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UWSEA PUB 90-19

11 Nov/90

Dumand II. Surveying the telescope so that we can point to the stars with at least 1 degree precision.

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Abstract.

The Dumand II telescope is intended to be surveyed in space such that it will have a pointing accuracy of better than 1 degree in star coordinates. The chain of coordinate transfers from star coordinates to satellite coords to ship coords then via sonar to sea bottom fiducial transponders and hence to the telescope array is examined. The weakest part of the link may be the sonar coordinate transfer from the ship to the seabottom fiducials. The author suggests that the Dumand II physicists will want to include in their system, the equivalent of a plumb bob, tape measure and transit in their environmental module.

For the Proceedings of the Dumand Meeting at Tohoku University. October, 1990

1. Introduction.

The first elements of the Dumand II telescope will be deployed in March of 1992. This will include the shore cable and junction box as well as the Junction Box Environmental Module, JBEM. The JBEM must contain the elements necessary to carry out the neccessary survey of the Dumand II telescope and to express the elements in star coordinates with a pointing accuracy of better than 1 degree.

The method that we have chosen is analogous to the method used by geographers to map earth features using photographs from aircraft. The geographers first lay out white spots on the ground which are surveyed to high precision in earth coordinates. The earth features are then related to the white spots via the photographs and hence to earth coordinates.

In Dumand II, the white spots are the transponder set which are surveyed to high precision via the chain of stars-satellite-ship-transponder. The telescope is then surveyed relative to the transponder set. Figure 1 shows the Dumand II telescope and its relation to the transponder set. Since the telescope elements are anchored at only one end to the sea floor and the other end is free floating, the telescope elements are likely to be in continual motion as they are wafted about by the sea currents. The sea currents are quite small at the deployment depth of 4500m. To account for this small motion, the local sonar survey of the telescope will be carried out with a frequency of the order of 0.1 Hz.

1.1 Conventional techniques for the Satellite bottom transponder survey.

It is generally accepted that the present Satellite-ship system has a standard deviation of about 1 meter in placing the ship in earth coordinates. The transponders placed on the bottom can provide round-trip transmission time information to the ship by responding to a sonar beep from the ship. Figure 2 illustrates the system. The round-trip time must, in turn, be converted to range and the ship must make at least 3 measurements from different positions to find the position of each transponder in 3-dimensional space. The conversion of the time to range is complicated by the variation in sound velocity through the ocean. This variation results from changes in temperature, pressure, salinity and the presence of ocean currents. The variability in sound transmission affects the sonar path both in time to range conversion as well as the refraction of the sound wave fronts.

Conventional wisdom characterizes the standard deviation of the sonar path to be about 1%. This would yield a standard deviation of about 50m in a 5000 m measurement from surface to the bottom. The average ocean profile has been measured and codes have been produced to take these effects into account. In general, if there are n parameters to describe the sonar path, and 3 parameters to charactize the space coordinates of the transponder, one would need to make n+3+1 = m measurements to find all of the

unknowns. More than m measurements would check the efficacy of the measurements. Conventional wisdom from the marine specialists have informed us that the surveying accuracy by this method is about 1 meter.[1] Figure 2 shows the circles of confusion circa 1982 when the circle of confusion for the ship's position was of order 100m and so is not a reflection of today's accuracy. The final transponder locations had circles of confusion of about 100m in the 1982 example from Creager et al. Creager et al used standard ocean parameters and did not carry out an in-situ measurement of the sound velocity profile of the ocean and this may have contributed to the uncertainty of their measurement. Dumand II should certainly carry out the sound velocity profile measurement in-situ by using a standard ocean sounding instrument at the time of the sonar survey of the transponders.

If we assume that the spatial accuracy is 1 m and we space the transponders by about 1000m, then the angular accuracy of the transponder placement is 1E-3 which is well under the 1 degree requirement. We could tolerate spatial standard deviations of several meters for the transponders.

1.2 Conventional considerations for measuring the OM's using the transponder array.

Assuming that the ocean currents have a constant flow in space, the strings of OM's will form a catenary curve. In figure 3, we show the calculated configuration for a string in a current of .5m/s, .3m/s and .1m/s; and with a float buoyant force of 1000 pounds.. By measuring the ranges of three fiducial points on the strings from the transponders, we will be able to predict the spatial coordinate of each OM. To obtain a 1 degree pointing accuracy from a pair of OM's spaced apart by about 10m, we would need to know the OM's position to 0.17 m. We estimate that we would need to know the position of the 3 fiducial string points to .10 m. [2]

How can we know the fiducial positions to .1 m if the transponders are known only to several meters? Consider in the horizontal plane, the subset of the pinger on the JBEM, one transponder, and one of the hydrophones on the string1. We will measure the three sound transmission times between the three components to high accuracy. With knowledge of the sound velocity, these can be converted to ranges. From these 3 ranges, we can deduce the interior angles of the triangle. If we repeat this process for string 2, we can deduce the relative position of string 1 to string 2 with good accuracy. Of course, this can be repeated for all the strings. This set of relative measurements, of course, do not measure the relative alignment to the star coordinates.
In summary, the local measurements of time can obtain good accuracy in relative angles but cannot determine the angle in star coordinates.

The elements that contribute to the uncertainty are the sound velocity, the uncertainty of the transponders positions and the timing accuracy of the sonar pulse. The sound velocity can be routinely determined to about .5m/s or 3 parts in 1E4 by conventional methods using the Niel Brown Unit. This produces an uncertainty of .17 m for a single

measurement. The measurement of transmission time will be quite good because we will digitize and record the waveform of the beep and not just the threshold time. In this way we can obtain ranging accuracies of small fractions of the wavelength. The uncertainty due to the measurement of arrival time will be .003m and so is neglible. Since the fiducial hydrophones on the strings will be swept by the currents, each measurement constitutes a new measurement that will allow us to determine the sonic path by fitting a set of measurements. Once again we may be able to overdetermine the problem with many measurements to obtain the required accuracy.

1.3 Cautionary Tales from Accelerators.

In almost every accelerator experiment in which the author participated from Berkeley to Brookhaven, the apparatus has been surveyed by lab professionals using the standard survey instruments. In these cases, the ultimate judge of the accuracy of the survey is the tracks that are reconstructed from the detector. The proper reconstruction of the tracks have never been smooth. It has almost always turn out that the surveyor while measuring positions with an accuracy of .001" will have made some errors of 1" or 1'. The reason for this is that the surveying instruments never had clear sight lines but must transfer measurements from offset measurements.

Since the chamber tracking at the beginning always has many uncertainties of trigger and electronics, it was very difficult to carry out the search for errors from the tracks. The greatest efficacy was obtained by the physicists going out to the apparatus with plumb bobs, long tape measures and chalk lines on the floor. This usually discovered the gross errors very quickly and the correct survey was obtained rather quickly.

In the Dumand II telescope, I propose that we have the nautical equivalent of the plumb-bob, tape measure and chalk lines. This are not called for in the original Dumand II requirements. The local devices could include: A phased array for measuring elevation and azimuthal angles of the transponders as well the range. We might also include a high sensitivity video camera for optical surveying of at least some of the transponders and the string fiducial marks. The technical feasibility of these will be discussed in later sections.

1.4 Angle is most important...not the absolute position.

In Dumand II, we are chiefly interested in our ability to point to stars and not to the geographical location on earth. For example, if we err in our earth location by 100m, but if we know earth North accurately, we would make an error in angle of only 100/E7 = 1 E-5. This is much smaller than our required error. What's important to us is the angle and not the absolute position on earth. I believe that the use of our own angular surveying measurements could give us what we want in a straight-forward manner. The use of the conventional satellite-ship-transponder survey would be less useful if they did not attain the circles of confusion of a few meters in a way in which we could verify the measurement.

1.5 What else can go wrong?

Since the measurment of the OM's depend on relating the OM's position to the position of the 3 fiducial hydrophones, we need a model for the shape of the OM string. If the string can be approximated by a circular arc, then we can determine the OM's to high accuracy. However, if the strings take on a more complicated shape, we would be unsuccessful in determing the OM positions. The non-circular-arc shape could result from several factors. The currents may not be uniform in space. This would include the bottom effects and the effects of the strings themselves. Non-uniformities in the bottom may produce eddying effects which would produce non-circular-arc displacements. Flow past the OM's, the enclosures and the strings will produce eddies which may produce fluttering of the OM's as well as complicated displacement patterns. We note that the flow of a water current of .5m/sec past a .44m sphere has a Reynold's number of 2 E5. This is in the period turbulent region and has the equivelent Re of a .44m balloon in a 6m/sec breeze (14 mph) breeze. The balloon would flutter quite violently in the wind. The good news is that the frequency of the flutter do not scale with Re. fL/V scales with Re so that the Benthos sphere would flutter with 10x lower frequency. The bad news is that this may still be a problem. Further investigation is warranted. The laminar flow regime for .44m spheres begin at a velocity of less than 1 mm/sec.

Our informants have told us that the observed vibrations are usually attributed to the strumming of cables and not to the flapping of Benthos spheres. The strumming of the cables can usually be reduced by adding streamline fairings or "fuzzy" mooring cables which are in the standard techniques. We should use the "fuzzy" mooring cables to avoid problems. The strumming of the cables could have a seriously bad effect on the hydrophone signals and hence impair the acoustical survey. In any case, we have a complicated system of spheres attached to cables under tension which has many natural modes of oscillation. It's important that we keep the frequencies of natural oscillation well away from the frequencies generated by the periodic turbulent flow.

The monitoring of the on-board accelerometers, water velocity meters should keep us informed of the oscillations of the telescope.

The measurement of the positions of 3 fiducial hydrophones at a sufficiently high frequency may detect the flutter but is unlikely to provide the neccessary information to give us good knowledge of the string shape and hence the positions of the OM's. Possible solutions to this include the use of the TV surveying instrument to locate the OM's as well as the possibility of using an imaging sonar system to locate the position of each OM. The UW group are collaborating with **Williamson and Associates**, an ocean Engineering Company in Seattle who are trying to obtain the resources to produce an imaging system which can be deployed for long periods in the bottom. The JBEM will be made with provisions for the deployment of a imaging sonar system.

2. The Junction Box Environmental Module.

The Junction Box Environmental Module, JBEM, will be deployed directly on top of the Junction Box, JB, and will be commissioned at the same time as the JB. The purpose of the JBEM is to be the command center for the underwater survey and to provide aide in the docking and other underwater connection procedures such as the connection of the OM's to the JB. The following sections will discuss the conventional survey apparatus and some suggested addenda to supplement the conventional apparatus.

2.1 Conventional survey apparatus.

Following conventional practice for undersea survey, we have included acoustic measuring system to map the positions of fiducials on the optical module strings. The basis for this is the set of 4 acoustical transponders arranged in a square around the periphery of the OM strings. The distance of each transponder from the center of the Dumand octagon is approximately 1000m. This distance is chosen to provide a good angular measurement. If the circle of confusion of each transponder is 1m, then the angular accuracy would be 1E-3 which is better than our requirements. The transponders emit an approximately 15 KHz pulse in response to a trigger pulse from the pinger on the JBEM which is triggered on a regular interval on command. The travel time of the sound pulses from both the transponder and the pinger are recorded by the hydrophones mounted on the OM strings. These travel times are proportional to the ranges from the known positions of the transponder and the pinger. We make the conversion from travel time to range by using the velocity of sound deduced by measuring the physical conditions of the water. The pressure, temperature and salinity which determine the velocity is measured by the Niel Brown Unit which is included in the JBEM. At the same time, the motion of water is measured by the Niel Brown Unit to correct for the velocity of sound as a function of direction. The positions of the hydrophones on each of the OM strings is shown in figure 3.

For each hydrophone on the OM string, we will measure 5 ranges. This overdetermines the position of each hydrophone in 3-dimensional space and so provides an error matrix for each measurement for use in the propagation of uncertainty in our track reconstruction of muons. Figure 6 shows the crossing arcs of the ranges from the various transponders used to reconstruct the spatial position of the hydrophones. Since the reconstruction accuracy vary as 1/sin(theta) of the crossing angle, we must choose transponder positions with yield optimal accuracy. At the same time hydrophones on the JBEM will record the travel time from the transponders to provide a constant calibration to the system. The arrangement of the pinger, the transponders and the fiducial hydrophones are shown in figure 5.

Each of the pulses emitted will have a unique frequency to identify the source of the pulses. The sound wave received by the fiducial hydrophones will have its waveform digitized and sent to shore for later analysis. In this way, we can derive the maximum

accuracy from the travel time to each hydrophone. By utilizing the entire pulse train, we will be able to find the travel time to within a small fraction of a period of the pulse. The Data Acquisition System (DAQ) is shown in figure .4(b) Note that the parallel data streams from each of the fiducial hydrophones are serialized by a TAXI system and transmitted to shore via optical cable. The optical cable will have a capacity of 512 Mbytes/sec which is more than enough bandwidth for the 200 KHz digitization of each of the hydrophones.

Video Cameras. For guidance during the docking of the JB as well as the assembly of the cables of the OM strings to the JB, we will operate 2 video cameras. Illumination for video camera operation will come from the gas discharge lamps mounted on the JBEM. These are shown if figure 4(a). The cameras are black and white cameras and the illumination will be provide light in the blue-green part of the spectrum. This is chosen to maximize the range of the cameras. With a camera with 1 Lux sensitivity, we will be able to observe operations for a range of more than 10m. One of the cameras will have a wide angle lens and will observe a half-angle of about 30 degrees. The second camera will have a longer focal lens and be mounted on a tilt-pan unit and will have a half-angle observation of about 5 degrees. The video signals will be fed into the JBEMC optical cable to shore by digitizing the signal at a rate of 14MHz and sending the data stream via the TAXI system as shown in figure .4(b).

Direct Sound Velocity Meter. Accurate Ranging information depends on having accurate measurements of the sound velocity. On the field experience indicates that the measurement of sound velocity using the Niel Brown Unit (NBU) information has an uncertainty of about .5m/s. This is a marginal accuracy for our goals. It would be good to make direct measurements of the sound velocity in a fixed range in the JBEM. For practical purposes, the fixed range is likely to be less than 10 m. Accurate information could be obtained by an interferometer technique. This could be the acoustical equivalent of a Fabry-Perot interferometer. This is easy to carry out on shore using variable distance. Underwater, it would be more easy to carry this out using variable frequencies. The Fabry-Perot interferometer could be part of the hydrophone system shown in figure 4(a) by using a CW variable wave generator. Since the velocity meter would have to operate continually in situ for 10 years, it might be advantageous to have an even simpler meter. We have devised a design for the equivalent of an underwater organ pipe (Nemo Organ Pipe) for the velocity measurement. An organ pipe sounded by and edge tone produces a highly acucurate frequency spectrum which is a function of the sound velocity. The Nemo Organ Pipe is used as the resonant part of an electronic circuit to produce the highly accurate frequency. Figure 7 shows the schematic design for the Nemo Organ Pipe. The frequency of resonant oscillations in a resonant cavity of fixed dimensions is not trivially related to the velocity of sound propagated in the open. However, this problem is similar to the relation of a EM wave-guide dimensions and its resonance frequency as a function of c. We must study this problem further.

2.2 Phased Array

Because the calibration of the pointing angle of the array in earth coordinates is extremely important, it would be well to have some independent checks on the pointing angle. We propose two methods which we plan to implement in the JBEM. Each of these methods depend upon the use of a tiltmeter for zenith angle, and the use of a flux-gate compass for the azimuth angle.

We can measure the azimuth and zenith angle of each of the transponders by measuring the differential travel time from each transponder using two hydrophones which are spaced by a known distance along a beam. The angle of the beam can be measured by the flux-gate compass and the tiltmeter. Because we are utitilizing the entire wave train from each acoustic pulse, we can derive the arrival time to a small fraction of a wavelength. We estimate that the range can be measured to 1/30 of a wavelenth of .10m, or sigma = 3.3mm . If the paired hydrophones are spaced apart by d=10m, we have a uncertainty of angular measurement of
sigma/(d cos(theta)).
For a fixed alignment of the pair of hydrophones, we would have an accuracy of 1/3 degree for 94% of the azimuthal angles. A similar analysis holds for the vertical angle measurements. We show the schematic for the phased array arrangment in figure 4(a)

2.3 Longer Distance Video

Since our requirements for angular calibration accuracy are unique in ocean engineering, it would be well to make certain of our measurements. Acoustical waves vary appreciably due to variations in the physical parameters in the water. This unmeasured variation is probably the limiting factor in the acoustical survey accuracy. We note that light rays are affected only slightly by the known variations in ocean water. An optical survey would be independent of the acoustical survey. Realizing that the range of light is rather short, the system must contain a highly sensitive video camera and the presence of bright lights. It would be neccessary to use fiducial lights at the survey locations. Our estimates show that optical survey is possible with specialized cameras and ordinary lights up to a range of about 300m. It would be very good if we could illuminate corner cubes at fiducial spots using lights from the camera mounting for this job in order to simplify the set-up. However, we have estimated that this process is not feasible because of the light backscatter from the water would obscure the weak light reflected from the distant corner-cubes.

We have examined the feasibility of using lights mounted on fiducial points which could be viewed by the video-camera-transit mounted on the JBEM. Our analysis has taken into account both the exponential attenuation and inverse square spreading loss suffered in propagating light from an omni- directional source to a distant camera. The 40 m length used to characterize the attenuation was verified for the Dumand site during SPS trials. The results of our analysis are tabulated in Figure 9. For 100 W of luminous

power, the light intensity at a distance of 200 m is of order 10^{-4} lux (note: 1 lux = 10^{12} visible photons/cm^2/s.) This means that a camera mounted at the junction box must be at least that sensitive in order to measure a fiducial point on any of the string bottom controllers.

Fortunately, the art of low-light video imaging has progressed sufficiently for our purposes. Specialized cameras are readily available with sensitivities as low as 10^{-6} lux. Camera sensitivities for various technologies are depicted in Figure 9. For comparison, typical camcorder sensitivity is about 3 lux. The most sensitive cameras usually feature thermoelectric cooling to allow longer integrating times, improving the signal to noise ratio.

Our proposed video survey system involves mounting one of these specialized cameras on a pan-and-tilt unit to form an undersea "transit". Camera enclosures and pan-and-tilt units (355°x190°) designed especially for deep water are available. Orientation to magnetic North can measured by a flux-gate compass attached to the pan-arm. Three accelerometers can be mounted on the pan-tilt base to measure which way is down, an electronic undersea "plumb bob". In conjunction with the video signal, these measurements can provide an optical survey of fiducial lights mounted on string bottom controllers or transponders in a short baseline configuration. We recommend such a survey to complement (or double-check) the conventional acoustic survey of string positions.

2.4 Considerations for a smaller array of transponders which are hard-wired to the JBEM.

Because of the finite lifetimes (< several years) of the battery-powered transponders and the diminished timing accuracy of the threshold seeking receivers as compared to the timing that we can achieve by recording the sonar waveform, there is some advantage of deploying a set of transponders which are hard-wired to the JBEM. Figure 10 shows a possible arrangment which shows a set of 5 transponders mounted in a circle of about 100m radius. These could be deployed at the same time as the JB and JBEM. The distance of the outer transponders could be set by the cable length and a system for hydrodynamically outward-pulling system. These transponders would have both hydrophones and pingers so that we could survey them to high accuracy using the techniques that were described in the previous two sections. Since these transponders are closer to the Dumand II OM fiducial hydrophones, the requirements on water velocity accuracy is not so great so that the survey will have higher accuracy.

2.5 Imaging Sonar.

For ranges equivalent to the Dumand telescope, the use of imaging sonar has been successfully used to observe relative positions with resolutions of .1 m. To make imaging sonar, it is necessary to make an array of transducers which emit and receive a

well-defined sonar beam. In present systems, the beam is scanned through the interesting area by a rotating the array physically or by towing the array through the interesting volume. Both of these techniques of scanning are not likely to be suitable for long term deployment. We are exploring the production of the scanning sonar beam by a phased array by using a electronic switching and delay. Such a device could lay on the ocean floor and scan the beam over the Dumand Array. The Benthos spheres make excellent targets for the scanning array. If this is successful, we can measure the positions of every Benthos sphere directly. This has a big advantage over the use of only three fiducial points on each of the OM strings if the OM strings obtain a form which is not described by a simple curve. We show a schematic of the imaging sonar system in figure 11.

Since the phased array imaging sonar system is not yet developed, we will leave a socket for the future deployment of such a device.

References.

1.(a) Creager et al, J. Geophysical Research 87 B10, 8387 (1982).
(b) See Robert C. Spindel and Peter F. Worcester, Scientific American, October, 1990, pp 94, 99. They quote a positioning error of about 1m for a sonar range of 3700m.
(c) Private Communication. Hugh Bradner, Scripps.
(d) Private Communication. Bruce Howe, Applied Physics Laboratory, University of Washington, Seattle. In the project quoted in (a), Howe says that they have achieved absolute accuracy in position on the sea floor of about 15 m. The relative positioning accuracy was estimated to be 1-2 m. This was obtained with about 4 hours of surveying time. He felt that 1-2 m accuracy was possible with about 2 days of measurements and with proper measurements of the displacement between the antennae for the satellite measurement and the transducer for the acoustic measurement. Because of the separation of the two transducers, this measurement must take into acount he pitch and roll of the ship.
(e) Private Communication. Robert Odam. APL, UW, Seattle. They have observed a descrepancy of 9m between a depth gauge measurement and an acoustic measurement. They believe that this large a descrepancy should not exist if the data is properly used. This informs us that in Dumand II, we will have an independent check on positions by using the depth gauges at the fiducial positions.

2. **Positioning Accuracy for OM's.** In the most stringent case, we would measure the wavefront angle from two OM's spaced apart by 10m. In this case, 1 degree pointing accuracy depends on the positioning of the OM's to .1m. Most events will have hits on many OM's including pairs which are spaced by 40m. The positioning accuracy then increases to 0.4m. If the positioning accuracy of the OM's turns out to be 1.0m, then a one degree aiming accuracy would require the reconstruction of an event with 6 struck OM's which are spaced by 40m.

Appendix. Equipment in JBEM

1. Hydrophones. We plan to use Benthos .AQ-1. hydrophones with built-in preamplifiers AQ201 which have a frequency window of 1Hz to 10KHz. The preamps will drive cables varying in length of 5 to 330 meters before the signal is digitized.
2. Transponders. We plan to use Sonar Dynamics transponders which have a frequency output of about 10-20 KHz and a lifetime of pings or 5 years.
3. Tilt-meter, accelerometers. We plan to install sets of three solid state accelerometers which will measure the tilt and the accelerations at these sites on the JBEM as well as on some of the strings.
4. Niel Brown Unit. This is a standard ocean instrument used to measure pressure, temperature, and salinity of the water as well as the 3-dimensional water flow velocity. This will be carried out at the JBEM as well as on several of the OM strings. See E.G.and G. Ocean Instruments.

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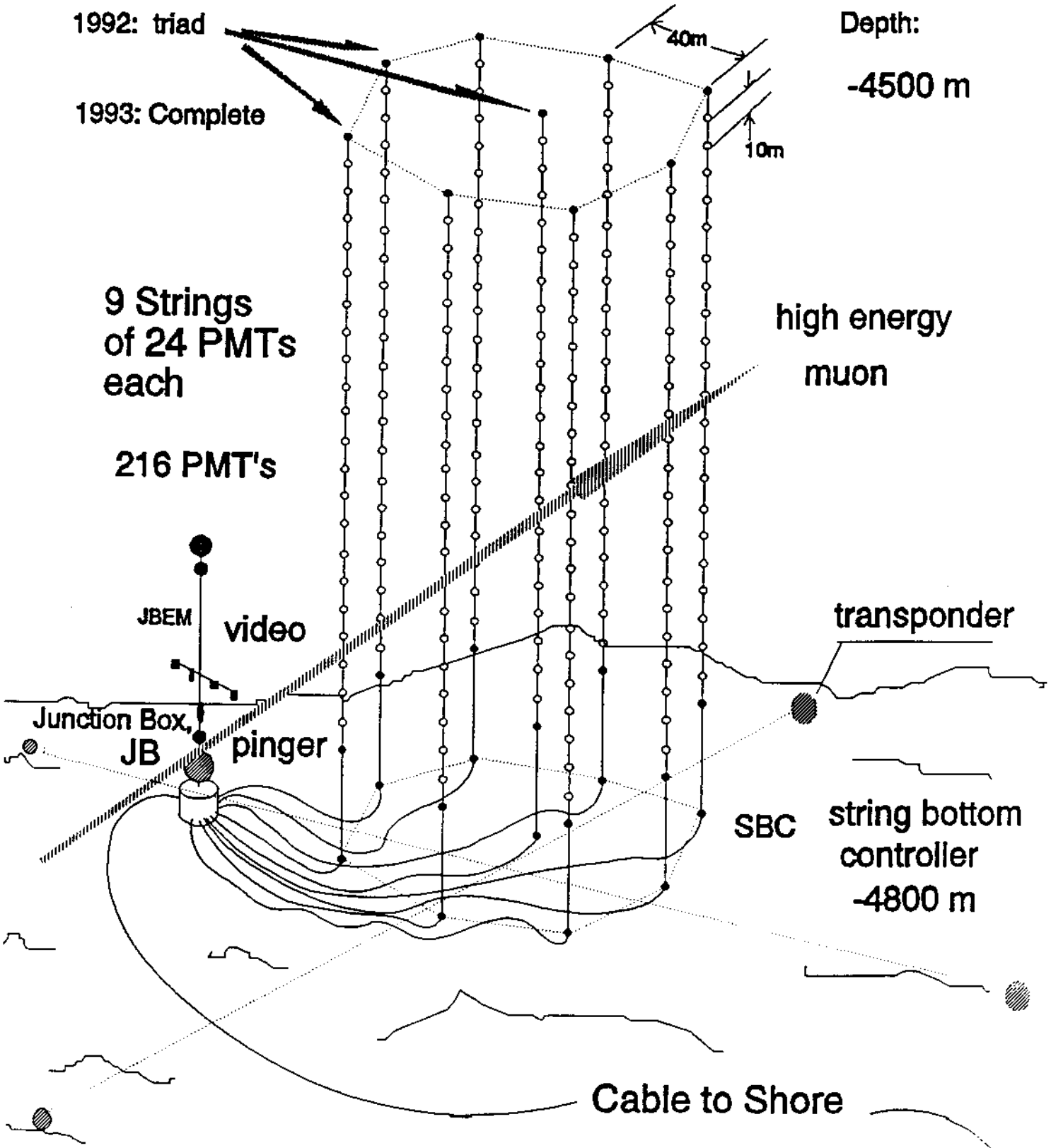
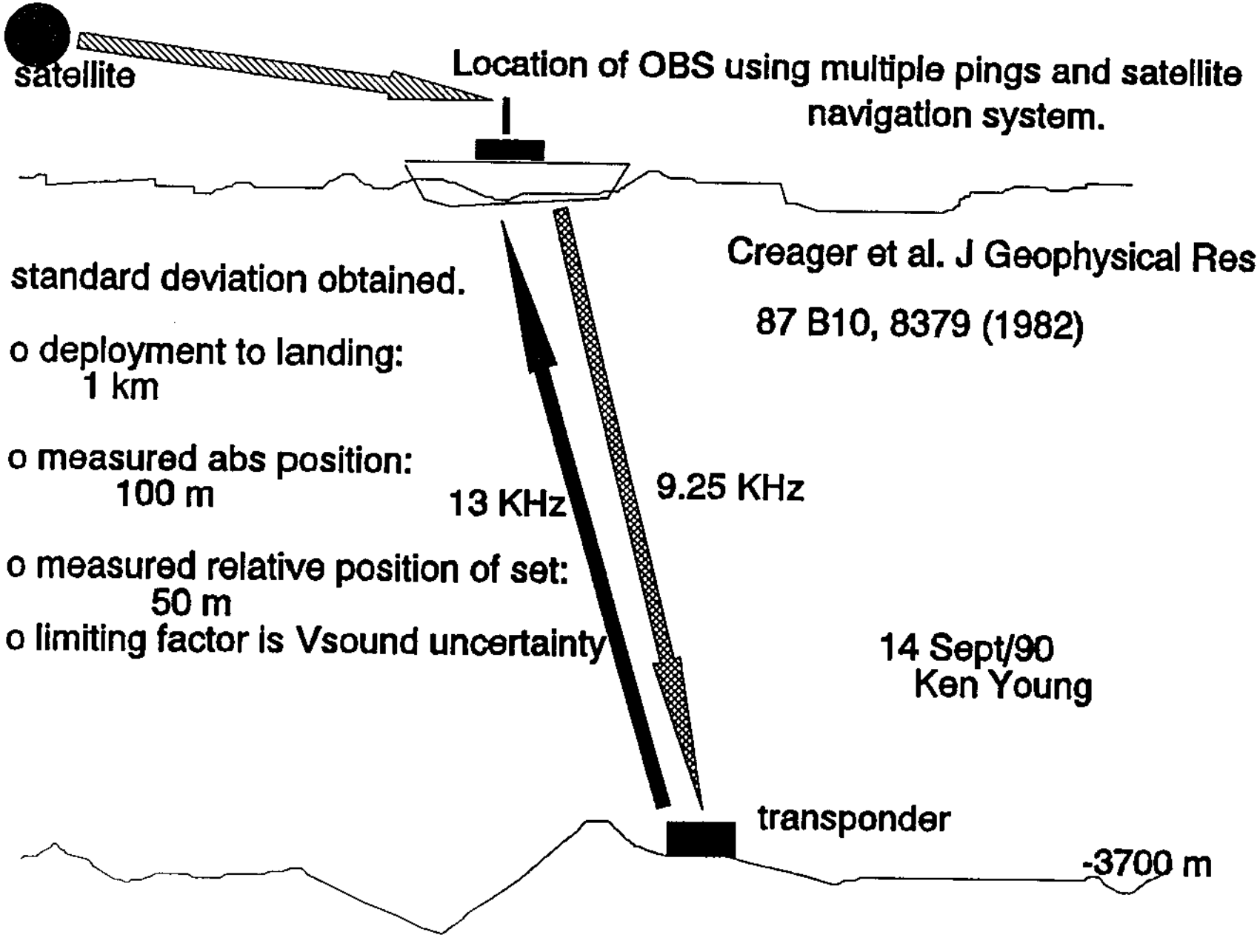
Dumand II. Octagonal Neutrino Telescope

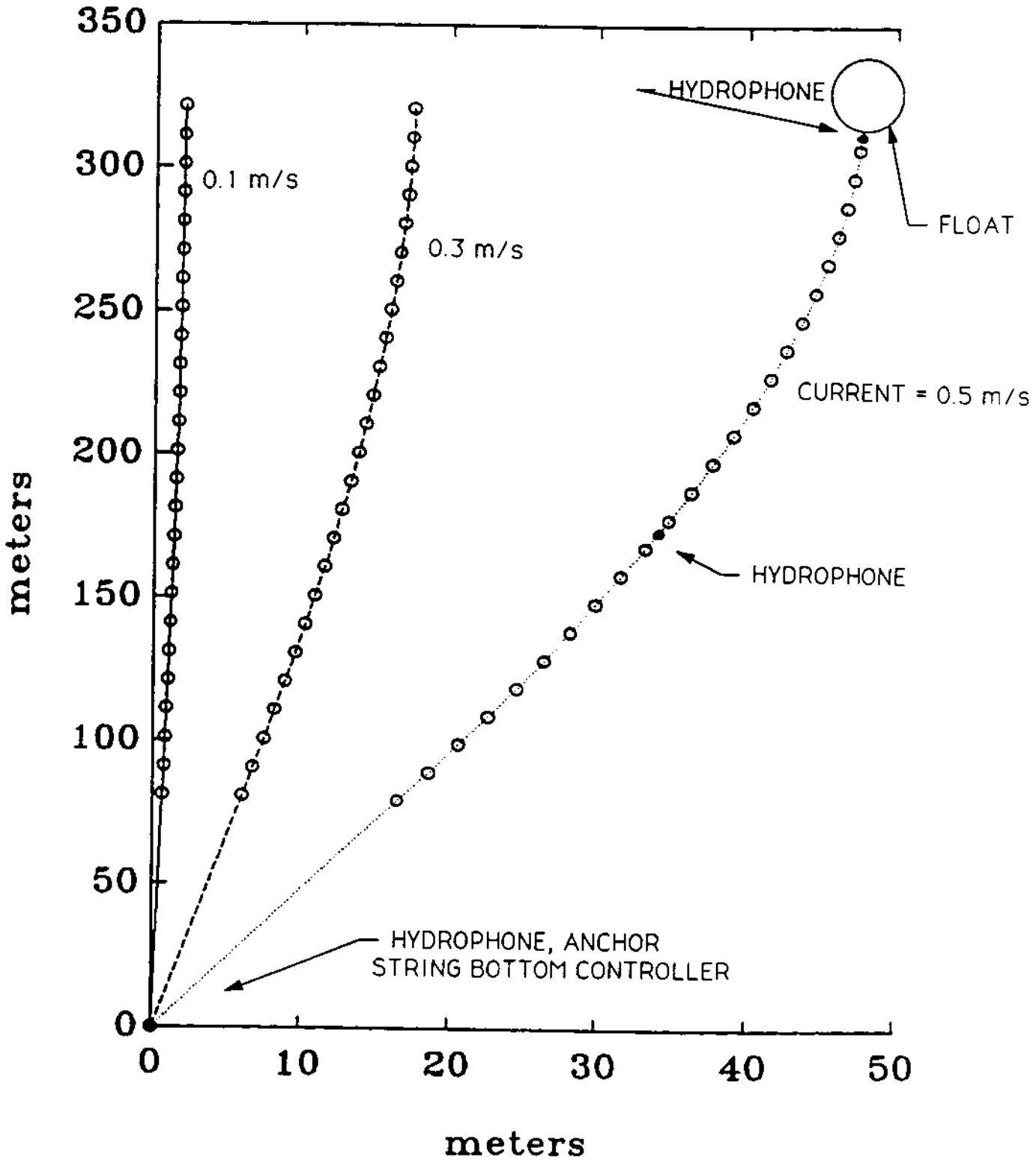
Array dimensions: 200 m high, 100m diameter



1. Overall view of the Dumand II telescope.

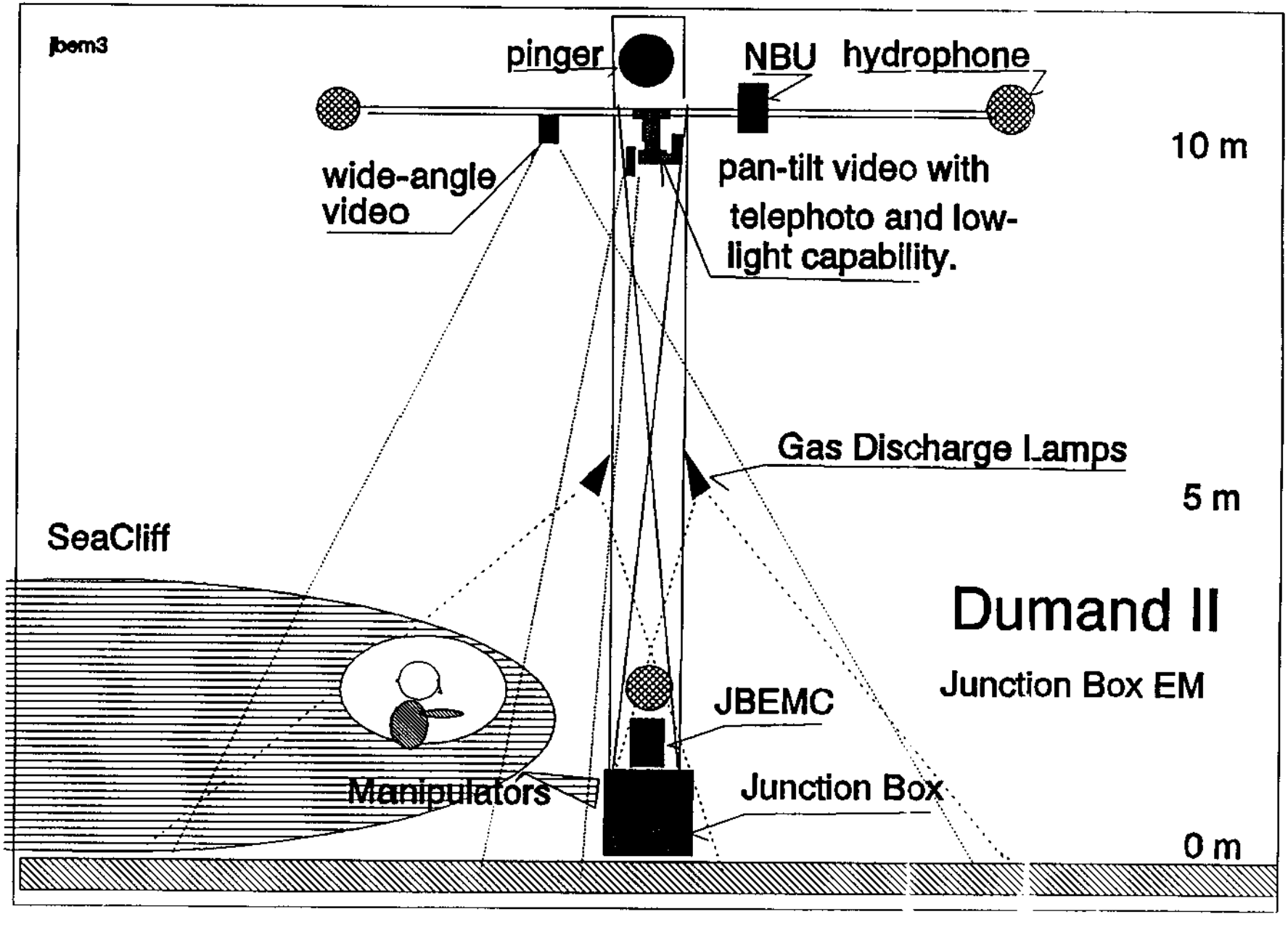


2. Surveying the fiducials at the sea-bottom.

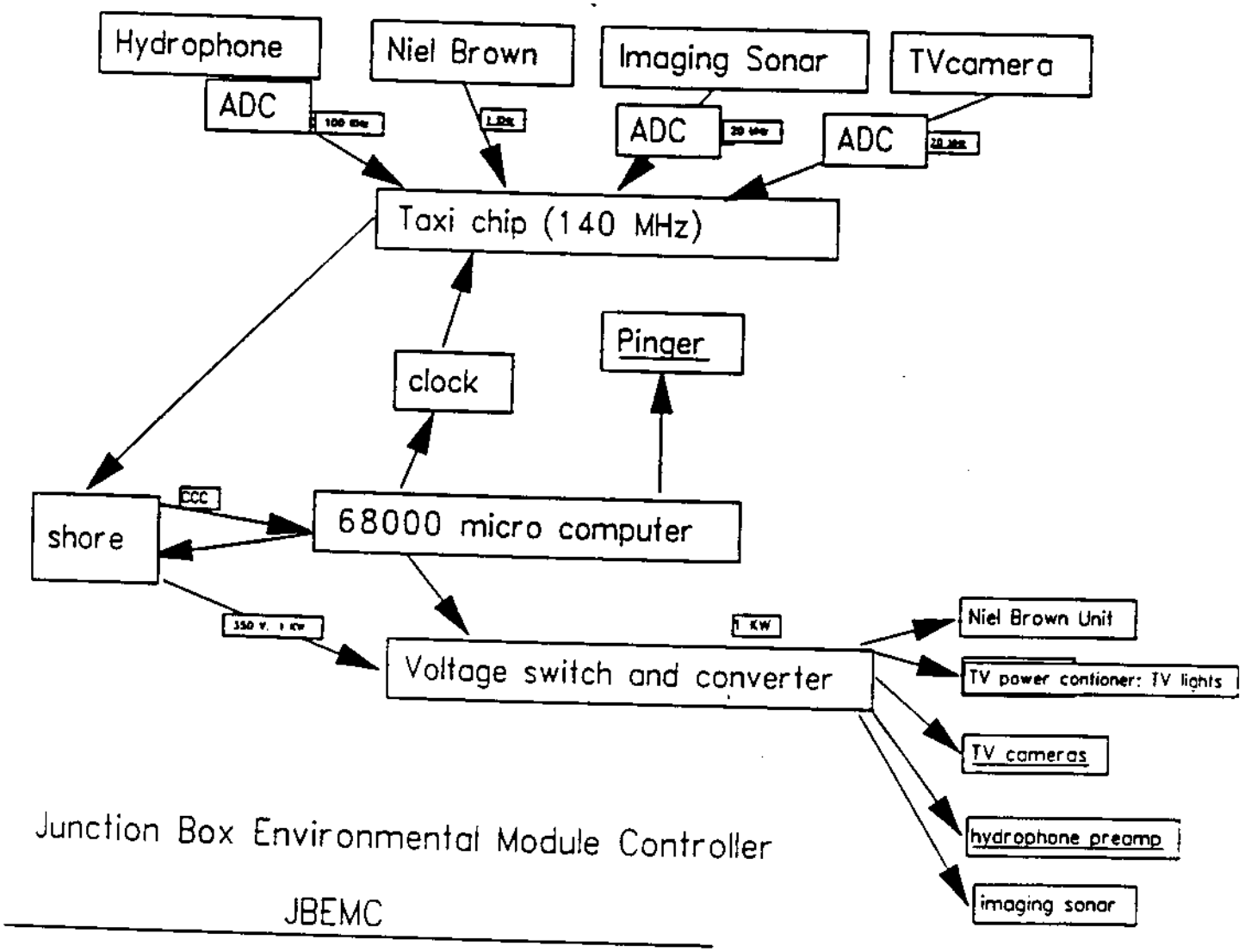


STRING PROFILE

3. Calculated shape of an OM string.



4 (a) Junction Box Environmental Module JBEM



4 (b). Data Acquisition System for the JBEM.

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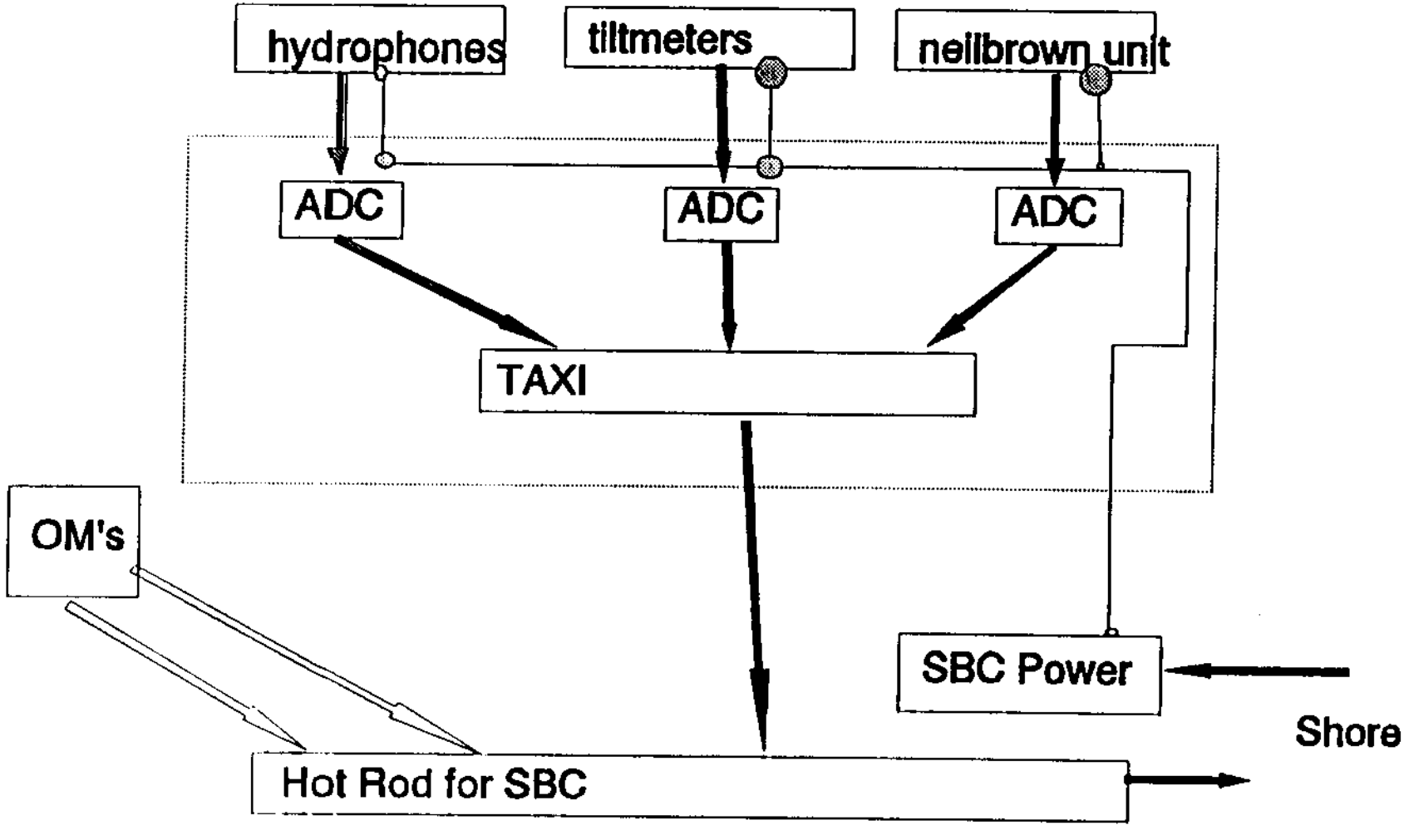
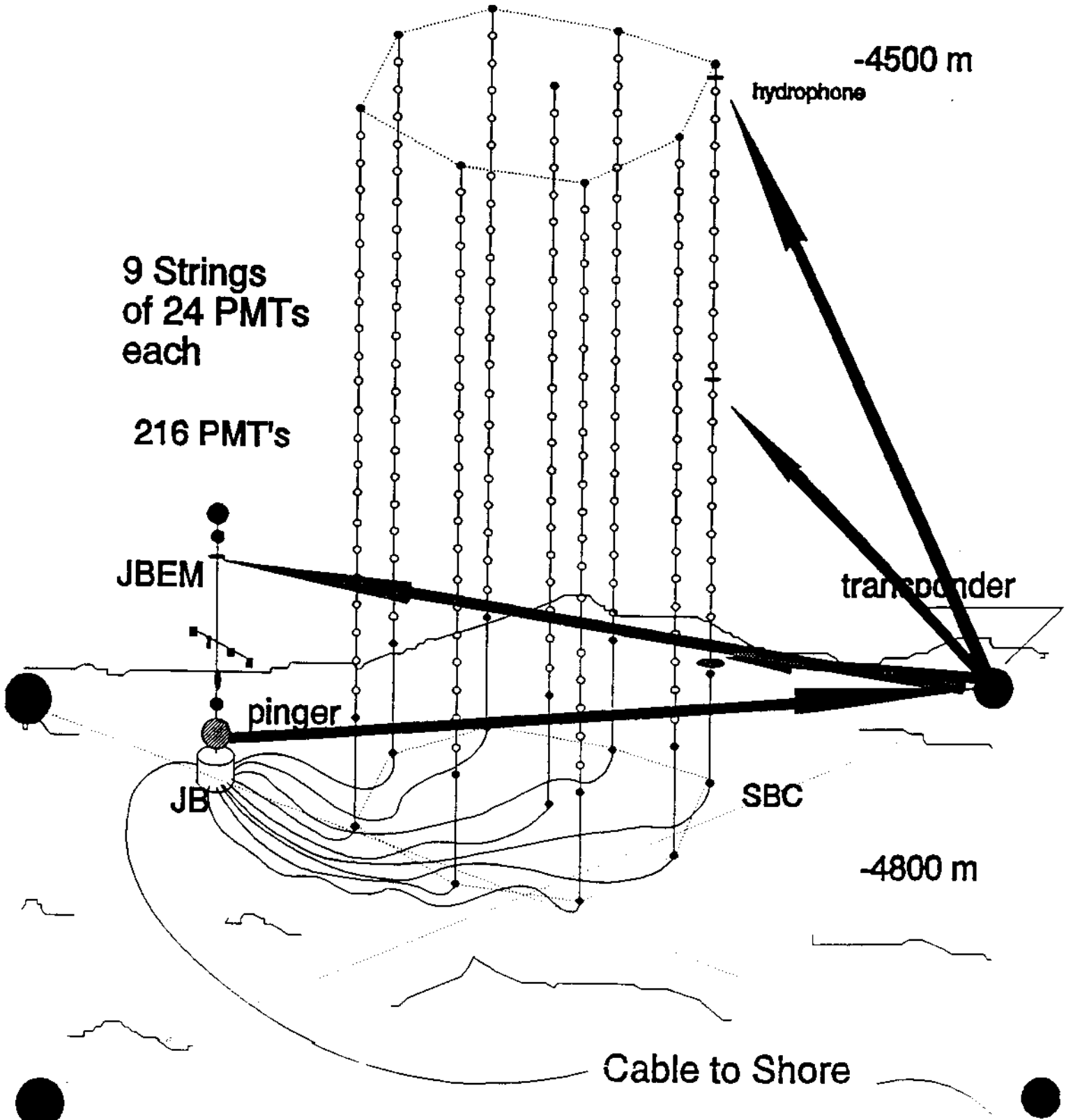
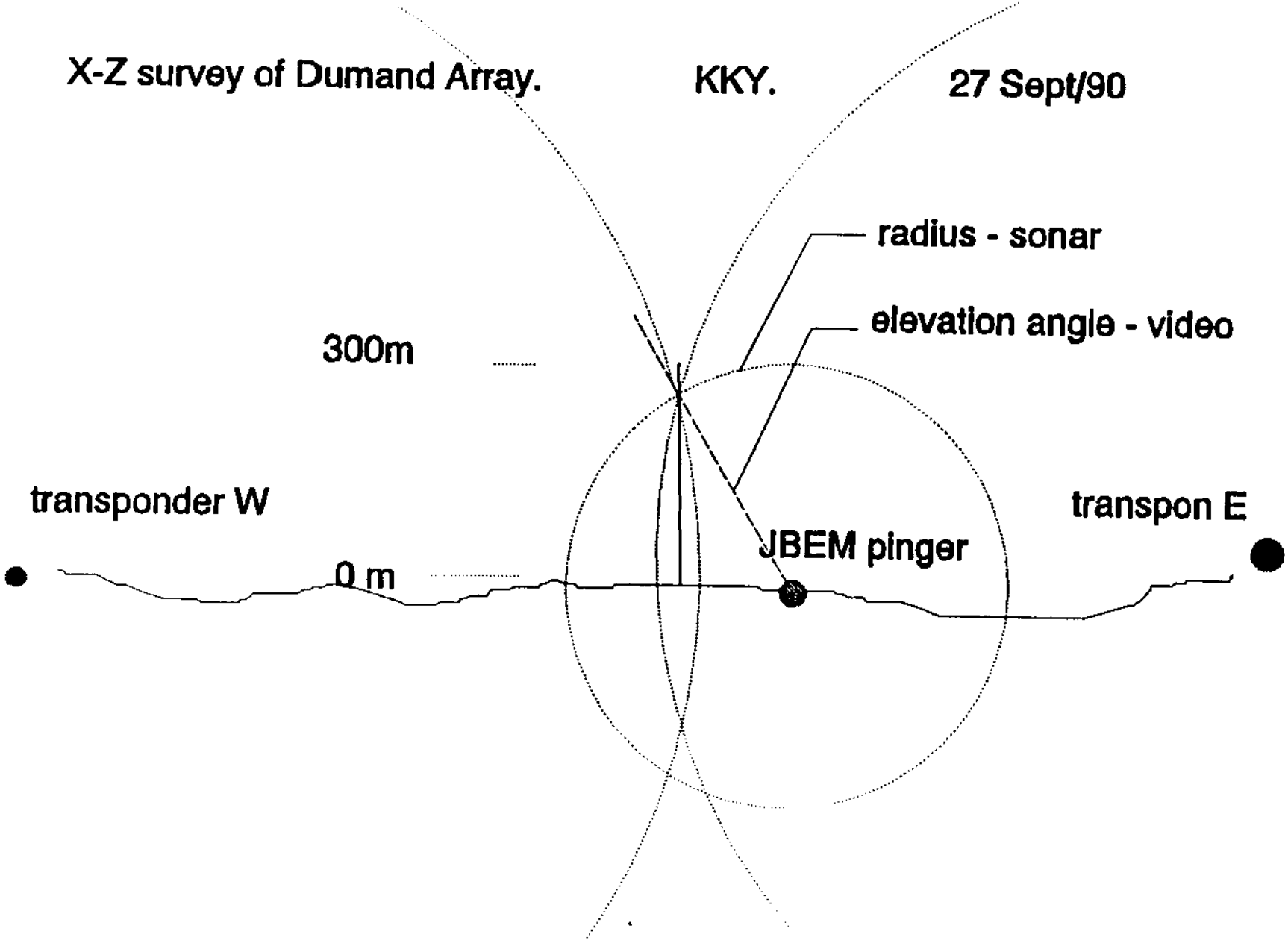


Hydrophone DAQ for SBC. This must mount within SBC enclosure.

4 (c) Hydrophone data acquisition for the SBC



5. Schema for the acoustic ranges.



6. Reconstructing positions from the ranges

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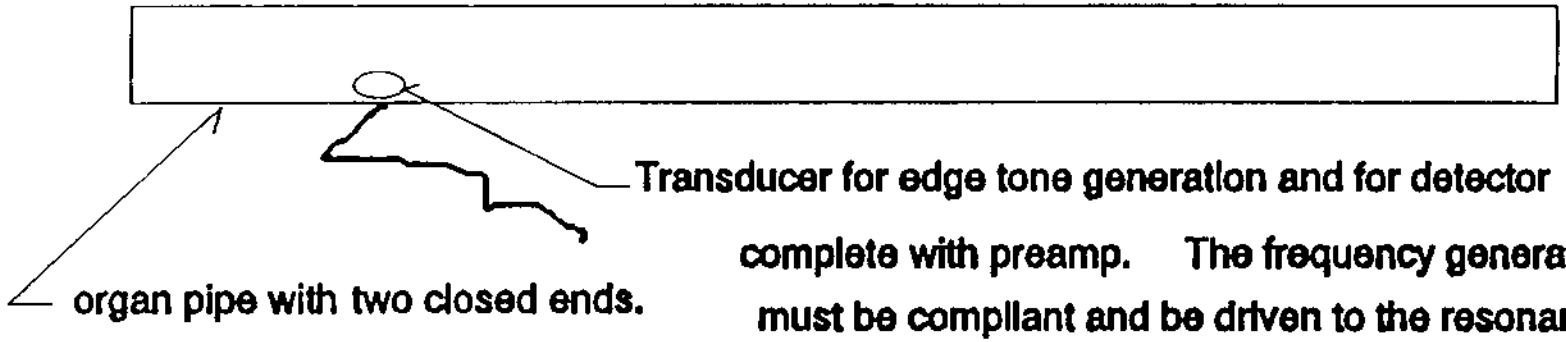
Velocity Meter interferometer

Nemo organ Pipe

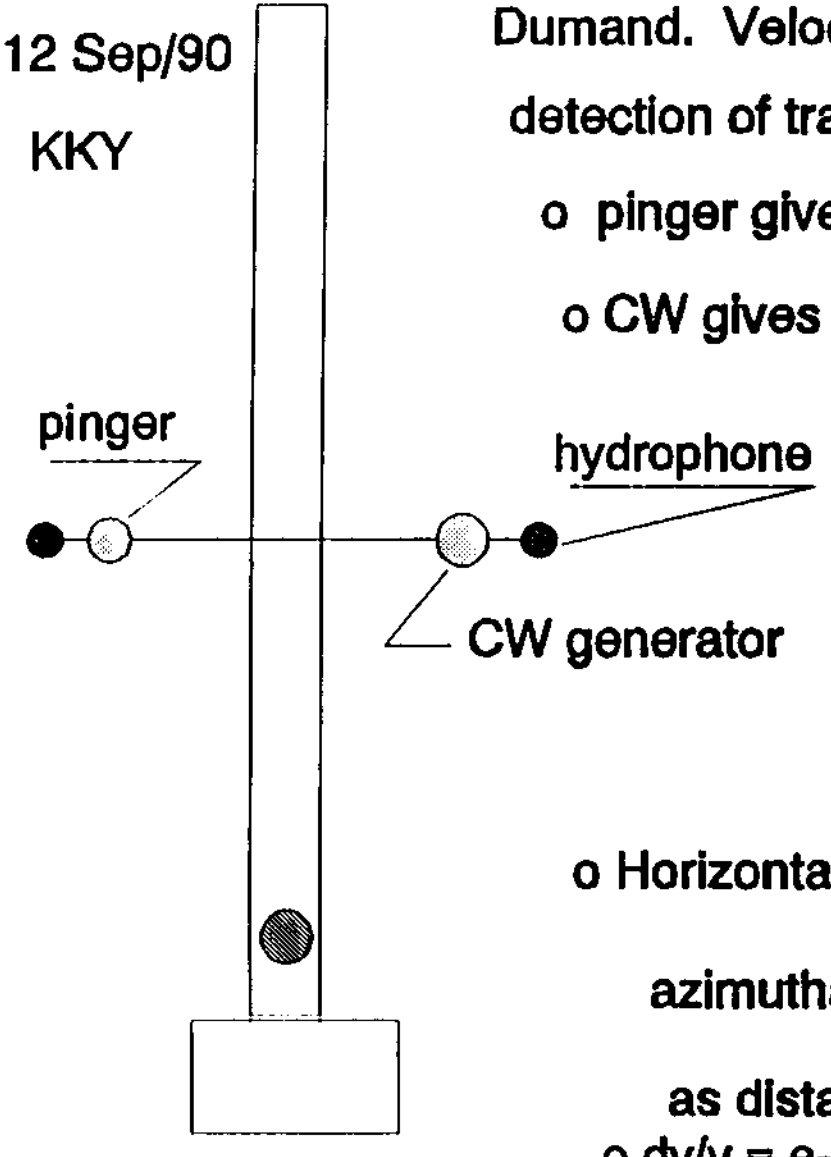


Output of receiver is analyzed for frequency peaks. This should contain both the fundamental as well as the overtones. This will yield the sound velocity in the pipe for many frequencies thereby directly measuring the dispersion of the sound. The derived velocities must be corrected for the differences of velocities of free waves versus waves confined in a tube.

7. Nemo Organ Pipe. resonant sound velocity meter.

12 Sep/90

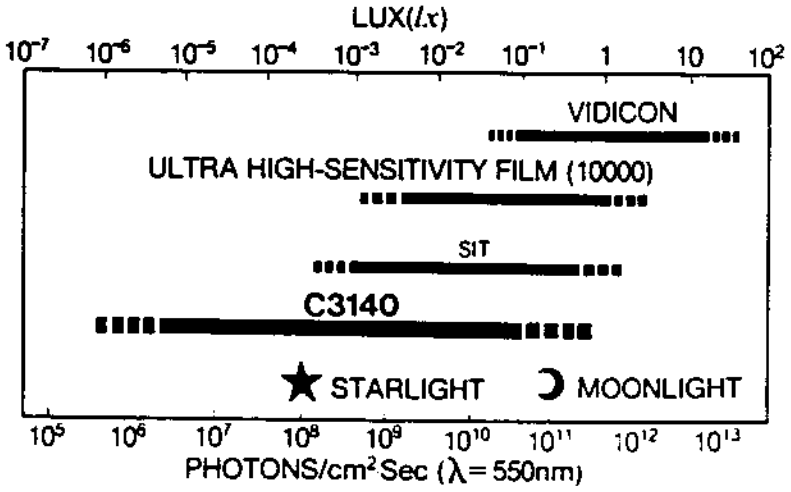
KKY



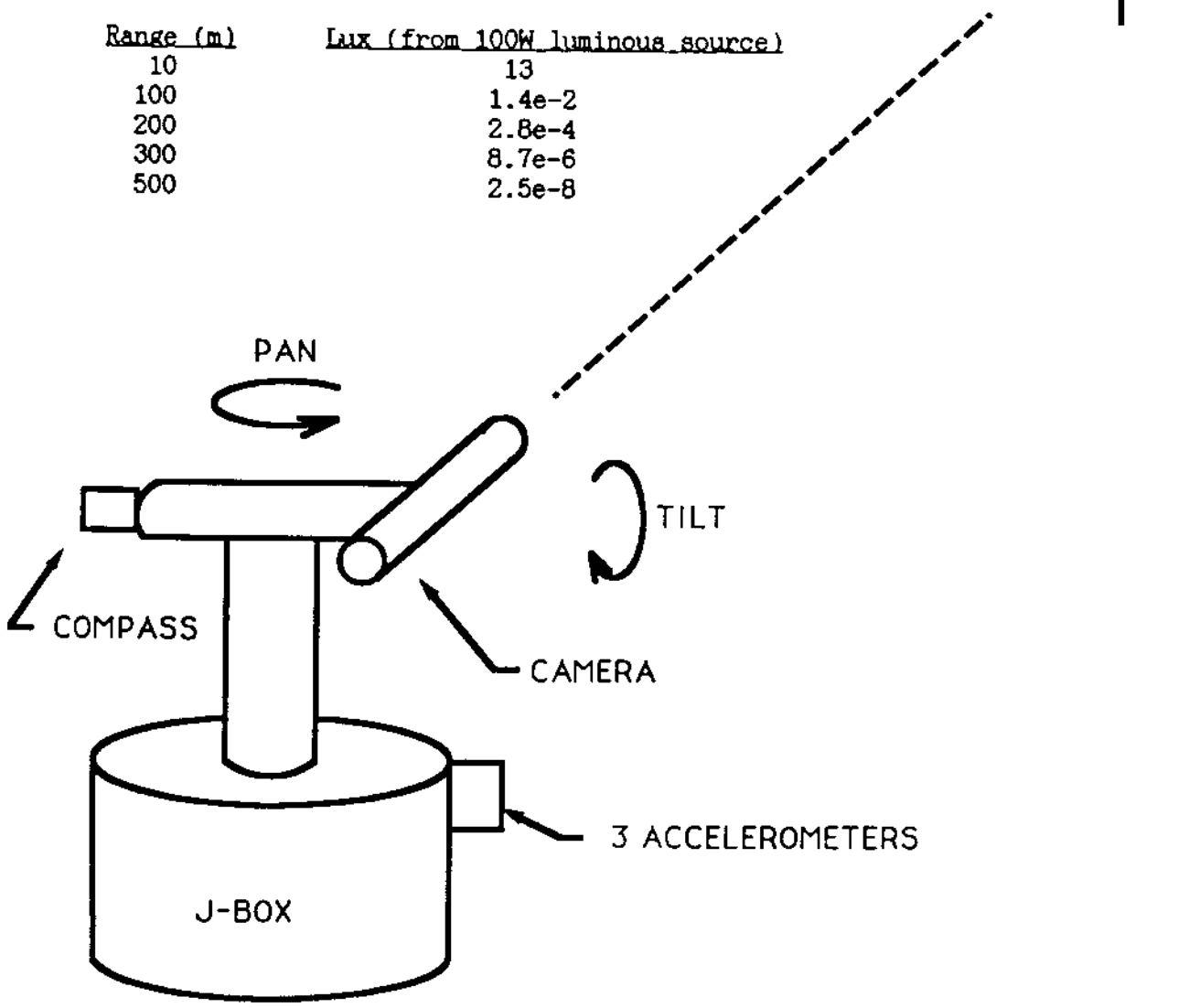
Dumand. Velocity of sound and azimuthal angle detection of transponders.

- o pinger gives rough measurement of velocity.
- o CW gives phase measurement of wave to give fine measurement.
- o Horizontal spread of hydrophones gives a azimuthal reading of transponders as well as distance.
- o dv/v = e-3 because of 1 cm size of transducer.

8. Phased dual hydrophone for direction finding and for an

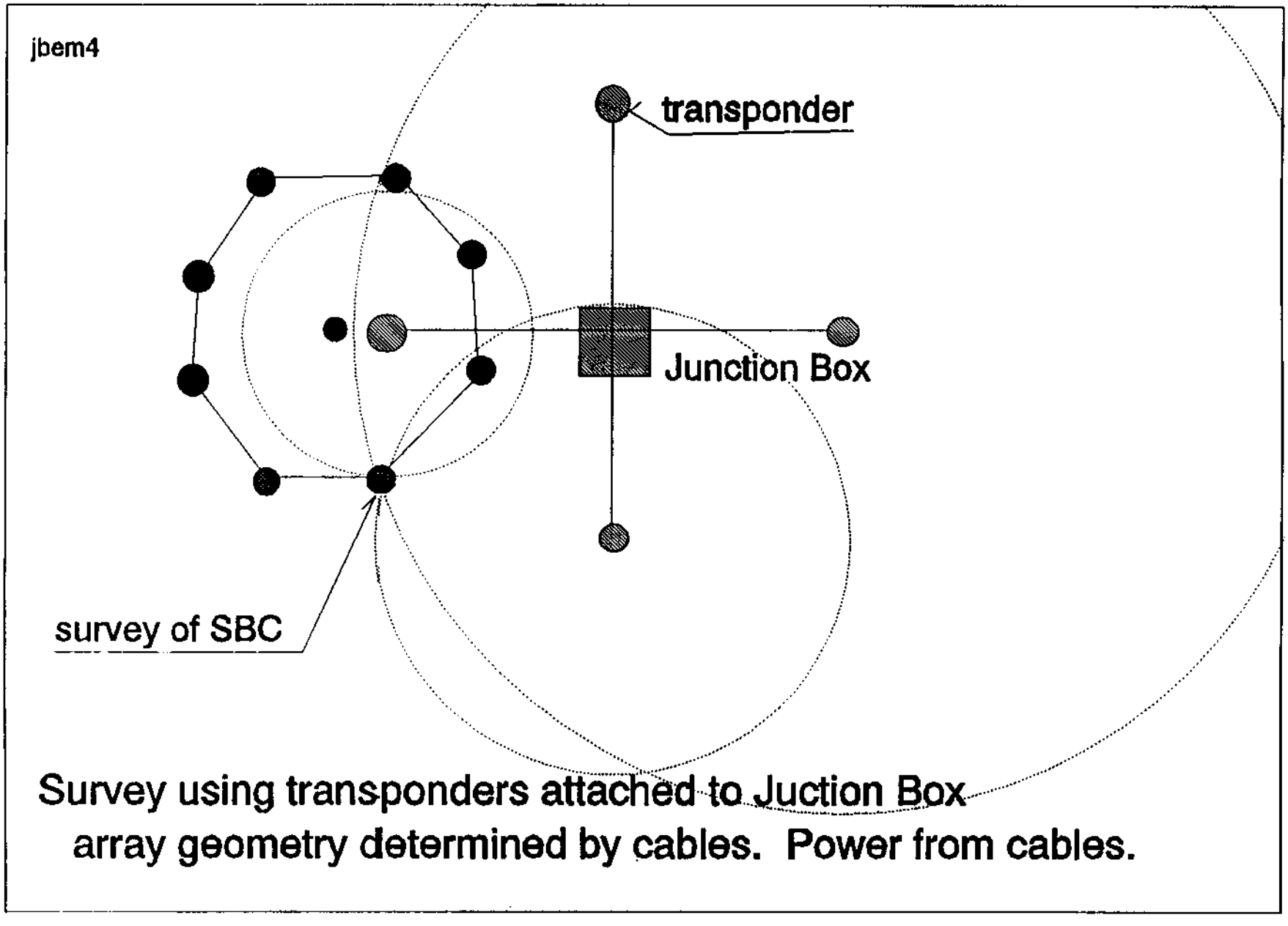


Range (m)	Lux (from 100W luminous source)
10	13
100	1.4e-2
200	2.8e-4
300	8.7e-6
500	2.5e-8

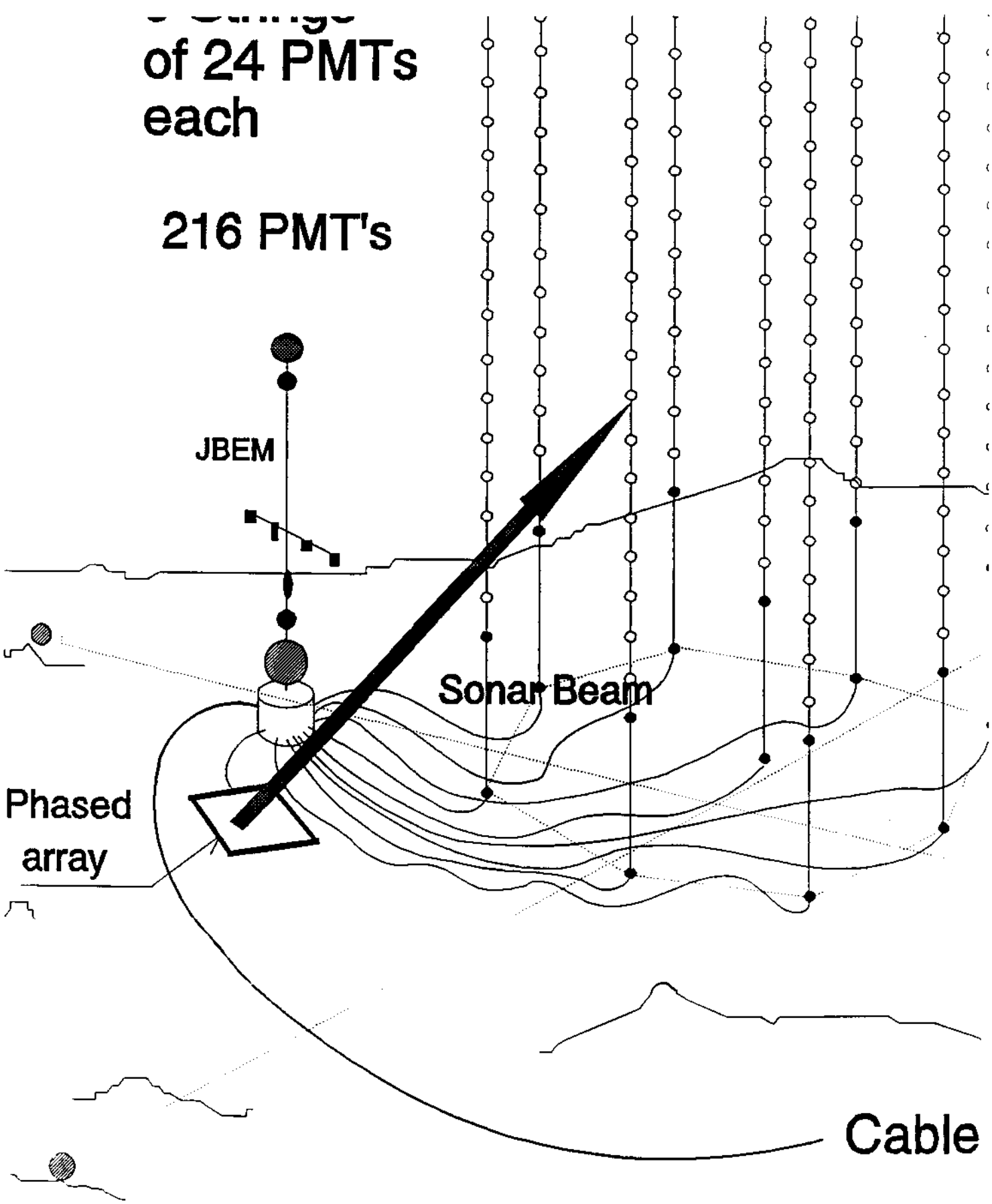


VIDEO SURVEY SYSTEM

9. Schematic for the video surveying of bright fiducials.



10. A system of hard-wired transponders for the array. The range circles are shown to illustrate the good measurements that are possible.



11. Schematic for an imaging sonar system using a phased array.