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SOME INSTRUMENTS USED BY DIVISION 10, NDRC AT DUGWAY PROVING GROUND FOR THE CONTINUOUS RECORDING OF MICROMETEOROLOGICAL CONDITIONS

October 1, 1945

by

S. W. Grinnell, Research Associate

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SOME INSTRUMENTS USED BY DIVISION 10, NDRC AT DUGWAY PROVING GROUND FOR THE CONTINUOUS RECORDING OF MICROMETEOROLOGICAL CONDITIONS

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SOME INSTRUMENTS USED BY DIVISION 10, NDRC AT DUGWAY PROVING GROUND FOR THE CONTINUOUS RECORDING OF MICROMETEOROLOGICAL CONDITIONS

By

S. W. Grinnell, Research Associate

Abstract

The problem of designing suitable portable instruments for the recording of micrometeorological data, which is required to supplement chemical sampling results in Chemical Warfare field tests, was encountered by the NDRC Laboratory at Dugway Proving Ground. A consideration of the desirable characteristics for these instruments, as brought out by experience and by helpful discussion with members of the Technical Operations Division, resulted in the design of self-recording instruments for measuring wind speed, wind direction, and temperature gradient by electrical methods. The details and performance of these instruments are discussed so as to enable the consideration and possible construction of similar instruments to be undertaken elsewhere.

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SOME INSTRUMENTS USED BY DIVISION 10, NDRC AT DUGWAY PROVING GROUND FOR THE CONTINUOUS RECORDING OF MICROMETEOROLOGICAL CONDITIONS

I. INTRODUCTION

One of the original objectives of the NDRC Laboratory at Dugway Proving Ground was to study and assess the effect of micrometeorological conditions on the behavior of chemical agents. It soon became apparent that at this station by far the most important contribution to the CWS program could be made by focusing attention on the measurement of the micrometeorological conditions during the actual CWS field trials, and that the effort spent on the development and operation of instruments for this purpose would be highly justified.

The object of this report is to describe the most successful of these instruments, the reasons underlying the choice of their various components, and some details of their operation. The actual records are not discussed, as they have already served their primary purpose of contributing to the data on the field tests and as nothing significant would be added thereby to what is already known about micrometeorological behavior.

During the period over which these instruments were in use, there was not sufficient time nor personnel to carry on an adequate program devoted primarily to micrometeorological research. Such results as were obtained, however, indicate that similar instruments can be of great value in micrometeorological surveys where a large amount of data, continuously varying with time, must be recorded and examined.

The effectiveness of such research, or of the continuation of this part of the general Chemical Warfare program, will be considerably enhanced by careful advance consideration of the instrumental problems; it is especially desirable when standardizing on equipment with certain definite characteristics, that these characteristics be chosen to harmonize with the means and purpose of the investigation. It is not intended in this report to enable the instruments described to be copied without regard to their principles of operation, but rather to aid in decisions as to the proper choice and design of new equipment, and thus increase to some extent the array from which to select the means most suitable for fulfilling the conditions laid down by various micrometeorological problems.

II. PRACTICAL REQUIREMENTS FOR MICROMETEOROLOGICAL EQUIPMENT USED IN CWS FIELD WORK

A. The General Problem

At a proving ground the behaviour of munitions must be evaluated with far greater exactitude than would ever be employed in solving problems under actual combat conditions; a figure of ±20% might well be taken as a desirable (but not necessarily obtainable) over-all accuracy for the assessment of the efficiency of functioning of a chemical munition where the agent is distributed in the form of a cloud.

The usual practice will then be to function the munition in a selected area over which samplers are distributed and to state the effectiveness of the experiment in terms of the quantity of agent indicated by the sampler, usually in terms of either a time-concentration curve or a total dosage.

These chemical sampling results are dependent on the characteristics of the munition, on the influence of the munition and agent on the natural air flow pattern, and on the course of the air flow pattern itself during the experiment. The effect of the latter may ordinarily be stated to a sufficient degree of approximation in terms of a wind speed representative of the area, a representative wind direction, and a representative temperature gradient.

Depending on the stability of the lower layers of the atmosphere, these factors normally vary from instant to instant and from point to point over the target area; in addition it is seldom feasible to place an instrument, and much less an operator, in the vicinity of the center of the target area. Therefore an estimate of the over-all accuracy of the results of the experiment should include information from more than one location on the target, or else a study at one location of the variation of the meteorological factors with time; this will ordinarily be qualitatively similar to the variation with distance.

Over short periods of time, such as the duration of a non-persistent cloud at moderate wind velocities, it will ordinarily be found that the natural fluctuations in the micrometeorological quantities being measured will determine the limits of accuracy, rather than the instrumental accuracy or that of the chemical sampling. In many cases it is desirable to have the micrometeorological records immediately available for rapid inspection directly after the experiment, and to supplement the record with visual notes.

For the above reasons it becomes highly advantageous to have the equipment automatically continuously recording by writing directly in ink on a moving chart already calibrated at least approximately according to the quantity being measured. The system chosen for accomplishing this end consists of self-contained battery-operated portable equipment for translating the quantities being measured into milliamperes, and spring driven Esterline-Angus recording milliammeters (usually 1.0 milliampere full scale) equipped with chronograph side-pens for timing.

Since this system is capable of operating without attention for periods up to a week, there is also considerable economy of man-power where extended measurements are to be made or where the records are to be used for verification of forecasts or in other micrometeorological studies. In addition it has proved useful in measurements on wind profiles, temperature profiles, and gustiness. The rated accuracy of the meters, ± 1% of the full scale value, is sufficiently high for nearly all purposes.

B. Accuracy Requirements for Wind Speed Measurements

The effect of wind speed alone, as reflected by chemical sampling, will be primarily to govern the length of time over which the cloud remains in the vicinity of the sampler; this time will be inversely proportional to the wind velocity. Taking a figure of ± 20% as the desired accuracy limits, this would indicate a desirable accuracy of ± 20% in the wind velocity measurement. At wind velocities above 2 mph this instrumental accuracy is easy to obtain, and to make allowance for other effects of wind velocity, it would be more conservative to set the desirable instrumental accuracy, except for wind profile studies, at ± 5% of the reading and to set the desirable (but not always attainable) figure for the accuracy of the representative wind speed over the target area at ± 10%.

C. Accuracy Requirements for Temperature Gradient Measurements

The influence of temperature gradient on the total dosage indicated by chemical sampling may be taken roughly as a three-fold effect for a variation in temperature gradient from -1°C lapse to neutral, and a three-fold effect for a variation in temperature gradient from neutral to +1°C inversion, where the temperature difference is measured between 2m height and .3m height. If the variation of the total dosage with temperature gradient is considered uniform throughout this region, then an accuracy of ± 20% in total dosage will correspond to an accuracy in the measurement of temperature gradient of ± 1/15°C; consequently an accuracy of ± .05°C in the measurement of temperature gradient can be set as the desired goal.

Under lapse conditions, where the temperature gradient is continuously fluctuating, and where there is considerable short-period vertical turbulence, it is doubtful if temperature gradient measurements to this degree of accuracy bear any significant relation to the results of an individual experiment; therefore under those conditions the accuracy requirement may be made much less strict. Similarly, under inversion there are various complicating effects which serve to emphasize that the above method of estimating the accuracy requirements serves only to present a rough idea of the useful instrumental accuracy requirements and does not necessarily apply to individual situations. The use of temperature gradient as an empirical factor for indicating the degree of atmospheric turbulence is in itself subject to a large number of qualifications, and in the selection of measuring equipment for this purpose extreme accuracy may well be sacrificed for a gain in simplicity of the equipment, at least until the actual field experiments show that increased instrumental accuracy will lead to some practical improvement in the interpretation of the data.

III. EQUIPMENT FOR THE MEASUREMENT OF WIND VELOCITY

A. Comments on Anemometer Characteristics

The anemometers available at this station consisted of the following types:

1. Friez ML-80 3-cup anemometer, with totalizing dial to the nearest .1 mile of air and with 1/60 mile and 1 mile electrical contacts.

2. Friez 339-L 3-cup anemometer, with magnetic mercury switch to give 1 contact per revolution of the anemometer.

3. The Lane-Wells light 3-cup anemometer developed by Division 10, NDRC, at the California Institute of Technology, equipped with a delicate magnetic contacting device making contact for one half the time of each revolution of the shaft and originally furnished with a case containing batteries, leads, and an electrical counter.

4. The Keuffel and Esser 6 inch (model 5967) and 4 inch (model 5958) Biram Anemometer with totalizing dial graduated in feet of air.

5. The British Meteor No. 4 light 3-cup anemometer with totalizing dial graduated in feet of air. The mechanical characteristics of the Lane-Wells anemometer were evidently made to be similar to this one, except for the indicating mechanism.

Although all these types were used successfully, the 3-cup anemometers making one contact per revolution (or modified to make two or more) appear the most practical for general use; they are non-directional and several anemometers can be made to indicate remotely on simple electrical counters. The current actuating these counters can be controlled by means of a single switch, thus facilitating the accurate timing of the record from one or more anemometers and obviating the necessity of approaching the anemometer stand during the course of the measurement.

The sensitivity and reliability of these anemometers is fixed by the delicacy of the bearings and the effective area and moment of the surfaces exposed to the wind. Since the force of the wind varies approximately with the square of the wind velocity, it is evident that a four-fold improvement in the delicacy of the bearings will result in only a two-fold improvement in the lower limit of wind velocity to which the anemometer will respond, and therefore although there is a wide variation in the ruggedness of the different anemometers, the useful lower limit of wind velocity to which the instruments will respond does not vary greatly.

The weight of the cup system does, however, influence the rapidity of response of the anemometer to changes in wind velocity and also affects adversely the accuracy with which the anemometer will indicate the mean velocity of a fluctuating wind.

The duration of the periods over which it is desired to obtain an indication of velocity influences the choice of the proper anemometer in two ways: one is the limitation imposed by the response period of the anemometer itself; the other is the limitation imposed, on a contacting anemometer, by the frequency of the contacts. Besides being fixed initially by the mechanical design of the anemometer, the frequency of the contacts must be kept below the maximum rate to which the relays and electrical counters will respond. This rate is usually less than 10 contacts per second and the rate corresponding to the highest wind velocity to be encountered should be kept well below this in order that reliance will not be placed on faulty readings.

The above restrictions on counting rates may be removed by substituting various electronic counting arrangements for the simple relay and counter circuit, but then the inertia of the rotating part of the anemometer comes into consideration and in addition the natural fluctuations of wind speed from point to point render somewhat doubtful the true significance of the enhanced time resolution of the anemometer; for example, even with perfectly-responding anemometers placed 1 meter apart under ordinary lapse conditions, simultaneous readings of less than about 1 minute duration may well show differences up to several per cent in the feet of air passing each position, simply due to local variations in the airflow pattern.

When the anemometers are to be used with the recording system about to be described, still other factors must be taken into consideration. At slow paper speeds a too-faithful rendition of the most rapid wind-speed fluctuations will tend to obscure the record by causing the pen trace to overlap on itself. This makes the record difficult to interpret when the wind-speed trace must be averaged over successive intervals of time, and in any case does not add to the significance of the record where a large area is to be represented. For studies of gustiness and vertical turbulence, it will be necessary to take cognizance of the time-response characteristics of the anemometer and in some cases to choose deliberately certain anemometer characteristics which may or may not be met by the equipment described in this report.

One simple approximate criterion of the time of response of an anemometer is the time required for the rotating system to coast in still air from an indicated wind speed of 8 mph to an indicated wind speed of 2 mph, when the instrument is equipped with a direct-recording speed indicator;this time must be corrected for any electrical time lag introduced by the electrical recording mechanism.

When equipment is to be transported and set up in the field it is ordinarily subjected to considerably rougher treatment than it would receive in the laboratory. In addition, the lighter types of anemometer can be permanently distorted by being subjected to high wind velocities. Therefore there is a definite disadvantage in using a more lightly-constructed anemometer than necessary in field equipment, particularly where it may be left unattended for 24 hours or more and hence unintentionally subjected to high wind velocities.

Similarly the bearings and contacting mechanism of all the anemometers vary in their susceptibility to dust, amount of maintenance required, and in their ability to withstand continuous exposure over long periods of time. For portable equipment, such as is mainly considered here, the bulk and weight of the anemometer and its associated equipment must also be taken into consideration.

In Table I an attempt has been made to summarize all of the above-mentioned properties of the different anemometers, based on their extended use in portable equipment for the purpose of obtaining continuous wind-speed records. It will be seen that there is an inverse relationship between ruggedness on the one hand and sensitivity and speed of response on the other. There appears to be a practical limit of usefulness of any rotating anemometer of about 1½ mph wind speed. This limit also applies approximately to wind vane systems capable of continuous exposure and to unaspirated temperature-gradient devices. Since wind speeds below 1½ mph are not usually encountered in field tests conducted in the open, there appears to be good reason to consider the measurement of micrometeorological conditions at wind speeds below 1½ mph as a separate problem, requiring the use of an entirely different type of apparatus.

The most satisfactory compromise among the anemometers listed appears to be the Friez 339-L anemometer. This instrument can be further improved by the addition of a second small alnico magnet to the shaft, thus actuating the hermetically-sealed magnetic mercury switch twice per revolution and thereby increasing the effective time-resolution. A further improvement could be made by providing additional dust-protection to the precision ball-bearing race comprising the upper bearing. This anemometer also has an essentially straight-line calibration curve, thus allowing the recording system to be essentially direct-reading over a wide range of wind-velocities.

B. The Principle of Operation of the Relay-Type Frequency Meter

The most attractive system found in the laboratory for directly recording wind velocity has been the use of the relay-type frequency-meter (practical range 10 to 600 contacts per minute) with a spring-wound Esterline-Angus Recording Milliammeter and a 3-cup anemometer making 1 or 2 contacts per revolution.

This type of circuit, shown in Figure 1, was originally developed to give on a microammeter a visual indication of average wind-speed, and is referred to by W.E.K. Middleton (page 138, "Meteorological Instruments", second edition; University of Toronto Press, 1943) as a condenser discharge anemometer. As adapted here for continuous recording in portable equipment, it operates as follows (see Figure 1):

When the anemometer contacts are closed, the relay is energised and C_1 is charged through the lower relay contact to the full voltage of Battery B. When the anemometer contacts are opened condenser C_1 discharges almost completely into the smoothing condenser C_2 (much larger than C_1) and eventually the charge passes through the milliammeter. This process is repeated for every make and break of the anemometer contacts, the quantity of electricity being transferred each time being equal to $V_b \times C_1$, where V_b is the battery voltage and C_1 is the capacity in farads. The current through the milliammeter is, then, equal to $F \times V_b \times C_1$, where F is the number of anemometer contacts per second.

Since the resistance of the milliammeter is fairly high, the voltage drop across the terminals T will be an appreciable fraction of V_b, and C_1 will not be completely discharged if the milliammeter already shows a deflection. The exact formula relating I_m, the current in milliamperes passing through the milliammeter, to F is given below:

$$I_m = \frac{1000\ C_1\ F\ V_b}{1 - C_1\ F\ R_m}$$

R_m is the resistance of the milliammeter in ohms.

The number of contacts per second corresponding to each successive mile per hour of wind speed can be obtained from the anemometer calibration curve, milliamperes against wind speed; it is nearly linear, and can be made to correspond in some way to the lines on the chart paper. Since the anemometer will not turn at all below a threshold of 1/2 to 1 mph, the zero deflection of the milliammeter may be set intentionally a little toward the center from the first chart line and then the uniformly spaced chart divisions will correspond quite well over the entire range of wind speeds to uniform steps in miles per hour.

The smoothing condenser C_2 must be chosen to be large enough so that each individual pulse from C_1 will cause, even at the lowest wind speeds, only a tolerable wavering of the recording pen. A much larger value of C_2 will unnecessarily reduce the speed of response of the system, tending to give a weighted time average of the wind speed over the past period of time.

The over-all speed of response of the system thus depends on the response-time of the milliammeter when shunted by C_2, which must be made larger the fewer the number of anemometer contacts per second, and the relation between the inertia of the rotating cup-system and the resultant force exerted on the cups by the wind. It follows, therefore, that at the higher wind speeds a smaller value of C_2 may be used than at the lower wind speeds, and that the over-all response-time of the system can be profitably kept low at the expense of having the individual contacts mar the record somewhat at the lowest wind speeds.

The advantage of using this type of system for recording wind speed over the method of producing pen-marks on a moving paper for each anemometer contact (or for a certain number of anemometer contacts) lies in the ease with which the record can be immediately scanned, the feasibility of obtaining good time resolution at low paper speeds, and the tremendous amount of work saved in working up the records.

Although for some statistical work the use of electrical counters periodically photographed might be expected to lead to higher accuracy and give directly by subtraction, after development of the film, a number which can be used directly, there is ordinarily no indication by this method of the range of wind-speeds leading to this average number, and hence the information obtained is quite limited. The accurate study of wind profiles appears to be the primary example of where the counting method would be better, and here the simultaneous use of a continuous recorder at one level at least would add considerably to the value of the data.

The range of paper speeds covered by the spring-wound Esterline-Angus meter fits in quite well with this system; this range includes paper speeds of 3/4, 1 1/2, 3, 6, and 12 inches per hour (the timing can be relied on to the nearest twentieth of an inch) and 3/4, 1 1/2, 3, and 6 inches per minute. The chart paper comes in 100 ft. rolls, and the 8-day clock movement and the inking system have shown themselves to be completely reliable over the entire range of outdoor conditions encountered.

The minute-speeds are controlled by a governor, and the chart speeds are more variable. Therefore some form of auxiliary timing is desirable, and several time checks should be made during the course of a run; the meters will run satisfactorily for over two hours without re-winding.

C. The Relay-Oscillator Keep-Alive

Experience with the Esterline-Angus meters in the field has indicated that far more satisfactory records are obtainable if in addition to the measuring current a small low-frequency alternating current is passed through the moving coil. This "keep-alive" current, just sufficient to cause the pen to tremble visibly, serves to make the pen continuously assume its true equilibrium position; if it is not present the pen will not follow the maximum fidelity the rapid fluctuations in the measuring current, and particularly at low paper speeds the pen will move in jumps.

The most economical way of obtaining this small alternating current, of a frequency of from 3 to 10 cycles per second, is by the use of a relay oscillator similar to those developed by R. L. Ives, 1st Lt., CWS, at this post. This relay oscillator controls by means of auxiliary relay contacts the application of direct current to the primary of a small transformer the secondary of which is connected either in series with the recording meter or in parallel through a small condenser and a resistor of 10,000 ohms or more. Alternatively the application of a continually reversing direct current voltage, controlled by the relay oscillator, will accomplish the same purpose when the recording milliammeter is properly connected into the circuit.

A diagram of the shunt-type relay oscillator with transformer is given in Figure 2, and the explanation is as follows:

When the battery B is first connected, condenser C is charged through resistance R_1 and as soon as the voltage across the condenser becomes high enough, the relay armature is pulled down and a pulse of current is sent through the transformer. When the connection at the upper relay contact is broken, however, the relay armature is not immediately released because the current stored in C continues to flow through the relay coil. Since the air-gap in the magnetic circuit is reduced when the armature is held down, the armature can be held down by a current considerably smaller than that necessary to pull it down initially. Finally the condenser current through the relay coil decreases sufficiently to allow the spring tension to release the armature, and the cycle can then be repeated.

In practice it has been found that considerable experimentation is required to get a given type of relay to function dependably over long periods of time; the exact analysis of the action is complicated and there are numerous variations possible in the circuit design. The time the relay remains in the open and closed positions depends on the capacity of C, the battery voltage, the relay resistance, the resistance R_1, the adjustment of the armature-spring tension, and the setting of the magnetic air-gap and relay contacts. The inertia of the armature and the resonant frequency of the condenser relay-inductance combination appear to have quite an effect on the stability of operation.

In some cases the series relay-oscillator circuit, illustrated in Figure 10, has proven somewhat simpler to get into operating condition; the timing of the on-off periods of the relay is unsymmetrical, and consequently the zero of the milliammeter is shifted by a fraction of a division when the keep-alive is operating. Keep-alives of both types, at voltages ranging from 2 to 12 volts and currents ranging from 35 to .8 milliamperes, have given month-long uninterrupted service, and would appear to last indefinitely.

D. The Device Used for Recording Wind Direction

The most practical method found, in the course of this work, for translating the orientation of a wind vane into milliamperes deflection of the recording milliammeter consisted of the well-known potentiometer method. A fixed voltage is maintained between adjacent extremities of a circular set of resistances, the position of the wind vane determines the position of a variable contact on this resistor, and the voltage between one lead to this resistor and the variable contact is an indication of the position of the vane. This voltage is recorded on an Esterline-Angus milliammeter, which has in series with it the proper resistance to give a convenient range in chart divisions to the 360° traverse of the wind vane.

As the wind vane is turned through its complete traverse, the voltage varies progressively until the point is reached where the adjacent resistor leads are located, at this point the voltage indicator jumps suddenly from the high-scale reading to the low-scale reading and the pen sweeps clear across the paper. If the wind direction varies rapidly back and forth across this point, the record becomes somewhat obscure, especially at slow paper speeds, but this point can always be oriented toward the least likely wind direction.

The resistance ring may consist either of a set of fixed contacts, corresponding to a definite number of steps in wind direction, or else of an annulus continuously wound with resistance wire. Devices of the latter type, manufactured as complete assemblies for remote recording and indication are commercially obtainable (Electronics, 18, No. 7, page 346, July, 1945); in one case only 2 gram-millimeters of torque are required to overcome the contact and bearing friction.

In order to have strict proportionality between direction and milliamperes indicated, the current drawn by the recording meter must be small compared to that passing through the resistance, or in other words the resistance of the milliammeter and the resistor in series with it should be at least 20 times that of the resistance ring. For best response, the total resistance in series with milliammeter should be about equal to the external critical damping resistance of the milliammeter; for maximum battery economy, however, some deviation from linearity and some overdamping of the milliammeter is usually allowable.

It was found that a system recording wind direction to 16 steps (corresponding to N, NNE, NE, ENE, E, etc.) was adequate for most purposes, and that 8 directions sufficed for verification of forecasts and some other recording purposes. In studying the records, there was some advantage in having them already broken up into definite steps which could be more easily followed on the record, particularly if the steps were not quite uniform or if there had been a change in battery voltage.

There were already available to the laboratory several Friez 363-C wind vanes, and therefore these were adapted for recording purposes. These wind vanes consist of the vane proper, to be placed on a vertical shaft on which was mounted a cam, and a pipe bearing on the upper end of which is mounted a ring of 8 contacts, corresponding to 8 wind directions.

As the vane turns, one contact is closed, then the next contact closed without opening the first one, then the first contact opened, etc. so that a ring of eight lights (corresponding to N, NE, E, etc.) will indicate 16 directions; e.g. if N and NE are both lighted, the direction is NNE.

By means of the resistance assembly shown in Figure 3A, this system was adapted to record rather than indicate, and to cover the full 16 directions rather than only the 8 that the simple potentiometer circuit would accomplish. The resistances R_1, all equal and low compared to R_2, form the simple potentiometer circuit, and the branches R_2 to the vane contacts serve to make the voltage at the contacts half-way between that at two adjacent junctions of R_1. However, when the connection to X_2 is made simultaneously to two adjacent direction contacts, the resultant voltage is very nearly half-way in between that recorded by either contact alone.

As drawn, for example, and used with a chart-paper with 10 large divisions corresponding to 1.0 milliamperes full scale, the calibration may be adjusted as follows, taking the voltage between X_3 and X_2:

NE, .05 ma ENE (contact made to both E and NE), .10 ma; E, .15 ma;

ESE, .2 ma SE, .25 ma; SSE, .30 ma; S, .35 ma; SSW, .40 ma;

SW, .45 ma; WSW, .50 ma; W, .55 ma; WNW, .60 ma; NW, .65 ma;

NNW .70 ma; N, .75 ma; NNE .4 ma.

When the voltage is measured between X_3 and X_1 (this is accomplished by turning switch SW, in Figure 4 from position 1 to position 2) the deflection should be .8 ma; this adjustment can be made by properly setting the rheostat R_1 of Figure 4.

It will be observed that the current-indication for NNE is the same as that of SSW. This seldom causes confusion since with a variable wind the .4 ma indication is approached in one case by a series of steps and in the other case by a sweep nearly half-way across the chart paper.

The assembly of resistors R_1 and R_2 is compactly mounted directly under the vane contacts, as shown in Plates I and IV, thus only 3 leads are required from the instrument-box to the vane-head. This system has another advantage in that a failure of one of the contacts is indicated by a zero deflection of the milliammeter, which does not occur for any true direction. A further discussion of the circuit constants and design is contained in Section V of this report, where the completed instruments are described.

E. The Vacuum-Tube Frequency Meter for Use with the Photoelectric Cell and Interrupted Light Beam

In order to make full use of the good time-resolution of a lightly-constructed rotating anemometer, the frequency of pulses resulting from the rotation of the anemometer must be higher than can be handled satisfactorily by an ordinary relay. In this case a vacuum-tube frequency meter can be usefully employed in the frequency range of from 10 cycles to many thousand cycles per second. The design of one such instrument is described in Reich: "Theory and Application of Electron Tubes" (McGraw-Hill, 1939). Other methods of obtaining currents either directly proportional or logarithmically proportional to pulse frequencies are contained in the literature on radioactivity measurements.

The instrument described in Reich (see this book for the original reference citation), was modified for use with a photocell and Biram anemometer, and is shown in Figure 7. A further discussion is given later in this report (Section V) but the general working principle can be given as follows:

The 1H4-G triode on the left hand serves to amplify the interrupted photocell current, producing in each of the transformer secondaries first a positive pulse and then a negative pulse each time the light falling on the sensitive plate of the photocell increases to a maximum and then falls off to a minimum. The secondary connections are arranged in such a way that when the pulse is positive on the grid of the lower 1H4-G triode (on the right-hand side of the drawing), it is negative on the grid of the upper triode; these grids are both heavily biased negatively by means of the batteries B_4 and B_5, B_6 so that the vacuum tubes normally pass no plate-current at all; from the polarity of the pulses it can be seen that during a succession of pulses, first one triode and then the other becomes conducting.

When the lower triode becomes conducting, C_1 becomes charged to the full plate voltage, and this charging current also passes through the milliammeter. When the upper triode becomes conducting, the condenser C_1 is discharged, and thus becomes ready for a repetition of the cycle. The similarity of this circuit to that of the relay-type frequency meter is apparent, and the approximate formula is the same:

$$I\,ma = F \times V_b \times C_1,$$

where F is the number per second of the interruptions of the light beam by the anemometer blades, V_b is the battery voltage, and C_1 is capacity of C_1 in farads.

In practice, C_1 can never be completely charged and discharged through the triodes, because of their high impedance at low plate voltages, but if the capacity C_1 is small enough, and the frequency F is low enough, the current in milliamperes is closely proportional to F over a wide range of frequency. This straight-line range can be extended by selecting low-impedance tubes and by reducing the capacity C_1 and increasing the voltage V_b proportionately, or by increasing the sensitivity of the milliammeter. In practice, the calibration seems to be essentially independent of individual tube characteristics, and independent over a wide range of the exact voltage of the pulses in the transformer secondary; they must merely exceed a certain minimum value.

The lowest useful frequency is largely determined by the inefficiency of the transformer in reproducing slowly-varying pulses and by the wide sweeps of the recorder pen when the frequency becomes low enough to coincide with the natural period of the moving coil. Pulse frequencies above about 20 cycles per second do not disturb the average DC reading of the milliammeter.

The chief advantage of the photoelectric system is in the absence of a large smoothing condenser across the terminals of the milliammeter and consequent increase in the time-response characteristics to those of the milliammeter itself. For lightly-constructed rotating systems the absence of all forms of delicate electrical contacts greatly simplifies the construction of the anemometer and increases its reliability; the entire cost of the photoelectric circuit and its accessories represents only a fraction of the cost of the delicate machine work otherwise necessary, especially when the instruments are not mass-produced.

Another interesting application of the vacuum-tube frequency meter to micrometeorological problems is in the study of the rate of deflection of horizontal and vertical vanes. This can be accomplished very simply by placing on the rotatable shaft supporting the vane a disk or sector containing a series of perforated holes, which thus allow flashes of light to strike the cell as the vane deflects to and fro. The output of the frequency meter, possibly smoothed by a shunt condenser, will then be proportional to the rate of change of the angle of orientation of the vane.

This quantity bears an interesting relation to the atmospheric turbulence, and may be a useful adjunct to the temperature gradient observations.

F. A Direct Recording Approximate R-Value Device (Ratiometer)

A more fundamental index of atmospheric turbulence than is the temperature gradient, continuous records of the R value may in some cases prove a valuable supplement to other means of measuring turbulence. The R value (uncorrected) is usually considered as the ratio of the wind speed measured at 2m height to that measured at 1m height. This is ordinarily measured by running simultaneously two totalizing anemometers for a definite period of time, translating their indications into miles per hour or feet per minute, and dividing the 2m velocity thus obtained by the 1m velocity.

For best quantitative use, these measurements must be accurately made, as a change in R value (over smooth ground) from 1.10 to 1.20 corresponds roughly to a change in temperature gradient from $-1^{\circ}C$ lapse to $+1^{\circ}C$ inversion. For some purposes, however, an automatically continuously recorded R value accurate to only ± 2% unless corrected by a calibration curve, will provide interesting information.

The automatic device for recording R value measures R upon the following principle: When the 1 meter counter has measured 100 counts, the excess counts on the 2 meter counter gives the decimal to be added to 1 to give the true ratio of the revolutions during this period of time of the 1 and 2 meter anemometers. Because of the nearly straight-line calibration of the anemometers, this ratio is very nearly that of the feet of air passing the anemometers, at least for R values less than about 1.40; it can be corrected to give the true R value by means of a calibration table involving the approximate average wind velocity during the period of measurement.

The electrical circuit for automatically measuring and recording successive values of R by this method (with a 5 second "blank" interval between each measurement) is illustrated in Figure 7. It functions as follows:

The impulses from the 1 meter anemometer actuate the 1m counter (where 100 pulses produce 1 revolution of the index needle) and the relay Y_1; because of the condenser-limiter circuit, containing C_1 and R_1, Relay Y_3 is actuated for a small fraction of a second only, regardless of the duration of the pulse from the 1m anemometer. Each time Y_3 is actuated, the charge from condenser C_3 (charged to a definite voltage by B_1) is transferred to C_5. In a similar manner, the charge from condenser C_4 (exactly equal but of opposite sign) is transferred to C_5 for each pulse from the 2m anemometer. The resultant charge of C_5, and hence the voltage across its terminals is, then, very nearly proportional at any time to the difference between the number of pulses coming from the 2m and 1m anemometers.

When 100 pulses have been received from the 1m anemometer, the contacts on the 1m counter are closed, and Relay Y_5 is actuated. Because of the time-delay circuit C_6, R_6, this relay remains down for a period of about 5 seconds. During this time Relays Y_7 and Y_8 are also actuated, and as a result the 1m and 2m counters and relays Y_1 and Y_2 no longer respond to the contacting of the anemometers, and the vacuum-tube voltmeter, VT_1, VT_2, etc., records the voltage across C_5 by the maximum excursion of the pen of the Esterline-Angus milliammeter.

During this period, a voltage is also applied to the circuit of Relay Y_6, but this relay does not close immediately because of the time-delay circuit C_7, R_6. When this relay does close, however, the terminals of C_5 are short-circuited, and the E-A milliammeter deflection returns to the value corresponding to R = 1.00. At the end of the

5-second interval determined by the time-delay of Relay Y_5, Relays Y_6, Y_7, and Y_8 are de-energized, and the counting cycle is resumed. The envelope of the excursions of the E-A milliammeter pen then represents the R-Value, and if chart paper with 10 major divisions is chosen, the zero indication of the vacuum-tube voltmeter set at 0 milliamperes, and the values of B_1, B_2, C_3, C_4, and C_5 are properly selected, the correspondence of the measured R value to the milliamperes deflection will be as follows: R = 1.00, 0.0 ma; R = 1.10, .10 ma; R = 1.2, .20 ma; R = 2.0, 1.0 ma.

The circuit constants corresponding to Figure 6 are given in Section V of this report, but a further detailed discussion of the circuit is not given since the device is of only secondary interest and in its construction the working details soon make themselves apparent.

A direct calibration of the device under working conditions can be made by recording the 1m and 2m counter readings during each pause and comparing them with the milliammeter readings. This milliammeter should be connected also to a keep-alive, so that the pen may follow accurately the momentary milliammeter current. Despite the large number of relays involved, the device proved highly practical for the purpose intended, and the daily record of the course of the R value could be easily followed on the chart as soon as the chart was unrolled.

IV. THE PORTABLE PHOTOELECTRIC GALVANOMETER FOR TEMPERATURE MEASUREMENTS

A. General Remarks on the Use of Thermocouples

Although mercury thermometers of various kinds have been used in skilled hands very successfully in micrometeorological work, there is a definite need for improved methods of recording temperature gradient, and to a somewhat lesser extent soil-surface and air temperatures. Recording equipment based on various liquid- and solid-expansion principles leave much to be desired in that they are slow in response, usually of insufficient accuracy, and quite delicate if sufficiently sensitive.

The simplest and best electrical method for the measurement of these temperatures was found to be the use of thermocouples, single or multi-junction, with a sensitive remote indicating or recording millivolt meter. For temperature gradients, an instrumental range of 2.5°C inversion - 0 - 2.5°C lapse has been found to be suitable for gradients between the 2 meter and 1 meter heights, and the range 5°C inversion - 0 - 5°C lapse for gradients between the 2 meter and 0.3 meter heights. For surface and air temperatures an over-all range of 100°F is satisfactory. The recording instrument should have an over-all accuracy of at least ± 2% of the full-scale deflection, and the zero-point should be stable to within ± 1/2% of the full-scale deflection, although in some cases this accuracy might be sacrificed for portability. Although there is a wide range of choice in commercially available millivolt-meters which are satisfactory in other respects, as far as known here these all require considerable power, commonly from 10 to 120 watts at 110 volts 60 cycles, for their operation. Therefore in the interests of battery-economy and independence from an external power supply special units recording on a spring-wound Esterline-Angus milliammeter were designed in the laboratory. Despite the sensitivity, ruggedness, and economy in battery-drain of these instruments, their electrical characteristics compare very favorably with those of any of the 110 volt commercial instruments known here.

Other means of measuring temperature gradient, such as the use of resistance elements with electrical recording, suffer by comparison with thermocouples in that the measuring element does not follow as closely the true air-temperature, and that the accuracy of each separate element in these devices must be such that over a wide range of temperatures, neutral conditions must be indicated correctly to within some $\pm 1/15^{\circ}C$; with good thermocouple wire these conditions are automatically met, and the elements are easily reproducible. By careful attention to details the usual objection to the use of thermocouples, i.e. that the electrical equipment and technique required for use with them is too delicate, has been overcome.

B. The Principle of Operation of the Photoelectric Galvanometer

Portable low-resistance microammeters and galvanometers of either the reflecting or pointer type are obtainable with sufficient sensitivity to give a satisfactory indication of temperature gradient when a thermocouple of several junctions is used. Since these instruments respond to the current passing through them, the total resistance of the circuit must be adjusted and kept constant if a given number of scale divisions is to always represent one degree of temperature.

These instruments may be modified and used in conjunction with a recording milliammeter in such a manner that the combination records in terms of temperature nearly independently of circuit resistances below about 50 ohms. Circuits for accomplishing this are shown in Figures 8 and 9. Referring to Figure 8, the two 6SJ7-G pentodes together with R_3 and R_4 form the arms of a Wheatstone bridge, with the recording milliammeter connected between the two plates and the emf. applied (positive) to the junction of R_3 and R_4 and (negative) in series with R_5 to the two cathodes. R_5 serves to provide a negative biasing voltage drop to the two grids, thus keeping the average plate current at the proper operating value for the two tubes.

The small flashlight bulb serves to illuminate the photocells with a rectangle of light which, for the zero reading covers about half of each photocell plate. Good efficiency of illumination is obtained by the use of the condensing lens, which forms a real image of the filament on the surface of the galvanometer mirror. The lens in front of this forms the rectangular spot of light on the photocell plates by imaging the sharply defined aperture in front of the condensing lens.

With the emf. input terminals short-circuited, the zero-setting knob of the galvanometer is adjusted until the light intensity falling on the two photocells is equal, as indicated by a zero deflection of the milliammeter, which occurs when the plate-currents of the two pentodes are equal. These plate currents are governed by the photocell currents flowing through R_4 and R_5, the voltage drop acting on the grids.

When an emf. of, say 1 millivolt, is now applied to the input terminals, the galvanometer will deflect, shifting the light spot so as to increase the light on one photocell and decrease that falling on the other. This causes an unbalance in the bridge-circuit, and thus a current flows through the milliammeter and R_6 in series with it.

The connections are such that the voltage drop across R_6 due to the milliammeter-current opposes the input emf; consequently the galvanometer deflects only just enough for the current through R_6 (originating from the light-unbalance on the photocells) to be nearly equal and opposite to the input emf.

If R_6 were made equal to zero, the photocell-vacuum tube-milliammeter would be serving merely as a device to greatly amplify the galvanometer deflection, since a shift of only a few millimeters in the position of the light spot would then serve to change the milliammeter current from zero (light on the photocells balanced) to the full scale reading of 1 milliampere. The voltage drop across the galvanometer to produce this would, for example, be only about .02 millivolts.

If R_6 is made equal to .98 ohms, a current of 1 milliampere through it would produce a voltage drop of .98 millivolts, and, as before, the voltage drop across the galvanometer would be .02 millivolts, so the total impressed input voltage to give this deflection would have to be 1.00 millivolts; the milliammeter reading for smaller input emfs. would be proportional provided that the voltage drop across the galvanometer coil was even approximately proportional to the residual deflection. If the galvanometer resistance were 20 ohms, and the external resistance (e.g. the resistance of a thermocouple supplying the input emf.) were, say, 10 ohms, a current of .001 milliamperes would flow through the galvanometer coil in order to produce the residual deflection, and an input emf. of 1.01 millivolts would be required to produce a 1.00 millivolt indication on the milliammeter.

The above consideration serves to show how nearly the photoelectric galvanometer becomes a potential-operated device. If R_6 is decreased to .18 ohms, the full-scale reading of the milliammeter corresponds to .2 millivolts, and the effect of adding 10 ohms series resistance to the input emf. circuit will be to decrease the reading to .18 millivolts. In this case the calibration has been made more dependent on the value of the external resistance, and on the linearity of the residual galvanometer deflection, for the sake of increased over-all sensitivity.

The figures given above are quite representative of the performance of the apparatus to be described. The galvanometer itself, used as a deflection instrument with an external resistance of 10 ohms, will require about 500 microvolts for a full scale deflection and will have a response time of about 4 seconds. Because of the negative feed-back features of the circuit in which it is used, the entire response-time of the recording photoelectric galvanometer is only a trifle more than one second. The galvanometer coil does not swing freely because as soon as it deviates from its equilibrium position, the current through R_6 changes in such a manner that the voltage impressed on the coil forcibly returns it into balance.

The above principles were first used by the Weston Electrical Instrument Co. in their 110V operated Galvanometer Amplifier, and similar applications have since been described several times in the literature. (E.g. E. V. Potter, Electrical Engineering: 63, 5, p. 175, May, 1944 and Gabriel Asset, Electronics: 18, 2, p. 126, February, 1945.)

The distinctive features of the photoelectric galvanometers described in this report lie in the low current-consumption of the illuminating bulb and vacuum tubes, the use of rugged portable galvanometers and microammeters of standard design, and in the tolerance of a considerably greater residual deflection of the galvanometer than is ordinarily used. With thermocouple circuits, where the resistance of all couples can be approximately controlled by merely cutting off the same length of wire for each couple, the accuracy is not appreciably impaired even if 10% of the voltage to be measured is used for the residual deflection of the galvanometer; this allows the use of a less sensitive photocell-amplifier system and makes for more stable performance without recourse to the use of specially constructed galvanometers.

There is, however, one draw-back to the above scheme which must be borne in mind in the field use of the equipment: If an input emf. of several times the full-scale value is applied to the terminals, the current through R_6 will not be sufficient to oppose this emf. and the light spot will be thrown completely off the photocells. Once this happens, the light spot cannot return unless the amplifying system is momentarily shut off; therefore some latitude must be allowed in deciding on the full-scale reading. It so happens that for the temperature measurements referred to, it is not difficult to estimate the maximum readings expected.

The final calibration of the instrument, usually in terms of degrees per chart-division, is made empirically by adjusting the length of the resistance-wire comprising R_6 until the proper reading is obtained in terms of the known temperature difference of the two ends of a thermocouple wire. The best grades of thermocouple wire are so uniform, and give so nearly a straight line calibration of emf. against temperature-difference, that for the purpose intended here it is satisfactory to assume a constant emf. per degree, measured at an average temperature of 70°F, over the entire range from 30 to 130°F.

In the design and use of these photoelectric galvanometers, considerable laboratory and field experience must be gained in order to establish the proper techniques of operation, the proper ranges and sensitivities to employ, and the estimation of the true accuracies obtained. For example, the use of shaded fine-wire thermocouples in the measurement of temperature gradient greatly simplifies the equipment as compared to the use of heavily-constructed aspirated stands. However, since considerable controversy has been raised over the validity of the unaspirated measurements made under the different meteorological conditions, it would be unwise to rely on a particular instrument for these measurements without intercomparison with other instruments. The experimental work undertaken here indicates that under most conditions a simple shade consisting of two aluminum disks above the couple and one below, arranged to offer minimum resistance to the air-flow and minimum heat-conductivity to the support, gives almost identical results at wind velocities above 1½ mph, with those from a heavily aspirated stand, except under strong lapse conditions. In this case there is some doubt as to the cause of the discrepancy and from a practical standpoint exact measurements under the continuously-fluctuating lapse conditions are of far less importance than under neutral and inversion conditions.

Similarly, in the measurement of soil-surface temperatures, it has been common practice here to check the reading of the couple which is laid in close contact with the ground by taking comparative readings with mercury thermometers, both of the surface temperature and of the temperature of water in a Dewar vessel. In addition, maximum and minimum thermometers are sometimes left at the recording station. Thus, as little as possible is taken for granted about the performance of any single instrument, and occasional difficulties are anticipated and corrected before the trouble can seriously influence any field results.

As an example of the advantages of such a procedure, the following incident will be related:

Shortly after the installation of a recording photoelectric galvanometer for the measurement of soil-surface temperatures, it was found that although the thermometer checks made during the day-time were satisfactory, the minimum surface-temperature recorded at night was higher than the minimum recorded air-temperature, although a good inversion had developed during the night. The eventual cause of this trouble was traced to the fact that the surface of the soil increased in electrical conductivity with the nightly increase in relative humidity, and that both the storage battery operating the filaments and the thermocouple made good electrical contact with the ground. From the diagram in Figure 7 it is apparent that there is a potential of some 90 volts between the storage battery and the thermocouple. The leakage currents thus produced at night affected the galvanometer, and when the storage battery was properly insulated from the ground the trouble disappeared. For this reason it is always desirable to especially insulate the filament-heating battery and to use it for no other purpose, such as furnishing current to the wind-speed and direction devices.

The entire circuit leading to the input emf. terminals should be tested for the effect of stray thermoelectric emfs. In some cases rather cheap symmetrically-constructed multipoint switches were found to be satisfactory while more expensive ones, probably containing nickel-silver contact springs, were found unsuitable. Very little trouble has been encountered in this regard, however, and in a typical test the photoelectric galvanometer with the far end of the input leads short-circuited was left running unattended for a four-day period during clear winter weather; the entire deviation of the zero-reading from all causes never exceeded 1/2% of the full-scale reading.

No serious difficulties were encountered in transporting and setting-up the above equipment in the field; many times it was transported over miles of rough road in a jeep, with only a small layer of excelsior or newspaper to protect it from the jolting, although such rough treatment certainly is not to be recommended. It indicates, however, that these instruments cannot justly be accused of being "laboratory instruments only, too delicate for use in the field".

V. DETAILS OF CONSTRUCTION OF THE MICROMETEOROLOGICAL EQUIPMENT

A. General Remarks on the Choice of Components

As indicated previously, the initial decision was made that all the equipment should be battery-operated and of maximum portability; this decision and the desire for maximum reliability are the chief factors in the ideal choice of the components. Because of the war-time difficulty in obtaining quickly many of the parts considered most suitable, in many cases the ideal design was modified to make use of components already at hand. Even with an unrestricted choice of components, considerable thought must be devoted to the proper solution of a large number of small problems having to do with the consistent design of a group of these instruments.

The choice of the batteries to use is one of those problems. For low-voltage purposes, dry cells will function satisfactorily without excessive voltage drop when the discharge rate is such that their service-life, calculated from their approximate ampere-hour capacity, exceeds 800 hours. They start to freeze, however, and become rather unsatisfactory, at sustained temperatures below 20°F, and unless the current drain is much less than the limit indicated above, lead-acid storage batteries will have to be used.

The standard No. 6 dry cell and the 6 volt "hot shot" type ignition battery (such as the Burgess Uniplex #4F4) may be counted on to supply at low current-drains about 40 ampere-hours of useful life, so for continuous recording purposes, they may well supply average currents up to 50 milliamperes. All dry-cells, of course, can equally well supply for short intervals currents of perhaps 50 times their rated continuous capacity, provided that between each discharge period there is a rest interval long enough to reduce the average current over the whole time to a value below the continuous rating.

The standard-sized flashlight cell (the type D cell, about 2 inches high by 1¼ inches in diameter) has a capacity of about 4 ampere-hours, indicating a practicable continuous current-drain of about 5 milliamperes.

When continuous currents higher than those stated above are required or when extremely low temperatures are encountered, storage batteries are desirable; the greater constancy of voltage output is an additional advantage when they are used with the photoelectric potentiometers and wind direction devices. The 120 ampere-hour good-quality automobile storage battery gave excellent service over a period of a year, and was the largest type employed, as the heavier batteries were considered no longer portable. Another type of storage battery, which appears ideally suited for continuous recording purposes, is the Willard Charge-Retaining storage battery, produced by the Willard Storage Battery Co. of Cleveland, Ohio. This battery is especially constructed to deliver small currents for periods up to a year without the necessity of re-charging whereas normally the lead-acid storage batteries should be recharged every thirty days whether used or not. One type of 6 volt Charge-Retaining storage battery, type CR-2-3, of about the same physical dimensions as 4 No. 6 dry cells in series and of the same capacity, 40 ampere hours, was used extensively for over a year in a wind-speed and direction recorder having a continuous current drain of .08 amperes. The performance was such that, despite the inconvenience of recharging and keeping the exterior free from sulphuric acid, the adoption of this type for all-weather continuous stations is strongly recommended.

In the selection of relays for keep-alives, relay-type frequency meters, and as light duty power-relays, the most experience was gained with three different types. The Advance (Advance Relay Co., Los Angeles, California) Series 500 double-pole double-throw relays were used successfully for keep-alives and in relay-type frequency meters controlled by the Friez 339-L anemometer. Although these relays are supplied for 6 volt operation at a current as low as 6 milliamperes (coil resistance, 1000 ohms) the relays for use with the 339-L anemometer had a more rapid response time when chosen with a 250 ohm coil (operating current, 24 milliamperes) and worked best as relay oscillators with a 150 ohm coil (operating current, 40 milliamperes). Since the relays in these circuits were drawing current only about 1/5th of the total time, the battery-drain was still quite low and yet they were extremely stable in operation because of their more positive characteristics, as compared with the higher resistance relays.

For use in the plate-circuit of small battery-operated vacuum tubes, the Advance Series 850 single-pole double-throw relay performed very satisfactorily after the initial adjustment, as long as the operating conditions were held constant. With excess current in the relay coil, the high-permeability cores would become permanently magnetized and unless demagnetized again by the application of a diminishing AC current, the characteristics would gradually change, requiring continual readjustment of the relay contacts, air-gap, and spring tension. These relays had a coil resistance of 10,000 ohms and would operate reliably on currents as low as one milliampere.

The only relay found that would work well with the Lane-Wells anemometer was the relay originally furnished with it, a Sigma Model 4AP 2000 ohm, 3 volt, relay (Sigma Instruments Co., Boston, Mass.). An attempt was made to use instead for this purpose an Advance type 850 10,000 ohm relay on $22\frac{1}{2}$ volts with a spark-suppressing circuit. In spite of the complete lack of a visible spark (as observed with a magnifying glass in a darkened room) when the connection to this relay was made and broken, after several days operation the polished contacts of the Lane-Wells anemometer showed marked pitting and the functioning of the anemometer and relay combination started to become unreliable. The Sigma relay, however, proved entirely satisfactory as long as sparking produced by the load on the relay contacts was reduced to a minimum.

The high voltage supplies to the relay-type frequency-meters and photoelectric galvanometers were usually made up of Burgess No. 2308 45 volt batteries of a nominal capacity of 4 ampere hours. With a maximum current-drain of 2.5 milliamperes, these batteries gave good results even when minimum air-temperatures below $0^{\circ}F$ were encountered for several successive nights at a time. More compact arrangements could have been secured by use of smaller sizes than this; for the relay-type frequency meters where the maximum drain would only be 1 milliampere and the average current drain perhaps 1/3 of this, the use of the smallest size $67\frac{1}{2}$ or 45 volt batteries, of 1/2 to 1 ampere hour capacity, seems feasible. The shelf-life of these small batteries, while probably less than the larger sizes, has been much improved in recent years and their performance on a weight-basis as compared with the larger batteries is better than would be expected.

The vacuum tubes dealt with ranged from the $1\frac{1}{2}$ and 2 volt low filament-current types (.50 and .60 amperes) to the standard 6 volt cathode heater types (current .15 amp. and .3 amp.). Although the cathode heater types were supposedly more rugged, surprisingly enough no tube failures of any type were encountered despite considerable unnecessarily rough treatment of equipment containing the $1\frac{1}{2}$ and 2 volt tubes. Therefore the chief value of the 6 volt types lies in their usually superior amplifying characteristics and in an increased flexibility of design since the cathodes may be connected independently of their common filaments. In the vacuum-tube frequency meter, for example, the 6 L5-G 6 volt .15 ampere cathode-heater tubes could be used with a common filament battery; they gave somewhat better results than the 1 H4-G (2 volts .06 ampere filaments) shown in Figure 7.

Although there is some advantage in standardizing on a 6 volt system because this is also a standard voltage for counting relays and the chronograph pens on the Esterline-Angus recording milliammeters, there is a pronounced advantage in battery-economy in the use of a 2 volt or 3 volt system with the $1\frac{1}{2}$ volt or 2 volt vacuum tubes.

For the illumination of the photocell systems, 2.2 volt and 6.2 volt flashlight bulbs gave excellent service. These are less long-lived than the 6 volt automobile head-light bulbs ordinarily used, but by running them at about 60% of their rated voltage in efficient illuminating systems, their expected continuous service life rose from 50 - 100 hours to well over 60 days.

After using this equipment in the field under adverse circumstances such as before dawn on cold winter mornings, many points came to be appreciated which were not apparent in the laboratory. The replacement of binding posts by high-quality, easily connected, water-proof plugs was one of these, as was the use of the chronograph pens with easily-operated push-buttons for making time checks and the allowance of plenty of working space around the recording motors to simplify the changing of chart rolls and rate gears.

When the instruments were left out in the rain, in some cases undesirable electrolytic conduction and corrosion took place where voltages higher than 6 volts existed between various metal parts and instrument stands or which part of the circuit was grounded. In general it seems best to use self-contained independent battery-supplies for the different instruments. The best practice would appear to be the building of separate instrument-boxes housing one recording motor, the electrical equipment, and any delicate parts such as anemometers and wind-vane heads which should be removed from the instrument stands before transporting. More than one recording motor together with other equipment in one box makes a load too heavy to be lifted carefully by one man and too heavy to be transported on foot over long distances by two men.

The instrument-cases were constructed of 3/4 inch plywood, perhaps a little heavier than necessary, varnished inside, and covered with aluminum paint on the outside. The use of a highly reflecting paint is desirable in order to reduce the temperature extremes inside the boxes and in order to increase their visibility from a distance. These boxes, of screwed and glued construction, stood up well under continuous exposure to the weather for about a year; greater improvement in this regard would result from the use of Bakelite-impregnated plywood and a more lasting outside finish.

Some of the features of the instrument cases can be seen in the photographs in Plates IV and V. The recording motors were mounted on and surrounded by rubber stoppers, to lessen transportation shocks; in order to allow complete access to them, one side and about 1/3 of the top of the case were made removable, and a metal cover was provided to afford more complete protection from rain and dust. It is desirable that the relays, although completely as possible protected from the dust, be easily accessible in the field for occasional cleaning and readjustment of the contacts, and they be mounted with the contact-faces vertical.

B. Circuit Constants for the Wind Direction Device Shown in Figure 3A.

For the twelve volt system, the eight resistors, R_1, were 75 ohm 1 watt carbon resistors, and the 16 resistors, R_2, were 1000 ohm 1 watt carbon resistors. These resistors were mounted directly underneath the contacts on the vane-head in a compact assembly. They were selected for uniform value from about twice the number actually used.

The resistance between terminals X_1 and X_3 was about 578 ohms, corresponding to a current of about 18 milliamperes at 10.4 volts. Since this voltage was to correspond to a milliammeter deflection of .8 ma (see section III, D) and the milliammeter resistance was about 1400 ohms, the extra resistance to be added in series (R_7 of Figure 4) was about 8500 ohms, since the average internal resistance of the potentiometer-ring could be taken as about 500 ohms. The total effective series resistance is sufficiently close to the critical damping resistance of the milliammeter, 15,000 ohms, to allow a nearly maximum rapidity of response.

Another combination of R_1 and R_2, used with the equipment shown in Figure 5, had values of 5 ohms for R_1 and 200 ohms for R_2, all 1 watt carbon resistors. The total resistance between X_1 and X_3 was thus about 39.5 ohms, corresponding at 1.65 volts (this was the voltage used on the light bulb in the anemometer) to a current of about 42 milliamperes. Here, for a maximum reading of .8 milliamperes between X_3 and X_2, the total series resistance, including an average internal resistance of the potentiometer-ring of about 110 ohms and the 1400 ohm milliammeter internal resistance, should be 2060 ohms. This system, supplied by a 2 volt storage battery, required about 3 seconds to respond fully to a change in wind direction, instead of the 3/4 seconds required by the 12 volt system.

C. Circuit Constants for the Wind Speed Recording Circuit Shown in Figure 3B.

B_1 3 volt relay battery; Burgess 2F2H, Size 4 3/4" x 2 5/8" x 2 5/8".

B_2 45 to 90 volt portable B battery. (For example, two Burgess No. 5308 batteries.)

C_1 Spark-Suppressing Condenser; 10 mfd 25 volt electrolytic condenser. (The internal resistance of this condenser was already high enough, so an additional series resistor did not have to be added.)

C_2 Limiting Condenser; 4000 mfd. 12 volt electrolytic.

C_3 Storage Condenser; high quality impregnated paper condensers, 400 volts working voltage. Total value for B_2 of 45 volts, to indicate 8.0 mph at .5 milliamperes, is made up to 4.75 mfd, for the Lane-Wells anemometer.

C_4 Smoothing condenser; 1000 mfd 12 volt electrolytic, giving an electrical time delay of about 4 seconds for indicated velocity decrease from 8 mph to 2 mph.

R_1 Current-limiting resistor; 200 ohm 1 watt carbon resistor.

R_2 Spark-suppressing resistor; 600 ohm 1 watt carbon resistor.

R_3 Current-limiting resistor; 5 ohm 1 watt carbon resistor.

Y_1 Sigma Model 4AP Relay; 2000 ohm, 3 volt operation, single-pole double-throw.

Y_2 Advance Model 500 Relay; 150 ohm, 3 volt operation, double-pole double-throw.

6V counter; 10 ohm "Autelco Jr." 5 figure, made by Automatic Electric Co., Chicago, Illinois.

When used with the Lane-Wells Anemometer, which makes contact for 1/2 of each revolution, the total relay current will be about 27 milliamperes, corresponding to 13.5 milliamperes continuous current drain. Battery B_1, having a nominal capacity of 20 ampere hours should therefore be capable of 60 days continuous service. The entire circuit shown in Figure 3B was fitted into the wooden carrying case originally furnished with the Lane-Wells Anemometer. This is illustrated in Plate IV, except that the relay Y_2 is the Advance type 850 instead of the type 500.

The dotted portion of the circuit shows how a 6 volt auxiliary counter can be plugged into the circuits. One set of Relay Y_2 contacts, drawn above the relay coil, alternately charges C_2 from the 6 volt anemometer battery and then discharges it through the 10 ohm 6 volt counter; this short-period pulse is enough to cause the counter to register, but since a continuous current does not flow during the major part of the time that the anemometer contacts are closed, great battery economy results, and there is no inductive spark when the relay contacts have opened.

This type of circuit, a limiter circuit, was suggested by Lt. R. L. Ives, CWS, who has used it extensively in various similar applications. With a 10 ohm counter, and the Lane-Wells anemometer, the continuous current of a direct relay connection will be .3 amperes and .6 amperes if the anemometer stops in the "on" position. With the limiter circuit shown, the continuous current is proportional to the wind velocity, and at 8 miles per hour, about 2.4 contacts per second, it will be the equivalent of slightly less than 60 milliamperes. A number of counters, therefore, can be operated simultaneously from one switch and a fairly small 6 volt dry battery, for intermittent service.

D. Circuit Constants for Recording and Control Circuit, 12 volt, shown in Figure 4

B_1, B_2	Burgess Uniplex No. 4F4 6 volt dry batteries, or for extended operation at low temperatures can be Willard Charge-Retaining 6 volt 40 ampere-hour lead storage batteries.
C	150 mfd 50 volt electrolytic condenser.
CP	Chronograph Side-Pens on Esterline-Angus recording milliammeters.
R_1	Control for setting deflection of wind direction recorder; for chart paper of 10 major divisions, the deflection should be set to .8 milliamperes when SW_1 is in position 2.
R_2	450 ohm 1 watt carbon resistor.
R_3, R_4	10 ohm 1 watt carbon resistors; these limit the battery current in case the relay contacts touch simultaneously while being adjusted.
R_5	5000 ohm 1 watt carbon resistor, for suppression of contact-spark due to transformer inductance.
R_6	1500 ohm 1 watt carbon resistor; to limit the keep-alive current in the wind speed recorder pen.
R_7	8500 ohm 10 watt wire-wound resistor.
Relay	Advance Model 500 Relay; 1000 ohm, 6 volt, double-pole double-throw.
SW_1	Single-pole double-throw Toggle Switch
SW_2	Push-Button type Microswitch for actuating Chronograph Pens.
SW_3	Double-pole single-throw Toggle Switch; for completely removing batteries from circuit.
T_1, T_2	Doorbell transformers, 10 watt, 110 volts, to 10 volts, 60 cycle. (More efficient transformers could probably be found for this purpose.)

X_1, X_2, X_3 Connections to Wind Vane (Figure 3A).

X_4, X_5 Connections to Relay-Type Frequency Meter (Figure 3B).

This control box, shown in Plate IV, was self-contained for all the equipment shown. It was, as a result, somewhat heavier than desirable; it would have been better to have broken it up into two boxes, with connecting plugs.

E. Circuit Constants for Wind Speed Recording Apparatus Shown in Figure 5

B_1 Grid bias battery, Burgess No. 5540 7½ volt C battery or equivalent; the grid bias voltage is adjusted by selection of the appropriate battery terminal until the relay current varies between zero and about 2.0 milliamperes as the light is cut off and on the photocell.

B_2 45 volt battery, as Burgess No. 2038

R_1 Current-limiting Resistor; 200 ohm 1 watt carbon resistor.

R_2 12 ohms of resistance wire, wound on form and adjusted until filament voltage is 1.45 volts with freshly-charged storage battery.

R_3 2 ohm, 4 watt wire wound rheostat.

R_4 5 megohm 1 watt carbon resistor.

Relay Advance type 850; 10,000 ohm coil 1 milliampere operating current, with contacts adjusted and spring tension increased for maximum reliability of operation at high wind speeds.

C_3 .5 mfd. 400 volt tubular paper condenser; this acts to increase the useful speed of response of the relay.

Bulb Mazda 2.2 volt penlite flashlight bulb, with lens moulded integrally with glass bulb; lamp operated at 1.65 volts, about .18 amperes.

P.E. Cell - Cetron CE-20-C miniature photocell (caesium - caesium oxide surface), dimensions about 2 1/2" x 5/8".

VM 2 volt voltmeter, resistance 400 ohms or higher.

1 A5-G Battery-type output pentode; 1.4 volt filament at .05 amperes.

The Friez ML-80 anemometer is modified by removing the shaft, turning off the worm gear which engages the gear-train of the counting mechanism, and boring a hole through the turned-down portion of the shaft. This hole should be about 1/3 the diameter of the shaft at this section.

The bulb is mounted inside the counter case, at the same level as the hole in the shaft, and the photocell is mounted outside the housing on the opposite side in a weather-proof light-proof housing. The distance between the bulb and the photocell should be as short as possible, for maximum light on the cell; an aperature in front of the light bulb prevents appreciable stray light from reaching the photocell when the hole in the shaft is perpendicular to the bulb-photocell axis.

F. Circuit Constants for the Ratiometer Shown in Figure 6

C_1, C_2	2 mfd 400 volt paper condensers.
C_3, C_4	.01 mfd 600 volt tubular paper condensers.
C_5	16 mfd 600 volt impregnated paper condensers (selected for high internal resistance).
C_6, C_7	100 mfd 50 volt electrolytic condensers.
R_1, R_2	250 ohm 1 watt carbon resistors.
R_3, R_4	500 ohm 1 watt carbon resistors.
R_5	250 ohm 1 watt carbon resistor.
R_6	5000 ohm 1 watt carbon resistor.
R_7, R_8	5 megohm 1 watt carbon resistors.
R_9	4000 ohm 1 watt carbon resistor.
R_{10}, R_{12}	5,000 ohm 1 watt carbon resistor.
R_{11}	10,000 ohm wire wound 5 watt potentiometer.
VT_1, VT_2	1 H4G triodes, 2 volt filaments at .06 amperes each.
Y_1 to Y_8 inclusive	Advance Model 850 Relays; 10,000 ohms, 1 milliampere operating current, single-pole double-throw.

24 volt supply: 4 Burgess No. 4F4 Uniplex dry batteries in series.

2 volt supply: Willard Charge Retaining Lead Storage Battery type CR-2-3, with the three cells connected in parallel (120 ampere hours, total).

90 volt supply: 2 Burgess No. 2308 45 volt batteries in series.

B_1, B_2 90 volts each, small portable B batteries.

Keep-Alive for recording-milliammeter not shown.

G. Circuit Constants for the Photocell and Vacuum-Tube Frequency Meter Shown in Figure 7

B_1, B_2, B_3	Two-volt flashlight lead storage batteries, 1.6 ampere hours capacity, dimensions equal to two size D flashlight cells in series. (Made by the Ideal Commutator Dresser Company, Sycamore, Illinois.)
B_4	Two 7½ volt Burgess No. 5540 C Batteries, in series.
B_5, B_6	Two 7½ volt Burgess No. 5540 C batteries, in series.
B_7	Burgess No. 5308 45 volt B battery.
B_8	Two Burgess No. 5308 batteries in series.
C_1	0.1 mfd. 600 volt tubular paper condenser.
C_2	10 mfd. 50 volt electrolytic condenser (for smoothing out oscillations at lowest anemometer speeds).
R_1, R_2	0.1 megohm 1 watt carbon resistors (for limiting positive grid current of vacuum tubes).
R_3	4000 ohm 1 watt carbon resistor (to limit damping effect of C_2).
R_4	5 megohm 1 watt carbon resistor.
1 H4-G	Two-volt triode for direct operation from 2 volt storage battery; .06 ampere filament.
Bulb	Mazda 2.2 volt penlite flashlight bulb, with lens moulded integrally into glass bulb; lamp operated directly from 2 volt storage battery carried on vane and serving to counter-balance Biram anemometer; lamp mounted so as to offer as little wind-resistance as possible.
Lens	Bausch & Lomb Hastings triple aplanat magnifier; to form real image of end of light bulb on pinhole aperture.

P.E. Cell Cetron CE-20-C miniature phototube (caesium - caesium oxide surface) approximately 2 1/2" x 5/8", mounted in light-proof housing so as to offer as little wind-resistance as possible.

The Biram anemometer, photocell, light bulb, and battery were mounted with a vane on the vertical shaft of a Friez 339-L anemometer, with an insulated slip-ring for the cathode return from the photocell. The anode was grounded to the shaft. Because of the high value of the grid resistor, R_4, the two-conductor cable connecting the photocell leads to the frequency meter must be well-insulated and the capacity between the two wires must not be too great. This apparatus is shown in Plates I and III. The apparatus is not suited to continuous recording, but is useful in gustiness measurements at low wind-velocities.

H. Circuit Constants, for the Photoelectric Galvanometer (Reflecting Type) Shown in Figure 8

R_1, R_2 10,000 ohm 1 watt carbon resistors

R_3 5,000 ohm cathode resistor

R_4, R_5 10 megohm 1 watt carbon resistors.

R_6 For .4 millivolts full-scale, slightly less than 0.4 ohms, carefully made from manganin wire soldered to copper or brass, and adjusted to give the proper full-scale reading on the recording milliammeter.

Bulb 6.2 volt 5-cell focusing flashlight bulb; current about .25 amperes.

Condensing Lens Bausch & Lomb 7x Hastings triple aplanat magnifier.

Image-Forming Lens The lens originally furnished with the galvanometer; this forms a sharp image of the rectangular aperture on the photocells at a 6 inch distance.

Galvanometer: Element for General Electric Portable Type Galvanometer, Model 32C230G10 (consists of mirror galvanometer and housing only). Sensitivity .32 microamperes per millimeter (6 inches distant from mirror); period, 2.3 seconds; coil resistance, 8.8 ohms; external critical damping resistance, 20 ohms.

Photocell RCA Type 920 twin photocell (contains two complete units in one glass envelope).

6SJ7-G High mutual conductance cathode heater-type pentodes; rated filament voltage, 6 volts at .3 amperes. These tubes should be selected to have as nearly as possible identical characteristics, combined with low grid-current.

90 volt battery Two Burgess No. 2308 45 volt B batteries in series - current drain about 2 milliamperes.

The galvanometer unit is housed separately from the control equipment shown in Figure 10. This enables it to be carried separately in order to give the unit more protection from mechanical shocks. The filament voltage - supply carried in the control box is adjusted to 5.2 volts; the total filament and bulb current is then about .8 amperes.

I. Circuit Constants for the Photoelectric Galvanometer (Shadow Type) Shown in Figure 9

R_1, R_2 5,000 ohm 1 watt carbon resistors.

R_3, R_4 10 megohm 1 watt carbon resistors.

R_5 2,000 ohm 1 watt carbon resistor.

R_6 9 ohms, wound from resistance wire and adjusted so that there is 1.35 volts across the filaments of the 1S5 pentodes, when the over-all filament voltage has been adjusted to 5.4 volts.

R_7 About 1.4 ohms, carefully made of manganin wire soldered to copper or brass and adjusted to give 1.6 millivolts full scale range. (This range corresponds to a temperature range of plus or minus 5°C in the measurement of temperature gradient when a 4-junction couple is used.)

1S5 Battery-type pentodes; 1.4 volt filament at .05 amperes.

Photocells - Two RCA type 927 (similar to the Cetron CE-20-C) mounted just far enough apart so that the shadow of the vane cuts off half the light on each photocell cathode.

Shadow Vane - A small piece of aluminum foil, about 1/4 inch wide, cemented to the lower visible portion of the microammeter pointer. This additional weight to the moving system must be counterbalanced in order that the instrument may not be sensitive to levelling.

Microammeter - Weston Model 430; 0 to 30 microamperes; coil resistance about 160 ohms. A rectangular aperture was sawn in the back of the case, and the photocells and vacuum tubes mounted directly on the back of the case.

Bulb 6.2 volt 5-cell focusing flashlight bulb, mounted over the front glass of the meter with enough side-play to allow the adjustment of the zero to be made by slightly shifting the position of the bulb.

90 volt supply - Two Burgess No. 2308 B batteries in series. Note that with filament-type vacuum tubes, the circuit requires a separate lead from the 90 volt minus terminal.

5.4 volt supply - From 6 volt storage battery with 6 ohm rheostat and indicating voltmeter for adjustment to 5.4 volts; current-drain about .23 amperes.

The principles of operation of this instrument are similar to those of the reflecting type photoelectric galvanometer, except for the methods of varying the light on the photocells. The construction is simpler and more compact and the battery consumption considerably lower, but the maximum sensitivity is not as high; the effective amplification of the photocell-vacuum tube combination is not as high, nor is the sensitivity of the pivoted moving coil microammeter as high.

In order to have maximum light on the photocells, the distance between them and the bulb should be made as short as possible. It should be noted that in adapting a meter of this type, the effective full scale range, 1.6 millivolts, is about 1/3 of the original full-scale range, 4.8 millivolts. Therefore there was a 3-fold gain in sensitivity, at no apparent loss in accuracy and a tremendous improvement in time of response, since when used alone in low-resistance circuits, the microammeter was greatly over-damped.

J. <u>Circuit Constants for the Control Circuit and Keep-Alive for Use with the Photoelectric Galvanometer, Shown in Figure 10</u>

B_1, B_2	1½ volt size D flashlight batteries (7.5 microamperes current-drain)
C_1	1000 mfd. 12 volt electrolytic condenser.
C_2	1 mfd. 400 volt paper condenser.
R_1	25 ohm 1 watt carbon resistor
R_2, R_3	5,000 ohm 1 watt carbon resistors.

R_4	10,000 ohm 1 watt carbon resistor.
R_5	2 ohm (for current of .8 amperes) or 6 ohm (for current of .25 amperes) 4 watt wire wound rheostat.
R_6	1 ohm 1 watt carbon resistor.
SW_1	On-Off toggle switch.
SW_2	Push-button type Microswitch.
B_3	Two Burgess No. 2308 45 volt batteries, for 90 volt supply to vacuum tube circuits.
Relay	Advance type 500 6 volt 150 ohm relay, double-pole, double-throw.

6 volt battery - 120 ampere hour automobile-type lead storage battery.

The complete control circuit, including batteries and shock-mounted Esterline-Angus recording milliammeter, is built into an instrument case, as shown in Plate V; the connection to the case containing the photocells, vacuum tubes and galvanometer is made by plugs.

The basic design of the photoelectric galvanometer may be extended to cover a wide range of uses; several ranges of temperature may be covered by providing a switching arrangement to select different values of R_6 (in Figure 8), and the input emf. can at the same time be switched to different sources. The instrument would work well, for example, in conjunction with a hot-wire anemometer for the recording of low wind velocities.

VI. SAMPLE RECORDS FROM THE MICROMETEOROLOGICAL EQUIPMENT

Figures 11 to 16, inclusive, serve to illustrate the type of records obtainable with the equipment described. The original width of the scale on the chart-paper is 4½ inches, but for purposes of reproduction the scale has been somewhat reduced.

In the comparison of the three types of anemometers shown in Figure 11, the small details of the curve from the Biram anemometer are evidently real, since curves from two Birams side by side have both shown the same minute variations. If the Lane-Wells anemometer had been fitted with a light-interrupter photocell device, with vacuum-tube frequency meter, the recorded curve would undoubtedly be similar to that from the Biram, as the electrical time-delay intentionally introduced with the relay-type frequency meter is the chief cause of the slower over-all response shown by the Lane-Wells curve. At approximately 3½ minutes time, however, the Biram anemometer stopped completely, while the Lane-Wells continued to turn at about 8 pulses per minute, corresponding according to the calibration chart to about .65 miles per hour. This is just about the threshold of the Biram anemometer.

The still slower response of the Friez 339L anemometer is quite apparent,, thus indicating that there would be little to be gained by decreasing the electrical time-delay. Furthermore, if the time required for a satisfactorily complete response from the 339L be considered as 30 seconds, it is easy to see that if the area to be represented by its wind speed record is large, then rapidity of response to highly localized conditions becomes of less importance.

These same considerations apply to the records shown in Figures 12 and 13. On still slower paper speeds such as 3 inches per hour, the inferior response time of the Friez ML-80 becomes of an advantage, however, in that the average velocity is more easily estimated from the simpler curve. In any case, it is evident that the maximum and minimum velocities recorded depend on the total response-time of the recording instruments. Figures 12 and 13 also show the original time-marks made by the chronograph pens.

The wind direction record illustrated in Figure 14 is reasonably easy to interpret, although taken at a slow paper speed. At 1000 h, the direction record shows the effect of a wind shift through NE, and the pen sweeps clear across the paper. The characteristic of recording the wind direction in definite steps makes the record somewhat easier to follow, than would be the case if a continuously varying potentiometer were used.

The variations in the record of temperature gradient, shown in Figure 15, under lapse conditions, do not seem to be closely associated with wind speed, but more probably with the instantaneous vertical component of wind velocity. The extent of these fluctuations decreases as neutral conditions are approached (where they are non-existent) and then under inversion conditions the fluctuations behave in a different manner, being then closely associated with wind speed in a qualitative but not quantitative manner. Under slight lapse, neutral, and inversion conditions, a high accuracy in the expression of the temperature gradient is fully justified.

The records of surface temperature, such as is shown in Figure 16, are considered to be significant to ± 2°F, as read directly from the recorded curve; they are usually in agreement with the mercury thermometer measurements within this limit, provided the thermocouple is in good contact with the soil and has a bright surface. As is usually the case with meteorological measurements, any justifiable attempt to utilize a higher accuracy of measurement than this will require an intensive survey in order to determine how representative a single spot reading really is. In the use of a fine-wire couple with the felt-pad method of exploring surface temperatures, a fast automatic recording system such as those described is extremely convenient.

If a larger number of comparative sample records from different instruments had been included in this report, it would serve chiefly to emphasize the desirability of standardizing the equipment used at the various CWS stations in order that the records of the quantities measured could be easily compared, in order to reduce to standard practice the operation of the instruments, and in order to avoid duplication of instrumental research activities at the various installations. This does not mean that the development of new and better instruments should be inhibited, or that the standardization should be undertaken without careful consideration of all the factors involved, but it is felt that the information now available from a variety of sources can be successfully utilized to result in a considerable saving of manpower and in improved data in any future Chemical Warfare research.

This report should not close without a word of appreciation for the support and encouragement given the NDRC Laboratory at Dugway Proving Ground by the Commanding Officer and those under him. In particular, acknowledgement is due to 1st Lt. R. L. Ives, CWS, and Captain Earle C. Fowler, CWS, for their help and advice in connection with the construction and operation of these instruments, and to the staff of the Technical Operations Division for attending to the mechanics of the publication of this report.

TABLE I

CLASSIFICATION OF FOUR ROTATING ANEMOMETERS WITH RESPECT TO DESIRABLE FEATURES

Type of Anemometer	Friez ML-80 with Photocell	Friez 339-L	Lane-Wells	Biram K.& E. #5967
Impulses per revolution	2	1	1	10
Impulses per second at 8 mph wind speed	2.6	1.21	2.38	11.39 (on 4 mph basis)
Minimum approximate velocity to which anemometer responds	3/4 to 1 mph	3/4 mph	1/2 mph	1/2 mph
Time required to coast in still air from 8 mph indication to 2 mph indication	24 sec	18 sec	9 sec	--
Time required to coast from 4 mph indication to 1 mph indication	32 sec	22 sec	14 sec	10 sec
Maximum wind velocity to which anemometer should be subjected	100 mph	35 mph	25 mph	6 mph
Reliability of contacting mechanism	good	excellent	fair	fair
Resistance to continued use and exposure	excellent	good	fair	very poor
Suitability for use in portable equipment	fair	good	excellent	fair

TEXT FOR PLATES I TO VII

Plate I

Left to right: (1) Friez ML-80 3-cup anemometer, fitted with photocell; (2) Keuffel & Esser 6 inch Biram anemometer (Model #5697), mounted on vane with light, battery, and photocell; (3) Friez 339-L anemometer; (4) (in foreground) Friez 363-C wind-vane head, contacts exposed to show potentiometer-ring of resistors installed in compact arrangement; (5) Lane-Wells anemometer.

Plate II

Wind-speed and direction apparatus installed and operating in the field. Left to right: Friez 339-L anemometer and 363-C wind vane (on top of hill); control panel with rheostat and voltmeter for adjusting wind direction voltage; recording milliammeter for wind speed, Willard C-R-2-3 storage battery; external binding posts for anemometer and wind-vane connections and for recording milliammeter for wind direction (housed separately, not shown in photograph).

Plate III

Left to right: Self-contained vacuum-tube frequency meter; wind vane mounting for Biram anemometer; self-contained relay oscillator keep-alive with multitap output transformer and terminals and push-button for supplying 6 volts to chronograph pens.

Plate IV

Complete equipment for 12-volt wind-speed and direction recorder.

Plate V

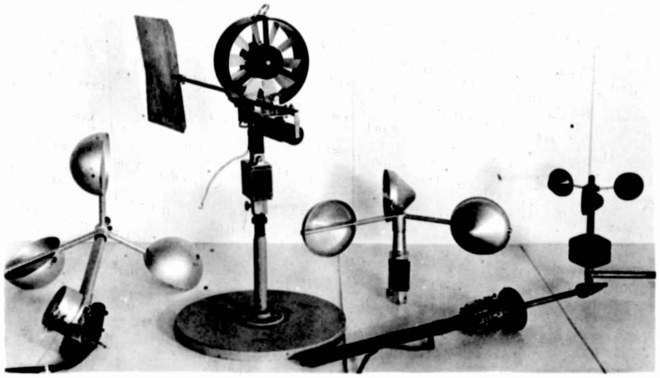
Self-contained unit for use with photoelectric galvanometer.

Plate VI

Photoelectric galvanometer, reflecting type. Left to right: 6SJ7-G vacuum tubes; housing for twin-photocell; condensing lens; battery terminals; galvanometer; input emf terminals and milliammeter terminals.

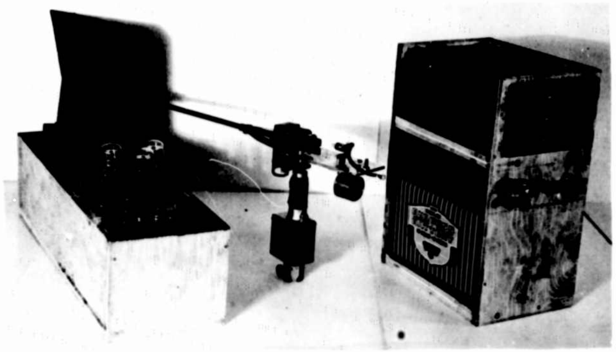
Plate VII

Photoelectric galvanometer, shadow type. The 6 volt flashlight bulb is mounted on top of the microammeter, and the compact assembly of photocells, vacuum tubes, and other circuit components is mounted in the rear.

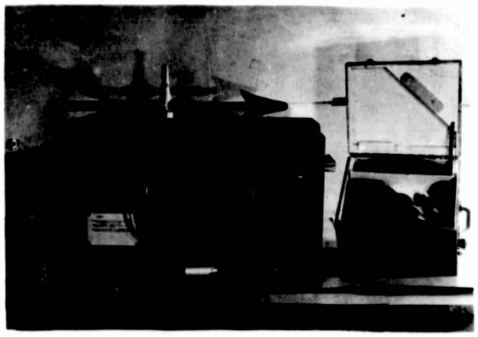


I

II

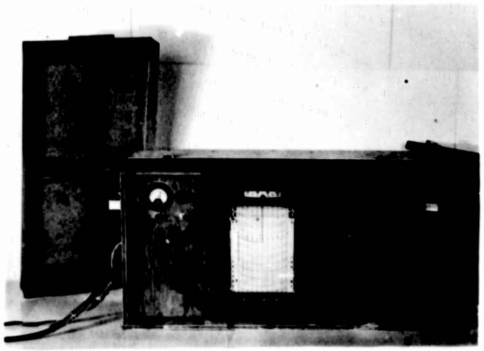


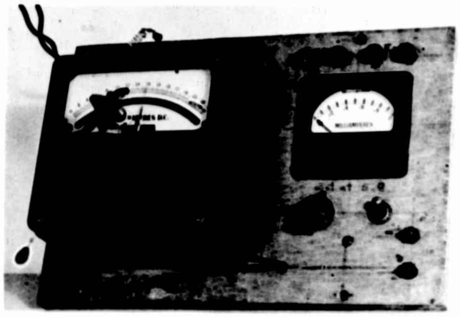
III



IV

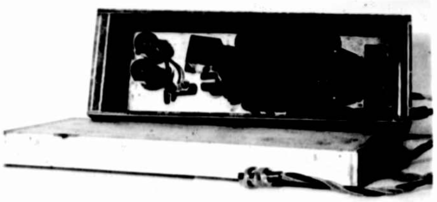
V



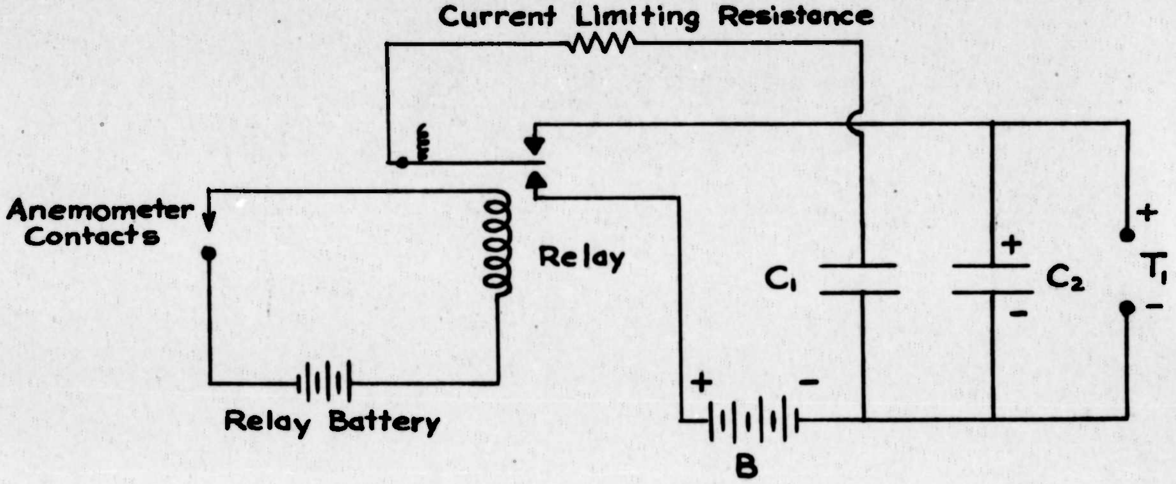


VII

VI



PLATES I TO VII
EQUIPMENT USED IN MICRO-METEOROLOGICAL MEASUREMENTS.
(FOR DETAILS SEE TEXT)



C_1	Storage Condenser - 4 mfd
C_2	Smoothing Condenser - 2000 mfd electrolytic.
T_1	Terminals of 0-1 ma Esterline - Angus Recorder.
B	Frequency - Meter Battery - 45 or 90 Volts

FIGURE 1 CIRCUIT OF RELAY-TYPE FREQUENCY METER

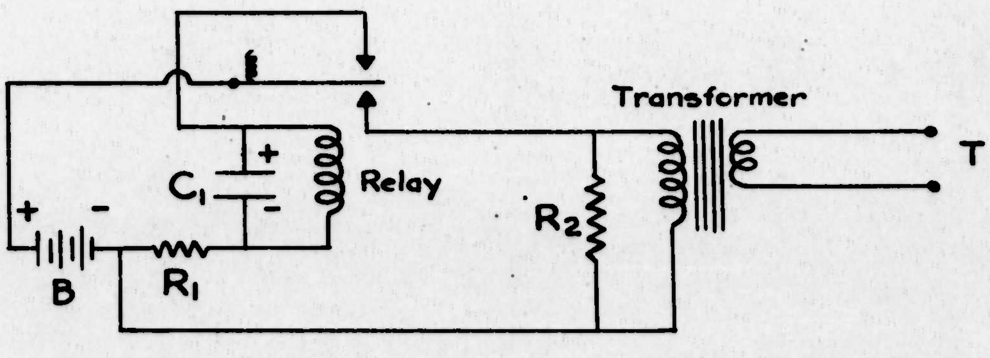
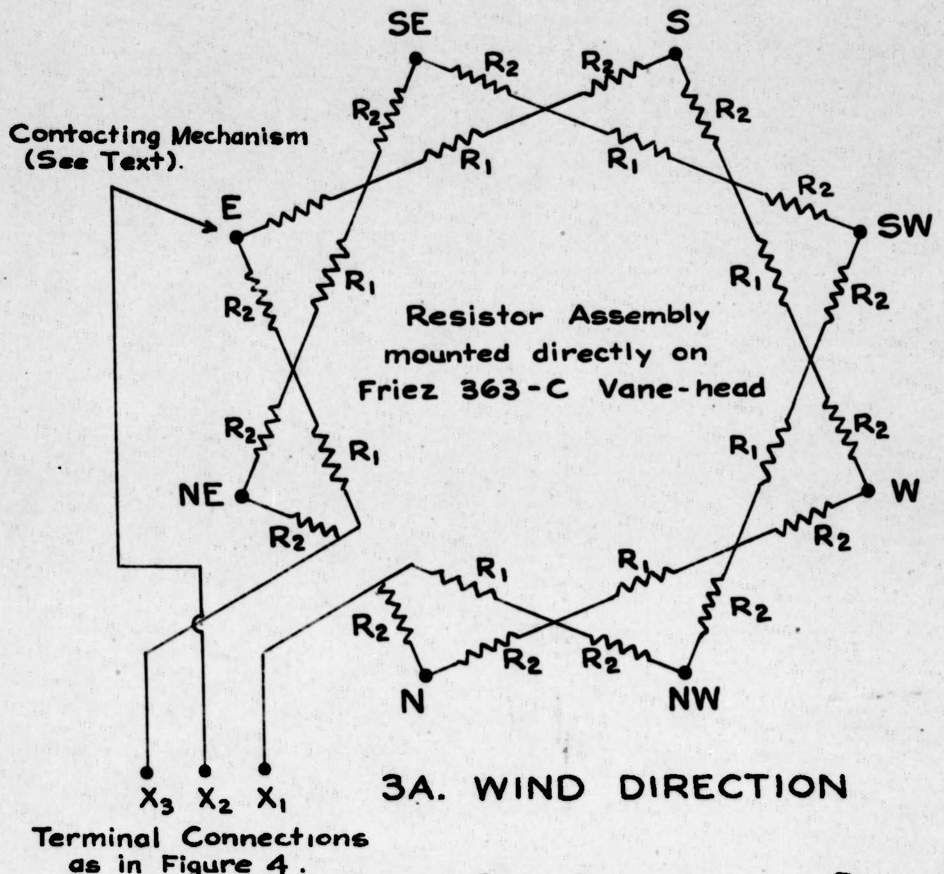
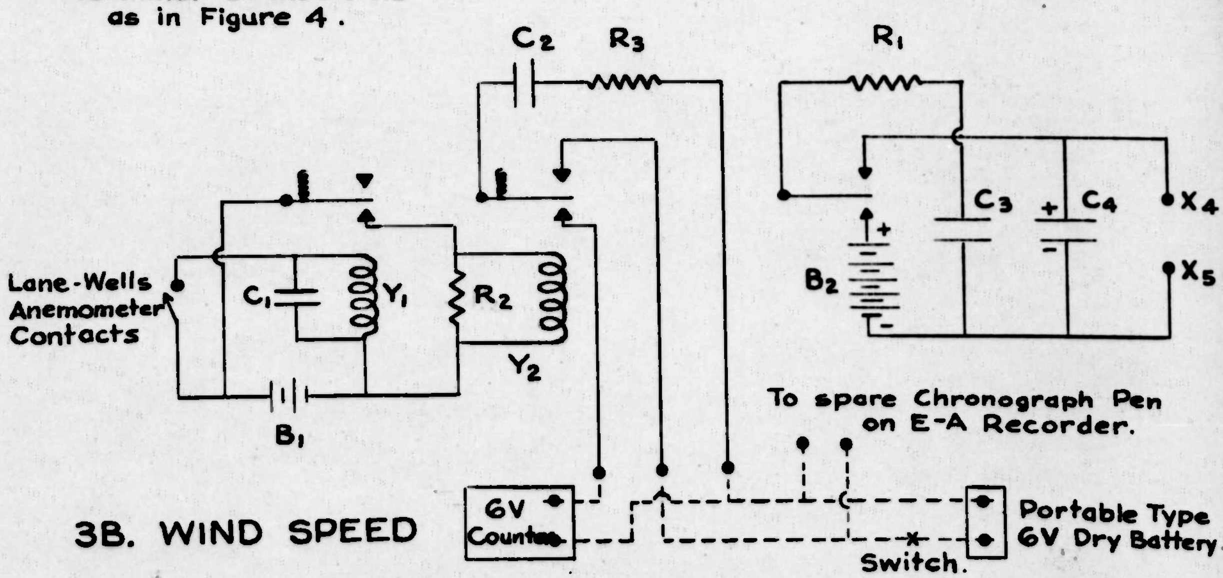


FIGURE 2 CIRCUIT OF RELAY-OSCILLATOR WITH TRANSFORMER FOR USE AS KEEP-ALIVE BY SERIES CONNECTION WITH E-A RECORDING METER.



3A. WIND DIRECTION



3B. WIND SPEED

FIGURES 3A AND 3B

WIND DIRECTION AND SPEED RECORDING CIRCUITS FOR USE WITH CONTROL CIRCUIT SHOWN IN FIGURE 4

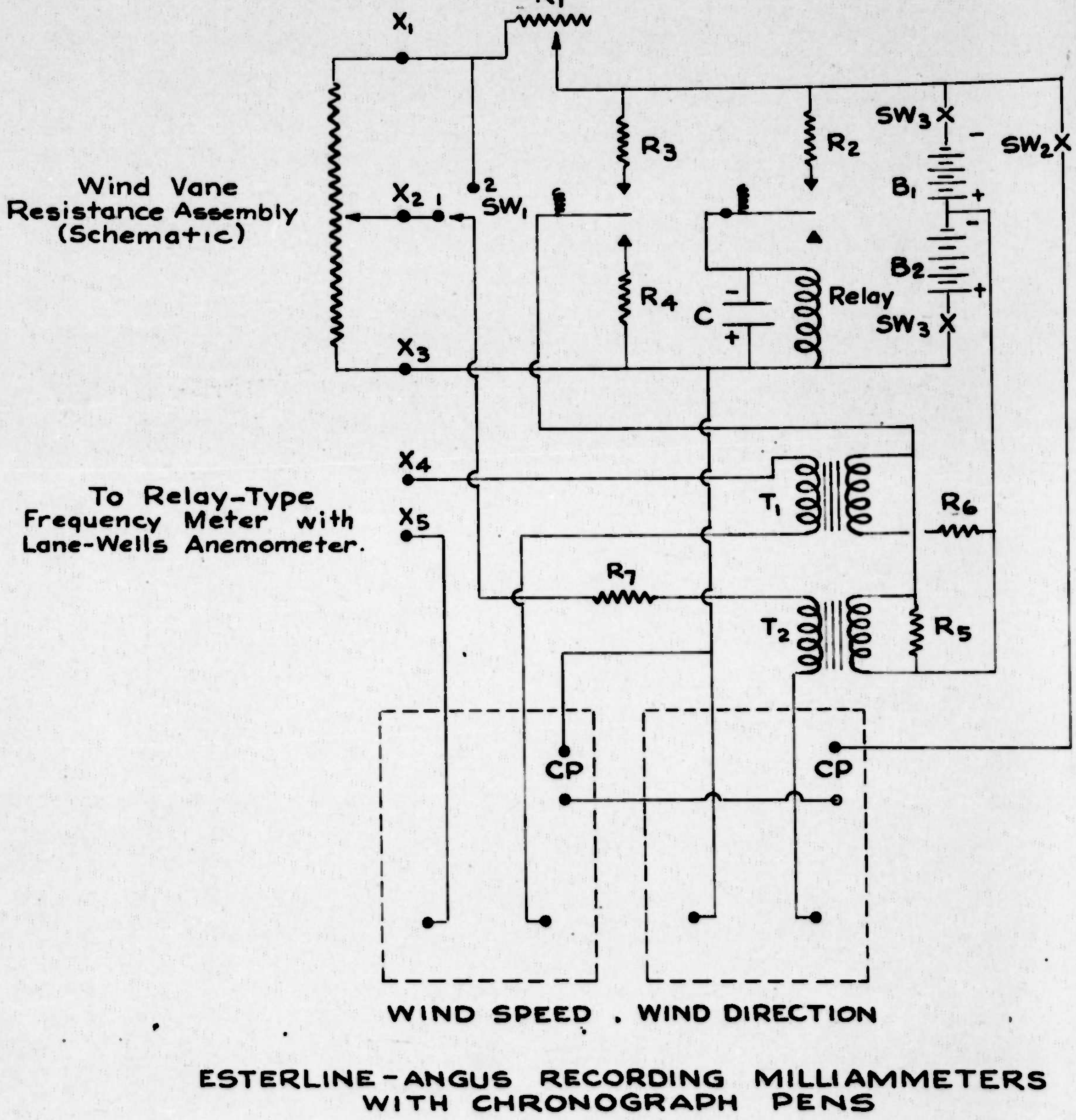


FIGURE 4

RECORDING AND CONTROL CIRCUIT,
12 VOLT, FOR WIND SPEED AND DIRECTION

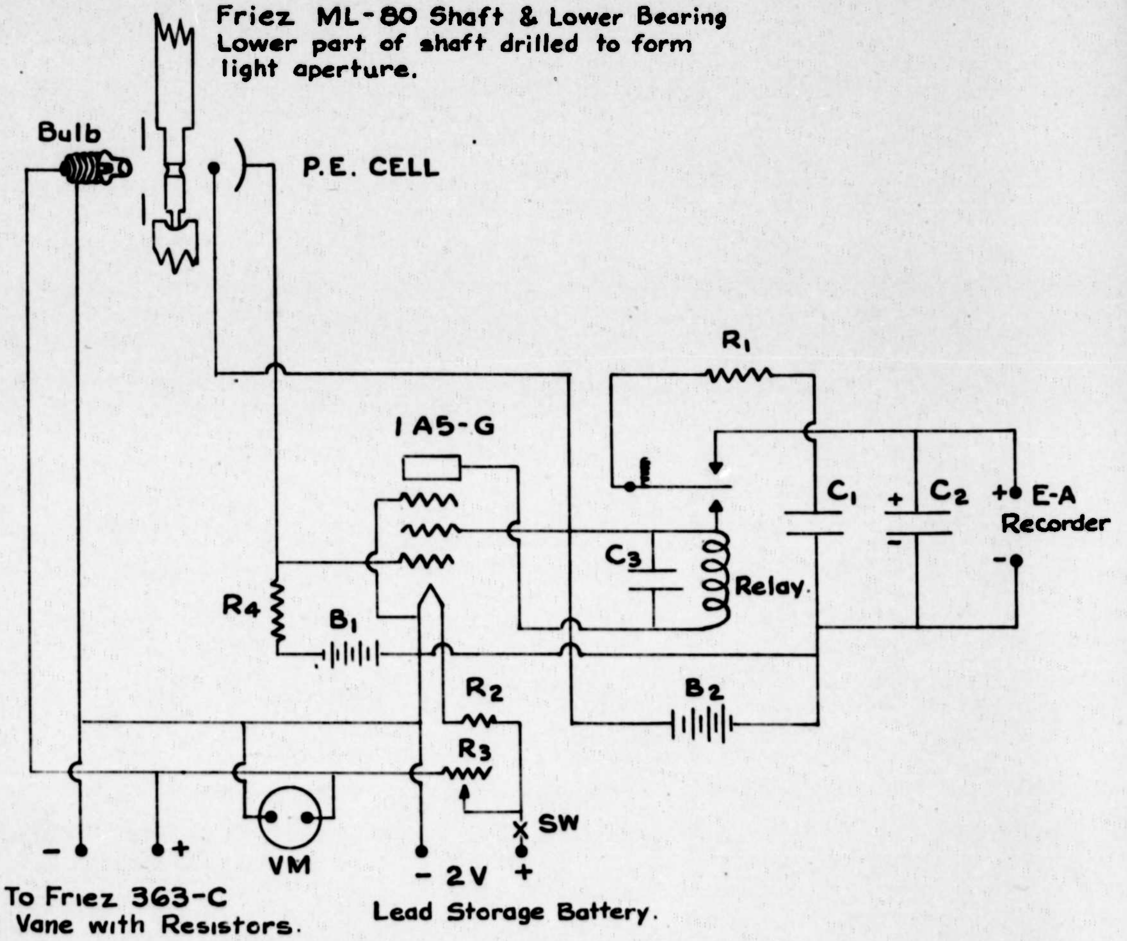


FIGURE 5

WIND SPEED RECORDING CIRCUIT USING FRIEZ ML 80 ANEMOMETER MODIFIED WITH PHOTO-CELL

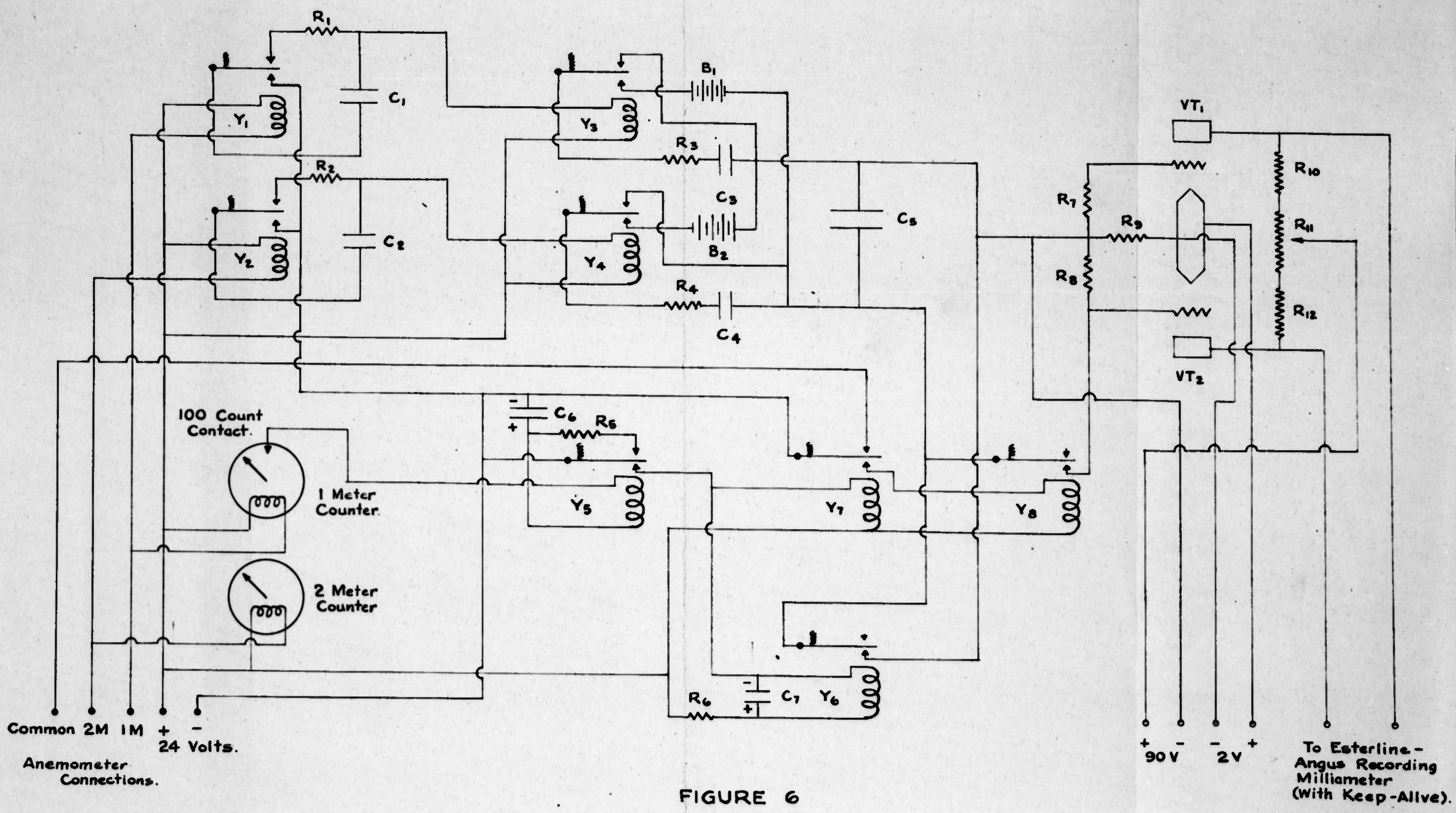


FIGURE 6

CIRCUIT DIAGRAM FOR RATIOMETER: FOR RECORDING DIRECTLY THE RATIO OF COUNTS FROM TWO ANEMOMETERS, AND HENCE FOR RECORDING APPROXIMATELY THE RATIO OF THE WIND SPEED AT 2 M HEIGHT TO THAT AT 1 M HEIGHT.

RESTRICTED

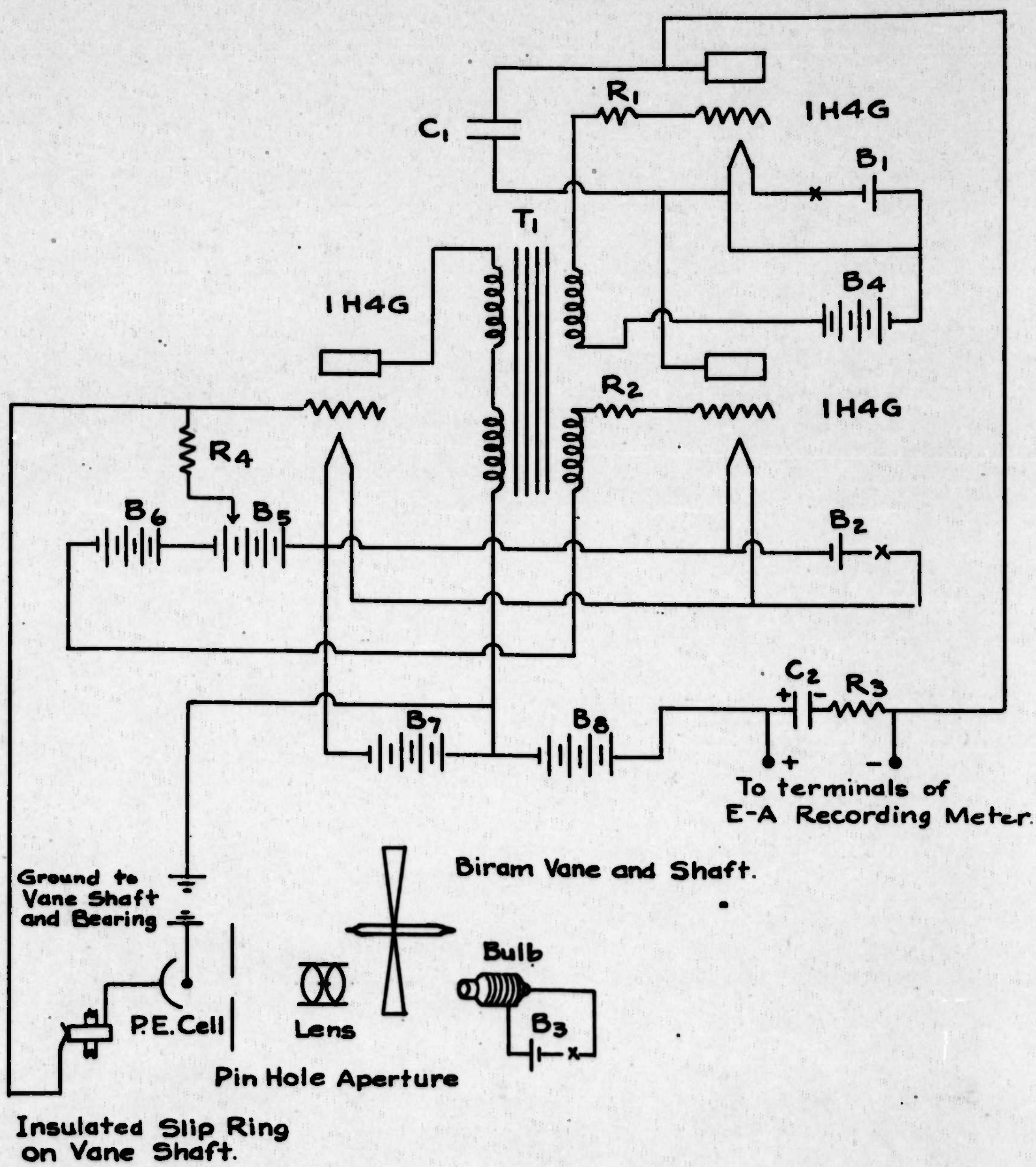


FIGURE 7

PHOTOCELL AND VACUUM-TUBE FREQUENCY METER FOR USE WITH VANE-MOUNTED BIRAM ANEMOMETER

RESTRICTED

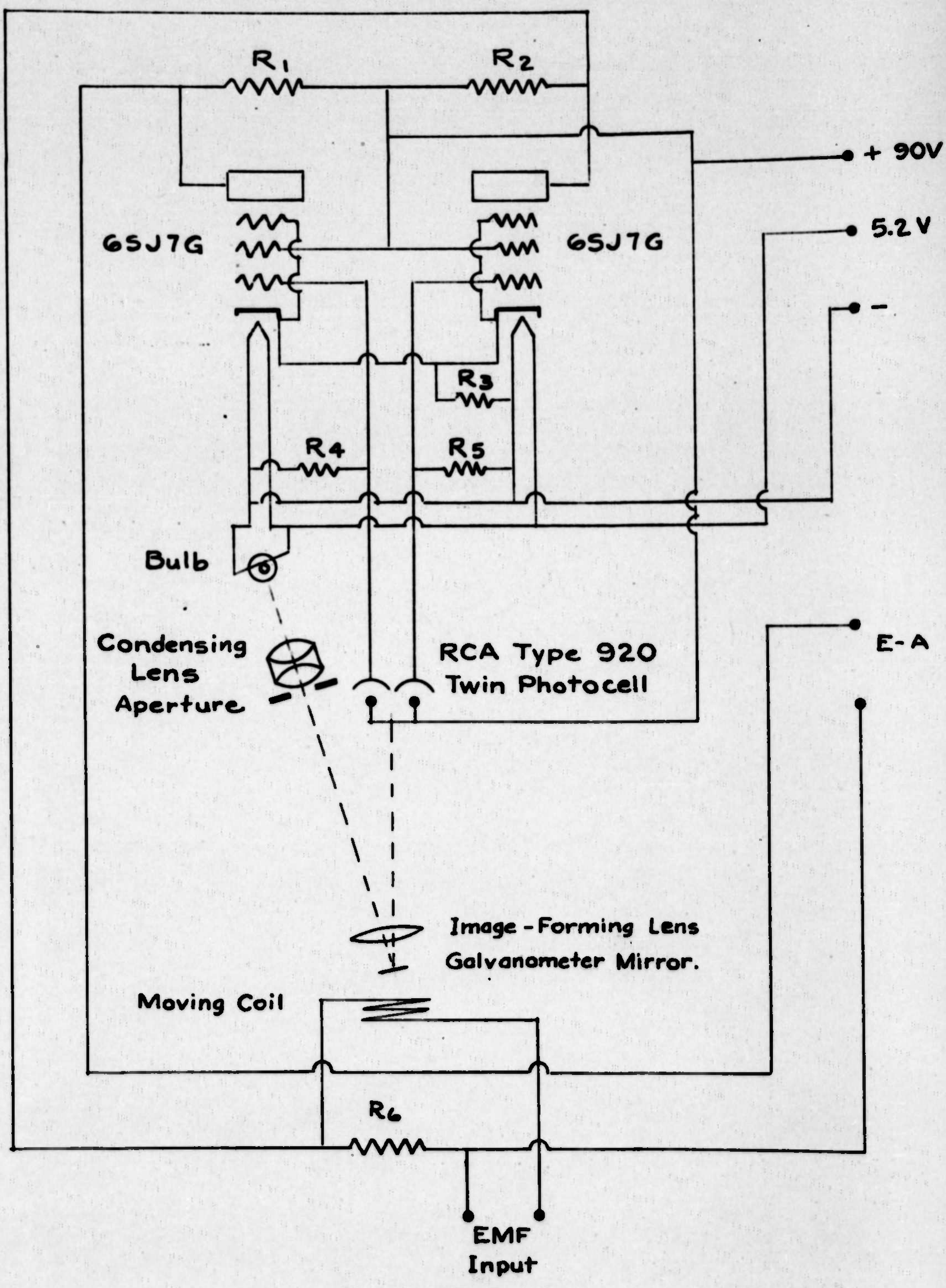


FIGURE 8

PHOTOELECTRIC GALVANOMETER
FOR USE WITH THERMOCOUPLES
REFLECTING TYPE

RESTRICTED

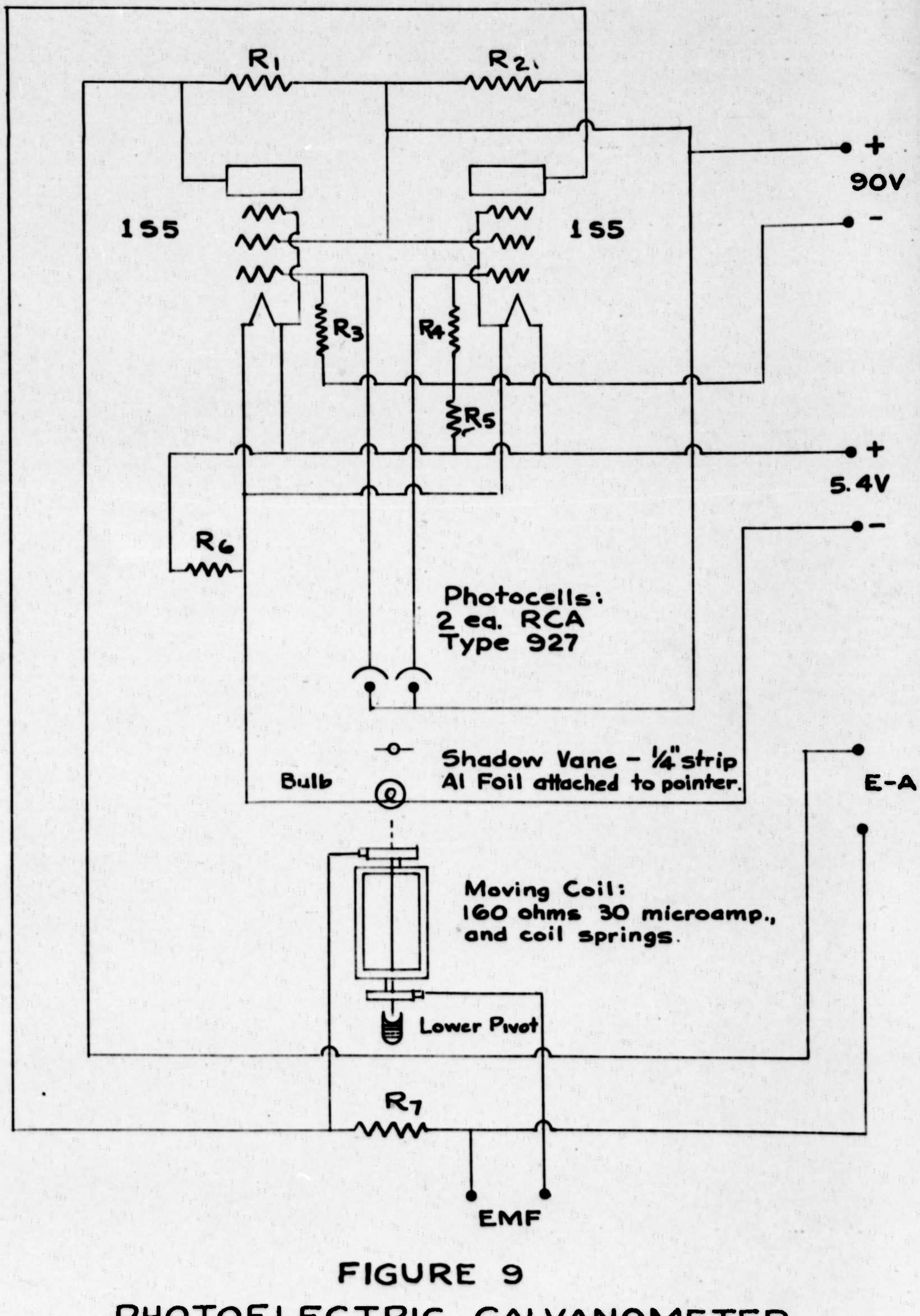


FIGURE 9

PHOTOELECTRIC GALVANOMETER FOR USE WITH THERMOCOUPLES SHADOW TYPE

RESTRICTED

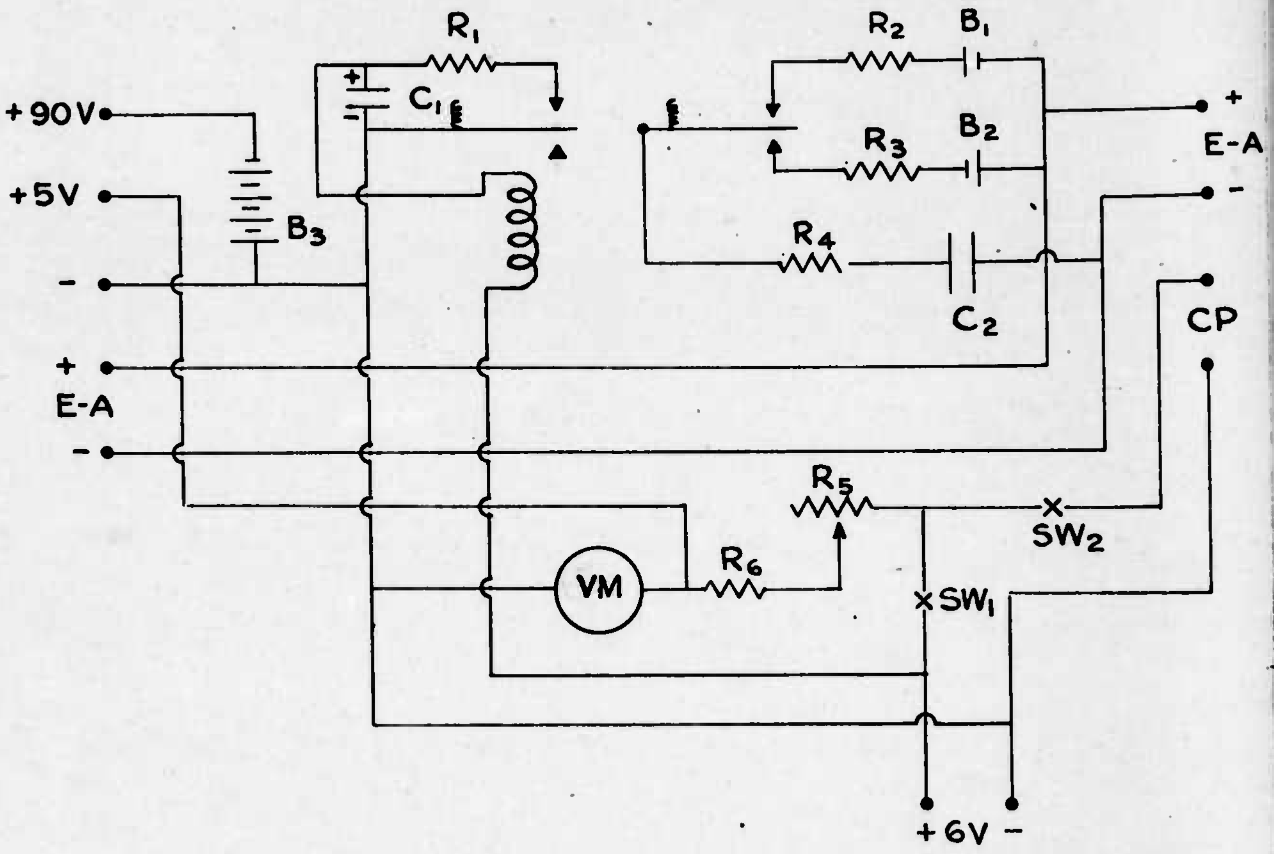


FIGURE 10

CONTROL CIRCUIT AND KEEP ALIVE
FOR USE WITH PHOTOELECTRIC GALVANOMETER

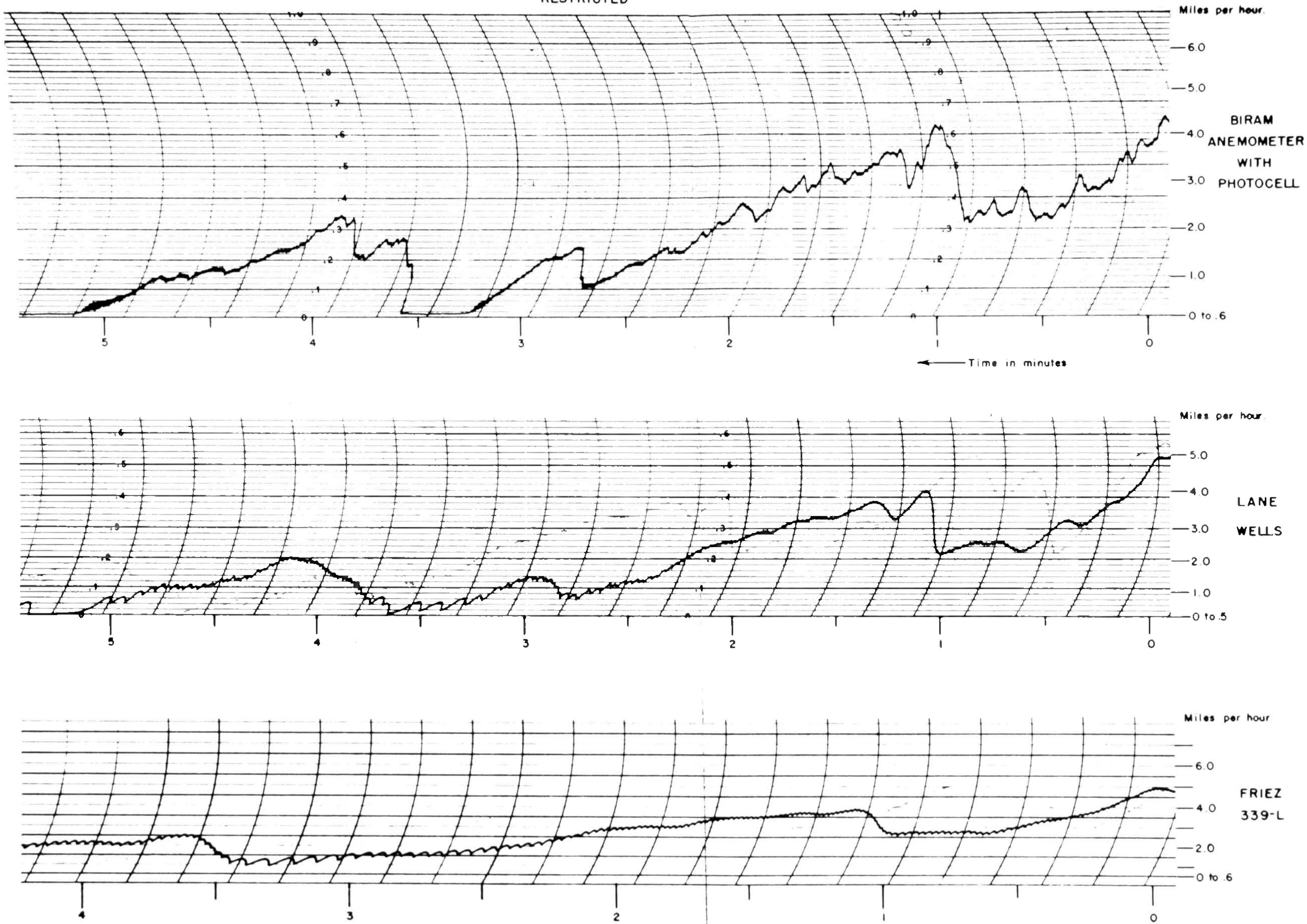


FIGURE 11

SIMULTANEOUS RECORD FROM BIRAM ANEMOMETER, LANE WELLS (TWO CONTACTS PER REVOLUTION), AND FRIEZ 339-L (TWO CONTACTS PER REVOLUTION) 1002, 17 AUGUST 1945; LAPSE CONDITIONS

CHARTS APPROXIMATELY 2/3 FULL SIZE

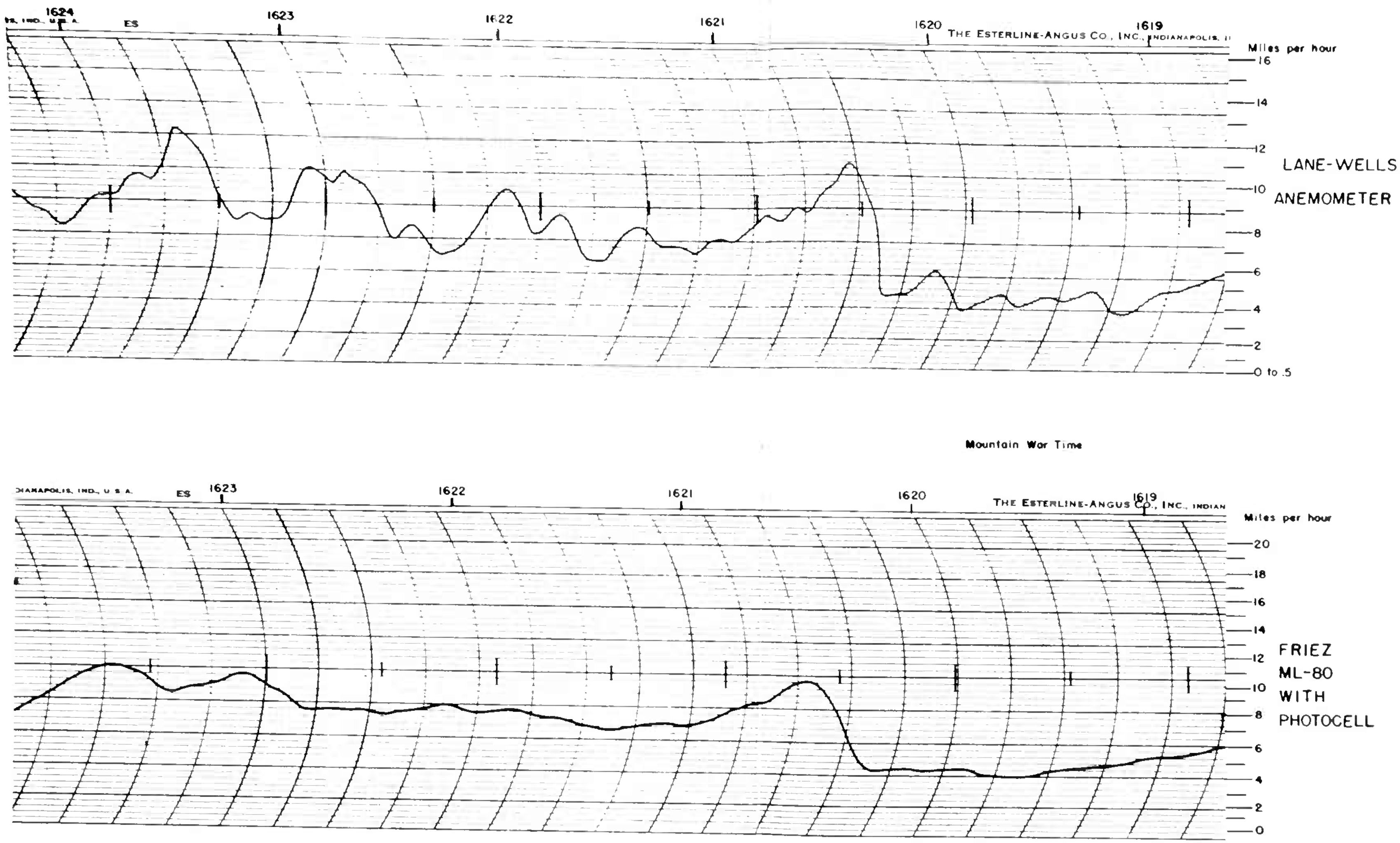


FIGURE 12

SIMULTANEOUS RECORDS FROM FRIEZ ML-80 ANEMOMETER AND LANE-WELLS ANEMOMETER (ONE CONTACT PER REVOLUTION) 1619 - 1624, 7 JULY, 1945 (LAPSE CONDITIONS

CHARTS APPROXIMATELY 2/3 FULL SIZE

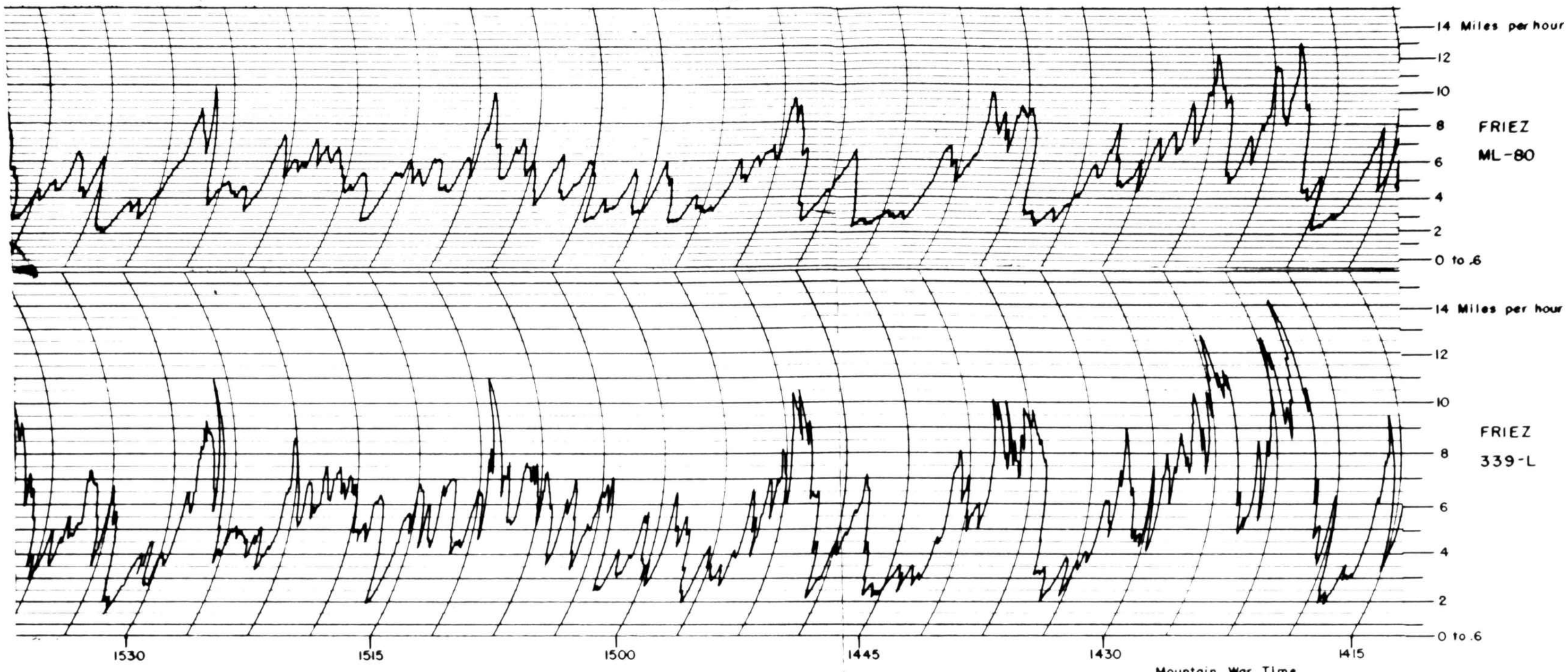


FIGURE 13

SIMULTANEOUS RECORDS FROM FRIEZ ML-80 AND FRIEZ 339-L ANEMOMETERS (TWO CONTACTS PER REVOLUTION) JULY 1945
LAPSE CONDITIONS. PAPER SPEED: 12 INCHES PER HOUR

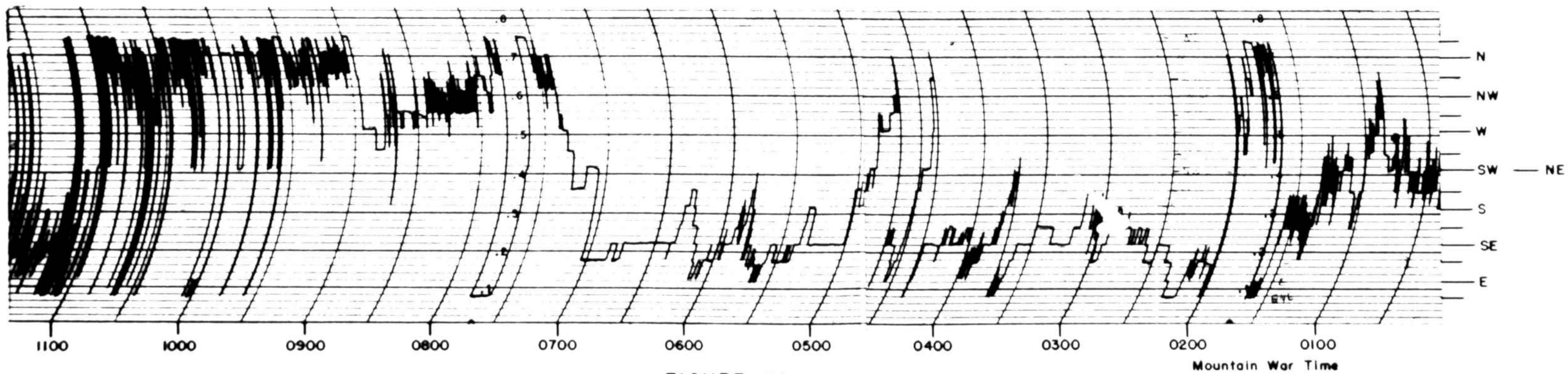


FIGURE 14

TYPICAL WIND DIRECTION RECORD, JUNE 1945. PAPER SPEED: 1 1/2 INCHES PER HOUR

CHARTS APPROXIMATELY 2/3 FULL SIZE

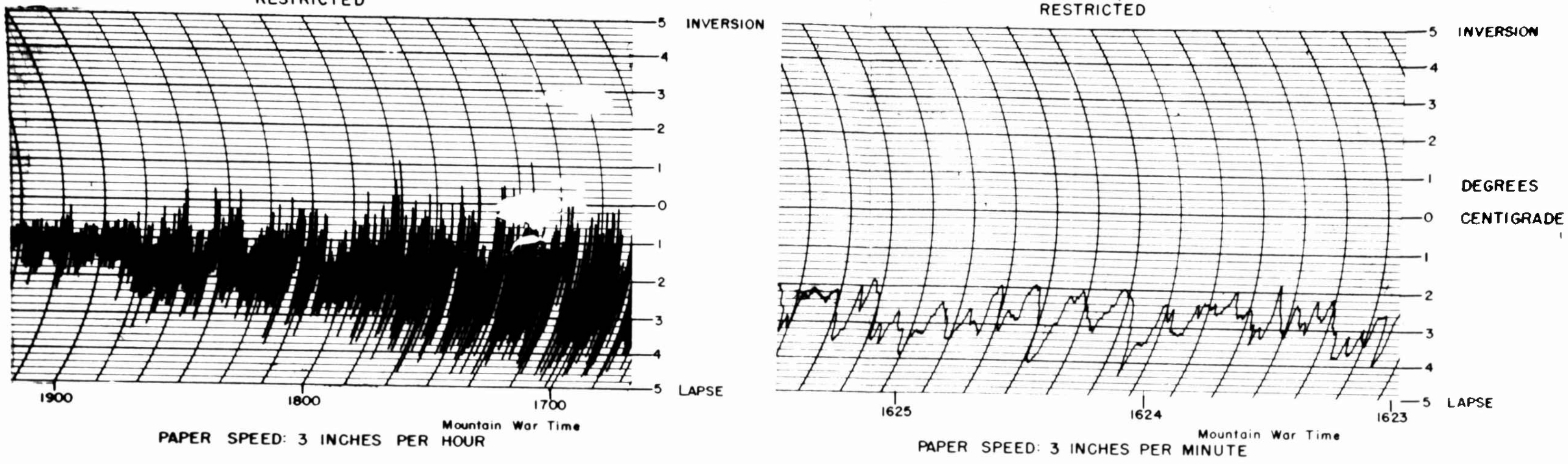


FIGURE 15

TYPICAL TEMPERATURE GRADIENT RECORD, 2 M TO 3 M; CLEAR DAY, LAPSE CONDITIONS; JULY 1945

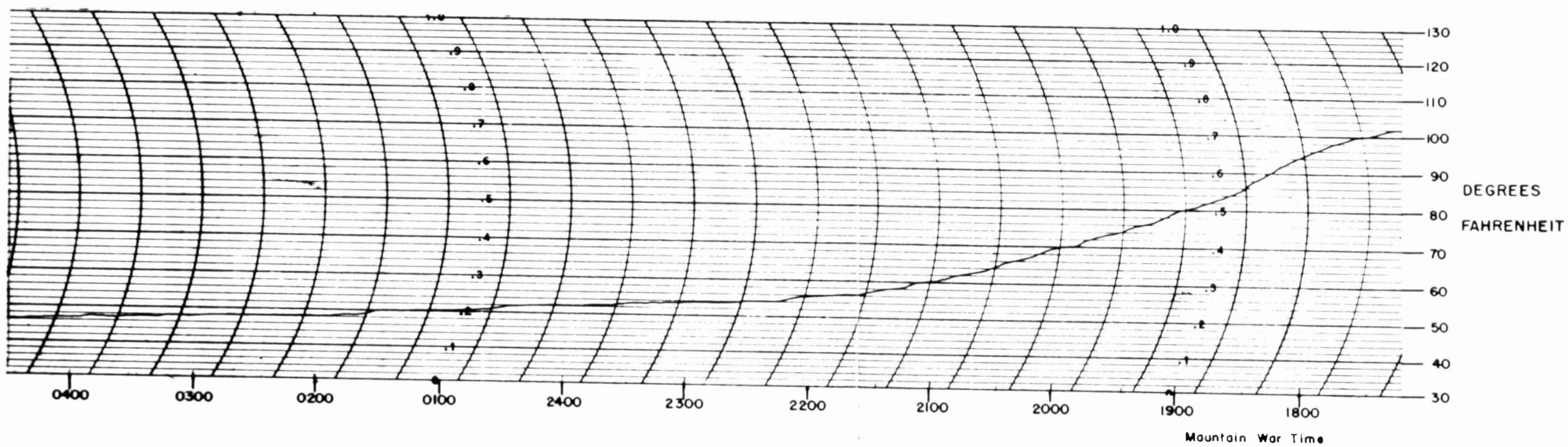


FIGURE 16

TYPICAL RECORD OF SURFACE TEMPERATURE, NO. 28 THERMOCOUPLE ON BARE GROUND; JUNE 1945

CHARTS APPROXIMATELY 2/3 FULL SIZE

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ABSTRACT:

A complete report of the general requirements for micrometeorological equipment used in C WS field work with respect to accuracy requirements for wind-speed measurements and accuracy requirements for temperature gradient measure is presented. The equipment for measurement of wind velocity is discussed and the following topics reviewed: anemometer characteristics, operation of the relay-type frequency meter, devices used for recording wind direction, the vacuum-tube frequency meter, and direct-reading approximate R-value recording device. Investigations were conducted in the field of portable photo-electric galvanometer and measurement of temperature gradient and air and soil temperature. The details of the construction of the micrometeorological equipment are presented in detail.

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