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AN IMPROVED RADIO SONDE AND ITS PERFORMANCE

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ABSTRACT

The radio sonde (radiometeorograph) described in Research Paper RP1082 [1] has emerged from the laboratory and been put into daily service in a widespread network of stations by the Government aerological services. The present paper describes improvements in component elements of the radio-sonde system and discusses performance. Actual performance in service is stressed. The major improvement introduced is in the element for measuring relative humidity. Laboratory and flight data on the accuracy of measurement with this element at temperatures down to −60° C are presented. The improved radio sonde is shown to be capable of measuring barometric pressure to an accuracy of 5 millibars, temperature to an accuracy of 0.75 degree centigrade, and relative humidity to an accuracy of 5 percent.

CONTENTS

[1] H. Diamond, W. S. Hinman, Jr., and F. W. Dunmore, J. Research NBS **20**, 369 (1938) RP1082.

I. INTRODUCTION

An earlier paper [1] [2] described a method of upper-air radio soundings for sending down from small unmanned balloons information on the barometric pressures, air temperatures, and relative humidities encountered. This method has been the subject of continued experimental work since the preparation of the earlier paper and has been adopted for routine use in an extensive network of weather-reporting stations. The present paper describes the more recent improvements in the system and gives an analysis of performance. Details of improvements and performance treated in other publications [2] are not covered except as found necessary to present a complete description.

As in the original development, the work on improvement of the system was carried on under the sponsorship of the Bureau of Aeronautics, United States Navy Department. Close cooperation was had in the work with Julien P. Friez & Sons, engineers of that company contributing many practical features to the commercial design of the radio sonde and ground-station equipment. The recorder shown in figure 7 is a development of the Friez company.

II. SERVICE REQUIREMENTS AND PERFORMANCE

Service use of the radio sonde began at the Naval Air Station, Anacostia, D. C., on June 1, 1938, and was extended to 12 Weather Bureau, Navy Department, and Coast Guard stations during the fiscal year 1939. The regularity and reliability of the results obtained warranted considerable expansion of the system, so that some 45 stations are in present operation, representing an annual use of 15,000 instruments. Figure 1 shows the network of stations in use. About two-thirds of these stations are operated by the Weather Bureau and the remainder by other agencies, such as the Navy Department, Coast Guard, Army, etc.; some of the stations shown operate seasonally. Because of the use of small unmanned balloons, soundings may be made from shipboard stations or from small islands where it would be impractical to use airplanes for carrying up recording instruments (the practice prior to the advent of the radio sonde). Thus, regular soundings have been made from Coast Guard cutters in the Newfoundland ice fields and in the South Atlantic as a service for the transatlantic air route.

1. REGULARITY OF OPERATION AND HEIGHTS OF SOUNDINGS

Maximum operating efficiency of the network of stations shown in figure 1 imposes the following three requirements: (1) The soundings must be made on a regular, uninterrupted schedule. (2) They must attain heights well into the stratosphere, of the order of at least 10 to 15 kilometers, since air mass movements occur up to these heights. (3) The data must be available for dispatching to central offices in time for the morning forecast, that is before 7 a. m. EST. The improvement in regularity of operation and in the maximum heights of the soundings, afforded by the radio sonde over the airplane method, is indicated in table 1.

The data tabulated compare the results obtained with the radio sonde for August to October, 1938, inclusive (a few months after

[2] Figures in brackets indicate the literature references at the end of this paper.

radio-sonde operation was inaugurated), and with the airplane method for the same months of the previous year. The two stations chosen, Oakland, Calif., and Sault Ste. Marie, Mich., represent locations where flying conditions are notably different, particularly during the late fall and winter months. The effect of adverse weather conditions upon the number of useful soundings with the airplane method is

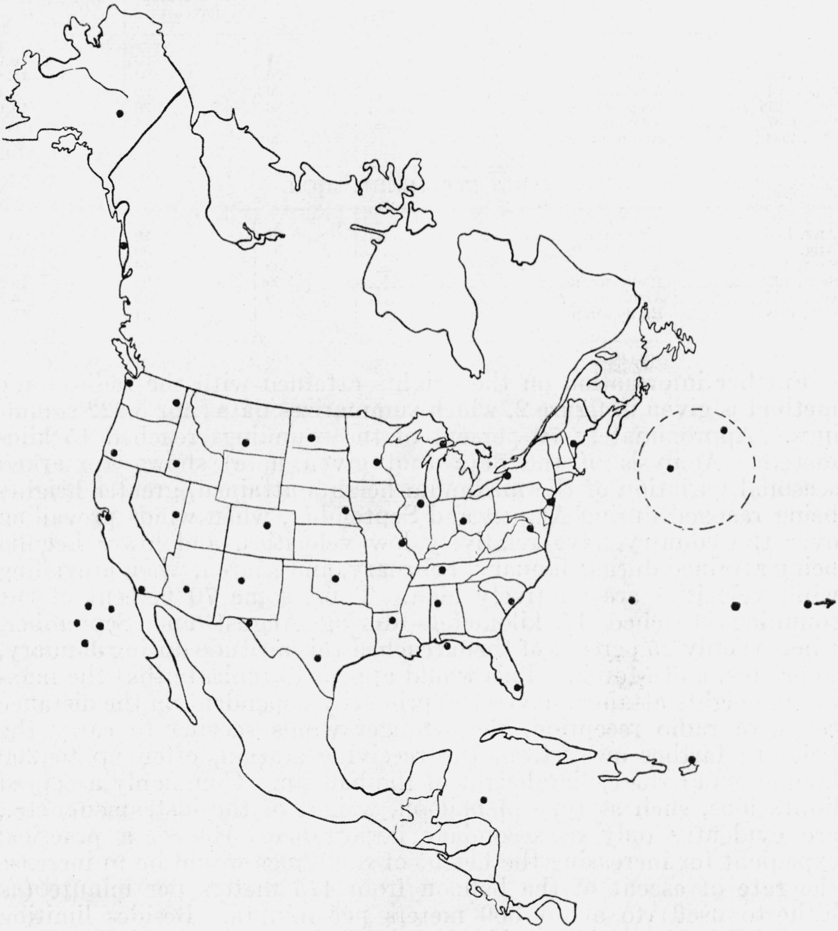

FIGURE 1.—*Network of aerological stations at which radio soundings are made.*

evident from the fourth column of the table. Because of adverse weather, airplane soundings at Sault Ste. Marie during the late fall and winter had limited utility despite the importance of information from this station during the formation of cold waves. There is no marked equivalent effect in the case of the radio sonde; soundings with this method are possible in practically all types of weather except during very strong winds and conditions conducive to ice formation on the balloon.

TABLE 1.—*Comparison of regularity and maximum heights of soundings with airplane and radio sondes*

OAKLAND, CALIF.

Month	Method of sounding	Number of soundings made	Number of soundings providing data in time for the morning forecast	Average of maximum heights attained, kilometers
Aug. 1937	Airplane	29	29	5.2
Aug. 1938	Radio sonde	30	30	14.5
Sept. 1937	Airplane	30	30	5.1
Sept. 1938	Radio sonde	30	30	18.9
Oct. 1937	Airplane	30	25	5.2
Oct. 1938	Radio sonde	30	30	15.8

SAULT STE. MARIE, MICH.

Month	Method of sounding	Number of soundings made	Number of soundings providing data in time for the morning forecast	Average of maximum heights attained, kilometers
Aug. 1937	Airplane	31	20	5.3
Aug. 1938	Radio sonde	30	30	12.6
Sept. 1937	Airplane	30	19	5.0
Sept. 1938	Radio sonde	29	29	16.0
Oct. 1937	Airplane	29	13	4.8
Oct. 1938	Radio sonde	31	31	17.8

Further information on the heights attained with the radio-sonde method is given in figure 2, which summarizes data [3] for 5,222 soundings. Approximately 70 percent of the soundings reached 15 kilometers. Analysis of the data (not given here) shows a marked seasonal variation of the maximum heights attained, greater heights being reached during August and September, when winds prevailing over the country have relatively low velocities, and lower heights being attained during January, February, and March, when prevailing wind velocities are relatively high. Thus, some 70 percent of the soundings reached 17 kilometers during August and September, whereas only 25 percent of them reached this altitude during January, February, and March. This would appear to indicate that the maximum heights attained have been primarily dependent on the distance range of radio reception, the stronger winds serving to carry the balloons farther away from the receiving station, often up to 200 kilometers at the ceiling height of the balloon. Commonly accepted limitations, such as type of balloon, weight of the instrument, etc., are evidently only of secondary importance. Hence, a practical expedient for increasing the height of soundings would be to increase the rate of ascent of the balloon from 175 meters per minute (as hitherto used) to about 300 meters per minute. Besides limiting wind drift, this would provide the additional advantage of decreasing the time taken for securing the required data.

An important limitation to the rate of balloon ascent practicable is the speed of response of the measuring elements in the radio sonde. All of the elements in the improved radio sonde permit using the higher rate of ascent specified. The important improvement in this respect lies in the electric hygrometer [3] for measuring relative humidity. Instruments using this device are employed at about one-fourth of the stations shown in figure 1 and are soon expected to replace the older type instruments, using hair hygrometers, at all the stations.

[3] Taken from Monthly Weather Review.

2. INSTRUMENT REQUIREMENTS

The instrument requirements for the radio-sonde system are rather severe. Measurements of pressure, temperature, and humidity are desired to heights up to 25 kilometers. In such excursions, the range of pressures encountered may be from 1,050 millibars at the surface to 25 millibars at the top, the range of temperatures from +40° to −90° C, and the range of humidities from 0- to 100-percent relative humidity. The present required accuracies of measurement are ±5 millibars throughout the range of pressures, ±0.75 degree

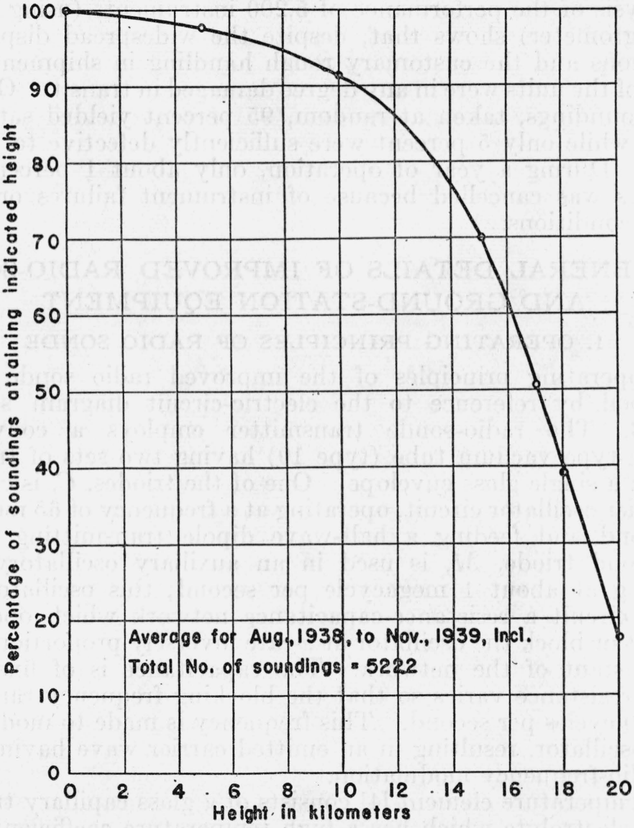

FIGURE 2.—*Analysis of heights attained by radio soundings.*

centigrade at temperatures above −50° C and ±5-percent relative humidity at temperatures above about −20° C.

The very nature of the service imposes special practical requirements. Considerations of economy dictate that the cost of a radio sounding should not exceed the amount hitherto expended for an airplane sounding ($25 to $35). The weight of the instrument should be kept sufficiently low (of the order of 1 kilogram) to allow its being carried aloft by a balloon of reasonable size, 5 to 6 feet surface inflation diameter. Rugged construction is essential so that the instrument may be shipped by ordinary transportation methods from the factory to the far-flung stations of the network (see fig. 1), and stored at these stations until used, without upsetting the original calibrations. Ease of handling by field personnel and minimum time for making the sounding and for evaluating the observations are additional conditions.

It will be evident from the foregoing considerations that the practicability of a radio-sonde design depends not only on its accuracy of measurement but also upon the ruggedness of the component elements and upon the possibilities of their manufacture by mass-production methods. The instrument to be described is fully capable of meeting all the requirements specified. The accuracies of the pressure and temperature observations in the field have been determined to be within the required tolerances, as will be shown later in the paper. An analysis of the performance of 5,200 instruments (using the hair-type hygrometer) shows that, despite the widespread dispersion of the stations and the customary rough handling in shipment, only 4 percent of the units were in any degree damaged in transit. Of a batch of 500 soundings, taken at random, 95 percent yielded satisfactory records, while only 5 percent were sufficiently defective to be called failures. During a year of operation, only about 1 percent of the soundings was cancelled because of instrument failures or adverse weather conditions.

III. GENERAL DETAILS OF IMPROVED RADIO-SONDE AND GROUND-STATION EQUIPMENT

1. OPERATING PRINCIPLES OF RADIO SONDE

The operating principles of the improved radio sonde may be understood by reference to the electric-circuit diagram shown in figure 3. The radio-sonde transmitter employs a conventional receiving-type vacuum tube (type 19) having two sets of triode elements in a single glass envelope. One of the triodes, *C*, is connected in a carrier oscillator circuit, operating at a frequency of 65 megacycles per second and feeding a half-wave dipole transmitting antenna. The second triode, *M*, is used in an auxiliary oscillatory circuit, oscillating at about 1 megacycle per second; this oscillator has in its grid circuit a resistance-capacitance network which operates to interrupt or block the oscillator at a rate inversely proportional to the time constant of the network. The capacitance is of fixed value, but the resistance varies so that the blocking frequency ranges from 10 to 200 cycles per second. This frequency is made to modulate the carrier oscillator, resulting in an emitted carrier wave having a variable audio-frequency modulation.

The temperature element [4] consists of a glass capillary tube filled with an electrolyte which has a high temperature coefficient of electrical resistance. Each element of the electric hygrometer [3] constitutes an electrical resistance formed by the leakage path across a thin film containing a hygroscopic salt between the two wires of a bifilar winding. It will be seen that the temperature tube and the electric hygrometer constitute electrical resistors which vary respectively in accordance with the temperature and relative humidity of the air to which they are exposed. Hence, when one or the other is connected in the grid circuit of the modulating oscillator to form the variable portion of the resistance in the resistance-capacitance network, the modulation frequency on the emitted carrier wave will be a measure of the temperature or humidity, respectively.

The pressure-switching unit performs two functions; one as a measuring instrument of barometric pressure in the specified range;

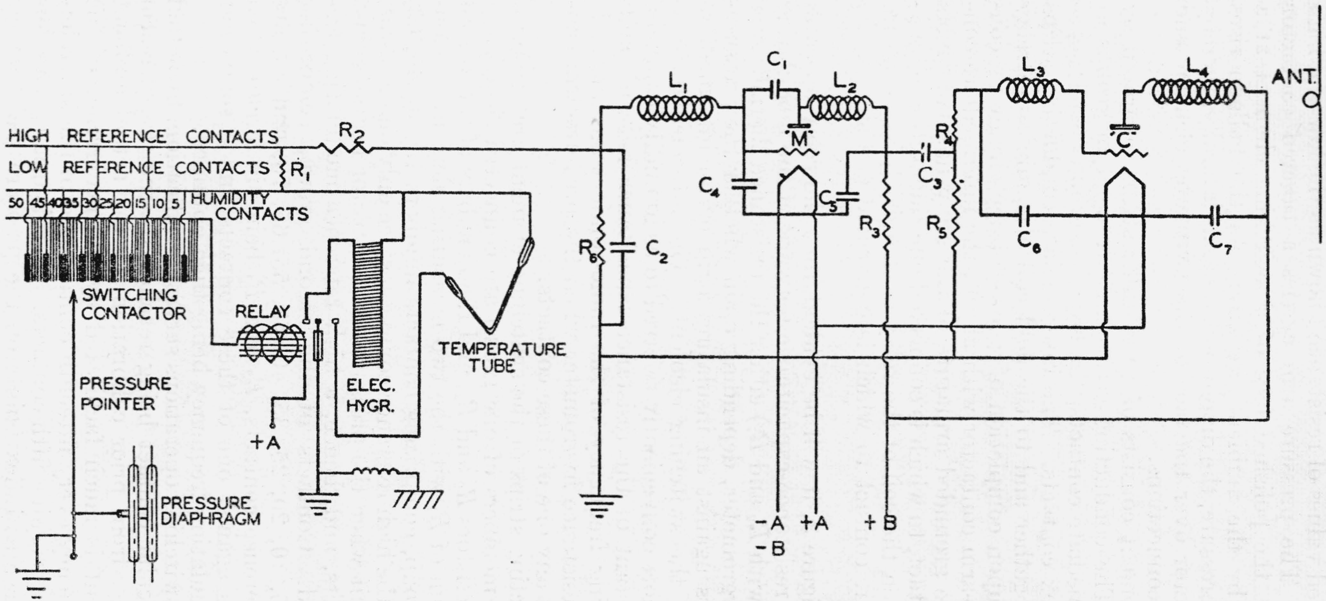

FIGURE 3.—*Electric-circuit arrangement of radio sonde.*

M = Modulating oscillator.
C = Carrier oscillator.
R_1 = 1,000 ohms.
R_2 = 40,000 ohms.
R_3 = 25,000 ohms.
R_4 = 1,000 ohms.
R_5 = 5,000 ohms.
R_6 = 1 megohm.

C_1 = 0.00025 microfarad.
C_2 = 0.07 microfarad.
C_3 = 0.05 microfarad.
C^4 = 0.00025 microfarad.
C^5 = 0.01 microfarad.
C^6 = 0.0001 microfarad.
C^7 = 0.00025 microfarad.

the other as a switch which connects into the resistance-capacitance circuit of the modulating oscillator, the temperature and humidity resistors and two fixed values of resistance known as the low and high reference resistors. The pressure arm carries a tapered contactor which bears against the polished face of a switching element at a position controlled by the ambient pressure. As the balloon rises into lower levels of pressure, the diaphragm expands laterally, thereby sweeping the contactor over the face of the switching element and making the desired connections.

The switching element consists of 80 metallic 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 and to the field coil of a miniature relay which is energized upon completion of a low-voltage circuit by contact of the pressure-arm contactor with any of the intermediate conducting strips. The grounded armature of the relay normally rests against its back contact, to which is connected one side of the temperature resistor. When the coil of the relay is energized, its armature bears against a front contact to which is connected one side of the humidity resistor.

By reference to figure 3, it will be evident that the relay operates to connect into the resistance-capacitance network of the modulating oscillator (in series with R_2 and R_1) either the resistance thermometer or the resistance hygrometer, depending upon whether the pressure-arm contactor bears against an insulating strip or an intermediate conducting strip of the switching element. The intermediate conducting strips are more conveniently referred to as humidity contacts, since the time constant of the resistance-capacitance network and, hence the modulating frequency of the radio-sonde transmitter, is controlled by the resistance hygrometer when the pressure-arm contactor bears against any one of these contacts.

The index conducting strips of the switching element are arranged in two groups; the members of one group are connected electrically to the junction of resistors R_2 and R_1, and the members of the second group to the junction of R_1 with the two measuring elements. Contacts of the first group, comprising contacts numbers 15, 30, 45, 60, and 75, are termed the high reference contacts, since only one resistor, R_2, remains in circuit when the pressure-arm contactor bears against one of these contacts, and, hence, a high reference modulating frequency is obtained. Contacts of the second group, comprising contacts numbers 5, 10, 20, 25, 35, 40, 50, 55, 65, 70, and 80, are termed the low reference contacts, R_2 and R_1 being in circuit when the contactor bears against one of these contacts and a somewhat lower reference modulating frequency being then obtained.

The sequence of switching operations serves as indication, by actual count, of the particular contact being reached by the pressure-arm contactor and, thus, from prior calibration, of the actual ambient pressure. This count is much facilitated by the occurrence of the high reference frequency every fifteenth contact and of the low reference frequency at intervening fifth contacts. In this usage, the reference frequencies serve as index points on the pressure scale. They are also useful in determining whether the balloon is ascending or descending.

To evaluate the temperature and humidity observations at the ground station, it is necessary to measure the received modulation frequencies and to interpret the measurements in terms of standard charts and scales which relate the frequency-resistance characteristics of the radio-sonde transmitter to the resistance-temperature characteristic of the temperature tube and the resistance-humidity characteristic of the electric hygrometer. The availability of the reference frequencies renders it practicable to carry out the measurements and evaluations in terms of the ratios (to either reference frequency) of the modulation frequencies produced when the measuring elements are in circuit. For convenience, the lower reference frequency is used as the control point, a nominal value of 190 cycles per second being employed for this reference.

By means of a proportional scale control in the frequency-measuring equipment at the receiving station, the lower reference frequency is made to read a predetermined nominal value regardless of its absolute value. The observed frequencies corresponding to the temperature and humidity connections are then seen to be measured in terms of the nominal reference frequency. As will be shown later, the ratio of the modulation frequencies corresponding to any two particular values of circuit resistance remains very nearly constant under all operating conditions. On this basis, it will be evident that the observed frequencies actually correspond to the values of the resistance in circuit referred to the value of the reference resistor (R_2+R_1). By keeping (R_2+R_1) constant within 0.5 percent and the shunt resistor (R_6) constant within 3 percent, it becomes possible to obtain very nearly the same relation between observed modulation frequency and circuit resistance for all radio-sonde transmitters, so that a standard frequency-resistance characteristic curve may be used in all soundings. Since the temperature tube and the electric hygrometer may also be produced to have practically identical variation of resistance with temperature and humidity, respectively, for all units produced, the measurement and evaluation of temperature and relative humidity become possible without requiring individual calibration of the component elements involved. This represents a material saving in the cost of the radio sonde.

The method of measuring relative rather than absolute modulation frequencies affords several additional operating advantages. The condenser, C_2, in the resistance-capacitance network need not be adjusted to secure the exact standard low reference frequency, since a variation of ± 10 percent can be taken care of readily by the proportional scale control in the frequency-measuring circuit. Moreover, reference-frequency drift in the radio-sonde transmitter, produced by variations in tube parameters due to varying battery voltages and by temperature effect on the condenser, C_2, can be handled similarly. Finally, the standard frequency-resistance characteristic may be modified at individual receiving stations to include small calibration corrections for the frequency-measuring equipment. The significance of these factors in reducing required manufacturing tolerances (and hence cost) is self-evident. The only assumptions made in following the procedure are that the frequency scale in the measuring equipment is substantially linear (within 1 percent) and that the resistors (R_2+R_1) and (R_6) in the radio-sonde transmitter may be held to within 1 and 6 percent, respectively, under the ambient-temperature conditions encountered during operation. These conditions are readily fulfilled.

2. CONSTRUCTIONAL DETAILS OF RADIO SONDE

Details of the radio sonde are shown in figures 4, 5, and 6. The temperature tube and electric hygrometer are fastened to opposite sides of a mounting plate which fits into the inner of two thin concentric aluminum tubes (see *e* in fig. 6). These form the radiation shields for protecting the temperature and humidity elements from heating by solar radiation. The container shown in figure 6 comprises a light cardboard case covered with a metallic foil. The front compartment houses the radio transmitter (*a*), the plug-in battery power supply (*b*), the pressure-switching unit (*c*), and the miniature relay (*d*). The rear compartment supports the radiation shield (*e*). The shield normally extends about two centimeters above its compartment and the top edge of the mounting plate is normally flush with the top edge of the shield. The temperature and humidity elements are ventilated by the flow of air through this shield produced by the upward movement of the balloon.

An important feature of the instrument is the thermal insulation provided for the radio-sonde transmitter and battery coupled with the thermal isolation of the temperature and humidity elements from the main radio-sonde assembly. There are two contradictory requirements in the design of a radio sonde: the radio transmitter and battery unit should be kept at as nearly constant temperature as possible in order to maintain stability of operation and conserve battery capacity, whereas the temperature- and humidity-sensitive elements should follow every variation of the ambient temperature. The first requirement is partially met by placing the transmitter and battery in a subcompartment formed by insulating material 1 centimeter thick (not shown in fig. 6). The requirement for complete thermal isolation of the temperature and humidity elements is readily carried out because only an electric connection of these elements to the remainder of the assembly is required. Data on the effectiveness of these features will be given later in this paper.

The complete instrument weighs slightly less than 1 kilogram and its present unit price in quantities of several thousand is about $25.00. An interesting feature of the instrument is that, with the radiation shield assembly slid down into its cardboard container, top and bottom flaps (tied back during the ascent) may be used for closing off this container. The instrument is then in convenient form for shipping or for return through the mail upon its recovery. Complete mailing instructions and the reward offered for its return are printed on the foil cover.

3. GROUND-STATION EQUIPMENT

Typical ground-station receiving and recording equipment are shown in figure 7. The receiving set (*a*) feeds an electronic frequency meter (*b*) which measures the frequency of the modulating signal from the balloon and converts it into a direct current proportional to the frequency. This is indicated by a microammeter on the electronic frequency meter and is simultaneously recorded by a recording microammeter (*c*).

An important operating feature of the electronic frequency meter is that the current is directly proportional to the frequency within

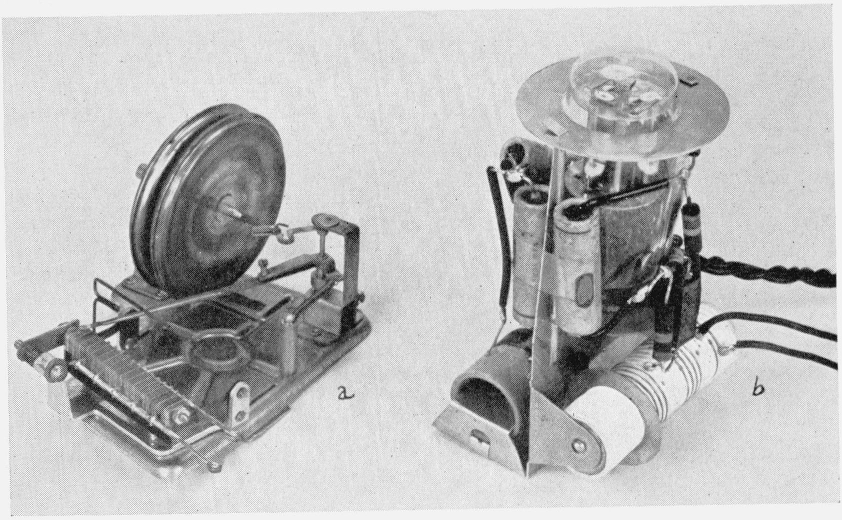

FIGURE 4.—*Component elements of radio sonde.*

a, pressure-switching element; *b*, radio-sonde transmitter.

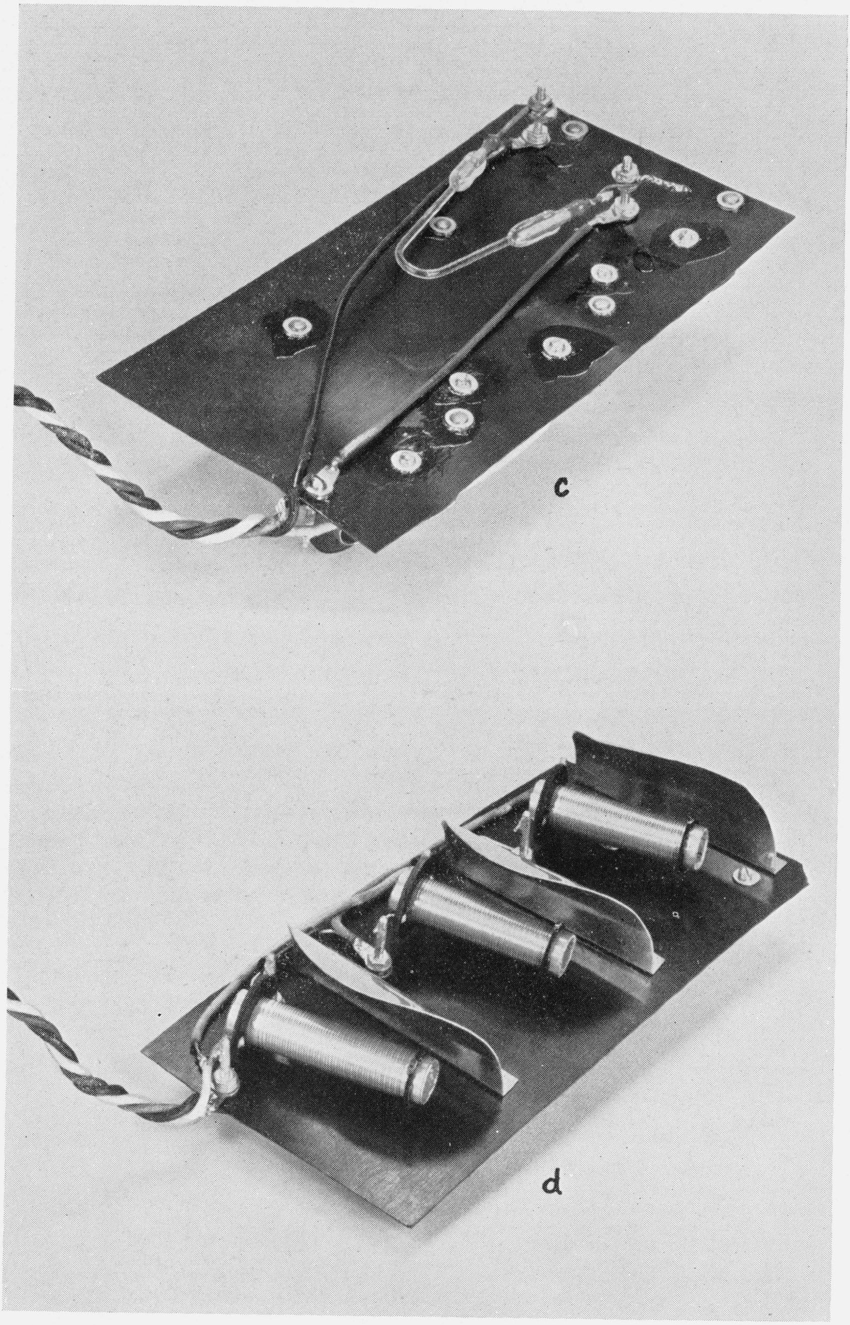

FIGURE 5.—*Component elements of radio sonde.*

c, temperature element; *d*, electric hygrometer.

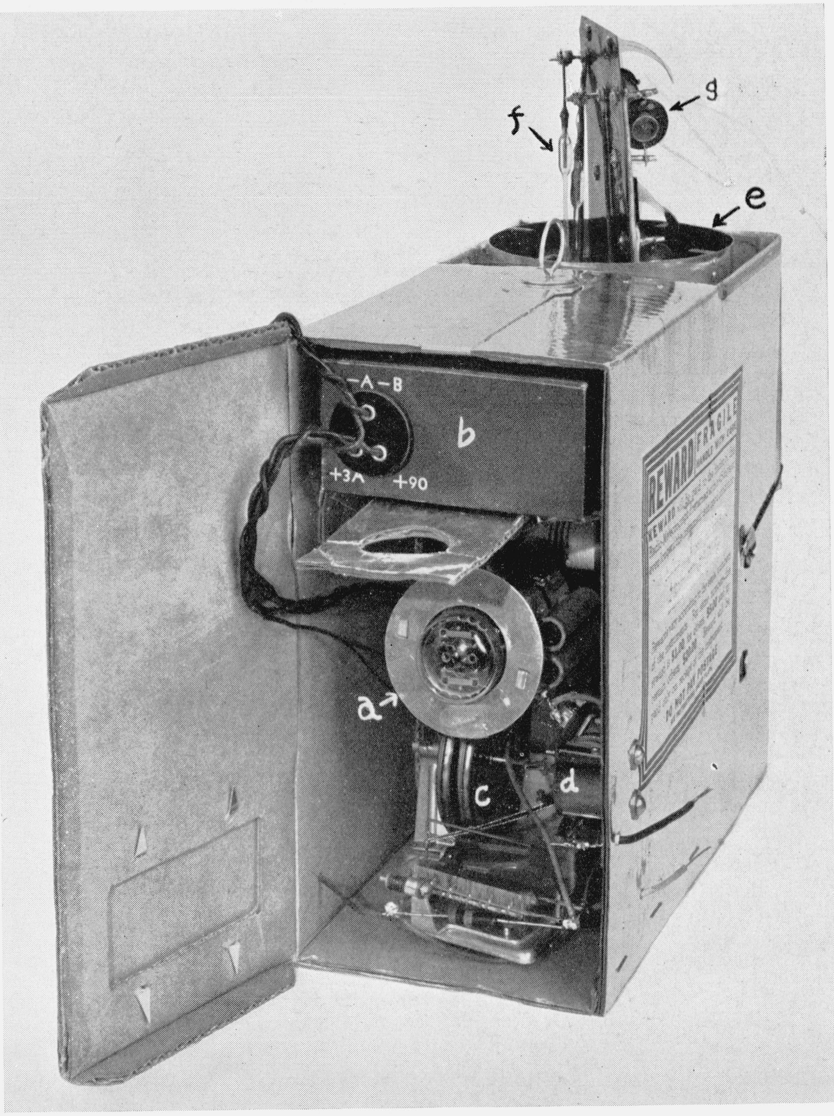

FIGURE 6.—*Radio-sonde component elements in their container.*

a, radio-transmitter; *b*, battery power supply; *c*, pressure-switching unit; *d*, miniature relay; *e*, radiation shields; *f*, temperature tube; *g*, electric hygrometer.

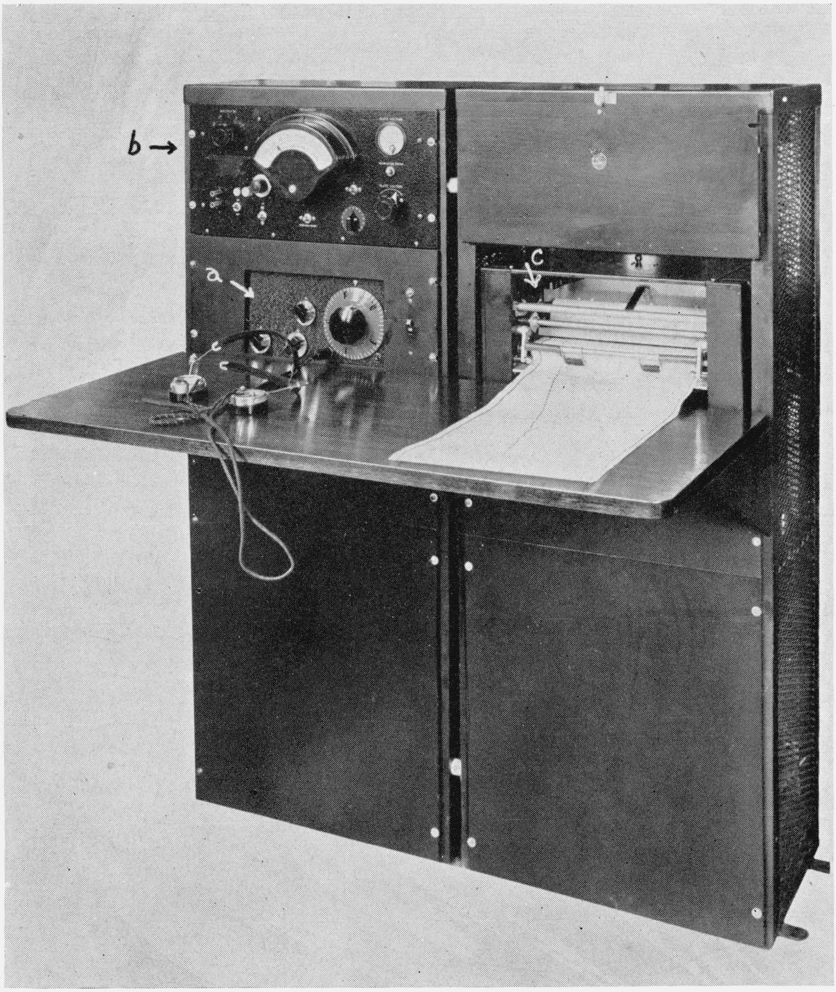

FIGURE 7.—*Ground-station receiving and recording equipment.*

a, receiving set; *b*, electronic-frequency meter; *c*, recording microammeter.

very narrow limits. Moreover, a control in the output circuit allows adjustments of the current corresponding to any frequency within the range, up to ±15 percent, without upsetting the linear relationship between the current and frequency throughout the range. The use made of this property in the temperature and humidity measurements has already been explained.

4. RECORD OF A TYPICAL SOUNDING

A record of a typical sounding, redrawn for reproduction, is shown in figure 8. The start of the record, corresponding to the release of the balloon, is at the bottom of the chart. The recorder chart has 100 equally spaced divisions corresponding to a full-scale range of 200 cycles per second; however, it is more convenient for station personnel to work in terms of the recorder divisions, which may be considered as arbitrary frequency units. For an approximate interpretation of the record, a scale of temperatures (for an average temperature tube) and scales of humidities (at two ambient temperatures) are marked on the chart.

The traces at the extreme right of the chart represent the high-reference frequencies, while the traces just to the left of these represent the low-reference frequencies. The physical positions of the pressure-arm contactor as these marks were being traced by the recorder may be visualized by referring to the contact numbers shown at the lower edges of the high-reference traces. (See also figs. 3 and 4.) The altitude of the balloon corresponding to each high-reference trace is marked on the chart as of likely interest to the reader. Altitude is determined by the well-known hypsometric formula, using the pressure, temperature, and humidity observations.

The temperature and humidity traces are seen to form broken lines which plot the variation of these two meteorological factors as a function of the balloon altitude. The temperature traces are readily distinguishable from the humidity traces by the nature of their variation. Each interruption of the temperature plot designates that the pressure-arm contactor has just reached a humidity or reference contact; each interruption of the humidity plot indicates that the contactor has just left a humidity contact. Light dotted lines have been added between adjacent humidity traces to emphasize the sharp variations obtained.

5. EVALUATION CHARTS

Special charts are employed for facilitating the evaluation of pressure, temperature, and humidity from the recorded observations. Since the pressure-switching units are individually calibrated, the evaluation of pressure is made directly from the calibration chart.

One arrangement for evaluating temperature employs a special slide rule. The fixed scale is graduated in recorder divisions, spaced to represent, on an arbitrary logarithmic scale of resistance, the standard frequency-resistance characteristic of the radio-sonde transmitter. The sliding scale is graduated in temperature divisions which plot the temperature-resistance characteristic to the same arbitrary logarithmic scale of resistance. In this way, adjustment of the sliding scale with respect to the fixed scale provides for automatic correlation of the transmitter characteristic with the temperature-tube characteristic. It allows the actual value of resistance of the temperature tube at a given temperature to vary within rather

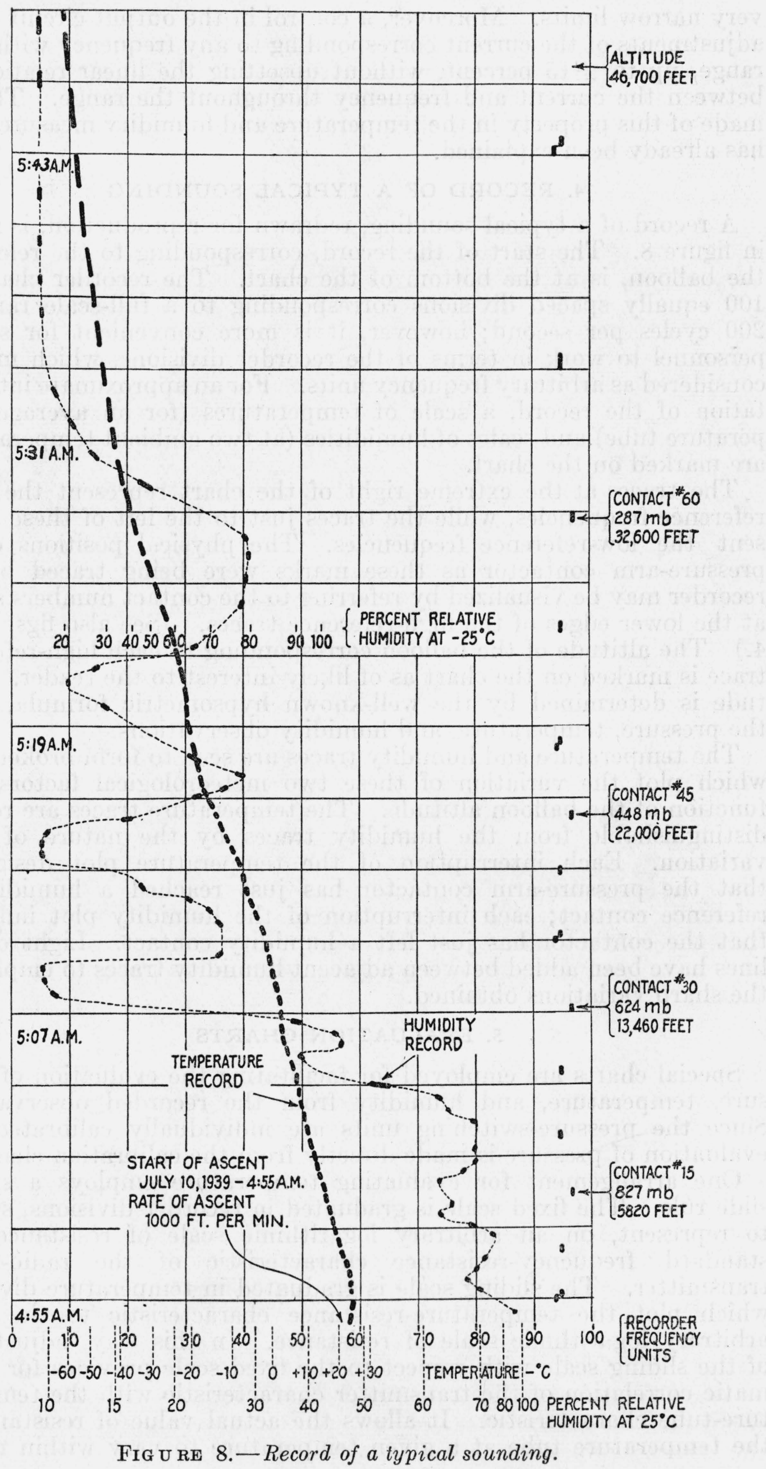

FIGURE 8.—*Record of a typical sounding.*

wide limits (thereby reducing the accuracy to which the bore of the tube must be held in manufacture), so long as its law of variation of resistance with temperature corresponds to the standard electrolyte used.

Just prior to the release of the radio sonde, the operator measures the true temperature at the ground surface and the corresponding observed trace on the recorder. These data are used in setting up the slide rule. Evaluation of observed temperatures from observed recorder traces during the sounding are then carried out by means of the cruiser on the slide rule.

The chart used for evaluating the humidity observations is shown in figure 9. It facilitates the application of a temperature correction

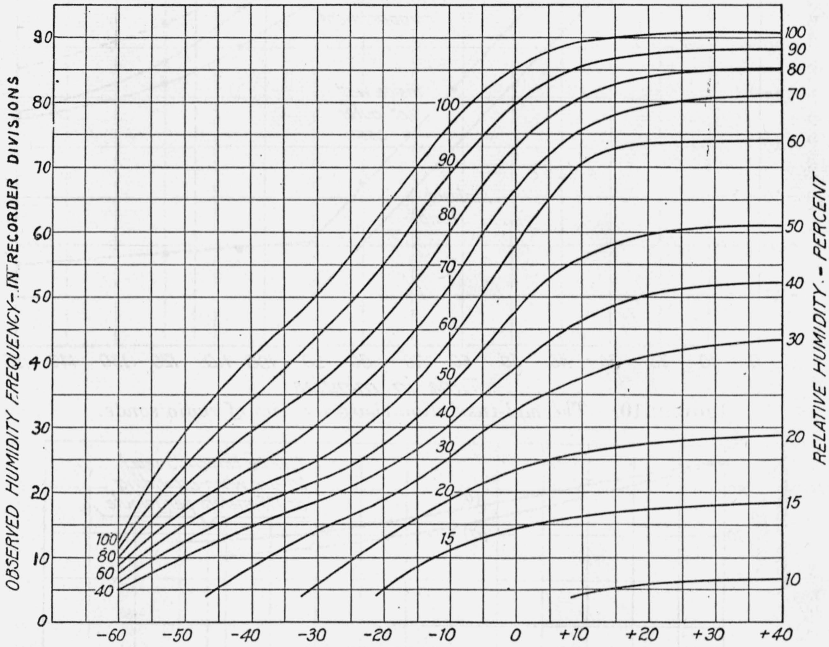

FIGURE 9.—*Charts for evaluating the relative humidity from the observed recorder frequency and the temperature at which the observation is made.*

to the humidity readings. The ordinate scale is in arbitrary frequency units corresponding to divisions on the recorder chart. The scale of abscissas represents the temperature at which the humidity measurements are made. Each curve is for a constant relative humidity. Knowing the frequency of the observed humidity trace and the corresponding observed ambient temperature, the relative humidity is determined by interpolation on the chart. Reasonable control of the manufacturing processes makes it possible to obtain electric hygrometers which conform very closely to the standard characteristics of figure 9.

IV. PERFORMANCE OF COMPONENT ELEMENTS

The following sections will present the results of numerous tests on component elements of the radio sonde under idealized conditions in the laboratory and under actual field conditions.

1. RADIO-SONDE TRANSMITTER

The radio-sonde transmitter operates under conditions which can hardly be considered conducive to stable operation. The change of

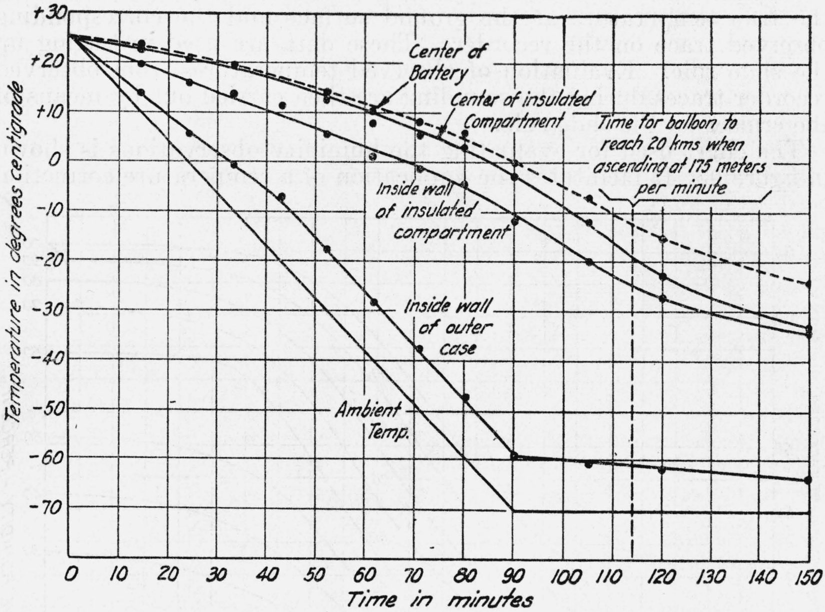

FIGURE 10.—*Thermal-insulation characteristics of radio sonde.*

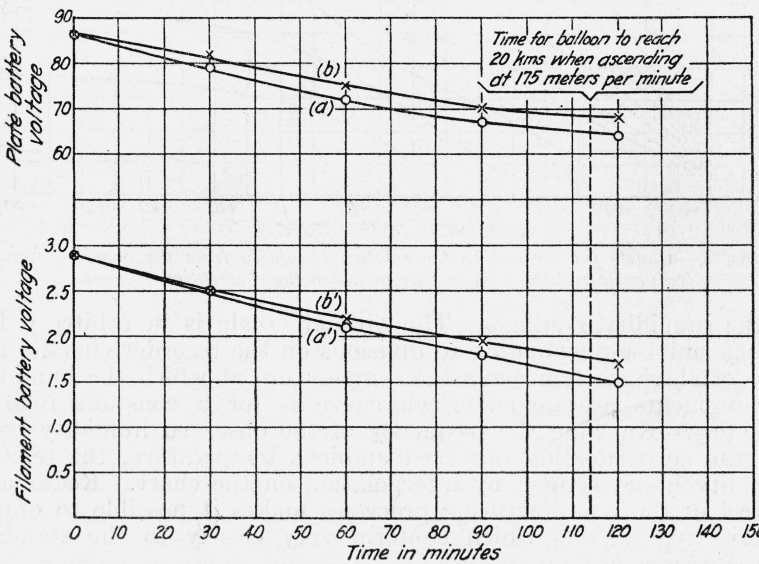

FIGURE 11.—*Variation of battery voltages with time during a radio sounding.*

ambient temperature within the radio-sonde case, during the course of a sounding, may exceed 100 degrees centigrade; the plate and filament battery voltages may decrease to 65 percent of their rated values. The important considerations in performance are: the frequency stability of the carrier oscillator, the variation of carrier power output with time, and the degree of maintenance of the audio-frequency (frequency-resistance) characteristic.

Figure 10 shows the variation of the temperature at selected points in the radio sonde when the ambient temperature variation and ventilation simulate those encountered during a typical radio sounding in the summer (when maximum ambient-temperature change occurs). The ambient-temperature change assumed corresponds to a balloon ascension rate of 175 meters per minute. On this basis, the balloon reaches 20 kilometers in 114 minutes. The temperature in the insulated compartment housing the transmitter and battery is then seen to be about −20° C. With the increased rate of ascent made possible with the improved instrument, say 300 meters per minute, the corresponding temperature at 20 kilometers would be approximately zero degrees centigrade. In either case, the insulated compartment is seen to afford considerable protection for the radio transmitter against the ambient-temperature change.

Figure 11 shows the variation in terminal plate and filament voltages as the radio sonde ascends at 175 meters per minute through a standard atmosphere. Graphs *a* and *a′* are for the radio sonde as used heretofore, without the insulated subcompartment. Graphs *b* and *b′* are for the radio sonde, using the insulated subcompartment. There is seen to be a material increase in the time to reach given terminal voltages when using the insulation.

(a) FREQUENCY STABILITY AND POWER OUTPUT OF CARRIER OSCILLATOR

Figure 12 shows the variation in carrier-oscillator frequency as a function of the various operating parameters. Graph *a* shows the variation with the temperature of the oscillator compartment. Graph *b* shows the variation with filament voltage; graph *c*, the variation with plate voltage; and graph *d*, the variation with time when both voltages vary as shown by graphs *b* and *b′* in figure 11. The variation of the carrier-oscillator frequency with antenna tuning is shown by graph *e;* since the antenna tuning remains substantially constant, very little of the variation shown in graph *e* actually occurs.

A study of figure 12 in combination with figures 10 and 11 indicates that the over-all carrier-frequency variation occurring during a sounding probably does not exceed 100 kilocycles per second. It would appear possible to reduce this variation to the order of 40 kilocycles per second through the addition of a tuning condenser having a negative temperature coefficient.

The power radiated from the dipole transmitting antenna averages 200 milliwatts at rated plate and filament voltages. At the end of 2 hours' operation under the average conditions encountered during a sounding, the average radiated power drops to about 75 milliwatts.

It is of interest to consider briefly the receiving problem at ground stations arising from the limited transmitter output. The problem is complicated by the fact that it is desirable to eliminate nulls in the vertical receiving response pattern, since the balloon elevation angles may be from 80 degrees at the beginning of an ascent to 5 degrees or less at the end. Nulls are eliminated by placing the receiving antenna at one-half wavelength or less above ground. This results in very low response at balloon distances of the order of 100 to 200 kilometers.

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Thus, with the balloon at 20 kilometers altitude and 150 kilometers distance, the field intensity set up at the receiving antenna (for 100 milliwatts output) is only 12 microvolts per meter.

An effective expedient to increase the distance range of reception

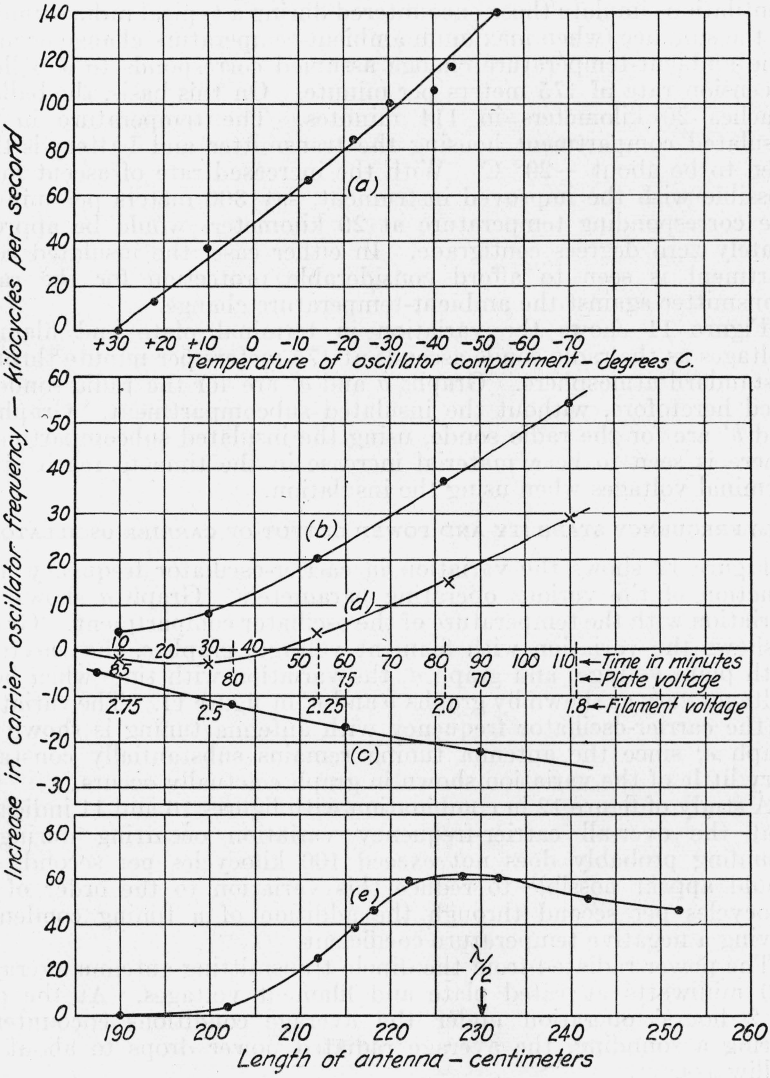

FIGURE 12.—*Graphs showing frequency variation of 65–Mc carrier oscillator.*

a, With temperature of oscillator compartment; *b*, with filament-battery voltage; *c*, with plate-battery voltage; *d*, with both voltages; *e*, with antenna length.

is to employ a second antenna placed one and one-fourth wavelength above ground and put into operation only when reception on the first antenna proves difficult. The vertical receiving response patterns for the two antennas are shown in figure 13; they are seen to intersect at 17 degrees. For the distance and height of balloon considered, the field intensity at the second antenna is approximately 18 microvolts per meter, an appreciable improvement. It will be evident that the improvement will be even greater at lower elevation angles or when the dielectric constant of the ground is lower than the assumed value of 15.

(b) MAINTENANCE OF AUDIO-FREQUENCY CHARACTERISTIC

As previously indicated, the radio-sonde transmitters are readily controlled to conform to a standard audio-frequency characteristic. This characteristic is shown by the solid curve in figure 14. The

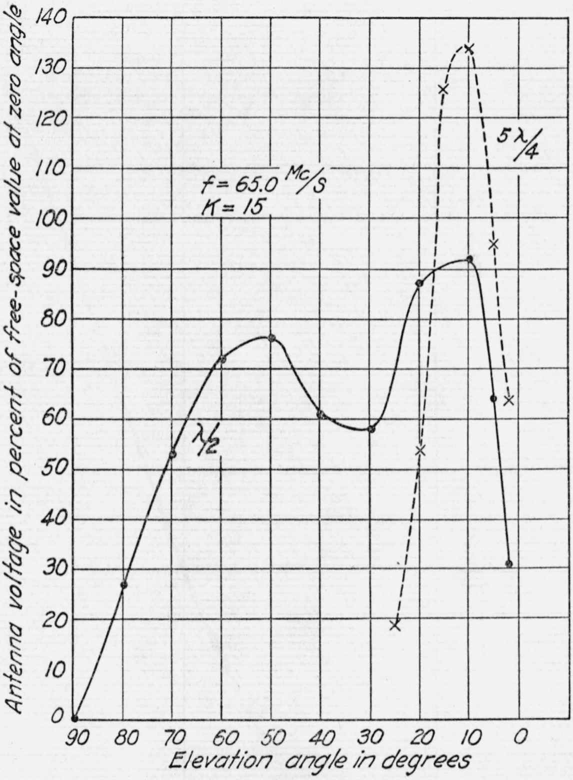

FIGURE 13.—*Vertical-plane directivity of receiving antennas at ground station.*

dotted curves on either side of the solid curve represent characteristics having the maximum deviation from the standard in 100 stock transmitters tested. It is to be noted, particularly, that whenever a deviation from the standard characteristic is noted, all points of the characteristic obtained lie on the same side of the standard curve. The characteristics for the transmitters tested were determined on the basis that the low-reference frequencies were all equal to 190 cycles per second; actual variations in the reference frequency ranged from +10 to −15 cycles. Thus, the abscissas in figure 14 represent indicated frequencies corrected for a reference frequency of 190 cycles per second; the ordinates correspond to values of resistance added in series with (R_1+R_2) of figure 3.

During a sounding, the absolute value of the reference frequency will be affected by variations in several of the operating parameters. These include the plate and filament voltages of the modulating oscillator, the condenser C_2 in the resistance-capacitance network, and the series resistance of the oscillatory circuit $L_1C_1L_2$. (See fig. 3.)

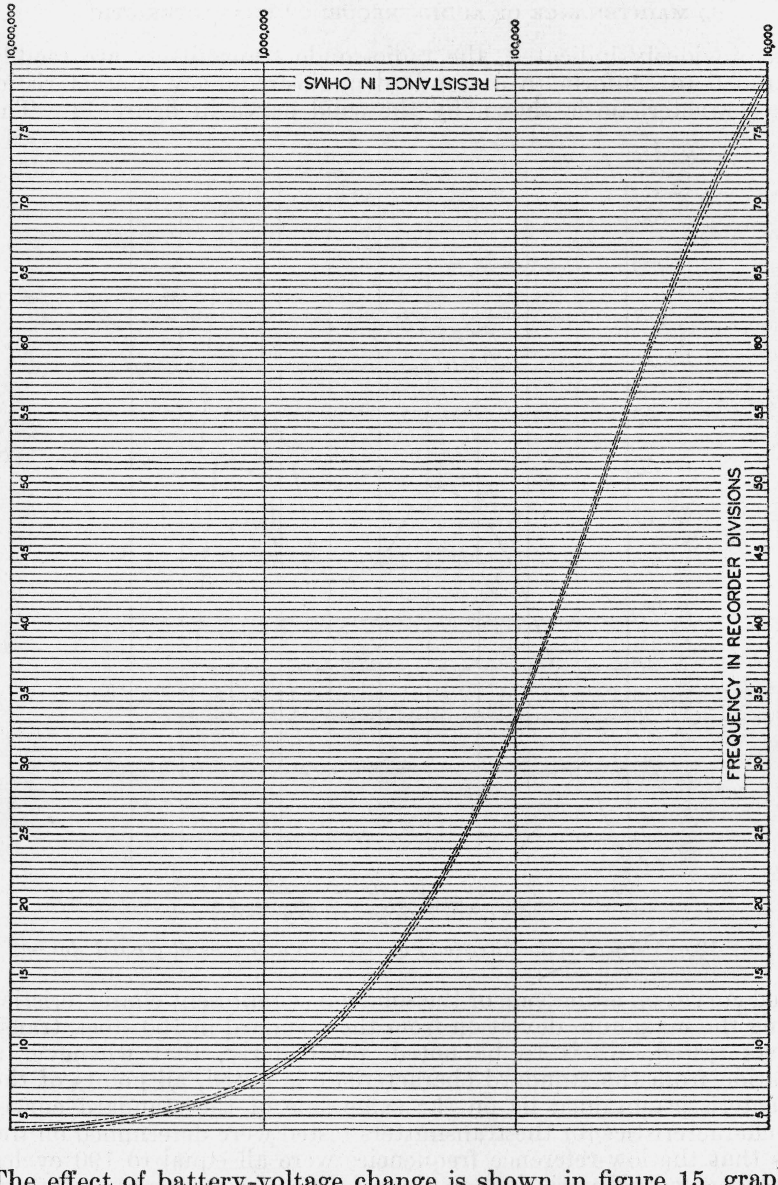

FIGURE 14.—*Range of variation of transmitter audio-frequency characteristic.*

The effect of battery-voltage change is shown in figure 15, graph *a*; here the abscissas represent the simultaneous variation of the plate and filament battery voltage during a sounding. The influence of the battery voltages upon the value of the "blocking" frequency is due to the attendant change in the transconductance of the tube, which affects the amplitude of the 1-megacycle oscillations and also the values of grid bias at which these oscillations begin and stop. As the battery voltages decrease in value, the amplitude of oscillation decreases, thereby increasing the time for charging the condenser C_2 of figure 3. Since the discharge time for this condenser depends only on the value of C_2 and of the resistance in parallel with it, the

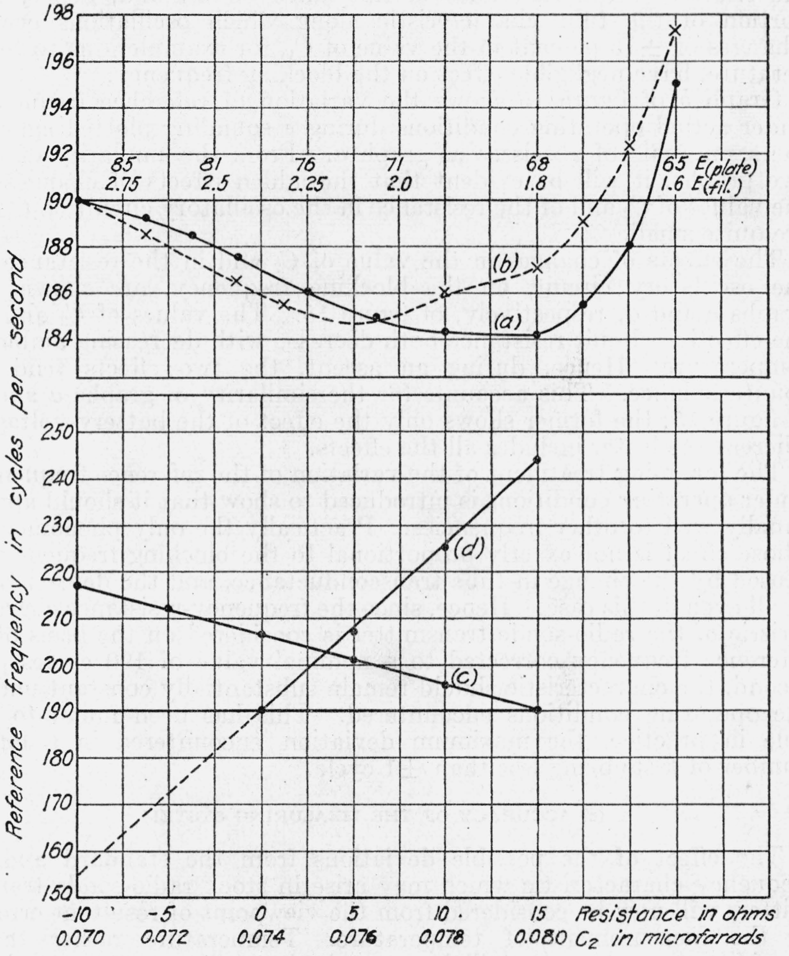

FIGURE 15.—*Graphs showing drift of low-reference frequency of modulating oscillator.*

a, with battery voltage change; *b*, with battery voltage change under operating conditions; *c*, with value of condenser C_2 (fig. 3); *d*, with resistance of oscillatory circuit $L_1C_1L_2$ (fig. 3).

total time per period varies with the amplitude of oscillation, increasing as the amplitude of oscillation decreases. Thus, there is a tendency for the blocking frequency to drop as the voltages decrease.

However, as the voltages decrease, the limits of grid bias between which oscillations are maintained vary, the extent of such variation depending upon the shape of the plate current-grid voltage characteristic of the triode. The variation due to this effect is initially quite small but becomes appreciable when the battery voltages approach about 60 percent of their rated values; the tendency is to produce an increase in the blocking frequency. The influence of the tuning condenser, C_1, is similar to this effect in that it controls the effective series resistance of the tuned circuit and, hence, the portion of the tube characteristic along which oscillations occur. Changes of ± 15 percent in the value of C_1, for example, due to temperature, have negligible effect on the blocking frequency.

Graph *b* of figure 15 shows the variation of reference frequency under actual operating conditions during a sounding plotted against the same scale of abscissas as graph *a*. From the similarity of the two graphs, it will be evident that the added effects of changes in the values of C_2 and of the resistance in the oscillatory circuit ($L_1C_1L_2$) are quite small.

The effects of changes in the value of C_2 and in the resistance of the oscillatory circuit, on the blocking frequency, are shown by graphs *c* and *d*, respectively, of figure 15. The values of C_2 and of the effective circuit resistance both decrease with decreasing ambient temperature. Hence, during an ascent, the two effects tend to counterbalance. This accounts for the similarity of graphs *a* and *b* of figure 15; the former shows only the effect of the battery voltages whereas the latter includes all the effects.

The foregoing treatment of the variation of the reference frequency under operating conditions is introduced to show that it should apply equally well to other frequencies. Practically the only phenomenon whose effect is not exactly proportional to the blocking frequency is caused by the change in tube transconductance, and the deviation is small even in this case. Hence, since the frequency-resistance characteristic of the radio-sonde transmitter is considered on the basis of a reference frequency corrected to a nominal value of 190 cycles per second, the characteristic should remain substantially constant under the operating conditions encountered. This has been found to be true in practice, the maximum deviation encountered in a large number of tests being less than ± 1 cycle.

(c) ACCURACY OF THE MEASURING SYSTEM

The effect of the possible deviations from the standard audio-frequency characteristic which may arise in stock radio-sonde transmitters will now be considered from the viewpoint of resultant errors in the measurement of temperature. Temperature rather than humidity measurements will be treated, since the accuracy requirements for the former impose a greater task on the measuring system. A temperature tube of negligible error will be taken so that the errors obtained may be attributed in entirety to the measuring system. This is generally the case in practice. To make the discussion complete, errors arising from the frequency-measuring and recording equipment will also be considered. In order to show clearly the effects treated, errors of reading and of adjustment of the reference frequency (which may introduce temperature errors up to ± 0.2 degree) will be taken as negligible.

Table 2 summarizes the effect of variation of individual transmitters from the standard audio-frequency characteristic. The dotted characteristics of figure 14, corresponding to maximum deviations encountered in practice, are considered. Were it not for the process of setting up the temperature-evaluation slide rule on the basis of the surface-temperature observation (conveniently referred to as the "temperature lock") the errors listed in column 2 of table 2 would be had. However, the "temperature lock" corresponds to a parallel lateral shift of the individual characteristic so that it intersects the standard characteristic at the observed frequency (generally in the range from 50 to 70 recorder divisions at surface temperatures). This one-point lock reduces the errors obtained to those shown in column 3 of table 2.

TABLE 2.—*Effect of maximum tolerances in transmitter characteristic*

[±1 cycle at 120 cycles per sec; ±½ cycle at 10 cycles per sec]

True temperature	Apparent error [1] in absence of ground temperature lock	Actual error
° *C*	° *C*	° *C*
+30	±1.9	0.0
+15	±1.4	.0
0	±1.1	±.1
−15	±.9	±.1
−30	±.8	±.1
−45	±.7	±.1
−60	±.7	±.2
−70	±.8	±.3

[1] Errors of successive readings have same sign except when transmitter characteristic crosses the standard characteristic. No case of such crossing of the characteristic has been observed in practice.

Table 3 summarizes the effect of reference-frequency drift occurring during a sounding. The drift assumed corresponds to that normally encountered in service. Column 3 of table 3 suggests large errors, provided corrections for reference-frequency drift are *not* applied. Such corrections may be made automatically by adjusting the proportional scale control in the frequency-measuring circuit so that the recorder trace corresponding to each received low reference frequency reads exactly 95 divisions, or the corrections may be applied to the temperature observations on a proportional basis. Theoretically, the application of the corrections should reduce the error discussed to zero, as indicated in column 4 of table 3. However, the reference-frequency drift may not be uniform between successive reference-frequency contacts. The last column of table 3 shows the possible errors arising in practice from likely variations in uniformity of drift.

TABLE 3.—*Effect of reference drift in transmitter*

True temperature	Average accumulated frequency drift	Apparent error without corrections for frequency drift	Actual error when corrections for drift are applied	Possible error due to nonuniform frequency drift between references
°*C*	*c/s*	°*C*	°*C*	°*C*
+15	0.0	0.0	0	0.0
0	.6	.9	0	.2
−15	1.2	1.1	0	.1
−30	1.9	1.2	0	.1
−45	2.7	1.2	0	.1
−55	3.6	1.3	0	.1
−55	5.0	1.7	0	.1

Table 4 shows the effect of using uncalibrated ground-station frequency-measuring and recording equipment. Calibrations made of a number of ground-station equipments yielded maximum deviations of the recorded traces from true frequency as indicated in figure 16. If this unit were used without calibration, the errors which would at first glance appear to be obtained in the temperature measurements are shown in column 2 of table 4. Again, the "temperature lock" (see point *L* on fig. 16) operates to make a frequency correction at the highest observed temperature (surface temperature), so that the effective errors in frequency measurement during the sounding correspond to the deviations from the base line, *A*, in figure 16 instead of from the *X*-axis. The actual errors in temperature measurement with an

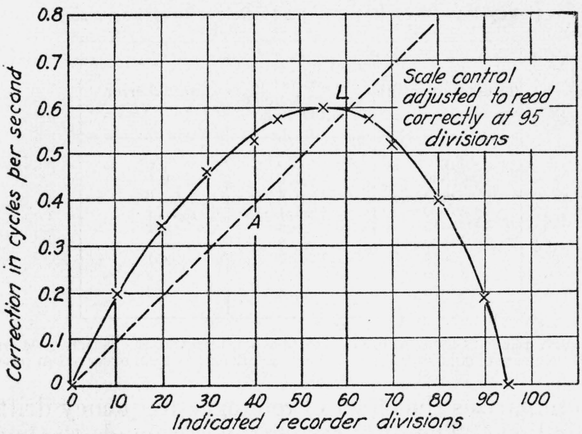

FIGURE 16.—*Effect of "temperature lock" in reducing errors caused by uncalibrated recorder.*

uncalibrated recorder thus reduce to the values shown in column 3 of table 4. These may of course be further reduced by calibrating the recorder equipment.

TABLE 4.—*Effect of errors in indication of frequency recorder*

True temperature	Apparent error for average recorder, uncalibrated	Actual error for average recorder, uncalibrated, with temperature lock as used	Actual error for calibrated recorder	True temperature	Apparent error for average recorder, uncalibrated	Actual error for average recorder, uncalibrated, with temperature lock as used	Actual error for calibrated recorder
°C	°C	°C	°C	°C	°C	°C	°C
+30	1.4	0.0	0	−30	0.3	0.2	0
+15	1.1	.0	0	−45	.2	.3	0
0	0.8	.1	0	−60	.2	.3	0
−15	.6	.1	0	−70	.2	.3	0

The foregoing analysis should serve to indicate that the application of corrections for reference-frequency drift coupled with the use of the "temperature lock" operate to provide an accuracy of temperature measurements which would not appear to be possible from a casual analysis of the system. This conclusion is fully corroborated by actual performance, as will be shown later in this paper.

2. PRESSURE-SWITCHING ELEMENT

The measurement of pressure on the basis of contact identification considerably increases the practical accuracy of the pressure observations. Obviously, the limitation to accuracy lies only in the performance of the pressure diaphragm and pressure-arm linkage; no errors are introduced by the method of recording and evaluation. Tests on a large number of units revealed that readings are repeated to within the calibrating accuracy, less than 1 millibar. Since the temperature and humidity observations are generally taken at the contacts (where accurate calibration is available), the possible accuracy of the pressure measurements is seen to be within 1 millibar.

This accuracy is not attained in actual use because of the temperature coefficient of the diaphragm and because of zero shift during shipment and storage. The temperature effect is maximum at ground-level pressure and decreases at lower pressure levels until nearly exact temperature compensation is had at about 150 millibars. Thus, if the calibration is carried out at room temperature, the reading at ground-level pressure may be in error by up to 10 millibars if the temperature of the diaphragm is, say, −40° C; however, the error at 150 millibars will be negligible. In service use it is customary to rely upon the temperature lag of the diaphragm to limit the temperature error at the higher pressure levels. Since the radiosonde container provides some thermal insulation of the pressure element, the error introduced is normally less than 3 millibars at usual winter surface temperatures. A more accurate procedure, under present consideration, is to apply temperature corrections to the pressure observations, based on the average behavior of a large number of pressure units. There remains also the possibility, avoided at present owing to its cost, of adding automatic compensation for the temperature error.

The zero shift operates to displace the calibration curve parallel to itself, so that all pressure readings are in error by very nearly the same amount. To correct for zero shift, a control is provided for moving the switching element laterally with respect to the pressure-arm contactor. This control allows setting the unit correctly at the ground-level pressure prior to an ascent, the adjustment being generally made at room temperature.

Some refinement in setting the control would result in increased accuracy over that now attained. The adjustment is at present made on the basis of visual observation of the position of the switching contactor on the surface of the switching element and may introduce an error up to 3 millibars. This, coupled with the residual error due to temperature effect, results in over-all error in practice up to 5 millibars. It is important to note that practically no scattering of readings occurs, the over-all error being of very nearly the same magnitude and of the same sign throughout the range of indication. Hence, the relative accuracy of successive pressure observations is generally within about 1 millibar.

During the design of the instrument, some difficulty was expected in practice from corrosive action on the contacts. Fortunately, such difficulty has not materialized. It is customary to clean the surface of the switching element with very fine abrasive paper just prior to use. This procedure appears to have solved the problem of securing good contacts even at locations such as Swan Island in the Caribbean and ship stations in the Atlantic and Pacific.

3. TEMPERATURE ELEMENT

A description of improvements effected in the electrical properties of the temperature element is given elsewhere [4]. With the development of a practical seal for the terminals, the useful life of the device has been increased to about a year. Comparative tests of units 1 month and 8 months old showed agreement within the accuracy of measurement, ± 0.2 degree centigrade. During several years of use of the temperature tube, the same electrolyte formula has been used and all temperature tubes have been found to give identical characteristics within the limits of measurement (± 0.2 degree centigrade).

(a) SENSITIVITY OF INDICATION

The sensitivity of indication obtained may be defined as the change in modulating frequency produced per degree change in temperature. For a given portion of the range of temperature indication, it obviously depends on the slopes of the frequency-resistance characteristic of the modulating oscillator and of the resistance-temperature characteristic of the temperature element. The former has greatest slope for low values of resistance while the latter has least slope for low values of resistance (that is, high temperatures). Two factors allow some leeway in adjustment of the two characteristics so as to obtain reasonably uniform sensitivity throughout the temperature range. One consists in shaping the audio-frequency characteristic so as to maximize its slope at the low-resistance end, by making (R_1+R_2) of figure 3 as low as considerations of stability will allow (40,000 ohms), and to reduce its slope at the high-resistance end by adding the 1-megohm shunt resistor (R_6). The second means for adjustment consists in varying the dimensions of the temperature tube so as to vary the tube resistance corresponding to a given temperature. Since the temperature coefficient of resistivity of the electrolyte used does not vary, this adjustment determines the portion of the audio-frequency characteristic utilized for a given portion of the temperature range.

The influence of the several possible adjustments on the sensitivity of temperature indication obtained may be seen from figures 17 to 19, inclusive. Figure 17 shows the effect of the value of series resistance used. Note that the sensitivity increases for the higher temperatures and decreases for the lower temperatures as the value of series resistance is reduced. The value chosen for use is 40,000 ohms. Figure 18 shows the effect of the shunt resistor. Note that only the lower temperatures are influenced appreciably. Above about 1 megohm, the slight advantage gained for sensitivity of indication of the lower temperatures is more than compensated for by the difficulty in receiving and measuring very low frequencies. A 1-megohm shunt is in present use. Figure 19 shows the influence of changing the resistance of the temperature tube. Increasing the tube resistance (correspond-

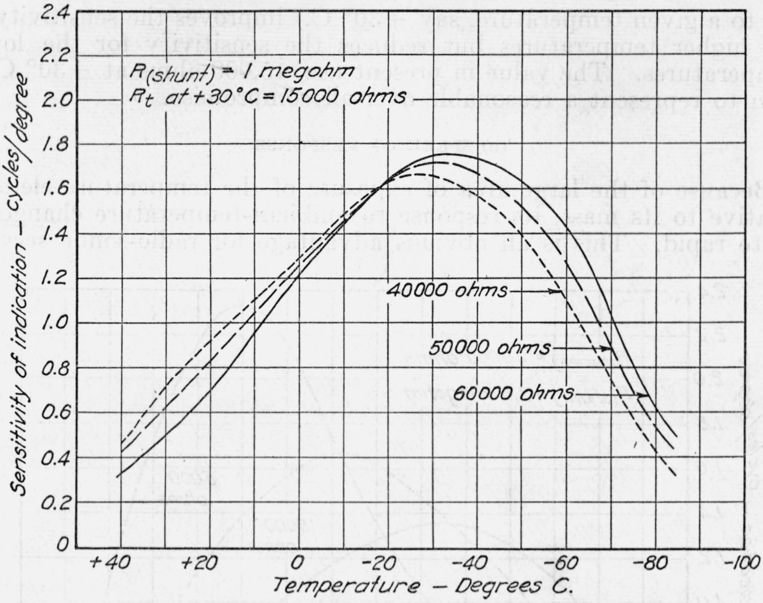

FIGURE 17.—*Effect of value of series resistor on sensitivity of temperature indication.*

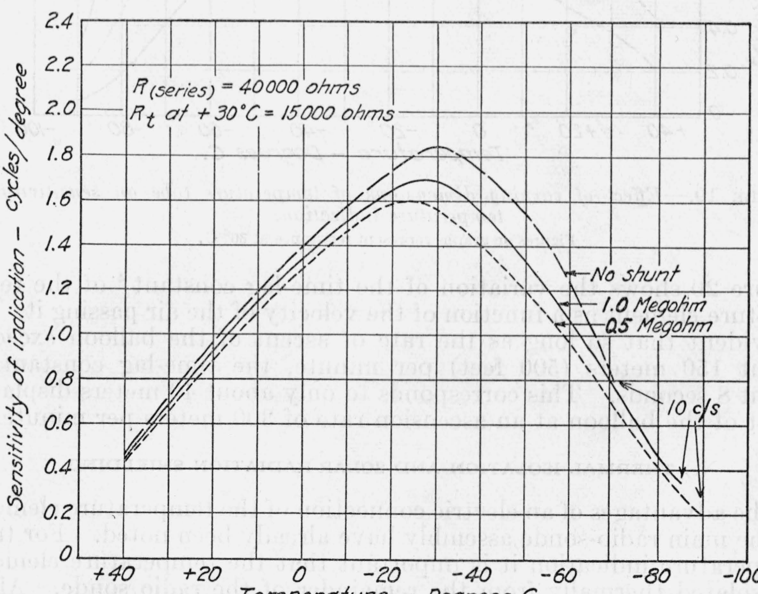

FIGURE 18.—*Effect of value of shunt resistor on sensitivity of temperature indication.*

ing to a given temperature, say +30° C.) improves the sensitivity at the higher temperatures but reduces the sensitivity for the lower temperatures. The value in present use, 15,000 ohms at +30° C, is seen to represent a reasonable over-all compromise.

(b) SPEED OF RESPONSE

Because of the large area of exposure of the temperature element relative to its mass, its response to ambient-temperature changes is quite rapid. This is an obvious advantage for radio-sonde service.

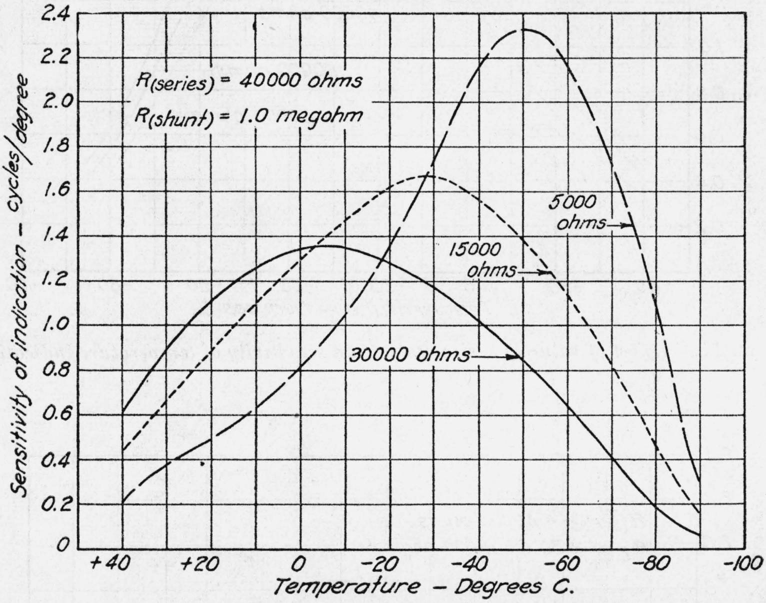

FIGURE 19.—*Effect of varying dimensions of temperature tube on sensitivity of temperature indication.*

Figures on graphs represent resistance at 30° C.

Figure 20 shows the variation of the time-lag constant [4] of the temperature element as a function of the velocity of the air passing it. It is evident that so long as the rate of ascent of the balloon exceeds about 150 meters (500 feet) per minute, the time-lag constant is about 8 seconds. This corresponds to only about 40 meters displacement of the balloon at an ascension rate of 300 meters per minute.

(c) THERMAL ISOLATION AND SOLAR-RADIATION SHIELDING

The advantages of an electric connection of the temperature element to the main radio-sonde assembly have already been noted. For true temperature indication it is important that the temperature element be isolated thermally from the remainder of the radio sonde. Also,

[4] The time-lag constant is the time required for the indication to show a change of $\left(1-\frac{1}{\epsilon}\right)$ of the total change, where ϵ is base of natural logarithm [5].

to make daytime soundings possible, effective shielding against solar radiation is essential. The design shown in figure 6 was adopted after numerous ascension tests of a large number of case designs affording a variety of exposures of the sensitive elements. The temperature measurements obtained in the stratosphere testified to the importance of thermally isolating the temperature element from the remainder of the radio sonde. To serve as a standard of comparison, an assembly comprising two completely detached units (except for the connecting wires) was tried; in this arrangement the radiation-shield assembly was suspended about 18 inches above the main portion of the radio sonde. This arrangement was found to give the coldest temperatures in the stratosphere. The design shown in figure 6, although giving stratosphere temperature indications up to 1 degree warmer, was adopted because of the more convenient handling. The older design,

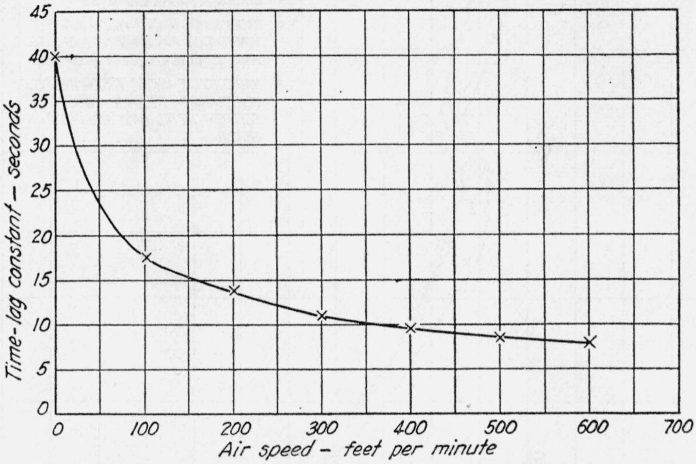

FIGURE 20.—*Variation of time-lag constant of temperature element as a function of ventilation.*

using a balsa-wood case, gave stratosphere temperature indications up to 2 degrees warmer. Other designs tested gave temperature indications up to 15 degrees warmer. Some of these were similar to designs used by other experimenters.

Sample results of the tests are shown in figure 21. Two instruments were attached to the same balloon, one having the case shown in figure 6 and the other having a round case made of balsa wood, with the sensitive elements mounted beneath the case and ventilated by eddy currents about the radiation shield. Two hours later a third instrument was released having a round case made of metal with the sensitive elements mounted beneath the case and similarly ventilated; to prevent heat conduction the radiation shield was thermally insulated from the metal case. It will be observed that the round-case instruments gave warmer temperature observations than the standard instrument, the divergence increasing as the altitude (and hence solar exposure) increased. A significant check is obtained at the point of bursting of the balloons. It will be noted that the temperature observations during the descent of the round-case instruments check the ascending observations of the standard instrument. The added ventilation due to the greater speed of descent (1,500 feet per minute), coupled with the fact that the air stream reaching the sensitive elements has not been warmed by passing over the case (as in the ascent), accounts for the colder temperature obser-

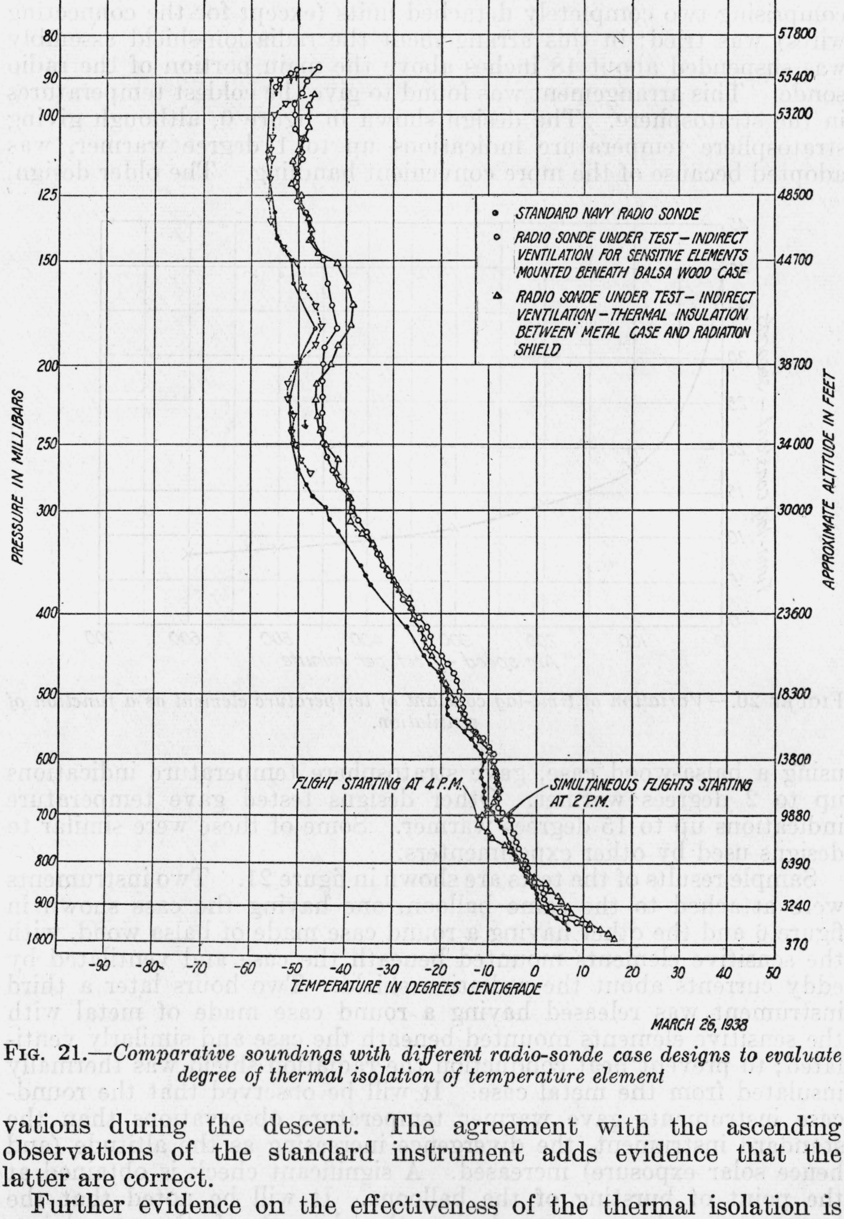

FIG. 21.—*Comparative soundings with different radio-sonde case designs to evaluate degree of thermal isolation of temperature element*

vations during the descent. The agreement with the ascending observations of the standard instrument adds evidence that the latter are correct.

Further evidence on the effectiveness of the thermal isolation is given in figure 22. The data were obtained from a sounding with a single instrument at noon on a September day. A special pressure-switching element [6] was used which gave accurate pressure measurements at 2-millibar intervals starting from about 145 millibars.

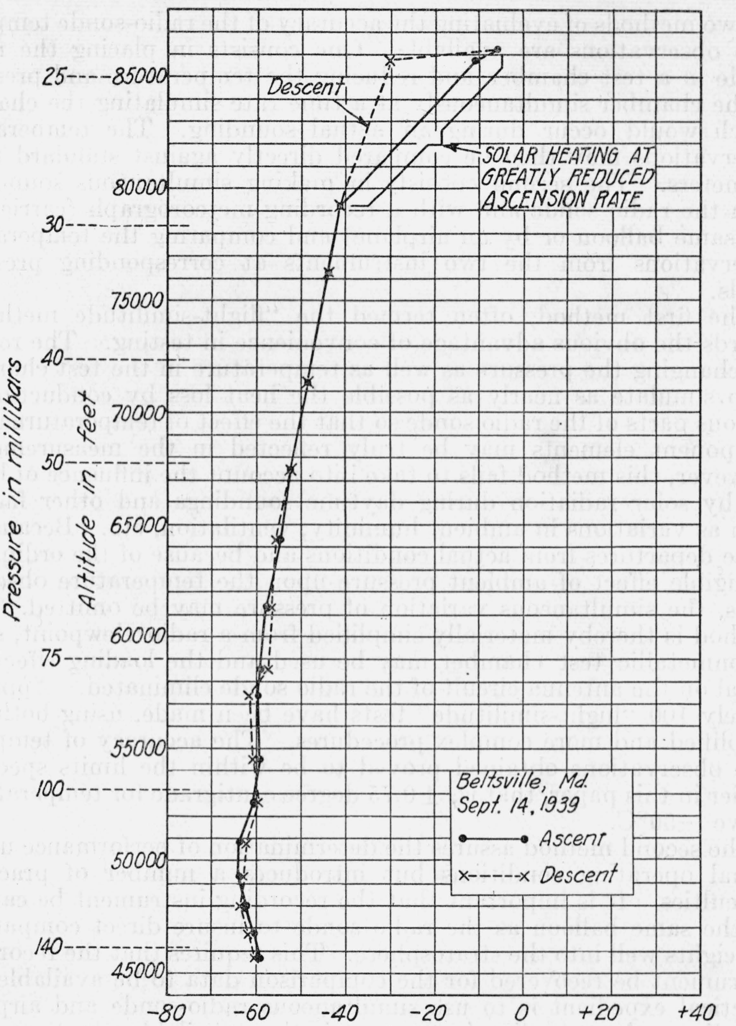

FIG. 22.—*Stratosphere sounding showing temperature observations during ascent and descent of balloon*

Measurements were obtained during both the ascent and descent of the balloon, the rate of ascent being 300 meters per minute and the rate of descent 500 meters per minute. At pressure levels below about 30 millibars, the balloons were obviously floating, so that the temperature element had insufficient ventilation. However, when the balloons broke, the temperature element soon assumed the ambient temperature. Note the close agreement of the ascending and descending values under considerably different ventilating conditions.

(d) ACCURACY OF INDICATION

Two methods of evaluating the accuracy of the radio-sonde temperature observations are available. One consists in placing the radio sonde in a test chamber and reducing the temperature and pressure in the chamber simultaneously at a time rate simulating the changes which would occur during an actual sounding. The temperature observations may then be compared directly against standard thermometers. The second consists in making simultaneous soundings with the radio sonde and with a recording meteorograph (carried on the same balloon or by an airplane) and comparing the temperature observations from the two instruments at corresponding pressure levels.

The first method, often termed the "flight-similitude method", affords the obvious advantage of convenience in testing. The reason for changing the pressure as well as temperature in the test chamber is to simulate as nearly as possible the heat loss by conduction in various parts of the radio sonde so that the effect of temperature upon component elements may be truly reflected in the measurements. However, this method fails to take into account the influence of heating by solar radiation during daytime soundings and other factors such as variations in ambient humidity, ventilation, etc. Because of these departures from actual conditions and because of the ordinarily negligible effect of ambient pressure upon the temperature observations, the simultaneous variation of pressure may be omitted. The method is thereby materially simplified from a radio viewpoint, since a nonmetallic test chamber may be used and the loading effects of metal on the antenna circuit of the radio sonde eliminated. Approximately 100 "flight-similitude" tests have been made, using both the simplified and more complex procedures. The accuracy of temperature observations obtained proved to be within the limits specified earlier in this paper, that is, ± 0.75 degree centigrade for temperatures above $-50°C$.

The second method assures the determination of performance under actual operating conditions but introduces a number of practical difficulties. It is important that the recording instrument be carried by the same balloon as the radio sonde to insure direct comparison to heights well into the stratosphere. This requires that the recording instrument be recovered for the comparison data to be available. A practical expedient is to use simultaneous radio-sonde and airplane soundings; the recording instrument is then available as soon as the airplane returns to the ground. However, the airplane cannot generally fly in the same portion of the air mass as the balloon and its ceiling height is limited.

A large number of comparison tests of this general class have been made, including approximately 30 simultaneous radio-sonde and balloon-meteorograph soundings for which the meteorographs were recovered and about 150 simultaneous radio-sonde and airplane soundings. The majority of these tests were made in the field, using stock radio sondes with no special handling. The results of 20 simultaneous soundings of the first type are summarized in graph 1 of figure 23, and the results of 25 of the second type in graph 2. The abscissas represent deviations between the radio-sonde observations and the observations of the comparison instrument, while the ordinates represent the percentages of the total observations falling within the specified deviations. In graph 1 temperature comparisons down to about −50° C are included, whereas in graph 2 the comparisons include data only down to −30° C. In considering the results, it should be noted that the deviations include the effect of errors in the comparison instrument as well as in the radio sondes. Also, since the pressure measurements with the two types of instruments were required in computing altitude in order that the temperature observations might be compared at equivalent altitudes, the deviations include the effect of possible errors in the observations of pressure.

The better agreement shown by graph 1 is attributed to the more direct comparison afforded when the two instruments are carried by the same balloon and hence traverse the same path through the atmosphere. In simultaneous radio-sonde and airplane soundings it is possible for the balloon to be as much as 75 kilometers from the airplane at the upper levels. To check the foregoing conclusion, a series of comparisons was made of simultaneous soundings with a radio sonde, a balloon meteorograph, and an airplane meteorograph (aerograph). The results of several of these are shown in the second paper of reference [2] and illustrate the better agreement between the two balloon instruments.

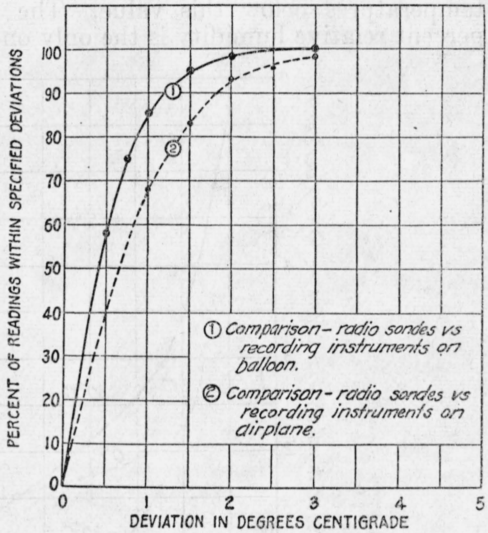

FIGURE 23.—*Summary of flight performance of temperature element.*

Using graph 1 of figure 23 as the basis for evaluating the accuracy of the radio-sonde temperature observations with the foregoing considerations in mind, it is evident that the specified accuracy of ±0.75 degree centigrade is undoubtedly attained in actual use.

4. ELECTRIC HYGROMETER

Details of the design of the electric hygrometer in its present form are given elsewhere [3]. Among the recent improvements are means for overcoming (a) the change of calibration of the device with time, (b) the presence of polarization effects, and (c) the lack of linearity of indication over the range of relative humidity measured. These improvements are described in the paper referred to; however, a few more words will be given here on the sensitivity of indication and speed of response. The accuracy of indication of the electric hygrometer will then be discussed.

(a) SENSITIVITY OF INDICATION

By using three elements (see fig. 5) coated with different lithium chloride solutions and interconnected with predetermined fading resistors, it is possible to provide for substantially constant sensitivity of indication throughout the humidity range corresponding to any desired ambient temperature. The combination in present use (see the calibration of fig. 9) was designed to provide practically constant sensitivity of indication at 0° C. The variation of sensitivity with humidity at this and other temperatures is indicated in figure 24.

It is important to note that the calibration of figure 9 is approximate for temperatures below about −15° C. Considerable difficulty is experienced in controlling and measuring relative humidity at temperatures below this value. The graph corresponding to 100-percent relative humidity is the only one which represents reasonably

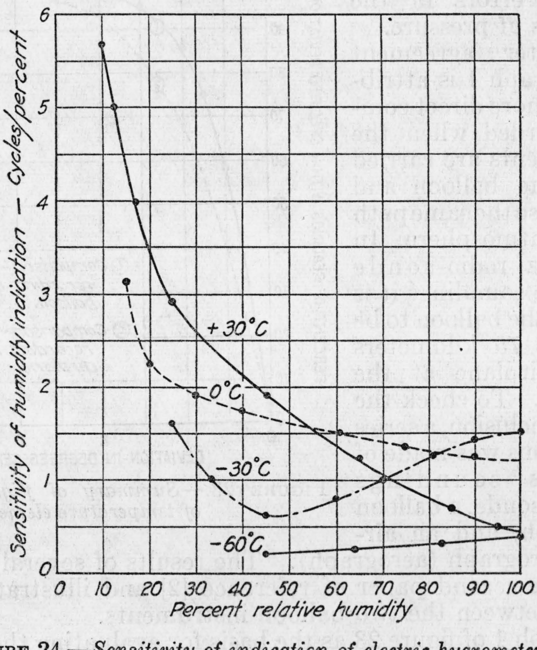

FIGURE 24.—*Sensitivity of indication of electric hygrometer.*

reliable data down to −60° C. It was obtained by placing the electric hygrometer in an ice enclosure and reducing the temperature of the whole mass by means of solid carbon dioxide. In this way it was found possible to maintain saturation within the enclosure, as witnessed by the fact that identical readings were obtained for decreasing and increasing temperatures. Further corroboration is afforded by the fact that this graph coincides with the locus of maximum recorded humidity frequencies at various low temperatures obtained in some hundreds of radio soundings. The difficulty in obtaining a reliable calibration of the electric hygrometer at low temperatures may perhaps be considered a disadvantageous aspect of the device. However, careful control in the manufacture of the device has resulted in substantially uniform characteristics, so that a calibration, once obtained, applies to all hygrometers.

(b) SPEED OF RESPONSE

The electric hygrometer has important advantages over other forms of hygrometers, particularly for radio-sonde application. In an earlier form of the radio sonde, still in use at about three-fourths of the stations of figure 1, a variable resistor controlled by the more conventional hair hygrometer is used for measuring relative humidity. Although useful observations are obtained, there are two limitations to this type. The first is that the hair hygrometer does not function effectively at temperatures below about 0° C; the second, that even at higher temperatures it does not respond sufficiently to the sharp changes in humidity encountered by a balloon ascending at the lowest practical rate (175 meters per minute). The electric hygrometer overcomes both of these defects. It is characterized by a rapid response to humidity variations at temperatures down to −60° C. Its rate of response is sufficient to permit any practical balloon ascension rate, as has been determined in actual tests at ascension rates of up to 400 meters per minute.

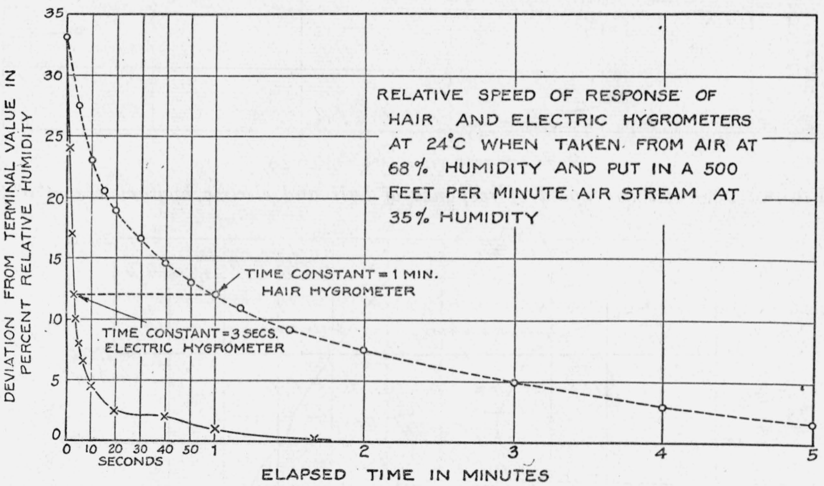

FIGURE 25.—*Relative speeds of response of hair and electric hygrometers at 24° C.*

The much greater speed of response afforded by the electric hygrometer over the hair hygrometer will be evident from figures 25 and 26. The data of figure 25, taken at room temperature, show a time-lag constant for the electric hygrometer of only 3 seconds compared with 60 seconds for the hair hygrometer. The data of figure 26, taken at 0° C, show a time-lag constant of 11 seconds for the electric hygrometer compared to 195 seconds for the hair hygrometer. Considering the zero-degree data and a balloon rate of ascent of 300 meters per minute, the indicated humidity would lag behind the ambient humidity by only 55 meters with the electric hygrometer compared with 975 meters for the hair hygrometer. Below 0° C the hair hygrometer becomes increasingly sluggish, until its time-lag constant becomes infinite at about −40° C [7]. On the other hand, excellent indicated changes in humidity have been obtained in soundings with the electric hygrometer down to −60° C, as will be seen from the following illustrations.

Figures 27 to 29, inclusive, show typical observations with the electric hygrometer which emphasize its high rate of response and indication at low temperatures. These illustrations correspond to the standard adiabatic charts used by meteorologists, in which the abscissas represent temperature and relative humidity and the ordinates

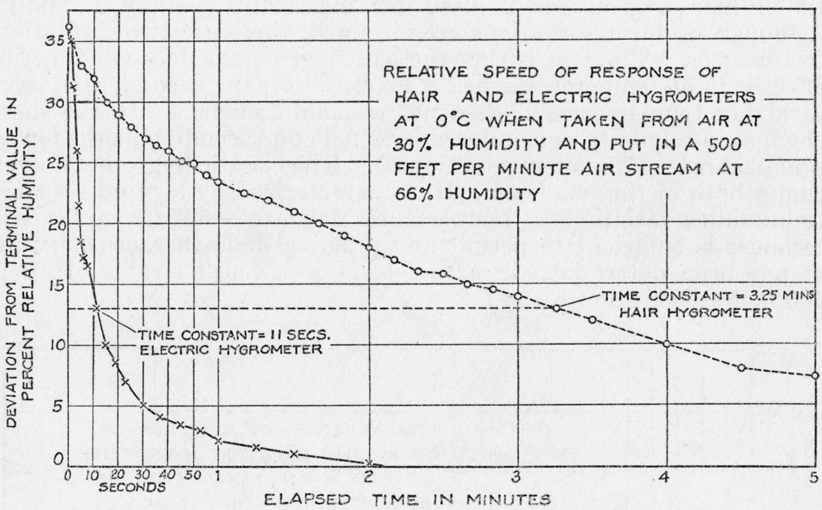

FIGURE 26.—*Relative speed of response of hair and electric hygrometers at 0° C.*

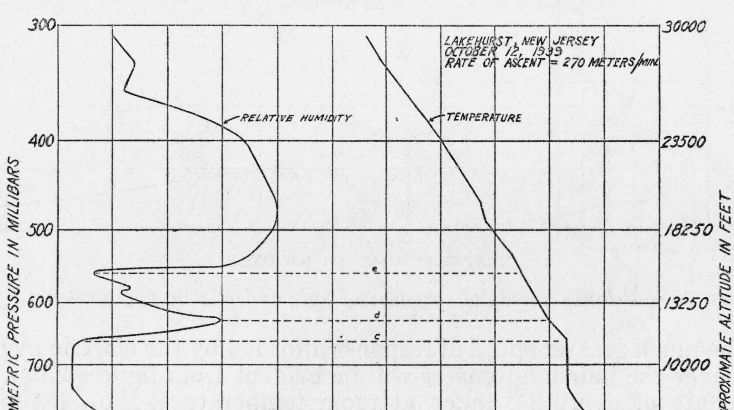

FIGURE 27.—*Results of sounding showing high speed of response of electric hygrometer and indication at low temperatures.*

represent barometric pressure. The temperature observations will serve to indicate the temperatures at which the humidity observations occurred. Discontinuities in the rate of change of temperature with pressure are generally accompanied by corresponding, often sharp, discontinuities in the rate of change of humidity with pressure; it will be observed that the electric hygrometer indicates these humidity variations quite well. Thus, in figure 27, note that humidity variations are indicated at temperatures below −20° C; in figure 28, at temperatures below −50° C; and in figure 29, at temperatures of about −60° C. Note particularly the excellent correlation between the changes in temperature-lapse rate and in the rate of change of humidity variation at points *a*, *b*, *c*, *d*, and *e* in each illustration.

Figures 30 to 31, inclusive, show comparative soundings with the electric-type and hair-type hygrometers. The greater range of humid-

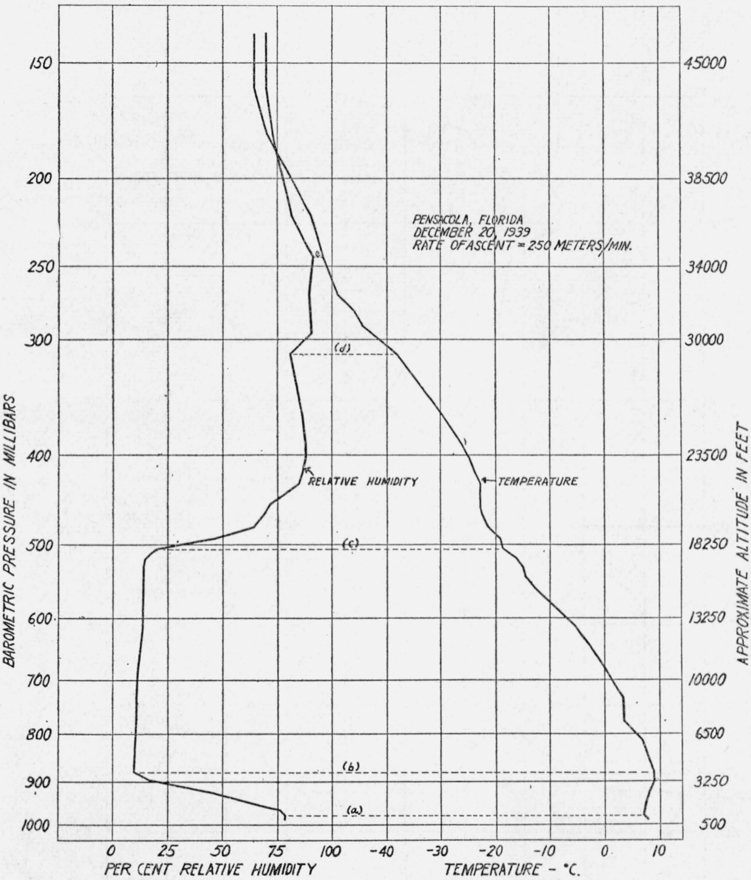

FIGURE 28.—*Results of sounding showing high speed of response of electric hygrometer and indication at low temperatures.*

ity indication with the electric hygrometer, indicating greater speed of response, will be apparent in each illustration. In the case of figure 30, separate balloons were used for carrying the hair-type and electric-hygrometer-type radio sondes. This comparative sounding is of interest in that the temperature remained above 0° C to a height of 7,500 feet; nevertheless, the hair hygrometer shows a marked lag in response. In the soundings corresponding to figure 31, both the hair-type and electric-hygrometer-type instruments were carried on the same balloon.

(c) ACCURACY OF INDICATION

The exact evaluation of the accuracy of the humidity observations with the electric hygrometer does not appear to be practicable in the present state of the art. Laboratory measurements break down for temperatures below about −15° C because of the lack of availability

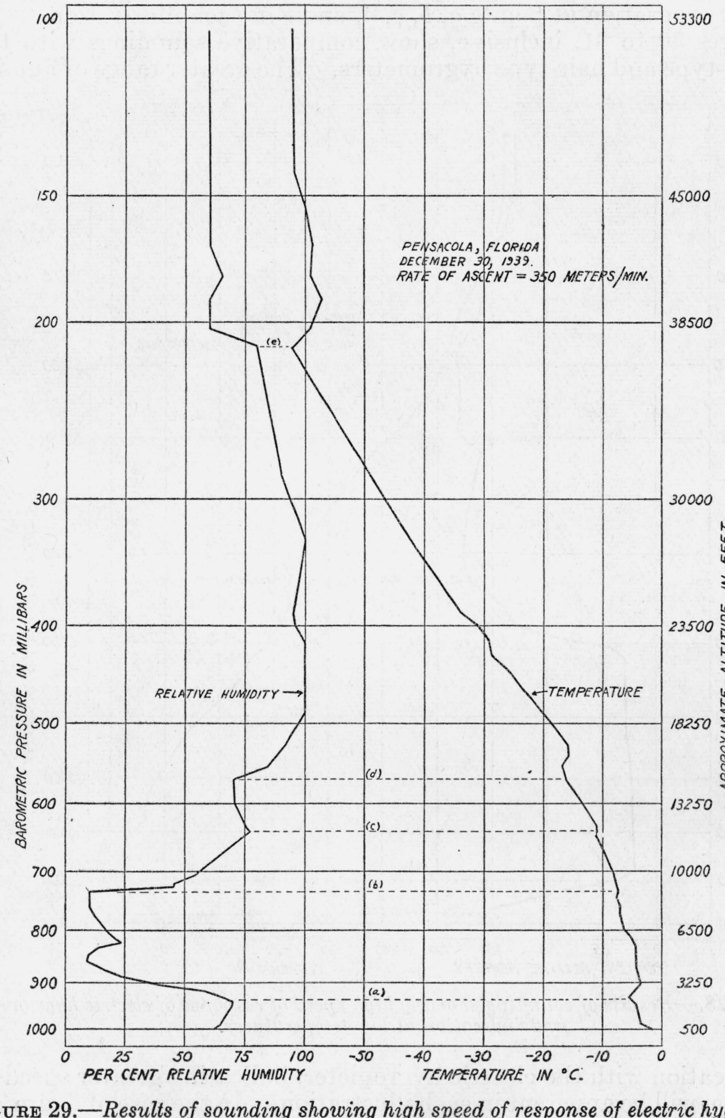

FIGURE 29.—*Results of sounding showing high speed of response of electric hygrometer and indication at low temperatures.*

of a standard comparison instrument. The determination of performance under actual flight conditions is even more difficult because of the low speed of response of the only practicable comparison instrument, namely, the hair hygrometer.

An approximate idea of performance may be had by reference to figure 32. The graphs for this illustration were prepared from data taken at the Naval Air Station, Anacostia, D. C., in the routine surface checks just prior to the soundings. Graph 1 summarizes data for approximately 350 instruments used during April 1, 1939, to March 31, 1940. Graph 2 summarizes the data for the last month of this period. The abscissas represent deviations between the surface humidity observations from the radio-sonde and humidity readings taken with a calibrated psychrometer; the ordinates represent the percentages of the total observations falling within the specified

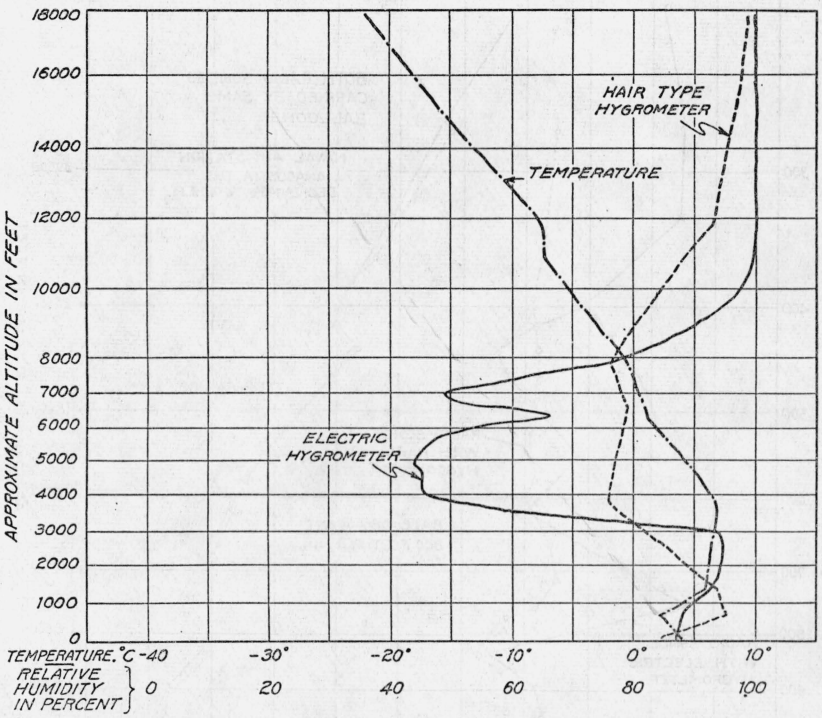

FIGURE 30.—*Comparative soundings with hair-type and electric-hygrometer-type radio sondes.*

Instruments on separate balloons.

deviation. In analyzing the graphs, it should be noted that the pyschrometer readings may be in error up to 3-percent relative humidity.

The improvement shown for the latest month arises from an improvement in the control of aging of the device, recently realized. Further improvement is expected from increased control of the manufacturing processes, now under investigation. On the basis of graph 2, the probable accuracy of the electric hygrometer at surface temperatures is seen to be about 5-percent relative humidity. This accuracy undoubtedly obtains to considerably lower temperatures.

To obtain an idea of the accuracy of indication under flight conditions, some 50 airplane soundings were made almost simultaneously with the regular radio soundings. Because of the better ventilation of the airplane instrument and its lower rate of ascent, 100 meters per minute compared with 175 meters per minute for the average radio sounding, the hair hygrometer in the airplane instrument could be expected to serve as a better comparison instrument. At the same time, the radio-sonde ascent was increased to about 250 meters per minute. Even under these conditions, only those soundings which

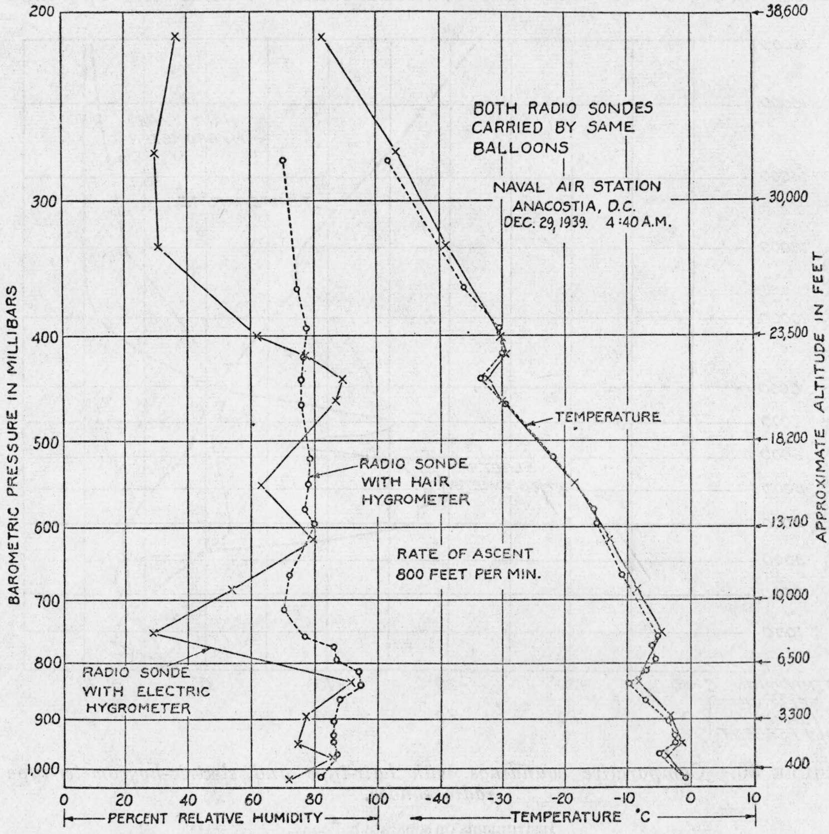

FIGURE 31.—*Comparative soundings with hair-type and electric-hygrometer-type radio sondes.*

Instruments on same balloons.

corresponded to relatively slow changes of relative humidity with height afforded useful comparison data. The data from seven such soundings are plotted in figure 33. The abscissas represent relative humidity and the ordinates barometric pressure. The solid curves correspond to the observations from the electric hygrometer and the dotted curves to the observations from the hair hygrometer. Note that whenever the humidity varies slowly enough so that the lag in the hair hygrometer is not important, the two sets of observations are in relatively good agreement.

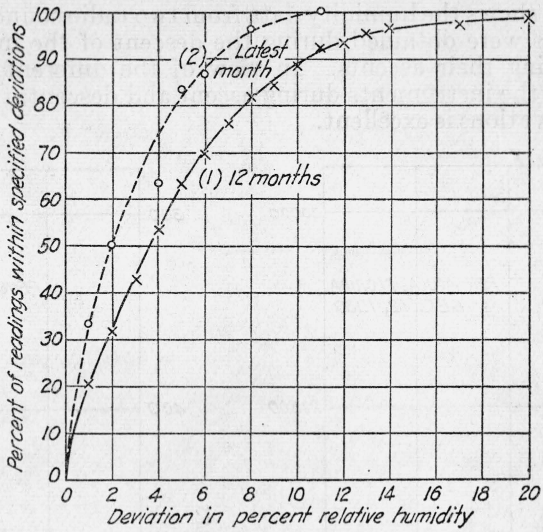

Figure 32.—*Analysis of ground checks on electric hygrometer at Naval Air Station, Anacostia, D. C.*

(1) April 1, 1939 to March 31, 1940; (2) March 1 to 31, 1940.

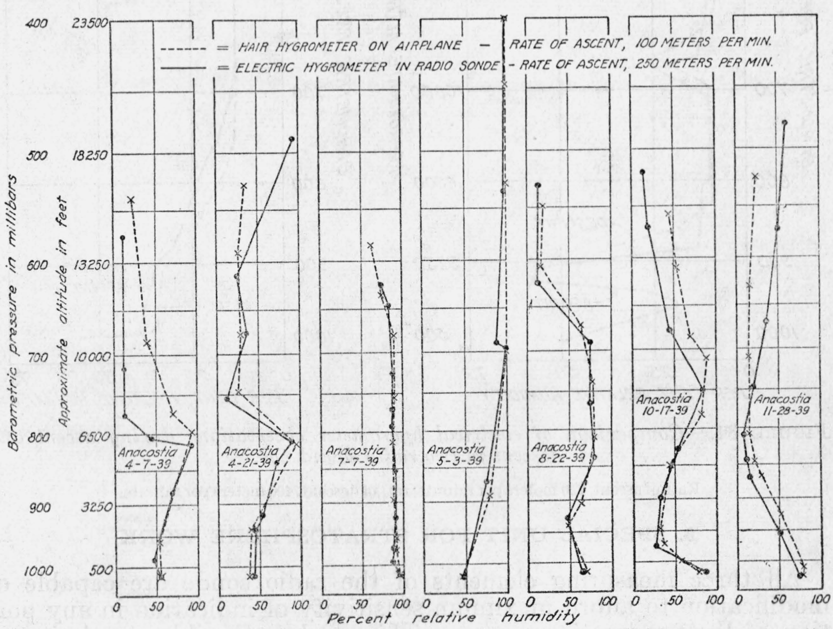

Figure 33.—*Comparative soundings with electric hygrometer in radio sonde and hair hygrometer in airplane instrument.*

Figure 34 shows the humidity data from two radio soundings in which observations were obtained during the descent of the instruments as well as during their ascents. In view of the different geographical locations of the instruments during ascent and descent, the agreement of the observations is excellent.

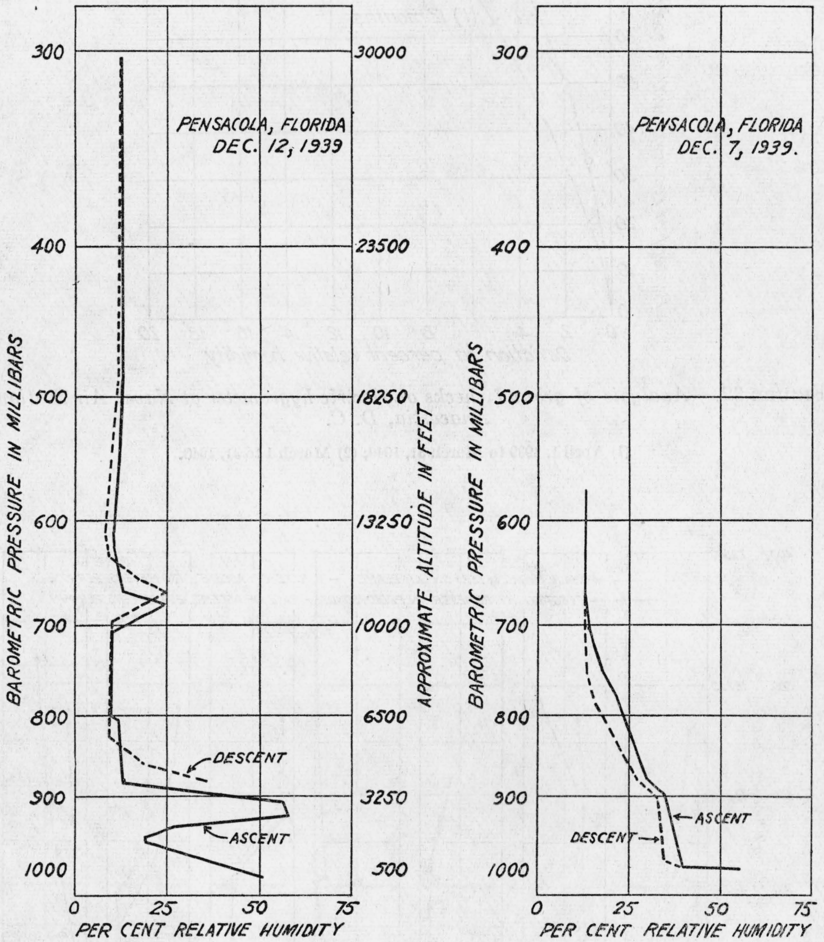

FIGURE 34.—*Comparison of electrical hygrometer observations during ascent and descent in two radio soundings.*

Rate of ascent, 250 meters per minute; rate of descent, 400 meters per minute.

5. SPECIAL UNIT FOR STRATOSPHERE WORK

All three measuring elements of the radio sonde are capable of modification to afford maximum sensitivity of indication in any portion of their respective ranges. This renders possible the design of an instrument specially adapted to stratosphere investigations.

Thus, for the pressure element, the arrangment devised by Brombacher, Goerke, and Cordero [6] may be used, giving measurements at approximately 2-millibar intervals below about 150 millibars. For the temperature element, a tube having a resistance of 5,000 ohms at +30° C may be used, giving a sensitivity of indication ranging from 2 cycles per degree at −50° C to 1 cycle per degree at −80° C. (See fig. 19.) For the humidity tube, a three-element unit employing sensitive coatings of 3, 6, and 9 percent lithium-chloride solutions, respectively, would give a sensitivity of humidity indications at −50° C equivalent to that now obtained at 0° C, namely, about 1.5 cycles per percent relative humidity.

In conclusion, acknowledgment is made to R. Chappel, L. E. Wood, and K. E. Whitney, of Julien P. Friez & Sons, Inc., for contributions to the practical design of the radio sonde and ground-station equipment, and to C. Brunetti, of Lehigh University, for determining the performance of the radio-sonde transmitter.

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WASHINGTON, June 5, 1940.