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A METHOD FOR THE INVESTIGATION OF UPPER-AIR PHENOMENA AND ITS APPLICATION TO RADIO METEOROGRAPHY

By Harry Diamond, Wilbur S. Hinman, Jr., and Francis W. Dunmore

ABSTRACT

Experimental work conducted for the U. S. Navy Department on the development of a radio meteorograph for sending down from unmanned balloons information on upper-air pressures, temperatures, and humidities, has led to radio methods applicable to the study of a large class of upper-air phenomena. The miniature transmitter sent aloft on the small balloon employs an ultrahigh-frequency oscillator and a modulating oscillator; the frequency of the latter is controlled by resistors connected in its grid circuit. These may be ordinary resistors mechanically varied by instruments responding to the phenomena being investigated, or special devices the electrical resistances of which vary with the phenomena. The modulation frequency is thus a measure of the phenomenon studied. Several phenomena may be measured successively, the corresponding resistors being switched into circuit in sequence by an air-pressure-driven switching unit. This unit also serves for indicating the balloon altitude. At the ground receiving station, a graphic frequency recorder, connected in the receiving set output, provides an automatic chart of the variation of the phenomena with altitude. The availability of a modulated carrier wave during the complete ascent allows of tracking the balloon for determining its azimuthal direction and distance from the receiving station—data required in measuring the direction and velocity of winds in the upper air.

CONTENTS

I. INTRODUCTION

The use of special radio equipment carried aloft in unmanned balloons for the investigation of upper-air phenomena has attracted the attention of a number of scientific workers during recent years. A large class of phenomena may be conveniently studied by such methods at relatively low cost. Examples of such phenomena include meteorological elements, such as barometric pressure, air temperature, humidity, wind velocity, cloud height, and vertical thickness; radio-wave propagation; light intensity in various parts of the light spectrum; electrical conductivity and voltage gradient; cosmic-ray intensities, etc. Measurements of these phenomena may be carried out at predetermined fixed altitudes or as a function of altitude. In general, besides providing means for translating the variation of the phenomenon to be measured into radio signals which may be interpreted on the ground, the apparatus carried aloft must also transmit information on the altitude of the balloon. In several of the applications, such as the determination of upper-air wind velocities and radio-propagation studies, it is also necessary to know the distance to the balloon, which may be determined by radio direction-finding methods. It is thus desirable that the type of radio emission employed on the balloon be continuous in order to facilitate direction finding.

This paper describes a radio method which fulfills the three requirements just outlined and appears particularly adaptable for the study of certain of the phenomena enumerated. The principal objective of our experiments has been the development of a radio-meteorograph system for use in the aerological service of the U. S. Navy Department, at the request of that Department. However, as will appear from a description of the method and apparatus evolved, its properties permit of a considerably broader field of application.

II. CLASSIFICATION OF PRIOR AND CONTEMPORARY DEVELOPMENTS

In general, most upper-air phenomena may be measured in terms of the deflection of mechanical instruments or of changes in the properties of electrical devices. For transmitting these measurements by radio to a receiving station on the ground it is necessary to convert the mechanical deflection or the change in electrical properties into an interpretable characteristic of the radio emission. Means for accomplishing this conversion may be divided into three general classifications according to their operation. In one class, the angular deflections from fixed references of the pointers of one or more mechanical instruments are interpreted in terms of time intervals. The various arrangements of the Olland type radio meteorograph developed in this country and abroad [1] [1] are representative of this class. A rotating contactor, propelled by a clock or other drive, makes contact as it passes pointers which are controlled by changes in pressure, temperature, and humidity, and thereby keys the radio transmitter. The time intervals between these contacts and others which the rotating contactor makes regularly with fixed points may be interpreted as definite values of pressure, temperature, and humidity. A special case of this class consists in converting electrical impulses into the

[1] Figures in brackets throughout this paper relate to references given on pages 391-392.

operation of a relay for keying the balloon transmitter, the frequency of keying being a measure of the intensity of the phenomenon producing the impulses. This method has been applied to the study of cosmic rays [2].

In a second class, the deflections of the pointers are interpreted in terms of some measuring scale independent of time. The radio meteorographs developed by Moltchanoff [3] and Bureau [4] and the pressure indications employed by Duckert [5] are representative of this class. In the Moltchanoff arrangement, the pointer deflections are interpreted in terms of coded signals repeated in distinctive groupings. In Bureau's arrangement, the pointers are grouped, as in the Olland method; however, the rotating contactor carries with it a means for mechanically modulating the transmitter, so that the angular deflection of a given pointer from its zero reference is interpreted in terms of the number of cycles of the modulation occurring between the corresponding contacts rather than in terms of the intervening time. In the Duckert instrument, the barometer serves to interrupt the transmitter at fixed pressure levels. By keeping track of the number of interruptions occurring from the beginning of an ascension, the pressure level corresponding to a given interruption may be determined.

In the third class, the deflections of mechanical instruments or the changes in properties of electrical devices are caused to vary either the carrier frequency or the modulating frequency of the balloon transmitter, and the values of the effects studied are interpreted in terms of the frequency. In the radio meteorograph developed by Väisällä [6], three condensers, controlled respectively by mechanical instruments responsive to pressure, temperature, and humidity, and two additional calibrating condensers are successively switched into the carrier oscillator circuit. The values of pressure, temperature, and humidity are interpreted in terms of the carrier frequency. Similarly, in the Duckert radio meteorograph, a bimetallic thermometer controls a condenser which varies the carrier frequency. Feige [7] devised a modification of the Duckert radio meteorograph for measuring cloud height and vertical thickness. He substituted a photoelectric cell for the bimetallic thermometer and employed a special milliammeter, carrying a variable condenser, for controlling the carrier frequency as a function of the current through the photocell, and, hence, as a function of light brightness.

Consideration of the several means described for translating variations in the phenomena under investigation into interpretable characteristics of the emitted signals reveals that they are more suited to the use of mechanical instruments than to electrical devices. In the two cases [2, 7] discussed in this section where electrical devices are employed, their variations are first converted into mechanical deflections before they are caused to control a characteristic of the radio emission.

III. BASIS OF OUR METHOD

In our experimental work, a method was sought which would not be restricted to the use of mechanical devices. The basis for this search is the fact that a number of the upper-air phenomena which it was desired to study are best measured by means of electrical devices. In particular, there appeared to be possibilities in such a method for eliminating the operational difficulties involved in the use of the several radio meteorographs described in the previous section. A study of such devices revealed that a considerable number of them were characterized by changes in electrical resistance as a function of the phenomena to which they were responsive. For example, the temperature coefficient of resistance of certain electrolytes is quite high, so that their variation in resistance may be used as a measure of temperature; the surface leakage resistance of certain glasses may be used as a measure of humidity; the resistance of an air gap ionized by a radioactive substance varies as a function of the barometric pressure; the equivalent resistance of a photoelectric cell varies as a function of light intensity or brightness; etc. Accordingly, a translating means was desired wherein the variation of electrical resistance was caused to vary a characteristic of the radio emission from the balloon, namely, the modulating frequency.

The negative transconductance circuit described by Herold [8] (of the voltage-controlled type), was adapted to this purpose since it provided a light-weight audio-frequency oscillator in which the generated frequency is approximately inversely proportional to the grid-circuit resistance. With this translating means, electrical devices having inherent resistance variation as a function of some phenomenon may be connected directly in the grid circuit, while the deflection of a mechanical instrument responsive to some phenomenon is readily converted into the variation of a grid-circuit resistor.

An added advantage of the negative-transconductance circuit is that the generated audio frequency is also a function of the bias voltage on the control grid so that electrical devices producing a variable current through a constant grid-circuit resistor may also be made to vary the modulating frequency of the emitted radio wave. For example, a Geiger counter may be connected in a suitable resistance-capacitance network to supply a variable current to the grid-circuit resistor, the average value of this current being directly proportional to the frequency of the counter breakdown. The generated audio frequency, varying in accordance with the resultant variations in the grid-bias voltage, will then be a measure of the cosmic-ray intensity. Similarly, the variation in electrical charge on collecting conductors may be used to produce a proportional variation in the grid-bias voltage, and, hence, the generated audio frequency of the modulating oscillator may be made a function of atmospheric potential gradient or conductivity.

A particular advantage of the translating means just described is that the continuous emission from the balloon on a constant carrier frequency facilitates the application of direction-finding methods at the ground station.

IV. TRANSMITTING-CIRCUIT ARRANGEMENT

A circuit diagram of the radio transmitting equipment used on the balloon is given in figure 1. The transmitter employs a type-1A6 tube for the audio oscillator, a type-32 tube as an audio amplifier, and a type-30 tube as a radio-frequency oscillator. The audio oscillator operates on the negative characteristic produced between grids 2 and 4 of the 1A6 tube. Its frequency-determining circuit consists primarily of the charging condenser C and of the total resistance of the control-grid circuit. In this circuit, V is the device whose electrical resistance varies as a function of the phenomenon to be measured and R and R_2 are limiting resistors to fix, respectively, the lower and upper limits of the frequency range covered. (A range of from 20 to 200 c/s has been employed in practically all of our experiments). The generated frequency is, however, also dependent to considerable extent upon the value of the charging resistor, R_3, upon the plate-battery voltage, the internal-battery resistance (which adds to the charging resistance), and, to lesser degree, upon the filament-battery voltage. The frequency is also affected by radio-frequency feedback into the grid circuit which operates to change the effective control-grid bias. The voltage-regulating neon tube in figure 1 is employed to minimize the effect of variations in the plate-battery voltage and in its internal resistance. The audio amplifier serves to reduce the radio-frequency

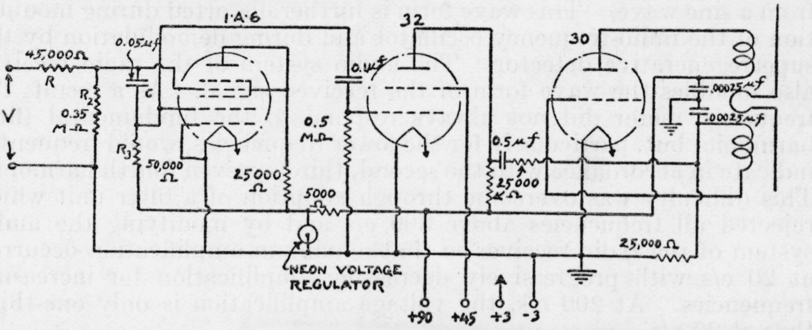

FIGURE 1.—*Electric-circuit arrangement of the radio transmitter used on the balloon.*

feedback and at the same time presents a high impedance load to the output circuit of the audio oscillator.

Grid modulation of the radio-frequency oscillator is employed, nearly complete modulation of the emitted carrier being obtained. In our experiments we have used carrier frequencies ranging from 50 to 200 Mc/s, the upper frequencies in this range being generated by means of a special type 955 acorn tube having low filament power consumption, furnished by the Radio Corporation of America.

With the various precautions used for increasing the frequency stability of the audio oscillator, as indicated, the generated frequency corresponding to a given grid-circuit resistance remains constant within ± 3 percent for changes in the filament-battery voltage of from 3 to 2 v., for changes in the plate-battery voltage of from 90 to 65 v., in the plate-battery resistance of from 100 to 1,500 ohms, in the transmitter temperature of from $+35$ to $-20°$ C., and in the antenna load of from 100 to 20 percent. These variations represent the extreme limits encountered in the usual upper-air studies.

V. GROUND-STATION RECEIVING EQUIPMENT

Figure 2 shows the ground-station receiving and recording equipment used with this method. The superregenerative receiving set, A, feeds an electronic frequency meter, B, through a suitable amplifier and electric filter unit, C. The electronic frequency meter operates to deliver a series of direct-current pulses to its indicating meter, the average value of which ranges from 0 to 500 μa as the frequency varies from 0 to 200 c/s. This current is filtered to an average value and the voltage drop obtained by passing it through a resistor is applied to the input terminals of a high-speed recording millivoltmeter, *D*. The complete setup is essentially a recorder which converts the audio-frequency notes received in the radio-receiver output into a graphic chart. The abscissa scale of the chart may obviously be calibrated directly in terms of the phenomenon measured, provided the generated audio frequency in the balloon transmitter is a known function of the phenomenon.

In the first use of the receiving setup, considerable difficulty was experienced due to varying wave form of the received audio-frequency note. The frequency meter responds to the predominant harmonic of the voltage applied to its input terminals. The wave form produced by the audio oscillator in the balloon transmitter departs considerably from a sine wave. This wave form is further distorted during modulation of the radio-frequency oscillator and during demodulation by the superregenerative detector. The audio system of the radio receiver also modifies the wave form of the received signal. As a result, the frequency meter did not always respond to the fundamental (first harmonic) but, particularly for the lower frequencies, would frequently indicate in accordance with the second, third, or even fourth harmonic. This difficulty was overcome through adoption of a filter unit which rejected all frequencies above 300 c/s and by modifying the audio system of the radio receiver so that maximum amplification occurred at 20 c/s with progressively decreasing amplification for increasing frequencies. At 200 c/s, the voltage amplification is only one-third that at 20 c/s.

The limited frequency response of the audio circuits coupled with the operation of the frequency meter to respond only to the predominant note of a signal renders the receiving system quite free from interference. An interfering signal must have a single note below 300 c/s which is of greater intensity than the desired signal before it can take over the operation of the frequency meter and recorder.

The receiving setup is practically automatic in its operation. There is little need for retuning, except just after the transmitter has left the ground. Two separate automatic volume-control features take care of the large variation in received voltage as the distance of the balloon transmitter from the receiving station increases. The first is inherent in the operation of the superregenerative detector, while the second is provided by the frequency meter which operates accurately for a range of input voltages of from 2 to 150 v.

VI. APPLICATIONS OF OUR METHOD IN SIMPLIFIED FORMS

The operation of our method is best illustrated by means of several simplified applications. In figures 3 and 4 are shown experimental models of electrical devices designed to respond to temperature and humidity, respectively. The temperature device consists of a glass capillary tube filled with an electrolyte having a high temperature coefficient of resistance, so that its resistance is a function of temperature. The humidity device consists of a bifilar winding on the etched surface of a glass tube, the surface leakage resistance as meas-

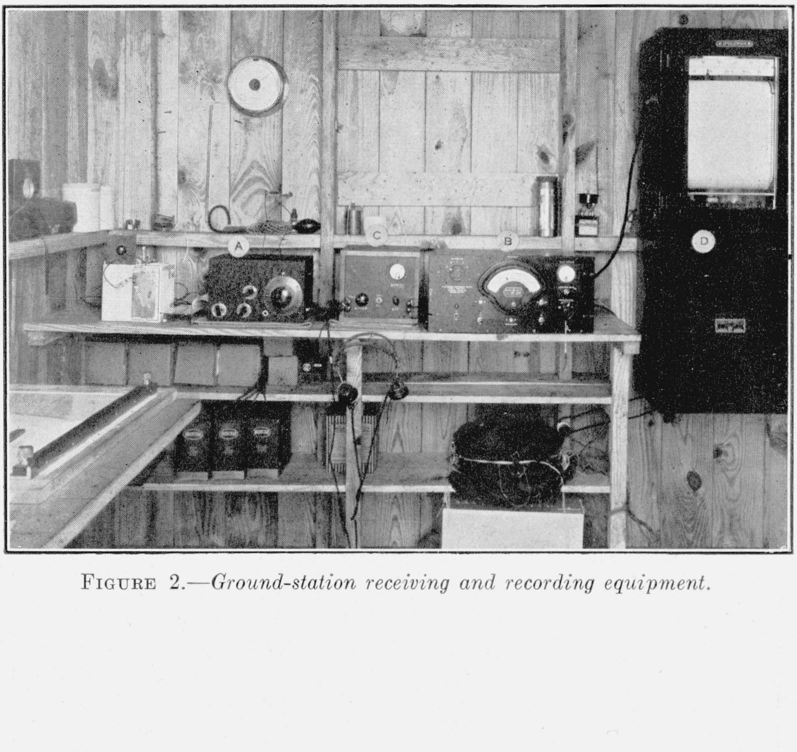

FIGURE 2.—*Ground-station receiving and recording equipment.*

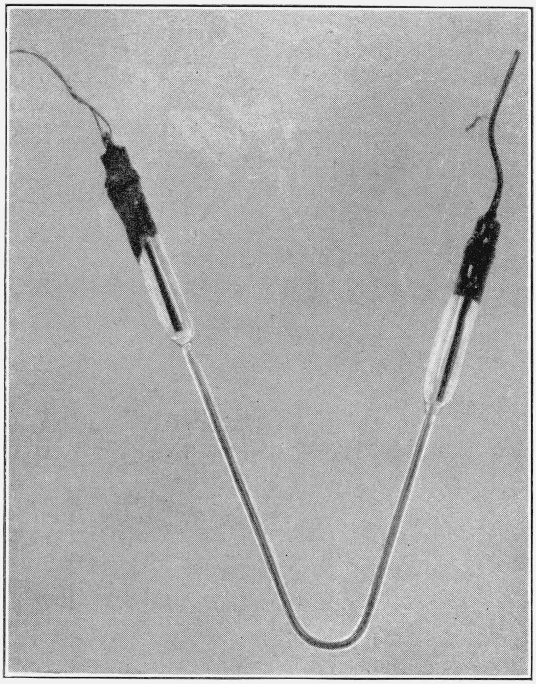

FIGURE 3.—*Capillary electrolytic thermometer.*

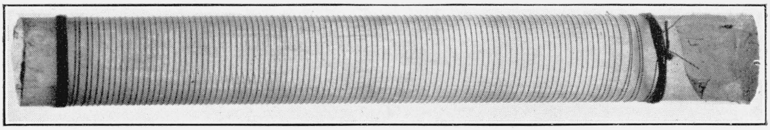

FIGURE 4.—*Electrical hygrometer.*

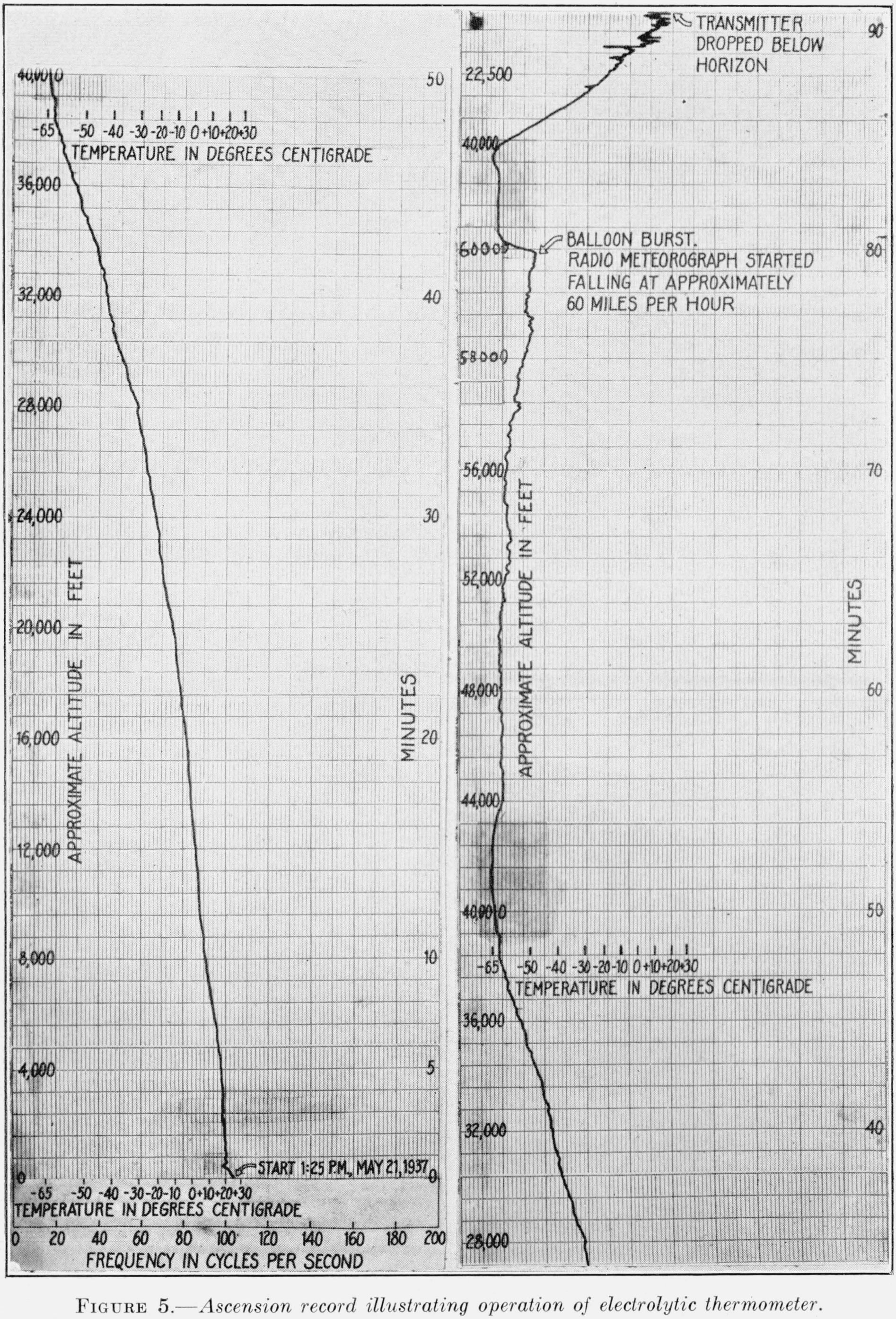

FIGURE 5.—*Ascension record illustrating operation of electrolytic thermometer.*

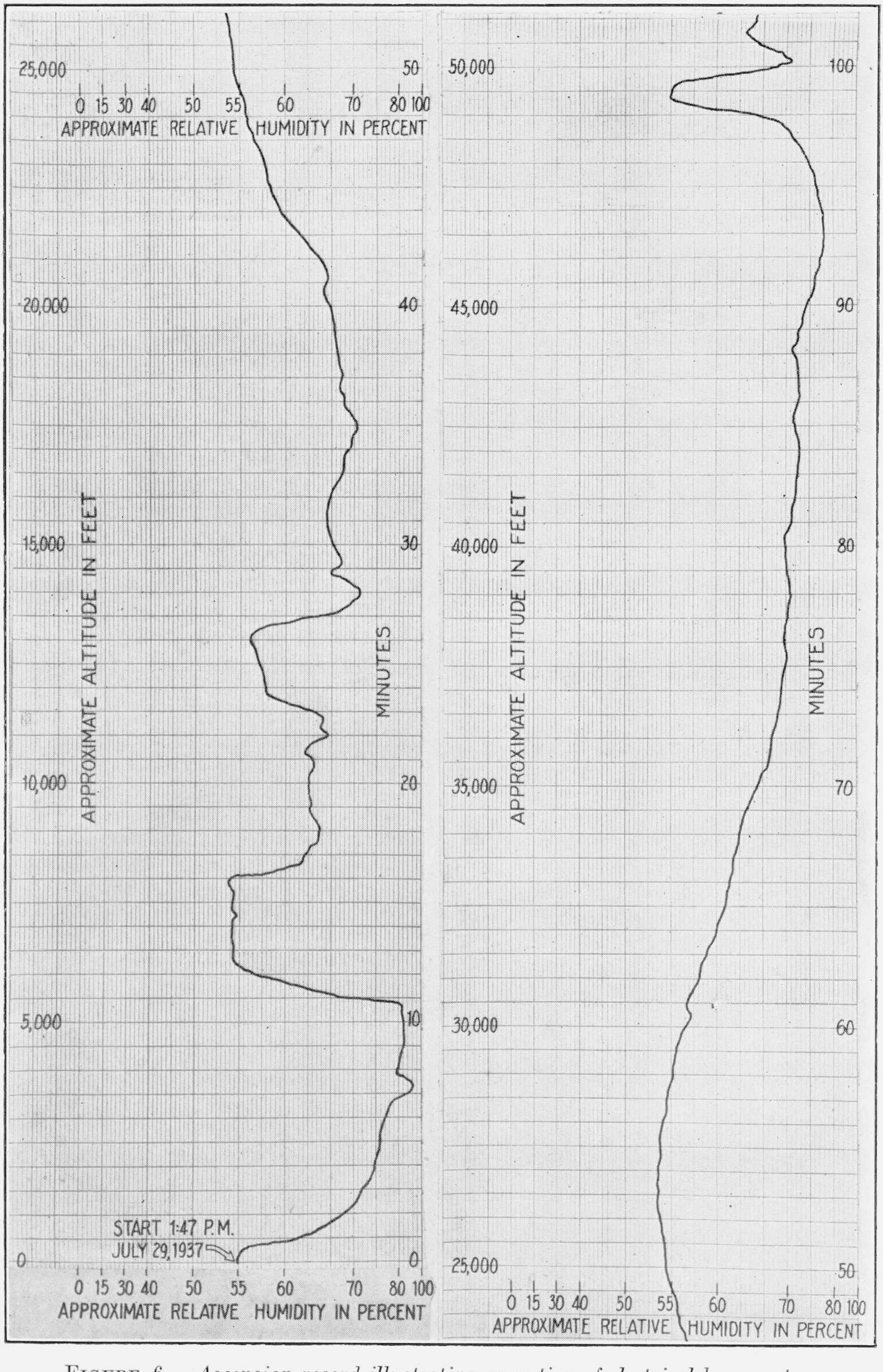

FIGURE 6.—*Ascension record illustrating operation of electrical hygrometer.*

ured between the two wires being a function of humidity. Further description of the two devices will be given in later sections. Figures 5 and 6 show typical charts obtained at the ground receiving station from ascension tests in which the temperature and humidity tubes, previously calibrated, were respectively connected in the grid circuit of the audio oscillator. The abscissas give the values of the received audio frequency and also the corresponding values of the functions measured. The ordinates show the estimated altitude of the balloon based on the amount of balloon inflation at the surface altitude. The balloon rate of ascent is approximately constant (except when the balloon is close to its bursting point) and, hence, the altitude is directly proportional to the elapsed time from the beginning of the ascent.

VII. MEASUREMENT OF CLOUD HEIGHT AND THICKNESS

A record obtained from an ascension test in which a photoelectric cell was connected in the grid circuit of the audio oscillator to give information on the variation of light brightness with altitude is shown in figure 7. Such data give a direct measure of the height to the tops of existing clouds and the visibility conditions above each cloud. The window of the photoelectric cell was pointed downward to eliminate the effect of direct sunlight upon emergence from the clouds. Heavy overcast with intermittent rain occurred on the day of the test.

Referring to the record, the abscissas represent brightness, the reference mark "dark" corresponding to complete absence of light. The ordinates represent altitude or elapsed time. As the balloon ascended it will be noted that the brightness was quite low and steady except for minor fluctuations, until the balloon reached approximately 3,800 ft. In the altitude range of from 3,800 to 5,200 ft, the increase in brightness with height indicates the presence of a cloud layer some 1,400 ft thick. The balloon, penetrating the light-absorbing layer, is moving toward the region of higher brightness.

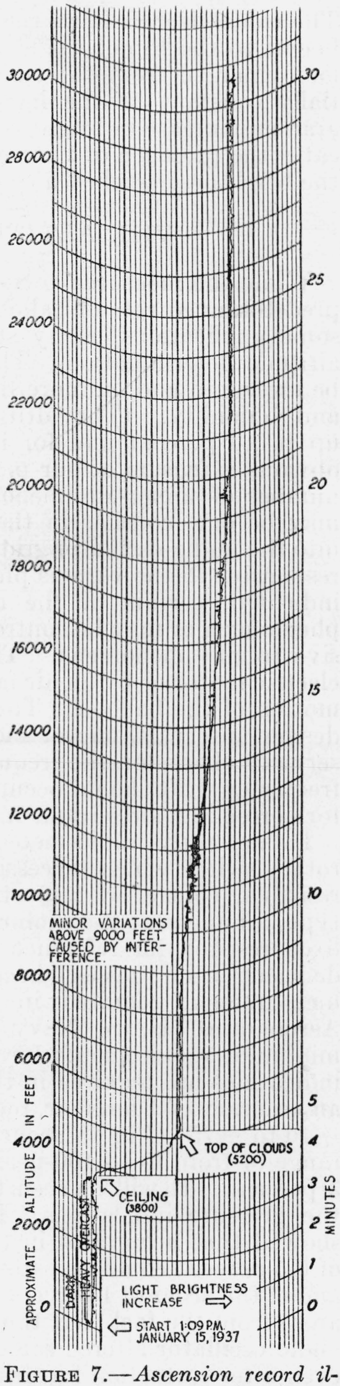

FIGURE 7.—*Ascension record illustrating use of photoelectric cell in measuring ceiling and height of top of clouds.*

The chart clearly shows the height of the "ceiling" (3,800 ft) and the height to the top of the cloud layer (5,200 ft). At 5,200 ft the balloon emerged from the cloud and the brightness remained substantially constant at the increased value until about 9,000 ft. The gradual increase in brightness from 9,000 to 20,000 ft probably indicates the presence of haze in this altitude region. Above 20,000 ft the brightness reached a constant value.

VIII. ALTITUDE DETERMINATION

While the measurement of altitude in terms of elapsed time and a predetermined rate of balloon ascent may be sufficiently accurate for some applications, many studies require considerably more precise altitude determination. This requires that the barometric pressure be measured and, in more rigorous applications, also the temperature and humidity. (The altitude correction for temperature may be up to 10 percent and for humidity up to about 0.5 percent.) An obvious extension of our method to include the measurement of any number of upper-air phenomena, of which the barometric pressure may be one, consists in the use of a rotary switch which connects into the audio-oscillator grid circuit, in any desired succession, resistors responsive to the various phenomena to be measured. As previously indicated, certain of the resistors may vary inherently with the phenomena or may be controlled mechanically by instruments responsive to the phenomena. The switch may be driven by a spring or electric motor or by an air fan which operates by virtue of the upward motion of the balloon. The switch may also connect into circuit, at desired intervals, one or more fixed calibrating resistors which may serve as checks on the frequency stability of the audio oscillator. If frequency drift should occur, the reference frequencies provide means for correcting the various measurements on a proportional basis.

In an early radio-meteorograph model, we used a fan-driven rotary switch which successively connected into circuit three variable resistors, controlled respectively by a barometer of the diaphragm type, a bimetallic thermometer, and a hair hygrometer, and a fourth, fixed resistor, for reference purposes. This arrangement was found deficient in one respect because of the unusual precision of pressure measurement required in radio meteorography. The Bureau of Aeronautics, U. S. Navy Department, formulated the following minimum requirements for radio meteorograph operation: Pressure indications are required in the range of from 1,050 to 150 millibars to an accuracy of 1 millibar, temperature indications in the range of from +40 to −75° C to an accuracy of 1°, and humidity indications in the range of from 0- to 100-percent relative humidity accurate to within 3 percent. It will be seen that the required accuracy is greatest for the pressure indications. Experiments with the method described showed that accuracies in the frequency measurements of the order of 0.5 percent could be expected under carefully controlled conditions and of the order of 1 percent in routine operation. The chief difficulty arose from the fact that the frequency-resistance characteristic of the audio oscillator altered somewhat under operating conditions so that, even after correction for drift on the basis of the reference frequency, a residual error of about 0.5 percent remained. While this error was

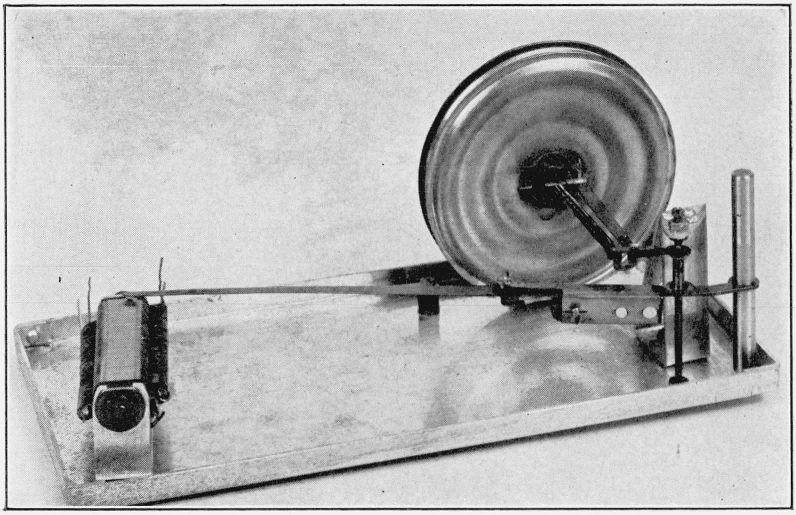

FIGURE 8.—*Experimental model of one form of the pressure-switching unit.*

not sufficient to affect the required accuracy of temperature and humidity indication, it was much too large for the pressure measurements.

To increase the accuracy of pressure measurement, we adopted a novel method [2] of indication which at the same time introduced several additional operating improvements. This method makes use of the fact that the pressure element deflects continuously in one direction as the balloon ascends, and employs this motion for carrying out the switching operation in the balloon transmitter. The sequence of switching operations serves for absolute indication of the barometric pressure in discrete steps, thereby obviating the need for interpreting pressure in terms of either time or frequency. A greater accuracy of indication is inherent in this arrangement. At the same time, the need for any other form of motive power for carrying out the switching operations is eliminated. Other advantages of this type of pressure indication will be considered in the following section.

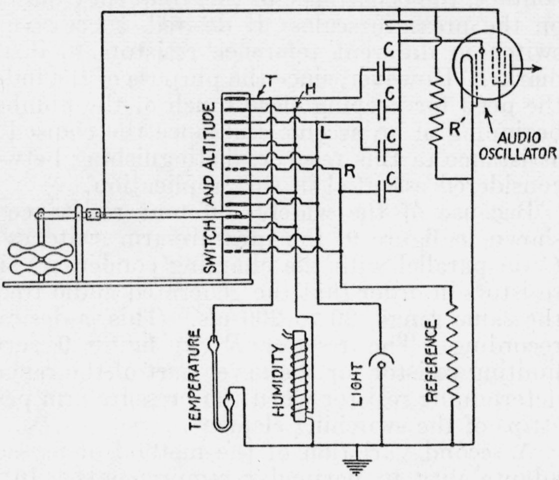

FIGURE 9.—*Schematic drawing of pressure-switching circuit arrangement as employed in the measurement of three properties of the atmosphere in addition to altitude (barometric pressure).*

1. PRESSURE SWITCHING

An experimental model of one form of pressure-switching with which we experimented is shown in figure 8, and the corresponding electrical circuit arrangement in figure 9. The pressure diaphragm operates a pointer which moves over a simple switching element consisting of electrical-conducting strips separated by insulating strips. The face of the switching element is polished so that friction opposing the arm movement is negligible. Contact of the pressure arm with a given conducting strip is therefore a direct measure of the barometric pressure to which the diaphragm is subjected. It is necessary only to provide means for identifying the particular conducting strip being contacted to secure an absolute-pressure scale. This is accomplished by the sequence of switching into circuit the several devices employed and by the regular spacing of the conducting strips to which the reference resistor is connected. In figure 9 are shown elements responsive to temperature, humidity, and brightness, and the reference resistor. The symbols *T*, *H*, *L*, and *R* refer to the

[2] Some months ago there came to the attention of the authors a description of a temperature-switching arrangement (see reference [9]) applied to the switching of lights for use of meteorographs at night, somewhat similar to the pressure-switching method which we have developed.

conducting strips on the switching element to which these are connected. The pressure arm moving over the conducting strips of the switching element successively connects into circuit the three devices in the order named and then repeats the sequence. After each two groups, the reference resistor is switched into circuit. Since it produces a substantially fixed frequency which occurs every seventh contact, the occurrence of this frequency may serve as an index mark on the pressure scale. If desired, successive seventh contacts may switch in different reference resistors to distinguish between index marks. However, since the purpose of the index marks is to eliminate the need for keeping close touch of the number of contacts from the beginning of an ascent, and since the elapsed time is of considerable assistance in this respect, distinguishing between index marks is not considered essential in this application.

Because of the widely different resistance ranges of the devices shown in figure 9, the pressure-arm switches in suitable condensers C (in parallel with the charging condenser) simultaneously with the resistors in order that the generated audio frequencies may remain in the same range, 20 to 200 c/s. This is desirable for convenience in recording. The resistor R' in figure 9 serves as the frequency-limiting resistor for the lower part of the range. It is the frequency-determining resistor when the pressure arm passes over the insulating strips of the switching element.

A second variation of the method of pressure-switching shows its adaptability to particular requirements. In routine radio-meteorograph operation, it is desirable that the balloon equipment be as simple as possible in order to reduce weight and to keep the unit price within the cost of the present airplane ascensions made for upper-air soundings. Also, the readings of temperature and humidity should be made at as many altitude levels as possible in order to obtain a nearly continuous picture of their variations. Accordingly, the radio meteorograph designed for use by the Navy Department [10] does not include the photoelectric cell; also, the electrical circuit of the pressure-switching unit is arranged so that temperature readings are obtained when the pressure arm is on an insulating segment and humidity readings when the pressure arm is on a conducting segment (exclusive of the index contacts).

A description of this instrument will form the chief subject matter of the remaining portions of this paper. However, before entering into this description, a brief outline will be given of the advantages of pressure-switching in combination with the frequency scale for measuring the upper-air phenomena investigated. The advantages are:

1. The method provides for great flexibility in the measurement of upper-air phenomena, a large class of mechanical and electrical devices being readily employed.

2. Readings of the phenomena being measured are obtained directly as a function of pressure, which may be readily converted into height. The record obtained at the ground station is plotted in this form and is easy to interpret.

3. Observations are obtained at predetermined pressure levels, independent of the rate of ascent of the balloon. This permits of using any practicable rate of ascent, thereby reducing the time required for a given set of observations. The use of electrical devices is of par-

ticular value in this respect since they are inherently faster in response than mechanical instruments.

4. The possibility of higher rates of ascent provides other important advantages: (*a*) Since the balloon will not drift so far, there is a greater chance for recovery of the instruments, particularly in near-coastal regions; (*b*) the shorter range permits taking check observations during the descent of the equipment; (*c*) battery requirements may be reduced appreciably; (*d*) better ventilation may be had of instruments requiring ventilation, such as the temperature and humidity devices.

5. The accuracy of pressure indication is practically equal to the accuracy of the instrument itself and does not depend upon any translatory means.

IX. NAVY RADIO METEOROGRAPH

1. PRESSURE-SWITCHING CIRCUIT ARRANGEMENT

The electrical circuit arrangement of the pressure-switching unit used in the Navy radio meteorograph is shown in figure 10. The

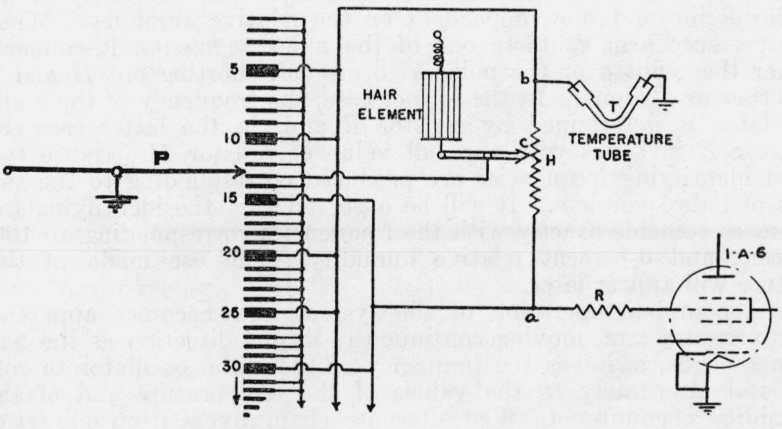

FIGURE 10.—*Electric-circuit arrangement of the pressure-switching unit employed in the Navy radio meteorograph*

grid circuit of the audio oscillator includes three resistors, *R*, *H*, and *T*, in series. Resistor *R* is of fixed value. *H* is a special resistor which is controlled by a hair hygrometer, so that the position of the contact point *c* varies in accordance with the relative humidity, being at the point *a* for 100-percent value, at the point *b* for 0 percent, and at intermediate positions for intermediate values of the relative humidity. *T* is a special resistor which varies inherently with the temperature. (*See* fig. 3.) The switching element consists of 75 conducting strips separated by insulating strips. The conducting strips are arranged in groups of four adjacent intermediate contacts, the adjacent groups being separated by wider index contacts. The intermediate conducting strips are all connected together, while the index contacts are connected in two sets. Referring back to figure

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10, the three resistors are electrically connected to the switching element as shown. The point *a* is connected to one set of index contacts, (numbers 15, 30, 45, etc.); the point *b* is connected to the second set of index contacts, (numbers 5, 10, 20, 25, etc.); and the variable-contact point *c* is connected to the intermediate conducting strips of the switching element. Pressure arm, *P*, which moves over the switching element, is electrically connected to ground as is also the lower end of resistor *T*.

It will be seen that so long as the pressure arm rests on one of the insulating strips of the switching element, the series circuit formed by *R*, *T*, and *H* is undisturbed. Since *R* is fixed and the full value of *H* is in circuit, the frequency of the audio oscillator is controlled by the value of resistor *T* and hence by the temperature. Assume now that the pressure arm contacts one of the intermediate conducting strips. The contact *c* is thereby connected to ground, shorting out a portion of resistor *H* (*c* to *b*) together with the variable resistor *T*. The value of resistance remaining in circuit consists of *R* and a variable portion of *H* depending upon the position of point *c* and hence on the value of the relative humidity. The frequency of the audio oscillator is now dependent on the relative humidity. When the pressure arm contacts one of the index segments, it connects either the point *a* or the point *b* to ground, shorting out *H* and *T* together or *T* alone. In the former case, the frequency of the audio oscillator is determined by resistor *R* and, in the latter case, by resistor *R* in series with the full value of resistor *H*. Hence two fixed identifying frequencies are produced corresponding to the two sets of index contacts. It will be observed that the identifying frequencies coincide exactly with the frequencies corresponding to 100-percent and 0-percent relative humidity. The use made of this feature will appear later.

The complete operation of the system now becomes apparent. The pressure arm, moving continuously in one direction as the balloon ascends, switches the frequency of the audio oscillator to correspond alternately to the values of the temperature and of the humidity encountered. The alternate changeovers from one set of frequencies to the other indicate that the pressure arm is just reaching or is just leaving one of the intermediate contacts and has attained definite deflection positions which may be determined. When the pressure arm reaches successive fifth conducting segments, the frequency of the audio oscillator attains predetermined fixed values which positively identify these contacts so that they may serve as index marks for the absolute-pressure scale. The two identifying frequencies used serve an additional purpose in that they provide periodic checks during the progress of a flight on the degree of frequency stability of the audio oscillator. If any accidental variation should occur, for example, due to varying battery conditions, the recorded value of temperature may be corrected for the indicated variations. Corrections to the humidity readings need not be applied even in such event. Upon completion of a record, two lines may be drawn in on the chart to connect the recorded values of the two sets of identifying frequencies. These two lines frame the scale of humidity indications, thereby automatically transferring the plot of humidity indications to a corrected frequency scale.

2. TEMPERATURE CAPILLARY TUBE

A description of the temperature capillary tube is of interest at this point. A photograph of a practical form of this device was shown in figure 3. The glass capillary tube has an over-all length of 8 cm, a bore diameter of 0.75 mm, and a wall thickness of 0.4 mm. The dimensions were chosen on the basis of the following practical considerations: (a) The capillary bore and wall thickness had to be as small as practicable to insure rapidity of response of the electrolyte to ambient temperature changes; (b) the capillary length was required to be as short as possible to afford a maximum of mechanical sturdiness; (c) the bore diameter and wall thickness had to be large enough to permit commercial production to the required tolerance at low cost; (d) finally, the range of electrical resistance obtained, using a given electrolyte, was required to be of an order such as to produce a substantially uniform scale of frequency vs. temperature in the circuit of figure 10. Full compliance with these requirements is realized in the design shown in figure 3. Capillary lengths of the required bore are purchased to a tolerance of 10 percent. Measurement under a microscope permits selecting from these a percentage (of the order of 25 percent) within 1 percent of the desired bore. The selected capillary tubes are bent into U-form and two small glass bulbs are fused on its ends. The wells provide a low-resistance contact between the electrolyte and the terminals of the tube. The wells are sealed with miniature rubber stoppers through which extend the copper terminals. One of the terminals consists of a very fine copper tube through which the capillary tube is filled in a vacuum chamber. The end of this copper tube is soldered to complete sealing of the device.

The choice of an electrolyte suitable for use in this application was the subject of considerable experimental work. In our early experiments, we used a sulphuric acid solution of 1.30 specific gravity, and, with special care in calibration and use, many successful flight measurements were made. The solution served for determining the practicability of measuring temperature by this method, but was subject to a number of practical defects. Its resistivity was too low to permit the use of the capillary dimensions indicated. The solution froze at −70° C, whereas readings are sometimes required to lower temperatures. The process of electrolysis gave a resistance which, for a given temperature, varied with the current passing through it, hence a given capillary tube had to be calibrated in combination with the particular audio oscillator with which it was to be used. The attendant polarizing action produced a serious lag in indication of the true temperature due to the charging required of the equivalent battery each time the tube was switched into circuit by the pressure-switching unit.

We are indebted to D. N. Craig of the National Bureau of Standards for experimental work which eliminated these difficulties. First experiments showed that the addition of as much copper sulphate as could be taken into solution, in combination with the use of copper terminals, caused an electroplating action to take place which tended to eliminate the production of gases at the terminals and hence the polarizing action. Consideration was given to the addition of alcohol to the mixture to secure an effectively higher resistivity; however, this further limited the amount of copper sulphate which could be taken into solution.

Finally, a different electrolyte was adopted consisting of hydrochloric acid, cuprous chloride, and alcohol. Use of predetermined ratios of these ingredients permits obtaining a wide range of resistivities so that the required resistance may be had with a capillary tube of the specified dimensions. Tests showed that the solutions do not freeze at temperatures above −78° C. Ample cuprous chloride is taken up by both the hydrochloric acid and the alcohol to practically eliminate the polarizing action. As a result, the capillary tube resistance corresponding to a given temperature remains constant for a wide range of current passing through it and may therefore be calibrated independently of the audio oscillator with

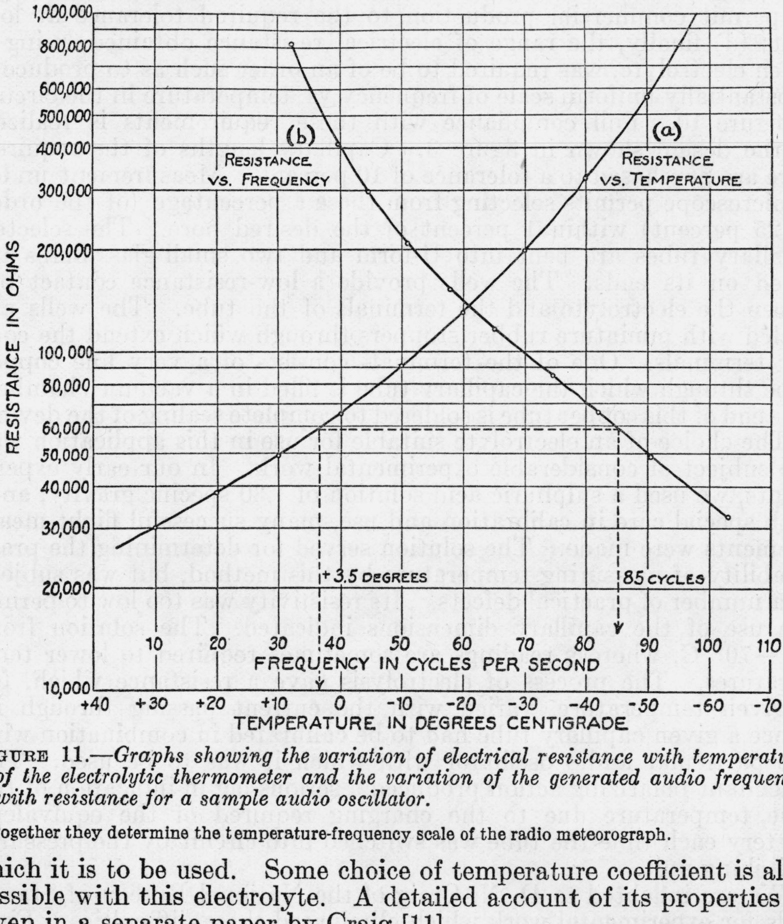

FIGURE 11.—*Graphs showing the variation of electrical resistance with temperature of the electrolytic thermometer and the variation of the generated audio frequency with resistance for a sample audio oscillator.*

Together they determine the temperature-frequency scale of the radio meteorograph.

which it is to be used. Some choice of temperature coefficient is also possible with this electrolyte. A detailed account of its properties is given in a separate paper by Craig [11].

The solution employed in our experiments, chosen to give a resistance of 30,000 ohms at +30° C, consists of 24 percent (by volume) concentrated hydrochloric acid, 76 percent of ethyl alcohol, and 2.7 g of cuprous chloride for each 100 cm^3 of the resultant combination. The variation of resistance with temperature for a typical capillary tube is given by curve *a* of figure 11, while curve *b* shows the resistance-frequency characteristic of a typical audio oscillator. The corresponding variation of modulation frequency with temperature when

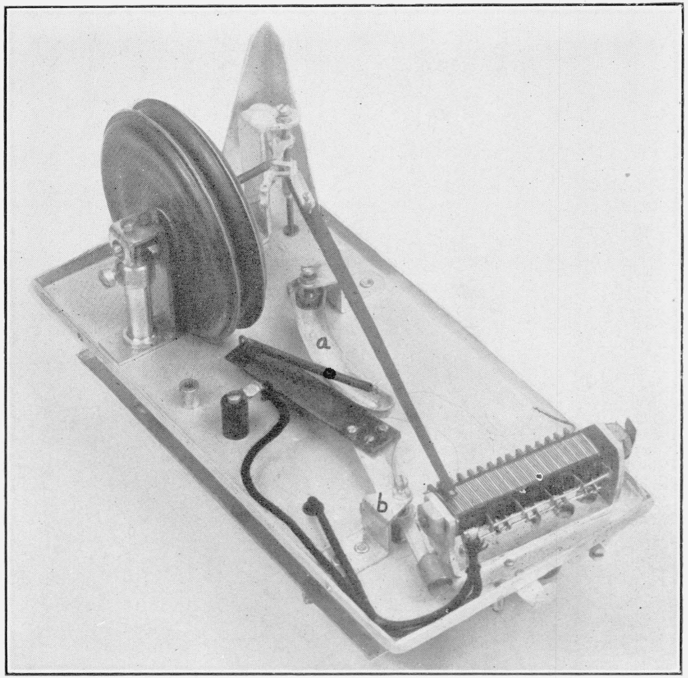

FIGURE 12.—*Meteorograph unit.*
Front view.

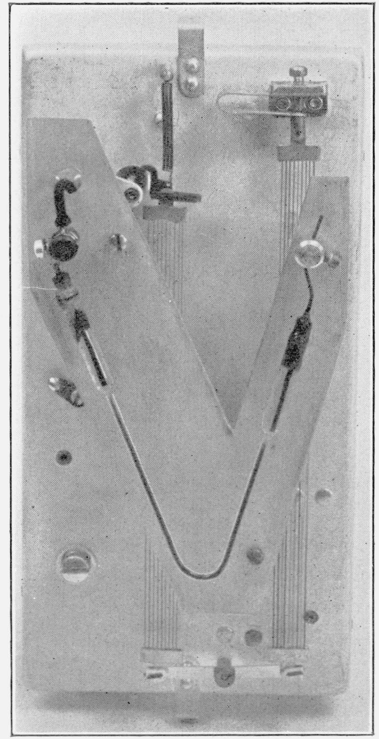

FIGURE 13.—*Meteorograph unit.*
Rear view, with radiation shield removed.

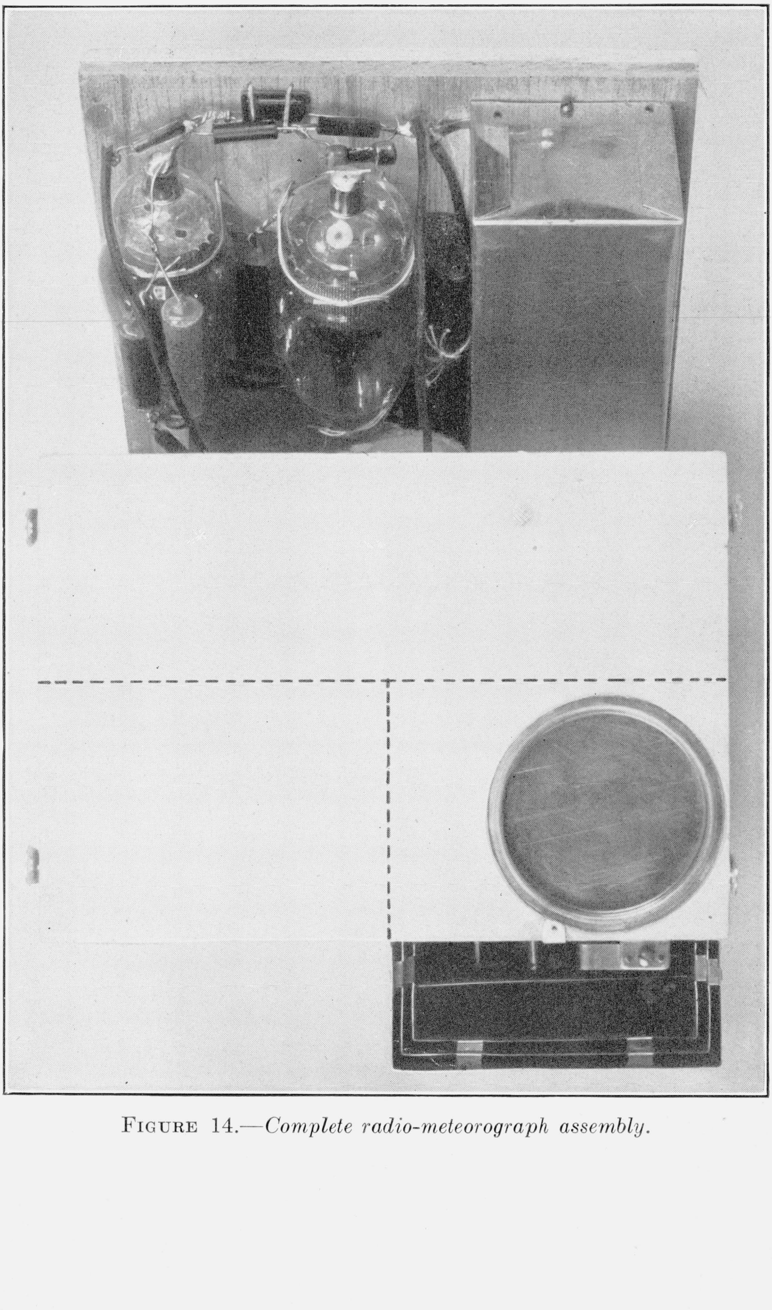

FIGURE 14.—*Complete radio-meteorograph assembly.*

the capillary thermometer is connected in the grid circuit of the audio oscillator may be evaluated from these two curves, as indicated in figure 11.

Aside from the advantage of eliminating mechanical parts, the capillary thermometer offers several other advantages over the bimetallic thermometer usually employed in radio meteorographs.

One advantage is its property of responding very rapidly to temperature changes. The time-lag constant of the tube in an air stream of 10 mph is 2 sec compared with 5 sec for the fastest bimetallic thermometer. The high rate of response of the temperature device is of particular value in the method of pressure-switching. Since readings are obtained corresponding to fixed pressure values, the total number of readings obtained during an ascension does not depend upon the rate of balloon ascent. Hence, a high rate of ascent would be desirable in order to reduce the total time required for securing a complete set of observations. The response of the temperature device is believed sufficient for any practical rate of ascent. At the present time, the hair hygrometer appears to be the limiting factor of the radio meteorograph in this respect.

Another advantage of the capillary temperature device lies in the simplicity of its connection to the body of the meteorograph; only two small connecting leads are required. This and the length and small diameter of the capillary tube contribute considerably to the avoidance of heat transfer from the meteorograph.

3. METEOROGRAPH UNIT

Figures 12 and 13 are two views of the meteorograph which incorporates the pressure-switching unit, the temperature tube, and the hair-controlled hygrometer. In fig. 12 the pressure diaphragm, linkage, and arm are clearly shown. The end of the pressure arm carries a platinum tip which slides over the polished surface of the switching element. The conducting segments of the switching element stand out in the photograph as white lines, particularly the index contacts, which are of greater thickness. The conducting segments are of coin silver 0.005 in. thick and the insulating segments of Bakelite 0.015 in. thick. Double or triple segments are used for the index contacts, as desired. For convenience in manufacture and assembly the segments are punched out to the desired shape from material of the required thickness. Holes in the center provide for their assembly on a rod having a threaded end. The assembly is made with a jig so that the connecting tabs forming an integral part of the conducting segments may be properly aligned. After assembly, the segments are pressed together by a nut on the threaded end of the rod. The face of the unit is then polished.

At *a* in figure 12 is shown a small metal cam which is swung about its shaft by two hair elements operating in series (on the other side of the base plate). A wire-wound resistor mounted to pivot at the point *b* is held in contact with the cam by a spring. As the cam moves under the action of the hair hygrometer, the resistor is forced to follow it due to the spring. A rolling contact is thereby obtained between the metal cam and the resistor. This contact moves from one end of the resistor to the other as the relative humidity varies from 0 to 100 percent. The arrangement is therefore ideally suited to serve for resistor *H* shown in figure 10. This satisfactory arrangement was developed for us by Julien P. Friez & Sons, Inc.

Figure 13 shows the other side of the meteorograph unit with the radiation shields removed. The hair-drive for the metal cam and the temperature capillary tube are seen in this view. The thin metal plate normally mounted between the hair elements and the temperature tube is cut away to permit a view of the hair elements. This plate serves as a shield against the radiation of heat from the base plate to the temperature tube. The ventilated outer radiation shield protects the temperature tube from direct solar radiation.

4. COMPLETE RADIO-METEOROGRAPH ASSEMBLY

The complete radio meteorograph consists of a radio-transmitting unit, a battery unit, and a meteorograph. The entire assembly of the three units is contained in a balsa-wood box, 6 by 6 by 4½ in. The total weight is 2 lb. in the current design and is capable of considerable reduction through refinement of the component units. In its present design, the transmitter is capable of over 4 hr. of efficient operation under ground conditions.

Figure 14 is a top view of the complete instrument. The balsa-wood box is divided into three individual compartments: for the radio transmitter, the batteries, and the meteorograph. Separate access is possible to each compartment for convenience in adjusting and calibrating. A small cover plate at the top of the meteorograph compartment permits ready access to the switching element for checking the instrument just prior to its ascent. The electric-circuit arrangement of the radio transmitter was described in connection with figures 1 and 10. The carrier frequency of the transmitter is 65 Mc/s.

The battery unit consists of two 45-v batteries for the plate supply and a 3-v dry-battery unit for the filament supply. The plate batteries weigh slightly over 4 oz each and have a capacity of 65 ma-hr. The filament battery weighs 2 oz and has a capacity of 750 ma-hr. The total plate current required by the transmitter is 15 ma and the filament current is 180 ma. The battery unit is packed in rock-wool insulation in order that it may retain its original heat as long as possible during an ascent. In the course of an ascent, the ambient temperature may drop to −75° C, while the batteries cease to operate when they drop to −20° C. Because of the effect of the low ambient temperatures upon the battery capacity, the operation of the transmitter during an actual ascent is limited to an average of 2 hr.

5. SAMPLE RECORD OF AN ASCENSION

Some 75 ascensions have been made using the radio meteorograph described. These have shown the system to be practicable and have provided gratifying records. Fifty of these ascents were made at the U. S. Naval Air Station, Anacostia, D. C., under service conditions, and the records obtained were compared with aerograph observations obtained simultaneously in a Navy airplane. The results of these comparisons are described in a separate paper [12]. The excellent agreement obtained indicates that the accuracy of indication of pressure, temperature, and humidity, while not quite within the requirements set forth in section VIII, is sufficient to warrant the use of the instrument to replace the present airplane soundings.

A sample record, obtained on September 2, 1937, is shown in figure 15. The speed of the graph paper through the recorder was ½ in./min, the distance between successive horizontal lines on the graph paper representing 1-min intervals. The scale of abscissas on the chart is on a frequency basis, 0 to 200 c/s (left to right). For ease in interpretation, the corresponding temperature and humidity scales are also marked on the chart. The start of the run, corresponding to the release of the balloon, is at *A* at the bottom of the chart.

It is convenient to consider the recorder pen as producing a temperature plot which is a function of time and hence of the ascent of the balloon. This plot, represented by the lower-frequency traces at the left of the record, is not continuous, being interrupted at predetermined altitude levels of the balloon by contact of the pressure arm with the conducting strips of the switching element. The modulating frequency of the emitted wave then changes to either the humidity or the reference values. At each interruption, the recorder pen sweeps laterally to the right to record these values, returning again to the left when the pressure arm leaves the corresponding conducting strip and the modulating frequency is again proportional to temperature. A line drawn through the frequency traces (at the right of the chart) which relate to the intermediate or humidity contacts will, therefore, represent the variation of humidity as the balloon ascends. Similarly, vertical lines through the two sets of reference frequency traces represent the 0- and 100-percent points of the scale of humidity values. The horizontal traces of the record made by the recorder pen in sweeping from the temperature traces to the humidity (and index) traces, and vice versa, show that the pressure arm has reached definite points of deflection and may be evaluated in terms of pressure, based on previous calibration. Note that the humidity readings occur in groups of four, while the index traces define the 5th, 10th, 15th, 20th, etc., contacts. On the record, the values of the barometric pressure corresponding to the beginning of contact of the pressure arm with the index conducting strips are shown, forming an ordinate scale of pressure values. The balloon altitude at these points, corrected for the indicated temperature and humidity, are also shown. Similar data are not inserted for the other contacts for the sake of clarity of the record.

At the time of releasing the balloon, the barometric pressure at the ground surface was 1,018 millibars, the temperature 24.8° C, and the relative humidity 100 percent. The pressure arm was on the third intermediate contact and gave a reading of 100-percent relative humidity. When the balloon reached an altitude of about 570 ft., the pressure arm left this contact and the first reading of temperature was obtained. From this point on the reader can trace for himself the motion of the recorder pen under the influence of the received signal frequency as the balloon ascended.

When the balloon reached an altitude of 34,000 ft., the pressure arm being then just above the 65th contact, a special pressure-operated releasing device opened the string connection between the balloon and a small parachute to which the radio meteorograph was attached. The parachute then opened and the equipment descended back to the earth's surface. This releasing device was employed in certain of our tests to prevent the equipment from reaching the normal ceiling heights of 65,000 to 75,000 ft, since it was desired to obtain check temperature readings during the descent of the equipment while the batteries were still in good condition and the balloon not too far away from the receiving station. Referring to figure 15, check readings were obtained down to the 5th contact, the equipment being then within 1,200 ft. of the ground.

The temperature readings during the descent agreed with the corresponding readings during the ascent within less than 1° C, testifying to the accuracy of the frequency-translating means and the independence of the temperature tube of rate of motion through the air. The

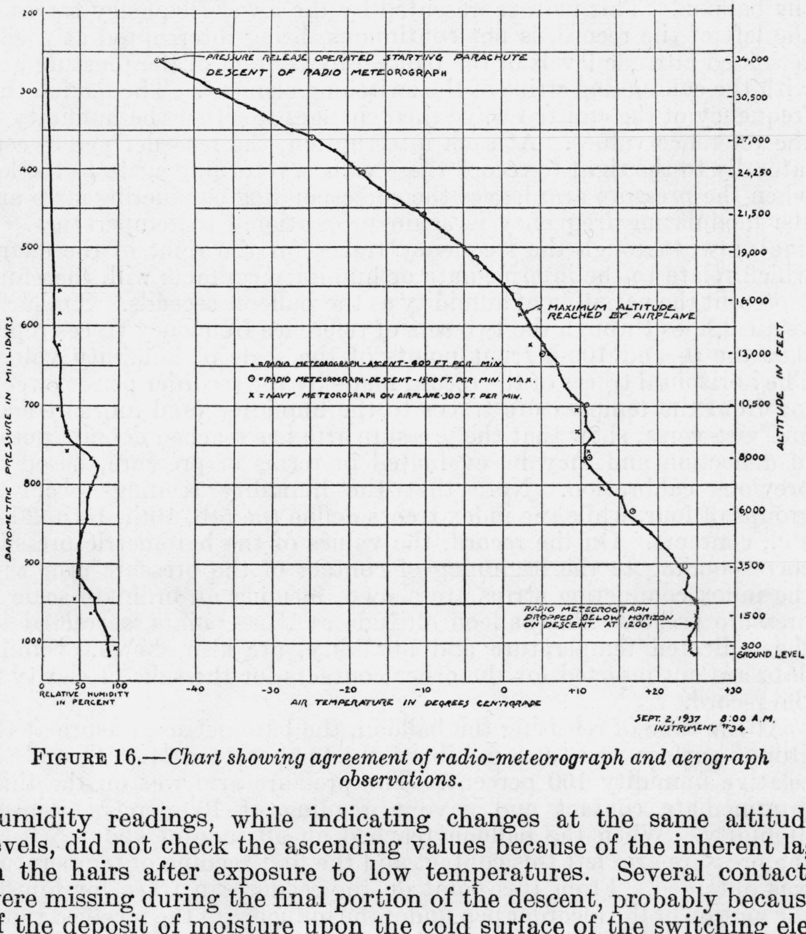

FIGURE 16.—*Chart showing agreement of radio-meteorograph and aerograph observations.*

humidity readings, while indicating changes at the same altitude levels, did not check the ascending values because of the inherent lag in the hairs after exposure to low temperatures. Several contacts were missing during the final portion of the descent, probably because of the deposit of moisture upon the cold surface of the switching element as the radio meteorograph entered the warmer air masses of higher water-vapor content. It is unlikely for this to happen during an ascent, because the air is then breathing outward from the partially sealed compartment housing the switching element.

The meteorologist examining the record of figure 15 would be interested chiefly in the points where the temperature variation with increasing altitude departs from a normal cooling rate and either

FIGURE 15.—Sample radio-meteorograph ascension record.

ceases to decrease or actually increases. These are termed temperature-inversion points. Information is required on the extent of the inversions, the altitudes at which they occur, and of the corresponding values of relative humidity. These data are plotted on an adiabatic chart for further computation. An advantage of the type of record shown in figure 15 is that the significant data required may be used without consideration of the remaining data.

An indication of the order of agreement obtained between the radio-meteorograph and aerograph observations may be had from the chart shown in figure 16. In this chart the ordinates represent values of the barometric pressure in millibars and the abscissas values of the temperature in degrees centigrade and of relative humidity in percent. The full lines represent the radio-meteorograph data corresponding to the record of figure 15. The crosses represent the aerograph data obtained simultaneously. It will be seen that the temperature readings agreed within 1° C and the humidity readings within 5-percent relative humidity except at abrupt changes. The close agreement of the temperature and humidity plots testifies to the agreement of the pressure readings.

6. CALIBRATING PROCEDURE

The procedure of calibrating the complete radio meteorograph in preparation for a flight test is of interest. The procedure has been simplified to the point where it is carried out completely in terms of resistance measurements.

The meteorograph unit is placed in a pressure chamber and an ohmmeter is connected between the upper end of the humidity resistor and ground. See figure 10. Evacuation of the pressure chamber at the rate of about 75 millibars per minute is then begun. As the pressure arm passes over the index contacts, the ohmmeter will read either zero resistance corresponding to one set of index contacts or the total value of the humidity resistor corresponding to the second set. For intermediate contacts, the ohmmeter will read the value of a portion of the humidity resistor depending on the humidity conditions in the pressure chamber. Between contacts the ohmmeter will show the value of the humidity resistor in series with the temperature tube (or with a fixed resistor substituted for the temperature tube, if more convenient). For each contact, the value of the pressure is recorded corresponding to the instant of making the contact. A complete calibration of the pressure unit can be carried out in 10 to 15 min. The data may be tabulated in any convenient form. Using a special graph paper for plotting the data, in which the ordinates are spaced proportionally to the spacing of the conducting strips in the switching element, we have found it feasible to restrict the calibration to the index contacts only, thereby further reducing the time for a calibration. Repeated calibrations of a number of instruments over a period of a month, several of which were from recovered radio meteorographs, showed that readings are repeated to within an accuracy of one millibar.

The temperature correction for the pressure unit is next determined. To reduce cost, no attempt to compensate for temperature during manufacture is made, other than that the diaphragm is evacuated as completely as possible. This automatically provides for temperature compensation at the lowest pressure level. However, there is an appreciable change in pressure indication with temperature at ground pressure. The difference per degree centigrade change in temperature may be readily determined by observation of the position of the pressure pointer at room temperature and in a cold temperature chamber; it is of the order of 0.3 millibar per degree centigrade. This correction factor tapers off linearly to zero as the pressure to which the pressure diaphragm is subjected is reduced to the lowest value. The temperature correction is applied at the ground pressure level on the basis of the temperature obtaining at the time of ascent and at lower pressure levels on the basis of estimated temperatures within the compartment housing the diaphragm. When the higher expense justifies, there is no primary difficulty in compensating the pressure element for the effect of temperature at all pressures.

Calibration of the temperature device has been simplified so that but a single temperature tube of a batch filled with the same solution need be calibrated over the complete temperature range. The ratio of the resistance of this tube at any temperature to its resistance at +30° C is determined. For all of the other tubes, only the resistance at +30° C is measured. Since the same electrolyte is employed in all of the tubes, the same variation of resistance with temperature will obtain. In practice it has been found that the use of the same proportion of ingredients will produce an electrolyte having the same temperature coefficient of resistance. Hence, the same calibration will hold for temperature tubes filled in different batches. Repeated calibrations of a number of tubes, several after recovery, showed that they maintain their calibration within 1° C over a period of a month.

Calibration of the humidity device is obtained by placing the meteorograph unit in a humidity chamber and measuring the resistance between points *a* and *c*, figure 10, corresponding to various values of humidity. Since the resistance-humidity relationship is quite linear, two readings corresponding to, say, 10- and 90-percent relative humidity are usually sufficient.

Calibration of the audio oscillator of a given transmitter is accomplished by inserting a series of 10 standard resistors successively in its grid circuit and measuring the corresponding value of the modulating frequency on the frequency meter of the receiving set-up shown in figure 2. To facilitate conversion of the frequency traces on the record received at the ground station into corresponding values of temperature and humidity independently of the combination of temperature tube, humidity resistor, and audio oscillator employed, the frequency-resistance characteristic of the oscillator is plotted on special graph paper, and special auxiliary sliding temperature and humidity scales are employed. The operation of these scales is described in a separate paper [12].

With the calibrating procedure outlined, a radio meteorograph may be taken off the shelf, completely calibrated, and prepared for an ascent within 90 min. If the instrument has been previously calibrated by the manufacturer, the check calibrations necessary to insure its accurate operation, together with the preparation of the instrument, balloon, parachute, etc., for ascent, take about 45 min. With the aid of the special graph paper, sliding scales, etc., the record can be evaluated and plotted on the standard adiabatic chart used by meteorologists within a few minutes of the time the signals corresponding to the highest altitude of the interest have been recorded. In our service tests the 400-millibar pressure level (approximately 23,500 ft) has been arbitrarily taken as that altitude.

X. ELECTRICAL HYGROMETER

In section VI, a brief description is given of a resistance device which varied inherently with the moisture content of the air. A photograph of the device is shown in figure 4 and a record obtained in an ascension flight in figure 6. The development of an electrical hygrometer was undertaken to find a substitute for the hair hygrometer universally employed in upper-air soundings. Complete details of this development are given in a separate paper [13]. A serious defect of the hair-type hygrometer is its inability to respond to abrupt change in humidities encountered by rapidly ascending balloons. This lag in response increases rapidly with decreasing temperature. Hence the hair hygrometer gives only a qualitative measurement of the variation of humidity with altitude. It was believed that an electrical device for measuring humidity would provide much more rapid response to humidity variations, especially at the low temperatures.

The development of the unit shown in figure 4 was based on an observation that the resistance between the two wires of a bifilar winding on a glass tube was influenced quite markedly by humidity. An extensive investigation of this phenomenon was undertaken, the work including the study of the effect of different types of glass, roughness of the glass surface, coatings over the glass, binders over the coatings, spacing of the wires, and wire size and composition. Over 150 samples were made up and tested. All of the units were found to vary in electrical resistance with relative humidity, and, in lesser degree, with temperature. The temperature effect was different for different samples and the amount of temperature correction required for a given sample was found to be a function of the relative humidity to which it is exposed, increasing with increasing humidity. A simple graphical arrangement permits applying the appropriate correction factor on the basis of the observed temperatures and relative humidities obtained during an ascent.

The record of figure 6 shows the rapidity of response obtained with the electrical hygrometer. In comparative laboratory tests at room temperatures in an air stream of 10 mph, the time lag constant for this device was found to be 3 sec compared with 40 sec for the hair hygrometer. The indicated variations in humidity at the higher altitudes in the record of figure 6 shows the operation of this device when exposed to low temperatures at which the hair hygrometer could not possibly respond. As previously indicated, the altitude scale of figure 6 is only approximate.

XI. OTHER APPLICATIONS OF THE GENERAL METHOD

In the foregoing text, we have limited our description to arrangements wherein the device for pressure indication is also utilized to carry out all of the switching operations of the balloon transmitter. In certain applications it is convenient to employ auxiliary means for accomplishing the switching. An example of this class is the investigation of Stair and Coblentz [14] on the measurement of ultraviolet solar intensities in the stratosphere. In this application, based on our method, the variation in resistance of a photoelectric cell equipped with several light filters is converted into a variable modulation of the emitted carrier. At predetermined altitudes, the pressure-switching unit introduces fixed resistors in the grid circuit of the audio oscillator for the purpose of altitude determination. Between the altitude measurements, a motor-driven wheel successively interposes several filters over the photocell to determine the spectral quality of untraviolet in the solar radiation.

A second example in which auxiliary switching is employed is shown in figure 17. In this arrangement, a miniature motor-driven switch

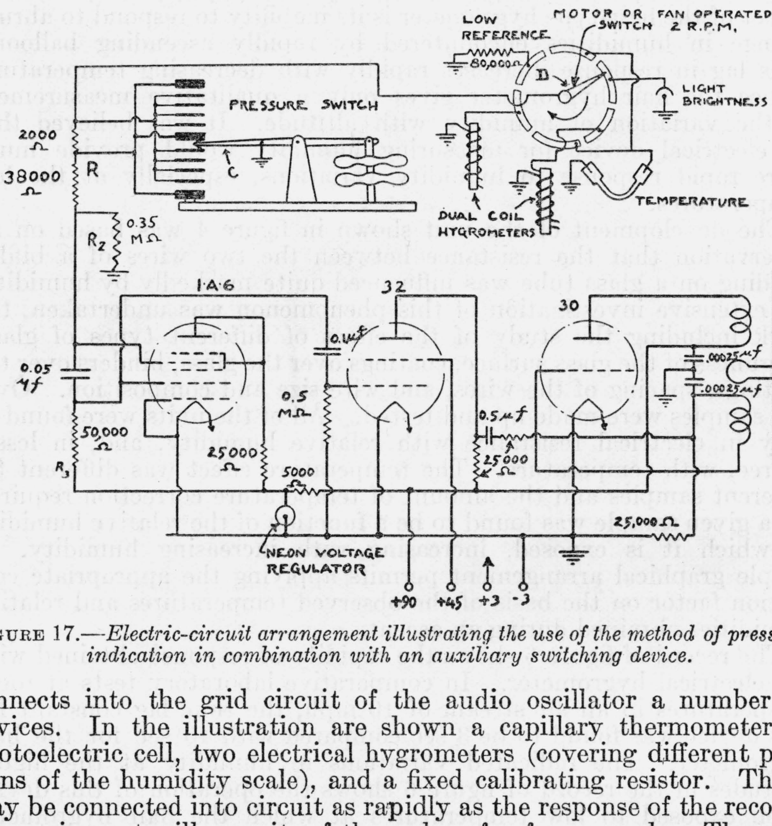

FIGURE 17.—*Electric-circuit arrangement illustrating the use of the method of pressure indication in combination with an auxiliary switching device.*

connects into the grid circuit of the audio oscillator a number of devices. In the illustration are shown a capillary thermometer, a photoelectric cell, two electrical hygrometers (covering different portions of the humidity scale), and a fixed calibrating resistor. These may be connected into circuit as rapidly as the response of the recording equipment will permit, of the order of a few seconds. The arm of the pressure-switching unit, upon reaching a conducting strip, short-circuits whatever device happens to be in circuit, giving a fixed frequency. The latter represents a point on the altitude scale. For the purpose of providing index marks on the altitude scale, only a portion of resistor *R* is left in the grid circuit when the pressure arm reaches the index contacts. An advantage of this arrangement over the one shown in figure 8 is the possibility of its extension to the measurement of a large number of phenomena without requiring an unduly complicated pressure-switching element.

The writers express their appreciation to L. L. Hughes of the Bureau's radio section for his skillful construction and contributions to the mechanical design of numerous experimental models; to D. N. Craig of the battery section for cooperation in the design of the temperature capillary thermometer; to J. P. Schrodt and C. L. Snyder of the battery section for assistance in determining battery requirements; and to W. G. Brombacher of the aeronautic instruments section for advice and data on meteorological instruments and calibration procedure and equipment. Special acknowledgment is made to Commanders J. B. Anderson and W. M. Lockhart, of the Bureau of Aeronautics, U. S. Navy Department, for advice on the meteorological aspects involved in the development of the radio meteorograph, and to Julien P. Friez & Sons, Inc., for cooperation in the mechanical design of the instruments.

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