DUMAND NOTE 80 - 4, Jan. 31, 1980 (Revised)

PRELIMINARY REFLECTIONS CONCERNING A SMALL-SCALE DUMAND EXPERIMENT: DUMAND M.

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I. INTRODUCTION

The concept of a small-scale DUMAND M installation, as a preliminary to the full-scale DUMAND G (these suffixes stand respectively for Megaton and Gigaton) has always been an alluring one, from the standpoint of proving out the technology on which DUMAND G will eventually be based. Since no operation in the deep ocean on the scale 6f DUMAND has ever been carried out, it seems plausible that the expenditure of a relatively small amount of money in testing the techniques to be used on the full-scale installation would more than re-pay itself in improvements in technique and in experience, not to mention they exposing of any unforeseen difficulties or bugs in operation.

To date that concept has not been aggressively pursued. Considered purely as a preliminary to DUMAND G, the motivation is adequate only if a decision to build DUMAND G has already been made, or is dependent only upon the demonstration of feasibility. An additional motivation must be present to make DUMAND M a worthy goal in its own right. Such a motivation would be the scientific knowledge to be obtained by the installation.

The scientific usefulness of a DUMAND M installation is now being re-examined, particularly by scientists with a strong background in cosmic -ray muon physics. As a result of this re-examination, which is still in progress, it appears quite possible that such justification can be advanced; that a DUMAND M project, with a cost in the vicinity of a few million dollars, can be justified on the basis of new cosmic-ray information to be obtained in addition to the technological reasons mentioned above. For this reason we now set forth the scientific justification and the technical gains to be achieved.

II. MUON PHYSICS WITH DUMAND M

Previous muon spectroscopy in cosmic rays has been carried out both on the surface and in underground installations. A primary focus of interest has been the energy and directional spectrum of muons, because of the relation of the muons to the pion and kaon parents produced by the primary interactions high in the atmosphere. Thus, even though muons are third-generation (or higher) reaction products, they cast light on the primary interactions that produce them. In this regard, there is currently great interest in prompt muon production (observed at accelerators) and in multiple muon production, which is expected in both weak and strong interactions.

The largest previous magnetic muon detectors have been DEIS[1] and the MUTRON[2], with maximum detectable momenta of 7 and 10 TeV, respectively; associated with the latter is the "Pair Meter" [3], which is capable of making measurements at even higher energies, but is limited by the available flux. The largest underground muon detectors are those at Homestake, South Dakota,[4] and at Baksan[5], whose areas for muon detection are 200 and 110 m^2 respectively; they determine muon energies from their ranges in the overlying rock. A complete summary of current muon spectra and their sources has been given by Allkofer et al.[6]

In contrast to previous installations, the proposed DUMAND M (see Figs. 1 and 2) would have an area for vertically incident muons of 10^4 m^2, and several times that for horizontally incident muons (see Table 1.) For the horizontal muons, the device would be a large-area detector with little or no capability for energy measurement except through range measurements in the overlying ocean. Within an angular range of 0.026 ster. near the vertical the detector will be capable of measuring muon energies of 2 TeV and above, with an accuracy we estimate as about 40%. The aperture would be 2600 m^2·ster; the aperture of the MUTRON, for comparison, is 0.1 m^2·ster.[7] Since the method of measurement is the measurement of dE/dx, the instrument would necessarily be especially well suited to studying the modes of energy loss of energetic muons. It would yield no information on the sign of the muon charge, or the charge ratio.

The total muon counting rate would depend strongly on what depth is chosen for the apparatus. Here a conflict arises. From the standpoint of muon physics, a depth between 2 and 3 km seems the most appropriate, while from the standpoint of modeling the full-scale DUMAND G array, the same 5-6 km depth is desirable, and in fact the same actual site. If the depth is the same as that contemplated for DUMAND G, the total muon rate will drop to something less than 1 sec^{-1}, which is not negligible, but is a factor of 20-50 below the more desirable 2-3 km depth. This hurts not so much at the single muon level, but makes a big difference for multiple muons and measurements of anisotropies. On the other hand, one can argue that if the main object of the investigation is the highest possible energies, then the increased depth and lower counting rate is not nearly so harmful, since the particles lost in going deeper will in great part be the less energetic ones. The final choice of depth will require considerable thought.

Figs. 1 and 2 show two possible geometries for a DUMAND M array. Fig. 1 shows a cubic lattice, Fig. 2 a hexagonal one. The individual strings are identical in the two arrangements, and are the same as those described in the "Standard" array for the 1978 Summer Workshop[8]. The arrays are nearly the same in other respects as well; Table 1 enumerates their properties.

TABLE 1. DESCRIPTION OF TWO POSSIBLE DUMAND M ARRAYS.

Property.	I. Cubic	II Hexagonal
Base dimensions	100 x 100 m	Hexagon 60m on a side
String spacing	33.3m	30. m
Base area, m^2	10,000	9350
No. of strings	16	19
Modules/string	18	18
Module spacing on string,m	37	37
Total modules	288	342
Active string length,m	620	620
Array volume, m^3	6.2×10^6	5.8×10^6
Solid angle for vertical traversal of entire array	0.026 ster	0.024 ster.

It should be remarked that the string spacing and module spacing along the string can readily be altered depending upon the module density required. It is even conceivable that a design that allows string spacing to be varied after installation can be achieved.

<u>Properties of the Geometry Proposed</u>. - The general shape of detector selected, a vertical prism, is chosen so that there will be at least one dimension long enough so that muon energies can be measured. From Monte Carlo work[9] this distance needs to be at least 400m, and preferably 600m; 1000m would be still better, and more detailed study may make it desirable. In DUMAND G the horizontal distances range from 800 to 1600m; the strings determine the 620m vertical distance.

In addition to being able to measure at least some muon energies, it is also desirable to detect at least some neutrinos so that we learn how. For this purpose we need to observe and measure cascades as well as muons. From the volume of the array, we expect about 0.5 neutrino interactions per day of 1 TeV and above. The great majority of these will be in directions other than the vertical. They will, however, produce nuclear cascades, which will be readily detectable down to a fraction of a TeV. These can be compared with EM cascades, which will be produced at all energies by muons, and thus labelled. We will therefore have all the information needed to evaluated neutrino detection in a full-sized array.

Since a 1-TeV hadronic cascade is visible for at least 80 meters, the fiducial volume for cascade detection is unclear; we need more calculations on what signals are to be expected.

If the spacing of modules through out the array were scaled down to 20m, and all dimensions scaled accordingly, the volume would shrink to 1.66×10^6 tons, and the top and bottom areas to 3600 m^2. There would be a factor of 3 loss in muon rate, and about 4 in neutrino rate. Thus the intermodule distance is a most important parameter that will require further study.

III. List of Possible Experiments.

1. Muon Spectra at 10 TeV and above. The vertical spectrum is measured up to about 10 TeV,[6] where the energy resolution disappears. THe expected rates for vertical acceptance are: 100 hr^{-1} above 1 Tev, 1 hr^{-1} above 10 TeV. Thus we get about 10^4 yr^{-1} at 10 Tev and above, and about 100 yr^{-1} at 100 TeV and above.

In addition to these muons, whose energies are individually determined, there is the very much larger (more than 100 x greater) flux of muons that traverse the lateral walls of the array. From the direction of these muons, (which we cannot determine with high accuracy) one can put a lower limit on their energywhen they enter the ocean; this is where the DUMAND advantage of knowing the density and path length comes in. Thus one can obtain a muon spectrum in the same way that previous underground experiments have done so. We know the absorber better; but it may turn out that the uncertainty is no smaller if the direction of the muon is not well enough determined.

2. Search for muon anisotropies at high energies. The much greater muon fluxes allow a search for muon anistropies to carried out to higher energies than previously feasible. The angular uncertainty referred to above is not a function of azimuth, so that azimuthal variations can be sought at all angles with the vertical.

3. Study of the Landau-Pomeranchuk-/Migdal effect.[10] This is a predicted decrease in electron interaction (increase in the radiation length) at ultra-relativistic electron energies. This requires studies of the distribution of ionization in the longitudinal development of EM cascades. Our muons should provide large EM cascades up to 10 TeV or above in sufficient numbers to make possible this study, provided the detectors are capable of observimg such variations in the energy distribution in thecascade. Monte Carlo investigations will be required to see wheter the effects predicted are observable, and under what conditions.

4. Multiple Muons. - The study of multiple muons is relevant to several different subjects. Dimuons, trimuons, etc. are related to specific nucleonic structure properties such as charm production, etc. They can be produced by the decay of heavy particles like the Z^o. However, in the majority of cases, multiple muons originate in high-energy cascades which produce many mesons as potential muon parents.

One of the more interesting reasons for studying multiple muon production is to cast light on the primary cosmic-ray spectrum in the region around 10^{15} eV, where there is considerable doubt as to the relative abundance of protons and heavy nuclei like Fe^{56}. The multiplicity of muons produced in a 10^{15} eV cascade is very different if the primary is a proton from what it would be if the primary is an Fe^{56} nucleus of the same total energy; the energy distribution is also very different. Consequently an important experiment would be to measure muon multiplicity and energy distribution simultaneously with the measurement of total cascade energy. Such experiments are being designed for EAS arrays. The adaptation of DUMAND to such an experiment would be highly desirable, because of its capability of observing much greater rates at high multiplicities.

There are two difficulties. One is the question of how well we can measure high multiplicities; the resolution of the array is poor, and a shower of ten muons within a diameter of , say 20 meters, may be difficult to distinguish from 5 or 15. On the other hand, for the purposes of the experiment, the required resolution may not be very high; it makes little difference whether there are 10 or 15 muons, provided binning into intervals of multiplicity can be done well enough. The required resolution needs more study.

The other, more difficult problem, is the ascertainment of the energy of the air shower in which the muons originate; this is necessary if conclusions about the primaries are to be drawn. The energies are too low for the fly's eye type of detector, whose threshold is just below 10^{17} eV. Alternatives include the measurement of the surface density of electrons or muons, and detection of the Cerenkov light produced in the atmosphere by the shower. Any of these alternatives demands an installation at the ocean surface above the array, to sample the air shower which gives rise to the multiple muon signal. The muon data from the array should locate the core of the shower at the ocean surface with reasonable accuracy (ca. 40 meters); and the geometry of the array restricts the area to be sampled for shower density to about a square kilometer or less. Thus the auxiliary equipment needed is perhaps a dozen or so particle detectors, scattered over about 1 km^2. Such an array would pose no problems on land; deploying it on the surface, on the other hand, is a considerable problem that needs much thought.

IV. TECHNICAL PROBLEMS SOLUBLE WITH THE DUMAND M ARRAY.

The DUMAND array would be expected to yield data in two important classes of information.

A. Array Operation

1. Site Properties. Long term observations on currents, temperature, salinity, water transparency, bioluminescence, biofouling, ocean flora and fauna, etc.

2. The performance of all array components in the ocean over an extended period of time. Adequacy of all testing and monitoring procedures, controls, location devices, etc.

3. Testing of all hardware and software systems; determination of failure rates, operating conditions for best results, etc.

B. Array Capabilities.

1. Measurement of muon trajectory resolution capabilities: accuracy of determination of location, direction, energy, and number of muons.

2. Study of nuclear cascades produced by neutrinos. This will provide experience in identifying and measuring the energy and direction of nuclear cascades, and comparing the results with Monte Carlo predictions.

3. Can we distinguish between hadronic cascades and EM showers? If so, how well, over what energy range and with what degree of confidence? How do the results compare with Monte Carlo predictions?

4. How do the array measuring capabilities discussed above vary with module spacing? How well do observed variations agree with Monte Carlo predictions? (This query assumes that different spacings are available, either being provided ab initio, or else through some mechanism for changing the spacing, perhaps by moving sensor strings.)

V. REFERENCES

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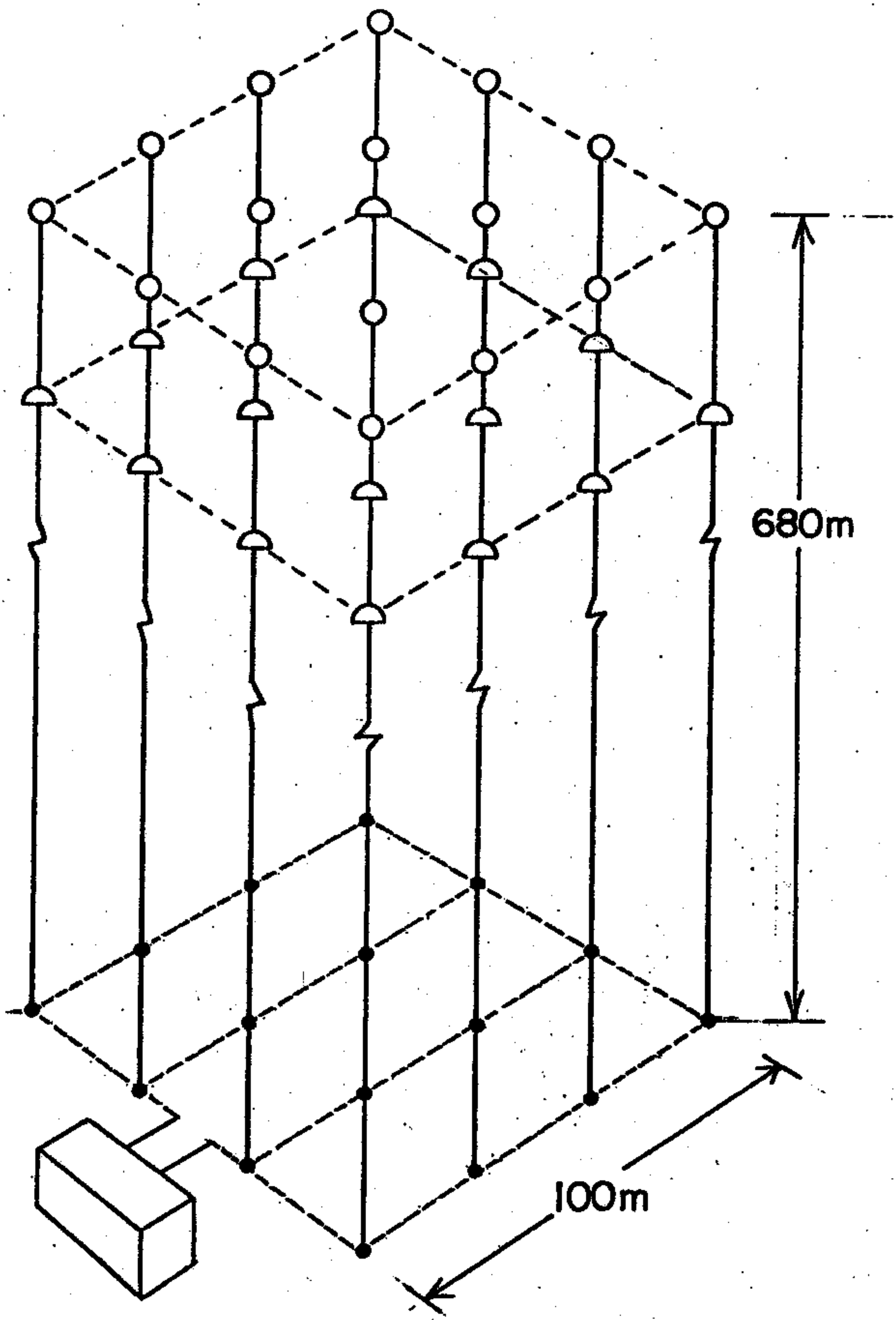

Fig. 1. Cubic array of detector modules. The array consists of 16 strings on 33.3m spacings on a 100m square. Each string is of the kind described in the 1978 Standard Array, with 18 detector modules on 36.6 m spacings covering 622 meters of a 672m-long string; the lowest module is 50m above the sea floor. Cables supply power from and conduct data to a central junction box.

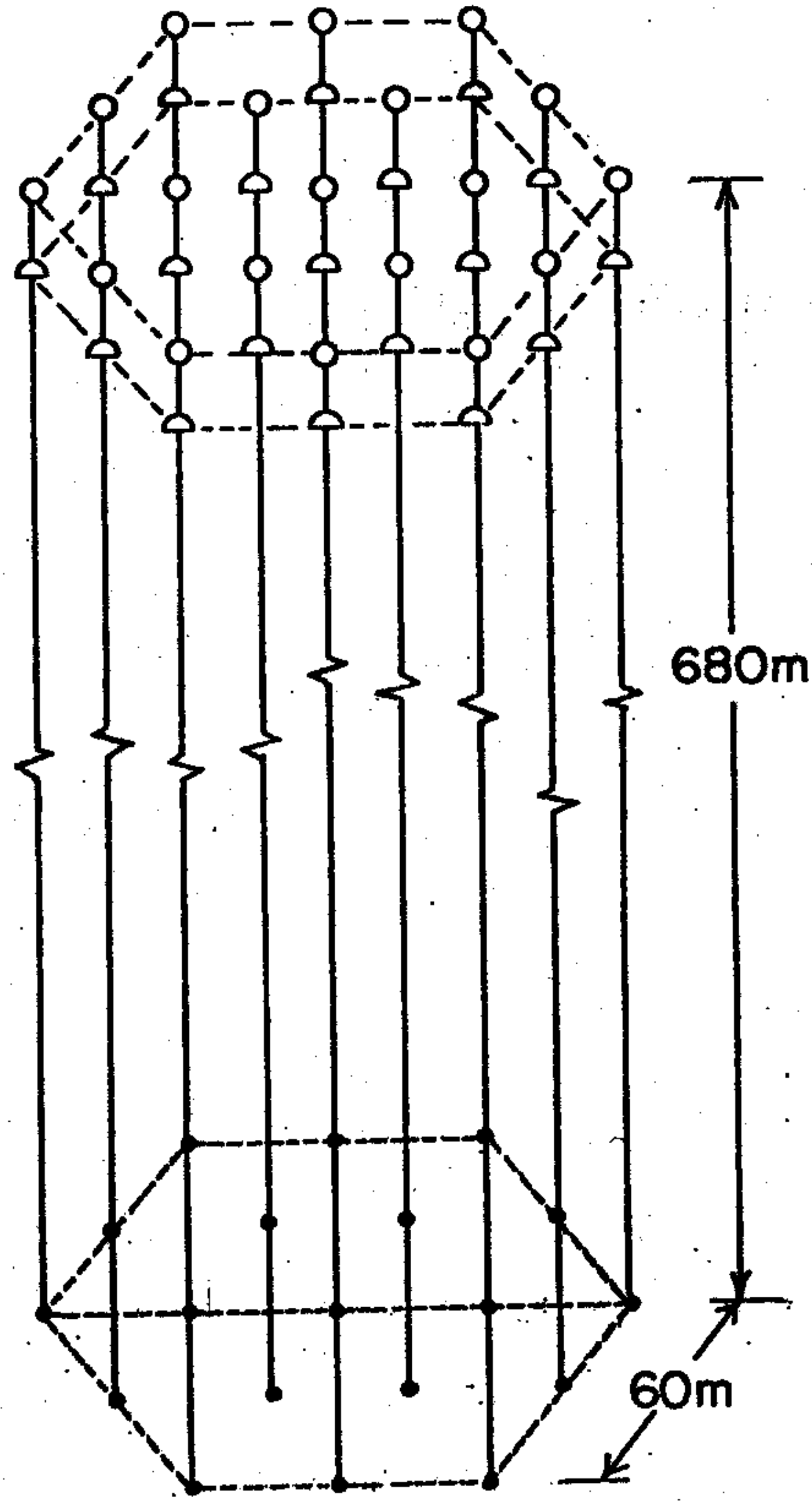

Fig. 2. Hexagonal array of detector modules. The string spacing is now 30m on a hexagon of 60m side, and 19 strings are required. See Table 1 for complete data.