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MUON STRING RESULTS AND DUMAND STATUS

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Abstract

The Muon String, composed of five 13" phototubes spaced 5 m apart, was designed to measure the muon intensity and angular distribution versus depth in the ocean, where the overburden can be well determined. After successful initial tests in pressure tanks and in the ocean, the Muon String was lost at sea at the DUMAND site before any significant muon data was obtained. The three year DUMAND feasibility study is nearly complete, and an international collaboration has formed, which proposes to place an array of 756 phototubes, occupying a volume of $1/2 \times 1/4 \times 1/4$ km^3, in the ocean off of Hawaii at a depth of 4.7 km. While the primary objective will be neutrino astronomy, the array will also make significant contributions to cosmic ray physics, high energy neutrino physics, and ocean science.

I. Introduction

The DUMAND (Deep Underwater Muon and Neutrino Detector) Feasibility Study is in the middle of the third year. Activities have included site measurements, as well as studies of detector, array, and fiber optic cable design; signal processing techniques; deployment concepts; and scientific capabilities. I wish to describe here the present status of DUMAND, including the results of the Muon String Test.

II. Muon String Test

The Muon String Test was originally proposed as a way for the DUMAND physicists to gain ocean experience, while doing useful muon physics.[1] This experiment, which was really separate from DUMAND, was designed to measure the muon intensity and angular distribution versus depth in the ocean, where it is possible to determine the overburden precisely, yielding improved muon depth-intensity curves. Physicists involved in this test were from the Universities of Hawaii, Wisconsin, and California at Irvine; the Marine Physical Laboratory of Scripps in San Diego; and the Institute for Cosmic Ray Research, Tokyo.[2]

The Muon String consisted of five 13" EMI phototubes, enclosed in pressure tolerant 17" Benthos spheres, spaced 5 meters apart, as shown in Fig. 1. Muons are detected by means of Cerenkov light. As determined from DUMAND feasibility measurements, the deep ocean off of the Hawaiian Islands is extremely clear ($\lambda \sim 30$ m in the blue-green wavelength region)[3-4], and a Monte Carlo program estimates the effective cross section of the Muon String to be approximately 700 m^2.

While DUMAND expects to use fiber optic cables for signal transmission, cables of the necessary type are not yet available commercially, forcing the use of standard oceanographic cable for signal and power transmission for the Muon String. In order to use conventional High Energy Physics electronics, it was necessary to place the electronics package in the ocean near the phototubes. The electronics pressure housing was built by mounting three 11" radius aluminum hemispherical shells on each side of a 4" thick aluminum plate, which was machined at the University of Wisconsin. Conventional CAMAC crates were mounted in two of the spheres, and the power supply occupied the third one. A smart CAMAC crate controller, an Interface Standards IS11, containing an LSI 11/02 microprocessor, was used. The electronics is shown in Fig. 2. Most CAMAC modules (discriminators, coincidence units, etc.) were programmable, allowing them to be set remotely, along with the phototube high voltage. Data was communicated to a microprocessor on the surface using a Computrol Megalink (1 Megabaud) DMA modem. The "downstairs" program was downloaded from the computer at the surface, and it was possible to make program changes even while at sea. The smart crate controller continuously monitored scaler rates and sensor values. Quantities checked with sensors were phototube high voltages, CAMAC supply voltages, temperature, pressure, and orientation. LED's and radioactive sources in each of the Benthos spheres allowed calibration of the phototubes.

The first tests were conducted in pressure tanks at the Pearl Harbor Naval Shipyard. On Nov 2, 1981, the empty Benthos spheres and the electronics package were tested to 3000 psi. On Nov 10, the entire system was tested to 1000 psi, and signal transmission and computer communications were successfully carried out. The first ocean deployment of the empty modules was achieved on Nov 30 to a depth of 1 km. On Dec 18-19, the Muon String with three 13" and two 8" tubes was deployed 10 miles off the leeward side of Oahu to a depth of 0.8 km, using the University of Hawaii research vessel, the Kana Keoki. One of the Benthos spheres containing an 8" tube leaked a small amount of water and failed to work properly. Rates, both singles and fourfold coincidence rates, were obtained, and a muon signal of 3 hz was seen above background during some runs. Timing and pulse height information for the individual tubes was not obtained during this test.

The final deployment took place from the USN De Steiguer at the actual proposed DUMAND site off of the leeward side of the Big Island of Hawaii during the period of March 1-10, 1982. The string was lowered to a depth of 1.5 km, and we were in the process of plateauing phototube high voltages. High singles rates were obtained, around 3×10^5 hz with the tube sensitive to 1 photoelectron, so it was decided to lower the array to 2.5 km, hopefully below the level of bioluminescence. Unfortunately, during the lowering, the package at the end of the cable was lost, before obtaining the desired extensive muon statistics. A double 1/2" steel cable, which connected the electronics package to the oceanographic cable and was designed to carry 20 times the static weight of the Muon String, broke, presumably because of excessive dynamic forces. The cause for the breakage is still under investigation. Although the instrumentation package worked well, a simple mechanical connection failed. This provided a valuable, although expensive, lesson to the experimentors involved. Analysis is currently in progress to track muons on the runs that were obtained. The singles rates at 0.8 and 1.5 km are greater than expected from K^{40} alone and are possibly due to bioluminescence. The submersible ALVIN also found large bioluminescence rates above 1.5 km.[5] In summary, although the muon data was lost, the electronics package ("the most sophisticated package ever deployed", according to some oceanographers), worked well, and much valuable experience was gained.

III. DUMAND STATUS

Currently, the International DUMAND Collaboration is preparing a proposal for the construction of DUMAND. Member groups of the collaboration are the University of Hawaii; University of Kiel; California Institute of Technology; Vanderbilt University; University of Bern; Purdue University; University of Wisconsin; Institute for Cosmic Ray Research, Tokyo; University of California, Irvine; Scripps Institution of Oceanography; and University of Aachen. Member groups assume major responsibilities for components of the DUMAND array. In addition, there are Associate Groups, which include the University of Chicago (Astrophysics), Naval Ocean Systems Center, Naval Ocean Research and Development Activity, Naval Research Lab (Cosmic Ray Lab), Harvard Smithsonian Center for Astrophysics (Mt. Hopkins), and Northwestern University. The proposal is presently in draft form and will be submitted to funding agencies at the end of August. A total cost of about $10M over five years is estimated for the basic development, construction, and deployment of the array. Next year, activity at the DUMAND center (pre-engineering design) will continue at the same level while the proposal is being considered.

A.) Design

The DUMAND array will be located on the ocean bottom at a depth of 4.7 km approximately 25 km from Keahole point on the Island of Hawaii. Laboratory space suitable for the shore end of this project is presently available at Keahole point. The detector modules (21) would be spaced 25 m apart on vertical strings. The strings are arranged into a 6 x 6 square array with 50 m spacing between strings, giving a total of 756 detectors. The volume of water enclosed is 3.1×10^7 m^3. The effective volume for 2 TeV neutrinos interacting either inside the array or in the surrounding water and producing a muon that reaches the array is 2.5×10^8 m^3, equivalent to a detector mass of 250 megatons. A Monte Carlo program,[6] which was written to investigate the resolution of this array, predicts a muon energy resolution using dE/dx of 50% for muons above 1 TeV and a muon angle resolution between 15 and 45 mr, depending on the track direction and length. For events occurring inside the array, the energy resolution of hadron cascades above 0.5 TeV is also about 50%. However, little directional information is available until very high hadron energies are reached.

The detector modules would consist of 13" EMI or 16" Hamamatsu phototubes enclosed in 17" Benthos spheres. Simple electronics in the sphere would generate a pulse whose length would correspond to time over threshold. This pulse would be transmitted to the string bottom module over an optical fiber (one per sphere). Power would be distributed from the string bottom module along a single power cable to all the spheres along the string. A microprocessor in each detector module would communicate with the outside world along the power cable and would carry out simple control functions, such as controlling the phototube high voltage and discriminator threshold.

A Signal Processing Workshop was held in March 1982. The use of fiber optic cables (one per string) was assumed for data transmission to shore. Pulses from each detector module would be digitized (time and pulse height) and multiplexed onto the fiber optic cable by the string bottom module each 13 μsec period, filling the available bandwidth of 44 Mbaud per fiber - a commercial standard for which standard components are available. Digitizing is done in the string processor to avoid sending fast clock pulses to each photodetector module. If more than one signal was detected during this period, then either the biggest signal or the signal (if any) that was time coincident with the string module above or below it would be sent. The latter scheme was proposed by Charles Roos (and promptly dubbed Charley's ruse) and allows one to pick out one photoelectron pulses associated with muons in the midst of a large K^{40} background. The bandwidth available will accommodate all noise counts up to a 77 Khz rate, which is approximately the expected rate due to K^{40} decays in the ocean and implies that essentially all pulses that may contain useful information can be transmitted to shore where the neutrino events can be extracted from the background.

A new idea concerning deployment advanced at the Signal Processing Workshop[7] is to use a phased deployment scheme, where first a single string is deployed and tested, then a plane of strings is deployed and tested, and then additional planes are deployed until all six planes are in place. Each plane is independent and has a separate cable to shore. This allows modification to be made to planes deployed later based upon the experience gained from earlier ones, allows the use of a smaller and less expensive ship for the deployment of the various phases, and allows for the possible recovery of individual planes from the ocean floor, if necessary. However, entanglement of strings becomes a potential problem, unless the strings aren't released until deployment is finished, which removes one of the main attractions. It will be necessary to have this scheme examined carefully by the ocean engineers.

On shore, a set of parallel processors would use simple algorithms, such as testing to see if the phototube times are consistent with causality, to extract possible neutrino and muon events from the data stream (1.6 gigabits per second). Possible events would then be handed over to a standard computer, with the capabilities of a VAX, for further analysis and possibly be written to tape. Simple causality algorithms have been shown to reduce the number of events for further consideration by a factor of 10^4.[8] The processors could be built from state of the art electronics, and the consensus of those at the Signal Processing Workshop was that the data rate could be adequately handled.

B.) Scientific Objectives.

The scientific objectives of DUMAND are (1) high energy neutrino astronomy, (2) cosmic ray physics, (3) high energy neutrino physics, and (4) ocean science and geophysics. Neutrinos may be produced either atmospherically by cosmic rays or extraterrestrially. The expected rates versus energy for the former using an energy dependent volume for the DUMAND detector are shown in Fig. 3. Thousands of events per year are expected above a neutrino energy of 1 TeV, which is orders of magnitude greater than the rates expected for the Case Wittwatersrand Irvine (CWI)[9] underground detector and the Irvine Michigan Brookhaven (IMB)[10] proton decay detector. The DUMAND detector will be the only significant source of TeV neutrino events in the forseeable future.

The expected event rate for extraterrestrial neutrinos is much less certain because of the uncertainites in astrophysical calculations. We have calculated for DUMAND the Minimum Detectable Flux (MDF), which is basically the flux which would give 10 events per year when the background is negligible in the angular region of the sky being considered, which is usually the case for point sources. When the background is more than one event per year, as it is when one is looking at more diffuse sources, then a 5 σ effect is required. The MDF for neutrinos above 1 TeV is 2×10^{-10} $cm^{-2}s^{-1}$. This is again orders of magnitude more sensitive than what can be accomplished in mines. With this sensitivity, DUMAND should be able to detect supernovae in our local cluster of galaxies out to M31, active galaxies like Centaurus A (if powered by black holes)[11], and other sources like SS433.[12]

Some experimental indication of the flux of high energy neutrinos expected is obtained from observations of high energy gamma rays using the atmospheric Cherenkov technique,[13] assuming that neutrinos will be produced with similar fluxes at these energies. Several sources of TeV gamma rays have been seen, but the brightest TeV source seems to be Cygnus X-3. The flux of gamma rays is measured in the range of 10^{-10} $cm^{-2}s^{-1}$ above 1 TeV, within the range of sensitivity of DUMAND. DUMAND as a neutrino telescope would be comparable to γ detectors in sensitivity.

DUMAND will also have a significant capability to do cosmic ray physics. It will extend the measurements of the muon energy spectrum up to 100 TeV, allow the study of direct muon production up to 2000 TeV, and study the spectrum and composition of primary cosmic rays up 3000 TeV.

There will be about 600 ν_μ charged current interactions above 1 TeV per year occurring inside the DUMAND array. Although this is a relatively small number of events, this will be the only source of TeV neutrino events for some time to come. DUMAND would also be sensitive to neutrino oscillations, by using the variation in atmospheric neutrino path length through the earth.[14]

IV.) Summary

The three year feasibility study has shown DUMAND to be quite feasible - technically, scientifically, and economically; and a proposal by an international collaboration to place an array of 756 detectors in the ocean is nearly complete. The array will make significant contributions to neutrino astronomy, cosmic ray physics, high energy neutrino physics, and ocean science.

References

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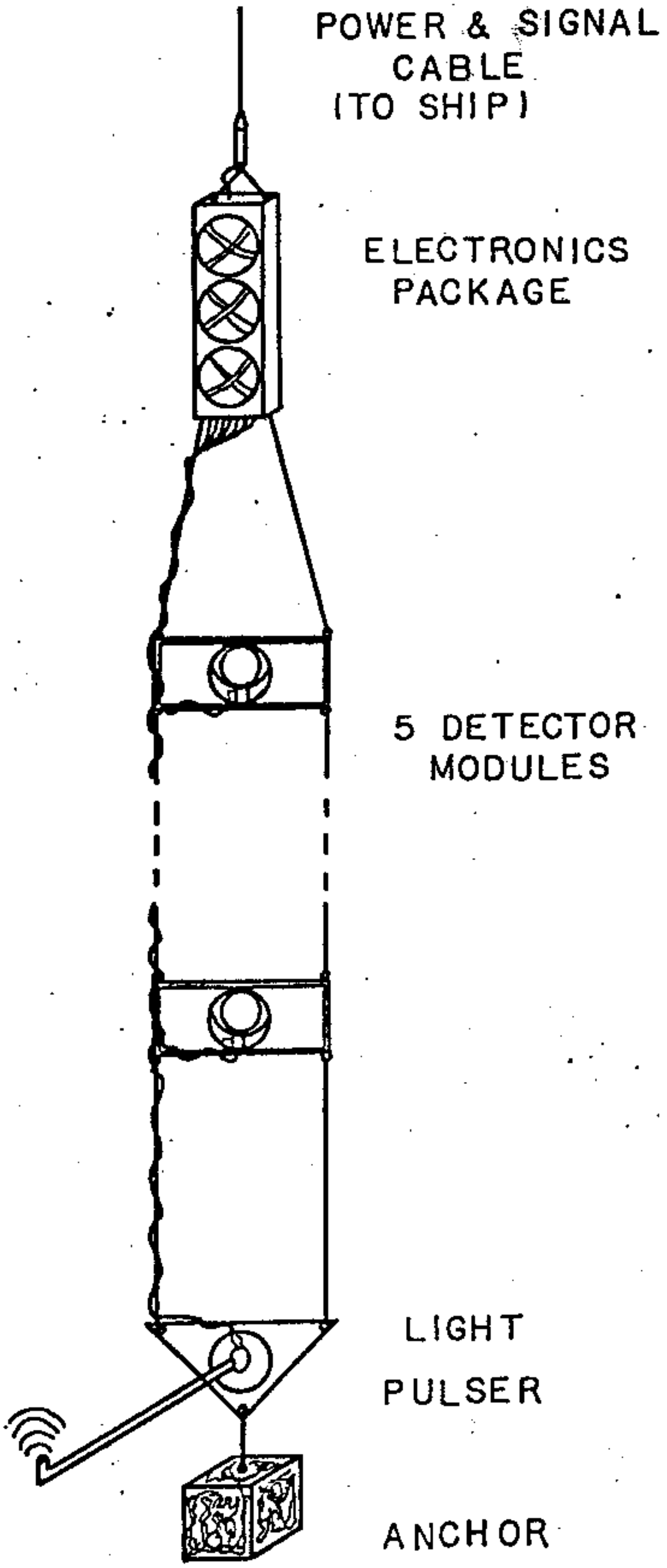

Fig. 1 Muon String

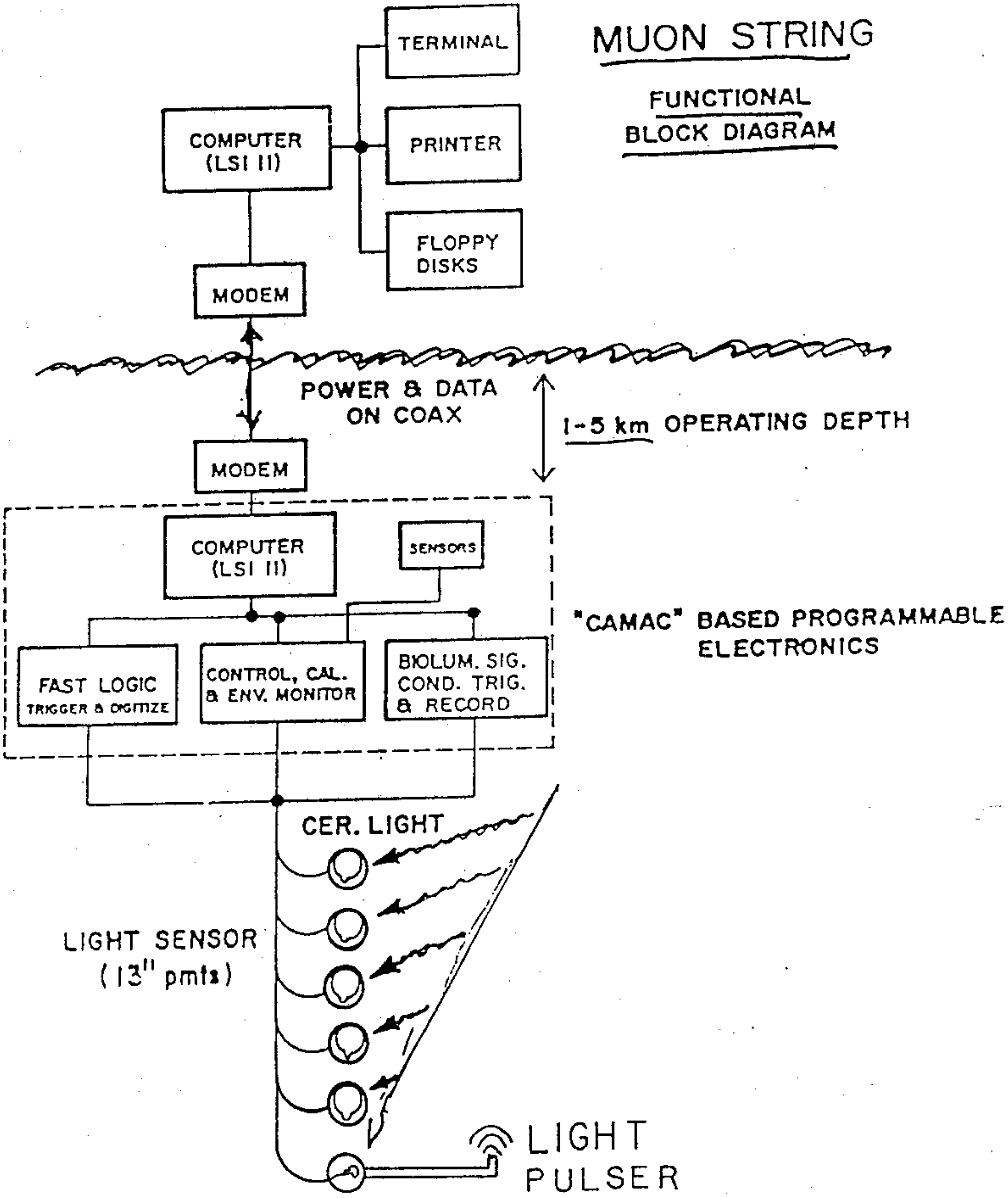

Fig. 2 Electronics and Computer System for the Muon String.

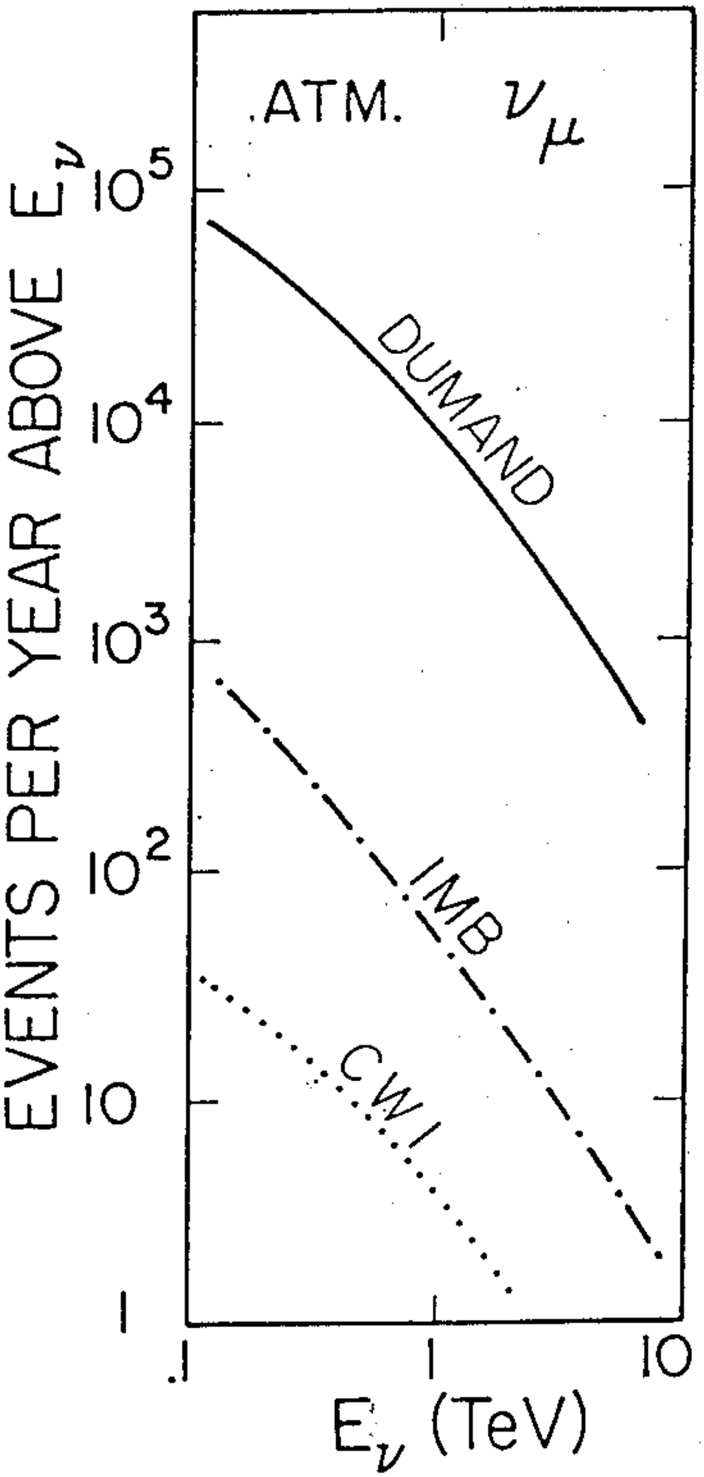

Fig. 3 Predicted ν_μ charged current event rates for the DUMAND array and other experiments.