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HEAT FLUX AND SURFACE STRESS ON AND NEAR AN ISLAND
IN THE TRADE WIND REGION

Report No. 1

Contract No. DA-36-039 SC 90784
DA Task No. 3A99-27-005-09

First Semi-Annual Progress Report

June 5-December 5, 1962

Prepared for:

U. S. Army Electronics Research and Development Laboratory
Fort Monmouth, New Jersey

Woods Hole Oceanographic Institution
Woods Hole, Massachusetts

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OBJECTIVE

- a. To elucidate the effect of sea surface conditions on the vertical flux of heat and momentum.
- b. To establish relationships between a variable irradiation, heat flux and land surface temperatures.

Prepared by: E. B. Kraus

Woods Hole Oceanographic Institution
Woods Hole, Massachusetts

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PURPOSE

The purpose of this investigation has been stated already under the heading of "Objective" on the title page. It is believed that this objective could be pursued effectively through careful instrumental observations on and near a flat island across the trade wind current.

In particular it is proposed to compare the vertical fluxes on the windward side where waves should have had a fetch of several hundred miles at least, with the fluxes across the much smoother sea surface on the sheltered leeward side.

The controlled steady state conditions that are expected from our experimental site could also help in the pursuit of the second objective which is to relate the vertical heat flux and the surface temperature at different distances from the shore line to irradiation, soil characteristics and the characteristics of the air stream over the open sea.

The present program is closely related to two other projects. Dr. Zeigler of this Institution and a group which studies the under-water movement of sand near ocean beaches require information on the wave spectrum outside the breaking zone which will be observed under the present program. In turn, we hope to gain from their observations close in shore. These technical advantages, as well as logistic consideration, made co-operation desirable. The selection of a field observation site was therefore governed by considerations relating to both projects.

Mr. Earlston Doe of the Bedford Institute of Oceanography, Halifax, Nova Scotia, developed equipment to measure the flux of momentum directly. He intends to participate in our field work with his equipment and this should be of mutual advantage.

ABSTRACT

The present report deals with the work actually carried out under this contract during the months June to November, 1962.

Following a brief theoretical introduction, instrumental specifications, developments and selections as well as the determination of a suitable operation site are described.

PUBLICATIONS AND CONFERENCES

On May 10 and 11, 1962, Dr. Eric B. Kraus attended the Tropical Research Planning Conference held at Asbury Park, N.J., under sponsorship of the U. S. Army Signal Research and Development Laboratory.

On August 7 and 8 and August 9, 1962, Mr. Robert Heinmiller attended the Conference on Low Level Winds held at El Paso and Dallas, Texas, respectively, under sponsorship of the U. S. Army Signal Missile Support Agency and the American Meteorological Society.

FACTUAL DATA

1. Theoretical Introduction

It is proposed in the first instance to use the Monin and Obukhov¹ approach to the study of the vertical fluxes. This theory gives the following relationship between the wind profile, the stress, and the heat flux.

$$\frac{\partial U}{\partial z} = \frac{U_*}{kz} \left(1 + \alpha \frac{z}{L} \right) \quad (1)$$

with

$$L = - \frac{U_*^3 c_p \rho T}{k g H} \quad (2)$$

and

$$\rho U_*^2 = \tau$$

U = wind velocity

U_* = friction velocity

c_p = specific heat at constant pressure

ρ = air density

T = air temperature

τ = stress

H = vertical heat flux

g = gravitational constant

k = von Karman's constant (0.4)

α = Monin-Obukov constant (0.6)

¹ Monin, A.S., and Obukhov, A.M., Works of the Geophysical Institute Acad. Sci., U.S.S.R., No. 24, 151 (1954).

A modified version of the Monin-Obukhov profile has been given by Swinbank².

It has the form

$$\frac{\partial u}{\partial z} = \frac{u_*}{kL} \left(1 - e^{-\frac{z}{L}}\right)^{-1} \quad (3)$$

Equations (1) or (3) can be readily integrated with height. If the mean wind velocity u is observed on at least 3 levels we can solve the integrated equation together with (2) for u_* and H . In theory at least, this should make it possible to determine the stress and the heat flux from observations of the wind profile alone.

Similarity considerations permit us to write up equivalent equations for the temperature profiles. They have the form

$$\rho c_p \frac{\partial T}{\partial z} = \frac{H}{u_* k z} \left(1 + \alpha \frac{z}{L}\right)$$

or

$$\rho c_p \frac{\partial T}{\partial z} = \frac{H}{u_* k L} \left(1 - e^{-\frac{z}{L}}\right)^{-1}$$

in the Swinbank version. Integration of the last two equations and observations of the mean temperature on at least three levels, should permit a second determination of the stress and of the heat flux without any recourse to wind observations. The two determinations of the two fluxes could then serve as a check upon each other.

The approach involves the assumption of similarity between the temperature and the wind profiles. This is probably justified. More dubious may be the fact, that the whole theory of profiles and vertical fluxes has

² Swinbank, W.C., "Wind Profile in Thermally Stratified Flow". Nature, Vol. 186, No. 4723, pp. 463-464 (1960).

been derived from the observation of flow over rough, solid surfaces. It is by no means sure that the same consideration is applicable to the movable air-sea interface. If it was found, that the flux determinations from the wind profile and from the temperature profile do not tally with each other it would have to be concluded, either that our observations are not sensitive enough or that the existing theory is not applicable. If the latter was found to be the case it would be disappointing, but it would still be a result of value at this stage, because of the wide spread use of profile equations in air-sea interaction studies.

2. Instrumentation

a) General Requirements

For the first objective it will be necessary to establish two buoys on the windward and leeward side of the selected island. These will have to be in water sufficiently deep to avoid bottom effects. On the windward side this will require probably a site with the depth of at least 100 fathoms, possibly more. The site has to be sufficiently distant from the shore to avoid significant effects from refracted or reflected waves. The buoys will be designed to provide a stable platform. They will be tightly tethered with floatation entirely below the water surface. Design and construction of the buoys will be described fully in the next semi-annual report.

Each buoy is planned to carry a 50-foot instrument mast. This will be used to record temperature and wind velocity at four levels. Provisions are made further on each buoy to measure wind direction (at one level), instantaneous wave height (that is, the instantaneous distance of the sensors from the sea surface) and water surface temperature. For the second objective

it will be necessary to measure the temperature profile and the wind profile at several sites on the selected island. It will also be necessary to measure irradiation and to determine soil conductivity.

b) The Recording System and Instrumental Specifications

In order to facilitate the interpretation of the various observation required for this project, it was decided from the beginning to record the output of all the different instruments in a way which would be basically similar and which could be processed automatically.

It requires a high degree of accuracy to measure over sea the deviations of the actual wind and temperature profiles from the logarithmic profile. The following tabulation shows the specifications that were laid down before instrumental development was started.

Table 1

Preliminary Specifications

Recording System

The instruments will be grouped on instrument masts or buoys. Each grouping will include 4-5 anemometers, 1 wind vane, 5-6 thermometers. Recording for each group of instruments should be within the same weather and water proofed housing. The records should be in a form which permits automatic processing. Provision for later change to telemetering would be desirable.

Instrument installations should be capable of 7 days unattended operation.

Anemometers

1. Range of survival	to 25 m/sec
2. Range of operation	2-15 m/sec
3. Sensitivity	0.5% of range
4. Linearity	1%
5. Time constant	1 sec
	(this figure is negotiable)
6. Min. starting speed	0.5 m/sec

The aim of the above specifications is to determine differences of mean wind speeds at different heights at the same locations. The means may cover periods of 15-30 minutes. Accuracy of the mean differences should be ascertainable to the order ± 2 cm/sec.

Thermometers

1. Range of operation
 - a) sea based instruments 10°C
 - b) land based instruments 20°C
2. Center of operational range
 - a) sea based 24°C
 - b) land based 27°C(adjustment to other values should be possible)
3. Sensitivity 0.001 parts of range
4. Linearity 1%
5. Time constant 1 sec

Other specifications to be compatible with those given for 0.001" Diam. Aluminized wire or ultra small aluminized thermistor in Table 2 of article by Ney, Maas & Hutch in Journal of Meteorology 1961, Vol. 18, pp. 60-80.

During summer several recording and sensing systems were considered. It was decided finally to use for all data a recording system developed originally for maritime current meters by the Geodyne Corporation of Waltham, Massachusetts. The firm undertook an adaption of this recorder for wind and temperature profile measurements. Its adaption as a wave measuring device is being carried out by Mr. Heinmiller of this Institution.

c) The Wind Profile

The Geodyne Wind Recorder, Model A--141, is shown in Figure 1 without its outer water proofed casing. For the present purpose this instrument was modified for multiple anemometer recording at a distance.

The operation of this 6-volt battery powered instrument is as follows. A 16 mm moving film camera, housed in a light-tight waterproof polyvinylchloride case, is focused on a linear array of 18 light pipe ends

(fiber optics) which appear as dark lines on the developed film when they are illuminated. Eight of the pipes are terminated at miniature lamps which are flashed by the four anemometers - two for each anemometer - (once per revolution and once per ten revolutions). Seven are terminated at an optical Gray-Binary encoding disc coupled to the wind vane which records the direction to an accuracy of 3° . One fiber optic channel is a reference signal and one is a read pulse. Both of these facilitate the automatic reading which is done using a Digital Equipment Corp. Programmed Data Processor-1 Computer with a specially-developed reader attachment. This Computer-Reader either puts the record on magnetic or punch paper tape for listing or further processes the data. An example of the type of film record is shown in Figure 2 along with both high-contrast negative and positive prints. The latter is used for reading. This record was obtained from a standard current recorder with one current meter and a compass as well as a vane. Figure 3 shows an example of a histogram plotted by the PDP-1 and photographed from the CRT X-Y Point Plotter output without manual interference.

Digital film recording was chosen not only because it can be processed automatically, but also because it is a rugged reliable method requiring very little power and having very high data packing density. The technique used both in the A-141 Wind Recorder and the Temperature Recorder provides for approximately 10,000 $1/8$ " blocks of data to be recorded on 100 feet of film. Both the duration and the interval between these blocks may be varied. At present, the duration is 5 seconds and recording is continuous. However, an interval timer can provide recording intervals of from one to twelve per hour. Approximately 200 bits per inch along the film may be resolved and

measured in each of the 18 available channels by the Computer-Reader. Hence 200 sets of four anemometer speeds and one vane direction may be recorded on each inch of film.

The anemometer cups used in the modified A-141 Wind Recorder are the three cup assembly Number 170-41 manufactured by Beckman & Whitley of San Carlos, California. This extremely lightweight assembly was chosen not only to meet the requirements for high sensitivity and rapid response, but also because a number of other workers in this laboratory have used them. The initial units, when tested in the MIT Round Hill low-velocity wind tunnel, exhibited however rather higher starting velocities than were thought desirable. Typical values ranged from 2.75 to 3.85 meters/sec. These values were found to be due to unexpected friction in the new miniature instrument ball bearings. After rebuilding, the starting velocities were reduced to a range of from 0.9 to 1.2 m/sec. In the course of tracking down this difficulty, a substantial improvement was made in the switching method. This was changed from a mechanical linkage to magnetically actuated reed switches. These switches have gold-plated contacts sealed in an inert gas and are found to have an operating life in excess of 100×10^6 operations.

A further substantial redesign has recently been completed by Geodyne. This new design is shown in Figure 4. Its starting torque is less than 0.7 m/sec. Operating near the threshold of the wind tunnel, it may in fact be better than we can measure reliably. It is a single spindle dual jewel bearing design with one magnetic reed switch. It requires a transistorized counter within the recorder to extend the recording range from starting speed to above 50 m/sec. It has now been decided to use this

new type of wind sensor for all wind measurement on the present project, not only because it is more sensitive, but also because it is inherently more rugged and completely weatherproof - a desirable feature where measurements are to be made close to the air-sea interface.

As has been mentioned, the A-141 Wind Recorder may be operated either continuously or at preset intervals using a self-contained interval timer. A complete circuit diagram is shown in Drawing A-263, Figure 5.

d) Temperature Profile Measurements

The development of a multiple, digital temperature recorder using again film as the recording medium was also subcontracted to Geodyne Corp. A prototype, now being tested prior to delivery, is shown in Figure 6 and diagrammatically in the Block Diagram Drawing A--292, Figure 7. It uses the ultra-small Veco thermistor in a bridge circuit as the sensing element. As Ney, Maas and Hutch³ point out, the important qualities for an air temperature sensor are its size, shape, heat capacity and the radiation properties of its surface. At sea level, the necessary requirements are met by the Veco unit as shown in the following table which is taken from data in the quoted paper:

Table 2

Thermistor Characteristics

	Standard Thermistor	Ultra-Small Thermistor
Time constant	10 sec	500 m sec
Infra red error	13°C	0.2°C
Sunrise effect	1.9°C	0.3°C

³ Ney, Maas and Hutch, J. of Met., 1961, Vol. 18, p. 60.

The ultra-small Veco thermistor has a bead diameter of 0.010 inches and 0.001 inch diameter platinum iridium leads. In accordance with the manufacturer's recommendations, an extremely thin film of Eastman 910 adhesive is used to insulate the leads which project beyond the glass bead. It is expected that no ventilation or reflective coatings will be necessary for use at sea level, but the validity of this assumption is still to be tested as part of the present investigation.

The temperature recorder automatically sequences five remotely located thermistor probes (there is provision for more) and measures and records in binary form this information in approximately 2.6 seconds. The recorder is the digital film type described in the preceding section and the record is processed and read in exactly the same fashion as the wind profile record using the specially designed PDP-1 Computer-Reader. The operation of this instrument can best be understood by referring to Figure 7. The 50 cycle clock generator controls each step in the operation and provides the bridge supply voltage. There are two counters, A and B. The B-Counter selects and connects the remote thermistors to the bridge. The A-Counter balances the bridge by switching in precision resistors and records this in binary form by switching corresponding lamps which are exposed through a fiber optic array on the film. The binary number is 10 level, therefore giving a precision of 1 part in 1000. Bridge error detection is provided by a unique amplifier design which is clamped during the first, or most unbalanced half of the bridge balance cycle to prevent blocking. To minimize errors due to self heating, the thermistor power dissipation is kept below 10 micro watts.

As in the wind recorder, the temperature recorder may be operated continuously, in which case each set of digital temperature records is spaced along the film for ease in identification, or at preset intervals controlled by the interval timer. Power is provided by specially packaged 12 volt dry batteries housed in the PVC waterproof cases and the complete recorder is similarly contained in a PVC case for complete protection as shown in Figure 6. Electrical inter-connectors are made using cables run through waterproof packing glands.

e) Wave Recorder

A small scale model of a wave recorder which records data digitally in the same form as the wind and temperature recording system has been built and has worked satisfactorily. A full scale model is now being constructed.

A resolution of 2" was chosen for the first model. The gauge in its present form consists of a line of magnetic switches down the center of a stainless steel pipe of two inch diameter. A fiber glass ball containing two permanent magnets surrounds this pipe. This ball floats on the water surface and is able to ride up and down the pipe, actuating one switch at a time. The switches are connected to the light of the recorder through a digital diode matrix which codes the instantaneous position of the floating ball by a binary number.

Routine observations from buoys at the field testing site will be carried out either with this instrument or with a standard resistance wave wire. At the present stage the relative advantages of the two systems have not yet been fully evaluated. The wave wire is more sensitive and has a much quicker response. On the other hand, it is a more delicate instrument

and its power requirements may be prohibitive for use on a buoy. Our digital wave recorder is rugged and has no special power requirements, but its present sensitivity may be insufficient although it can be improved by putting the switches closer together down to a possible limit of $\frac{1}{2}$ inch and by using a smaller float.

3. Selection of an Observational Site

An exploratory flight was carried out to the Caribbean Islands from November 9-24 by the Institution's R4D plane to select a suitable working site. The same island was to be used not only for the present project but also for the observation of sand movements under water. The meteorological requirement called for a small flat island, preferably elongated across the trade wind stream; great wind steadiness with relatively high velocities; low rainfall; facilities to charter boats for the servicing of buoys. The geological requirement called for clear water; beaches of suitable grain size; moderate sand movements close to the shore.

Surface inspections were carried out on the following islands: San Salvador (Watling Island), Grand Turks, St. Kitts, St. Martin, Antigua, Barbados, Aruba, and Curacao.

In addition, beaches and the meteorological possibilities of the following islands were inspected from the air: Eluthera, Cat Island, Mayaguana, Caicos, St. Croix, Anguilla, Barbuda, St. Barts, Guadeloupe, Marie Galante, Dominica, Martinique, St. Lucia, St. Vincent, Canouan, Bequia, Moustique, Mayreau, Union, Carriacore, Ronde, and Bonaire.

The ideal site for further more prolonged investigations has to satisfy not only rather stringent topographic, meteorological and geological specifications, but it should also be of easy access, provide adequate living conditions and some local assistance. An attempt has been made to classify these various aspects in Table 3 for those islands which appeared to us most suitable. Such a classification is of course necessarily subjective and qualitative. It will provide however some ready indication of our findings.

It will be seen from Table 3 that Aruba would be most suitable from the meteorological point of view. Our technical specifications could probably be met equally well in Bonaire, which however was not inspected from the ground. Also there would be no shop facilities available in Bonaire while Aruba is a site of a very large ESSO refinery. Barbuda would be almost as good as the Dutch ABC Islands from the meteorological point of view but living and technical facilities there are poor and there is no good road system on the island. St. Martin is ideal for beach studies. Unfortunately, winds are much less steady there and the island is not suitable topographically for our present meteorological work.

The climate of Aruba is semi-arid. During the period 1931-60 the mean annual rainfall amounted to 17.03 inches with a maximum in November. The mean diurnal amplitude of the dry bulb temperature is less than 2°C and that of the wet bulb temperature less than 0.5°C .

Heavy storms appear to be unknown. In fact, there is no record of any wind velocities above 35 knots or 18 m/sec which is well below the survival specification of our equipment. On the other hand, calm conditions

TABLE 3

CLASSIFICATION OF CARIBBEAN ISLANDS FOR PROJECTED ENERGY TRANSFER
AND SAND MOVEMENT STUDIES

	Aruba	San Salvador	Anguilla	St. Margin	Barbuda	Barbados
Wind steadiness	0	2	1	1	1	1
Mean wind strength	0	1	1	1	1	1
Weather	0	2	1	1	1	2
Topographical suitability	0	0	0	3	0	2
Shape factor (1)	0	0	2	1	0	2
Beach conditions	2	2	0	0	0	3
Beach exposure (2)	0	1	1	0	2	0
Island road network	0	1	1	0	2	0
Local shop facilities	0	0	3	2	3	1
Availability of locally trained observers	0	0 (?)	3	1 (?)	3	1
Availability of charter boats	0	3	1	1	3	0
Living conditions	0	1	2	0	2	0
Living costs	2	0	1	2	2	1
Ease of regular access from Woods Hole	0	0	2	1	3	1
Proximity to probable operational area of W.H.O.I. ships	3	2	0	0	0	0
Aerodrome suitable for B5D	0	0	3	0	3	0

- (1) Size and elongation across trades
 (2) Absence of reefs and obstructions

Symbols: 0 = Excellent
 1 = Good
 2 = Adequate
 3 = Poor or impossible

are also very rare. The extra-ordinary steadiness of the wind in the region is indicated by Table 4 which is based on observations from the neighboring island of Bonaire.

Table 4
Relative Frequency (in 0/00) of Wind Velocity
for Indicated Directions
Kralendijk, Bonaire

Degrees	Calm	Wind Velocity in Knots						Total
		1 - 3	4 - 6	7 - 10	11 - 16	17 - 21	22 - 27	
010	0.4							0.4
020				0.2				0.2
030			0.1					0.1
040			0.4	0.6	2.5	0.2		3.8
050		0.1	0.4	0.8	2.3	0.5	0.1	4.2
060		0.1	0.8	3.0	8.6	2.8	0.1	15.4
070			1.5	6.9	20.8	12.8	0.1	42.1
080		0.1	2.5	20.3	93.9	29.8	1.3	147.9
090		0.4	2.9	16.4	72.6	36.3	2.6	131.2
100		0.2	3.5	28.7	109.1	47.4	5.4	194.3
110		0.5	3.3	35.2	138.8	66.3	4.8	248.9
120		0.4	2.2	14.9	68.8	44.2	6.4	136.9
130		0.2	0.7	3.8	14.9	13.2	4.3	37.1
140		0.2		0.9	6.7	5.4	0.7	13.9
150		0.4	0.2	1.3	6.1	4.7	0.5	13.2
160		0.2	0.8	1.4	1.9	0.6	0.1	5.0
170		0.1	0.6	0.8	0.5	0.2		2.2
180			0.1	0.2				0.3
190				0.2	0.1			0.3
200			0.2	0.1		0.1		0.4
210			0.1		0.2			0.3
220								
230			0.2	0.1				0.3
240		0.1		0.4				0.5
250			0.1	0.1				0.2
260		0.1						0.1
270								
280			0.1	0.1				0.2
290								
300								
310				0.1				0.1
320								
330								
340								
350			0.2					0.2
360		0.1						0.1
Total	0.4	3.2	20.9	136.5	547.9	264.5	26.4	999.8

The daily variations are small as shown in Table 5.

Table 5

Mean Wind Vector at Indicated Times

Kralendijk, Bonaire

Hour (E.S.T.)	00	03	06	09	12	15	18	21
Velocity (Knots)	12.3	12.2	12.2	15.3	15.5	15.0	13.8	13.1
Direction (Degrees)	097	105	105	109	112	102	091	093

Conditions at Aruba are said to be characterized by slightly stronger and even more steady winds than on Bonaire, which is a somewhat wetter island.

PROGRAM FOR NEXT INTERVAL

The coming six months will be used mainly to test the equipment on hand and to learn about its limitations.

It is planned to design or complete the following equipment:

Stable instrument buoys,

Timing devices to establish simultaneity of all records,

Wave Recorders.

Following a test and trial period, additional recorders for wind profile measurements and temperature profile measurements will be ordered, as part of the complete equipment needed for field observations.

PERSONNEL

Dr. E. B. Kraus, Principal Investigator (half-time).

Dr. Kraus is a staff member of the Woods Hole Oceanographic Institution, visiting Professor of Meteorology at Yale University, and Research Associate of the Bingham Oceanographic Laboratory. He moved to the U.S.A. from Australia in 1961.

Robert Heinmiller (full-time).

Mr. Heinmiller graduated in physics at MIT in 1962.

George H. Belt (summer student).

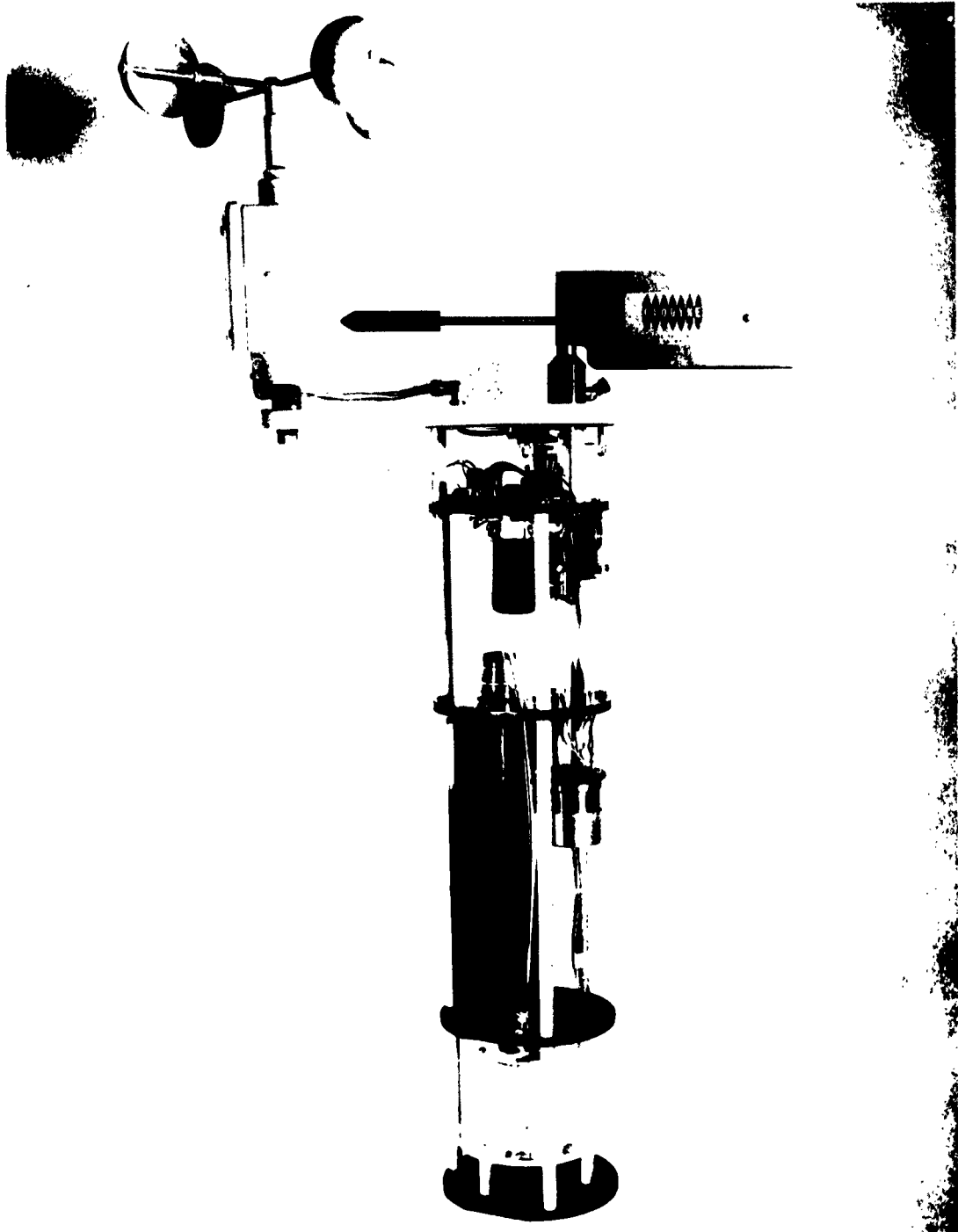


Figure 1 Geodyne Model A-141 Wind Recorder Mechanism

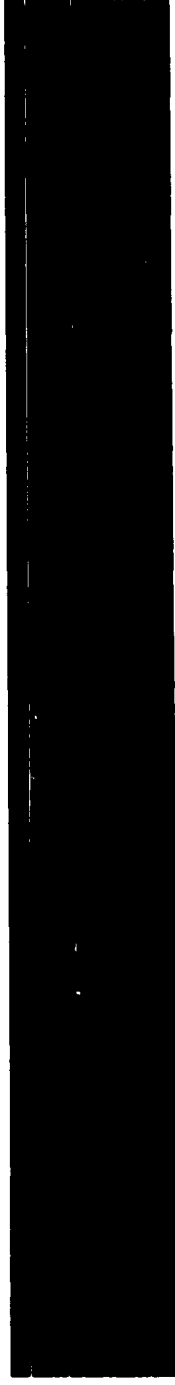
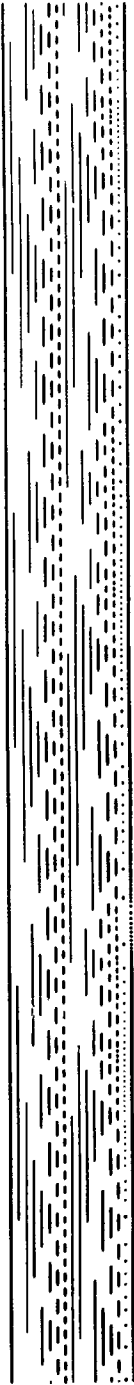


Figure 2 **Section of Digital Film Recorder (top) with High Contrast**
Negative and Positive Prints

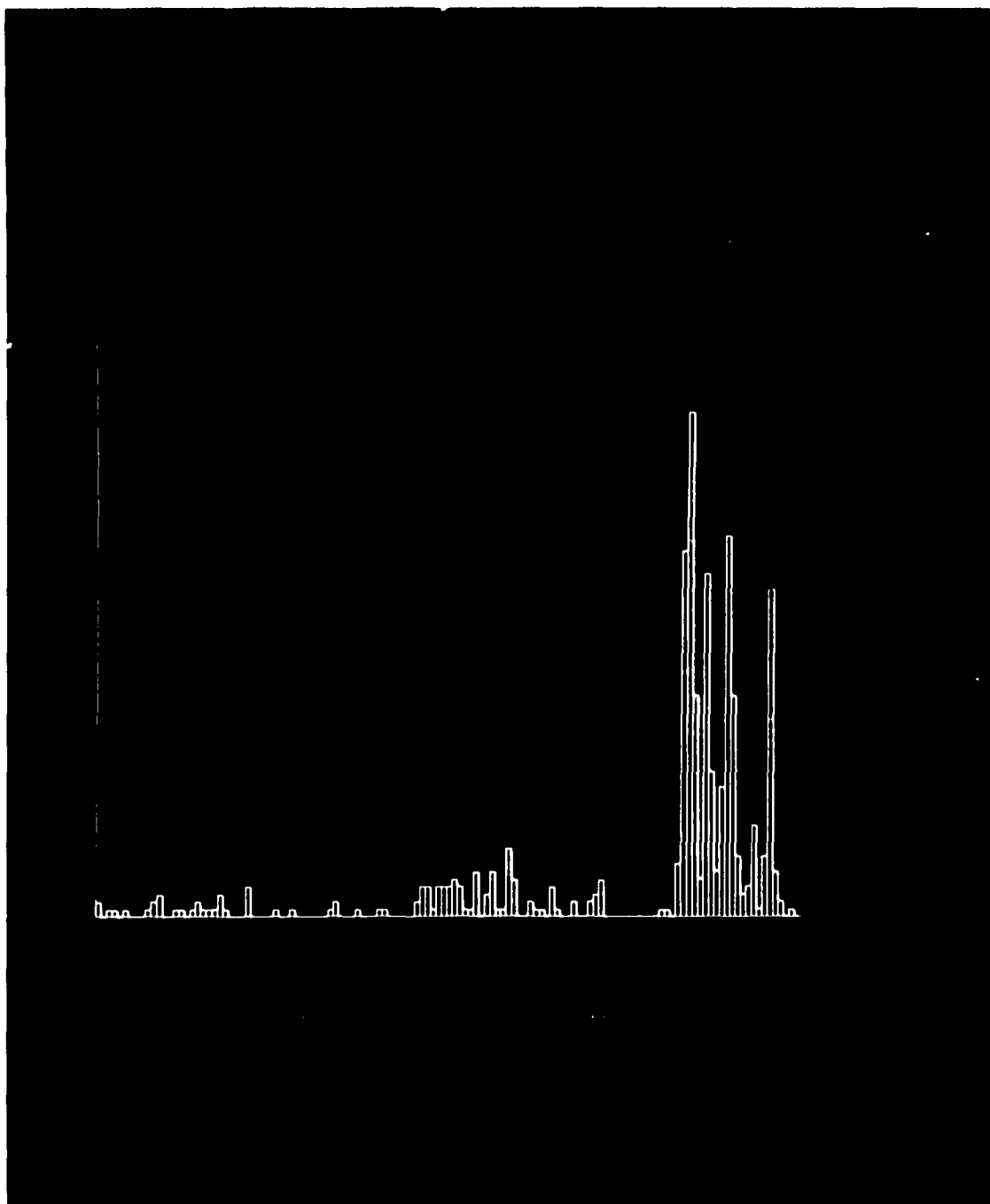


Figure 3 Vane Direction Histogram Plotted by Computer-Reader and
Photographed from CRT X-Y Point Plotter

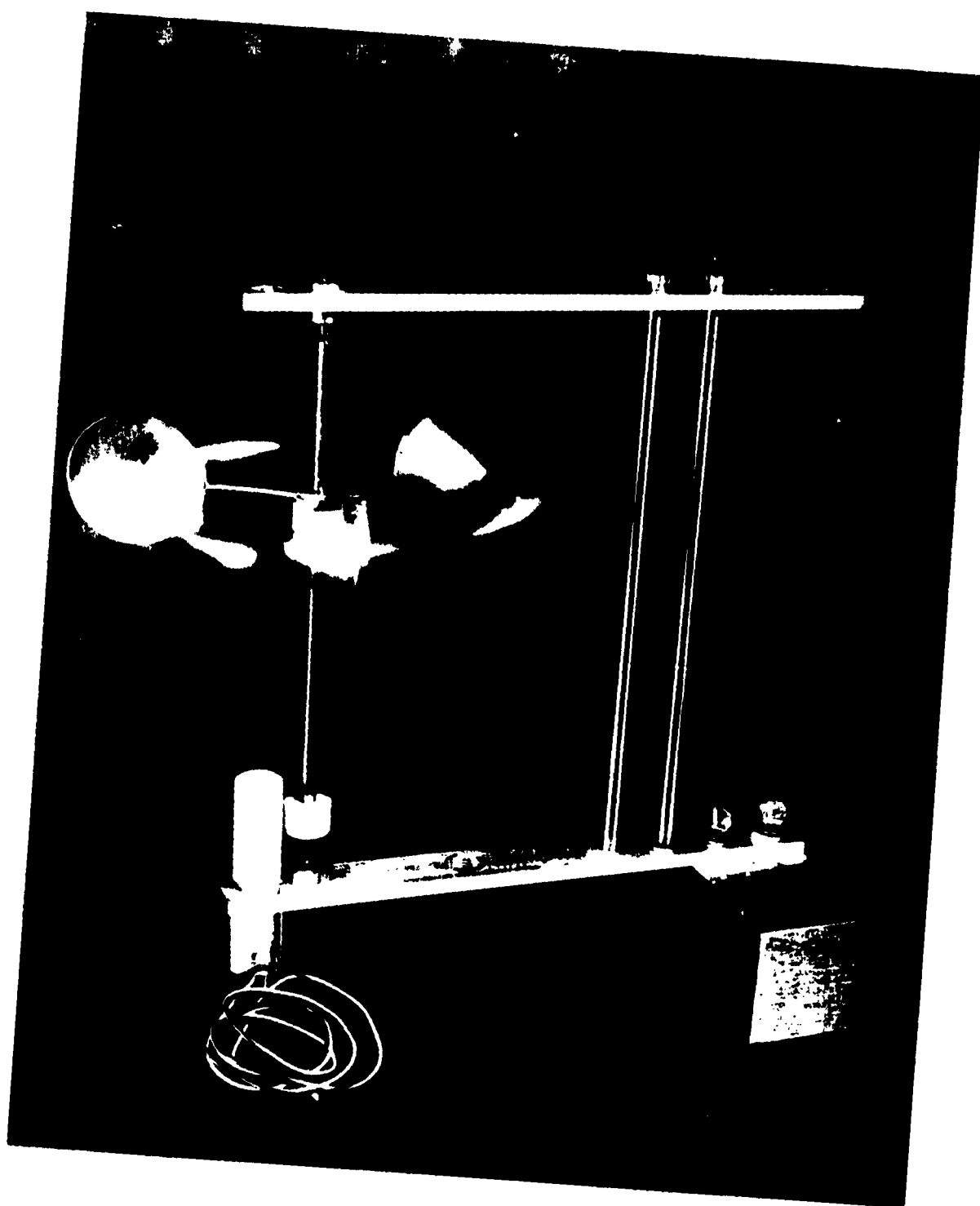


Figure 4
Prototype Sensitive Jewel-Bearing Waterproof Magnetic
Switching Anemometer

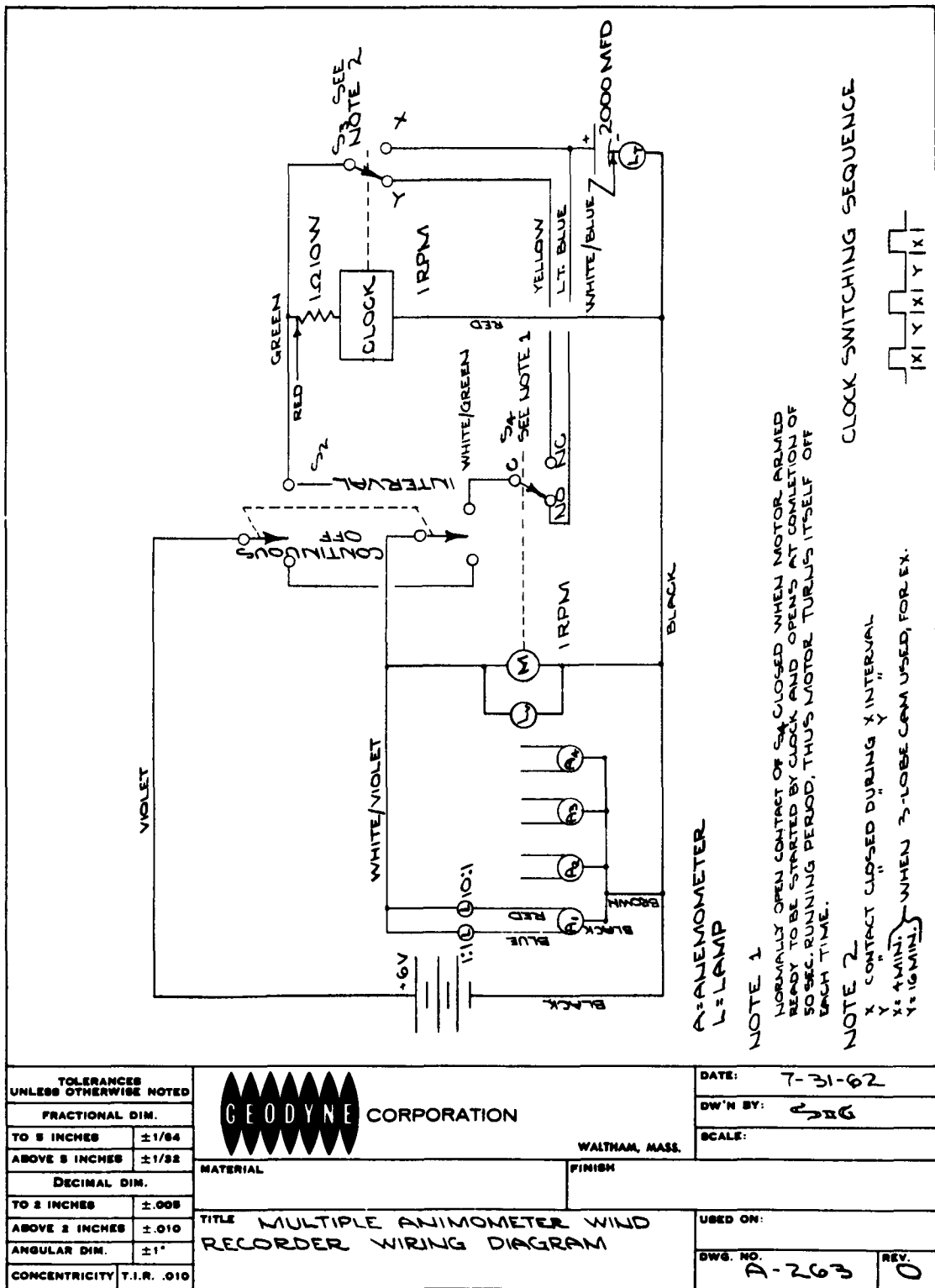


Figure 5 Multiple Anemometer Wind Recorder Circuit Diagram

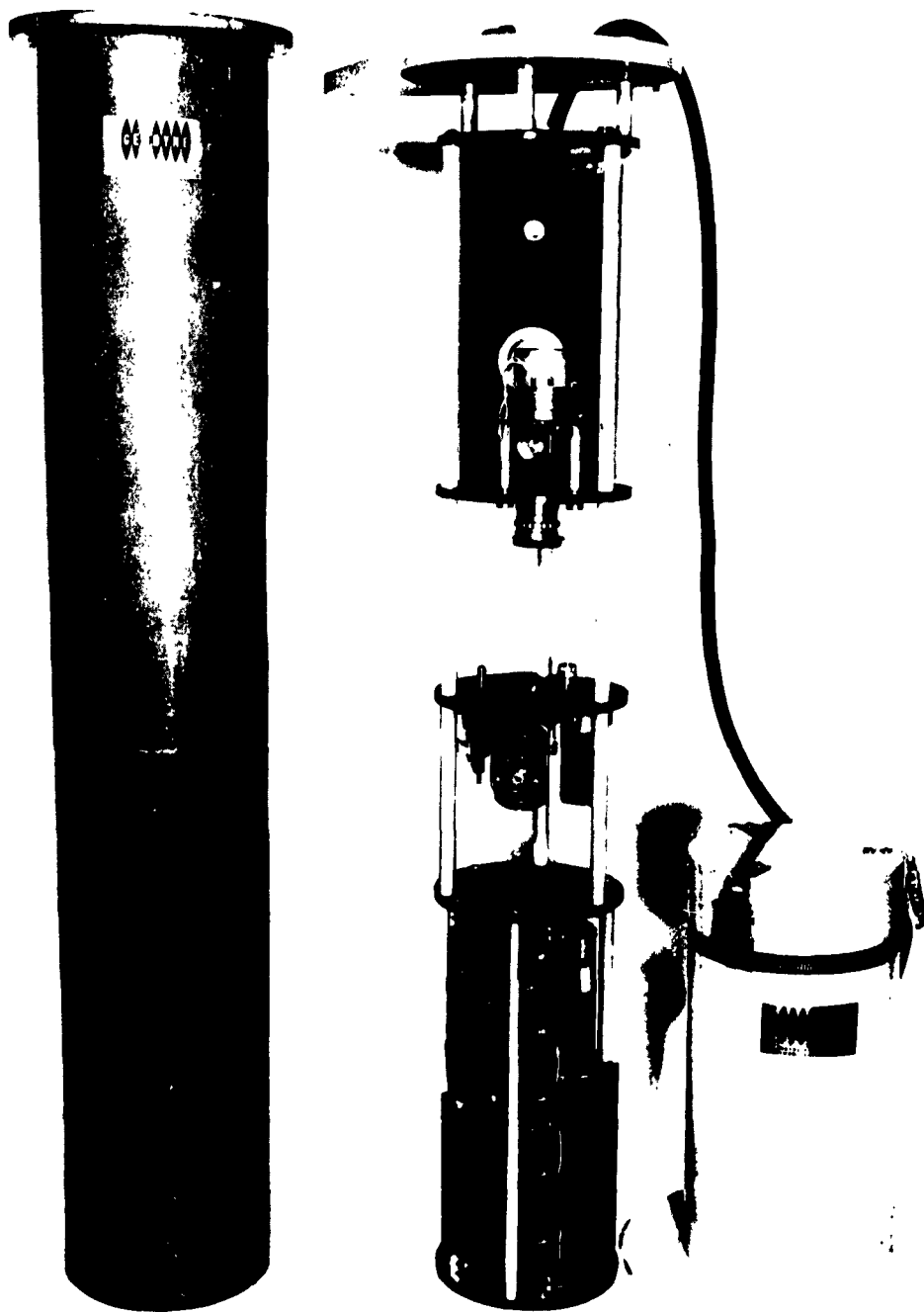


Figure 6 **Geodyne Digital Temperature Sequencer and Recorder Complete with PVC Housing and Battery Case**

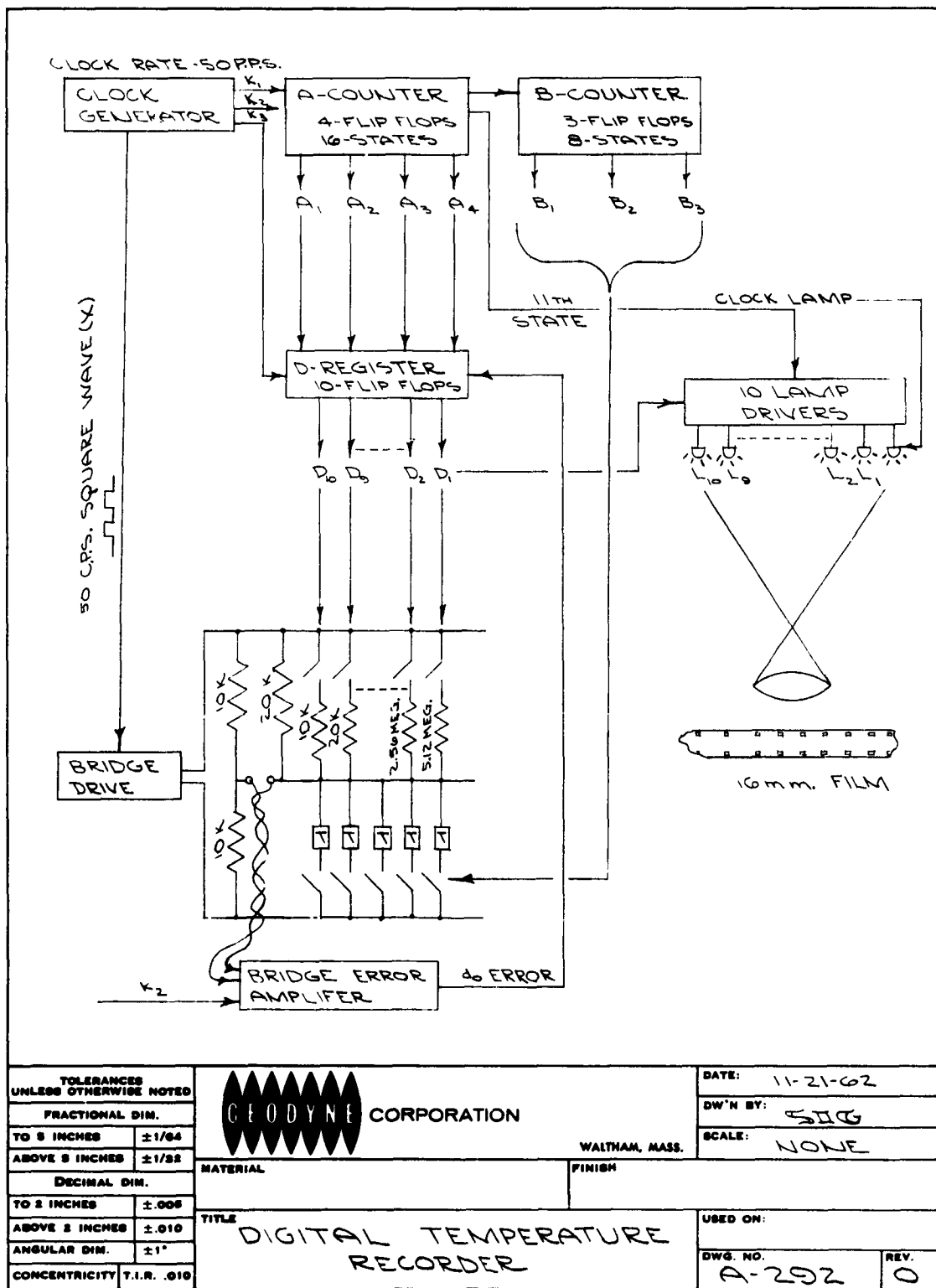


Figure 7

Functional Block Diagram of Digital Temperature Sequencer and Recorder

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