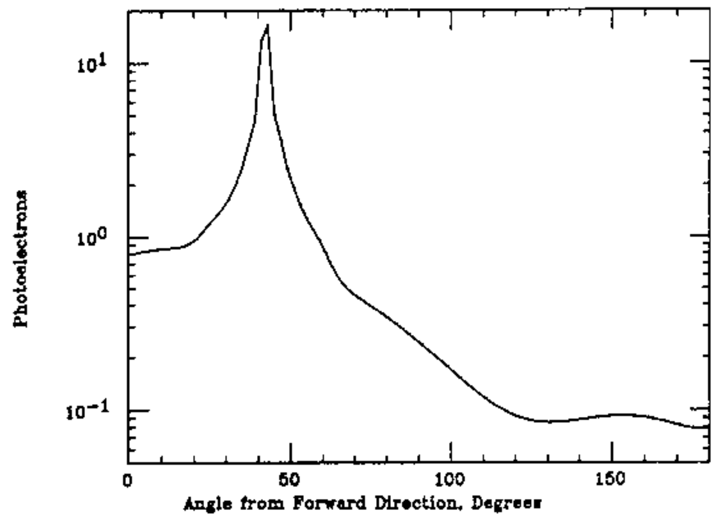


Figure 18: Trigger codes: 1=fittable, 2=T2, 4=T3, 8=TE