The birth of high-energy neutrino astronomy: A personal history of the DUMAND project

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DUMAND is a project to build a Deep Underwater Muon And Neutrino Detector offshore near the island of Hawaii. At present under construction, it hopes to inaugurate the field of high-energy neutrino astronomy. Potential sources of high-energy neutrinos are listed, and estimates of neutrino intensity given. The paper is concerned with the physics, technology, and history of the project, which started informally in 1973. It survived through a series of summer conferences until it was funded as a feasibility study in 1979 and established in the Hawaii DUMAND Center, at the University of Hawaii. Over a dozen collaborating groups have contributed to the successful construction and operation of DUMAND I, the SPS or Short Prototype String, which established the benign character of the ocean environment and demonstrated its suitability for DUMAND II, a 216-phototube array now under construction. DUMAND II, recently funded, will have more than 20 times the area of any existing detector and a mass of almost 2 million tons; this size is minimal for the intensities and cross sections anticipated. The project became feasible—both technically and financially—through important technical advances in data transmission via fiber optics, high-speed computer technology, special photomultiplier tubes made by Hamamatsu and Philips, remotely controlled undersea vehicles with manipulative abilities, and many deep-sea electronic and oceanographic components. It is supported by an international collaboration with 15 collaborating institutions in the U.S., Europe, and Japan. It is scheduled to install a three-string test array (TRIAD) by late 1992, and the complete nine-string array is scheduled for operation in late 1993.

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I. INTRODUCTION

DUMAND stands for Deep Underwater Muon And Neutrino Detector. The name also refers to a particular detector, the one now being constructed for installation 30 km off the coast of Hawaii, the "Big Island." Its objective is nothing less than the establishment of a new branch of science—high-energy neutrino astronomy. Like high-energy gamma-ray astronomy, its techniques are borrowed in part from high-energy physics, and its potential sources are deduced from high-energy phenomena observable throughout the universe. The name DUMAND is used both to describe the aim of the detector and to specify a particular one, the second to bear the name, called DUMAND II. DUMAND I was a small experimental detector whose purpose was to demonstrate the feasibility of DUMAND II; in this it was entirely successful.

This paper has a dual purpose: to explain the reasons for the enterprise and to detail its curious history.

A. Why neutrinos?

Neutrinos are notoriously difficult to detect, with minuscule cross sections. What do they offer that cannot be more readily learned from more accessible radiations?

The answer to that question is unambiguous. Neutrinos arise only in weak interactions, which are closely associated with hadronic interactions. These very often produce unstable particles—both mesons and baryons—that decay, producing neutrinos. They are produced in electromagnetic interactions only at extremely high energies. Like light quanta, they are uncharged, unperturbed by electric or magnetic fields, and thus their direction of arrival points back to their source. But unlike light quanta, they can penetrate vast distances through matter and thus, in principle, can reveal what goes on inside regions forever opaque to electromagnetic radiation. Thus neutrino astronomy offers possibilities of exploring regions inaccessible by any other means. An example is the interior of the sun, which is experimentally accessible only via solar neutrino detectors.

However, DUMAND is aimed neither at solar neutrinos nor at those arising in the catastrophic gravitational collapse of a massive star to produce a supernova, a process in which neutrinos play a major role. Both of these involve neutrinos in the energy range of at most a few tens of MeV. DUMAND is aimed at neutrinos in the GeV range and above, and its technology is accordingly quite different from that of detectors of lower-energy particles. Since the source of high-energy neutrinos is the decay of high-energy unstable hadrons—primarily mesons—the major constituent will be muon neutrinos, as shown by cosmic-ray and accelerator experiments. High-energy muon neutrinos will produce muons when interacting with matter; it is these muons that DUMAND is interested in detecting. What are the requirements for such a detector?

First, because of the very small cross sections of neutrino interactions and the relatively weak flux to be expected from distant sources, it has to be very massive: millions, even billions of tons. Second, it has to be transparent; the muons produced have very long ranges, up to kilometers of water, and will produce detectable Cerenkov light in a transparent medium. In such a detector the light from a minimum-ionizing particle can be detected at relatively long distances—up to tens of meters—and so the photomultipliers needed to observe and measure the muon direction can be spaced relatively far apart. Hence instrumenting large volumes of detector becomes possible. DUMAND thus represents a feasible method for instrumenting very massive detectors.

B. Choice of detector medium

The need for a very massive, transparent, inexpensive detector medium constrained the choice to only two possibilities: air and water. (It is only very recently that a third choice became known—namely, highly transparent Antarctic ice. This will be discussed later; see AMANDA, Sec. XIII.B.)

1. What about air?

Consider the atmosphere itself as a detecting medium; many gamma-ray astronomy experiments use it thus. The atmosphere above 14 400 square meters weighs a million tons. This corresponds to a square 120 m on a side, which is certainly not unreasonable. However, since DUMAND is to be an omnidirectional detector, it needs to be able to see muons from any direction; gamma-ray telescopes look in only one direction—up. The notion of

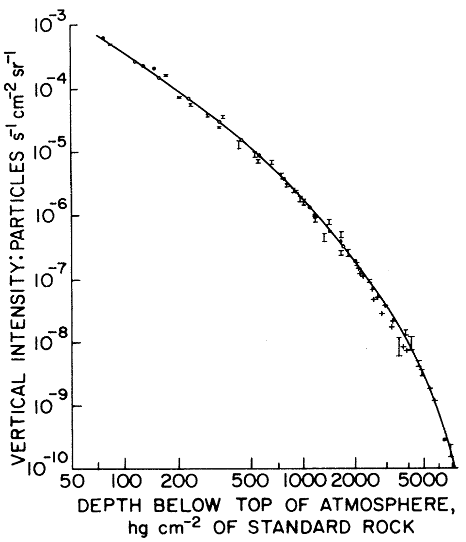

FIG. 1. The vertical cosmic-ray muon depth-intensity curve for "standard rock"—nearly the same as seawater. The larger the array, the greater the depth necessary to reduce the cosmic-ray background to a tolerable level (from Barton and Stockel, 1968).

instrumenting this volume of atmosphere—or even the lowest quarter of the mass, which takes us to an altitude of over a mile—is indeed daunting. Moreover, the incident cosmic rays produce an enormous number of muons in the atmosphere (see Fig. 1), which at sea level provide a background rate of 1 $\min^{-1}\mathrm{cm}^{-2}$. If in addition we remember that gamma-ray astronomy, which faces a similar task, is able to observe no more than about ten percent of the time, water begins to look more and more inviting.

2. Lake or ocean?

To make this decision, we must ask how we can distinguish extraterrestrial neutrinos from those produced in the atmosphere by cosmic rays, which will constitute the major background on the Earth's surface. Since we shall detect muons, we need to be concerned with the atmospheric muon background.

The Earth's atmosphere is a prolific muon source. The muons arise from hadronic interactions in the atmosphere of incoming cosmic-ray protons and heavy nuclei. In these interactions mesons are emitted that decay into muons, many of which reach the Earth's surface. Muons are not readily stopped, and high-energy muons can penetrate for kilometers into water.

As a result, to get a large volume of transparent detector and be deep enough to reduce the cosmic-ray background to a tolerable level, one needs to go deep into a lake or ocean.

A fresh-water lake would certainly be preferable to the ocean, from the standpoint of background noise in the photomultipliers and corrosiveness of the medium. The ocean is contaminated with light from two sources — bioluminescent fauna and flora, which are found at all depths, and Cerenkov light from the radioactive decay of ^{40}K, an unavoidable constituent of seawater. However, the deepest lake in the world is Lake Baikal, which contains 80% of the world's fresh water. Unfortunately it has two serious disadvantages. It is frozen over for three months or more every year; and its maximum depth is 1.2 km. That depth does not sufficiently reduce the cosmic-ray muon background in a large detector, though a small one can be used. In fact, Russian scientists have been doing their own neutrino detection experiment there over the last decade, using a small detector. To be able to run a large detector array, one needs to go to a depth of 4 km or more. Figure 1 shows a depth-intensity curve for vertical cosmic-ray muons.

A possible alternative would be a cavern or artificial excavation, filled with water. However, the cost and engineering difficulty of such an excavation make it impractical or, at least, very expensive (see, however, the description of LENA in Table VI below), and no suitable natural caverns have been found.

Another alternative approach is to accept a shallower depth and to eliminate the cosmic-ray muon background by means of suitable software and hardware provisions. This is the approach that has been taken by GRANDE and related projects (see Table VI below and Sec. XIII). It is a feasible one, provided the very high rejection efficiency required (to ca. 1 part in 10^8) can be achieved; it may also turn out to be considerably more expensive, although the GRANDE proponents deny this. The upward-looking extensive air-shower detectors are not used in anticoincidence. The GRANDE proposal claims that the vast majority of downward muons do not trigger GRANDE because of the directional nature of Cerenkov radiation and timing considerations. The small number that do trigger are eliminated by reconstruction of the track.

The GRANDE approach has the great advantage of making the array far more accessible. Technical obstacles include making the array light-tight by means of a plastic envelope, and purifying the water inside this envelope to achieve the desired transparency. This approach is discussed in more detail in Sec. XIII.

In the end, DUMAND decided the ocean was the best bet; and one by one, as we shall see, the many problems associated with working in the ocean have been overcome.

C. Using the ocean

The ocean is certainly not a convenient place to work and involves very great difficulties. Among these we might mention the need to withstand very high pressure (100 atmospheres per kilometer of depth), the great difficulty of installation and of accessibility in case repairs are required, the possible interference with sensitive photomultipliers by bioluminescent plants and animals, and the prevailing background of Cerenkov light from radioactive substances in the ocean, particularly ^{40}K. All this is in addition to the problems of supplying power to the array and encoding and transmitting all the data to shore.

To make it worthwhile to attack and conquer all these difficulties there must be an overriding advantage. There is: the availability of a practically infinite, cost-free transparent medium in which Cerenkov light from fast charged particles can be detected for many tens of meters. This satisfies the primary need of a high-energy astrophysical neutrino detector: a transparent medium with millions of tons available—preferably billions—at an affordable price.

In addition, once the installation is completed, the deep ocean is a comparatively benign environment, especially in comparison with the atmosphere. It is free from large predators; it is not subject to thunderstorms; the currents are in general very mild; it is an infinite heat sink, and the temperature is constant at 3.9 °C. We have also shown (see Sec. VIII) that glass surfaces remain transparent and unclouded after 19 months there, so that deep ocean growth and sedimentation are not a problem.

Ocean transparency was originally thought to be a problem: it was feared that the attenuation length for the blue-green region, where water is most transparent, might be as short as 10 m; had this been so, the density of phototubes would have had to be considerably greater than that finally decided on. The attenuation length at the site selected for DUMAND has turned out to be 30 m or better.

The problems DUMAND faces in dealing with the ocean include those of environmental adequacy—insuring that the equipment will operate properly in the ocean environment; monitoring, to ensure continued proper operation; servicing and replacement; and initial installation.

Engineering the equipment to withstand the environment is straightforward and offers few problems. However, we had two environmental problems that demanded experimental investigation: how serious is bioluminescence at the chosen location, and can we cope with the prevalent ^{40}K background light? Both of these were investigated in the course of the feasibility study, in which the SPS (short prototype string) was lowered to the ocean bottom near the proposed site and the bioluminescent and ^{40}K backgrounds observed. As we shall see, they were found to be tolerable.

The greatest difficulties are encountered with the requirements for servicing and replacement, and initial installation—deployment, to use the proper nautical term.

Servicing and replacement offer only two possibilities: the provision of built-in spares, or the physical replacement of portions of the equipment. The latter is a difficult and expensive operation and will only be undertaken when absolutely necessary, or in connection with another operation such as expanding the array. The best remedy for servicing is to design for long life and to provide spares where possible.

Finally we come to deployment. From the very beginning, this has been one of the main concerns of the project, the subject of many workshops and conferences, and one of the keys to making the project practical. In the early days, when proposed DUMAND arrays were very large, the deployment was the largest nonmilitary ocean project ever suggested. There were doubts about its feasibility, and the projected cost was high and difficult to estimate. As the array shrank, the deployment problem became more and more practicable; the expensive oil-drill ships were replaced by smaller and less expensive vessels, and the techniques became simpler and easier. We have given an extensive treatment of the deployment problems, since their solution was one of the major requirements for establishing the feasibility of the project.

II. AIMS OF DUMAND

A. Introduction

The principal aims of the DUMAND project are to study

(1) High-energy neutrino astrophysics; principally to detect extraterrestrial point sources of high-energy neutrinos;

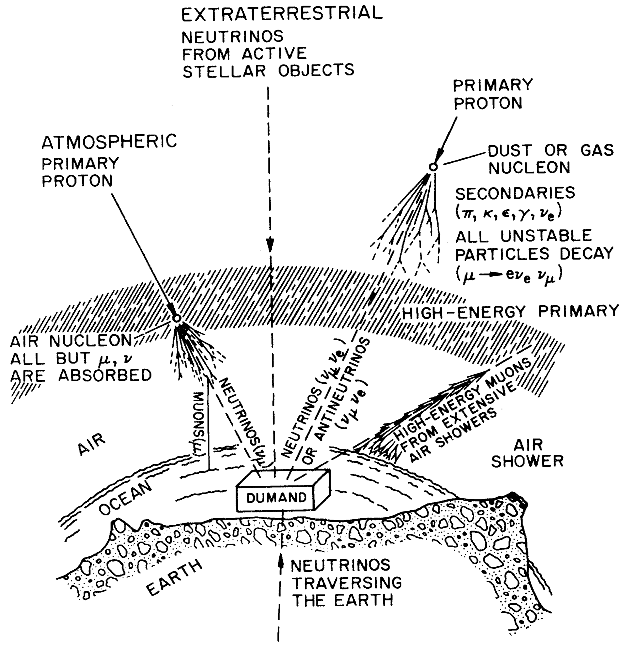

FIG. 2. The concept of the DUMAND experiment. Cosmic-ray protons (or other nuclei) of very-high-energy strike matter, either in the Earth's atmosphere or elsewhere in the cosmos. The resulting hadronic secondaries decay into neutrinos, which penetrate to the DUMAND array and are detected. Downgoing muons produced in the atmosphere with energies greater than about 3 TeV can also be detected and analyzed (DUMAND Proposal, 1988, p. 13).

(2) Particle physics, via indirect observation of ultrahigh-energy (UHE) hadronic interactions, both in extraterrestrial sources and in the DUMAND II detector; and also to study neutrino oscillation, using both extraterrestrial neutrinos, if found, and atmospherically produced cosmic-ray neutrinos. Furthermore, if a neutrino beam from a high-energy accelerator can be directed at DUMAND II, we can also study neutrino oscillations under more exactly specified conditions.

(3) Cosmic-ray physics, mostly relating to primary composition and muon studies, especially at energies above 10^{15} eV. The atmospherically generated neutrinos, produced in the spherical atmospheric shell surrounding the Earth, provide a uniform isotropic source whose path length through the Earth to the DUMAND detector varies with zenith angle from a few km to over 12 000. It will be a challenge to disentangle the combined effects of neutrino absorption and oscillation. It has been suggested that such measurements might constitute a source of geophysical information by "x-raying" the Earth with neutrinos (DUMAND proposal 1982, p. 77; DUMAND proposal 1988, p. 66; Volkova, 1987).

Incidentally, DUMAND can contribute to studies in geophysics and ocean science. It has already made contributions to these fields, as well as to ocean technology (DUMAND proposal 1982, p. 76; DUMAND proposal 1988, p. 65; and references given in Sec. III.F).

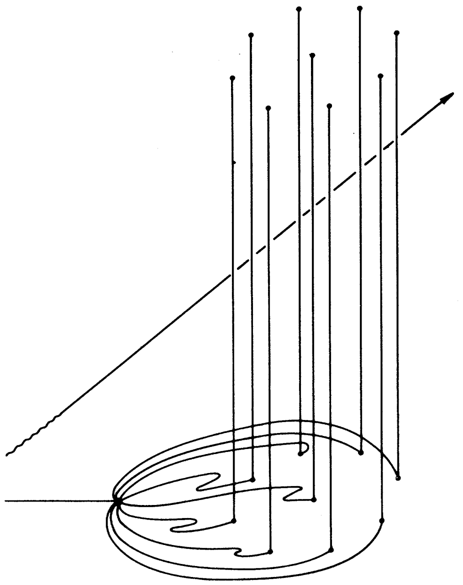

FIG. 3. The DUMAND II Octagon array. There are 9 strings, each anchored at the bottom and held taut by a flotation module at the top. The octagon is a regular one of side 40 m; the ninth string is at the center. Each string contains 24 sensor modules, one environmental module, and two calibration modules; in addition there are five hydrophones per string. Each string is connected to the junction box independently (DUMAND Proposal, 1988, p. 15).

Figure 2 is a pictorial representation of the major aims of the array. Figure 3 shows a sketch of DUMAND II. Table I shows the physical characteristics of the array. Figure 4 shows a plot of possible astrophysical observable neutrino sources, and Table II a tabular representation of their properties.

The dimensions of DUMAND II (see Fig. 3), constricted though they appear as compared with earlier designs (see, for example, Table V below), still provide a detector of high-energy neutrinos at least 15 times larger than any other now in existence. No larger one has been

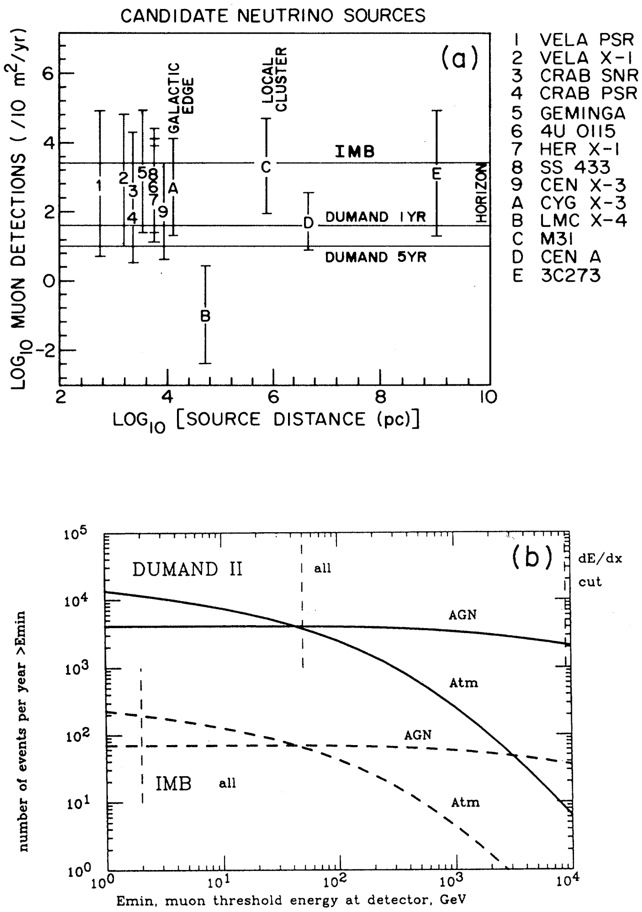

FIG. 4. The extraterrestrial source detection capabilities of the DUMAND array. (a) Candidate neutrino sources. Vertical lines with error bars show the number of muon detections expected from a particular source per year, per square kilometer of detector, vs source distance. Horizontal lines indicate the sensitivity of the IMB and DUMAND detectors for one year of operation (except for DUMAND 5-yr line) (DUMAND Proposal, 1988, p. 42). (b) The expected event rate in the DUMAND II and IMB detectors due to active galactic nuclei (AGN). The number of expected events per year above energy E is plotted against energy. Detector energy threshold are indicated by vertical dotted lines: 2.5 GeV for IMB, 25 GeV for DUMAND. The dE/dx cut at 10 TeV, the average AGN muon energy, indicates the probable threshold above which rough energy measurements should be possible from the total amount of light in the event (Learned and Stanev, 1991).

TABLE I. Summary of the physical characteristics of DUMAND II.

Array dimensions	100-m diameter × 230-m high
String spacing	40-m side
Number of strings in array	8 in octagon, 1 in center
Sensor spacing along strings	10 m
Number of optical sensors/string	24
Total number of optical sensors	$9\times24=216$
Height of first sensor above bottom	100 m
Depth of bottom	4.8 km
Sensor pressure envelope	17-in. (43.2-cm) O.D. glass sphere
Optical sensor	16-in. photomultiplier
Volume of array, contained	1.8×10^6 m^3
Target area for through-going muons	23 000 m^2 horizontal, 7850 m^2 vertical up-going, 2500 m^2 down-going
Effective target volume for 2-TeV muons	1.0×10^8 m^3
Effective target volume for 1-TeV cascades	7.0×10^5 m^3
Muon energy threshold	20–50 GeV
Track reconstruction accuracy	$0.5^0-1.0^0$
Cascade detection threshold	~1 TeV
Down-going muon rate	3/minute
Atmospheric neutrino rate for through-going muons	3500/yr
Atmospheric neutrino rate for contained events above 1 TeV	50/yr
Point-source sensitivity	$4-7\times10^{-10}$ cm^{-2}sec^{-1} in a year above 1 TeV
Contained-event sensitivity	1×10^{-8} cm^{-2} sec^{-1} in a year above 1 TeV

approved for construction.

Before we review the various experimental possibilities of DUMAND, we first describe the capabilities of the detector.

B. High-energy neutrino astrophysics

The most exciting prospect for DUMAND is opening a new branch of astronomy: high-energy neutrino astronomy. Low-energy neutrino astronomy has already had an enormous impact: the direct observation of neutrinos from Supernova 1987A has enriched the fields both of neutrino physics and of gravitational stellar collapse. The solar neutrino deficit experiments at Homestake (Davis *et al.*, 1990), at Kamiokande (Hirate *et al.*, 1990), and most recently at SAGE (SAGE, 1990) have led to startling new data, which may require nonzero neutrino

TABLE II. Tabulation of various high-energy gamma-ray sources proposed as candidates for neutrino sources. Sources of data: Grindlay *et al.*, 1975; Turver and Weekes, 1981; Bhat *et al.*, 1985; Weekes, 1988, 1989.

Source name	R.A. hh: (mm)	Dec. (deg)	Dist. (kpc)	γ-ray Energy (TeV)	γ flux at Earth (cm^{-2}s^{-1})	Luminosity (erg s^{-1})	Dec. Eff.	Assumed diff. spec. Index γ	μ/yr DUM II $\epsilon_{\nu/\gamma}=1$ Min γ	$\epsilon_{\nu/\gamma}=30$ Max γ
Vela PSR	08:33	−45	0.5	5	1.8×10^{-12}	3×10^{32}	0.68	2.0–3.5	0.1	1506
Vela X-1	09:00	−40	1.4	1	2×10^{-11}	2×10^{34}	0.66	2.0–4.0	0.2	126
Crab SNR	05:33	+22	2	2	1.1×10^{-11}	2×10^{34}	0.52	2.0–4.0	0.2	438
Crab PSR	05:31	+21	2	1	7.9×10^{-12}	6×10^{33}	0.5	2.0–4.0	0.06	38
Geminga	06:49	+18	0.5–2.1	6	9.5×10^{-12}	3×10^{33}	0.5	2.0–3.2	0.49	1506
4U 0115	01:15	+63	5	1	7.0×10^{-11}	6×10^{35}	0.42	2.0–4.0	0.47	273
Her X-1	16:57	+35	5	1	3×10^{-11}	3×10^{35}	0.5	2.0–4.0	0.24	141
SS433	19:09	+05	5	1	$<10^{-10}$	$<4\times10^{35}$	0.54	2.0–4.0	<0.88	<510
Cen X-3	11:19	−60	5–10	1	$<5.2\times10^{-12}$	$<2\times10^{34}$	1.0	2.0–4.0	<0.08	<48
Cyg X-3	20:32	+41	≥11	1	5.0×10^{-11}	3×10^{36}	0.5	2.1–4.0	0.4	234
LMC X-4	05:32	−66	55	10^4	5×10^{-15}	1×10^{38}	1.0	2.0–4.0	8.2×10^{-5}	4.8×10^{-2}
M 31	00:41	+41	670	1	2.2×10^{-10}	2×10^{40}	0.5	2.0–4.0	1.8	1050
Cen A	13:24	−43	4400	0.3	4.4×10^{-11}	3×10^{40}	0.68	2.0–4.0	0.14	6
3C 273	00:12	+02	6×10^5	5	$<9\times10^{-12}$	$<3\times10^{45}$	0.56	2.0–3.3	<0.4	<1506

masses and neutrino oscillations. It is possible that nothing new will be discovered by high-energy neutrino astronomy, but it seems unlikely. It has been pointed out by Berezinsky and Ginzburg (1981) that failure to see high-energy neutrinos from the galactic center will be a significant observation, serving to distinguish between black hole and spinar models of active galactic nuclei. Other null observations have been highly significant—e.g., the Michelson-Morley experiment.

As I was going up the stair
I met a man who wasn't there!
He wasn't there again today!
I wish, I wish he'd stay away!

(Mearns, 1922)

This is an appropriate time to remark that, of all the branches of astronomy, those that deal with the electromagnetic spectrum, from radio to gamma rays, share the important characteristic that the radiation moves in straight lines, and a telescope therefore points back at the source. This is not true for charged particles, which are deflected by magnetic fields. Thus cosmic-ray protons, although of great intrinsic interest, do not carry information concerning their source in their direction of arrival. However, all forms of electromagnetic radiation are susceptible to absorption, and therefore, no matter what wavelength we select, there will be parts of the universe that will be inaccessible to it.

Neutrinos, on the other hand, can penetrate even the interiors of stars. There are no known processes that can deflect a neutrino, with the exception of gravitation, which will deflect neutrinos as it does light—very little. But for energies far above their rest mass (if any)—which probably means thermal energies or above—the gravitational effects on their trajectories will be negligible for practical purposes, and therefore the direction in which a neutrino arrives points back at its source, and a neutrino detector that measures its direction is a neutrino telescope.

1. Likely extraterrestrial sources: gamma-ray sources as neutrino indicators

Where ought one to look in the sky for likely sources of high-energy neutrinos? What reasons are there for supposing that such sources exist?

To answer the first question, we first turn to the second. In the first place, the Earth is bombarded by cosmic rays, which include protons and heavier nuclei, as well as a few electrons. Their energy extends up to 10^{20} eV. High-energy nucleons, in traversing the cosmos, must often encounter matter and thereby produce nuclear interactions. These will produce pions and kaons, both charged and neutral. The charged mesons, upon decaying, will produce neutrinos. The neutral pions will produce gamma rays. Thus, as a first indicator of where to search for neutrino sources, we turn to high-energy gamma-ray sources.

Not all high-energy gamma rays come from nuclear interactions, however, some can be produced by electromagnetic processes such as synchrotron radiation. They can be distinguished, at least in principle, by their spectra and polarization.

Below we list likely neutrino sources, among which high-energy gamma-ray sources will be found. However, this listing serves only as a partial justification for an interest in high-energy neutrino astronomy; one can readily list astronomical high-energy phenomena that are poorly or not at all understood and that deserve investigation by all available means. The list is not needed as a set of targets for aiming the detector, since the proposed neutrino detectors are omnidirectional and will be sensitive to neutrinos from whatever direction they arrive.

2. Gamma-ray and other possible neutrino sources

Figure 4(a) shows a plot of the most likely gamma-ray sources and their intensities; Table II is a detailed list of their properties and gives references.

(1) Binary pulsars. Cygnus X-3 is the prototype candidate source; it is a sporadic source of very-high-energy gamma rays (>1 TeV); its luminosity in high-energy gamma rays is estimated as 10^{38} ergs/sec and the observed flux at 9×10^{-11} $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ (DUMAND 1988, p. 66). The flux from such sources is often periodic, with known periods. This is helpful in suppressing background.

(2) Pulsars in supernova shells. Calculations (Berezinsky, and Prilutsky, 1976) suggest that most of the luminosity goes into ultrarelativistic particles.

(3) SS433. This is supposed to be an accreting neutron star. Eichler (1980) has suggested it as a particularly powerful neutrino source. Begelman *et al.* (1980) have estimated the luminosity as 10^{41} ergs/sec.

(4) Galactic center. This is a possible significant source of neutrinos (Berezinsky *et al.*, 1975). It is a powerful, rapidly fluctuating source of positron annihilation radiation. Lingenfelter *et al.* (1981) found that a model with a massive accreting black hole explains the observations.

(5) Active galactic nuclei (AGN). Until recently little was known about these poorly understood bodies, and many models were proposed, among which neutrino observations might distinguish (Silberberg and Shapiro, 1978; DUMAND 1979, p. 262; Kafatos *et al.*, 1981). Recently, great interest has been aroused by a paper by Stecker *et al.* (1991), which points out that recent UV and x-ray observations favor a model in which accretion disk shock acceleration will produce neutrinos at energies of 10 to 10^7 TeV, in quantities far exceeding the cosmic-ray background, and at readily detectable intensities. Not enough is known of the characteristics, intensity distribution, and number of AGN sources to permit informed guesses as to the possible spatial and intensity distribution likely to be encountered. Thus we cannot predict whether individual point sources will be visible, or whether there will be a diffuse background, such as that

observed with x rays. Still, from the predicted overall intensity, Learned and Stanev (1991) have calculated that such intense very-high-energy neutrino sources might well render the Glashow resonance ($\nu_e + e^- \rightarrow W^-$) observable, and would result in rates of detected neutrinos in DUMAND of several thousand per year above 10 TeV. One can expect much activity in this area in the near future. Figure 4(b), from Learned and Stanev, illustrates the very high intensities of AGN neutrino-induced events to be expected according to these considerations.

(6) Quasars. The production of neutrinos in the very-large-energy bursts (10^{57} ergs) that occasionally occur have been explored by Scott *et al.* (1978) and Eichler (1979). Recent estimates for 3C273 predict a just-detectable neutrino flux at DUMAND (Protheroe and Kazanas, 1982).

(7) Neutrinos from cosmic-ray proton interactions outside the Earth's atmosphere. These include two distinct sources: proton collisions with stellar and interstellar matter, and very-high-energy proton collisions with the pervading microwave background radiation.

The latter, first mentioned by Berezinsky and Prilutsky (1976), will provide an omnidirectional flux, which will differ from that produced in the Earth's atmosphere by one power less of energy dependence. The decay length of charged pions is 55 meters per GeV/*c* of momentum; for kaons the figure is 7.5 meters. If we take the atmosphere as 55 km thick, the decay length of a 1-TeV pion is just the height of the atmosphere; higher-energy pion decays will be suppressed as $1/E$. For kaons the equivalent threshold is about 7 TeV.

Proton collisions with matter will produce neutrinos only if the mesons produced in the collisions have free space to decay in before they are destroyed by collisions. Thus it requires a low-density medium to produce many neutrinos. The neutrinos produced in this way come mainly from the region of the galactic center.

3. Results of searches to date; prospects for the future

Berezinsky, Castagnoli, and Galeotti (1985) have examined the usefulness of "small" underground detectors for searching for extraterrestrial high-energy neutrino sources. Aside from strong local sources in our galaxy, they were pessimistic about the prospects for finding any extragalactic sources. Published results to date confirm these predictions (see Boliev *et al.*, 1983, 1990; Takita, 1989; Adarkin *et al.*, 1990; Becker-Szendy, 1991). No sources have been seen to date.

Berezinsky (1990) has recently reviewed the minimum detector size desirable for high-energy neutrino astronomy. He has reiterated his earlier findings and has in addition made new calculations for two quite different domains of high-energy neutrino astronomy: the range 1–100 GeV and the range $E > 10^7$ GeV. As before, he finds for small detectors—i.e., those in the 1000 m^2 range—that only events in our own galaxy will be observable (the successful detection by small detectors of SN 1987A, in the Magellanic cloud, stretches this point only slightly). For extragalactic events, he postulates a necessary size of 0.1–1.0 km^2. DUMAND II, at 25 000 m^2, falls just below these values; it is neither small nor large.

These calculations serve to substantiate our own gut feelings. I have myself watched the progression of steadily decreasing size shown in Table V, Sec. V, at first with pleasure (to see it become more practical), but later with increasing pain; and I have a gnawing fear that the process has gone just one step too far. The danger is, of course, that if DUMAND II sees no neutrino sources, the funding agencies will decide it has failed and, instead of expanding it, will kill it. This illustrates the dilemma of all new exploratory devices; if it fails, was it a bad idea or a bad design for a good idea? It is also the motivation for attempting to insure that, in the absence of observable extraterrestrial neutrino sources, the scientific results obtainable with DUMAND II should still justify its construction.

C. Neutrino oscillations

The discovery of K^0-$\bar{K}^0$ mixing prompted the suggestion by Pontecorvo (1958) that neutrino-antineutrino mixing might occur. The possibility of mixing different neutrino flavors awaited the discovery by Lederman, Steinberger, Schwartz, *et al.* (Danby *et al.*, 1962) that electron and muon neutrinos were distinguishable. It was first suggested by Maki, Nakagawa, and Sakata (1962), and later, independently, by Pontecorvo (1967). For mixing to occur, it is necessary that the neutrino masses be different; thus for massless neutrinos no mixing is possible. Just to complicate matters, a third flavor—the tau neutrino—was added by Perl *et al.* (1975, 1976).

In consequence, a search for neutrino mixing is the most sensitive method for looking for neutrino masses (actually, for mass difference between different flavors.) This is a question of great cosmological significance, since finite neutrino masses may offer at least a partial solution to the "dark matter" dilemma (the observable matter in the universe is insufficient to account for the gravitational motions observed.) Neutrino oscillations are discussed at length in the review article by Kuo and Pantaleone (1989). They discuss both vacuum oscillations, which can occur in free space, and matter oscillations, which are induced by the passage of neutrinos through matter. At present evidence is accumulating to the effect that matter oscillations may be responsible for the unexpectedly low intensity of solar neutrinos, which has been unexplained for over twenty years.

The observable effect of oscillations is the transformation of one flavor of neutrinos into another. Thus a beam of originally pure muon neutrinos can be transformed into a mixture of flavors if oscillation occurs. The distances required for oscillation to occur depend on the energy of the neutrino; for energies in the cosmic-ray domain they will be large—at least hundreds of kilometers.

In view of the recent preliminary SAGE results (SAGE, 1990) on the nearly total disappearance of low-energy electron neutrinos from the sun (as well as the earlier results (Davis and Evans, 1973; Davis *et al.*, 1990; Hirata *et al.*, 1990), we shall have to rethink what sort of neutrinos might reach the Earth from distant astrophysical sources. The solar neutrinos that disappear have presumably oscillated to low-energy muon (or tau) neutrinos, which are currently very difficult to detect, since they do not have enough energy to produce a muon (or tauon). Muon neutrinos passing through a massive object might oscillate to electron or tau neutrinos, which at high energies might be possible to identify under favorable circumstances. Until the mass differences between the three generations of neutrinos are determined, it will not be possible to predict with confidence the matter and vacuum oscillations they will undergo over astronomical distances. At the moment all we can say is that the flavor distribution of neutrinos from distant sources may be essentially independent of its value at the source. It is possible that for extremely-high-energy neutrinos from within our galaxy the oscillation effects may be suppressed sufficiently to allow some remnant of the source composition to persist.

In concluding this very brief discussion of possible astrophysical sources, we must remark that, in view of our very incomplete understanding of high-energy astrophysical phenomena, the most surprising result of all would be that there were no surprises.

D. Cosmic-ray physics; auxiliary air-shower detector

The neutrino spectrum from cosmic-ray interactions in the atmosphere is quite predictable and, as we have noted, falls off more rapidly with energy than do those of their parent pions and kaons, which run out of path length for decay before they interact with the atmosphere. There is one exception: a small fraction—no one knows just how small—of the neutrinos may be produced "directly," either in the primary collision or from the decay of particles of very short ($\ll 10^{-9}$ sec) half-lives, e.g., tau mesons.

Because of this, at high energies the direct muons assume more and more importance, and ultimately comprise the greater portion of the spectrum. Figures 5 and 6 show the calculated spectra of muons and neutrinos, respectively, at sea level, as given by Mitsui and Minorikawa (1985, 1986).

These neutrinos are produced uniformly in the atmosphere, since the latitude effect disappears at the TeV energies that concern us. They produce an isotropic background in the array (aside from possible absorption or oscillation effects in the Earth). Their significance as a background for a search for point sources depends on the angular resolution of the detector. Since this is in the range 0.5–1.0 degree, it turns out that the cosmic-ray background in one angular bin is less than 1 count per year. Thus DUMAND observations will be signal limited rather than background limited. The expected total rate of such cosmic-ray neutrino events is about 3500/yr of 50 GeV or above.

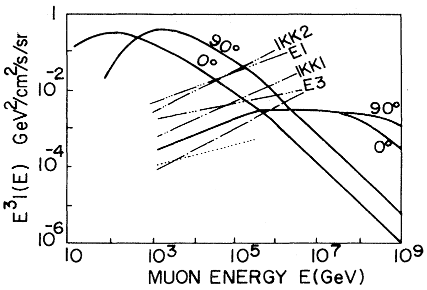

FIG. 5. Differential cosmic-ray muon spectra at sea level. The solid lines show the vertical and horizontal conventional spectra, and the lower solid lines, intersecting the conventional spectra above 10^5 GeV, the prompt muons, as calculated by the authors. The results of Inizawa *et al.* (1985) are shown in the single-dot-dashed line just below $E3$; the dotted line is due to Castagnoli *et al.*, 1984; the lines marked IKK1 and IKK2 are from Inizawa *et al.*, 1985; E1 and E3 are from Elbert *et al.*, 1983 (Mitsui and Minorikawa, 1985, 1986).

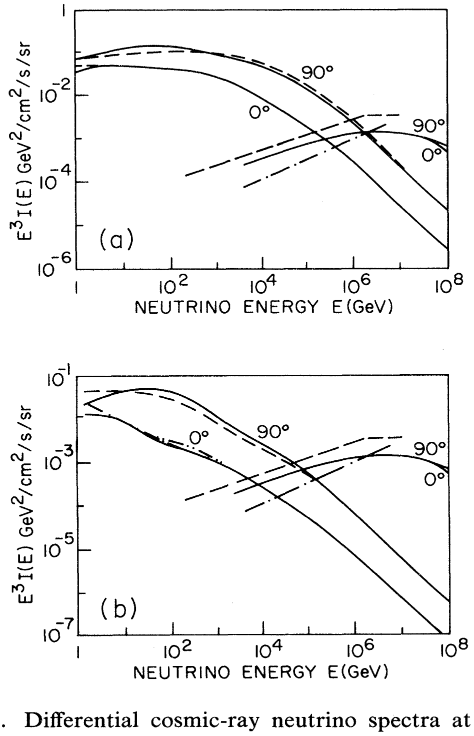

FIG. 6. Differential cosmic-ray neutrino spectra at sea level (Mitsui and Minorikawa, 1985, 1986). (a) Solid curves show author's calculation for conventional and prompt muon neutrinos. The dashed lines are from the calculations of Volkova, 1980; the dot-dashed line is due to Inizawa and Kobayakawa (1983). (b) Same as (a) for electron neutrinos. The dot-dot-dash line shows the calculations of Osborne *et al.* (1965).

Cosmic-ray muons will reach the array over an angular range from the zenith to an ill-defined angle where their intensity becomes negligible, in the range 75° to 80°. Cosmic-ray neutrinos will reach the DUMAND array from all directions, but will traverse very different paths through the Earth, depending on their zenith angle. From 75° to 180°, the distance traveled through the Earth changes from perhaps 50–100 km to 12 000 km. Oscillations will be very different over so large a range of distance. Thus careful studies of composition vs angle could be rewarding, especially if the different neutrino species can be identified; but this does not look too hopeful.

DUMAND is not capable of high accuracy in measuring neutrino energies. The resolution may well be no better than 50%, if that (Roberts, 1978). Still, the shape of the cosmic-ray spectrum with a minimum of absorber will be furnished by the spectrum of downward-going muons. As the zenith angle of the atmospheric muons changes, the path length through which these neutrinos travel will vary from a few km to nearly the diameter of the Earth. The change in spectral shape will be due to a combination of neutrino oscillations and neutrino absorption. Neutrino oscillations will affect the low-energy end of the spectrum, and absorption will be evident in the high-energy end; thus it may be possible to disentangle these effects. Present theory (based on the W propagator) has the total cross section for neutrino interactions changing slope and becoming flatter above about 10 TeV, an energy above that of any presently conceived accelerator. Figure 7 shows the predicted behavior (Halprin, 1976).

One other interesting possibility remains for discussion. The cosmic-ray primary spectrum changes slope at around 10^{15} eV. This has been ascribed to change in the composition of the primaries, with heavy primaries dominating above this energy (Juliusson, 1975).

Such an effect, if it exists, will certainly show up in DUMAND, in two ways. First, the primary muon spectrum will feature far more multiple muons if the primaries are heavy; and second, the neutrinos produced by massive primaries will be of much lower energy than if the primaries are protons.

In response to the cosmic-ray interests of many members of the DUMAND collaboration, the 1980 workshop considered a variety of possibilities for expanding the usefulness of the underwater array for cosmic-ray studies. These were carried out by a working group consisting of J. Elbert, P. K. F. Grieder, M. M. Shapiro, G. R. Smith, F. W. Stecker, and V. J. Stenger. The group considered two possibilities for air-shower detectors to be used in conjunction with DUMAND. One was the construction of a "fly's-eye" air-shower detector on shore, looking at the atmosphere directly over the submerged DUMAND array; the Utah fly's-eye detector (Bergeson *et al.*, 1977; Mason *et al.*, 1977) had just come into operation. The other was a submerged muon detector array, located just above DUMAND but 30–40 m below the ocean surface.

The reasons for wanting an air-shower detector in conjunction with the deep ocean muon detector were given in a paper by Elbert, Gaisser, and Stanev (1980). The additional data would facilitate the distinction between events produced by protons and those produced by heavy primaries like iron at energies of 10^{15} eV and above. They would also be useful in the study of prompt muons, which are indicators of charm and heavier flavors.

It is interesting to note that the Gran Sasso underground installation is being supplemented by an auxiliary

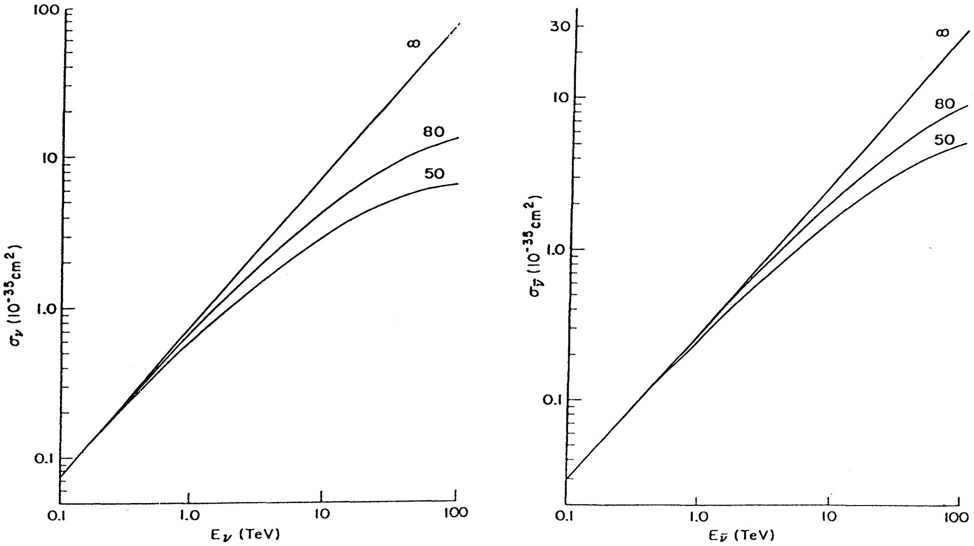

FIG. 7. Theoretical predictions (Halprin and Oakes, 1978) from the W-propagator model, of the muon neutrino and antineutrino cross sections for interaction with a proton, for three different assumed W masses (in GeV/c^2).

detector, EAS-TOP, on the surface of the mountain above it, for the purpose of studying air showers. Similar plans have been made at other underground detectors.

E. Particle physics

The highest-energy leptons that can be produced by the SSC will have energies below 10^{13} eV. The cosmic-ray spectrum extends to at least 10^{20} eV. Thus any data obtained by DUMAND in this energy range will be of value. The experimental observations of interactions in this energy range will be interesting; quite possibly new phenomena may be observed.

We have already discussed the use of DUMAND for measuring total absorption cross sections for TeV-energy neutrinos.

Another obvious use for DUMAND in particle physics is its use for very-long-baseline neutrino oscillation studies. If a beam from an accelerator—e.g., the Fermilab proposed Main Injector—were directed at DUMAND, there would be a long baseline (over 6000 km) in which muon-neutrino oscillations could be observed in DUMAND. Such an experiment, with a well-understood primary beam and thousands of events per year, could yield important data on neutrino oscillations. Stenger has recently investigated the possibility of studying neutrino oscillations using the atmospheric cosmic-ray neutrinos, and finds the prospects highly encouraging (Stenger, 1990).

F. DUMAND detection properties

DUMAND has some important and unique properties as a detector that must be kept in mind. First, of course, is its large size. Most important is the fact that it is simultaneously sensitive in all directions in the sky. However, for a fraction of each day (see Fig. 8), the cosmic-ray background beclouds a cone of about 75° zenith angle, so that sources within that cone are daily partially obscured. The obscuration is not total; a strong point source within the clouded region would still be observable, but diffuse sources would be harder to see.

The region from 56° S to the south pole is in view at all times. Figure 8 is a plot of sensitivity of the array vs declination. The location of DUMAND near the equator (latitude 19.5° N, longitude 156.3° W) is an advantage in decreasing the partial obscuration due to cosmic rays.

Since many astrophysical sources are highly variable in time, telescopes that look in only one direction and/or are sensitive only at night have great difficulty in studying rapidly varying sources. It is likely that the omnidirectional 24-hour sensitivity of DUMAND may prove extremely valuable.

As the direction of a source changes with respect to DUMAND during the course of the day, the path through the Earth taken by neutrinos from the source that reach DUMAND will be constantly changing. For high-energy neutrinos—above a few TeV—absorption in the Earth may become appreciable. A strong extraterrestrial point source would thus be welcome as a probe for absorption measurements.

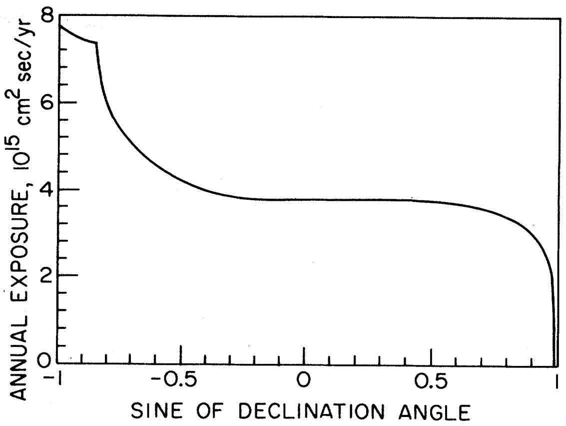

FIG. 8. Relative sensitivity of DUMAND over the celestial sphere. The southern hemisphere beyond latitude 50° South [where sine (decl. angle) $=-0.69$] is continuously visible; the remainder is hidden for part of each day by atmospheric neutrinos from cosmic rays, which obscure most of the upper hemisphere (DUMAND Proposal, 1988, p. 26).

III. DUMAND HISTORY: EVOLUTION AND BEGINNINGS

A. Prehistory

This section is concerned with work on underwater neutrino detection prior to DUMAND.

In the 1976 DUMAND Workshop, Riel (1976) gave a paper on underwater neutrino work prior to the initiation of DUMAND. It included the following information.

(1) A paper was given by Uberall and Cowan (1965) at the 1965 CERN conference on experimental neutrino physics. It suggested a downward-looking phototube looking at a water target ca. 10 m thick; it explicitly suggested using the ocean or a deep lake.

(2) A paper by Riel and Cha (1970) described an underwater test of a shipborne "light trap." This consists of a relatively large volume of water containing a dissolved wavelength shifter and enclosed by lucite plates 5 ft. square, $\frac{1}{4}$ in. apart. The results indicate that such a light trap, using an EMI 9579 photomultiplier tube, can view 100 m^3 of water.

(3) Bogatyrev, in a 1970 paper that has just come to our attention (Bogatyrev, 1971), suggested the construction of three widely separated detectors for supernova detection, so that the direction of the signal might be determined. Each was to consist of 10^7 tons of distilled water, at a depth of several km underwater to reduce background. It would have an estimated range of detec-

tion of 10^7 light-years, thus including the Andromeda galaxy. He proposed the construction of cylindrical pressure-tolerant phototubes of large cathode area for this purpose, and also said that seawater might be usable if wavelength shifters were used. This was a remarkably prescient proposal; it is a pity none of us knew of it.

The paper of Markov in the 1960 Rochester Conference proceedings is often cited as the first reference to a deep ocean neutrino detector (Markov, 1960). It refers to earlier work by Markov and Zheleznykh (without references) and mentions, in passing, the possibility of detectors in a lake or ocean, of 1000 m^2. Belayev *et al.* (1978) state that A. E. Chudakov was the first to suggest a deep-ocean neutrino detector; unfortunately they give no references.

It seems clear that the idea of an ocean neutrino detector had occurred to many physicists independently, though none (other than Markov) seem to have committed it to print. However, it is equally clear from the scale of the detectors proposed that what they all had in mind was a study of neutrinos generated by cosmic rays bombarding the atmosphere, either for the cosmic-ray interest or as a natural source for experiments on neutrino properties such as cross sections.

The idea of neutrino astronomy (other than the study of solar neutrinos, which had been underway for many years) arose independently, from two different impulses. One was the notion of detecting gravitational stellar collapse, for which the theory, unsettled in 1975 (and still incomplete in 1990), was at least firm in expecting an enormous burst of neutrinos in the 10-MeV range.

The other, more ambitious, was aimed at high-energy neutrinos; its foundation was the conviction that pulsars, with their enormous teragauss magnetic fields and high rotation rates, must be accelerating charged particles to cosmic-ray energies and might in fact be the long-sought source of the cosmic rays. And high-energy charged particles, wandering through the galaxies, must strike matter in their journey, and thus necessarily generate pions, kaons, and therefore their decay products: neutrinos.

While these ideas were current, the implications were not clear. A detector for galactic supernova neutrinos would be of manageable size—a few hundred, perhaps a few thousand tons of detector, a cost in the few millions of dollars. The major drawback was the unknown rate at which supernovas occurred. There have been only five in our galaxy in the last thousand years that produced visible supernova explosions. Questions arose as to how many there might be that are hidden from us by dust, clouds, or other intervening matter; but they received no convincing answer. Thus a supernova detector had better have an alternative, more reliable, experimental aim if it were not to sit idle for decades or centuries, waiting for the phone to ring. The two detectors that saw the 1987A supernova, IMB and Kamiokande, were both originally constructed for different purposes, and there are now many other detectors capable of detecting supernova neutrinos from our own galaxy.

I have not found any clear proposals, earlier than DUMAND, for a large detector for high-energy neutrinos. The first DUMAND conference, in 1975, found the conferees unsure of how big a detector should be for high-energy neutrinos and of what its astrophysical objectives might be. It was not until the 1976 conference that this aim crystallized. There are no current proposals for the extremely large and expensive detectors required to see supernova explosions as far as the local (Virgo) cluster.

B. A brief history of the origins of DUMAND

1. The beginning

The DUMAND project began as an information meeting of several physicists attending the 1973 Cosmic-Ray Conference in Denver (Reines, 1974); among these were F. Reines, J. G. Learned, H. Davis,[1] P. Kotzer, M. M. Shapiro, G. T. Zatsepin, and S. Miyake. (I was not there, not having been previously involved in cosmic-ray work.) They were concerned by the anomalous cosmic-ray depth-intensity curves that had earlier been obtained by Keuffel's group in Utah (Bergeson *et al.*, 1971). If these results were correct, they implied the possible existence of a muon component whose angular distribution did not follow the usual $\sec\theta$ dependence, but was isotropic. Such a component could be caused by a strongly produced short-lived muon parent with a considerable branching ratio into muons.

One possible explanation offered was that the presently accepted depth-intensity curves for muons traversing rock were in error because of possible variations in density of the rock along the muon trajectory. If this were the case, an experiment to determine the depth-intensity relation in water, whose composition was unambiguous, would settle the question. Experiments to illuminate this question had already been carried out in 1965—1968 by Davis and Learned (1973) to a depth of a few hundred meters in convenient lakes. Thus the possibility of a muon detector deep in the ocean was of much interest. (Incidentally, the "Keuffel effect" languished and died at about this time; the Denver conference proceedings contained a paper by the Utah group, in which the earlier experiment, carefully repeated (Bergeson, *et al.*, 1973), showed no sign of the anomalous component).

Having hypothesized such a deep ocean detector, the conferees noted that a large underwater muon detector

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[1] Historical footnote: Davis took his degree under my direction at the University of Rochester; at this time he was on the faculty of the University of Washington, where Learned had taken his degree under Davis. R. Becker-Szendy, a student of Learned's, has been looking for extraterrestrial neutrinos at IMB. Thus four successive generations of physicists have been intimately involved with high-energy neutrino astronomy.

would obviously be a neutrino detector as well, since muon neutrinos can produce a muon on interacting with a nucleon. Since most of the members of the committee had already been interested in investigating the neutrino component of cosmic rays, they realized that such a neutrino detector would have interesting and useful properties and decided to encourage further consideration. They did this by forming an *ad hoc* committee to continue work on the subject. The proposed underwater detector was named DUMAND, standing for Deep Underwater Muon And Neutrino Detector, by Fred Reines.

This committee did meet at intervals. It finally decided to invite participation by a wider group of experts in the fields involved in designing, implanting, and operating a deep ocean neutrino detector. These would include, in addition to high-energy physicists, oceanographers, ocean engineers, submarine cable specialists, phototube experts, biologists, and others as they might be needed. The job of organizing the meeting—the first DUMAND Workshop—was shouldered by Jere Lord of the University of Washington. The formal history of DUMAND begins with that meeting, which was held in Bellingham, Washington, at Washington State College, in July 1975. It is discussed in more detail in the next section.

The 1975 conference set up a new DUMAND Steering Committee, which continued to function until the feasibility study was funded in 1980. It was chaired by F. Reines, with A. Roberts as secretary and J. G. Learned as vice-chairman. Among its members was Howard Blood, director of the Naval Ocean Systems Center (NOSC) in San Diego, NOSC's unwavering support has been of inestimable value to the project to this day.

2. 1975—1980: Before funding

The initial DOE funding of a feasibility study of DUMAND began in 1980. Between 1975 and 1980, DUMAND survived by virtue of work carried on by a few dedicated participants and by running some important and valuable summer workshops. Funding for these, which involved small sums, was readily available from government agencies; and Scripps Institution of Oceanography and the University of Hawaii were willing hosts, as were the Russian participants who organized the 1979 Khabarovsk-Lake Baikal conference.

During that period there were full-scale workshops in 1976 (in Honolulu), in 1978 (at Scripps), and in 1979 (in Khabarovsk-Lake Baikal). In addition there were smaller workshops on deployment and acoustic detection, chaired by H. Bradner, at Scripps in 1977, and a full-scale symposium in Honolulu in 1980, chaired by J. G. Learned. Since then there have been several specialized workshops on signal processing and on ocean engineering and deployment. In addition, there have been special sessions on DUMAND at the 15th ICRC (International Cosmic-Ray Conference) in Plovdiv (1977), the 16th in Kyoto (1979), and the 17th in Paris (1981).

Also, during this period individual DUMAND members worked on specific problems. Roberts, and later V. J. Stenger, wrote Monte Carlo programs to study the efficiency of DUMAND detectors. One of the first problems to be studied was the accuracy with which the direction of a muon track could be determined. This depends on the size of the array and length of the track, but it soon became clear that accuracies of 1° or better were achievable. Since, at multi-GeV energies, the muon direction is practically, the same as that of the incident neutrino producing it, this meant that point sources could be readily identified; and with this degree of accuracy the uniform cosmic-ray background would be negligible—at least for upward-going muons, where the prolific cosmic-ray muons from above would not interfere.

Attempts to estimate the energy of incident neutrinos were less successful. Even with the enormous DUMAND G, the cubic kilometer array, estimates of muon energy were no better than 50%, and worse for smaller arrays. From the observed range, a lower limit on muon energy can be set, while at multi-TeV energies there are occasional bursts of small cascades along the track that give some indication of the energy.

Studies of ^{40}K background showed that photomultiplier tubes much larger than 16 in. would have background rates exceeding 100 K/sec. Predicted rates were later verified by the results of the Short Prototype String (see Secs. III.D, III.E, and III.F). Estimates of the effects of bioluminescence indicated that the array would be reasonably immune to local short-lived outbursts; this seems also to be the case. The existence of the DUMAND project and the prospect of an experimental handle on neutrino astronomy led a considerable number of theoretical astrophysicists to give more attention to the consideration of possible high-energy neutrino sources. Between 1976 and 1980 there were quite a few publications by authors such as Berezinsky and Zatsepin (1977), Gaisser and Halprin (1977), Silberberg and Shapiro (1978, 1979), Berezinsky and Volynsky (1979), Eichler (1979, 1981), Stecker *et al.* (1979), Fichtel (1980), Halzen (1980), Schramm and Steigman (1980), Stecker (1980), Berenzinsky and Ginzburg (1981), Kafatos *et al.* (1981), and others, on possible sources of high-energy neutrinos and their intensities. Such papers continue to appear, although at a lower rate. Despite the uncertainties inherent in such calculations, the results have been sanguine enough to keep expectations up and enthusiasm high. Many of these results are contained in Fig. 3 and Table II.

3. The 1978 proposal

In January 1978 a proposal to fund a one-year design study (DUMAND Proposal, 1978) was submitted simultaneously to several funding agencies by the DUMAND executive committee, then composed of Blood, Bradner, Learned, Reines, Roberts, and Wilkins. (At this time the remaining members of the DUMAND Steering Committee were D. Cline, W. V. Jones, D. Schramm, and L. Sulak.) It nominated Reines as principal investigator and proposed to locate the project at Scripps, on the UCSD campus in San Diego. From today's perspective, the proposal was not well conceived, and it is not too surprising that it was rejected as premature.

C. DUMAND history: the move to Hawaii

The funding of DUMAND studies by the Department of Energy gave rise to the establishment at the University of Hawaii of the Hawaii DUMAND Center. This found a home in the high-energy physics group, which was under the direction of Vincent Z. Peterson. As a result of the funding, both John G. Learned and I moved to Hawaii to work full time on DUMAND, starting in January 1980. In addition, several faculty members of the physics department joined the project; these included Peterson and V. J. Stenger; Fred A. Harris was also associated with it for several years. Several graduate students also joined; they included John Babson, Daniel O'Connor, and Geoffrey Taylor.

We obtained engineering assistance from the Hawaii Institute of Geophysics; this was especially valuable, since the engineers there were experienced in ocean projects. In addition we had, thanks to George Wilkins, who had joined us in 1976, help from the Kaneohe branch of the Naval Ocean Systems Center (NOSC), and also the cooperation of the director, Howard Blood, and of Howard Talkington, of the parent laboratory, NOSC in San Diego. These ocean engineering experts were invaluable in orienting us in the problems of working in the ocean and in giving assistance whenever it was possible for them to do so. DUMAND was a unique ocean engineering project, and NOSC felt they could profit by helping us. That symbiotic relation has continued to the present.

We also had excellent relations with the Scripps Institution of Oceanography, located on the LaJolla campus of the University of California in San Diego. These were channeled through Hugh Bradner, a veteran of the Alvarez bubble-chamber group at Berkeley and now a full-fledged oceanographer. Through Bradner and the director, William Nierenberg, we were able to use Scripps for the summer studies of 1977 and 1978 and have had other studies there since then.

D. Formulation of the SPS project

It was clear that the demonstration of feasibility of DUMAND would require an ocean deployment of a sufficient number of optical modules to demonstrate that they would function satisfactorily in the ocean and would yield data allowing muon tracks to be observed, and their direction measured with sufficient accuracy. It would be necessary to find an appropriate site for the final installation and to verify that ocean conditions were sufficiently benign to allow the array to function. In addition a shore cable would have to be feasible; that meant not too long, and not traversing too inhospitable an ocean bottom.

The obvious solution to the feasibility demonstration was to produce a string of perhaps half a dozen optical modules of the type to be used in the final array (see Figs. 17 and 18 below) and to lower the short prototype string (SPS) into the ocean on a cable capable of supplying power and also transmitting data and control messages. The SPS would be deployed from a ship capable of holding station with sufficient accuracy and remaining in position for a sufficiently long period—a day or two—to obtain enough cosmic-ray muon data to satisfy the requirements. The electronics for operating the optical modules and collecting the data would have to be on shipboard.

There were several ships located in Hawaiian waters that could be used. In addition, for one cruise we were permitted to use a navy ship that happened to be available, through the good offices of NOSC. (Since ship rentals run from \$3000/day up, this was a nontrivial gift.) The one best suited for our purpose was the SWATH ship S. S. Kaimalino. (SWATH stands for Small-Water-Area Twin Hull.) Such ships are much more stable in heavy seas than conventional monohull ships and accordingly are much easier to work in.

The division of the project into separable tasks having been formulated, the various jobs were parcelled out to the collaborating groups, and a time was set for final delivery to the Hawaii DUMAND Center of completed components. The original schedule called for the string to be assembled in 1982. Before then site studies, using current meters, and measuring water transparency, could be carried out.

E. Operation of the SPS

A total of fourteen ocean voyages were made over the course of six years in testing the SPS and studying ocean environment. Two of these merit special attention.

In 1982, the second deployment of the muon string, with five optical modules, ended in its loss at sea when the suspending cable parted, although it was rated at 20 times the actual load. In 1985, on a cruise known as TTR IV, another string was lost when the explosive bolts, designed to release it after a planned sojourn on the ocean floor, failed to release the string when fired. The location of the loss was accurately known, however, and nineteen months later a Scripps oceanographic vessel equipped with side-scan sonar (which gives detailed pictures of the ocean bottom) located the string and retrieved it. The loss had its bright side, since the retrieved modules, on examination, showed neither surface deterioration nor any appreciable accumulation of sediment, organic growth, or other accretions.

F. Results of the SPS deployments

The results of the entire SPS study are recorded in some detail in the 1988 DUMAND proposal for the construction of DUMAND II (first proposed in 1982) and in exhaustive detail in O'Connor's thesis (O'Connor, 1990). They have also been published in the open literature (Aoki *et al.*, 1986; Bradner *et al.*, 1987; Clem, 1989; Matsuno *et al.*, 1989; Babson *et al.*, 1990; Webster *et al.*, 1990). They can be summarized as follows:

(1) The cosmic-ray muon flux in the ocean follows very closely the values calculated from Miyake's empirical range-energy relation, which is derived mostly from underground measurements (Miyake, 1963; Miyake *et al.*, 1964). That formula is as follows:

$$E=(a/b)[\exp(bh)-1]$$

where

$$a=1.84+0.076\ \ln\{E/[em_\mu c^2(E+eA)]\}\ \mathrm{MeV/gm\,cm^{-2}}\ ,$$

$$A=11.3\ \mathrm{GeV}\ ,$$

$$b=3.9\times10^{-6}\ \mathrm{g^{-1}\,cm^2}\ ,$$

E is the muon energy in MeV ,

and h is the depth in units of $\mathrm{gm\,cm^{-2}}$.

A more recent fit, valid to depths of 11 000 $\mathrm{hg/cm^2}$, has been given by Krishnaswamy *et al.* (1977).

(2) The angular distribution of the cosmic-ray muon flux is in agreement with that calculated from Miyake's formula.

(3) The attenuation length of light at various depths was measured in the course of calibrating the optical module sensitivities. The water was remarkably clear at all depths, and the measured attenuation length at a wavelength of 410 nm was 47±22 m.

(4) Environmental data: water temperature 3.9°, as expected; water currents, so low as to be almost unmeasurable; as previously observed, bioluminescence is strongly correlated with strong motion, and minimal with string at rest on the bottom. This is in accord with earlier data and is apparently a peculiarity of the unidentified organisms responsible for the bioluminescence. The observations on bioluminescence have been published (Webster *et al.*, 1990).

IV. ARRAY DESIGN

A. Early neutrino detectors

We outline here the evolution of the design of the DUMAND array. It took some time before the array assumed a definite configuration, since that could not be determined until the purpose of the array had been well defined. At first it was not clear just which areas of neutrino astronomy were to be explored, or even whether the array was to be used primarily to do high-energy physics experiments using cosmic-ray neutrinos produced in the atmosphere, and only secondarily for neutrino astronomy. It required time for the various possibilities to be examined, sorted out, and assigned priorities.

The array geometry also interacted strongly with the type of sensor to be used. At first the unavailability of large phototubes—i.e., those with photocathodes 12 in. in diameter or larger—turned all our efforts toward the use of various wavelength-shifter expedients to increase the effective size of the sensors.

Previous experience with the attitude of American photomultiplier manufacturers—particularly RCA—had led us to expect that the development of new phototubes for us was out of the question unless we were prepared to finance it completely. Since that was impossible, we did not even consider new tubes until our Japanese collaborators informed us that Hamamatsu was willing to design and build new tubes to our specifications with their own money, on the hope that we (and others) would eventually become a market for them. (The English firm EMI was also willing to undertake such development, but unfortunately had insufficient development funds.) Despite the fact that so intelligent an approach was so clearly un-American, we welcomed it gratefully, and it is on the Hamamatsu 16-in. hemispherical photocathode photomultiplier that the entire DUMAND design was eventually based. Incidentally, Hamamatsu's gamble has probably paid off; there have been many other users for large phototubes based on the 16-in. tube developed for us. (As we note in Secs. III and V, the Dutch Philips Co. also was willing to gamble on designing a photomultiplier tube for DUMAND.)

We divide our discussion into what we call—perhaps arrogantly—the "pre-DUMAND" era (before 1973) and the DUMAND era, following 1973. We consider as related to DUMAND any proposal for using a large body of water as a neutrino detector. This excludes such neutrino detectors as the Baksan 100-ton liquid scintillator (Chudakov *et al.*, 1973), the Homestake mine solar neutrino detector (Davis and Evans, 1973), and other smaller detectors such as those in the Kolar gold fields (Menon *et al.*, 1968), and the South African Witwatersrand detector (Reines *et al.*, 1968).

With this restriction in mind, we note that the nomination for the earliest suggestion of a large detector for neutrino astronomy is usually Markov's paper in the 1960 Rochester High-Energy Conference (Markov, 1960). As we saw in the previous section, what Markov proposed at that time was a 1000-m^2 detector in a lake or the ocean; this is clearly a much more modest concept than the original DUMAND idea of a 10^9-ton, 1.6-km^3 instrumented volume at a depth of several km in the ocean. That concept matured slowly and was first presented by Roberts, Blood, Learned, and Reines, for the DUMAND Steering Committee, at the Aachen Neutrino Conference in 1976 (Roberts *et al.*, 1976). (A smaller, 3×10^7-ton alternative was also mentioned.)

B. The 1975 DUMAND Conference

The summer study of 1975, hosted by Western Washington State College at Bellingham, Washington, was the first of a series of summer studies that kept DUMAND alive until it was first funded in 1980. Organized by J. Lord of the University of Washington in Seattle, it was directed by Peter Kotzer, a former student of Lord's. It brought together for the first time experts in particle and high-energy physics, cosmic rays, ocean engineering, oceanography, photomultiplier design, and communication. It immediately became apparent how important the cross-fertilization so produced would be for the project. It was at this meeting that I first came into the project, and I found the atmosphere extremely stimulating.

The conference, as may be seen from its proceedings (DUMAND 1975), came to no firm conclusions as to the proper role of a very large deep underwater muon detector, but it outlined the considerations on which such a choice would be made. The possible uses were for high-energy neutrino astronomy, supernova detection, and cosmic-ray studies. The ocean experts considered many possible sites for a detector whose requirements were a deep-water site (4.5 km) with transparent water, close to shore, with industrially advanced shore facilities, including preferably an advanced physics laboratory. An undersea cable to shore would supply power to the array and return data to land. They recommended two possible sites in the Hawaiian Islands, one off the west coast of Hawaii and the other north of Maui. The ocean engineers considered detector systems, both enclosed and open, and concluded that enclosed systems were not feasible for anything as large as DUMAND. They also recommended a configuration of optical detectors they called a beaded string; in it the optical modules were attached to a cable anchored at the bottom and suspended in the water by a flotation module at the top. To this configuration DUMAND has remained faithful; it is simple, convenient, and practical.

C. Choosing the DUMAND objective

It was at the Aachen conference in early 1976 that the distinction between three possible uses for a DUMAND array was first described, with each christened by a mythological name:

UNDINE: UNderwater Detection of Interstellar Neutrino Emission

ATHENE: ATmospheric High-Energy Neutrino Experiment

UNICORN: UNderwater Interstellar COsmic-Ray Neutrinos

UNDINE was intended to represent the detection of extragalactic gravitational stellar collapse. Detectors for gravitational stellar collapse in our own galaxy could be much smaller, and could be located in a mine or lake. Unfortunately, the frequency of gravitational collapse in any galaxy was (and still is) only poorly known, but is so low as to make such detectors uninteresting unless they have other purposes as well. However, a sufficiently large detector—one capable of seeing gravitational stellar collapse in the Virgo cluster—would be seeing many such events per year; this was the idea of UNDINE. One difficulty that surfaced later was that originally the spectrum of stellar collapse neutrinos was thought to extend to over 100 MeV; when that was found not to be the case, the design became considerably more difficult.

ATHENE was intended to do high-energy neutrino physics, using neutrinos produced in the atmosphere by cosmic rays. As we saw in Sec. II.B, this source suffers from the extra $1/E$ spectrum falloff, due to the fact that muons and neutrinos produced from pion or kaon decay are suppressed by the limited decay path available in the atmosphere. This has an interesting corollary: the best estimate of the number of "prompt" muons or neutrinos—including those directly produced, if any, and those due to the decay of very-short-lived parents such as tauons—is a few times 10^{-4} of the total. Examining the energy spectrum, we note that for every factor of 10 in energy, the prompt particles increase relatively to the delayed ones by a factor of 10. Thus, as illustrated in Fig. 5, when the energy has gone up a factor of 10^4, the prompt particles will be at an intensity level comparable to the delayed ones. Thus the muons that penetrate to DUMAND will probably be mostly prompt ones, since the minimum energy necessary to reach DUMAND is ca. 5 TeV at the surface. These considerations are discussed by Berezinsky and Volynsky (1979).

UNICORN, a search for high-energy extraterrestrial neutrinos, appeared to be a most intriguing possibility. Some sources could be identified, e.g., collision of cosmic-ray protons in interstellar matter. Others, still unrecognized, probably exist. However, in view of the unknown intensities, a very large detector—say 10^9 tons— may be needed. It was unclear at this time whether UNICORN and ATHENE events could be distinguished. It was recognized, however, that a large detector for UNICORN would be suitable for ATHENE as well.

Thus the question of detector choice resolved itself into a decision whether to pursue the detection of stellar collapse neutrinos—which were in the range of at most tens of MeV—or to look at neutrinos predominantly in the GeV and TeV range. That question was further considered at the 1976 workshop, which definitely favored ATHENE and UNICORN (with a sympathetic tear for UNDINE). By the time of the 1978 workshop, the issue had been definitely settled in favor of the ATHENE-UNICORN array. UNDINE was returned to her sunless and solitary abode, there to be wooed and won by other suitors. In Vol. 3 of the Proceedings of the 1978 DUMAND Summer Workshop, we find a description of the first "standard" DUMAND array—a term used to define an official standard meant for use by the entire collaboration until further notice (Roberts, 1978a).

It is worth noting that UNDINE influenced strongly the design of IMB, and probably of Kamioka as well, since some of the same people involved in those projects took part in the UNDINE study at the 1976 DUMAND meeting. The water Cerenkov scheme for large detectors is now almost a standard.

D. The 1976 DUMAND Conference

The 1976 Conference in Hawaii, hosted by the University of Hawaii, was the first international DUMAND meeting. It included scientists from Japan, Switzerland, Germany, and Russia; the Russian contingent consisted of A. E. Chudakov, V. S. Berezinsky, B. A. Dolgoshein, and A. A. Petrukhin. Russian participation in DUMAND was strong at this time, and continued strong until it was abruptly cut off by the Reagan administration.[2] Even after their connection with DUMAND had been severed, they continued with Russian undersea detectors in Lake Baikal and in the Mediterranean.

The conferees passed a concluding resolution (DUMAND 1976, p. 633) ending with the statement "We view DUMAND as a vehicle most appropriate to collaboration on the peaceful exploration of this scientific frontier by interested scientists throughout the world."

They also made a concluding "statement" (DUMAND 1976, p. 634) in which they wrote that the establishment of a detector designed for neutrinos of 10 TeV and above was a suitable and important aim for a DUMAND array.

E. Basic structure of the DUMAND array

Having settled on the detection of high-energy neutrinos produced in the atmosphere or in outer space by high-energy interactions, we note that the predominant flavor of neutrinos so produced is the muon neutrino. It is produced more abundantly than either of the other two flavors, and it has the all-important property that, on interacting with a nucleon, it produces a muon, which carries off a large fraction of its energy. (Neutral-current interactions, which produce no muon, were first discovered in 1973 and have never influenced the array design.)

The muon, alone among charged particles, can traverse very long distances in dense media; its lifetime is long, its interactions are weak and electromagnetic alone, and large energy losses are possible but infrequent. Some atmospherically produced muons even penetrate 5 km of ocean to reach DUMAND. It is this property of muons that makes possible sparse detectors like DUMAND, where detector modules can be spaced many tens of meters apart and still reconstruct muon trajectories accurately. It also multiplies the effective volume of the detector, since muons entering from the lower hemisphere can only be due to neutrinos.

Detectors optimized for electron or tau neutrinos must be much denser, since the secondaries will be short range (except for muons). DUMAND can see such neutrinos, but we do not know how well, since few studies have been made as yet.

F. Acoustic detection

The 1976 Workshop was also notable for the proposal, made independently by Theodore Bowen of the University of Arizona (Bowen, 1976) and B. A. Dolgoshein (1976) (who credited the suggestion to unpublished work of A. Askarian), that we investigate the possibility of acoustic detection of neutrinos in the ocean. The sudden release of the neutrino energy in the ocean was equivalent, according to H. Bradner (1976), to that released by the detonation of 10^{-8} g of explosive and should generate an acoustically detectable signal in the water.

The proposal generated great interest. Acoustic waves in the ocean travel very long distances, and the prospect of instrumenting cheaply many cubic miles of ocean to detect neutrinos was an alluring one. Bradner reported on the conclusions of the *ad hoc* study group formed at the meeting and outlined the plans to investigate experimentally at existing accelerators the acoustic pulses produced by particle beams.

We shall not describe that work in detail (Bowen *et al.*, 1977); it was carried out at the Brookhaven National Laboratory, started but not completed at Fermilab. The conclusion was that acoustic detection of neutrinos was indeed feasible, but that the energy threshold for detection was in the region of 10^{16} eV. Neutrinos of this energy are absent in cosmic-ray-generated events in the atmosphere, since the decay length of a 10^{16}-eV pion is 5.5×10^{5} km, or somewhat more than the distance to the moon. Such neutrinos might, however, be incident from outer space (Berezinsky, 1976).

That was not the end of the story. All array designs since then have included at least a few hydrophones on each string, whose purpose is to monitor the instantaneous location of the string. Strings are fixed on the bottom, but are suspended by flotation modules; they are consequently free to move a few meters under the influence of vagrant ocean currents. The hydrophones serve the purpose of monitoring the exact position with respect to the calibrated network of ocean-bottom acoustic transponders. Thus hydrophones are available, just in case some of these very-high-energy neutrinos should drop by.

G. The 1978 DUMAND "Standard" Array

The 1978 array is shown in Figs. 9–11. It is a hexagonal array, 800 m on a side. Its construction is based on a

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[2] The severing of the Russian link was done with elegance and taste. We were told, confidentially, that while we were perfectly free to choose our collaborators as we liked, if perchance they included Russians it would be found that no funding was available for us.

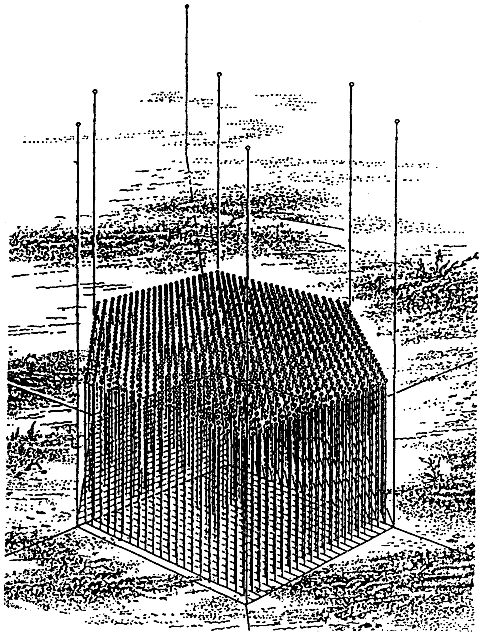

FIG. 9. The first DUMAND array: DUMAND G, the 1978 model. See text for details (Roberts and Wilkins, 1978).

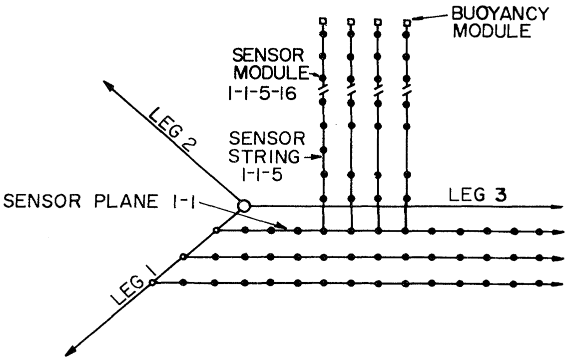

FIG. 11. Ground-plane view, showing how sensor strings are attached to the row cables to form sensor planes (Roberts and Wilkins, 1980).

Y-shaped central distribution cable. The three legs of the Y, 120° apart, are each 800 m long, and from each of them 20 parallel rows arise, 40 m apart, marking the base of the strings attached to each row at 50-m intervals. These are shown in Figs. 10 and 11. The sensor strings are 500 m long, with 18 sensors per string, spaced 50 m apart. The array thus comprises 60 sensor planes with 1261 strings of 18 modules each, for a total of 22 968 optical modules. We ignore for the moment the acoustic detector modules attached as outriggers to the array.

Several points deserve mention. The optical modules were still undefined. At that time they were expected to be complex multitube systems using wavelength-shifter techniques to effectively multiply the photocathode area. Also, the development of optical fibers had not yet reached the point where the attenuation was low enough, the cost moderate enough, and auxiliary optical transmitters and receivers cheap and reliable enough to be adopted for our use. Consequently we still had to plan on using copper cables for data transmission to shore. This entailed not only the need for several repeaters in the shore link, but an overall bandpass of only a few MHz, and therefore a need for a large amount of data filtering and compression at the ocean bottom. All of that must be executed by equipment physically inaccessible and subject to modification only by previously programmed alternatives controllable from shore.

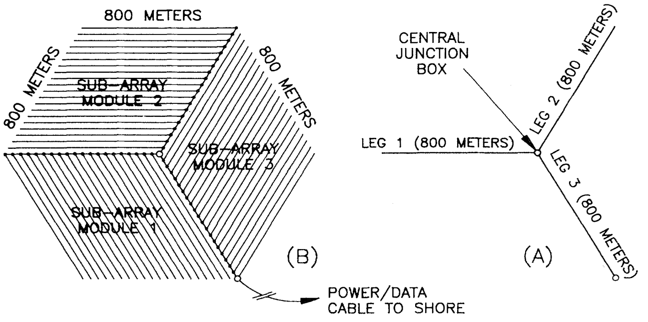

FIG. 10. Plan view of DUMAND G. Note: View *B* is not a perspective view of a cube, but a ground-plane view of the hexagonal array. (A) The three primary power/data support cables; (B) The 60 row cables that support the array's 1261 vertical sensor strings (Roberts and Wilkins, 1980).

Daunting though this prospect might have seemed, its effect was not to discourage the already committed, but to point out where progress was needed. That progress was not long in coming.

In 1979, at a DUMAND conference hosted by the Russians in Khabarovsk and Lake Baikal, Wilkins was able to announce a result toward which all his efforts had been bent for many years: optical fibers were now ready for use in undersea cables (Wilkins, 1980). The advances that made this possible included the production of multimode fibers with attenuations of 0.47 db/km and single-mode fibers with the (then) unbelievable attenuation value of 0.2 db/km at 1.55 microns. Not only were optical fibers becoming practical, they were eliminating the need for repeaters. In addition reliable operation of quaternary laser transmitters at 1.27 μm and InGaAsP avalanche photodiodes at 1.257 μm and beyond were reported. Full duplex operation was demonstrated over 8-km lengths, and 100-Mb/sec communication at 1.3 μm with 10^{-9} bit error rate was reported over 53 km of cabled, multimode fiber with 25 fusion splices. DUMAND specifications now call for fibers optimized at 1.300 μm and 1.550 μm, with less than 12 db attenuation over the 40-km length (DUMAND II

Specifications 1989).

These advances removed the low-data-rate barrier imposed by copper transmission lines. Instead of a maximum data rate in the 2–5-Mbaud range, we could look forward to data rates in the hundreds of Mbaud (and even gigabauds). This made possible the total elimination of data-analysis hardware from the ocean bottom and allowed it all to be transferred to land. The array could then have the ideal characteristic for any remote and inaccessible sensor: it would send *all* its data to shore—background, noise, and signal—and sort them out on dry land. There are many reasons for desiring this approach; an important one is that in a field as new and as little understood as neutrino astronomy (or even high-energy physics at TeV energies) it would be unwise to throw away any data, since it might turn out that the discard was more valuable than the retention. (Another argument that surfaced later was that one man's noise is another man's signal; thus the cosmic-ray neutrino background, interesting to physicists studying cosmic rays or neutrino oscillations, is a noise background for high-energy neutrino astronomers intent on point sources. Similarly, we find biologists interested in the bioluminescent background that contributes to the photomultiplier tube noise level. The bioluminescent background can normally be neglected, since it affects a small fraction of the array during 20–25% of the time, as best we can tell.)

H. The life and death of Sea Urchin; the final solution

On January 1, 1980, the Hawaii DUMAND Center formally came into being. It was supported by a grant from DOE and by funds from the state of Hawaii. On that date John Learned and I started work in Hawaii. Our directive: to assess the feasibility of the DUMAND project. We were joined by V. Z. Peterson, Director, and V. J. Stenger, later Deputy Director. Fred Harris of the High-Energy Physics group contributed to the effort, and we had two graduate students to begin with, Daniel O'Connor and John Babson. By this time there was a formal DUMAND collaboration, which is listed in Table III.

TABLE III. DUMAND Collaboration, as of 1982.

University of Hawaii
University of Kiel
University of Bern
California Institute of Technology
Purdue University
Vanderbilt University
University of Wisconsin
Institute for Cosmic-Ray Physics, Tokyo
University of California, Irvine
Scripps Institution of Oceanography
Technische Hochschule Aachen

DUMAND Associate Groups[a]

University of Chicago (Astrophyics)
Naval Ocean Systems Center
Naval Ocean Research and Development Activity
Naval Research Laboratory (Cosmic Ray)
Northwestern University
Harvard-Smithsonian Astrophysical Laboratory (Mt. Hopkins)

[a] Institutions expressing interest and making contributions to DUMAND, but not formally affiliated.

I took as my first job a study of wavelength-shifting systems. The largest available photomultiplier tube (PMT) had a diameter of 8 in., and a multiplication of the effective area was essential if we were not to fill the ocean with PMT's. In this effort I had an able collaborator, Donald McGibney, on leave from Naval operations at Pearl Harbor. Engineering assistance was furnished by Robert Mitiguy of the Hawaii Institute of Geophysics, who was to play an important role in the evolution of DUMAND.

We spent two years developing a system consisting of glass tubes, about 3/4 in. in diameter and six to eight feet long, filled with wavelength-shifting solution, optically coupled to the 17-in. Benthos glass pressure sphere that would contain the phototube. The calculated optical gain was about 10. We found the best fluor available to be Hostasol Yellow, a proprietary product of Hoechst & Co.

Perhaps the most difficult aspect of the design was the coupling of the large number of glass tubes to the glass sphere. If it were rigid, the deployment problem would be horrendous; the tubes were inherently fragile, and the idea of implanting thousands of Sea Urchins in the ocean was terrifying. Folding the glass tubes in like the ribs of an umbrella would facilitate protecting them, but then the problem of erecting them in position at the ocean bottom and guaranteeing a good optical seal to the glass sphere was hardly a trivial matter. Sea Urchin is illustrated in Figs. 12–14 and described in detail in a published paper (Camerini *et al.*, 1982).

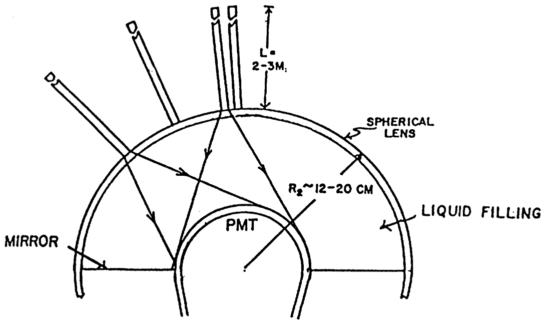

FIG. 12. Cross section of the Sea Urchin detector module. A 17-in. Benthos glass sphere sustains the ocean pressure. A liquid filling matches the glass index of refraction and transfers the diverging cone of light from the spine to the relatively small photomultiplier tube. The spines are radial glass tubes about 2 cm in diameter and 3-m long (more if attenuation is low enough) (Hinterberger *et al.*, 1980).

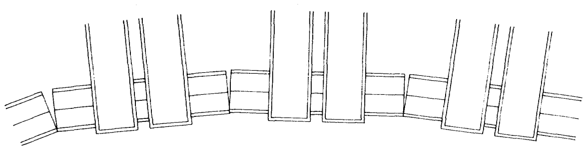

FIG. 13. Detail of Sea Urchin construction. This shows how the glass tube "spines" can be mounted in a flexible matrix, which can be flattened into a plane for transportation (as in Fig. 14) or fitted around the glass sphere holding the PMT, as in Fig. 12 (McGibney *et al.*, 1980).

In the end, the problem went away; a benevolent *deus ex machina* intervened, in the form of a commitment from the Hamamatsu Corp. of Hamamatsu City, Japan, to design and construct for us a PMT with a 16-in.-diameter hemispherical photocathode, the largest that could fit into the largest glass pressure sphere available, the Benthos 17-in.-o.d. sphere. How this came about is discussed earlier in this section.

Thanks to this happy circumstance, one of our major headaches disappeared. The Hamamatsu tube would not be quite as sensitive as the Sea Urchin, but the difference could easily be compensated by decreasing the PMT spacings somewhat. We would now end up with a simple, sturdy design of the optical sensors that would be relatively easy to fabricate and deploy.

Later, after the death of Sea Urchin, we found that the (European) Philips Co. was also willing to gamble on designing a PMT for DUMAND. It was based on an existing x-ray image intensifier; it will be discussed in more detail in Sec. V. Present plans are to use equal numbers of Hamamatsu and Philips tubes in DUMAND II.

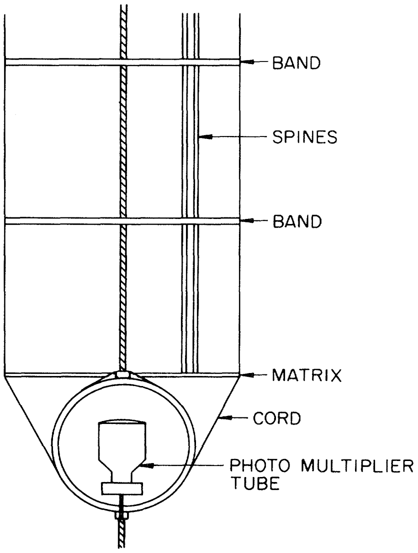

FIG. 14. Sea Urchin with spines, firmly held in matrix, rotated to a parallel orientation for transport, and secured in place by bands (McGibney *et al.*, 1980).

V. THE INCREDIBLE SHRINKING ARRAY

The 1978 DUMAND Standard Array, on closer examination, assumed more and more awesome proportions. While the fiscal atmosphere for large scientific projects was not yet as inimical as it became in the 1980's, the magnitude of the 1978 array was formidable enough: 1261 sensor strings, each with 18 complex sensor modules—Sea Urchin is a paradigm for one—to be deployed on the ocean bottom at a depth of five km! The oceanographers were amazed—this project was larger than any other peacetime ocean project by a factor of the order of 100. The size of the array was based on relatively scant information on the expected neutrino intensities and was difficult to justify in detail; the general idea was that neutrino cross sections are small and high-energy neutrinos are scarce, so the detector had better be large.

The first change in the 1978 array came at the 1980 conference in Honolulu, after DUMAND had been approved for a feasibility study. It was a design for DUMAND G2 (Roberts and Wilkins, 1980)—the original array was called DUMAND G, G standing for gigaton. G2 was a relatively minor modification of G. Instead of the hexagonal layout of G, with its central Y, G2 had a rhomboidal ground plan (see Fig. 15). There were 21 rows of 21 strings each. The rhomboidal plan made the strings a close-packed hexagonal array. The string spacing and row spacing were 40 m each.

DUMAND G2 achieved a reduction in the number of optical modules from 22 698 to 6615; in area, from 1.8 km^2 to 0.866; in volume from 1.22 km^3 to 0.60. The use of Sea Urchin for the sensor modules decreased the individual module cost estimate by a factor of two compared with the estimated cost of a direct-view module containing several small PMTs. In view of the uncertainty of source strength estimates, this decrease in size was judged tolerable, the saving in cost being estimated as a factor of four.

We pass over the cost estimates, except to note that real concern with cost was now apparent for the first time. This is a measure of the approach to reality of the array design.

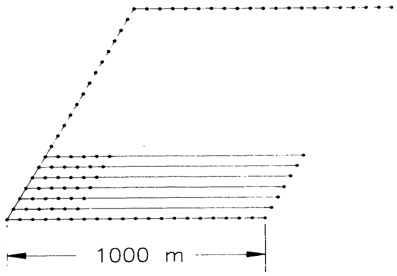

FIG. 15. Ground plan of DUMAND G2. This array consists of 21 rows of 21 strings each, in a rhomboidal arrangement that produce a close-packed hexagonal string array. Dots show string locations. Spacing is 50 m, so ground area is just under 1 km^2 (Roberts and Wilkins, 1980).

A. First suggestions for smaller arrays

At the 1980 Conference suggestions were made for the first time that a smaller array might be worth looking into, and a committee, with myself as chairman, and including O. C. Alkofer, C. C. Grupen, and R. Silberberg, was formed to consider the subject. No important conclusions were reached; but the proceedings list the arrays suggested (Roberts, 1980a), as follows.

(1) S. Miyake suggested a very small array, 100 m on a side, with 10-m spacing of strings and detector modules, intended for cosmic-ray muon studies. This became known as MINI-DUMAND.

(2) The array committee proposed a scaled-up version of MINI, 500 m on a side, with 50-m spacing. This would use the same number of PMTs, but have a volume 125 times greater and an area 25 times greater. Appreciably smaller than DUMAND G or G2, this became known as MIDI, and reappeared, in a somewhat diminished form, as the 1982 Standard Array (Fig. 17 below).

(3) At a general meeting, a combination of MINI and MIDI was suggested: a "graded" array, with a dense center and sparser outer volume. This suggestion does not seem to have been followed up.

Further discussion of these proposals required considerable Monte Carlo study of their properties. Much of that (at least as far as single-muon detection is concerned) had been accomplished by the end of the workshop and was reported by Roberts and Stenger (1980a), as follows:

(1) With conservative values of PMT sensitivity, the MINI array is oversensitive. A minimum-ionizing muon triggers more than 50 PMTs when the threshold is set at 2 photoelectrons. Hence the spacings were increased to 15 meters. The results were excellent: the angular resolution improved, as did the timing information. This array was called MINI2.

(2) MIDI was highly satisfactory for single-muon tracks from 0.3 to 100 GeV. The spatial resolution was considerably better than MINI2, and the range of energies wider. These two arrays are described in Table IV.

While these are only preliminary results, they show that smaller arrays than G2 are perfectly capable of producing good data, though of course their event rates will be smaller.

B. Further work on small arrays

In December 1980 a deployment workshop convened to consider techniques for deploying the smaller arrays that had been suggested at the 1980 DUMAND conference. The assembled deployment experts did so, but decided to add another even smaller array, called MICRO. In all three cases—MINI, MIDI, and MICRO—their instructions were to consider both low- and high-sensitivity detector modules, since at this time no final choice was yet possible.

Thus, in addition to MINI and MIDI, the MICRO array was introduced. It was thought of at the time as primarily a test bed, like the SPS, but it bears an uncanny resemblance to the eventual array, DUMAND II.

As shown in Fig. 16, MICRO is a hexagonal array consisting of two concentric hexagons. The inner has 6 strings, the outer 12; with the central string, this makes a total of 19 strings.

In the low-sensitivity version, the unit spacing is 16 m; this is the side of the inner hexagon and the sensor spacing on strings. In the high-sensitivity version, the unit is 50 m. In both versions there are 19 strings and 209 sensors (there are only 11 sensors per string.) It was at this meeting that Monte Carlo simulations revealed that the best arrangement of sensors used a larger separation between strings than between sensors on the same string (Roberts and Stenger, 1980b).

The small size of this array led to suggestions for using a "glide-body" technique for deployment. This is discussed later under the topic of Deployment.

TABLE IV. Properties of several DUMAND mini-arrays. CUBE and HEXAGON are two versions of MINI. Only the cubical version of MIDI is shown here.

Property	Cube	Hexagon	Midi (cube)
Number of strings on a side	11	7	11
Spacing between strings (m)	15	16.12	50
Spacing along strings (m)	15	15	50
Total number of strings	121	127	121
Sensors per string	11	11	11
Total number of sensors	1331	1397	1331
Length of bottom edge (m)	150	96.72	500
Array height (m)	150	150	500
Area of bottom (m^2)	22 500	24 304	0.25 km^2
Volume of array (m^3)	3.37×10^6	3.65×10^6	0.125 km^3
Typical diagonal (m)	212	230	800
Average number of sensors/track	12	11	8
Maximum distance of an interior point from nearest sensor (m)	16.77	15.14	53.5

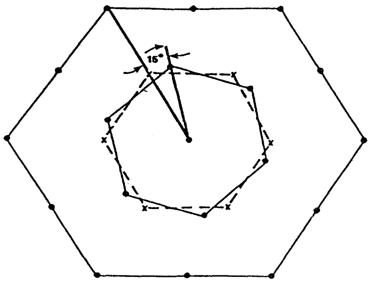

FIG. 16. The hexagonal version of MICRO. It has 19 strings. The inner hexagon has been rotated 15° to avoid alignments of strings (Jones, 1980).

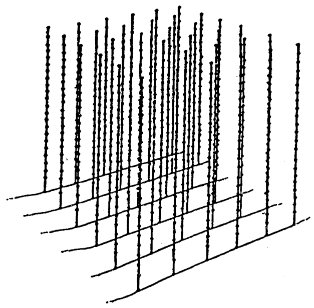

FIG. 17. The 1982 Standard Array. There are 36 strings in 6 rows of 6. String and row spacing is 50 m, while the 21 modules on each string are 25 m apart. The total number of modules was 756. There is a separate cable for each row, so that only one row is deployed at a time (Roberts, 1984).

C. The 1982 standard arrays

Between the 1980 International DUMAND Symposium and the 1982 DUMAND Signal Processing Workshop there occurred the 1981 Annual Neutrino Meeting, which took place that year on the island of Maui, hosted by the University of Hawaii. At that meeting two important innovations were proposed. In a paper by Roberts, Stenger, Peterson, and Learned (1981), a "Phase I" DUMAND detector was proposed. This was intended to be an inexpensive detector suitable for detecting neutrinos in the range 0.1 to 50 TeV. It consisted of a square array of six rows of six strings each, with 50-m spacing; the ground plan was thus 250 m×250 m. Each string would have 21 sensors spaced 25 m apart, thus 500 m high. The sensors were Sea Urchins (see Figs. 12–14). The installed cost of the array was estimated as $5–7 million.

At the Maui meeting another paper of interest was presented by a large group of the burgeoning DUMAND collaboration (Blackinton *et al.*, 1981). It described the immediate objective of the DUMAND project: the construction and ocean deployment of a string of five phototube detectors (which at this time were thought of as using several EMI 13-in. diameter hemispherical photocathode tubes in 17-in.-Benthos housings) as the first stage of testing the DUMAND concept. This project, later called the SPS or Short Prototype String, was carried out using 16-in. Hamamatsu PMTs and demonstrated the capability of DUMAND to operate satisfactorily in the actual background of ocean radioactivity and bioluminescence.

The design studies were being assisted by this time by extensive Monte Carlo calculations, which were now under Professor Stenger's direction.

D. The 1982 signal-processing workshop

At this meeting the "Phase I" array (Fig. 17) first expounded at the Maui meeting the year before (Roberts *et al.*, 1981) became the 1982 Standard DUMAND Array. An important change had occurred, however; by this time Sea Urchin had been gladly abandoned in favor of simple PMT sensors consisting of a 17-in. Benthos pressure sphere encasing either a 16-in. hemispherical photocathode Hamamatsu PMT or a 12-in. EMI PMT. This change was expected to simplify enormously the packaging and deployment problems. The resulting array, comprising 36 strings with 756 sensors, had a volume of 31 million cubic meters of water and a ground area of 62 500 m^2. This is equivalent to a target mass effectively many times greater, because the muons produced by high-energy neutrinos have long ranges, and thus the nominal target volume is enhanced by the surrounding water (Reines, 1978; Roberts, 1980b). This made it at least 100 times larger than any previous high-energy neutrino detector.

Also at this meeting, it was publicly announced that the first muon string deployed in the ocean had been lost at sea when its support cable parted.

This accident, due in part to an uncooperative ship captain (who insisted on literally following his own interpretation of his written orders in the face of adverse wind and sea conditions and agonized appeals from the scientists), was eventually ascribed to "snap loading." The cable load—in this case the muon string—is connected to the ship by a long, relatively inelastic cable. This ship is subject to wave motion; it rolls, pitches, and yaws as the ocean decides. Should the downward motion of the cable support be faster than the terminal velocity of free fall in the ocean of the load—which is perhaps 1 m/sec—the cable will go slack. When the ship rises again, the condition of snap loading occurs, when the load is suddenly subjected to a constraint to move up rapidly which it cannot follow; the tension in the cable goes up by a large factor—as much as 20 or more—and the cable breaks. This problem becomes progressively more serious as the sea state worsens. [This is a simplified treatment of the subject, neglecting the elastic properties of the cable. A more detailed, complete discussion is given by Liu and Wilkins (1984).]

TABLE V. Major parameters of the successive stages in the evolution of DUMAND II. The effective volume of a DUMAND array is generally considerably larger than its physical volume. This phenomenon, especially imporant for the smaller arrays, is due to the fact that neutrino interactions occurring outside the array can produce muons that traverse the array. The increase of effective volume can be as large as a factor of ten or more for small arrays (Reines, 1978; Roberts, 1980b). Similarly, the floor area of an array is not the same as its effective area. For veritical muons they are not very different, but the effective area for a nonspherical array is a function of its shape and the neutrino direction. For low-energy neutrinos additional corrections may be required.

Name	Date	Type of array	No. of strings	No. of sensors	Floor area (m^2)	Enclosed volume ($m^3 \times 10^6$)
DUMAND G	1978	Hexagonal	1261	22 698	1 660 000	1290
DUM G2	1980	Rhomboid	441	6 615	866 000	600
MINI	1982	Square	121	1 331	10 000	1.0
MINI2	1982	Square	121	1 331	22 500	3.375
MIDI	1982	Square	121	1 331	250 000	125
MICRO A	1980	Hexagonal	19	209	2 660	0.383
MICRO B	1980	Hexagonal	19	209	25 980	11.69
82 STD	1982	Square	36	756	62 500	15.625
DUMAND II	1988	Octagonal	9	216	7 728	1.777

There are several cures for snap loading; among the best is a device called a "ram tensioner" (Liu and Wilkins, 1984) in which the cable is provided with a length of slack whose tension is controlled by a weight and whose motion is damped by a large shock absorber. The combination effectively removes the risk of snap loading except for conditions so extreme that one has no business putting a load into the ocean.

After the loss of the muon string, which caused uncomfortable financial strains, the use of a ram tensioner on all subsequent tests was adopted.

The 1982 DUMAND "Standard" Array remained the standard until the 1988 proposal for DUMAND II was being worked on, when the smaller octagon array for DUMAND II was adopted.

E. The DUMAND II array

The completion of Phase I of DUMAND—the successful deployment and operation of the short prototype string—cleared the way for a proposal for the construction of DUMAND II, an operational array designed to see extraterrestrial neutrinos. That proposal was submitted to the Department of Energy in July of 1988. It received scientific approval in a peer review by HEPAP—the High Energy Physics Advisory Panel—in May, 1989. It underwent further review, culminating in a review session at the DUMAND Center in Hawaii by a DOE panel who examined the budget in detail. Final allocation of funding was made in April, 1990, nearly fifteen years from the date of the first DUMAND Workshop.

The "Octagon" array proposed in 1988 was considerably smaller than the 1982 standard, which had 36 strings and 756 sensors. The Octagon array consisted of 9 strings, each with 24 sensors (plus environmental and test modules), for a total of 216 sensors. They were arranged in a regular octagon of 40 m on a side, with a ninth string at the center (see Fig. 3). This is the minimum array, with uniform angular acceptance, that can determine a muon trajectory in any direction. To do this requires signals from at least three noncollinear strings. No further shrinkage is plausible. The successive stages in the evolution of DUMAND II are summarized in Table V.

The motivation for the last cut is primarily financial. The approval of the DUMAND project was simultaneous with the rejection of other valid and important nonaccelerator projects, whose major drawback was cost.

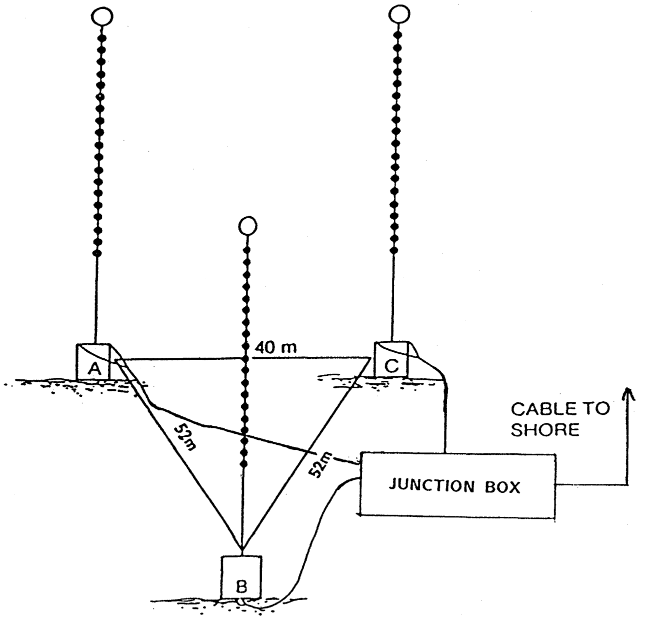

FIG. 18. The initial deployment of DUMAND II is to be this TRIAD of strings, consisting of the center string and two adjacent octagon strings. Its primary purpose is to verify the operation of hardware and software, and our estimates of background and cosmic-ray rates (Pokrofski *et al.*, 1988b).

The U.S. contribution to the cost of DUMAND II is under $5 million, the rest (a roughly equal amount) being made up by the important financial contributions of foreign collaborating groups in Europe and Japan. *Thrift, Horatio, thrift.*

F. Initial deployment of the TRIAD

In order to test thoroughly all aspects of deployment, construction, and operation, it is planned initially to deploy three strings—the TRIAD (Fig. 18)—and operate them long enough to check out all aspects of installation and operation. This might take several months, during which the remainder of the array can be prepared. The TRIAD, including the central and two outer strings, will be able to reconstruct muons traversing it, so that the analysis hardware and software can be tested.

VI. DUMAND SENSOR DESIGN

The design of the DUMAND sensor is a fundamental parameter of the array. The sensitivity of the sensor determines the spacing of sensors along the string and the spacing between the strings. The angular dependence of the sensitivity, together with the orientation of the PMTs within the array, determines the sensitivity of the array as a function of angle. The mechanical properties of the sensor determine how the sensors must be packaged for deployment, a factor which can have an important bearing on costs. It will also affect the environmental risks associated with both deployment and operation. We must eternally be grateful that it was never necessary to justify to the EPA the introduction into the bottom of the ocean of thousands of glass tubes containing solutions of wavelength-shifting fluors in toluene, which Sea Urchin might have required. (Actually, Sea Urchin was abandoned before the EPA became involved in monitoring such operations.)

The most basic properties of the sensor module are the PMT characteristics. These include the sensitivity as a function of direction of the incident light (which depends on the collection efficiency as a function of the cathode source location), the spectral variation of sensitivity, the noise background of the PMT, its sensitivity to the Earth's magnetic field, its voltage vs gain characteristic, and its expected lifetime. In addition the variation of collection time across the photocathode surface, the width of the output pulse, and the ability to distinguish between initial signals of one, two, or more photoelectrons are important.

A. Discrimination against the ^{40}K background

One of our basic problems is to discriminate against the constant background due to Cerenkov light from the ^{40}K unavoidably present in the ocean. The disintegration of one potassium atom produces on the average about 43 Cerenkov photons in the wavelength range of interest (Roberts, 1978a). Except for those few atoms that disintegrate within a foot or two of the sensor tube—Geelhood (1982) estimates the fraction as 1/400 of all decays—the signal from any individual ^{40}K disintegration will be a single photoelectron. Thus a PMT capable of distinguishing between single photoelectrons and two or more can readily be biased to get rid of most of the ^{40}K noise at the expense of a slightly higher threshold for real signals. If the gain of the first dynode of the PMT is in the usual range of 4–8, the distinction between output pulses induced by one photoelectron striking the first dynode and those produced by two will be blurred. There will be overlap of the two distributions, and biasing out the one-photoelectron signal will entail some loss of true signals. If the first dynode gain is as high as 20, however, the two distributions will have only a small overlap, and the single photoelectrons can be biased out with little loss of true signals. Tubes that make this distinction are referred to as "smart"; those that do not are "dumb." We see that a high-gain first dynode is highly desirable.

Of the two tubes ultimately developed for DUMAND, the Hamamatsu tube will soon have a high-gain first dynode and will become smart. The Philips tube (Bosetti and Samm, 1988), with an image-intensifier-like high-voltage first stage and phosphor target viewed by a conventional PMT, has a signal at the photocathode of the secondary tube that averages 40 photoelectrons for a single electron striking the first-stage phosphor, and is thus not merely smart, but brilliant. It is, however, more ex-

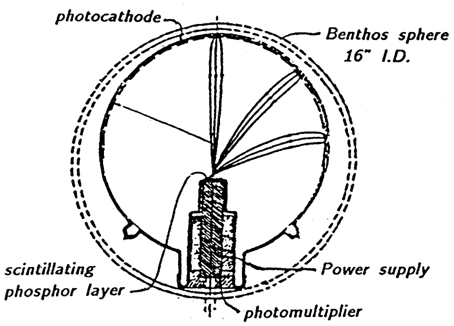

FIG. 19. The Philips "smart" photomultiplier tube (PMT). It consists of a large (ca. 14-in.) x-ray image intensifier, with a hemispherical cathode and a fast phosphor at the electron-optical focus. In the parent tube, an image of the emission from the photocathode was formed at the anode and could be further amplified by image-intensifier tubes. In this application the image-intensifier amplifier is replaced by a conventional small PMT that fits into the reentrant opening, so that its cathode is as close as possible to the phosphor screen. As a result, with 20-kV acceleration on the photoelectrons, the light generated by a single photoelectron at the scintillator screen is sufficient to produce about 40 electrons from the small PMT cathode. Discrimination between one- and two-photoelectron emission from the photocathode is consequently very good; the tube is "smart." The high-voltage supply for the first stage is built into the tube (Bosetti and Samm, 1988).

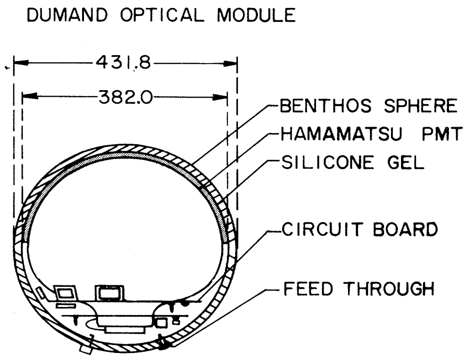

FIG. 20. Cross section of the optical module with the Hamamatsu 16-in. PMT installed. The Hamamatsu tube is a conventional Venetian-blind dynode PMT (DUMAND Proposal, 1988, p. 13).

pensive and not yet in production. It is shown in Fig. 19.

The optical module containing the Hamamatsu 16-in. PMT (Model R2018) is shown in Fig. 20.

An important parameter of PMT operation is the time spread of a single-electron initial pulse at the output. To keep this narrow (10 nsec or less), the time spread through the dynode structure must be small, and the time of collection of photoelectrons over the entire photocathode must also be small. The Hamamatsu tube has been improved and now has good properties in this regard.

However, the Philips tube has poorer multiple-pulse resolution. This is because of the intermediate phosphor, which functions as a high-gain first dynode. If the phosphor had zero decay time, everything would be fine. Unfortunately, the fastest phosphors presently available have decay times of the order of 30 nsec, so that the output pulses from the Philips tube, even for a single-photoelectron event, are distributed over a relatively long time. This is an important drawback when one desires to look at events in which there is more than one muon. In events in which the muons have a common or closely spaced origin, the separation at ocean depths due to multiple scattering in the ocean is likely to be a few meters. To distinguish two muons with this separation implies a time discrimination of only a few nsec. Here the Philips tube is at a decided disadvantage—unless phosphors with much shorter decay times and comparable efficiencies can be found.

B. The bioluminescence problem

In addition to the ^{40}K background, DUMAND is subject to the possibility of interference from bioluminescent organisms in the ocean. When the project was started, very little was known about the possibilities or prevalence of bioluminescent light sources in the deep ocean; very little had been done to study such sources. In fact, the studies undertaken by DUMAND are now the primary source of data in that field (Aoki *et al.*, 1986; Babson *et al.*, 1990; Bradner *et al.*, 1987; Clem, 1989; Matsuno *et al.*, 1989; O'Connor, 1990; and Webster *et al.*, 1990).

The first DUMAND paper on deep ocean bioluminescence is one by Elizabeth Kampa (Kampa, 1978), who was one of the first to observe deep ocean bioluminescence. It was provocatively entitled "Serpents in an Astrophysical Eden." She discussed the three types of biohazards to which any ocean equipment is susceptible: mechanical, bioluminescent, and encrusting or fouling.

Of these, the first is concerned with hazards to the equipment from large animals traversing the array. At mid-ocean depths this would be severe; at the ocean bottom it is negligible. Large animals do not venture so deep; there is nothing there to attract them.

The last—biofouling—also had a hopeful prognosis. As long as deployment could be carried out in a reasonably sterile way—e.g., by protecting the array from contamination until it reached the ocean floor—no entrained life forms would grow. The greatest menace is barnacles, which will grow at 10 000-meter depths if their larvae are transported there. The unintentional 19-month sojourn of TTR4 on the ocean floor, discussed elsewhere, shows this not to be a problem.

Finally, there is bioluminescence, the most serious of the three dangers. This is to be expected. The main questions are how often, how bright, and how long are the flashes.

As to intensity, the number 10^{-8} watts/cm^2 keeps recurring, as Kampa points out (Kampa, 1978); it is a good average of the peak intensity of the bioluminescent pulse. The spectral characteristic is ingeniously matched to the transmission characteristics of seawater, peaking in the blue-green (Kampa and Boden, 1957; Kampa, 1978).

The variety of sources covers the entire evolutionary range (except the very top end). The frequency of flashing is anything from random to clustered. The time constants, as compared to PMT time constants, are long. The fastest flashes have millisecond rise times and durations of appreciable fractions of a second. This means that on the nanosecond time scale of the PMT the bioluminescent flashes constitute a random background of varying intensity, not a coherent one.

These predictions of Kampa were verified when the first DUMAND descents in the ocean began. The best data obtained by DUMAND are superior to any previous work at these depths (we had bigger and better PMTs and more sophisticated electronics.) The DUMAND work also confirmed what had been previously observed in several cases: the bioluminescent background was excited by the motion of the cable-suspended array in the water. When the array was moving, the bioluminescence was strong. When it was parked on the bottom, the rates decreased markedly. At DUMAND depth (4500 m), in a location near the projected site, an array sitting on the ocean bottom was undisturbed by bioluminescent flashes for at least 75% of the time (Aoki *et al.*, 1987). This has been taken as showing that bioluminescence will not seriously interfere with DUMAND operation.

The data obtained by the SPS at various depths in the ocean constitute a significant contribution to the knowledge in the field. In particular, the information we obtained about the frequency and motion sensitivity of bioluminescence at the bottom—so essential to our experimental design—is probably among the best available on the subject (Webster *et al.*, 1990; Aoki *et al.*, 1987). There have also been significant Russian measurements in the Black Sea and the Atlantic Ocean (Bannykh *et al.*, 1987), and in the Pacific Ocean and Japan Sea (Abin *et al.*, 1987). These measurements are in good accord with ours.

C. Variation of sensitivity with angle

The optical modules contain, in addition to the PMT, the associated high-voltage supply and the necessary control electronics. Although the PMTs themselves allow light to enter from all directions, the bottom of the tube is obscured, and thus the angular sensitivity of the optical module falls off considerably for light in the upward direction. Since the neutrinos of greatest interest arrive from below, the optical modules will all be mounted facing down. Atmospheric muons from above are thus discriminated against to some degree. It should be remembered that a fast muon produces Cerenkov light with a cone angle of 42°, so that even downward muons remain detectable, albeit with lower efficiency. It is calculated that the array has only one-third the effective area for downward muons as for upward (see Table I).

VII. SIGNAL PROCESSING

A. Background light in the ocean: ^{40}K decay

The storing, filtering, and treatment of the data from the DUMAND array have constituted from the beginning a worrisome and difficult task. Consider that we have an array of sensors, with a large constant background due to the light produced by ^{40}K radioactivity in the ocean. With a 16-in. hemispherical phototube, this turns out to produce a background rate of 80 000 to 100 000 counts/sec. Observations in the ocean confirm this figure. This is sufficiently high to warn us that much larger phototubes might be swamped by the ^{40}K background unless connected in coincidence. (There is also a small neutron background due to spontaneous fission of the tiny uranium content of the ocean, but this is negligible unless one is concerned with events in the MeV energy range.) Thus dealing with the ^{40}K background has always been of prime concern.

If the muon track yields enough light at the detector, we can bias the detection system to suppress the ^{40}K signal by setting a threshold at a high enough value. How high it needs to be depends on the PMT properties.

Of course, connecting tubes in coincidence will also decrease the background; but this is an expensive solution. If we were to double the number of phototubes the argument that we could do better by increasing the size of the array rather then lowering the background would be unanswerable, since other methods for getting rid of background and noise are available. Thus, in selecting events for analysis, we do use the equivalent of coincidence techniques (by applying the causality requirement—of which more later), which effectively removes most of the ^{40}K background. In other words, much of the background is removed by software coincidence techniques.

As we saw in Sec. VI, bioluminescence is not likely to be a serious problem; its effect will be to raise background rates intermittently in small portions of the array—perhaps even single modules.

We have thus established that the phototubes can survive the ocean background and still yield useful data. That still does not tell us how to handle the data; how we do that depends strongly on how many phototubes are in the array and on how large the array is.

B. Signal processing: topological considerations

Topologically viewed, a DUMAND array is an inverted tree, characterized by the same nodes as a tree structure. In a tree, there are nodes between trunk and main branches, between main branches and smaller branches, and so on down to twigs and finally leaves. In the large DUMAND arrays, there are nodes between individual modules and the junction where string data are collected; the processor at this point has been called the string bottom controller or SBC. Strings may be collected into rows, so there may be a row junction and therefore a row processor. In a very large system like DUMAND G, there are three sets of rows, called legs, so that there would be a leg processor. Finally the legs would meet at the ocean junction of the cable to shore, so there must be a central junction box processor to send the data to shore. Thus there were five nodes in the DUMAND G tree: at the sensor, the string bottom, the row end, the leg end, and the cable termination.

Of course, some of these could simply be passive addition circuits where no active signal processing takes place; but even in such circuits there can be collisions when more than one signal arrives at a given time. Thus it was very soon realized that every signal would have to bear an ID indicating its origin and a time stamp indicating its time of origin; otherwise an event could never be resolved.

Furthermore, the data-handling capabilities of the various branches of the network determine how much processing is necessary before the signals can be forwarded. In Sec. IV, we have noted the profound difference that the switch from copper to fiber-optic data transmission made in the data-handling capability of the transmission path and the equally profound effect in simplifying the underwater installation.

As the array shrank, so too did the number of nodes in the signal network. If optical fibers were cheap enough, one could consider an ideal system in which each sensor had its own fiber to shore, and there would be only one underwater node, the sensor module itself. Underwater cable technology has not yet reached that stage, nor is it necessary for small arrays.

In the earliest array, DUMAND G, there were five underwater nodes. In DUMAND G2 these were reduced to four and remained at that level until the 1982 array, with six rows of six strings each. In the 1982 proposal for the 1982 Standard Array, the number of underwater nodes had been decreased to two—one at the sensor and one at the string bottom—by running a separate shore cable for each row, with a separate fiber for each string. The combining of string and row data was done on shore, where the electronics was free from the constraints inherent in ocean-bottom operation.

With DUMAND II, the octagon array, the rows disappeared. Thus, like 1982 Standard Array, DUMAND II has only two nodes: the optical module and the string bottom.

For maximum system reliability, the number of nodes in a communication system should always be minimized and the nodes made as passive as possible. The more active the node, the greater the possibility of failure.

C. Signal processing: first attempts

Let us first consider the original DUMAND G, with a minimum of 22 698 sensors. The first serious attempts to set up a signal-processing protocol were made by two groups at the 1978 Workshop: Akerlof, March, Snow, and Theriot (1978) and Cowan, Gilbert, and Redfern (1978). It is interesting to compare their approaches. It should be remembered that the all-important simplifying causality condition—which introduces the constraint that two events cannot be causally related if the later one lies outside the light cone of the first—was first pointed out by Roberts in 1982 (Roberts, 1982), so that it did not enter their considerations.

Akerlof *et al.* (1978) introduced signal processors, in the order of decreasing complexity, as follows: at the shore cable termination, the highest node in the system, a sophisticated minicomputer. At the end of each row, or plane, an end station, to manage plane-to-plane communication and fast trigger logic; at the bottom of each string, a string station, that relays fast logic signals and watches over string welfare; and at each sensor or group of sensors, a simple data-handling system to digitize and store signals and generate fast logic pulses.

The paper describes in detail the functions executed at each level, points out the necessity of increasingly careful engineering design as the number of nodes increases, and notes the extraordinarily severe reliability requirements, in view of the impossibility of servicing.

Cowan, Gilbert, and Redfern (1978) analyzed the data-handling problem, arriving (independently) at the same conclusions as Akerlof *et al.*, and thus concentrated their attentions on the most expensive portions of the data-handling system—the 1261 string data handlers and the 22 698 sensor data handlers. They restricted the sensor logic to determining that a signal of two or more photoelectrons had been received, and this was relayed to the central processor at the shore cable terminal. The central processor must then decide whether a real event has been observed. It is assumed that 80 microseconds are available for this decision; this is reasonable only if some sort of pattern-recognition algorithm is assumed.

Two modes of operation are suggested. In the first, if the central computer is satisfied that an event has occurred, it calls for an array dump. Since several thousand sensors may have signals during the allotted time interval (which depends on the array size), the dump may take several milliseconds, and during that interval the array would be dead.

In the alternative mode, the central computer looks for signals that might indicate a muon track. If it finds them, it triggers a dump order for those modules which might have observed the muon.

It was clear that neither of these analyses, circumscribed as they were in time and facilities, could do more than discover some of the more important problems to be solved. Historically, the long-term, secular shrinkage of the array and the introduction of fiber-optics data transmission were the most important keys to finding a solution to the signal-processing problems.

D. The 1980 signal-processing workshop

For this workshop the standard array was the 1978 array, modified by the introduction of Sea Urchin as the sensor. The properties of photomultipliers that might be available were presented by experts from LBL and EMI. More important, Wilkins announced that fiber optics had now reached the stage of development that the shore cable, as well as intra-array cables, could count on using them instead of copper data-carrying cables. We have already discussed the significance of this change.

However, as March pointed out, with 22 698 sensor modules, the combined ^{40}K rate would still tax even the fiber-optics capabilities, so that steps to remove the bulk of the ^{40}K rate were still necessary. From the overall viewpoint this change is very desirable; it means that far less equipment needs to be at the inaccessible array location, and all the important analysis is to be done on shore, where servicing, changes, etc. are straightforward and relatively inexpensive. This one change alone made the entire operation far more feasible.

A number of interesting and plausible schemes were discussed, but their inability to use the still unborn causality technique to eliminate most of the unwanted signals required them to devise other, less effective techniques. Since these are now of historical interest only, we move on to the 1982 Signal-Processing Workshop.

E. The 1982 signal-processing workshop

The status of DUMAND for the 1982 workshop had changed in some important respects. There was a new standard array: the 1982 Standard, consisting of 36 strings in 6 rows, with 21 modules per string. The string spacings were 50 m, the module spacings on the string 25 m. This independent choice of string and sensor spacings, a consequence of Monte Carlo calculation, resulted in arrays with fewer sensors per unit volume and better angular resolution. In addition, Sea Urchin was now dead, and the sensor was a 17-in. glass sphere enclosing either a 12-in. EMI tube or a 16-in. Hamamatsu tube.

An important introductory paper by the DUMAND staff, given by Learned (Learned, *et al.*, 1982), listed in the following important design goals:

Deployment and Topology

1. Require as small a ship as possible, as few as possible.
2. Minimize the deployment time and exposure to weather changes.
3. Have minimum underwater connections, preferably none.
4. Maintain continuity of connections through deployment.
5. Have many points of retreat.
6. Be modular (not whole array at once).
7. Be reversible (allow retrieval during or after deployment).
8. Permit growth.

Data network

1. Transmit all data down to 1 photoelectron (p.e.) level to shore.
2. Distinguish between 1 and 2 p.e. level at each module.
3. Have a minimum number of nodes (if not multiply connected).
4. Minimize the complexity of electronics at sea.
5. Push electronics toward beginning and end of data chain.
6. Design simple ocean electronics.
7. Connect modules in parallel to the string bottom.
8. Do fast time digitization at the string bottom.
9. Allow one data channel per string to shore.
10. Fill the time-position-coded data stream with best data in sample interval.

These principles have withstood the test of time very well.

Two important algorithms for data reduction were introduced at this meeting. One, the causality condition of Roberts (1982), can be simply stated: the events due to a real particle must lie within the light cone of that particle. Since the light cone of a muon embraces only a fraction of the array volume, we can at a stroke forget everything outside that cone. This requirement alone eliminates at least 95% of the ^{40}K background.

The other, proposed by Charles Roos (1982), inevitably came to be known as Charley's ruse. It consisted, in its basic form, of replacing each single PMT by a pair—later versions were more baroque—and putting these in coincidence to eliminate ^{40}K background. This is itself a good idea, but it always has to compete with alternative dispositions of the same number of phototubes to make a bigger array. It is also philosophically objectionable whenever the possibility exists of sending all the data to shore: one should never throw away data when they can be retained. There are schemes that indicate a Roos pair by an additional bit and that do not involve discarding data. The Roos pair has survived in that adjacent modules on any string are routinely examined for coincidences within the light cone; such data are used for triggering.

Two data-processing papers were given at the 1982 Signal-Processing Workshop. Brenner *et al.* (1982) discussed the DUMAND data-acquisition system, and Theriot *et al.* (1982) the on-shore processing, which was now far more extensive than when most processing had to be underwater. Learned (1982) also presented a detailed deployment scheme which also affected signal processing, since it involved running separate cables to shore for each row.

The signal-processing scheme described in the paper of Brenner *et al.* is, for the first time, fairly complete. It adopts the technique of assigning a separate optical fiber to each row, so that there are six data fibers and one control and communication fiber in the shore cable. This simplifies the array data distribution at the shore end. In the eventual DUMAND II array, there is a separate fiber for each string. That technique is limited not so much by fiber costs as by the technology of getting large numbers of fibers into one cable.

Provision is made for a standard clock signal and for accurate timing of signals from each detector; this is essential to any analysis scheme to distinguish events from each other. The timing is also essential to applying the causality criterion, as well as the Roos algorithm.

Without going into much greater detail, it is perhaps sufficient to note that the scheme here proposed is close enough to the present DUMAND system to justify the statement that it can be regarded as a prototype system. Subsequent array shrinkage has simplified the problem even further.

The paper of Theriot *et al.*, on shore processing proposes a special data processor into which the string of data from the array is fed. The data from each module is a 24-bit word; its location in the data stream determines the detector ID. Time differences between sensor signals are compared with a $6\times6\times21$ array that contains the relative time for each counter with respect to a fixed point. Thus, to perform the causality test, all that is required is a table look-up and a comparison with a standard.

We note that we have now reached a level where there are no serious unsolved problems left. The array is small enough to be deployed by available means; the deployment is not thought to be difficult or particularly expensive, since it requires no drill ships. The signal processing uses existing techniques; the sensors will use PMTs already in small-scale production. This is not to say that no further improvements are possible, but only that all the questions about feasibility now seem to have been answered. Further developments will be in the way of simplifications, improvements, economies, and the like.

F. The 1982 DUMAND proposal

The 1982 proposal was for the construction of the 1982 Standard Array. The proposal differed in some interesting ways from the processing scheme described by Brenner *et al.* in the 1982 workshop almost a year earlier. One more node had been eliminated from the data network. Where the Brenner scheme used one shore cable with six fibers, assigning one fiber to each row, the proposal now requested six shore cables, one for each row, with six fibers per cable. Thus there was a separate fiber for each string.

This produces a system in which we spend more for cables and deployment but, by eliminating an undersea node, arrive at a much more reliable system. The use of separate cables for each row split the deployment into six independent operations, with no necessary time connection between them. The array could be run with any number of rows from one to six.

G. The string bottom controller

The node at the bottom of the string—the sole remaining one aside from the module itself—can be eliminated only by an independent data path to shore from each module. We can envision cheaper optical fibers and cables that contain more fibers, but even so, not all the functions of the string bottom controller can be transferred to shore; some will still need to be carried out on the ocean bottom, if not in the string bottom controller, then by the module. These include the exact timing and encoding of the module response and the module ID. These are most economically performed at the string bottom controller; thus we do not expect that device to disappear. The design of the string bottom controller has now been simplified to the point that it can be expected to be reliable, if the usual design precautions for reliability are followed.

The string bottom controller made its physical debut in its use with the SPS—the short prototype string. This ship-deployed array had a short string of five to seven modules, and the data were processed and sent to the mother ship via the string bottom controller and a fiber-optic cable. The design used was not a prototype for a larger array and fell far short in simplicity and reliability, but the experience gained in using it was invaluable for the next stage of design.

H. The 1988 signal-processing workshop

Between 1982 and 1988 there was a signal-processing workshop (in 1986), but its proceedings were never published and no complete record of its work remains.

The 1988 workshop was held after the completion of phase I of DUMAND, the SPS, and just before the submission of the 1988 proposal for DUMAND II. Thus most of its conclusions are embodied in the proposal—but not all. The most important of these was the realization that the design of the shore data-processing station would be greatly simplified—to say the least—if the data were time ordered before being sent to shore. This had not been done in the string bottom controller or in earlier designs for it. This change, it was said, made the shore data-handling problem practical; without it, it would have been necessary continually to sort in time order all the incoming signals, in real time. For this purpose, even a Cray supercomputer might not have sufficed. It turned out that modifying the string bottom controller to accomplish this was not too difficult.

The 1988 workshop was notable for its emphasis on reliability. As the array neared realization, the importance of reliability and the disastrous effects of critical component failure began to sink in. Long-term reliability is an old bugaboo to transatlantic telephone engineers and to space scientists, but it had never before raised its ugly head to snarl quite as disagreeably at designers of high-energy physics experiments. High reliability is certainly very desirable for complicated equipment such as that found in colliding-beam experiments; but the equipment is readily accessible for replacement or repair. The workshop severed to indoctrinate the collaboration with the overriding need for reliability and to pinpoint the places most at risk.

I. The 1990 DUMAND trigger workshop

This workshop, held at Seattle in July, 1990, was devoted to the problem of determining the optimum triggers for the DUMAND II array. With the exception of the opening paper by Learned on "Physics Goals and Triggering DUMAND II" (Learned, 1990a), it is of interest mainly to experts in signal-processing hardware and software. Its proceedings are available (DUMAND Trigger, 1990).

J. Final signal-processing scheme

1. 1989 scheme

As of late 1989, the proposed signal-processing scheme was as follows. Of the 24 sensors on each string, 12 would be multiplexed in one section of the string bottom controller into a single time-ordered data stream and used to modulate a 1.3-μm laser transmitter. The other twelve would be multiplexed in another section of the string bottom controller and used to modulate a 1.55-μm laser. Both lasers would be optically multiplexed to a single fiber, which accordingly carried all the data from the string. This division was necessary because the time required to multiplex all 24 signals into one signal was long enough to produce undesirable dead times.

2. 1990 scheme

Since 1989 new developments in high-speed data handling have made significant improvements possible. Faster microchips and improved coding methods now allow all 24 modules to be multiplexed on a single wavelength at a 500-MHz clock rate without introducing dead time. Wavelength duplexing to get the output of an entire string on a single fiber is no longer necessary. Thus we have doubled the data-handling capacity of the available fibers; we could now accommodate 18 strings on the present cable instead of the nine now being used, or alternatively, double the number of modules per string. If the power requirements of the array can be similarly economized, it may be possible some day to double the array without requiring a new cable.

VIII. AUXILIARY EQUIPMENT

The array must be provided with equipment to monitor its performance and the environment insofar as it affects performance. Thus changes in water transparency must be measurable, and protocols to monitor it must be available. In addition, the sensitivity of the PMTs is of paramount importance and must be continually checked; such checks will also reveal otherwise unnoticed failures. Not only the hardware needs monitoring; so also does the software, so that some scheme for checking on software operation is also necessary.

The solution to these problems is the inclusion in the array, at locations between the optical modules, of calibration modules that are equipped to deliver on command light signals which can be used to monitor not only PMT sensitivity, but changes in ocean transparency. There must be a sufficient number to provide redundancy, so that any negative result can be independently checked.

In DUMAND II each string, in addition to the 21 sensor modules, carries two calibration modules, designed to measure the sensitivity of the optical modules, and one environmental module, carrying sensors that check on ocean conditions—temperature, currents, and so on.

As we mentioned earlier, there will be five hydrophones on each string. These have several functions. One is to note the configuration of the string, which will vary with ocean currents, since it is secured only at the bottom. The location of the hydrophones on the string can be ascertained by using the acoustic transponder network. The location of the string modules at any given time, necessary for accurate track reconstruction, is thus determined. These locations will not change quickly; except for violent events like tsunamis, ocean currents do not vary rapidly, but over many minutes.

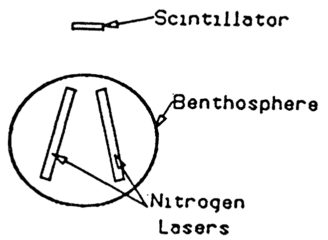

FIG. 21. Schematic representation of an optical calibration module. Primary and backup nitrogen lasers are shown inside the Benthos glass pressure sphere; they illuminate an external scintillator, which is visible to modules on adjacent strings. Calibration modules are mounted in several locations along selected strings (DUMAND Proposal, 1988, p. 15).

In addition, the hydrophones will be monitored to look for the possibility of very-high-energy neutrino interactions—10^{16} eV or more—which should produce acoustically detectable signals. Possible sources for such neutrinos can be imagined; but in any case, if the data are there, we will record them.

The optical signal generators that check PMT response are nitrogen lasers contained in a Benthos pressure sphere. Outside the sphere, in the water, is a scintillator that fluoresces when excited by the laser. Figure 21 shows the geometrical arrangement. The signal is strong enough to be picked up by sensors in adjacent strings. The intensity of the received signal depends not only on the brightness of the source and the PMT sensitivity but on the attenuation of the medium; thus changes in the water transmission can be detected.

The acoustic network is activated by interrogation signals from acoustic transponders. One such will be located at the cable junction box. When it interrogates the network, the responses will be received by hydrophones on all the strings; we have seen that the timing of the responses determines the instantaneous location of the string modules.

C^3: Command, control, and communication

These important functions include the need to have the array communicate its status to shore and the ability of the shore operator to change operating parameters, such as the PMT high voltage or discriminator setting. It must be possible at any instant for the shore operator to obtain a complete picture of the array status. The C^3 system exists for this purpose (Babson, 1988; see also Roberts, 1988). It is so essential to array functioning that a complete standby system is also provided.

The C^3 function is also used within the array to allow the string bottom controller to monitor the functioning of all the modules on the string. The string bottom controller can thus serve as a relay for requests from shore for such information.

Some queries for information demand high bandwidths for either query or response; most do not. For the narrow-band inquiries, the system used on the SPS, in which C^3 was duplexed on the power line with a low-speed modem, can be retained (at higher speeds, however). This technique can be used, for example, for communication between string bottom controller and string modules. In the 1990 communication scheme, communications between array and shore used a separate dedicated optical fiber, and so could be broadband. As modified in 1990, the fiber used to transmit data to shore was also used to send C^3 messages from shore to array, on a different wavelength; this is possible because the string bottom controller can now handle all 24 modules at one wavelength. The main advantage of this scheme is to simplify the shore installation.

IX. DEPLOYMENT: PART 1

A major concern of the DUMAND project from the beginning has been the question: how do we get it into the ocean? It has been interesting to watch as the initial open-mouthed disbelief of the ocean engineers that anyone could seriously consider so hare-brained a project gradually gave way to the cautious admission that perhaps there might be a way, to the eventual confident statement that it was a "piece of cake."

This process extended over many years and many different versions of the array. The physicists have watched and listened, made suggestions, altered the array, and finally seen the emergence of schemes everyone confidently asserted were perfectly feasible and even affordable. All of this took a long, long time.

A. The deployment operation

Before discussing individual deployment schemes, it will be useful to say a few words about deployment procedures in general. An ocean deployment is undertaken to place a given set of equipment—usually sensors of various sorts and associated apparatus—at a designated location on the ocean bottom. For this purpose the equipment must be brought to the general area where it is to be deployed—usually by ship, although planes have been used (e.g., for purposes such as mine-laying). If the location where the equipment is to go must be accurately known—as, for example, with DUMAND—precise navigational systems must be employed. Let us examine the procedure, which depends in part on how close to land the deployment site is. Highly accurate deployment is possible in mid-ocean, but it is easier near land.

To do accurate emplacement, the vessel that runs the operation (if there is more than one) must be equipped with appropriate navigational equipment. Nowadays most vessels have satellite navigation, which is capable of yielding very accurate fixed when a navigation satellite is above the horizon, which is less than half the time. (When and if geostationary navigation satellites become available, this restriction will be removed.) Between satellite fixes other, less accurate, means must be employed. If the vessel is within line of sight of land, it can use radar tranponders at known locations to get accurate position fixes—within a few meters—at any time. Other long-distance navigational systems, e.g., LORAN, are not accurate enough for our needs, which require an absolute accuracy of 10 m or better.

The ship can thus determine its exact location. How does this get transferred to the ocean bottom? The current technique uses acoustic tranponders. These devices can be dropped to the ocean bottom, running on batteries that will last for years. They can interrogate each other, or they can be interrogated from shipborne interrogators. If three or more acoustic transponders are placed on the bottom, a ship that knows its location accurately from radar and satellite fixes can determine with an accuracy of a few meters exactly where all the acoustic transponders are on the bottom. This sets up an absolute coordinate grid from which the location of any submerged interrogator near the transponder net can be determined.

This is the technology used by most ocean experiments. It is mature, commercially available, and easy to use. The location of each string can be accurately determined with respect to the acoustic transponder net.

B. Other deployment techniques: underwater robots

In the ocean, equipment meant to remain on the bottom a long time may need to be anchored. Equipment may need to be recovered; in that case it is often useful to provide means for locating it. Samples of seawater, bottom cores, or ocean flora and fauna may be desired.

All these purposes require specialized equipment. Sometimes cables need to be plugged into receptacles, to transmit power or data. Sometimes fairly complex operations are required. For very complex or unpredictable operations, such as the exploration of wrecks, manned submarines may be required; these have recently become available for great depths, but are necessarily expensive to operate and difficult to borrow. For more routine operations, underwater robots (usually unmanned) of various sorts are used. These may be self-contained, with internal programs, or they may be controlled from a mother ship via connecting cable or via acoustic signals. The variety of such devices is too great to enumerate (see, however, Bradner, 1988). A general class of such devices is encompassed in the abbreviation RCV, for Remotely Controlled Vehicle, or ROV, Remotely Operated Vehicle.

Underwater vehicles capable of operating at 5-km depths have been rare. Only recently have there been vehicles capable of moderately sophisticated operations at such depths; and even when they exist, their availability to DUMAND is not to be taken for granted.

Thus deployment scenarios, until recently, tried to avoid a need for underwater robots. The one function they can perform that would be most advantageous to DUMAND is to make and break electrical and optical connections. The design of the array calls for underwater connectors of the highest possible reliability. Robots make possible the deployment of a DUMAND array in small sections that can be connected together on the ocean floor, as opposed to the need to deploy the entire array as a single unit if no underwater connections are possible.

There is another alternative, which was suggested for an earlier DUMAND array (DUMAND Proposal, 1982). It divided the array into several subsections, each with its own cable to shore, thus making possible deployment of one section at a time (but imposing the need for great care not to damage already installed sections). This is feasible, but it has the disadvantage that communication between sections is now possible only via the shore station.

Since both the ROV and connector problems now appear to have acceptable solutions, in DUMAND II the deployment will be one string at a time, with an underwater robot plugging in the necessary cables. Such a combination greatly decreases the hazards of underwater deployment; the simpler the operation, the safer and more reliable it is.

C. Early DUMAND deployment schemes

We now return to a consideration of individual deployment schemes. Consider how the initial project appeared. The original 1978 DUMAND Standard Array comprised 60 sensor planes, each with 21 sensor strings (see Fig. 10). Each of these strings was anchored at the ocean bottom and suspended vertically by a flotation module at the top. The sensor modules were not well defined; modules on each string were attached to it at intervals. The project was larger than any previous deep underwater deployment by at least a factor of 100.

At the 1978 workshop, the task of devising a deployment procedure was entrusted to a deployment group chaired by Arthur Schlosser, an experienced ocean engineer of the Naval Ocean Systems Center at San Diego. Following are some quotations from his summary report (Schlosser, 1978, p. 121).

"1. . .deployment of the DUMAND array is feasible, utilizing existing ocean technology. . .

"2. . .the dominant constraint [is] the need to deploy and implant the array in large modules . . . Each deployed unit must represent an appreciable fraction of the total array volume."

Here a digression is in order. The purpose of this constraint was clearly economic: ship time is extremely expensive, and the time spent at sea ought to be minimized. For example, the ships best equipped for lowering a large package to the ocean floor at a predetermined location are ships equipped with heavy-lift cranes and a center "well" in which large items can be overboarded and lowered. The prototype of such vessels is the oil-drilling ship, which normally lowers a long string of drill pipe, adding to it section by section at the top, until the bottom end reaches the destination. Such ships rent for \$50 000/day and up.

In addition, several alternative plans were discussed (Schlosser, 1978). In all of them, a common feature was that each sensor string—float, sensors, cable, and anchor—would be packaged into a canister 8.8-m high and 1.6 m in diameter, to be implanted on the bottom, then opened to allow the string to be deployed upward by its flotation module. A group of such canisters, bundled together for easy transport—perhaps an entire row—would be deployed at once. Note that the proposed canister dimensions allow a volume of just under 1 m^3 per module and thus do not take into account large wavelength-shifting systems, which at that time had not yet been investigated seriously.

Several different schemes for deploying these bundles were suggested.

(1) Template approach (Schlosser, 1978, p. 148). Sections of the array are assembled in a rigid structure and lowered from an oil-drill ship to the ocean floor. The process is repeated until the entire array is deployed. This scheme requires the largest deployment vessel—the expensive oil-drilling ship. It also requires the assembly and towing to the final site of large underwater structures—always a hazardous operation.

(2) A cable with an RCV (remotely controlled vehicle) attached is used to slide down deployment modules, each of which carries the canisters for a single plane (Schlosser, 1978, p. 149). The RCV guides the assemblage to the right point, then picks up the individual string canisters one by one and moves them to their proper location. The problem of making underwater connections was not explicitly considered.

(3) This concept, eventually discarded because of its unacceptably high risk, contemplated laying out the 21 canisters of each sensor plane near the ocean surface, supported beneath the surface by floats. Two workboats, each supporting and RCV with heavy-lift capability, are attached to the ends of the sensor plane. The surface floats are now disengaged, and the entire plane is lowered by coordinated control from the RCVs supporting the ends.

(4) In this approach, no drill ship is needed, only a small ship. Each canister is separately packaged, and a "smart" navigation module or clump is temporarily attached to it. The unit is allowed to fall to the ocean bottom under the guidance of the clump. The smart clump navigates with respect to a net of acoustic transponders at known locations on the bottom and deposits the canister at the desired location with an error of 3 m or less (Schlosser, 1978, p. 151). After connecting the canister to the row cable, the clump is retrieved and ready for the

next string canister. This process has to be repeated 1261 times, once for each string.

This approach was one that was to become more and more attractive as the size of the array diminished. It did not take long to appreciate the virtues of being able to deploy the array from a ship renting for \$3000–5000/day as opposed to an oil-drilling ship at \$50 000 to \$100 000 per day—especially if the small ship were based in Hawaii and we need not pay for the transit time to Hawaii and back from the mainland, as one would for an oil-drill ship.

(5) After considering all four approaches, the committee came up with a fifth, a synthesis of features from the others. This approach was the one finally recommended (Schlosser, 1978, p. 154).

It requires two ships—an oil-drill ship and a smaller workboat equipped with an RCV. It also requires an existing submersible barge called a LARP (Launch And Recovery Platform.) The 21 string canisters comprising a sensor plane, preconnected into their final configuration, are loaded aboard the LARP and towed, submerged, to the deployment site (Fig. 22). At this point one end of the sensor array is attached to a lowering line from the drill ship and the other end to the workboat. The entire system is buoyed by floats until it has cleared the LARP, which is then removed (Schlosser, 1978, p. 155). The workship end of the sensor row is equipped with a thruster controlled from shipboard, to allow precise orientation and location of that end of the string. The drill-ship cable likewise has a smart clump that controls the location of the other end.

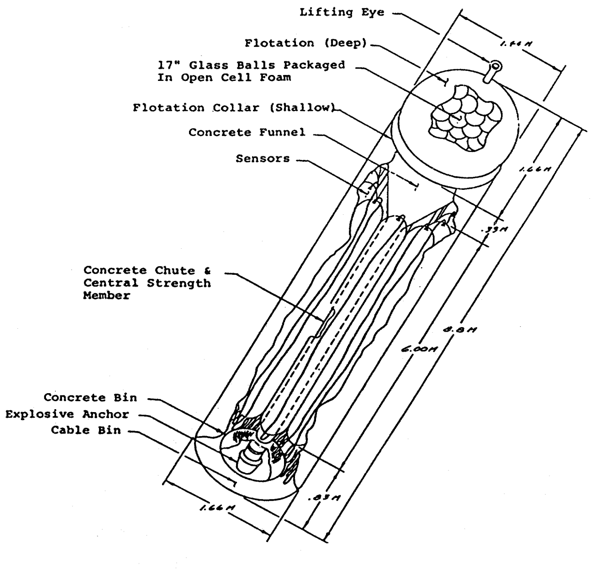

FIG. 22. An early canister design, intended for strings using Sea Urchin. When many strings needed to be simultaneously deployed—as was necessary before ROVs and reliable underwater mateable connectors—individual strings had to be protected during deployment in a container from which they would be released after emplacement. The canister was the answer (Schlosser, 1978).

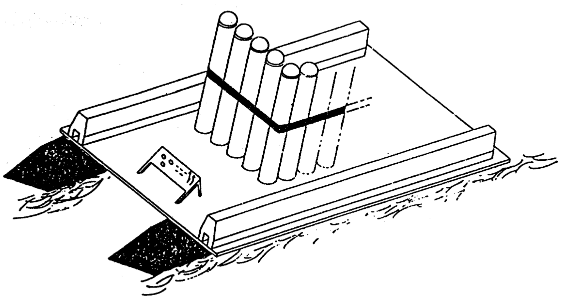

FIG. 23. All the canisters comprising a single sensor plane can be transported on a LARP, a submersible Launch and Recovery Platform (Schlosser, 1978).

Figures 9–11 show the array to be deployed; it contains 60 rows or planes of sensors, each row containing 21 strings with 18 sensor modules on each string. Figure 22 shows the design of a canister containing a single string, and Fig. 23 shows how the entire row is transported on the LARP.

The entire row is lowered slowly to the bottom and carefully positioned (Figs. 24–26). The smart clump connects the row to the Y-cable already installed on the ocean floor (Fig. 25), and the workship ensures that the row is correctly oriented and emplaced. The row is then released; the operation is complete.

A new operation is needed for each row, so that a total of 60 deployment operations are required. If three days are required for each operation, the entire deployment would take a minimum of six months of sea time. At \$50 000/day, this comes to \$9 million for drill-ship rental alone.

We note that even this mammoth array did not faze the ocean engineers. However, they were careful not to estimate the total cost of the operation. What they did was very valuable: they broke down the deployment process into segments, each of which could be carried out by available means. (There is some doubt about how they proposed to make underwater electrical cable connections, since at this time there were no well-engineered,

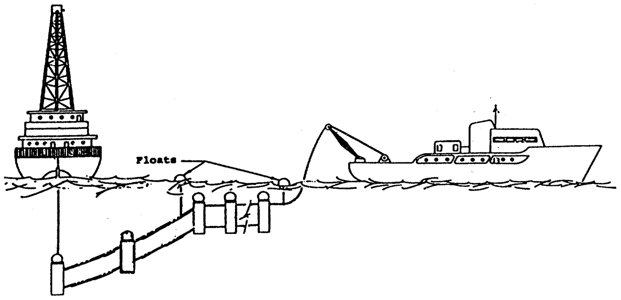

FIG. 24. The 1978 preferred deployment scheme. The canisters comprising a plane are being transferred to the drill ship (Schlosser, 1978).

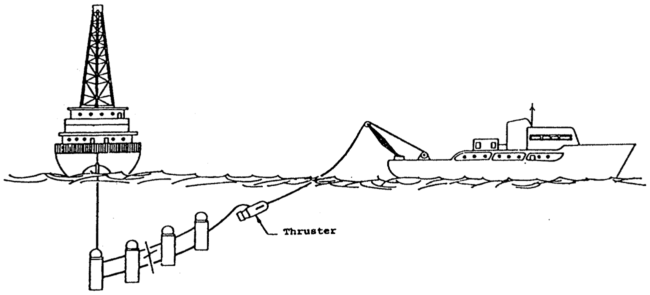

FIG. 25. The sensor plane is guided to its assigned location by a recoverable thruster. A powered "clump" on the drill string connects each string to the row cable (Schlosser, 1978).

dependable deep ocean electrical connectors.) Many of the techniques discussed here have survived into current deployment plans.

We have spent a considerable time describing this first attempt at outlining a deployment scenario, since it was the prototype for all later deployment planning. As the array shrank, the deployment problems became more and more tractable.

X. DEPLOYMENT: PART 2

A. The 1980 DUMAND Symposium

The 1980 DUMAND Symposium, held at the DUMAND Center in Honolulu, marked the establishment of DUMAND as a going project and the beginning of a serious attempt to find an array design that stood a better chance of approval than the mammoth 1978 Standard Array. There were two independent efforts: one to modify the original DUMAND G array, and one to consider medium and small arrays. These have been considered above in Sec. V.A.

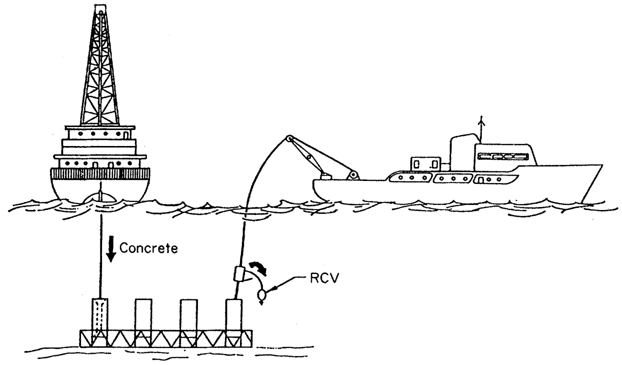

FIG. 26. The canisters have been located on the bottom and attached to their supply cable. The attendant tug can now release its cable and turn its attention to the next row (Schlosser, 1978, p. 154).

The first of these, the G2 array, is essentially a refinement of the original DUMAND G, explicitly including the Sea Urchin detector and thus increased spacing and fewer sensors. A sketch of the rhomboidal array of DUMAND G2, which uses 6615 sensors, one-third of DUMAND G's minimum allotment, is shown in Fig. 15.

As reported in Sec. IV, the working group reported on three arrays, called MINI, MIDI, and MICRO. They are discussed in Sec. V.

B. The 1980 deployment workshop

The next deployment workshop, which was held at Scripps in December 1980, followed a year in which the DUMAND Center at Hawaii had been in operation and in which the 1980 International DUMAND Symposium at Honolulu had allowed a reevaluation of array design. At this workshop, the deployment of the MINI, MIDI, and MICRO arrays was considered. (The MICRO array was intended for the demonstration of feasibility only, and thus was a forerunner of the SPS single ship-deployed string. It is shown in Fig. 16. It consists of 19 strings with 11 sensors each, a total of 209—almost exactly the same as DUMAND II.)

This workshop considered a wide variety of methods for deployment. It was also noteworthy in considering the addition to DUMAND of a supplementary array of subsurface detectors at a depth of 30–50 m, which would function as a cosmic-ray shower detector and enhance the value of DUMAND for cosmic-ray studies.

Three distinct deployment methods were studied at this workshop. They are known as the surface-supported (drill-ship) method, guided placement with an ROV, and the master buoy with glide bodies. Let us examine these.

1. Drill-ship deployment

The first we already know: the drill-ship technique. But there are some surprises here. The group considered three different arrays, all with 121 or 127 strings. The array shapes were cubic or hexagonal. The two cubic shapes were our old friends MINI and MIDI, and the hexagonal array a rearrangement of the MIDI strings.

A new twist in canister design was achieved by making the canisters with a central pipe, so that they could be stacked on an oil-drill pipe for deployment. The canisters with a central hole were promptly rechristened "bagels." The purpose of the modification was to allow a long string of canisters to be deployed in one pass, with the drill ship setting each one down at its appropriate location. The system is already hard-wired, so no underwater connections are required, nor is any ROV. Figure 27 shows how deployment can be accomplished in a single pass by a drill ship, in the absence of an ROV or underwater mateable connections. The entire array, prewired, is deployed in one all-or-nothing operation; the risk associated with such a technique is clearly far higher than that associated with deployment in independent sections.

Two different canister designs were envisaged for string deployment, depending on whether a "low-sensitivity" sensor—i.e., a direct-view PMT—or a "high-sensitivity" sensor—namely, Sea Urchin, was to be used. They are shown in Figs. 28 and 29, respectively.

2. Master buoy deployment

This scheme is one that had been previously described by Talkington in a paper in the 1980 Symposium (Talkington, 1980). It was applied there to the MICRO array (Fig. 16), consisting of 19 strings of 10 modules each. The basic geometry is circular; a central string is surrounded by six strings on a 50-m-radius circle, and these in turn by an outer ring of 12 more strings on a 100-m-radius circle. Figures 30–31 show the master buoy which deploys the array and a profile of the installed array, respectively.

In this system, as in the previous one, the entire array is hard wired before deployment and is deployed as a single unit. The idea is to package each string in a "glide body" with folding wings (Fig. 32).

The glide body is a sort of underwater glider. It has no internal means of course correction; it is meant to be carefully oriented and released at such a height above the sea floor that it will land at its required destination. The absence of appreciable underwater currents makes this a

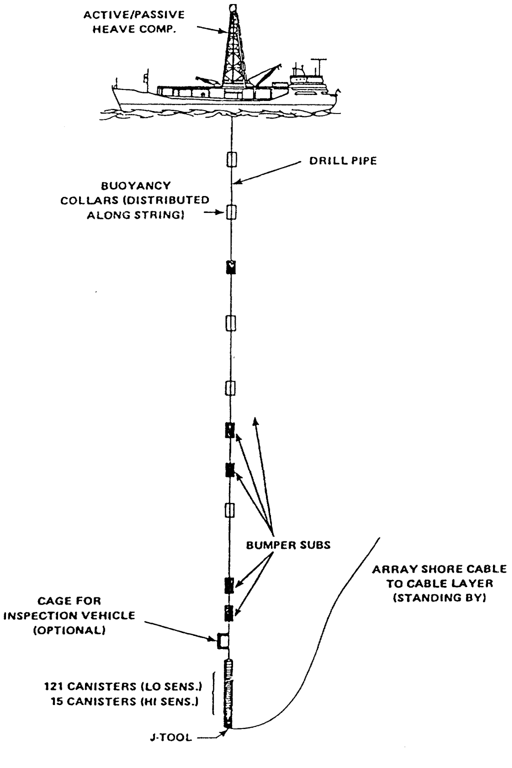

FIG. 27. The 1980 deployment concept for implanting a MINI or MIDI array with 121 strings. The canisters are either for "low-sensitivity" sensors—i.e., PMTs—shown in Fig. 28, or "high-sensitivity"—Sea Urchin—shown in Fig. 29. The J-tool allows canisters to be released from the drill string one at a time. Note that the drill ship can lower and implant the entire array in a single operation (Schlosser, 1980c).

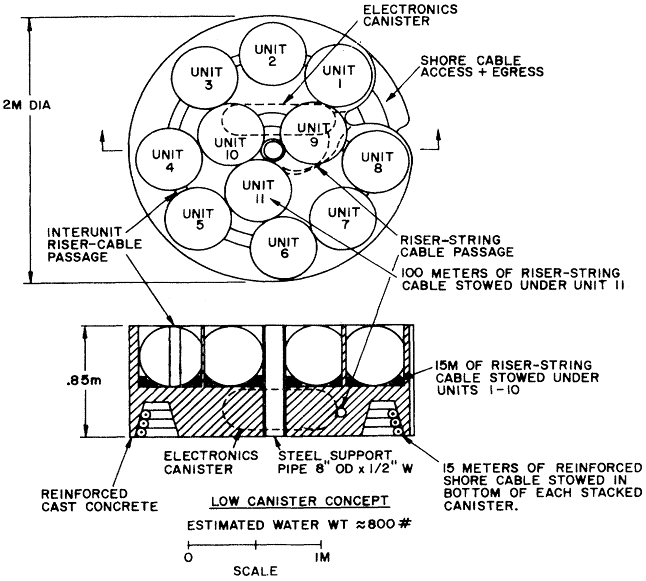

FIG. 28. Canister design for "low-sensitivity" PMT sensors (Schlosser, 1980c).

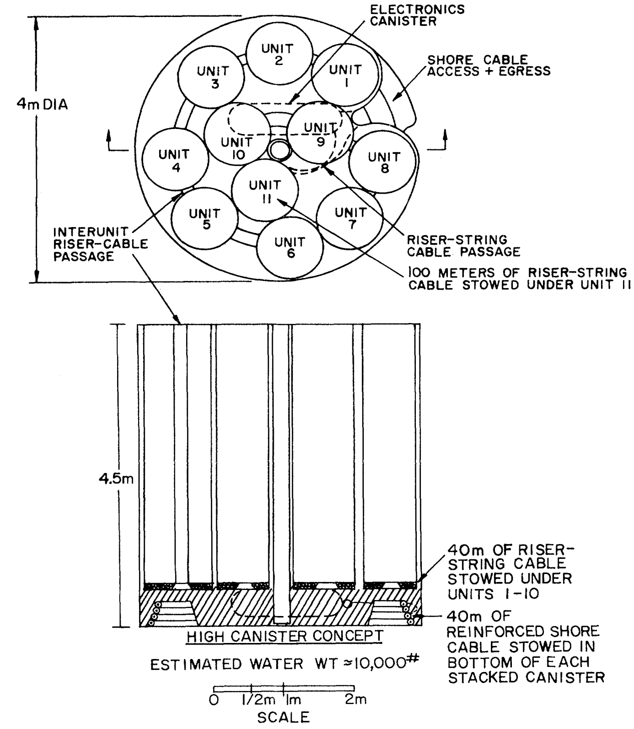

FIG. 29. Canister design for "high-sensitivity" Sea Urchin detectors (Schlosser, 1980c).

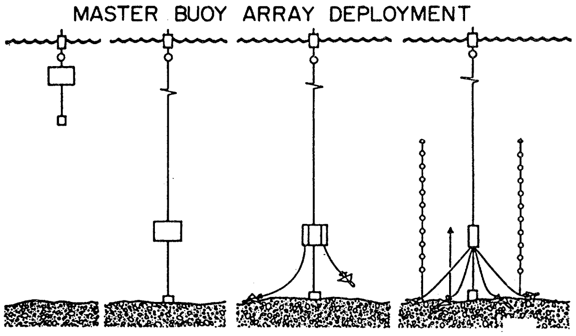

FIG. 30. Master buoy deployment scheme (1982). This is the first deployment scheme to dispense with the drill ship. It is intended for arrays like MINI and MIDI, or smaller. The four stages shown here describe the lowering of a master buoy containing "glide bodies," which, when released, glide along a predictable path to designated bottom locations and there release sensor strings (Jones, 1980).

feasible operation. The accuracy with which it can be carried out is remarkably good. Since the DUMAND requirements for precision in string location are not very exacting—errors up to five meters or so are perfectly acceptable, provided the actual location is known accurately—the use of glide bodies offers the possibility of installing relatively complex prewired arrays. If necessary, the deployment of the entire DUMAND II array could have been performed in this manner.

The deployment is shown in Fig. 33. The master buoy, with an anchor on a cable 100 m long beneath it, is lowered until the anchor grounds on the sea floor. The outer ring of 12 glide bodies is then released, and the 12 gliders then glide to their predestined position (without guidance) with an error estimated as about 5 m. They remain connected by cable to the center master buoy. The master buoy is then repositioned by lowering it closer to the ocean floor. The six glide bodies of the inner circle, and the central string, are then deployed.

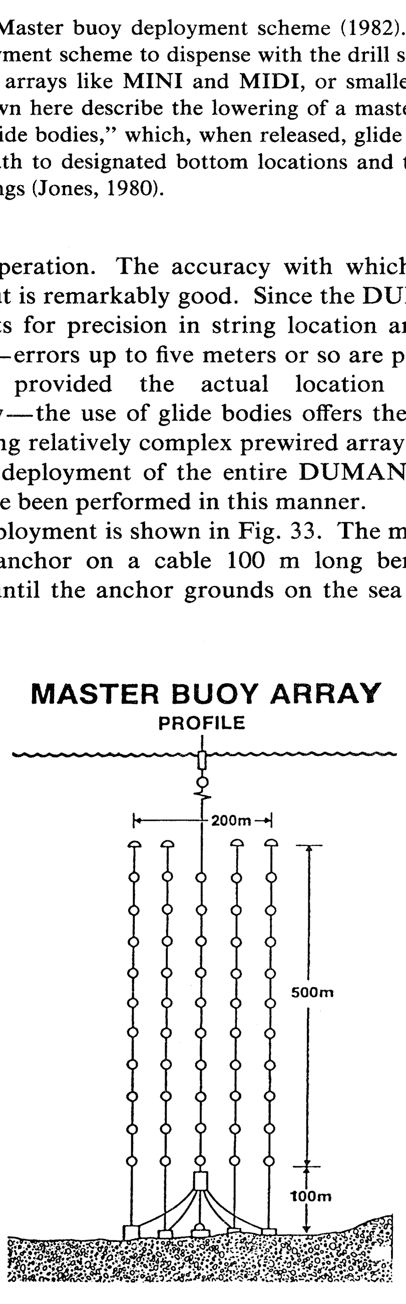

FIG. 31. A master buoy deployment of the MICRO array (see Fig. 16).

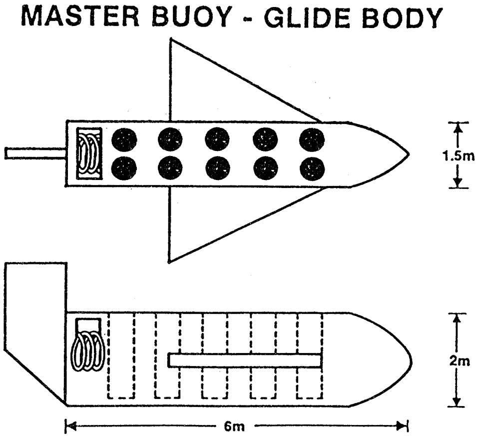

FIG. 32. The glide body, which doubles as a canister carrying a sensor string.

This is not a new technique; it has been successfully used for similar purposes, and the characteristics of the glide bodies are known and can be relied upon. Talkington's scheme envisioned the primary power supply as contained in the master buoy; but the cable that lowers the master buoy could either be the shore cable or bring the shore cable along with it.

At the 1980 Deployment Workshop, the master buoy group, chaired by R. E. Jones of NOSC, studies this approach in more detail. In particular, they considered arrays using two different sensors—one of the workshop's basic charges. These represent a PMT sensor and the Sea Urchin, respectively, and were referred to as the low- and high-sensitivity sensors. It should be remembered that at this time the largest PMT available was the EMI 12-in. photomultiplier tube.

With these sensors, the array spacings for low and high sensitivities were 15 m and 50 m, respectively. Some difficulty was anticipated with the smaller spacing in the deployment of the inner circle, for which the flight paths are uncomfortably short. With the 50-m spacing, improved accuracy could be obtained by lowering the master buoy for the deployment of the inner circle.

3. Glide-body deployment of MINI

This mode of deployment of a larger array, comparable to MINI, was studied. The array consists of seven hexagons, each like MICRO with 19 strings, with six of them arranged in a hexagon surrounding the central one. The scheme is shown in Fig. 31. The resulting array has 133 strings, each with 10 sensors, making 1330 sensors in all.

The deployment scheme is modified to make this deployment feasible. The scheme is best understood by reference to the detailed figures (Figs. 34–39).

C. Subsurface array

In response to the cosmic-ray interests of many members of the DUMAND collaboration, the workshop

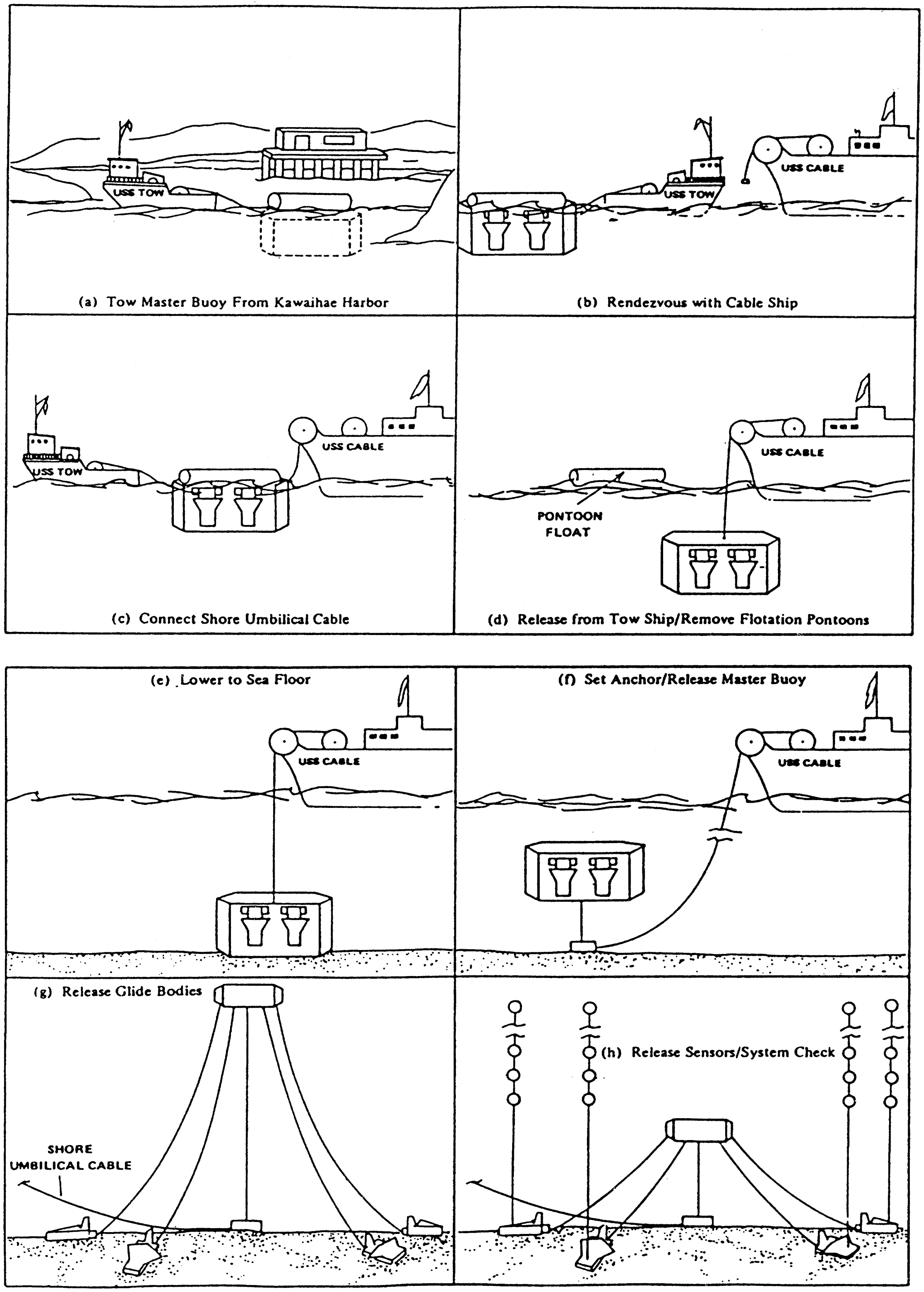

FIG. 33. Master buoy deployment procedure for deploying MICRO (Jones, 1980).

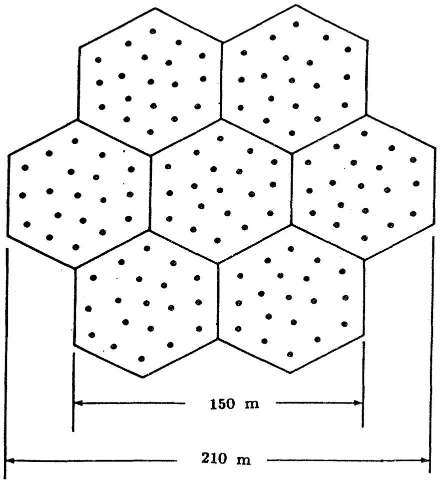

FIG. 34. MINI array to be deployed by master buoy. It consists of seven hexagonal arrays of 19 strings each, each of which is like MICRO (Jones, 1980).

considered a variety of possibilities for expanding the usefulness of the underwater array for cosmic-ray studies. The cosmic-ray advantages of such a supplementary array have been discussed in Sec. II. Two possibilities for an auxiliary array came up (Elbert, 1980): a "fly's-eye" detector of atmospheric showers like the one in operation in Utah; and a subsurface array of muon detectors, located 30–40 m below the ocean surface directly over the DUMAND array.

The location of DUMAND, 20–30 km off shore, was judged to be too far for a fly's-eye detector, which also suffers from being operable only on cloudless moonless nights—about 10% or less of the time. On the other hand, the subsurface array would be operable at all times, and consequently the deployment workshop undertook to examine this possibility more closely.

We shall not discuss the subject in detail; we simply state some of the conclusions:

(1) The proposed array assembly and installation are considered to be very difficult—far more so than the DUMAND installation.

(2) No such subsurface array has ever been moored in depths over 3000 m.

(3) To maintain such an array at a specified depth would require substantial engineering development.

(4) The dynamics of such a moored array require new modeling techniques before they can be understood.

(5) At best, such an installation would be marginally feasible and probably extremely expensive.

XI. DEPLOYMENT: PART 3

A. The 1984 deployment workshop: DUMAND program

By the time of this workshop, the first since December 1980, many changes had taken place in DUMAND. The support of DOE for the DUMAND Collaboration was

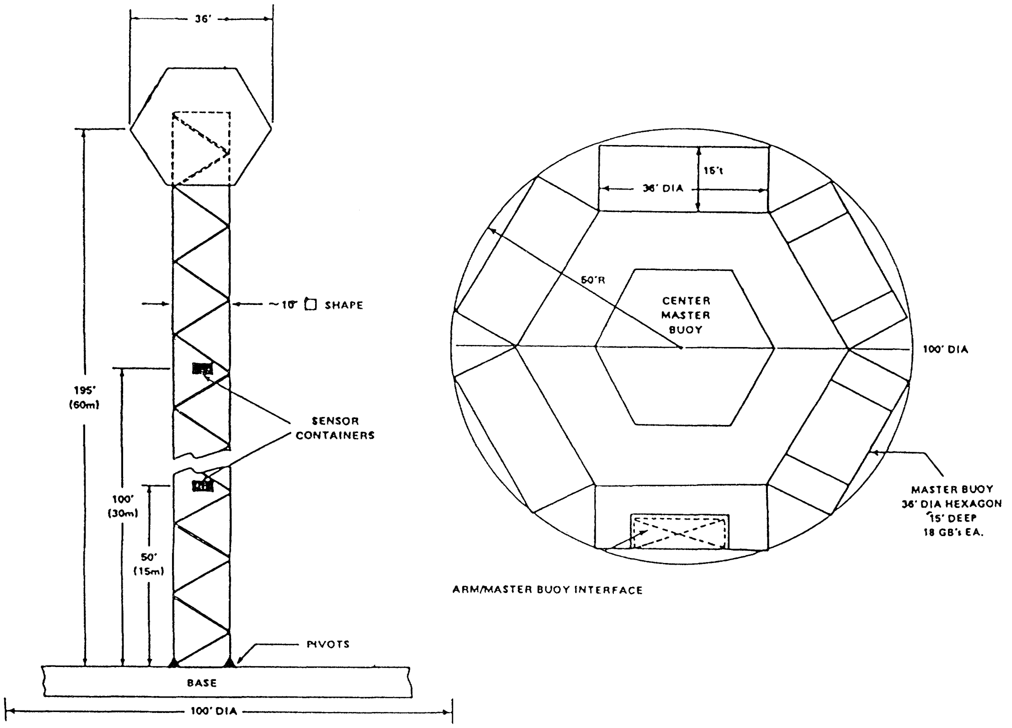

FIG. 35. Design of master buoy for deploying a hexagonal MINI array with 133 strings. It is deployed as 7 MICRO arrays of 19 strings each (Jones, 1980).

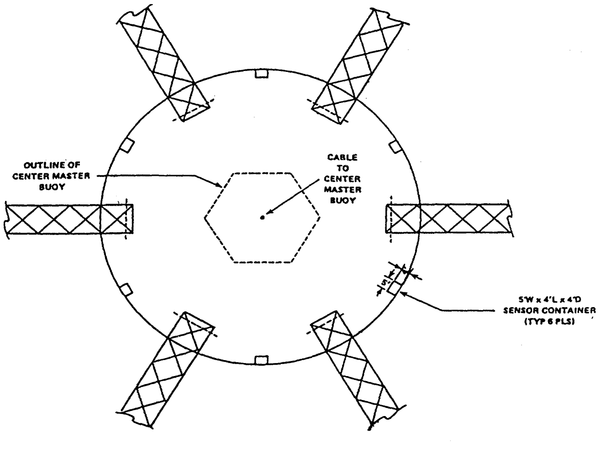

FIG. 36. Base plate of MIDI master buoy, showing 6 arms deployed (Jones, 1980).

now assured, and the program for DUMAND was now clear. It consisted of three parts.

PART 1. Construction, deployment, and ocean testing and operation of the SPS, the Short Prototype String. This ship-suspended five-module array would serve several purposes:

(a) It would verify the operation in the ocean of the entire system, including the control system in the string bottom controller. The string should be capable of detecting cosmic-ray muons and reconstructing their trajectory (with an unavoidable ambiguity of the azimuth of the track with respect to the string).

(b) It would measure the ^{40}K background noise and its pulse-height spectrum.

(c) It would observe bioluminescence as a function of depth, time, and sensor string motion.

(d) After shipboard test of the SPS had been completed, it might be worthwhile to run the SPS on the ocean bottom for an extended period; if so, a scheme for attaching it to a shore cable and shore station would be necessary.

In addition, however, there were two important later deployments. There were the following:

PART 2. Construction and deployment of the TRIAD. TRIAD (Fig. 18) is a three-string array, to be installed and operated on the ocean bottom for a period of several months. For this to be possible, a DUMAND shore cable would have to be installed, a shore station constructed, and the three strings deployed. Thus the TRIAD would serve as a test for the deployment of the full DUMAND array, and a preliminary operation of a small ocean-bottom array. The TRIAD would be larger than any existing neutrino array, since its area is 3000 m^2. However, while it could detect muons and determine their direction, its purpose would be primarily to verify that we could in fact work on the ocean bottom and were prepared to install the full 36-string DUMAND 1982 Standard Array.

PART 3. Following a shakedown period of operation of the TRIAD—estimated as six months—installation of the full DUMAND array would begin.

At this time the accepted procedure following a suggestion of Learned, at the 1982 Signal-Processing Workshop, that each of the six rows of six strings should have its own shore cable. This meant that six separate shore cables would have to be laid. The deployment procedure would then have to be such that later deployments would not disturb previously installed rows.

The reason for this more complex cable system was not stated explicitly, but it was in fact the nonexistence of a reliable method for making underwater optical cable con-

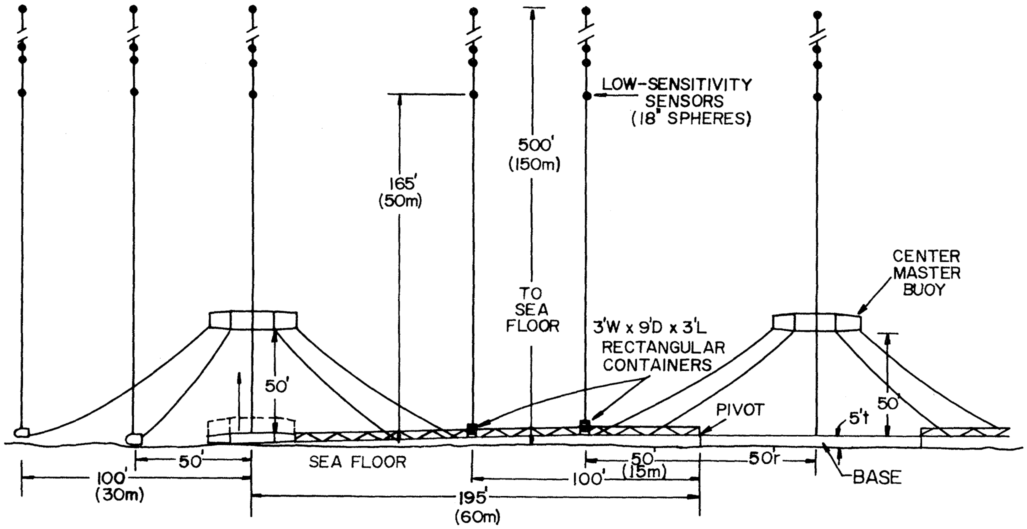

FIG. 37. Cross section of deployed MINI array, showing one outer hexagon and the center one (Jones, 1980).

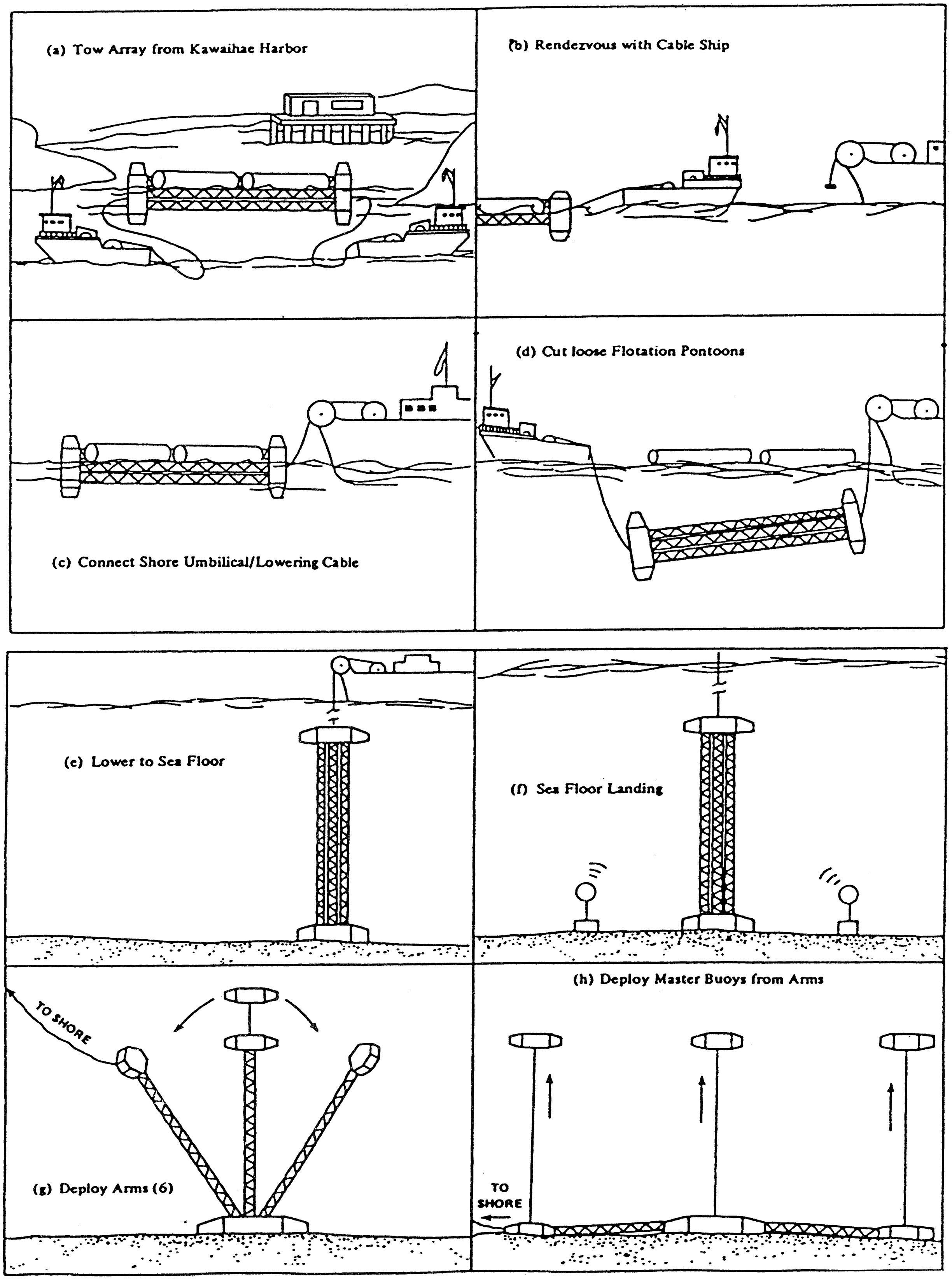

FIG. 38. The successive stages of master buoy deployment of MINI, from loading at harbor to deploying of submaster buoys (one for each hexagon) (Jones, 1980).

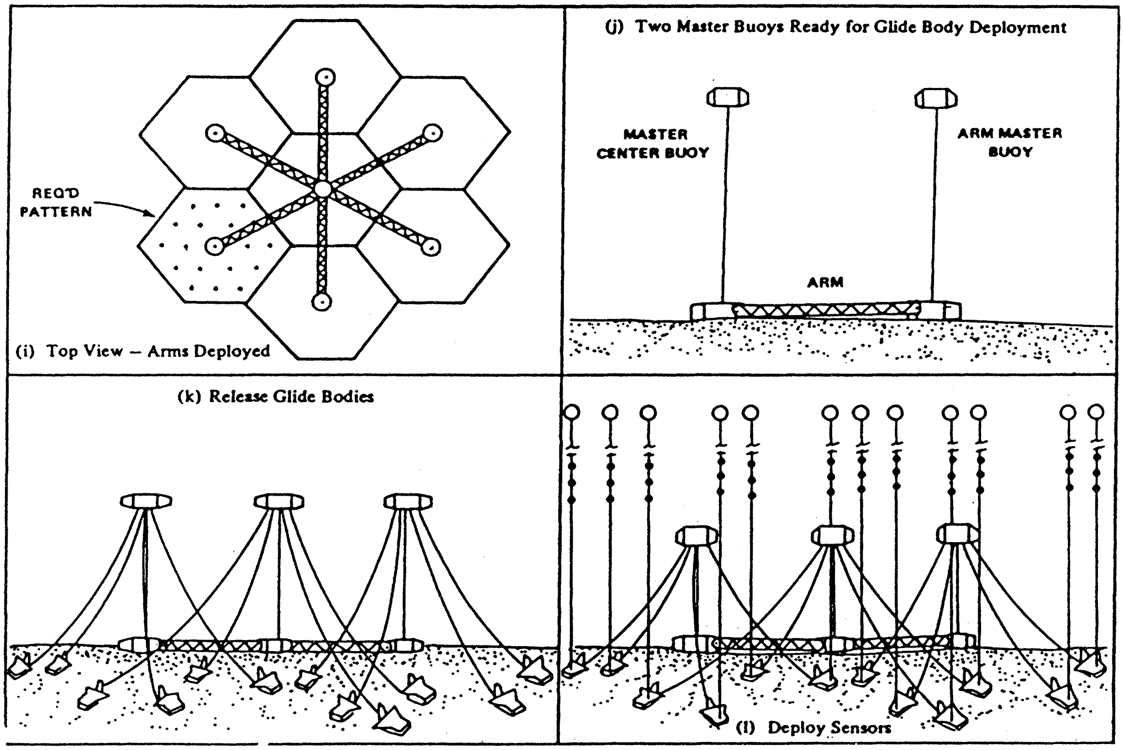

FIG. 39. Final stages of deployment: all arms deployed, submasters released. Then glide bodies carrying strings are released, and finally, sensor strings are released (Jones, 1980).

nections. Without such a possibility, the entire array would have to be prewired and deployed as a single unit. This would simplify cable laying and put all six optical fibers in the same cable. But it would also make the deployment operation appreciably more complex and fraught with serious difficulties. It was to avoid these that the more reliable route of six independent cables to the six rows was adopted. It was not until around 1984 (Wilkins, 1984) that prototypes for reliable deep underwater optical and electrical connectors were produced. The deployment of a single cable to shore, terminating in a junction box on the ocean floor, did not become practical until these connectors actually went into production, five years later.

B. Proposed deployment procedures

We now review the three deployment procedures proposed at the 1984 workshop. It is interesting to note that the most conventional of these was proposed by DUMAND physicists, Steven Dye and John Learned. The other two were by John Craven and George Wilkins, both highly experienced ocean engineers. We deal with them first.

Craven's proposal (Craven, 1984) was based on the reasonable concept that the right way to guarantee that sensor canisters are deployed on a straight line at proper separation is to provide the equivalent of a railroad track—in this case more like a cable-car track, since the canisters are not self-propelled. In his proposal the track is a slotted cylinder, and the entire 250×250 m system of six tracks is to be fabricated in a harbor, towed underwater to the DUMAND site, and there lowered to the ocean floor. This is clearly the most difficult part of the operation.

Once the tracks are in place, the canisters can be lowered to the ocean floor in a train. Strings threaded through the tracks provide for pulling the train of canisters into position. The problems of connecting the individual rows together are not addressed.

Wilkins (1984) proposed a free-fall deployment scheme. Individual canisters have attached to them temporarily a guidance unit, which, under control from the mother ship, guides the freely falling canister to the proper position on the ocean bottom, with an accuracy of 1–2 meters. This scheme depends on the ability to make optical and electrical connection to the canister on the ocean bottom and the availability of a guidance unit readily moved from one canister to another.

We come now to the deployment scheme of Dye and Learned (1984). This is the most conservative of the three. It requires two ships, neither very large. One carried a row of canisters, preassembled and preconnected to each other. The other carries the electro-optical cable to shore. The air weight of a row of canisters is about 30 tons; this is large but not unmanageable for an oceanographic vessel of average size.

The proposed procedure is to float the entire row of canisters near the surface, and then to attach the ocean end of the shore cable. This splicing operation can be done on board ship. Next the entire row is lowered to the bottom, the shore cable being paid out at the same time. The shore cable does not sustain the weight of the row, which is taken by the other ship. When the row is near the bottom, the individual canisters must be located properly; since they are already spaced apart the proper amount, all that is required, in principle, is to stretch the row cable taut.

Once the row is on the bottom, it should be possible to test it, if the shore end of the cable is free and suitable test apparatus available on the cable ship. In fact, this test could be carried out as soon as the shore cable is spliced to the row and the row is deep enough to be dark.

All that remains now is for the cable to be laid to shore and connected at the shore end.

C. The 1988 deployment workshop

This workshop differed from most previous ones in that, after many vicissitudes, the DUMAND array had finally shrunk as far as it possibly could without vanishing altogether, and the proposal for DUMAND II had been finally frozen and was on the point of being submitted. Consequently the problems of deployment were more sharply defined than previously (and, in consequence of array shrinkage, considerably easier). The answers obtained thus had an excellent chance of describing the deployment as it would actually occur.

There were still two persistent questions. It had now long been clear that DUMAND deployment would be greatly facilitated by two developments:

(1) The availability of reliable underwater make-and-break electrical and optical connectors.

(2) The availability of a reliable underwater robot capable of performing the make and break operations and of performing other simple tasks.

There were three candidates for the robot at this time. One (Bradner, 1988) was the Scripps Institution RUM (for Remote Underwater Manipulator), which in several incarnations had been in operation at Scripps for some twenty years and was now available in a new improved version. Another was the Argo-Jason master-slave system developed at Woods Hole, which had distinguished itself in retrieving objects from the wreck of the *S.S. Titanic.* The third was FOCUS, a still nonexistent dream device that the Hawaii Institute of Geophysics (HIG) was actively seeking support to construct (Note—and has now received).

Two of these devices actually existed, but there were no assurances that they would be available to us when needed. There were consequently two schools of thought. One wanted to design a deployment scenario making use of the robot; the other distrusted its uncertainty and wanted a deployment scheme that did not require its availability. The two schools proved incompatible and consequently the workshop ended up providing two deployment schemes, one with a robot, the other without (Pokrofski, 1988b).

During the period between the workshop and the publication of its proceedings, there were some important developments. The Scripps owners of RUM turned out to be willing—even anxious—to schedule its use with DUMAND. The Woods Hole owners of Argo-Jason were less enthusiastic, but not unfriendly. The HIG FOCUS project made encouraging advances in obtaining funding and began design work; however, its initial phase will not include manipulative abilities, but only surveillance.

Under these circumstances, the tentative decision was made to adopt the scheme requiring the RUM—which, as we have already seen, is usually simpler. Since then FOCUS has been funded (though not yet for all the capabilities required by DUMAND). However, it has also turned out that RUM is no longer being supported by its funding sponsor and will no longer be available. Thus, as of November 1990, no deployment robot was officially available to DUMAND; consequently a search is under way to find one suitable for our use and available to us. This is not a cause for great concern, as yet, since two new candidates have appeared, both of which satisfy our requirements: the Seacliff manned submarine and the ATV (Advanced Tethered Vehicle), a development of NOSC, San Diego. Both these avenues are presently being explored.

The deployment scheme using the ROV was described in the proceedings of the 1988 workshop by George Wilkins (1988c). It is a detailed scheme that includes a preliminary survey of the route to be followed in laying the shore cable, as well as the technology of ferrying and deploying the array itself, in an area of the sea bottom in which acoustic transponders have been installed.

The detailed procedure given here was later expanded into a "White Paper" (Wilkins, 1988a) on deployment that was part of the DUMAND presentation to DOE in applying for funding. It was accompanied by a video tape that illustrated the process in detail. That video tape (VHS) is available to interested parties from the DUMAND Hawaii Center.

D. The final deployment scheme

In brief, the deployment takes place in the following stages.

(1) Survey of possible cable routes. For safe cable-laying it is necessary to avoid cliffs or sharp edges.

(2) The shore cable, whose ocean end is terminated by a junction box carrying connectors into which each string may be plugged, is deployed. Since the electro-optical cable is small (about 1 cm diameter), it can be laid

by as small a vessel as a fishing boat, but one that is provided with equipment for splicing together the individual sections of the cable or repairing breaks.

(3) The junction box carries an acoustic transponder, which enables the string-deploying vessels to find it. First a network of acoustic transponders is laid down. From their locations the coordinates of the desired locations of the strings are worked out, and deployment of the strings can start.

(4) Strings are deployed one at a time from a small vessel—e.g., the *S.S. Kaimalino,* a SWATH ship (small-waterline-area twin hull), with far more stability in rough seas than a conventional single-hull vessel. It is shown in Fig. 40, with the stage I SPS deployed beneath it. As the string is lowered, its location with respect to the transponder net is monitored, so that it can be set down accurately at the desired location.

(5) The connection of string to junction box is made by the ROV (Fig. 41). This phase of the operation can be carried out as each string is lowered, if the ROV is available, or it can wait until several or all the strings are in place and then be done several or all at one time.

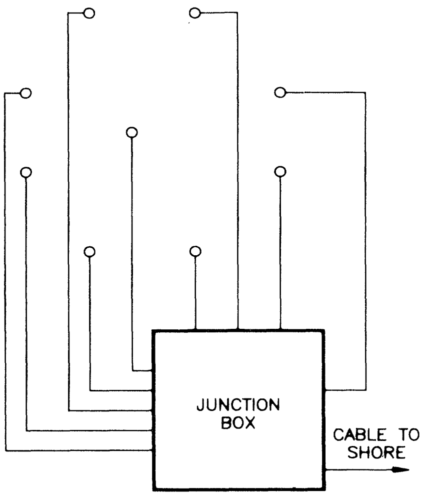

FIG. 41. The nine strings of DUMAND II plug into a junction box, which connects to the shore cable. The connections are made by an ROV or manned submarine (Wilkins, 1988a).

It is planned that the shore power supply will be ready when the shore cable is installed, so that as soon as a string is plugged into the junction box, it can be thoroughly tested from shore. Then, if there is a malfunction, it can either be corrected, or the string can be retrieved for repair. Figure 42 shows a DUMAND II string (without the string bottom controller, environmental, or calibration modules).

The successive stages of deployment of a single string are illustrated in Fig. 43. The concept of a canister has now been dispensed with, since the strings are now individually deployed. Each one has been loaded aboard in a large shipping container fitted out to allow testing and easy deployment through the SWATH ship well. Furthermore, it is planned for each string to carry a battery as part of its anchor, which can supply power to the string

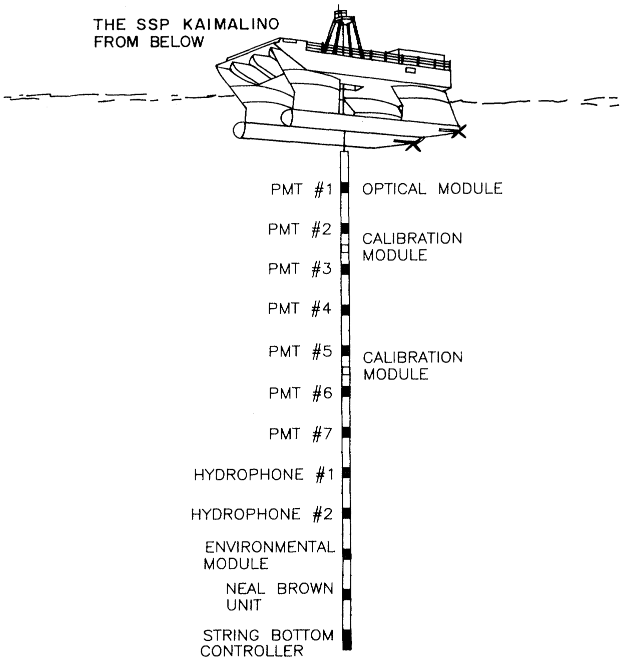

FIG. 40. The SWATH (Small-Waterline-Area-Twin Hull) ship *S.S. Kaimalino,* with the SPS shown deployed from it. This ship is well equipped for directly lowering sensor strings (Yumori, 1988).

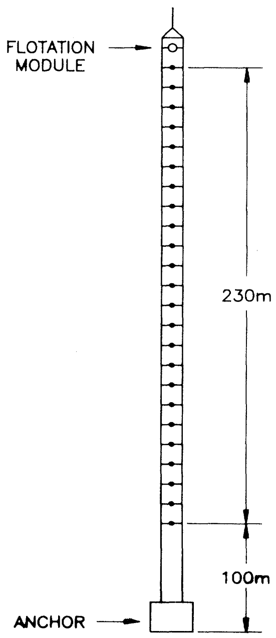

FIG. 42. The DUMAND II String configuration; the environmental module, two calibration modules, and the five hydrophones are not shown (Pokrofski *et al.*, 1988a).

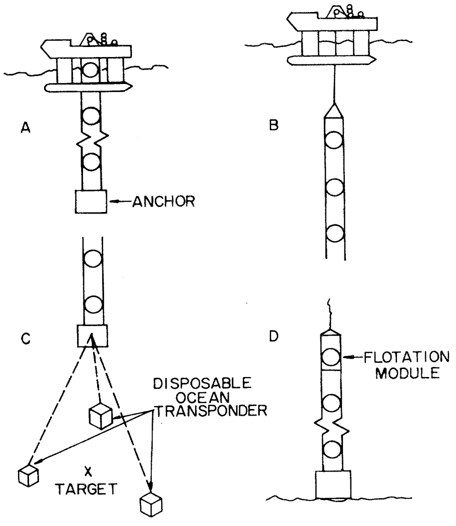

FIG. 43. Steps in string deployment of DUMAND II. Each deployment requires a separate trip by *Kaimalino,* which can carry only one string at a time. Batteries in the anchor allow powering the string during and after deployment to check operation; the string can be retrieved if inoperable (Wilkins, 1988b).

for a few hours. This allows a considerable amount of testing to be carried out during deployment, while the string is still attached to the deploying vessel. If any malfunction develops, the string can be hauled back on board and either repaired or replaced.

XII. PRESENT STATUS OF DUMAND

As of January 1, 1991 the status of DUMAND and its proposed calendar were as follows.

(1) Following scientific and fiscal approval and review, DOE funding for DUMAND II (the construction and operation of the octagon array) was approved in April 1990. All the collaborating groups have agreed on their contributions and are busily engaged in fulfilling them. Funds for construction and for new personnel have now been made available, and hiring is under way.

(2) The electro-optical cable that supplies power and carries data to and from the array has been ordered.

(3) The schedule calls for TRIAD to be installed by late 1992. Work on the remainder of the array will continue while experience in operating TRIAD and analyzing data from it progresses.

(4) Starting as soon as possible, the installation of the remaining six strings and their connection to the junction box will be carried out. It is hoped that by late 1993 the entire DUMAND II octagon will be in operation.

A. Recapitulation

1. Review of scientific goals

As the project progressed, and the background of relevant theory and experiment grew, the scientific goals were somewhat modified. This is most evident in the particle physics aspects. One example of such a change is that experiments designed to identify the W boson and measure its properties are no longer of concern to DUMAND. However, at this point, it is clear that the SSC is almost certainly the largest accelerator likely to be built, lacking some major breakthrough in accelerator technology. That being the case, the energy region above a few TeV for the study of neutrino properties seems safely reserved to cosmic-ray experiments.

2. Retrospective

We have covered in some detail the vicissitudes and travails of a project somewhat outside the ordinary course of high-energy particle physics, which nonetheless is being supported through high-energy physics channels. High-energy astrophysics is normally supported via NASA; but NASA will support only projects based in the atmosphere or in outer space, and not on the surface of the earth or below it (with the exception of ground-based telescopes). Thus NASA supports neither surface-based gamma-ray astronomy nor subsurface neutrino astronomy. We are grateful to the Department of Energy for taking a less parochial view of its responsibilities.

One aspect of DUMAND's history remains troublesome. That is the inordinate length of time between conception and execution—seventeen years, in this case. A considerable portion of that—perhaps the largest part—is due to the nature of the project itself. It took a long time for the experimenters and their consultants to convince themselves that the project was feasible at all; a long time for all the novel technical problems to be solved; a long time before the magnitude of the project decreased to something presently thought to be affordable; and a long time for the experimenters to master the unfamiliar and inimical nature of the medium in which the apparatus is to be constructed. Sailors have long known what we learned painfully, that the sea is an unforgiving medium. We must remember, too, that the crucial development of long-distance undersea fiber-optics wideband data transmission came along only in 1979, and commercial production even later.

In retrospect, one could wish that the DUMAND II array were more like the 36-string 1982 DUMAND Standard Array; in a less stringent financial environment that might well have been possible. However, we can hope that the performance of DUMAND II will be such as to justify an expansion of at least that order for the next stage. To quote myself, in a somewhat different context (Roberts, 1948), "*This machine is just a model for a bigger one, of course . . . .*"

XIII. OTHER NEUTRINO DETECTORS

Table VI is a compendium of present-day underground and underwater detectors; it is primarily concerned with detectors capable of useful observations on high-energy neutrinos. It is not exhaustive, having omitted most radiochemical solar neutrino detectors, such as the gallium and boron detectors. It does include those detectors that look for solar and supernova neutrinos via nonchemical procedures.

A. IMB

One of the most successful underground detectors has been the IMB installation in the Morton salt mine, near Cleveland. Like DUMAND (which may well have inspired its design) it consists of a large volume of water viewed by photomultipliers that detect Cerenkov light from charged particles. Because it is aimed at lower-energy particles, the density of PMTs is far higher. (This process has been carried to its ultimate limit in LENA, where the walls are tiled solidly with PMTs.)

The original purpose was to place a more stringent lower limit on the lifetime of the proton against decay. In this it succeeded admirably; the results served to exclude a popular variant of the standard model, namely the SU(5) version. In addition, it was one of the two detectors that observed the neutrinos from the collapse of supernova 1987A, and it has looked for low- (and high-) energy extraterrestrial neutrinos from other processes, so far without success. Its area is well under 1000 m^2, so that failure is hardly surprising.

B. GRANDE

A recent proposal has been made for a gamma-ray and neutrino detector, called GRANDE. This stands for Gamma-Ray And Neutrino DEtector. The proposal is to install a dense phototube array below the surface of water in a disused quarry in Arkansas. The proposal claims that the cosmic-ray muon background is adequately reduced since most downward muons do not trigger the array, because of the directional nature of Cerenkov radiation and timing considerations. The ambient light is to be reduced to zero by surrounding the entire array with a black opaque plastic light shield. This also acts as container for the water inside, which needs to be purified to become sufficiently transparent. The apparatus would be able to detect both upward-coming high-energy muons, and downward-going extensive air showers. More details can be found in Haines, 1987, and in the proposal. The estimated cost of GRANDE is uncertain, but will at least equal that of DUMAND II. Its effective area is about the same. GRANDE, on the other hand, appears to be much more difficult to expand to the 1-km^2 range.

C. Gran Sasso

Another large installation of underground detectors is being built at Gran Sasso (Italy), in an underground excavation at an equivalent depth of 4000 m of water. The installation is expected eventually to include several large independent components. One of these components is a Large-Volume Detector (LVD), consisting of 1800 tons of liquid scintillator; another is ICARUS (Imaging Cosmic and Rare Underground Signals), proposed as a 4500-ton liquid argon time-projection chamber. A third is MACRO (Monopole, Astrophysics, Cosmic-Ray Observatory), which will eventually include a liquid scintillator sectional detector 76 m long and 12 m wide—thus approaching 1000 m^2 in area; there are also 20 layers of limited streamer tubes and a sandwich of plastic etch detectors. In addition, on the mountain above this installation, there is a surface extensive air-shower detector array called EAS-TOP, which can be operated in coincidence with the subterranean detectors.

This is a very ambitious and expensive project; it is at present in operation with only a fraction of the ultimate complement of detectors. For neutrinos its area is small compared to DUMAND (about one-tenth); it is rather to be compared with IMB. The equipment is described in several publications (Frascati, 1984), and preliminary results are given by Klein (1989).

D. Russian neutrino detectors

Russian activity in neutrino astronomy since their forced divorce from DUMAND has been considerable. It has recently been summarized in a paper by John Learned (1990c), in which he describes a cruise aboard the Russian oceanographic vessel D. Mendeleev.

The Russian high-energy neutrino effort is considerably more extensive than the American. In the first place, neutrino astronomy is one of the three major priorities in high-energy physics. The Baksan Neutrino Observatory has been in operation for many years, operating a very large tank of liquid scintillator (for low-energy neutrino astronomy). There are collaborations with Italian scientists at Mont Blanc and Gran Sasso. Markov, though retired, is Department Chief of Neutrino Telescopes in the Ocean and Antarctica, Institute of Nuclear Research (INR). Markov and Zheleznykh oversee neutrino activities at the Institute of Energetics and the Institute of Antarctic and Arctic, Moscow; Institute of Oceanology; Kiev Institute of Materials; Physical Institute of the Academy of Sciences; Lebedev Institute; and Institute for Physical and Technical Measurements (the equivalent of the U.S. National Institute of Standards and Technology).

An experiment by INR is planned in the Atlantic next year; it is a search for acoustic signals from neutrinos of 10^{15} eV or above. Optical measurements in the ocean are aimed at setting up a detector equivalent to DUMAND II, but in or near Europe; a site 4 km deep in the Medi-

TABLE VI. Underground/underwater detectors (DUMAND is omitted).

Name	Area (m^2)	Description
IMB (LoSecco *et al.*, 1985)	400	Originally Irvine-Michigan-Brookhaven, now includes many others. Located in Morton Salt mine, Cleveland, Ohio. Water Cerenkov detector. Energy range: a few MeV up. Initial aim: to study proton decay. Also detected SN 1987A.
Kamiokande II (Hirata *et al.*, 1990, 1991; Totsuka, 1990)	ca. 700	Acronym for Kamioka Nuclear Decay Experiment. Located in Kamioka metal mine, Gifa Prefecture, Japan. Aim: to study proton decay. Water Cerenkov detector. Saw SN 1987A. Energy range: a few MeV. Solar neutrinos detected via nuclear interaction; direction of origin observed, thus solar origin verified.
Soudan 2 (Kochoki *et al.*, 1990; Allison *et al.*, 1990; DasGupta *et al.*, 1990)		Located in mine in Tower, Minnesota. Fine-grained calorimeter, 1000 tons, to study proton decay, neutrino oscillations, cosmic rays.
Homestake (Cherry *et al.*, 1987)		First solar neutrino detector, located in Homestake gold mine in Lead, South Dakota, using radiochemical detection; now augmented by a scintillator detector and surface air shower array.
Gran Sasso laboratory: several detectors (Bellotti, 1988, 1990); Italy. Located in excavation adjoining Mont Blanc Tunnel.		
a. MACRO (Bari *et al.*, 1988; Marchieri-Chiesa *et al.*, 1990)	ca. 1100	Monopole, Astrophysics, Cosmic Ray Observatory. Multipurpose detector for muons, gamma rays, neutrinos, magnetic monopoles. Energy range: MeV up to TeV. Initial modules in operation, remainder in construction.
b. LVD (Calicchio *et al.*, 1988; Anzivino *et al.*, 1990)	ca. 800	(Large-Volume Detector) ca. 2300-ton liquid scintillator, 1000 tons steel. Aims: study of proton decay, neutrino oscillations, solar B^8 neutrinos; supernova detection.
c. ICARUS (Bellotti, 1988, 1990)	?	(Imaging Cosmic and Rare Underground Signals.) Very large liquid-argon time-projection detector; status unclear.
d. EAS-TOP (Aglietta *et al.*, 1990; Bellotti, 1990)		Extensive Air-Shower detector above (on TOP of) Gran Sasso laboratory, capable of operation in coincidence with underground detectors. Now in operation.
Baksan Neutrino Observatory (Andreyev *et al.*, 1990; Bakatanov *et al.*, 1990)		Located in Baksan Valley, North Caucasus, U.S.S.R. Large liquid scintillator installation, in operation since about 1981. Proton decay, solar neutrinos, supernova neutrinos.
Kolar gold field (KGF) (Adarkar *et al.*, 1990)		Located in Mysore, India. Small but very deep detector in gold mine. Underground muons and neutrinos.
Lake Baikal (Bezrukov, 1987)	2000	Similar to DUMAND: water Cerenkov detectors. In operation only when lake is frozen (two months/yr); equipment suspended from surface. Like DUMAND, but smaller, shallower.
SuperKamiokande	ca. 10^4	Construction approved; cost ca. $70 million. Solar, supernova neutrinos. Search for high-energy neutrinos, exotic particles; also neutrino oscillations.
GRANDE (Haines, 1989; Adams *et al.*, 1990)	10 000 to 60 000 (various revisions)	Gamma-Ray and Neutrino DEtector. Combined high-energy neutrino, gamma-ray detectors in shallow water depth in disused quarry in Arkansas. Would see downward-going gamma rays, upward-going neutrino-produced

TABLE VI. (*Continued*).

Name	Area (m^2)	Description
		muons. Energy range: GeV–TeV. To see upward-going muons requires anticoincidence cancellation of downward-going muons to at least factor of 10^8. Also requires light to be excluded from entire detector setup by plastic enclosure. Not yet approved.
SNO-Sudbury Neutrino Observatory (Chen, 1988; Evans *et al.*, 1990)	ca. 300	Located at Sudbury, Ontario, Canada. For solar and supernova neutrinos. Large water Cerenkov detector that can use ordinary, heavy, or O^{18}-enriched water. Proposed for heavy water, at present, to study solar and supernova neutrinos. Cost ca. $70 million.
LENA (proposed) (Koshiba *et al.*, 1989; Baldo-Ceolin, no date)		(Lake Experiment on Neutrino Activity). Koshiba has proposed three versions, varying in size and purpose. LENA is similar to GRANDE, but larger, and uses artificial excavations instead of natural water bodies. Intended as part of Gran Sasso complex.
LSD (Aglietta *et al.*, 1985; Dedykin *et al.*, 1985)		Large Scintillation Detector, Mont Blanc (Italy, Switzerland). Status unclear.
INT (proposal)		Italian Neutrino Telescope. An Italian lake project, similar to GRANDE, to be associated with Gran Sasso. Also see LENA.
AMANDA (proposal) (Barwick and Halzen, 1990; Barwick *et al.*, 1990)		Antarctic Muon and Neutrino Detector Array. Proposed high-energy neutrino detector using phototubes and/or acoustic and/or radio detectors installed in holes (and then frozen in) in highly transparent Antarctic ice. In preliminary study stage. A collaborative project of University of California, Berkeley, and University of Wisconsin, possibly others.

terranean is under consideration. Also under consideration are sites in the Black Sea and Atlantic. Bioluminescent studies have been carried out by Petrukhin's group in the Indian ocean and by INR in the Atlantic; and a group numbering about 50 under Domogatsky and Bezrukhov are deploying detectors in Lake Baikal. Communication among these groups is not very good. Learned estimates that the amount spent on neutrino astronomy in Russia is equivalent to $10 million per year.

E. "Fourth-generation" detectors

Other plans for neutrino detectors were discussed at a small workshop in late 1989 aboard the Mendeleev, at harbor in Civitavecchia, Italy. These centered about a world-class detector, of area in the 1-km^2 range. A fourth-generation DUMAND-type detector, with 10 000 optical modules, costing perhaps $100 million, was discussed; we shall say more about it in the next section. It is remarkable how small a sum that can be made to appear by proper comparisons.

Other detectors presently under consideration include a GRANDE-type detector, but much larger—about 100 000 m^2—to be built near Gran Sasso at an altitude of 1000 m, in a specially constructed pit. The SINGAO project, a large collaboration of Italian and English universities, is proposing a very large air-shower array, including 15 000 m^2 of resistive plate chambers and 3000 2-m^2 shower counters spread over 9 km^2, to study downgoing air showers and upgoing neutrinos. Learned (1990b) has given a recent summary of neutrino detectors.

A new and interesting possibility is offered by the studies now in progress on AMANDA, which stands for Antarctic Muon and Neutrino Detector Array. A group including collaborators from the University of California at Berkeley and the University of Wisconsin is studying the possibility of using the highly transparent and very thick antarctic ice as a medium for neutrino detection, via either Cerenkov light, using PMTs implanted in holes in the ice and then frozen in; or possibly acoustic or radio-wave detection of very-high-energy events. The radio emission comes from unequal motion of positive and negative particles produced in high-energy showers, in analogy to the electromagnetic pulse observed from nuclear explosions in the atmosphere or above it. The intestinal fortitude required to contemplate so daunting an operation can only command the highest admiration.

F. The next stage of DUMAND

It may well be thought premature to discuss the next stage of DUMAND before DUMAND II is completed, much less in operation. On the other hand, a historical survey such as this provides a platform for asking where we now stand and where we are going.

For very large high-energy neutrino detectors (1 km^2) it is not yet clear whether the GRANDE route—a natural or artificial lake—will be feasible. DUMAND can reach that destination relatively economically, according to preliminary Monte Carlo calculations (Roberts, 1991) by expanding the present array to about 100 strings, spaced 100 m apart, and 1-km long, giving a contained volume of 1 km^3. Such an array also has the advantage of improved angular resolution, by a factor of 5 or more, thus aiding in eliminating isotropic background and greatly improving angular accuracy.

However, to reach the 1-km^2 range, already suggested as an ultimate goal (Learned, 1990b), an international collaboration looks like an appropriate mechanism, since the cost will probably be in the $100 million range. Such an array would be perhaps 40 times as sensitive as DUMAND II. So great an increase is equivalent to that obtained in optical astronomy in going from a 30-in. mirror to a 200-in. one.

XIV. POSTSCRIPT: THE TWILIGHT OF THE ACCELERATOR ERA

The last sixty years have seen nuclear and particle physics blossoming under the reign of the particle accelerator. The Cockcroft-Walton voltage doubler, the cyclotron, the linear accelerator, the synchrocyclotron, and the synchrotron have made possible an era of unexampled progress in understanding the structure of the nucleus, in identifying the families of leptons and hadrons, all leading to what we now call the Standard Model of elementary particles. We should note that it was not until 1954 (see, for example, the proceedings of the annual Rochester conferences) that particle physics began to advance more rapidly in accelerator experiments than in cosmic-ray studies; the positron, the muon, the pion, the kaon, and the hyperons were all first observed in cosmic-ray experiments. Since 1954 we have grown accustomed to thinking of particle physics as an accelerator-associated field.

That era is now ending. It was enormously successful, and it is ending not because accelerators could not contiue on the same road, but because we can no longer afford it. The cost of the SSC is such as to preclude any idea of bigger machines, in the absence of breakthroughs in accelerator technology that will sharply reduce costs. Thus we have seen accelerators bring us from 10^6 to 10^{13} eV, and we have no hope at present of going higher on that route. It is true that some SSC interactions can explore very high Q^2, comparable to cosmic-ray proton beams of nearly 10^{18} eV; but they cannot produce high-energy secondary beams, which require a large c.m. momentum.

But despite the enormous success of accelerator physics, cosmic rays and nonaccelerator particle physics have not died; they are alive and well and attracting ever-increasing numbers of physicists anxious to avoid the large-accelerator-establishment atmosphere, where it takes a large auditorium to accommodate the members of an experimental group. Cosmic-ray physics has now evolved into particle astrophysics and has become an important branch of astronomy, with recognized specialties like gamma-ray, x-ray, and neutrino astronomy. Since the energies of cosmic rays extend to 10^{20} eV, there are seven decades of energy to be investigated. Furthermore, there are mysteries aplenty in the skies, all begging for solutions. What is the dark matter? Is the Big Bang theory complete? Do neutrinos have mass?

Other nonaccelerator particle physics accomplishments include significant lower limits on the proton lifetime against decay, double beta decay, monopole and other exotic particle searches, and dark matter searches.

It is time to recognize that, barring some unexpected breakthrough in accelerator technology, the future of particle physics, aside from the SSC and its smaller offspring, now lies in nonaccelerator work. The Russians have explicitly recognized this, in making neutrino astronomy third in priority in high-energy physics. We have yet to make such an explicit statement; in fact, it is not clear that we all realize the need for it. The Field committee, in its preview of astronomy in the eighties, did not even mention neutrino astronomy, which, in the detection of SN 1987A and the new developments of solar neutrino detection, provided an outstanding result of that decade. The Bahcall committee, previewing astronomy in the nineties, discussed solar neutrino and supernova neutrino astronomy, but failed to mention high-energy neutrino astronomy (although its subsidiary working papers mention it briefly). As a consequence, high-energy astrophysics is, if not an orphan, still a foundling without a home, living from hand to mouth. Let us hope that this will soon be remedied.

ACKNOWLEDGMENTS

For a project with the unique history of DUMAND, it is totally impractical to try to list the scores—even hundreds—of people from all the branches of science and engineering who have contributed to the project; it would be like trying to credit all those who contribute to the design and construction of a large accelerator. The lists of attendees at DUMAND conferences and workshops will contain many—but not all—of them. At the risk of omitting many who deserve mention, I shall single out a few whose help and contributions have been

outstanding in getting DUMAND started, but I shall not attempt to credit all those who contributed to the feasibility study. Fred Reines was the moving spirit who started the ball rolling. For five years (1975–1979) I was the only full-time worker on DUMAND, thanks to the support of Fermilab and its director, Robert R. Wilson. The other major supporters during that period wee John Learned, presently technical director; George Wilkins, fiber optics and undersea cable expert, oceanographic advisor, and a dedicated member of the DUMAND team since 1976; Hugh Bradner, of the Scripps Institution of Oceanography, particularly valuable as a high-energy physicist turned oceanographer; Victor Stenger of the University of Hawaii (later Deputy Director), who took on the major responsibility for Monte Carlo calculations; and Howard Blood and Howard Talkington of the Naval Ocean Systems Center, who lent strong support and assistance at all stages of the program. From the cosmic-ray and astrophysical communities, Ben Berezinsky, Maurice Shapiro, and David Schramm gave us strong encouragement and valuable advice. The University of Hawaii High Energy Physics group and its director, Vincent Z. Peterson, supported the project enthusiastically from its first conference in Honolulu in 1976 to the present day, and were instrumental in obtaining university and federal support for it. In the U.S., the DUMAND project is supported by the Department of Energy and the National Science Foundation.

It is appropriate at this point to thank the many ocean engineers and physicists who volunteered their time and effort to this project; among these we must especially single out Howard Blood, Howard Talkington, and Arthur Schlosser of what is now called the Naval Ocean Systems Center, of San Diego. Among the graduate students who worked on the program we must single out Daniel O'Connor for his devotion and significant contributions; and among the HIG engineers Robert Mitiguy, who has been a valuable friend and ally in initiating us into the hazards of the ocean deeps.

For their advice, assistance, and encouragement in the preparation of this review, I am greatly indebted to M. Bloch, L. Brown, L. Hoddeson, J. G. Learned, D. Schramm, M. M. Shapiro, D. Theriot, L. Voyvodic, and the staff of the Hawaii DUMAND Center.

APPENDIX A: LIST OF DUMAND PUBLICATIONS

NOTE: In the list of References, these publications are referred to in the abbreviated form shown in quotation marks.

1. "DUMAND 1975." Proceedings of DUMAND 1975 Summer Study, Bellingham, WA, July 1975, edited by P. Kotzer (Western Washington State College, Bellingham, WA, 1976).

2. "DUMAND 1976." Proceedings of 1976 DUMAND Summer Workshop, Honolulu, HI, September 1976, edited by A. Roberts (Fermilab, Batavia, IL, 1977).

3. Report on 1977 Summer Workshop, Moscow, June 1977. A. Roberts, ESN, 31-9, September 1977, p. 370 (Office of Naval Research, London Branch, 1977).

4. "DUMAND Signal 1977." Proceedings of LaJolla 1977 Workshop on Signal Processing (mainly acoustic signals in DUMAND), edited by H. Bradner (Scripps Institute of Oceanography, LaJolla, CA, 1978).

5. "DUMAND 1977." Proceedings of San Diego Summer Workshop on Ocean Engineering, August 1977, edited by G. Wilkins (Naval Ocean Systems Center, San Diego, 1978).

6. "DUMAND 1978." Proceedings of the 1978 DUMAND Summer Study, LaJolla, CA, volume 5, edited by A. Roberts *et al.* (DUMAND, Scripps Institute of Oceanography, LaJolla, CA, 1978).

Vol. 1: Array Studies, 351 pp., edited by A. Roberts.

Vol. 2: UHE Interactions and Neutrino Astronomy, 213 pp., edited by A. Roberts.

Vol. 3: Oceanographic and Ocean Engineering Studies, 213 pp., edited by G. Wilkins.

7. "DUMAND proposal 1978." University of California, San Diego (Scripps Institute of Oceanography, LaJolla, CA, 1978).

8. "DUMAND 1979." Proceedings of Khabarovsk–Lake Baikal DUMAND Meetings, September 1979, 376 pp., edited by J. G. Learned (Hawaii DUMAND Center, Honolulu, HI, 1980).

9. "DUMAND Signal 1980." Proceedings DUMAND Signal Processing Workshop, Honolulu, February 1980, edited by A. Roberts (Hawaii DUMAND Center, Honolulu, HI, 1981).

10. Proceedings of 1980 DUMAND Summer Symposium, Honolulu, HI, July–August 1980. In 2 volumes, edited by V. J. Stenger (Hawaii DUMAND Center, Honolulu, HI, 1981).

11. "DUMAND Deployment 1980." Proceedings of DUMAND 1980 Deployment Workshop, LaJolla, CA, December, 1980, edited by A. Roberts (Hawaii DUMAND Center, Honolulu, HI, 1981).

12. "DUMAND Signal 1982." Proceedings of DUMAND 1982 Signal Processing Workshop, Honolulu, HI, February 1982, edited by A. Roberts (Hawaii DUMAND Center, Honolulu, HI, 1982).

13. "DUMAND Proposal 1982." DUMAND Proposal (abridged), by International DUMAND Collaboration, November 1982 (Hawaii DUMAND Center, Honolulu, HI, 1982).

14. "DUMAND 1984." Proceedings of 1984 DUMAND Workshop on Ocean Engineering and Deployment, La-Jolla, CA, August 1984, edited by A. Roberts and G. Wilkins (Hawaii DUMAND Center, Honolulu, HI, 1984).

15. "DUMAND 1988." Proceedings of 1988 DUMAND Workshop on Ocean engineering and Deployment, January, 1988, and Proceedings of 1988 DUMAND Workshop on Signal Processing, March, 1988; both at Honolulu, HI, published as one volume, edited by A. Roberts (Hawaii DUMAND Center, Honolulu, HI, 1988).

16. "DUMAND Proposal 1988." DUMAND Proposal, by International DUMAND Collaboration, 1988 (Hawaii DUMAND Center, Honolulu, HI, 1988).

17. "DUMAND II Specifications, 1989" October 1989 (Hawaii DUMAND Center, Honolulu, HI, 1989).

18. "DUMAND Trigger 1990." Proceedings of 1990 DUMAND Trigger Workshop, July 1990, edited by J. Wilkes and K. Young (Department of Physics, FM-15, University of Washington, Seattle, WA, 1990).

19. "DUMAND Optical 1990." Proceedings of 1990 DUMAND Optical Module Workshop, October 1990, edited by S. Tanaka and A. Yamaguchi (Bubble Chamber Physics Laboratory, Tohoku University, Sendai, Japan, 1990).

APPENDIX B: PRESENT DUMAND COLLABORATION

Technische Hochscule Aachen
University of Bern, Switzerland
Boston University
California Institute of Technology
University of Hawaii
University of Kiel
Kinki University, Osaka
Vanderbilt University
University of Kobe, Japan
Okayama Technical Institute
Scripps Institution of Oceanography
Tohoku University, Sendai, Japan
Institute for Cosmic-Ray Research, University of Tokyo
University of Washington, Seattle
University of Wisconsin

APPENDIX C: CHRONOLOGY

1. Prehistory: Before 1973

Neutrino Detectors; first ocean and lake experiments.

2. DUMAND 1973-1975: The early days

1973. Denver Cosmic-Ray Conference: preliminary thoughts on a deep ocean detector for cosmic-ray neutrinos. Establishment of an *ad hoc* DUMAND Steering Committee.

1975. First DUMAND Conference, at Western Washington State College, Bellingham, Washington. Conference Chairman F. Reines; editor of Proceedings, P. Kotzer. Establishment of new Steering Committee, including nonphysicists. Oceanographers select Hawaii as preferred site. No clear experimental aim established.

3. Early development of DUMAND, from 1976 to 1977 Proposal

1976. Neutrino Conference Aachen paper, by members of the DUMAND Steering Committee. ATHENE, UNICORN, and UNDINE described. Adherents begin to gather. The University of Hawaii high-energy physics group becomes interested.

1976. DUMAND Conference, at the University of Hawaii, Honolulu. This is the first international DUMAND conference. Conference Chairman and editor of Proceedings, A. Roberts.

Acoustic detection of neutrinos is proposed by Bowen and Askarian, independently. This method is experimentally investigated over the next two years, and found to be feasible, but with an energy threshold in the vicinity of 10^{16} eV. ATHENE, UNICORN, and UNDINE are carefully considered. UNDINE is rejected.

1977. 14th International Cosmic-Ray Conference, Plovdiv. Session on DUMAND.

1977. Moscow Workshop, by invitation of G. Zatsepin and others. Soviet physicists anxious to collaborate, offer to supply several thousand phototubes for DUMAND.

1977. Scripps Workshops on Signal Processing, and on Ocean Engineering. Chaired by H. Bradner.

1978. Proposal for large DUMAND array submitted to NSF, DOE, others. Project to be centered at Scripps. Proposal rejected.

4. 1978-1980. Pre-Hawaii period

1978. Summer Workshops at Scripps: three two-week workshops on Array Studies, UHE Interactions and Neutrino Astronomy, and Oceanography and Ocean Engineering. Conference Chairman, A. Roberts. 1978 Standard Array proposed. UNDINE (detection of supernovae) again rejected in favor of ATHENE and UNICORN (studies of high-energy astronomical and cosmic-ray neutrinos).

1979. 16th International Cosmic-Ray Conference, Kyoto. Session on DUMAND.

1979. Khabarovsk-Lake Baikal Conference. Russian plans for installation in Lake Baikal.

1979. Establishment of DUMAND Collaboration (see Table III). Submission of proposal to DOE for feasibility study at University of Hawaii. Proposal approved.

5. 1980. Establishment of Hawaii DUMAND Center

Funded by DOE. Purpose: To investigate the feasibility of a DUMAND detector. Director, V. Z. Peterson; Deputy Director, V. J. Stenger; Technical Director, J. G. Learned.

1980. Signal-Processing Workshop, Honolulu. Wilkins announces feasibility of fiber-optics undersea cables for data transmission, thus enormously simplifying the signal-processing problem and moving it from ocean bottom to shore.

1980. Honolulu International DUMAND Symposium, Honolulu. J. G. Learned, Conference Chairman; V. J. Stenger, editor of Proceedings.

1980. Deployment Workshop, Honolulu.

1981. International Cosmic-Ray Conference, Paris. DUMAND session.

6. First deployment of short prototype string

1981–1982. Activation of the DUMAND Collaboration. Reagan administration excludes Russian collaborators.

1982. Submission of Proposal for construction of a 36-string DUMAND array. Proposal envisages first deployment of test strings, then 6 planes of 6 strings each. Each plane has its own cable to shore and is thus to be independently deployed. The proposal is submitted by the DUMAND Collaboration.

1982. Signal-Processing Workshop, Honolulu.

1983. DOE approves only the construction and testing of the Short Prototype String (SPS).

7. 1982–1984. Losses at sea and subsequent recovery

The first loss at sea (1982) of the muon string was due to the breaking of the supporting cable, an event traced to snap loading and rectified in subsequent launchings by the use of a ram tensioner.

Another string, the so-called TTR-4, was placed on the bottom in 1985, to be recovered when timed explosive bolts released it. The explosive bolts fired, but failed to release the string. Recovery, 19 months later, was by a Scripps oceanographic vessel equipped with side-scan sonar. Recovered unit was remarkably free of corrosion or marine growth.

1984. Ocean Engineering Workshop, Scripps Institution, La Jolla.

8. 1987. Successful completion of SPS testing

Cosmic-ray muons detected to 4.5 km depth, and ocean backgrounds of radioactivity and bioluminescence studied, recorded, and subsquently published.

9. 1988. Proposal for Stage II of DUMAND, called DUMAND II, submitted to DOE

DUMAND II is a 9-string array in the shape of a regular octagon with a central string. DUMAND has shrunk as far as it can without disappearing. The makeup of the DUMAND collaboration is somewhat altered for Stage II.

1988. Signal-Processing Workshop, Honolulu.

1988. Ocean Engineering Workshop, Honolulu.

10. May 1989. Scientific approval of DUMMAND II recommended by HEPAP (High Energy Physics Advisory Panel)

November 1989. DOE Review committee studies and approves DUMAND proposal.

11. April 1990. Funding for DUMAND II approved by DOE

Collaboration makeup changed, with some members withdrawing, others joining. Present collaboration shown in Appendix B.

12. July 1990. Trigger Workshop, Seattle, WA.

13. October 1990. Optical Module workshop, Sendai, Japan.

APPENDIX D: REFERENCES TO INTERNATIONAL COSMIC RAY CONFERENCES (ICRC)

10th ICRC, Calgary, 1967: Proceedings, Calgary, Alberta, June 19–30, 1967, edited by Margaret D. Wilson (National Research Council of Canada, Ottawa, Canada).

13th ICRC, Denver, 1973: Conference Papers, Conference on Cosmic Rays, Denver, August 17–30, 1973 (University of Denver, Denver, CO).

14th ICRC, Munich, 1975: Conference Papers (Max-Planck-Institut fuer Extraterrestrische Physik, Munich).

15th ICRC, Plovdiv, Bulgaria, 1977: Conference Papers (Bulgarian Academy of Sciences, Plovdiv).

16th ICRC, Kyoto, 1979: Conference Papers (Institute for Cosmic-Ray Research, University of Tokyo, Tokyo).

17th ICRC. Paris, 1981: Conference Papers (Section d'Astrophysique, Centre d'Etudes Nucleaires, Saclay).

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18th ICRC, Bangalore, India, 1983: Conference Papers, edited by N. Durgaprasad, S. Ramadurai, P. V. Ramana-Murthy, M. V. S. Rao, and K. Sivaprasad (P. V. Raman-Murthy, Tata Institute of Fundamental Research, Colaba, Bombay).

19th ICRC, LaJolla, CA, 1985: Conference Papers, NASA Conference Publication 2376 (Scientific and Tech-

nical Information Branch, NASA, Washington, D.C.).

20th ICRC, Moscow, 1987: Conference Papers, edited by V. A. Kozyarivsky, A. S. Lidovsky, T. I. Tulipova, A. L. Tsyabuk, A. V. Voedovsky, and N. S. Volgemut (Nauka, Moscow).

21st ICRC, Adelaide, 1990: Conference Papers, edited by R. J. Protheroe (Department of Physics and Mathematical Physics, University of Adelaide, Adelaide, Australia).

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NOTE: Abbreviated references to DUMAND publications—e.g., DUMAND 1977—will be found in full in Appendix A. ICRC stands for International Cosmic Ray Conference; references to these meetings will be found in full in Appendix D.

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Aoki, T., T. Kitamura, S. Matsuno, K. Mitsui, Y. Ohashi, A. Okada, D. R. Cady, J. G. Learned, D. O'Connor, S. Dye, P. W. Gorham, M. McMurdo, R. Mitiguy, M. Webster, C. Wilson, and P. Grieder, 1986, Nuovo Cimento C **9**, 642.

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