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RESEARCH AND DEVELOPMENT STUDIES FOR A LOW-LEVEL FREE-AIR VELOCITY MEASURING SYSTEM

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RESEARCH AND DEVELOPMENT STUDIES
FOR A LOW-LEVEL
FREE-AIR VELOCITY MEASURING SYSTEM

PURPOSE

This report describes the findings of a research and development program intended to evolve a system for measuring the speed and direction of a free-air movement at any selected point between the ground and an elevation of 1000 ft. The measurements were to include the horizontal and vertical components of air velocity vectors with speeds ranging from about 1 to 50 fps.

The system was intended for field use, with an output signal of an electrical character that would permit recording the vector components of the velocity at a ground station remote from the sensory instrument suspended aloft by a moored balloon.

The instrument was developed to utilize the inherent air speed and directional properties of a thermistor electrical element. The significant characteristics of this element had been clarified in an earlier development program for a two-dimensional wind anemometer, and were summarized in a previous report [1]*. The findings of the earlier program served as a starting point for the development of the three-dimensional measuring system described herein.

This report will review briefly the pertinent speed and directional measuring characteristics of the thermistor, and will then proceed to expand on the manner in which these characteristics were utilized in designing a complete measuring system.

For convenience this treatment has been broken down into four phases which may be briefly described as follows:

1. The Sensing Unit

The inherent measuring characteristics of the thermistor have been exploited by stably mounting it in the air stream to be

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*Numbers in brackets refer to the Bibliography on p. 29.

measured. A number of problems were encountered relative to the local mounting of the sensing elements in the air stream, and in the limitations of the basic output signal.

2. The Signal Correction

The basic signal produced by the thermistor is non-linear, sensitive to ambient-temperature variations, and is produced as a result of balancing a bridge circuit. Special developments were necessary for the correction of each of these.

3. The Signal Transmission System

The signal generated in the sensing unit, which is borne aloft by the balloon, must be transmitted to the ground readout station. A number of alternate methods of transmission were possible, but the final selection was primarily dependent on the load-lift limits imposed by the balloon system.

4. The Balloon Support System

The moored balloon which supports the sensing unit aloft provides a stable, oriented, suspension system which may be readily assembled in the field, and controlled to position the sensing unit at any selected point in space.

ABSTRACT

This report describes the development effort involved in creating an instrument capable of measuring the speed (0 to 50 fps) and direction of an air-flow vector at any selected point ranging from 0 to 1000 ft above the earth's surface.

The sensitive instrument element was an electrically heated thermistor rod producing an electrical signal variation as a result of the convective cooling action of the measured air flow.

The electrical signal from the elevated instrument station was conveyed to the ground readout station by a transmission cable.

The instrument was stably supported and selectively positioned in the air flow by a tethered kite-type balloon.

The development resulted in a complete and practical field measuring instrument having good accuracy and response.

FACTUAL DATA

1. The Sensing Unit

a. Thermistor Characteristics

The thermistor, which is a semiconductor material, may be electrically self heated so that exposure to the cooling action of flowing air will produce a related sensory electrical signal.

Under an earlier development program, the basic speed and directional measuring characteristics of a selected and commercially available rod form of thermistor were evaluated. The following information is derived from the report of this program [1].

The basic rod employed was Unit No. 517613-1 as made by Friez Instrument Division, Bendix Aviation Corporation, Baltimore, Maryland, and consisted of a cylinder of 0.018-in. diameter and 1.5-in. length with attached end conductor wires.

For the purpose of making speed measurements, this rod when held normal to an air flow at room temperature, and included in a bridge circuit, yielded a signal as shown in Fig. 1. The bridge shown in the figure was initially balanced at zero air velocity with an electric current flow sufficient to heat it to about 250 F. This temperature was sufficiently high to make small variations in the ambient room temperature quite negligible. The bridge was rebalanced at each velocity by varying the total current through the bridge. The thermistor current was measured by a series ammeter. Since the resistance of the thermistor was held constant at 2000 ohms, the voltage across the thermistor may be calculated from Ohm's Law.

An analysis of this data indicates the following significant features:

1) If the bridge circuit is to be used for continually indicating or recording a variable, natural air flow, the circuit must be continually adjusted for balance by either manual or automatic methods.

2) The curve is in agreement with other experiments and analyses which have established that the current or voltage must vary approximately as the 1/4 power of the speed. Eventual recording or other use of the speed value may make it highly desirable that the signal vary linearly with speed. In general, nonlinear signals may be linearized by suitable electronic circuits.

3) The data curve applies to only one ambient-temperature condition and is, therefore, only one member of the family of curves needed for a full calibration. Natural variation of air temperature will require signal temperature compensation in the circuit if a single linear calibration curve is to be used in interpreting the flow speed.

The directional sensitivity of a thermistor rod depends on the fact that the thermal-dissipation characteristics of an electrically heated cylinder change markedly with its orientation in an air stream.

The directional characteristics of a single thermistor rod 517613-1 rotated in a plane parallel to the stream, and about an axis perpendicular to the center of the rod axis are shown in Fig. 2 as taken from the previous report [1]. This demonstrates a definite ability to measure direction as a voltage-sine function for any 90-degree quadrant of the horizon, but with no discrimination as to which of the four quadrants. The discrimination was extended by utilizing two closely spaced parallel rods rotated about their longitudinal axis of symmetry. The circuit and data are shown in Fig. 3 as taken from this earlier report [1]. In this, the longitudinal rod axis was vertical and normal to the plane of the air stream, and the rods were spaced at about 1/16 in. center-to-center. The introduction of a positive and negative voltage signal extended the discrimination to 180 degrees.

Additional distortions of the lobe form shown in Fig. 3 will result if the plane of the rod pair is tilted with respect to the plane of the air stream. This variation is demonstrated in Fig. 4, which is also taken from [1].

From the foregoing, it is apparent that the thermistor rod has basic characteristics which make it adaptable for development in a three-dimensional measuring system. The following describes the manner in which those characteristics were applied to the current problem.

b. The General Scheme

Since the general approach to the problem of measuring air speed was fairly well defined in the previous study [1], the prime problem in the current development centered in the directional determination.

In the initial directional considerations, an attempt was made to exploit the sensitivity of various arrangements of stationary rod pairs. These investigations disclosed certain possible improvements in the techniques of handling paired thermistors but failed to disclose rod and shielding combinations which would provide a unique signal for each possible direction of the air stream.

In a second consideration of the problem, the focus reverted back to the use of the basic sensitivity of the single rod thermistor as shown in Fig. 2. Analysis of possible arrays of single rods in three-dimensional space disclosed that a simple arrangement of three mutually perpendicular rods could produce three separate voltage signals which could be computed to yield the desired vector coordinates. The simplicity of the rod arrangement and the nature of the equations were intriguing but failed to lead to a simple system because the form of the equations involved numerous sums, differences, and power operations on the three basic voltage signals. All of these necessary computer operations were deemed capable of practical solution by standard electronic computer techniques in a bench assembly. However, extended consideration failed to disclose a workable means of conveying the complex signal from the sensory rods to the computer circuits via a long conductor cable, or, alternately, of reducing the computer weight to permit sending it aloft.

These considerations also established that eventual signal accuracy would depend on a high order of dimensional accuracy and quality control in the thermistor rods and the array assembly since the lobes of the signal curve must be nearly perfect circles.

A summary review of the merits and deficiencies of the various systems finally led to a change in application of the thermistor in which the weight limitations, cable-transmission limitations, and thermistor-quality limitations appeared to be reconciled.

This new system depended on the directional sensitivity of the thermistor rod pairs but abandoned the stationary rod array and utilized only the most sensitive orientation of a movable array to actuate a movable support system for the array. The system which is to be described is shown schematically in Fig. 5. The signal from the array is directed to an electrical drive in the mounting system. A servo arrangement is provided which continually orients the rod to correspond with the direction of the air-velocity vector.

Since the air stream is three dimensional, an array-support system rotating about two spatial axes will suffice to maintain universal-directional orientation.

As shown in Fig. 5, servomotor M, which is mounted in an established orientation on the operating platform, produces rotation of its shaft and the attached assembly in response to a voltage initiated by thermistor rod pair CC. The sign and magnitude of the voltage signal from rod pair CC are in accord with the inherent sensitivity shown in Fig. 4. The magnitude of the driving voltage signal is a function of the magnitude of the component of the air-velocity vector along the axis XX. Proper response of the servomotor M to this voltage will rotate the shaft and assembly about axis Z, seeking the null position where the X component becomes zero.

In a similar manner the rod pair BB is sensitive to vector angularity in the ZY plane; it initiates a voltage signal which drives the shaft of the servomotor N to seek the null position for rod pair BB. It is to be noted that rod pairs CC and BB lie in planes at 90 degrees to each other.

A concurrent action by the two motors continually modifies the orientation of the combined rod assembly so that the velocity vector tends to be parallel to the directional array.

This system in itself serves only to maintain proper orientation of the thermistors and produces no useful output signal. However, if the rotating shafts are fitted with position transmitters S and T, the resistance variations produced in these units may be readily transmitted and remotely interpreted as a basic measure of the directional components of the velocity vector.

The output directional signal just described serves to give only the relative magnitude of the angles of the vector components. While numerous methods might have been employed to evaluate the speed or absolute magnitude of the velocity, in this case it was decided to measure it by an independent thermistor rod A, as shown in Fig. 5. The air-speed characteristics of the single rod were well established in earlier studies [1], and the signal characteristics appeared well adapted to the transmission problems involved in the assembly.

The general scheme shown in Fig. 5 was progressively developed and led eventually to the sensing unit shown in Fig. 6(a), and the circuit diagram of Fig. 7, together with the auxiliary control unit shown in Fig. 6(b), and the circuit diagram of Fig. 8. The units were borne aloft by the moored-balloon system and their output signal was cable-transmitted to the ground readout station for correction and use. The control unit was provided as a housing for those parts of the circuit which had to be borne aloft with the sensing unit but did not need to be directly attached to it. These parts were removed to the separate housing so that their weight would not burden the movements of the sensing unit and their bulk would not disturb the air motion near the sensing elements.

The actual fabrication of Fig. 6(a) differs from the original scheme of Fig. 5 in the following respects:

1) The servomotor M and position transmitter T were shifted to a position above servomotor N. This shift permitted the shape of the sensing unit to better conform to the local-mounting system eventually developed in accord with the over-all balloon support system. The shift permitted a compact design contributing to the physical stability of the unit when exposed to aerodynamic forces.

2) To further decrease the over-all dimensions of the assembly, the servomotors were removed from their positions at the ends of axes X and Z (see Fig. 5), and were placed parallel and adjacent to the axes of the position transmitter and slip rings. The motor shafts were then gear-connected to the transmitter shafts.

3) To simplify the sensing of a unique directional signal, the sweep of the rod pair BB was restricted to 140 degrees, which provided a continual presentation of the "front" of the instrument to the oncoming air.

The remainder of this section will deal with the development of the units shown in Fig. 6.

c. The Speed Signal

The speed thermistor [element (1) in Fig. 6(a)] was originally a full 1-1/2-in.-long rod thermistor 517613-1. It was subsequently determined that an equally workable signal could be obtained from a 3/4-in. length of this rod, and that a more compact and rugged unit would result. This unit was used in the initial phases of the development but was eventually replaced by thermistor rod 523337-1 which had a length of 3/4 in. and a diameter of 0.020 inch. The characteristics of this rod were very similar to those of 517613-1 but the switch was made at the recommendation of the maker, the new unit being more readily available and of more uniform characteristics.

From Fig. 2 it is apparent that the rod thermistor will be capable of delivering a useful indication of speed variation only if this indication can be divorced from variations due to directional changes. Fortunately, the shape of the curve is insensitive to minor angular variations near the zero axis; thus, minor misalignments or hunting action of the directional mounting system will not introduce significant speed errors unless the angular rates of air directional change are rapid.

The speed thermistor is directly connected to the bridge circuit on the ground via the two slip-ring assemblies on the sensing unit and the two conductors in the signal transmission cable. The operation involves maintaining the thermistor at approximately 250 F and requires current varying from 11 to 30 ma. The self-balancing, linearizing, and temperature-correction operations which are required to deliver a useful signal are performed at the ground station. The operations are more fully described in the section dealing with signal correction and in the block diagram of Fig. 9.

d. Directional Sensing

In the earlier schemes for measuring direction with heated thermistor rod pairs, the emphasis dealt with achieving nearly circular curves in data such as those shown in Figs. 2 and 4. In the current method of employing the directional sensitivity of the thermistor, the emphasis is on the steepness and voltage magnitude in the zero angle or null position. This differential voltage is, of course, dependent on the differential cooling between the members of the thermistor pair which is dependent on the proximity and mounting of the pair. In the initial tests, thermistor rods 517613-1 were employed but as in the case of the speed thermistor these were later changed at the manufacturer's suggestion. The new rods for the pairs were Unit No. 523337-2 and were used in their manufactured length of 3/4 inch.

A number of tests were made using various mounting procedures. From these it was decided to cement the rod pair to opposite sides of a long rectangle of insulating paper having a width of two rod diameters. This provided an effective thermal and electrical insulator and a rugged assembly having good differential voltage characteristics. The basic source of the differential voltage created by this differential cooling is demonstrated by the typical test data given in Fig. 10. This data represents the voltage variation across only one of the paired thermistors. The voltage variation across the complete pair represents the differential resulting from combining two such curves.

It is to be noted that the magnitude of the differential voltage from this system would vary with speed but the sign and null position would remain in correct relation for producing a suitable actuating voltage despite the magnitude variations.

It is also to be noted that two nulls could occur in the differential diagram. This would seemingly produce an ambiguity but the circuit arrangement and polarity of the relay and motor system serve to make one of the nulls stable and the other unstable in the servo follower action. The unstable null might on rare occasions deliver a 180-degree error signal, but in continually shifting natural winds it is unlikely that this would occur and then only for a brief time.

In the final arrangement, the rod pair is heated by a d-c current supplied from the ground. The heating current is approximately 10 ma per thermistor and produces a differential voltage across the pair which varies from zero in the null position to about 20 volts when the misalignment is 90 degrees. This voltage, which varies in both polarity and magnitude, actuates the servomotors M and N (see Fig. 5) which rotate the directional pairs BB and CC toward the null or zero-voltage position. The differential voltage from the thermistor pair is not directly suitable for a servomotor drive but will serve to actuate a sensitive relay, which will in turn actuate a more stable motor-powering system.

A number of types of servomotors and power supplies were given consideration, but the high resistance of the long lines from a ground power supply finally led to the selection of a miniaturized d-c motor which could be powered in a practical manner by lightweight 4-volt storage batteries suitable for carrying aloft.

This system required a careful selection of components including:

1. A relay of lightweight and low-voltage starting conditions.

2. A lightweight motor of good-starting torque and low current drain.

3. A potent but lightweight battery capable of maintaining a minimum voltage drop over a practical operating period.

The components finally selected are:

1. A relay Micropositioner No. AYLZ 4584S as made by Barber-Colman Company, Rockford, Illinois; 2300-ohm coil, pull-in current 0.00014 amps, contact rating 0.5 amps at 26 volts, weight 0.39 lbs. The pull-in current of this relay corresponds to approximately ± 3 degrees of deviation of the thermistor pair from the null wind direction at 40 fps and ± 10 degrees of deviation at 5 fps as determined in wind tunnel tests. (See Fig. 2 for the basic nature of this deviation).

2. The relay operates the miniaturized servomotor Type SS-18 as made by Globe Industries Incorporated, Dayton, Ohio; 6-volt motor, planetary gear reduction of 192, maximum output speed of 68 rpm, weight 0.5 ± lbs. The ball-bearing motors are lubricated and sealed for operation under a wide range of ambient conditions.

3. The motors are operated by a 4-volt, silvercell storage battery, type HR 1, as made by Yardney Electric Corporation, New York, New York. The 8-unit battery pack weighs 0.5 lbs and has an operating life of about 16 hours when fully charged.

4. The servomotors are stabilized by the resistor-capacitor network shown in the circuit of Fig. 8. This network feeds a signal into the relay coil, which simulates the velocity signal of the servomotor. This results in increased damping of the system without

increased friction. It would appear that the accuracy of positioning could be materially improved through the use of an a-c transistor-amplifier servosystem.

e. The Directional Signal

The foregoing description of the directional sensing elements related only to those parts of the system which sensed the air-stream direction and actuated the servo, to drive the thermistors toward the aligned or null position. If it is assumed that this function is correctly performed, it then remains to employ the action to produce a suitable output signal in accord with the arrangement shown in Fig. 5.

In the case of the signal for angular variations in the vertical plane, the function is achieved by the position transmitter which is shown as item S in Fig. 5 and item 7 in Fig. 6(a). The transmitter is included in the mechanical drive shaft between the thermistors and the servomotor and is a variable resistance in the form of a miniaturized, precision linear potentiometer. The unit is Model RVG-14 as made by the Gamewell Company of Newton Upper Falls, Massachusetts, and weighs 0.05 lb. Because of a blind spot in the 360-degree sweep of this resistance and because of a desire to stabilize the aerodynamic form of the whole sensing unit, the angular sweep of the vertical thermistors was arbitrarily restricted to ± 70 degrees of arc above and below a horizontal alignment. Thus, velocity vectors having an angle with the Y axis (see Fig. 5), which approach and then exceed 70 degrees, will cause the entire head to quickly rotate 180 degrees around the Z axis to maintain the "front" of the sensing unit facing the velocity vector.

This sudden switch in the head will produce a momentary confusion in the direction and speed signals. The signaling technique is considered workable, however, because the occurrence of angles exceeding ± 70 degrees is believed to be rare in normal air movements, and their occurrence would be accompanied by other obscuring difficulties in the balloon-supporting system.

The confinement to ± 70 degrees of travel was mechanically accomplished by arranging a slipping clutch with stops set 140 degrees apart on the gearing train, between the motor (item 6) and the potentiometer (item 7), as shown in Fig. 6(a).

In the case of the signal for angular variations in the horizontal plane, the function is achieved by the position transmitter, which is shown as item T in Fig. 5 and item 5 in Fig. 6(a). The transmitter shaft remains stationary with the vertical axis, or shaft, of the sensing unit, while the transmitter housing rotates with the entire sensing unit. The transmitter unit is Microtorque Potentiometer Type eight, 10,000 ohms, as made by G. M. Giannini Company, Pasadena, California, and weighs 0.037 lbs.

The directional signals from the two transmitters are energized by two small, mercury dry cells located as shown by item 8 in Fig. 6(a). With the exception of providing a local adjustment for the zero voltage value of the null position [this is accomplished by the four 5000-ohm resistors shown in Fig. 8 and as item 3 in Fig. 6(b)] the directional signals are not further manipulated in the components which are borne aloft. The signals are carried to the ground readout station via the slip-ring assembly and two of the conductors in the signal cable. This connection is shown in the block diagram of Fig. 9 and the subsequent operations in the resolver unit are separately described in the account which follows.

2. The Signal Correction

a. General

The velocity-measuring system was based on King's [3] form of the equation for heat transfer from a cylinder

$$\frac{P}{(T - T_o)} = A + B\sqrt{V} \qquad (1)$$

where P is the power dissipated, V is the air velocity, $(T - T_o)$ is the temperature difference between the cylinder and air, and A and B are constants depending in a complex way upon the thermal properties of the gas. For a range of velocities of 0 to 50 fps and a temperature range of -20 to +100 F, A and B are accepted as constants in the system under consideration.

The behavior of a thermistor anemometer is very similar to that of the more generally known hot-wire anemometer, and similarly, it can be operated at either a constant temperature or constant current.

The resistance of a thermistor as a function of temperature is approximately

$$R = R_o e^{B\left(\frac{1}{T} - \frac{1}{T_o}\right)} \qquad (2)$$

where R is the resistance at temperature T (degrees Kelvin),
R_o is the resistance at reference temperature T_o, and
B is a constant of the material.

When this equation is combined with King's equation, a relationship results which is difficult to adjust for temperature variation.

By operating at a constant temperature, the complex resistance variation of the thermistor is avoided and a temperature correction in accord with Eq. (1) is possible. The constant temperature method is, therefore, employed in this development.

b. Self-Balancing Bridge

Operation of the thermistor anemometer is accomplished by placing the speed-measuring element in one arm of a Wheatstone bridge supplied with a variable source of electric power. When the power input is varied, the temperature and thermistor resistance change to give a resistance balance at some predetermined value. A different power is required to maintain this balance for different speeds of air flow at a constant temperature.

Manual adjustment of the electric power is difficult under conditions of varying air speed.

Two methods of automatically adjusting the bridge to balance are apparent: either a servomechanism or an all-electronic system which would mechanically adjust the power input. The servosystem would have some advantages for compensation of the signal, as will be mentioned later. However, the electronic system was used as it was better able to take advantage of the fast response of the thermistor.

The system is shown in Fig. 11. The amplifier is a simple, transformer-coupled audio amplifier with a voltage gain of approximately 100. The connection shown causes the amplifier to oscillate. These oscillations heat the thermistor which brings its resistance close to the value required for balance. This reduces the amplitude of oscillation and a condition of equilibrium is soon achieved.

Since a true balance would stop oscillations, some departure from constant-temperature operation is necessary. However, if the amplifier gain is sufficiently high this error source can be ignored.

The use of a feedback system also has an advantage from its effect on the time response of the thermistor. The time constants shown in Fig. 14 of the previous report [1] may be reduced to approximately 1/25 of the values shown.

The use of a transformer-coupled amplifier requires careful control of the gain-frequency characteristic at the high- and low-frequency end of the amplifier pass-band, if oscillation is to be avoided on the wrong side of balance. The resistor R_1, R_2, C_1, C_2 (Fig. 11) and R_3, C_3 across the transformer reduces the slope of the gain-frequency plot to less than the six decibels per octave required for stability. The circuit oscillates at about 300 cycles and has the transient response of a heavily damped resonant system.

The requirement for lightweight cables few in number, connecting the sensing and control units aloft to the ground station, introduces the need for a number of compromises in the entire system, as will be discussed later.

However, among these influences is the resistance of the instrument cable, which is introduced in series with the speed thermistor, the bridge, and the amplifier on the ground. The capacity of the cable which is across the thermistor is also an influence. These effects reduce the sensitivity and increase the time response of the system. It is also necessary to keep a constant length of wire in the system during a calibration, if the calibration is to be meaningful.

c. Linearizing and Temperature Compensation

The self-balancing bridge, speed-measuring system delivers an electrical output which is a function of the 1/4 power of the velocity and the 1/2 power of the difference between the thermistor temperature and the ambient air temperature.

It was desirable to convert the measured speed into an electrical signal which varied in a linear manner with speed. A number of systems can be devised using non-linear resistances, vacuum tubes or servomechanisms.

For moderate speed of response a servomechanism would be favored, especially if coupled with a servo-type, self-balancing bridge.

In order to achieve a speed of response of the same order as the electronic self-balancing bridge, a biased diode squaring circuit was used in accord with the findings of Kovasznay [4]. The circuit is shown in Fig. 12.

The output of this circuit will be proportional to the square root of the air speed and the temperature difference. This electrical signal was passed through the "potentiometer network" (R_1, R_2, R_3), shown in Fig. 12, whose output voltage versus rotation, for a constant input voltage, approximates a curve $1/(T - T_0)$ versus T_0. This potentiometer is driven by a servosystem whose rotation is proportional to temperature. The voltage output from the potentiometer network is proportional to the square root of the air speed. This electrical output is a complex wave. In order to subtract a constant term [term A in Eq. (1)] the output was first rectified and filtered to give a direct-current output at constant speed and then a constant voltage was subtracted. The resultant voltage was again squared by a second biased diode circuit to give an electrical output which would vary directly as the air speed.

d. The Temperature-Measuring System

Measurement of the ambient temperature of the air flowing over the speed thermistor is not an end objective of this system, but it is an essential step in evaluating the air speed when employing King's equation.

In this system, the air temperature is sensed by a rod thermistor located in the control unit, as shown in item 4 of Fig. 6(b) and in Fig. 9.

The temperature-measuring and compensating circuit is shown in Fig. 13. The series resistance R_1 was chosen in accord with the recommendation of Staley [5] to give a nearly linear relationship between the rotation of potentiometer R_2 and the temperature.

The temperature-measuring system shown in Fig. 9 requires a pair of conductors between the sensing element aloft and the circuitry on the ground. Since the number of conductors must be limited, to reduce the balloon-lift problem, and because temperature changes aloft occur rather slowly, it was decided to make temperature measurements periodically by temporarily borrowing the two conductors normally used for transmission of the speed signal. A manually tripped relay system accomplishes the switch-over whenever it may be desired and the motor-driven potentiometers automatically adjust the circuit to a new temperature value in about 15 sec.

An alternate temperature-compensation system which was not investigated but seems to offer considerable simplification may be described as follows:

The self-balancing bridge could be transferred from the speed thermistor, by a relay, to an identical thermistor, which was shielded from air movement but not from temperature. (This would require some care in housing design.) If the output of this system, which would be a function of temperature, were automatically adjusted to some arbitrary magnitude at the output of the first squaring circuit, the speed reading would be compensated for temperature change when the self-balancing bridge was returned to the speed-measuring thermistor. This system, it would appear, should eliminate the need for a separate temperature-measuring system and its calibration and also the need for a non-linear potentiometer network.

e. Resolution of Velocity Components

The speed signal is fed into a sine-cosine potentiometer driven by the elevation servosystem. This resolves the signal into horizontal and vertical velocity components. The horizontal components are fed, in turn, to a second sine-cosine potentiometer which is driven by the azimuth directional servo. This resolves the signal into its North-South and East-West velocity components.

The speed signal is a direct current. There would be a possible advantage in many applications in having this signal in the form of an amplitude-modulated alternating current. This could be accomplished if, at the point in the linearizing circuit where the signal is rectified and filtered to give direct current, the current were immediately chopped into a rectangular wave form. The zero speed component of electrical signal could still be subtracted from this rectangular wave form without error and the remaining signal would be a rectangular wave whose amplitude is proportional to the square root of the speed. This rectangular wave would be subject to less drift due to tube variation when it was passed through the second squaring circuit. It could also be amplified with an a-c type amplifier at any time, to change the level or impedance as necessary.

3. The Signal Transmission System

The problem of conveying the velocity signals from the instrument station aloft to the observer's station on the ground was of paramount importance in the circuit design because of the necessity of minimizing the associated weight to be carried by the balloon system. Consideration was given to radio transmission and cable transmission, with the early conclusion that cable transmission would be more practical. This decision was based on the belief that suitable circuit design could reduce the total number of required conductors to those available in the three tethers plus the four available in a suitable commercial signal cable. While many multiple-conductor cables were commercially available, only a limited few possessed a high strength, small size and light weight consistent with the balloon-handling requirements.

The cable considered most workable was a four conductor No. 9263-HF-NB (4) as made by the Suprenant Manufacturing Company of Boston, Massachusetts. This cable had an outside diameter of 0.103 in., a weight of 3.9 lbs, and a resistance of 300 ohms per 1000 ft. In this cable each conductor was made up of six steel strands twisted around a center copper strand. This conductor was then insulated with a heat-stabilized polyethelene compound to a nominal thickness of 0.010 inch. The insulated conductors were twisted together and jacketed over-all with a nylon braid.

The three tethers had an original resistance of approximately 900 ohms per 1000 ft. The tether resistance was later reduced to 300 ohms per 1000 ft by a copper plating. The added weight of the copper was undesirable but the reduction in resistance was considered essential.

The self-balancing, speed-measuring bridge uses two of the instrument cable conductors. It would have been desirable to use three conductors and a tether ground return to eliminate the inherent effects of the cable on the signal. The same requirements hold for the temperature-compensating bridge. Only two conductors were used for both units and these were shared, on an alternate time basis, by relay switching the pair of conductors from one unit to the other. Power for the relay was obtained from the directional system power-supply lines.

The d-c voltage signal from the elevation-position potentiometer was also superimposed on one of these two wires, and filtered from the a-c bridge voltage at the ground station. In order to prevent influence of the position system on the speed signal due to the shunting of one of the instrument wires by the directional potentiometer, a high resistance was connected in series with the potentiometer slider, in accord with the positioning elements shown in Fig. 14. This made the elevation-position system subject to stray current-leakage effects which might arise in cables and plugs during periods of excessive moisture.

The azimuth-position transmission system requires three conductors. Two of these are supplied by the instrument cable and the third by the grounded tether. The grounded tether is shared with the elevation-position system. It was necessary to reduce the resistance of the grounded tether to less than 500 ohms per 1000 ft by the use of copper plating, as previously mentioned. This reduced the interaction between the two direction systems to a tolerable level.

The directional thermistors on the sensing unit aloft required nearly 90 volts at 40 ma for heating the thermistors. The two remaining tethers were the only conductors available for supplying this power. They had a total resistance, when extended, of nearly 3600 ohms. This would require a supply voltage on the ground of 230 volts. By copper plating these tether lines, loss was reduced to about 40 volts with a total supply of 130 volts. This voltage was divided ± 65 volts from ground, thus reducing the dangers of accidental personnel contact to a low level.

In retrospect and on a speculative basis, it appears that some changes in the transmission might be given further consideration. Among these considerations is the possibility of using radio transmission of the directional signal, which would free two conductors in the instrument cable for use in power transmission to heat the directional thermistors. This would eliminate the necessity of plating two of the tethers and the hazard to personnel represented by these uninsulated, powered tether wires.

Consideration might also be given to connecting the position transmitter to a compass element for aximuth reference and to a gravity pendulum for elevation reference. This would make it unnecessary to orient the equipment, thus eliminating the heavy tripod tether system.

4. The Balloon-Support System

a. General

The support system employed in this instrument program was basically the same tripod-tethered kite balloon as that developed in the earlier two-dimensional anemometer studies [1], with a number of changes leading to improved operating convenience.

The prime intent of the support system was to provide an instrument station of such stability that the lateral, vertical, and rotary motions in use would be of such magnitude and speed as to be an insignificant influence on the basic air-motion measurement in the selected region.

The support was intended to permit positioning the instrument at any selected point between the ground an an elevation of 1000 ft.

The support system employed is shown schematically in Fig. 15 and the elements of this assembly are: the balloon and its tether, the instrument station, the tripod-tether system and its ground anchors, and the trailer-mounted reel.

b. The Balloon and its Tether

The balloon was a helium-filled, streamlined, fabric bag of coated nylon. The bag was provided with stabilizing fins and a bridle system which allowed it to generate considerable stable aerodynamic lift. The unfilled balloon weighed 24.5 lbs and when filled with helium to its 600-ft capacity, provided a net zero-wind lift of 12 lbs. The lift increased to about 25 lbs in a 35-mph wind. The bag was 8 ft in diameter and 22 ft long.

The selected balloon was a standard commercial production (Model S-600) of Seyfang Laboratories, Atlantic City, New Jersey.

The balloon was connected to the instrument head by a 100-ft length of braided nylon line of 180-lb test and 1/16-in. diameter. This line was supplied by Ashaway Products, Incorporated, Ashaway, Rhode Island, under their designation No. 180-OX.

The length and resilience of the line served to dampen the variations in dynamic pull exerted on the instrument by the gyrations of the balloon when flying in turbulent air.

c. The Instrument Station

The function of the instrument station was to provide mounting for the rotating sensing unit plus attachment for the balloon tether, the signal transmission cable, and the tripod tethers. An assembly of these elements is shown in Fig. 16 and consists of a central anchor piece, rigidly attached to a support cage which in turn carries the sensing unit.

The "anchor piece" is located at the center of convergence of the four tether lines which are directly attached thereto, and is also the center of convergence for the signal-transmission cable which attaches through a gimbal. During field operations, the tripod tethers normally remain essentially fixed in the direction of their respective pulls on the anchor, but the balloon tether and the signal cable are assumed to vary their direction of pull as the wind varies. The variations in the balloon tether are provided for by a simple clip attachment, but a more complex arrangement is necessary for the signal cable. The signal cable by-passes the support cage through the frame of the yoke triangle and the gimbal attachment.

The system represents an attempt to arrange all forces so as to minimize any possible tipping or rotation of the instrument station. The compromise design makes reasonable provision for all of the major line forces, but some unbalance remains due to the gravity- and aerodynamic-drag forces acting on the pendant sensing unit. An inherent small error of orientation will be introduced into the directional signals from this source.

The sensing unit is a demountable piece which is readily clipped into the support-cage pivot and connected to the circuit by the cable plugs, as shown in Fig. 17.

The control unit is also readily removed from the lower part of the yoke assembly by line clips and cable connectors. It is readily broken down into two parts to expose the rechargeable storage batteries, as shown in Fig. 18.

d. The Tether System

The three ground tethers serve a dual function, providing both stability to the instrument-station tethering, and electrical conductors to serve the instruments.

In order to minimize the aerodynamic-drag and negative-lift forces acting on the tethers, they have been made of a minimum size consistent with their load-carrying function. They are made of stainless steel music wire of No. 10 gage (0.024-in.) having a weight of 636 ft per lb and a breaking strength of about 130 lbs. The wire was obtained from Malin and Company of Cleveland, Ohio, and was a hard, stainless steel of standard analysis 18-8, Type 302.

In original planning, the three tethers were to serve solely as tethers. However, in subsequent considerations of the signal-transmission problem, the need arose for more than the four conductors provided in the regular signal-transmission cable. Since lightweight, tension cables with a greater number of conductors were not available, the three tethers were pressed into service as conductors. Two of these conductors were ultimately selected as d-c power lines for conveying the heating current to the directional thermistor pairs, and the remaining tether was used as a general ground.

The relatively long length and high electrical resistance of the steel tether wires necessitated a high voltage for delivery of the thermistor current. The problems of insulation and personnel safety associated with the high voltage eventually led to a decision to reduce the electrical resistance of the wires by plating on a layer of conductive copper. A layer 0.003-in. thick was applied, leading in eventual field operations to a safe differential voltage of about 65 volts. The weight of the copper on the lines imposed an additional burden on the balloon and contributed to limiting the height to which the instrument might be elevated.

In order to establish the triangular tether pattern, a system of ground anchors is required, as shown in Fig. 15. The actual anchorage may be provided by either dead weight or screw anchors. The anchor restrained the tether by means of a tie-off line terminating in a pulley which allowed free travel of the tether.

In the earlier system [1] the anchor line was of short length and much of the horizontal limb of the tether lay on the ground. In the revised system, in which the uninsulated tether has an elevated voltage, the tether must be kept above the ground. This was accomplished by increasing the length of the anchor line to 200 ft. Selection of the same braided nylon line as that used in the balloon tether provided a high-strength, small-sized insulating material.

e. The Reel and Trailer Mount

The anchor assembly shown in Fig. 15 provides a flexible means for controlling the vertical or lateral position of the instrument station in free space. The key to this control is the mechanized central reel which is shown in close-up in the photos of Fig. 19.

The trailer-mounted reel consisted of a gas engine, a controllable power-transmission system, four independently controlled reels and a pulley support head.

The gas engine was a 2.5-hp, single-cylinder, four-cycle, standard unit with a rated speed of 3600 rpm.

The gas engine was directly connected to a 2-hp, positive-displacement, hydraulic transmission which permitted a simple, infinitely variable, and reversible control of the output shaft, with speeds ranging from 0 to 1200 rpm.

The transmission output shaft was connected to each of four worm-gear reducers via individual Vee belts and individual lever-throw clutch units. Manual manipulation of the four clutch levers by the operator standing on the trailer deck [to the right in Fig. 19(b)] permitted operation of any of the reels, either separately or together, to effect a horizontal or vertical shift of the instrument station aloft.

The worm-gear reducers served to reduce the shaft speed and increase the torque of the engine to a more usable reeling value, and provided a non-reversing, reel-locking action when the engine was not operating.

The output shafts of the reducers supported the reels, which consisted of standard automobile wheels capable of storing several thousand feet of line. The eventual maximum reeling speed was about 200 fpm.

Each of the four reels was provided with a standard counting unit, arranged with a friction drum riding on the outer strands of the reeled line in such a way as to give a dial count corresponding to the number of feet of line reeled out. The counter was arranged to subtract as the wire was retrieved.

The counters were very useful in the field operations, since the layout distance for any desired size of tripod base triangle could be readily established by the lengths of wire paid out radially from the central reel. The length of transmission cable paid out from the fourth reel was a good, rough measure of the height of the instrument station above the ground.

The tower above the reel was arranged in such a way that the three radial tether lines were raised about 9 ft above the ground [see Fig. 19(b)] to permit unobstructed ground traffic in the vicinity of the trailer. The reel and all components necessary for the operation of the measuring system are transported aboard a standard 3/4-ton, utility-type trailer suitable for hauling by a jeep.

The trailer box provided housing for the balloon, helium bottles and miscellaneous tools. The trailer deck provided anchorage for the reel, the ground readout station, and the gas-electric generator unit.

5. System Characteristics and the Test Program

From a variety of special bench tests, wind-tunnel tests, roof-top tests, and limited field tests of the complete system, the more significant characteristics and performance qualities have been evaluated. More extensive tests are needed to establish and extend these evaluations, but the list which follows is believed to be a fairly realistic summary.

Speed - The system can sense air speeds ranging from 0 to 50 fps with a fairly constant error of ± 2 fps over the entire range. The error stems from a number of sources, but the major part is probably due to inherent deficiencies in the temperature-compensation circuits employed for signal correction. The upper limit of speed, as controlled by manageability and stability of the balloon-support system, has not been established in the limited field test which did not exceed values of 30 fps.

Horizontal Directional Determinations - The directional indication represented by the "azimuth angle" readout dial covers a full 360 degrees of sweep; it is estimated to involve an error of ± 10 degrees at 5 fps, ranging to ± 3 degrees at 50 fps. These values relate to bench tests of the circuit elements and will be further affected by the tilting stability of the instrument station. Limited field tests of this stability indicate that the station may be stable within ± 8 degrees.

Vertical Directional Determinations - The directional indication represented by the "elevation angle" readout dial is effective only over a sweep of ± 70 degrees from the horizontal. The error values are the same as for the horizontal direction described.

Recorded Velocity Components - Tests of the sensing system in a rooftop mounting, fitted with a chart recorder readout, disclosed that the wind structure under the existing conditions was composed of transient changes beyond the response capabilities of the system. Recorder facilities suitable for use with the system in the field were not available for the tests. This indicates that some difficulties might be encountered with field recordings in the lower strata of the atmosphere where small-scale turbulence structure frequently exists.

Response Time - The time response of the speed-readout system is a small fraction of a second, but the response of the directional-readout system is of the order of 1 to 8 sec, with the lag diminishing when air speed increases. The slow response of the pairs is inherent to their make-up, as discussed previously [1]. It appears unlikely that the response time of the paired arrangement of thermistors will be speeded until new forms of thermistor materials become available or power is supplied to each thermistor from a feedback system, as employed in the speed thermistor. On the other hand, the servosystem can readily be accelerated by suitable selection of presently available components. The tests gave some indication that the rotational stability of the instrument station, as represented by its reactive torque limits, may also serve to limit improved response.

Temperature Range - The operating temperature range of the thermistor elements has been tested and compensated from -20 F to +120 F. The greatest accuracy results in the range from 0 to 100 F because of inherent thermistor characteristics. The upper and lower operating-temperature limits are not known but the entire system operated satisfactorily in a field test at 10 F.

Elevation Range - The maximum elevation of the instrument station depends on a complex combination of circumstances. In the limited field tests conducted with this instrument assembly, it appears that a controllable height of about 500 ft may be obtained. It is possible that with other types of winds, and ground triangle arrangements, a somewhat greater or lesser maximum height might result in a given test. Some increase in height could be accomplished by a more stringent use of lightweight materials in a reconstruction of the air-borne components. Present weights of the instrument station components are as follows: sensing unit 1.18 lbs; control unit 2.13 lbs; yoke, gimbal, cage, and harness 0.86 lbs. A substantial increase in height under low wind conditions could be obtained also by use of a larger commercially available balloon, but it is probable that such a balloon would dangerously overload the tether system under high wind conditions.

Humidity - The system in its present state of development is not intended for operation under conditions of free precipitation. The basic thermistor signal is insensitive to humidity effects, according to the findings reported [1], but the total system has not been tested under conditions of prolonged, high humidity.

Pressure - The thermistors are slightly sensitive to ambient atmospheric pressure conditions (see [1]) but this sensitivity will not be significant in normal operations conducted in accord with specified operating procedures.

Radiation - The system is not significantly affected by variations in solar radiation, according to the findings [1].

Thermistor Stability - Early in the program, a test bank of thermistor rods was subjected to a continuing exposure to roof-top conditions, to ascertain the long-time drift stability when the instrument was in use. The program was inadvertently based on periodic measurements of static resistance values, which proved to remain essentially constant with time. At a late date it was realized that the large static resistance values were unlikely to change significantly with exposure, but the progressive build-up of contaminants on the exterior of the rods might significantly affect the dynamic thermal-dissipation characteristics. Since the thermistor rods had been statically resistance calibrated initially but not velocity-calibrated, the exposure tests lacked a comparative base. Lack of sufficient time to initiate another program, and a substitution for the thermistor rods employed, led to inconclusive results with regard to thermistor stability. It is, however, believed that the stability characteristics of the thermistor are as good as, or superior to, those of other parts of the system, and a periodic calibration of the sensing unit is recommended.

Power Requirements - The system required a 115 volt a-c, single-phase power supply with a current of 4 amps. This may be supplied from an external source or by the gasoline-electric generator furnished as part of the system. Rechargeable storage batteries and long-lived dry cells are included in the equipment.

CONCLUSIONS

The following conclusions seem reasonably well defined by the laboratory and field studies described herein.

A practical portable measuring system has been developed for the field evaluation of the magnitude and direction of low-level free-air movements in an elevation ranging from 0 to 500 ft and in a speed ranging from 0 to 50 fps.

A short, oriented thermistor rod connected to a linearized, temperature-compensated, self-balancing bridge circuit proved capable of supplying an electrical output signal for air speed evaluation. The system operated with a fairly constant error of ± 2 fps over the range from 0 to 50 fps, with a response time that was a small fraction of a second.

Suitably mounted pairs of thermistor rods proved capable of sensing and electrically actuating a servosystem to maintain the rod pairs in continuous alignment with the air stream. The alignment mechanism drove a directional signal generator yielding an output signal of air direction accurate to within about ± 10 degrees. The response time varied from 1 to 8 sec.

The signals generated by the thermistor elements proved adaptable to cable transmission from the instrument station aloft to the readout station on the ground.

The signal readout could be supplied as an indicating system for speed, azimuth angle, and elevation angle, or alternately as a recording system supplying the magnitude of the three Cartesian coordinates of the air vector.

A kite-type balloon tethered to the ground by three lines supported the instrument station at elevations ranging to 500 ft with a stability of lateral, rotary, and tilting motion which contributed a small, eventual signal error. This error is believed to be of the same order of magnitude as other errors inherent to the system.

A centralized powered reel included in the tether system permitted easy lateral and vertical positioning of the instrument station in free space.

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[2] Stewart, H. J. and MacCready, P. B., Jr. Report on Investigation of Atmospheric Turbulence. California Institute of Technology, Contract CWB-8118 and 8125, 1952.

[3] King, V. L. "On the Convection of Heat from Small Cylinders in a Stream of Fluid." Philosophical Transactions of the Royal Society of London, Series A, Vol. 214, pp. 373-432. 1914.

[4] Kovasznay, Leslie G. Development of Turbulence Measuring Equipment. National Advisory Committee for Aeronautics, Technical Note 2839, January 1953.

[5] Staley, R. C. "Performance Characteristics of Sanborn Rod Thermistor." Bulletin of the American Meteorological Society, Vol. 33, No. 2, February 1952.

IDENTIFICATION OF PERSONNEL

The program was under the general direction of Dr. Lorenz G. Straub, Director of the Laboratory, and was executed by John F. Ripken and John M. Killen, with the assistance of Gordon H. Flammer, Frank R. Schiebe, and Goffe J. Erickson.

Loyal A. Johnson edited the manuscript with the assistance of Mildred McEnroe.

PUBLICATIONS, LECTURES, AND REPORTS

A series of three quarterly progress reports was prepared and submitted to the Evans Signal Laboratory during the course of the contract. The reports were entitled Research and Development Studies for a Low-Level Free-Air Velocity Measuring System, and carried issue dates and St. Anthony Falls Hydraulic Laboratory Memorandum Numbers as follows: M-55, August 1956; M-56, November 1956, and M-57, February 1957. The reports were authored by John F. Ripken and John M. Killen.

The following special reports were also issued during the course of the contract:

Design Plan for a Low-Level Free-Air Velocity Measuring System, by John F. Ripken and John M. Killen, Memorandum No. M-54, July 1956.

Operating Manual for a Low-Level Free-Air Velocity Measuring System, by John F. Ripken, John M. Killen, Frank R. Schiebe and Goffe J. Erickson, Memorandum No. M-59, February 1957.

Preliminary Technical Procurement Specifications for a Low-Level Free-Air Velocity Measuring System, by John F. Ripken and John M. Killen, Memorandum No. M-60, March 1957.

Engineering Report on a Low-Level Free-Air Velocity Measuring System, by John F. Ripken and John M. Killen, Memorandum No. M-61, April 1957.

RECOMMENDATIONS

The measuring system described herein was developed under a program in which the available time for full field tests was all too brief. As a result of this, the capabilities and deficiencies of the system for various end uses have not been clearly established. It is, therefore, recommended that the experimental model supplied under the contract be given extensive field tests to determine its fitness in the measuring problems for which it was originally intended.

It was the original intent of the program to provide a system which would measure air values up to a height of 1000 ft. However, the eventual weight total for the developed instrumentation limited the operating height to about 500 ft for the symmetrical, equilateral tether system prescribed for general use. If a greater operating height is desired in specific tests, it is suggested that consideration be given to the unsymmetrical tether systems developed by Stewart and MacCready [2]. Use of such methods may, however, require a revision of the symmetry of the attachments in the existing instrument station anchor piece. Consideration may also be given to the use of the larger model S-1004 balloon by Seyfang, or to supplementary, paired, smaller balloons attached to the tether of the current balloon system. The technique of using supplementary pairs has been described by the Dewey and Almy Chemical Company, Cambridge, Massachusetts, manufacturer of small kite balloons.

In the event that field measuring needs require an accuracy in excess of that possible with the existing system, consideration should be given to basic improvement in the stability of the instrument station, and to correction of the inherent errors involved in the present method of manipulating the electrical signal. Some improvement in accuracy is certainly possible along the present lines of approach, but the practical limits may not be much greater than those offered by the present system. A more drastic, and possibly more fruitful, improvement program might be founded on abandoning any attempt to stabilize the instrument station, and proceeding instead to provide directional orientation relative to gravity and magnetic axes of reference established at the instrument station.

In the present development, no material effort was given to shortening the response time of the instrument, as the available response was believed to be in accord with Signal Corps needs. In the event that a shorter response is found to be desirable, the present instrument has considerable potential for improvement. The most basic improvement is concerned with the inherent response of the thermistor element. Certain improvement possibilities for the thermistors were discussed in the earlier report [1].

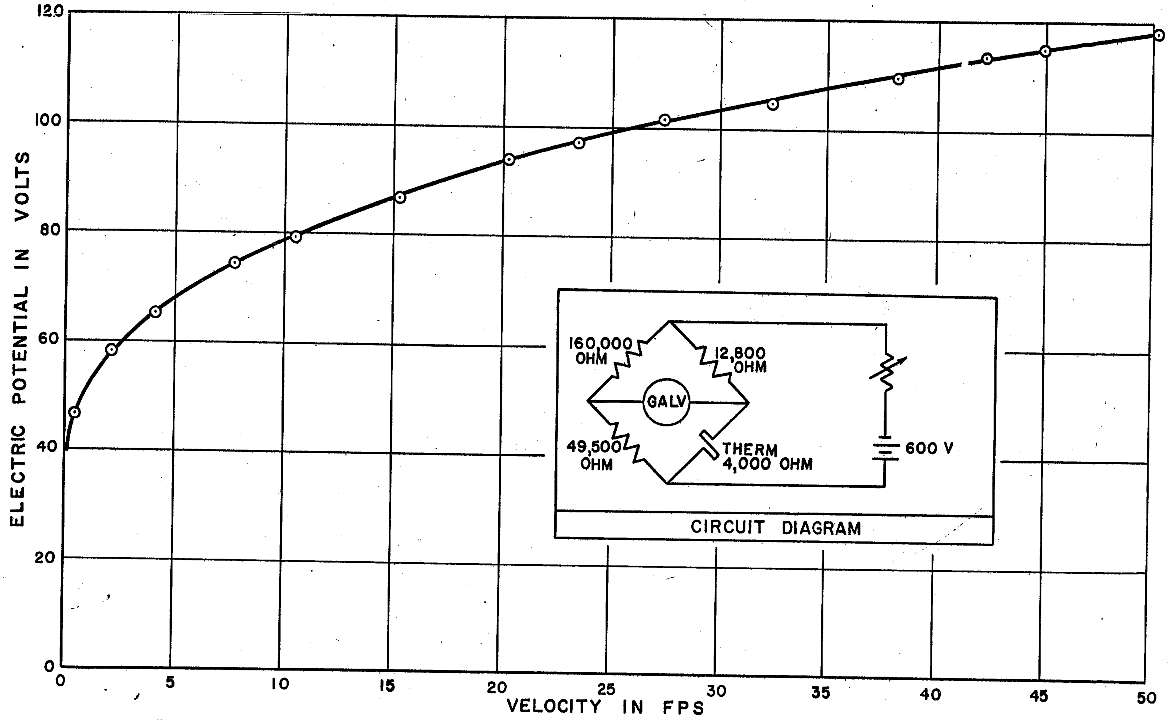


Fig. 1 - Velocity Calibration at Room Temperature of Bendix-Friez 517613-1 Rod Thermistor for Constant-Temperature (or Resistance) Operation

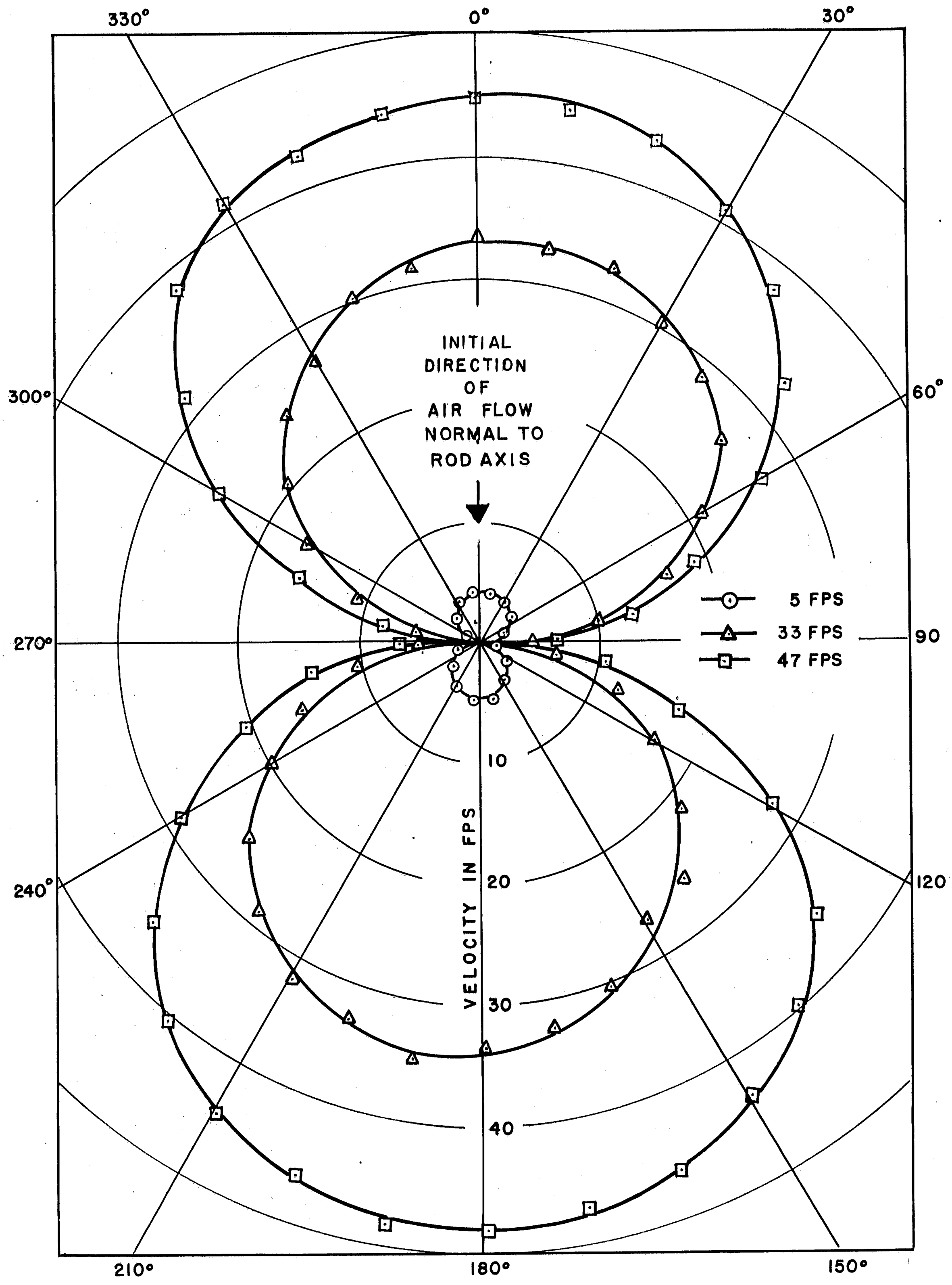


Fig. 2 - Directional Characteristics at Room Temperature of a Single Bendix-Friez 517613-1 Rod Thermistor Rotated in a Wind Under Constant-Temperature Conditions

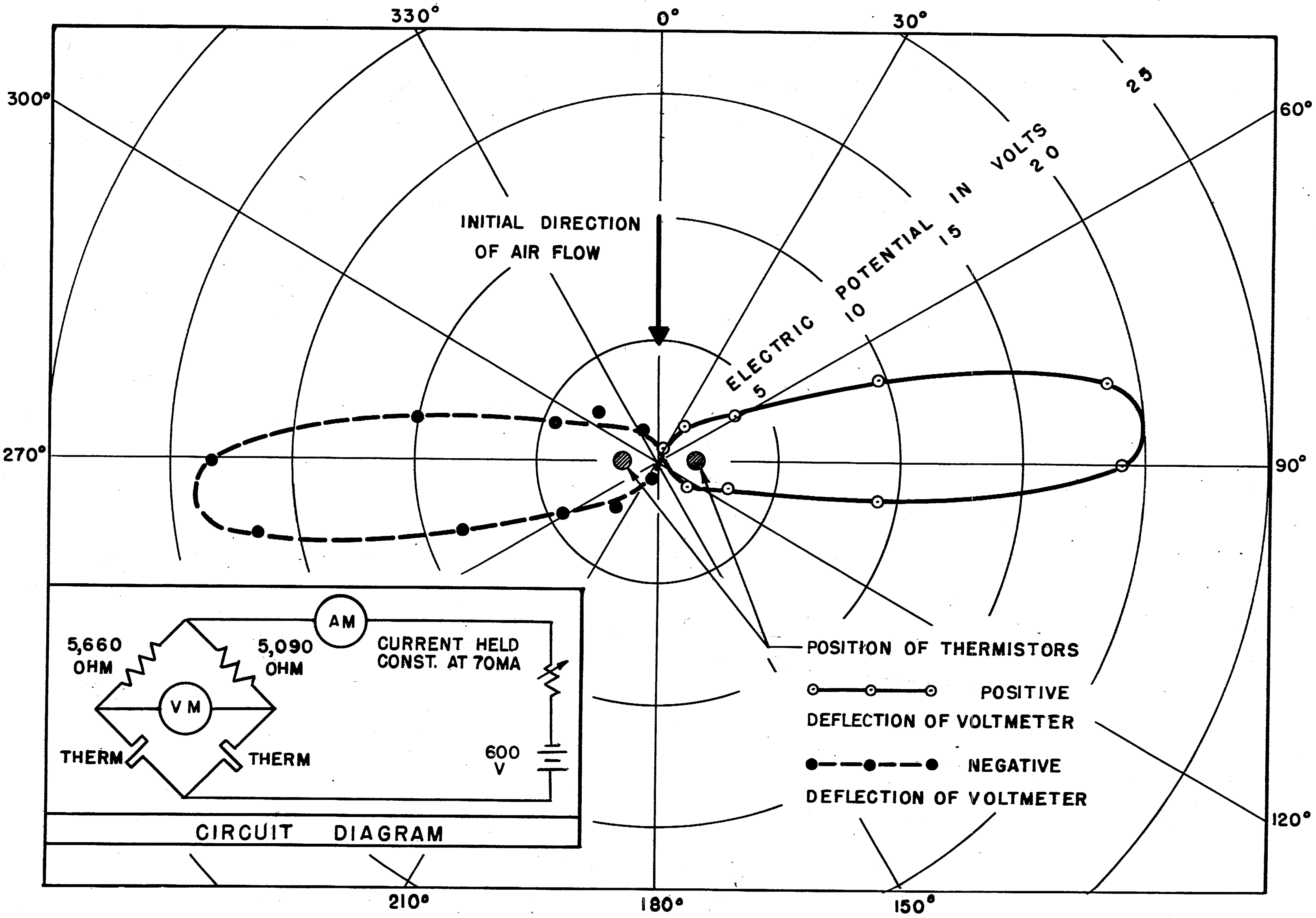


Fig. 3 - Directional Characteristics at Room Temperature of a Parallel Array of Bendix-Friez Rod Thermistors

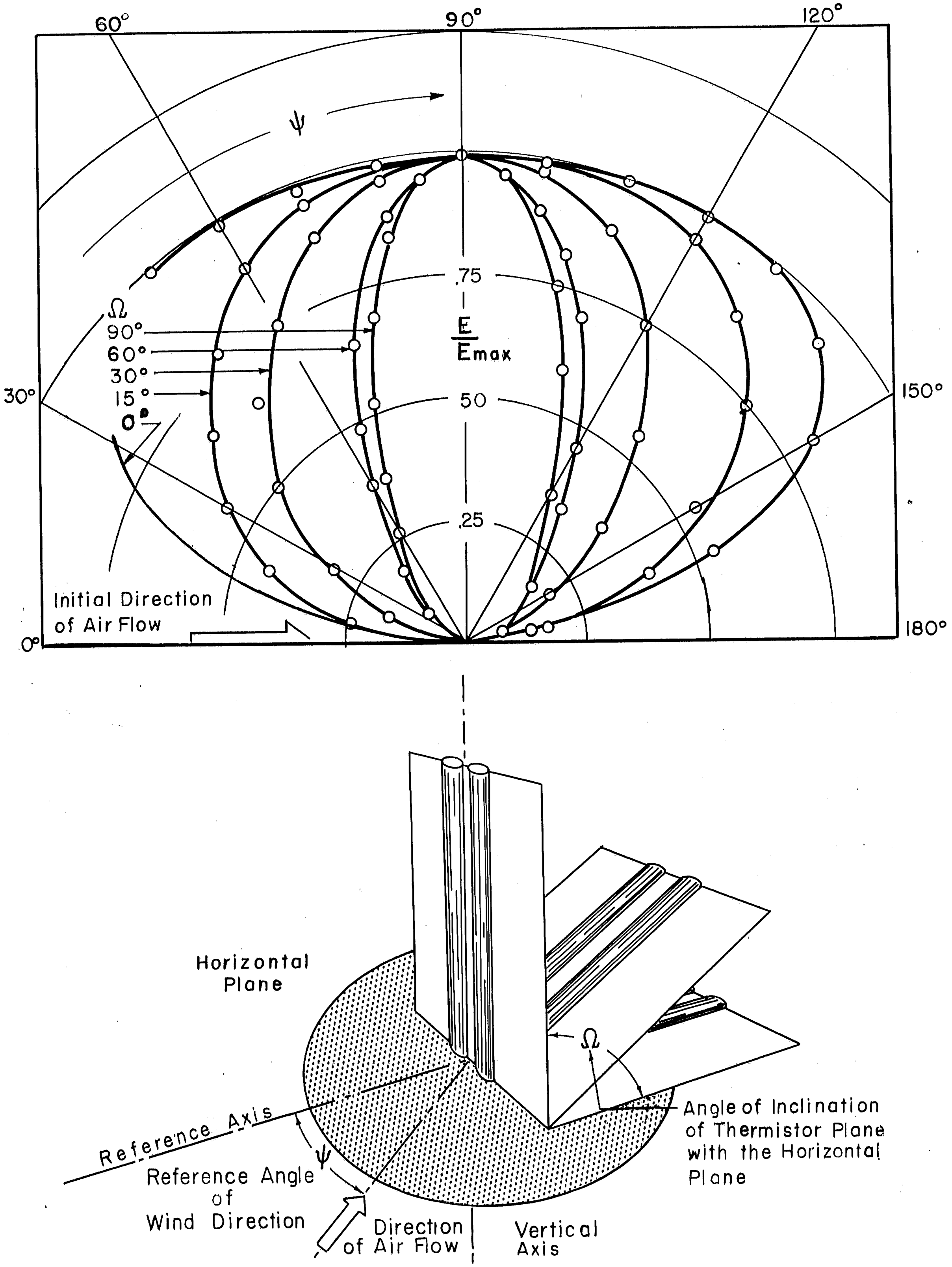


Fig. 4 - Directional Characteristics and Arrangement of a Tilted Pair of Rod Thermistors

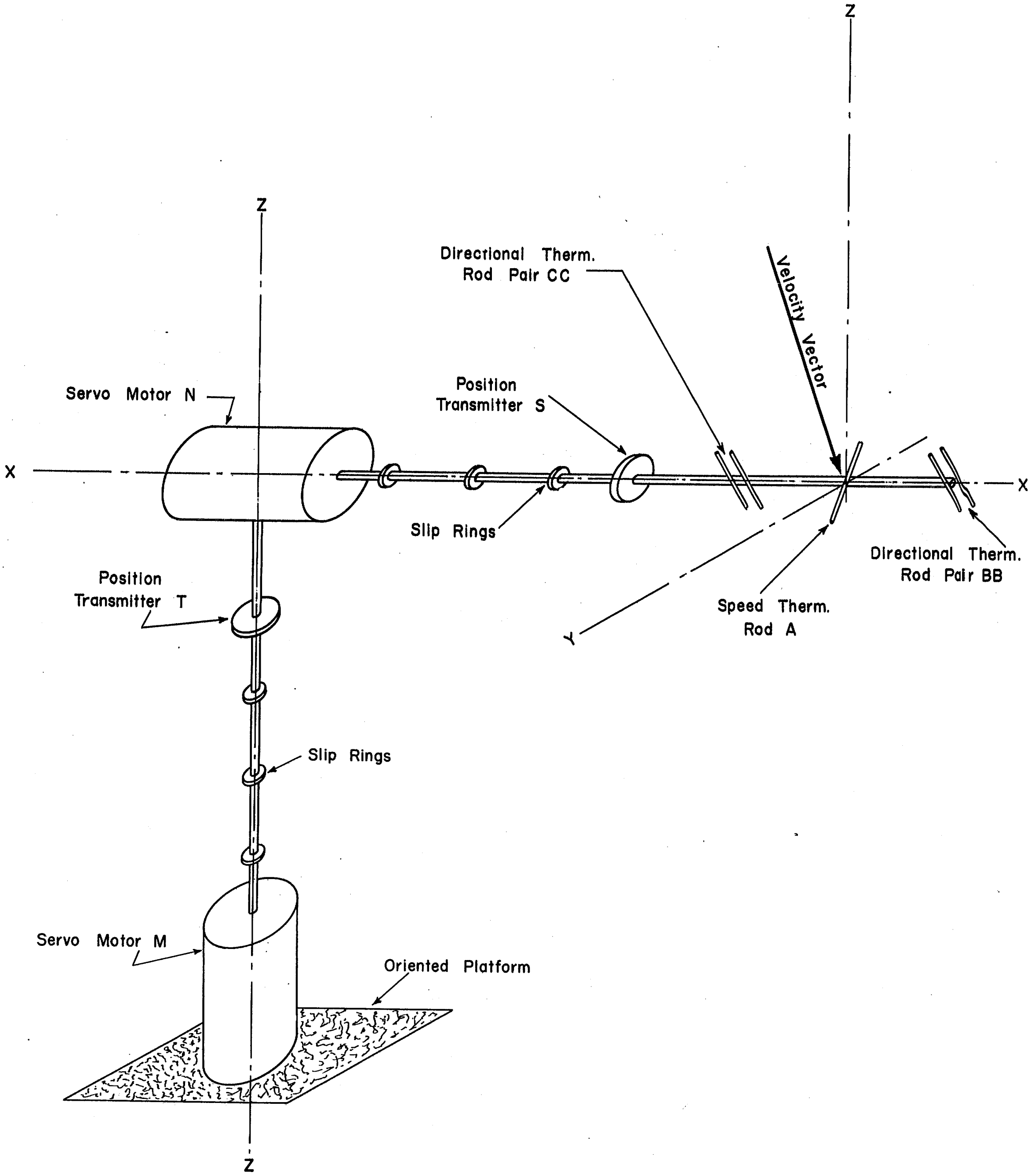
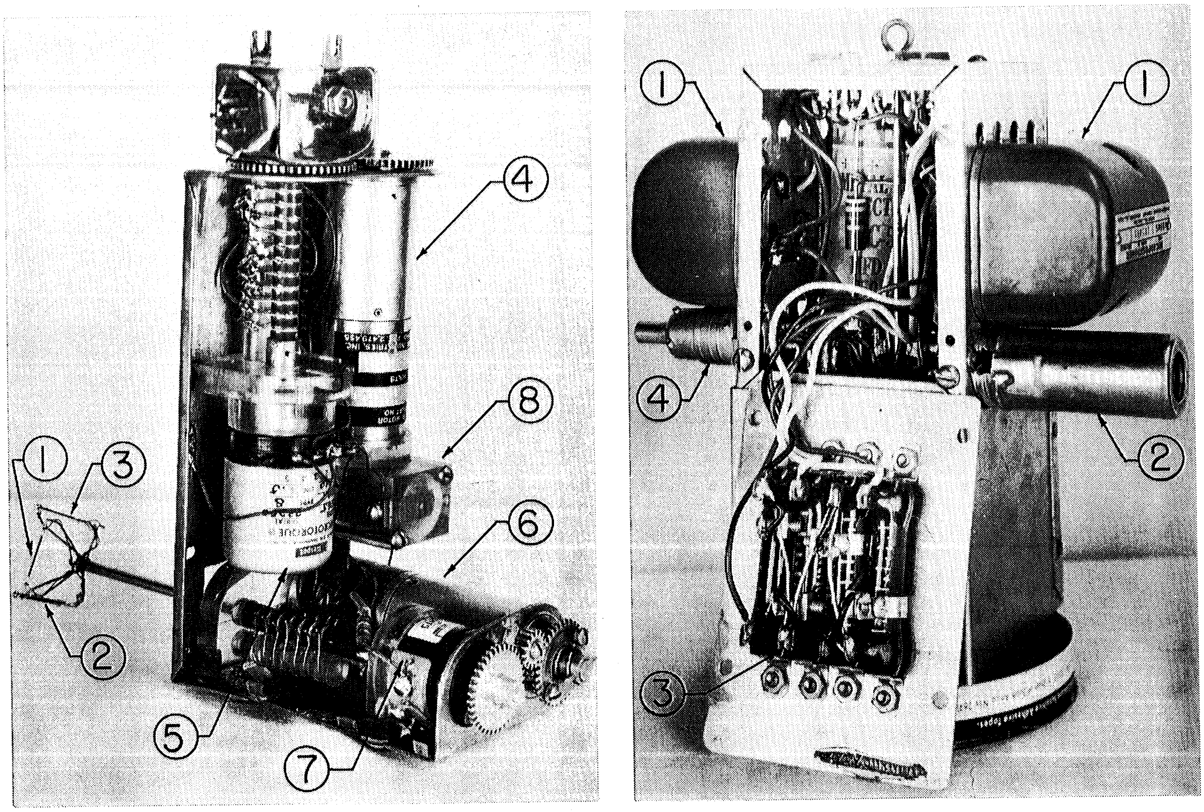


Fig. 5 - Schematic Arrangement of a Thermistor Actuated, Servo-Driven, Air Velocity Measuring System



(a) Sensing Unit

① Speed Thermistor
② Elevation Thermistor Pair
③ Azimuth Thermistor Pair
④ Azimuth Drive Motor
⑤ Azimuth Position Transmitting Potentiometer
⑥ Elevation Drive Motor
⑦ Elevation Position Transmitting Potentiometer
⑧ Batteries

(b) Control Unit

① Micro Position Relays
② Thermistor Switching Relay
③ Rotation Balancing Resistors
④ Temperature Thermistor

Fig. 6 – The Sensing and Control Units

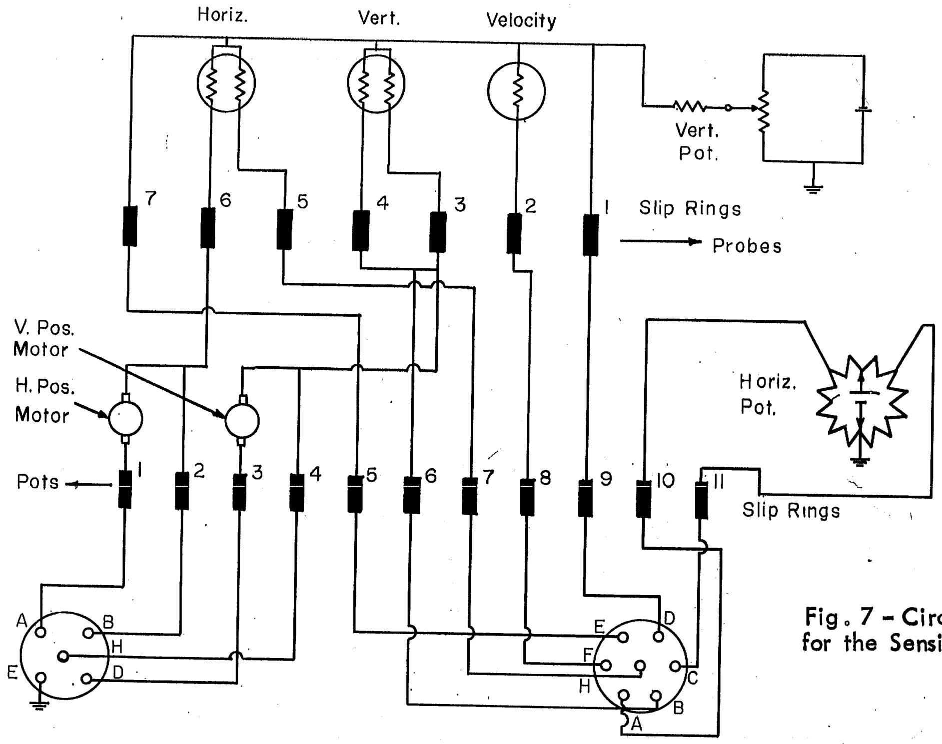


Fig. 7 - Circuit Diagram for the Sensing Unit

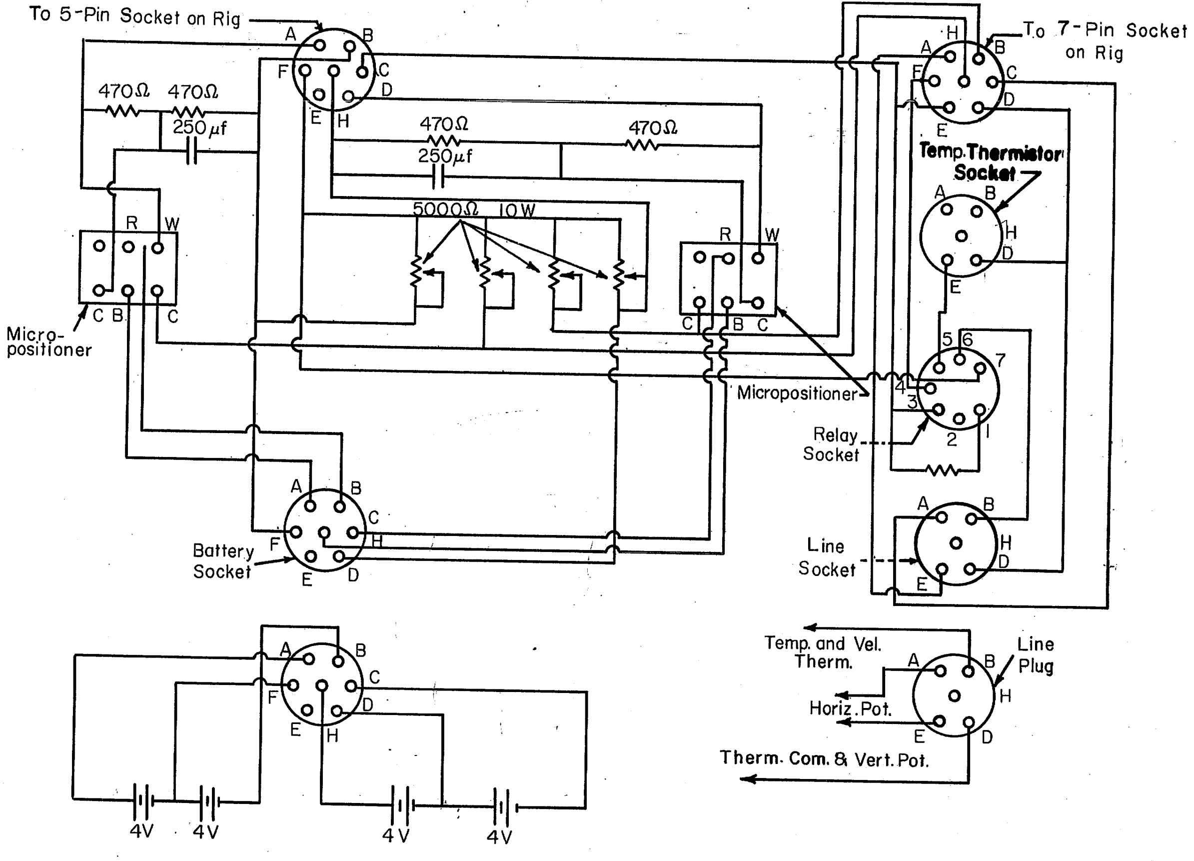
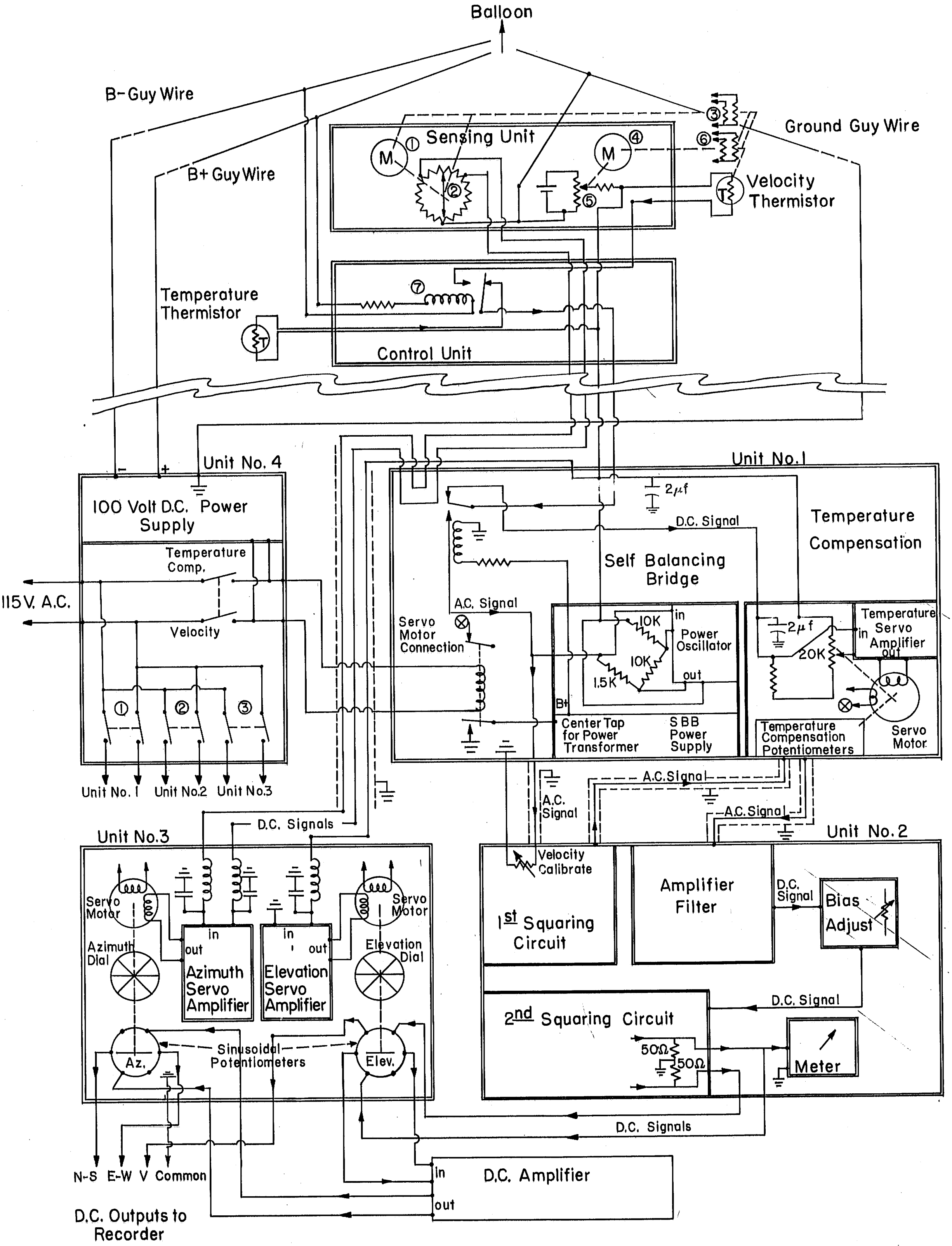


Fig. 8 - Circuit Diagram for the Control Unit



1 Azimuth Drive Motor
2 Azimuth Transmitting Unit
3 Azimuth Positioning Thermistor Pair
4 Elevation Drive Motor
5 Elevation Transmitting Unit
6 Elevation Positioning Thermistor Pair
7 Thermistor Switching Relay

Note: Equipment is Shown in the Temperature Compensation Condition.

Motor Drive Systems are Omitted to Simplify Schematic.

Fig. 9 - Block Diagram of the Complete Measuring System

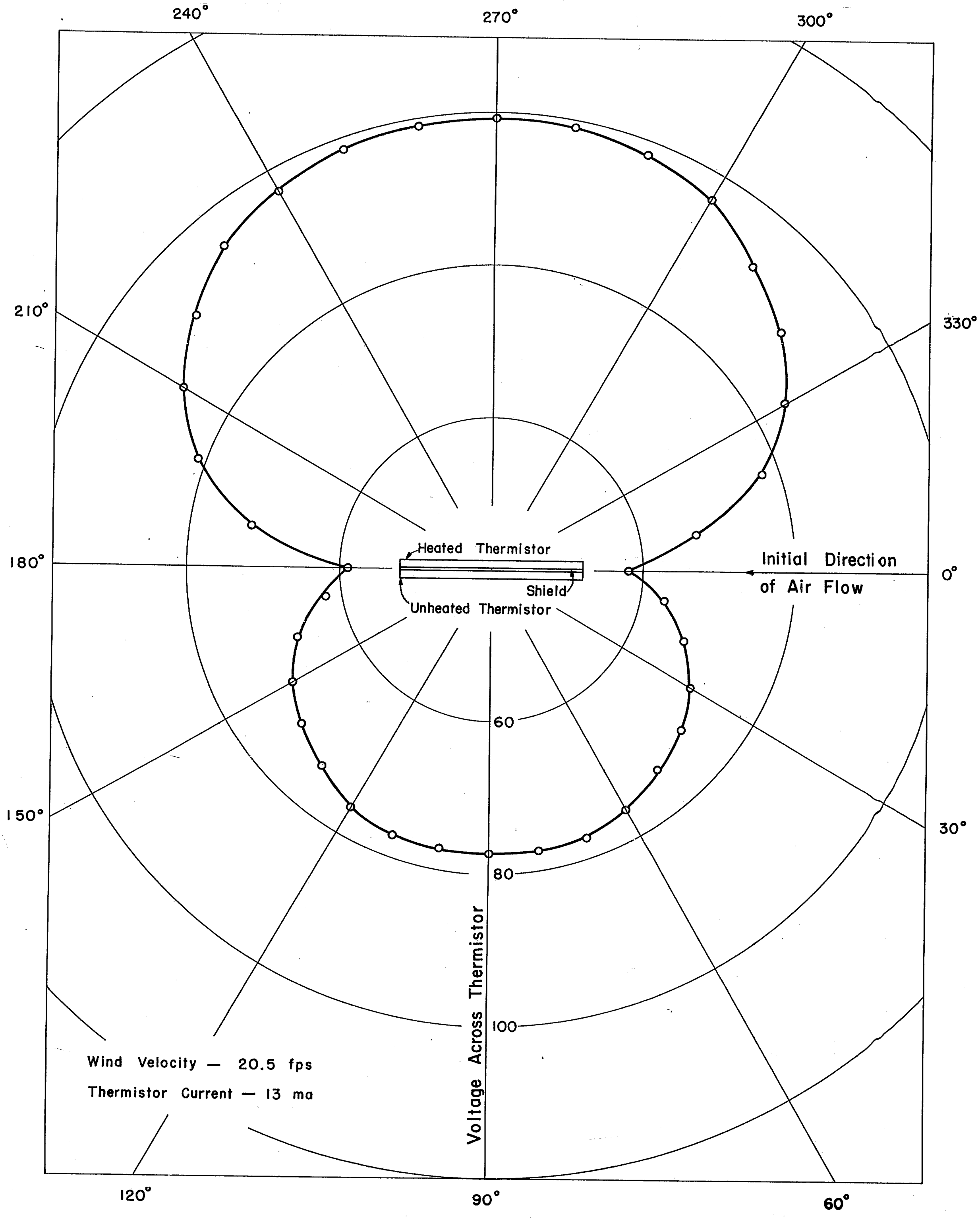


Fig. 10 - Directional Properties of a Single Heated Thermistor Shielded by a Flat Paper Rectangle and an Unheated Thermistor

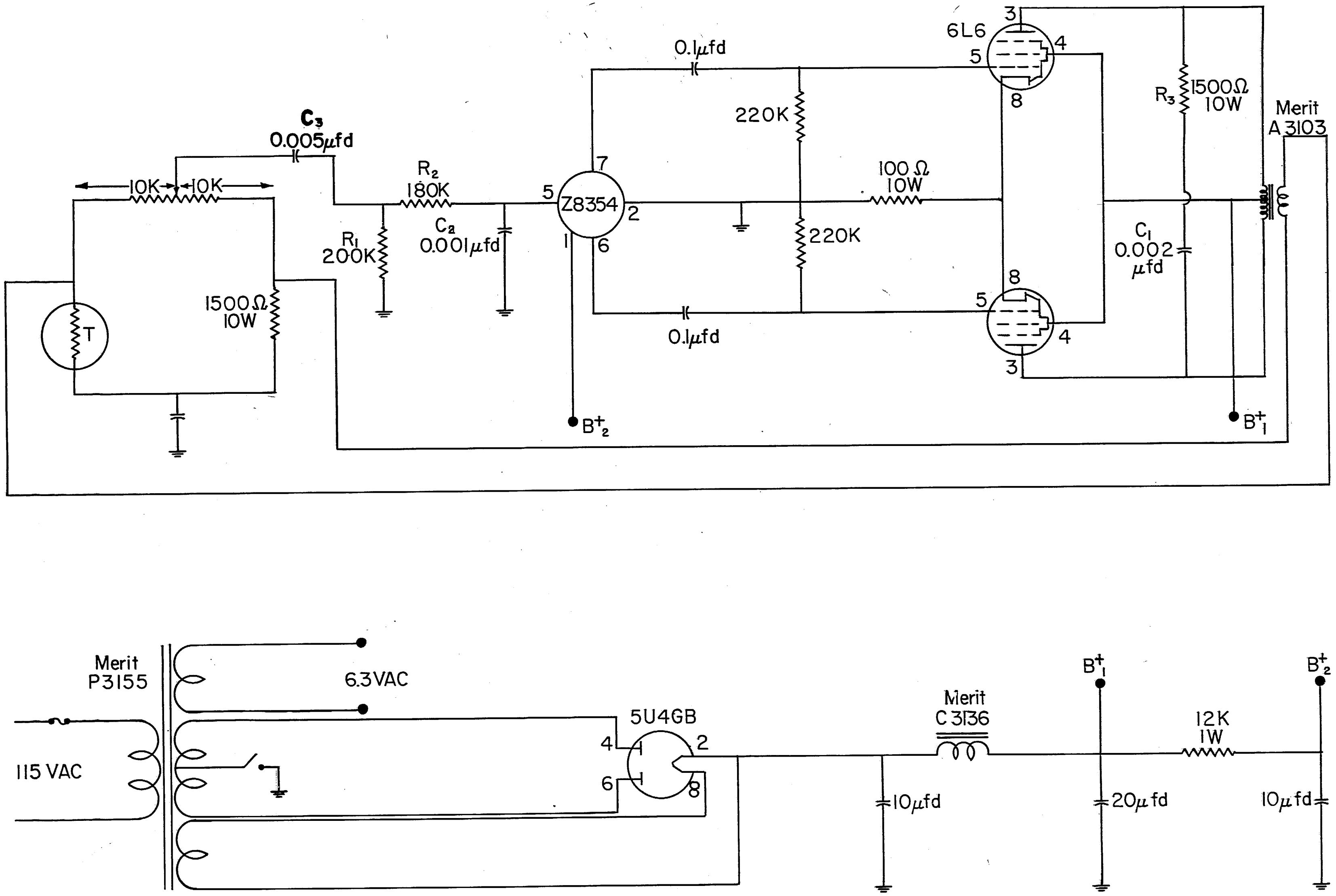
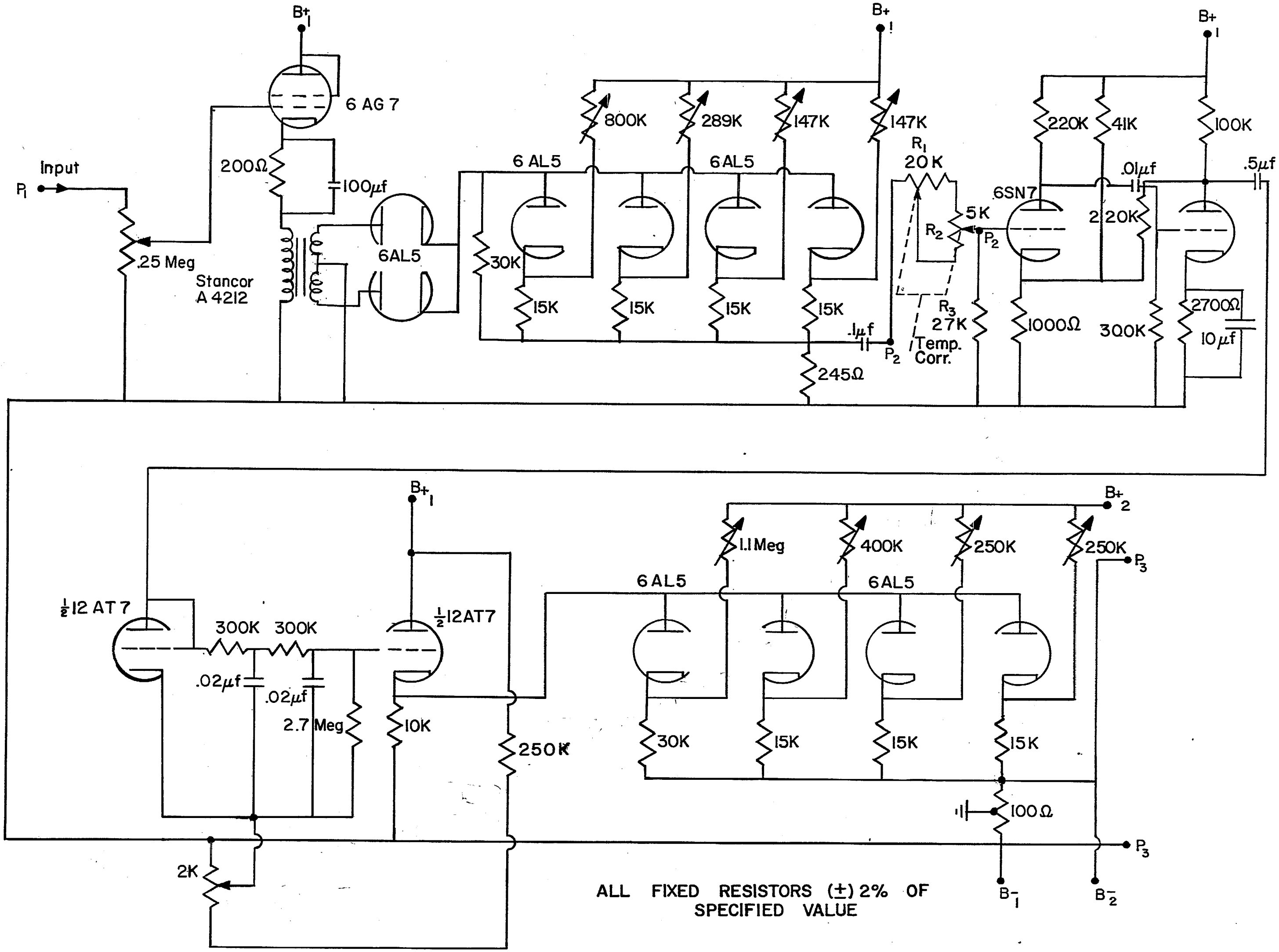


Fig. 11 - The Self-Balancing Bridge Circuit



ALL FIXED RESISTORS (±) 2% OF SPECIFIED VALUE

Fig. 12 – The Linearizing Circuits

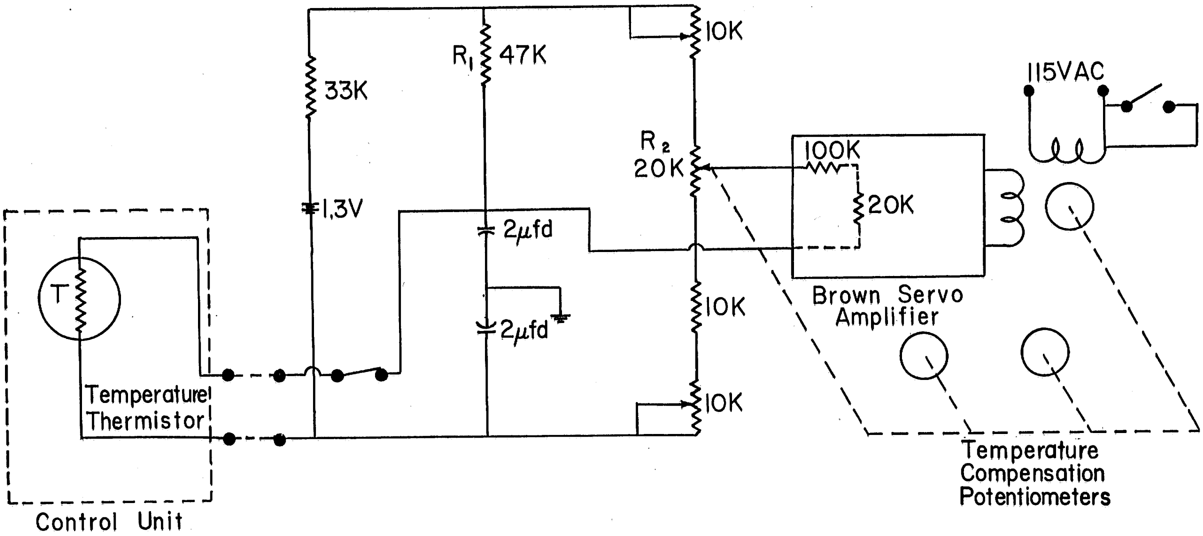


Fig. 13 - The Temperature Measuring and Compensating Circuit

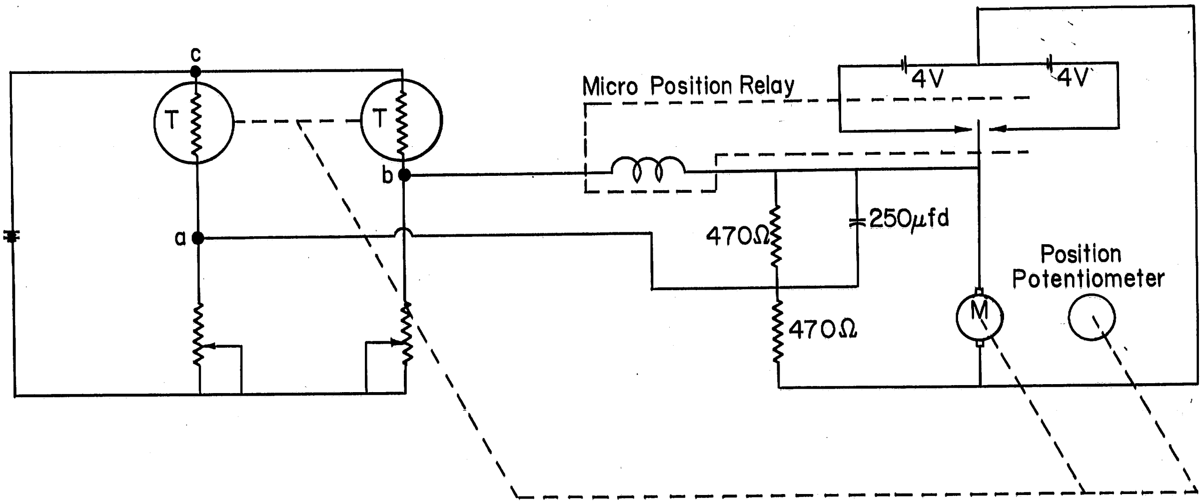


Fig. 14 - The Basic Directional Circuit

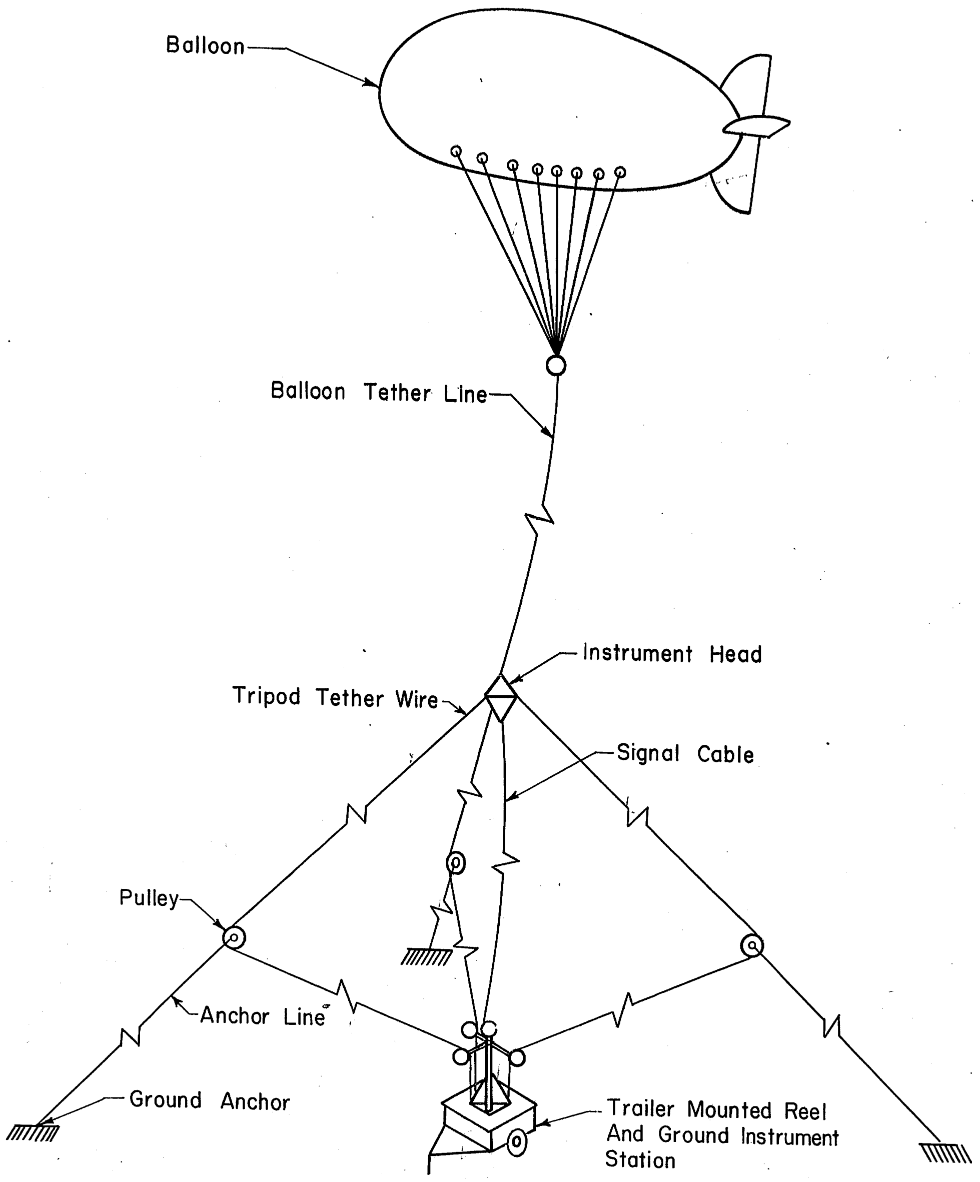
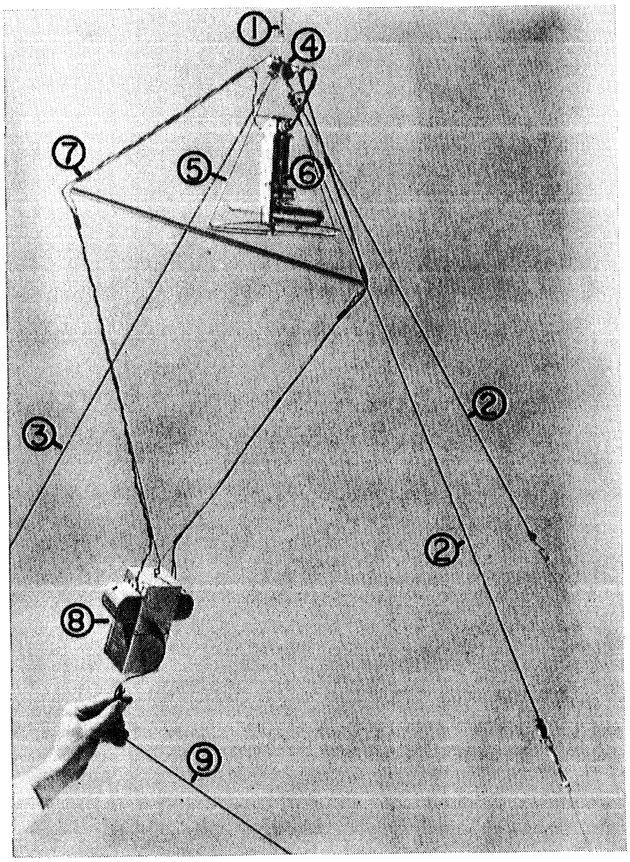


Fig. 15 – Schematic Sketch of the Balloon-Support System



① Balloon Tether Line
② Tripod Tether Line (Powered)
③ Tripod Tether Line (Grounded)
④ Anchor Piece Surrounded By Gimbal
⑤ Support Cage
⑥ Sensing Unit
⑦ Yoke
⑧ Control Unit
⑨ Signal Conductor Cable

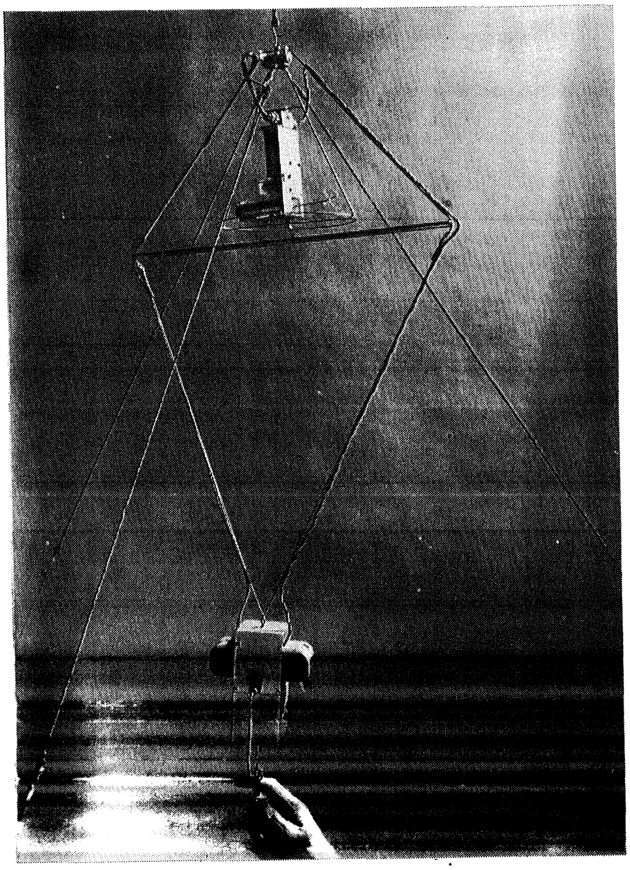
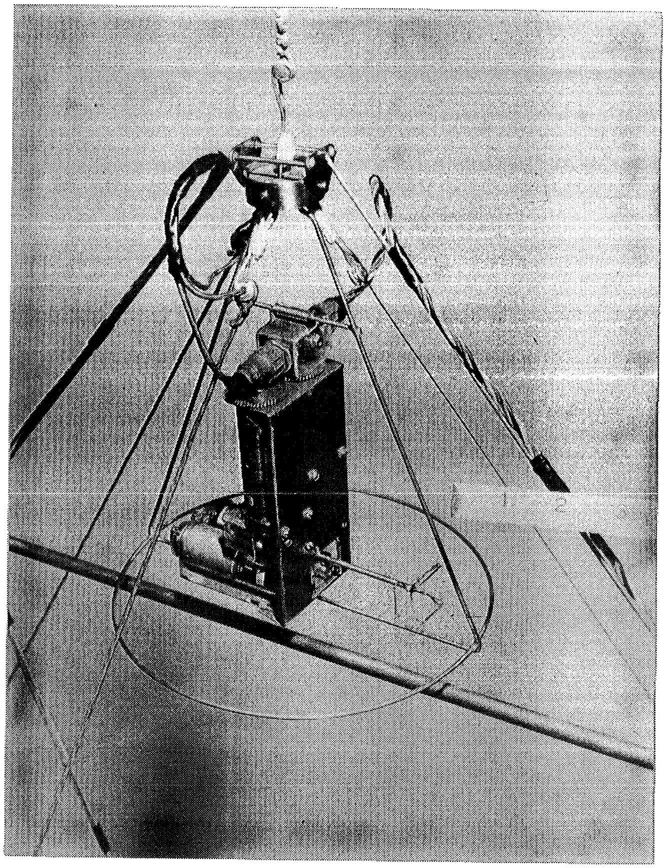


Fig. 16 – Support System for the Instrument Station

Note: Minor changes in control unit were made after this photo



① **Sensing Unit**
② Cable Connectors
③ Pivot Bearing
④ Speed Thermistor
⑤ Directional Thermistor Pair
(Y-Z Plane)
⑥ Directional Thermistor Pair
(X-Y Plane)

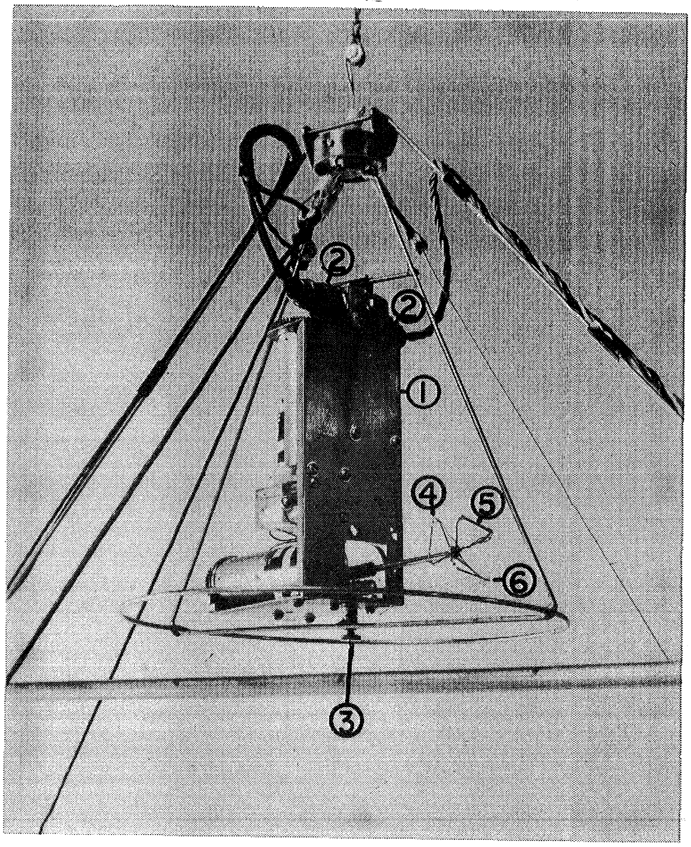


Fig. 17 - The Sensing Unit Mounted in the Support System

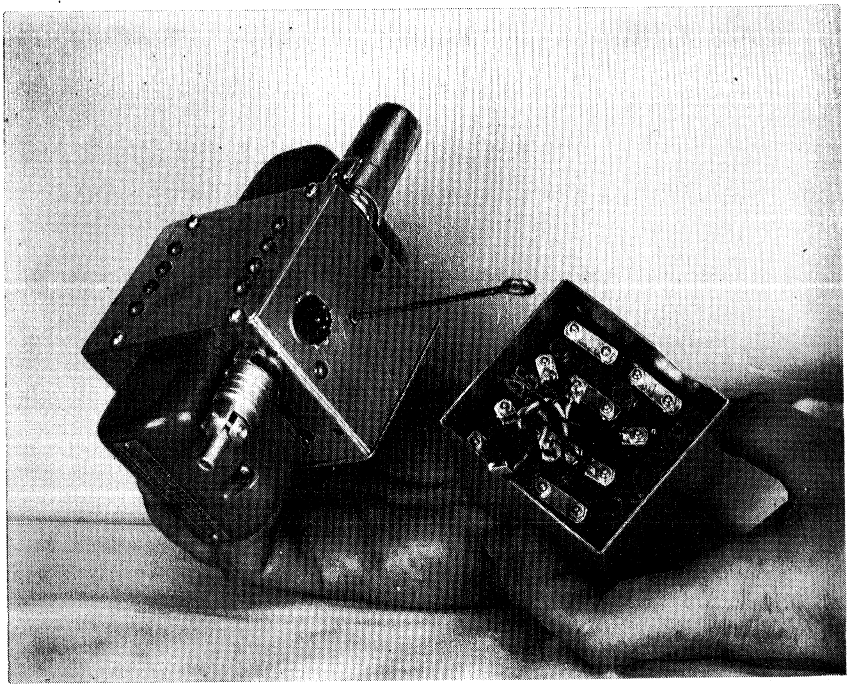
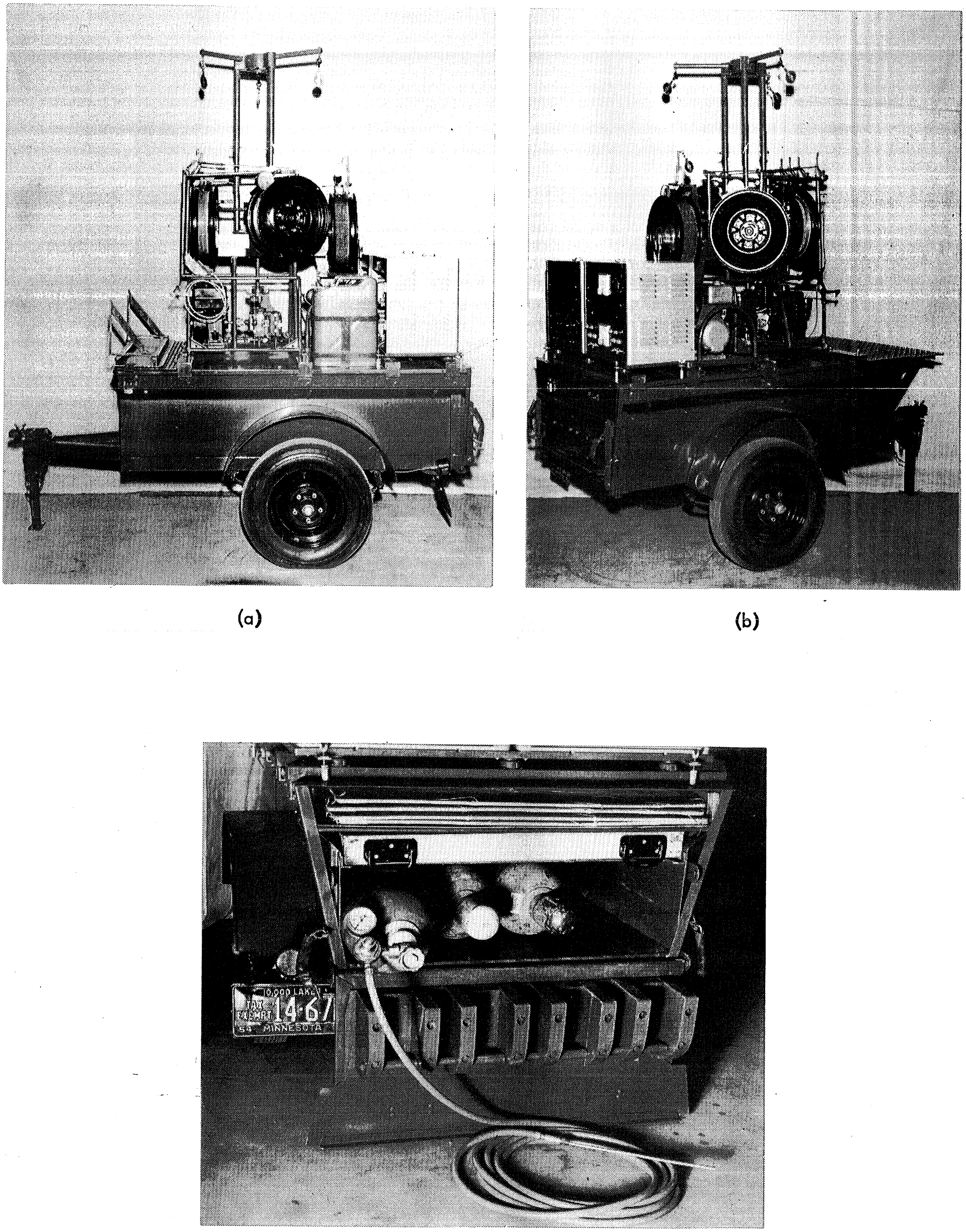


Fig. 18 – The Control Unit Dis-Assembled



(a)

(b)

(c)

Fig. 19 - The Trailer Mount