THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING
Department of Meteorology and Oceanography

AN INVESTIGATION OF ATMOSPHERIC TURBULENT TRANSFER PROCESSES OVER WATER

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by

Floyd C. Elder
Associate Research Meteorologist

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Donald J. Portman
Project Director

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ABSTRACT

Measurements of wind and temperature profiles were made on the U. S. Lake Survey, Lake Michigan Research Tower during the summer of 1965. The tower was located near Muskegon, Michigan, one mile from shore in fifteen meters water depth. The measurements are described and available data are listed.

Selected wind profiles are studied in relation to existing wave characteristics. Roughness length and drag coefficient are calculated for cases when wind speeds were greater than, equal to, and less than the speed of the dominant waves.

I. INTRODUCTION

The research program, "An Investigation of Atmospheric Turbulent Transfer Processes over Water," was initiated at the University of Michigan in June 1963 under U. S. Weather Bureau sponsorship. A contract called for the instrumentation of a tower in Lake Michigan to measure and to record the mean profiles of wind speed, temperature, and water vapor on a continuous basis. The work was continued under subsequent contracts and is described in the final reports (Reference 6 and 7).

The research tower, shown in Figure 1, was designed, constructed and maintained by the U. S. Army Corpos of Engineers, and Engineer District, Lake Survey (hereinafter termed U. S. Lake Survey). As described in previous reports, the tower consists of a structure extending 16 meters above the water surface and located in 15 meters of water about one mile from shore near Muskegon, Michigan. Submarine cables connect to shore to provide power and communication. An instrumentation load of about 200 pounds can be supported. The tower and instrumentation are fully described in Reference 6 and 7.

This report describes the measurement programs of 1964 and 1965 and gives a brief account of instrument modification. Analysis of some of the data collected during 1964 is presented and data from 1965 are tabulated.

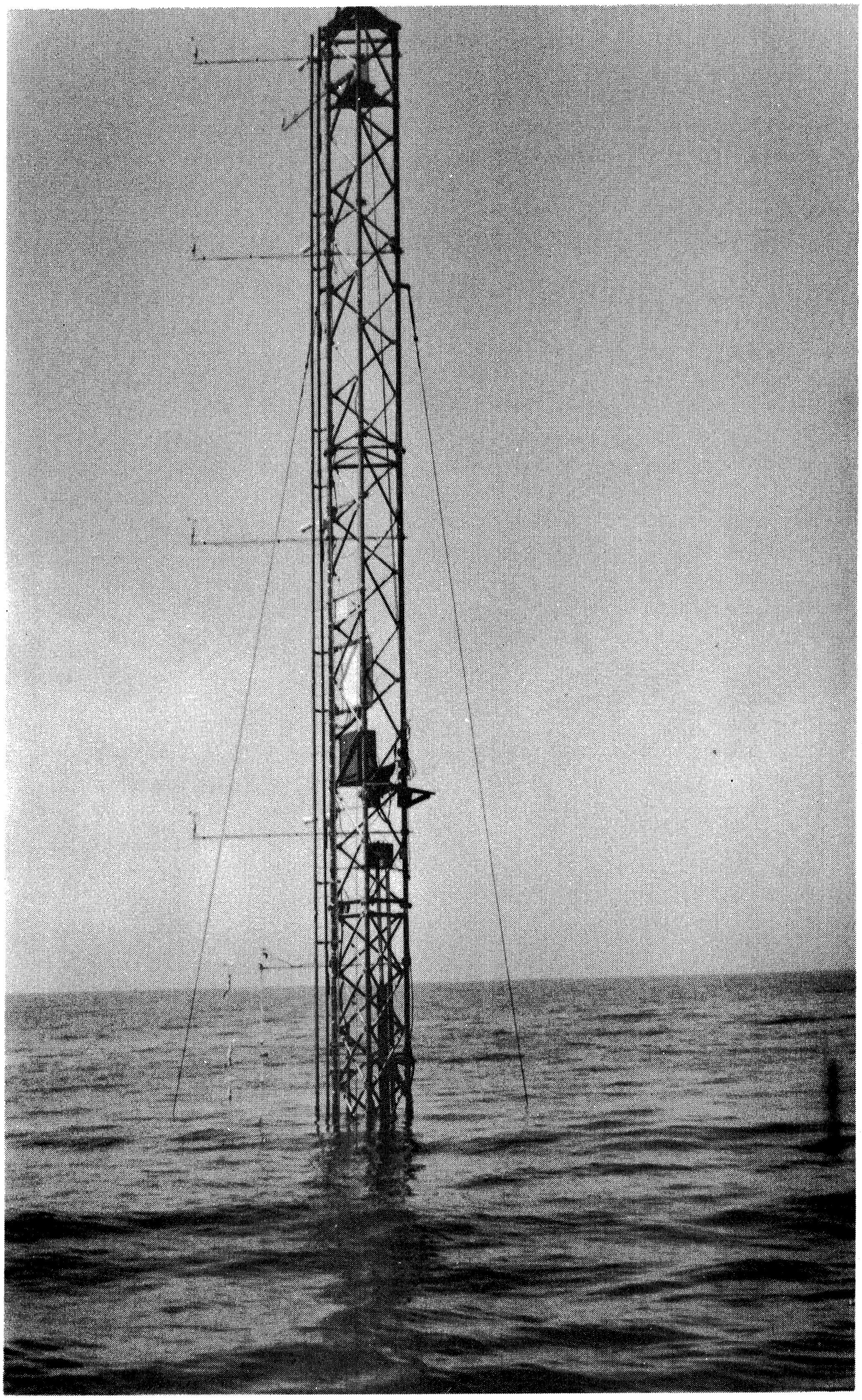

Figure 1. U. S. Lake Survey, Lake Michigan Research Tower

2. 1964-65 PROGRAM

2.1 Program of September 1964

The automatic telemetering and digital data recording systems discussed in previous reports (Reference 6 and 7) were completed and delivered by the manufacturer during August 1964. They were transported to the shore station at Muskegon and were tested prior to installation on the research tower.

Several deficiencies in performance were encountered but were corrected. On August 21 it was decided that performance was satisfactory and installation of the telemetering system on the tower was started. This necessitated removal of the temporary paper chart recording system from the tower and terminated data recording. The system installation and testing were completed by September 2. Sensor modifications required by the change in recording systems were completed and first trials of actual data recording were made on September 10.

One major problem of recording data in digital format on magnetic tape developed immediately. There existed no way to examine the tape to determine that data had been properly recorded. Returning tapes to the computer for evaluation caused up to two days delay in determination of existing problems.

Data sequences were recorded on September 10, 12, 15, 16, 17, 22 and 23 with immediate computer reduction to determine system performance. A certain amount of malfunction was encountered but by the last period a large portion of the record was acceptable. Careful calibration of the temperature sensors, however, was never possible so that accuracy of the data was not known.

During a severe storm on the morning of September 24, the tower collapsed and all instrumentation was immersed in the water. The storm, beginning on September 23, produced sustained winds of greater than 20 knots for over 18 hours. This resulted in wave heights greater than 15 feet (full scale for the wave height recorder) at the research tower. Failure of the tower structure was studied by personnel of the U. S. Lake Survey. An internal report (Reference 2) outlining the probable cause of failure and modifications required to prevent such failure in the future was prepared.

The tower site was visited on September 26 but waves were too high to permit an attempt to recover equipment. On September 28 the U. S. Lake Survey assembled a team of divers and a recovery vessel. With the exception of two small items, all instrumentation was removed from the sunken tower and raised. The tower structure was removed from the tripod support and raised the following day and transported to the Corps of Engineers Boat Yard at Grand Haven. A picture of the collapsed tower after recovery is shown in Figure 2. All instrumentation has been

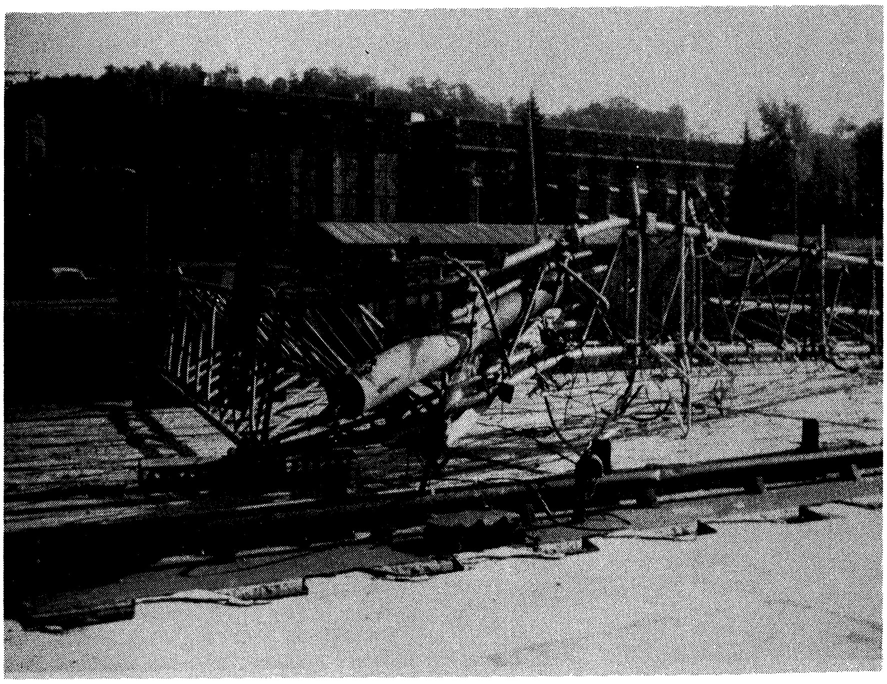

Figure 2. Collapsed Tower after removal from Lake Michigan, September 1964

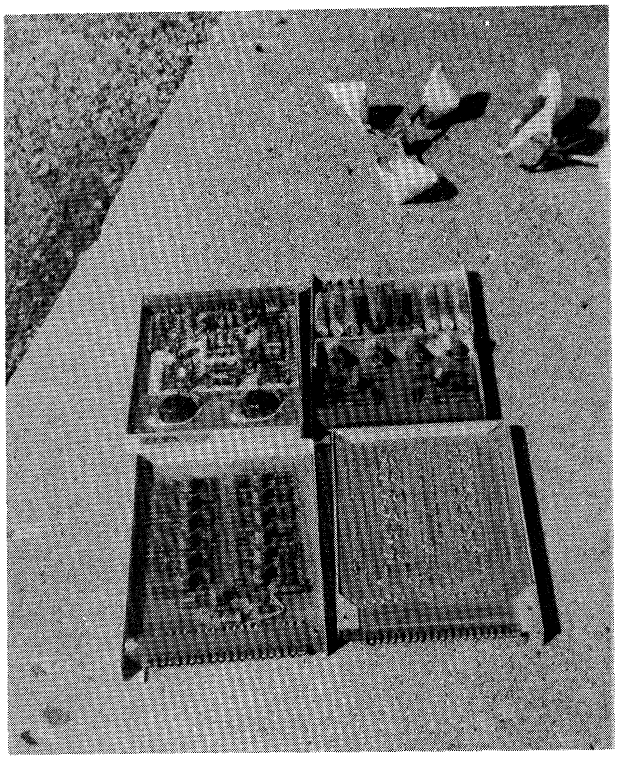

Figure 3. Anemometer Cups and Printed Circuit Components after removal from Collapsed Tower

removed but much of the wiring remains entangled in the twisted tower.

Damage to the instrumentation was extensive making impossible further measurements during 1964. Actual breakage of components was less than would have been expected. As shown in Figure 3, the anemometer cups were badly bent but other equipment was structurally undamaged. However, the electrical circuits were broken. The fuse apparently failed to interrupt power for some time after equipment immersion so that electrolysis could act on all circuits.

All equipment was returned to the laboratory and assessed for salvage. Anemometers and aspirated radiation shields were returned to the manufacturer for reconditioning. The electrical equipment contained in the measurement and telemetering systems was determined to be a complete loss with only the mounting and cases reusable.

2.2 Reconstruction of Measurement and Telemetering System

At the time of the tower failure, the automatic telemetering and recording system appeared to be on the verge of successful operation. Experience gained during construction and testing of the system indicated, however, that some changes could result in significant improvement. Since the original components of the telemetering system were not salvageable, it was decided to incorporate improvements in reconstruction where possible while retaining compatibility with the shore recording system that remained undamaged. This meant that the basic functional design of the system would remain as previously described (Reference 6) but individual components would be changed to incorporate improvements. A block diagram of the reconstructed telemetering system is shown in Figure 4. This system differs from that previously described only in the details discussed below.

The 12-bit binary counters, used with each three-cup anemometer to measure total air movement at each level between successive 2-minute recordings, were believed to have performed satisfactorily. They were replaced, therefore, by similar counters, Model 6502 made by Information Instruments Incorporated, Ann Arbor, Michigan. Detailed information may be obtained from the manufacturer.

The Wheatstone Bridges used as measuring circuits for the temperature and dew point sensors were reconstructed using the original design. Linearization of the thermistors was provided for in only one range instead of the three ranges as done previously.

The major problems encountered in testing the original system and the major change in redesign were in the data commutator. The original commutator, as described in Reference 6, consisted of reed switches actuated by a magnet rotated by a

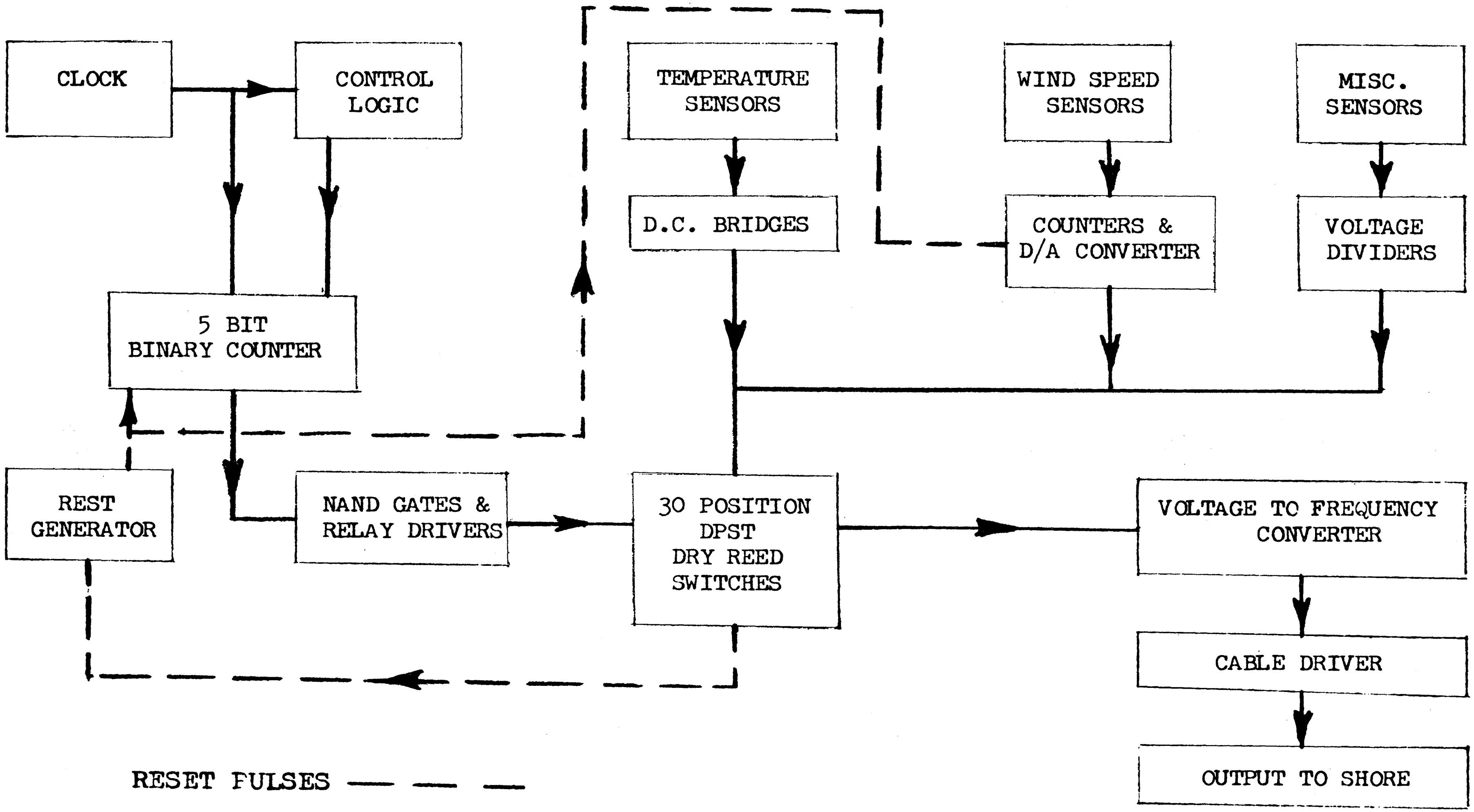

Figure 4. Block Diagram of Rebuilt Telemetering System

stepping motor. Difficulty in physical alignment of the magnet and damping of the stepping motor caused some unreliability in operation. It was decided, therefore, to design and to build an electronic switch to replace the electromechanical mode of commutation.

In the block diagram the commutator is shown as three components, a 5-bit binary counter, NAND gate, and a 30position reed switch. The basic timing clock remains unchanged. Every two minutes a series of clock pulses is generated at a 15 cps rate. The series is terminated by the commutator switch as it advances to the end of its cycle.

The 15 cps clock signal is accumulated by the 5-bit binary counter. Accumulation of pulses by the counter actuates the magnetic reed relays through a series of NAND gates. Each successive pulse advances the counter to the following binary stage. At each stage one of the NAND gates is set, causing its relay driver to close the double pole magnetic reed relay of that channel. Thus, the reed relays are successively actuated at the 15 cps rate provided by the clock signal. Upon closure of the 30th relay, the clock signal is stopped and the binary counter reset to its zero point. The commutator is then inactive until the 2-minute cycle timer again actuates the clock signal.

Transmission of the data to the shore recording system over a coaxial cable was accomplished through use of a Vidar Model 260A voltage to frequency converter and a cable driver. The original units were damaged beyond repair but had proven satisfactory in the short period of use. They were replaced, therefore, by new equipment of the same type.

2.3 1965 Measurement Program

On April 15, 1965, the area near the tower location was examined with personnel of the U. S. Lake Survey to locate the tripod support which had been left standing when the tower was removed. It was found collapsed on the bottom, apparently as a result of horizontal pressure from ice floes. The tripod top was about 10 feet below water level, indicating that ice penetration was at least to this depth.

The tripod was removed, repaired, and the tower installed on May 6. Cables from shore, used the previous year, were located and attached to the tower by May 31. The tower was ready then for instrumentation.

The sensor and telemetering systems were installed and first automatic recording of temperature and wind profiles was accomplished on June 10. The telemetering system scaned the array of sensors at two-minute intervals transmitting each variable value to shore for recording on digital tape. Air temperature and wind speed were measured at nominal heights of 15, 12, 8, 4, 2, 1, and 0.5 meters with reference to the mean water surface. Wind direction was measured at 15 meters only while dew point temperature was measured at 15, 8 and 4 meter heights. Water temperature was measured at surface, -4, -8, and -16 meters in addition to water radiation temperature. The mean water surface elevation with reference to the zero height level was also recorded in each two-minute data sequence. Wave heights were recorded in analog form on a separate recording system installed and operated by U. S. Lake Survey.

2.4 Summary of Data Recorded in 1965

After installation of the instrumentation, data were recorded during all periods when system performance was considered to be satisfactory until the end of the contract period on August 31. A total of 778 hours of profile data were recorded. Some data were, however, not readable by the computer due to format errors. Table 1 lists all periods for which readable data were obtained and shows which sensors were installed and provided meaningful data during each of the periods.

The data were recorded on magnetic tape in binary code in parts per thousand scaled to the range of each particular sensor. Raw data were subjected to screening for gross inconsistencies by computing averages over one-hour periods and testing each datum point for departure from the average. Data that departed from the average by greater than a chosen amount were rejected and a new average was computed.

Hourly average values of all the measured variables were converted to BCD format and written on magnetic tape for listing or for further computation. The maximum and minimum two-minute wind speed contained in each hour average were also included. All data heights were adjusted to actual height above the mean water surface existing during the hour of observation.

The hourly averages were listed and briefly examined. Because of the large volume of data, even in the form of hourly averages, they are not reproduced in this report. Table 1 shows the periods for which various data are available. Machine-listed tabulations or magnetic tapes, can be made available to the sponsor or to others through arrangements with the sponsoring agency. Wave height data are retained by the U. S. Lake Survey and could be obtained by arrangements with that agency.

TABLE I

TABULATION OF DATA AVAILABLE FROM 1965 MEASUREMENT PROGRAM

Date/Time						Air Temperature							Water Temperature					Wind Speed							Dew Point		
Begin		End		Wave Height	Wind Dir.	15M	12M	8M	4M	2M	1M	0.5M	Sfc.	Sfc. Rad.	-4M	-8M	-16M	15M	12M	8M	4M	2M	1M	0.5M	15M	8M	4M
6-10	2100	6-11	0900			x		x	x						x	x	x	x	x	x	x						
6-11	1705	6-11	1905		x	x		x	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x		x
6-15	1527	6-16	0427		x	x		x	x						x	x	x	x	x	x	x				x		x
6-16	1446	6-17	0646		x	x		x	x	x	x				x	x	x	x	x	x	x	x	x		x		x
6-17	1020	6-17	1220		x	x		x	x	x	x	x	x		x	x	x	x	x	x	x	x			x		x
6-17	1952	6-18	0752		x	x		x	x	x	x	x	x		x	x	x	x	x	x	x	x			x		x
6-18	0934	6-18	1634		x	x		x	x	x	x	x	x		x	x	x	x	x	x	x	x			x	x	
6-18	1634	6-19	0634		x	x		x	x				x		x	x	x	x	x	x	x				x	x	
6-19	0815	6-21	0715		x	x		x	x				x		x	x	x	x	x	x	x				x	x	
6-21	1423	6-22	1023	x	x	x		x	x	x	x	x			x	x	x	x	x	x	x	x			x	x	
6-22	1047	6-23	0947	x	x	x		x	x	x	x	x			x	x	x	x	x	x	x	x			x	x	
6-23	1117	6-24	1217	x	x	x		x	x	x	x	x			x	x	x	x	x	x	x	x			x	x	
6-24	1217	6-24	1617	x	x	x		x	x	x	x	x			x	x	x	x	x	x	x	x	x		x	x	
6-29	1750	6-30	0650	x	x	x		x	x						x	x	x	x	x	x	x				x		x
6-30	2253	7-1	0853	x	x	x		x	x						x	x	x	x	x	x	x						x
7-1	0800	7-1	1100	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x			x
7-1	1525	7-2	0325	x	x	x		x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x			x
7-2	0842	7-2	0942	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x				x
7-2	1245	7-6	1245	x	x	x		x	x				x	x	x	x	x	x	x	x	x						x
7-6	1644	7-7	0844	x	x	x		x	x				x	x	x	x	x	x	x	x	x						x
7-7	1532	7-8	1005	x	x	x		x	x				x	x	x	x	x	x	x	x	x						x
7-8	1156	7-8	1456	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			
7-8	1456	7-9	1640	x	x	x		x	x				x	x	x	x	x	x	x	x	x						
7-10	0835	7-13	0835		x	x		x	x					x	x	x	x	x	x	x	x						
7-14	0203	7-15	0818		x	x		x	x					x				x	x	x	x						
7-17	1200	7-18	0700		x	x		x	x		x	x	x	x	x	x	x	x	x	x	x	x			x		x
7-18	1330	7-20	0809		x	x		x	x				x	x	x	x	x	x	x	x	x				x		x
7-21	0838	7-21	1238		x	x		x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x
7-21	1725	7-22	0925		x	x		x	x					x	x	x	x	x	x	x	x				x		x
7-22	1030	7-22	1530		x	x		x	x		x	x		x	x	x	x	x	x	x	x	x	x	x	x		x
7-22	1711	7-23	0811		x	x		x	x					x	x	x	x	x	x	x	x	x	x	x	x		x
7-23	0959	7-23	1059		x			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x
7-23	1900	7-23	2200		x			x	x				x	x	x	x	x	x	x	x	x				x		x
7-27	1805	7-28	0818		x	x		x	x					x	x	x	x	x	x	x	x				x		x
7-28	1010	7-29	0810		x	x		x	x					x	x	x	x	x	x	x	x				x		x
7-29	0931	7-30	0631		x	x		x	x					x	x	x	x	x	x	x	x				x		x
7-30	1010	7-31	1210		x	x		x	x					x	x	x	x	x	x	x	x				x		x
7-31	1217	8-2	0817		x	x		x	x					x	x	x	x	x	x	x	x				x		x
8-2	0842	8-2	1042		x	x		x	x					x	x	x	x	x	x	x	x				x		x
8-4	1552	8-5	0446		x	x		x	x					x	x	x	x	x	x	x	x				x		x

3. PRELIMINARY ANALYSIS OF SELECTED WIND PROFILES

3.1 Introduction

The importance of wind profile characteristics in interpretation of wave spectra has been emphasized by Pierson (1964). He has shown that a relationship derived for wave heights in terms of wind speed at one level will not necessarily hold for speeds measured at a different level. The literature does not contain, however, any general agreement concerning the relationship between the vertical flux of momentum and the shape of wind profiles over wave surfaces. The range of disagreement is shown by the variation in drag coefficients based on 10 meter wind speeds reported by Sheppard (1963), Sheppard (1958), Deacon and Webb (1962), Brocks (1959) and Portman (1959). A tabulation of drag coefficients reported by various investigators is reported by Roll (1965).

The application of wind profile measurements to the estimation of vertical momentum flux and thereby to estimation of surface drag or wave generation requires at least four assumptions if the method is to yield successful results. The assumptions are: 1. the existence of a constant flux layer in which the profile measurements are made, 2. the lack of, or allowance for, the effects of thermal stability, 3. precise knowledge of heights of wind measurements, and 4. the existence of steady state conditions for wind and waves. Lack of fulfillment of any or all of these assumptions may lead to inconsistent results in estimation of momentum flux.

Miles (1957) suggested a means of momentum transfer in the region near wave crests other than by horizontal shear stresses. In his model, energy is extracted from the air flow at a height above the water surface where the mean speed equals the phase speed of the wave. Because there is normally a broad spectrum of wave speeds, the region of influence is a zone extending up to the level at which the mean wind speed equals the speed of the fastest component of the wave spectrum. The height at which the energy transfer occurs is called the "critical height." In the case of a broad wave spectrum, it becomes a layer the upper boundary of which could be considered the critical height. Hereafter, the critical height is so defined.

As pointed out by Stewart (1961), the Miles model requires a zone below the height at which the mean wind speed equals the fastest wave speed and in which the turbulent shear stress may decrease as the surface is approached. Thus, the assumption of constant momentum flux is not valid throughout this layer and the mean wind speed should not be expected to be a logarithmic function of height.

If the Miles hypothesis is valid and a zone exists where the shearing stress is not constant, then inconsistencies in computed drag coefficients may be expected when one or more of the wind speed measurements is made in this zone. If the wind speeds at all measurement heights are greater than the fastest component of the wave speed, the momentum transport may be expected to be constant and the wind profile should be logarithmic under conditions of neutral stability. Drag coefficients computed from wind measurements in this region may be expected to show a consistent relationship to wind speed at a given height but it remains to be shown that they are uniquely related to wave characteristics.

The influence of stability on the wind speed profile has been extensively studied for cases of flow over solid terrain. Much of this work is summarized by Deacon (1962). A stability parameter usually is included in the generalized formula for the wind profile to account for the turbulent heat flux. Determination of the stability parameter is difficult, particularly if the temperature profile is not measured. In a recent contribution Swinbank (1964) developed a general expression for the wind profile with only the Obukhov length as a stability parameter. His model permits computation of the friction velocity, in the presence of thermal influences, from wind speed measurements at three levels.

Computation of drag coefficients from measurements of wind require the determination of friction velocity unless the shearing stress is measured directly. The latter has been accomplished in only a few cases. Unless wind measurements are available from more than two heights, it is usually assumed that the profile is logarithmic to obtain a friction velocity. The lack of consideration of thermal influences on the wind profile may, therefore, contribute to erroneous values of drag coefficient determined from many experimental measurement programs.

Wind measurements from which drag coefficients are derived usually are made from fixed towers, floating spars, or ships where the height of instrument exposure is either fixed or changing in response to only the long waves. The height of the measurements with reference to even the mean water level is not exactly known and wave characteristics often are not measured. Steadiness of wind and wave conditions can usually be inferred if both records are available but may not be considered in some experiments. These two factors may also contribute to erroneous relationships in wind profile determinations of drag coefficients.

3.2 Wind Profile Analysis

In August 1964, several periods of observational data that included wind and temperature profiles and analog records of wave heights were obtained at the Lake Michigan Research Tower. The data and a description of instrumentation are included in a previous report. Periods of data were selected for each of three categories: (a) wind speed greater than, (b) equal to, and (c) less than the speed of the predominant waves.

The wind speed profiles, obtained from measurements at 2, 4, 8, and 16 meters with reference to mean water level, were processed to obtain a drag coefficient based on 10 meter wind speeds where the drag coefficient is defined as

$$C_{10} = \left(\frac{U_*}{U_{10}}\right)^2$$

Here U_* is the friction velocity and U_{10} the mean wind speed at 10 meters.

Thermal stratification was significant in some of the cases so that a stability parameter was included to account for buoyancy effects in the wind profile. Wind speeds were measured at four levels so that the Swinbank method of stability parameter determination could be applied. The expression relating the wind speed ratio to the stability parameter (often termed the Obukhov length), L, as given by Swinbank (1964) is

$$\frac{U_{16} - U_2}{U_8 - U_2} = \frac{\ln\left[\dfrac{\exp(\frac{16}{L}) - 1}{\exp(\frac{2}{L}) - 1}\right]}{\ln\left[\dfrac{\exp\frac{8}{L} - 1}{\exp\frac{2}{L} - 1}\right]}$$

Here U_{16}, U_8, and U_2 are the mean wind speeds at 16, 8, and 2 meters. L is the stability parameter and is determined by graphical solution for the various combinations of the wind speed ratio. After determination of L, U_* is determined by the relationship as given by Swinbank,

$$U_8 - U_2 = \frac{U_*}{k} \ln\left[\frac{\exp(\frac{8}{L}) - 1}{\exp(\frac{2}{L}) - 1}\right]$$

where K is von Karman's constant = 0.4. The friction velocity and drag coefficients were computed for each of the wind profiles obtained from an average of about 30 minutes of wind measurements. The results are included in Table II.

3.3 Wave Analysis

Wave heights were measured by a pressure sensor immersed to about three meters below mean water level. Data were recorded as a continuous analog record on magnetic tape. Periods of data were selected near the times for which drag coefficients had been computed and were analyzed by the U. S. Army, Coastal Engineering Research Laboratory to obtain the spectra of wave heights. The

TABLE II

FRICTION VELOCITY, DRAG COEFFICIENTS, WAVE SPEED AND ROUTHNESS LENGTH - AUGUST 1964

Date/Time	U_{10}(cm/sec^{-1})	U_*(cm/sec^{-1})	C_{D10} x 10^{-4}	Wave Speed(cm/sec)	Roughness Lengths, Z_o(cm)
8/2 1802	424	8.8	44.3		4.1 x 10^{-6}
8/2 1838	491	17.5	12.8		1.5 x 10^{-2}
8/2 1920	486	16.2	11.1	622	6.3 x 10^{-3}
8/2 1956	531	20.7	15.2		3.7 x 10^{-2}
8/2 2026	529	17.4	10.8		5.5 x 10^{-3}
8/3 1124	321	5.6	3.2		9.2 x 10^{-7}
8/3 1200	362	6.5	3.2	653	1.5 x 10^{-6}
8/3 1700	699	16.7	5.7		5.6 x 10^{-5}
8/3 1736	619	15.1	6.0	528	7.6 x 10^{-5}
8/5 1212	718	17.1	5.7		5.1 x 10^{-5}
8/5 1242	772	23.4	9.2		1.9 x 10^{-3}
8/5 1318	800	23.4	8.6		1.3 x 10^{-3}
8/5 1354	888	23.1	6.8		2.1 x 10^{-4}
8/5 1430	867	25.4	8.4		1.0 x 10^{-3}
8/5 1506	928	36.1	9.5	544	3.4 x 10^{-2}
8/7 0800	598	15.8	7.0		2.5 x 10^{-4}
8/7 0842	541	19.2	12.6	715	1.3 x 10^{-2}
8/7 1736	768	23.2	9.1		1.9 x 10^{-3}
8/7 1806	782	28.5	13.3	684	1.8 x 10^{-2}
8/8 1200	1118	34.2	9.5	809	2.1 x 10^{-3}
8/8 1230	1200	36.6	9.3		2.1 x 10^{-3}
8/8 2030	55	3.0	30.3	809	6.7 x 10^{-1}
8/9 1200	508	20.4	16.2		5.0 x 10^{-2}
8/9 1230	518	20.6	16.0		4.1 x 10^{-2}
8/9 1700	393	19.2	23.9	840	2.7 x 10^{-1}

method of analysis has been described by Caldwell and Williams (1961). This analysis provides an estimate of the spectral distribution of wave height averaged over a 20-minute period. Peak heights occurring within the period of averaging are also provided. The height spectra were then corrected for the frequency-dependent, depth attenuation of wave amplitude.

The period and height corresponding to the maximum of each wave spectrum was determined from the spectral analysis. Peak heights were also determined. Phase speed of the dominant waves was calculated using the relationship

$$C = \frac{gT}{2\pi}$$

where C = phase speed
g = acceleration of gravity
T = wave period.

The height of the wave crests above mean level is desired for comparison with the wind profiles. As an approximation, this value is taken as one half the wave height and is called the wave amplitude. The average amplitude of dominant waves, amplitude of peak waves and phase speed of the dominant waves are included in Table III.

TABLE III

WAVE CHARACTERISTICS, AUGUST 1964

DATE/TIME	AVERAGE WAVE AMPLITUDE (cm)	PEAK WAVE AMPLITUDE (cm)	PHASE SPEED (cm/sec^{-1})
8/2 1900	5.5	25	622
8/3 1200	7.7	18	653
8/3 1730	6.2	19	528
8/5 1500	9.1	31	544
8/7 0830	10.3	42	715
8/7 1800	6.1	22	684
8/8 0810	15.0	53	684
8/8 1210	13.3	50	809
8/8 2030	3.4	11	809
8/9 1730	1.6	4	840

3.4 Results

A graph of drag coefficient vs. 10 meter wind speed is shown in Figure 5. The data have been divided into the three categories as described above. The speed of the dominant waves, without regard to direction, was compared to the wind speed. Cases where the two-meter wind speed exceeds the wave speed are entered as "+", those where the wave speed equals the wind speed at some point on the profile as "=", and those where wave speed exceeds the wind speed at 16 meters as "-" on Figure 5. For comparison, the results of several previous investigations are shown on the Figure.

From the limited number of cases considered, it appears that when the wind profile measurements are made well above the "critical height," as defined by the Miles hypothesis, drag coefficients have a general agreement with the findings of Sheppard (1963) and Portman (1959). When the wave speed equals approximately the wind speed, the drag coefficients show a wide range of scatter. When the wave speeds exceed the wind speed the results are indefinite due to the few cases considered.

It should be noted that the first case is one of active wave generation. The wind exceeds the wave speed near the wave crests and wave growth is rapid. The second case is during diminishing wind or wind having blown for several hours so that long, fast-moving waves have developed. The third case is one where the waves consist of swell remaining from previous wind and may actually be a wave-driven wind as studied by Harris (1965). The results herein reported are based on a small number of cases and with no documentation of wave direction relative to wind direction. They, therefore, must be considered tentative. Confirmation of these findings must come from analysis of more data covering a wider range of conditions.

3.5 Wind Profiles in Relation to Wave Amplitude

In cases of air flow over fixed surfaces in the absence of thermal influences, the wind profile is found by experiment to depend upon a length which is characteristic of the surface roughness. For this case, the profile is closely defined by

$$\frac{\overline{U}}{U_*} = \frac{1}{k} \ln \frac{Z}{Z_o}$$

where Z_o, the roughness length or dynamic roughness, is generally about an order of magnitude smaller than the physical roughness elements. The roughness length is interpreted physically as the point at which velocity becomes zero. Here, the roughness elements have no mean movement so that the velocity equals that of the roughness elements.

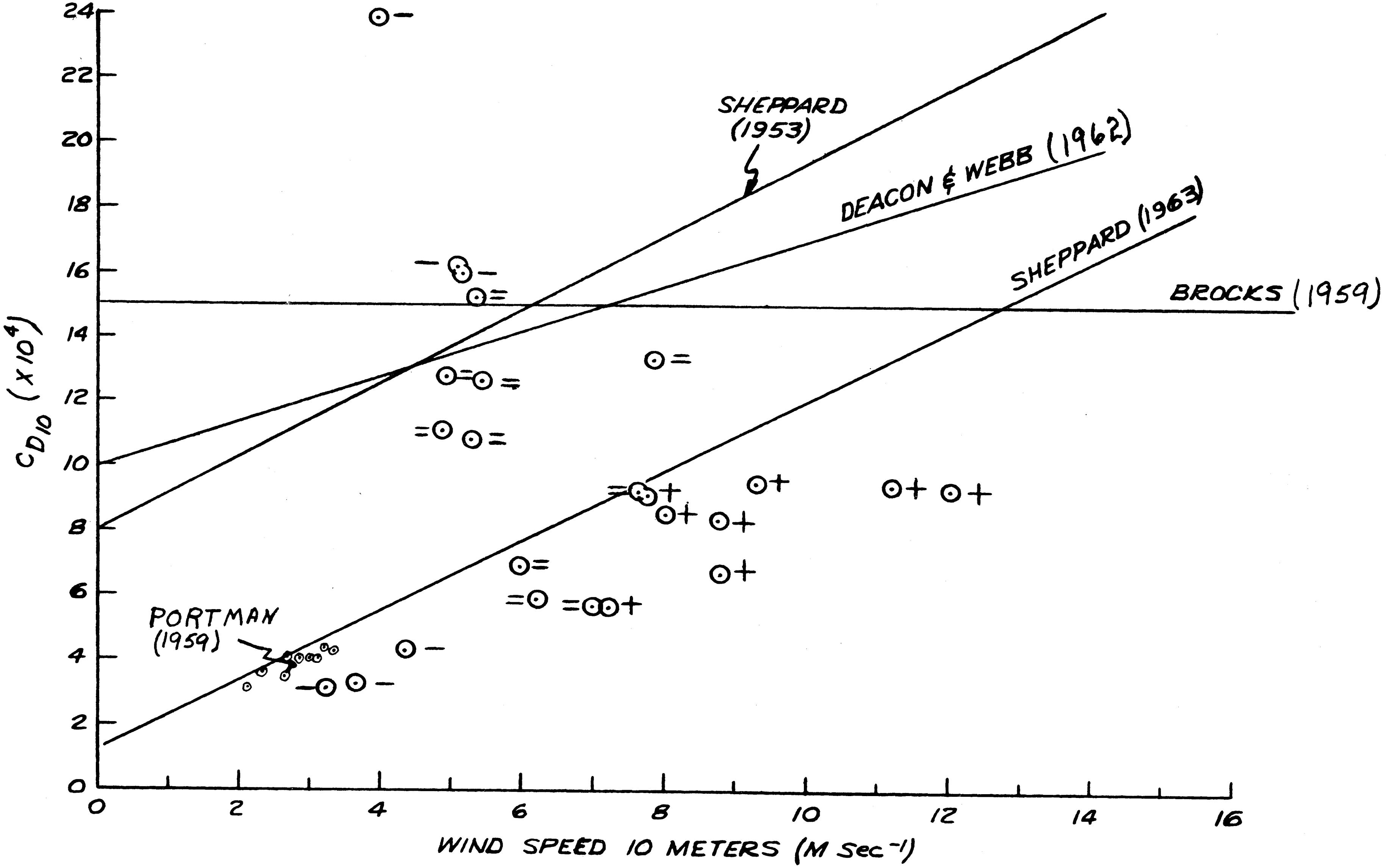

Figure 5. Drag Coefficient vs 10 Meter Wind Speed

In the case of wind blowing over water, the waves constitute the roughness elements although, according to Stewart (1961), the portion of the wave spectrum contributing the dominant drag has not been established. If the analogy can be made to flow over the land, one would expect values of the dynamic roughness derived from wind profiles to be related to the wave heights. However, attempts to relate the two factors have led to a wide disagreement as shown by Roll (1965). The values obtained, such as those shown in Table II, are usually several orders of magnitude smaller than the wave amplitude.

If it is assumed that some portion of the wave spectrum actually constitutes the roughness elements that result in drag, then it would seem that the wind profile should be related to the movement of these wave elements and not to a fixed reference. Thus, if a profile of wind speed with reference to the wave speed were considered, a roughness length related to wave height might result.

To investigate the relation of the wind profile (relative to wave speed) to the wave heights, several cases were selected from August 1964 when profiles and wave height spectra were available. The dominant waves were selected and the wave speeds computed as in the previous section. As before, no measure of wave direction was available. The cases were divided, as above, into categories where the dominant wave speeds were greater than, equal to, or less than the wind speed on the wind profile. Values of wind speed were converted to wind speed less the dominant wave speed.

Figures 6, 7, and 8 show the profiles of relative wind speed plotted vs. height above mean water level. The three cases might be considered separately. The cases where the wave speed exceeds or equals the wind speed below the 16 meter tower height cannot be used to determine a roughness length. In these cases, the wind profile, if determined by the wave roughness, could be related to a portion of the spectrum other than the dominant waves since the relative speed is negative with respect to these waves. As stated above, the processes discussed by Harris (1965) may be significant in this case.

The three cases where the wind speed exceeds the wave speed at a level very near the wave crests are of primary interest. Here the values of (U-C) are positive. The profile on August 5 is nearly logarithmic while the two cases on August 8 show curvature. The profile curvature is evidence that factors other than the shearing stresses have influenced the wind profile and logarithmic law stated above may not be rigorously applied to determine parameters such as the dynamic roughness. However, by using the values of friction velocity derived in the previous section, approximate values of the roughness length can be computed.

The mean wind speed at 10 meters relative to the dominant wave speed were used with the friction velocity previously

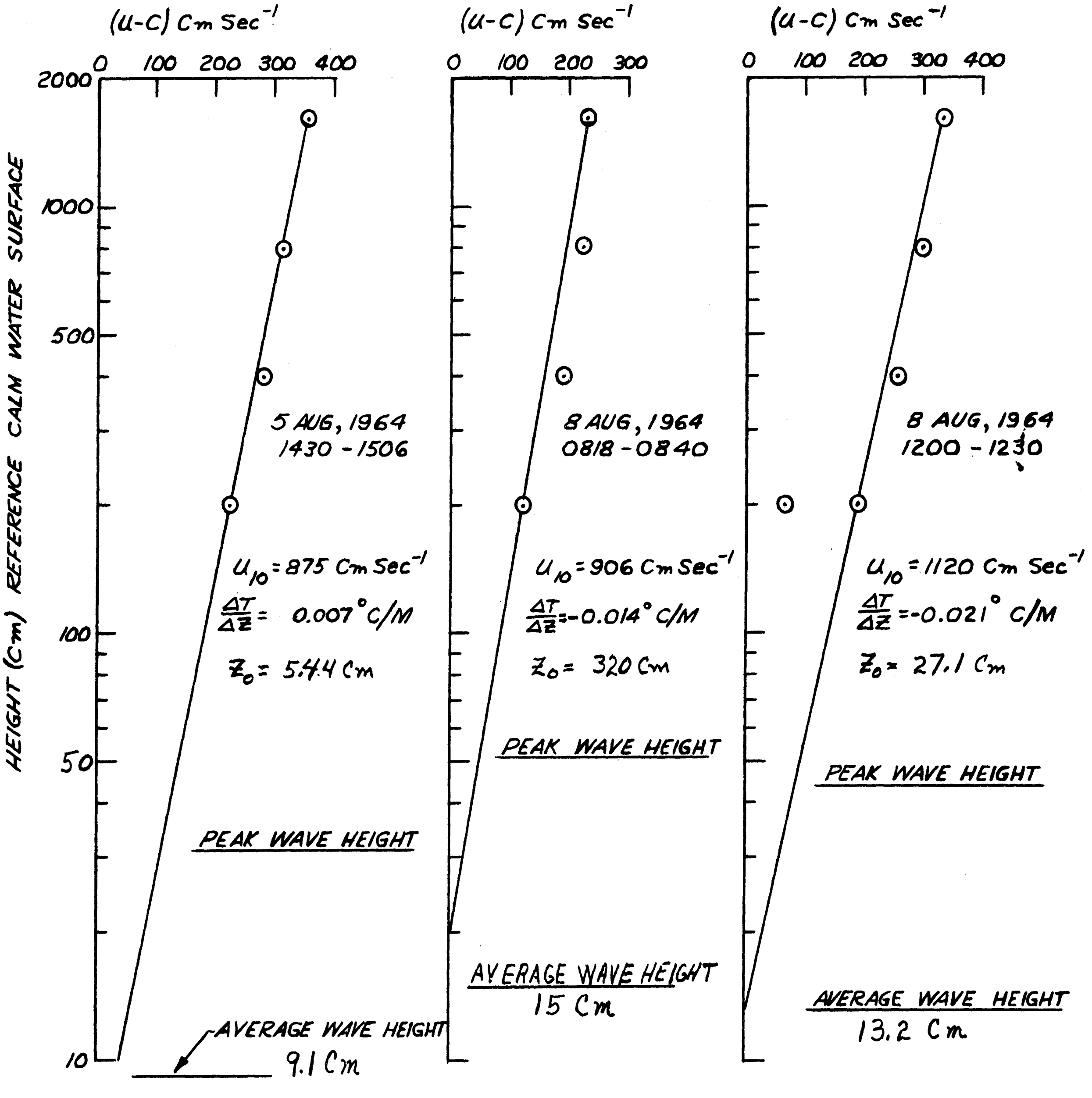

Figure 6. Wind Profiles; Wind Speed Greater than Wave Speed

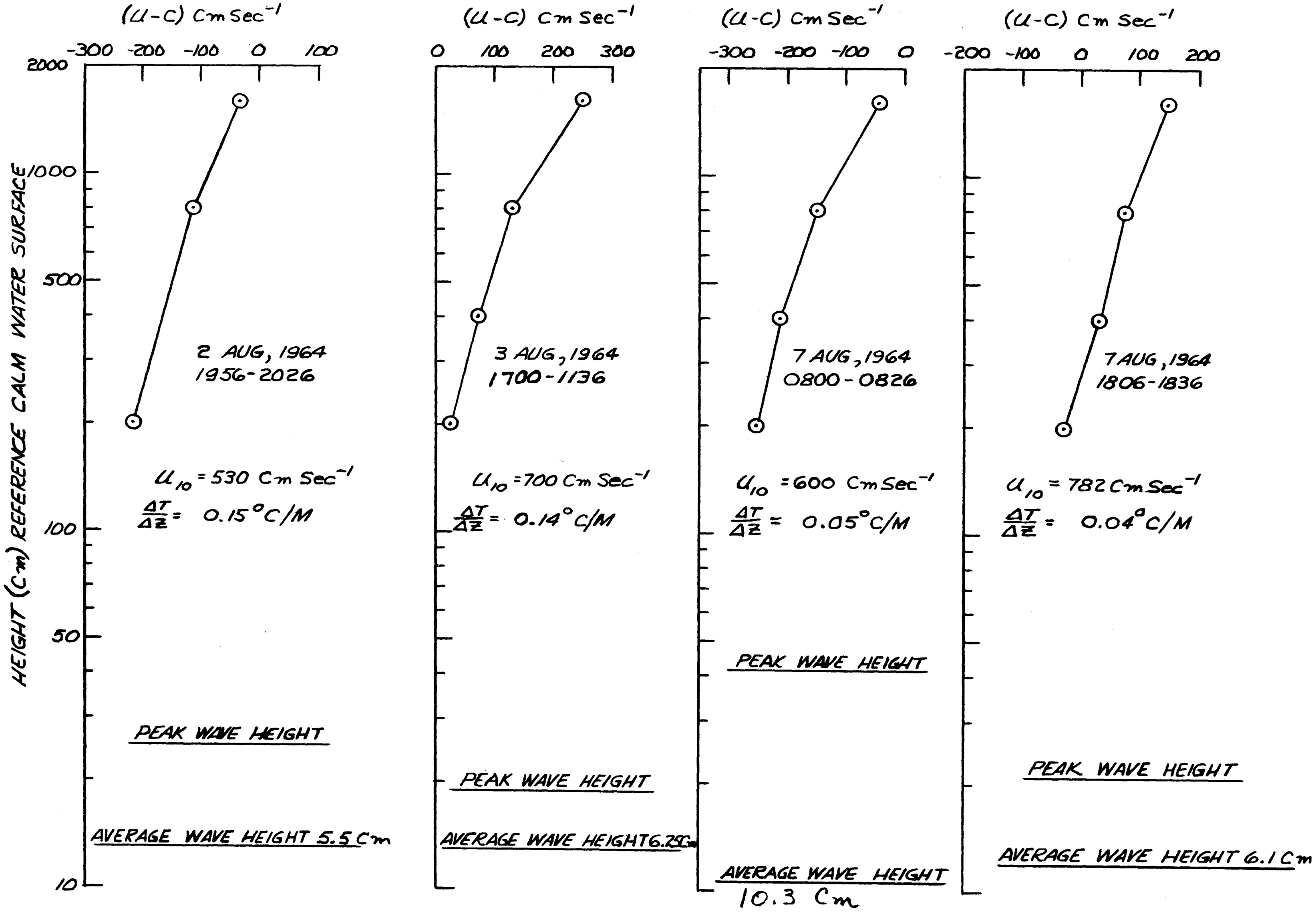

Figure 7. Wind Profiles; Wind Speed Equal to Wave Speed

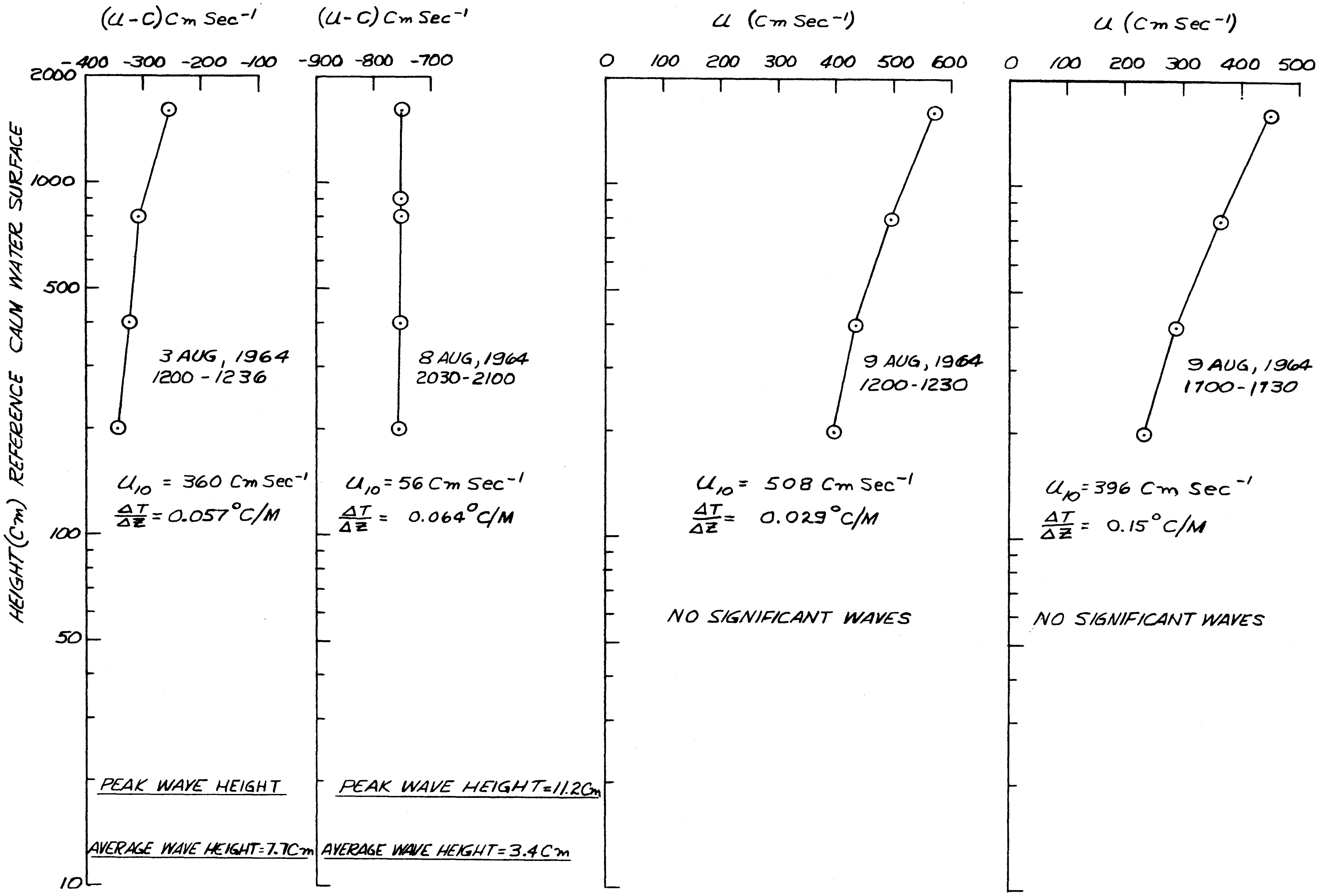

Figure 8. Wind Profiles; Wind Speed Less than Wave Speed

determined to compute a roughness length from a logarithmic profile assumption. The values, as computed, are entered on Figure 6.

It is seen that the value for 1430, August 5, is within a factor of two of the amplitude of the dominant wave. The very strong curvature in the 0818, August 8, profile caused the computed friction velocity to be large and results in a very large roughness length. In the 1200, August 8, case, the curvature is less pronounced and the computed value is again within a factor of two of the average wave amplitude. It may be noted that if only the 16 and 2 meter wind speed measurements are considered on 0818, August 8, the roughness length would be 11.9 cm, a value near the wave amplitude.

The few cases considered cannot give clear evidence of an existing relationship. The three cases of active wave generation do appear to indicate a relation between wave amplitude and a roughness length when the wind is considered relative to the moving waves. The relationship will, of course, depend upon which portion of the wave spectrum is used to compute the relative velocity. The approximate factor of two obtained here may be contrasted to the values obtained when wind speeds are considered relative to a fixed surface as entered in Table II. Many more cases must be examined to determine if the observed relationship is valid.

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