AN INSTRUMENT SYSTEM TO MEASURE TURBULENCE FROM AN UNDERWATER HABITAT

SCOTT TIFFIN

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by

Scott Tiffin, B.A.Sc.

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ERRATA

1. There are two of page 58, noted as page 58a and page 58b.

2. There are two of page 62, noted as page 62a and page 62b.

3. The unit Hertz should read Hz, not hz, wherever it appears in the text.

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ABSTRACT

An instrument system was developed to measure oceanic turbulence from an underwater habitat in subarctic waters off the coast of Newfoundland. From a literature search of existing experimental techniques and instruments, it was seen that there was a large number of instrument systems capable of measuring turbulence, but that most were impractical without further development. After analyzing present instrument techniques, we chose DISA hot film anemometry equipment, and set up a three channel system for simultaneous three dimensional measurements. The instruments were operated from the habitat LORA 1 by SCUBA divers who also carried out Rhodamine B dye studies to delineate the turbulence. Difficulties with the two battery powered DISA anemometers subsequently reduced the system to one channel which used a DISA 55D01 anemometer with a conical probe. Two experiments were performed and preliminary analysis was presented to demonstrate the capability of the system. The data was compromised somewhat by problems associated with low mean velocities and oscillatory velocities from wave action, but spectral analysis showed the characteristic -5/3 slope and gave viscous dissipations of about 5×10^{-3} cm^2/sec^3 with turbulence intensities about 0.1. In one case, the

turbulence was associated with a highly unusual oscillatory bottom current. In summary, with SCUBA divers to perform the experiments and with dye being used to delineate the water motion, DISA hot film equipment is entirely satisfactory for oceanic turbulence measurements.

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1. INTRODUCTION

The ability to study turbulence in the world ocean has always lagged well behind the need to understand it. Turbulent eddies, occurring as random fluctuations of velocity in a continuous range of sizes, frequencies and energies, dominate many oceanic processes of importance to man. At scales of many kilometers, eddies stir large water masses with motions that persist for months. Simultaneously, smaller fluctuations reduce concentration gradients of the differing fluid bodies until at the smallest scales, eddies of millimeter size are dissipated by viscosity, leaving molecular actions to complete the ultimate diffusion. In this way suspended and dissolved materials such as sediments, pollutants and nutrients are dispersed, and the density, salinity and temperature of differing water masses are mixed.

The analytical description of turbulence is so complex, in fact, essentially unsolveable, and the range over which turbulence appears in the sea is so vast, that our understanding of the phenomena is incomplete. Large gaps exist in our knowledge of the nature of the turbulent stresses that apply drag forces to ice sheets, and the mechanisms involved in the transfer of energy at the air-water interface. Even the nature of the generation and decay of turbulence is poorly understood.

There is a need for basic theoretical knowledge of turbulence and for a detailed description of its occurrence and effects. Theoretical studies are best performed in the precisely controlled environment of a laboratory, not in a difficult marine environment, so it will be more rewarding at this point to mount a program of accurate quantification and description of ocean turbulence by in-situ measurements.

Until the last several years, investigations of oceanic turbulence were few and sporadic because instrument technology was not sufficiently advanced to cope with the hostile marine environment. Now, a rapidly expanding instrument capability has created a large range of devices able to measure turbulence. Some of this equipment is still under development and some is only suitable for use in laboratories. At Memorial University of Newfoundland, Faculty of Engineering, we hoped to begin a program of ocean turbulence research with special emphasis on Arctic and underwater applications. In this instance, the experiments would be conducted from the university's underwater habitat LORA 1, with SCUBA divers handling the instrument system. Water temperatures around - 1°C for six months and seasonal ice cover would provide unique opportunities for measurement.

Because our primary effort was to study the phenomena and not to develop new instrumentation, we carried out an extensive literature search to select proven equipment, or at least choose instrumentation that would require the least amount of development. The result was a complementary combination of Rhodamine dye and DISA hot film anemometry. Preliminary experiments were then made in order to develop underwater measurement techniques and evaluate the usefulness of the system.

2. STATE OF THE ART

2.1 Experimental Techniques

Previous ocean turbulence experiments seem to fall into four basic categories. First, there are the well known towing tests, of which Grant, Stewart and Moilliet's work (1968) is the classic example. Their instrument package, using hot film anemometry as the basic sensors, was mounted in a sophisticated underwater housing and towed behind a ship. The ability to investigate large areas can be an advantage, but ship and cable motion introduce false signals and make precise positioning of the instrument difficult. The sensors also tend to collect microscopic detritus which affects their operation, and a high frequency response in the transducer is required because of the towing speed. If the towing speed U of the probe is large enough, the velocity signal u(t) can be identified with $u(\frac{x}{U})$. This hypothesis, known as the frozen field approximation is valid only if the turbulence intensity $\frac{u}{U} \ll 1$, as Hinze (1959) explains. This can be an important constraint in experiments where high turbulence intensities are found. Nevertheless, towing tests are capable of generating excellent data, as attested to by the recent work of Gibson et al (1973) and Nasmyth (1970).

They used arrays of towed heated sensors to measure turbulence in upper layer coastal waters. Both investigators concentrated on spectral analysis to find dissipation limits and to relate the temperature field to the velocity field. Nasmyth's work also included simultaneous salinity measurements upon which spectral analysis was performed. The salinity measurements allowed him to describe the turbulence structure completely.

The second technique entails placing a cluster of turbulence sensors at the point of interest by suspending it on a taut buoy or lowering the assembly to the bottom. Both variants are now well documented. For example, Russell (1973) used an array of moored current meters to delineate the large scale eddy structure of the Labrador Current. Bowden (1956) in his classic study, placed an electromagnetic transducer on the bottom of a tidal estuary to measure turbulent Reynolds stresses. These instruments are usually oriented into the mean flow by a vane apparatus but the response ambiguity of the vane is a practical drawback to the technique. Even with such a limitation, fixed location experiments give very good results.

The third technique requires the experimenter to dump dye in large quantities on surface waters and monitor the large scale diffusion by means of aerial photography. Alternatively, the tracer can be injected via an outfall and its dispersion measured with some suitable technique. For example, Takeuchi (1973) used an infrared line scanning system on an airplane to measure the diffusion of heated effluent from an electric power plant.

Finally, dye methods may be used to delineate small scale turbulence. Woods (1971) used a team of SCUBA divers to photograph trails from dye pellets, with impressive results. He actually photographed generation of turbulence from the breaking of an internal wave.

Classifying previous experimental work in such a way helped to optimize the research program described in this report. Fixed location transducers take recordable and precise data, but the sensors must be oriented properly into the flow, positioned accurately, and positioned in an area of interest. This is difficult to achieve by remote control, but SCUBA divers can accomplish these tasks. In addition, human observers lend flexibility to experiments. Dye studies with divers alone yield rather general and subjective data, but with instruments at hand to quantify the data such shortcomings are resolved. With a facility such as the habitat LORA 1, a combination of SCUBA diving, dye studies and fixed location transducers offered a high probability of obtaining good results from a large number of experiments.

2.2 Instrument Techniques

Generally speaking, transducers for ocean turbulence have evolved from water current meters and from air turbulence equipment. So on one hand we must attempt to improve the speed of response and spatial resolution of a current meter perhaps fundamentally unsuited to our needs and on the other adapt an air technique to resist corrosion, detritus, wetness and pressure. Only in a few cases has instrumentation been initially designed to work in a marine environment, and here, the techniques are new and unproven.

The newness of the field probably contributes to a confusion about definitions of system performance. The most common and useful terms such as spatial resolution, frequency resolution, response time and threshold velocity do not seem to be uniformly defined in the literature although precise definitions do exist. Since few authors mention the definitions of these system parameters, a literature survey cannot present a uniform set of conventions, so descriptions presented herein must be noted with caution.

It appears that in the sea, stationary instruments sensing velocity fluctuations need not have a frequency responding capability greater than 20 hz, although for towing tests a frequency response of about 1.5 khz seems necessary because of the high towing speeds. At the approximate cutoff limit of 20 hz the eddies have a characteristic size of a few centimeters. Any smaller eddies that do exist are affected so strongly by viscosity that no appreciable kinetic energy is left in them. Nevertheless, as Gregg (1973) points out, the residual motion of eddies smaller than the cutoff can still stir temperature differences to an approximate limit of a millimeter. These limits define the ultimate resolution that an instrument measuring either velocity, salinity or temperature must be capable of. Experimental results generally support this hypothesis in the case of velocity and temperature fields, but no transducer has yet been made able to resolve the salinity cutoff limit.

As mentioned before, the largest eddies of salinity, temperature and velocity are bounded only by the size of the basin in which they are found. This gives a characteristic time scale of months and a length scale of many kilometers for these eddies. With such a large spread of scales, no single turbulence measuring system can be successful over more than a limited range.

2.2i discrete particle techniques

Turbulence measuring techniques may be classified by the Lagrangian system where the flow is marked and followed, or by the Eulerian system where the flow is measured by a static transducer at a fixed point.

All Lagrangian techniques depend on the injection of some contaminant into the flow, and the subsequent tracing of the contaminant. The well known technique of flow visualization using bubbles ionized from platinum wire could be extended for use in the ocean, although it seems not to have been tried. Donohue (1973) demonstrated that the technique was useful in depicting boundary layer turbulence in drag reducing polymer flows, but found the wires worked better in pure water. In the ocean, one would have to overcome problems of corrosion, detritus and lack of a contrasting background.

Discrete particles and high speed photography have been used by Snyder et al (1971) and Kennedy (1965) for turbulence studies in the laboratory. Their techniques lead to a discrete time series of a few points along the particle trajectory and to rather cumbersome data processing techniques. Spatial and temporal resolution are determined mainly by particle diameter, camera field of view and camera repetition rate. To avoid the drawbacks of photography, Jones et al (1973) used radioactive pellets as tracers, obtaining continuous analogue signals. Although much development work would be needed to adapt this last system to underwater use, it is conceivable that the photographic experiments could easily be carried out in situ.

2.2ii dye

It is simpler to work with dye than with discrete particles, and many experiments have been undertaken using it to identify turbulence at large and small scales. Sternberg (1969) used dye to detail small scale boundary layer features near the sea bottom at great depths. Three dye streaks were used, each a different colour, so that a velocity profile of the bottom 1 meter could be built up.

Only initial results such as a few shear stress estimates and drag coefficients were reported in that paper and surprisingly, no further experiments with it have been published.

Hale (1970, 1971) and Woods (1971) both used SCUBA divers to obtain dye observations around thermoclines. Hale experimented with liquid dyes injected horizontally into water layers from metering and pumping equipment mounted on a tower in Lake Huron. Initial work was carried out to develop dye darts to mark a vertical column of water, but it was Woods who obtained great success with this technique. Instead of liquid dyes, Woods used dried chemicals compacted into pellet form. This gave a long lived and uniform trace, with the added advantage that eddies in the Von Karman vortex street shed by the pellet could be used as a linear scale in analyzing the photographs.

For many sites, however, there are serious practical limitations to small scale dye studies. Visibility is often too poor for good photography. If the turbulence intensities are too great, as often occurs in the near shore environment, then the dye will diffuse rapidly into a large pale blob. Dye studies at these scales are best when the water column is stratified and individual phenomena such as internal waves can be delineated.

Such difficulties did in fact occur in our work and were the major reasons for our not pursuing dye studies past preliminary stages. At the habitat site, visibility limits were less than 10 meters and the Rhodamine dye became invisible after 2 or 3 minutes. Nevertheless, if sophisticated photography techniques such as high speed rigidly mounted stereo cameras were employed, this dye work could have been taken much further, with the results originally hoped for.

In a typical experiment, three divers were needed; one for photography, one to inject the dye via a syringe through a meter long tube to a needle mounted on a stand, and one to follow the diffusing blob, carrying a scale to be photographed. Communications among the three divers, using only hand signals, were difficult. Dangling scales and operating hand held cameras through ¼ inch neoprene mittens required more skill than was initially available for scientific results to be obtained. Woods (1971) who has done the best work in the field, used professional Navy divers.

Another difficulty with the technique is that dyes are very messy, even with sophisticated handling systems, and the smallest drop that is spilled inside the habitat quickly stains large areas bright pink. A considerable amount of effort is needed, then, to develop this potentially useful technique.

Rhodamine B dye has been used extensively at large scales, as mentioned previously. A number of recent papers attests to the continuing usefulness of the technique. Bowden (1973) reports on a large number of diffusion studies in the Irish Sea, where both vertical and horizontal spreading rates were observed and related to wind, tidal currents and environmental parameters of stability. Kullenberg (1973) has performed a similar set of experiments with Rhodamine B dye, finding that the dye tended to be located in layers with very sharp boundaries and a nearly homogeneous vertical concentration distribution.

2.2iii propellor

For Eulerian measurements of velocity, temperature and salinity, a large number of instrument systems are now in use. Propellor meters are commonly used for velocity fluctuations, and cover the entire range of eddy sizes. For measuring scales of several kilometers, large, slow responding, commercial current meters are suspended on taut mooring lines. Usually, the current magnitude and direction are sampled intermittently, and the package must be retreived to get the data. Although this is one of the oldest techniques for measuring velocities, equipment reliability is still in need of improvement. Russell's work (1973) in the Labrador Current illustrates some of the pitfalls. He used an array of moored current meters to relate the large scale eddy structure to iceberg movements but several of the instruments failed to operate. Cruise scheduling usually does not allow for second attempts and often does not allow for long enough stops to obtain adequate data from such slow recording instruments. In a series of experiments using similar instrumentation in the Gulf Stream, Webster (1969) obtained enough data for extensive spectral analysis using standard three dimensional turbulence theory. This illustrates a fundamental problem with all experiments at large scales. The assumptions of homogeneity and isotropy are implicit in most analyses, but in a stratified ocean, turbulence is clearly neither homogeneous nor isotropic when we deal with eddies that are kilometers in size. With present theory, all we can do is note the problem and proceed as though it does not exist.

At intermediate scales such as those found in tidal estuaries, pivoted vane current meters are used to align automatically with the mean flow. Cannon (1971) measured kinetic energy spectra in Chesapeake Bay for several 50 hour experiments using two meters at right angles to each other. Similar instrumentation was used by Gordon and Dohne (1973) in Chesapeake Bay, with emphasis on Reynolds stress analysis. These meters have response times around .1 second, with the pivoted vane responding in about 1 second. Size resolution is limited to approximately 1 meter.

For small scales, only one instrument has been developed that uses propellors. Smith (1970, 1972) has modified a miniature propellor current meter to respond to turbulence. The propellors are 3.5 cm in diameter and directionally sensitive, with a threshold velocity below 1 cm/sec and a frequency response up to 10 hz. A triaxial array of these meters was tested extensively in a tidal estuary and then used successfully to measure turbulent stress below ice in the Arctic. Despite possible difficulties with fouling in areas of heavy biological contamination, this system would have been our choice for the habitat experiments. Unfortunately, it is not available commercially.

2.2iv electromagnetic

The state of the art for electromagnetic induction transducers is similar to that of the propellor meters. A large number of commercial electromagnetic current meters have recently appeared with some systems claiming to have response times low enough (.2 sec) to be useful for small scale turbulence. This type of transducer might be superior in principle to the small propellor meters because it has no moving parts to foul. The mode of operation is described by Faraday's law of electromagnetic induction; that electromotive forces are induced in a conductor moving relative to a magnetic field. At the tip of the probe is a coil which generates the magnetic field. Electrodes farther down the probe sense the variations in the field caused by changes in the flow. Probes are typically 20 cm in diameter, with a zero threshold velocity, and are able to sense two perpendicular velocity components.

Our experience with one of these devices, however, has been most unsatisfactory. It proved to be much slower in response time than was claimed and generated so much electrical noise as to be useless for turbulence work. After a few hours operation, it ceased functioning. The manufacturer, Engineering Physics Company (EPCO), would not provide adequate servicing of the instrument, so it was not used again.

Appell and Woodward (1973) of the National Oceanographic Instrumentation Centre in the United States had similar problems. They carried out extensive tests on the same EPCO meter, noting that boundary layer changes and air bubbles affected the readings. Due to the shape of the probe, the angle of flow in the horizontal plane of the electrodes could cause changes in the predicted output as large as 10%. Vortex shedding was found to induce vibration at high velocities and increase the output by 20%. Appell and Woodward concluded these meters are "in an advanced prototype stage of development".

Despite the potential of this rugged and simple transducer, development is taking a long time. Faraday himself attempted (unsuccessfully) to use the technique to measure velocities in the Thames River during a tidal cycle. Kolin (1944, 1954) did much research in developing electromagnetic flowmeters. Then Bowden's classic work of turbulent Reynolds stresses in a tidal estuary appeared in 1952. After another report in 1956 using his electromagnetic device, the concept became dormant and no further experiments have been published. Mih (1973) has developed an electromagnetic transducer (or magnetohydrodynamic transducer, as he calls it) which is capable of resolving velocity fluctuations around 1 mm. However, the probes in this system were only the sensing electrodes - the driving coil was approximately a meter in diameter, surrounding the channel flow. Much work would be needed to adapt his particular system to the ocean environment.

2.2v vortex

Two other devices which offer possibilities for oceanic turbulence research are vortex meters and fluidic meters. These are as simple and rugged as the electromagnetic current sensors, and with more development could prove useful. The vortex meter operates by passing an ultrasonic beam through the vortex street shed from a cylinder, and sensing the modulation frequency caused by the vortices. Appell and Woodward (1973) found the commercial device produced by J - Tec to have a threshold velocity between .1 and .2 knots. Below that speed, no vortices were formed. In the range .2 to 1.5 knots, the sensitivity decreased by 10%, probably because the vortices did not modulate the acoustic beam properly. This was noted when the meter was rotated within the horizontal plane up to angles of $\pm 30^{\circ}$. Proper alignment into the direction of the flow is essential. The J - Tec device could conceivably discern eddies of the order one centimeter, although it has not yet been used for turbulence work. Clearly, developmental work is needed for the vortex transducer.

2.2vi fluidic

A recently developed device called a fluidic velocity sensor offers the possibility of a low cost, low velocity anemometer. Its operation is based on a free unbounded jet of fluid issuing from a nozzle onto two total head pickup ports. Any ambient flow travelling across the jet causes it to deflect such that the differential pressure across the two pickup ports is changed and is registered by a pressure sensitive meter. The working fluid is the same as the ambient fluid except that it is filtered.

Although the concept is very promising, it seems as though few researchers are interested in its potential. The only paper that could be found on the subject is by Allen, Singh and Bray (1973) who reported ~~initial~~ work on optimizing the pickup port configuration. A Canadian company, Fluidynamic Devices, is marketing a transducer claimed to have a threshold velocity less than 1 cm/sec and a spatial resolution of a few centimeters. Since it was designed as a current meter, no estimates of frequency response have been given. In this type of transducer, frequency response is a function of the jet velocity, jet length, distance between pickup ports and size of pickup ports related to diameter of the jet. Knowing that the probe dimensions are small and the jet velocity high, we can guess that the frequency response will be adequate to an upper limit of a few hertz. Personal communication with Fluidynamic Devices has indicated to us that the systems has performed satisfactorily as a current sensor in the sea. Even though much development and testing is required before these sensors are useful for oceanic turbulence study, the fluidic transducer has great potential.

2.2vii doppler

An important class of turbulence meters employs the Doppler shift principle. A radiated source of energy, focussed at the point of interest, undergoes a change in frequency upon reflecting off suspended particles. The basic equation describing this phenomenon is

$$f_D = \frac{v}{\lambda}(e_s - e_i)$$

where f_D = Doppler frequency

λ = wave length of incident radiation

v = velocity vector of particle

e_s = unit vector of scattered beam

e_i = unit vector of incident beam

Doppler anemometers using lasers as energy sources are presently the subject of intensive research, and several commercial systems exist. Of the many excellent papers appearing on laser anemometry, Melling and Whitelaw's work (1973) is especially useful because it gives a good summary of the latest progress in the system's optical design. Research by Simpson et al (1973) has produced a detailed comparison of laser and hot film anemometry in separating boundary layer flows. They conclude laser anemometry can provide measurements at least as accurate as hot film anemometry, although low frequency response and threshold velocity seem to have not yet been investigated. The unquestionable advantage of laser anemometry is the lack of flow disturbance.

In laboratory flows, the emitting and receiving subsystems of the laser anemometer can easily straddle a glass walled flume, but these subsystems are cumbersome, complex, delicate and require high power and good alignment. In the habitat area, with heavy biological contamination, it would be a boon to use an instrument that depends on the particulate matter, but there are many ocean areas where the system would fail because of water clarity. Laser anemometers have yet to be used in the sea because of these difficulties.

The use of sound energy would seem the logical alternative choice to circumvent the problems of lasers, and a well developed ocean acoustics technology has been used to produce several experimental acoustic Doppler anemometers. Sending and receiving transducers are mounted near the same point and the sampled area is projected some tens of centimeters ahead of the instrument. There is, of course, no flow disturbance, and this is one of the important reasons so many researchers have recently been investigating acoustic systems. Taira (1971) developed a three dimensional system which he used to measure the spectra of wave particle velocities. Some discrepancies between his results and theory are probably caused by the same instrument problems that have been noticed by others. Wiseman (1969) described low signal to noise ratios at low particle contamination levels, a problem similarly found with laser Doppler meters. This might make low velocity fluctuations (~ 1 mm/sec) hard to measure. Appell and Woodward (1973) add that calibration is difficult because of reflection of acoustic energy from the basin walls. Care must be taken to position the unit so that sampling in its own wake is avoided. Nevertheless, optimism prevails about the possibility of acoustic Doppler anemometers, with Bohlen (1971) citing an easily obtainable spatial resolution about 1 cm, a "high" frequency response and ± .5% accuracy over a range of 400 cm/sec. With more development, this will be a useful instrument.

2.2vii optical forward scatter

A variant on the laser Doppler techniques is reported by Liu and Karaki (1972). They designed an optical system which measured forward scattered light from particles in a turbulent air stream. It comprises a light source, a fibre optic lead and lens, and a photomultiplier tube. Concentration fluctuations in the fluid stream cause differences in the amount of light scattered, which is then related to velocity. With a sampling volume of approximately a mm^3 and a frequency response comparable to a hot wire anemometer (~ 30 khz), this instrument could prove useful in the oceans if reduced to a compact package.

2.2ix hydrodynamic

The hydrodynamic aspects of ocean turbulence have been exploited by lift and drag transducers. Triaxial measurements of turbulence in the sea-air interface zone using a spherical drag probe were carried out by Smith (1970) and then turbulent wind forces on Arctic ice sheets were measured by Banke and Smith (1973) using the same instrumentation. The concept was so successful that Earle et al (1970) modified it for use in the oceans. Their transducer is a sphere about 7 cm in diameter, which is fixed rigidly to a probe holder. A slightly larger sphere is mounted around this first sphere, and between the two are compressed sponge rubber supports. The rubber provides a restoring force so that the displacement of the outer sphere with respect to the inner one is proportional to the force applied to the outer sphere. Three small, mutually perpendicular ferrite discs are mounted on the inner side of the outer sphere and their impedance relative to sensing coils on the inner sphere is a measure of the displacement from hydrodynamic drag forces. Spatial resolution is a relatively large 7 or 8 cm, and the frequency response is 3db down at 40 hz. Calibrations of the instrument were performed in flows with velocities from 10 to 150 cm/sec. No report has yet appeared on the use of this interesting transducer in the sea, which suggests that it is probably still very experimental.

Siddon (1971) described a hydrodynamic lift probe capable of measuring turbulence, and Siddon and Osborne (1973) reported its use in a freely falling instrument package delineating the small scale velocity field in the sea. The technique employs a tiny axi-symmetric side force sensor which is exposed to an oncoming flow directed along the probe axis. A modulating side force is impressed on the device as it penetrates the transverse velocity field. The force is then detected by making the probe nose piece of a moderately flexible substance in which is embedded a piezoceramic bimorph beam like those used as phonograph pickups. Two components of turbulence can be measured, with a spatial resolution around 2 cm, a lower frequency limit about .05 hz, and an upper frequency limit of about 16 hz. This lift probe could become an important turbulence instrument because the response seems well understood, the device is fairly rugged and plankton contamination does not affect it.

2.2x pressure

Kostiuk et al (1971) have designed a pressure transducer for use in turbulent boundary layers. A stress sensitive transistor is coupled to a diaphragm which is deflected by turbulent forces. It measures one component of turbulent pressure to a frequency about 50 hz with a spatial resolution about 5 cm. Although not useful for the type of experiment envisaged in our work this would be a useful device for investigating turbulent forces on structures.

2.2xi salinity

Instrumentation for fine salinity and temperature structure in the oceans is much less developed than for velocity. The disparity is mostly because there has been less interest from a turbulence point of view in the temperature and salinity structure, but also partly because salinity and temperature cut off lengths are much smaller. A probe capable of resolving the finest salinity fluctuations has yet to appear, although Gregg and Cox (1971) have developed a transducer with a resolution almost a centimeter. Salinity probes all rely on a pair of electrodes that sense electrical conductivity.

2.2xii temperature

Temperature fluctuations can be successfully resolved using fine thermistor beads. Bowman and Sagar (1971) mounted thermistors in glass-capillary tubing and towed the instrument at sea. Gregg et al (1972) report their use of thermistors in a freely falling probe. They are inexpensive enough to use in quantity and Fowlis (1970) has constructed a grid of these beads for detailed examination of laboratory flows, examing velocities simultaneously at many points. Typical response times are around 20 ms, temperature resolutions 5×10^{-4} °C and spatial resolutions ½ cm. Fouling can occur, although it does not seem to be a serious problem. These transducers are not directionally sensitive.

2.2xiii heated sensors

Thermistors are members of a large class of transducers called heated sensors. The heated sensor is a low resistance metal wire or deposited film (covered with a insulating quartz film) that forms one leg of a Wheatstone Bridge. When flow fluctuations remove heat from the probe, power is supplied by the electronics to follow or counteract the change depending on whether the system is made sensitive to velocity or temperature.

Heated sensors have enjoyed a long pre-eminence in air turbulence as the only device capable of high frequency response and small spatial resolution. Their characteristics have been exhaustively researched over several decades and at least three established companies make complete systems. With the recent interest in the seas, it is logical that many efforts have been made to apply heated sensors to the marine environment. The results have been mixed, and at best the success in ocean experiments must be carefully qualified. Continued difficulties with hot film equipment indicate the sensors may be fundamentally unsuited to ocean research. However, until the present time alternative instrumentation was not available.

3. HOT-FILM ANEMOMETRY

Only two instrument systems were well enough developed, robust and sensitive enough to satisfy our criteria. The electromagnetic meter initially seemed superior to heated sensors because it was so much more rugged, but its failure to respond to the turbulence without generating electrical noise, and its rapid failure to operate caused us to use heated sensors. From the several manufacturers of these systems we chose equipment made by DISA. DISA offered the most complete range of instruments and backup services and has found widespread acceptance in laboratory research. Consideration was also given to Thermo-Systems, who offer as much experience in marine use, and choice of their equipment may have been equally worthwhile.

Because the principle of operation depends on the cooling action of a flow over a heated resistance element in a Wheatstone bridge, anemometers may be made sensitive to velocity or temperature fluctuations simply by front panel rearrangements to the bridge. In the velocity measuring mode, the schematic of the electronic circutry is as shown in Figure 1. The variable resistance, called the overheat control, in one arm of the bridge causes an unbalance which is sensed between points a and b. This causes the servo control system to feed current back into the bridge, heating the probe. When the probe experiences heat loss to the fluid, its resistance changes and the resulting unbalance causes the feedback loop to increase the bridge current, maintaining constant probe temperature. The transducer's behaviour is analyzed using the well known relationship

$$Q = A + B\ (\rho U)1/2\ (T - T_f)$$

developed by King (1914), where

Q is heat transferred from probe to fluid

U is fluid velocity

T is probe temperature

T_f is fluid temperature

ρ is fluid density

A and B are constants depending on probe dimensions and fluid heat capacity and conductivity.

Heat loss Q is related to bridge voltage and current by Q = volts x amps.

(Note that fluid density effects are neglected as they are of second order.)

The ability of the anemometer to measure either temperature or velocity is basically due to the output voltage e being a function of temperature θ and velocity U at the same time;

$$e = S_\theta \cdot \theta + S_u \cdot U$$

where $S_\theta = f_1 (T - T_f)$ = temperature sensitivity of the probe

$S_u = f_2 (T - T_f)$ = velocity sensitivity of the probe

such that the unwanted sensitivity, S_u or S_θ can be minimized at will. For the velocity configuration, temperature influences can be minimized in two ways. One is to nullify the effects of temperature fluctuations with a compensating probe connected to the opposite arm of the bridge and exposed to the same flow. Unfortunately, the frequency response of this compensating is limited to about 100 hz, and the probe is not readily available from DISA. The second way is to operate at a large overheat that is, make $T - T_f$ large. However, the increased thermal stress reduces the probe's life and may cause errors from autoconvection as found by Frey and McNally (1973). A large overheat also makes calibration difficult because the increased heat output results in formation of bubbles on the probe. Usually, one sets the overheat at the highest ratio before bubbling occurs, and ignores the minimal temperature sensitivity.

A modified bridge is illustrated in Figure 2 for temperature measurements. Velocity sensitivity is kept to a minimum by allowing the film temperature to follow the fluid temperature, that is, by operating the probe at a very low overheat level with constant current applied to the bridge. The changes in probe resistance then correspond to temperature fluctuations. Since some power is dissipated in the operation, there is a slight velocity sensitivity, which Chappell and Moilliet (1964) found to be about 10^{-4} °C/cm/sec.

Some theoretical limitations to heated sensors are described by Hinze (1959). Probably the most serious of these is that the King equation holds only for a steady flow of low intensity turbulence, and for wires, not films, which have a completely different shape.

With the validity of the theoretical relationships compromised, it is difficult to place estimates on the errors. For turbulence intensities less than .1, it is tacitly assumed no appreciable errors are introduced. Palmer (1973) recorded turbulence intensities using hot film equipment in Lake Ontario up to .7 which is not an unusual figure in water. Although his data seem reasonable in comparison with others, in a strict sense it is uncertain, and his various data runs are only self consistent.

Aside from the obvious theoretical difficulties, heated sensors are more severely limited by physical considerations.

Hot wires, employed so successfully in air are completely unsuited for ocean work because of fragility and susceptibility to contamination. Although Kolesnikov et al (1958) claim success in measuring turbulent stresses under Arctic ice with a hot wire probe, their report is ambiguous and their results have not been duplicated outside the USSR. Film probes of either conical or wedge tip configuration are more rugged and will shed particulate matter better. Grant et al (1962), and Resch (1970) found conical probes to be the best for shedding detritus, but even so, Grant experienced fouling about every 15 minutes. His solution was an in situ probe washer.

Under the normal laboratory head of a few inches of water, the bubbling problem mentioned previously causes considerable difficulty by occuring at random times even at very low overheat ratios. Water contaminated with microscopic detritus increases the risk of bubbling by providing abundant nucleation sites, and highly aerated and agitated surface water contains large amounts of disolved gas which enhances bubbling. The whole problem is further compounded at low velocities when hydrodynamic drag on the bubbles is small and they are not swept away. Fortunately, at depth, under a head of many meters of sea water, increased pressure will inhibit bubble formation.

Aside from bubbling, Frey and McNally (1973) noticed calibration drift so severe under normal operating conditions that calibration became a necessity immediately before and after each experiment. They also found that their conical probes were not at all directionally sensitive, in fact a higher output voltage was obtained with the probes perpendicular to the flow rather than in line with it. Their transducers failed at random times, anywhere between a few seconds of operation and 20 hours, with the only indications of impending failure being an increase in cold resistance and increasing calibration drift. Many laboratory researchers, such as Morrow and Kline (1971) have to use filtered and deionized water to increase the reliability of their sensors. Ruggedness is relative; hot film probes are still extremely delicate.

Considering all these difficulties, it is surprising that some excellent studies using film probes have arisen. Resch (1970) studied the response of cone and wedge probes in an elaborate testing apparatus and found his measurements accurate and repeatable. He proposed a heat transfer equation for conical probes and investigated correction factors to reduce calibration drift. Unfortunately, the corrections seem too awkward to apply in field use. There are also the very successful field studies mentioned before by Grant et al (1968), Nasmyth (1970) and Gibson, Vega and Williams (1973) where hot film probes performed well in difficult towing conditions. As Gibson et al conclude, "The situation is like comparing democracy to other forms of government; hot film probes are the worst possible sensors for oceanic turbulence, except for all others that have been tried."

4. THE INSTRUMENT SYSTEM

4.1 Instruments

In the study described in this report a DISA 55D01 Anemometer and 55D25 Auxiliary Unit with quartz coated 55R42 conical hot-film probes were used, plus two DISA 55D05 battery-powered anemometers with quartz coated 55A801 wedge probes, so that a 3-component system became possible. The battery powered anemometers were scaled down versions of the 55D01 anemometer and lacked many of the 55D01's features. We hoped to discover if the battery anemometers would be suitable for our use in the marine environment, and at the same time make substantial financial savings in the costs of instruments. It was decided to take velocity measurements only, and not to do automatic temperature compensation because the special probe for this purpose was not available. To monitor any large and slow temperature fluctuations that did occur, a Bendix S-2 temperature probe was set up.

All this equipment, plus oscilloscope, digital volt meter and miscellaneous support instruments were located inside the underwater habitat. Data recording was originally carried out in the habitat but was later moved to the shore support station, partly because of the bother of using the instrument transfer capsule and boat every time data was taken. The calibration device was also designed for use in the habitat so that calibrations could be carried out immediately before and after each experiment if necessary. Data is transmitted to the shore support station and recorded in analogue form on a Lyrec FM tape recorder. This analogue record was later digitized on a PDP 12 computer and analyzed using an IBM 370 computer.

4.2 Probe Housings

The first few dives made with the DISA system ended with the probe connections leaking or the probes breaking. In these initial attempts with wedge probes, the electrical connections were waterproofed with silicon sealant and the probes protected with a plexiglas cap or a plastic tube. Repeated failures led us to a rather elaborate solution for mounting, protection and waterproofing. One design was made for wedge probes and another for conical probes. Basically, both are hollow brass cylinders which contain the electrical connections, with watertight elements on each end sealing around the cables and probes. A sliding sheath fits around the cylinder and locks in place over the probe to protect it when not in use. In Figure 3, which is a general view of the conical probe housing, the sleeve is slid back so that measurements can be taken. A mounting bracket then clamps onto the cylinder behind the sliding sleeve. A cutaway view of the wedge probe housing is depicted in Figure 4, and the sealing elements, called the silicon nut and the O ring nut can be seen. The O ring nut is a conventional type seal, with the O ring being squeezed by the screwing action. Silicon nut refers to the seal used on the coaxial cable. The cable passes through the nut and through a cone shaped element in the O ring nut. The space between the cone and the cable is filled with silicon sealant, which, when set, is compressed by the "piston" on the silicon nut.

This type of seal was chosen because of the irregular nature of the surface of the coaxial cable which might have caused an O ring seal leak. In the case of the conical probe, an O ring could not easily be obtained to fit the small 3mm diameter of the coaxial cable that was moulded to the probe. Commercial waterproof connectors would not fit this small size, nor could they adapt to the special mounting configuration of the wedge probe.

The probe housings are then mounted in the triaxial bracket that the diver is adjusting in Figure 5. The bracket in turn clamps to an instrument tower which has adjustable legs for uneven terrain, and one diver can move the whole assembly about. The photograph in Figure 6, although distorted by a wide angle lens, shows the ease and precision with which the experimenter can monitor and set up the apparatus.

4.3 Habitat

The underwater habitat LORA 1 is located in a small bay off the North Atlantic near St. John's, Newfoundland, some 200 meters from shore in 12 meters depth of water. The sea temperature hovers around $-1.8^{\circ}C$ for several months and never goes above $13^{\circ}C$. In late winter and spring severe jammed Arctic pack ice may cover the site for three or four months and depending on the season and storm conditions, visibility ranges from 5 to 40 meters. The design wave is about 5 meters and thermoclines may occasionally be observed in the vicinity. Detailed descriptions of the habitat and its surroundings are given by English (1973) and English and Dempster (1973).

An umbilical carrying air, power and communications stretches between LORA 1 and the shore support station, the operations base. Originally, the umbilical also served as the data link to the tape recorder in the shore station, but there was too much 60 cycle noise generated by the power cable, so three separate coaxial cables were laid nearby to be used for data transmission. Normally, divers swim from the shore support station to the habitat, but when equipment transfers are to be made, they motor to the site in an inflatable rubber boat kept nearby. The equipment is packed in a steel housing and winched down from the boat as shown in Figure 7.

Since LORA 1 is at ambient pressure, the divers enter via an open water hatch on the underside. Figure 8 gives a general outside view of LORA 1, and the hatch is evident to the right in Figure 9. An average relative humidity of 60% and temperature of 22°C make for a fairly comfortable shirtsleeve environment, although large swells passing overhead can cause annoying pressure changes. Five hours of work per day was the limit allowed for this research to avoid the need for decompression, although extra support equipment and the complete toilet, kitchen and sleeping facilities present do allow much longer stays for special activities. After two years of continuous use, the habitat system runs smoothly and despite the fact that LORA 1 was constructed at a very low cost (the hull was originally a fish digestor tank) the facilities are safe, reliable and flexible. Once divers are on site, they usually switch to habitat supplied air systems, or hookahs. The diver in Figure 10 who is injecting dye to delineate the turbulent structure is wearing a Unisuit which is dry and has adjustable buoyancy. The next two shots in the series, Figures 11 and 12, show a typical dye spread, with an end view of the habitat seen in the background. In the summer, divers may wear wet suits and leave their mittens off, but for most of the year the extreme cold means a full Unisuit is desired, especially when the sort of weather shown in Figure 13 descends.

4.4 Calibration

Several different schemes are available for calibration. The optimum design for our purposes was a relatively inexpensive one, capable of being mounted in the habitat so that calibration could be done immediately before and after each experiment. We chose a rotating tank from all the possibilities outlined in Appendix 3. A variable speed DC gearmotor rotates a circular tank filled with water, as Figure 14 illustrates. When the water rotates as a solid body at a set speed, the velocity at the probe is easily and accurately calculated.

5. EXPERIMENTAL RESULTS

Difficulties with electrical grounds plagued the experiments from the beginning, and many unanticipated problems with the instruments arose from operating within an electrically conducting medium like seawater. It was necessary to bypass the original data transmission cables by laying separate coaxial cables in an attempt to reduce 60 cycle noise pickup from the power line. This operation was only partly successful because it was found that most of the electrical noise came from a ground loop between the habitat and shore support station. The ground loop was then eliminated by floating all the instruments in the shore support station and grounding them at the habitat. Nevertheless, occasional voltage differences seemed to build up in a random way between the habitat and shore support station. Twice the voltage build up was manifested by mild shocks to the shore support station operator and an instrument blew a fuse on the first such occasion. It is not felt this electrical problem disrupted the experiments once underway.

The battery powered anemometers had separate electrical problems of their own. They functioned properly when used with conical probes, but were highly erratic with wedge probes. The difficulty was associated either with the probes shorting electrically to seawater ground across the quartz insulating film at the tip, or through the brass probe housing. Insulating the probe's metal parts from the housing showed that the anemometer would function, but only at a reduced output voltage.

Several complete experiments measuring turbulence in three dimensions were recorded and digitized to develop the system before any calibrations were done. During calibration it became apparent that the battery powered anemometers were fundamentally unsuited to the work. Whether on batteries or on a DC power source, the anemometers would not supply enough power to match the cooling of the flow on the probe at the velocity range in which we had to work. Continued problems with grounding were experienced and the battery anemometers drifted badly. Finally, one anemometer began to generate a noise level 10 times what it was before, so both were set aside and it was decided to continue with the 55D01 anemometer only.

In calibrating the hot film transducers, it was noticed that it was more difficult to obtain accurate readings with the wedge probes than with the conical probes.

The wedge probes tended to display a sort of "hysteresis effect" drawn in Figure 15. Voltage readings while the water velocity was stepwise increased tended to be substantially higher than voltage readings taken at the same velocities when the water velocity was stepwise decreased. No extensive measurements of the phenomenon were taken as it soon became apparent that if the rotating tank flow were allowed to stabilize for about twenty minutes the wedge probes gave repeatable measurements. This would lead one to think that the cause was in some property of the flow, except that simultaneous measurements with the conical probe never gave evidence of such behaviour. Certainly, small second order currents could be set up in the fluid before it reached steady state, and the wedge probe, being more directionally sensitive than the conical probe could register the second order effect. This seems not to be the case, though, because dye injected into the flow indicated only simple radial and vertical velocity gradients caused by wall friction and bottom friction. Not enough dye work was performed to completely rule out second order transient currents, but it seems more likely the "hysteresis" effect was controlled by mechanical vibration of the tank. At higher rotational speeds, the gearing system imparted large amounts of vibration to the flow, which was clearly seen as tiny concentric ripples on the surface. At the point where vibration began to increase rapidly, the probe voltages would level off or sometimes decrease 5-10%. Perhaps the vibration changed the boundary layer flow over the wedge probe. This response is puzzling, especially since it seems not to have been reported in the literature.

Aside from the "hysteresis" problem, wedge probes were generally difficult to handle during calibration as it was necessary to dismantle the probe housing, clean the probe, mount it on a special probe mount and carefully seal the assembly with a waterproof sealant. As often as not, the assembly would leak, the probe would short to ground and the whole procedure would have to be repeated. The conical probe, on the other hand, has the sensor mounted integrally with its support and coaxial cable which is some 20 cm long. With the probe housings we designed, it was only a simple matter to place the conical probe in its calibration mount without dismantling the rest of the assembly.

In the course of our experimental work, we encountered a rather serious limitation. If the mean current is very small, the oscillatory motion of wave induced disturbances can cause an absolute reversal of the direction of the velocity vector. If a probe is fixed so that oncoming flow is called positive, the flow will be negative on occasions, coming from behind, and the probe will sample its own wake. In addition, the probe will not record whether the velocity is positive or negative because positive voltages only are indicated for any cooling action. If we have a sinusoidal current that has negative velocities, as in Figure 16(a), the measured result is the voltage signal of Figure 16(b), where the lower portion has doubled back on itself, creating a spurious curve. It was thought that examining the autocorrelation of the velocity signal as shown in Figure 16(c) would allow us to estimate the magnitude of the current reversal.

A sine curve is transformed by the autocorrelation into another sine curve. When the original curve is distorted as drawn in Figure 16(b) the autocorrelation curve is still sinusoidal, however, the negative portion is less in magnitude than the positive. If a turbulent signal (Figure 16(d)) were superimposed on the sine curve the result is a further distorted autocorrelation graph near the origin (Figure 16(e)), provided that the length scales of turbulence and currents are similar to those actually found in the habitat area. These rough sketches simply illustrate that this mode of analysis is an awkward one, and once the oscillating current becomes nonsinusoidal and irregular, it will be even more difficult to analyse the autocorrelation of the turbulent signal and to estimate the magnitude of the current reversal.

It is obvious that direct current measurements are desirable, and in the next section we describe a technique to obtain them which is suited to the habitat area. Although we could estimate the magnitude of the oscillatory motion by watching dye patches, we were not able to record and measure the motion quantitatively because photographic equipment was not available at the time. We also attempted to measure the currents with small propellor current meters, but the flow was too weak to be recorded. In any case, as the analysis described in the next few pages shows, we overestimated the magnitude of the current reversal, and in actuality it was probably not very significant.

Two separate experiments were performed, the first comprising a 15 minute record of the turbulence at 2/3 meter from the bottom, which we call run 1 bottom, and a second 15 minute record at 5 m from the bottom which we call run 1 top. Similarly, the second experiment, which was done on another day, comprises run 2 bottom and run 2 top. Both experiments were in the same 11 meters depth of water and both were done in the same kind of weather. For the first experiment, it was calm, with a 10 second swell ruffled slightly by wind. It was hoped to contrast this test with data from a stormy day but unusual December weather provided only weeks of very quiet seas, so we were forced to settle for a second experiment with a similar 10 second, 1/3 meter swell with no wind whatsoever.

Dye injection showed itself to be a very useful tool during the experiments, for it was used to indicate the mean current direction so we could rotate the probe housings into the current. The dye diffused very slowly in both runs in the first experiment and in run 2 top during the second experiment, indicating that the turbulence intensity was quite low. In contrast, the dye diffused in an almost explosive manner during run 2 bottom and exhibited an obvious and strong oscillatory motion coupled with a slight corkscrew action. This unusual motion decreased rapidly in intensity until it was not discernable at a height of about one meter off the bottom. The dye patch of run 2 top at the same time was showing very little diffusion and very little translatory movement.

In all four runs the dye clearly showed up currents and turbulence intensities. Although run 2 bottom was markedly different than run 2 top, dye in the first experiment showed the two runs to be similar, with a gentle oscillation superimposed on the mean velocity. It was difficult to estimate in which run the currents were stronger for the first experiment, but it seemed the turbulence intensity was less for run 1 bottom. Assuming the turbulence was partly generated by wind stress, a decrease in intensity as one went to the bottom would be expected. In all cases, the dye patches diffused uniformly in a spherical manner. When oscillations occurred, the blobs were transported bodily with no noticeable shearing motions.

The data shows that the dye tests coincided with what was measured by the hot film probe. If we construct a histogram of the occurrence of different velocities for each run, we get the probability density functions of the turbulence shown in Figure 17. The central moments of these distributions, listed in Table 1, verify the divers' relative estimates of dye patch velocities. Run 2 bottom had the greatest mean current of all, at 2.03 cm/sec, and run 1 top had a greater mean current than run 1 bottom. From the first and second moments we can calculate turbulence intensities of the four runs. Note that the turbulence intensity of the run 2 bottom is .19, a value significantly greater than the other three runs, which is as observed from the dye. We probably do not have to worry about the nonlinear anemometer response difficulties mentioned before that are associated with turbulence intensities greater than about .1 because our largest intensity is only a little larger than that approximate limit, and the other intensities are much smaller.

The third and fourth moments, the skewness and the kurtosis, are all very small. Although there is a definite non zero value of occurrence at zero velocity for two of the curves in Figure 17, and run 2 top even increases slightly at zero, this is partly due to computer program error and in any case, the occurrences are less than 2%. As can be seen in Figure 16(b), the voltage curve has a larger mean value than it would if distortion didn't occur. Looking at the probability distributions in Figure 17, it is obvious that even if the mean velocity were lowered by .5 cm/sec, the "tails" of the curves are so small that negligible negative velocity would occur. In other words, we need not worry about the negative velocity problem for these data.

The same conclusions may be drawn from the autocorrelation curves. Figures 18 and 19 show the autocorrelations to a lag of 10 seconds and as such look vaguely as predicted by Figure 16(e). Extending the lags to 100 seconds shows in Figures 20 and 21, how the following cycles become uniform and have a slight positive mean value. Note that in the case of run 2 bottom, the current seems modulated both by a 10 second component and 75 second component. These extended autocorrelation curves in Figures 20 and 21 are not intended to be useful for turbulence analysis, but are only presented to illustrate the current reversal problem in the absence of direct measurements.

The 10 second lag autocorrelation graph are also not very useful to describe the turbulence. The oscillating currents obscure the turbulence autocorrelation so that only crude visual estimates can be made of the microscales and integral scales. For all cases, the microscale, or approximately the smallest size of eddy present would have a time scale of about 0.5 to 1.0 seconds. The integral scales, the largest eddies, have an associated time scale of 3 seconds. Run 1 bottom in Figure 18 is the only curve that resembles a usual autocorrelation function of this type of turbulence. Even here, there is a large peak at 10 seconds, approximately the observed wave period. In any case, the curves are consistent, and show approximately the same surface wave period. Surprisingly, the overwhelming fluctuating component of $\rho(\tau)$ for run 2 bottom shows that the current velocity was sinusoidal, even though it was not driven by sinusoidal surface waves.

Detailed analysis might glean further information from the autocorrelation curves, but it is more fruitful to examine the power spectra in Figures 22 and 23. Notice how clearly the 10 second swell shows up in all graphs except that of run 2 top, where we know from the dye trace that the wave influence was minimal. The wave peak tends to obscure the curves, but the approximation of -5/3 for the slope seems to be possible for the lower frequency portions. A -5/3 slope in part of the turbulence power spectrum is predicted by the theory of the well-known Kolmogorov model as presented by Hinze (1959). In our experiments, the so-called inertial subrange, where the -5/3 power law holds, falls in the range of frequencies between 10^{-3} and 10^{-1} hz. The model predicts that a specific relationship exists among energy, frequency and dissipation in the inertial subrange. The dissipation is a widely used measure of the energy which ultimately decays by the action of viscosity at small scales and is important because it indicates how much energy is put into the turbulence at large scales and how much cascades down through the spectrum until it is ultimately dispersed at the viscous sink. Although the Kolmogorov model predicts a peak at low frequencies where most of the energy is found, the experiments did not sample long enough for this peak to be delineated. Thus the spectra here show only a more or less continuous decrease in energy. All the runs seem to show a definite change in slope around .5 hz but the increase in scatter of the data just means that the signal energy is so low that random noise is obscuring the trace.

The numerical algorithm for computing spectra assumes the turbulence is both homogeneous and isotropic, that is, it has the same quantitive structure in all parts of the flow, and its statistical features have no preference for any direction. This is obviously incorrect at large scales in the oceans, where horizontal distances are much larger than vertical distances, but at the small scales of the inertial subrange the assumption is probably good. The cascade of energy through smaller and smaller scales effectively disorganizes the turbulence, and all memory of the generating situation is lost. Remember that the dye traces all diffused in a uniform, spherical manner, which indicates that the turbulence was relatively homogeneous and isotropic. It appears possible to use the theoretical formula $\Phi = \alpha \epsilon^{2/3} \left(\frac{2\pi f}{U}\right)^{-5/3}$ to calculate the dissipation

where

Φ is the energy density (cm^2/sec)

α is a universal constant (more or less) equal to .5

f is the frequency (sec^{-1})

U is the mean velocity (cm/sec)

It is not clear, however, from the limited data gathered that the spectra shown have a 5/3 slope over any significant range (say a decade) of scales. One might then question the validity of the assumption of the existence of inertial subrange for which this formula applies. In addition, the strong influence of surface swell may also limit the validity of applying this formula. Nevertheless, we found values of ϵ calculated by this method to be about 5 x 10^{-3} cm^2/sec^3 for all runs. Such a figure seems acceptable as it is an order of magnitude greater than some dissipations reported by Grant et al (1962) but an order of magnitude less than those reported by Gibson et al (1973).

We are unable to give a complete explanation to the strange situation of the second experiment, where a strong sinusoidal current swept through the bottom one meter of the water column at approximately the same frequency as the surface swell, with very little motion being recorded in the rest of the column. Salinity was not measured, but we know from the cold resistance of the hot film probe that the temperatures were the same at both positions to an accuracy better than 1.C^{O}. Figures 17 and 20 show that this type of current also occurred in the first experiment, but was much less marked. Thus it is not likely the current was just a local perturbation, but was part of a general and repeating circulation pattern. Since the bottom turbulence intensity was weaker than the turbulence intensity closer to the surface during experiment one, we can conclude that wind stress played the dominant role in generating the turbulence that day, and that during the second experiment, current shear stress was the generating mechanism. The strange current patterns are indicative of just how much remains to be discovered about fluid motions in the sea.

6. DISCUSSION AND RECOMMENDATIONS

Despite the many uncertanties and negative attitudes about using hot film sensors in the ocean, it is clear that in the application described here the practical difficulties associated with such probes can be overcome, and consistent and fairly accurate readings can be taken. Wedge probes are perhaps less desirable than conical probes, except that wedge probes are directionally sensitive. Two wedge probes failed in the course of our work, one after a few minutes use and the other after a few hours. In both cases, the cold resistance of the probes increased just prior to failure, as has been noticed by others such as Frey and McNally (1973). The wedge probes displayed some ambiguity in calibration and were also difficult to handle because the joint with the probe holder needed to be waterproofed. Nevertheless, the two wedge probes used in the underwater work were still operating after about 18 hours and gave no sign of impending failure. The one conical probe used was operated for over 25 hours during a time of some 10 months without being cleaned, was cycled several times through a pressure gradient of two atmospheres, exposed to temperatures down to $-1.8^{\circ}C$ and exhibited less than a few percent calibration drift. It even survived repeated gnawings from curious fish. At an overheat of 1.2, no problems occurred with bubbling or fouling investment, there are two areas where the housings could be improved. The conical probe housing might have a more delicate probe mounting system which would extend farther from the barrel so that there would be less chance of flow disturbance. The wedge probe housings can be made slightly smaller using the same design, but it is recommended that if a triaxial array is to be used, all three probes should be conical probes with improved housings so as to offer the least flow disturbance. Another improvement that could be made is to devise a system to seal off the water inside the protecting sleeve when it is extended to measure the probe's output voltage at zero velocity. This must be done to accurately estimate the mean velocity if the probe is to be used to measure both mean and fluctuating components. What we did was simply to wrap soft foam rubber over the openings to seal off velocity fluctuations. Some residual effects of the velocity were felt because the seal was not perfect, and the voltage in this condition could be seen to have a slight sinusoidal component from the wave motion. A mean voltage was estimated from the trace and probably was accurate to ± 5%.

The rotating tank calibration device is good in concept, and provides an easily and accurately adjustable range of velocities. In the interest of faster calibrations it might be better to avoid accelerating the fluid to a on either the wedge or cone probes even though the waters were usually heavily contaminated with organic detritus. Whether or not we can conclude DISA probes are superior to the Thermo-Systems probes that gave Frey and McNally (1973) so much trouble is problematical, but we certainly achieved more positive results.

It was shown that the DISA battery anemometers were not suitable for this work, but the 55D01 anemometer was suitable, and no problems were found in its use. The newest DISA anemometer, model 55M, would be a still beter choice (although an expensive one) because of its ability to accept a 100 m probe cable using internal bridge balancing. For cable lengths longer than 5 m the 55D01 has to use external resistors to balance the bridge at high frequencies, which severely limits its usefulness. We found that the high frequency unbalance could be ignored up to a cable length of about 12 m but at that point, the unbalance started to increase noise levels at a rapid rate.

The probe housings were the key to the success of the experiments and proved easy for divers to manipulate even when wearing neoprene mittens. The designs are entirely satisfactory as they stand, but if one is willing to make the uniform velocity by rotating the probe instead of the water. This would necessitate slip rings to carry the probe current to the rotating assembly. Such a design was used by Frey and McNally (1973) but they found the slip rings too noisy and had to bypass them and wind up a long probe cable instead. In the author's experience with mounting hot film probes on high speed drums, even cheap slip rings will be completely noise free as far as the probe is concerned. Since we discovered that vibration could cause serious calibration errors, it is important that the drive train selected for the calibration system be of good quality.

In general, the hot film equipment performed well. Once the system is set up in the habitat it is only a simple matter to perform as many experiments as desired in as many different conditions as the environment will provide. We found that running a complete three dimensional experiment took less than two hours from the time the divers entered the water until they left. Although the experiments we performed were only of 15 minutes duration, they should be lengthened to provide better information at the low frequency end of the energy spectrum. The Lyrec tape recorder will give a maximum recording time of about 150 minutes on seven channels, and with several tapes a complete profile throughout the water column can easily be taken in an afternoon.

Note that the Lyrec tape recorder, although designed for turbulence work, is not suited to low frequency application. There are two basic problems. The first is that the circuitry is designed with high pass filters which remove all frequencies below 2 hz in an effort to reduce drift. These filter circuits had to be inactivated before we could use the tape recorder. Second, the Lyrec has a control which biases out the mean component of a signal in order to reduce the signal voltage so it can be amplified further for maximum sensitivity. Because most turbulence experiments do not rely on the heated sensor to give the mean component of the signal, there is no provision for measuring this bias voltage. We had to resort to further modifications of the circuitry which were not entirely satisfactory and admitted an error of about 5% into the measurement of the bias. With further work, however, this error can be reduced to insignificance.

The investment that must be made to expand these experiments will be in the development or acquisition of sophisticated computer programs to handle the data. Digitising went smoothly on the PDP 12, but the IBM Fortran programs used for analysis are not capable of handling more data or generating more accurate answers without extensive revision. It may also be necessary to develop a system to record the current reversals in such a way as to eliminate any errors in the turbulence signal. Such a system could entail a small, fast-responding directional vane for each turbulence transducer. The current directions would be recorded for several vane positions simultaneously with the turbulent signal, and digital processing could easily invert the velocity signal at the proper times. If current reversals are to be expected, it might be better to calibrate and place the probes perpendicular to the expected flow to avoid sampling in the wake of the probe housing.

At the time of the second experiment, when the turbulence intensity was .19, the dye trace diffused in a more vigorous way than we had noticed before, even on days with 1 meter waves and strong winds. This indicates that we are not likely to encounter turbulence at intensities much higher than this at the site, so future experiments will not be faced with the inaccuracies resulting from anemometer monlinearities at high turbulence intensities.

Working underwater from a habitat offers unique possibilities for research. If equipment needs to be repaired, it is only a simple task for a diver to step outside and recover the item. Enough instruments and tools can be kept on hand that standard laboratory techniques and in part, laboratory precision, can be carried to the center of the field study. To have first hand visual experience within such a study proved in many ways to be a great advantage, for we were able to fix malfunctioning instruments, we could judge directions of currents, intensities of turbulence and recognize areas of interest such as the unusual condition in the second experiment. Changes in the program were easily and quickly carried out to meet these different environmental conditions. Perhaps we can best sum up working in the habitat by the following example. Where a remote experimenter would view with alarm the occasional burst of erratic noise which routinely disrupts hot film signals, thinking bubbling or fouling was taking place and possibly changing the calibration, we could tell by visual inspection that neither of these was happening - it was only a fish swimming past the probe.

7. CONCLUSIONS

1. Use of SCUBA divers and the habitat LORA 1 allowed the design of a very effective combined dye and hot film transducer system which has clear advantages over use of the sub-component measuring systems alone.

2. Hot film anemometry is presently the only system generally available for measuring small scale oceanic turbulence.

3. DISA hot film anemometry equipment is suitable for use in the ocean provided proper handling and transducer mounting equipment is designed.

4. Conical probes are easier to use than wedge probes.

5. Measurements of the turbulence at the habitat site indicated characteristic - 5/3 spectral slopes, viscous dissipations of about 5×10^{-3} cm^2/sec^3 and intensities about 0.1. Unusual oscillatory bottom currents were noticed, and surface wave action made measurements more difficult.

6. Other turbulence transducers, less expensive and fundamentally more rugged than hot film devices are in various stages of development. The fluidic probe and the vortex probe are potentially useful commercial devices, with the electromagnetic flowmeter looking the most promising at this point. If the miniature propellor system and the hydrodynamic lift probe become commercially available, they should also be suitable for small scale oceanic turbulence measurements.

APPENDIX 1

COMPUTER PROGRAMS

1. ADTAP2

1.1 Purpose

This is a library program on the PDP 12 that digitizes analogue tape records and creates IBM compatible digital magnetic tapes.

1.2 Technique

ADTAP2 uses an internal real clock in the PDP 12 for synchronization. The program is available in both source code and object code form on the DIAL-MS console tapes which are Linctapes 10 and 11. Documentation, and some information on programming for use of mag tape in 370 FORTRAN is found in the printout and is included here. Note that analogue imput voltages must be scaled to within $\pm$ 1 volt.

1.3 Listing

```
*20
/PROGRAM - ADTAP2
/
/AUTHOR - A.N. BETZ
/
/DATE WRITTEN  - 26 FEB 73
/DATES REVISED -  9 OCT 73
/   16 NOV 73  - 20 NOV 73
/PURPOSE - SAMPLE VOLTAGES ON ANALOG
/       CHANNELS 10 TO 17 AT A RATE
/       DETERMINED BY SETTINGS OF THE
/       RIGHT SWITCHES AND TRANSFER DATA
/       TO IBM 370 COMPATIBLE 9 TRACK
/       800 BPI MAGNETIC TAPE IN BINARY
/       16 BIT 2S COMPLEMENT FORM.
/
/TAPE FORMAT - DATA IS WRITTEN ON TAPE
/       IN 8-CHANNEL RECORDS SINCE
/       EACH CHANNEL REQUIRES 16 BITS
/       OR 2 BYTES, A RECORD IS 16 BYTES
/       LONG. RECORDS ARE BLOCKED 256 TO
/       A TAPE BLOCK, GIVING A BLOCK SIZE
/       OF 4096 BYTES.
/        THE TAPE IS UNLABLED, AND IS
/       TERMINATED BY A STANDARD END OF
/       FILE MARK.
/COMPUTER CONFIGURATION - PDP12 WITH AT
/       LEAST 12K WORDS OF MEMORY, TC58
/       MAG TAPE CONTROL, TU10 9 TRACK
/       MAG TAPE TRANSPORT, AD12 ANALOG
/       TO DIGITAL CONVERTERS, AND KW12
/       REAL TIME CLOCK.
/
/OPERATING INSTRUCTIONS -
/       **FOLLOW INSTRUCTIONS EXACTLY!**
/       1 LOAD PROGRAM FROM LINCTAPE IN
/         THE USUAL MANNER DESCRIBED IN
/         THE DIAL SYSTEM USERS MANUAL.
/       2 MOUNT A WRITE-ENABLED MAGNETIC
/         TAPE ON TU10 TRANSPORT 0.
/       3 SET LEFT SWITCHES TO 0200
/       4 SET RIGHT SWITCHES TO SAMPLING
/         RATE DESIRED (SEE TABLE).
/       5 PLUG SIGNAL SOURCES INTO
/         ANALOG CHANNELS 10 TO 17.
/       6 SET MODE SWITCH TO PDP8 MODE
/         AND PRESS 10 PRESET KEY.
/       7 PRESS START LS KEY TO SET TAPE
/         TO LOAD POINT MARKER.
/       8 TURN ON SIGNAL SOURCE AND
/         PRESS CONTINUE KEY TO BEGIN
/         SAMPLING.
```

```
/        9 TO TERMINATE SAMPLING, SET ON
/          RIGHT SWITCH 0. THIS WILL
/          CAUSE AN END OF FILE MARK
/          TO BE RECORDED ON TAPE AND THE
/          TAPE TO BE REWOUND.
/       10 TURN OFF SIGNAL SOURCES
/       11 REMOVE MAGNETIC TAPE FROM
/          THE TU10 TRANSPORT AND REMOVE
/          THE WRITE-ENABLE RING FROM THE
/          REEL.
/
/SAMPLING RATES -
/        SWITCHES  RATE
/          0000     10 HZ
/          0001     20 HZ
/          0002     50 HZ
/          0003    100 HZ
/          0004    200 HZ
/          0005    500 HZ
/          0006   1000 HZ
/          0007   2000 HZ
/
/HALTS - FOUR HALTS ARE PROGRAMMED
/        HALT1-MEMORY ADDRESS 0300
/              TAPE CONTROL NOT READY
/              HARDWARE PROBLEM.
/
/        HALT2-MEMORY ADDRESS 0303
/              ERROR OCCURRED ON WRITING
/              A TAPE BLOCK. CHECK TAPE
/              STATUS REGISTER (DISPLAYED
/              IN ACCUMULATOR) TO FIND
/              CAUSE. THIS WILL USUALLY
/              BE A PARITY ERROR DUE TO
/              IMPERFECTIONS IN THE TAPE.
/              THE RUN IS ABORTED AND YOU
/              MUST START AGAIN FROM THE
/              BEGINNING.
/
/        HALT3-MEMORY ADDRESS 0314
/              TAPE DRIVE NOT READY
/              INDICATES TAPE NOT TURNED
/              ON-LINE, OR HARDWARE
/              PROBLEM.
/
/        HALT4-MEMORY ADDRESS 0330
/              NORMAL END OF JOB
/              DEAD END HALT
/
        EJECT
```

```
/PROGRAMMING HINTS FOR IBM 370 FORTRAN
/       16 BIT BINARY IS "INTEGER*2"
/       AND IS READ USING "A2" FORMAT.
/       LABEL PARAMETER FOR DD CARD
/       IS "LABEL=(,NL)"
/       DCB PARAMETER FOR DD CARD
/       IS "DCB=(RECFM=FB,LRECL=16,
/       BLKSIZE=4096,DEN=2)"
/
/NOTES ON DATA REPRESENTATION
/
/       THE FIRST TAPE BLOCK (256 RECORDS)
/       IS ALL ZERO VALUES.
/       DATA VALUES ARE IN THE RANGE -511 to +511
/       EQUIVALENT TO -1 V. TO +1 V. AT THE ANALOG
/       INPUT
/
/
/
/
/
/SAMPLE PROGRAM IN 370 FORTRAN
/       PROGRAM JUST READS AND PRINTS RECORDS
/
/
/  //E3XXXX00 JOB (3XXX, X00B, 5, 5), NAME,
/  //     CLASS=B,REGION=100K,MSGLEVEL=(1,1)
/  //REDPRNT  EXEC FORTGOLG
/  //FORT SYSIN DD *
/         INTEGER*2 VALUES (8)
/      10 READ (9,6,END=100)Values
/       6 FORMAT (8A2)
/         WRITE (6,7)VALUES
/       7 FORMAT (1X,8I4)
/         GOTO 10
/     100 STOP
/         END
/  /*
/  //GO. FT09001 DD DSN=SAMPLES, UNIT=TAPE,
/  //       DCB=(RECFM=FB,LRECL=16,BLKSIZE=4096,DEN=2),
/  //       DISP=(OLD,KEEP), VOL=SER=XXXXXX,
/  //       LABEL= (1,NL)
/
         EJECT
```

2. SPSS300

Purpose

This is a Subroutine Package for Social Sciences Program which was chosen to produce a least squares fit on the calibration data.

2.2 Technique

Multiple linear regression is used and a polynomial equation is fitted to the data.

2.3 Program Control Cards

As it stands, the program is satisfactory. Should a user desire more data points in the calibration, or want to go to a higher order equation, the following cards will be explained. Detailed description of SPSS300 will be found in any computer systems reference library.

2.3.1 Number of Data Points

This card starts with # OF CASES.

In column 16 type the desired number of points is integer format.

2.3.2 Order of Equation

A COMPUTE card is necessary for each power of x.

From Column 1, type COMPUTE, then in Column 16, type X2 = X**2 for the second order.

For the third order another COMPUTE X3 = X**3 .

card is necessary, and so on.

All variables in the regression must be listed on the REGRESSION card. For a fourth order equation, in column 16 of this card type

VARIABLES = X Y X2 X3 X4 /REGRESSION = Y with

X X2 X3 X4 (3)

2.4 Data Cards

Column	Identification	Format
0-6	voltage	F
6-12	velocity	F

2.5 Sample Deck

```
//E3010602 JOB (3010,602F,5,2),TIFFIN,CLASS=F,REGION=150K,
// MSGLEVEL=(1,1)
// EXEC  SPSS300,PARM=10000
//SYSIN DD  *
RUN NAME        LEAST SQUARES FIT
VARIABLE LIST   X Y
INPUT MEDIUM    CARD
INPUT FORMAT    FIXED(2F6.4)
# OF CASES      10
COMPUTE         X2=X**2
COMPUTE         X3=X**3
REGRESSION      VARIABLES=X Y X2 X3 / REGRESSION=Y WITH X X2 X3 (2)
STATISTICS      ALL
READ INPUT DATA
0.    0.
.5    1.
.8    2.
1.0   3.
1.33  4.5
1.5   5.82
1.7   8.
1.83  10.1
2.17  16.6
2.32  20.
FINISH
/*
//
```

3. DIST

3.1 Purpose

DIST analyses the turbulence signal and produces the first four central moments of the frequency distribution. The relative and absolute frequency histogram is plotted.

3.2 Technique

As mentioned before in the description of the digitizing program ADTAP2, the first block of data is all zeros, so it is necessary to skip this part of the tape. In the conversion of the voltage data to velocity there are four parameters of interest. LYREC represents the bais voltage used by the Lyrec tape recorder to eliminate most of the mean component of the turbulence signal. AOUTVO is the DISA anemometer output voltage at zero flow velocity. Thus it is necessary to subtract AOUTVO from the signal voltage to obtain the true reference zero, and add LYREC to the signal voltage to establish the correct magnitude above this zero. The third parameter is AMFAC which contains the corrections due to transmission cable resistance, scaling of the tape recorder output to the PDP 12 and the correction described before to the Lyrec tape recorder bias control. Finally, the series of parameters A1, A2, A3, A4 represent the calibration coefficients obtained from the least squares fit program, where A1 is the constant, A2 the coefficient of X, A3 the coefficient of X**2 and A4 the coefficient of X**3.

3.3 Subroutines

Subroutine HISTGM is a slightly modified version of HISTGM found in the Waterloo Fortran Subroutine Library. Its function is to prepare the histogram. Note that negative velocities are recorded as zeros by the calling program DIST.

3.4 Program Control Cards

DIST carries out its functions for each channel for which it receives the following pair of cards. That is, if three channels are to be sampled, then there will be three sets of these following two cards.

3.4.1 First Card

Column	Identification	Variable Name	Format
1-80	output page headings describing problem	Title (20)	20 A4

3.4.2 Second Card

Column	Identification	Variable Name	Format
1-2	not used		2X
3-9	calibration coefficient	A1	F 7.0
10-16	calibration coefficient	A2	F 7.0

Column	Identification	Variable Name	Format
17-23	calibration coefficient	A3	F 7.0
24-30	calibration coefficient	A4	F 7.0
31-40	tape recorder bias voltage	LYREC	F10.0
41-50	anemometer output voltage	AOUTVO	F10.0
51-60	amplification factor	AMFAC	f10.0
61-65	number of channels to be sampled	ICHAN	I5
66-70	sample rate	K	I5
71-80	number of points sampled	NMAX	I10

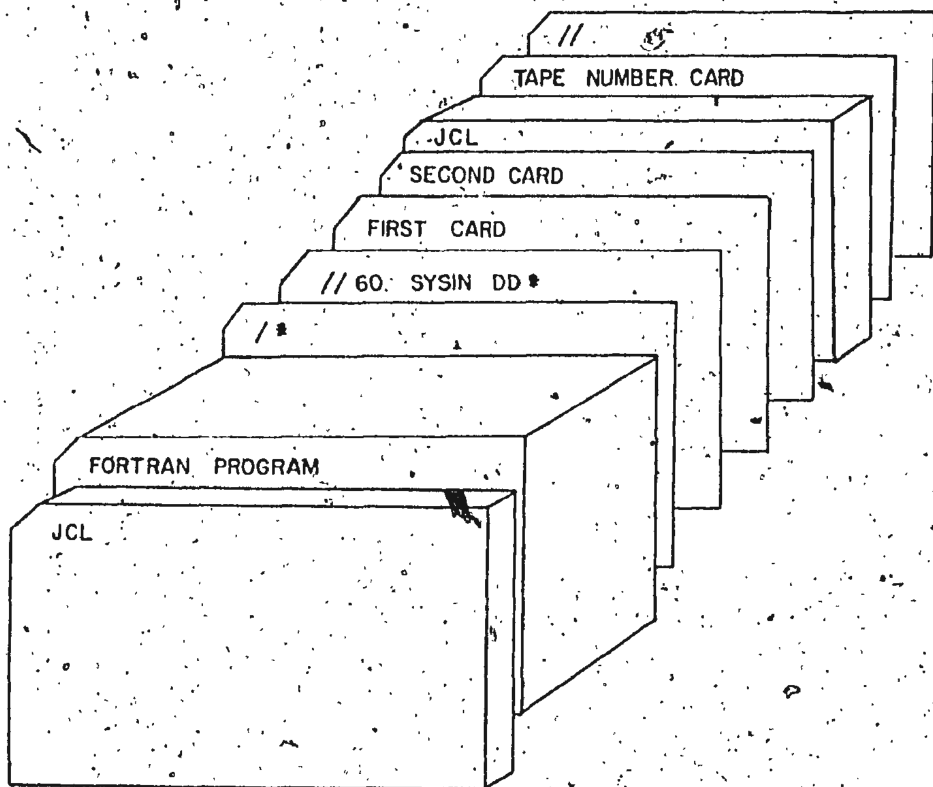
The second last card in the deck identifies the mag tape used. This must be changed with each tape. The card reads:

// DISP = (OLD, KEEP), LABEL=(,NL) VOL=SER=XXXXX

where XXXXX identifies the tape.

3.6 Sample Deck

Sample Deck



3.7 Listing

```
//E3010699 JOB (3010,699B,10,2),TIFFIN,REGION=100K,CLASS=B,MSGLEVEL=1
//STEP2 EXEC FORTGCLG                    DIST
//FORT.SYSIN DD *
C       *** DIST ***
C
C       BY RIC SOULIS   SEPTEMBER 1973
C       TO REDUCE TAPED CURRENT METER DATA
C
        INTEGER*2 REC(8)
        INTEGER F(20),JUNK(6),Y(20)
        REAL CMID(20),OM(4),LYREC,CM(3),TITLE(20),RF(20)
        COMMON/$FDHIT/JINT,F,MAX,MIN,JUNK
        COMMON/FDH$$$/Y,CMID
        DATA      IRD/5/,IPR/6/,IN/10/
C
C       INITIALIZATION
      1 JINT=20
        MIN=0
        MAX=0
        DO 2 J=1,JINT
      2 F(J)=0
        N=0
        LINES=50
        DO 3 J=1,4
      3 OM(J)=0
        NEG=0
C
C       READ CONTROL PARAMETERS
        READ(IRD,1010,END=800)TITLE
        READ(IRD,1000,END=800)A1,A2,A3,A4,LYREC,AOUTVO,AMFAC,ICHAN,K,NMAX
        WRITE(IPR,2070)TITLE
        WRITE(IPR,2060)A1,A2,A3,A4,LYREC,AOUTVO,AMFAC,ICHAN,K,NMAX
C
C       SKIP FIRST BLOCK ON TAPE
        REWIND IN
        DO 4 I=1,256
      4 READ(IN,1020)REC
C
C       CALCULATE MAX VELOCITY
        CARR=LYREC-AOUTVO
        VOLMAX=CARR+1.
        VELMAX=(A1+A2*VOLMAX+A3*VOLMAX**2+A4*VOLMAX**3)*AMFAC
C
C       SETUP CLASS INTERVALS
        SCALE=VELMAX/JINT
        DO 100 J=1,JINT
    100 CMID(J)=SCALE*(J-0.5)
C
C       READ A RECORD
    200 DO 230 KK=1,K
    230 READ(IN,1020,END=220,ERR=910)REC
        N=N+1
```

```
C
C       REVISE ACCUMULATORS
        VOL=REC(ICHAN)/511.+CARR
        VEL=(A1+A2*VOL+A3*VOL**2+A4*VOL**3)*AMFAC
        IF(VEL.LT.0.0)NEG=NEG+1
        IF(VEL.LT.0.0)VEL=0.0
        ICLASS=IFIX(VEL/SCALE)+1
        F(ICLASS)=F(ICLASS)+1
        DO 210 J=1,4
  210   OM(J)=OM(J)+VEL**J
        IF(N.LT.NMAX)GO TO 200
C
C       CALCULATE MONEMTS ABOUT ORIGIN
  220   DO 300 J=1,4
  300   OM(J)=OM(J)/N
C
C       CALCULATE CENTRAL MOMENTS
        CM(1)=OM(2)-OM(1)**2
        CM(2)=OM(3)-3.*OM(2)*OM(1)+2.*OM(1)**3
        CM(3)=OM(4)-4.*OM(3)*OM(1)+6.*OM(2)*OM(1)**2-3.*OM(1)**4
C
C       CALCULATE RELATIVE FREQUENCIES
        DO 310 J=1,JINT
  310   RF(J)=FLOAT(F(J))/N
C
C       TABULATE RESULTS
        WRITE(IPR,2070)TITLE
        WRITE(IPR,2000)ICHAN,OM(1),CM
        WRITE(IPR,2010)
        DO 400 J=1,JINT
  400   WRITE(IPR,2020)J,CMID(J),F(J),RF(J)
        WRITE(IPR,2050)N
        WRITE(IPR,2040)NEG
C
C       PREPARE HISTOGRAM
        DO 410 J=1,JINT
        IF(F(J).GT.MAX)MAX=F(J)
  410   IF(F(J).LT.MIN)MIN=F(J)
        CALL HISTGM(TITLE,LINES,N)
        GO TO 1
C
C       END OF JOB
  800   WRITE(IPR,2030)
        STOP
C
C       HERE FOR I/O ERROR
  900   WRITE(IPR,3000)J
 3000   FORMAT('0I/O ERROR IN FIRST BLOCK , RECORD',I5)
        GO TO 1
C
  910   M=N+1
        WRITE(IPR,3010)M
 3010   FORMAT('0I/O ERROR IN READ ATTEMPT',I6)
        GO TO 220
```

```
C
C     FORMAT STATEMENTS
 1000 FORMAT(2X,4F7.0,3F10.0,2I5,I10)
 1010 FORMAT(20A4)
 1020 FORMAT(8A2)
 2000 FORMAT('0DATA REDUCTION FOR TAPE CHANNEL',I6/
     *  '0MEAN',T30,E13.5/' CENTRAL MOMENTS - SECOND',T30,E13.5/
     *    T20,'THIRD',T30,E13.5/T20,'FOURTH',T30,E13.5)
 2010 FORMAT('-FREQUENCY DISTRIBUTION'/
     *    '0CLASS  MIDPOINT',10X,'FREQUENCY',6X,'RELATIVE FREQUENCY')
 2020 FORMAT('0',I5,F10.3,13X,I6,17X,F7.3)
 2030 FORMAT('1JOB COMPLETED')
 2040 FORMAT('0NUMBER OF NEGATIVE VELOCITIES',I7)
 2050 FORMAT('0NUMBER OF DATA POINTS READ',I10)
 2060 FORMAT('0PARAMETERS FOR THIS PROBLEM'/ '0CALIBRATION COEFFICIENTS
     *A1',T32,F10.4/T27,'A2',T32,F10.4/T27,'A3',T32,F10.4/
     *T27,'A4',T32,F10.4/
     *  '0LYREC',T32,F10.4/' AOUTVO',T32,F10.4/' AMFAC',T32,F10.4/
     *  '0CHANNEL NUMBER',T32,I10/' SAMPLE RATE',T32,I10/
     *  ' NUMBER OF POINTS REQUESTED',T32,I10)
 2070 FORMAT('1',20A4)
      END
      SUBROUTINE HISTGM(TITLE,LINES,IN)
      INTEGERF(20),Y(20),JUNK(6)
      REALCMID(20),TITLE(20),LINE/'- - '/,BLANK/'  '/,$$$$/'$$$$'/,GRAPH
     *20)
      COMMON/$FDHIT/JINT,F,MAX,MIN,JUNK
      COMMON/FDH$$$/Y,CMID
      DO333III=1,20
333   GRAPH(III)=BLANK
30000 WRITE(6,40006)TITLE
60002 IF(MIN.EQ.0)MIN=1
      NMAX=MAX-MIN+1
      SCALE=FLOAT(LINES-7)/FLOAT(NMAX)
      SC=1./SCALE
      DO334J=1,JINT
334   Y(J)=(F(J)*SCALE+.5)
      N=LINES/30
      IF((LINES-N*30).LE.3*(N-1))N=N-1
      NSKIP=N*30+30-LINES
  297 IF(NSKIP.LE.0)GO TO 298
      DO 299 I=1,NSKIP
  299 PRINT40020
298   K=(MAX*SCALF+1.5)
      FREQ=MAX*100./IN
      LINES=LINES-7
      DO80005I=1,LINES
      LL=K-I
      IF(LL.EQ.0)GOTO60001
      DO80004J=1,JINT
80004 IF(Y(J).EQ.LL)GRAPH(J)=$$$$
      WRITE(6,40007)FREQ,GRAPH
80005 FREQ=FREQ-SC*100./IN
      M=7+5*JINT/4
60001 WRITE(6,40005)(LINE,I=1,M)
      WRITE(6,40008)(CMID(M),M=1,JINT,3)
      WRITE(6,40009)(CMID(M),M=2,JINT,3)
      WRITE(6,40010)(CMID(M),M=3,JINT,3)
      LINES=LINES+7
```

```
50001 RETURN
40005 FORMAT(' ',33A4/)
40006 FORMAT('1HISTOGRAM FOR ',20A4//)
40007 FORMAT(F9.2,9X,20A5)
40008 FORMAT('   FREQ %',6X,7(G12.5,3X))
40009 FORMAT(' ',19X,7(G12.5,3X))
40010 FORMAT(' ',24X,7(G12.5,3X))
40020 FORMAT(' ')
      END
/*
//GO.SYSIN DD *
RUN 28 TAPE ENG008 CHANNEL 1
  -4.0587 3.6940-5.3446 2.3694     .411      0.080      1.05    1    5     12000
/*
//GO.FT10F001 DD UNIT=TAPE,DCB=(RECFM=FB,LRECL=16,BLKSIZE=4096,DEN=2),
//    DISP=(OLD,KEEP),LABEL=(,NL),VOL=SER=ENG008
//
```

4 PREP AND BMD02TX

4.1 Purpose

BMDO2TX is a modified version of BMDO2T which is a Library program performing spectral and correlation analysis. The modified version will accept up to 60,000 data points. Although BMDO2TX has the capability to do cross correlations, cross spectra and related statistical analyses, it was used here only to give a list and plot of autocovariances and power spectral estimates with a linear plot and a linear logarithmic plot. PREP is a program that prepares the data and calls BMDO2TX from disk.

4.2 Technique

PREP uses the same statements as DIST to read and convert the data. Detailed specifications on BMDO2T and the Fast Fourier Transform technique will be found in any computer systems reference library.

4.3 Program Control Cards

4.3.1 First Card

This is identical to the first card described in DIST.

4.3.2 Second Card

This is identical to the second card described in DIST.

4.4 JCL Cards

The tape number card is identical to that described in DIST.

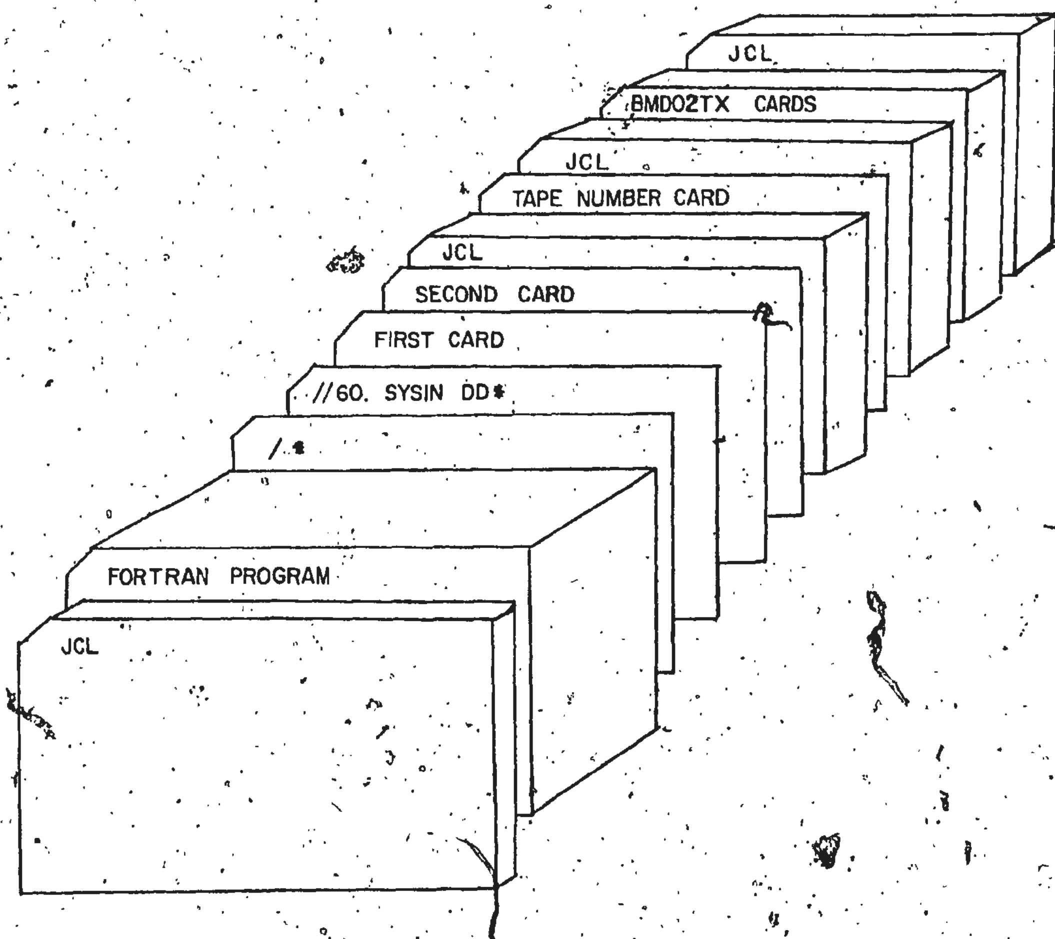
4.5 BMDO2TX Cards

There are three cards in this section, a PROBLEM card, a SELECT card and a FINISH card. To change the number of channels read and the operations performed, it will be necessary to refer to the detailed documentation on the program in a systems reference library. However, it will probably be useful to vary the sample rate and the number of points used to display different aspects of the data. It was found useful to use a lag of .05 seconds to display detail at high frequencies, and a lag of .5 seconds to show trends at low frequencies.

4.5.1 PROBLEM Card

Column	Identification
1-6	type PROBLEM (mandatory)
7-12	type RUN 1
13-29	blank
30-31	type 01
32-35	blank
36-42	type 1990101
43-47	type sample rate or constant time interval in seconds, e.g. .05
48-53	punch the time unit as SECOND
54-68	blank
69-70	punch 73
71-72	punch 0
73-80	type in number of data points with format I10

4.6 Sample Deck



4.7 Listing

```
//E3010698 JOB  (3010,601S,10,2),TIFFIN,CLASS=S,REGION=500K,MSGLEVEL=1,
//     TYPRUN=HOLD
//STEP2 EXEC FORTGCLG          PREP
//FORT.SYSIN DD *
C
C     ****PREP****
C     BY RIC SOULIS NOVEMBER 1973
C     TO PREPARE S.TIFFIN'S DATA FOR BMD02T
C
      INTEGER*2 REC(8)
      INTEGER OUT
      REAL LYREC
      REAL  VEL(20000),TITLE(20)
      DATA IRD/5/,IPR/6/,IN/10/,OUT/11/
C
C     READ CONTROL PARAMETERS
      READ(IRD,1010)TITLE
      READ(IRD,1000,END=800)A1,A2,A3,A4,LYREC,AOUTVO,AMFAC,ICHAN,K,NMAX
      WRITE(IPR,2000)TITLE
      WRITE(IPR,2060)A1,A2,A3,A4,LYREC,AOUTVO,AMFAC,ICHAN,K,NMAX
      CARR=LYREC-AOUTVO
C
C     SKIP FIRST BLOCK ON TAPE
      REWIND IN
      DO 1 I=1,256
    1 READ(IN,1020)REC
C
C     READ NMAX RECORDS AND CONVERT TO VELOCITY
      DO 100 I=1,NMAX
      DO 120 KK=1,K
  120 READ(IN,1020,END=800)REC
      VOL=REC(ICHAN)/511.+CARR
  100 VEL(I)=(A1+A2*VOL+A3*VOL**2+A4*VOL**3)*AMFAC
      I=NMAX+1
  800 I=I-1
      WRITE(OUT)(VEL(J),J=1,I)
C     END OF JOB
      WRITE(IPR,2030)
      WRITE(IPR,2040)I
      WRITE(IPR,2050)(VEL(J),J=1,100)
      STOP
C
C     FORMAT STATEMENTS
 1000 FORMAT(2X,4F7.0,3F10.0,2I5,I10)
 1010 FORMAT(20A4)
 1020 FORMAT(8A2)
 2000 FORMAT('1',20A4)
 2030 FORMAT('-INPUT FOR BMD02T(X) PREPARED')
 2040 FORMAT('0',I10,' POINTS TRANSFERRED')
 2050 FORMAT('0THE FIRST 100 ARE',(' ',10F10.3))
 2060 FORMAT('-PARAMETERS FOR THIS PROBLEM'/ '0CALIBRATION COEFFICIENTS
     *A1',T32,F10.4/T27,'A2',T32,F10.4/T27,'A3',T32,F10.4/
     *T27,'A4',T32,F10.4/
     &    '0LYREC',T32,F10.4/' AOUTVO',T32,F10.4/' AMFAC',T32,F10.4/
     *   '0CHANNEL NUMBER',T32,I10/' SAMPLE RATE',T32,I10/
     *   ' NUMBER OF POINTS REQUESTED',T32,I10)
      END
```

[redacted]

```
/*
//GO.SYSIN DD *
RUN  1   TAPE   002897   CHANNEL 1
 -0.0587 3.6944-3.3446 2.3694     .5930     0.045     1.05   1   50     1200
/*
//GO.FT10F001 DD UNIT=TAPE,DCB=(RECFM=FB,LRECL=16,BLKSIZE=4096,DEN=2),
//    DISP=(OLD,KEEP),LABEL=(,NL),VOL=SER=002897
//GO.FT11F001 DD UNIT=SYSDA,SPACE=(TRK,(25,10),RLSE),
//    DISP=(NEW,PASS),DCB=(RECFM=VBS,LRECL=X,BLKSIZE=4000)
//STEP3 EXEC PGM=BMD02TY
//STEPLIB DD DSN=RLTF195.BMD.LOAD,DISP=SHR
//FT03F001 DD DSN=*.STEP2.GO.FT11F001,DISP=(OLD,DELETE)
//FT05F001 DD *
PROBLM RUN1              01    1990101.50  SECOND              73    1200
SELECT YES          01B  01 01
FINISH
/*
//FT06F001 DD SYSOUT=A
//
```

APPENDIX 2

LIST OF TURBULENCE INSTRUMENTATION MANUFACTURERS

For Disa equipment in Canada, write

R. W. Spafford
Canaden Products Ltd.
Box 1411, St. Laurent
Montreal 379
P.Q.

CGS Datametrics hot film equipment may be obtained from

C.G.S. Datametrics
127 Coolidge Hill Road
Watertown, Mass. 02172
U.S.A.

Thermo-Systems hot film anemometers may be obtained from

Thermo-Systems Inc.
2500 Cleveland Ave. No.
St. Paul
Minnesota 55113

EPCO electromagnetic flow meters are made by

Engineering-Physics Company
12721 Twinbrook Parkway
Rockville
Maryland 20852
U.S.A.

For the fluidic anemometers, write

FluiDynamic Devices Limited
3216 Lenworth Dr.
Mississauga, Ontario

The address for commercial vortex meters is

J-Tec Associates Inc.
317 Seventh Av. S.E.
Cedar Rapids
Iowa 52401
U.S.A.

APPENDIX 3

CALIBRATION SCHEMES FOR HOT FILM PROBES

An obvious choice for a calibration rig if the equipment is available, is to mount the probe and anemometer on a towing carriage and pull it down a flume. Palmer (1973) calibrated his probes this way. This is an accurate method but requires the availability of an expensive and elaborate towing tank system, and suffers from the drawback of the experimenter not being able to change the temperature and salinity of the water if desired.

Resch (1970) describes an elaborate closed circuit recirculating pump system which again offers excellent control of velocities, but must be specially made for corrosive salt water. Again, this system is expensive and cumbersome.

For a fast and cheap method of calibrating hot film probes, Gallagner (1973) has devised a system comprising of a 3.5 l beaker of water, several feet of clear flexible tubing and an upright lucite tube three inches in diameter by about a foot long. The probe is hung sensor down behind a screen suspended from the top of the lucite tube. Water flows from the constant head breaker (adjusted by hand and sighted by eye) via the flexible tubing to the base of the lucite tube and then overflows at the top. This gives fairly accurate results at low velocities, with an error of about 4 to 5%.

Rotating tank systems are more expensive than Gallagher's method, but should be a little easier to use once set up, in addition to being more accurate. Rotating tank systems are small, portable and relatively cheap; that is why we decided on such calibration device. Brunelle, Gauthier and Pichon (1969) describe a calibrator that uses a small variable speed DC motor to drive a plexiglas tank filled with water, and give the results of their extensive investigations into its performance. The rotating tank we built verifies the utility of the concept, but illustrates that a slight change in design would result in a superior machine. Instead of rotating the water, and having to wait for the velocity field to become uniform at each speed setting, it is better to rotate the probe instead, and use a slip ring for the probe cable. Frey and McNally (1973) used such a design and found it satisfactory except that their slip rings generated too much noise and had to be bypassed using a long cable. In the author's experience with hot film probes mounted on high speed rotating drums, even cheap slip rings will not interfere with the system, so this system is the one recommended.

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	EXPERIMENT 1		EXPERIMENT 2	
	Run 1 bottom	Run 1 top	Run 2 bottom	Run 2 top
1st Moment (mean)	1.25	1.19	2.03	1.22
2nd Moment (variance)	.090	.107	.141	.087
3rd Moment (skewness)	.005	- .007	- .002	- .012
4th Moment (kurtosis)	.032	.048	.148	.038
Turbulence Intensity	.076	.087	.186	.077

TABLE 1

CENTRAL MOMENTS AND TURBULENCE INTENSITIES

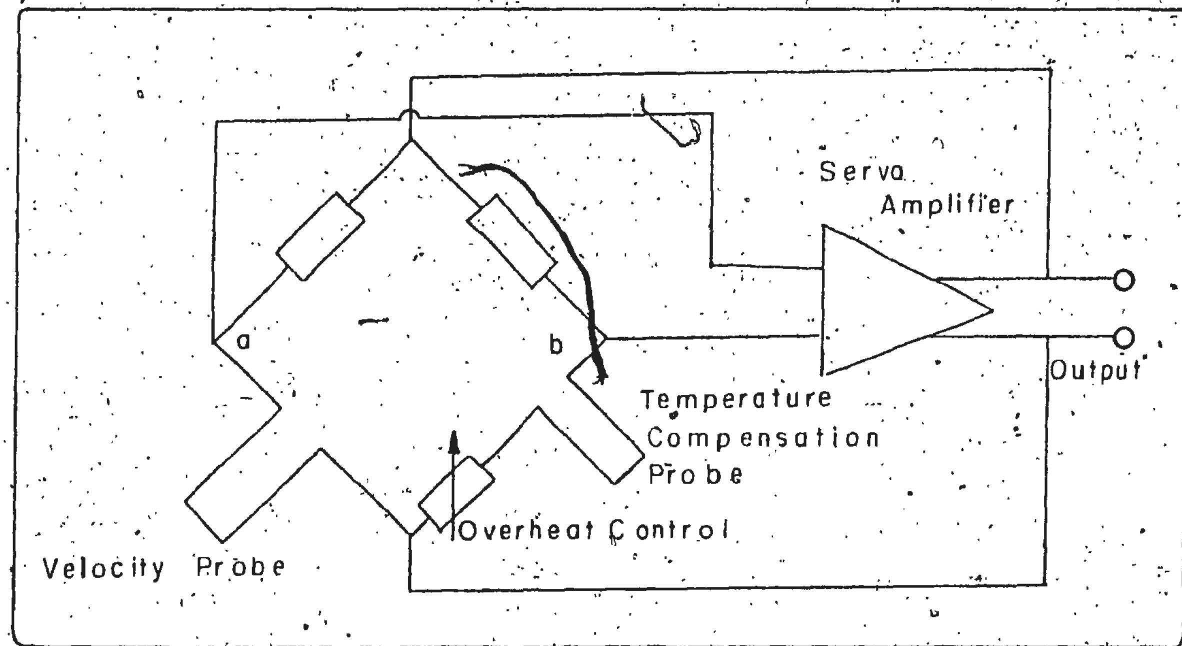


FIGURE 1 - VELOCITY BRIDGE

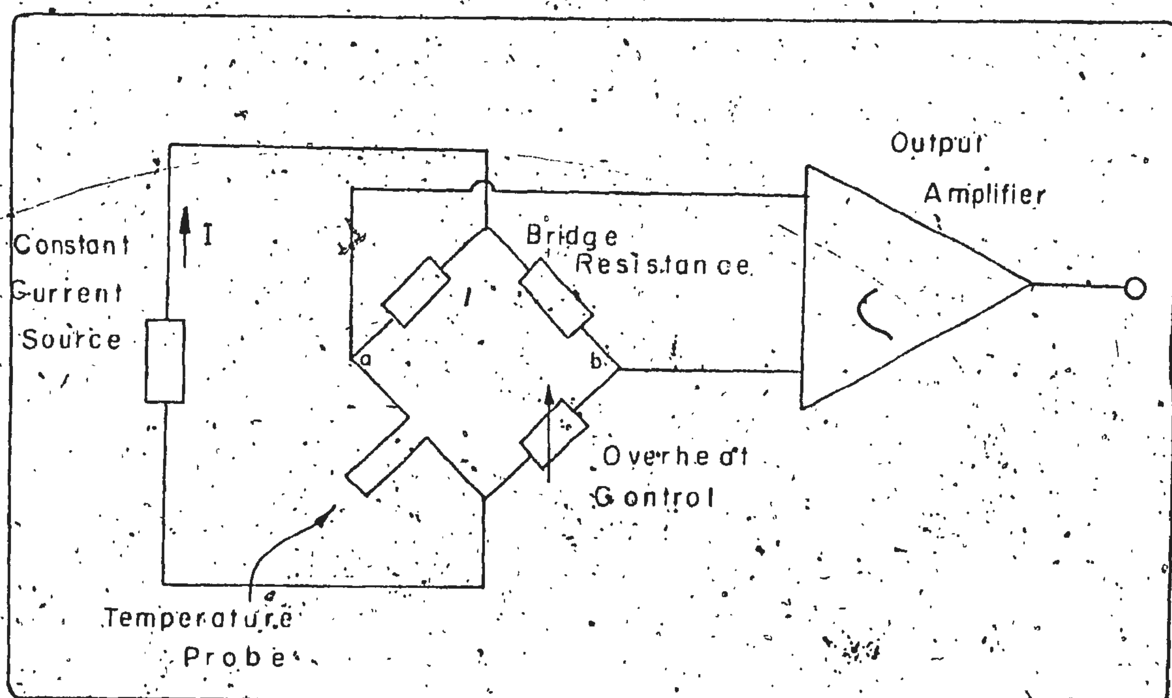


FIGURE 2 - TEMPERATURE BRIDGE

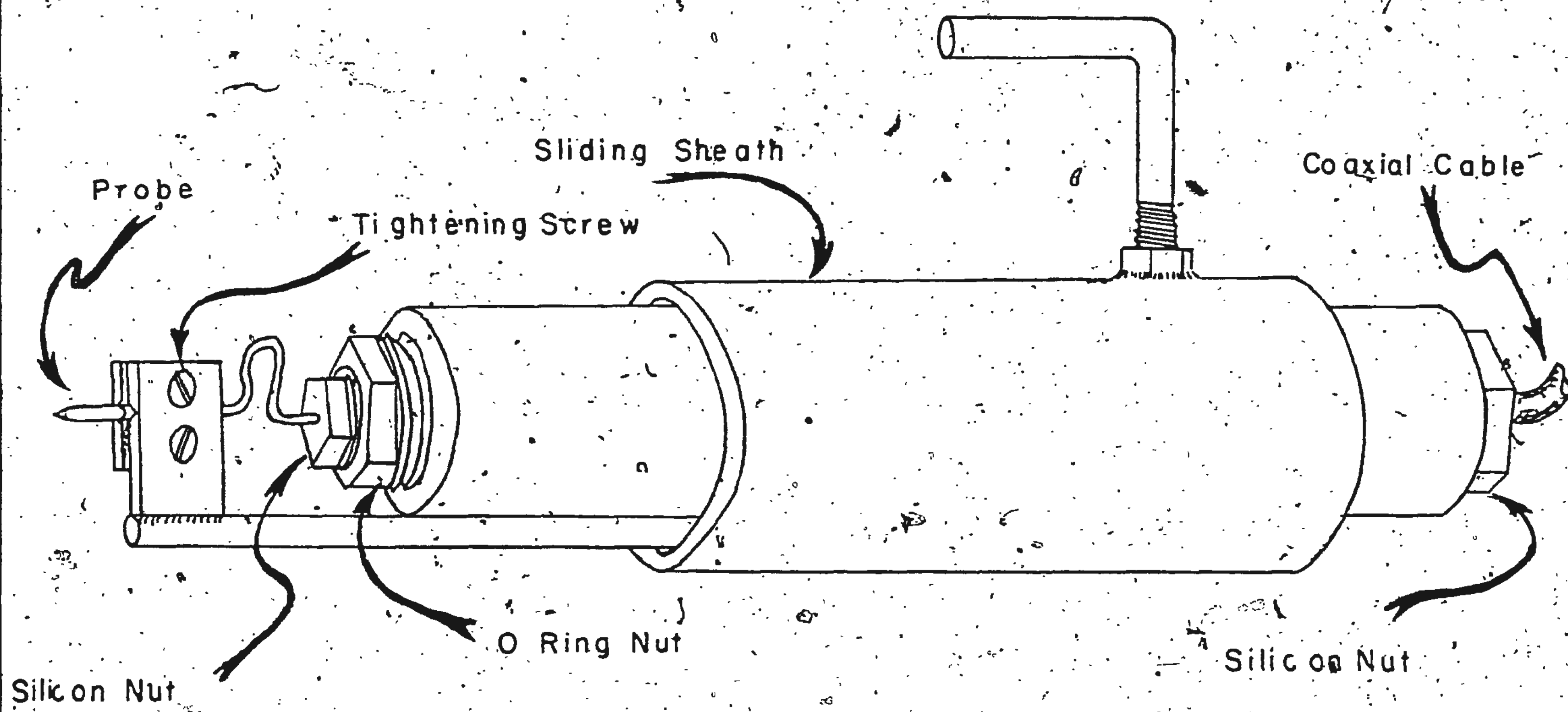


FIGURE 3- PROBE HOUSING for CONICAL PROBE

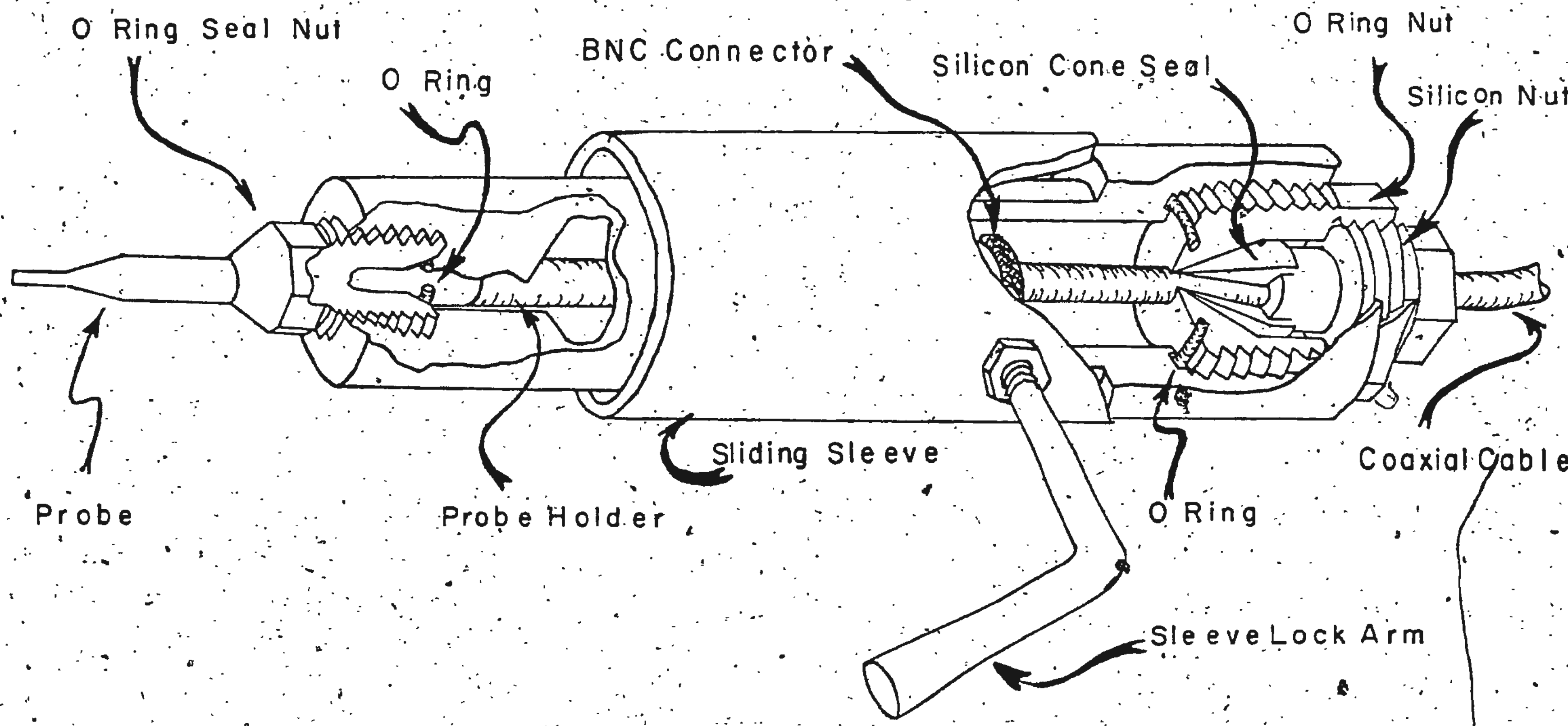


FIGURE 4 PROBE HOUSING for WEDGE PROBE

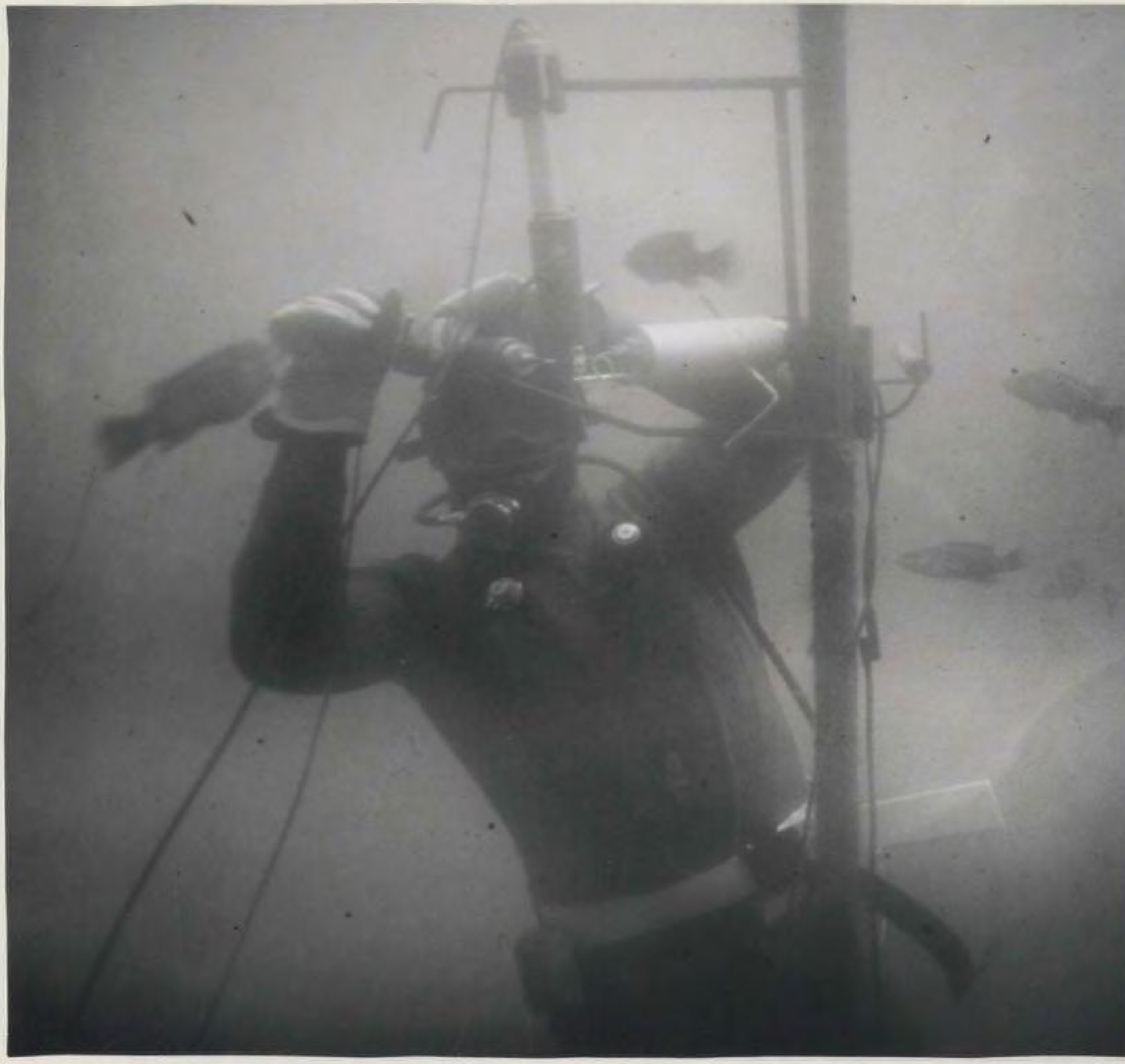


FIGURE 5

FIGURE 6

FIGURE 7

FIGURE 8

FIGURE 9

FIGURE 10

FIGURE 11

FIGURE 12

FIGURE 13

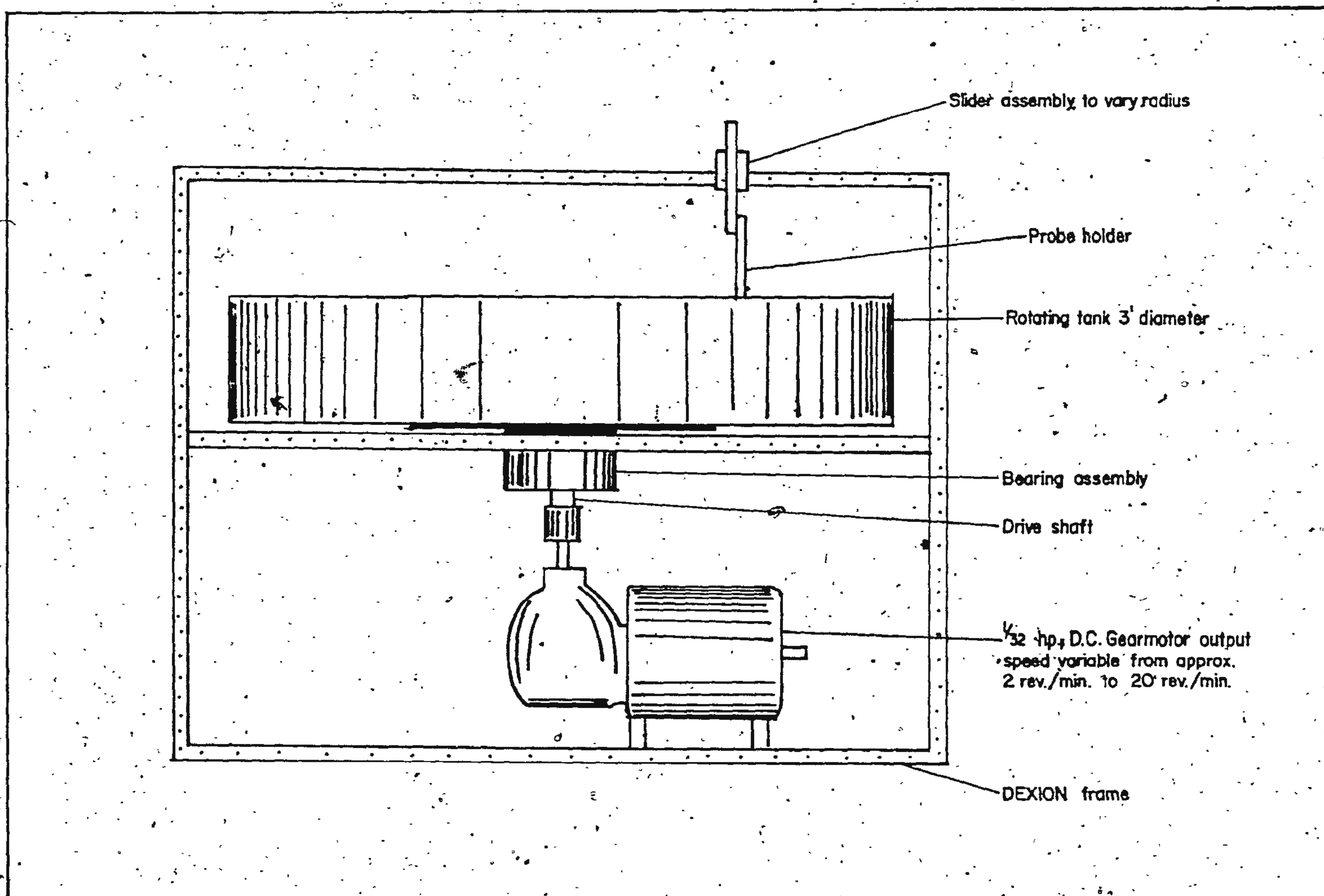

Slider assembly to vary radius
Probe holder
Rotating tank 3' diameter
Bearing assembly
Drive shaft
1/32 hp., D.C. Gearmotor output speed variable from approx. 2 rev./min. to 20 rev./min.
DEXION frame

FIGURE 14

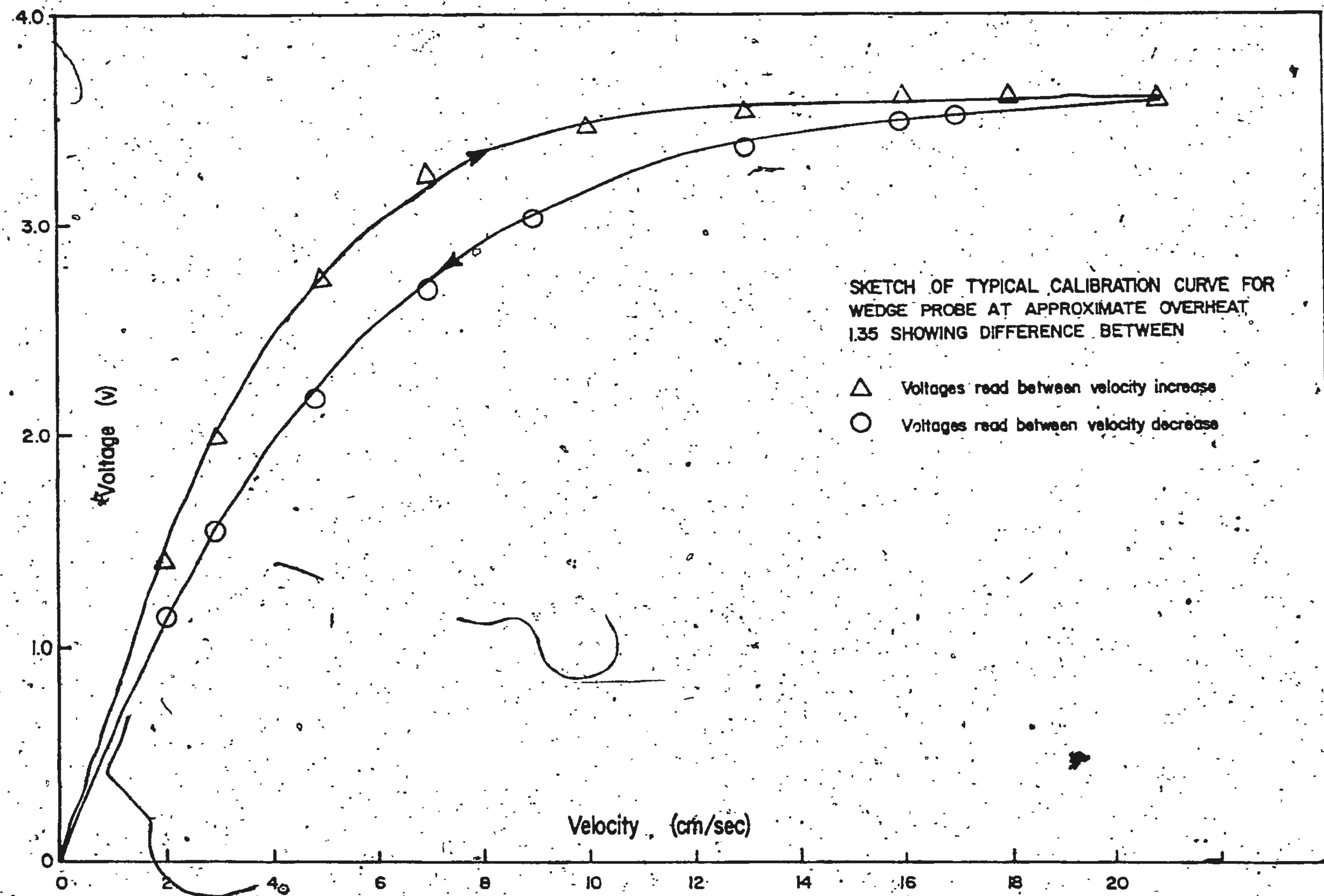

SKETCH OF TYPICAL CALIBRATION CURVE FOR WEDGE PROBE AT APPROXIMATE OVERHEAT 1.35 SHOWING DIFFERENCE BETWEEN
Voltages read between velocity increase
Voltages read between velocity decrease
Voltage (v)
Velocity (cm/sec)
4.0
3.0
2.0
1.0
0
0
2
4
6
8
10
12
14
16
18
20

FIGURE 15

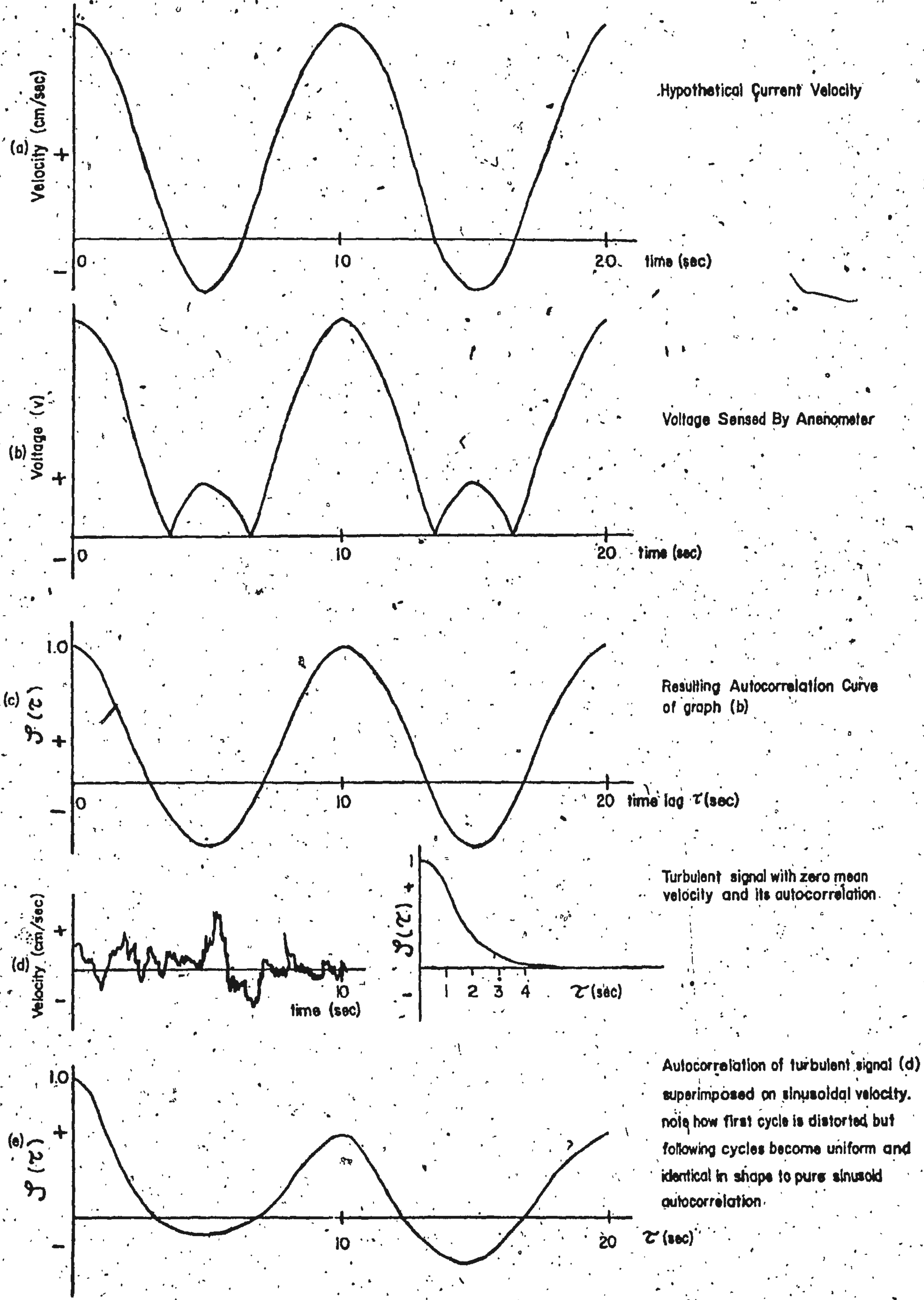
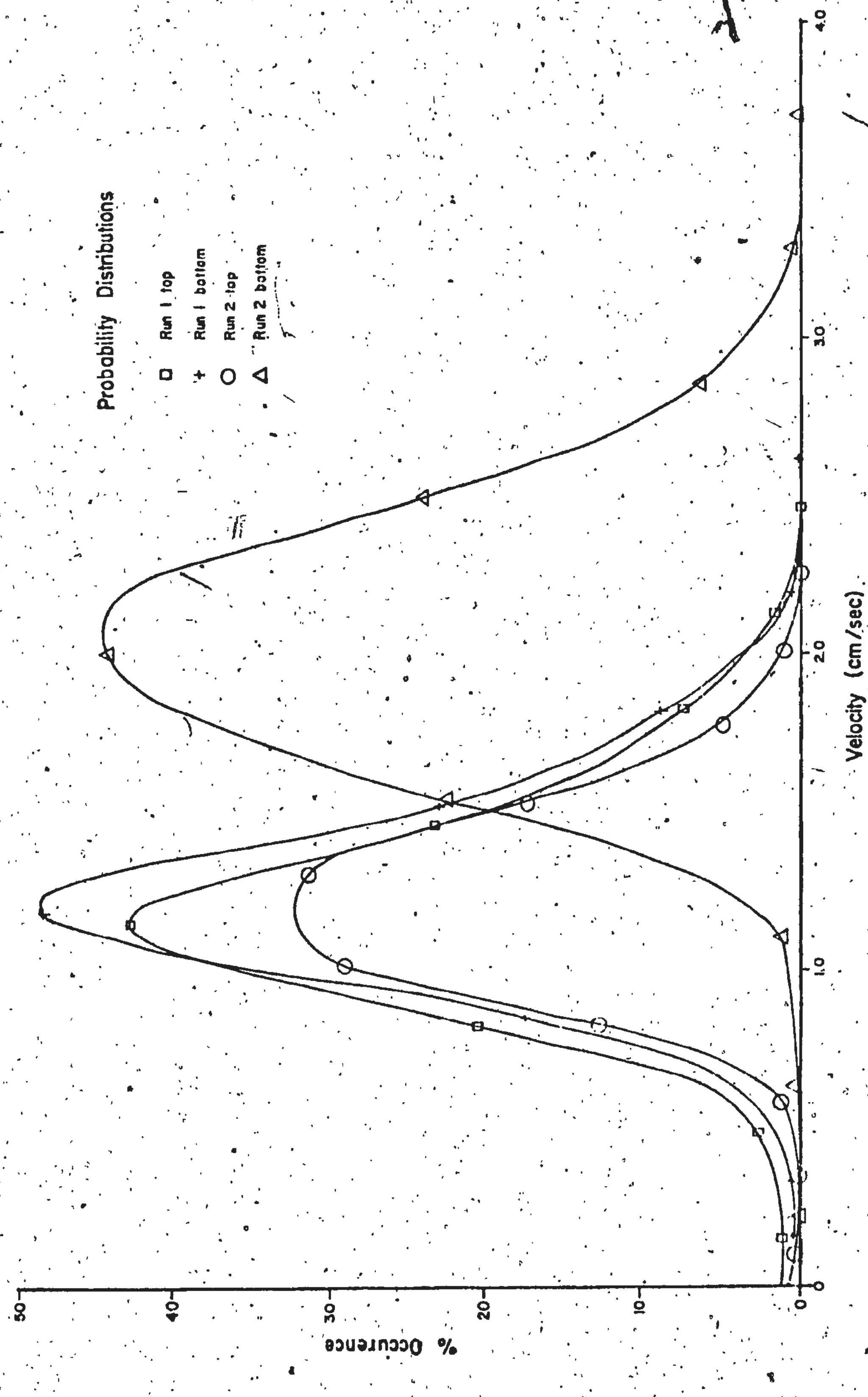
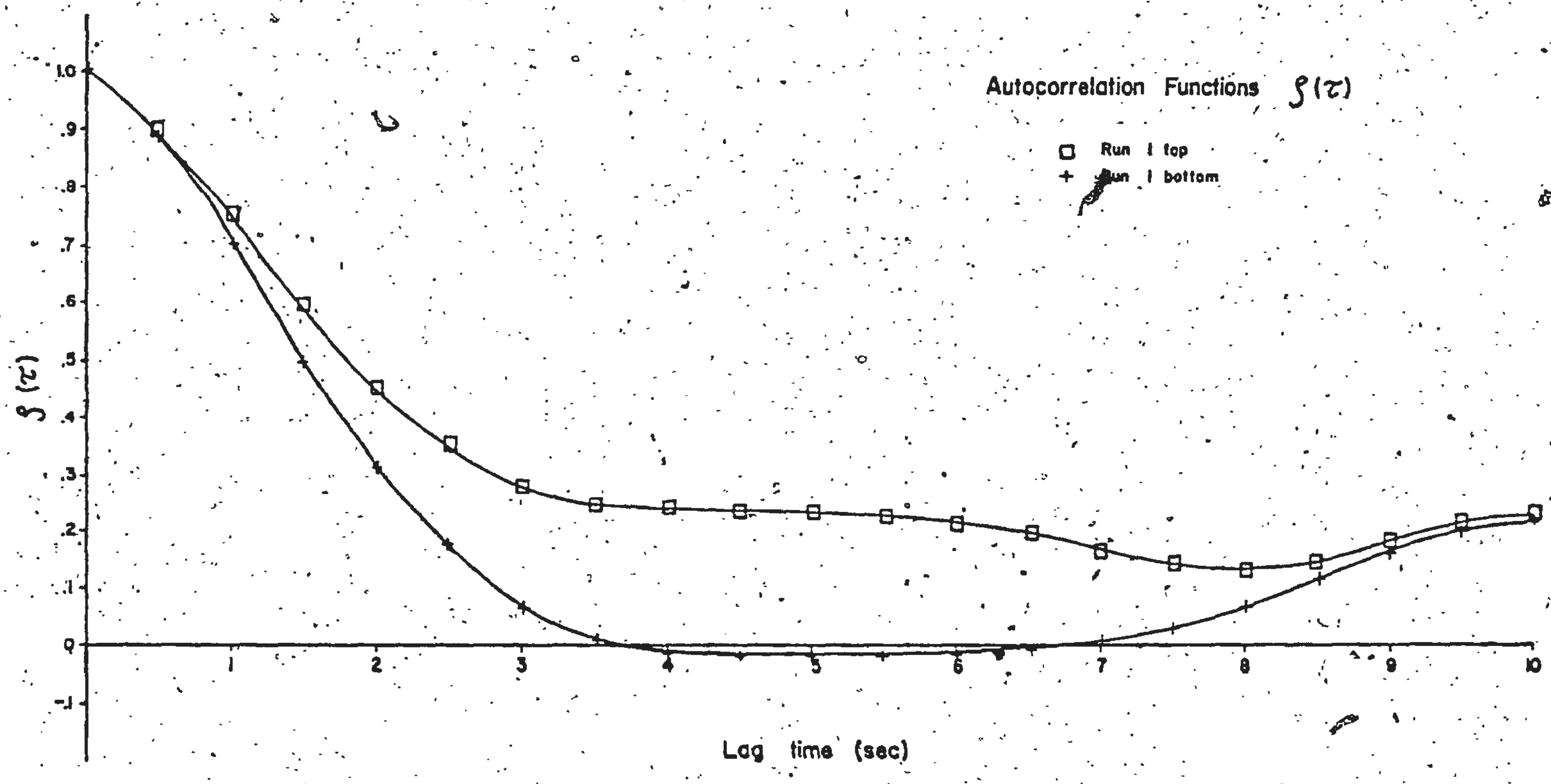

Hypothetical Current Velocity
(a)
Velocity (cm/sec)
+
-
0
10
20
time (sec)
Voltage Sensed By Anenometer
(b)
Voltage (v)
+
-
0
10
20
time (sec)
Resulting Autocorrelation Curve of graph (b)
(c)
1.0
+
-
0
10
20
time lag τ (sec)
Turbulent signal with zero mean velocity and its autocorrelation
(d)
Velocity (cm/sec)
+
-
10
time (sec)
1
1 2 3 4
τ (sec)
Autocorrelation of turbulent signal (d) superimposed on sinusoidal velocity. note how first cycle is distorted but following cycles become uniform and identical in shape to pure sinusoid autocorrelation.
(e)
1.0
+
-
10
20
τ (sec)

FIGURE 16



Probability Distributions
Run 1 top
Run 1 bottom
Run 2 top
Run 2 bottom
% Occurence
Velocity (cm/sec)
0
10
20
30
40
50
1.0
2.0
3.0
4.0

FIGURE 17



Autocorrelation Functions $\rho(\tau)$
Run I top
Run I bottom
$\rho(\tau)$
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
1
2
3
4
5
6
7
8
9
10
Lag time (sec)

FIGURE 18

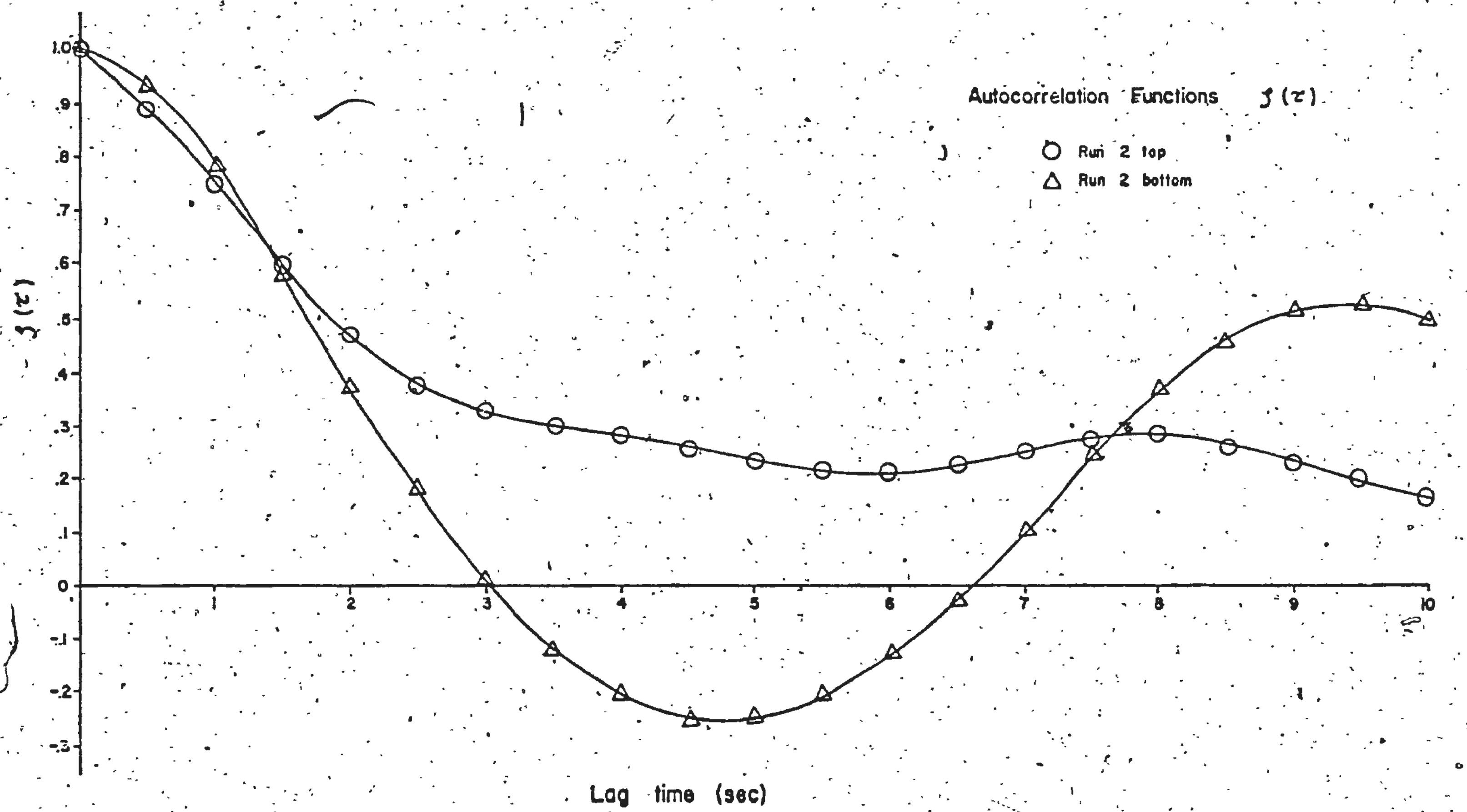
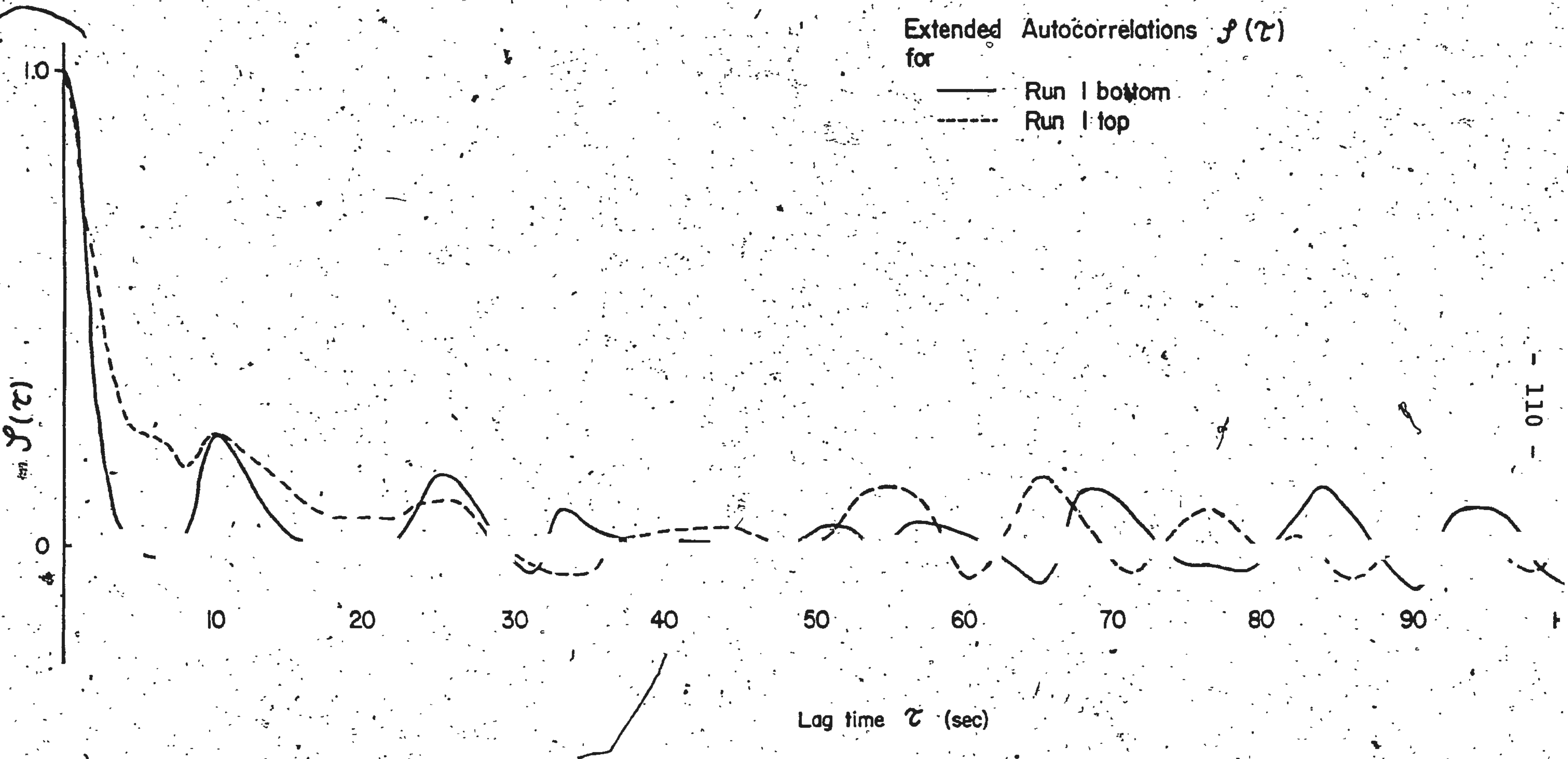

Autocorrelation Functions $\rho(\tau)$
Run 2 top
Run 2 bottom
$\rho(\tau)$
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-.1
-.2
-.3
1
2
3
4
5
6
7
8
9
10
Lag time (sec)

FIGURE 19



Extended Autocorrelations $\rho(\tau)$ for
Run I bottom
Run I top
$\rho(\tau)$
1.0
0
10
20
30
40
50
60
70
80
90
Lag time τ (sec)

FIGURE 20

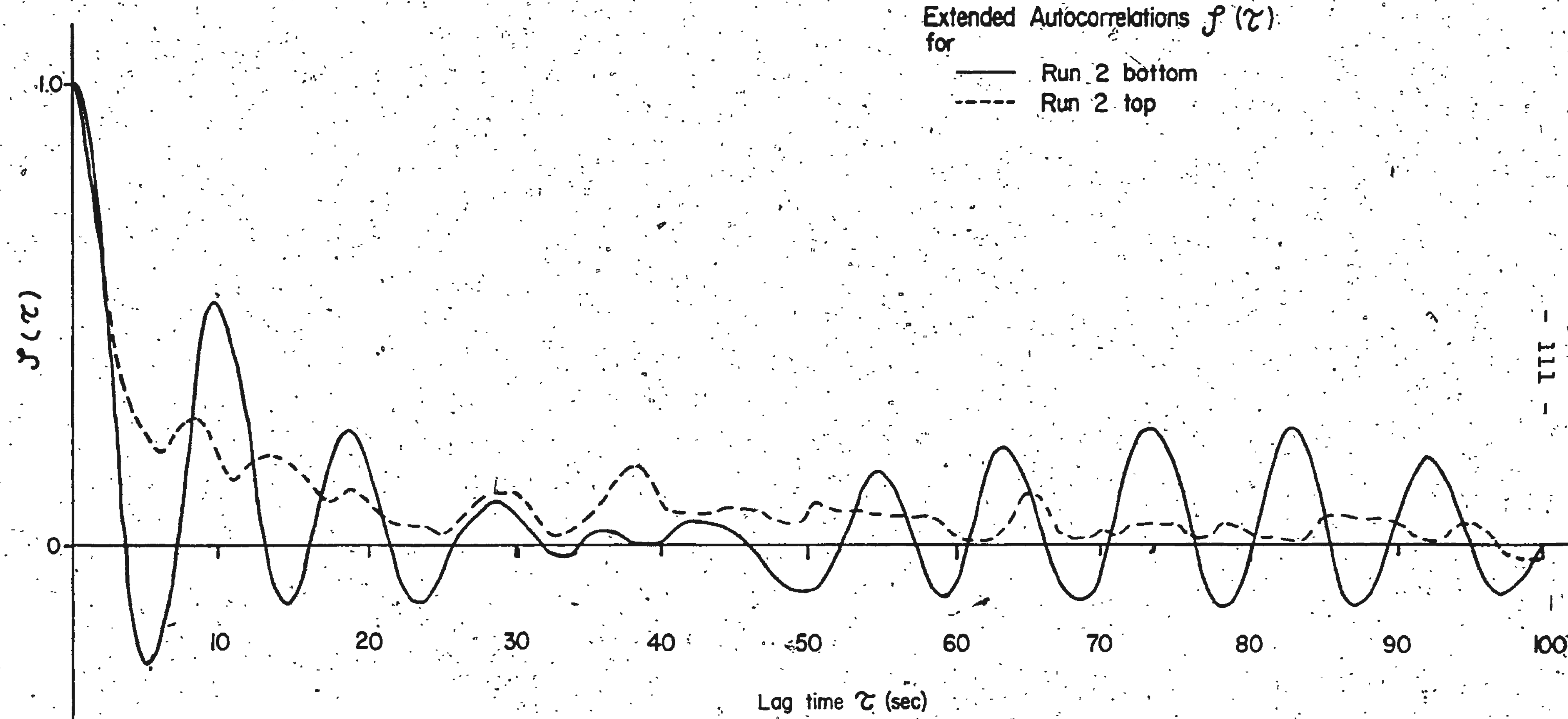
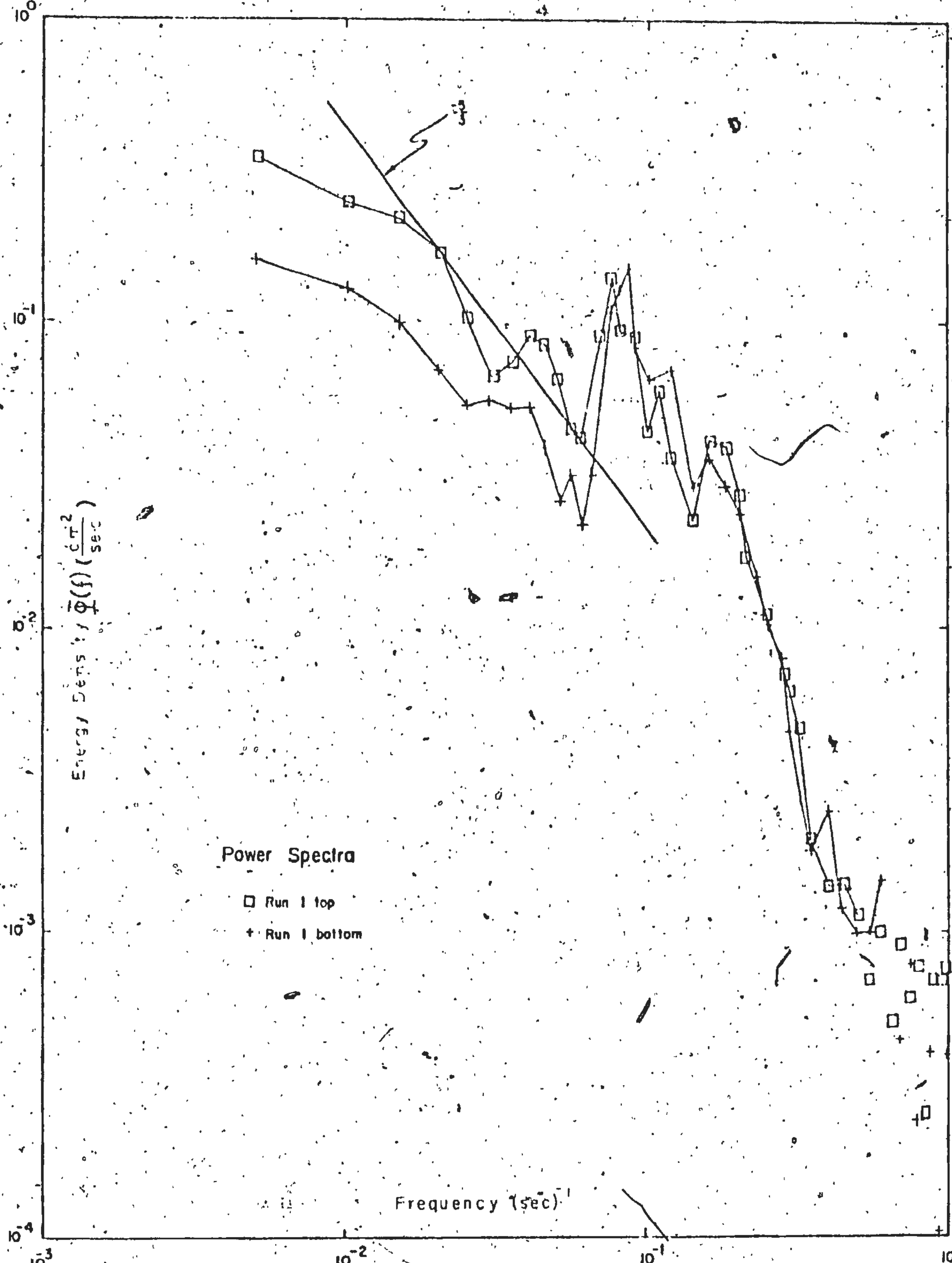

Extended Autocorrelations $\rho(\tau)$ for
Run 2 bottom
Run 2 top
$\rho(\tau)$
1.0
0
10
20
30
40
50
60
70
80
90
100
Lag time τ (sec)

FIGURE 21



Power Spectra
Run 1 top
Run 1 bottom
Frequency (sec)$^{-1}$
Energy Density $\overline{\Phi}(f)$ $\left(\frac{C^{\circ 2}}{sec}\right)$
$-\frac{5}{3}$
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}

FIGURE 22

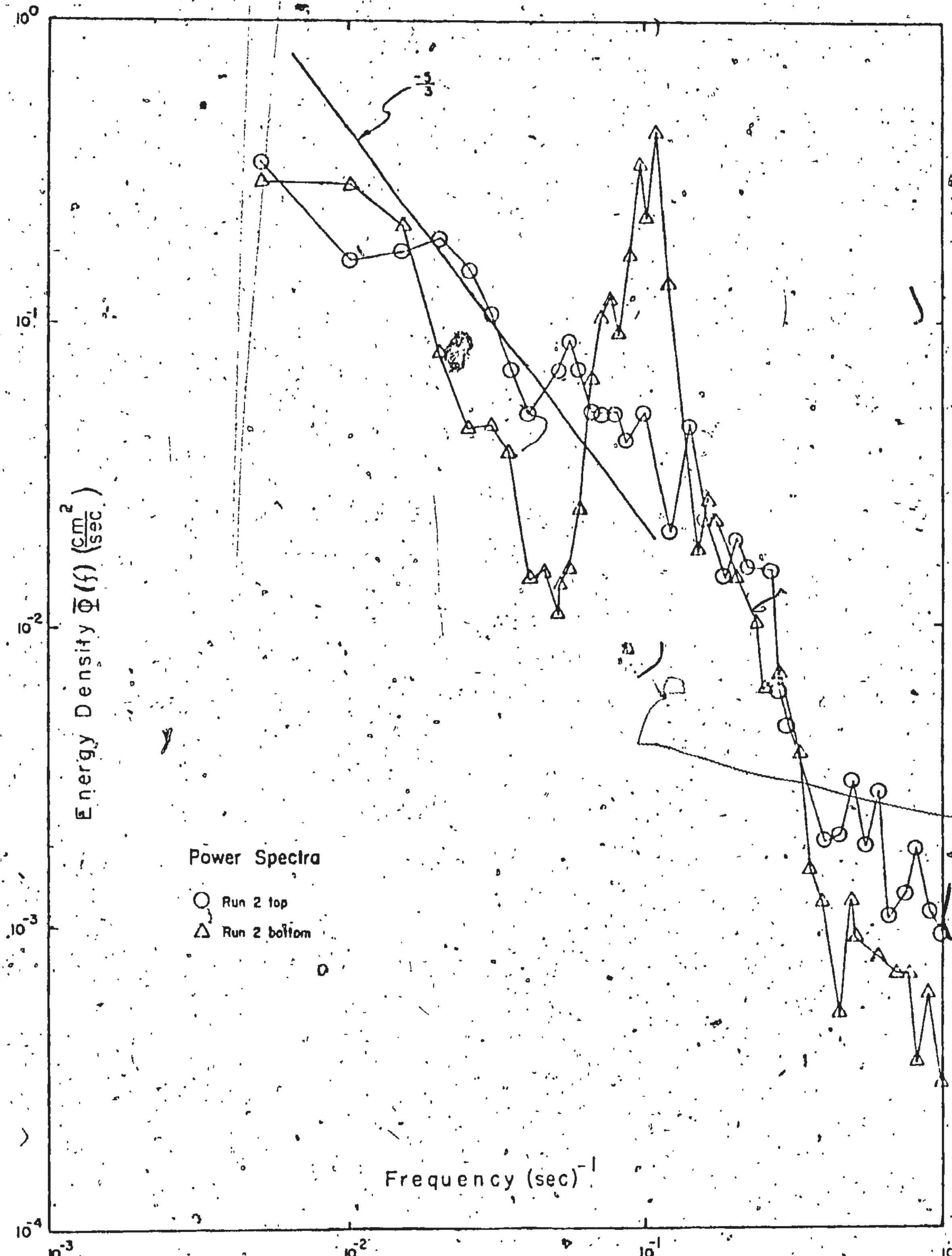

10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$-\frac{5}{3}$
Energy Density $\overline{\Phi}(f)$ $\left(\frac{cm^2}{sec}\right)$
Power Spectra
Run 2 top
Run 2 bottom
Frequency $(sec)^{-1}$
10^{-3}
10^{-2}
10^{-1}
10^0

FIGURE 23