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REPORT ON THE FIRST YEAR OF OPERATION OF THE HAWAII DUMAND CENTER.

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ABSTRACT

This report summarizes the accomplishments of the Hawaii DUMAND Center in its first year of operation, 1980. It also includes related work on site studies. and discusses relations to past and present work.

Our major accomplishments in the past year include the following:

1. Extensive experimental and theoretical work on the design, construction, and testing of a highly sensitive optical detector, called Sea Urchin, and comparison with alternative detectors.

2. Initiation of the first DUMAND underwater experiment: a measurement of the cosmic-ray muon spectrum, to be carried out with a string of five prototype DUMAND sensors, which we call the Muon String. This experiment is in some important ways superior to any previous underground or underwater muon spectrum measurements; the effective detector area is larger, allowing the spectrum to be observed to higher energies; and the overburden is far more accurately known. First ocean tests will be in 1981.

3. Workshops on our two most urgent engineering problems, signal processing and deployment, have led to conceptual solutions of practically all previously unsolved problems in these fields, at costs far lower than those initially estimated.

4. Monte Carlo studies of array designs have led to the design of smaller, more efficient and less expensive arrays for the detection of muon neutrinos and muons. They have, somewhat unexpectedly, shown that the high-sensitivity Sea Urchin, which turned out to be expensive to deploy, is not required for arrays presently under consideration.

5. Continued studies on new ideas for experiments with DUMAND have given some promising leads. The use of DUMAND in connection with other detectors for high-energy cosmic-ray interactions in the atmosphere has been studied, and presently we are studying multiple muon detection in DUMAND, and the detection of electron neutrinos.

The greatest promise of DUMAND still appears to us to be the foundation of the new science of high-energy neutrino astronomy, with particle physics and cosmic-ray work occupying the role of vital and possibly very exciting additional aims.

INTRODUCTION

This report is a review of the work of the Hawaii DUMAND Center during its first year of operation. For readers unfamiliar with the previous history of DUMAND, we begin the report with a short summary of it, and we now precede that summary by an even shorter introduction to identify DUMAND.

DUMAND (Deep Underwater Muon And Neutrino Detector) is a project that took form in 1973, and first achieved a formal organizational structure in 1975; the next section discusses its history from that point on. Here we explain its purpose, and its peculiar individuality as a scientific project.

DUMAND proposes to use a large volume of the ocean - between a few million and a few billion tons - as a very large detector, primarily for neutrinos. Neutrinos are electrically neutral, and interact with matter only rarely (via the so-called weak interaction only). The average neutrino can readily traverse the entire universe without interacting. Thus, to detect neutrinos, very large detectors are required. Even at accelerators producing intense neutrino beams, neutrino detectors weigh from tens to thousands of tons.

To make million- or billion-ton detectors is impractical except with water as the detection medium. Fortunately water is a good Cerenkov radiator; that is, whenever a fast charged particle is produced by a neutrino interaction ,traverses it, it emits detectable amounts of Cerenkov light. The design problem of DUMAND has therefore been: how can we instrument a large volume of ocean water with highly sensitive light detectors (photomultiplier tubes) and collect data that will give scientifically useful results?

From the beginning it was clear that DUMAND would require the collaboration of experts in many fields. It needed physicists, astrophysicists, oceanographers, ocean engineers, signal processing experts, marine biologists, and others. DUMAND now includes them all.

Since neutrinos are produced copiously at accelerators, the question arises: why does one need DUMAND in addition to accelerator work? The answer lies in the wider energy range encompassed by DUMAND, and in its ability to answer important questions in cosmic rays and in astrophysics. The highest energy neutrinos expected from an accelerator in the foreseeable future will be produced by the Fermilab Tevatron, whose 1000 GeV beam will produced neutrinos in usable quantities up to perhaps 600 GeV. DUMAND will overlap that range at the lower end, and will extend it to at least 10 TeV, opening an energy region otherwise inaccessible. DUMAND will also answer important questions in cosmic rays, and will, we hope, be the world's first true high-energy neutrino telescope, observing neutrinos incident on earth from outside the solar system. A summary of problems that can be attacked with DUMAND is given in Sec. 10. Suffice it to say that a number of astrophysicists now predict neutrino fluxes that must be detectable by DUMAND, or else theorists must be wrong. Some of these predictions deal with the highly significant question of the enigmatic source of power in active (and perhaps all) galaxies.

The cost of DUMAND was first estimated to be in the $100M range. That was clearly too high; and we have, by means of hard work and sustained effort, been able to bring it down. As shown in Sec. 4, arrays have now been designed from which significant data can be obtained, and which cost well under \$10M. Sec. 7 describes a 5-module detector now under construction, the muon string, that allows a phased approach to array design.

In addition to reviewing our first year's accomplishments, we have included a very brief report of investigations on potential DUMAND sites, as carried out by other investigators from Scripps, the Hawaii Institute of Geophysics, Oregon State University, and elsewhere.

A bibliography of proceedings of DUMAND conferences and workshops is appended, as is also a list of internal DUMAND reports for the year.

1. BRIEF RECAPITULATION OF EARLIER WORK ON DUMAND.

The active existence of DUMAND can be roughly dated from the first DUMAND Summer Workshop in Bellingham, Wash., in 1975. In that workshop, the DUMAND Steering Committee was formed, and the tenuous DUMAND organization first proposed. The site requirements for DUMAND were first formulated, the first survey of possible sites made, and the conclusion that the Hawaiian Islands were the best available site became all but inescapable.

At that time it was not yet clear whether neutrinos from gravitational stellar collapse would be detectable in DUMAND, or what the event rate might be. Following the 1975 Workshop, possible physics projects with DUMAND were given names, which fell into disuse shortly, but appear in the 1976 proceedings. UNderwater Detection of Intergalactic NEutrinos (UNDINE) characterized gravitational stellar collapse; ATmospheric High Energy NEutrinos (ATHENE) described the study of cosmic-ray produced neutrinos; and UNderwater Interstellar COsmic Ray Neutrinos (UNICORN) a search for extraterrestrial high-energy neutrinos. These subjects formed the basis for the 1976 DUMAND Workshop in Honolulu, and marked the introduction of the University of Hawaii as a strong supporter of the project.

At the 1976 meeting DUMAND achieved something like its present orientation, in that the possible areas of investigation were mapped out, and the appropriate experts were present to keep the discussions realistic. The 1976 meeting also saw the suggestion for acoustic detection of neutrino events in the ocean.

The acoustic approach proved interesting; in principle it might have made possible very large DUMAND detectors. Unfortunately, it did not survive the intensive investigation that followed (1976-79), led by Learned and Sulak, including considerable experimental work with particle beams at the Brookhaven National Laboratory. The basic difficulty was that the threshold for detection of acoustic signals lies in the energy region 10^{16} eV, where by threshold we mean a signal detectable at a distance of 1 km. Even at that range, each acoustic detector would consist of a complex array of phased hydrophones, and the highly directional nature of the signal required a high density of such detector arrays - several hundred per km^3 - to be useful. It became clear that optical detection was far more practical, for the energy region (0.1 - 1000 TeV) where atmospheric fluxes are well known and extraterrestrial fluxes most readily detectable.

The 1976 workshop also concluded that the detection of extragalactic gravitational stellar collapse, at a reasonable event rate (10/year) was extremely expensive; it required a detector volume of about $3x10^7$ m^3, instrumented by phototubes sufficiently closely spaced to see 10-100 MeV electrons (about 1 meter apart.) It became apparent that the future of DUMAND lay with the detection of high-energy neutrinos and muons, in the GeV and TeV range; that conclusion remains valid today.

The question as to whether DUMAND could measure the direction and energy of muons was among the first investigated. Such questions demand Monte Carlo modeling; and first Roberts, and later Stenger constructed and elaborated such programs. Roberts showed that a large DUMAND array could measure muon energies to 50% or better, and determine directions accurately.

In 1977 there were two small one-week workshops in San Diego and LaJolla, one on deployment and one on acoustic detection. In 1978 we held a full-scale Summer Workshop, with three two-week sessions respectively on Array Studies, Physics and Astrophysics with DUMAND, and Ocean Engineering Problems. It was at this meeting that for the first time we designed, for heuristic purposes, a DUMAND Standard Array, later called DUMAND G.

The problem of optical background in the ocean occupied attention from the beginning; it is clearly outlined in the 1975 Proceedings. A large assembly of optical sensors, each subject to high background from Cerenkov light produced by radioactive solutes in the seawater - mainly K^{40} - and to wandering bioluminescent organisms, is not the easiest system in the world for which to design a triggering system, or from which to collect and process data. Following the 1975 workshop, work on measuring the background in seawater was undertaken by Roberts at Fermilab. It soon became evident that PMT signals from the K^{40} background consisted almost entirely of single photoelectrons. Therefore phototubes with sufficient pulse height discrimination to distinguish one-electron pulses from two or more would be able to suppress the background to a considerable extent. Present PMT design for DUMAND is based on this discrimination. The alternative, of using coincidences from several detectors (or a segmented detector) has been considered, but is likely to be much more expensive.

Meanwhile Monte Carlo work on arrays was progressing. The verified capability of measuring inelastic neutrino scattering was supplemented by studies on optimization of the arrays themselves. These were strongly motivated by the very high cost of the 1978 Standard Array, and the realization of the very strong cost dependence upon sensor separation. The cost of a large array would be largely determined by sensor sensitivity and water transparency.

It also became clear that different arrays might be required for different purposes. The initial aim was muon detection and measurement, allowing the widest separation and least expensive arrays. Work on improving detector sensitivity by using the wavelength-shifter technique accelerated after the

1978 workshop; and in 1979, following a suggestion of Roland Winston, the Sea Urchin concept was born. However, in the absence of explicit DUMAND funding, little serious experimental work on sensors could be undertaken.

In 1979 two important meetings summarized the status of DUMAND. The 18th International Cosmic Ray Conference in Kyoto devoted two full sessions to DUMAND; and the Soviet Union played host to meetings at Khabarovsk and Lake Baikal. At these meetings it became possible to announce that support for DUMAND had been promised by ONR, DOE, and the State of Hawaii; the Hawaii DUMAND Center had been born.

To summarize the status at the end of 1979: much Monte Carlo work had been done on array design, but much more remained. The need for a high-sensitivity detector impelled the decision to push experimental work on Sea Urchin, despite misgivings about its probable size, weight and fragility. In signal processing, we were not yet sure how to handle the data. In ocean technology, we had been assured by the 1978 Workshop that deployment was possible; but available deployment schemes required many cable connections to be made at the ocean bottom, thus requiring a remotely operated deep-water undersea manipulator. Some observations on underwater transparency at the proposed sites had assured us that our estimate of a 20m optical attenuation length was conservative.

2. FORMATION OF HAWAII DUMAND CENTER (HDC)

Although the annual workshops explored many important aspects of DUMAND and periodically stimulated activity among DUMAND supporters, it was clear that only a continuing full-time effort would produce the detailed information necessary to establish the scientific benefit and technical feasibility of DUMAND. A multi-agency request for major funding of a DUMAND central laboratory located at the Scripps Institution for Oceanography, submitted in early 1978, was turned down for a variety of reasons; among the most compelling was the advice that reorientation of the proposed operation as a feasibility study was more appropriate at the current state of development. With that view we could not disagree.

There were two encouraging aspects to this setback, however. One was the sympathetic (if mildly skeptical) attitude of the DOE High Energy Physics staff, who are accustomed to radical new proposals; and the successful funding of the $76,500 request to ONR by the Hawaii group for DUMAND site studies. The growing interest in DUMAND by members of the Hawaii High Energy Physics Group (UH-HEPG) was also important, since an on-site DUMAND feasibility study could readily be attached to this existing organization.

Prior to the Kyoto Cosmic Ray conference in August 1979, the extent of local support for DUMAND was explored by Prof. V.Z.Peterson, principal investigator for the Hawaii group's contract. A University commitment to support one full-time research physicist for DUMAND was obtained. Modest funding of ocean-related DUMAND studies by the Governor's Marine Affairs Coordinator (Dr.

John Craven) helped to match prospective DOE and ONR support. With the blessing and encouragement of the DUMAND Steering Committee, the concept of a Hawaii DUMAND Center was realized. Prof. Peterson cabled to Kyoto the good news of "assured adequate support" for at least a two-year feasibility study; the chairman of the DUMAND Steering Committee, Prof. F. Reines, announced this development to a meeting on DUMAND at the Kyoto conference.

Elements of DUMAND -- The main elements of the Hawaii DUMAND Center are the professionals involved, the facilities available, and the organizational structure to support it. The only full-time staff are two long-time DUMAND supporters, Dr. John Learned and Dr. Arthur Roberts, who also hold additional University academic titles, as Visiting Associate Professor and Adjunct Professor, respectively. Their arrival around January 1, 1980 marked the effective beginning of the Hawaii DUMAND Center. Of the UH physics faculty, V.J.Stenger and V.Z.Peterson are the most active in DUMAND, the latter being director of HDC. F.A.Harris and M.D.Jones have also participated in DUMAND activities, and two graduate students, L.R.Glen and D.J.O'Connor are commited to DUMAND physics.

From late 1979 to September 1980 the DUMAND staff was augmented by Dr. Donald McGibney, on leave from the Center for Naval Analyses, who took a major part in experimental investigations of wavelength-shifting sensors.

Ocean-related DUMAND activities in Hawaii have been coordinated by Prof. Jim Andrews (UH-Oceanography), principal investigator of the initial ONR DUMAND grant. Prof. Andrews is now on leave to ONR, and Prof. Dick Stroup has assumed responsibility for the project. Marine biologist David Karl, (UH-Oceanography) has also participated actively in DUMAND efforts, most recently in making a DUMAND presentation to the director of NSF.

Frequent visitors to HDC on DUMAND problems include Profs. D.B.Cline, U. Camerini, and R. March from Wisconsin, and H. Bradner from Scripps. The Oregon State team of oceanographers, led by Prof. Ron Zaneveld, has played an active role in deep ocean light attenuation studies. Many short-term visitors, from government laboratories, universities, and commercial companies, have contributed their time and expertise in HDC-sponsored workshops on signal processing and on deployment.

The support staff for HDC effort is provided in part by the existing staff of the UH High-Energy Physics Group. This includes computing, electronics, and secretarial support. Additional technical support from the Hawaii Institute of Geophysics (HIG) Engineering Support Facility has been helpful in the development of optical sensors, and for technical assistance on the design and construction of the muon string.

Space for offices and laboratory work has been provided in the physics building, including offices and laboratory space. Additional facilities are used at HIG, and miscellaneous university services as well.

3. SITE STUDIES 1980

We summarize here the results of environmental studies of the DUMAND sites, which have been supported by ONR through contracts with Scripps, under Prof. Hugh Bradner, and with the Hawaii Institute of Geophysics, under Prof. J. Andrews.

Three cruises of the UH Research Vessel Kana Keoki were made during 1980 in support of environmental studies at the candidate DUMAND sites. Prior to 1980 bathymetric, structural and sediment data had been obtained for the Maui Basin site[1]. In 1980 similar data was obtained for the Keahole site. Also carried out during 1980 were vertical profiles of optical transmission in 6 wavelength bands, hydrocasts for measurement of suspended particulates, and 8 months of moored currentmeter and transmissometer monitoring near the sea floor in both basins. Recent work has been focussed on the Keahole basin as the prime DUMAND site.

Bathymetry and structure - The Keahole Basin has a flat floor with a 4800m closure. The structure is similar to that of the Maui Basin with a thick (>600m) fill of acoustically stratified sediments. The inner part of the basin, at the base of the island slope is occupied by a field of large boulders. These appear on the echo-soundings and seismic profile as a region of irregular depth with multiple hyperbolic echoes. Direct observation of the zone by personnel of NOSC identified the source of these returns as a boulder field.

Sediment - The basin sediment is largely island derived occuring as silty clay with interspersed ash layers. There was no identification of turbidities in the cores collected but from grain size and mineralogy it is clear that there is considerable down slope transport.

Transparency - Vertical profiles were made in both basins with a multispectral transmissometer, contributed by an Oregon State University group under R. Zaneveld[3], that uses a lm collimated path and 6 wavelength bands between 400 and 650 nm[2,3]. At all depths below 200m water clarity was equal to the clearest ocean water measured to date. Attenuation lengths (1/e) were >40m in the blue-green., at great depths (ca. 4km.). An instrument using uncollimated light sources, with a variable path length up to as much as 84m, developed by Bradner and Blackinton[4], was used in the Keahole Basin and gave values of 30 ± 5m at 1000 and 1500m depths.

Moored transmissometers with a lm collimated light path operating in the red (660 nm) were emplaced with the deep current meters in both basins at 10m above the seafloor. The Keahole instrument detected a small nepheloid layer reaching to 300m above the seafloor. During its deployment, a decrease in collected light at both sites was observed - 19% in two months at Keahole and 6% in three months at Maui. These changes - especially at Maui - are compatible with estimated sedimentation rates. At 3800m depth at Keahole hydrocast samples showed 20-50 μg/l of particulate material.

Currents - The current meters were moored at 10m and 150m above the seafloor at both sites. Measured currents did not exceed 11 cm/sec (1 hour average) at either site, and were normally in the 4-5 cm/sec range. The dominant spectrum was the semidiurnal tide. The average drift at the Maui site was 2 cm/sec over two months. Keahole was comparable although no directional data was recorded.

The environmental parameters so far measured appear compatible with array design possibilities. Long term monitoring of the environment is required to confirm this as little deep ocean data exists at the time span of interest. Bioluminescence, fine scale turbulence and biofouling (deep sea bacterial growth) and surface absorption of nutrients are critical areas for future work.

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4. MONTE CARLO ARRAY STUDIES.

Monte Carlo studies have been of great importance to DUMAND from the earliest stages. Serious efforts were started by Roberts in late 1977 and early 1978 to determine whether a DUMAND array could not only detect muons, but also measure their direction and energy[1]. By the summer of 1978, it was clear that these quantities, and corresponding quantities for cascades, could be measured well enough to allow the measurement of the y-distribution of inelastic neutrino scattering at energies up to 5-10 TeV[2]. Thus the first application of Monte Carlo techniques was to studies of possible experiments.

The application to optimization of DUMAND arrays was initiated by Stenger in 1978, and his initial results reported at the Kyoto cosmic ray conference and the Khabarovsk meeting[3,4]. Following the establishment of the HDC, this work was greatly accelerated and expanded, and a considerable number of studies have since appeared[illegible]. Until the end of 1980, these were primarily concerned with the detection of muons and of ν_μ, which constitute about 97% of the neutrinos produced in the atmosphere by cosmic rays, and a somewhat smaller fraction (it is believed) of the as yet undetected extraterrestrial high-energy neutrino flux.

Studies of the detection of electron and tau neutrinos are just beginning. Their importance will depend on whether or not there exist neutrino oscillations. If they do exist, extraterrestrial neutrinos can be expected to be in equilibrium, and their flavor will convey little or no information concerning their source. DUMAND can detect neutrino oscillations over a wide range of L/E (see Sec. 9), and thus this question may be answerable.

The purpose of array studies during the past year was the optimization of muon and ν_μ detection; how well they have succeeded can be seen by examining the successive DUMAND arrays which have been studied as heuristic models. The first DUMAND arrays studied were (a) DUMAND G, the 1978 Standard Array, and (b) DUMAND G′, the same array as modified by the introduction of Sea Urchin; these were not computer-modeled. Computer modeling was first used for DUMAND G2[9], a very large array, with wider spacing, using measured values of water transparency and Sea Urchin detectors. Fig. 4.1 shows these arrays. With computer modeling, major economies begin to appear.

Many additional configurations have been studied since then, and the most recent results of such studies, to date, are the three arrays shown in Fig. 4.2, now known as MIDI, MINI, and MICRO. MINI is an array with narrow (15m) spacing. Now, the Monte Carlos have shown that for the detection of muons above 100 GeV or so, there is no advantage in narrow spacing; the only reason found to date to justify narrow spacing is the measurement of the direction of cascades. Widely spaced arrays (50m) allow cascade detection and a rough determination of cascade energy. These studies are still in progress.

Fig. 4.3 shows the progression of DUMAND array cost estimates as continuing studies provide improved estimates of array performance. The most significant advance achieved during the past year was the discovery that even with widely spaced strings, a narrower spacing of sensors in the z-direction (along the string) would allow the substitution of low-sensitivity sensors (13" hemispherical-cathode PMT's) for Sea Urchin, at a great savings of cost, difficulty, and time, and with little loss in performance[8]. That single advance is expected to save us a year or more in construction time, and very significant amounts of money as well.

Fig. 4.4 shows the angular sensitivity of MICRO.

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9. Proposed Modification of DUMAND G: DUMAND G2, by A. Roberts and G.A.Wilkins, DUMAND 1980, 1, p. 116.

FIRST ATTEMPTS AT ARRAY DESIGN

ARRAY NAME	DUMAND G (1978 STANDARD)	DUMAND G′ 1979	DUMAND G2 1980 (MAXI)
PROPERTY Mass, Tons	$1.3x10^9$	$1.3x10^9$	$0.7x10^9$
No. of Sensors	22,695	22,695	6615
Sensor Type	Cylindrical WLS	Sea Urchin	Sea Urchin
Sensitivity (stengers)	2.5	6.	6.
Sensor Spacing,m	40	40	50
Array floor plan	800m hexagon	800m hexagon	1000m rhomboid
Array height,m	1000	1000	1000
Volume Gain for Detection of 2-TeV neutrinos (1TeV muons):			
Gain Factor	2.1	2.1	2.7
Effective Vol.,m^3	$2.8x10^9$	$2.8x10^9$	$1.9x10^9$
Counting rate, muons of 200 GeV and above from atmospheric neutrinos:			
Events/year	$3x10^5$	$3x10^5$	$2.1x10^5$
Normalized Minimum Detectable Flux (MDF) of Extraterrestrial Neutrinos of 1 TeV and above, neutrinos/cm^2 sec:			
MDF	$0.8x10^{-10}$	$0.8x10^{-10}$	$1.x10^{-10}$
Angular Accuracy of Muon Direction,mr	5	5	5
Estimated Cost, $M	89.	54.	19.

Fig. 4.1

ARRAYS CURRENTLY UNDER CONSIDERATION

PROPERTY	MIDI	MINI	MICRO
Ground Plan	500x500m	150x150m	250x250m
String Spacing	50m	15m	50m
No. of Strings	121	121	36
Sensor	13" PMT	13" PMT	13" PMT
Vertical Spacing	25m	15m	25m
Vertical Ht.	500m	300m	500m
Sensors/String	21	21	21
Total No. of Sensors	2541	2541	756
Volume, Cu. M.	1.25×10^8	6.7×10^6	3×10^7
Array Radius, km	.25	.075	.125
Volume Gain for Detection of 2-TeV Neutrinos	6.15	22.2	12.5
Effective Vol. m^3	$.8 \times 10^9$	$.15 \times 10^9$	$.4 \times 10^9$
Counting Rate, Muons from Neutrinos of 200 GeV and above: Events/Year	5×10^4	1×10^4	3×10^4
Normalized Minimum Detectable Flux (MDF) Neutrinos/cm^2 sec MDF	2.5×10^{-10}	1.5×10^{-9}	6×10^{-10}
Angular Acc. mr	5	12	15-50
Cost, Estimated	\$10-15M	\$5-10M	\$3.5-7M

Fig. 4.2

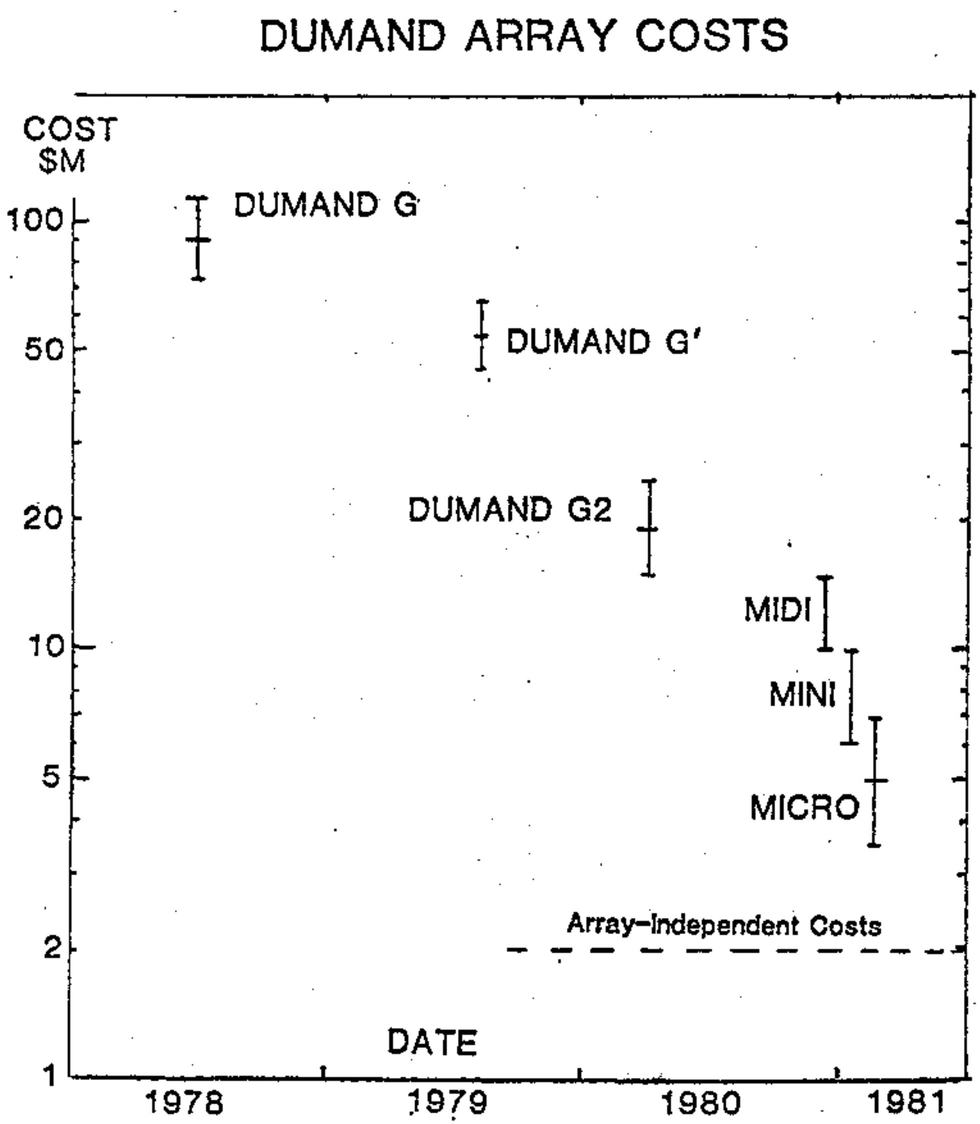

Fig. 4.3

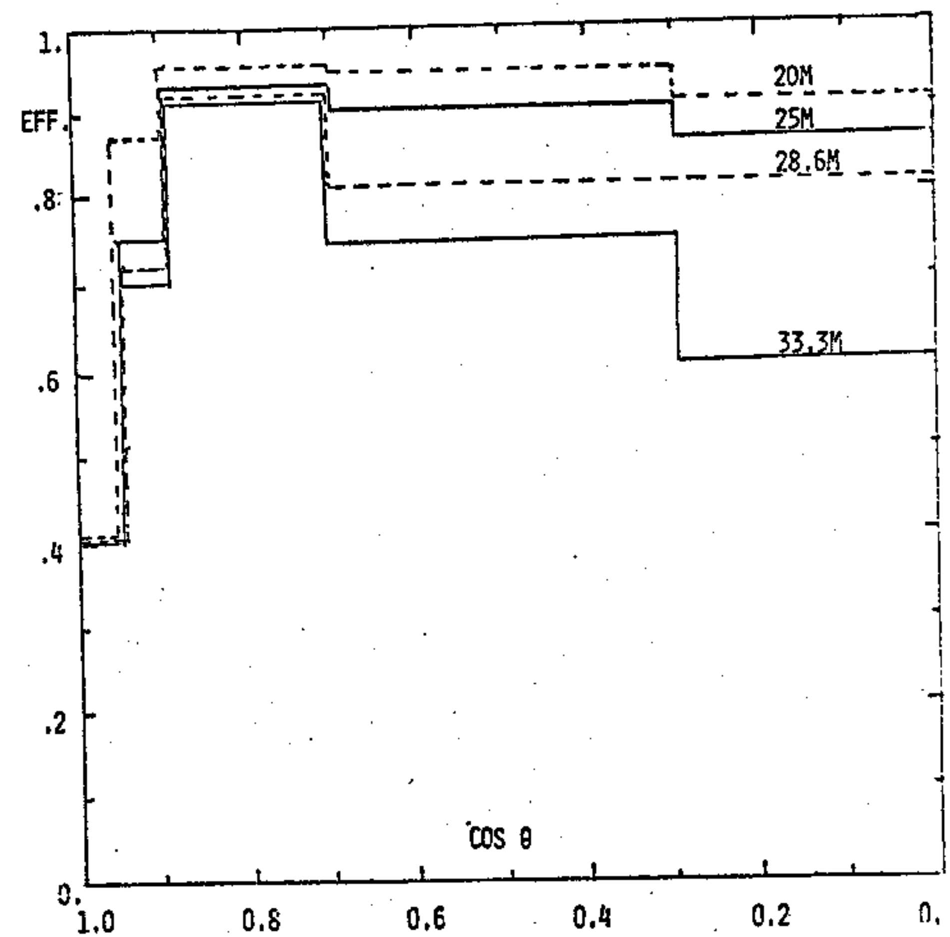

Fig. 4.4 Efficiency of detection of the MICRO array, as a function of zenith angle θ and sensor spacing; the 5 curves shown are for sensor spacings from 20 to 33.3m. The larger spacings show decreases in efficiency for muons near the horizontal. All show the "hole" near θ = 90°. Muons just above minimum ionization were used; the curves are valid down to 200 GeV or less; at higher energies, efficiencies should increase.

5. DEVELOPMENT OF OPTICAL SENSORS.

Development of optical sensors has proceeded along two major lines. First, considerable effort went into basic component studies, and later initial model testing, of a "Sea Urchin" wavelength-shifting optical sensor. Other types of wavelength-shifting sensors (WLS) were also actively studied, on paper, by computer, and in the laboratory, but it was finally concluded that the Sea Urchin is nearly optimal as a WLS sensor.

In parallel, work on phototubes was carried on at DUMAND and by the proton decay groups, testing PMT's from various manufacturers, and working with them to develope new large area PMT's. This work, which included computer simulation of PMT electron optics, has now borne fruit, and several new tubes are becoming available. Other things being equal, direct-view tubes are preferable to WLS detectors because of simplicity.

A. Light Collectors.

While light collectors have been discussed before (see Proceedings of '79 and earlier DUMAND meetings) the one with most promise was Sea Urchin[1-4], so named because of its appearance (See Fig. 5.1). The high efficiency results from an excellent phase-space match between the light emitted from the ends of the spines and the PMT cathode centered in the pressure housing (see Fig. 5.2). Originally it was hoped that optical gains as high as 25 could be achieved; in practice[4] they did not reach 10.

Initial work at HDC centered on spine materials. It was hoped that relatively rugged plastic spines, doped with fluor, could be used, because of their durability. They turned out to be expensive, not sufficiently transparent, and subject to aging and crazing. Hollow glass tubes filled with solvent and fluor were the best and least expensive solution. Efforts at optimization resulted in the selection of toluene as solvent, and Hostasol BG, a commercial proprietary fluor[3], as solute. Details of these experiments are given in references 1-4.

As part of the development work, the quantum efficiency of the fluor was determined[4], and the optical efficiency of the system determined by direct measurement[4]. The observed efficiency was less than that predicted by the Monte Carlo program[2] we had written to study spine optics. This, we believe was due to the failure of the program to take into account reabsorption and reemission of fluorescent light in the fluor, which occurs because the fluorescent emission spectrum overlaps the absorption spectrum.

Among the engineering problems considered (of which some were solved) were the problem of pressure equalization on the spines, using a sliding free piston; attachment to the sphere, folding for transportation, etc. A half-scale model was constructed and is still available for additional testing if needed.

The conclusion of the experimental work, mostly carried out by D.

McGibney and A. Roberts, was that a sensor with sensitivity about 6 stengers (equivalent to a PMT cathode of area $0.3m^2$) could be manufactured for about $1500, would weigh about 1.5 tons in air, and -200 lb in water, and would fold into a volume of 1m diameter, 3.5m long. The difficulties of deploying this size module are discussed in sec. 8.

Because of concern over the size and complexity of Sea Urchin, a search was made for other detector geometries approaching its efficiency, and competitive in cost. None were found[5,6]. Monte Carlo studies were equally fruitless.

B. Phototubes.

For several years DUMAND members (particularly J. Learned) have been in touch with PMT manufacturers, seeking to stimulate construction of large area photocathode tubes with modest timing accuracy (several ns) and low cost.[7,8] These efforts were helped enormously by the requirements for such tubes for proton decay experiments. The Cleveland group purchased 2400 5" PT's from EMI; from studies of them it fed back much information to the manufacturers, and also to Hamamatsu in Japan, who are also making large area tubes. That cooperation has resulted in a 13" PMT, expected shortly from EMI. (See Sec. 7). Hamamatsu, under similar stimulation from a Japanese group as well as DUMAND, has produced a sample 20" diameter PMT. Either of these tubes will be adequate for DUMAND arrays (see Sec.4). They will be much more effective if they can be made with high-gain first dynodes that allow one-electron noise pulses to be distinguished from larger signals. Hamamatsu had succeeded in making such tubes; EMI is not yet certain of them. RCA has successfully manufactured them for many years.

Mechanical and electrical packaging problems do not appear to offer serious problems (though no manufacturer, as of now, regularly produces pressure envelopes large enough for a 20" tube.) The experience of the proton decay experiments continues to be of considerable value to us, in terms of evaluating the performance and reliability of large numbers of tubes.

In sum, we have now developed adequate light collectors; prototypes will soon be tested in the muon string, and given PMT's of the type discussed, we have a solution adequate for presently contemplated DUMAND arrays.

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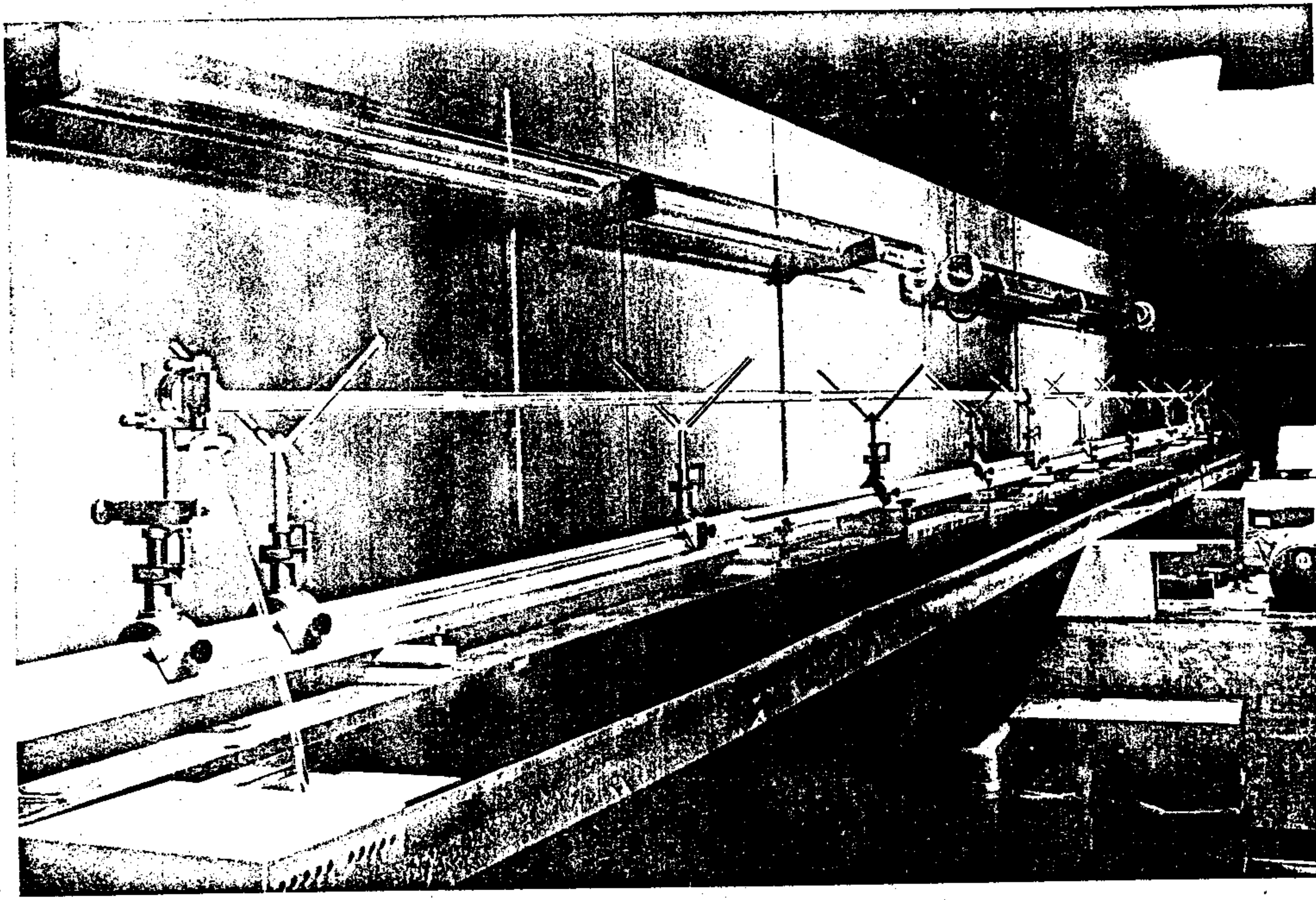

Fig. 5.1 Laboratory set-up for test of wavelength-shifting light traps. Spines from 1 to 10m in length and 1 to 10 cm in diameter were studied.

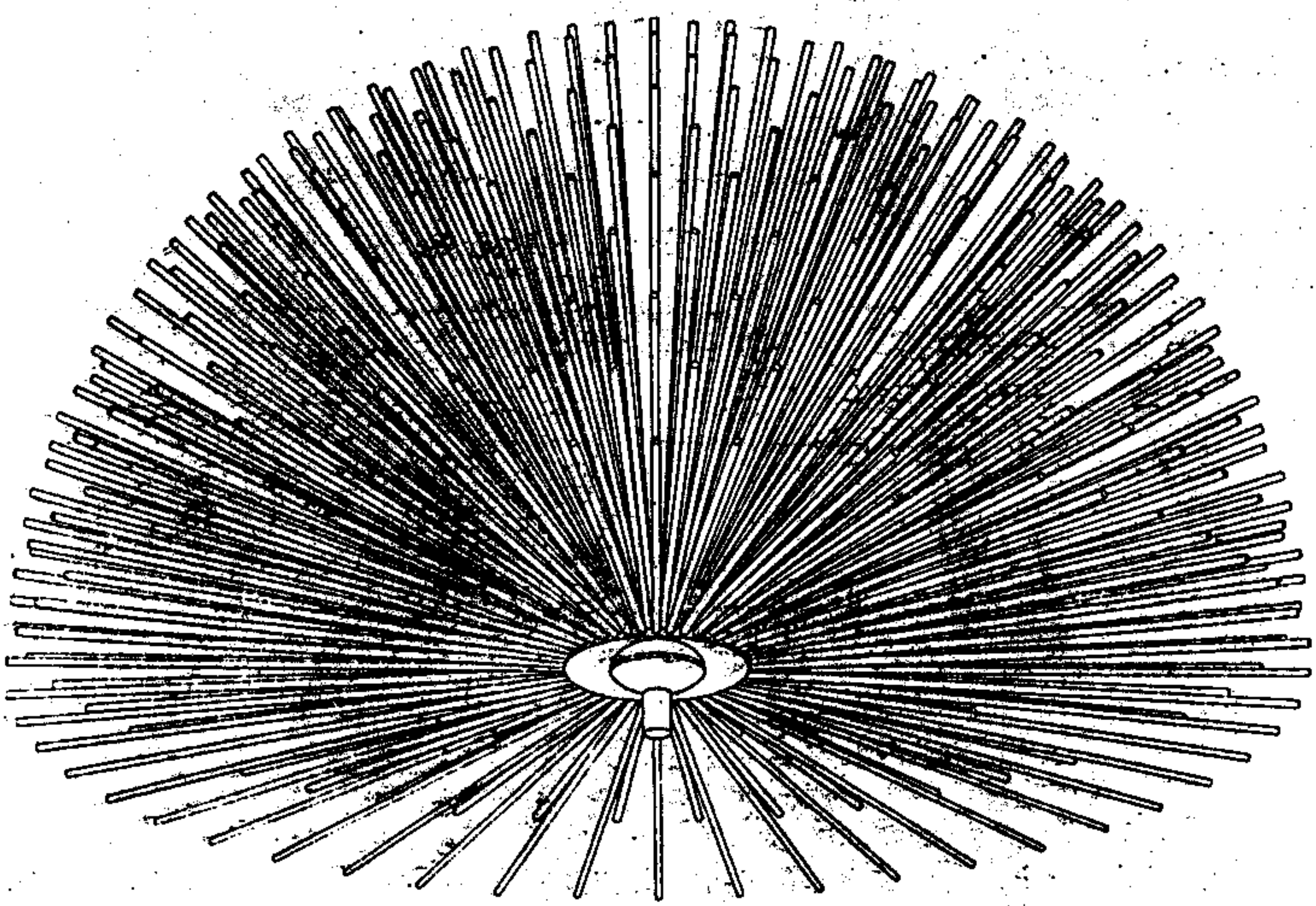

Fig. 5.2 a). Drawing of Sea Urchin, showing hemispherical configuration and relation of phototube to spines.

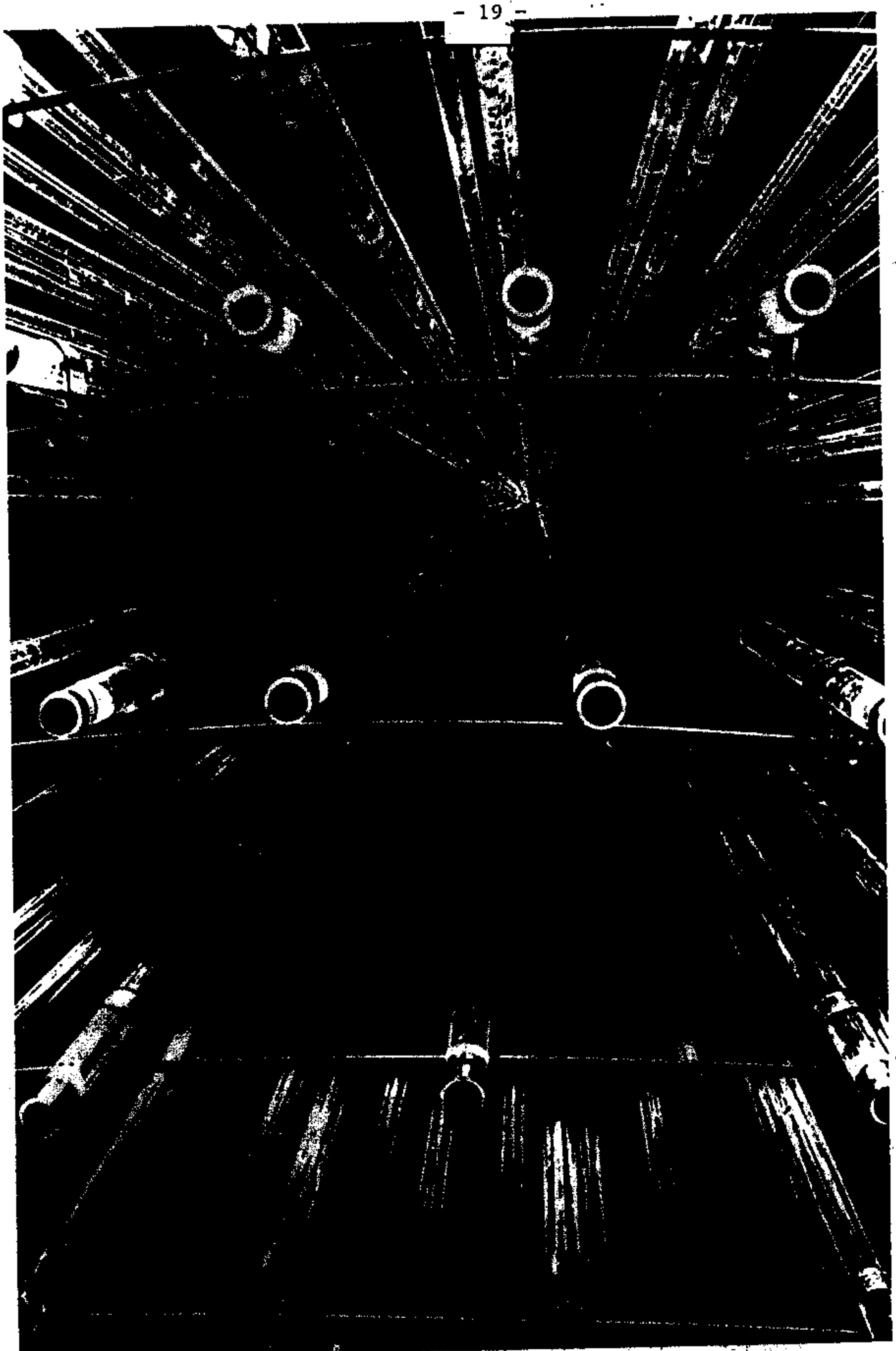

Fig. 5.2 b) Photograph of part of half-scale model of Sea Urchin. Spines are held by assembly jig. Tubes are sealed with mirrored free piston plug.

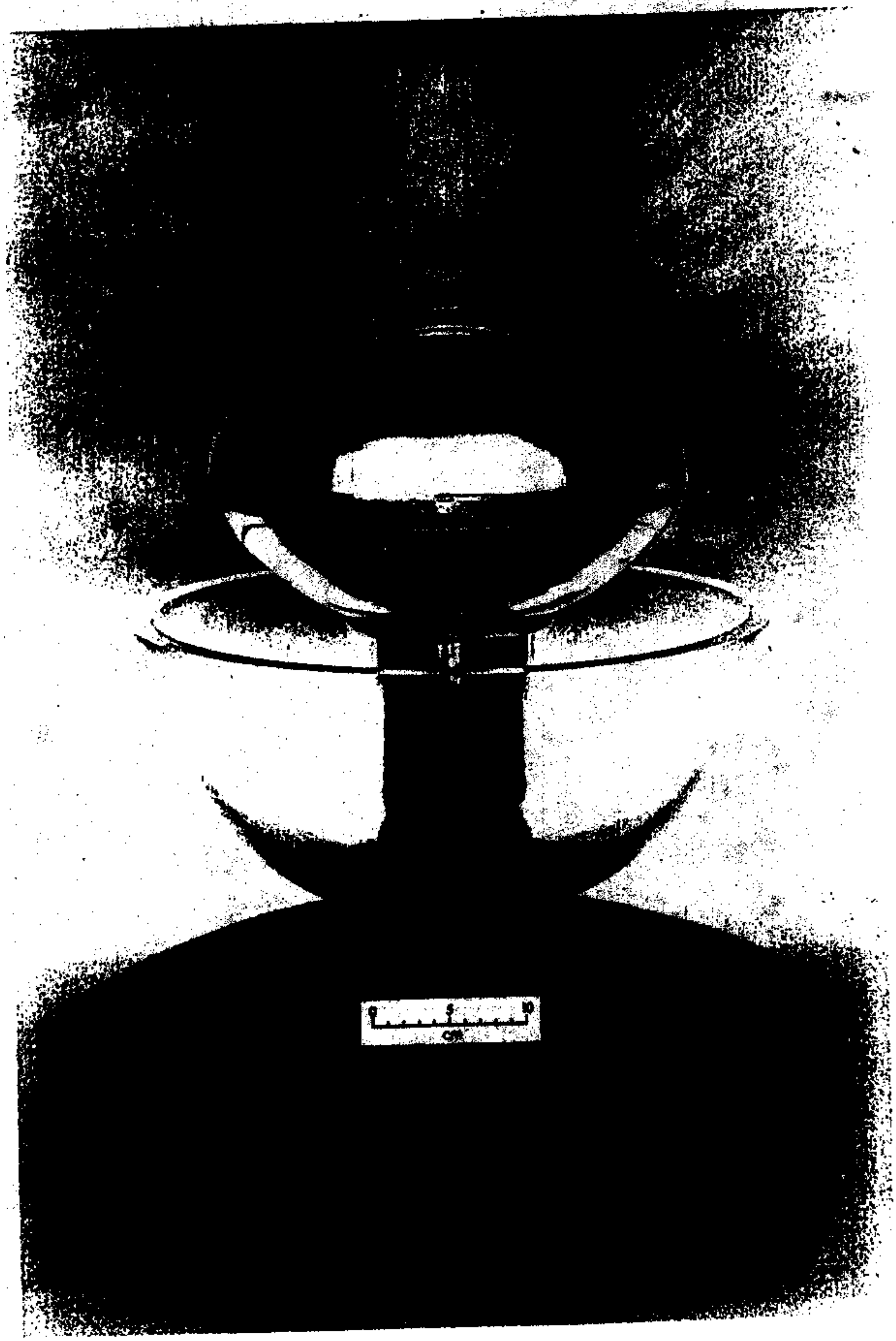

Fig. 5.3 Photograph of 13" EMI hemispherical-cathode photomultiplier tube installed in a 17" Benthos pressure sphere housing; the top hemisphere is removed. Cable entry and electronics are at bottom.

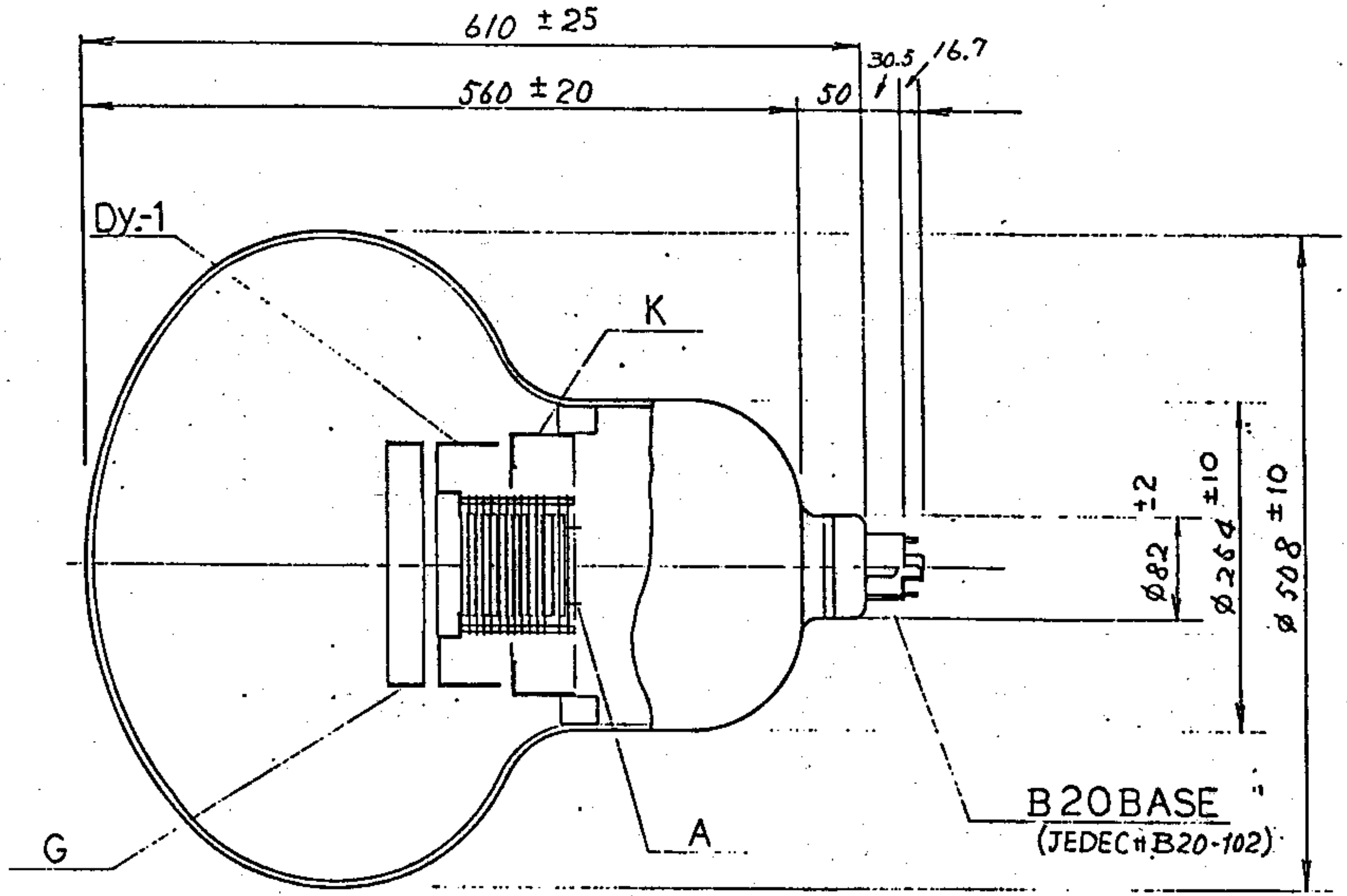

Fig. 5.4 Outline of the new Hamamatsu 20" photomultiplier.

Unit : mm

R1449x (20"PMT)

6. SIGNAL PROCESSING

In February, 1980, a signal-processing workshop was held at the Hawaii DUMAND Center in Honolulu. A group of 22 physicists, communication engineers, marine engineers, cable specialists, and photomultiplier engineers considered the unique signal-processing problems of DUMAND. Attendance was sponsored by the home institutions of the conferees. The proceedings, edited by A. Roberts, appeared in June.

The workshop considered the most difficult of all possible DUMAND signal-processing problems: the instrumentation of the original 1978 Standard Array, DUMAND G, with 22,695 sensors. It was asked to consider the problems of collecting, filtering, encoding, recording, and analyzing the data to be received, including high individual sensor background rates and an estimated 40 through-going muons per second.

Three distinct types of data-processing approach were suggested. Whether they would all be practical with the "MAXI-DUMAND" as described above is not known; but at least one of them would. That question now appears moot in any case, with the rapid improvement and simplification of DUMAND arrays. Present DUMAND concepts envisage well under 1000 sensors for the first DUMAND array, and 6600 as an upper limit. At that level, probably all three approcahes will work, though perhaps not equally well.

One of these concepts, the simplest in principle (and modestly dubbed the "dumb" array by its author, G. Wilkins) envisages all data from the array being transmitted to shore and analyzed there. This approach has only recently become feasible, with the advent of practical optical fiber data transmission systems with gigabit capacities, using relatively inexpensive cables and components.

This approach has important advantages. It minimizes electronics on the ocean floor. It minimizes — perhaps eliminates — electronics at critical junction points where a failure would disable an entire string of sensors, or even a row of strings. We can now try to design all the electronics to be either ashore or in the individual sensor module. From a reliability standpoint, this is the best arrangement, since an ocean bottom electronics failure can at most disable a single sensor module.

As a result of the workshop, we no longer have any serious concerns about the data-processing problem, which the previous year we had regarded as one of DUMAND's major unsolved problems. None of the experts present at the workshop dissented from this view.

7. MUON STRING.

During the first year of the HDC we spent some time converging on a first (ocean) particle detection experiment. Several designs were discussed and rejected.[1,2] Finally it was realized that the newly produced 13" hemispherical phototube of EMI (in the spring of 1980) made possible a substantial and simple underwater muon counting experiment. We wanted an on-line experiment that would be retrievable in order to learn to cope with the environment and make the necessary iterations as we gained experience. Lowering the detectors from a ship seemed a good start, and five detectors in a vertical string proved the simplest useful configuration.[3]

As Monte Carlo calculations have shown, this instrument should have an impressive effective area for muon detection, >700 m^2[4]. Previous underwater detectors have had only several square meters area[5,6]. Until recently the largest underground detector, the CWI detector in South Africa, had an area of ~110 m^2. The largest of the new generation underground detectors (the Cleveland proton decay experiment) has ~400 m^2 muon detection area. Thus this detector, with a mere 5 large photodetectors in the ocean, can extend the upper limit of the measured cosmic ray spectrum, and increase statistical precision in cosmic ray muon depth-intensity measurments.

Moreover, much of the imprecision of previous underground work is due to uncertainties in overburden density and composition[8] (which enters exponentially in the range), whereas under the ocean we should be able to monitor the pressure to more than ten times better precision (to 0.1%, compared to ±5% underground).

The experiment will also be able to measure some of the characteristics of the angular distribution, depending upon the time resolution that is actually achieved by the photomultipliers. Fig. 7.1 shows a sketch of the muon string and its associated equipment. Figure 7.2 shows the depth-intensity distribution expected between 1 and 5 km depth. Figure 7.3 shows the intensity as a function of angle for various depths. Figure 7.4 shows a cross-section of one of the five detector modules. Table 7.1 indicates a possible schedule for a 10-day data taking sequence that would achieve better than 1.2% statistical uncertainty in the total rate down to 4.9 km depth, and better than 7% statistical uncertainty in the largest useable angle bin (60°-75°) at 3.0 km.

At first it was hoped that the detectors could be operated with little electronics in the ocean, but lacking a fiber-optics cable with sufficient mechanical strength and electrical power handling capability (next year, perhaps) we were forced to utilize coaxial cable. We have borrowed an armored 5.7 km RG-8 equivalent cable from the Marine Physical Laboratory at Scripps.[9] The cable losses will permit a bandwidth of several megahertz, at most. Thus we were forced to design a system with fast electronics in the ocean.

We decided to use off-the-shelf, modular, high-energy-physics style electronics (CAMAC) placed in a pressure housing as shown in Fig. 7.1. The housing design, utilizing six 22" diameter, aluminum hemispheres placed on opposite sides of three holes in a 2′ x 6′ x4" aluminum plate, was originated by

H. Bradner at Scripps for ocean bottom seismometry some years ago. We have borrowed the hemispheres from Bradner and the plate is at present being machined under the supervision of U. Camerini and colleagues at the Physical Science Laboratory at the University of Wisconsin. We should also note help on software from R. March of Wisconsin, and other laboratory and electronics help from F. Reines' and J. Schultz's groups at U.C. Irvine.

An overall block diagram is shown in Fig. 7.5. We plan to use microcomputers at the surface station and in a "smart" crate controller below. Both power and communications will be transmitted via coaxial cable; the former as high voltage (1 kV, 60 Hz) and the latter as high frequency (fsk) coded digital data.

The modems will handle 1 megabaud (DMA) transfer rates. This rate is greater than required for the problem but puts the communications channel well away from the power supply sidebands, and will simplify programming as well. Both computers are of the type LSI-11/2 (Terak on top and Interface Standards below), so that much high energy physics experience and some software can be utilized. In fact we plan to use the Fermilab "Multi" system for experimental control at the surface. The decision to use these computers and programmable logic has directed much of our local effort to software. This decision was made to speed construction, to create a system that could evolve as we gain experience operating in the ocean, and to acquire a system that would be reusable in other situations.

As of this writing (4/81) 95% of the electronics is on hand, as are the pressure housings and cables for the phototubes; and most mechanical and electrical hardware has been designed and constructed (e.g. the portable frame to support the 1000-lb electronics package, etc.).

A major outstanding problem is the actual deployment of the string. At first we planned to use the Kana Keoki, the HIG research vessel. However, in January we learned of the availability of a vessel called the "ORB" (for Oceanographic Research Buoy) which belongs to MPL in San Diego. This 21.3m x 13.7m barge can be (and has been) moored in deep water, has a dry center well with motion-compensating winch, and has crew facilities (for up to 20), lab space and power more than adequate for our needs. Indeed it seems to be nearly an ideal vessel to moor at the Keahole site for a month-long period, and from which to collect data. Negotiations are still in progress, but it is possible that ORB will be transported to Hawaii by the U.S. Navy in early July. Failing this, the next time window for shipping ORB to Hawaii will be six months hence.

Other than muon counting, the string should observe an average of one upcoming muon from neutrinos per 2.5 days and thus make the first underwater neutrino observations. Other types of events (cascades, etc.) will be observed but the spatial resolutions of the instrument will not permit distinguishing these. One "far out" type of observation may be possible, in that we plan to deploy a CCD TV camera along with the other instruments. Given a sufficiently luminous event (say of the "anomalous cascade" type observed at the Kolar gold fields[10]) we may be able to image the interaction.[3] Extrapolations indicate a possible observation frequency of 1/20 days.

The detector will also make (perforce) observations of ocean backgrounds. The irremovable background of K^{40} decay induced light will provide a built-in calibration and stability monitor. We will also utilize "internal" calibrations from various rates[4], plus LED strobes and radioactive sources on each photodetector to provide redundant calibration, including effective ocean transparency[11]. The detector will be the most sensitive light sensor ever lowered into the ocean, and will thus enable us to do unprecedented studies of bioluminescent background light (if it is present). In order to explore the unknown time structures and density of such backgrounds we will utilize a programmable waveform digitizer that will function as a remote multichannel storage oscilloscope allowing us to take snapshots of pulses, observing their temporal nature and somewhat of their physical extent. If they are bright enough we may be able to obtain images of them with the CCD TV. (Later versions of the string could easily carry a strobe light and high resolution camera if that is warranted).

In summary, we have designed and are constructing an underwater experiment to be operated during 1981 in the ocean near Hawaii. The detector should be able to produce new and interesting cosmic ray results, make the first underwater observations of neutrinos, conduct a search for "anomalous cascades", study in situ ocean background, and make unprecedented sensitive deep ocean observations of bioluminescence, - all in addition to providing invaluable ocean experience for both the equipment and the experimenters.

TABLE 1

A 10-day data acquisition schedule for a 700 m^2 effective area muon string. Count rate totals at each 8 depths are shown with resulting statistical errors. Also shown is worst useable angular bin (60^o-75^o).

WATER DEPTH (KM)	EQUIVALENT ROCK DEPTH (KM)	PROPOSED DATA COLLECTION TIME (DAYS)	ALL ANGLES			60^o-75^o		
			RATE (1/s)	# COUNTS	STAT. ERROR (%)	RATE (1/s)	# COUNTS	STAT. ERROR (%)
.93	1.0	.06	19.5	1.01×10^5	.31	1.22	6.3×10^3	1.26
1.42	1.5	.13	4.68	5.26×10^4	.44	.192	2.2×10^3	2.2
1.96	2.0	.40	1.45	5.01×10^4	.45	.0389	1.3×10^3	2.7
2.50	2.5	.50	.523	2.26×10^4	.66	9.22×10^{-3}	400	5.0
3.09	3.0	1.00	.208	1.80×10^4	.75	2.42×10^{-3}	209	6.9
3.68	3.5	1.50	.0891	1.15×10^4	.93	6.82×10^{-4}	88	10.6
4.30	4.0	2.00	.0402	6.95×10^3	1.2	2.04×10^{-4}	35	16.8
4.88	4.5	4.50	.0189	7.35×10^3	1.2	6.35×10^{-5}	25	20.0
	TOTAL	10.09 DAYS						

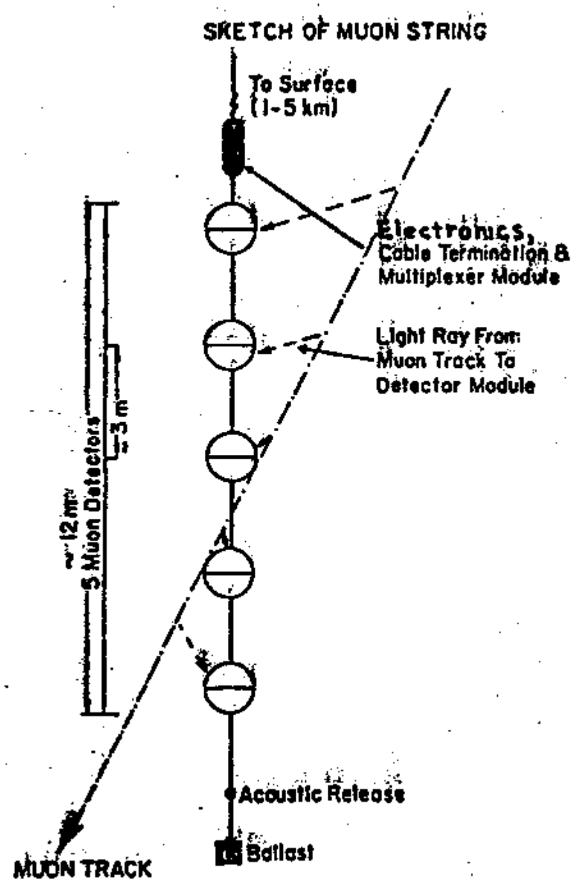

Fig. 7.1. Sketch of the muon string.

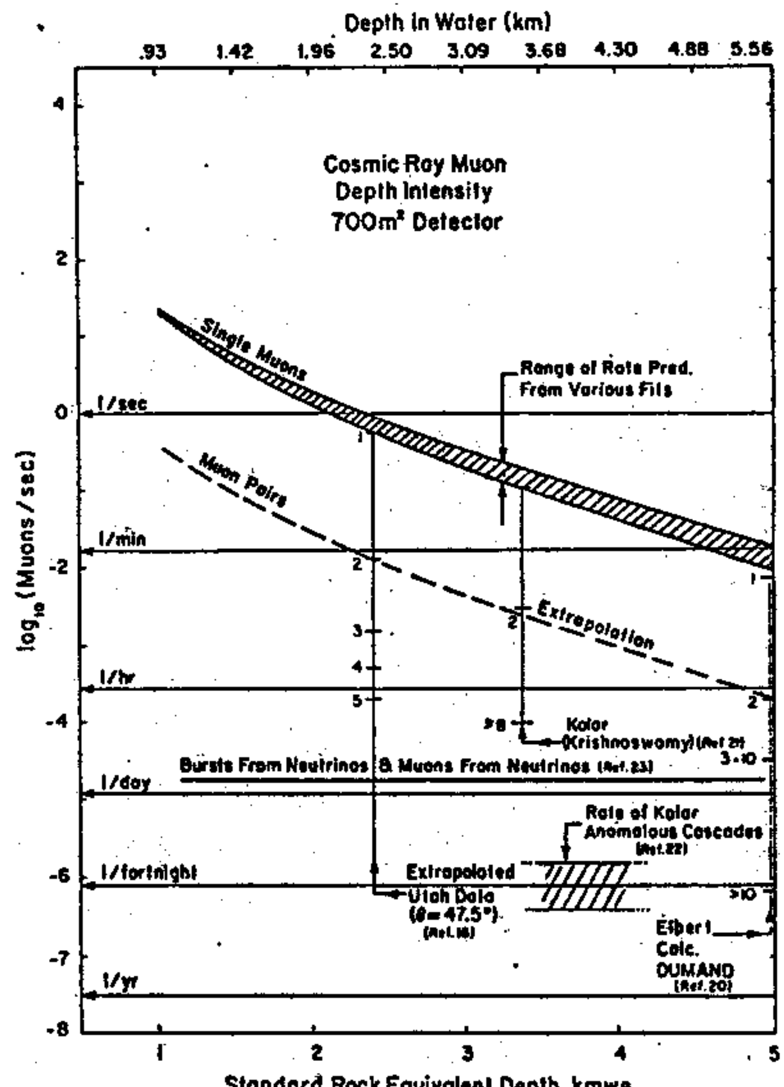

Fig. 7.2. Cosmic-ray muon intensity vs. depth.

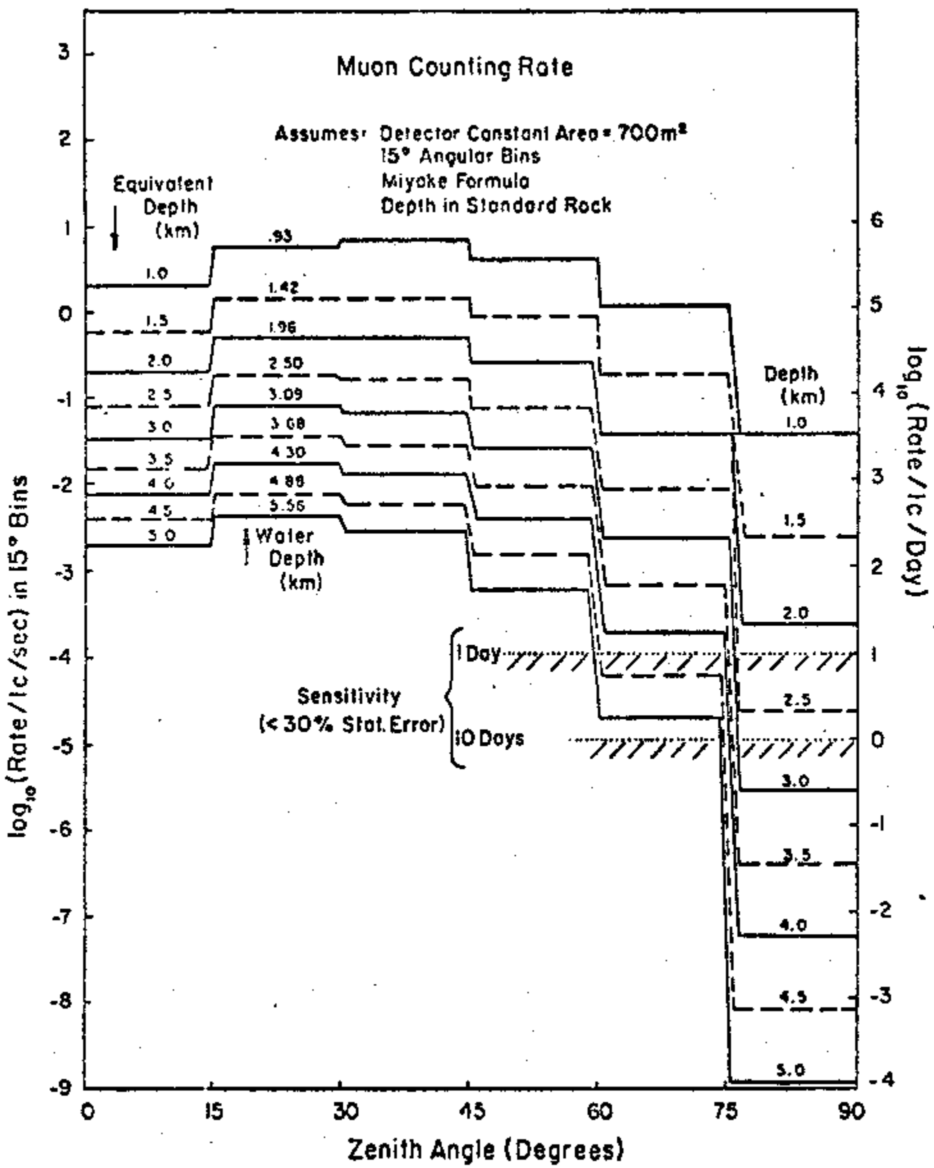

Fig. 7.3. Cosmic-ray muon intensity vs. angle at several depths.

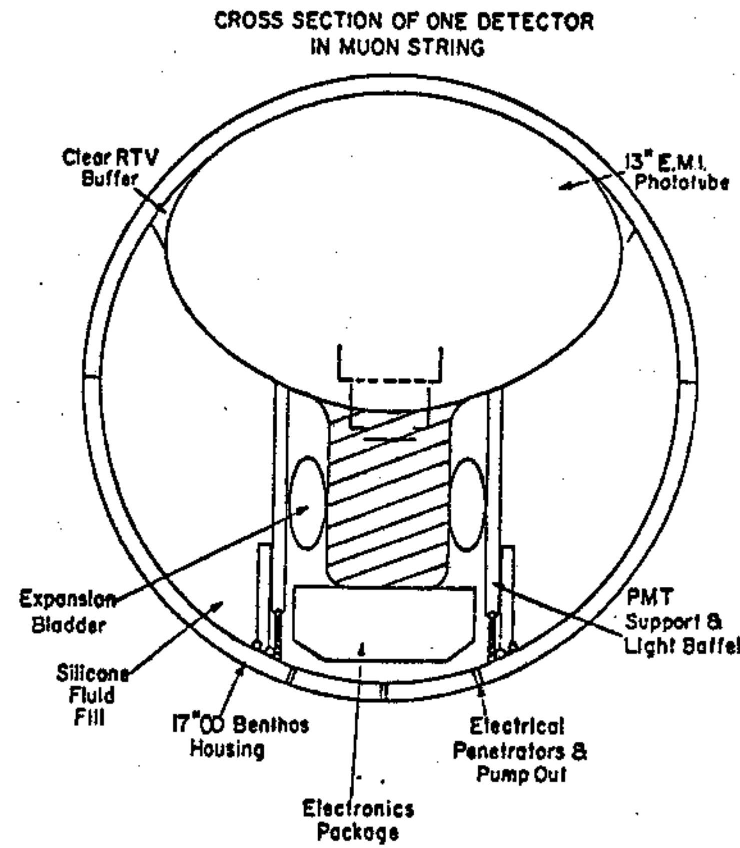

Fig. 7.4. Cross-section of a single detector module: a 13" PMT housed in a 17" Benthos glass sphere.

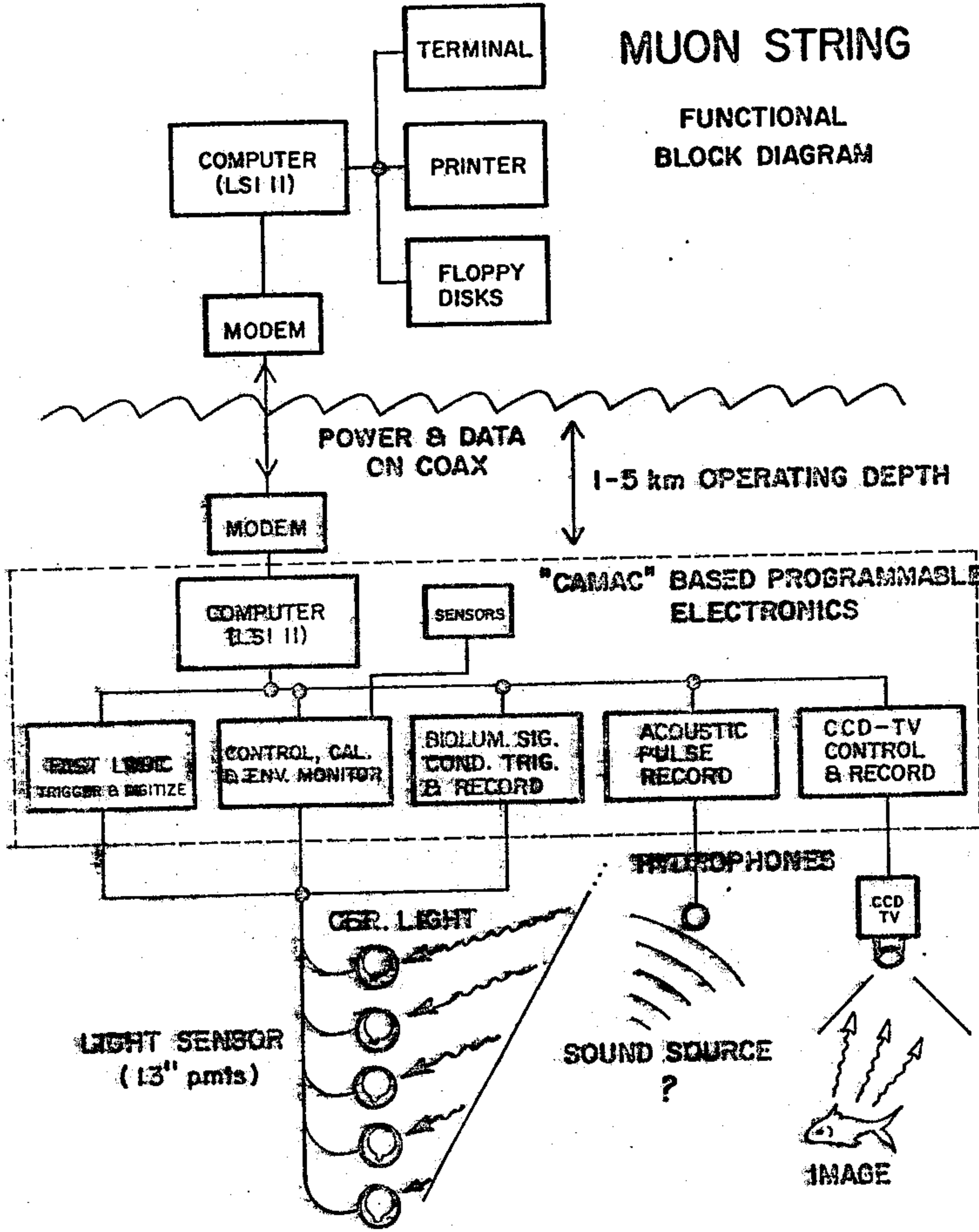
MUON STRING
FUNCTIONAL
BLOCK DIAGRAM
TERMINAL
COMPUTER
(LSI II)
PRINTER
FLOPPY
DISKS
MODEM
POWER & DATA
ON COAX
1-5 km OPERATING DEPTH
MODEM
"CAMAC" BASED PROGRAMMABLE
ELECTRONICS
COMPUTER
(LSI II)
SENSORS
TRIGGER & DIGITIZE
CONTROL, CAL.
& ENV. MONITOR
BIOLUM. SIG.
COND. TRIG.
& RECORD
ACOUSTIC
PULSE
RECORD
CCD-TV
CONTROL
& RECORD
CCD
TV
LIGHT SENSOR
(13" pmts)
SOUND SOURCE
?
IMAGE

Fig. 7.5

8. DEPLOYMENT OF DUMAND

The deployment aspect of DUMAND includes the problem of packaging the individual strings and connecting them together, in such a manner that they can be safely transported from shore to the final site, lowered to the ocean floor, and properly emplaced on the bottom. It includes anchoring the strings, releasing them from their containers, and providing means for measuring the location of each sensor at any given instant. In addition, the entire array must be connected to the cable that supplies power and conveys data to shore.

Deployment problems like this have been encountered before and solved[1]; but never on the scale, or for the period of operation DUMAND envisages. DUMAND therefore poses a challenge to ocean engineers.

The first deployment workshop, a one-week seminar in 1977 at the Naval Ocean Systems Center at San Diego, was of value in orienting the ocean engineers to the problems encountered[2]. As in all later workshops, the physicists played only an auxiliary role, explaining the requirements and the limitations, and asking questions about the proposed solutions. At the first workshop, the DUMAND arrays, in retrospect, were not sufficiently well defined to allow explicit solutions; in particular, acoustic detection had not yet been excluded as the primary detection scheme, and occupied a considerable fraction of the group's attention.

At the 1978 Workshop, a definite array, the 1978 Standard (DUMAND G) was presented, and the engineers went to work on it. They came up with five distinct feasible deployment procedures, of varying difficulty and cost[3]. The least expensive was about $15M, for an array of total cost $89M. It used the tested technology of the oil industry's drill-ship. Industry and naval experts agreed on the feasibility; but the procedures required a considerable amount of activity on the ocean bottom, including plugging cables into sockets with the aid of a remotely controlled deep-water manipulator.

As the DUMAND array steadily shrank under the assault of physicists intent on reducing its cost, the deployment problem, like other problems, began to look more readily manageable. During 1980, many new array configurations were discussed, most of them considerably smaller than DUMAND G, or even DUMAND G2. (See Fig. 4.2).

By itself, this was not a sufficient change to require a new deployment workshop. However, the simultaneous development of the Sea Urchin detector[4-6], a massive high-sensitivity device with hundreds of fragile-looking glass spines protruding from it, moved many people to ask whether such structures could be deployed successfully. Eventually those voices grew loud enough so that a deployment workshop was convened.

The Workshop was held in LaJolla in December, 1980. It considered three possible deployment schemes, and rejected one. The two remaining ones are drill-ship deployment[7], somewhat modified from the 1978 version; and a "master-buoy" scheme[8], in which a cluster of "glide bodies", each carrying one complete string, is mounted around a master buoy which is lowered to just above the ocean floor. The glide bodies are then released, and glide at a predetermined angle along a trajectory that lands them in the desired location. They are then anchored and release their strings. They remain connected to the master buoy by cable, so that the master buoy becomes a central junction box. The master-buoy scheme has already been successfully used for deployments, although not on the scale envisaged for DUMAND.

Both these schemes have the enormous advantage for DUMAND that they require no underwater connections to be made, thus eliminating the need for an underwater remote-controlled manipulator. The entire array is pre-wired and connected to the cable from shore before deployment; it can therefore be monitored before, during and after deployment. The reliability is thereby increased at least an order of magnitude. The Proceedings of the Workshop have now been published.

The fears of the ocean engineers concerning Sea Urchin proved to be well founded. Even under the most favorable packaging assumptions, both Sea Urchin and a proposed substitute, a cylindrical cathode PMT of equivalent sensitivity, were so heavy and large that the string-packaging problem became very difficult. Not that deployment was impossible; it simply became more difficult and expensive, by a factor of about 3.

The alternative sensor considered by the workshop - the "low-sensitivity sensor" consisting of a single 13" PMT, was far easier to deploy, and much more rugged as well.

This conclusion was sufficiently clear to emphasize the fact that the use of large high-sensitivity sensors, of whatever sort, implied high costs of deployment. Consequently it became important to see whether there could be found ways of achieving similar results - retaining wide sensor spacing - with the low-sensitivity sensors.

As it turned out, almost immediately a substitute for the high-sensitivity sensor was found[9]. It was almost ludicrously simple; it involved using what we now call asymmetric array spacing, in which the z-separation of the sensors (i.e. their spacing along the strings) is less than the x- and y-separation, i.e. the string spacing. In the MIDI and MICRO arrays, the 50m string spacing is supplemented by 25m z-spacing; thus the array uses two low-sensitivity 13" PMT sensors for each Sea Urchin previously required. This has the effect, for horizontal tracks, of making the effective spacing the z-spacing; while for vertical tracks, it remains the string spacing. Consequently we find the array has a sensitivity "hole" in the vertical directions (as shown in Fig. 4.4) over a narrow range in which the efficiency of detection is reduced. The price is a small one, in view of the very great benefits the change confers.

One consequence of this discovery is that there no longer appears to be a requirement for a high-sensitivity detector like Sea Urchin. Far from being a disappointment, that is a welcome benefit; it saves a very great amount of engineering development, and probably advances the date of a working array by a year or so. All that is in addition to a considerable cost decrease.

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9. STUDIES OF DUMAND PHYSICS AND ASTROPHYSICS.

I. Monte Carlo Studies.

While our main work on Monte Carlo simulations has had the purpose of determining the response of arrays to muons and electromagnetic cascades, a parallel effort is designed to determine the ability of DUMAND to do useful physics and astronomy with a given array. A program has been developed which simulates neutrino events with a neutrino energy spectrum as expected from atmospheric or extraterrestrial sources and kinematic variables distributed as predicted by the "standard theory" (Weinberg-Salam + QCD). The quantities which would be measured in the array, muon and hadron cascade energy and direction, are simulated with error distributions following the results of the array Monte Carlo.

Events are generated with statistics comparable to an actual experiment, e.g., one year's data. Then, using the simulated measured quantities (E_μ, E_H, θ), we can evaluate the sensitivity of the array as a detection device with both systematic and statistical errors taken into account.

This procedure was first used in 1978 to show that, in one year's run with a 1 km^3 array, the effect of an 80 GeV W-boson would be seen as a 5σ effect in the $y = E_H/E_\nu$ distribution. This was reported by V. Stenger at Kyoto[2] and Khabarovsk[3], confirming earlier reports by Roberts[1] from a different Monte Carlo program. In 1980 it was shown that, if neutrino oscillations of the type suggested by the Irvine experiment exist, they would be detectable by DUMAND as a modulation of the zenith angle distribution of ν_μ charged current events (see Fig. 1). These results were reported at the Telemark Wisconsin Mini-conference on Neutrino Mass[4] and at DUMAND 80[5].

<u>Sensitivity to Extraterrestrial Neutrinos.</u> — The program has also been used to estimate the sensitivity of DUMAND to extraterrestrial neutrinos. These results were presented at DUMAND 80[6] and will also be reported at Neutrino 81 and at the 17th International Cosmic Ray Conference in Paris in July. They indicate that a flux of 10^{-10} $cm^{-2}s^{-1}$ above 1 TeV is detectable in moderate sized arrays. Such a flux is 3 orders of magnitude above the lower limit estimated by Berezinsky[7] for the cosmological high energy neutrino background, but about at his upper limit. A minimum flux from the region of the galactic center can be calculated with reasonable certainty[8] and is estimated to be about $2{\times}10^{-10}$ $cm^{-2}s^{-1}$ above 1 TeV in a $2^\circ{\times}70^\circ$ window. We are about at the threshold for this. So while the detection of diffuse extraterrestrial neutrinos with DUMAND is not certain, important limits will at least be set.

<u>Survey of Potential Discrete Neutrino Sources</u> — For discrete sources, neutrinos of detectable intensity at the earth translate into energy fluxes of the order of 10^{39} to 10^{40} ergs/s at a distance of 10 kpc[7]. SS433 at 3 kpc is emitting 10^{41} ergs/s. As Eichler has pointed out[9], only a small fraction of this need appear as high energy neutrinos for it to be seen with DUMAND.

Estimates for the magnetic energy loss during the early stages of pulsar formation range as high as 10^{43} ergs/s[10]. A large fraction of this energy can appear as high energy neutrinos produced in the surrounding shell. Thus supernovae in our galaxy (very rare) and the dozen or so galaxies within a few

Mpc ought to be detectable.

Even higher energy rates occur in the nuclei of active galaxies. The four Seyfert galaxies within 10 Mpc are good candidate sources. The radio galaxy Cen A at 4 Mpc has been seen in TeV γ-rays[11] and would be one of the first places to look for neutrinos. The black hole model of active galactic nuclei suggest ν production of the order of 10^{43} neutrinos/s[12]. If Cen A were such a source it would produce ≅1000 events per year at this rate. Other such sources could be detected out to 60 Mpc.

Study of Neutrino Interactions. -- More recently we have been taking another look at the capability of DUMAND to study neutrino interactions. Thus, the possibility of detecting and identifying electron neutrinos is now under study. Another problem has always been the difficulty of obtaining directional information about the hadron cascade, although energy determination to about 50% seems feasible. Some directional information, to about 100mr, is possible in a densely-packed array (15-20 m spacing) but this would be necessarily small and the event rates correspondingly low.

Another way to get directional information on the hadron system has occurred to us. At accelerator energies dilepton production by neutrinos is about 1% of all charged current events. Such events can occur outside the array and still be measured so the effective volume can be quite large. In fact, we find that there will be ≅200 dimuon events per year detected by a moderate sized array (such as MICRO). Not only can we study charm production with these events, but use them as a means to reconstruct the inclusive variables x, Q^2 and W for deeply inelastic scattering. More work on developing this possibility is now in progress.

II. Studies on Cosmic-Ray Applications.

In addition to the cosmic-ray studies inherent in the observation of atmospherically produced muons and neutrinos, other aspects of cosmic-ray physics have occupied our attention. First among these is the study of very high energy interactions in the upper atmosphere, the branch of cosmic rays called high-energy shower studies.

In the region above a poorly defined threshold in the region of 10^{16} eV, there is little serious expectation of accelerator competition for the next ten to twenty years. Much study had been devoted to what can be learned from cosmic-ray studies in that energy region.

In the past, high-energy shower studies have given important information; such parameters as multiplicities, scaling, transverse momentum distributions, have been supplemented by still mysterious phenomena like Centauro events and strange decays like the Kolar Gold fields experiments examples. Many cosmic ray results have been verified by later accelerator experiments.

It has become clear in recent years that high-energy cosmic-ray showers demand attack by a variety of observational tools; not much more can be learned from large-area shower detectors alone, by gamma-ray detectors alone, or by muon detectors in deep mines alone. A mix of detectors is required, in which several critical shower parameters can be measured simultaneously, to enable the shower to be uniquely characterized[13].

Recent DUMAND workshops have devoted time and effort to the question of how DUMAND might best be used. Elbert[14] first pointed out that multiple-muon events in DUMAND would make a significant contribution to the problem of determining shower parentage. The 1980 DUMAND Symposium considered auxiliary detectors, which in combination with DUMAND would give important information on shower structure and origin[15-17]. Both a Fly's-Eye detector on land nearby[18] and a sub-surface array above DUMAND[19] were considered. The 1980 Deployment Workshop devoted considerable effort to the question whether a sub-surface array (at a depth of 30 - 50m) above the DUMAND array was feasible from the ocean engineering standpoint[20,21]. Despite strong initial misgivings, it found no reason to rule out such an array on the basis of feasibility, although no optimum design was proposed. Recently we have become aware of similar arrays successfully deployed in the ocean for other purposes[22]. Thus, our present attitude is that we will keep all options open, and continue, as manpower may permit, to investigate the feasibility of such arrays.

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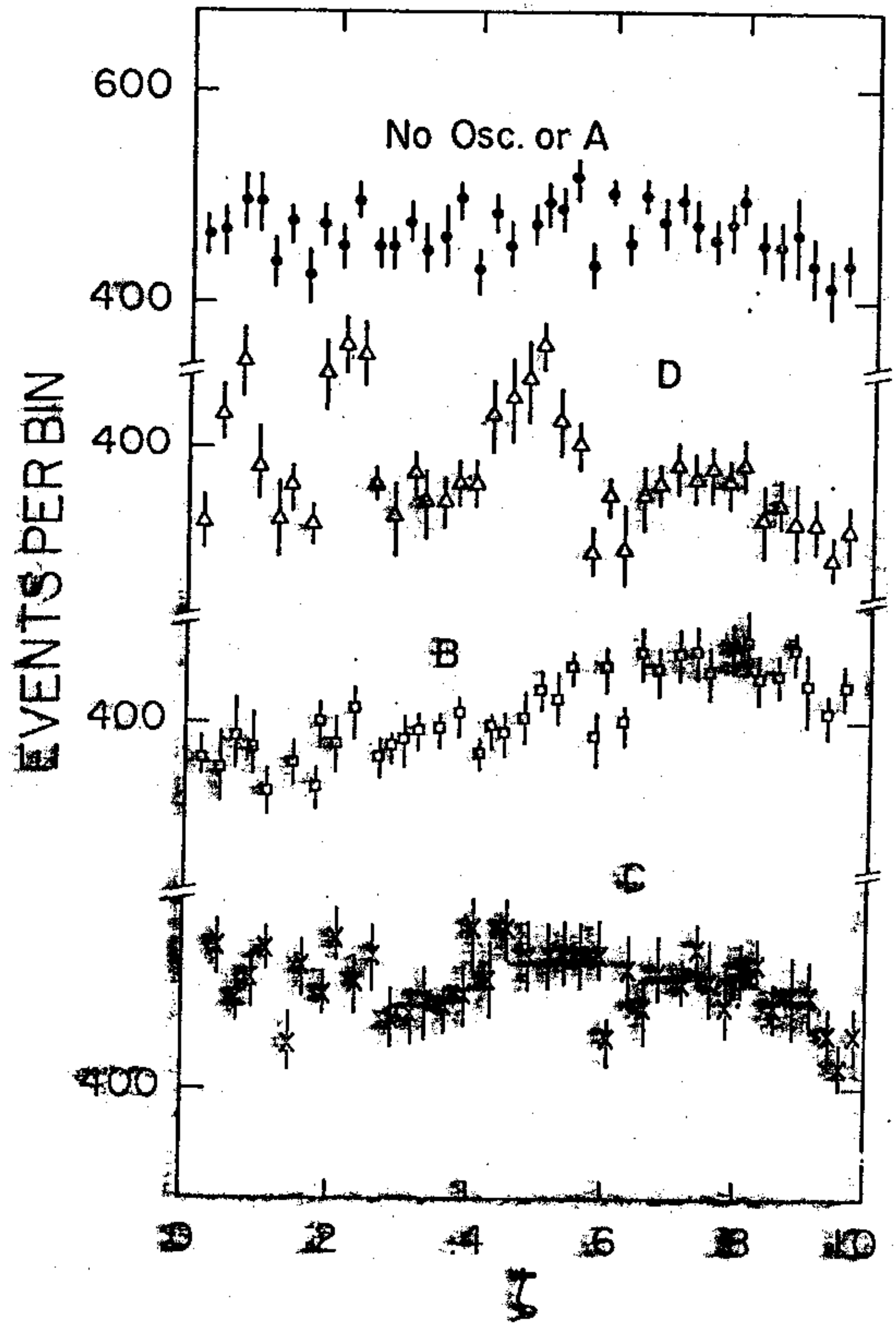

Fig. 4.1 [illegible] result of a one year experiment measuring the zenith distribution of ν_μ charged current events. The variable $\zeta = \ln(\cos\theta^*)/\ln(\cos\theta^*_{max})$ where θ^* is the zenith angle at the production point at top of atmosphere. The different results labelled A,B,C,D correspond to different oscillation possibilities.

10. A SHORT SUMMARY, WITH REFERENCES, OF THE PHYSICS AND ASTRONOMY POSSIBLE WITH DUMAND

In this section we list the various physics experiments and astronomical observations which have been suggested for DUMAND by a wide range of authors. No attempt has been made here to clearly distinguish those whose feasibility has been established from those which are highly speculative. The purpose of this list is to provide a compact guide, with complete references, to the ideas being considered. Those which have been subjected to the hard light of Monte Carlo analysis are discussed in Section 9.

High Energy Physics

1. Observation of effect of W-propagator in y-distribution and energy spectrum (Brown 78, Halprin 78, Halprin and Oakes 78, Roberts 78, Stenger 79a).

2. Study deep inelastic neutrino interactions in TeV region (Tung 78, Halprin and Oakes, 78). Crudely measure inclusive variables x, Q^2, W.

3. Study multiple muon production by neutrinos at TeV energies (Cline 78, Stenger 79b).

4. Search for ν oscillations in angular anisotropy, which is a function of L, in $\nu_\mu \to \nu_\mu, \nu_e, \nu_\tau$. Wide range of L/E and unique combination of L,E. (Stenger 80b). Matter oscillations (Pakvasa 80). Separation of mass eigenstates for extraterrestrial sources (Pakvasa and Tennakone 74).

5. Search for $\bar{\nu}_e e^- \to W^-$, direct channel "Glashow" resonance at 6000 TeV (Berezinzky and Okun, 79). Matter oscillations enhanced because of large cross section difference for $\bar{\nu}_e$ compared with ν_e.

6. Direct total cross-section measurements for ν_μ at energies of 5-10 TeV and up, by "earth-in, earth-out" observations on atmospherically generated neutrinos.

7. The "desert". Can DUMAND find an oasis? Non-orthodox possibilities (Berezinsky and Okun 79).

8. Directly produced ν_τ's. Can we detect?

9. Directly produced τ's above 3000 TeV reach DUMAND, leave golden signature (Learned 80). Predicted rates low but easy to look for.

10. New phenomena at superhigh energies (Markov and Zheleznykh 79).

High Energy Neutrino Astronomy

1. Diffuse ν's from galactic center. Minimum flux calculable with reasonable certainty (Stecker 78). On threshold of detectability (Stenger 81).

2. Diffuse ν's from early universe. Calculated flux uncertain by 5 orders of magnitude (Berezinsky 76,78,79,80). Even small DUMAND can set useful upper

limit (Stenger 80a, 81).

3. ν's produced in shell around young pulsar (Eichler 78, Silberberg and Shapiro 78,79). Tells us whether pulsars are major source of high energy cosmic rays.

4. ν's from binary pulsars (Eichler 78).

5. SS433 and like objects can be major source of ν's (Eichler 80).

6. ν's from active galactic nuclei. Distinguishes black hole from magnetoid (Silberberg and Shapiro 78,79,80, Berezinsky and Ginzburg 81)

7. Discriminate matter from antimatter in ν sources via ratio of one muon to zero muon events, Glashow resonance (Learned and Stecker 79, Berezinsky and Ginzburg 81).

Cosmic Ray Physics

1. Measure μ spectrum to 1000 TeV, 100x current energy. Important "geophysical" measurement. With EAS learn about hadron interactions, help calibrate EAS technique, develop models (Allkofer 80).

2. Direct muon production, new flavor production. $N_\mu(E > 1000\text{TeV}) = 3\times10^4\ y^{-1}$ in 4×10^7 tons (Silberberg and Shapiro 80). Study spectrum, angular anisotropy (Allkofer 80). DUMAND a good filter of low energy muons, so signal enhanced (Halzen 80).

3. Multiple muons. Separation gives p_T distribution (Elbert 78). Test whether p_T^{-8} or p_T^{-4}, new flavors (Halzen 80). Detect $Z_o \to \mu^+\mu^-$ or other heavy objects with two muon decay.

4. Measurement of cosmic-ray neutrino spectra: ν_μ and possibly ν_e. (Allkofer 78)

5. Learn about photonuclear cross sections above 200 GeV, where theoretical calculations disagree (Silberberg and Shapiro 80, Allkofer 80). At least determine energy loss parameters (Grupen 80). Test QED, QCD.

6. Nuclear composition of primary cosmic ray "beam" determined by study of multiple muon rates (Elbert 78) and spectrum (Silberberg and Shapiro 80). Combine with EAS (Elbert 80, Grieder 80). At highest energies ($>10^{17}$ eV) where cosmic rays appear to be extragalactic, Fe should photodisintegrate out of beam.

7. Angular anisotropy. See if the highest energy muons point to given region the way the highest energy cosmic rays in EAS studies seem to be coming from the general direction of the center of the Virgo cluster, at right angles to the place of our galaxy (Edge 78).

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11. DUMAND'S ORGANIZATIONAL STRUCTURE.

Recently there have been several serious discussions of the optimum organizational structure for DUMAND in the future, if available resources are to be put to the best use. This may seem premature, given the present central mission of DUMAND – to conduct a feasibility study. However, in seeking multi-agency funding, enlisting unpaid expert assistance on deployment and other problems, responding to foreign groups interested in joining in DUMAND's work, we find that some sort of model of DUMAND's future organization is needed.

In the early days of DUMAND the entire program was managed by the DUMAND Steering Committee (DSC), composed of DUMAND enthusiasts elected by the membership of the loosely-knit DUMAND organization. Fred Reines has been the chairman of DSC from its beginning, and A. Roberts its secretary. This group organized the annual Workshops, obtained funding for them, and did all the between-workshop analysis and planning. DUMAND owes its survival to 1980 largely to its persistence and vision. The committee used its contacts in high energy physics, astrophysics and cosmic rays to establish contacts between DUMAND and the scientists working in those fields. Strong contacts were established in this way with cosmic-ray physicists in the Soviet Union, West Germany, and Japan.

After the 1975 decision to investigate the Hawaii site more carefully, and following the success of the 1976 Hawaii DUMAND Workshop, the DSC expanded in number and met more frequently. Major summer Workshops at Scripps and San Diego were carried out. Modest funding for additional workshops at LaJolla and Honolulu was obtained from DOE, NSF, ONR, NOAA and NASA. The acoustic method was thoroughly explored, both theoretically and experimentally, and in 1978 preliminary cost estimates were made for the First DUMAND Standard Array. In 1979 a feasibility study located in Hawaii finally became a reality.

Our experience with the present Hawaii DUMAND Center (HDC) organization and its relation with the DSC indicates no serious conflicts. The pattern of decision-making has changed, however, and there is need for further changes in the future, if and when actual design construction gets under way. The director of HDC (V. Z. Peterson) has little free time for DUMAND. He spends that time primarily in supervising the Hawaii and DOE funding for the feasibility study. The core of the HDC are the two full-time staff members, J. Learned, and A. Roberts. In addition, Prof. V. J. Stenger devotes a major fraction of his research time to DUMAND.

The DUMAND efforts of Learned, Roberts, Stenger and Peterson, plus technical and computing support, are funded through the High Energy Physics contract with DOE, supplemented by one University position. Oceanography work is funded through ONR contracts with the University of Hawaii (Institute of Geophysics) and Scripps (UC-LaJolla) with Prof. Jim Andrews (UHM) and Prof Hugh Bradner (Scripps) as prime movers. Coordination of these efforts is achieved by occasional meetings, personal contact, and the holding of workshops on specific topics. To date that mixture has proven to be entirely satisfactory.

The one HDC experimental physics project, the Muon String, is being supervised by J. Learned, and has strong support from the entire group. It also has considerable cooperative support from the Hawaii Institute of Geophysics and from Scripps; Sec. 7 describes it in more detaiil. This project is necessarily small compared to any permanent ocean-deployed DUMAND array. Even so, it strains the meager resources of a feasibility study.

The role of the DUMAND Steering Committee has now evolved from a planning and executive group to one more nearly resembling a visiting or advisory committee. It provides independent judgment and criticism on the course taken by HDC. This appears to be a natural evolution, and so far no difficulties have arisen from this new relationship, which we believe will be satisfactory for the remainder of the feasibility study.

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