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OCEAN TECHNOLOGY EMPLOYED BY THE DUMAND PROJECT

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Abstract

The ocean technology involved in the Deep Underwater Muon and Neutrino Detection (DUMAND) experiment, located in Hawaii at Keahole Point, is discussed. DUMAND is a particle astrophysics experiment, whose goal is to detect and study sources of high energy neutrinos and other highly penetrating particles. These are detected by means of the light produced by Cerenkov radiation from charged particles in seawater. The detector is situated in the deep ocean (4800 m) to shield it from cosmic ray backgrounds and utilize seawater as both target and detection medium. Highly sensitive optical modules, containing photomultipliers capable of detecting single photons, arrayed on vertical strings are deployed throughout a volume of two million cubic meters. Rejection of natural background light (from K-40 and bioluminescence) requires very fast (ns) coincidence techniques. This paper describes new or unusual aspects of the ocean technology required to deploy, power, control, and acquire data from this undersea array.

The DUMAND Experiment

The scientific goal of the DUMAND (Deep Underwater Muon and Neutrino Detection) experiment is to search for and study the properties of astrophysical sources of very high energy neutrinos believed to be produced where huge amounts of gravitational energy are converted into radiation. The DUMAND-II detector can be considered to be an omni-directional neutrino telescope. Neutrinos (neutral, massless particles with extremely weak interaction with matter) can penetrate the earth with ease. DUMAND uses 4.5 km of water above the array a shield. The deep underwater location of DUMAND greatly reduces the background flux of muons resulting from the interaction of cosmic rays in the atmosphere. Figure 1 illustrates this concept.

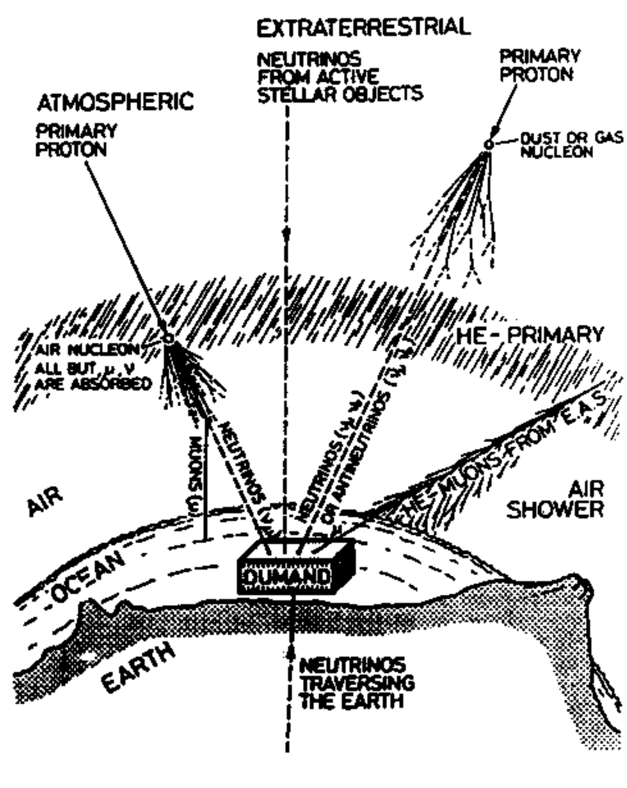

Figure 1. Neutrino detection by DUMAND

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Neutrino astronomy has been the dream of a small group of particle physicists worldwide for several decades, and is now beginning to be realised in the case of low energy solar neutrinos. Previous neutrino experimenters went underground in mines to shield their detectors from cosmic rays, but this limits a detector's size. A comparable DUMAND effort exists at Lake Baikal in the Soviet Union, where detector strings are deployed by cutting holes in the thick winter ice.

The signature of a neutrino interacting within or near the DUMAND detector is a long, straight muon from a direction anywhere in the range from 20° above the equator to straight up through the center of the earth. The muons track is defined by a space-time correlated series of straight-line fast pulses from photomultiplier tubes (PMTs) which respond to the Cerenkov radiation emitted by relativistic muons (charged particles) in water. Space-time coincidence techniques enable us to select muons from the otherwise overwhelming ambient light background from K-40 beta-radioactivity and bioluminescence in seawater. These coincidence techniques, widely used in experimental particle physics at accelerators, enable us to reject random noise backgrounds by factors of 10^8 or greater.

Array configuration:

The basic design of the DUMAND-II array employs 216 PMT-based optical modules (OMs) at known positions throughout a cylindrical volume 240 meters high and 105 meters in diameter. Nine vertical strings, each string linking 24 buoyant optical modules, will be tethered to the ocean bottom, as shown in Figure 2:

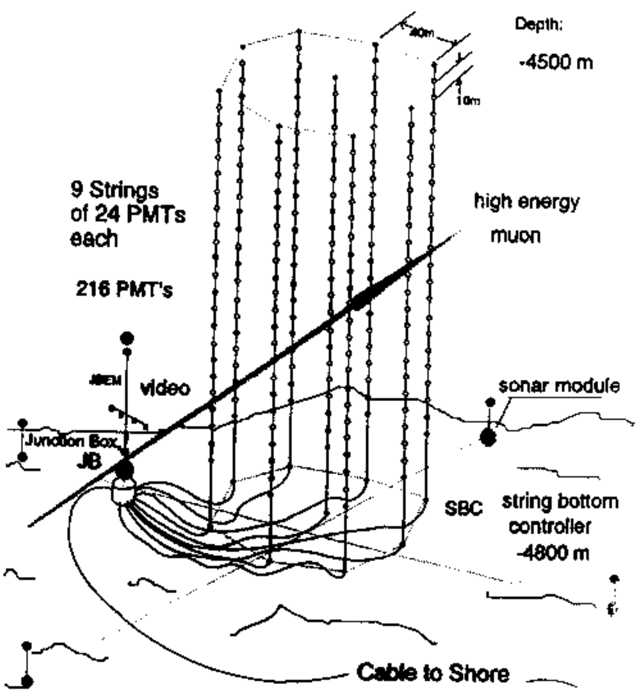


Figure 2. DUMAND-II Array, string configuration

The spacing between strings (40 m) and modules along each string (10 m) are optimised to achieve maximum effective area for the detection of through-going muons. The precise location of each OM will be continually determined by acoustic ranging. Given the spatial location of each OM, and the time (within 1 nanosecond) of each photon-induced OM pulse, tracks through the array can be constructed. Data from each string's OMs are transmitted to the String Controllers located at the center of each string, where they are digitised and transmitted via optical fibers to shore-based computers. Once on shore, the data are further filtered and analysed. A fast Trigger Processor on shore reduces the fraction of background events. Software track reconstruction off-line further reduces the background and reconstructs muon tracks.

The location chosen for the DUMAND experiments is at Keahole Point, the western-most point on the Big Island of Hawaii. A sketch of the DUMAND-II array location is shown in Figure 3:

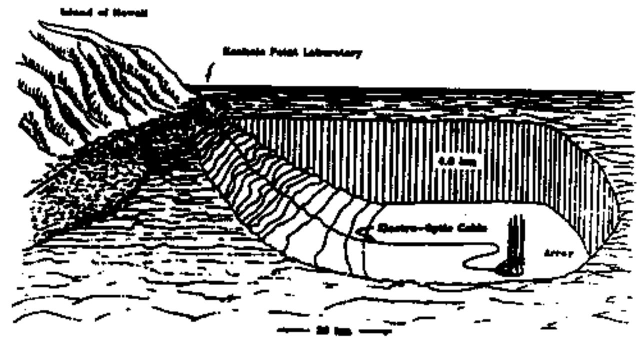


Figure 3. DUMAND-II located off Keahole Point.

Two major advantages of this tropical volcanic island location are: deep, clear water close to shore; and a near-Equator site which enables DUMAND to view (through the Earth) almost the full solid angle of the heavens. DUMAND is sensitive to neutrino-produced muons over about 2.4 steradians of solid angle at any given time.

DUMAND-I: Technical Feasibility Study

From the beginning, it was clear that DUMAND would be a major project, involving major costs. Thus the peer review of our initial DUMAND proposal [1] for DUMAND-I, in competition with related proposals, was very thorough. The scientific goals were accepted; the main problems were doubts about technical feasibility. Thus our major task was to show that modern Ocean Technology has made it possible to overcome the perceived difficulties.

The concerns expressed during peer review included: the hostile environment of the deep ocean; the relative inaccessibility of the equipment for repair and maintenance; and the difficulty of remotely operating delicate and sophisticated equipment at the seafloor. Thus in 1983 the Committee proposed that the DUMAND team first perform a preliminary "technical feasibility" experiment (labelled DUMAND-I) to demonstrate that the ocean technology problems could be overcome and reasonable experimental results could be obtained. We were challenged to assemble and deploy a single string of DUMAND-sensors and demonstrate technical feasibility by measuring the flux and angular distribution of ordinary cosmic ray penetrating particles (muons), all at the proposed site.

The feasibility study involved developing our present basic optical sensor, based on large, spherical phototubes with fast response time. It also required developing a new type of electro-optic undersea cable to deliver power to the optical detectors and transmit data back to ship/shore. We also had to design compact pulse digitising circuits to be housed within the optical modules, and develop the command/control techniques for remote control of the equipment from ship/shore. The result was working hardware [2] which was operated from shipboard on a number of cruises.

The basic sensor unit for DUMAND-I, based on a large, spherical photomultiplier tube (PMT) developed by Hamamatsu Corporation in Japan, is shown in Figure 4 (see Reference [1]):

The specially-designed PMT (O.D.= 38 cm) fits comfortably within the 16-inch (ID) Benthos glass pressure sphere (two glass hemispheres). A flexible silicone layer mechanically buffers and optically couples the PMT to the sphere. (In the DUMAND-II version a mesh of mu-metal magnetic shielding imbedded in the silicone reduces the effect of the Earth's magnetic field on PMT electron focussing.) The angular sensitivity of each optical sensor was measured in a water tank.

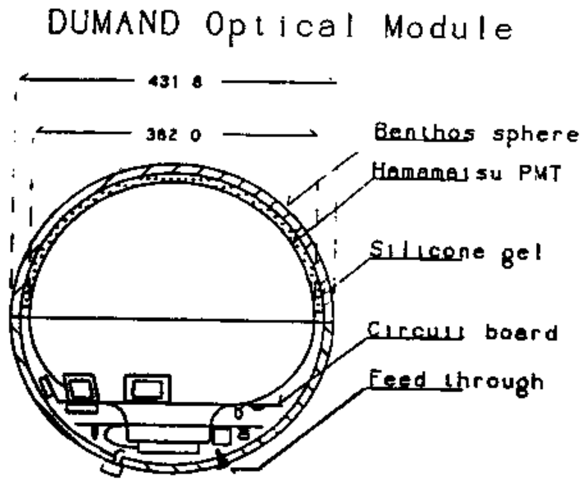


Figure 4. DUMAND-I Optical Module

In DUMAND-II an alternative PMT (made by Philips Corp. in Europe) is planned to be used along with the Hamamatsu OM. Each PMT has its own advantages, but both have excellent time resolution.

Besides the PMT, each optical module contains the HV DC power supply for the PMT and the integrated circuit electronics to generate a pulse-width modulated signal which provides time-over threshold (integrated charge) for each PMT pulse. An electro-optic interface circuit transmits the output data down the string to the String Controller via multimode fiber optics. This electronics is all mounted on a circuit board which surrounds the tube base.

The optical modules are mounted with the PMTs facing downward in DUMAND-II (upward in DUMAND-I), optimising the sensitivity for muons from up-going neutrinos. Thus the circuit board obscuration in the backward direction is not serious.

The glass pressure housing sustains a pressure differential of about 500 atmospheres at 4800 m depth, so that leak-tight electrical and fiberoptic penetrators are especially important. In DUMAND-I we were able to use commercial electrical feedthroughs, but had to develop our own fiberoptic penetrator. For DUMAND-II the Swiss firm DIAMOND SA has developed a very satisfactory fiberoptic penetrator.

In DUMAND-I a String Bottom Controller (SBC) provided the main deep ocean electronics center for (a) distributing fixed-voltage DC power to all OMs, (b) providing OM command-and-control functions, (c) digitising the OM pulsed data, and (d) converting parallel inputs into a single serial output for transmission via monomode fiber to the ship data acquisition center.

The data acquisition center in DUMAND-I was onboard the Navy ship SSP KAIMALINO, a SWATH-type twin (submerged) hull stable platform which proved ideal for this experiment. The high stability of the KAIMALINO, and an on-deck motion compensating system, enabled our team to simply deploy the test string through the center well without major difficulty, even in moderately heavy seas. Figure 5 is a sketch of the DUMAND-I string of 7 OMs (plus optical calibration modules and String Bottom Controller) suspended below the KAIMALINO.

It is worthwhile noting that the contra-helix armored electro-optic cable, designed by George Wilkins, was only 7.9 mm. in diameter, yet was strong enough to be used to deploy the DUMAND-I string. It also delivered 2 KW of electrical power and transmitted fiberoptic signals at 50 Mbd.

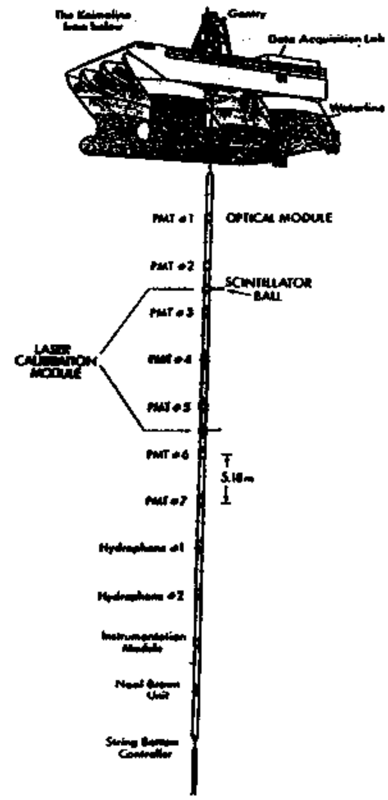


Figure 5: Prototype string suspended from KAIMALINO

A high ambient photon flux, due to radioactivity and bioluminescence, exists at all depths in the ocean. This background flux is much greater than the Cerenkov photon flux from cosmic ray muons. For example, each PMT in DUMAND-I had a background counting rate (single photoelectron threshold) of about 50,000 counts/sec. For comparison, our signal of detected cosmic ray muons was only about one event per 15 to 60 seconds (2 to 4 km depth). Background rejection and signal event signature was required in both on-line adjacent-PMT pulse association and off-line space-time correlation criteria. By demanding ≥ 5-fold space-time coincidences, we were able to reduce the random coincidence background to levels below the muon signal.

Stimulated bioluminescence (due to ship motion) was easily detected during DUMAND-I, and produced several times the K-40 radioactivity single-PMT counting rate. However, the coincidence requirement effectively eliminated this background.

The results of the DUMAND-I experiment, have been published in the Physical Review [3] in an article entitled "Cosmic Rays in the Deep Ocean." Different parts of this work were subjects of three PhD theses [4].

DUMAND-II: Multi-String Array under Construction

The successful completion of the Technical Feasibility Study (DUMAND-I) led to a new proposal [5] to construct a sufficiently large array of strings to have a high probability of detecting the most intense predicted neutrino point sources; i.e., those associated with well documented X-ray sources such as Cygnus X-3 and LMC X-4 which have also been reported to emit very high energy gamma-rays. A popular theoretical model explaining high-energy gamma-rays from such X-ray emitters would also predict high-energy neutrinos [5]. Computer simulations led to a decision to propose, as DUMAND-II, an array of 9 strings (24 OMs per string, or 216 total OMs). The projected area of this array is 20,000 m^2, roughly independent of direction. Neutrino-produced muons originating anywhere within the range of the muon, which traverse the instrumented volume, will be detected. The increasing range of muons with energy, multiplied by the increasing probability of neutrino interaction with energy, approximately compensates for the predicted decreasing energy spectrum of neutrino flux. Thus the signal rate is nearly constant as a function of neutrino energy, but the signal/background ratio improves since the background decreases with neutrino energy. Our calculations show that we can expect to detect 10 to 50 events/year, for neutrino events above 1 TeV, from each of the most intense sources. If successful, DUMAND-II would truly open a "new window on the Universe," as one enthusiast has stated.

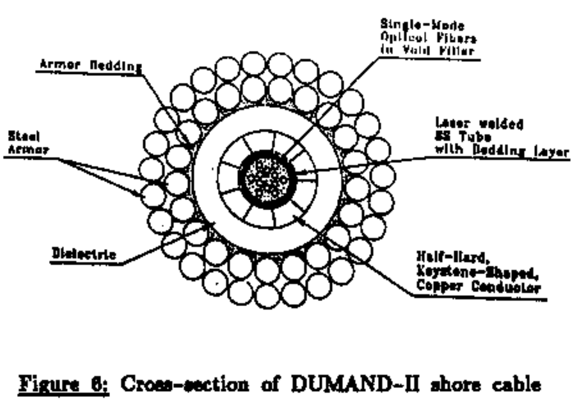
The DUMAND-II proposal was prepared by a slightly different international collaboration of physics groups and was submitted for consideration by USA (Department of Energy and National Science Foundation) and foreign (Japan, Germany, Switzerland) authorities in July 1988 [5]. The University of Hawaii continues to be the lead group, with management of the enterprise in the hands of the Hawaii DUMAND Center (part of the UHM High Energy Physics group).

In February 1989 the High Energy Physics Advisory Panel (HEPAP) convened a subpanel to review this DUMAND-II proposal. Of the three related cosmic ray proposals presented, DUMAND-II was the only project recommended. After over a year of further reviews (including a detailed Technical/Cost review in Honolulu) DOE agreed to commit its share ($4.8 Million) towards construction costs. Other collaborators have achieved full or partial success with their respective agencies. Thus by April 1990 the DUMAND-II Construction project was formally launched.

The new Ocean Technology features of DUMAND-II which merit special attention are: (a) a 35-40 km electro-fiberoptic Shore Cable that will terminate in a Junction Box on the ocean floor; (b) multiple strings, each with 24 OMs, which must be deployed in a definite pattern on the ocean floor and connected to the Junction Box; (c) submersible manipulator operations which connect the various strings to the Junction Box; and (d) transmitting data to shore at 500 Mbd via 12 monomode optical fibers. The data acquisition and command/control center will be a new building located on the Keahole Point site of the Natural Energy Laboratory - Hawaii (NELH).

Each of these new challenges is being met in the course of conceptual and engineering design for DUMAND-II construction. The present status of each new subproject will be briefly described.

<u>Shore Cable and Junction Box</u>: The first (long-term) construction item for DUMAND-II has been the Shore Cable (also designed by George Wilkins), which is scheduled for delivery in July 1991. A sketch of the cross-section is shown in Figure 6:



<u>Figure 6:</u> Cross-section of DUMAND-II shore cable

The cable will supply 5.5 KVA of DC power at 350 volts to the Junction Box at the ocean-floor terminus, from a 20 KVA (1000 volt) power supply on shore. A total of 12 monomode fibers are carried inside the inner metal tube, providing one fiber/string plus command/control communication and spares. The total cost of the cable is $430,000. When the Junction Box is ready, the Shore Cable plus attached Junction Box will be deployed (from shore outward) by a commercial cable-laying ship.

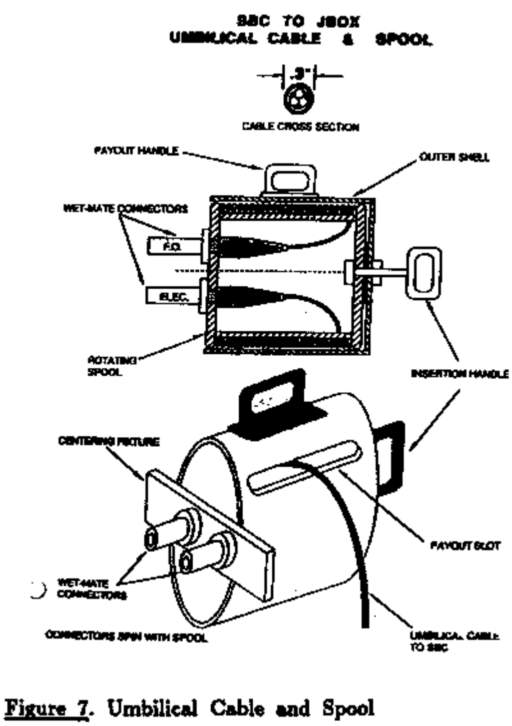
In view of the shoreline damage incurred at NELH by Hurricane Iwa, it has been decided to utilise slant drilling to pass the cable from shore to about 60-foot water depth.

The Junction Box design at Hawaii (by Chris Converse) is now (June 1991) nearly finished and purchase orders for the major components (underwater electrical and fiberoptic connectors, umbilical cables, payout packages) are signed. The Junction Box is the critical apparatus for connecting all nine strings to the Shore Cable. We expect this mechanical operation to be carried out by the Navy manned submersible SEA CLIFF.

<u>Lowering Strings into Position</u>: In principle, assuming benign ocean currents, the KAIMALINO could again be used to lower the strings, one at a time, into pre-determined positions to form an octagonal footprint on the ocean bottom. The essential ingredients are (a) an acoustic feedback system to rapidly update the surface ship where the string bottom (anchor) is relative to the desired final position, and (b) well-controlled ship motion in the desired direction to correct errors.

We are making the following studies on this potentially difficult operation: (1) This fall, a long-term measurement of the vertical profile of currents at the DUMAND site will be undertaken; (2) Makai Ocean Engineering has been retained to run well-tested computer programs that will simulate string displacement in the presence of various assumed currents. If needed we can employ an active thruster for placement.

<u>Connecting Strings to Junction Box:</u> A critical step in the deployment operation is connecting the umbilical cables (string-to-J-box cables). Pairs of electrical and fiberoptic connectors must be inserted into specially prepared housings by a submersible equipped with sophisticated manipulators.



<u>Figure 7</u>. Umbilical Cable and Spool

After consultation, we have tentative approval from the Navy to utilise the submersible SEA CLIFF, which is well equipped for such operations in the deep ocean. (Recently the SEA CLIFF was very successful in locating and recovering the United Airlines Flight 811 cargo door from the ocean bottom near Hawaii. This operation required precision use of manipulators.) DUMAND will provide a TV camera and illumination of the J-Box to assist the SEA CLIFF. A test operation will be conducted off the California coast sometime in late 1991.

OM Position-Determination by Acoustics: Determining the exact position (within 20-30 cm.) of each Optical Module is important in order to reconstruct the muon trajectory and determine its direction in space. We plan to utilize acoustic signalling between transducers on the ocean floor and hydrophones on each string (5 hydrophones/string). Our initial assessment was that this could be readily achieved by acoustic ranging from a carefully surveyed array of transponder/responder transducers placed on the ocean floor. Figure 8 shows the Seattle group's plan for acoustically locating the string hydrophones - and by interpolation, the OMs - using pulses from ocean-bottom transducers already surveyed in place.

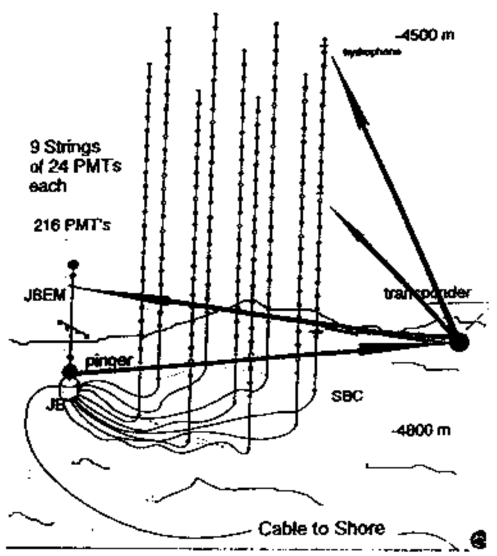


Figure 8. Acoustical surveying

Recently the Seattle group has adopted the plan of using "chirping" (frequency modulated acoustic signalling) to improve the precision of position location at short and long ranges. Using short pulses, frequency modulated from 10 - 30 KHz, the position determination of each OM should be better than 10 cm. By convoluting the received chirp with a replica to obtain high accuracy timing, the Seattle group has obtained an accuracy of 1 cm in conditions of very low signal to noise ratio, and multiple reflections. These are conditions which will sometimes be encountered in DUMAND-II, so a robust sonar method is a necessity. A prototype system has been built that is tailored to the DUMAND-II system requirements.

Another orientation problem under investigation at Seattle is DUMAND-II's ability to determine muon spatial direction (zenith and azimuth) for astronomical pointing. Even with satellite Global Positioning and a well-surveyed pattern of transponders on the ocean floor, this remains a challenge to meet the DUMAND-II target of 0.1 degree overall error.

Calibration of OM Timing and Sensitivity. Another ocean-related problem is to calibrate the timing and photon-sensitivity of each Optical Module, internally to the array and periodically in time. The Vanderbilt group undertook the task of solving this problem for DUMAND-I, using a pulsed 337 nm laser beam scattered from a wavelength-shifting scintillator sphere to produce blue-green light that is a good match to the spectrum of Cerenkov light in seawater. Overlapping OM regions of coverage from two Calibration Modules were used [2]. In DUMAND-II the same basic solution will be used but 15 Calibration Modules will be required to cover the larger area.

Conclusion

The DUMAND-II project, although motivated for particle astrophysics research, depends critically on Ocean Technology for success. Due to 10 years of persistent and innovative work by many individuals, both within and outside of the DUMAND collaboration, it appears that the DUMAND detector can and will be constructed and deployed by the target date of 1993-94.

Acknowledgements

This report summarises effort by the collaborating scientists and engineers of both DUMAND-I [3] and DUMAND-II. Primary support for the USA effort (both construction and operations) has been provided by the Department of Energy (High Energy Physics program). The US National Science Foundation has also provided ship time and support for the Vanderbilt University task. The University of Hawaii has made major personnel commitments in support of DUMAND. Japanese support for at least 50% of the Optical Modules is being provided by the Ministry of Science, Education, and Culture (Monbusho), administered via KEK (National Accelerator Laboratory of Japan). European contributions have been available through the Swiss National Science Foundation (Bern effort) and German funds derived from BMFT for Aachen and Kiel tasks.

We are especially grateful for the friendly and helpful expert advice on Ocean Technology matters provided by colleagues at Scripps Institution of Oceanography (Drs. F. N. Spiess and V. C. Anderson, Mr. Tony Boegeman), at the Applied Physics Laboratory in Seattle (Dr. R. Spindel), and at the Naval Ocean System Center (Mr. Howard Talkington and associates). The NOSC-Oahu KAIMALINO operating crew, scheduled by Harry Chalmers, have contributed ingenuity and resourcefulness which helped make our cruises successful.

References

[1] "Proposal to Construct a Deep-Ocean Laboratory for the Study of High-Energy Neutrino Astrophysics, Cosmic Rays and Neutrino Interactions" (DUMAND-I proposal), Hawaii DUMAND Center, October 15, 1982. The collaborating groups were: Bern, CalTech, UC-Irvine, UCSD (Scripps), Hawaii, Purdue, ICRR-Tokyo, Vanderbilt, and Wisconsin (Madison).

[2] S. Matsuno, et al, Nucl. Instrum. Methods A236, 359 (1989).

[3] J. Babson, et al, Phys. Rev. D42, 3613 (1990).

[4] PhD theses by J. Babson (Univ. of Hawaii, 1990), J. Clem (Vanderbilt University, 1990), and D. O'Connor (Univ. of Hawaii, 1991).

[5] "DUMAND II: Proposal to Construct a Deep-Ocean Laboratory for the Study of High Energy Neutrino Astrophysics and Particle Physics," Hawaii DUMAND Center report HDC-2-88, submitted to DOE and NSF on July 27, 1988. The collaborating groups for this proposal were: Aachen, Bern, California (Irvine), CalTech, Hawaii, Kiel, Kinki, Scripps, ICRR-Tokyo, Vanderbilt, and Wisconsin (Madison). Since then, CalTech and Irvine have withdrawn from the collaboration, and Boston University, Tohoku University, and University of Washington, Seattle have joined.