DUMAND II System Description

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Foreword

This document is intended to present an overview of the DUMAND II (the Octagonal Array) system design. It will not generally present alternatives or much justification, but simply state the configuration as of this writing. We begin with a short overview, and proceed to more detailed descriptions of each subsystem. This document is organized by functional entity, the specifications are oriented to physical entities. The Specifications should be consulted for precise numerical definitions.

In this updated version (May '91, the first full update in one year) there have been many changes due to evolution of the system design, detailed design choices and some expansion of scope. Major changes will be noted in: the digitizer (refinement of design to a single 32 channel GaAs chip with more on chip buffering); String Controller (SC, ex SBC) location moved to string center; the demise of the RUM III ROV and shift to (better choice anyway it turns out) the manned submersible Sea Cliff; formalization of agreement by AT&T to lay our cable; recognition of surprisingly good bottom route for cable laying with new site choice slightly closer to shore; evolution of design of acoustic surveying system (elimination of EMs in every string, 5 instead of 3 hydrophones per string but wired directly to the SC, and four responders wired directly to the Junction Box); and further refinement of the trigger design (for muon triggers, total energy triggers, and some slower triggers for fast light sources and possible supernova detection).

Contents

Introduction

The Array is to consist of nine strings of 24 photomultiplier modules (Optical Modules, OMs) each, configured in an octagon with one string in the center. The strings float upwards, being anchored on the flat 4800 m deep bottom, 30 km West of Keahole Point. The Octagon is 40 m on a side and the modules are spaced 10 m apart, beginning 100 m above the ocean floor. There are also three laser calibration modules (CMs) on each of 5 strings (center, N, S, E, and W strings), located near the top, middle and bottom of the instrumented section. The central string has an environmental module (EM), with ocean current monitoring and such. Each string has five hydrophone units, for purposes of array position survey and monitoring.

The strings are connected to a Junction Box (JB) via 200 m long umbilical cables along the ocean floor. The connection is to be carried out by a manned submersible (the Sea Cliff), or alternatively by a robot operated from the surface (eg. the Advanced Tethered Vehicle, ATV). The JB terminates a 12 fiber cable from shore, which cable also carries DC power to the array. Attached to the JB is a special EM, intended mainly for monitoring bottom conditions prior to and during string emplacement, and ongoing acoustic surveying of the array orientation.

The cable comes up the 20% slope to the Big Island along a carefully surveyed path, and goes through the surf zone in a preplaced pipe, and then into a new laboratory building at the Hawaii Natural Energy Laboratory (HNEL). There are power supplies, analysis and monitoring computers, special data handling hardware, data recording equipment, precise clocks, and communication links to the outside world, located at the laboratory.

The individual OMs detect Cherenkov radiation from a passing muon. Sideward and upward going muons are produced by neutrinos (see the Proposal for details of the physics). The light pulse is transformed into an electrical signal by the photomultiplier, converted to a pulse–width modulated pulse within the OM and sent via (1300nm) multimode fiber to the String Controller (SC), located at the string center (formerly at bottom, note change). All modules connect to the SC in parallel. The SC digitizes the arrival times to 1 ns accuracy, as well as the pulse width. The width of the pulse is proportional to the logarithm of the pulse detected by the photomultiplier. There are two kinds of OM. The Japanese version (JOM), with Hamamatsu PMT, has a second integrated output pulse for large pulses, to help discriminate between single and multiple muons. The European OM (EOM) has the Philips PMT, and produces only one (charge integrated) pulse output.

Laser emission in the CM is monitored by a photodiode. The diode output pulse is encoded by the CM and transmitted to the SC in the same way as for OMs. The hydrophones are each connected to the SC with 3 wires and a shield, instead of fiber and two wires as with OMs and CMs, and the acoustic signals are digitized in the SC. The OM, CM and HM data are multiplexed, along with SC monitoring data, and sent to shore on a dedicated optical fiber per string. The data is multiplexed on one 500 Mbd data stream, encoded (5b/4b) to 625 Mbd, to shore via 1550 nm laser on single mode fiber. The data is blocked into two counts per 40 bit word, each word transmitted in 160 ns. The expected noise rate per module is 64K counts per sec (Kcs), but we use 100Kcs for design purposes. The fast data goes straight to shore, having only one connection to pass through, at the Junction Box.

On shore the nine serial data streams are put onto 32 bit parallel buses, one for each string, at a maximum rate of one word per 80 ns. Special built trigger processors (9) detect close neighbor coincidences and communicate with a data harvesting processor via standard VME bus. All data is written into temporary storage at the Trigger Processor, which also keeps track of OM noise rates and other housekeeping information. EM and C^2 data (see below) are stripped off for forwarding to their own processors.

The Command and Control signals are independently sent from shore to each SC, on a different color (1300 nm) from the shoregoing fast data. The return signals are multiplexed in with the fast data to shore. These nine (full duplex) links provide the ability to control the array configuration, power-up modules, set high voltages and discriminators, read count rates directly from OMs, access a large number of diagnostic monitoring points, command the calibration sequence, structure the EM data, and provide the ability to reprogram the ocean bottom computers if required. All communications go through a main C^2 computer on shore to individual SC computers. The SC computers relay communications to their local modules, each of which has it's own microprocessor.

The fast timing is accomplished via independent two phase 500 MHz clocks of moderate stability at each string. These clocks are calibrated continuously on the shore end by special circuitry, which updates the incoming data to common Universal Time (from the shore based time standards). The digitizer sends the prompt time of the string clock every 1024 data words. These are used to calculate a running difference between SC time, at the digitizer, and UT. The SC digitizer, a specially designed GaAs LSI chip, digitizes the arrival time of 32 channels of data to 1 ns precision, including the possibility for coincident arrival times, via a two level buffer scheme.

The power for the array is conditioned on shore to about 1000 VDC, dropping to 350 VDC at the junction box, 5.5 KW delivered power. The junction box contains a replaceable DC–DC voltage regulator and crowbar circuit for overvoltage protection. The string power is carried by the individual umbilical cables to the SCs where it is further transformed to the various DC voltages needed locally. The power is converted to 48 VDC at the SC for transport up the strings to the individual modules. The individual modules can be switched at the SC via the C^2 link.

There is an environmental monitoring package at the JB (the JBEM), which floats above and contains various instrumentation, including acoustic transponder (under shore control), and television and lights for monitoring activity at the JB. It is connected to shore on one of the 12 fibers, using the same connections as for a string, and interchangeable with a string. There are thus two spare sets of connectors and fibers to shore.

There are also four responder packages attached to the JB, and deployed by the submersible (or robot) used for connections to strings. These serve the purpose of generating chirped acoustic pulses which are received by the 5 hydrophones on each string, digitized by the CM, and sent to shore. Few centimeter level resolution of the relative locations of the hydrophones is expected. A second, stand alone, battery powered, set of transponders is to be dropped at the time of shore cable and JB placement. These are to be used for navigation of the string placement.

A Array Geometry

The array geometry has been arrived at via substantial Monte Carlo calculations. The main design parameters were to achieve a one degree, or better, resolution for neutrino induced muons, and an effective area for collecting them of about 20,000 m^2 in the lower hemisphere. The precision of placement required is not great (few meters), but in order to reconstruct the muon directions accurately we must know the positions as installed with a much greater precision (less than a meter). We will discuss the accuracy of the measurement of modules positions relative to each other, and the accuracy of the ensemble, separately.

In order to meet the desired angular reconstruction accuracy of muon tracks relative to the array we must know the relative positions of the modules to an uncertainty of less than one meter. This will be easily achieved in the vertical direction within one string by controlling the module spacings, which we can easily do to several centimeters. The string placements will not be precisely on the nominal octagonal pattern, so we must measure them in situ. We plan to do this acoustically, employing the five hydrophones on each string to give both horizontal spacing, and vertical offsets. This can be accomplished to a few centimeters accuracy. Thus with module relative positions determined to within 10 cm, the uncertainty in position will be negligible compared to the other sources of error (the 20 cm PMT radius, the PMT timing jitter of <5 ns, and 1 ns digitizing roundoff).

The array will sway slightly with the ocean current, typically with a twelve hour period due to the tidal cycle. Anticipated motions are typically a few centimeters, with a maximum of several meters at the string top. The angular deviations of typically much less than one degree will be monitored by the acoustic system, as well as by tilt sensors in the OMs. The acoustic system also checks against any unforeseen motion of the strings relative to each other. A further cross check is provided by the optical calibration system, which is overdetermined and, though mainly intended for OM timing calibration, can be used for redundant position information.

Having determined the direction of a muon relative to the array, that information must be transformed to astronomical coordinates. First we calculate earth coordinates, and then using the event time transform to celestial coordinates. We must know the orientation of the array in geographical coordinates therefore, to a precision which is better than the desired neutrino direction accuracy.

A deep ocean acoustic transponder field of 4 battery powered units is placed around the array location prior to deployment, and used as position reference and navigation network during deployment operations. The array network is dropped one kilometer out from the center of the nominal array location, at the four points of the compass. The JB forms a fifth reference mark, having its own transponder carried along at deployment. The 4 responder units attached to the JB form an inner rectangle, but under shore power and signal connection (via the JBEM). A ship is sailed in a grid pattern over the array, multiply recording the distance from the ship to the transponders, while the ship position is determined (to about 1 meter at any moment) by microwave transponder monitoring of position to fixed shore locations. Surveying the shore positions, and cross referencing with the Global Positioning System (GPS), yields the ocean bottom locations to a precision of the order of one meter or better. More importantly the azimuthal orientation of coordinate system defined by the transponder net can be measured to less than 0.1 degree. Differential timing of the pulse arrivals from the network to the string hydrophones completes the survey process.

The strings are kept vertical by the buoyancy of a float package at the string top, which keeps tension in the string and prevents tilting of the string in the ocean bottom current. We have measured bottom currents to be typically less than 1 cm/sec. We design for operations in currents up to 10 cm/sec, and survival in currents up to 1 m/sec. At 10 cm/sec and with a net string tension of 1000 pounds, the calculated deviation from the vertical is less than 2° (depends upon current profile, etc.).

The anchor needs to be sufficiently stable to prevent motion during the worst currents to be encountered, which we take to be 1 m/s, 10 times worse than any observed value. We have set the anchoring mass to be 2 metric tons. The anchor package additionally has bottom piercing cleats, and a back-up self burying anchor for unanticipated current levels.

The optical modules start at an altitude of 100 m above the bottom, to be clear of potential turbidity near the ocean floor, and extend over a further 230 m in height. The float package is attached to the top, via a mechanical swivel, allowing it to rotate. The instruments mount between two parallel riser cables, spaced 60 cm apart. Spacer rods, and lifting points, are placed between the riser cables at 5 m intervals, alternating with modules (thus there will be spacers every 2.5 m n the riser cables). The pairs of cables will not twist up in horizontal current flow. At present we are uncertain as to how much rotation we can expect over the entire string length due to asymmetry in flow around the modules.

We will monitor orientation in order to account for shadowing by cables (<5% effect even so). (Gain shift with orientations relative to the earth's magnetic field in not expected to be a problem for the Philips PMTs because of high accelerating voltage, and the Hamamatsu PMTs will be magnetically shielded).

B Optical Data and Triggering

Herein we present a discussion of the fast data path, from photomultiplier to computer tape. The Cherenkov pulses are detected by the individual photomultipliers, which are of two types, each having certain strong points. The Japanese version of the OM (the JOM), very similar to that already employed in the Short Prototype String (SPS) tests, employs the 15 inch Hamamatsu photomultiplier, specially designed for DUMAND. This large area PMT was constrained to fit inside the standard oceanographic pressure sphere: The Benthos 16 inch instrument housing which is readily available and well tested in the ocean. The PMT has now gone through several iterations in design, each one significantly better suited to our needs. The latest version of the Hamamatsu PMT has a time resolution jitter of <5 ns FWHM at 1 PE, averaged over the forward hemisphere (it was 12 ns in the version employed in the SPS).

Spectral sensitivity is typical of multi-alkali photocathodes, peaking in the UV range, limited by glass transmission on the short wavelength side (to about 300 nm) and by photocathode sensitivity on the long wavelength side (to above 500 nm). The materials used for the optical module housing do not degrade the sensitivity by more than 10%. (These materials will be monitored during construction.) Cherenkov light seen through water at 10 m distance is a very good match to the PMT sensitivity, peaking at about 400 nm, and being limited by atomic and molecular absorption and Rayleigh scattering to the same spectral region as the PMT.

Another characteristic of the Hamamatsu PMTs which has been improved with time is the first stage gain in the electron multiplier structure. This determines the ability of the PMT to resolve one from two photoelectrons (PEs). Based on our measurements with the SPS, the background light in the ocean is a expected to produce 64Kcs in the PMT, mostly single photoelectron pulses. Discriminating between 1 and 2 PEs is thus a powerful tool in finding real muon events in the presence of background light. The Hamamatsu PMTs used in the SPS had a pulse height distribution such that about 25% of the 1 PE pulses had pulse heights greater than the mean of 2 PE signals. The improved PMTs are much better in this regard (which is typical of large area venetian blind multiplier structure PMTs).

A magnetic shield has been designed and tested for the Hamamatsu PMT, making gain shift with orientation negligible. The shield consists of a loose grid of mumetal screen (less than 2% obscuration), placed between the glass pressure housing and the PMT, buried in the optical gel (silicon rubber compound).

The other OM to be manufactured by the European collaborators (EOM) econsists of a Philips PMT of a novel design, mounted in the same type of Benthos glass pressure housing. The Philips PMT is really an image intensifier, with a secondary small PMT detecting the light produced by the first stage phosphor. Electrons are accelerated to about 20KV between the photocathode and the aluminized phosphor, which produces hundreds of photons per PE. (Because of the high accelerating field the earth's magnetic field is not expected to cause gain shifts). A standard 2 inch (magnetically shielded) PMT fitting into a re-entrant region in the larger glass housing then collects a huge pulse for each PE. Thus this 2 component PMT has a very good effective first stage gain, giving 5 times better 1 PE separation than the earlier Hamamatsu PMT versions, and also very small timing jitter on account of the high acceleration voltage between the photocathode and phosphor.

The EOM does not do as well as the JOM on resolving two pulses occurring close in time, as happens due to two muons passing through the array. From the cosmic ray physics standpoint, the detection of multiple muon pulses is desirable, though not first line in physics criteria. The EOM pulse has a sharp leading edge, but decays rather slowly with time (over a period of 50 ns). The JOM does rather better, being able to resolve pulses separated by about 20 ns. The digitization electronics will have the ability to handle multiple pulses at the 1 ns level, and thus we can take advantage of whatever multi-pulse resolution the PMTs provide.

The electronic circuits in the OM enter this issue, because they transfer the PMT pulse into a width modulated output pulse. One may think of the OM output pulse length being simply time-over-threshold, though it is actually integrated and stretched. The relationship between pulse output length and PMT pulse charge is naturally logarithmic, providing constant fractional pulse height resolution. Close second pulses may produce confusing pulse lengths. The EOM integrates long enough that the charge will be simply normally included in the EOM output pulse duration. The JOM, however, will produce a second pulse for PMT outputs exceeding a predetermined threshold (adjustable from shore). The first JOM pulse will be time-over-threshold, while the second will be of duration proportional to the logarithm of the true integrated PMT output charge.

Despite these differences, the OMs are interchangeable in terms of system compatibility. After study it was determined to mix the EOMs and JOMs alternately on the individual strings, with all modules facing downwards.

The OMs are captured in an acrylic plastic hardhat, which hardhat also clamps over the parallel string cables, and serves to protect the OM during handling prior to deployment, protect cable connections to the OM, and streamline the whole affair.

The OMs each contain a microcomputer which communicates, via modem on its power line, to the SC computer, and thence to the shore C^2 computer. The primary functions of the OM computer are to set the PMT high voltage and discriminator voltage (and verify those settings). Secondarily the computer can report various conditions, most importantly the locally measured PMT count rate. The unit is also programmed to ramp up the voltage in a safe manner. The program contains a default, fail safe, option (should communications fail) that will turn the PMT on and stabilize it at the nominal setting, or at the maximum acceptable noise rate (100Kcs). A misbehaving module can be disabled by the SC computer turning off it's power.

We anticipate that there could be periods of high bioluminescent activity ($<1\%$ of the time). It is important to protect the PMT should dangerously high light levels occur. This is most simply accomplished by having a high base resistance, so that the acceleration voltage collapses under high light levels. Over longer periods (>1 sec) the processor can sense the situation and take action to lower the HV. We must know this has occured, however, in order to know the state of sensitivity of the array at every moment (which is necessary if one is to employ the most powerful track fitting techniques, which include utilization of information on which OMs were not hit as well as those that were triggered). The fast signal for a PMT in overload condition is for the OM output to remain in the ON condition (on shore a START is received without a STOP), for a minimum duration of one second. The C^2 network is designed so that we can poll the entire array status once per second, which will monitor for PMT overload and other noteworthy conditions. Note that the PMT rates will be measured each second by scaler reading on shore as well.

The OM data is received by the SC digitizer circuit, at present under redesign. In the SPS the least count was 5 ns, and one (specifically designed) macrocell array chip was utilized per channel. Redesign was necessary as improved PMT timing made it desirable to digitize to 1 ns least count. We have also taken advantage of the rapid advance in ASIC technology to place 32 channels per chip and to include the buffer memory stack that was external to the chip in the SPS design.

The digitize operates by simply strobing the time of arrival of the pulse(s) start (or stop) into a 42 bit wide FIFO stack. The stack includes bits for each channel, so that simultaneous hits in several channels will yield several bits set in the address field (32 bits total). Upon readout if there is more than one address bit is set the time is transmitted for each hit (this condition will be rare for signals overlapped with noise). The wide stack is 10 deep, and flushed at a constant rate of one word per 3 ns. There is then a 100 word deep by 16 bit wide buffer to allow for multiple muon events or big blasts lighting the full string from the side. This is flushed at the shore transmission rate of one word per 80 ns.

The digitizer words are doubled up, with 4 added parity bits, into the Hot Rod multiplexor chip at one 40 bit word per 160 ns. This chip further encodes the data in the scheme known as 4b/5b, which simply makes for regularly occurring transitions, without paying the factor of two bandwidth penalty of Manchester encoding. The Hot Rod transmitter and receiver chips make this operation transparent to us. When no OM (and CM) signals are present, as will be the case most of the time (about 80%), the Hot Rod will transmit it's own synchronization sequence.

The digitizer will pass along words from the hydrophones, the EM, and from the SC computer (C^2 data), as bits in the rollover word, every 1 microsecond. This time is close to the time for a particle travelling at the speed of light in vacuo to cross the array on the diagonal. Thus most physics events we expect (traversing muons, and light from particle cascades which have 10 m typical dimensions) will be contained within one or two rollover cycles, and one microsecond is a natural search time. Rollover potential ambiguities are prevented by the time correction circuit on shore.

On shore the serial data stream is received and error detected. The times are corrected by the time compensation circuit, which keeps a running tally of the string time versus UT. This then means that all times are in comparable units right from the beginning of the trigger finding, and times between strings may be compared. (Fine timing correction, at the several ns level, due to variations in PMTs and cable lengths, is accounted for later in software). The parallel data streams (at 1 MHz) for hydrophones, EM and CM are stripped off at this point and sent serially to their individual shore systems. The OM and CM data words are presented to the trigger processes on a 32 bit parallel buss. The 9 trigger cards are the major pieces of electronics to be constructed for the shore station. They consists of two major sections: the trigger finding, and the data storage. Aside from these there are housekeeping functions, such as keeping scaler rates of all interesting quantities (mostly PMT noise rates), and test outputs and diagnostic capabilities.

The trigger finding scheme takes advantage of the fact that muons passing near strings tend to produce multiple hits on at least one string in traversing the array. The second time difference (T3) in neighbor triples of hits is in fact usually below 15 ns. One of these will also usually have more than 1 PE of amplitude. A second trigger (T2) asks for 4 or more PE in any neighboring pair (1 + 3, or 2 + 2) within a 96 ns coincidence time window. We thus find that we will be able to operate an efficient single muon trigger employing only trigger searching within a single string data stream.

Random noise can produce triggers too, and will do so frequently. We eliminate noise triggered data at a later stage in computer filtering, and can do so to a high degree, leaving an effectively pure sample. The important task is to make the hardware trigger sufficiently efficient to pass most real events, but not so loose as to swamp the computer with trying to fit noise events. The noise rate that will pass this simple one layer trigger cannot yet be determined precisely because we do not yet know the rate for multiple PE counts in the new style modules in the real deep ocean. We can guarantee an efficient muon trigger with a single layer trigger which will have a random rate of the of <1000/sec.

A simple second level trigger will be implemented to further decrease the trigger rate reaching the computers to about 1/sec. This will look for cross-string combinations of hit clusters, or an excess of hits from throughout the array in one microsecond (the TE trigger).

Once a trigger occurs the data harvesting computer will read the appropriate memory section on each trigger card, collecting all data in a time window of a few μs around the trigger (programmable window). The on-line routines have yet to be written, but should be able to cut the random events down to a negligible rate in a maximum of a few ms on a μVAX. Full fitting may take 1 sec per event, and this may be in a second layer machine, not yet determined. In any case, since the real physics rate is only a few events per minute, the data stream will be dominated by monitoring data. It may be possible to pass the data amongst collaborators in real time.

Several other triggers will be implemented for long-shot physics searches. One is intended for catching fast moving bright objects of the variety hypothesized as quark nuggets or nucleon decay generating magnetic monopoles. These would move with galactic velocities, of 10^{-3} to 10^{-4} c, and thus have durations through the array of 1 to 10 ms. The signature would consist of PMTs sequentially becoming saturated in light level as the object nears them, and thus going into shutdown state. If, as in the case of the nugget, the light is incoherent thermal radiation, then there will not be coincidences to generate normal triggers of the array. Thus we plan to collect this type of event by watching for, and recording, shutdown sequences in the OMs.

Another long shot for DUMAND II, is the detection of a galactic supernova. Because we have optimized the array sensitivity for high energy muons, we have spaced the modules so far apart that few coincidences between modules would occur due to the typical 20 MeV interaction in water from the wave of neutrinos due to a supernova. The only chance we have is to look for the slight increase in multi-PE hits at each OM which views SN generated neutrino interactions. Again, actual ocean measurement of the pulse height spectrum of the modules is needed to determine our sensitivity. I think the best we can hope for in present geometry is confirmation of another detection elsewhere. In any case, we plan to implement a recording of not only single PE noise rates for each PMT, each second, but also another rate at a higher (adjustable) threshold, typically 2 PE. THE signature would then be an increased multi-PE rate over a few second duration. Uniformity of response over the entire 2 megaton array volume would discriminate this from any bioluminescent phenomena.

C Calibrations

The calibration modules are very similar to those employed in the SPS. The major difference is that we do not need the "dork", the fiber bundle to carry the light away from the string axis. The center string affords the most symmetric location for the calibration modules, illuminating the surrounding 8 at distances not varying much over several vertical steps. Because the PMTs face downwards the sensitivity is greater from below, and we place the modules offset downwards by about 20 m from the natural locations. Because the modules in the center string itself cannot view the light pulse from the CMs in that string, we are motivated to place modules in other strings. After much debate it was decided to place CMs in 4 outside strings (N, S , E and W). This gives us redundancy of coverage, and helps in postion monitoring, OM dynamic range, and angular response.

Physically the CMs are packaged, as before, in a Benthos housing, and supported in a plastic hardhat, just as the OMs. The laser illuminates a piece of scintillating plastic, and it is this light that the PMTs respond to. It is intended to mount two lasers in each module, providing an onboard spare.

Electrically the CM appears to the SC exactly as an OM, except that it uses twice the power. The C^2 communication protocols are all the same, but there are special commands for setting up the laser pulsing sequence. The laser firing is monitored by incorporating into the system a diode that produces a pulse whenever the laser fires. The output pulse from the laser monitor is treated just like an OM signal from there onwards, except at the trigger processor it generates an automatic event trigger. Thus we are protected against unwanted laser firings generating false events (which can be identified by their topology anyway). In the case of a runaway laser we may simply shut off its power.

Note that the calibrator's job is mostly to provide the definitive inter-string time offset measurement. Secondary tasks include water transparency monitoring, relative PMT timing calibration (within a string), and redundant string relative position measurement.

Pulse height calibration of modules will be accomplished via the variable output of the lasers. Signals with low probability of detection yield the one photoelectron (1 PE) amplitude. We can then extrapolate to higher light levels via the CM monitor pulse. Of course we will have laboratory calibrations for angular response, which should not vary with time (since it depends upon geometry). Absolute sensitivity can be gotten from the response to the background ocean K^{40} generated light. Time slewing (timing shift dependance upon light level), prepulsing (early hits at high light levels, due to direct illumination of the first dynode), and after pulsing (typically high secondary pulses due to ion feedback and other mysterious PMT processes), can all be studied in the ocean using the CM.

D Environmental Monitoring and Acoustical Surveying

The environmental monitoring task is, again, very similar to that carried out in the SPS. We will have one environmental module (EM) in the central string, which will directly measure the ocean current (vector), the pressure, temperature and salinity. There will also be one special EM located at the JB. The task of these EMs is to provide us with all necessary data about the local environment: the ocean current, precise depth, and sound velocity. As with many other quantities, we have built in redundant measurement capability (as much as practical from the standpoint of economic and reliability considerations).

Acoustics will be employed, as discussed above, to calibrate and monitor the relative location of the instruments and relate their orientation to the outside world. Incidentally we will be able to carry out some exploratory research, such as listening for the sounds of ultra high energy showers, employing the sensitivity and the high frequency bandpass available via these hydrophones.

There are five hydrophone and amplifier packages incorporated into each string. The hydrophone's output signals are digitized by the SC and sent to shore in the fast data stream. Several rate options are available, up to 100K samples per second of the analog waveform (50 KHz bandwidth). Pulse recognition for the transponder pulses will be carried out on shore.

There will be one special EM package attached to the JB at the time of deployment. The main motivation for this is to provide ocean current information at the time of string deployment. This package will include a TV and light system for use during deployment and robot connection operations. One TV camera will be fixed for observing the JB connection area in detail, and the second camera will have pan and tilt to observe a larger field of view. They will both be high resolution, monochrome (color is not useful at distances more than a few meters in water).

The JBEM will also be connected to 3 fixed local hydrophones and outrigger responder units. The responder units, placed at a distance of roughly 200 m from the array, will produce chirped acoustic pulses to be received by the hydrophones, providing the major means of ongoing string orientation measurement. We anticipate a resolution of several centimeters for this system, much better than accomplished by most commercial ocean systems, because we can trigger the pulse with great time precision (compared to the speed of sound) and record the actual pulse waveform for full analysis on-shore.

The JBEM will have it's own dedicated fiber to shore, and will connect to one of the 12 standard (two wire and one single-mode fiber) outlets at the junction box.

The tilt and orientation function carried out by the EM in the SPS configuration, have been reallocated to the individual modules in DUMAND II since inexpensive and precise transducers have become available. These will be placed in the OMs. The tilt information is somewhat redundant to the acoustic position monitoring, but the orientation is not otherwise measured.

E String Configuration

The String of modules has been described briefly earlier. Here below we want to give a bit more detail on the actual configuration of the instruments and cabling, the floatation package at the top, and the String Bottom Controller and other gear located at the lower, anchoring end of the String.

The string of 24 OMs begins at 100 m above the bottom (tare height), and continues every 10 m. The EM resides at the top of the center string, for maximal current and tilt sensitivity (and a second EM is located near the ocean floor at the junction box). The CMs are placed near the 1/3 points, but slightly lower to account for the PMT sensitivity being downwards, as indicated in the specifications. The hydrophones are at the string bottom, and roughly at the 1/4 height points of the active section. The CM resides in the center of the array, in order to minimize the cable distance to the modules. (And the fibers are to be zero timed at the digitizer, to facilitate trigger coincidence finding). The relationship of string tension and anchor mass was discussed in I, above.

The cabled region of the String consists of 330 m of double cable, separated horizontally by 60 cm distance. The two sides are nearly symmetrical and each consist of four separate sets of cables mechanically joined: a load carrying cable, and an electrical and fiber optic cable bundle, two up, two going down from the SC. The load bearing cable is made of Kevlar, to have little in-water weight and minimum stretch. The signal and power carrying cable consists of triplets of a wire pair and a multi-mode fiber. The triplets for the hydrophones consist of three wires, with a foil shield. The modules are hooked up alternately from one side and then the other.

The cables pass along side each module, with the module hardhat clamping over the cable. The hardhats, to be vacuum formed of UV transmitting acrylic, not only fix the module relative to the cable, but provide protection for the cable breakouts and connectors. We know from many previous tests that bioluminescence is stimulated by turbulent flow. While the currents and level of bioluminescence at the array depth are minimal, we attempt to minimize any bioluminescence by making the design as streamlined as possible. An additional benefit is the minimization of drag and subsequent array tilt in any currents encountered.

The connectors to the modules will be from commercial sources (unlike the SPS where we had to fabricate our own optical penetrators). The optical and two electrical wires will make separate penetrations, with a cast breakout from the triplet cable. The connectors will be give an extra layer of protection by casting them over, protecting all metal surfaces.

There are several ways to recover a String for repair. One is to lower an active device (with sonar, propulsion, video, and a hooking capability) and simply pull up the complete assembly, String and anchor. The umbilical cable must first be disconnected from the Junction Box, which can be accomplished with the robot, or by remote command of a long life acoustic transponder at the string bottom, which transponder can be activated to cut the umbilical cable.

The String is designed for release at the anchor as well, so that recovery can be accomplished even without the use of the robot. In this instance the String will float to the surface by itself, and can be recovered by a ship. The ideal vessel would be the same vessel as used for deployment, just reversing the String deployment operation, but in an emergency any oceanographic vessel would do (or even a commercial fishing boat). The string is designed so that it will float in a vertical orientation with the float package broaching the surface. The float package carries radio beacons, strobe lights and a radar reflector to aid in location.

F Shore Cable and Junction Box

The shore cable consists of a central metal tube containing 12 single mode fibers, surrounded by copper conductors, insulation, and a double layer of contrahelically wound steel wire armoring. The outer diameter is 13 mm, and the cable is fabricated in about 8 km lengths, with splice cases required at the junctions. The shore end connects to the ocean at a depth of about 20 m, through a slant drilled pipe from about 50m back from the shore line at the Keahole Point station. The shore end will go into the laboratory via a conduit entering under the building, to the room containing the high voltage DC power supply (and battery backup and spare supply).

The Junction Box terminates the cable from the shore station to the array location, and provides the fanout of power and signals to the individual Strings. It is the location for the connections to be made with robotic vehicles. It must not fail. It is also a device with which we have no experience in our previous ocean exercises preparing for DUMAND. For all of these reasons it is a focus of design effort and care. On the positive side the Junction Box is largely a passive device (by design) and involves mostly simple technology. We can also, and have, designed for backup measures, and will also thoroughly test appropriate components.

The Junction Box will be lowered with the cable at the terminus of the cable laying operation from shore. One design concern is to insure that the shore cable termination in the Junction Box has appropriate mechanical properties, preventing any crimping, securely transferring the load to the Junction Box, and handling the transition from lowering to setting down on the ocean bottom without cable damage or having the Junction Box in other than the desired orientation. The Junction Box design is not yet complete, but we have a design that answers all concerns raised so far.

The connections to be made are twofold for each String (J Box to be wired for 12 Strings): the fast data to shore and the command and control network from shore on a single fiber, and the 350 V DC power distribution (two wires). The strings occupy nine ports, the JBEM, one port, and there remain two spares.

The Junction Box power conditioning is not passive, due to the design choice of DC power transmission. We are very concerned about reliability of this unit, and inorder to relieve the system of total dependency, we have designed for a replaceable voltage regulator package. The idea is to make the regulator such that it can be pulled out from the Junction Box, and a spare inserted in it's place. The regulator box will also have a crowbar circuit for overvoltage protection. Individual power connectors will be protected by breakers, in case of string short circuit.

The shore cable contains one isolated power path, and sea water return. The junction box will have a single point ground, and will have the sea water return connection located at a distance of 100 m with sacrificial anode (some debate about it being cathode, not resolved yet).

Mechanically the Junction Box will be about 3 m long by 2 m wide and high, and will weigh about 1 ton in air. The umbilical cables will be transported to the J Box by the submersible or robot, being payed out of a canister under small tension. The transport canister will have the two connectors mounted integrally. Protective caps will be removed, and the connector canister will be pushed into the desired docking location on the J Box.

G Command and Control

The command and control network begins on shore with a dedicated computer (VAX station). This machine is interfaced to the others in the shore station via Ethernet. This station will control the operation of the array. Outgoing commands are delivered to each string fiber separately. Return signals, multiplexed into the rollover words appear as a greatly oversampled 9600 baud serial data stream (1 Mbd).

At the SC the C^2 signals are received by the SC computer. As in the SPS, the SC computer passes on communications to the modules, and controls operations in the SC, including some monitoring functions. The C^2 shore computer will also monitor and control the shore power supply for the array, and take care of other shore station housekeeping functions and alarm condition monitoring.

The C^2 network has the capability to turn on and off the power to all modules, monitor many voltages and currents throughout the array, and set the various voltages for the PMTs and discriminators. It will be the source of startup sequences, calibration operations, and shutdowns. We intend to have default programs at each level (SC and module), so that should outgoing communications fail the system would go into a nominally useful configuration by itself (fail safe). There will also be the ability to reprogram the SC and module computers with updated software, as well as updated default parameters.

H Absolute and Relative Timing

It is planned to derive all timing and frequencies in the array from a Master Clock on Shore. The Hewlett-Packard Time Standards are the devices of choice, as they are compatible with the National Bureau of Standards (NBS) portable clocks, and can be easily synchronized with NBS, giving us both relative and absolute time (UTC). We will receive reliable updating from the Global Positioning System Satellite network. The 1MHz output from these clocks is the easiest to use for our standard. We need absolute time to a precision of about $1\mu s$ in order to study the emissions from some rapidly rotating objects (a current example is the 1.6 ms pulsar, PSR1957+20 which shows signs of possessing TeV gamma emissions).

We realized that having accurate clocks in the ocean was an unnecessary complication, since we can just as well use independent and fairly stable clocks in each string, and employ the continuously arriving time information at shore to calibrate the string clocks. By having the digitizer send the string clock time at the array every so often (1024 words), without the stack delay, we can keep running track of the time offset of the string clock from UT. A fairly simple circuit on shore can then update the received PMT hit times into UT as they arrive (also doing away with ambiguities of string clock rollover). The OM fiber optic signals will be variously delayed at the SC in order that coincident pulses at the OMs will produce the same clock time from the string digitizer. Thus all OM times from all strings will be in compatible time scales even prior to the trigger processor, and they will arrive in order of reception at the PMTs. (Fine timing correction, on the order of a few ns, due to PMT calibrations, is only needed for final event fitting and will be applied in software later). Note that the time will be corrected to the UT of arrival at the shore station. Correction to absolute time of event at the array will be via calculated and premeasured electronic and cable delays. This can probably be accomplished to a few ns, several orders of magnitude better than likely to be needed (except perhaps in relation to the Fermilab experiment).

I Power Supply and Distribution

The power supply to the array has been chosen as DC, after much study. Various complex tradeoffs are involved in both power system and cable design. The plan is to use a 1000 V DC supply at the shore, which will drop under the full 5.5 KW array load to 350 V at the Junction Box. The ocean power supply design is made difficult by the unreliability of high voltage power transistors (otherwise we would have used less current and higher voltage). AC would be much easier to transform, but there is a total lack of experience with long AC power carrying cables in the ocean, and there is a large penalty in weight and cable size as well. The solution arrived at is to deliver a lower voltage than desirable from the cable design optimization standpoint.

There will thus be minimal hardware at the J Box, with parallel DC–DC supplies and breakers for each SC. The output voltage is chosen as 350 VDC (the same as rectified 220 VAC) permitting use of reliable, off the shelf DC–DC switching supplies at the SC. In order to have stability of the system, particularly during power up, we need voltage regulation at the ocean end of the cable. The voltage regulator package at the junction box steepens the load line.

The power supply return from the Junction Box is via the ocean, a well tested practice. The umbilical cables to each string will be isolated from the local ground for safety. The SC case will be at local ground, but the modules' 48 VDC will float relative to the rest of the system. This gives us some protection against a short to seawater at one point in the string. Note that the SC computer will be able to disconnect any of the modules' power (and communications) from the rest of the system in case of a module flood or short circuit. Again here, default programs in the SCs will bring up modules one at a time, with automatic disconnection upon overcurrent.

J Data Distribution and Remote Access

Because of the fact that the experiment is located 30 km by cable away from the shore station, it is not hard to envisage that it may be operated remotely from anywhere in the world. In fact this is just what we plan to do, made especially convenient by the location of collaborators around the globe, so that no-one will have to take night shift! The possibility to do this is enhanced by the low data rate of physics events, which can be handled on available networks (HEPNET, SPAN). The University of Hawaii Campus Research Network (CRN) has appropriate connections to all major networks, including the Pacific Research Network, giving us a high speed link directly to the University of Tokyo. We plan to link the Keahole Point Laboratory with the CRN to complete the links.

Within the shore station the computers (VAX machines) will be linked together and to the CRN via ethernet connection. This will permit remote system users to log into any one of the machines for software development, debugging, or ordinary monitoring. (Of course we plan to have onsite personnel, particularly during the first few months of operation.)

It is important to have rapid and equitable data distribution to the entire collaboration, and we can thus plan to do this on-line. Data will also be logged at the shore station, employing 8mm tape for archival purposes. Interesting event categories will be stored on disk for immediate retrieval.

Obviously appropriate computer security measures will have to be implemented, particularly since the remote access would potentially permit destructive changes to be made to power supplies.

K Cable and Junction Box Deployment

The cable route has been studied in some detail. Expert consultants recommended a smooth route down the slope from Keahole Point to the flat ocean bottom near the array location. It now appears that the slope of the Big Island, West of Keahole Point, down which our cable will pass, is quite a bit better than we had anticipated. The survey data acquired in the site survey in January 1991, demonstrates that the route need not be controlled better than to a precision of about 1 km, and that the bottom character is mostly sediment, with few boulders and cliffs. Moreover, the near slope bottom area seems the best in terms of bottom smoothness, which will reduce the cable run somewhat (32 km perhaps).

There are some remaining cautions about a location so close to the ankle of the slope, so a current study at the new site is dictated to be sure of the safety of the location. The caution is enhanced by the observation of a lack of sediment at the chosen site. While this is good for placing the anchors without danger of sinking into the mud, it may also indicate benthic currents off the slope. (The acceptable fallback would be to relocate several kilometers farther into the basin.)

The cable deployment will be carried out (as a training exercise) by an AT&T cable service vessel which is normally based in Hawaii (supported by a consortium of cable companies for the purpose of emergency cable repair throughout the Pacific). This group has more experience with deep ocean cable laying and repair than any other, and we could hardly be more fortunate than to have their help. They consider the cable laying a fairly simple activity, to be carried out in a few hours. There are still some concerns to be addressed on the overboarding process for the junction box. The intention is to lay the cable down the slope, junction box last (a much debated issue, but probably either direction would work).

L String Deployment

The deployment operations are described in the White Paper, so we shall not reiterate them entirely here. The String deployment will be very similar to our experience with the SPS. The first change is that we will employ a shipping container for test and transport of the String. The String modules will be suspended along the opposite sides of the container, from which they will be pulled out one–by–one for placing in the water. We intend to use the Kaimalino for this operation also. The major change (aside from 3 times as many modules as in the SPS) is due to the need for a heavy string anchor (2 T). To take care of the handling problem we will use two winches attached to the gantry, alternately lowering and raising each. The ship's crane will then be used to move the modules into position for lowering. This method is quite straightforward, and we can predict, based upon our previous experience, that deployment of the full string will take less than 1.5 hours, from container to submersion.

Should problems arise at any time during this operation, the procedure can be reversed without penalty (other than time!). Once in the water, the String will be lowered at 60 m/min to the vicinity of the ocean bottom, taking about another 1.5 hours for the descent. The lowering line is a passive Kevlar line, with acoustically commanded release at the bottom to detach the string.

The ship will navigate by using the microwave transponder network to shore. As the string enters the bottom transponder network we can obtain data on the location of both the String top and String bottom from the battery powered transponders. These devices send a pulse out to the fiducial transponders, and measure the round trip time for a return pulse, which they then relay to the surface (and we can listen for these pulses from the EM located on the JB, connected on–line to shore). We can get the position of the string within about 1 m by this method, and guide it during lowering into the correct area. (The first String is easy, but for subsequent lowerings one must be careful to come down close to the correct location to avoid the possibility of collision). The method of emplacement is to simply wait until the string comes into the desired location, while keeping it several meters above the bottom, and to drop the final few meters in several seconds. If we are unsatisfied with the location we have only to pull up and try again. The response of the string at the bottom is very slow so this operation may take several hours (a computer program has been developed in Hawaii to predict the motion, and to guide the ship to avoid overshoot, etc.).

At first we considered active anchoring into the ocean bottom, but it appears that will not be necessary. The anchor package will simply have spikes that sink into the bottom. A backup, self emplanting emergency anchor will also be attached to the package.

After satisfactory placement of a String, the acoustic cable release is activated, and the lowering line retrieved. The String is now ready for connection. We estimate the deployment lowering and placement operation cycle to take less than 12 hours. Thus with allowance for crew rest time, we can plan to deploy one string per day, comfortably. Waiting for a decent weather window could delay operations up to one week, but our experience with the Kaimalino indicates that we can operate in the sea state situations that exist more than 90% of the time in the area off Keahole Point.

There remain some concerns about the ability of the Kaimalino for adequately responsive station keeping for this operation. This is under study at present, but alternative vessels have been identified as backup possibilities.

M String Connection

The String connection operation will require the use of a submersible or robot, as discussed earlier. The device of choice is the manned submersible USN Sea CLiff, operated by the SUBDEVGROUP out of San Diego. This submarine has the strength and dexterity we require. The operation is extremely simple, in human terms, but nothing is trivial in the deep ocean. The String bottom package includes a cable canister for the umbilical cable. The first task is to approach the string from a safe descent distance several hundred meters away (precluding the possibility of tangling with the 350 m tall String). In this operation we use the transponder network for relative bottom navigation, and the microwave transponder network to stabilize the ship position. The EM on the JB will also give us bottom current information, permitting us to choose the current set we desire by timing the setdown.

The submarine or robot pulls a pin to release the cable container, and then moves the container to a holder on it's framework. This holder allows the cable to pay out as the crawler then moves off towards the Junction Box. When the JB is reached the vehicle moves alongside the JB. Protective caps must be removed from both ends of the connections. The robot arm is used to put the cable canister into stowage position, making the connections as the canister is guided into it's slot on the J Box.

The operation may be reversed, though we have not found a satisfactory method of rewinding the cable. If we do not find such a scheme we would plan to simply gather the cable in a basket attached to the sub or robot, and leave this basket at the String base for recovery with the String. The cable and reel are designed to be slightly less than buoyant in water, but will weigh less than 100 pounds total in water weight.

N Repair and Replacement

String replacement has largely been covered in the above sections. We have considered the desirability of individual module replacement, but find the added cost prohibitive, and that a better strategy is to wait until a threshold fraction of module failures is reached, and then replace a whole String. We have budgeted for one complete String replacement per year. Monte Carlo simulations indicate that operations will be minimally effected up to about 10% failures in the array. A complete String failure is cause for recycling at the earliest opportunity.

If the main cable should fail, we must probably completely replace it, since the conventional wisdom says that we will not be able to retrieve it without snagging on the complex slope (nevertheless we would try). We would employ a vehicle to detach the strings from the Junction Box, and to attach a hauling line to the Junction Box. A disaster recovery scenario would involve not having any deep ocean vehicle immediately available. We could remotely detach the Strings and recover them individually. Then we could dredge for the main cable, and pull up the junction box, further recovering as much cable as possible. This could be carried out with the Kaimalino or a ship of opportunity, and would allow us to recover 90% or more of the capital equipment in a one week effort.

A less dreadful scenario would involve the failure of the power conditioner in the Junction Box. The design is such that a submarine or robot could be used to install a replacement directly, and thus the delay time is probably governed by vehicle availability. It is for operations such as this that we are encouraging the development of a Hawaii based remotely operated vehicle system (FOCUS).