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Progress Report

AN INVESTIGATION OF THE STRUCTURE OF TURBULENCE  
OVER WATER SURFACE WAVES

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## ABSTRACT

A hot-wire anemometer system, a fast response resistance wire thermometer and a thermocouple circuit were used in an attempt to measure the structure of turbulence, the turbulent fluxes of heat and momentum and the mean vertical temperature difference over ocean waves. The sensors were mounted on a research buoy near the Buzzards Bay Entrance Light Station, about 4.5 miles southwest of Cuttyhunk, Massachusetts. The amplified outputs of sensor circuits were recorded via frequency modulation with a seven channel magnetic tape recorder. During a three-week period a total of about 7 hours of measurements were obtained. Concurrent measurements of wave heights and wind profiles with instruments attached to the same buoy were made by personnel from the Massachusetts Institute of Technology.

To study data reliability (1) the recorded information was converted to voltage analogs and recorded on a paper chart and (2) spectral analyses were made for all channels of information for a representative six minute interval. It was found that a high noise level was present in all recordings and that it could be accounted for by voltage and frequency fluctuations in the power supplied for the magnetic tape recorder. The noise level masked the temperature measurement outputs which, apparently, were very small because of the nearly neutral thermal stratification during the experiments. On the basis of the preliminary analyses it appears that meaningful velocity spectra and cross spectra for frequencies less than 1.5 Hz may be computed from the recordings; higher frequency information is probably obscured by the high noise level.

An Investigation of the Structure of Turbulence over  
Water Surface Waves

PREFACE

Late in 1966 the authors were invited to participate in an air-sea interaction experiment planned for the summer of 1967 by Professor Eric Mollo-Christensen and his students and colleagues at the Massachusetts Institute of Technology. The goal of the experiment was to study various small scale interaction dynamics whose characteristics could be observed at a single location. Measurements were made, accordingly, with sensors located on a buoy anchored within 400 feet of the Buzzards Bay Entrance Light Station, approximately 4.5 miles southwest of Cuttyhunk Island, Massachusetts.

Our participation consisted primarily of an attempt to adapt and use a hot-wire anemometer system to measure simultaneously the three rectangular components of the wind a meter or two above surface waves. Although the system has been used successfully in micrometeorological experiments over the ground, its use on a buoy presented many serious practical problems involving mounting arrangements, extension electrical cables, and suitable electrical power for magnetic tape recording.

Preparation for our part of the experiment could not begin until June and the work was to be completed by October 31, 1967, with the first three weeks of August designated as the time for measurements on the buoy. It was learned in mid-June that a temperature measurement system with response characteristics compatible with those of the hot-wire anemometer system was available commercially and could be supplied in time for the

measurements. The instrument would make it possible to measure the Reynolds flux of sensible heat over a frequency range seldom achieved in atmospheric turbulence investigations. Through the efforts of Professor Eric Mollo-Christensen an instrument was procured and we were able to try it out during the measurement period.

The success of our experiment cannot yet be judged because, for a variety of reasons, we have not been able to make significant progress in data processing. Our most difficult problem, as it is now evident, was the sensitivity of the recording system to variations in frequency and voltage of the electrical power supplied by the generator of the R/V SCHROCK, the oceanographic research vessel generously provided by the Massachusetts Institute of Technology for our experiments. Numerous other difficulties were encountered in our attempt to operate equipment, meant for laboratory use, in the salt spray on the buoy. The motions of the R/V SCHROCK and the rubber boat -- used to get to the buoy -- seemed at times destined to defeat every minor task associated with handling the velocity and temperature probes with their very delicate filaments.

The work was performed under Contract N00014-67-A-0181-0005 from the Office of Naval Research. We are grateful to Dr. Donald Martineau, of that office, for his encouragement and support. We are indebted to Professor Eric Mollo-Christensen and his colleagues for providing the many facilities that our program required, including the three-week assignment of the R/V SCHROCK and the arrangement for room and board on the island of Cuttyhunk. We especially appreciate the enthusiastic cooperation given by Lt. Cdr. Richard Seesholtz whose wind profile measurements are necessary for relating measurements of the Reynolds stress to the mean shear.

Finally, the contributions and assistance provided by Messrs. Allen Davis and Frank Haurwitz of the University of Michigan are gratefully acknowledged. Without them the experiment could not have been conducted.

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## INTRODUCTION

Knowledge of the nature of air flow immediately adjacent to the ocean surface is necessary to clarify and to refine present ideas of wave generation and of momentum, heat and mass transfer processes at the air-sea interface. Especially critical for further theoretical developments is information on the extent of direct influence of waves on the air layer overlying them. Apparently the depth of the influenced air layer is highly dependent on both wind and wave conditions. This fact may lead to serious errors in estimating vertical fluxes if standard empirical relationships (Deacon and Webb, 1962) are used. If improvements are to be made in such estimates, a substantial increase of knowledge of the flow structure over water waves is necessary.

At this time two questions stand out as being especially significant for constructing valid transfer theories for air-sea interaction. One is the degree of variation of the turbulent momentum (Reynolds flux) with height in the layer a few meters thick over waves. Most transfer theories depend upon an assumption of constant flux with height; the extent to which this may be true for different conditions of wave generation and decay is not known. Until direct measurements of momentum flux at different heights for different conditions are made the questions cannot be answered.

The second question has to do with the high wave number range (small scale) of turbulence which may be considered statistically steady. In contrast with larger eddies, these much smaller eddies are isotropic and ineffective in transport processes. The concept, however, of an isotropic range, even in shear flow, is the basis of theoretical arguments which simplify the description of turbulent flow and make possible certain general laws. The actual existence of such a range, however, has not been established.

These questions and others appear unresolvable until a significant set of simultaneous observations of velocity component fluctuations, temperature fluctuations and water surface topography have been obtained for a number of different situations. The goals of the investigation reported here were to develop techniques with appropriately small and fast responding instruments and to use them to obtain information on the structure of turbulence over water waves. The information ideally is to be obtained in the form of spectra and cross spectra of temperature and wind velocity components and to relate them to wave statistics, height, wind speed and thermal stratification. The work reported here is to be regarded only as a beginning; the relatively few hours of observation actually achieved represent a small but necessary step forward in understanding air-sea interaction dynamics.

#### EXPERIMENTAL PLAN

The experimental plan was to measure simultaneously and continuously, for periods of from 10 minutes to several hours,

the following variables:

- (1) The three rectangular components (along wind,  $u$ ; cross wind,  $v$ ; and vertical,  $w$ ) of the instantaneous wind velocity vector;
- (2) The instantaneous temperature at a point as close as possible to the wind velocity sensors;
- (3) The average temperature difference between one meter above and one meter below the wind velocity and instantaneous temperature sensors.

The sensors were to be mounted on the buoy so that their height above the water could be varied and so that wind from the south-east through southwest would not be disturbed before reaching them. It was desired to record only with statistically steady and uniform wind, temperature and sea conditions and to obtain samples of various combinations of conditions.

A seven-channel magnetic tape recorder was used to record all sensor outputs simultaneously. It was operated aboard the R/V SCHROCK which was anchored about 200 feet downwind from the buoy. Figure 1 shows the ship and the buoy during an experimental period and Figure 2 shows the various components of the systems and how they were divided between the buoy and the ship. For each experiment it was necessary to place sensors and components aboard the buoy and to extend the 200 ft cable between ship and buoy.

All measurements were accompanied by simultaneous measurements of waves and average wind (vertical) profiles made by Massachusetts Institute of Technology personnel as briefly described in Appendix B.

### EQUIPMENT

The sensors used to measure instantaneous wind components

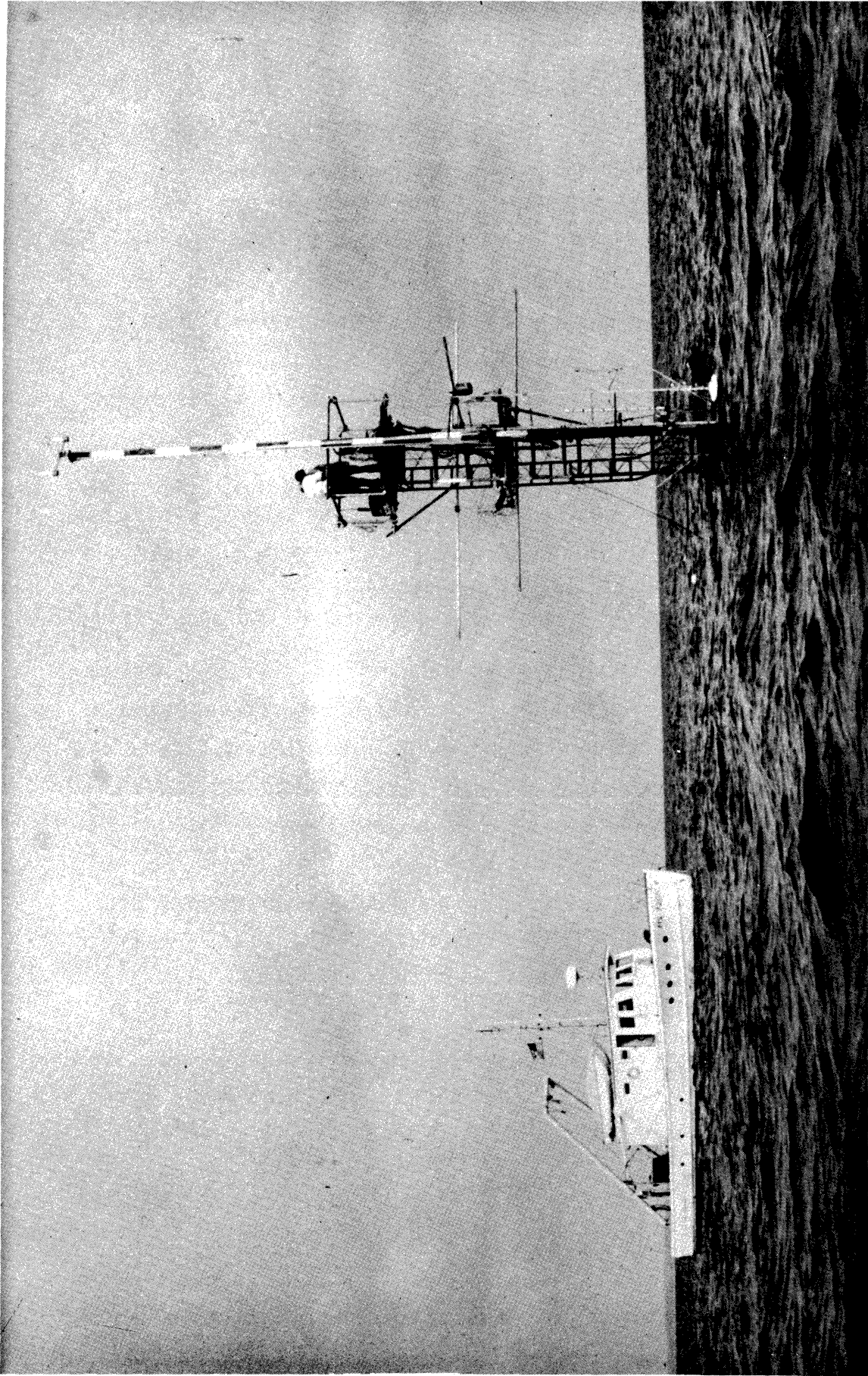


Figure 1. Cuttyhunk experiment site with R/V SCHROCK during a measurement period.

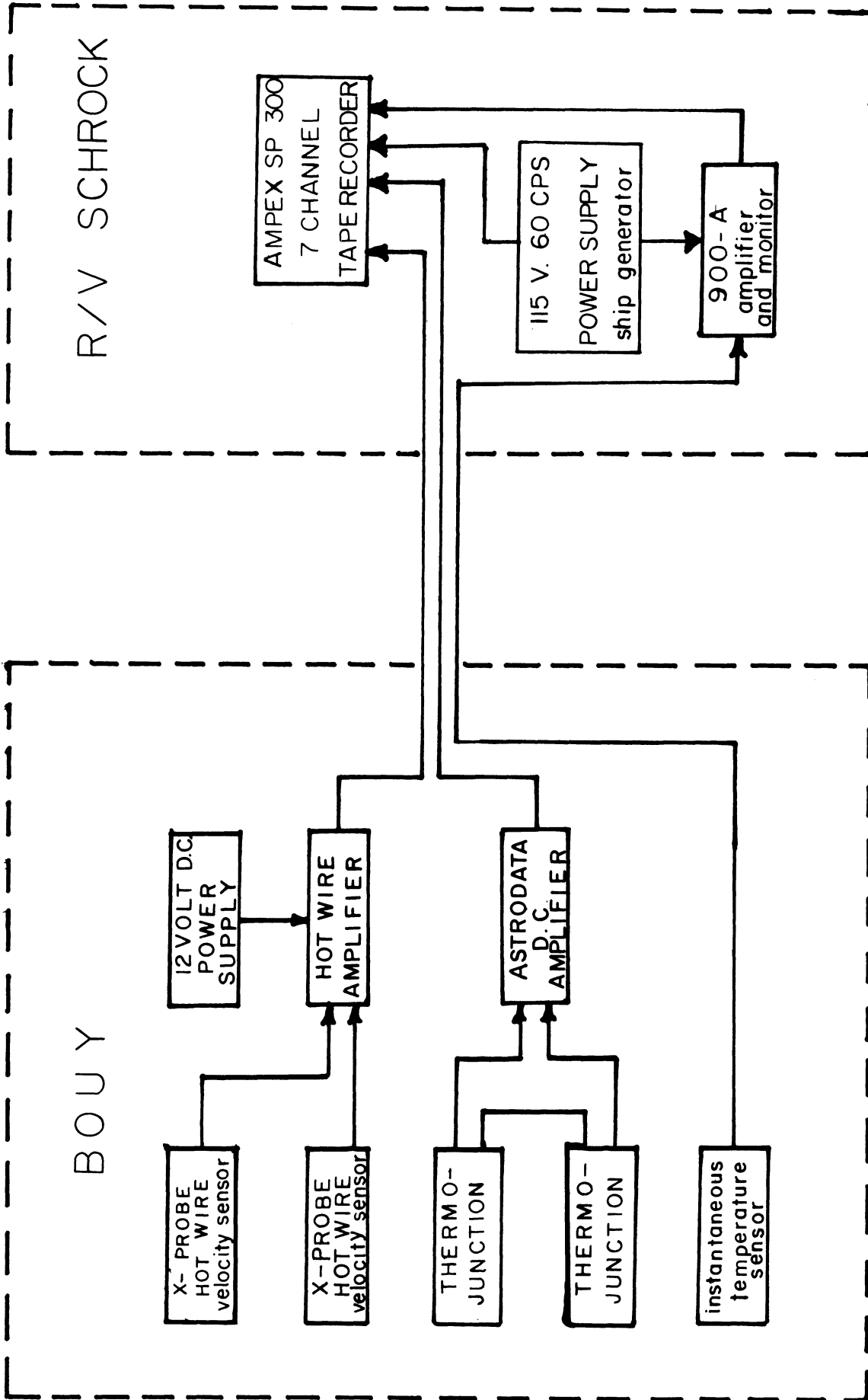


Figure 2. Block diagram of measurement systems showing location of the components.

and temperatures were fine wire filament resistors used in Wheatstone Bridge and amplifier circuits. The average temperature difference was measured with a thermocouple circuit. In both cases large voltage gains were required for recording. The sensors, their circuits, the recording system and the sensor mounting arrangement are described in the following paragraphs.

### Wind Component Measurement System

Sensors. Two Flow Corporation Model HWP-X-W12X-L24 (X-type) hot-wire probes were used simultaneously. Each probe consists of two tungsten filaments mounted at right angles to each other, crossed at their centers where they are 0.03 inches apart. Each filament is 0.1 inches long and 0.00015 inches in diameter and has a time constant of about 0.0004 sec. The u and v components are obtained from two wires mounted in the horizontal plane and the vertical component is obtained from two wires mounted in the vertical plane. Figure 3 shows the space orientation of the probes with the instantaneous temperature sensor as used in the experiment.

Bridge-Amplifier Circuits. Each filament of the probe forms one arm of a Wheatstone Bridge in a Model M-5 Hot-Wire Amplifier Unit designed by Kovasznay, Miller and Vasudeva (1963). The Model M-5 Unit is a closed-loop feedback system consisting of a bridge circuit, a power amplifier and a high-gain differential amplifier. Because transistors are used in the amplifiers it is possible to obtain a stable and sensitive electronic circuit by means of careful impedance matching.

The hot wires were operated in a "constant resistance" (therefore constant temperature) mode by means of a separate feedback for each hot wire. In this way, sensitivity changes



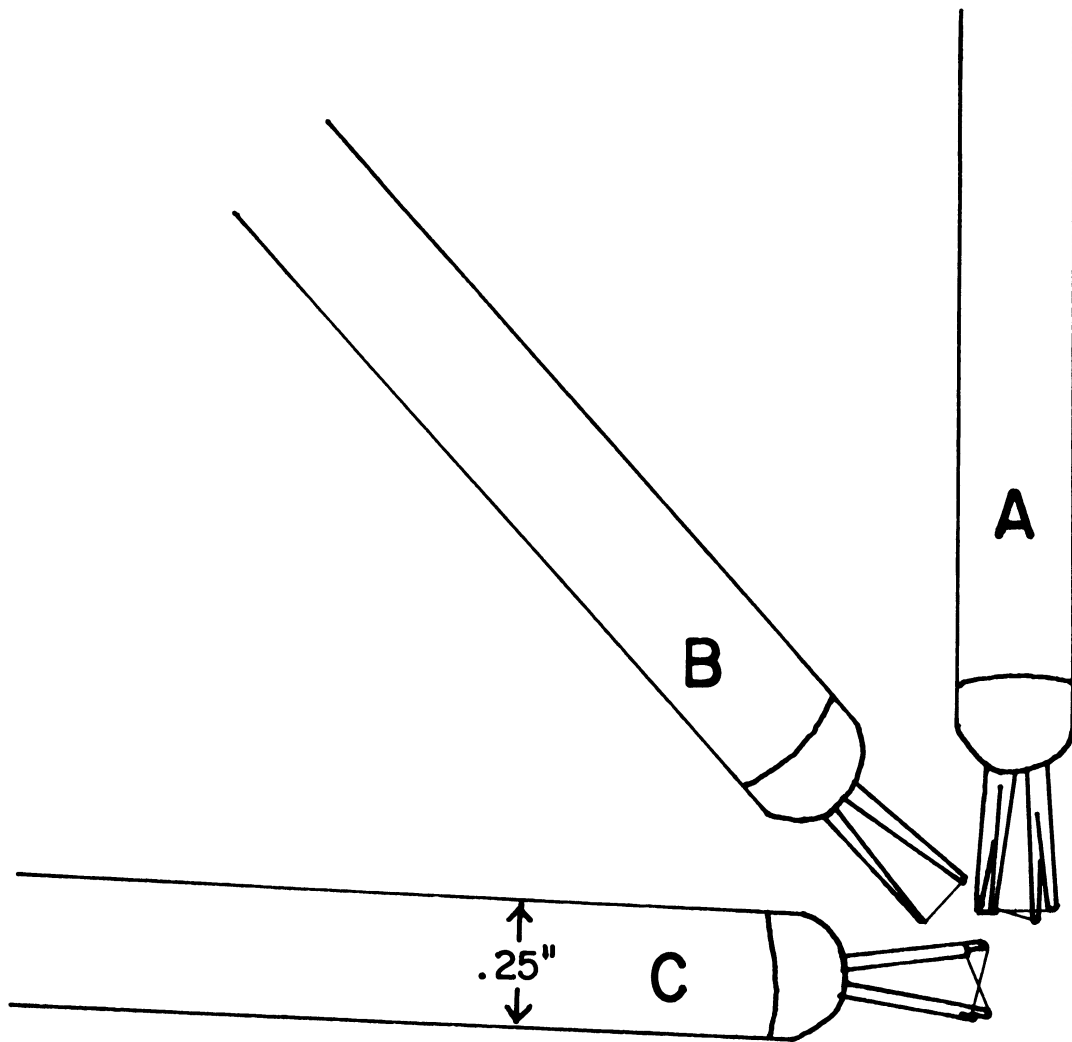


Figure 3. Drawing of the sampling space showing configuration of hot wire probes A and C and temperature sensor B. Probe A determines the horizontal components and Probe C the vertical and 1 horizontal component.

due to wind and temperature changes are avoided and it is possible to obtain accurate measurements of the relatively large fluctuations in atmospheric turbulence.

### Instantaneous Temperature Measurement System

Sensor. A Flow Corporation Model HWP-B probe was used. It has a single tungsten filament with the same diameter (0.00015 in) as that used for velocity measurements but is twice as long (0.2 in). The additional length was necessary to meet a 30 ohm resistance requirement imposed by the bridge-amplifier circuit. The probe was mounted as shown in Figure 3.

Bridge-Amplifier Circuit. The unit was designed for measuring either velocity or temperature. The tungsten filament forms one arm of a Wheatstone Bridge in the amplifier unit of a Flow Corporation Model 900-1 Constant-Temperature Anemometer Module. Temperature is measured with a filament current of approximately 2 ma, a current small enough to avoid significant heating and the consequent influence of velocity fluctuations. (Flow Corporation Bulletin 900 A) The system is operated in a "constant current" mode with the bridge unbalance caused by temperature fluctuations being amplified 50 times for the output signal. The manufacturer's specifications for this system are: frequency response from DC to 1 KHz, resolution  $.03^{\circ}\text{C}$  and noise level .33 mv rms.

The complete temperature measurement system also includes the Flow Corporation Model 900-2 Monitor and Power Supply Unit and the Model 900-3 Suppressor/Filter Unit. The latter unit provides a -1 volt DC carrier for the bridge-amplifier output signal. The DC offset was necessary for recording the analog signal.

### Average Temperature Difference Measurement System

Sensors. The temperature difference between two levels, 2 m apart, was measured with a thermocouple. Thermojunctions were made of No. 36 Brown and Sharpe gauge copper and constantan wire and were supported in radiation shields consisting of four horizontal aluminum plates. The shields and mounting arrangement have been described by Portman (1957).

Amplifier. The emf output of the thermocouple circuit was amplified by a battery-operated Astrodata Nanovolt Amplifier, Model 120. It can be operated for a maximum output of  $10^6$  times the thermojunction input signal. A smaller gain of  $5 \times 10^3$  was used, however, since it was sufficient for recording.

### Recording System

All data were recorded simultaneously on a seven-channel Ampex SP-300 Instrumentation Tape Recorder. Recording was in the FM mode with the tape running at  $3\text{-}3/4$  in  $\text{sec}^{-1}$ . At this speed the FM frequency range of the SP-300 is 0 to 625 cps and the rms signal-to-noise ratio is 38 db measured below 1.0 v rms. Of the seven available channels, four were used for the wind velocity components (one channel for each filament), one for the instantaneous temperature and one for the average temperature difference. The seventh channel recorded a one volt DC signal whose polarity was changed every 10 minutes to mark time intervals for all channels.

As noted above, the tape recorder was operated aboard the R/V SCHROCK on which the power was supplied by an ONAN (Studebaker), 115V, single phase, 60 cps, 12 KW generator.

### Sensor Mounting Arrangement

Figure 4 is a photograph of the sensor mounting arrangement as seen from the buoy platform, about 15 feet above the water. The wind vane at the top of the sensor support frame shows that, in this picture, the frame is correctly oriented for the wind direction because the vane shaft is parallel with the horizontal arm supporting the instantaneous wind component and temperature sensors. (See Figure 3 for a close-up view of the filament arrangement.) The horizontal arms supporting the thermocouple junction shields are perpendicular to the wind and afford, in this position, optimum aeration of the junctions. The main vertical element of the frame is a 2 in aluminum pipe and it is attached to a 3 ft horizontal pipe in a way that allows it to be turned around a vertical axis.

The 3 ft horizontal pipe was attached to the instrument carriage which was fastened to, and ran on, a vertical H-beam welded to a main vertical member of the buoy. The entire arrangement is seen from an upwind position in Figure 5 and the carriage itself is shown in Figure 6. In this way the framework could be moved vertically in order to adjust for changes in water level or to make measurements at different heights above the water.

The sensors for instantaneous wind components and temperature were at the same height and midway between the thermojunctions which were spaced 2 meters apart. The vertical framework for supporting wind profile anemometers and the wave gauge (left-hand side of Figure 5) was supported by 8 ft horizontal arms. The design of the support frame and the placement of the sensors was based partly on the findings of Gill, et al, (1966) who studied the influence of open triangular towers on the adjacent wind field.

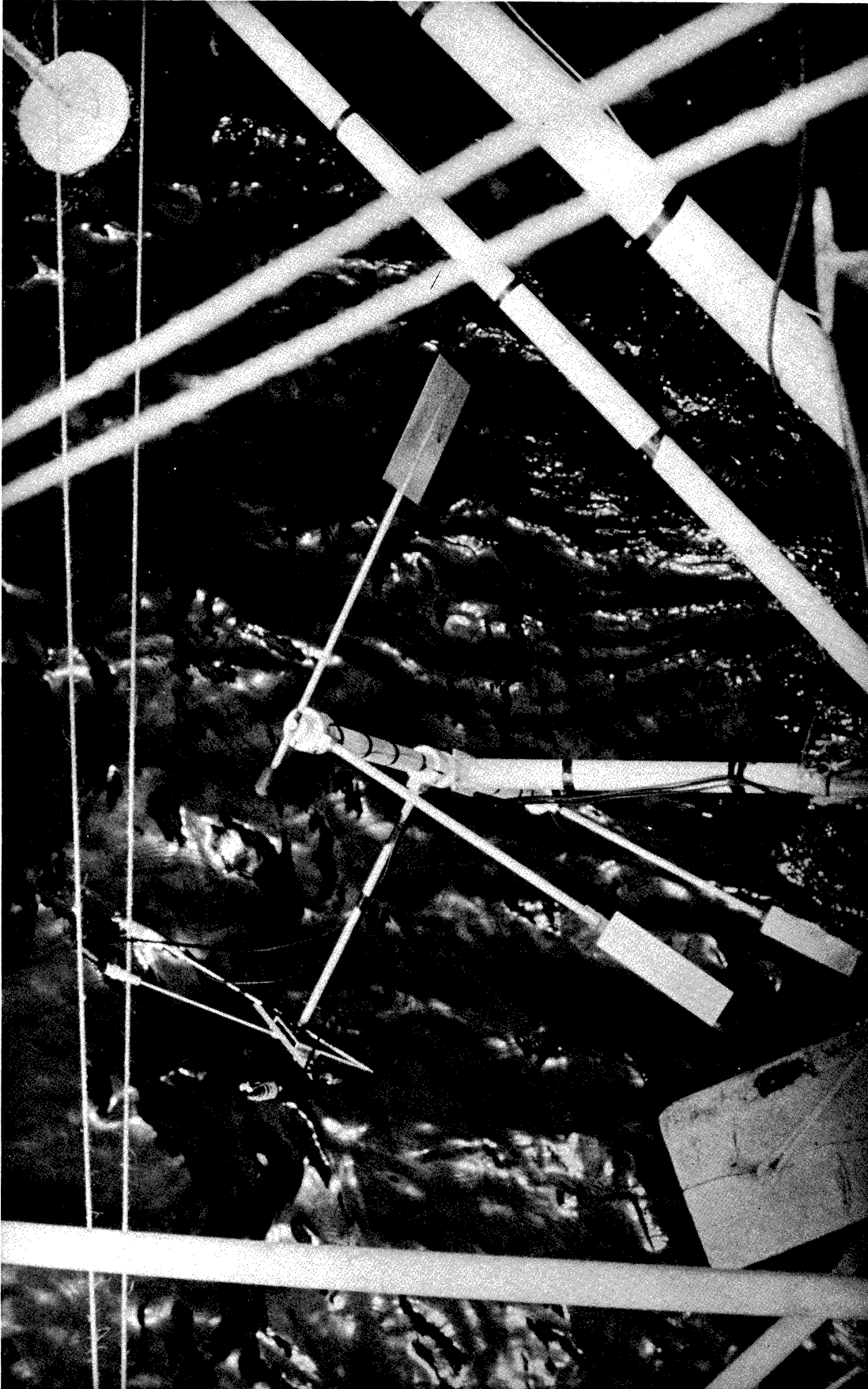


Figure 4. Top view of wind and temperature sensors in place during a measurement period.

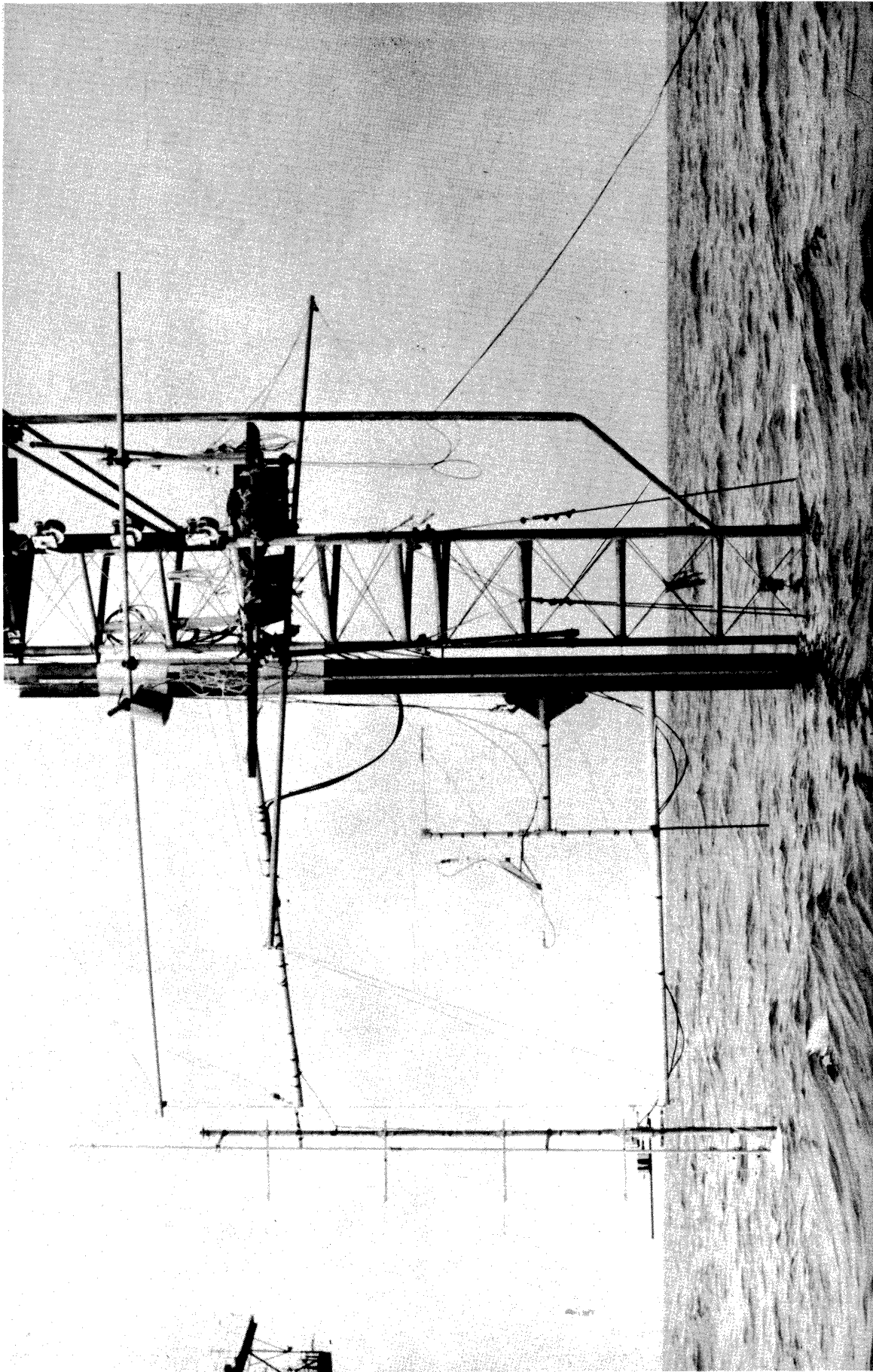


Figure 5. Side view of buoy instrumented with profile and turbulence sensors.

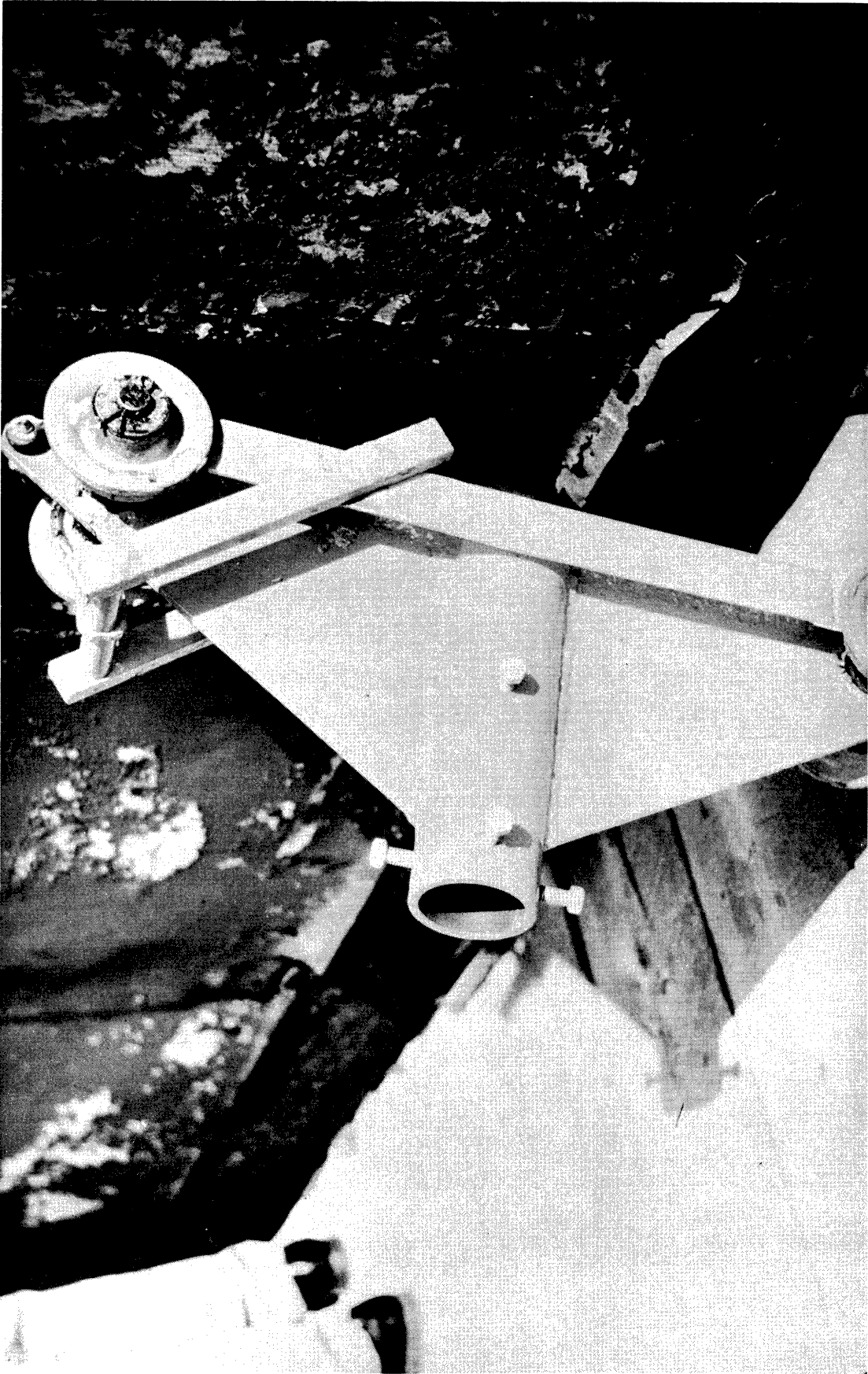


Figure 6. H-track carriage which enabled vertical movement of sensor support frame.



## SUMMARY OF MEASUREMENTS

Measurements were made on four separate afternoons for durations indicated in Table I. Instantaneous temperatures were measured during only two of the periods and only two hot wires were intact for the final measurement period. There were a little more than 7 hours of total recording time and it appears, from a cursory examination of the recordings, that there may be significantly fewer hours of reliable information. The accuracy and overall quality of the recorded information appears to be limited by an unusually high noise level induced in the recording system by variations in frequency and voltage in the electrical power supplied to the tape recorder. A second problem that may cause a certain inaccuracy in some of the data was the motion and tilt of the buoy. The motion could cause spurious velocities to be recorded and the variation in sensor orientation due to variations in tilt may cause problems in data processing. Samples of data and some aspects of the high noise level problems are discussed in the next section.

So far it has not been possible to extract reliable temperature information from the recordings. Since both temperature fluctuations and temperature difference recordings would be expected to have small values during periods of neutral or near neutral thermal stability it may be concluded that such conditions did, in fact, exist during the measurement periods. Sample measurements with mercury-in-glass thermometers support this conclusion. In all cases the wind was from the southwest and the sky was generally clear with occasional scattered, thin high clouds. The sea conditions varied from a half to one meter swell.



Weather and sea conditions and a number of operational difficulties severely restricted the amount of data collection. Fog and rain interfered with operations in the early part of the program when the sensor support frame was being installed. Later, during several days midway in the observation period, strong tidal currents caused the buoy to list to an extent considered unsafe for personnel and unsatisfactory for proper sensor orientation.

Some difficulty was encountered, prior to the first measurement period, in maintaining proper distance between ship and buoy. At the last moment it was learned that the buoy-to-ship connection cable for the instantaneous temperature measurements system was mistakenly supplied by the factory in a length of 150 feet when it should have been 200 feet. When it was found impractical to operate the ship this close to the buoy it became necessary to procure a longer cable and to return the temperature measurement system to the manufacturer for internal adjustment to assure best possible frequency response with the longer cable.

For each observation period 2 to 3 hours were required to install sensors, arrange cables and test and calibrate electronic circuits. As experience was gained in handling the equipment on the boats and buoy the set-up time decreased. Installing sensors and adjusting their height and orientation was an arduous task. The several installations were not achieved without a toll of broken filaments. These were replaced by spares but it was necessary to operate with only two of the four hot wires during the last observation period.

TABLE I

Summary of Measurements

Date	Sky Cond	Sea State	Turbulence Sensors				Duration of Measurements	
			Velocity Hot Wires*					Temperature Filament
			1	2	3	4		
9 Aug	Scattered	.5M swell	x	x	x	x	**	124 min.
15 Aug	Clear	.7M swell	x	x	x	x	**	113 min.
16 Aug	Scattered	1.0M swell	x	x	x	x	x	93 min.
17 Aug	Scattered	.5M swell		x		x	x	98 min.

\* 1, 2 and 3, 4 refer to filaments in horizontal and vertical planes respectively.

\*\* System was returned to manufacturer for adjustments.

PRELIMINARY DATA PROCESSING

It was found that voltage and frequency variations in the electrical power supplied by the ship's generator for the magnetic tape recorder caused excessive noise in the recordings. Data processing conducted to date, therefore, has been directed toward establishment of the degree of data reliability and the separation of information from system noise. Two methods of signal examination are being used; both are applied to the original recordings so that results are evaluated in terms of voltage fluctuations instead of the corresponding velocity or temperature fluctuations.

In one method an analog computer and strip chart recorder are used to provide simultaneous records from all channels so that one can study characteristics of common features that may be ascribed to system noise. In the other method spectral analysis is used to study frequency characteristics of recorded signals for both reference and information channels.

The results of both methods are compared with similar recordings made at the University of Michigan Willow Run Field Station. The Willow Run experiments were conducted after the buoy measurements and no changes were made in the recording or amplifying systems. Necessary filament replacement was made with the same types and sizes as were previously described. The measurements were made over a grass covered surface and the cable length from the hot-wire amplifiers to the magnetic tape recorder was 30 feet, about one-seventh that used between the buoy and the ship. The electrical power supply for the tape recorder, in this case, was the main transmission line that serves the airport facilities. Previous experience with this power supply has shown it to be adequately stable in both frequency and voltage. Wind speed, approximately 10 knots, and thermal stability, near neutral were comparable for both sets of experiments.

#### Simultaneous Analog Recordings

Selected portions of data obtained during each observation period, including both data and reference channels, were processed with an analog computer and recorded with a multichannel strip chart recorder, Brush Model Mark 200. (The reference channel was the  $\pm 1$  volt DC signal used to mark time.) The analog circuit shown in Figure 7 was used to offset the DC level of the signal from each channel and to amplify the remaining AC signal. Removing the DC level from the recordings enabled greater

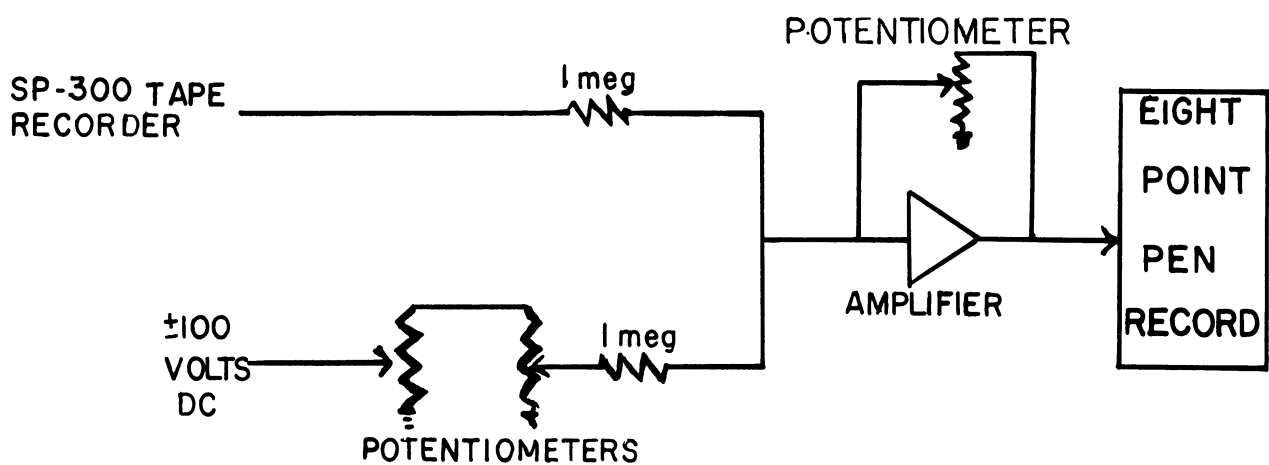


Figure 7. Schematic circuit diagram of analog circuit used to offset DC level and to amplify AC portion of recorded signals for strip chart recording.

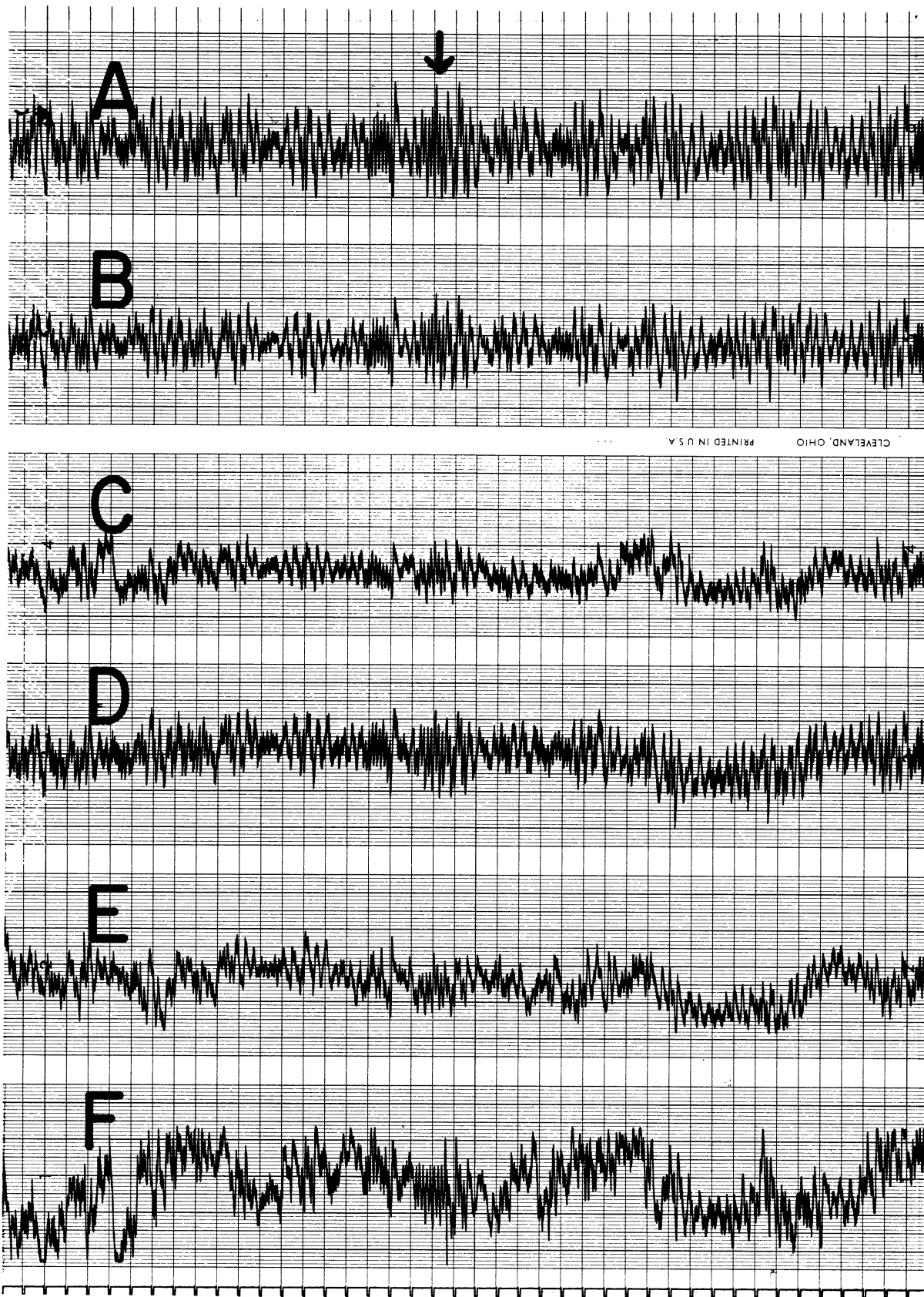


Figure 8. Sample strip chart recordings of signals from reference voltage (A) and from sensors (B,C,D,E,F) obtained at buoy measurement site.

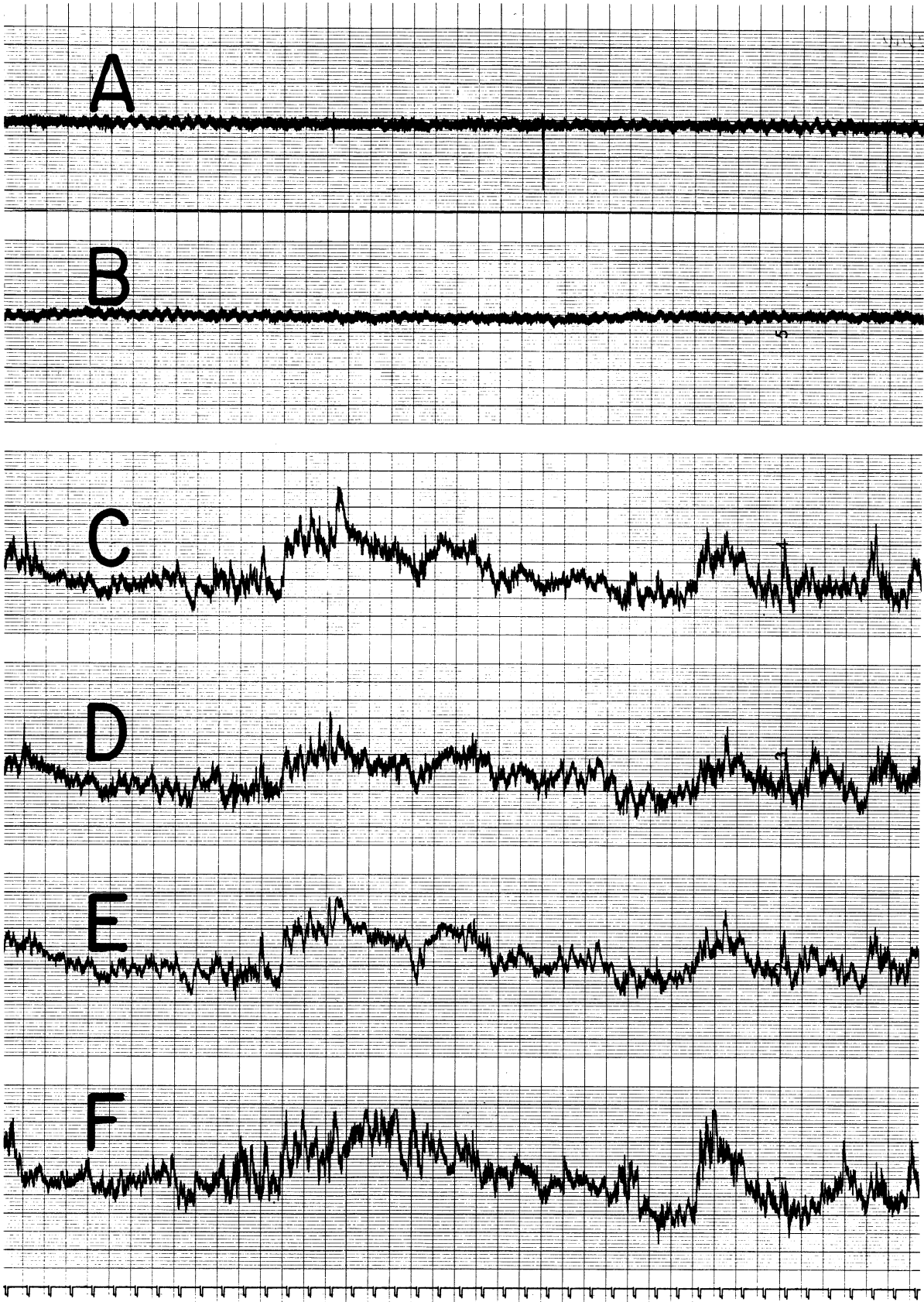


Figure 9. Sample strip chart recordings of signals from reference voltage (A) and from sensors (B,C,D,E,F) obtained at Willow Run measurement site.

amplification of the AC portion for strip chart recording. The same amplifications were used on all channels and direct comparison can, therefore, be made.

Typical results are illustrated in Figure 8 which shows a 43-second interval of the records obtained on 16 August. Channel A is the reference channel, B the instantaneous temperature recording and C, D, E, and F are the hot-wire filament recordings. These may be compared to Figure 9 which shows comparable recordings for the Willow Run experiments. The most striking difference between the two sets of recordings is seen in the reference channels. Channel A for the buoy data has fluctuations that are ten times the amplitude of those in channel A for the Willow Run data.

Further examination of the buoy records of Figure 8 reveals that, occasionally, identical fluctuations occurred simultaneously on the reference and data channels. An example of this is indicated by an arrow where it can be seen that all channels are dominated by the same instantaneous increase in signal strength. Although it is expected that all sensor channels may be well correlated for low frequency fluctuations, it is not expected that the reference channel will show the same fluctuations and one may conclude that such a characteristic is spurious.

### Spectral Comparisons

A six-minute record, selected from measurements on 17 August, was analyzed to obtain a power spectrum for each of the seven channels. Selection of the period for analysis was made by inspecting the analog recordings (and the experiment log book) to obtain a period when all sensors appeared to be operating correctly. The analysis was made with an analog system that uses an electronic wave analyzer (Quan-Tech Wave Analyzer Model 304) and a tape loop

transport (Honeywell Laboratory Recorder/Reproducer Model KAR 7490). Data, which were recorded in FM mode at a speed of  $3\frac{3}{4}$  in  $\text{sec}^{-1}$ , were transferred at the original recording speed to the continuous loop of the KAR 7490. The frequency-modulated signal was demodulated by the KAR 7490 system during the transfer. Spectral densities at different frequencies were obtained by running the tape loop at  $60$  in  $\text{sec}^{-1}$  while supplying the signal to the Quan-Tech Wave Analyzer. The time compression of a factor of 16 makes it possible to sample low frequency spectral densities. The bandwidth was 1 Hz and the wave analyzer voltage output for each frequency band was recorded on an Esterline Angus millimeter recorder.

Figures 10 and 11 show power spectra of buoy and Willow Run data respectively. Comparison of the reference channel spectra (dashed lines) in the two figures indicate, again, that an unusually high system noise level was present during the buoy measurements. At frequencies less than 10 Hz the buoy data noise level was approximately six times that for the Willow Run measurements. For the buoy data, furthermore, the noise level between 1 and 10 Hz seems to dominate the spectra completely. The high level of noise at these frequencies may be due to fluctuations in the power supplied by the ship's generator. The tape drive system of the Ampex SP-300 requires a constant 60 Hz frequency and if it is not maintained two effects causing noise could result. First, the tape would not move past the record head at constant speed and, second, the tape tension necessary to maintain tape-to-head contact is not constant.

Another possible cause of the difference between noise levels of the buoy and Willow Run recordings is the difference in cable length (cable between the hot-wire amplifiers and the recorder) for the two experiments. Tests of the possible



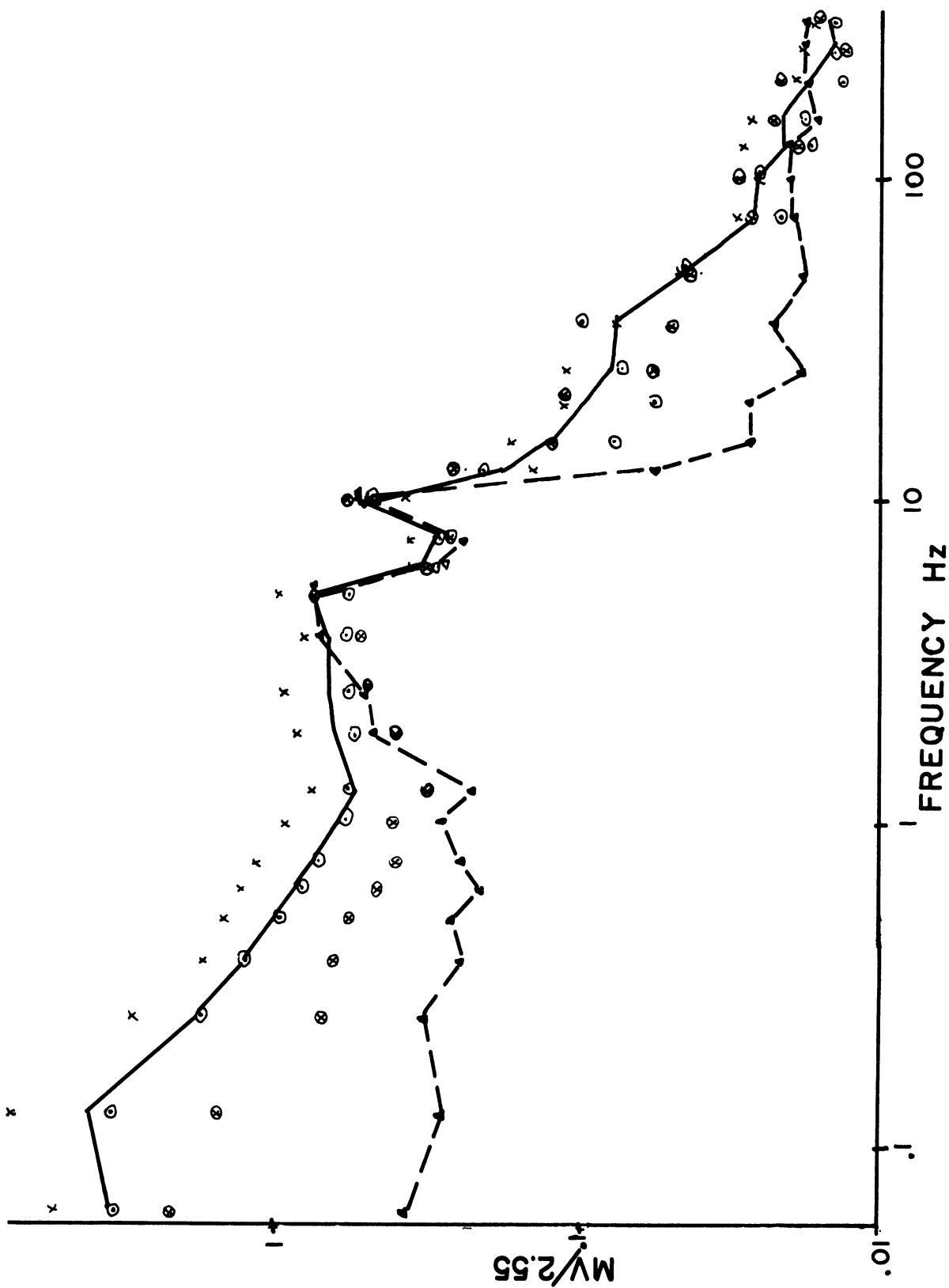


Figure 10. Sample power spectra of signals from sensors (solid line) and reference voltage (dashed line) recorded at buoy. Solid line represents average of three data channels.

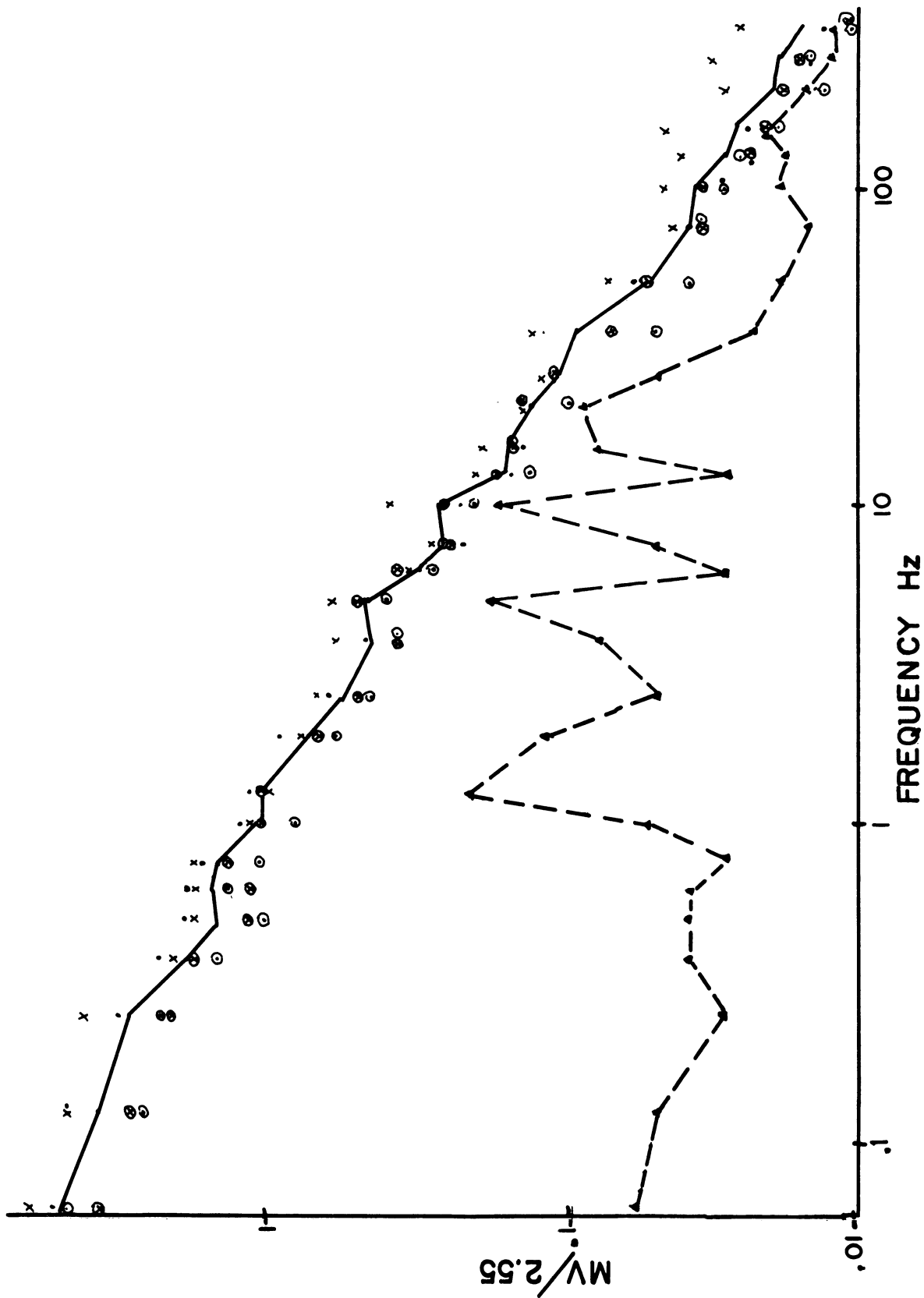


Figure 11. Sample power spectra of signals from sensors (solid line) and reference voltage (dashed line) recorded at Willow Run measurement site. Solid line represents average of four data channels.

influence of cable length were performed prior to the buoy measurements and are described in Appendix A. A comparison of the spectra (Figure 12, Appendix A) from these tests indicates that the increased cable length was not the cause of the apparent noise problem in the buoy data. The fact that during the buoy measurements the cable was essentially submerged (although it was attached to a string of floats to keep it near the water surface), was moving with the waves, and was attached to the buoy on which electro-mechanical instruments were in operation, could have significance. Influences such as these cannot be ascertained at this time but it appears that on the basis of past field experiences with this recording technique, as used by the authors and by other investigators, the most likely cause of the high noise level was the irregular power supply to the tape recorder.

Both the analog records and the spectra indicated that successful analysis of the data will depend on the possibility of separating signal from noise by filtering techniques. The example shown in Figure 10, however, indicates that the noise level is as high as the signal level over the frequency range of  $1\frac{1}{2}$  to 10 Hz. It is unlikely that it is possible to salvage the signal at these frequencies. For frequencies up to  $1\frac{1}{2}$  Hz, on the other hand, the noise level is relatively constant and it would appear that the low frequency information may be separated in this case from noise to yield useful information on turbulence components. It is planned to continue study of the noise characteristics in order to specify the assumptions necessary to extract valid information and, then, to carry on the computations necessary to obtain velocity component and temperature fluctuation spectra for all data for which reasonable reliability can be established.

## CONCLUSIONS

The goals of the investigation were to develop suitable measurement techniques and to use them to investigate the structure of turbulence over ocean waves. The extent to which the tasks were achieved may be summarized in a set of conclusions relating separately to success of techniques and to reliability and amount of data obtained. It must be recognized that some of the conclusions are subject to change because of the incomplete data analysis. It is possible, nevertheless, to make a number of statements useful to guide further investigations although it seems inappropriate to make specific recommendations prior to more complete data analysis and system testing.

### Equipment and Procedures

#### Wind Component Measurement System

The hot-wire anemometer system functioned satisfactorily in the salt air environment without special handling or protection. The 200 ft cable between the amplifiers and the recorder appeared to cause no problem.

#### Instantaneous Temperature Measurement System

The system used for these experiments appears to be suitable for the measurements desired. The high level of noise in the recording system and the apparently low level of temperature fluctuations experienced, however, do not permit a conclusive evaluation. The Willow Run experiments conducted following the buoy measurements indicate that no serious trouble should be expected in using the system on a stable platform in a marine environment. The major problem is handling the probe without breaking the filament. Since it is twice as long as the hot wires it is more easily broken.

### Average Temperature Difference Measurement System

The thermocouple circuit with the Astrodata amplifier, like the instantaneous temperature measurement system, cannot be conclusively evaluated because of the recording problems and because, apparently, most data were recorded during periods of neutral thermal stratification when the system would have a low output. Previous field use suggests that it is a satisfactory system.

### Recording System

The most serious difficulty encountered in the experiment was the high level of noise induced in the recording system by the fluctuations in voltage and frequency of the electrical power supplied by the ship's generator. Apparently this difficulty will make it impossible to evaluate reliably low level signals, such as those received from the temperature sensors, and all high frequency information. In other respects the recording system appeared satisfactory so that if adequate electrical power can be provided, the system can be expected to be useful in similar investigations.

### Mounting Arrangement

The sensor support frame proved to be a suitable and convenient device. A few difficulties were encountered during its use, however, and they increased the risk of filament breakage and the time required for installation and probe orientation. Although significant at the time of experimentation, they are not major difficulties and can easily be rectified by minor design changes for future experimentation. Some of the changes would depend significantly on the kind of buoy or tower used as a basic support.

### Experimental Plan

The overall experimental scheme, involving buoy, ship and

interconnecting cable, was a successful one for the conditions experienced. It is likely that more experience in handling the interconducting cable would permit use of the scheme in higher seas and in breaking waves. In addition to the problem of the high recording noise level, the one other important difficulty was the motion and list of the buoy. As explained in a foregoing section, the sensor supporting frame was attached to the buoy without the use of a gyro-mechanism or similar device to maintain a fixed orientation relative to the sea surface. Buoy motion, therefore, caused spurious velocity indications and the spatial orientation of the filaments was constantly changing. The significance of these effects and the possibility of their removal from the data is yet to be determined. For further experimentation it would be highly desirable to have a more stable platform.

## Reliability of Data

### Turbulence Component Data

On the basis of preliminary spectral analysis of a single six minute period, it appears that it will be possible to compute reliable spectra and cross spectra of the three orthogonal turbulence components for frequencies less than 1.5 Hz. It may be possible to compute as many as 30 or 35 ten minute spectra. The accuracy and reliability of the data will be restricted by an unusually high noise level and any influences of buoy list and motion that cannot be removed from the data.

### Temperature Data

Preliminary examination and a sample spectrum of the temperature data reveal that neither the instantaneous nor the average difference recordings are likely to yield useful numerical information. The absence of measureable signals from these systems, however, may be taken as a measure of the lack of significant thermal stratification during the experiments.

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## APPENDIX A

### Tests to Determine Effect of a 200 ft Cable in the Hot-Wire Anemometer System

Tests were performed to determine the performance of the hot-wire system when a 200 ft cable connected the amplifiers to the Ampex SP-300 tape recorder. The hot-wire system had never been operated with this arrangement and there was concern over possible resonance at high frequencies due to the increased capacitance on the output side of the amplifiers.

The tests were made in the wind tunnel of the Department of Meteorology and Oceanography at the University of Michigan. The tunnel speed was 8.5 m/sec and the hot wire probes measured the velocity fluctuations behind a cylindrical rod. The amplified signals from the sensors were transmitted over both a 10 ft and a 200 ft cable for recording on magnetic tape. Belden 2824 was used for both cables.

Spectral analyses were made by the wave analyzer technique described above. The results are shown in Figure 12, where the broken and solid lines correspond to the average values from two long and two short cable measurements respectively. These results indicate no apparent loss of signal at any frequency due to the long cable; the two spectra are almost identical within the range of frequencies which are of interest in the field investigation. Since the tests were made during July, before the field experiment, the results influenced the decision to use the ship as the recording platform and then to transmit all signals over a 200 ft cable.



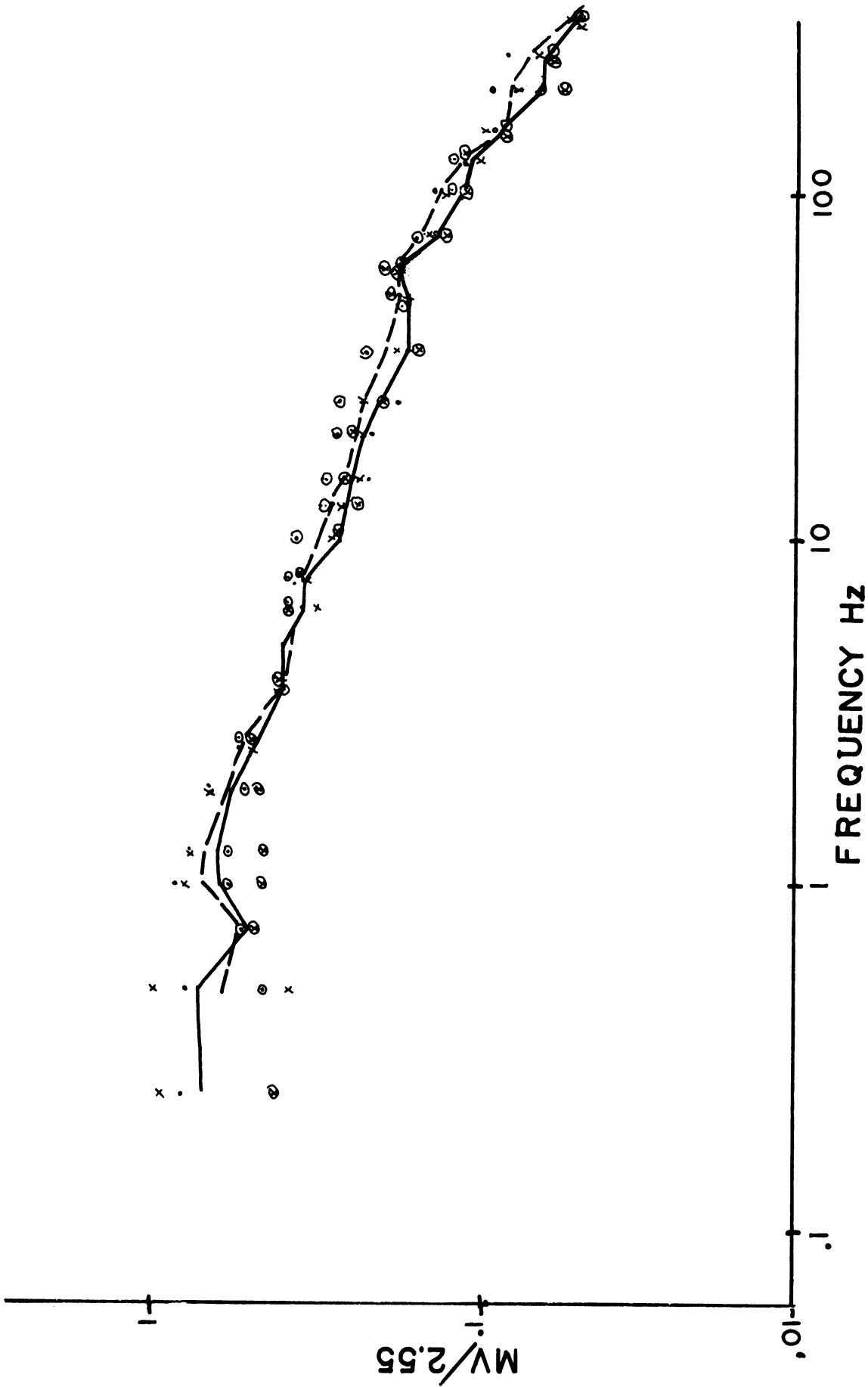


Figure 12. Average power spectra of signals obtained using 200 ft (dashed line) and 10 ft (solid line) transmission cables in wind tunnel tests.

## APPENDIX B

### Wind Profile and Wave Measurements by Massachusetts Institute of Technology Personnel

Waves were measured with a gauge consisting of a six foot length of plastic-encased steering cable suspended from an oscillator unit. The depth of water immersion determined the capacitance of the cable and the capacitance, in turn, determined the frequency of the oscillator.

The average wind profile was measured with fast response Thornthwaite (three cup) anemometers in two vertical arrays. The higher array was fixed relative to the buoy and consisted of four anemometers, one above the other at one meter intervals, with the lowest from one to two meters above the water. The other array consisted of three anemometers on a vertical shaft attached to a float that caused the three anemometers in this array, while remaining in a fixed position relative to each other, to follow the surface profile at heights of 15, 35, and 55 cm respectively. The wave gauge and anemometer outputs were supplied, via submarine cable, to a recorder operated at the Buzzards Bay Entrance Light Station.



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