TECHNOLOGICAL ADVANCES ACHIEVED IN DUMAND

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ABSTRACT

The requirements of DUMAND in PMT design, underwater Cerenkov light detection, signal processing, and deployment are described, and the methods by which they are achieved outlined.

INTRODUCTION.

The Hawaii DUMAND Center is engaged in establishing the feasibility of DUMAND, which stands for Deep Underwater Neutrino And Muon Detector. An extended and unremitting effort to arrive at a design, at once economical and effective, has resulted - not unexpectedly - in advances in several of the fields with which DUMAND is concerned. These include, among others:

1. The technology of detecting very weak Cerenkov light in the ocean; a task complicated by interfering signals, not only from bioluminescent organisms, but by the pervasive weak intrinsic glow of the ocean. That glow is due to the Cerenkov light produced by the radioactive elements dissolved in the ocean, chief among which is K^{40}.

2. The problems associated with processing signals produced in an array of between 500 and several thousand photomultiplier tubes, in arrays that occupy an appreciable fraction of a cubic kilometer. It is necessary to distinguish particle tracks from the high radioactive background, to reconstruct the tracks, and to measure their direction and energy. This is to be done in the presence of an additional background of cosmic-ray muons traversing the array at rates from 20 to 100/sec, which are themselves interesting and must be recorded.

It must also be possible to distinguish signals from a single muon from those produced by multiple parallel and simultaneous muons, and to obtain some approximate estimate of the number of muons traversing the array in a single event.

The signal processing is to be done under control from the shore, and must be reliable enough to continue working for five to ten years without any servicing.

3. The array is to be so designed that it can be preassembled, prewired, pretested, and deployed in a single operation. It will be connected to shore by an undersea composite cable using copper to supply power

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and optical fibers to carry data. Fig. 1 shows the array as we now envisage it. It is the smallest, least expensive array suitable for studying high-energy atmospheric muons and neutrinos produced by cosmic rays, and for searching for extraterrestrial high-energy neutrinos, thus opening the science of high-energy neutrino astronomy.[1]

In this paper we describe briefly the efforts to date at solving these problems. To summarize, we believe that feasible and cost-effective solutions to all these problems are now available; in many cases there are several alternative solutions.

SENSOR DESIGN.

The sensor design problem is defined by the intensity of the Cerenkov light as a function of distance from the track of a minimum ionizing particle. Fig. 2 shows a plot of that intensity, in quanta per square meter, in water in which the attenuation length for Cerenkov light is 20 meters. (This definition requires amplification, which would be out of place here; see Ref. 2) We note that it is desirable to be able to detect light fluxes of 30 quanta/m^2, or even less, in order to separate sensors by 50m. For convenience we have introduced as a unit of sensitivity the number of photoelectrons delivered to the first dynode of the PMT when it is exposed to a Cerenkov flux of 100 quanta/m^2. The higher the sensitivity the further apart the sensors can be.

Work on obtaining high-sensitivity sensors has followed two paths. First, we requested PMT manufacturers to provide PMT's with larger photocathodes; second, we also investigated the use of wavelength-shifting techniques to multiply the effective area of a PMT cathode. It now appears that the first of these approaches will yield satisfactory tubes. The WLS approach resulted in the development of a highly sensitive detector called Sea Urchin, which will be described in detail elsewhere[3]. It turned out to be less cost-effective, largely because of the costs involved in packaging and deployment.

PMT Development. - - The PMT tubes developed to date are all hemispherical-cathode tubes, designed to have as isotropic a sensitivity function as possible, and to fit inside a pressure-tolerant glass sphere that carries the ocean's hydrostatic pressure at the 5-km depth required. They are as follows:

1. EMI is developing a 13" (33-cm) diameter PMT, with a high-gain first dynode. We have received a working sample. Fig. 3 shows such a tube in a 17" O.D. Benthos glass sphere. EMI is planning improved versions.

2. Hamamatsu have built a working PMT with a 20" diameter hemispherical cathode (50 cm). We have tested it, and find it would be an excellent tube for us (assuming it meets our other requirements) if we had a glass sphere in which to package it. No such spheres are in production.

Hamamatsu are also working on a 16" tube to fit inside the 17" sphere.

SIGNAL PROCESSING IN THE PMT.

Discrimination. - - The first stage in signal processing is the rejection of PMT background. The uniform Cerenkov illumination in the ocean due to the decay of the normal constituent K^{40} is calculated[4] to be $150L_{20}$ quanta/sec cm^2, where L_{20} is the optical attenuation length[2] in units of 20m. Thus a hemispherical cathode of diameter 13" (33 cm) is subjected, in 20m water, to a flux totaling $150 \times 3\pi \times 16.5^2 = 3.22 \times 10^5$ quanta/sec, which at an average photocathode efficiency of .15 would give a background counting rate of 48K counts/sec.

Superposed on this background are a few true signals; we must devise a method for discriminating against the background.

If we examine the background closely, we find that it contains two components. The true radioactive background consists overwhelmingly of single quanta. Each decay averages about 43 quanta[4], and these are not far from isotropically distributed in direction, since the potassium beta rays have a maximum energy of 1.25 MeV, and are consequently strongly scattered in the seawater. Only a very occasional decay would yield more than one quantum striking the photocathode, and the chance of obtaining more than one photoelectron is thus quite remote, considering the mean cathode efficiency of 15%.

Thus, in the absence of other backgrounds, the ideal discrimination procedure would be to cut out all single-electron counts, and record only those with two or more primary photoelectrons. In principle this is possible if the first dynode of the PMT has a sufficiently high gain that one can adequately discriminate against single-electron pulses. The RCA 8850 and 8854 PMT's, with gallium phosphide first dynodes, are examples of such tubes. According to the PMT manufacturers, the discrimination against single-photoelectron pulses by means of high-gain first-stage dynodes is more difficult in large PMT's than small ones. Accordingly, the discrimination against the single-electron background may need additional selection beyond that provided by a high-gain first dynode.

Spurious Signals. - - However, that is not the entire story; all PMT's suffer from another background which is not so readily disposed of.

Because of the residual gas in the PMT, and the relatively long path travelled by the photoelectrons on their way to the first dynode, the probability of a photoelectron ionizing a gas molecule on the way is not negligible; it is of the order of a percent or so. The positive ion so formed is accelerated to the cathode, and strikes it with a considerable fraction of the cathode-dynode potential difference. The probability of the ion ejecting several secondary electrons is high; thus some small pulses will be accompanied by large, delayed spurious pulses. The average height of these pulses may be as much as four to six electrons. They will consequently pass the discriminator.

Since they are delayed by the travel time of the slow-moving positive ions - 0.5 to several microseconds - they simply provide an out-of-time background to the true events. Should the rate be too high, however, they can cause difficulties, by interfering with the track-finding algorithm. The fraction of such spurious delayed pulses varies in different tubes, depending on vacuum and other factors, from less than one percent to several percent. At several percent they might well be troublesome; however, if we go to segmented tubes, as discussed in the next section, it may be possible to reduce or eliminate this background.

Segmentation - - One procedure that has been suggested, and is being investigated, is segmentation of the multiplier structure. Suppose the multiplier structure is divided into m independent segments, where m is between, say, 4 and 10. We can now distinguish two cases. First, suppose the cathode is imaged on the first dynode, and there is no cross-talk between segments. Then a particular area on the cathode is always associated with the same multiplier segment, and the tube is equivalent to m smaller phototubes in parallel.

In the second case, the tube is not imaging; cross-talk does not occur between different segments, but photoelectrons from a particular point on the cathode are not uniquely associated with a particular segment. If there is appreciable cross-talk between different segments, so that a single photoelectron can produce appreciable output signals from more than one segment, then the segmentation is ineffective and not worth having.

As far as single photoelectrons are concerned, the two cases are indistinguishable; the chance of two independent photoelectrons ending up on the same segment is just the same. However, for large signals with more than one photoelectron originating at the same point, there is a difference. In the imaging case, the electrons all go to to the same segment; in the non-imaging case, they may or may not. If they do not, then the large single signal may counterfeit two or more independent simultaneous photoelectrons.

A true signal in DUMAND arises from diffuse illumination of the photocathode producing two or more simultaneous single photoelectrons from different locations on the cathode. These behave the same way as K^{40} single photoelectrons; they do not distinguish between imaging and non-imaging structures. Only the spurious multi-electron pulses produced by positive-ion bombardment behave differently. In the imaging case they remain in a single segment; in the non-imaging case they may spread into several. Any degree of behavior between these extremes is possible. We see that imaging or near-imaging behavior is desirable to suppress the spurious background. However, even if imaging turns out not to be possible, the suppression of the K^{40} background achievable by segmentation is still worth while.

Suppression takes place as follows. If we demand a two-fold coincidence between any two of the m segments, and the total background rate is N, the resolving time τ, the random coincidence rate C will be

$$C = [m(m-1)/2] \times [2(N/m)^2 \ \tau]$$

$$= N^2 \ \tau \ (m-1)/m$$

Thus the number of segments m is to a first approximation unimportant (except that it decreases both background rate and detection efficiency by $(m-1)/m$); what matters most is the overall counting rate. With m large, N = 5×10^4/sec and $\tau = 10^{-8}$ sec, the background rate is only 25/sec.

Other Data from PMT. - - The signal we have so far discussed is one for which we record both the time of arrival and the amplitude. If it is in fact feasible to perform the proposed discrimination, this will considerably ease the data transmission and reduction problem. However, if the proposed techniques do not result in quite so much reduction of spurious signals, we may well still find ourselves with several hundred or even several thousand counts/sec per PMT. We must be prepared to handle this rate.

Multiple Muons - - It is important to be able to distinguish events in which several closely-spaced parallel muons are observed. High-energy cosmic-ray primary interactions in the atmosphere produce a jet of pions, whose decay leads to the parallel muon bundles. In such events the most important distinction is among one, a few, and many; it is not essential to be able to count the number accurately.

Since the sensors are 50 meters apart laterally, 25 vertically, it is not easy to distinguish parallel tracks several meters apart. We have found this to be possible by using the timing information available in multiple signals. The typical track separation of a few meters, due to multiple scattering in the ocean, results in timing differences large enough to be distinguishable. We find by Monte Carlo methods that the change in pulse shape between single and multiple events (which is due to signals reaching the same PMT from more than one track, at slightly different times) is sufficient to distinguish readily between one and more than one track. More detailed distinction of the number of tracks may be possible, preliminary Monte Carlo results being encouraging; but this is a quantitative question that must be checked with real PMT's. Flash digitizers will be useful for this purpose.

SIGNAL TRANSMISSION

It appears that it will be highly advantageous to make the link between the undersea array and the shore station a fiber optics cable. The data capacity of such cables is far greater than that of copper cables; in addition the attenuation is much less (0.1 to 0.5 db/km). We would not need repeaters in either case, since the link is only about 45 km long. We expect that the technology of such undersea cables will be in hand to provide us sample cables by the end of 1982.[5] A 200 Mbit/sec cable appears to be readily possible. This will allow for considerable expansion in array requirements for the future.

It is not yet clear whether the individual strings require fiber optic cables. It depends on the amount of data to be collected from each sensor. In one scheme, conceptually the simplest, all data, including background, are transmitted to shore, and all discrimination, sorting, etc., is done there. The cable bandwidth is sufficient to handle this with fiber optics; and the scheme has the virtue of placing the least amount of electronics under water. It does require labelling for each count, so that it can be assigned to the correct sensor. In the remainder of this discussion, we will assume that pulse-height discrimination and signal digitization are accomplished at the sensor.

Distribution of Signal Processing - - In order to avoid the possibility of losing large sections of the array, it seems wise to restrict all signal processing operations to the individual sensor or to the shore computer. A string or row processor carries an inherent danger of losing an entire string or row if the processor malfunctions.

While this would be the ideal arrangement, it now appears that the closest approach to it would be that string and row processing, if used at all, would be simply in the nature of multiplexing or adding signals. Somehow all the sensor signals must be combined into one, or a few, fiber optics cables for transmission to shore. This process appears to be unavoidable; but at least it can be made highly redundant so that failures need not be damaging.

SENSOR LOCATION AND MONITORING.

The strings, anchored at the bottom, are kept nearly vertical because individual modules are buoyant, and by an additional flotation module at the top. As the ocean currents vary, the strings will follow them, and the position of an individual module with respect to the ocean bottom can vary by many meters. Such lack of rigidity in track-reconstructing detectors is hardly ideal; but it can be lived with if the position of the individual modules is known at the time of any particular event.

To keep track of sensor positions, it is expected that each string will be provided with several hydrophones. On the ocean bottom several pingers at known locations will periodically emit signals; from the time of arrival of these signals at a given hydrophone its location can be determined. It is not difficult to achieve an accuracy of better than one foot, which is sufficient for our needs.

In addition, we need to monitor the ocean transparency and the sensitivity of all the modules. Suitable light pulsers should fulfil those needs.

Bioluminescent animals are to be expected, but there is very little data on which to estimate the frequency or intensity of such flashes. They are readily distinguished from particle tracks by their duration, which ranges from tens to hundreds of microseconds for bacteria to tens or hundreds of milliseconds for large fauna. It will be desirable to make provision for recording such signals; the array will constutute the largest, by many orders of magnitude, ever used for bioluminescence studies. Experts predict little dead time from this source of interference.

DEPLOYMENT.

All array designs to date have deployed the sensors in the form of "strings" - a series of sensors tied to a common cable, anchored at the bottom, and kept extended by a flotation module at the top which maintains the string essentially vertical. Alternative systems - e.g. rigid skeletons - have proven so far to be either more expensive and less reliable, or impractical.

A string is not deployed in its extended form; it is packaged into a "canister" like that shown in Fig. 4, which is much easier to deploy, and which also acts as a protective housing during deployment and as an anchor afterwards. After the canister is emplaced, the top is released, and the string floats out.

No one has ever deployed so large or complex an assemblage of scientific equipment in the ocean; nor has anyone ever deployed a complex system at the depth proposed for DUMAND (4.5 km). Deployment has been studied in two major workshops[6,7], and at least three methods proposed; others are no doubt feasible as well. Rather than describe all, we select one that is almost certain to work; its main drawback is that it is expensive, requiring the use of an oil drill ship, for which rentals run from $55,000 - $100,000 per day. The Glomar Challenger, now under lease to NSF, would be ideal for this purpose. Figs. 5 through 9 illustrate deployment using a drill ship.

Since the full capability of the drill ship is not used (we use its great load-carrying capacity, but not its ability to drill - to rotate the drill pipe) efforts are under way to find ways of using less expensive ships that can perform the other required functions.

In all deployment methods suggested, the array can be assembled, prewired on the surface, and deployed as a single unit, already connected to the cable to shore. This implies that continuous testing of array operation is feasible during the deployment procedure, which can be halted if anything goes wrong. It assures a working array when deployment is completed.

ACKNOWLEDGMENTS

The work described here is largely the result of a DUMAND feasibility study now approaching the end of the second year of a three-year term. It is expected to culminate in a proposal for the construction of an initial

DUMAND array. Literally scores of people have contributed ideas and suggestions at many DUMAND meetings, symposia, and workshops, whose proceedings now occupy nearly a foot of shelf space. The major burden has been carried for the last two years by the Hawaii DUMAND Center, where the feasibility study is centered, and where the authors of this paper are located. The project has been supported chiefly by the University of Hawaii, the State of Hawaii, the Department of Energy, the Office of Naval Research, and the Naval Ocean Systems Center of San Diego. It has had the guidance of a steering committee chaired by Prof. F. Reines of UC Irvine, and has enjoyed the collaboration of many foreign colleagues as well.

SUMMARY

We see that solutions for all the major technical problems of DUMAND appear to be feasible. Further work is clearly desirable in many areas, but we now feel reasonably confident of success. In the area of phototube production, two manufacturers have produced phototubes with large hemispherical photocathodes that can be used; and there is good reason to hope that further improvements in performance can be anticipated that would simplify the array electronics and decrease the cost.

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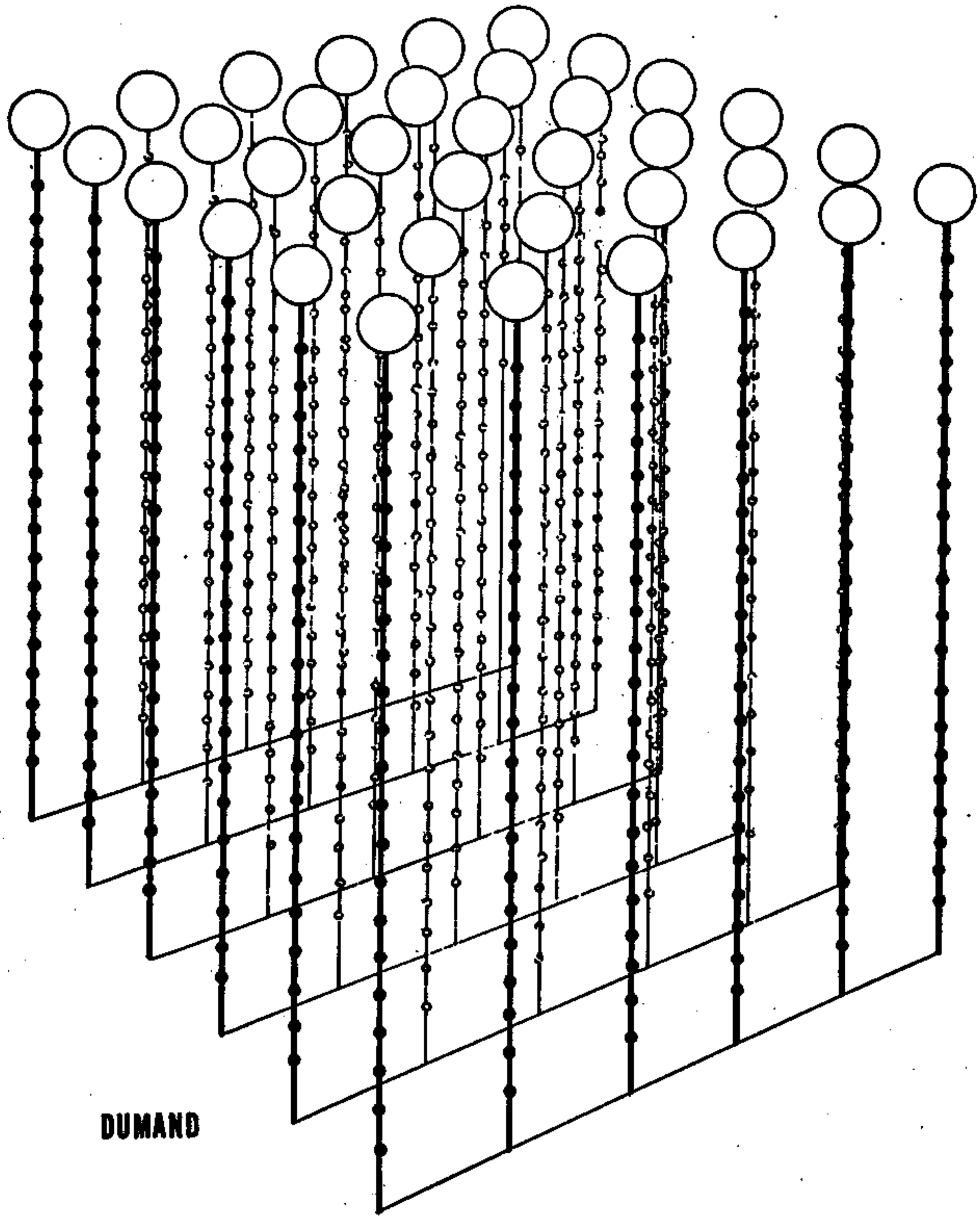

Fig. 1. The DUMAND array. It consists of 6 rows of 6 strings each, spaced 50m apart in a square of side 250m. Each string is 600m high, and contains 21 sensors 25m apart, starting 100m above the ocean floor. Strings are anchored at the bottom, and kept vertical by a flotation module at the top.

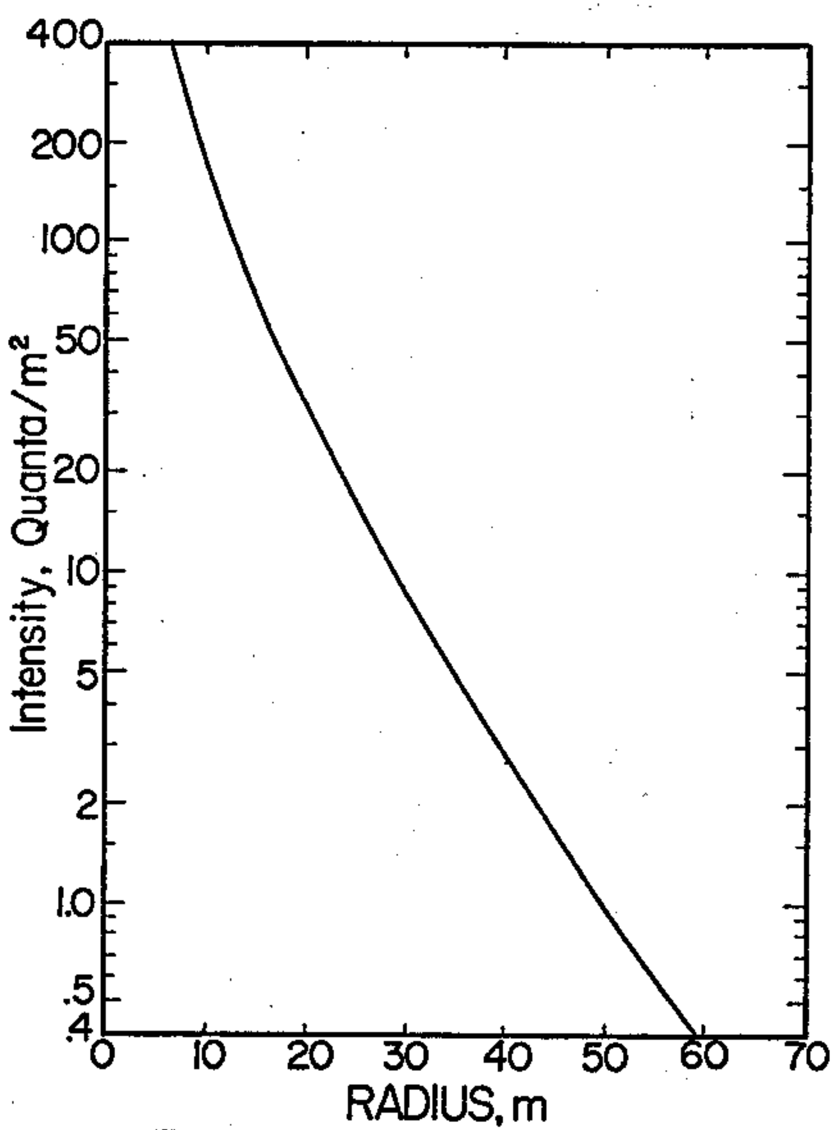

Fig. 2. Intensity of Cerenkov light from a minimum-ionizing particle, in 20m water, as a function of distance from the track.

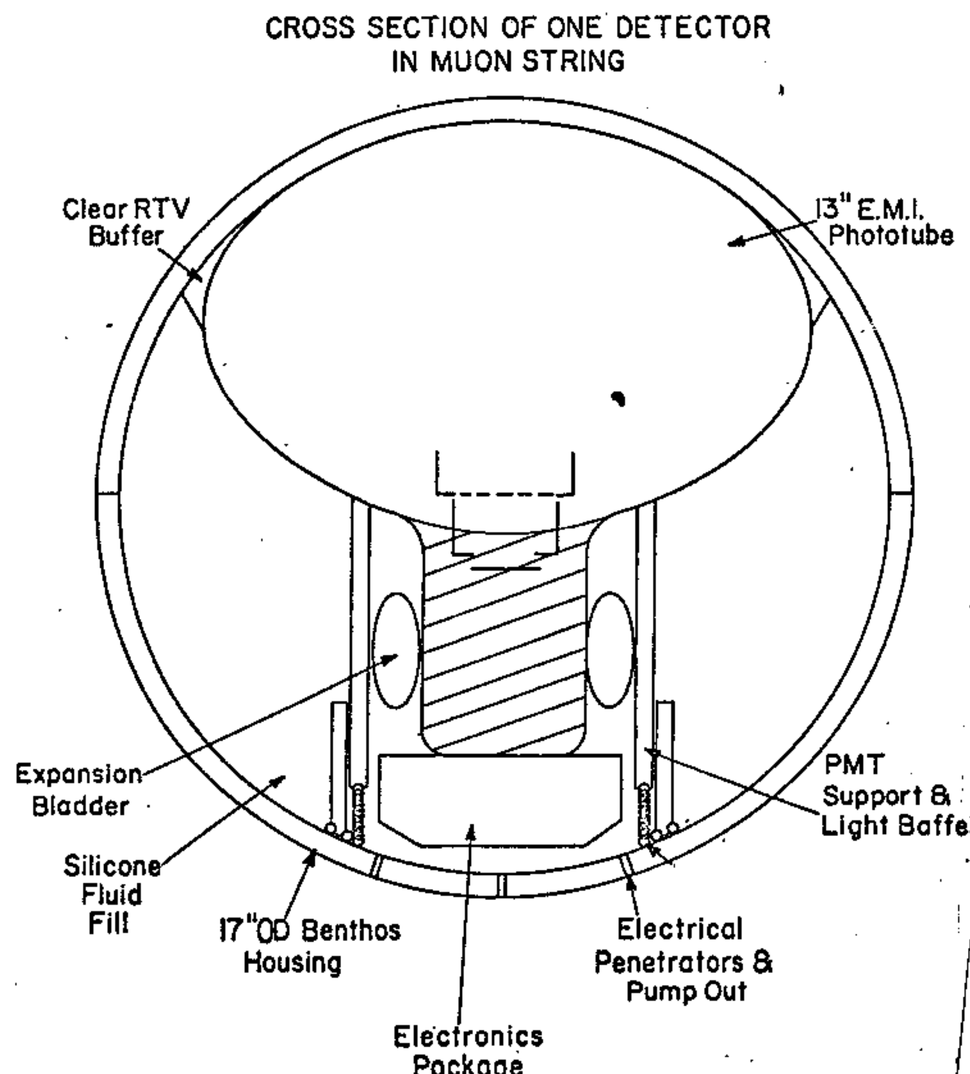

Fig. 3. Detector module: Pressure tolerant 17" diam sphere containing 13" PMT. This is one of the five modules in the "muon string", the first DUMAND test detector, to be deployed by cable from a ship early in 1982.

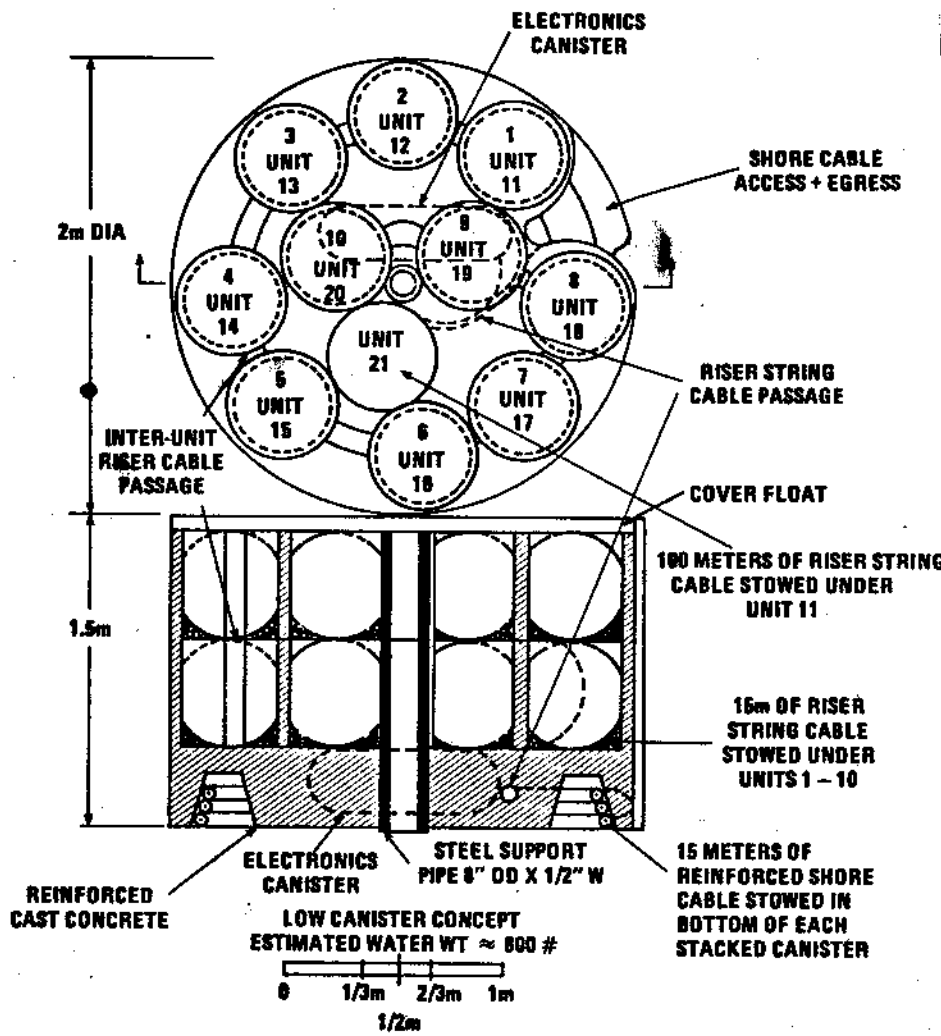

Fig. 4. Design for a canister to hold one of the strings of the array.

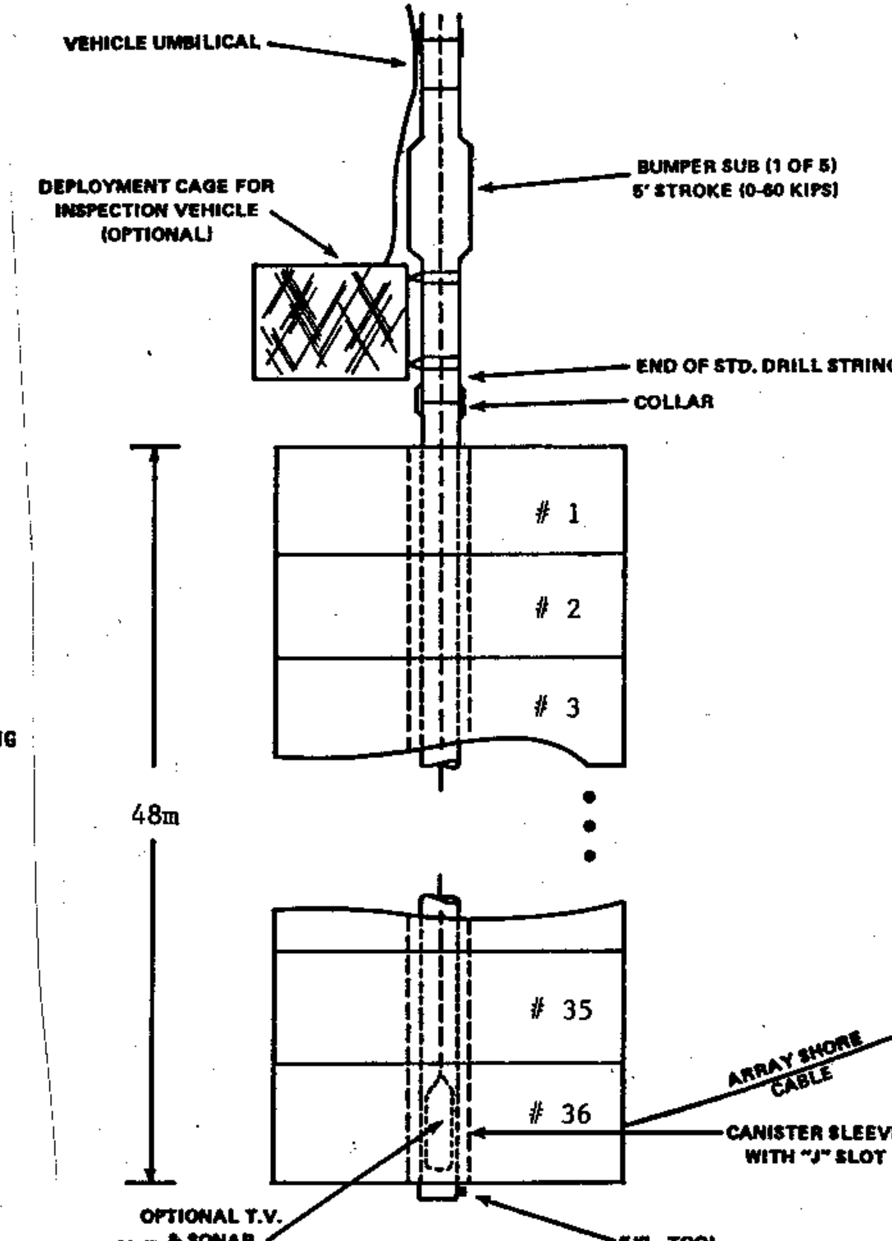

Fig. 5. The "bagel-on-a-string" concept, showing how all 36 canisters can be mounted on a "drill-string" – a long, jointed 5-in steel pipe assembled by an oil drill ship (as shown in the next figure) – and deployed all at once.

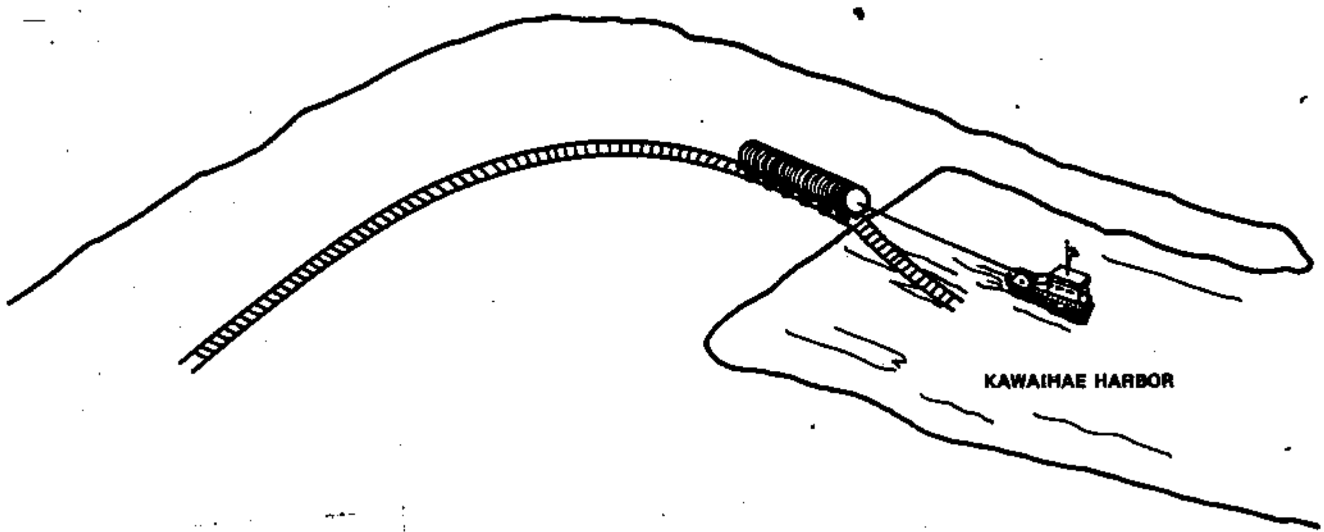

Fig. 6. The 36 canisters mounted on a 5" drill-pipe, used as a mandrel, mounted on a railroad préliminary to launching into a harbor; the assembly will be kept from sinking by floats.

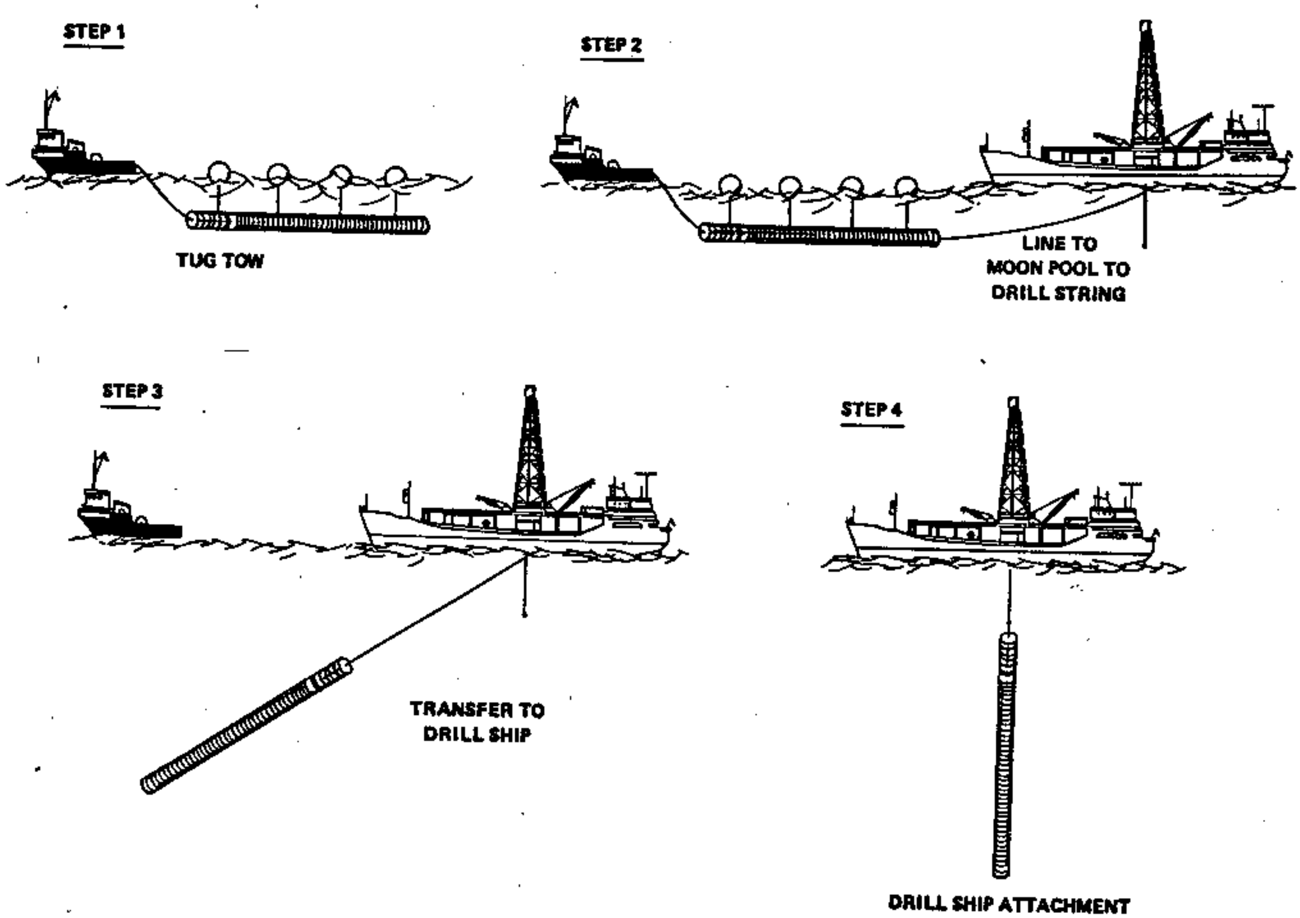

Fig. 7. Technique of transferring the drill string to the drill ship.

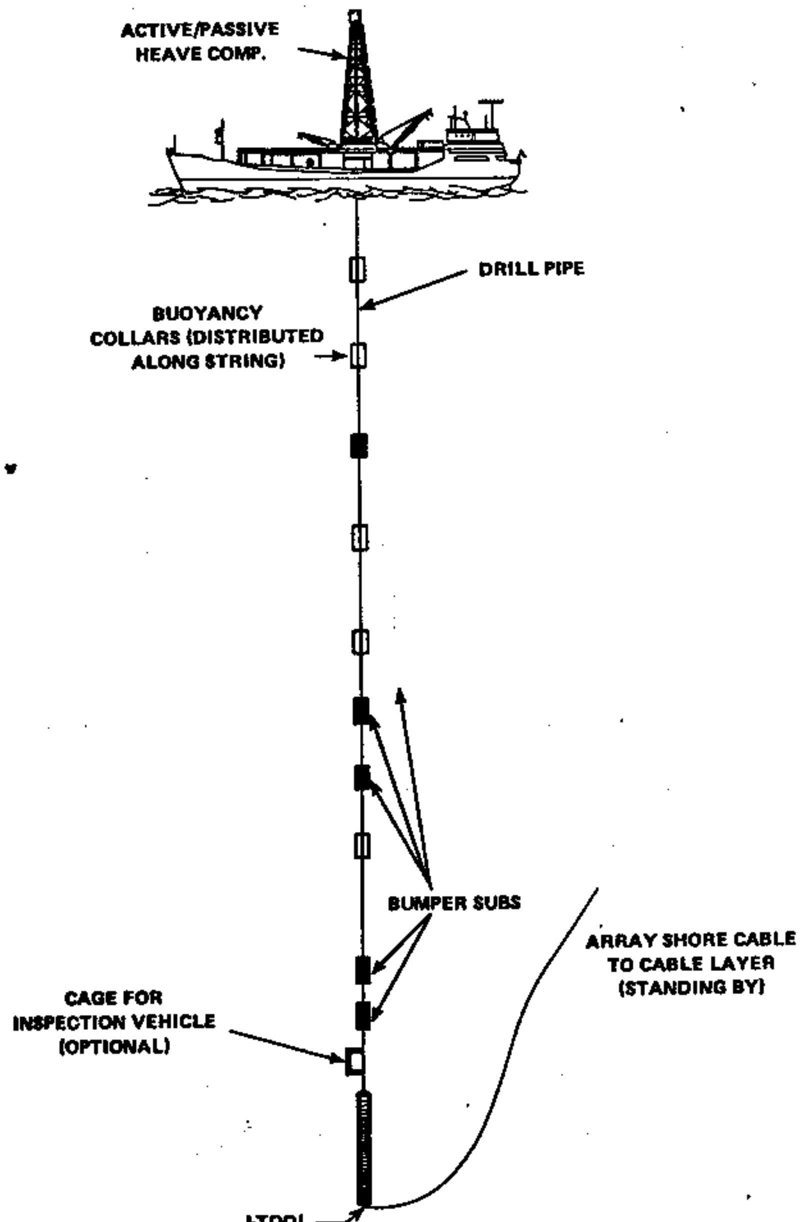

Fig. 8. Drill string completely assembled, with canisters ready to be deposited on the ocean bottom.

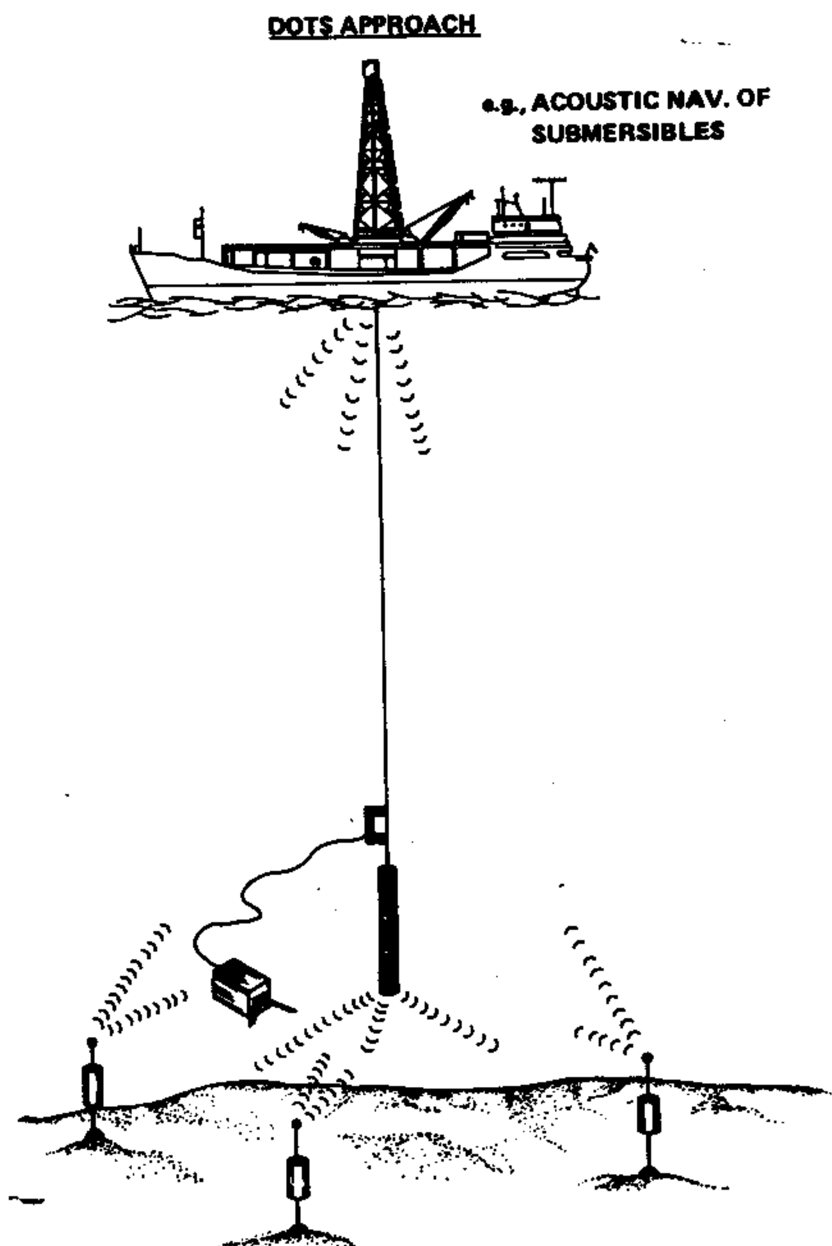

Fig. 9. Depositing the canisters on marked positions: the use of acoustic signals to locate the proper positions.