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THE DUMAND PROJECT

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ABSTRACT

We summarize the scientific background which has led to the DUMAND project and outline the anticipated goals, followed by a brief description of the system layout and its capabilities, together with some technical details of the detector modules. Subsequently we present the project schedule and construction strategy, and give an account of the present project status and its immediate future.

I N D E X

1. INTRODUCTION.

DUMAND which stands for Deep Underwater Muon And Neutrino Detector is a most unconventional project. The DUMAND detector system is a giant three-dimensional matrix consisting of 756 highly sophisticated optical detector modules that are distributed within a parallelepiped measuring 250•250•500 m^3, planned to be submerged and operated at a depth of almost 5 km in the Pacific ocean, approximately 25 km off-shore, west of Keahole Point on the "Big Island" of Hawaii. Figure 1 shows an artist's view of the DUMAND array on the sea floor.

The system is capable of detecting penetrating cosmic rays, in particular ULTRA HIGH ENERGY MUONS originating from even more energetic interactions of primary cosmic rays at the top of the atmosphere with nuclei of air constituents, and VERY HIGH ENERGY MUON NEUTRINOS and their antiparticles of TERRESTRIAL AND EXTRATERRESTRIAL ORIGIN that interact within the detector or its immediate vicinity, producing a detectable and reconstructable muon trajectory within the detector matrix. In either case detection is based on Cerenkov radiation produced by the relativistic muons in the ocean.

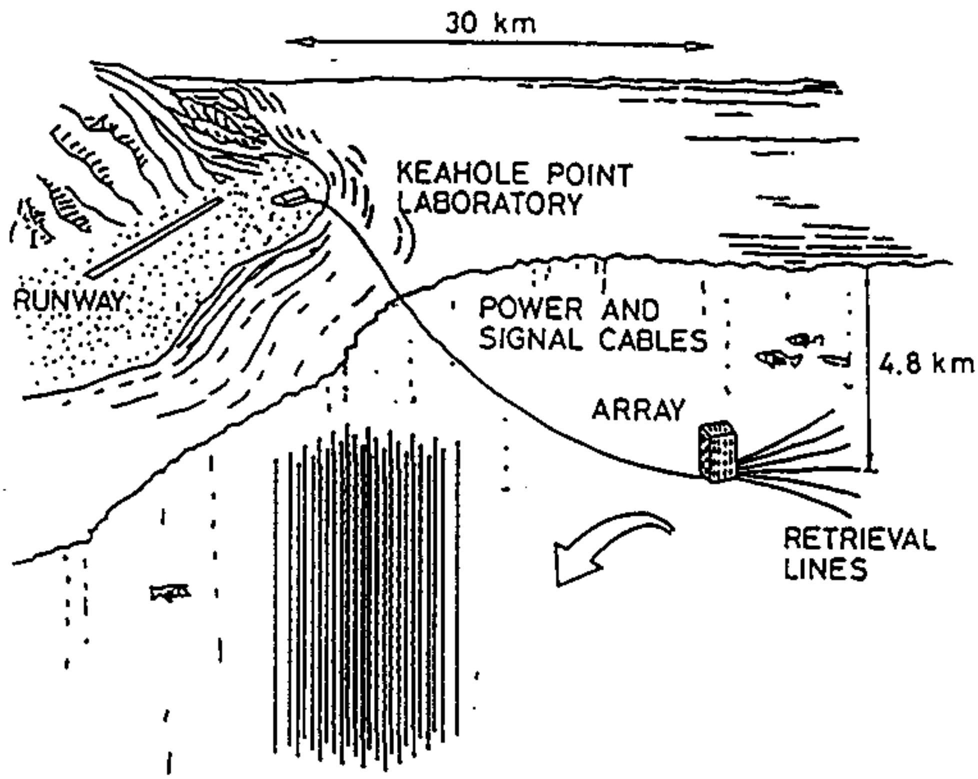
DUMAND uses the ocean simultaneously in many different ways: As a giant neutrino target, as active Cerenkov medium for high energy muons of atmospheric origin as well as for muons resulting from neutrino reactions in the ocean; it shields the detector from the undesirable low energy cosmic ray background, acts as homogeneous absorber for the muons under investigation and, finally, the overlaying water masses absorb the daylight completely and serve as dark room for the highly light sensitive optical detector modules.

This extraordinary project poses many new problems which lay far outside the domain of conventional experiments in cosmic ray or particle physics as well as astrophysics. The problems are partly due to the huge dimensions of the system but mostly to the unusual and to some extent hostile environment in which the experiment will be carried out. In particular the enormous pressure of 500 bar and the corrosiveness of the medium into which the sensor modules will have to be placed require new advanced technologies, and likewise data, control and command links. But also data handling, trigger processing, trajectory and in some cases vertex reconstruction in space and time represent challenging new problems and require new sophisticated hard and software. Some of these problems will be touched in section 4.

2. COMMENTS ON HIGH ENERGY MUON AND NEUTRINO PHYSICS UNDERGROUND

Before discussing the various aspects of the DUMAND project we will briefly summarize the present activities in the field of high energy muon and neutrino physics underground, outline the principal scientific aims and point out the shortcomings of current experiments and techniques that will be overcome by the DUMAND detector system.

The Keahole Point site



<u>Figure 1:</u> DUMAND site with array implanted. The figure shows the location of the array on the sea floor, the shore laboratory at Keahole Point on the "Big Island" (photo) together with the interconnecting electrical power and data cables. The latter consist of glass fibers. The retrieval lines on the right of the array serve to recover parts or all of the array in case of major failure.

TABLE 1: COMPARISON OF MAJOR UNDERGROUND DETECTORS

Detector	Mass tons	Depth mwe	Size m	E_μ TeV	p_t GeV/c	Status
Baikal (SU)	3000 Wc	1300	10 o*40	0.5	0.3	operating*
Baikal	$3*10^7$ Wc	1300	200*300 *400	0.5	-	proposed
Baksan (SU)	85 Sc	850	16*16	0.3	0.3	operating
DUMAND (US)	$3*10^7$ Wc	4500	250*250 *500	3.5	20	stage 1
Frejus (F)	912 Fe	4400	6*12	3	0.9-2.6	operating
Homestake (US)	150 Wc	4200	8*16	3	1.5-3	~~operating~~ shut down
Homestake	140 Sc	4200	8*24	3	15	operating
IMB (US)	8000 Wc	1570	17*23	0.6	0.5-0.8	operating
Kamioka (J)	2900 Wc	2700	16 o	1	0.9	operating
KGF (India)	140 Fe	7000	4*6	12	3-4	operating
KGF	375 Fe	7000	6*6	12	4	operating
KGF	- Pc	3400	12*20	2	1-2	proposed
KGF	- Sc	900	2*2	0.2	0.1	operating
LSD (I)	200 Sc	5200	7*8	4	1.5	operating
LVD (I)	10^4 Fe	4000	-	3	-	proposed
Macro (I)	- C	4000	12*110	3	-	proposed
NUSEX (I)	150 Fe	5000	3.5*3.5	4	0.8	operating
Park City (US)	1000 Wc	1700	10 o	0.6	0.3	shut down
Soudan I (US)	30 FeC	2200	3*3	0.7	0.1	operating
Soudan II	1100 FeC	2200	8*16	0.7	0.3	under constr.

Fe - iron; Wc - water Cerenkov, Sc - scintillator;
FeC iron concrete; C concrete; Pc - proportional counters.
* during ∝ 3 months per year.

2.1 General.

High energy cosmic ray muon and neutrino physics are closely related to one another not only because the particles belong to the same family but also because neutrinos and their antiparticles can only be observed indirectly, by means of muons resulting from neutrino interactions with nucleons. Thus, in principle muon neutrino experiments are suitable for muon work as well, but not necessarily vice versa. Many researchers are therefore tackling both kinds of problems simultaneously, even though the goals of muon experiments are generally very different from those of neutrino experiments. Moreover it is important to emphasize that high energy cosmic ray muon data play an important role not only for muon and neutrino physics, but also for many other aspects of pure high energy physics, general cosmic ray physics and even astrophysics. Please note that in the following, whenever we are referring to neutrinos, we mean exclusively muon neutrinos and not electron neutrinos, unless explicitly specified otherwise.

Table 1 shows a comparison of all significant underground detector systems now in operation, just recently shut down, or in the final planning phase, that are suitable for muon and neutrino work, including DUMAND. Of these only the proposed Russian Baikal lake experiment (Bezrukov et al., 1984) will have any resemblance to DUMAND.

Some of the detectors listed above have been designed originally to be operated primarily as proton decay experiments, such as those in the Morton Salt Mine (IMB), at Kamioka, Park City (HPW), Soudan, in the Mont Blanc tunnel (NUSEX) and one of the detectors at the Kolar Gold Fields. However, these experiments record muon and neutrino events as well. They also have limited capabilities for detecting magnetic monopoles and to study neutrino oscillations. The closely packed detectors can also record electron neutrino events, in principle. In the following we will focus our discussion on those aspects and experiments that are relevant for the DUMAND project.

2.2 High Energy Neutrino Astrophysics.

Neutrino astrophysics is a relatively young field of research. There exist a variety of theories that describe astrophysical processes that could efficiently produce electron or muon neutrinos. Neutrino fluxes and energy spectra have been calculated for a number of objects that are likely to be significant sources, such as pulsars, quasars and black holes (Stenger, 1984; Schramm and Steigmann, 1980; Lee and Bludman, 1985).

Initially experimental neutrino astrophysics had been concerned chiefly with low energy, keV and MeV electron neutrinos from the sun (Davis et al., 1968). More recently the search for extraterrestrial neutrinos has been extended to low energy antineutrinos from collapsing stars (Khalchukov et al., 1983) and, above all, to high energy muon neutrinos. Particularly the discovery of ultra high energy gamma rays from Cygnus X-3 (Samorski and Stamm, 1983a, 1983b), LMC X-4 (Protheroe and Clay, 1985) and other sources (Chadwick et al., 1985) have strongly stimulated the interest on high energy neutrino astronomy and astrophysics.

Gamma rays of this energy range (>1000 TeV) are most likely due to hadronic and not electromagnetic processes, i. e., they must result from high energy neutral pion decay, because electromagnetic processes would be too inefficient for their production. However, whenever high energy neutral pions are produced it is most likely that a comparable number of charged pions of either sign will also be produced. Their decay rate, which depends on their energy and on the density of the surrounding matter into which they propagate, determines essentially the production rates of energetic muon neutrinos and antineutrinos.

It is evident that the correlation between high energy gamma ray and neutrino fluxes from a common source, provided that there exists such a source, would reveal important astrophysical information not only on the source itself but also on its immediate surroundings. (Stenger, 1984; Lee and Bludman, 1985).

At present, there is no definite proof that the ultra high energy primary gamma radiation observed to arrive from the direction of Cygnus X-3 and other objects is of hadronic origin. However, the discovery of extraterrestrial sources of ultra high energy muon neutrinos that are at the same time emitters of high energy gamma rays would prove that the gamma rays are definitely of hadronic and not electromagnetic origin. Consequently, such objects would identify themselves unambiguously to be at the same time sources of high energy hadrons (protons and/or nuclei). Thus, for the first time we could point directly at sources of high energy hadrons, irrespective of the distance of the objects, since neutrinos are not subject to magnetic deflection like the bulk of the known primary radiation, which consists predominantly of charged hadrons.

Anisotropies occasionally claimed on the basis of air shower observations (Edge et al., 1978) are definitely of rather local character, even at high primary energies. This is evident from figure 2 which shows the radius of gyration of protons as a function of proton energy in a magnetic field of 3 μG.. This value represents probably a reasonable average for our galaxy.

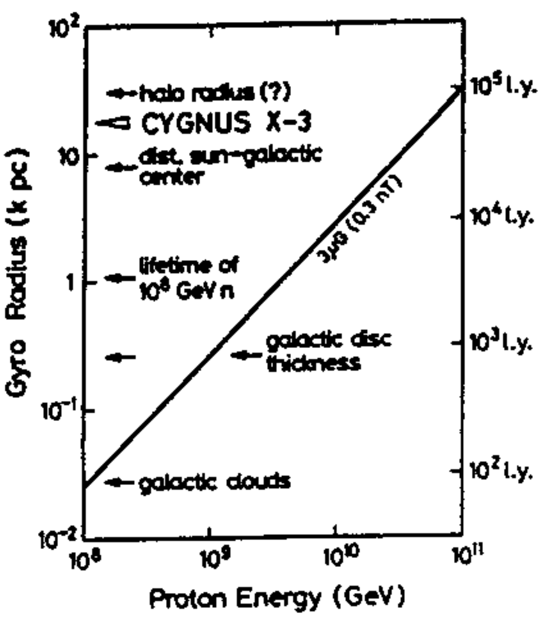


Figure 2: Radius of gyration of a proton in an average magnetic field of 3 μG versus proton energy. Astronomical landmarks are indicated for orientation. It is evident from this figure that source locations cannot be inferred from the arrival directions of the charged cosmic ray component with any reliability unless the sources are rather close. DUMAND, unlike gamma ray telescopes, will scan essentially the entire universe for potential high energy cosmic ray sources since high energy muon neutrinos identify locations of high energy hadronic processes.

Limited celestial scans in search of high energy extraterrestrial neutrino sources have been carried out with some of the new underground detectors (Alexeyev et al., 1981; Boliev et al., 1981; Cherry et al., 1981a; Battistoni et al., 1983; Losecco et al., 1985), unfortunately without much success.

One or several of the following reasons are probably responsible for the failure: The detector location was too shallow, the detector was too small or had an inadequate directional resolution. In the first case a large muon counting rate troubles the neutrino measurements (f. i. at Baksan, Chudakov 1983). On the other hand some of the smaller installations suffer from inadequate angular resolution combined with a low counting rate and, hence, poor statistics, thus obscuring faint extraterrestrial effects in a terrestrial neutrino dominated background. Theoretical estimates of the terrestrial (atmospheric) neutrino background have been carried out by various authors. For a summary of data see Allkofer and Grieder (1984).

2.3 High Energy Cosmic Ray Muon and Neutrino Physics, and Related Fields.

Some of the pertinent problems of cosmic ray physics at present are concerned with the exploration of the energy spectrum and chemical composition of the primary radiation at very high energies. At intermediate energies up to some 10 TeV, the primary spectrum had been deduced from the single muon spectrum at ground level using magnetic spectrometers (Erlykin et al., 1974; Allkofer et al., 1981; Thompson et al., 1977; Muraki et al., 1983), and from range-energy relations or burst size spectra obtained by the early underground experiments (Krishnaswamy et al., 1977; Crouch et al., 1978). At higher energies the data have been obtained exclusively from air shower studies.

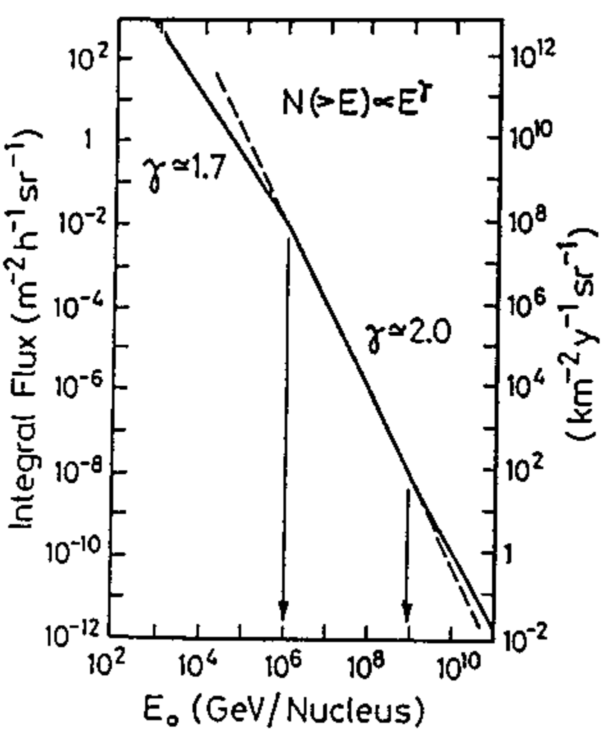


Figure 3: The currently accepted form of the integral primary cosmic ray spectrum. The cause for the two distinct changes of the slope is unknown. It could be a source, confinement, composition or interaction phenomenon.

Today the integral primary cosmic ray spectrum is known to exhibit two changes of slope. The first which goes gradually from about −1.7 to −2.0 occurs in the energy range between 100 TeV and a few times 10^3 TeV. The second change occurs in the vicinity of 10^6 TeV and brings the slope back to about the first value. It is not so well established as the first because of the much lower event rate. These features are illustrated in figure 3 which shows the all particle integral energy spectrum of the primary cosmic radiation as we know it today.

Of particular interest is at present the first change of slope, i. e., the one around a few hundred TeV. It is unclear, however, whether the differential spectrum gets simply steeper or manifests an enhanced intensity in this energy region, causing a short hump-like plateau in the integral spectrum as is emphasized in figure 4. The present data are inconclusive or even contradictory (Hillas, 1981, 1983).

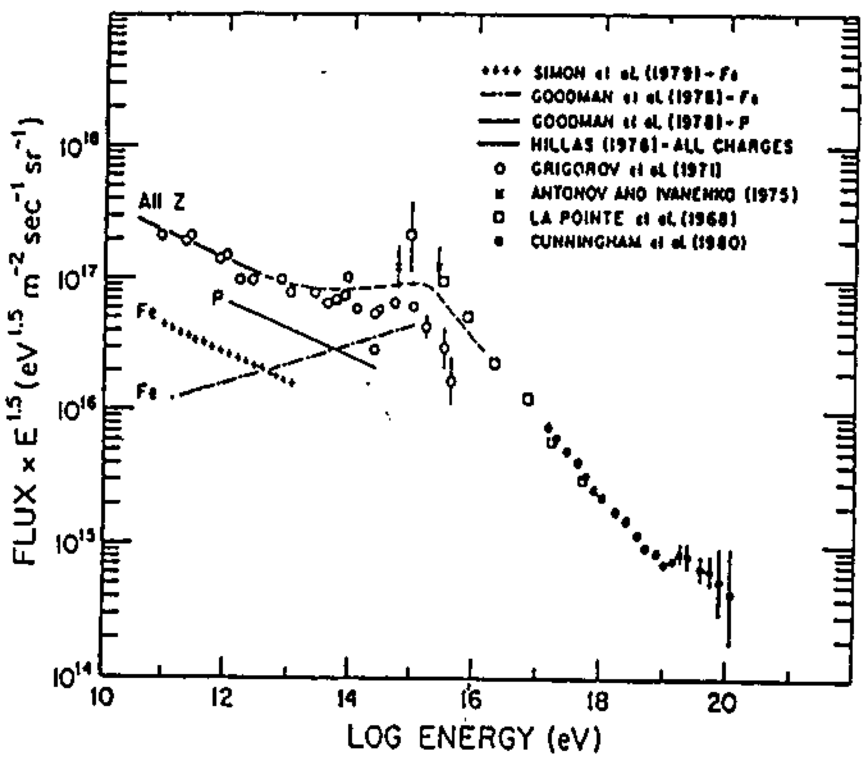


Figure 4: Shown is the integral energy spectrum of all particles and of two major constituents of the primary cosmic radiation arriving at the fringes of the earth's atmosphere, as deduced by direct and indirect methods. The latter are based on air shower observations in conjunction with model calculations. The iron group data are very controversial and need clarification urgently. High energy multiple muons offer an additional, independent method to solve the problem. But a very large detector such as DUMAND is needed.

A variety of reasons could provoke a change of slope of the primary spectrum at the earth's location in space (Peters, 1961):

a) A point source such as a pulsar or a supernova having its emission maximum at this energy.

b) A confinement phenomenon of our galaxy due to its own magnetic fields that cause a slow mass dependent cutoff, resulting from leakage of particles into intergalactic space.

c) Particular features of the spectral slopes of the different chemical constituents of the primary radiation, such as had been observed for iron at lower energies. (It had been noted that the energy spectrum of iron at energies below 1 TeV/nucleon shows a slightly lesser slope than that of protons (Simon et al., 1980). If this trend continues to 100 TeV and beyond, irregularities in the composite spectrum would be expected to occur in the crossover region).

d) A change in the nature of ultra high energy interactions.

The most recent direct measurements of the primary chemical composition extend to an energy of approximately 1 TeV/nucleon, however, with poor statistics (Abulova et al., 1981; Burnett et al., 1982, 1983). Individual nuclei have been detected to energies as high as 100 TeV. Data for higher energies have been derived from air shower observations, using a very indirect and rather controversial method (Goodman et al., 1979, 1982; Kempa and Wdowczyk, 1983; Grieder, 1984).

High energy muon experiments such as those that are being carried out deep underground offer a new approach to the problems outlined above which is essentially independent of the former method (Elbert, 1983). However, recent simulation calculations have shown that very large detector areas will be needed to distinguish proton from iron initiated showers reliably (Grieder, 1985).

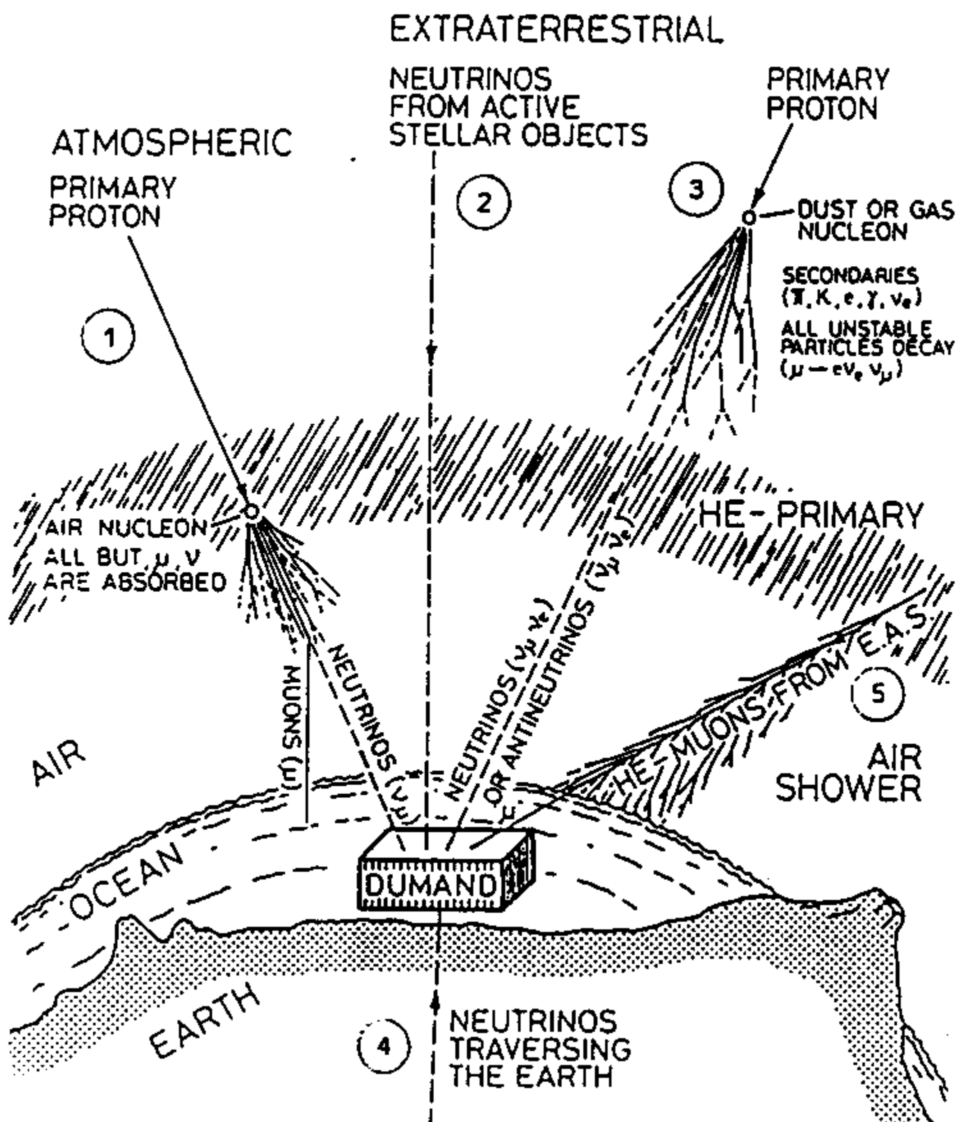
THE PRINCIPAL GOALS OF PRESENT UNDERGROUND MUON EXPERIMENTS CAN BE SUMMARIZED AS FOLLOWS:
Extension of the measurements of the cosmic ray muon spectrum to higher energies to investigate chiefly spectral features, but also anisotropies and time variations of the parent primary cosmic radiation in the energy range from about 10 TeV to over 10^5 TeV. Acquisition of data on multi-muon events to resolve the questions concerning the primary chemical composition in the energy region around 10^3 TeV where the slope of the primary spectrum changes. Studying of absorption and interaction features of high energy muons. Search for particular time sequences and hitherto unknown phenomena, such as those reported recently by several experimental groups concerning observations made in the direction of Cygnus X-3 (Marshak, 1984; Battistoni et al., 1985).

In some of the experiments listed in table I the topics mentioned above are studied as second priority tasks in conjunction with other first line objectives, such as for example proton decay. The present generation of underground muon and/or neutrino experiments cover a wide range of new topics, most of which remain inaccessible at ground level, in spite of the fact that so far none of the underground installations possesses a magnetic field.

The major problem which is common to all existing underground detectors is that they are by far too small. Their effective area is about two orders of magnitude too small to carry out reliable multiple muon measurements that can resolve the problem of the chemical composition of the primary radiation at high energies unambiguously. Moreover, their volumes are several orders of magnitude too small to detect energetic extraterrestrial neutrino sources of expected intensity, in spite of the relatively high angular resolution which some detectors have.

3. THE DUMAND SCENARIO AND ITS SCIENTIFIC OBJECTIVES.

The essentials of the muon and neutrino phenomenology of the DUMAND scenario are illustrated in figure 5. The principal scientific objectives of the project can be summarized as follows:



<u>Figure 5:</u> Muon and neutrino phenomenology. Shown are sources of terrestrial (atmospheric) (1) and extraterrestrial high energy neutrinos (2), (3), and of muons (5). Neutrinos of origin (1) produce an omnidirectional background in DUMAND (4); (2) and (3) show up as point and diffuse sources, respectively. Neutrinos from all directions are detectable (4), atmospheric muons (5) only within 70° of the zenith. DUMAND responds to muon and not electron neutrinos.

i) HIGH ENERGY NEUTRINO ASTROPHYSICS AND ASTRONOMY:
Search for and hopefully discover and explore extraterrestrial high energy muon neutrino sources. Determine neutrino intensity and slope of the spectrum. Correlate the neutrino intensity with that of high energy gamma rays, provided that the same object emits radiation of either kind. Identify likely locations of high energy cosmic ray sources, such as Cygnus X-3, the Crab Nebula and other objects.

ii) COSMIC RAY PHYSICS BETWEEN 10 AND 10^6 TeV:
Study cosmic ray muons of energy $\geq$ 3 TeV, their production, interaction, spectral index and arrival directions; look for local anisotropies. Derive primary spectrum and chemical composition in the range between 10 and 10^6 TeV. Study high energy hadronic interactions through muons and multiple muons.

iii) MUON AND NEUTRINO PHYSICS BEYOND SUPER COLLIDERS:
Analyze muonic neutrino and antineutrino reactions at energies well beyond the range of present and future accelerators. Search for new effects and new heavy flavor particles, neutrino oscillations, high transverse momenta, Rubakov type magnetic monopoles, and Cygnus X-3 like events.

Obviously, DUMAND and its support system make it possible to carry out a wide variety of research projects in other fields, such as oceanography, geophysics, climatology, environmental sciences as well as ocean biology, on the side.

4. DETECTOR SYSTEM, MODULES AND LAYOUT.

The detector system is shown in figure 6. It consists of 6 by 6 so-called strings which have orthogonal separations of 50 meters between neighbors. Each string has 21 highly sophisticated optical detector modules, separated 25 meters from each other.

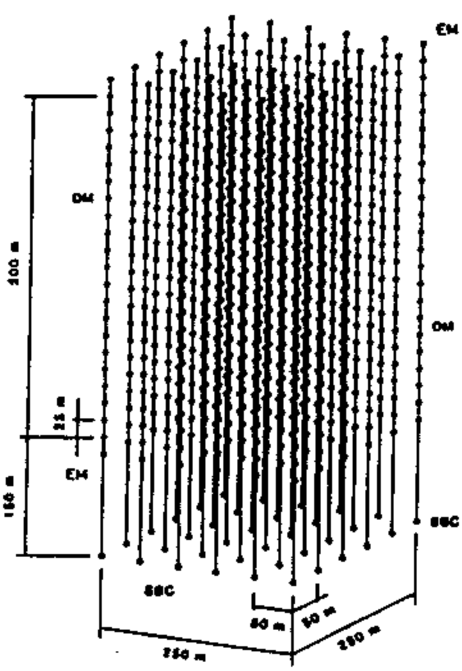


Figure 6: The DUMAND array. Shoun is the three- dimensional matrix with its 6•6•21 (756) Cerenkov detector modules (DM), the 108 environmental modules (EM) (36 each on top, at the lower end of the array and one horizontal plane in the center) that record all of the relevant environmental parameters and serve to locate the position of the detector modules accurately, using sonar techniques. Also shown are the string bottom controllers (SBC) at the end of each string on the sea floor. The latter are special custom made computer for data and command handling.

On top, at the bottom and in the center of each string will be an environmental module to record all significant environmental parameters. In addition these modules house sonar devices that allow to determine the string positions accurately at all times. The latter is needed for event reconstruction.

The bottom plane of the huge matrix will be suspended about 150 meters from the sea floor to avoid problems with bioluminescent animals or murky water on or near the ground.

The lower end of each string terminates at the string bottom controller which will be anchored to the sea floor. The purpose of this unit is to handle the data flow from all the modules on a string to shore, whereby the data from one row (6 strings) are further packed and sent to shore at a very high rate, using a single mono-mode optical fiber. Thus a total of six fibers will be needed to link the entire matrix to the shore station. Multi-mode optical links are used for the shorter distances between the detector modules and the string bottom controllers.

Additional tasks of the string bottom controllers are to perform logic functions (set specific coincidences between modules, etc.) and to handle, convert and transmit commands and data that are sent from shore to the matrix for controlling the operation of each detector module individually. Figure 7 shows the block diagram of the data flow from the modules to the shore station.

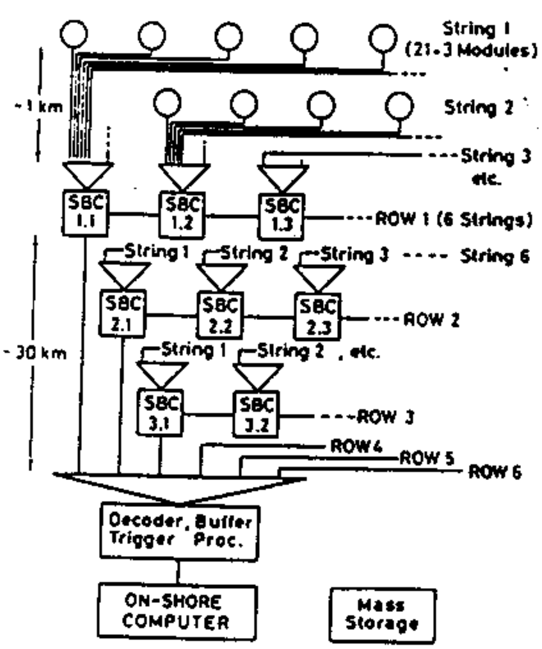


Figure 7: Block diagram showing data flow. All links shown are optical fibers. Modules can all be controlled individually from shore station (discriminator level, high voltage, operating mode, etc.) via slow command link riding on power lines.

The optical sensor modules consist of special 16 inch photomultiplier tubes that are mounted inside a 17 inch Benthos glass pressure housing. The phototubes can accept light from all directions but exhibit a somewhat reduced sensitivity for light from the backward direction. The associated electronics, including the high voltage power supply, discriminator, electro-optic converter, modem, processor and control circuits, are located around the tube neck, as shown in figure 8.

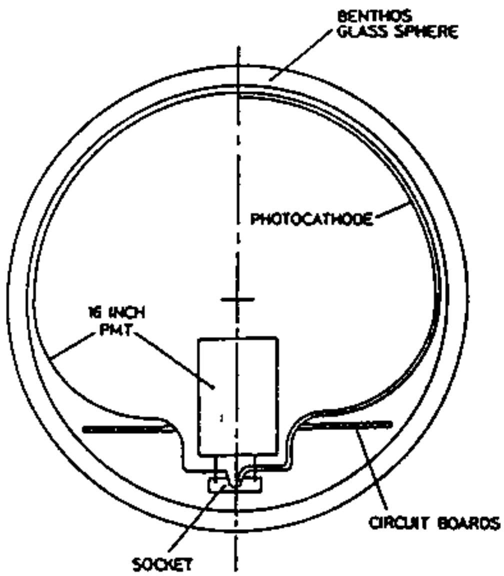


Figure 8: Cross sectional view of detector module. Shown is the photomultiplier with its photocathode coating (Hamamatsu special DUMAND tube), multiplier system and socket, mounted inside the 17" Benthos glass pressure housing. The print-boards which hold power converter, modem, a/d and d/a converters as well as processor and memory are placed around tube neck.

5. OVERALL SYSTEM CAPABILITIES AND EXPECTED COUNTING RATES.

The enclosed mass of the DUMAND detector system will be 33 megatons. This is more than 3000 times larger than that of the largest now existing underground detector. Its effective mass for detecting neutrinos of energy $\geq$ 2 TeV is almost 0.5 gigatons. This includes events that originate in the volume outside the array and produce a reconstructable muon trajectory in the array. The angular resolution for the muon trajectories depends on the angle of incidence and on the length of a trajectory within the matrix. For full traversals it varies from 15 to 45 milliradians.

5.1 Cosmic Ray Muons.

The energy threshold for vertically incident atmospherically produced muons to reach the array is about 3.5 TeV. The expected counting rate for muons of energy larger than 1 TeV at the detector level is expected to be over 1000 events per hour without applying angular cuts, and approximately a factor of ten less for those events that penetrate the top and bottom planes of the full matrix.

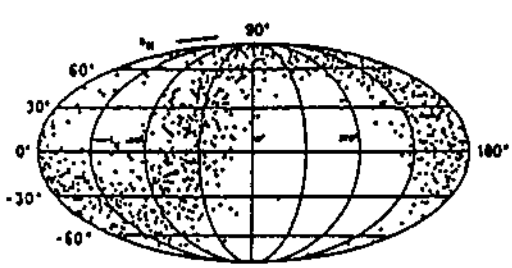


Figure 9: DUMAND cosmic ray response. Distribution in galactic coordinates of the source directions of 1000 randomly generated cosmic ray events of energy 10^8 GeV. Such events can be seen only within 70° of the zenith because of the rapid absorption of the muons in the deep ocean at large zenith angles.

Because of the rapidly increasing absorption of even very energetic muons in the ocean with increasing zenith angle, atmospherically produced cosmic ray muon events in DUMAND can only be accepted within a zenith angle of 70°. The projection of this cone of acceptance on the celestial sphere is shown in figure 9 above.

The fast rising energy loss of highly relativistic muons due to bremsstrahlung, as shown in figure 10 below, will be used by DUMAND for a rough energy determination.

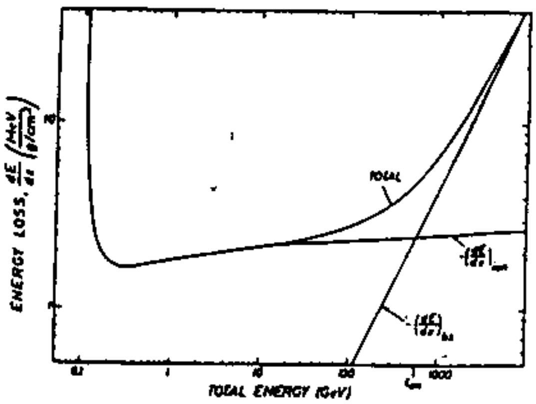


Figure 10: Energy loss of muons in matter. Shown is the composite energy loss due to ionization and bremsstrahlung as a function of energy. The steep rise beyond 500 GeV is due to muon bremsstrahlung and will be used for muon energy determination in DUMAND. Cerenkov radiation represents a negligible energy loss.

5.2 Terrestrial Neutrinos.

Charged current muon neutrino event rates due to terrestrial (atmospheric) neutrinos have been calculated for the DUMAND array. It is expected that the system will record a total of about 10^4 events per year due to neutrinos of energy ≥ 1 TeV. This rate is more than two orders of magnitude larger than that recorded by the IMB detector. An estimated 3000 events will occur that produce a recordable muon of energy ≥ 1 TeV. This includes events that originate in and outside the array.

5.3 Extraterrestrial Neutrinos.

The sensitivity of the detector matrix to extraterrestrial neutrino sources can be expressed in terms of the minimum detectable flux. The latter depends crucially on the atmospheric neutrino background. The minimum detectable flux for extraterrestrial neutrinos has been defined as a 4.5 σ effect over the general cosmic ray induced (atmospheric) neutrino background. Under the assumption that the neutrino spectrum has a slope of −1.5, a value of $2 \cdot 10^{-10}$ events/cm²s was obtained for the minimum detectable flux of neutrinos of energy ≥1 TeV. If background is less than one event per year the minimum detectable flux is defined to be that flux which yields ten events per year.

The dependence of the minimum detectable flux on neutrino energy is shown in figure 11a for discrete and diffuse sources. Its dependence on the slope of the spectrum is given in figure 11b. Enlarging the matrix by a factor of three does not significantly increase the array sensitivity because of its much larger effective volume and the relatively high neutrino energy for which the array had been optimized.

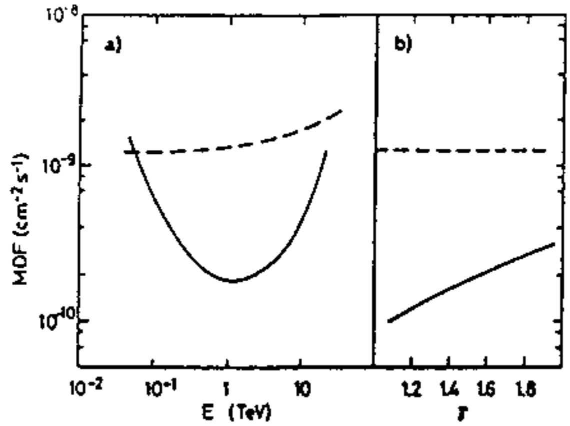


Figure 11: Minimum detectable flux (MDF) for both discrete (solid curves) and diffuse (dashed curves) sources of extraterrestrial muon neutrinos as a function of a) threshold energy E and, b) integral spectral index. For the diffuse source an apparent region of 20 deg. by 70 deg. was assumed. In b) the value of E is the optimum in each case.

Note that in principle the DUMAND detector system covers the full 4π steradians of the celestial sphere. However, because of the temporary obscuration of areas near the zenith by cosmic ray muons, the previously mentioned 70° cone about the zenith that will be used for recording cosmic ray muons must be ignored for extraterrestrial neutrino work. Consequently, for an isotropic distribution of sources in the sky, the experimentally recorded distribution will be complete but non-uniform, as shown below.

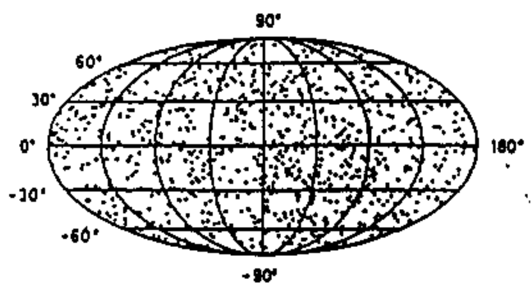


Figure 12: The DUMAND neutrino response. Shown is the distribution in galactic coordinates of 1000 randomly simulated atmospheric neutrino events. The distribution is complete but not uniform because of the temporary obscuration of areas near the zenith by cosmic ray muons (see figure 9 above).

Calculations based on a one-step process (no cascading) have been carried out by Stenger (1984) to estimate the neutrino flux from potential sources. The results are shown in figure 13. Points on or above the diagonal line marked DUMAND are detectable. These data must be considered as very conservative, they represent a lower limit for the expected neutrino fluxes.

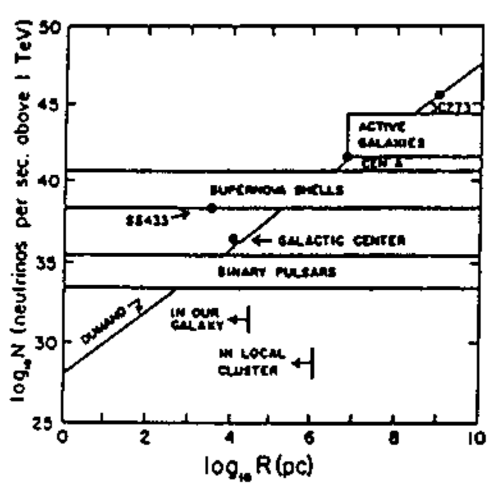


Figure 13: Extraterrestrial source detection capability of the DUMAND array. Shown is the source intensity in neutrinos per second above 1 TeV versus distance R in parsec. The bands indicate the range of different source types. The points are specific sources and represent lower limits. Anything above the diagonal line is detectable.

6. THE DUMAND SITE.

6.1 Location, Topography and Site Parameters.

The location of the DUMAND site is indicated on the map shown in figure 14. The site where the detector matrix will be installed has been surveyed several times in the past jointly by scientists from different institutions, including the Hawaii Institute of Geophysics, Scripps Institute of Oceanography and members of the DUMAND collaboration. However, some more surveying will be needed prior to the deployment of the final matrix.

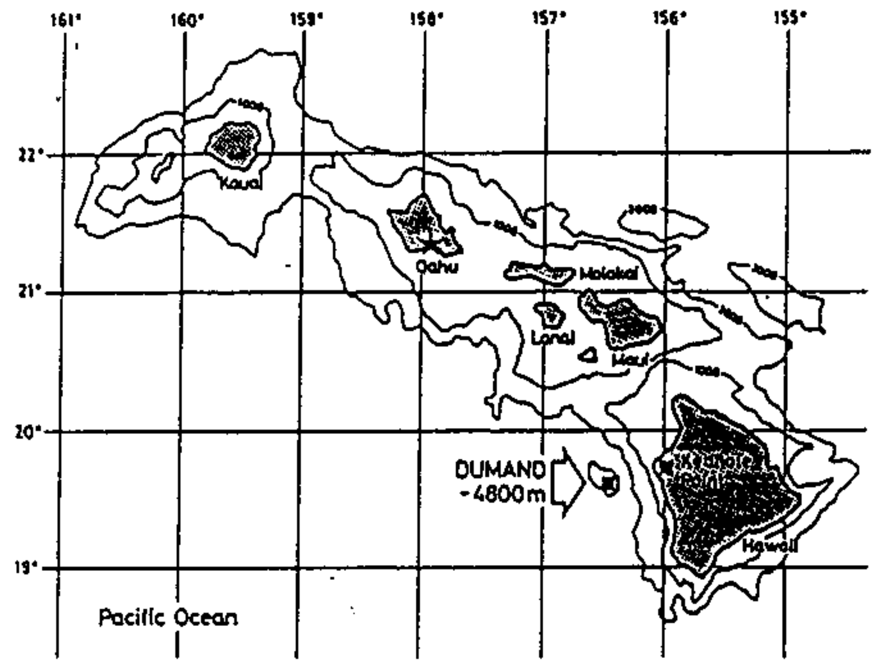


Figure 14: The Hawaiian islands. The DUMAND site is located about 25 km off-shore, west of Keahole Point on the "Big Island", as indicated. The Hawaii DUMAND Center located at the University of Hawaii at Manoa in Honolulu on Oahu is also shown.

Most of the significant ocean parameters are known around a depth of 4500 meters where the array will be installed, such as the composition and topography of the sea floor. Figure 15 shows an example of a sonar depth profile taken at the DUMAND site.

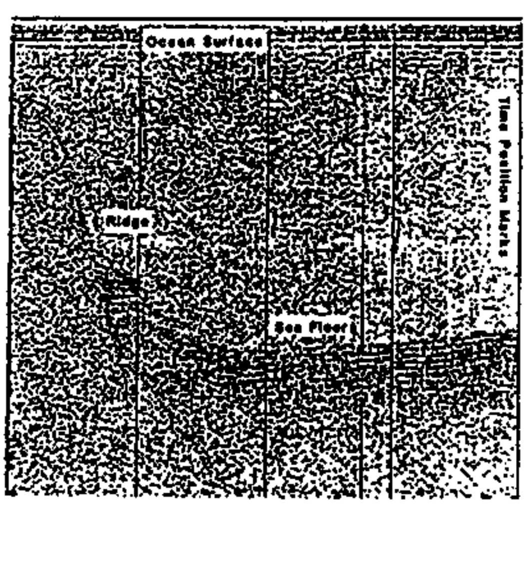


Figure 15: Sonar depth profile. Shown is an example of a sonar or seismic depth profile, recorded on board the research vessel Kana Keoki of the Hawaii Institute of Geophysics during a cruise over the DUMAND site.

In addition the deep ocean currents (≲ 5 cm sec^{-1}), the water temperature (+1.5 °C) and above all the optical attenuation in the visible range are also known. The latter is shown in figure 16. It is evident that the attenuation length is an important design parameter for the array.

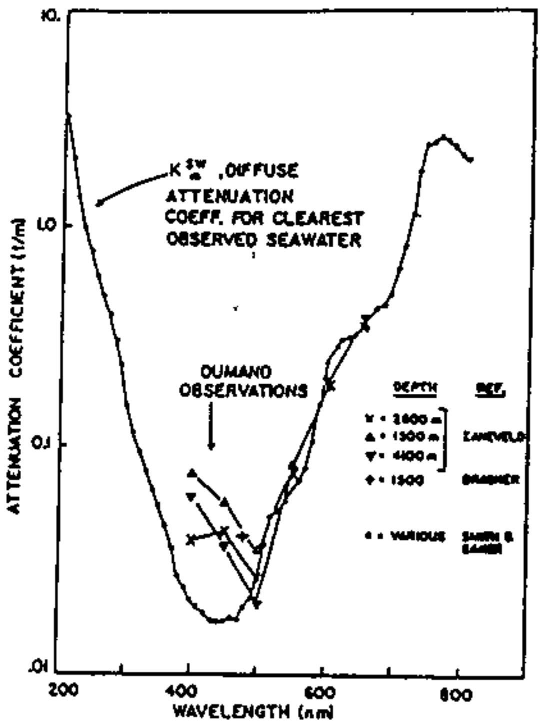


Figure 16: Attenuation coefficient of light in the ocean in the visual and near visual region at different depths in the vicinity of the Hawaii DUMAND site.

6.2 Environmental Problems and Background.

The optical background problem has also been investigated carefully. It is chiefly due to bioluminescence and Cerenkov light from potassium 40 radioactivity. The latter causes a counting rate of approximately 10^5 counts per second at the one photo electron level in a submerged module, which is no problem to handle.

Bioluminescence has initially been considered to be a very serious problem. However, the high light levels observed during ship tethered measurements which showed typical bioluminescence characteristics were mostly due to stimulated bioluminescence. This was caused primarily by the ship's motion that was transmitted via suspension cable to the detector module which stirred the surrounding water masses. Subsequently the local turbulence caused the bacteria in the water to release light flashes, thus producing the high background.

New measurements which included ship as well as bottom tethered detectors have shown that the latter records a bioluminescence level which is at least one order of magnitude or more lower than that recorded by a ship tethered detector. This is illustrated in figure 17. Thus, the bioluminescence level seen by a bottom tethered detector working under conditions similar to those of the final DUMAND array is of the same order as that caused by potassium 40.

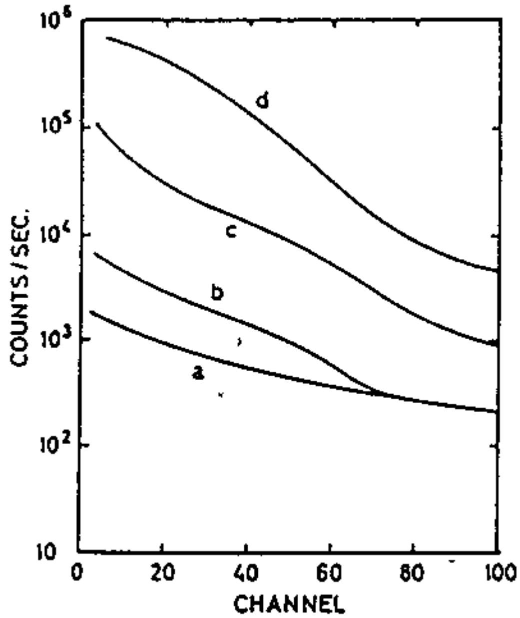


Figure 17: Optical background measurements with photomultiplier assembly in 17" Benthos glass pressure housing taken under following conditions: a) In cold dark room. b) bottom tethered at 4700 m. c) and d) ship tethered at 4500 and 2500 m, respectively, in the ocean at DUMAND site. c) and d) show increasing levels of stimulated bioluminescence from bacteria. b) represents almost exclusively Cerenkov flashes from K40 radioactivity in ocean.

Sedimentation is not expected to be a problem, it is known to be very small in this area. The frequent volcanic eruptions do not cause dust fall-out, only very local lava flows that cannot interfere with the array.

Biofouling is another topic that could cause problems. However, equipment recovered recently after having been on the sea floor near the DUMAND site for 18 months showed no signs of biofouling.

7. PROJECT SCHEDULE AND CURRENT STATUS.

7.1 The DUMAND Collaboration and its Long Range Program.

DUMAND has been planned and will be constructed within the frame of the International DUMAND Collaboration which includes scientists from the following institutions (The names of the respective representatives that form the "International DUMAND Council" are listed in parenthesis):

University of Hawaii (V. Peterson, V. Stenger, J. Learned)
University of California, Irvine (W. Kropp)
California Institute of Technology (B. Barish)
Purdue University (J. Gaidos)
University of Wisconsin (R. March)
Vanderbilt University (C. Roos)
University of Tokyo (T. Kitamura)
University of Bern (P. Grieder)

Coordination of the project is being directed by the Hawaii DUMAND Center (HDC), located at the University of Hawaii at Manoa, under the supervision of Prof. V. Z. Peterson.

The feasibility study for DUMAND had been completed towards the end of 1982 together with the proposal for the full project. Simultaneously much of the development and design work for the detector modules has been well under way at that time and is now completed. Originally the entire project had been subdivided into five stages as listed below.

Stage 1). Construction of a short prototype string (SPS) with 7 modules, including one simplified string bottom controller (SBC) for data handling and one environmental module (EM) for recording environmental parameters, to test the final design. Initially, the SPS will be operated at variable depth from a special ship, the SSP Kaimalino, a stable, semi submersible platform. Later on it will be placed on the sea floor at the final site, linked to shore and operated for a period of some months to study system performance and environmental effects, including sedimentation and biofouling.

Stage 2). Construction and deployment at the final DUMAND site of a full prototype string (FPS), consisting of 21 detector modules and 3 environmental modules. (Later on provisions will be made that some of the environmental modules can house small ocean and earth science experiments). Some of the environmental modules will house pingers to locate the string, and later on the array and its modules accurately by means of sonar techniques. The string will be linked to shore and operated during the construction phase of stage 3.

Stage 3). Construction and deployment of the first plane of detectors, consisting of 6 full strings of the type used for the FPS of stage 2, at the final site. The plane will be linked to shore and put into full operation.

Stage 4). Construction, deployment and linking to shore of the remaining 5 detector planes.

Stage 5). Running-in and operation of the full array.

All five stages listed above are intended to be used for scientific work and even the early stages are expected to yield valuable new data. The transition from one stage to the next is expected to proceed more and more continuous as the project advances. At present stage 1 is funded by American and Japanese agencies. It must be completed successfully to obtain the go-ahead for stage 2.

7.2 The Short Prototype String.

The layout of the short prototype string (SPS) is illustrated in figure 18a, below. It consists of 7 optical detector modules (DM), one environmental module (EM), two calibration modules (CM) and a power and control unit (PCU), which fulfills in a limited sense the functions the the very elaborate string bottom controller (SBC) of the final array.

The purpose of the SPS is to give the prototype system a thorough "in situ" engineering test. This implies in particular testing the performance of the following components and subsystems: The optical sensors, the data handling and command software of the module processor, the electro - optical data link including the control, communication and power systems, module calibration, and all aspects of the environmental module. Furthermore it is intended to demonstrate muon counting in the deep ocean, check background and determine a number of environmental parameters.

The separation of the modules is 5 meters as compared to the 25 meters in the final array. This much shorter module separation was chosen for a number of reasons. In particular to subtend a larger solid angle for muon detection and to facilitate module calibration and water transparency measurements.

For the ship tethered tests the SPS will be suspended from a stable ship as mentioned above. This will greatly reduce the hazards at sea and simplify operations during deployment and while carrying out the measurements. It will also strongly reduce stimulated bioluminescence background, as mentioned above.

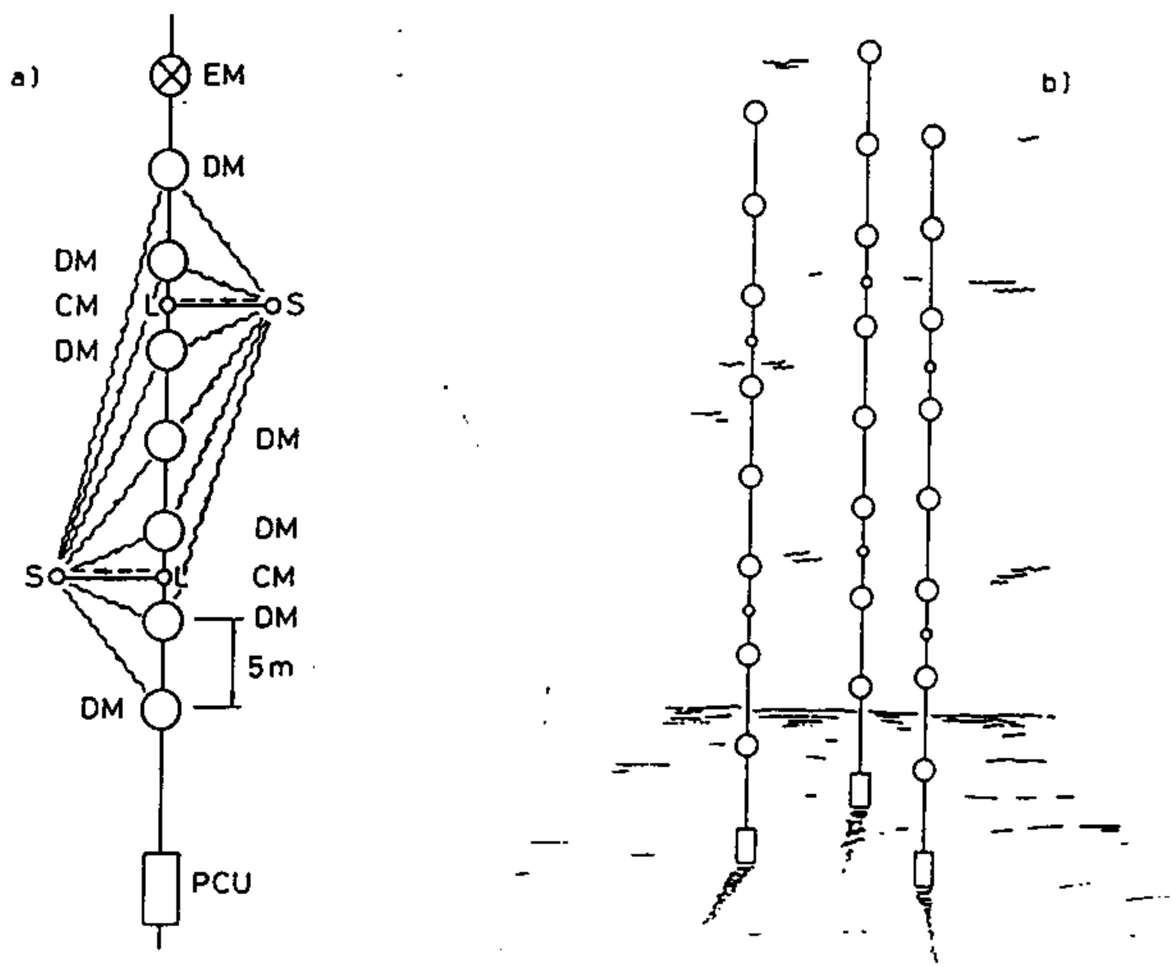


Figure 18: The short prototype string (SPS) with its detector modules (DM), two calibration modules (CM) with the light source (L) and the scatterer (S), an environmental module (EM), and the power and control unit (PCU) are shown in figure a). Command and data handling hard and software permit full flexibility for individual and joint operation of all subsystems. Figure b) shows the triad which consists essentially of 3 short prototype strings.

7.3 The Immediate Future.

In order to obtain as soon as possible scientifically relevant data from even the early phases of the DUMAND project, the collaboration plans as a next intermediate step after the successful completion of the SPS test phase, and before the systematic build-up of the full array, to construct, submerge and operate a so-called triad. The layout is shown in figure 18b above. The latter will consist essentially of three SPSs with a somewhat enlarged vertical spacing between modules. The strings will be arranged in an equilateral triangular geometry, as shown in figure 18b, having typical string spacing of about 25 m.

This detector system has an effective area of approximately 3000 m^2 and a solid angle resolution of roughly 10 msr. The triad which requires a muon energy of only 25 GeV at the detector level should be able to record neutrinos from powerful sources, such as are expected in LMC X-4 and other objects.

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