HDC 81-14

HDC 81-14A

HDC 81-15

DUMAND - Deep Underwater Muon and Neutrino Detector

J. G. LEARNED AND A. ROBERTS

REQUIREMENTS FOR PHOTOMULTIPLIERS FOR DUMAND

A. ROBERTS

DUMAND SIGNAL PROCESSING

A FAST EVENT-ANALYZING ALGORITHM AND ITS EFFECT ON ALLOWABLE SENSOR RATES AND PMT DESIGN.

DEC. 1981

Hawaii DUMAND Center
University of Hawaii
2505 Correa Rd.
Honolulu, HI. 96822

HDC 81-14

Nov 1981

REQUIREMENTS FOR PHOTOMULTIPLIERS FOR DUMAND.

J. G. Learned and A. Roberts
Hawaii DUMAND Center, Honolulu, HI.

ABSTRACT

We discuss the way in which the requirements of the DUMAND array affect the characteristics and design of the photomultipliers required. The size, sensitivity, background requirements, lifetime and other characteristics are considered. A summary describes the requirements concisely.

This paper lists and discusses the requirements for the PMT's needed for the DUMAND detector, as we now understand them. Some of these have already been discussed in some detail[1]. The requirements are sufficiently unusual to require a special PMT; the number of tubes required (1000 or more) is sufficient to warrant the design of a new type. This paper should not be regarded as a formal specification; it is intended as a general guide for PMT manufacturers interested in DUMAND.

It should be noted that there is at present no guarantee that the DUMAND detector will be constructed.

1.0 INTRODUCTION

The primary requirement for the DUMAND PMT is very high sensitivity. The DUMAND array is a lattice of PMT's designed to detect neutrino interactions. The larger the array, the more sensitive the experiment. It is consequently desirable to have as many detectors as one can afford, and to space them as widely as possible. The achievable lattice spacing depends upon the transparency of the ocean to Cerenkov light produced by the neutrino interactions, and also upon the sensitivity of the individual PMT sensors. It is accordingly highly desirable for the PMT's to be large, and as sensitive as possible. We have adopted as a measure of PMT sensitivity the number of photoelectrons delivered to the first dynode when the cathode is illuminated by a light flux of 100 quanta/m^2.

2.0 PHYSICAL CHARACTERISTICS.

The PMT is to be used at great depths in the ocean - up to 6 km - and must consequently be protected against hydrostatic pressure to about 600 atmospheres. This may be achieved either by a pressure-tolerant envelope or the use of an external pressure-tolerant transparent protective envelope. At this pressure only glass or ceramics are satisfactory; plastics creep. The largest presently available glass pressure container is a 17" O.D. (16"I.D.) Benthos[2] sphere, consisting of two hemispheres that seal together to form the envelope. Unless an economical source for larger spheres can be found, this limits the largest PMT that can be used to an O.D. of 16 inches.

A hemispherical cathode 16" in diameter has a radius 20.3 cm. Allowing a 3mm glass wall, we find an effective cross-section area perpendicular to the polar axis of $\pi\times20^2$ cm^2 or 1256 cm^2. The response to a photon flux of 100 quanta/m^2 is then

$$N_e = .1256 \times 100 \times \varepsilon$$

where

N_e is the number of photoelectrons produced, and
ε is the average cathode efficiency, including collection efficiency.

At ε=.25, N_e = 3.14; and at ε=.20, N_e = 2.5. Computer simulations of DUMAND calculations have indicated that N_e = 2.5 is a satisfactory sensitivity, if we require a minimum of two electrons for a trigger, and 3.0 if a 3-electron trigger is used. A minimum of 2.5 is thus required, and implies a phototube of about 16" diameter.

The spectrum of light incident on the PMT from the source is that of Cerenkov light, as modified by absorption in the ocean. Fig. 1 (from Ref. 4) shows a plot of that spectrum, which quickly narrows down to the range 400-520 nm. Consequently, for low noise and high sensitivity, the choice of a bialkali cathode is indicated.

2.1 Uniformity of Cathode: Isotropy.

One function of the PMT is to distinguish small signals in the presence of noise. The PMT will be subject to continuous random background light, almost all at the single-quantum level; we need to distinguish events with two photoelectrons from the background of single-electron noise. The signals we seek will produce larger pulses as well; but we have no requirement for good uniformity of pulse height (as e.g. for gamma-ray spectrometry). Thus DUMAND has no special requirement for cathode uniformity of response; the requirement will be for high average sensitivity.

Ideally it would be desirable to have the PMT sensitivity independent of the direction of the incoming light. For a hemispherical tube, one expects the sensitivity to vary as a function of polar angle with the PMT axis. It would reach a maximum at $\theta=0^o$, along the PMT axis, and about half as much at 90^o. As shown in Fig. 2, if the envelope is transparent, appreciable sensitivity over the total solid angle should be present. For DUMAND purposes the variation over all angles should not exceed a factor of two. Other geometries (a spherical photomultiplier or a cylindirical photomultiplier) may be acceptable, but as of now, a hemispherical-cathode tube seems most practical, and should yield acceptable angular sensitivity variation.

3.0 TYPES OF PMT BACKGROUND.

The DUMAND PMT presents a unique design problem. We want to trigger on infrequent, very short (ns), signals from a weak, diffuse light source; the signals may produce a total of 250 individual sensor triggers per second, comprising perhaps 25-50 events. These must be detected in the presence of a background that includes three major components, all much stronger than the signal: PMT noise, Cerenkov light from natural radioactivity in the ocean, and occasional interference from bioluminescent organisms. We consider these in turn, though not in the same order.

3.1 Bioluminescence.

The light from bioluminescent organisms is not expected to be a serious background, even though few measurements of it at the relevant depths or location exist. In the first place, few organisms of any sort are expected, because of the absence of any plant life in the eternal darkness of the depths. Available food includes the resident lifeforms, and the detritus that falls from above; and the major life forms resident at these depth are expected to include one-celled biota, and worms that live in the sediment. However, occasional visitors from lesser depths can be expected, especially if there are flashing lights, sheltering structures, and sources of heat.

The time scale of bioluminescent flashes from large organisms is such that flashes have risetimes of many milliseconds. The shortest risetime we have heard quoted is about 50 microseconds for bacterial colonies. These are all too long to be confused with the nanosecond Cerenkov signals. The intensities may be high enough to temporarily jam nearby sensors; but the frequencies of such events are not so great as to give serious alarm.

3.2 PMT Noise.

It is to be expected that PMT noise will consist of a spectrum of pulse heights, of which the greater part will be single electrons from thermionic emission by the photocathode. In bialkali cathodes at the ambient temperature expected - 0^{o} C. - a good bialkali cathode will have a thermionic emission rate of not over 10 electrons/cm^2 sec. As we will see, this is considerably lower than the rate produced by the external K^{40} signal.

Another component of tube noise consists of delayed large pulses due to positive ions produced by the accelerated photoelectrons, either in the residual gas, from the first dynode, or from the electron multiplier. These will be accelerated in the opposite direction and strike the cathode. On the average a positive ion will produce several photoelectrons[3], and thus the PMT will exhibit the phenomenon of afterpulsing; the presence of large pulses delayed a few microseconds from an initiating signal. It is not clear whether all large pulses arise in this way, but certainly a large fraction do. Such afterpulses of large size will prove to be critical in the performance of PMT phototubes for DUMAND.

3.3 Background light from K^{40} in the Ocean.

Of the many radioactivities present in ocean water, the only one of serious concern to DUMAND is that due to the potassium content; all potassium on earth contains a small amount of the isotope K^{40}, which has a lifetime of something under a billion years. It concerns us because it is a potent beta-emitter, its electrons producing in seawater, on the average, 43 Cerenkov quanta between 300 and 650 nm per disintegration. Consequently the ocean is everywhere a weak light-source, and it can be shown[4] that if the ocean transparency is such that the attenuation length for light at the wavelength of peak transparency is 25 meters -i.e. 25m water - a flux of about 120 quanta/sec cm^2 is present. At a mean cathode efficiency of 20%, this will produce a background rate of 24 photoelectrons/sec cm^2 from the photocathode. Since most decays are far away, the probability of two photons from the same disintegration striking the photocathode is small, and the background will consist mostly of single photoelectrons; there will be, however, a small but significant number of true two- or more electron counts from the K^{40}.[5]

The sum of tube noise and K^{40} background will be a net single-electron background rate of about 30-40/sec cm^2. Since a 16" hemispherical cathode has an area of 2610 cm^2, the expected single-electron background rate will be around 100K/sec. In addition, the large afterpulse rate will be 1/2 to a few percent of this amount, if we extrapolate from the behavior of present tubes, or 500-2500 counts per second.

4.0 REDUCTION OF PMT BACKGROUND.

The weak diffuse Cerenkov light produced by muons or neutrinos must be detected in the presence of the backgrounds just discussed. For that purpose we must first set a threshold signal of at least two photoelectrons reaching the first dynode, or the K^{40} background will swamp us. Our arrays have been designed to date on the assumption of a two-electron trigger. If the threshold were three photoelectrons, the array spacing might have to be decreased.

Elimination of the single-electron background is in itself not necessarily the complete answer to our problem. The residual rate of large pulses, due to the tail of internal tube noise, estimated above at several thousand per second, is also a serious difficulty.

4.1 Required Degree of Background Reduction.

The obvious and simplest mode of generating an array-wide event trigger is as follows: open a gate, whose duration is the transit time through the array, whenever a suitable sensor trigger is received, and declare an event trigger if within the gate time the proper number of sensor triggers is received. For a 500m array, the maximum transit time for a muon is of the order of two microseconds. An acceptable tentative event trigger may therefore be defined as at least k sensor triggers within 2 microseconds. The number k and the threshold for sensor triggering will have to be adjusted to keep the gate rate G at a tolerable level. Computer simulations indicate a desirable value of k=3.

4.2 Elimination of Single-Electron Background.

The usual method of discriminating against small background pulses is the use of pulse-height discrimination at the PMT output. With conventional dynodes the separation between 1, 2, 3..etc. photoelectrons is imperfect; Wright[6] estimates that 30% of the single-electron counts remain if the discriminator is set to accept all two-electron pulses. It would be hopeless to try uniquely to select two-electron pulses from a strong one-electron background. The problem can be much ameliorated - even solved, in principle - if a sufficiently high-gain first dynode is used. Existing tubes with high-gain first dynodes[7] provide much improved discrimination between one- and two-electron signals. Unfortunately, with the very high background we have, this procedure does not appear practical for us, especially in view of the fact that manufacturers tell us that high-gain first dynodes are difficult and expensive to produce in tubes with large dynode apertures. We therefore seek another method to reduce the single-electron background by the required factor of 100 to 1000, while losing as little as possible in sensitivity.

The light signals we detect are due to diffuse light, and consequently the photons that strike the PMT are uniformly and randomly distributed over the cross-section presented to the incident beam by the cathode. If we require two photoelectrons for a trigger, they will originate from uncorrelated and separate locations on the tube face.

4.2.1 Segmentation of multiplier structure and anode.

Another potential method of eliminating the single-electron background is through segmentation of the multiplier structure and the anode. If the multiplier consists of m separate segments, each isolated from all others so that the multiplication of any photoelectron is confined to a single segment, then separate anodes on each segment will contain signals from independent electrons. A single-electron initiating signal will produce only one output anode signal; two independent simultaneous input electrons in different segments will produce two simultaneous output signals. Signals due to two initial electrons can then be recognized by requiring a coincidence between any two output anodes. If there are m segments, there will be a loss of 1/m of the true event rate by the accidental coincidence of the two initiating electrons in the same segment. Depending on the geometry of the dynodes, there may also be some loss due to crossover from one segment to another. Leakage between segments is tolerable to the extent that it does not unduly increase the random coincidence rate between segments.

The required multiplier property, of segregating each cascade to a single segment, we will refer to as confinement. This procedure is of course particularly applicable to micro-channel plate (MCP) multiplier structures. For traditional tubes it may mean multiple dynode stacks, or conceivably, one dynode stack with a segmented anode.

4.2.2 Calculation of Single-Electron Background.

If the total single electron counting rate is R, and the resolving time for coincidences between segments is τ,, then the rate R_c of random coincidences between any two segments will be

$$R_c = m(m-1)/2 \times 2(R/m)^2\tau$$

$$= (m-1)/m \times R^2\tau$$

which is almost independent of m for large m. For the value $R = 1.0 \times 10^5$/sec, $\tau = 10^{-8}$sec, the random coincidence rate is

$$R_c = (m-1)/m \times 100/\text{sec}.$$

Without segmentation, the background rate would be tens of thousands per second.

4.3 True two-fold triggers from K^{40}.

Those K^{40} disintegrations that occur very close to the photocathode can occasionally produce true coincidences of two or more electrons. Their number has been calculated[5] in DUMAND Note 81-19, and for the 16" PMT is in the vicinity of 120/sec, just under 10^{-3} of the singles rate. We will reconsider this quantity when we consider background reduction.

4.4 Background Summary.

The contributing components of the background will be

1. True twofolds from K^{40}.
2. Random background from single K^{40} counts; reduced by coincidences if segmentation is used, by pulse-height discrimination alone if it is not.
3. Large background pulses occurring in more than one segment.

Our present estimates for Nos. 1 and 2 are respectively 120/sec and 100/sec, assuming segmentation. The third depends too much upon tube design to estimate. It must obviously be minimized.

5.0 TIMING ACCURACY.

Uniformity of collection time over the entire photocathode is clearly desirable; minimizing time jitter will decrease the resolving time for eliminating random twofold coincidences between segments, and will improve true event reconstruction accuracy. On the basis of computer simulations, we set a maximum FWHM on the output pulse in the vicinity of 10 nsec. Experience indicates that this is an achievable resolution at the single-photoelectron level.

6.0 LIFETIME AND GAIN.

It is desirable that the DUMAND array operate for ten years without the failure of more than 10% of the sensors. This requires a mean lifetime of 100 years for the PMT's. This requirement is unprecedented; it is difficult to measure or predict lifetimes in this range.

There is no obvious reason why most PMT's, properly treated, should not last indefinitely, following an initial burn-in of several hundred hours. Experience at Fermilab, CERN, and elsewhere indicates that conventional PMT's, so treated, do indeed have lives of the required order. However, experience to date with MCP's in PMT's has been that lifetime has been limited. Recent work seems to indicate that this can be ameliorated - perhaps even eliminated - by covering the MCP with a thin coat of aluminum[8]; this seems to eliminate the positive ion bombardment of the cathode that shortens its life.

MCP plates also seem to have a lifetime defined by the total charge transmitted by the plate. When this reaches values of the order one coulomb/cm^2, significant gain losses are observed. It seems possible that the gain can be restored by raising the voltage, and since we have no absolute signal requirements, this procedure would be acceptable. Reducing the overall gain demanded from the MCP would also increase the lifetime. It is to be hoped that some combination of such procedures will achieve the desired longevity.

7.0 SUMMARY.

We summarize the required properties of the DUMAND PMT as follows:

1. Size: Approximately hemispherical photocathode to fit inside 16" I.D. glass sphere.

2. Spectral sensitivity: Bialkali cathode or equivalent, with uniform and high sensitivity in the range 400 - 500nm.

3. Sensitivity: the average number of photoelectrons reaching the first dynode when the cathode is uniformly illuminated (wide beam) along the axis by a flux of 100 quanta/m^2 should be at least 2.5, preferably 3.

4. Uniformity of cathode sensitivity: not critical. Average cathode quantum efficiency (including collection efficiency) from 400 nm to 520 nm at least 20%.

5. Angular variation of sensitivity. There should be no gaps in angular coverage; it is desirable that the ratio of maximum to minimum response not exceed 2 (see Fig. 2). If the tube is of the hemispherical type it should not be silvered on the back hemisphere.

6. Tube noise: not to exceed 10 electron/sec cm^2 of cathode, at 0^oC. Large pulse (>1 photoelectron) signal-induced background to be minimized: preferably not over 1% of total counting rate.

7. Means must be found to decrease the single-photoelectron rate by a factor of 100 to 1000. Possible methods include pulse-height discrimination, with a high-gain first dynode, and/or segmentation. In the latter case a segmented anode is required with 6 to 15 segments. If parallel dynode structures are used, or a single dynode structure with segmented anodes, crossover between segments must be minimized. An MCP multiplier would satisfy this requirement ideally, provided it meets the other requirements.

8. The transit time of electrons through the PMT must be such that single photoelectron pulses shall have an output FWHM time jitter not to exceed 10-12 nsec. Tails of the time distribution should be minimized.

9. The lifetime of the tube under the specified operating conditions should be about 100 years; methods for specifying and measuring lifetime need to be agreed upon. The tube will be operated in an environment of 150-200 photons/cm^2 sec continuously.

10. The overall gain of the PMT under conditions satisfying requirement 6 shall be at least 10^6. A gain of 10^8 is desirable, since then no amplifier would be needed.

11. Magnetic Field Sensitivity. The tube must operate with no magnetic shielding whatever, in the earth's magnetic field. Variation of sensitivity with orientation will be unavoidable.

12. Output linearity is not important. In fact, for large pulses (> about 5 electrons) a logarithmic response would be desirable.

REFERENCES.

1. A. Roberts, DUMAND 78, Vol. 1, p. 139.

2. Model 2040-17, Benthos, Inc., North Falmouth, Mass. 02556.p33810

3. G.A.Morton, H.M.Smith, R.Wasserman, IEEE Transactions Nucl. Sci. NS-14, p. 443 (1967).

4. J.G.Learned, DUMAND Internal Note 81-17, Oct. 1981; ibid., DUMAND Internal Note 81-10, Apr 1981.

5. A. Roberts, DUMAND Internal Note 81-20, Nov 1981.

6. A.G.Wright, DUMAND 1980 1, p. 76.

7. B. Leskovar and C.C.Lo, IEEE Trans. Nucl. Sci. NS-19, p. 50 (1972); C.C.Lo and B. Leskovar, ibid. 1981 (to be published).

8. K.Oba, M.Sugiyama, Y.Suzuji, Y.Yoshimura, IEEE Trans. Nucl. Sci. NS-26, p. 346 (1979).

Addendum to HDC 81-14.

Since this report was written, HDC 81-15 has appeared. That report modifies some of the conclusions of the present paper, and the following supplement indicates how the conclusions of 81-14 should be changed.

1.0 Allowable Background Rate.

The major problem in DUMAND PMT design is getting rid of the K^{40} background. In this report, 81-14, we saw no feasible way of accomplishing that, aside from segmentation of the multiplier structure. In 81-15, it is shown that by raising the trigger threshold to three photoelectrons and using a high-gain first dynode, with uniformly high collection efficiency, the K^{40} background can perhaps be reduced to manageable proportions. While this is not an easy task to accomplish, it offers at least in principle an alternative to segmentation.

Raising the trigger threshold is not desirable; it reduces the effective sensitivity of the PMT and requires the array to have closer spacing than would otherwise be necessary. Investigation of that effect shows it to be tolerable. Fig. 5 of report 81-15 indicates the degree of contraction required: from a spacing of 50 x 50 x 22.7m to 45 x 45 x 17.5m.

The requirement for low noise can perhaps best be stated as follows: When operated in the ocean, where the expected K^{40} counting rate of single photoelectrons is expected to be about 10^5/sec, it must be feasible to reduce the total residual noise plus signal counting rate to ~1000/sec, by either setting the pulse-height discrimination threshold no higher than at three photoelectrons, or by segmentation and coincidence background reduction.

HDC 81-15: Fast Event-Analyzing Algorithm.

DUMAND SIGNAL PROCESSING
A Fast Event-Analyzing Algorithm and Its Effect on Allowable Sensor Rates and PMT Design.

A. Roberts, Hawaii DUMAND Center

ABSTRACT

A new event-filtering algorithm is proposed, requiring only a few microseconds, and capable of discarding about 99.9% of spurious event triggers. It passes the remainder to track-finding algorithms (as yet undefined) that may require milliseconds for track recognition. Such an event filter will allow a random individual sensor trigger rate approximately ten times higher than would otherwise be possible. It thus significantly eases the requirements on PMT background rates, and may make it possible to avoid segmentation of the PMT electron multiplier structure.

1.0 Required Degree of Background Reduction.

We wish to investigate the rate at which array-wide event triggers are produced by random counts in the individual sensors. This rate, and the speed with which the spurious gates can be rejected, will together determine the allowable sensor noise rates, and will therefore affect the requirements of the sensor PMT's.

The obvious and simplest mode of generating an array-wide event trigger is as follows: open a gate, whose duration is the maximum particle transit time through the array, whenever a suitable sensor trigger is received, and declare an event trigger if within the gate the proper number of sensor triggers k is received. For a 500m array, the maximum transit time for a muon is of the order of two microseconds. An acceptable tentative event trigger may therefore be defined as at least k sensor triggers within 2 microseconds. The number k and the threshold for sensor triggering will have to be adjusted to keep the gate rate G at a tolerable level. Computer simulations indicate a desirable value of k=3.

1.1 Notation.

Let R = individual sensor counting rate, however arrived at.

R_j = individual sensor counting rate when the sensor threshold is set for a minimum of j photoelectrons arriving at the first dynode.

M = number of sensors in the array (nominally 756),

t = duration of an event gate designed to find muon tracks in the array,

G_k = rate at which event gates are observed when the criterion for an event gate is the occurrence of k sensor signals within the time t,

$P(p,k-1)$ = probability, in a Poisson distribution whose mean is p, of finding k-1 or more events.

The relation among these quantities is

$$G_k = MR \times P(MRt,k-1)$$

As R increases, so does MRt, and for MRt>>1, P(MRt,k-1) approaches unity. Then G_k approaches the limiting rate MR.

2.0 Allowable Event Gate Rate.

We now ask what is the individual sensor trigger rate R that will produce an acceptably small spurious event trigger rate. That rate is defined by the equation for G_k given above, and the relation is plotted in Figure 1. A gate rate G_k is acceptable if it allows on-line analysis and rejection if the event is spurious - i.e., due to random noise coincidences.

Figure 1 shows, for t = 2 μsec, the relation between R, the individual sensor rate, and G_k, for k = 3 and 4. We assume that the array has 756 sensors, as presently planned.

What is the largest allowable G_k? If we carry out a complete track reconstruction it will probably take some milliseconds. We would like an algorithm in the microsecond range, since we want to handle as large a gate rate G_k as possible, and thus allow as high a sensor noise rate as possible. As we will see later, reducing the sensor noise rate is a major problem in PMT design.

We now describe a fast event-testing algorithm.

2.1 Fast Trigger Algorithm

Suppose we set up an array in memory with M x M elements*, where M is the number of sensors in the array (presently 756). The elements of the array contain the time difference between the sensors represented by the indices I and J - defined as the distance between them divided by c; a 16-bit word is thus more than adequate as an array element. If the interval between the two sensor counts is not equal to this quantity, plus or minus a quantity Δt, which we will see is of order 50-100 nsec (to allow for variations in light path), it is not time-like, and the two are not on the same track; the interval can be labelled as spurious. If there are q sensor triggers in the gate (q>k), the same can be done with all other intervals in the gate, of which there are q(q-1)/2. The criterion for acceptance of the event is the existence of k(k-1)/2 acceptable intervals, which define k true signals. This procedure should suffice to discard most random gates in a hurry. If the event survives, it can be passed along to track-finding routines.

As an example, if t = 2 μsec, and Δt, the allowable margin for error, is 0.1t (± 100ns), the probability that the correct interval be observed between random counts within the gate is p=Δt/t = 0.1; for three intervals (among three pulses), it is p^3, or 0.001. Thus we can reject 999 of 1000

*The required size is actually M(M-1)/2 = 285,390, since the IJ element = JI element, and the diagonal I=J is undesired. Its current cost would be about $3000.

totally random threefold gates. The calculation involves, for q triggers, the comparison of q(q-1)/2 pairs of numbers.

2.1.1 Verification of Fast Trigger Algorithm.

In order to test the concept of fast rejection of spurious intervals, I wrote two computer programs, called TDIFF and ALG. The former is an analytical calculation, using simulated muon tracks, of the deviation of the true time difference between sensor light signals from the stored time difference between sensor locations. It showed that only for small sensor separations could we expect relatively large discrepancies (i.e., up to 100nsec) between these quantities.

Program ALG is an algorithm for calculating the time difference between randomly chosen sensors, assigning random times to counts in them and going through the exercise of comparing these quantities to see how well we can reject them. The calculation made above, with a 2-μsec gate and ±100nsec error, was verified almost exactly; the number of random events satisfying these criteria, with three events required in a gate, was 10 out of 10000.

In addition, a study of "true" events, as produced by the DUMAND Monte Carlo program DUMC[1], indicated that in 140 intervals examined only one was outside the 100nsec tolerance; the mean absolute deviation was about 23 nsec. Figure 2 shows a histogram of the distribution of the difference between the "observed" time difference between photon signals at the sensors, and the time corresponding to their separation. Consequently we may have confidence that the proposed algorithm will neither lose true events nor allow too many spurious ones, with Δt = ±100nsec.

2.1.2 Consequences of Fast Event-Gate Screening.

One would hope to carry out this type of screening in a matter of microseconds - not over, say, 5 to 10. In addition, parallel processing can increase the rate of screening. Then gate rates G up to several x 10^5/sec may be feasible. This means that sensor trigger rates per module up to R about 1000/sec may be allowable.

Obviously, the choice of algorithm for deleting random events is of the utmost importance. With a 1-msec processing time, the maximum event gate rate G is about 1000/sec - somewhat more, perhaps, with parallel processing. From Fig. 1, this correponds to an individual sensor rate of 100-200/sec. A fast algorithm allows G to be several x 10^5, and the sensor rate R to approach 1000/sec. That difference is sufficiently significant to allow relaxation in the requirements for PMT's acceptable for DUMAND.

Let us now examine in detail how the PMT requirements will be affected. We first list the expected background sources, as given, e.g., in Report HDC 81-14 (Ref. 2).

3.0 Summary of PMT Noise Sources.

The contributing components of the PMT noise background are

1. True twofolds from K^{40}.
2. Random background from single K^{40} counts; reduced by coincidences if segmentation is used[2], by pulse-height discrimination alone if it is not.
3. Large background noise pulses, occurring in more than one segment.

We discuss these in turn.

3.1 True K^{40} Rate

Those K^{40} disintegrations that occur very close to the photocathode can occasionally produce true coincidences of two or more electrons. Their number has been calculated in DUMAND Note 81-20[3], and for the 16" PMT is in the vicinity of 120/sec, just about 10^{-3} of the singles rate.

4.0 Reducing the Random Noise Rate

The K^{40}-plus-tube noise single-electron counting rate for a single sensor is estimated[2] at about 10^5/sec. As we see from Fig. 1, this rate is far too high to allow any analysis of triggering in a 2-μsec gate; every such interval would contain about 100 counts on the average. In order to allow any analysis of gate triggers, the singles rate R must be reduced by at least a factor of 100, if we have a fast (1-μsec) processing algorithm, and by 1000 if the processing algorithm is slow (msec.).

4.1 High-Gain Dynodes vs. Segmentation.

With conventional dynodes (gain per stage about 4-5) a reduction of the singles rate to 30% of the full value can be expected from setting a threshold of two electrons[4]. This yields a rate R of 3×10^4/sec. With a threshold of 3 photoelectrons, another factor of 3, giving $R = 10^4$, is to be expected. This still leaves us at least a factor of 10 short of what is needed.

It was for this reason that the concept of segmentation was revived[2] as a method of reducing the random K^{40} background. If the multiplier structure is divided into m segments, so that any electron cascade is confined to only one such segment, then, since nearly all K^{40} counts are due to single photons, they will be registered in only one segment. On the other hand, true events with two or more simultaneous photoelectrons will in general fall in different segments, and can be selected by means of a coincidence circuit accepting two-folds between any pair of segments. The true rate suffers a loss of 1/m, the probability that the two electrons land in the same segment.

It is possible that a high-gain first dynode might produce the desired background reduction, provided we are willing to raise the individual sensor threshold to 3 photoelectrons at the first dynode. Figs. 3 and 4 show curves from a paper by Hayakawa and Hayashi[5], who calculated the background reduction as a function of threshold (two or three photoelectrons) and first dynode gain. We see that a first dynode gain of 15 will suffice to reduce the single sensor rate R by a factor of 100, provided the threshold is 3 photoelectrons. A first dynode gain of 25 yields a reduction by a factor of 1000.

It should be noted that in a real PMT the effective dynode gain includes as a multiplying factor the efficiency of collection of the secondaries produced at the dynode, which frequently varies across the dynode surface. Thus the dynode gain is not constant; and it requires only a moderate area of lower gain to smear out the distributions enough to decrease the background rejection factor materially. Thus, from the curves of Ref. 5, we calculate that if 10% of the dynode area has an effective gain of 10 instead of 25, the noise rate would be increased by a factor of 5.

4.2 Effect of Three-Electron Threshold.

The use of a three-electron threshold is approximately equivalent to reducing the effective sensitivity of the PMT by about one-third, as compared with a two-electron threshold. A Monte Carlo investigation of the effect of raising the threshold to three photoelectrons indicates that a sensitivity of 1.75 units at the two-electron threshold is equivalent to a sensitivity of 3.0 at the higher one; the effect is thus somewhat greater than the naive factor of one-third reduction.

The appropriate comparison for our purposes is between a), the segmented tube, with a threshold of j=2 photoelectrons and a sensitivity* of 3(m-1)/m, where m is the number of segments; and b), the unsegmented tube, with a sensitivity of 3 and a threshold of j=3 photoelectrons. Using our Monte Carlo simulation programs, we have made that comparison for the case m=6, so that we compare S=2.5, threshold 2 (the segmented tube) and S=3., threshold 3 (the unsegmented one). We have varied the array spacing, keeping the height fixed at 500m, until we found values that yield efficiencies as nearly identical as possible (and also satisfactorily high.) The simulation includes the variation of sensitivity of the PMT with the angle of incidence of the light.

Fig. 5 shows the comparison; we note the contraction of the array required to accommodate the higher threshold for the high-gain first dynode unsegmented tube.

The difference in spacing in the two cases results in different numbers of sensors and different array volumes; Table 1 summarizes the comparison.

Table 1. Comparison of Arrays with Segmented, Unsegmented PMT's.

PMT Type	Sens.	Thresh.	Array Spacing,m	Array Dim.,m.	Sensors	Vol,10^6 m^3
Segmented	2.5	2	50x50x22.7	250x250x500	828	31.25
Unsegmented	3	3	45x45x17.8	225x225x500	1044	25.3

The difference is clearly in favor of the segmented tube; but it is apparent that if necessary we could use the unsegmented one. The difference between the two arrays, though noticeable, is not critical to performance.

*in units of photoelectrons reaching the first dynode in a Cerenkov flux of 100 quanta/m^2.

4.3 Reduction of Background by Use of Segmentation.

The random background of twofold coincidences between segments, due to K^{40} decay, is estimated to be about 100/sec if PMT segmentation is used. It is given[2] by $N = R^2\tau\,(m-1)/m$, where we have taken for R 10^5/sec, and for τ 10^{-8} sec. Here R is the total singles rate of the sensor, and τ is the coincidence resolving time between any two of the m segments; m is between 6 and 15.

4.4 Sensor Background of Large Pulses.

This is a troublesome topic, because the numbers quoted differ widely, and because the observations on different PMT's are sometimes widely at variance. The conventional wisdom states that there is a background of large signal-induced pulses[6], delayed with respect to the signal causing them, which is due to positive ions produced somewhere in the tube by the primary photoelectron or the cascade it produces in the multiplier structure. These ions strike the cathode after a delay due to their time of flight, and produce pulses of several photoelectrons that are large enough to produce a sensor trigger, unless some means is found to get rid of them. Their abundance is estimated as from 1/2 to several percent, and varies widely between different tubes of the same type. This explanation has been disputed; but no convincing alternative has been advanced. Some tubes are claimed to have very low large-pulse backgrounds (0.1%). If this should be true, it would solve our background problem rather neatly.

If the standard interpretation is correct, a random singles rate of 100K/sec, which is what we expect from noise plus the K^{40} decays, will produce a large-pulse background of 500 to perhaps 2000 large pulses per second, considerably outweighing the other sources of background. If this number could be reduced by a factor of only 3-5, we would be in a much more favorable state.

4.4.1 Deadtime Gating.

The large-pulse background, judging by some data from Hamamatsu, might be reduced by perhaps a factor of 2 by introducing a short (50-100ns) deadtime, appropriately delayed, after each singles count. This is possible because perhaps half the afterpulses occur at a fixed delay after the initiating count. The total deadtime so introduced would be only .65 to 1.3%. We will refer to this method of decreasing afterpulses as deadtime gating.

1. Without deadtime gating, we estimate a contribution to the noise rate, from large background pulses in more than one segment, of 500-2000/sec; adding the contribution from 1 and 2, the total sensor rate R is 720-2200/sec, which is marginally too high for acceptance. From Figure 1, we infer that to keep G_3 from getting too large, R had better not much exceed 800-1000/sec.

2. With deadtime gating, the large pulse background becomes 250-1000, and the total rate R 470-1220/sec, for a total trigger rate G_3 of 50-500K. The lower end of the range would be acceptable; the upper end is more doubtful.

5.0 Variation of Gate Trigger Requirement.

We next consider the effects of raising the gate requirement to k=4 sensor triggers.

A significant decrease of background is obtained at low sensor rates, as we see in Figure 1 from the curve labelled G_4. We can now accept sensor rates R to at least 1000/sec. However, as the total trigger rate G approaches 1/t, where t is the event gate duration, increasing the required number of triggers k helps less and less.

This change produces significant decreases in track-identification efficiency, which can be compensated for only by decreasing the array spacing; it should therefore be used only if a high background rate makes it absolutely necessary. Figs. 6 and 7 show the difference between k=3 and k=4 for the two PMT types, with the array spacings of Table 1. With either PMT design, the 4-sensor gate trigger reduces track efficiencies, especially at low values of cosθ, where the tracks are shortest. To restore the efficiencies, a reduction in vertical spacing would be required.

A summary of background rates under various assumptions is given in Table 2.

Table 2. Contributions to the PMT Noise Background Rate, R_j
All rates in sec^{-1}

True K^{40} Rate	Random K^{40} Rate (m=no. of segments)	Large-Pulse Without dead-time Gate	Background With dead-time Gate	Total Sensor Rate R
A. Two-electron (j=2) sensor threshold, feasible only with segmentation.				
120	100 (m-1)/m ~100	500-2000		720-2220
			250-1000	470-1220
B. Three-electron (j=3) sensor threshold.				
1. With segmentation.				
60	0.2	250-1000		310-1060
			125-500	185-560
2. Without segmentation.				
60	100-1000	250-1000		410-2060
			125-500	285-1560

6.0 CONCLUSIONS

1. The availability of a fast (μsec) algorithm for discarding spurious event gates allows the individual sensors to operate at a counting rate 5 to 10 times higher than would be possible with a slow (msec) algorithm.

2. This relaxation on noise rate requirements allows us to reconsider PMT's in which the dynode structure is not segmented, and discrimination against noise is accomplished by means of a high-gain first dynode (gain

~25). It is necessary that the dynode gain be uniformly high, to avoid excessive noise background. This simplification is achieved at the expense of requiring three photoelectrons to trigger the sensor, rather than two; the effective sensitivity is thereby considerably reduced.

3. The segmented dynode structure has the advantage of a sensitivity considerably higher than the high-gain first dynode structure; it is, however, probably more expensive and more difficult to design and build.

4. Any means of decreasing the inherent large-pulse noise of the PMT, including signal-induced noise, will materially improve array performance.

5. The selection of true events via the technique of the event gate is already beginning to run into difficulties at ~1000 sensors and a 2-μsec gate length. Increasing either number materially will present greater and greater problems to the signal processor. At present no alternative approach has been suggested.

REFERENCES

1. See, e.g. V.J.Stenger and A. Roberts, Proc. 1980 DUMAND Symposium, Vol. 1, pp. 126, 136, 161; V.J.Stenger, ed., Hawaii DUMAND Center, Honolulu, HI., 1981 (hereafter DUMAND 80).

2. J. G. Learned and A. Roberts, "Requirements for DUMAND PMT Tubes," DUMAND Report HDC 81-14, Nov. 1981.

3. A. Roberts, DUMAND Note 81-20, Nov. 1981.

4. A. G. Wright, DUMAND 1980, Vol. 1, p. 76.

5. T. Hayakawa and T. Hayashi, DUMAND 1980, 1, p. 83.

6. G.A.Morton, H.M.Smith and R. Wasserman, IEEE Trans. Nucl. Sci. NS-19, p. 443 (1967).

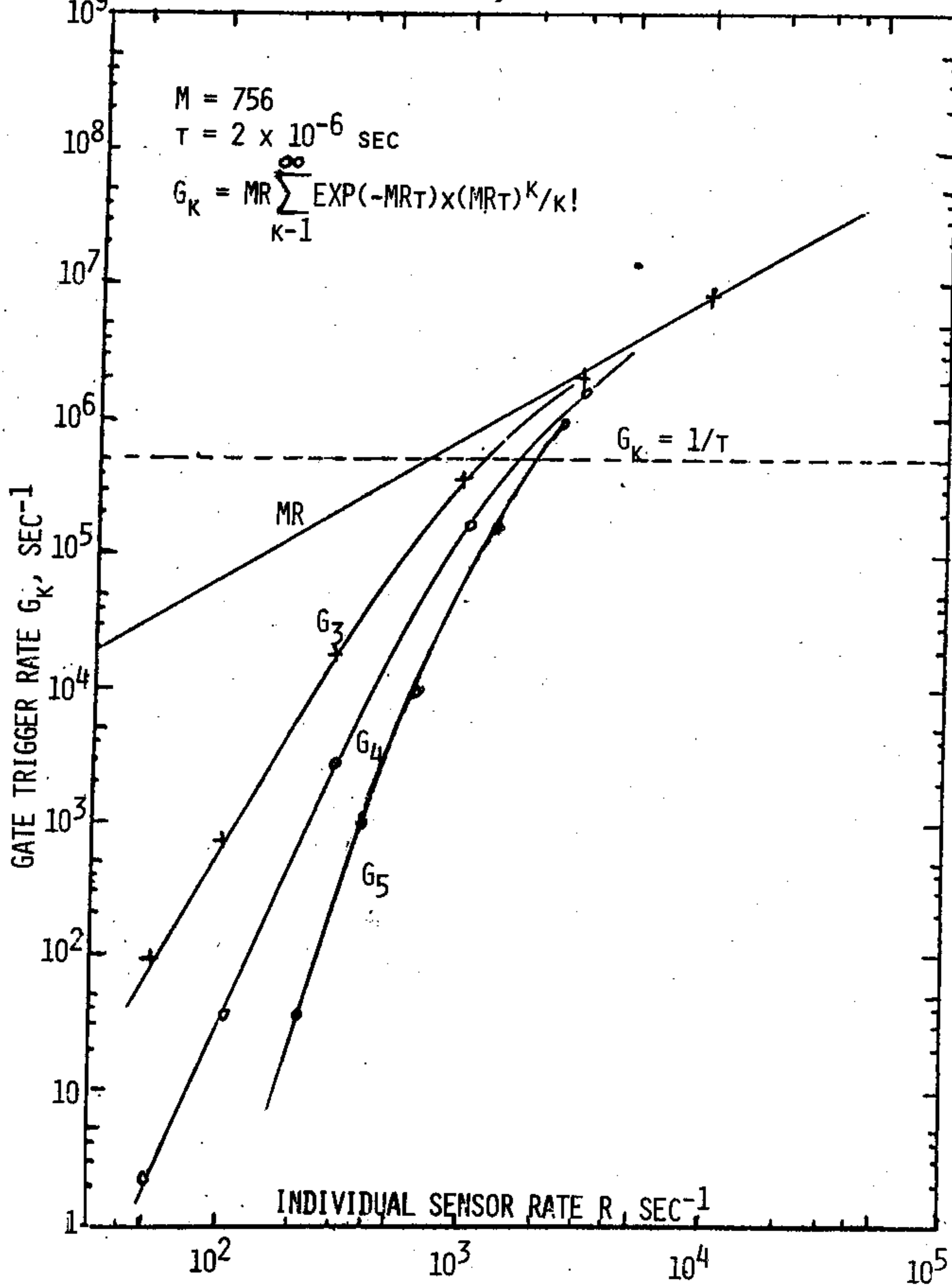


Fig. 1. Plot of event gate trigger rate G_k, where k is the number of sensor triggers required to generate the event gate, as a function of the individual PMT sensor rate R. M is the number of sensors in the array, 2×10^{-6} sec the event gate duration.

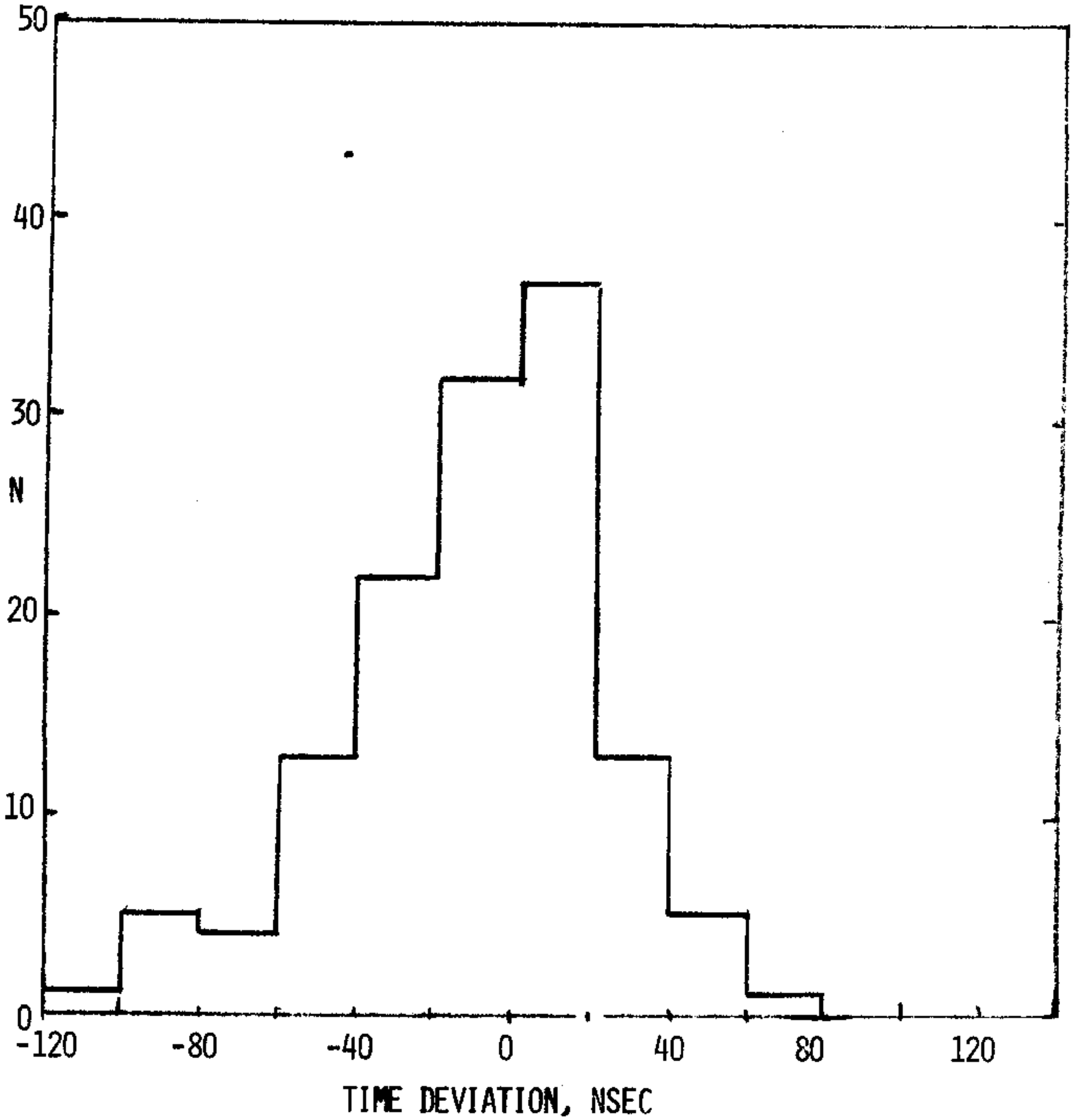


Fig. 2. Distribution in time of the difference between the times t_1 and t_2, where t_1 is the time interval between the arrival of light signals from a muon track at two different sensors, and t_2 is the distance between the sensors divided by c. This is a plot of data from Monte-Carlo simulated muon tracks in the proposed DUMAND array.

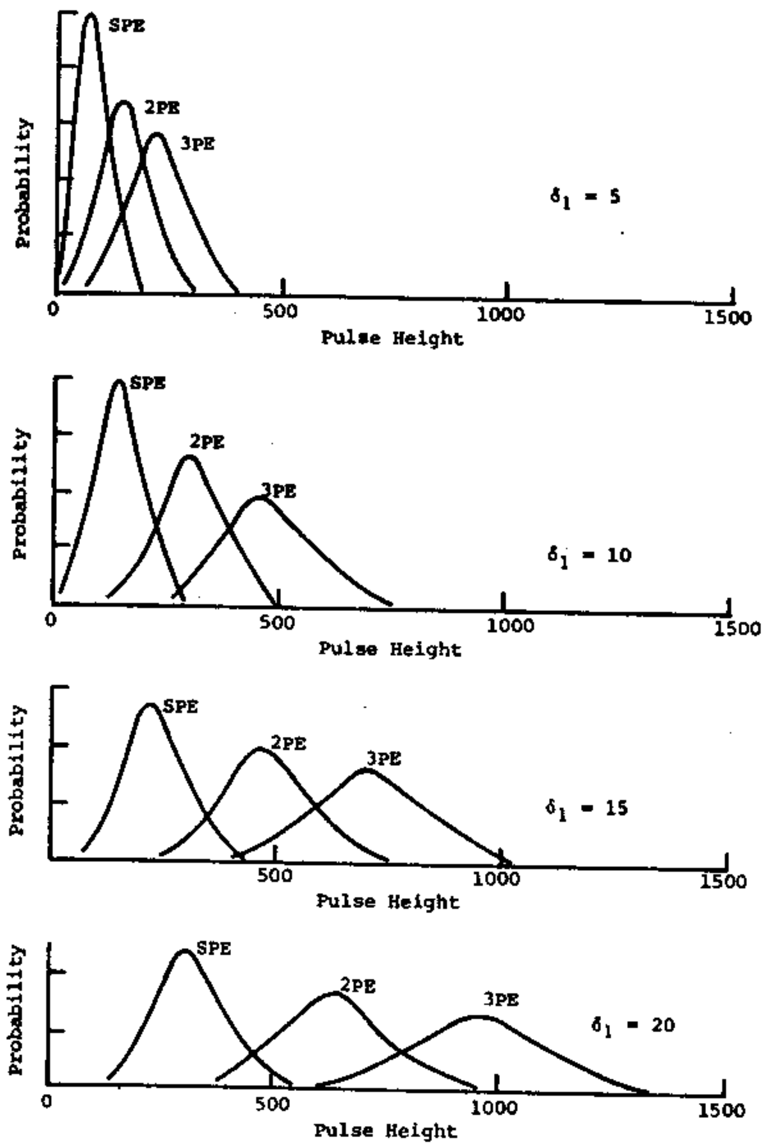


Fig. 3. Pulse height distributtions of a four-stage multiplier, assuming a Poíssonian distribution, as the gain δ of the first dynode is varied, for inputs of 1, 2, and 3 photoelectrons. The last 3 dynodes have gain 4. From Ref. 5.

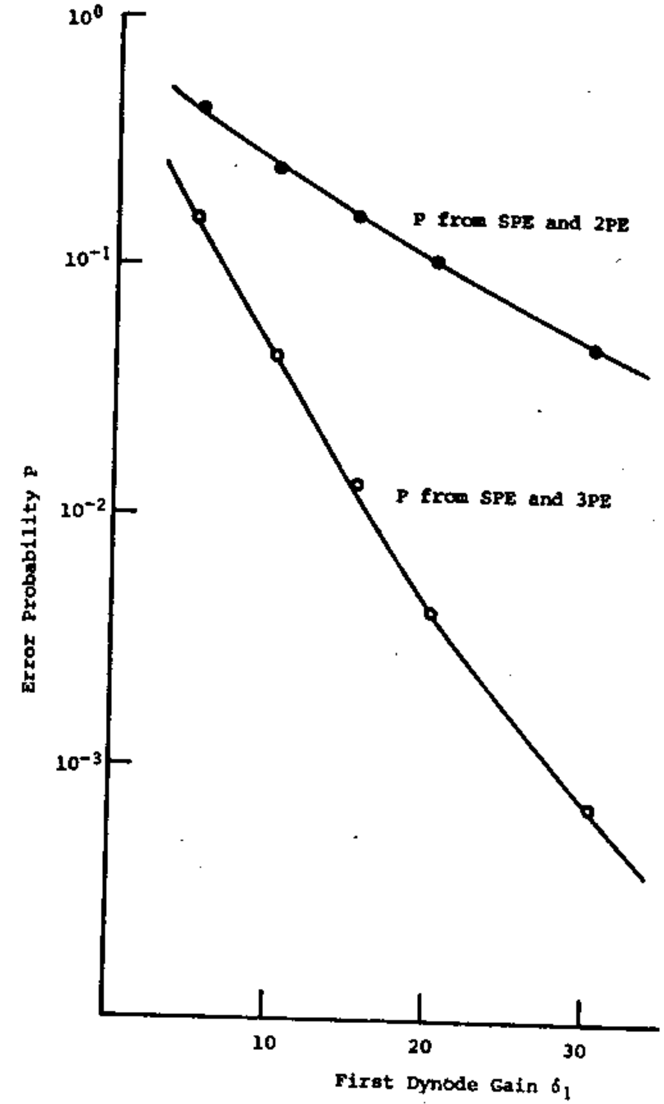


Fig. 4. The error probability (admixture of incorrect triggers) as a function of first dynode gain. Upper curve is for discriminating two photoelectrons from 1; lower for discriminating 3 photoelectrons from 1. The dynode gain is assumed uniform. From Ref. 5. Note that the discrimination, inadequate to obtain a rejection factor >100 in the first case, may be sufficient in the second.

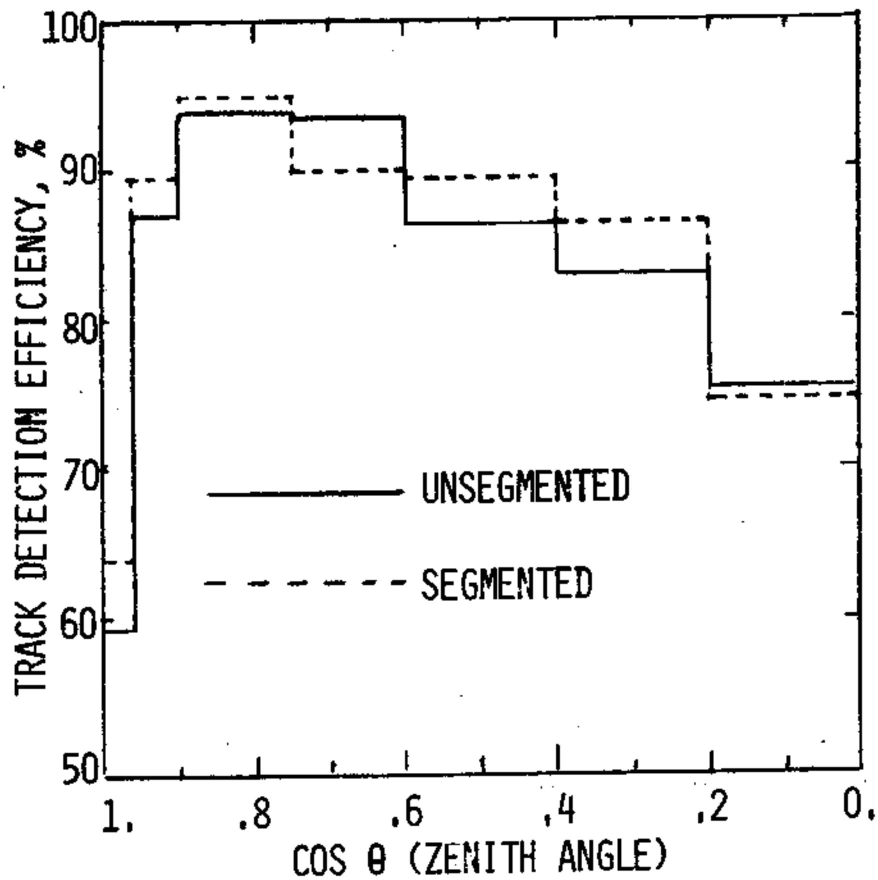
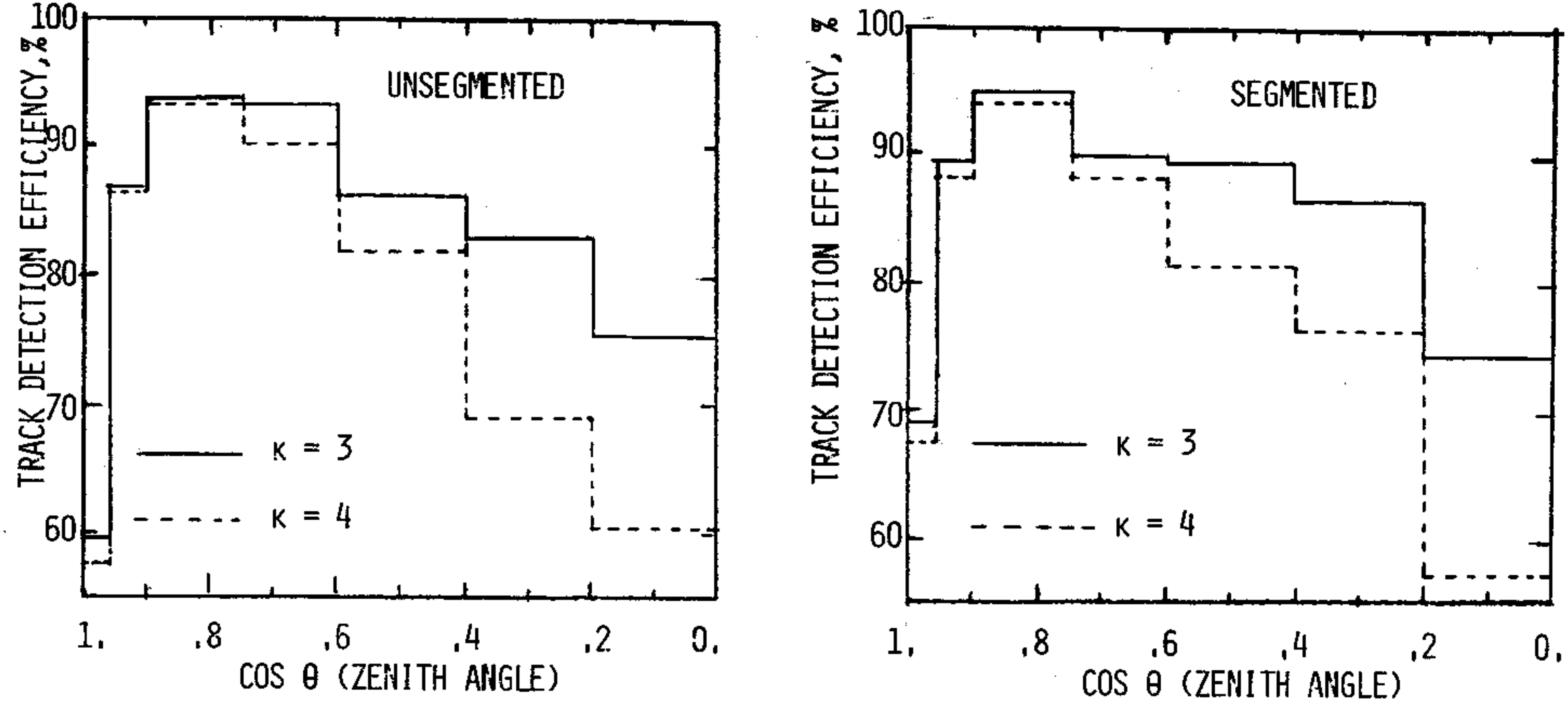


Fig. 5. Comparison of segmented and unsegmented PMT's. Constants for unsegmented PMT: sensitivity S=3, threshold j=3 photoelectrons; for the segmented PMT: S=2.5, j=2. Array spacings were adjusted to match the performances as closely as possible. For S=3, j=3, array spacing is 45 x 45 x 17.5m; for S=2.5, j=2, it is 50 x 50 x 22.7m. Data were simulated by Monte Carlo methods.



Figs. 6 and 7. Comparison of performance of arrays with event gate trigger requirements of k = 3 and 4 sensor triggers, respectively, for the same array spacing. Fig. 6, left, is for the unsegmented PMT, and Fig. 7 for the segmented PMT. The effect of raising k is greatest for the shortest tracks, with the fewest sensor hits - namely, at zenith angles near 90°. This effect can be counteracted by decreasing the vertical sensor spacing along the strings. Data are simulated by Monte Carlo techniques.