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CENTRAL RADIO PROPAGATION LABORATORY
WASHINGTON, D. C.

SURVEY OF METEOROLOGICAL INSTRUMENTS USED IN TROPOSPHERIC PROPAGATION INVESTIGATIONS

BY D. L. RANDALL AND M. SCHULKIN

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TABLE OF CONTENTS

List of Figures

List of Figures

List of Figures

List of Tables

PREFACE

The Central Radio Propagation Laboratory of the National Bureau of Standards is inaugurating a program of tropospheric propagation research. In order to evaluate the data with regard to effect of weather, it is necessary to obtain detailed meteorological information. The following report is a summary of existing low level meteorological techniques. Future addenda to this report will describe new instruments and techniques as they appear.

In preparing this survey, we are indebted to a great many people for assistance and information. It is impossible here to give credit to everyone, but some of the main contributors are:

Mr. George D. Lukes, Army Signal Corps, Evans Signal Laboratory.
Mr. L. P. Harrison, United States Weather Bureau.
Dr. Mary W. Hodge, United States Weather Bureau.
Mr. C. Harmantas, United States Weather Bureau.
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Mr. Francis W. Dunmore, National Bureau of Standards.
Dr. Harold Lyons, National Bureau of Standards.
Mr. Percival D. Lowell, National Bureau of Standards.
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Mr. Howard E. Bussey, National Bureau of Standards.

SURVEY OF METEOROLOGICAL INSTRUMENTS USED IN TROPOSPHERIC PROPAGATION INVESTIGATIONS

I. Introduction.

The purpose of this report is to survey instruments in use at the present (March, 1947) and those under development which measure the meteorological elements affecting microwave propagation in the lowest 5,000 feet of the atmosphere. Measurements of these elements are necessary to compute the refractive index and the liquid water attenuation of the air for microwave radio propagation. Future editions of this report will describe new instruments and techniques and their application to this work.

It is necessary to obtain more detailed meteorological information about this region of the atmosphere than the present radiosonde and surface observations give. The rapid ascensional rate of the Weather Bureau radiosonde balloon (600 feet/minute) together with the time lag of the instruments and the wide pressure, and therefore height, intervals at which temperature and humidity values are reported does not give a picture of the fine-grained temperature and moisture structure of the atmosphere. The liquid water content of clouds or falling rain can not be judged nor can the micrometeorological variations of wind, temperature and moisture be measured by the meteorological instruments in general use. The measurements in use at present are adequate for weather forecasting and studying the broader aspects of the weather phenomena, but for microwave propagation problems a more detailed knowledge is necessary.

Any sounding system for obtaining this information will consist of the following parts:

1. Measuring devices
2. Recording instruments
3. Lifting equipment

The greater part of this report will be devoted to measuring devices. Recording instruments and lifting equipment are aids in obtaining meteorological measurements.

Measuring Devices.

The discussion of these devices will include descriptions of instruments for measuring temperature, humidity, pressure (altitude), wind and liquid water content of air in clouds and rain.

The most widely used temperature measuring device in upper air soundings is the ceramic resistance element. It is nearly free from ageing, is sensitive and shows quick response to temper-

ature changes. The Dunmore electrolytic thermometer was extensively used, in early work, but has now been displaced by the ceramic resistor. The thermocouple, a sensitive and quick responding device, has been used experimentally, but has not been found easily adaptable to wiredsonde work. A fine wire electrical resistance thermometer perfected by Dr. Harold K. Schilling and his associates at Pennsylvania State College has been found practical for micrometeorological measurements of temperature near the ground. The sonic velocimeter, developed at Evans Signal Laboratory, is a balloon borne organ pipe apparatus for measuring temperature as a function of the velocity of sound.

The Dunmore strip hygrometer is at present most widely used for meteorological soundings. The new gold conductor type strip hygrometer, due to its nearly linear characteristic curve, greater freedom from ageing, and wider humidity range may soon be used in place of the present element. Dunmore's new gold wire cylindrical hygrometer and the Gregory humidiometer are suitable for use in tower installations, because of their more permanent nature. Spectral hygrometers are in the laboratory stage of development and so far are not satisfactory for atmospheric soundings. Dew point hygrometers are being improved. Micrometeorological measurements of moisture are possible with the radio frequency heat controlled dew point hygrometer under development at the University of Chicago Microwave measuring techniques hold the possibility of the most accurate determinations of humidity. In fact, atmospheric index of refraction may be measured directly using the "magic tee" bridge.

Altitudes for balloon soundings may be accurately computed by the hypsometric formula if pressure, temperature and humidity data are given. Heights measured by an altimeter must be corrected because its calibration is based on a "standard atmosphere". This is done by using temperature and humidity data. The height of the balloon supported wiredsonde instruments may be measured by the balloon elevation angle and the length of cord with the sag considered. This method is not accurate. Triangulation methods are accurate but require two or more observers to record positions during the flight. Also this method fails when darkness or poor visibility obscure the balloon. A wiredsonde system is now nearly completed at the National Bureau of Standards which will not fail on account of visibility conditions because a variable-inductance pressure altimeter is used to report heights.

Measurements of wind for low level soundings are important. Moisture gradients and temperature inversions, so important in low level sounding measurements, are often the result of wind turbulence or horizontal air movements. A propeller type anemometer, gives the most accurate measurement over a large range of wind velocities. Wind speeds above the ground may be determined by a free balloon sounding. Several types of radio direction finding and radar wind systems are described. So far no method has been perfected for making wind measurements with wiredsonde apparatus. Turbulence measuring devices are in the early stage of development.

The liquid water content of the air in clouds and rainfall is an important factor in the attenuation of microwaves. A surface rate of rainfall gauge is quite satisfactory for estimating liquid water content in rainfall. The newly developed General Electric cloud meter and cloud analyzer have been used for measuring liquid water content of clouds.

Indicating Meters and Recorders.

Indicating meters and recorders may be connected through cables to the instruments exposed in the lifting balloon or supporting tower, or they may be radio controlled indicators which record pressure, temperature and humidity. In either system portability is important. Pressure, temperature and humidity data in the wiredsonde system may be obtained by either visual meters or mechanical recorders. There are several types of mechanical recorders which can be used, depending upon the requirements of the work. Some of these are: Friez recorder, "Speedomax" recorder (L. & N.), Brown "Electronik" recorder and the General Electric photoelectric recorder. Self-recording meteorographs have become obsolete with the use of telemetering systems.

Lifting Equipment.

Wired balloons and kites have been used for lifting equipment in most low level sounding work. For wind speeds less than 10 miles per hour a balloon is suitable for supporting the instruments, but for speeds greater than 10 miles per hour it is necessary to use kites for lifting the measuring elements. The advantage of using a single device under any wind condition has led to the development of the kytoon*, a combination kite and balloon. The Seyfang balloon is similar in design to the kytoon but has a free lift of 7 lbs with helium, compared with the 1½ lb free lift of the kytoon.

Aircraft may be used for low level meteorological soundings. Their operation is expensive, and flights near the ground are hazardous. However, aircraft can support heavy loads and may reach a desired level. For continuous soundings close to the surface, towers and masts of ships are used. Descriptions are given of the meteorological towers at Oakhurst, New Jersey, and Rye, England.

*Kytoon is a registered trade name of the Dewey & Almy Chemical Company.

II. TEMPERATURE MEASURING DEVICES.

The earlier balloon meteorographs, airplane meteorographs, and radiosondes used bimetal strip elements to measure temperatu Later, the Dunmore electrolytic element was developed for use in radiosonde circuits. Dr. D. Norman Craig of the National Bureau of Standards improved the instrument further, but it was still fragile and expensive (39).

As a result of wartime research other developments were made in this field. The ceramic temperature element was introduced by Sanborn, and this element was found to be cheap, sturdy and equal as accurate and responsive as the Dunmore electrolytic element. The ceramic element is now generally used in sonde temperature me urements. The group under Dr. Harold K. Schilling at Pennsylvania State College introduced a new resistance wire technique for surf micrometeorological measurements, and the Evans Signal Laboratory introduced the sonic velocimeter principle for measurement of "virtual" temperature in balloon soundings. These developments w be discussed later.

A. Ceramic Resistance Element.

The ceramic resistance element is a resistor with a larg negative temperature coefficient. The temperature measuring prope ties of this element are nearly free from ageing. It is commonly made in the form of a thin rod. A typical calibration curve of resistance vs. temperature is shown in Figure 1:

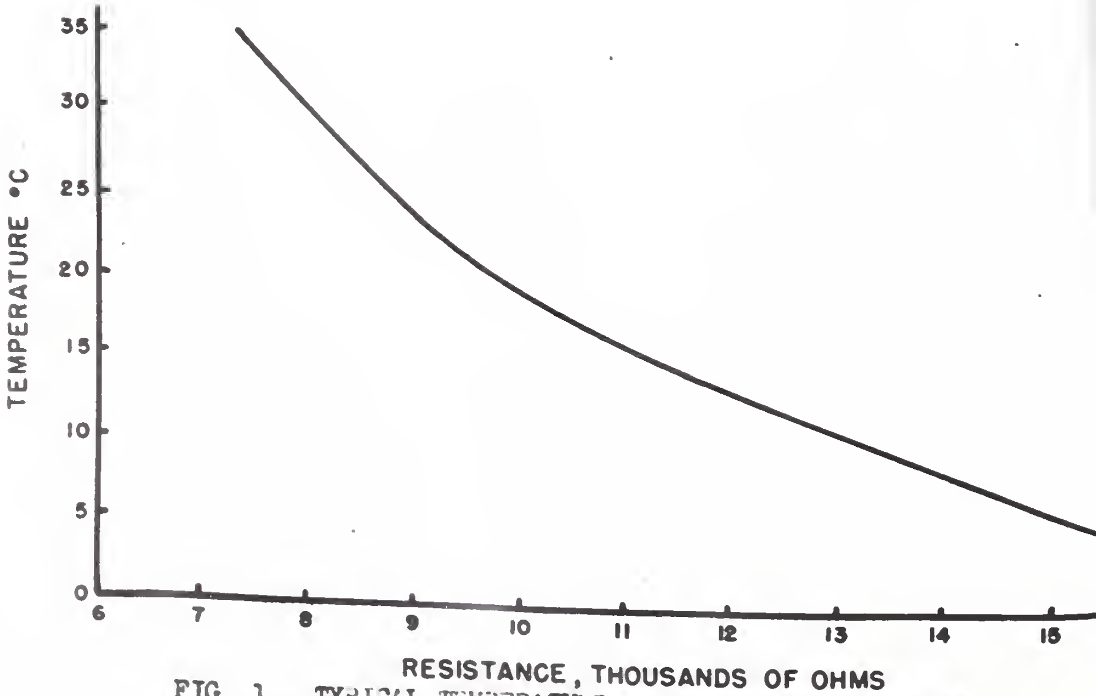


FIG. 1. TYPICAL TEMPERATURE -- RESISTANCE CURVE OF CERAMIC RESISTANCE ELEMENT (1).

The speed of response to a sudden change in temperature for any thermometer is expressed by the time lag constant (τ)[1]. The time lag constant is the time in seconds required for a thermometer to record 63% of a sudden change in temperature. The time required to record 90% of the change is obtained by multiplying the lag constant by 2.3; and for 99% by 4.6. The following table describes some of the ceramic resistors used in radiosonde and wiredsonde work.

Table 1. Time Lag Constants and Dimensions of Some of the Ceramic Resistors Now in Use (27).

Type Number	Manufacturer	Length (inches)	Diameter (inches)	Time Lag Constant for Ventilation Speed of 800 ft/min
1.	Washington Institute of Technology	1.0	.043	4.4 seconds
2.	Friez Instrument Company	1.5	.052	*
3.	Western Electric	1.0	.052	5.8
4.	Washington Institute of Technology	0.5	.025	2.4
5.	Washington Institute of Technology	0.25	.018	**

* Believed to be greater than 4.4 seconds and less than 6.0 seconds.

** Believed to be less than or equal to 1 second.

The curves of Figure 2 show how the time lag constants of resistors (#1, #3 and #4) vary with ventilation speed. Resistor type #1 is used as the standard element in the 600,000 type Weather Bureau radiosonde.

1. Strictly speaking the time lag constant (τ) should be used only for instruments to which Newton's law of cooling is applicable. However, (τ) is used loosely as a measure of time lag for hair or chemical salt element hygrometers. See Section III, Page 17.

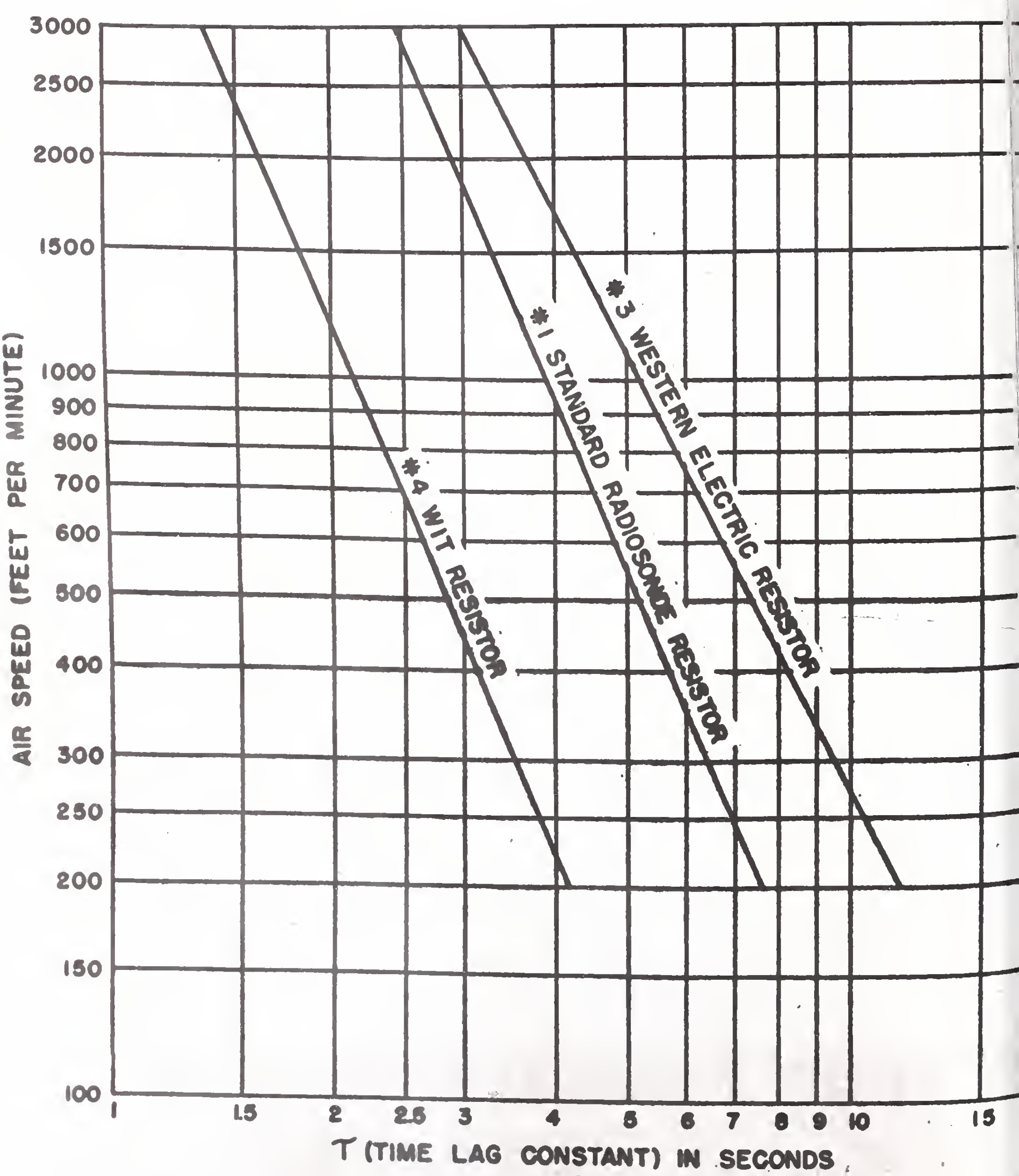


Fig. 2. AIR SPEED VS. TIME LAG CONSTANT CURVES FOR TH
TYPES OF RESISTORS. (27)

Different time lag constants can be measured depending on the element housing for the same ceramic element at the same ventilation speed. The type of air flow depends on the shape and size of the housing and influences the heat transfer between the resistor and the air. Certain types of air flow are more turbulent than others and are more effective in changing the temperature of the element. The time lag constant of a cylindrical ceramic resistor is given by the following equation:

$$\tau = \frac{SdD}{4h}$$

S = Specific heat of resistor substance.

d = Density of resistor.

D = Diameter of resistor.

h = Heat transfer coefficient between resistor and air and depends on shape and size of housing channel.

Figure 3 shows air speed-time lag curves for a W.I.T. standard (#1) type ceramic element. Curve No. 1 is for the element in a housing of the 600,000 type Weather Bureau radiosonde, and curve No. 2 is for the element in free air. The curves are different because the heat transfer coefficient of the air varies with the air channel.

When two of the ceramic resistors, measuring wet- and dry-bulb temperature are used in a special direct current vacuum tube voltmeter circuit the instrument is called an electronic psychrograph (1). By use of tables or charts it is possible to calculate the relative humidity and specific humidity or mixing ratio from wet- and dry-bulb temperature data. The electronic psychrograph has been used successfully in aircraft soundings and in low level surface soundings from masts of ships.

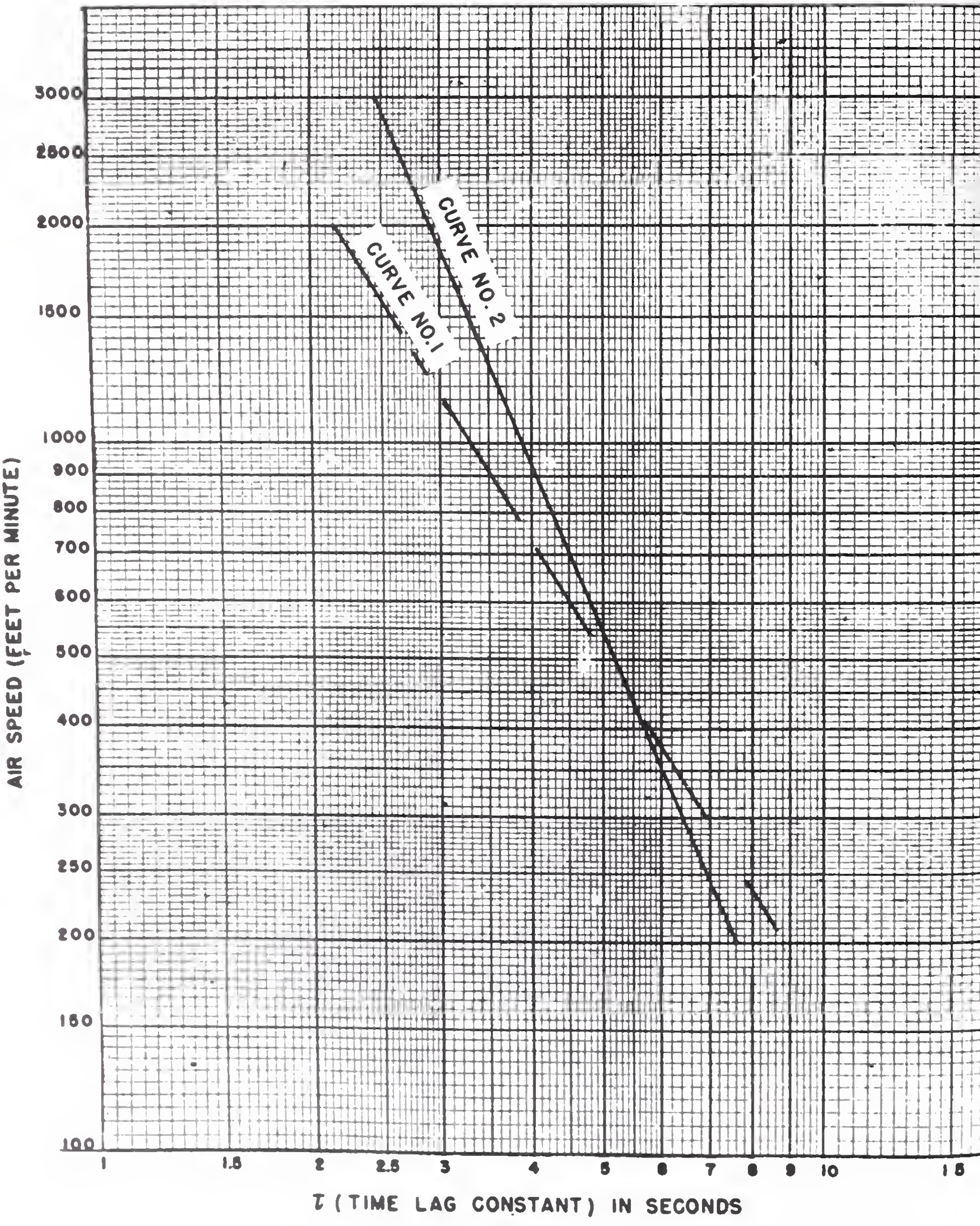


FIG. 3 AIR SPEED VS. TIME LAG CONSTANT CURVES FOR (1) W.I.T. STANDARD RESISTOR IN WEATHER BUREAU 600,000 TYPE RADIOSONDE AND (2) W.I.T. STANDARD RESISTOR IN FREE AIR. (27)

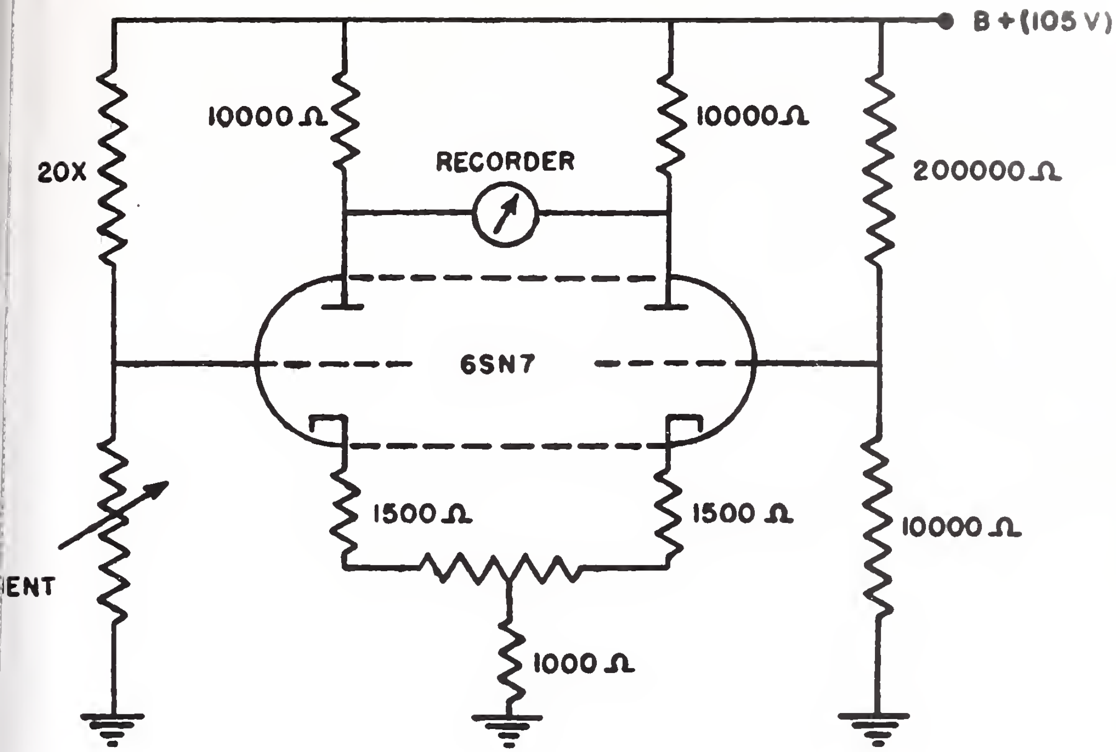


FIG. 4. SCHEMATIC CIRCUIT OF ELECTRONIC PSYCHROGRAPH (22)

"The resistance of the thermal element, X, controls the bias of one triode of the double triode, 6SN7, which acts as a vacuum tube voltmeter to compare the resistance of the thermal element with a standard resistance. A 1 milliampere recording meter is placed between the two plates. The resistances in the grid circuit are so chosen as to place 10 volts across the thermal element at the lowest temperature of each range. This voltage decreases as the temperature rises. The zero is set by means of a 100 ohm potentiometer in the cathode circuit. Calibration of the amplifier is obtained by switching a series of precision resistors in steps of 1000 ohms into the circuit in place of the thermal element. A range of roughly 25° C for full scale is used, and changes of 0.25° C can be measured. Sufficient overlapping is provided so that both wet- and dry-bulb can record on a single setting.

The stability of the instrument is such that changes of line voltage within the range of 95 to 120 volts do not affect

the meter deflections at zero or full scale deflection (when the tubes are balanced). There is little change (at most 1% of full scale deflection) when tubes are replaced." (22)

B. Resistance Wire Thermometers.

Other methods have been used for measuring air temperature with electrical circuits. British meteorologists have used several turns of nickel wire encased in a brass sleeve (2) where the exposed element is one arm of a Wheatstone bridge. The lag coefficient for this thermometer is 3½ minutes at a ventilation speed of 25 miles per hour (2200 feet per minute) and 6 minutes at 5 miles per hour (440 feet per minute). This thermometer is used in their tower installations. (See Figures 42 and 43.)

In this country the Leeds and Northrup Company have developed a copper wire resistance thermometer ("Thermohm") suitable for some atmospheric mean state temperature measurements. The thermometer element consists of a coil of copper wire enclosed in a brass sleeve. Temperature effects causing resistance variations in the lead wires connecting the measuring element and the bridge circuit are eliminated by the use of a three conductor cable. (See Figures 37, 38 and 39.) The time lag constant is 80 seconds in "agitated" air.

Instantaneous values of temperature at a point in space can be measured by especially constructed resistance wire thermometers. Dr. Harold K. Schilling (82) of Pennsylvania State College has used this type of thermometer together with a hot wire anemometer technique to study micrometeorology in connection with ultrasonic propagation. The same measurement technique may be applied to microwave radio propagation studies.

The apparatus consists of two temperature elements (see Figures 5 and 6) with their associated electrical circuits and auxiliary portable mast elements. Temperature readings of the two thermometer elements exposed on the portable mast are read on two galvanometers calibrated in degrees Centigrade. The difference in temperature between the two elements is read on a third galvanometer by switching the thermometer leads to a third Wheatstone bridge circuit. All meters are provided with linear temperature scales. The thermometer calibration scales are made for a battery e.m.f. of 1.48 volts. Current in the bridge circuit at any time is regulated by a 6 ohm rheostat.

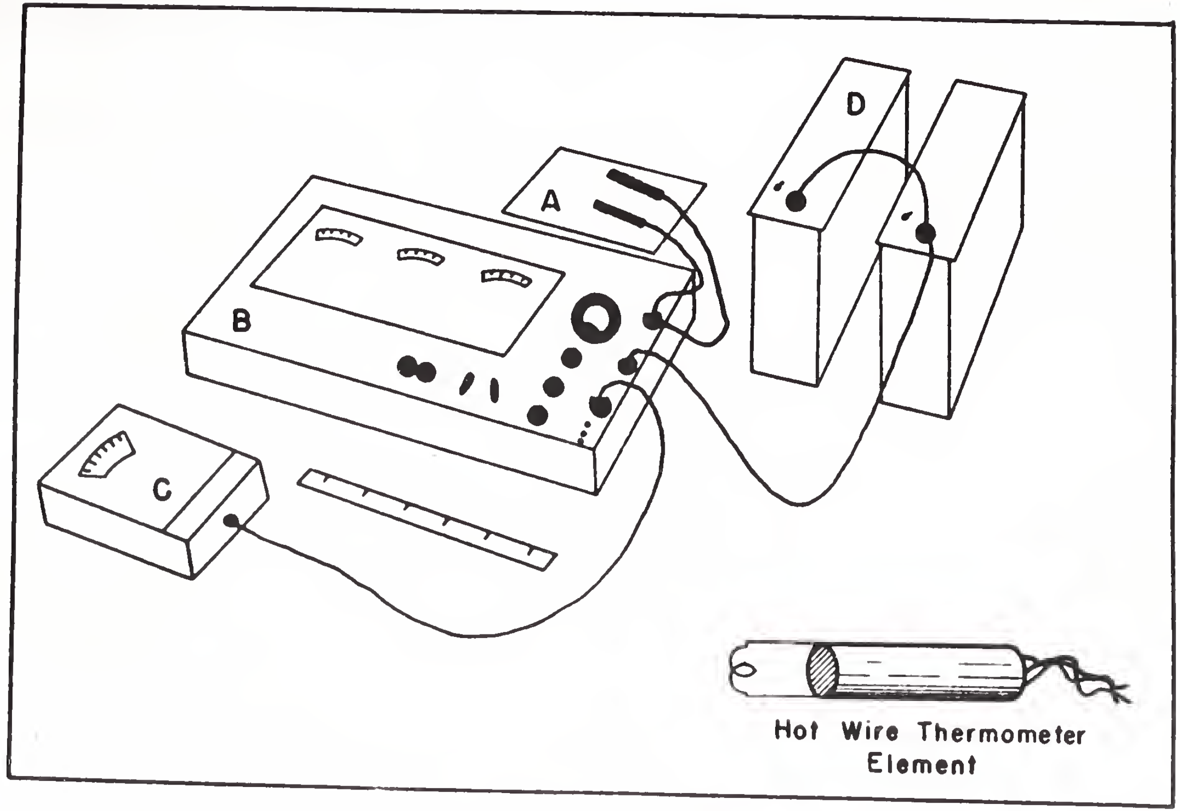
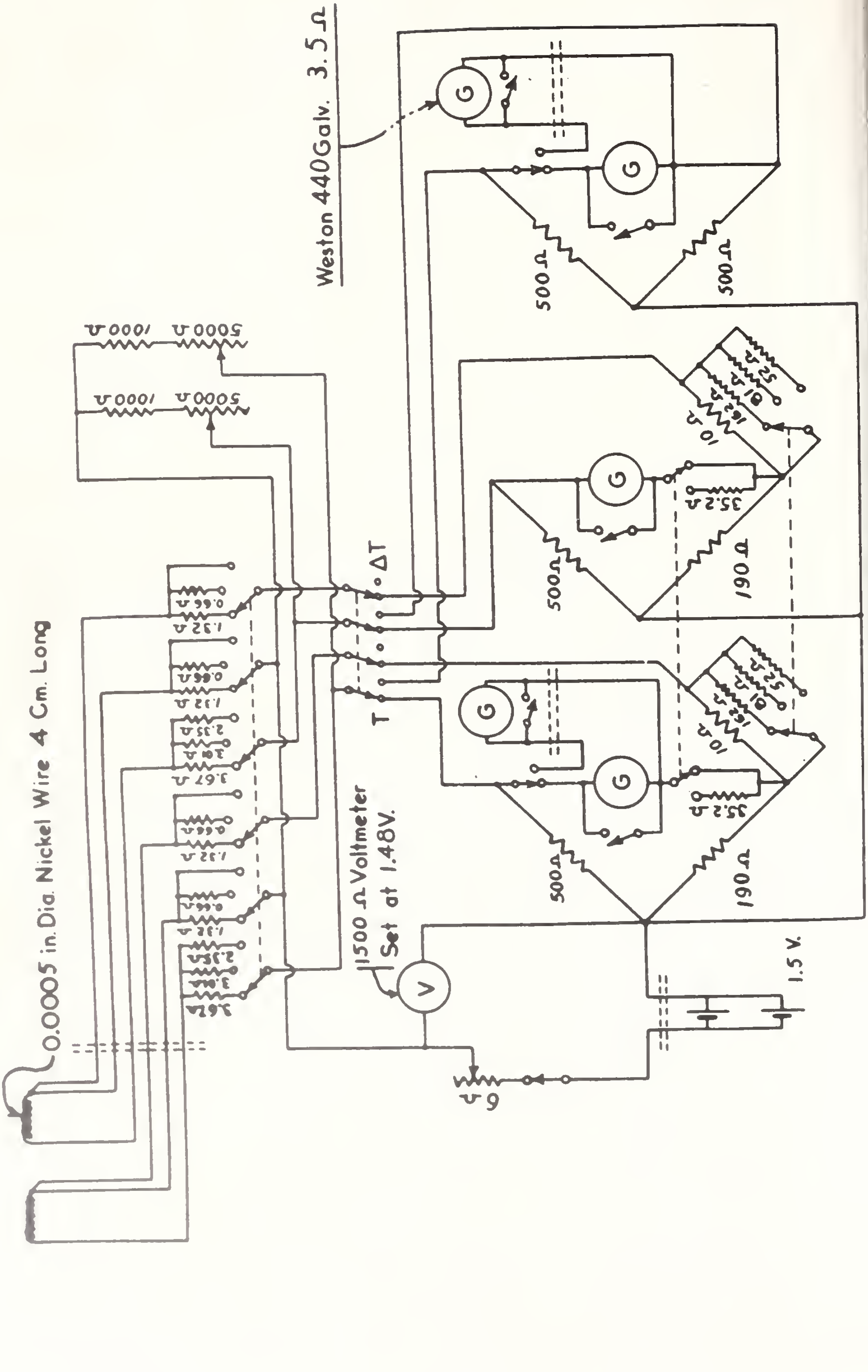


Fig. 5. Micro-Thermometer. Assembly. A, Sensitive Elements; B, Control Panel; C, Auxiliary Galvanometer; D, Batteries.


Weston 440 Galv. 3.5 Ω
0.0005 in. Dia. Nickel Wire 4 Cm. Long
1500 Ω Voltmeter
Set at 1.48V.
1.5 V.
6 Ω
5000 Ω
1000 Ω
500 Ω
190 Ω
35.2 Ω
10 Ω
162 Ω
81 Ω
52 Ω
0.66 Ω
1.32 Ω
2.35 Ω
3.04 Ω
3.67 Ω
ΔT
T

The temperature element of the Wheatstone bridge circuit thermometer is a nickel wire 0.0005 in (0.0127 mm) in diameter and about 4 cm long wound into a tiny coil of about 42 turns, approximately 9 mm long. It is suspended between two #14 highly polished rust proof bead needles. The element is designed to have a resistance of 24.1 ohms at 30° C. In operation the coil carries a current of about 2.7 ma. This current increases the temperature of the wire about 0.1° C. The leads connecting the thermometer element to the bridge circuit in the instrument panel are compensated for temperature by a variable resistor in parallel with the thermometer element. A special selector switch is provided to put in series with the lead wires, resistors which compensate for different lead lengths of #18 copper wire 20, 120 and 220 feet long. Three ranges of temperature are provided by changing the resistance of one of the fixed arms of the bridge with a selector switch. The total range of the thermometer is from -5° C to 60° C. A 35.2 ohm resistor is switched in series with the bridge circuit galvanometer for making preliminary measurements of temperature, but when more accurate measurements are desired the galvanometer alone is used to indicate temperature. The accuracy of the thermometer is then ± 0.1° C. It responds to temperature fluctuations of about 10° C at the rate of 4 per second.

C. Thermocouples.

Thermocouples may also be used in tower installations or balloons for measuring temperatures (4). In general, a thermocouple has a very small time lag and measures temperatures accurately. The response of a thermocouple is of the order of 40 microvolts per degree Centigrade. The temperatures may be read on either indicating or recording meters. Thermocouples can be made very small and hence, they are not sensitive to radiation and may be used without artificial ventilation. They have not generally been used in radiosonde or wiredsonde measurements because they are not readily adapted to radio circuits. Furthermore, one junction of the couple must be maintained at a fixed temperature and the material for providing this reference temperature which may be water-ice or dry ice (CO_2 solid) - alcohol bath adds additional weight to the equipment.

D. Sonic Velocimeter.

A novel method of measuring temperature has resulted from the development of the sonic velocimeter (38). This lightweight apparatus measures the velocity of sound, and indirectly "virtual" temperature by using the open organ pipe principle. (See Figure 7.)

Sustained oscillations are generated in the pipe by a telephone transmitter and receiver unit known as a "howler". The

telephone transmitter and receiver are mounted opposite each o in the walls of the tube and at mid-tube length. A sound wave passing through the air column of the tube is received by the ephone transmitter, amplified, and reemitted by the receiver i the air column. The vibration is thus regenerated in the tube the sustained oscillation is heard as a "howl". The density o air column in the tube controls the frequency of this sustaine "howl", since the length of the tube is fixed. The "howler" f is used to modulate a small balloon radio transmitter for uppe sounding work. An electronic frequency meter on the ground me the frequency of oscillation of the "howler". Hence, the velo of sound can be computed for any column of air passing through tube.

When the velocity of sound for a parcel of air is kn the "virtual temperature" may also be determined by the follow formula:

$$V = f\lambda = f2\ell = \sqrt{\gamma_m \frac{R'}{m_d} T'}$$

V = Velocity of sound
f = Frequency of oscillations in the open pipe
λ = Wavelength of sound wave
ℓ = Length of open tube
γ_m = Ratio of specific heat of moist air at constant pressure to specific heat of moist air at const volume
R' = Universal gas constant
m_d = Molecular weight of dry air
T' = Absolute virtual temperature

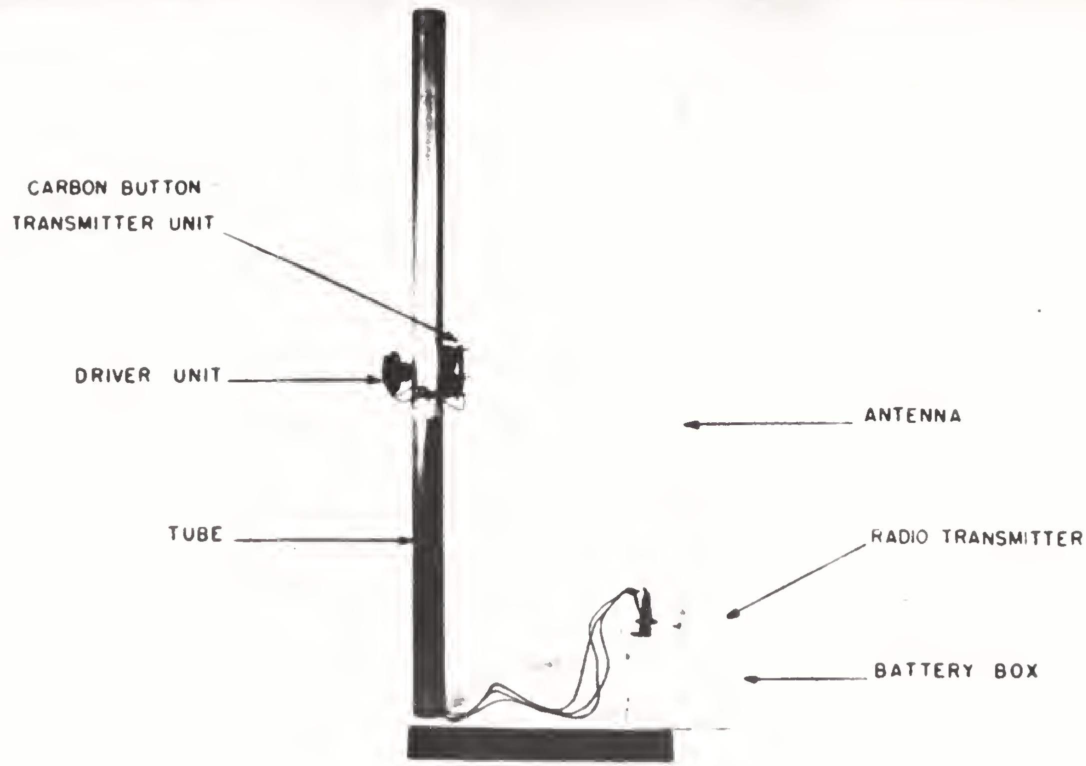
The absolute virtual temperature is related to the absolute te perature by the expression:

$$T' = T\ (1 + 0.6\ q)$$

T = Absolute temperature

q = Specific humidity in grams of water vapor per k of air.

The maximum specific humidity values experienced at the surfac do not usually cause the virtual temperature to be more than 2 above the actual temperature. At temperatures below freezing difference between virtual and actual temperature is negligib the instrument can be used to measure temperature without cor



SUSTAINED OSCILLATION TYPE VELOCIMETER

Fig. 7

DATE 10-10-44 SIGNAL CORPS GROUND SIGNAL AGENCY NO. SCGSA 12278

If independent temperature measurements are made in connection with the flight the velocimeter equipment can be used to compute specific humidity for temperatures above freezing.

Over the range 222 to 351° A it is observed experimentally that the frequency-absolute virtual temperature relationship is nearly linear. Frequency measurements can be made close enough to give an accuracy of 1/100 degree absolute. The time lag of the instrument is negligible. However, there are errors and defects inherent in the instrument. The tube length varies slightly in length with temperature change, hysteresis effects have been noticed in the "howler" diaphragms, and ice coatings form on the external "howler" mechanism causing failure of the instrument. Holes bored in the walls of the bakelite tube for mounting the "howler" tend to alter the acoustical properties of the tube.

The transient velocimeter (see Figure 8), a modification of the instrument just discussed, was developed in an effort to avoid some of the errors and defects existing in the sustained oscillation type due to the "howler". The open tube of this velocimeter is 4 feet long and 2½ inches in diameter. It has a natural frequency of 135 cps at normal room temperature. The temperature coefficient of expansion of the bakelite material is negligible. No holes of any kind are drilled in the tube, a pulse generator mechanism is attached to the lower end of the tube and it sends a shock wave into the tube at frequent intervals. The shock wave may be resolved into frequency components, one of which is the fundamental frequency of the tube, corresponding to the velocity of sound at the prevailing virtual temperature, and the fixed tube length. The pipe then resonates to this frequency, the "Q" of the tube being such that oscillations of appreciable amplitude persist for 0.7 second. A carbon button microphone, mounted inside at the center of the tube, picks up the resonant pressure wave and causes a corresponding modulation on the carrier frequency of the balloon transmitter.

At the ground a radio receiver detects the frequency modulated radio signal. An attached audio frequency meter at the output of the receiver then gives a frequency reading which is a measure of the virtual temperature. The conversion from frequency to virtual temperature is made by means of a calibration chart.

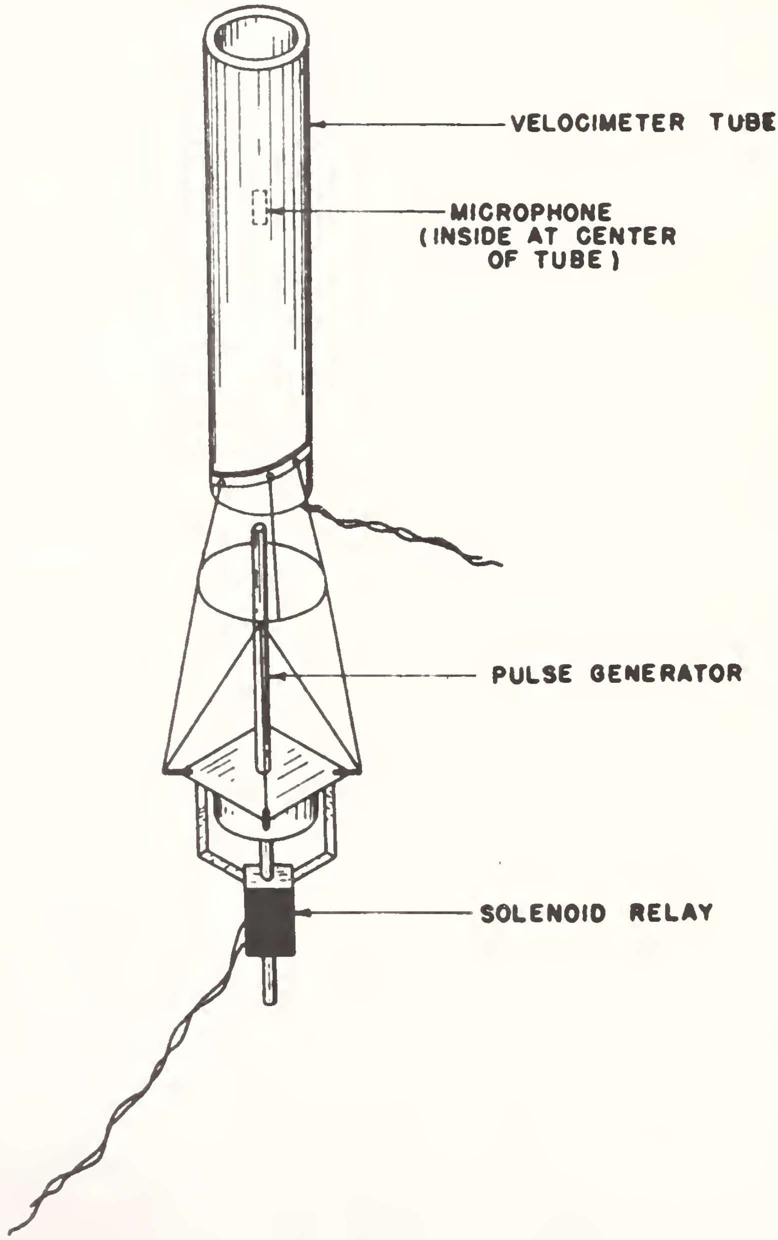


Fig. 8. TRANSIENT TYPE VELOCIMETER

III. HUMIDITY MEASURING DEVICES.

Improvements have been made in humidity measuring devices. The earlier equipment used hair hygrometers, but now hygroscopic salt elements are widely used. These elements are subject to some limitations especially at low temperature and low humidity. The automatically controlled and recording dew point hygrometer has become more important recently, but is still under development. The psychrograph, described in the previous section, is used for airplane sounding humidity measurements.

A. The Dunmore Electrolytic Hygrometers measure the effect of relative humidity on the resistance of a hygroscopic element. There are two types: the cylindrical hygrometer and the strip hygrometer.

The cylindrical hygrometer consists of a film of polyvinyl alcohol containing lithium chloride, on the surface of a thin cylinder on which there is a bifilar winding. When used in the radiosonde an accuracy of ±2.5 relative humidity units[1], measured for temperature above freezing, but when a source of alternating current is available the instrument may attain an accuracy of ±1 relative humidity unit.

When the moisture environment is suddenly changed, the hygrometer requires an interval of time to show the new relative humidity value. Analogous to temperature time lag terminology sixty-three per cent of this period, measured in seconds, is usually defined as the time lag constant. This constant depends on both the ventilation and the temperature. Tests made on the Dunmore cylindrical hygrometer show that at an air speed of 2.5 meters/second (492 feet/minute) the lag constant is 3 seconds at 24° C, and 11 seconds at 0° C (1). The instrument will record changes in relative humidity at temperatures as low as -60° C.

The electrical resistance properties of this early type hygrometer changed with age and it was necessary to replace the elements frequently to secure readings of unchanging accuracy.

A very recent model (28), which is nearly free from ageing, uses a bifilar winding of gold wire. It is claimed that it will not vary more than ±1.5 relative humidity units in a year. By using several of these, a relative humidity range of from 7% to 100% can be measured at room temperature. The time lag characteristic of the gold wire cylindrical hygrometer is

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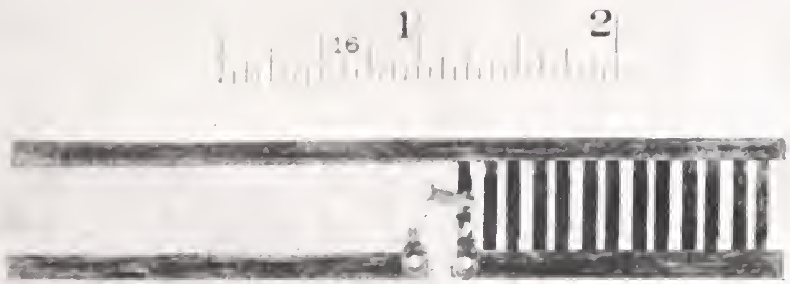
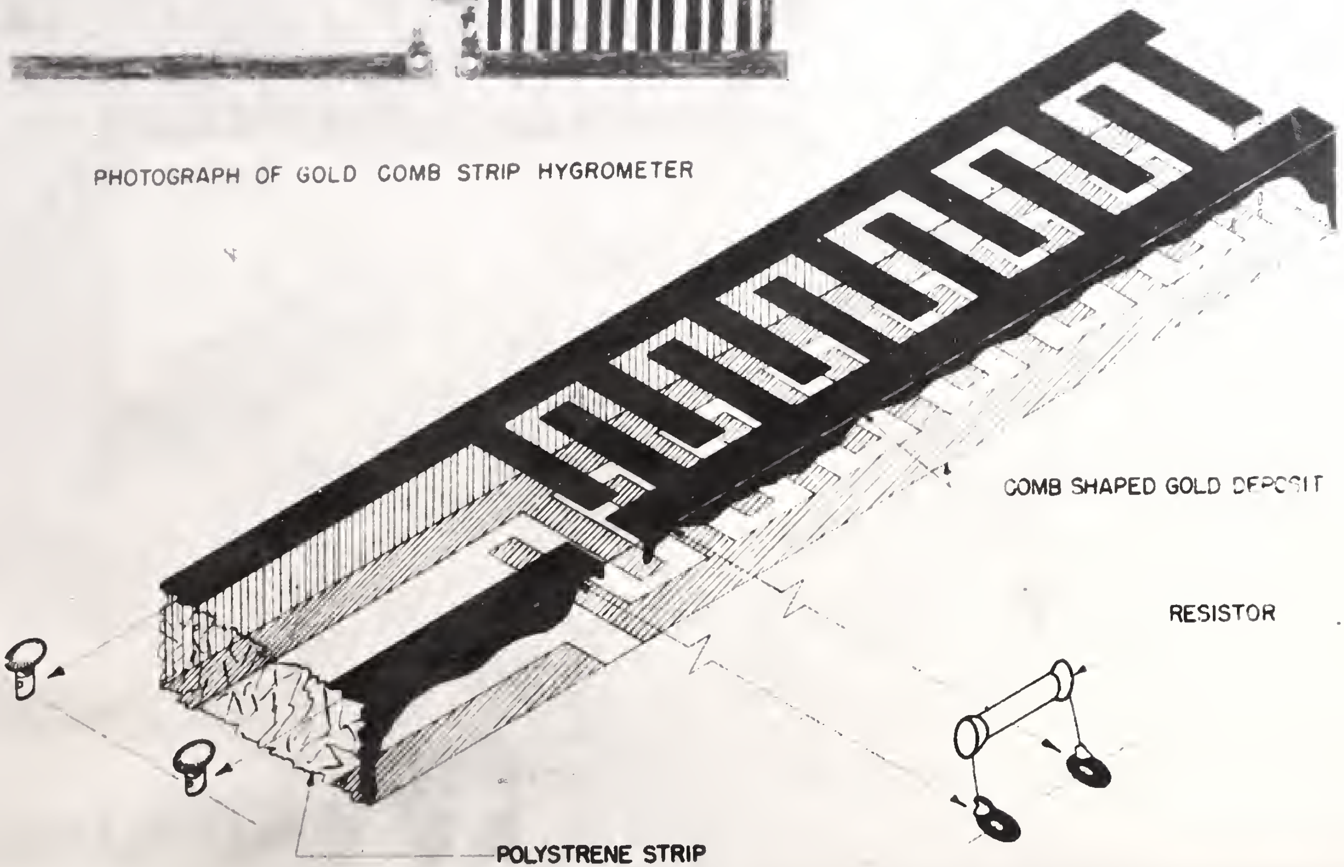
1. The term "relative humidity unit" is used to indicate per cent relative humidity, confusion between the terms per cent error and per cent relative humidity is thus avoided.



PHOTOGRAPH OF GOLD COMB STRIP HYGROMETER



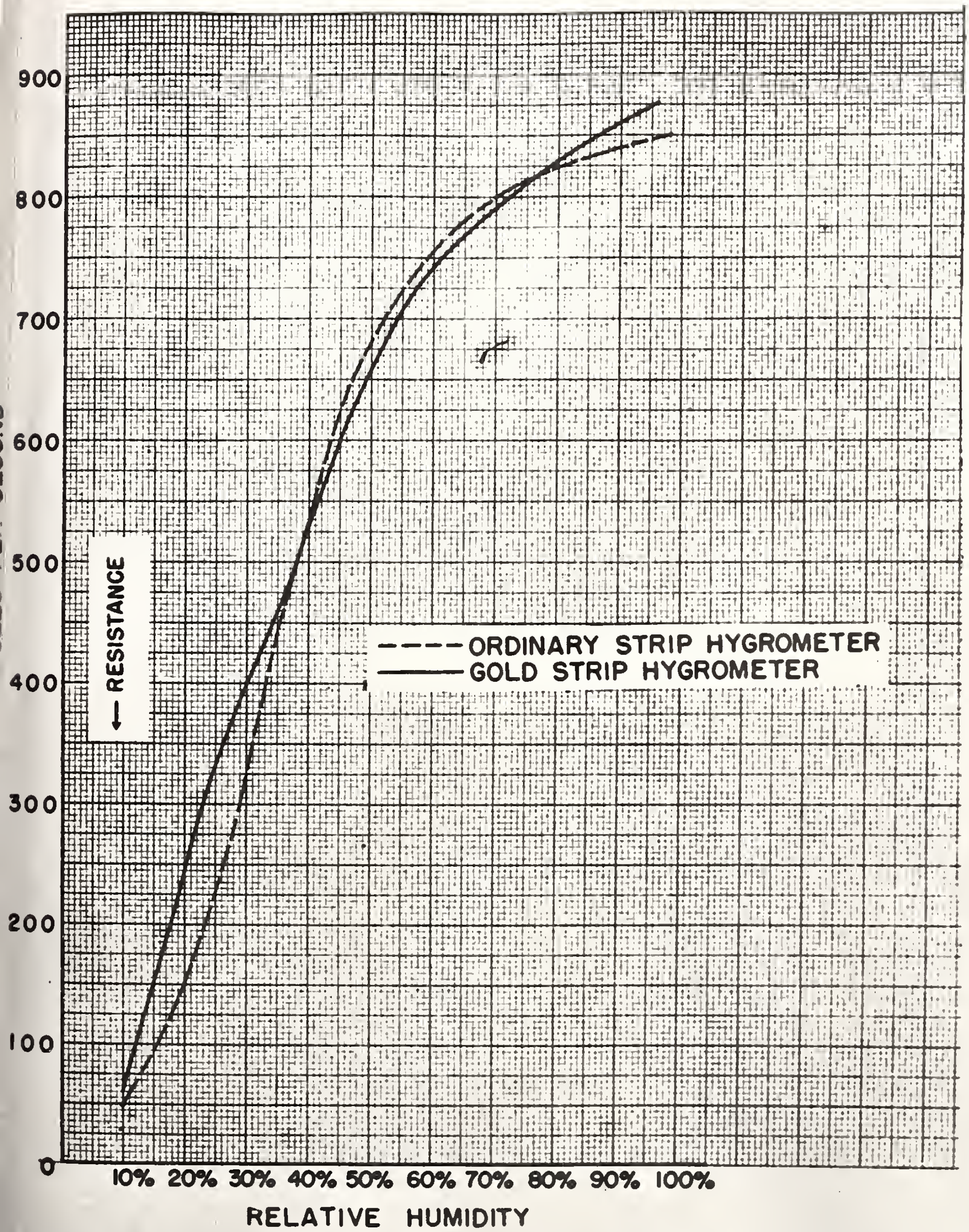


Fig. 10. THE CURVES SHOW THE SENSITIVITIES OF THE ORDINARY STRIP HYGROMETER AND THE NEW GOLD CONDUCTOR STRIP HYGROMETER.

about the same as the older type element. Although this new type element was not designed for meteorological purposes, it is suitable for use in tower installations or airplane soundings.

A limitation of the cylindrical type hygrometer for some applications is that a single element is sensitive to changes in relative humidity over a narrow range. Several of these elements, each covering a different humidity range, are used to secure coverage for the entire relative humidity scale. This arrangement becomes more cumbersome. However, the narrow range of the element is a distinct advantage, when it is used as a sensing device for precise humidity control in a room.

To make an element of greater sensitivity to moisture variations, a <u>strip hygrometer</u> has been developed. This consists of two spaced conductors supported along the edges of a thin and narrow piece of non-hygroscopic dielectric material. The strip and conductors are covered with a film of polyvinyl alcohol containing lithium chloride. After calibration, the strip must be stored in a sealed tube to preserve its electrical resistance qualities.

Tests made by the Weather Bureau on the strip hygrometer at room temperature indicate a high accuracy. The unpublished test data show that the greatest errors observed were of the order of ±2 relative humidity units. These errors occurred in the upper range of the humidity scale. This accuracy is observed only during the firs 30 minutes of exposure when direct current is used. For wiredsonde work, where alternating current is used, the strip has a longer life, but it is still necessary to use a new strip for each sounding because the resistance qualities of the hygroscopic material change with age.

Dunmore has developed a type of <u>gold-comb strip hygrometer</u> (Figure 9) which does not age rapidly and can be used repeatedly. The new gold element has not yet come into use for wiredsonde work. A gold filament is evaporated on to a thin rectangular polystrene stri so that an interlocking comb-shaped deposit of gold is formed along the two edges on one end of the strip. A straight gold band is deposited along each edge, on the other end of the strip. The gold band is made continuous on one side, but on the other side there is a gap between the comb-shaped conductor and the straight conductor. The entire strip is then dipped in the polyvinyl alcohol-lithium chloride solution. A resistor of about 40,000 ohms is placed across the gap.

At low humidities the resistance of the strip (Figure 10) is high and the characteristic curve of the strip (relative humidity vs. resistance) is nearly linear. As the humidity increases, the <u>ordinary-hygrometer-strip</u> characteristic curve flattens out. With the new arran ment, the resistor effectively blocks out the influence of the comb-sha conductor portion of the strip causing the resistance-humidity variatio to take place across the straight conductors with the result that the curve is more linear in all portions of the humidity scale. This parti eliminates the main inaccuracy of the old type strip in the high humidity range. This element measures as low as 10% relative humidity a room temperature which gives a range of 5 to 8 relative humidity units more than the ordinary strip. It is estimated that there may b a ± 5% shift in the characteristic curve in 2 months. The time lag constants of this hygrometer are similar to those of the original strip hygrometer. The gold conductor strip hygrometer shows a momentary polarization when used with direct current, but this effect is not cumulative. To avoid this difficulty, the Friez Instrument Company has adapted this design to radiosonde use. In this design tin is used instead of gold, although the tin conductors have a cumulative polarization which results in a drift of the humidity values. The tin strip is suitable for radiosonde use for a single sounding.

B. Gregory Humidiometer.

The Gregory humidiometer (2) also determines relative humidity hygroscopically as a function of electrolytic resistance. This instrument uses a lithium chloride or calcium chloride solution soaked in a clean cotton cloth. The resistance varies from 10,000 ohms at 30% relative humidity to as little as 50 ohms at 100%. It undergoes pronounced ageing during the first several days and then remains sensibly constant for a number of weeks. The impregnated fabric strips, made of fine woven Egyptian cotton, are stretched around a framework of 24 silver rods mounted in a circular holder. The rods are wired alternately in parallel, so that in effect twelve separate lengths of the fabric are electrically connected in parallel. The fabric is kept under tension by stainless steel springs to insure good contact with the silver rods.

The resistance of this element is a function of temperature as well as humidity. A correction is applied consequently to the recorded value of the relative humidity. A change of 10° C in temperature is roughly equivalent to a change of 5 relative humidity units at 30% relative humidity or a change of 3 relative humidity units at 90% relative humidity. For ventilation speed of 5 miles per hour and over a humidity range of 85% to 55% the lag coefficient of a Gregory element was found to be 90 seconds. This humidiometer is used in the British tower installations at Rye.

C. Dew Point Hygrometers.

For any given pressure, the temperature at which water vapor saturation just occurs is defined as the dew point. The dew point hygrometer is an instrument for measuring this temperature. In general, it consists of a polished metallic surface which is cooled until dew or frost begins to form. A heating-cooling process keeps the surface at the dew point temperature. Several systems have been devised for measuring this temperature.

The British have perfected a special frost-dew point

hygrometer (6) for use in an airplane which enables the humidity to be measured at stratosphere temperatures. This instrument ha been used for temperatures below freezing but its application to other temperatures is obvious. It consists of a copper thimble mounted above a Dewar flask containing gasoline cooled by solid carbon dioxide. Cooling is controlled by circulating gasoline around the lower edge of the thimble; whereas the heating contro is a small electric heating coil. The temperature of the surfac is measured by a thermocouple element. The upper surface of the thimble is viewed through a microscope until frost is observed and then the rate of cooling is adjusted so that individual crystals are seen neither to grow nor to evaporate.

In a modified form of this instrument (6), the indication of frost is done by a photoelectric cell. A beam of light is directed obliquely on to the face of the thimble and the light reflected diffusely by the frost deposit is focused on to a photo electric cell. A constant reading of the microammeter indicates a steady condition of the frost deposit.

The University of Chicago has perfected another modification of the dew point hygrometer (30) (see Figures 12 and 13). Light from a constant intensity source is reflected from the surface of a highly polished mirror (0.25" in diameter) on to a phot cell which controls the power output of a radio frequency oscilla tor used to heat the mirror surface by induction. The mirror is cooled by conduction by mounting on a copper rod, one end of whic is immersed in an alcohol-dry ice bath (-72° C). The heating-cooling process is adjusted so that the mirror is always kept at the dew point. Any detectable change in intensity of the reflect beam due to the clouding or clearing of the mirror surface, chang the photocell current, which in turn varies the plate current flo ing in the radio frequency oscillator. The mirror temperature is controlled by the cooling effect of the alcohol-dry ice bath and the heating effect of the induced radio frequency currents. As t mirror surface tends to become clouded by condensation of water vapor, increased current flowing in the plate circuit of the osci lator heats the mirror surface, evaporating the water. As the su face tends to become clear, the decrease in plate current flowing in the oscillator allows the dry ice-alcohol bath to cool the mir by conduction, and the control cycle is repeated. The resultant temperature of the mirror surface, the dew point temperature, is measured by a very fine wire thermocouple imbedded in the mirror surface and is traced by a quick response recorder. Temperature gradients in the reflecting surface are not greater than 0.1° C. Spurious heating effects due to infrared wavelengths in the incide light beam are excluded from the reflecting surface by use of an infrared filter.

Due to the small size and light weight of the mirror surface and the quick response of the heating and cooling system, this hygrometer can measure very minute fluctuations of dew point. At room temperature, a 6° C increase in dew point due to a puff of breath on the mirror surface can be recorded in 3 seconds. The total time lag varies with the magnitude of the change. The curve below is drawn for a series of total time lag measurements from data given in "A Method for the Continuous Measurement of Dew Point Temperatures," (30) by D. N. Frissman. The unit, total time lag, used here means the entire time required for the instrument to adjust itself to a change in moisture environment, and should not be confused with the unit τ previously used as a measure of time lag.

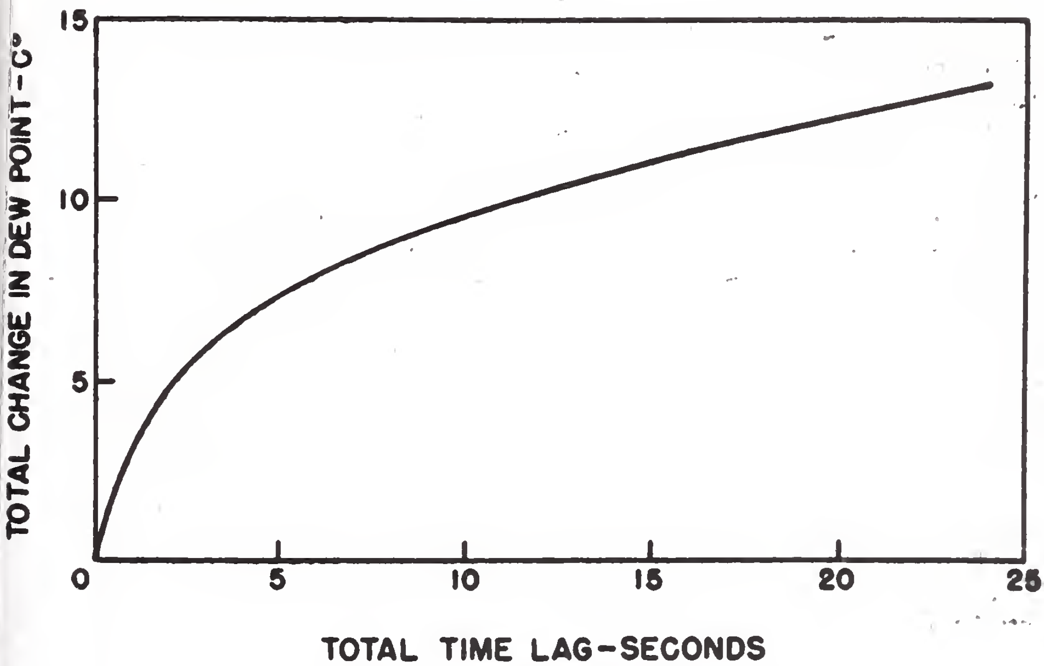


Figure 11. Total time lag curve for dew point hygrometer developed at the University of Chicago.

The photocell is much more sensitive than the eye to small changes of light intensity, hence it detects a "dew point" at a higher temperature than that seen on the mirror surface by the eye. A dew point about 3° C higher than that observed visually may be recorded by the photocell. Below -30° C this difference becomes greater. However, the dew point is defined with respect to the eye's ability to see condensation, hence it is necessary to adjust the rate of heating of the mirror surface due to induced currents so that the photoelectric dew point agrees with the dew point seen by the eye.

The photoelectric dew point hygrometer is very precise. A series of 52 observations were made in conjunction with visual dew point apparatus as a standard at the University of Chicago. Over the range of -0.1° C to -27.9° C the <u>difference in the average dew point</u> measured by the visual apparatus and the photocell apparatus was 0.1° C. The <u>average difference</u> in the dew point readings of the individual hygrometers was 0.4° C. The maximum difference for any one observation was 1.4° C. A second set of 14 tests was conducted over dew point temperatures ranging from -10° C to -35.5° C with results nearly similar to the first test. Below -36° C no satisfactory visual dew point readings were obtained for checking purposes. The instrument has been operated with ambient air temperatures from 30° C to -45° C and has measured dew points from 30° C to -52° C. At temperatures below freezing a deposit of liquid water may exist on the reflecting surface. The sudden solidification of liquid water to ice is marked by a sharp discontinuity in the trace. Thus it is possible to tell from the trace whether the dew point temperature is measured over ice or over liquid water.

The instrument is 18" high, 17" wide and 14" deep, and weighs 57 pounds. It operates from 60 cycle alternating current over a voltage range of 100-130 rms volts. It has been modified to operate from the power supply available in an airplane.

The principle of measuring the dew point by observing condensation on a temperature-controlled polished surface has been extended to the automatic electrical recording of relative humidity instead of dew point (29).

There are several sources of discrepancy between the photocell type and the visual type dew point hygrometers. Although some of these have been pointed out in the discussion of the particular instrument, they are mentioned again for clearness:

1. The photocell is more sensitive than the eye to moisture condensation on a given mirror surface and can detect a moisture deposit before the eye sees it. This is explained by the difference in sensitivity of the eye and the photocell to small changes of intensity of reflected light. The

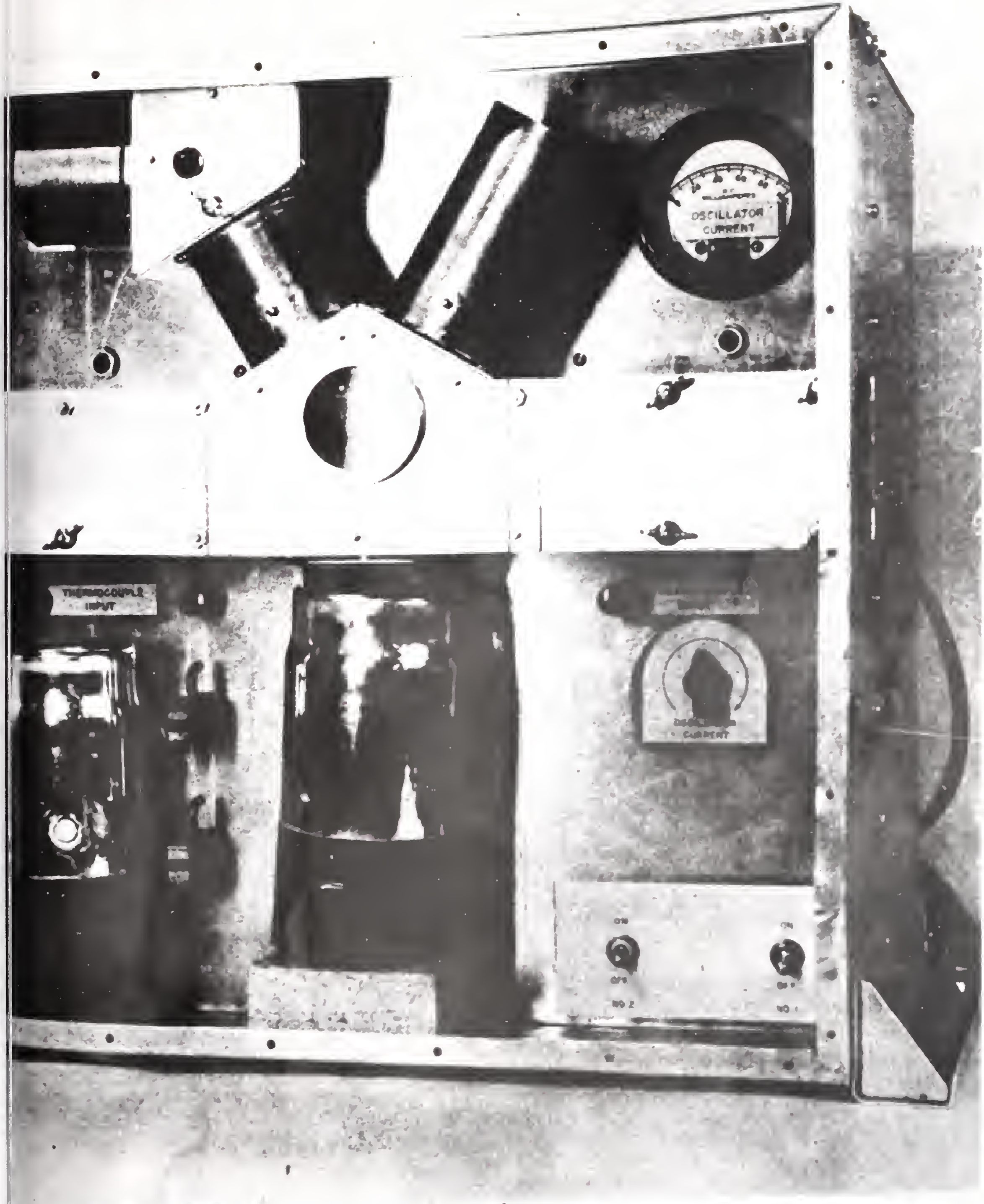
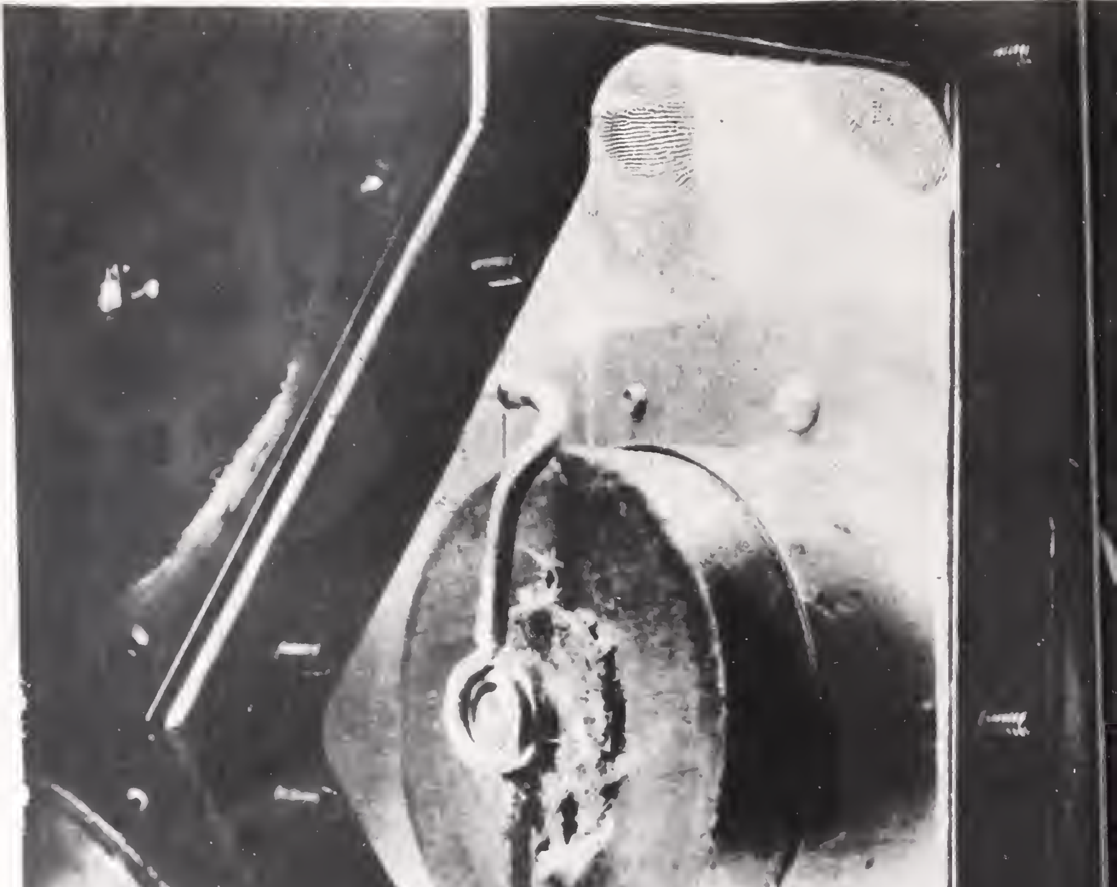


Fig. 12. DEW POINT HYGROMETER DEVELOPED AT THE UNIVERSITY OF CHICAGO (30).



photocell dew points are higher than the visual dew points unless an adjustment is made in the heat control system of the mirror surface, as is usually done.

2. At low temperatures (less than -30° C) an error is introduced because of continued cooling of the mirror surface below the dew point in order to produce a condensation or deposit detectable to the eye, whereas the more sensitive photocell will detect a smaller amount of condensation and hence record a higher dew point temperature. This is borne out by the increased time lag and errors observed at temperatures below -30° C (30).

3. The photocell dew point hygrometer is subject to the difficulty of not distinguishing between condensation in the form of liquid water, ice, or a mixture of water and ice, whereas the eye is able to make this distinction. Moreover, the saturation vapor pressure and hence the dew point temperatures are different over each state. The maximum error due to this is about 1° C for each 10° C below freezing.

4. A mixture of supercooled water and ice is unstable, since supercooled water crystallizes in the presence of ice. The dew point temperature increases rather suddenly when supercooled water forms ice because the temperature of the surface is increased by the heat of crystallization. This sudden change in dew point, which can be detected by a quick response dew point hygrometer, is not that of the ambient air.

D. Spectral Hygrometers.

From a theoretical point of view the spectral hygrometer is the answer to the meteorologist's difficulty in measuring humidity, because it measures absolute humidity directly at all temperatures without lag, but the practical difficulties are numerous. The spectral hygrometer consists of a light source which sends a beam over a given path, through a filter, and an optical spectrometer or grating on to an energy receiver. Two bands of the spectrum are used, one in which there is a great deal of absorption by water vapor, and one which is free from water vapor absorption. The actual bands chosen depend mainly upon the type of energy receiver used.

For an energy receiver, Foskett and Foster (25 and 26) of the Weather Bureau used two thermocouples whose outputs were sent in opposite directions through a sensitive galvanometer.

They used the band centered at 13,800 Å to show water vapor absorption with the [illegible] Å region for the non-absorption reference. The air path was varied from 1 to 50 meters.

This device requires a very sensitive galvanometer to read the thermocouple outputs. The auxiliary equipment and the skill required to operate it makes the instrument impractical for field use. Also the thermocouple readings are subject to drift due to ambient temperature changes.

At New York University, Hammermesh, Reines, and Korff (24) developed a spectral hygrometer attempting to make it portable as well as accurate. For a detector this instrument used two photoelectric cells with a direct current amplifier. Energy in the absorption band, 9,440 Å was measured by one photoelectric cell, and that of the reference band at 8,000 Å by another photoelectric cell. The path length used was 143 cms.

As an energy receiver, the photoelectric cell is sensitive with negligible time lag and is little influenced by ambient temperature. It can be used with electronic amplifiers to operate rugged portable meters or recorders. However, the photoelectric cell is not sensitive to the most pronounced water vapor absorption bands. As a result of this selectivity of absorption, less clearly defined water vapor absorption bands have to be used. The sensitivity of the photoelectric cell is not always the same, and hence comparisons made between two photoelectric cells are not reliable.

In its present state of development the spectral hygrometer is not suited for use in radiosonde or wiredsonde work. The instrument is very critical to adjustment and also is not portable. It could best be used for surface-level measurements where the humidity of the air over a long path length is desired.

IV. INDEX OF REFRACTION MEASURING DEVICES.

The microwave heterodyne cavity "Q" methods can be used to determine the quantity of atmospheric moisture or the refractive index directly. These methods were suggested by Dr. H. Lyons of the National Bureau of Standards, Central Radio Propagation Laboratory.

A. The heterodyne method consists of two frequency stabilized klystron oscillators operating at the frequency for which refractive index measurements are desired. These oscillators are stabilized over short periods of time to 1 part in 10^7 or 10^8 by means of a resonant cavity and "magic tees" in a microwave automatic frequency control discriminator circuit developed by Pound at the M.I.T. Radiation Laboratory (31, 32, 33, 34 and 35). The two oscillators are tuned to zero beat with the resonant cavity of one evacuated. When the evacuated cavity is filled with the gas being measured, the frequency will change and the beat note between the two oscillators can be measured. The index of refraction can be calculated from this measurement. By such a method the water vapor content of the air may be obtained at temperatures below freezing.

B. By methods using cavity "Q" meters, where both the change in frequency and Q of the cavity are measured, the complex dielectric constant or complex index of refraction may be determined. This method therefore gives also the loss factor or absorption coefficient of the gas, but is not as sensitive a method of measuring the conventional refractive index as the heterodyne method.

The heterodyne or "Q" meter methods are suitable for ground station measurements or, perhaps, for airplanes, barrage balloons or towers, but in general would require equipment too heavy for balloon sounding work.

V. PRESSURE AND ALTITUDE MEASURING DEVICES.

The value of a sounding depends on an accurate determination of humidity and temperature as a function of height. Height may be determined either directly by means of a distance measurement or in terms of pressure using the hypsometric equation.

A. Triangulation. The height of the measuring equipment can be determined very accurately by means of two theodolites located at the ends of a suitable baseline. Disadvantages of this system are that two additional observers are needed to operate the theodolites, and if clouds or low visibility obscure the balloon the system fails.

B. Length of Cord and Elevation Angle of Balloon. For wiredsonde work, the height of the instrument is frequently determined from the length of cord unreeled, and the elevation angle of the balloon. The sag of the cord between the reel and the balloon may be taken into account by considering the arc formed by the cord to be a portion of the catenary curve. Tables exist for such a determination (16). The wind distribution distorts the curve from a true catenary form, and a correction should be applied to these tables for this effect.

The Navy Radio and Sound Laboratory (81) at San Diego, California, has made tests on the accuracy of balloon heights obtained with the length of cable and elevation angle of balloon system. It was found that a correction of 9% gave a fairly accurate value of true altitude when 1000 feet of cable was unreeled. True altitudes were determined by several simultaneous readings by transits set up on a 1000 foot base line. The maximum correction for calm air was 10.4%. For 500 feet of unreeled cable a 4.2% correction gave accurate heights.

C. Height Determination by Hypsometric Equation (19). The altitude of the balloon may be computed from the measurement of pressure, temperature and humidity. The method is fundamentally one of numerical integration and is laborious even though special tables and charts are provided to simplify the work. The accuracy of this system of height determination was checked quite carefully in the balloon flight of the Explorer II, made under the auspices of the National Geographic Society and the Army Air Corps by Major A. W. Stevens and Captain O. A. Anderson (20). During the flight accurate and complete barometric data were obtained. The altitudes computed from these data were checked by photographs made vertically downward from the balloon, and by triangulation of the balloon from the ground. Heights found by the three independent methods checked quite well. Agreement within 0.36% was observed between the photogrammetric and the barometric altitudes.

A pressure cell is the most commonly used element for height determination. The expansion or contraction of the cell according to pressure variation is geared to a pointer. If the scale beneath the pointer is graduated in pressure units, the instrument is called an aneroid barometer. If the scale is graduated in height units in accordance with the pressure-altitude relation of a selected standard atmosphere, it is called an altimeter.

A "standard" atmosphere is defined by an assumption regarding the variation of temperature with height in the atmosphere. In this country the U. S. Aeronautic Atmosphere (NACA) has been used since 1926 for calibrating aviation altimeters and for all other aeronautic purposes. It is a slight modification of that adopted by the International Committee for Aerial Navigation (ICAN) where the air temperature is assumed to vary uniformly with altitude (0.0019812° C/ft.) to a temperature of -56.5° C instead of -55.0° C as in the NACA system. Above these respective levels, the temperature is assumed constant.

For reference the complete hypsometric formula is given by:

$$H_2 - H_1 \doteq \int_{P_2}^{P_1} \frac{dP}{\rho g} = KT_m \left[1 + 0.376\left(\frac{e}{P}\right)_m\right]\left[1 + \frac{g_s - g_m}{g_s}\right] \mathrm{LOG}_{10}\frac{P_1}{P_2}$$

$$T_m = \frac{\int_{\mathrm{LOG}_{10}P_1}^{\mathrm{LOG}_{10}P_2} T(d\,\mathrm{LOG}_{10}P)}{\mathrm{LOG}_{10}P_1 - \mathrm{LOG}_{10}P_2} = \frac{\sum^{n} T_i}{n}$$

where:

H_1 = Height of base of interval.

H_2 = Height of top of interval.

P = Pressure at intermediate levels.

P_1 = Pressure at base of height interval.

P_2 = Pressure at upper level.

ρ = Air density.

T_m = Mean temperature as defined above in $^\circ$K of the air between pressure levels P_1 and P_2.

T_i = The air temperature in the i th interval between P_1 and P_2.

K = 221.152 for H in feet or 67.4073 for H in meters.

n = Number of selected equal intervals of pressure between P_1 and P_2.

e = Water vapor pressure in same units as P.

$(e/P)_m$ = Mean value of (e/P) for air column between P_1 and P_2

g_s = Standard value of gravity.

g_m = Value of gravity at the midheight of the air column between P_1 and P_2.

If altimeters are to be used for accurate height determination, the following factors must be considered:

1. The height error introduced by the assumption of a "standard" atmosphere must be corrected. The difference between the true altitude at a point in the actual atmosphere and that indicated by an altimeter calibrated on the basis of a standard atmosphere can be computed. True heights for the actual atmosphere may be calculated by the hypsometric equation while the indicated heights of the standard atmosphere may be obtained by the following equation (17 and 18):

$$H_i = \frac{H_o + (B - H_o C) A \log_{10} \frac{P_o}{P}}{1 + CA \log_{10} \frac{P_o}{P}}$$

P_o = Pressure at height of station.

P = Pressure at height H_i in the same units as P_o.

A = 67.4073 for H_o and H_i expressed in meters and 122.862 for H_o expressed in feet.

B = 288 for H_o and H_i expressed in meters and 518.4 for H_o and H_i expressed in feet.

C = 3.264×10^{-3} for H_o and H_i expressed in meters and 1.791×10^{-3} for H_o and H_i expressed in feet.

H_i = Indicated height above sea level in meters or feet depending on values of constants A, B and C.

H_o = Height of station above sea level in meters or feet depending on values of constants A, B and C.

Table 2 shows mean corrections to be applied for various locations in summer and winter to the indicated heights computed by the above standard atmosphere relationship. If the density of the air column is less than that assumed by the standard atmosphere the altimeter will read too low, and conversely, if the density of the air column is greater than that assumed by the standard atmosphere the altimeter will read too high. The data used to construct this table were taken from monthly mean soundings computed by the Weather Bureau (8) on the basis of the hypsometric formula.

Table 2. Additive mean corrections to obtain hypsometric 3,000 m msl altitude from computed altimeter indicated heights.

Station (Elevation above mean sea level)	Month	Additive Mean Corrections (m)
El Paso, Texas	January	+ 13
(1195 meters msl)	July	+ 119
Fairbanks, Alaska	January	- 163
(134 meters msl)	July	+ 56
Washington, D. C.	January	- 106
(25 meters msl)	July	+ 125
San Juan, P. R.	January	+ 120
(15 meters msl)	July	+ 153

2. Ambient Pressure Changes must be noted and corrected. The movement of cyclones, anticyclones and fronts produce pressure changes which the altimeter records as changes in elevation even though the instrument is at rest on the ground. Pressure changes produced by diurnal variations of pressure is sinusoidal in form, having the maximum at about 11 A. M. and P. M. local time, and its minimum at about 4 A. M. and P. M. local time. For accurate use of altimeter readings in soundings a current weather map should be consulted, and a continuous record of ground pressure should be kept.

The pressure cell type of aneroid barometer or altimeter is also subject to certain errors caused by the instrument mechanism itself. Some of these are as follows:

a. Hysteresis (4). If a pressure cell be taken from

sea level up to an altitude of about 10,000 feet, and back again, as may be done in an airplane flight, the pressure cell will under a pressure change from about 1016 mbs. to 700 mbs. and back again 1016 mbs. As the pressure decreases, a certain relation between pressure and deflection will be observed, leading to a calibration curve AB, for the ascent (Figure 14). It will be found that the deflections do not follow the original curve, but the curve BC, if the plane descends immediately upon reaching 10,000 feet. This effect is known as hysteresis.

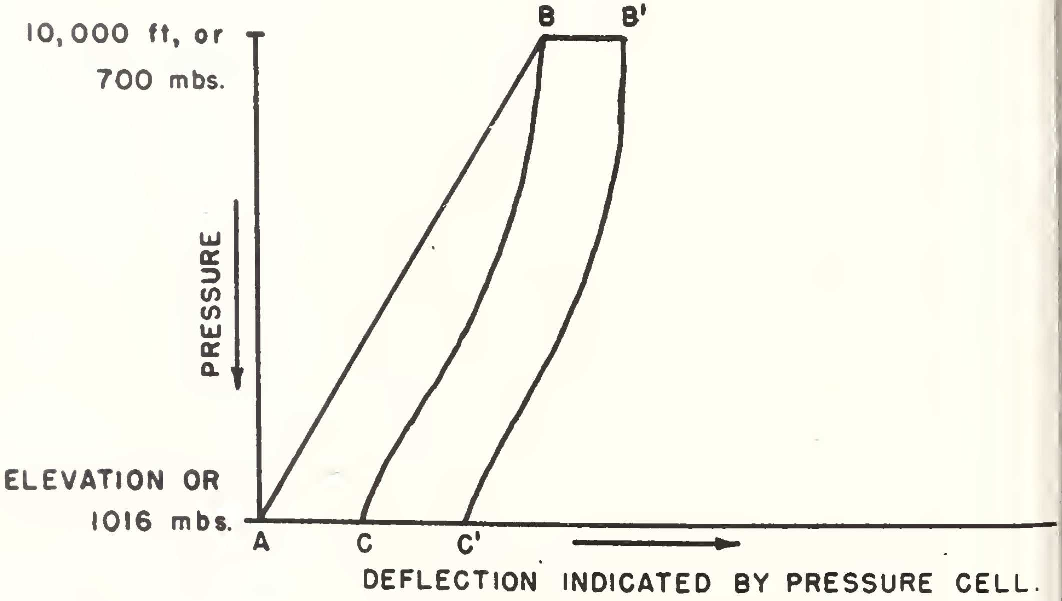


Fig. 14. PRESSURE CELL HYSTERESIS LOOP

The hysteresis is in general a maximum at approximately the middle of the pressure range of the cycle. The loop ABC becomes smaller with repetition of the pressure cycle from 1016 to 700 to 1016 mbs. until after four or five complete cycles when the area of the loop is effectively constant.

If the airplane remains at the 10,000 foot altitude for some time before coming down to the ground, the deflection gradually shifts from the point B to the point B'. This time lag error is known as shift. Upon returning to zero elevation from 10,000 fe he pressure cell reaches a deflection C' along the curve B' C'. he deflection gradually drifts from C or C' to A if the instrument emains at rest. These elastic errors vary directly with the emperature of the instrument, the range of pressure, the rate f change of pressure and vary inversely with the time taken for he cycle over a given pressure range.

3. Other errors which effect the accuracy of an instru-ent are scale errors and temperature errors. Scale error is the rror in the indication of the instrument at a temperature of 25° C. emperature errors are the effect of variation in instrument tem-erature upon the scale readings. High quality instruments are ompensated for variations in instrument temperature. A calibra-ion curve can be constructed which will show the magnitude of hese errors at various temperatures and pressures.

D. Radio Altimeter. Radio altimeters have been developed or height determination of aircraft. In general, the accuracy f these altimeters is quite high, with some types the error is ess than 50 feet at altitudes of 50,000 feet (21). The irregu-arities of a land surface complicate the height determination. adio altimeters are too heavy for low level sounding work where he measuring instruments are supported by a light balloon.

VI. WIND MEASURING SYSTEMS.

Wind and turbulence measurements give valuable information concerning atmospheric stratification and are useful in forecasting changes of the moisture and temperature distributions. Wind data require the measurement of direction and speed. For surface measurements the direction is given by a wind vane, and wind speed is measured by an anemometer. Upper winds are measured by following the path of a free balloon.

A. Wind Vanes and Anemometers.

(1) Wind Vanes.

Fundamentally all wind vanes consist of a body mounted unsymmetrically about a vertical axis on which it is free to turn. The end offering the greatest resistance to the motion of the air goes to the leeward. Most wind vanes consist of an arrow with a large tail mounted on suitable bearings. The tail is a vertical plate parallel to the longitudinal axis of the arrow. Different tail designs have been used for improving the response of this type of vane to changes in wind direction. In one design, the tail consists of two flat vertical plates forming a narrow "V". The best practice, however, is to make the tail as a symmetrical airfoil section with a vertical span 3 or 4 times the chord dimension.

(2) Anemometers.

Anemometers may be classed as pressure, rotational and hot wire types. The pitot tube (Dines pressure tube) and bridled cup types measure wind speed by the pressure imparted to a surface stopping the wind movement. The rotational type anemometers measure wind speed as a function of cup wheel or propeller rotation rate. The hot wire type anemometer uses the cooling effect of the wind on a body of high temperature (about [illegible]° C) as a function of wind speed.

a. Pitot Tube Anemometer.

The difference in pressure caused by the wind blowing into the mouth of an open tube and across the mouth of a second reference tube is used as a measure of the wind velocity. The pitot tube is directed into the wind by a vane. The reference tube is fed by a series of holes in a chamber coaxial with and surrounding the main tube. The pitot head and cylindrical chamber are connected to a pressure indicating device calibrated to indicate wind speed.

b. Bridled Cup Anemometer.

The bridled cup anemometer employs a multi-cup rotor mounted on a vertical axis which is turned by the wind against restraining springs. The spring torsion against which the wheel rotates is a function of wind speed. One complete turn of the wheel introduces the torsion measuring the maximum wind speed of the instrument. The Selsyn motor principle is used here for remote indication.

c. Cup-Wheel Type Anemometer.

The rotating (Robinson) cup-wheel type anemometer has long been used in the United States. Three or four cups are mounted with their open face in a vertical plane along equal length spokes, 90° or 120° apart. The wind stream strikes both sides of the cup wheel and the wheel rotates to the torque applied on that side of the wheel where the cups open into the wind stream. The rate of rotation of the cups is a function of wind speed.

A special 3-cup anemometer (1) for low wind speeds has been developed at California Institute of Technology. Whereas ordinary commercial anemometers are not adequate to measure very light winds (of the order of 1.6 feet/second), this instrument records wind speeds from 0.8 feet/second to 44 feet/second. Each rotation is registered on an electrical counter. For high wind velocities the counter may be switched to record only every one hundred revolutions.

d. Propeller Type Anemometer.

The rotating propeller or windmill type anemometer employs a wind-vane to keep the horizontal component of the wind stream flowing perpendicular to the propeller blades. The rate of rotation of the blades is nearly proportional to the air flow.

The Friez Instrument Division of Bendix Aviation Corporation has recently developed a propeller type anemometer for the more accurate measurement of stronger speeds (40 and 42). This system has nearly linear wind speed-revolution per minute calibration curve, whereas for speeds above 40 miles per hour, cup type anemometer curves usually depart from a straight line. The inertia of the propeller is small and response to changes in wind speed is very rapid. Over a range of 1.7 to 144 feet/second this instrument has a maximum error of 1.7 feet/second. The anemometer and vane assembly is compact and weighs only 12 pounds. It is designed to run for months without servicing.

There are several methods of indicating wind speed measured by cup-wheel and propeller type anemometers. The

shaft of the anemometer may be coupled to a generator and the voltage of the generator used as an indication of wind speed, or the turning anemometer shaft may close and open an electric circuit in which an electro-magnetically operated pen records the circuit interruptions on a clock driven drum giving an indication of wind speed. Three recently developed indicating systems are described below:

In the first an electrical contact at the base of the anemometer shaft closes a circuit in which a constant voltage source charges a parallel resistance-condenser combination. The charge of the condenser at any instant is a function of the number of anemometer impulses per unit time. The condenser integrates the charge and a high impedance voltmeter calibrated in miles per hour or other suitable units indicates the wind speed.

In the second system, which is especially useful for recording low wind speeds, a cogwheel coupled to the anemometer shaft, keys a triode oscillator capacitatively by turning between the grid and plate coils. The keying frequency is the speed of rotation of the cogwheel which is proportional to the wind speed and is indicated by a frequency meter calibrated in wind speed units.

In the third system (15), the Selsyn system, the continuous rotation of the anemometer drives a generator which is connected to a self synchronous motor through an electric circuit. The rate of rotation of the receiving synchronous motor is converted into an indication of wind speed by a disc and roller mechanism. Two flat circular discs, facing each other, are rotated in opposite directions by a constant speed motor. A shaft, coupled to the self synchronous motor passes in between the two rotating discs. This shaft is perpendicular to the axis of rotation of the discs, and carries a narrow cylindrical roller. The roller is frictionally coupled with both the face plates and is caused to move in the direction of the drive shaft as a result of two torques acting on it--one due to the receiving motor and the other due to the face plates. The changes in position of the roller in the direction along the drive shaft are transmitted to a pointer through a circular rack attached to the roller and a gear. The pointer, moving over a calibrated wind speed scale, can thus indicate wind speed in any desired remote location.

e. Hot Wire Anemometers.

While the cup-wheel and propeller type anemometers give very reliable and accurate indications of wind speed, they are too massive and not sensitive enough for the study of small scale air motions. An understanding of small scale atmospheric turbulence is required in the study of some microwave propagation problems. The hot wire anemometer (see Figures 16, 17 and 18) affords the radio-meteorologist a tool which is well adapted to this type of study because of its ability to measure nearly instantaneous wind speeds and fluctuations at a point in space.

The instrument consists of a hot wire element with an associated Wheatstone bridge circuit. The cooling effect of the wind stream on the hot wire anemometer element changes its electrical resistance, unbalancing the bridge and causing a milli-ammeter, calibrated in wind speed units, to give a deflection. The hot wire element is directional. The directionality can be expressed approximately by:

$$V_m = V \cos \alpha$$

where V_m is the measured air speed, V is the actual air speed and α is the angle between the velocity direction and a plane normal to the wire. Ambient temperature effects of the air are negligible in changing wind speeds measured by the anemometer because the element is maintained at a temperature of about 900° C.

Dr. Harold K. Schilling (82) and his associates at Pennsylvania State College have used this technique for micro-meteorological studies as is described below. Wind determinations are made by elements placed at two suitable positions along a mast. Assuming horizontal flow and uniform wind direction, instantaneous differences in wind speed at two anemometer positions are measured directly. The anemometer leads are switched to a second set of Wheatstone bridge circuits in which the difference in potential between the two anemometer arms of the bridges deflect a galvanometer whose readings are proportional to wind speed difference. The total range of the anemometer element is from 0 to 70 feet per second. For very low speeds the resistance of the milliammeter is lowered. The anemometer element has an accuracy of ± 0.1 foot/second. Minute fluctuations as rapid as 10 per second can be measured.

Construction Details and Operation of Instrument.

As developed by Pennsylvania State College the instrument consists of two hot wire elements, associated electrical circuits and an auxiliary portable mast for exposing the elements.

The hot wire element has been especially constructed for micro-wind-speed measurements. It consists of a platinum wire of 1 cm length and .0004 in. diameter. The platinum wire is soldered to two polished rust-proof darning needles spaced at a 9 mm interval. When heated this allows the platinum wire to sag slightly between the needles and affords protection against mechanical shock and vibration. The needles are inserted in the end of a tube through which the three-conductor 120 ft. cable leading to the instrument panel is attached. The needle support is made of a ½ inch diameter bakelite rod 4.5 inches long. Screw terminals are provided immediately in back of the needles for connecting to the cable.

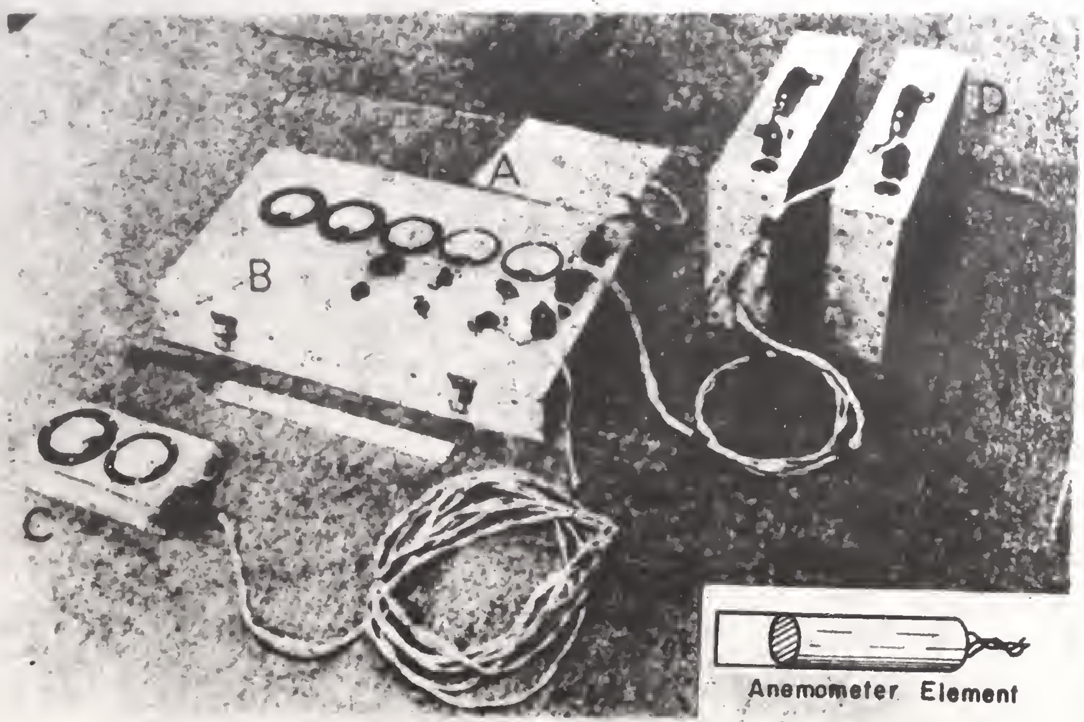
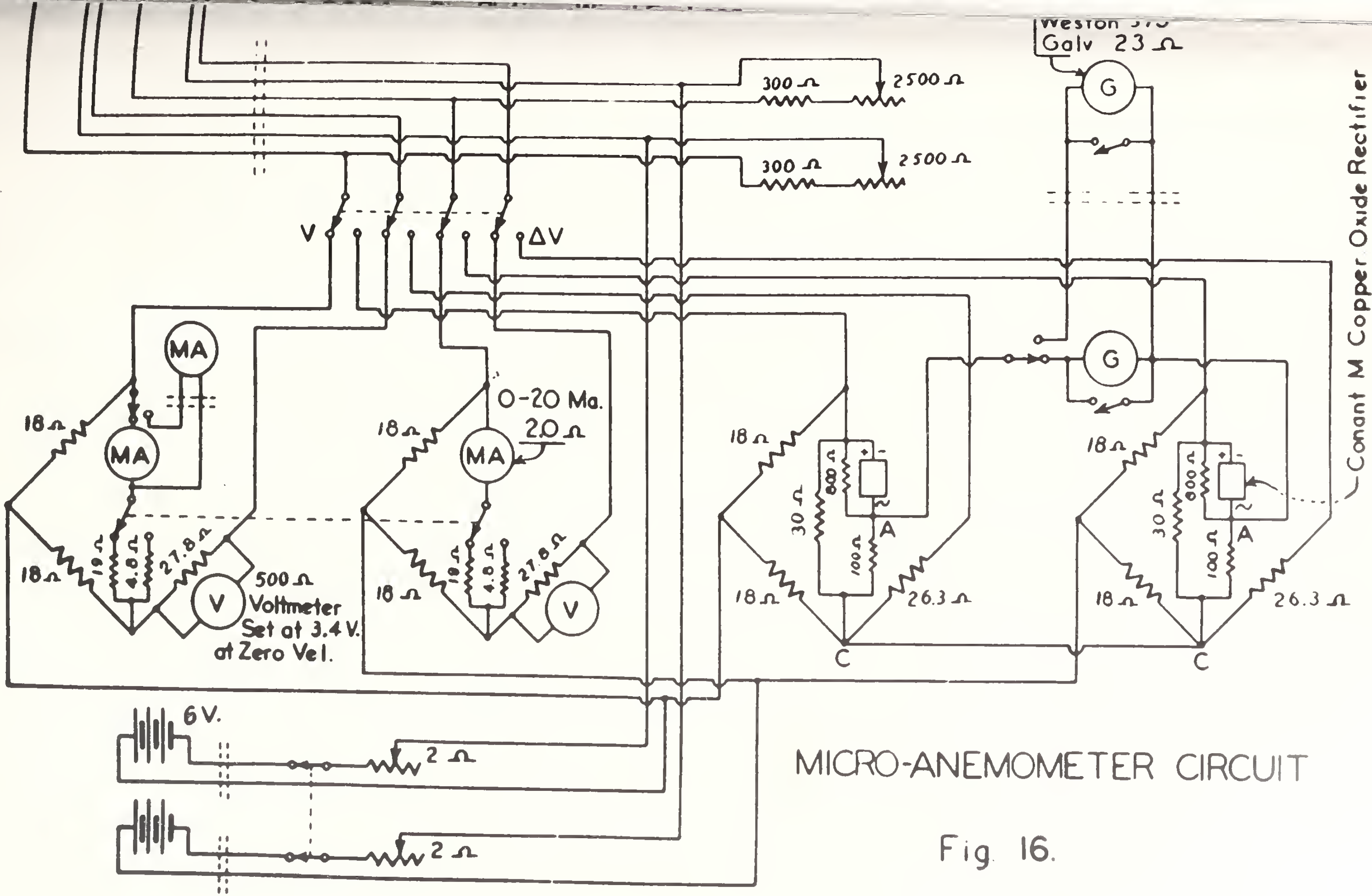


Fig. 15. Micro - Anemometer Assembly. A, Hot Wire Assembly; B, Control Panel; C, Auxiliary Galvanometer; D, Batteries.



MICRO-ANEMOMETER CIRCUIT

Fig. 16.

The associated electrical equipment consists of four Wheatstone bridge circuits to measure wind speeds and the wind gradients between the two anemometer positions. Two identic bridge circuits are used to indicate the wind speeds detected by the anemometers and two other bridge circuits are used for measur ing the instantaneous wind speed differences.

Errors in the recording of wind speed du change in resistance of the cables are corrected by using 3-condu cables and a variable resistance connected in parallel with the a mometer element. To set the wind speed measuring circuits for ze deflection, a voltmeter is provided which indicates a drop of 3.4 volts across a 27.8 ohm resistor in the anemometer arms of each o the bridge circuits. A rheostat in series with a six volt storag battery is provided for regulating the flow of current in each of two anemometer circuits.

The anemometer cables can be switched fr the wind speed circuits to the two bridge circuits used to measur wind speed difference. A galvanometer indicates the difference i wind speed. Linear readings are obtained by suitable resistors i series and parallel with a full wave copper oxide rectifier in ea anemometer arm of the two bridges.

Power is supplied to the anemometer circ by two 6 volt storage batteries. They are enclosed in convenient carrying cases. The connections to the 6 volt batteries and to t anemometers are made through plugs in the instrument circuit pane Plugs are also provided for portable milliammeter (wind speed in- dicator) and a galvanometer (wind speed difference indicator). T panel is mounted in a carrying case of about 20" x 10" x 4". Two collapsible aluminum camera tripods support the case.

Auxiliary masts (see Figure 17) are provided f mounting the anemometers. They are made of 40 inch aluminum pipe sections which can be fitted together. Out of each pipe end a sh fitted steel pin extends for joining to the next section. The fi section is set vertically on the ground. When more than four such sections are employed, guy wires must be used to support the mast. The hot wire elements are clipped to horizontal aluminum tubes 2 feet long, which are, in turn, fastened by swivel clamps to vertic sliding tubes, of 3 feet lengths. Thumb screw-locks on the sides secure the slide tubes in any position along the mast. Pairs of h wire elements at a fixed distance apart, can be mounted on the fix length slide tubes and can be moved easily up and down. This pro- vides a quick way of getting wind speed gradients at various heigh along the mast.

The general properties of the pressure ty rotational type, and hot wire type anemometers may be summarized a

17 Mast with Four Sensitive Elements

follows:

Table 3. Comparison of Different Types of Anemometers.

Anemometer Type	Directional Properties	Low Speed Response	Air Density Response	Spee Respor
Pitot Tube	Directional, Needs Vane	Fair	Affected by Density	Squa Law
Bridled-Cup	Non-directional	Fair	Affected by Density	Squa Law
Cup-Wheel	Non-directional	Good	Independent of Density	Appr Line
Propeller	Directional, Needs Vane	Good	Independent of Density	Line
Hot-Wire	Projection of Wind Vector on Plane Normal to Wire	Excellent	Affected by Density	Non-Li

B. Balloon Systems.

For determination of the wind velocity structure above the earth's surface a freely rising balloon is used. It is assumed that the horizontal translation of the balloon is an accurate measure of the wind flow aloft. All methods commonly determine the horizontal translation of the balloon at one minute intervals. The method of measuring the angles to the balloon in flight and of finding its heig give rise to several names which are used to indicate these methods. The names now in use are pibal, rabal and rawin.

(1) Pibal (52). The most common method of wind aloft measurement is by the free pilot balloon system. Extensive tests hav shown that when the balloon (30 grams) is given a free lift of 120 gr it rises at an ascensional rate of about 180 meters per minute. Fixe corrections have been applied for turbulence in the lower 1,000 meter of the ascent, but since the same corrections are applied to all sound ings in all locations for all wind speeds and at all times of day the adjustments are very crude. Elevation angle and azimuth angle are measured on the balloon position each minute by a theodolite, and the horizontal distance from the observation point is calculated using the assumed height for the ascensional rate. The balloon positions are

plotted on a celluloid protractor and the average velocity and direction of the balloon determined for each minute of the ascent.

(2) Rabal (52). In the rabal system a theodolite is used to follow a radiosonde balloon transmitter. The height of the balloon is not assumed, but is determined from the radiosonde record. This method will give more accurate results than the pilot balloon system. If the sounding is made during the occurrence of rain or snow, errors are not introduced as in the pibal system. However, if the visibility or ceiling is too low both systems fail. This type of failure does not occur in the rawin system to be described.

(3) Rawin observations are made by following the balloon and its attached equipment by means of a radio direction finder (RDF) or radar set. If radar is used either a target reflector or a pulse repeater is hung on the balloon. If radio direction finding equipment is used a radio transmitter is hung on the balloon. It is customary to use a baroswitch device in conjunction with the RDF balloon transmitter to furnish pressure (height) indications.

The use of radar sets and radio direction finding equipment for simultaneous observations of wind, pressure, temperature and humidity has led to coinage of two new terms. Radar-sonde signifies that the observation is made with a radar set, and that the slant range of the balloon is known. Rawin-sonde means that the observation is made with a radio direction finding set and that the slant range of the balloon is not known. However, the term rawin, itself, applies only when wind observations are taken using either RDF or radar equipment.

a. SCR-658 System.

The SCR-658 is most widely used for rawin-sonde measurements (see Figure 18). In this method a sounding is obtained by tracking the balloon on the radiosonde carrier frequency (400 Mc) with radio direction finder SCR-658 by an attached meteorological unit. The SCR-658 has a frequency modulation channel which converts the signal to amplitude modulation for use with the regular radiosonde recording equipment. When upper air wind measurements are not made simultaneously with the upper air meteorological sounding the balloon radio transmitter is modulated by a baroswitch which gives indications of height at fixed pressure levels.

Accuracy tests have been made on the measurement of elevation and azimuth angles in a series of 8 rawin balloon flights at Evans Signal Laboratory (49). Simultaneous readings of balloon position were taken at a single observation point by SCR-658 equipment and two theodolites. The results of the comparison are shown in the table. The average elevation angle and average azimuth angle of the two theodolites were used as a basis of comparison for the SCR-658 readings. The usual single theodolite pilot balloon computations were made with the two sets of data and the results compared.

Fig 18. RADIO SET SCR-658-T2

Rear View . Prepared for Operation

SIGNAL CORPS GROUND SIGNAL SERVICE

Table 4. Average Errors of SCR-658
(Compared with theodolite)

Azimuth angle	0.5°
Elevation angle	0.2°
Wind direction	2.9°
Percentage error in wind speed ...	9.9%

For elevation angles less than 15° the accuracy of wind finding decreases rapidly due to ground reflections. The average range of the SCR-658, when tracking the rawin transmitter, is about 25 miles.

b. Two Direction Finder System (48).

In this system (British) two loop type direction finders, located at the ends of a suitable base line take bearings on the balloon-borne 38 Mc transmitter. As in the single direction finder, SCR-658 system an altimeter keys the balloon transmitter to indicate heights.

c. Comparison of Radar and Radio Direction Finding Sets.

Several other types of radar and radio direction finding sets have been used for rawin observation work. The table below gives a comparison of the relative accuracies of several sets based on a review of accuracy tests of the following equipments (43, 44 and 49):

Table 5. Relative Accuracies of Several Types of Radio Wind Finding Systems.

Type of Equipment	Relative Accuracy	Quantities Measured
Signal Corps Radio Set SCR-584 (3,000 Mc radar)	Excellent	Elevation angle Azimuth angle Slant range
Navy Radar Set Mark 4 (700 Mc)	Very Good	Elevation angle Azimuth angle Slant range
Navy Radar Set Mark 12	Very Good	Elevation angle Azimuth angle Slant range
Signal Corps Radio Set SCR-658 (400 Mc Radio Direction Finder)	Good	Elevation angle Azimuth angle Heights from balloon altimeter

(Continued on Page 49)

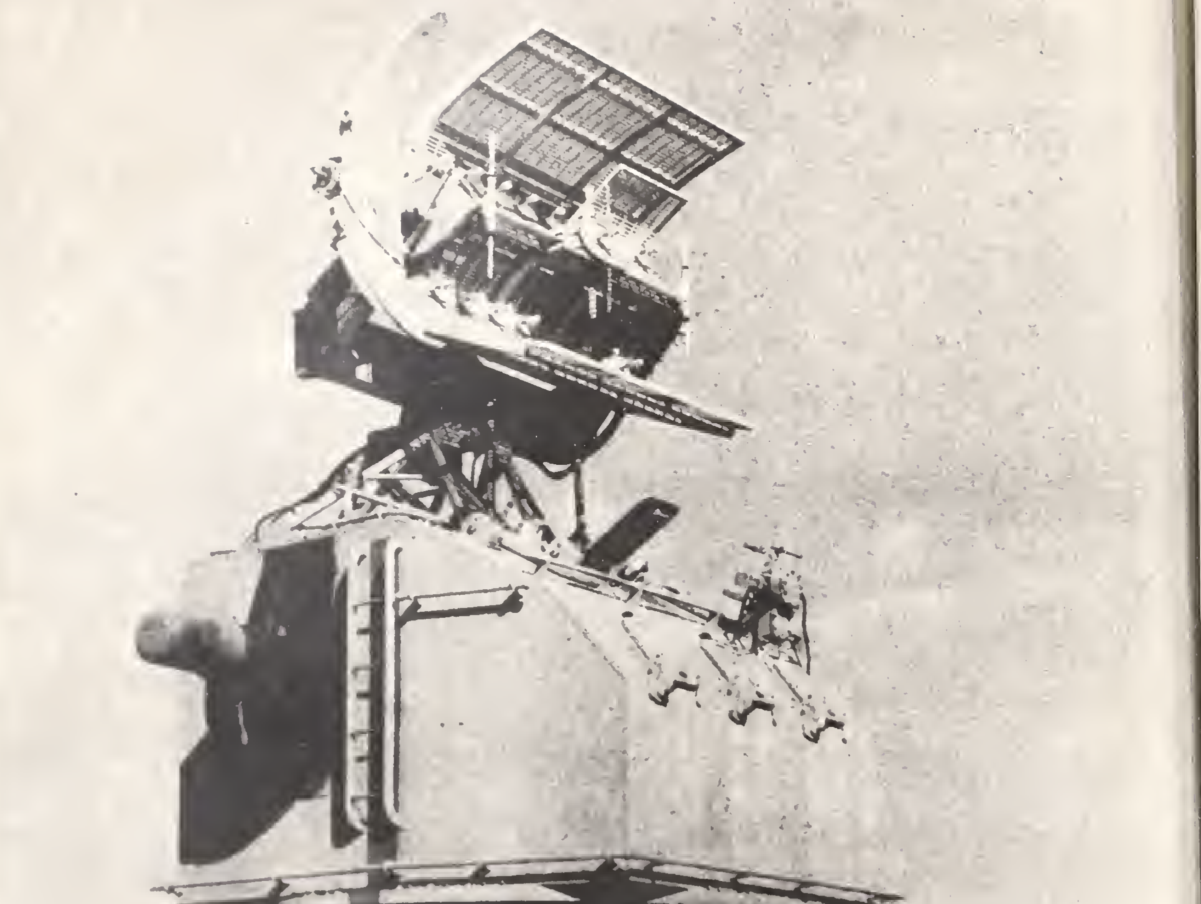


Fig. 19. A TYPICAL RADAR ANTENNA USED FOR TRACKING BALLOON REFLECTORS AND PULSE REPEATERS.

Table 5. Relative Accuracies of Several Types of Radio Wind Finding Systems. (Continued)

Type of Equipment	Relative Accuracy	Quantities Measured
Army Navy Radar Set AN/TPL-1 (2,800 Mc)	Good	Elevation angle Azimuth angle Slant range
Navy Search Radar SA (200 Mc)	Poor	Slant range Azimuth angle Height from balloon altimeter
Signal Corps Radio Set SCR-268 (200 Mc radar)	Poor	Elevation angle Azimuth angle Slant range

In the radar systems the cosine function is used to compute the horizontal position of the balloon, whereas in the radio direction finder (RDF) system the cotangent function is used. Identical errors made in reading the elevation angle of the balloon in the radar system will effect the horizontal position of the balloon much less than in the RDF system because the cosine function at small elevation angles is less sensitive to change than the cotangent function. Furthermore, the resultant error in horizontal projection of the balloon on the ground plane caused by a given random error of the radar set in reporting slant range is never as great as that caused by similar random error of the balloon altimeter in reporting height. For an elevation angle of 15° the error in horizontal distance is nearly four times greater for a random error in altitude of 1,000 feet than for a random error in slant range of 1,000 feet.

d. Meteorological Reflectors and Repeaters.

Several types of the more widely used reflectors and repeaters are described below. The statements of ranges obtained depend not only on the reflector or repeater, but on the site, the height of the balloon when lost and on the performance of the radar or radio direction finding set. The performance data reported is taken from flight tests made by the National Bureau of Standards in conjunction with the Bureau of Ships, Navy Department, except where noted.

(1) The ML-309/AP is a cubical corner reflect (51) of about 32½ in. edge (see Figure 20). Its eight interior r flecting corners are formed by stretching reinforced metal foil from three strips of balsa wood which mutually bisect each other right angles in a single point. The reflector is suspended by at taching three equal length cords from a balloon clasp to the ends the three balsa wood sticks. With a Mark 4 (700 Mc) radar the op mum range of this reflector is about 10,000 yards slant range. Ma imum slant ranges of 30,000 yards have been measured.

(2) The ML-306/AP is a collapsible stair-shap corner reflector (51) constructed of paper-backed laminated foil supported by a balsa wood framework (see Figures 21, 22 and 23). When opened there are 7 main panels 4' x 2' and 6 subpanels 2' x which partition the main panels forming 12 cubical corners 2' x 2 The launching of this device is easy because a time delay unit al it to unfold about 1 minute after release. Its shape is kept whe open by means of a system of cords which prevents it from unfoldi too far. The top ends of these cords terminate in a clasp which fastens to the balloon. The range of this reflector with a Mark 4 (700 Mc) radar is about 20,000 to 30,000 yards. Maximum slant ra of 45,000 yards have been obtained. (The ML-306/AP reflector was developed in 1943 at the National Bureau of Standards by Dr. H. Ly Mr. F. W. Dunmore and Mr. E. D. Heberling in conjunction with commercial contractors and the Bureau of Ships, Navy Department).

(3) The ML-392/AP reflector (51) is an ML-309/ reflector enclosed in a 350 gram balloon given a 1750 gram free li The balsa wood ribs are removed and the target is held open by the inflated balloon. The ascensional rate of the balloon using the ML-392/AP is about 1100 feet/minute while with the ML-309/AP attac externally to the same type 350 gram balloon the ascensional rate 900 feet/minute for equal free lifts. The average maximum slant r and altitude of the balloon enclosed type reflector using a Mark 1 radar is 30,000 yards and 38,000 feet respectively. This compared with the same target hung below the balloon gives about the same m imum slant range as the ML-392/AP. The enclosed target tends to i prove its corner angular accuracy with altitude due to the increas tension of the supporting lines attached to the expanding balloon.

Wire mesh reflectors (51) have also been developed to cut down target ascensional drag and to make square r flecting corners. The average ascensional rate using one of these reflectors, size for size and weight for weight is slightly better the externally attached ML-309/AP of similar dimensions.

(4) The Navy Type 10/AGE is a tunable reflecto consisting of 3 mutually perpendicular dipoles. Each dipole is co posed of two quarter wave sticks of metal-foil-covered balsa wood. quarter wavelength sticks are joined to each other by hinges so th when the vertical quarter wavelength piece is attached to the ball

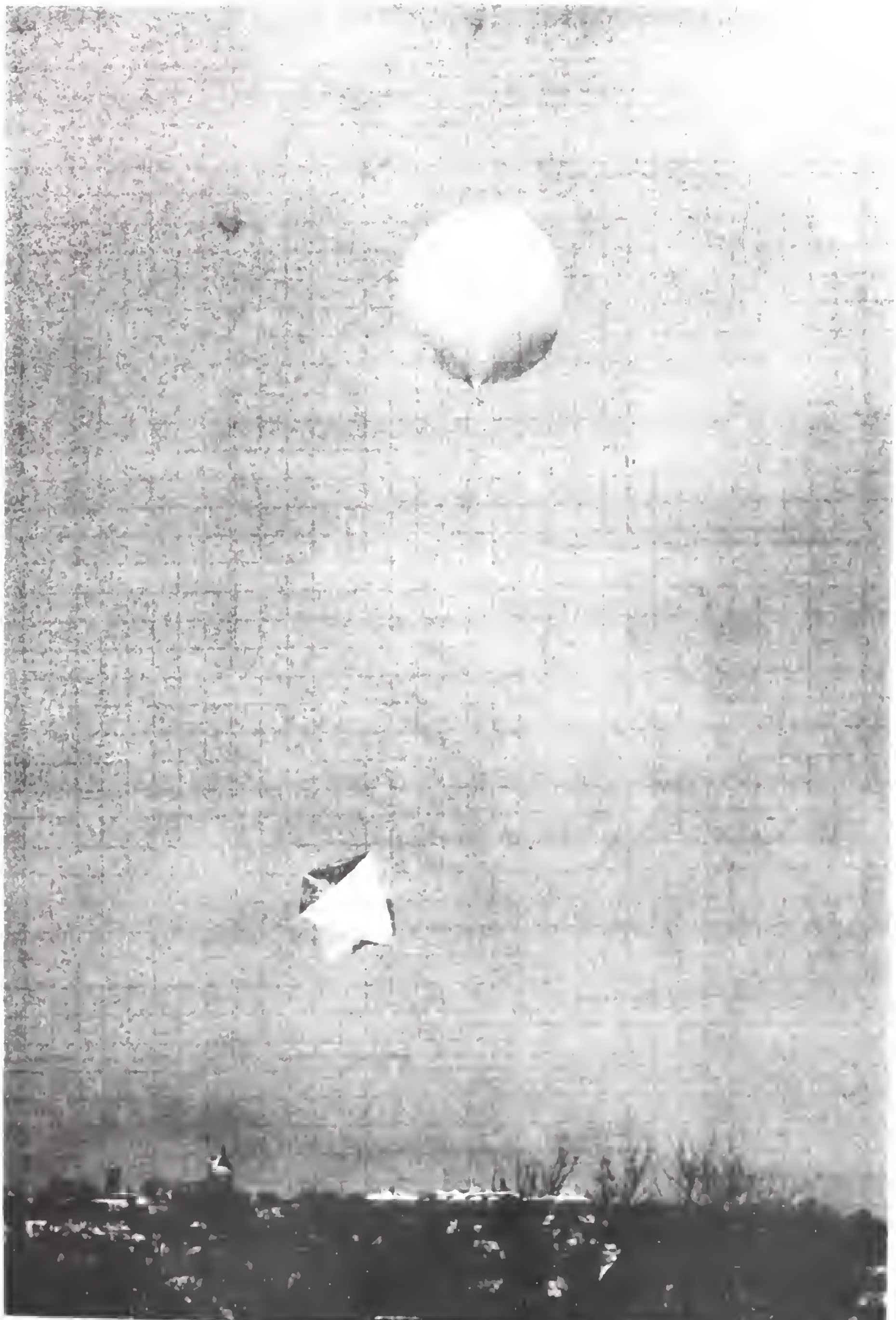


Fig 20 THE ML 309/AP REFLECTOR

Fig. 21 THE ML 306/AP REFLECTOR PRIOR TO FLIGHT.

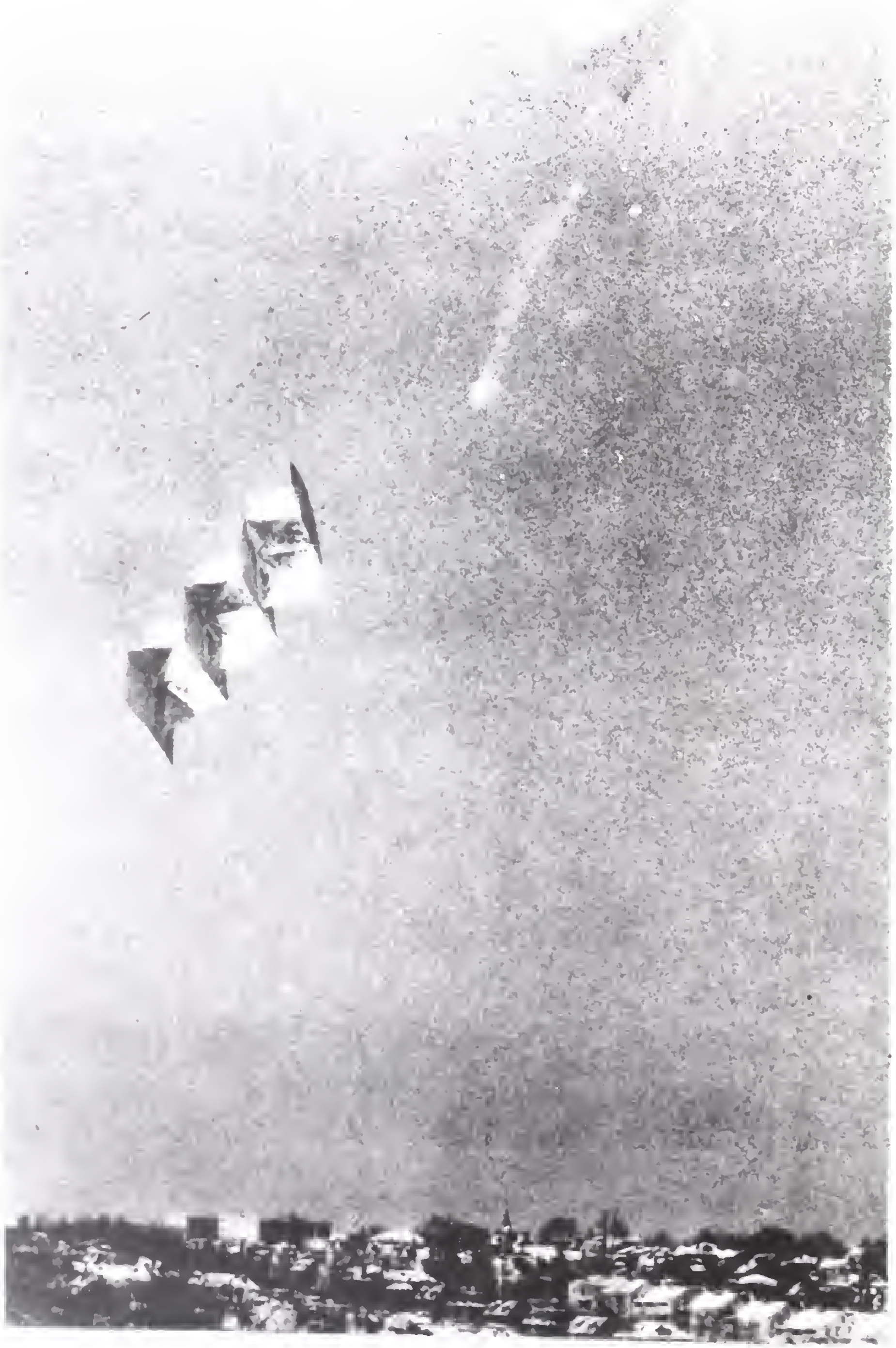


Fig 23. THE ML 306/AP REFLECTOR IN FLIGHT.

cord, the pieces hinged to it fall into position forming one vertical and two horizontal half wavelength dipoles. The horizontal dipoles are held in position by strings. If slightly opposite twists are given to the ends of the horizontal dipoles the reflector will spin during ascent. This gives a characteristic signal which may easily be tracked.

When this very compact reflector of 35 grams weight is unfolded it may be tuned for a given frequency by trimming the ends of the quarter wave sticks. Marks are provided for tuning to the following frequencies:

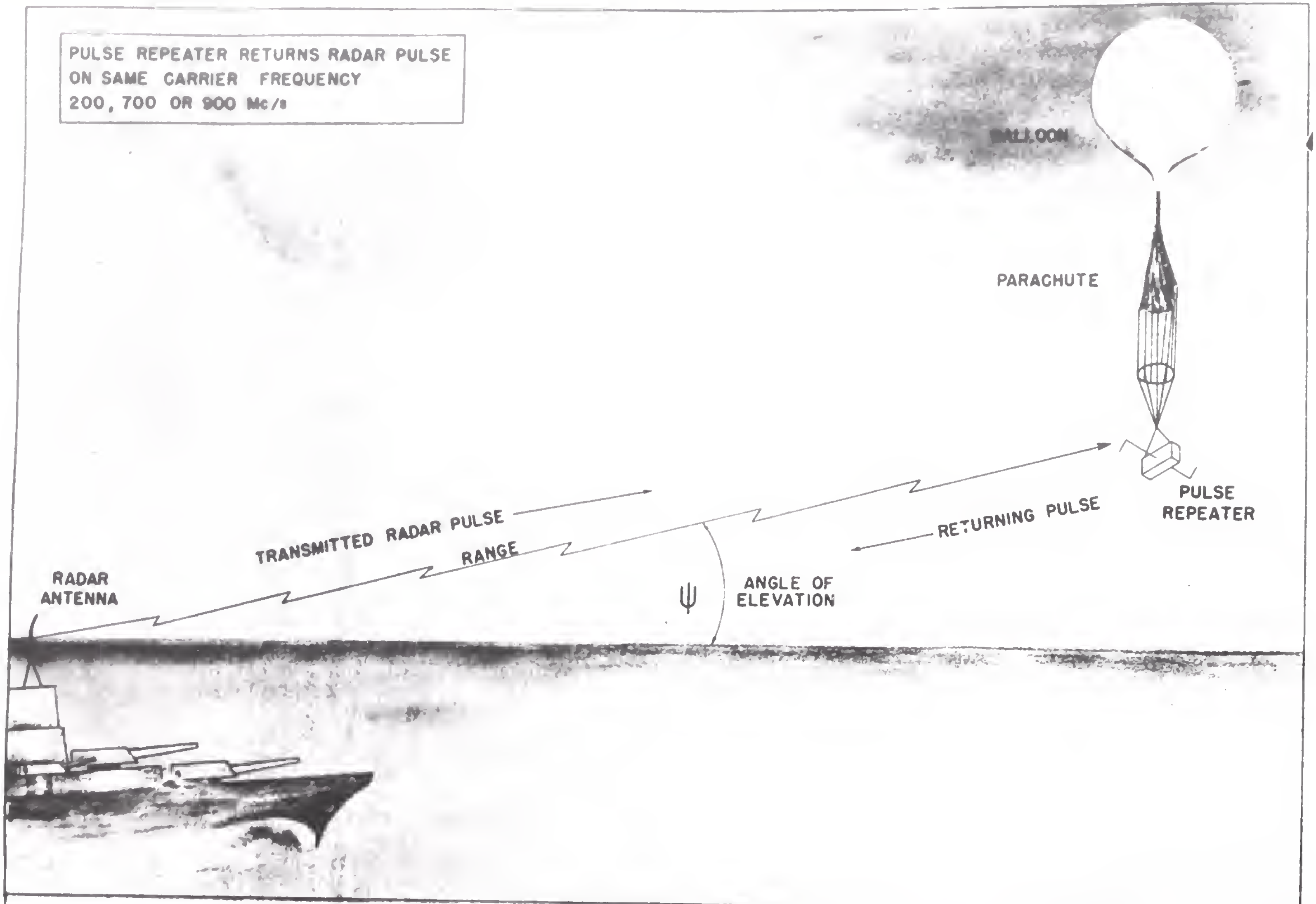
Frequency (Mc)	Length cut from each 16.8" quarter wavelength stick
175	0.0 inches
194	1.6 "
200	2.1 "
217	3.2 "
225	3.7 "

In a three flight test, using a single tuned reflector, an average slant range of 37,000 yards and an average maximum altitude of 30,000 feet were obtained. An SA (200 Mc) radar was used for tracking the target.

If the dipole is not cut to proper length, the ranges obtained are not quite as good. Using an SA (200 Mc) radar for tracking an uncut single reflector, in a 10 run test, a maximum average slant range of 26,000 yards, and an average maximum altitude of 20,000 feet were obtained. With two uncut targets suspended 10 and 15 feet below a 100 gram balloon, in a 7 flight test, an average slant range of 26,000 yards and an average altitude of 25,000 feet were obtained.

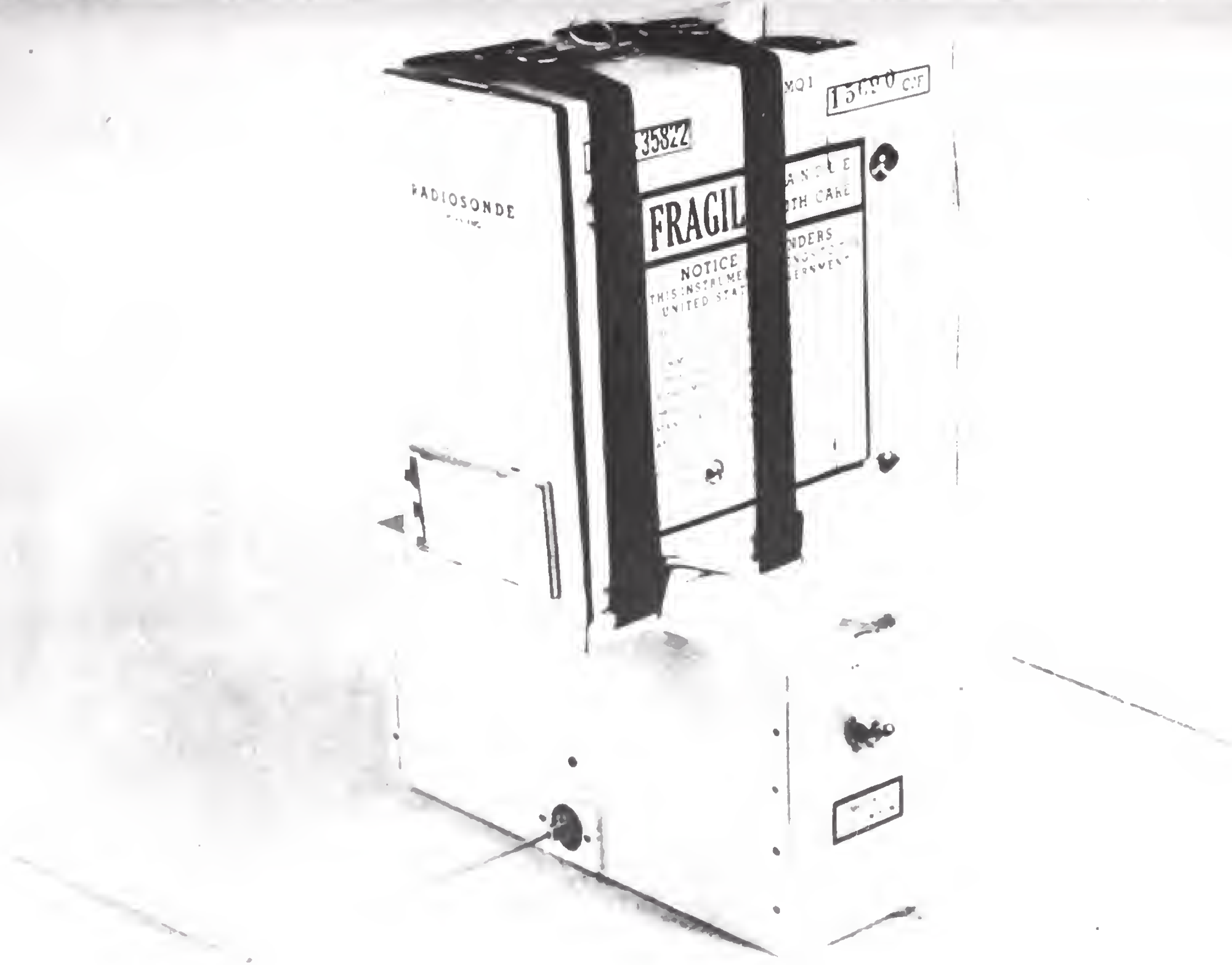
The ascensional rate, determined from a set of 10 test runs, of a single reflector attached to a 100 gram balloon of 550 grams free lift was found to be 770-860 feet/minute. In a 7 flight test, using two targets suspended 10 and 15 feet below a 100 gram balloon of 600 grams free lift, ascension rates of 794 to 1220 feet/minute were obtained.

(5) Pulse Repeater System (46). A pulse from the transmitting radar is picked up by a balloon receiver-transmitter (transpondor) which sends back a pulse, after a negligible fixed delay time, on the same frequency (see Figures 24, 25, 26 and 27). A radar set then measures the time elapsing between the transmission of the original signal and the reception of the reemitted signal, thus giving the slant range. The direction is also measured. The optimum range on the pulse repeaters using a Mark 4 (700 Mc) radar is about 75,000 to 150,000 yards. The average maximum slant range (51) is about 79,000 yards and the average maximum altitude about 50,000 feet. This

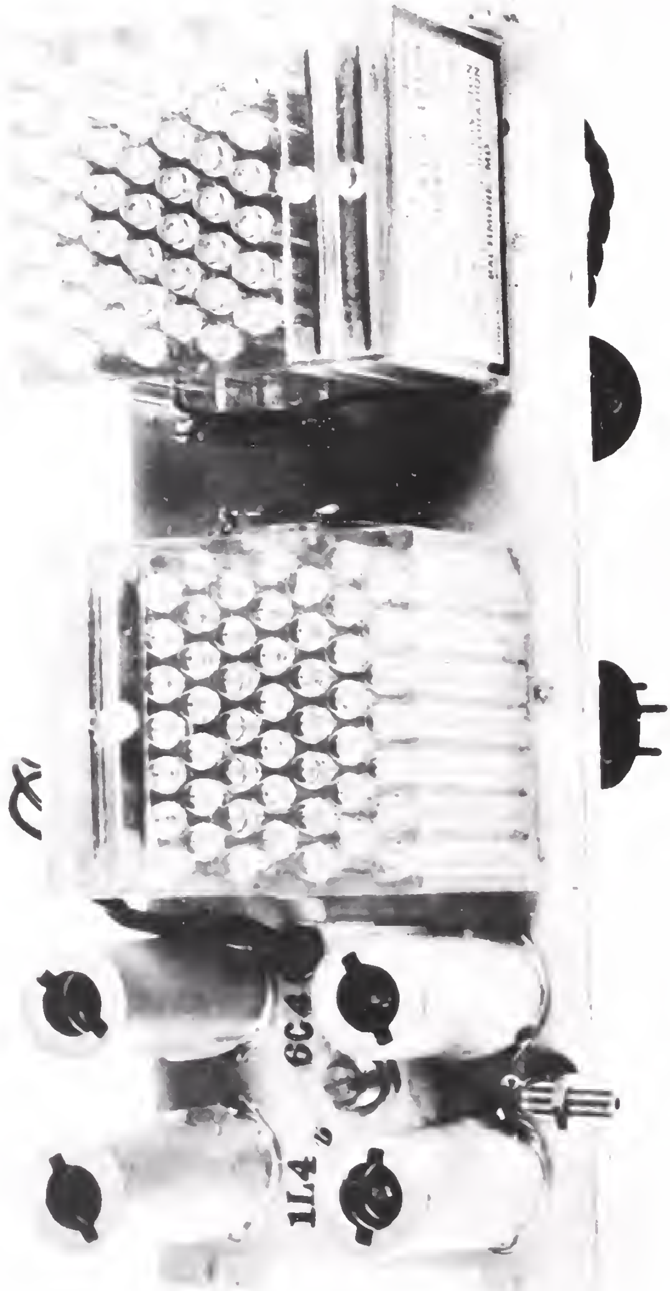


TRACKING A BALLOON-BORNE PULSE REPEATER BY RADAR FOR UPPER AIR WIND VELOCITY MEASUREMENT. DETERMINATION OF RANGE, AZIMUTH AND ELEVATION ANGLES GIVES BALLOON POSITION ... IS COMPUTED.

AND ELEVATION ANGLES GIVES



F[illegible] BALLOON RADAR SONDE EQUIPMENT SHOWING 200 MC [illegible] HEATER [illegible] TRANSMITTER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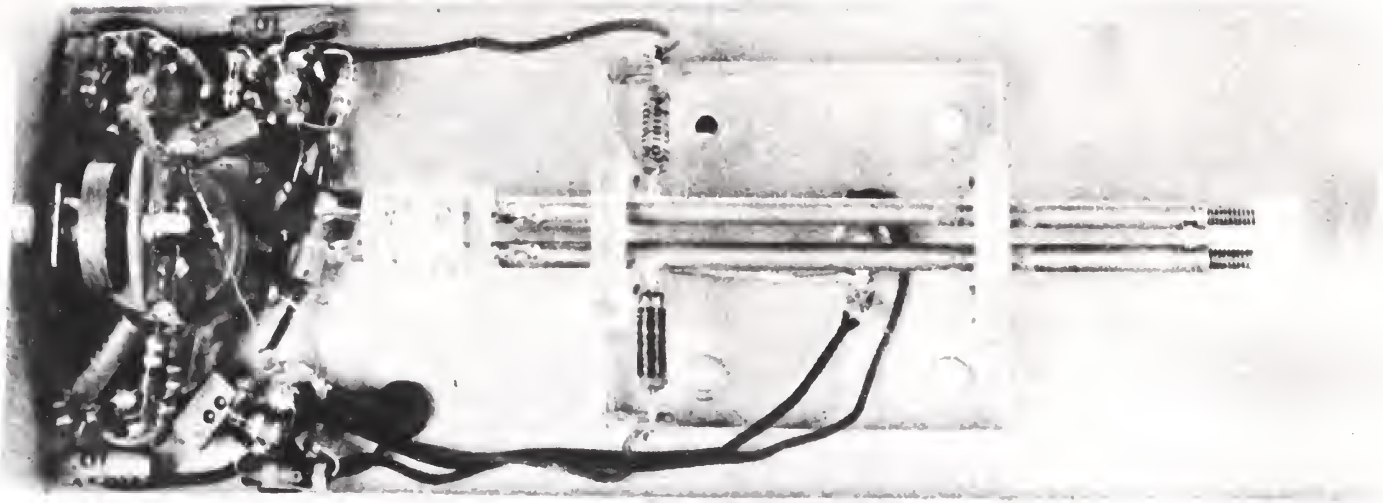

Fig 27 BOTTOM VIEW OF 700 MC PULSE REPEATER CHASSIS SHOWING RECEIVER–TRANSMITTER TUBE AND PARALLEL-LINE TUNED CIRCUIT. THIS IS THE PULSE REPEATER USED WITHOUT A RADIOSONDE SINCE A FIRE CONTROL RADAR IS EMPLOYED FOR TRACKING THE OVERALL CONSTRUCTION OF THIS UNIT IS SIMILAR TO THE 200 MC UNIT.

early type pulse repeater for which these data are given was designa d as the RT-35/AM. (The National Bureau of Standards initiated work o the pulse repeater system for meteorological balloons in 1942 at the request of the Bureau of Ships, Navy Department. These equipments we developed by Dr. H. Lyons, Mr. J. J. Freeman, and Mr. E. D. Heberlin.

Radar-Sonde System Using a Pulse Repeater. RT-92/AM is a recently developed pulse repeater (46). The repeater is sent aloft as part of the radiosonde balloon train, and simultane measurements of wind, pressure, temperature and humidity are made. slant range and azimuth angle of the balloon are measured with an SA radar (200 Mc) and the altitude is computed from the radiosonde data. The average slant range (51) is about 53,000 yards with an average ma imum altitude of 25,000 feet. However, maximum slant ranges of about 77,000 yards and altitudes of 59,000 feet have been obtained with th system.

(6) Continuous Wave Repeater System (47). Balloo altitude is reported by a pressure element. The change in range of the balloon is obtained by the variation in phase difference between audio note modulating a transmitted signal at one carrier frequency, and a note of the same audio frequency modulating a reemitted signal a new carrier frequency. Distance is then measured by the variation phase difference between the audio signals as the balloon moves off. Automatic tracking is used. (Work was started on this type of wind m uring equipment in 1938 at the National Bureau of Standards. Further development work of this system has been carried on in 1941 and 1943. It is still under development at the present time).

The reflectors described below have been dev oped and tested by the Army Signal Corps:

(7) The ML-307/AP is a cubical reflector (50) sim ilar to the ML-309/AP but is used with an SCR-268 (200 Mc) radar set. The average maximum slant range is 18,800 yards and the average maxim altitude about 18,600 feet. When it is used with a 100 gram pilot ba inflated with 45 cubic feet of hydrogen, the ascensional rate is 620

(8) The ML-307A/AP (Figure 28) is a modification the ML-307/AP balloon target. To increase the ascensional rate of th balloon and to prevent rain, snow, and ice from accumulating in the u pointing interior corner of the ML-307/AP, the three foil sheets form this corner were removed. The edges of the remaining cubical reflect of four interior corners was increased from 30" to 36". It was found the ranges obtained with this modified reflector were slightly greate those obtained with the ML-307/AP, while the drag on the ascending ba was considerably reduced.*

(9) The ML-350/AP (Figure 29) is a reflector targe consisting of three coplanar dipoles joined at their midpoints by a h which spaces the pieces at an angle of 60°. The dipoles are made of wood sticks 29" x ½" x ½" covered with aluminum foil to within ½" of e

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*The AAF Weather Service, using these targets, obtained ranges of 40,0 yards with the SCR-268 and 90,000 yards with the SCR-584.

Fig. - THE ML 307A/AP REFLECTOR.

end. The dipoles are suspended from a balloon clasp by three equal length cords which are fastened to one end of each stick. When tracked with the SCR-268 (200 Mc) radar the average maximum range and altitude of the ML 350/AP are 25,600 yards and 36,600 feet respectively. If carried aloft by a 100 gram balloon inflated with 45 cubic feet of hydrogen the ascensional rate is 1590 feet per minute.

This type of 3-dipole reflector can be assembled in the form of an equilateral triangle (Figure 30) with the metallic coverings insulated from each other. In 3 flight tests of this arrangement an average slant range of 28,110 yards was obtained. Two or more ML-350/AP targets may be suspended about 28" apart, one below the other. A 3 flight test of tandem reflector arrangements showed that the addition of more than two reflectors produced little increase in slant range. Maximum slant ranges of 35,000 yards and altitudes of 30,000 feet have been obtained with the two reflector suspension (center joined dipole type). However, with the corner reflectors the strength of the reflected signal varies inversely as the square of the wavelength.

C. Airplane System.

Wind aloft determinations and low level soundings can be made simultaneously in an airplane over a water surface, if the plane is equipped with both a pressure altimeter and a radio altimeter. The procedure is as follows:

(1) Determine an isobar by keeping pressure altimeter and radio altimeter readings constant.

(2) Then fly at right angles to this direction, keeping the radio altimeter constant.

(3) From the readings of the pressure altimeter, one may then determine the spacing of the isobars on a constant level surface, and hence the speed and direction of the gradient wind.

D. Turbulence Measurements Aloft.

Not only have observations of wind direction and velocity been made but also of wind turbulence aloft. At the University of Chicago a turbulence meter, essentially an accelerometer attached to the Diamond-Hinman type radiosonde, has been used. Tensions on the cord determine the audio-frequency of the transmitted signal. These frequencies are integrated by an electronic integrator and then indicated by a Speedomax recorder. Turbulence measurements have also been made from planes at the University of Chicago.

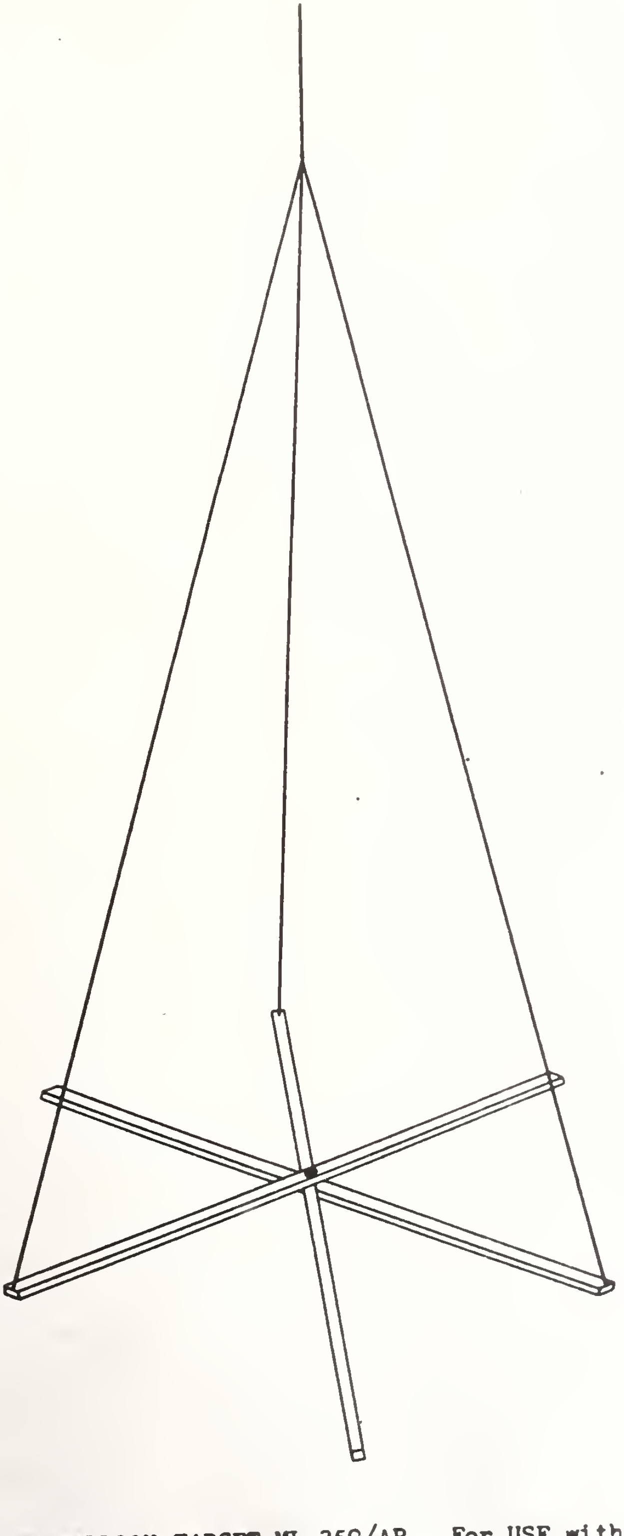


Fig. 29. PILOT BALLOON TARGET ML-350/AP . For USE with RADIO SET SCR-268

Side View . Prepared for Flight

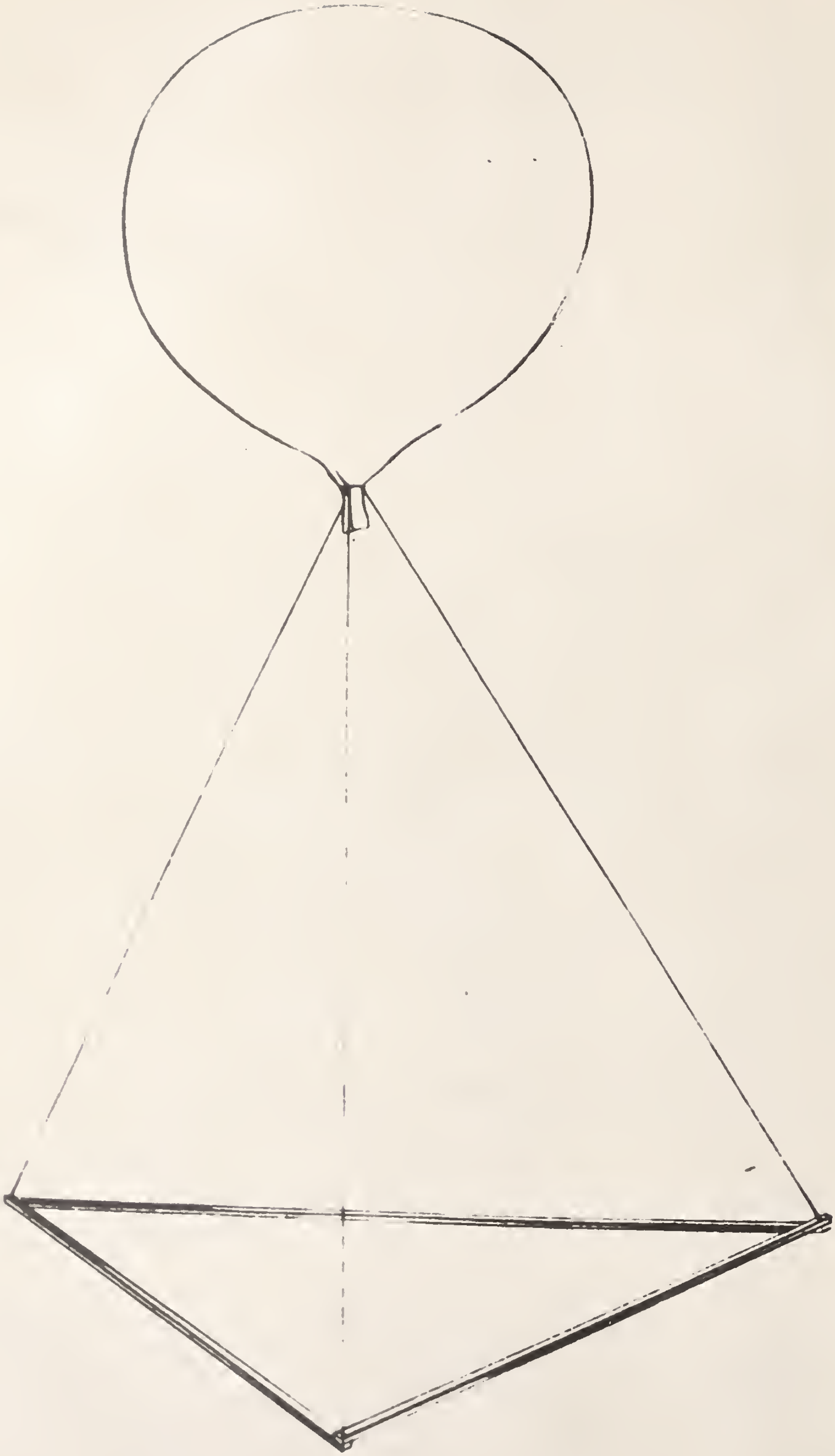


Fig. 30. TRIANGULAR ARRANGEMENT OF REFLECTOR ML 350/AP

VII. RATE-OF-RAINFALL MEASURING INSTRUMENTS.

A. Use of Data in Radio Propagation Problems.

The atmospheric attenuation of microwaves results largely from absorption by gases and from absorption and scattering by water droplets.

The attenuation due to gases arises primarily from oxygen and water vapor in the atmosphere. The percentage of oxygen either by volume or by weight, is known from numerous measurements and is fairly uniform within the troposphere. The amount of water vapor varies greatly with time and locality. Van Vleck's theoretical treatment (56) shows that the variation of this absorption with temperature and pressure is complicated. For a given temperature, pressure and humidity (20° C, 1013 mbs, and 6.3 gm/kg specific humidity) the combined absorption by oxygen and water vapor, as a function of radio wavelength, is shown by the solid curve in Figure 31.

The attenuation of microwaves due to water droplets is a function of the number of drops per unit volume along the path, their temperature and the size of the individual drops. These data are not measured by weather stations; however, a related element, rate of rainfall, is regularly observed. By using an empirical relationship of drop size distribution to rate of rainfall, the necessary data for computation of attenuation in db/km at various wavelengths for given rainfall rates is obtained. Ryde and Ryde (58) made such computations using Laws and Parsons (57) drop size data as given in Table 6, Page 72. The dashed curves in Figure 31 showing the microwave attenuation associated with three representative rates of rainfall were constructed from the results of Ryde and Ryde (58).

When the drop diameter is very small compared with the wavelength (less than 1/100) the computation reduces to a special case where the mass of liquid water per unit volume of air and the temperature are the only variables. This requirement is met in fog and fair weather clouds and even in rain for wavelengths greater than 35 or 40 cms. Raindrops greater than 0.6 cm in diameter are unstable and do not persist in rain.

The variation of water droplet attenuation due to temperature (55) may be introduced as a correction factor to be applied to the attenuation values graphed in Figure 31. When the drop size is very small compared with the wavelength, as in fog and clouds not associated with rain, the temperature correction factor is quite large, varying from 2 at 0° C down to 1/2 at 40° C. On the other hand, for radiation at less than 3 cms wavelength, through rain, where the drop size is a larger fraction of the wavelength, the temperature correction decreases and is usually less than ± 20% in the same temperature range, from 0° C to 40° C.

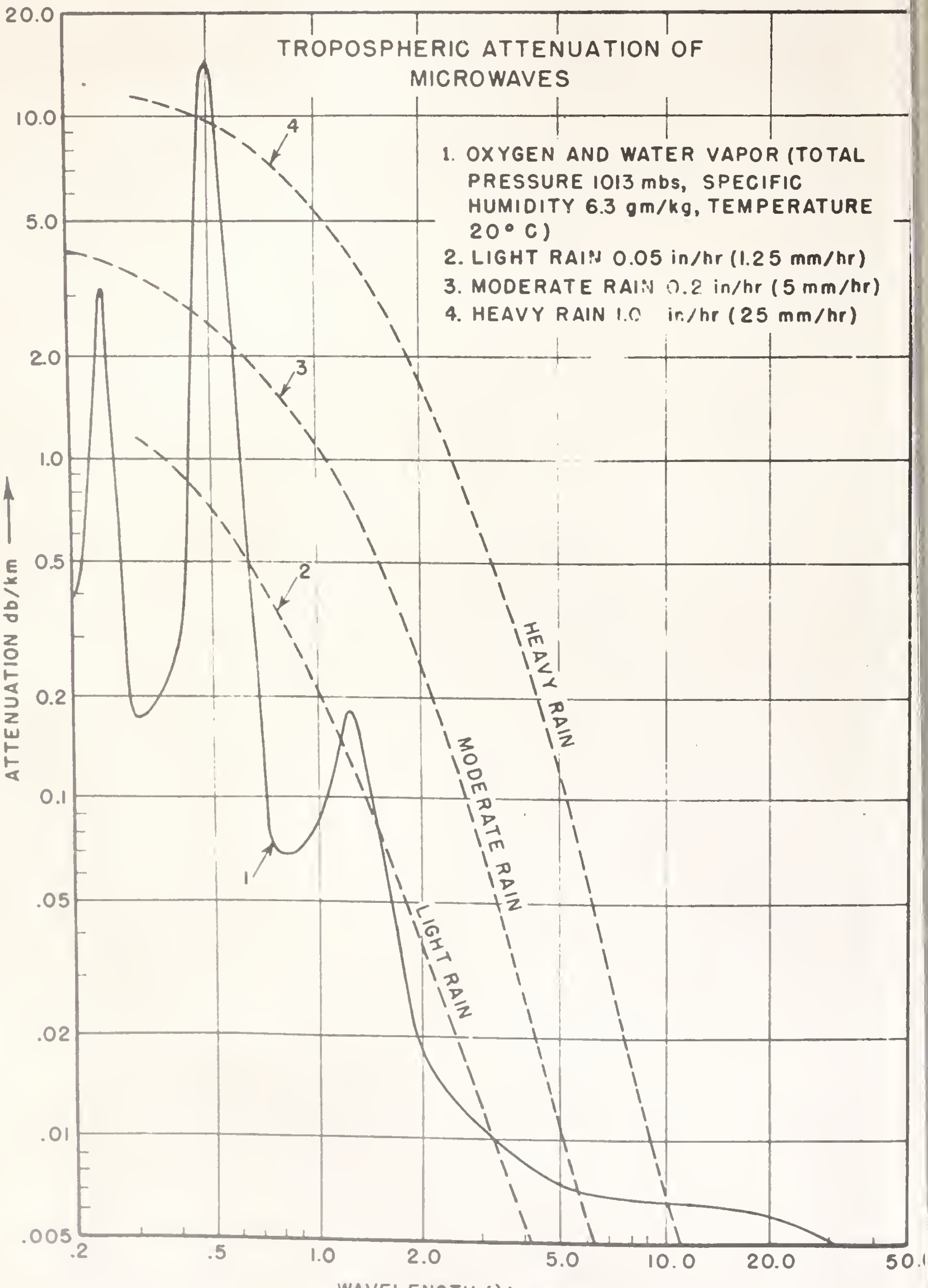

TROPOSPHERIC ATTENUATION OF MICROWAVES
1. OXYGEN AND WATER VAPOR (TOTAL PRESSURE 1013 mbs, SPECIFIC HUMIDITY 6.3 gm/kg, TEMPERATURE 20° C)
2. LIGHT RAIN 0.05 in/hr (1.25 mm/hr)
3. MODERATE RAIN 0.2 in/hr (5 mm/hr)
4. HEAVY RAIN 1.0 in/hr (25 mm/hr)
HEAVY RAIN
MODERATE RAIN
LIGHT RAIN
1
2
3
4
20.0
10.0
5.0
2.0
1.0
0.5
0.2
0.1
.05
.02
.01
.005
ATTENUATION db/km
.2
.5
1.0
2.0
5.0
10.0
20.0
WAVELENGTH (λ) cm

Fig. 31.

In other words, the temperature correction factor for intervening rain is smaller than that for fogs and clouds not associated with rain.

From the above, the radio engineer can see the variables involved in computing microwave attenuation due to size and temperature of water droplets. In radar surveillance and for radar storm detection purposes the microwave radio engineer is also interested in back-scattering (echo) produced by water drops of various sizes. This echo energy from droplets (62) varies directly as the sixth power of the droplet diameter D, inversely as the fourth power of the wavelength λ, and inversely as the square of the distance of the scattering particles from the radiating source. For effective echoing for storm detecting radar it is then desirable to have comparatively short wavelengths so that the ratio D^6/λ^4 is a maximum. Rain, as it is found in thunderstorms, hurricanes, and cold fronts consists of relatively large droplets and returns much more microwave energy than the smaller droplets found in fair weather clouds.

The meteorologist is also interested in improved means of tabulating rates of rainfall, measuring drop sizes, water content of clouds, etc. With a suitable radar set such as the AN/APQ-13 (3 cm wavelength) or AN/CPS-1 (10 cm wavelength) areas of large water droplets (see Figures 32 and 33) such as those associated with thunderstorms, cold fronts or hurricanes may be regularly detected at distances of 50 to 100 miles. Very intense storms have been "seen" as far as 200 miles. Over this radius the extent, direction and rate of motion of areas of rainfall can be observed. Storm detection radar observations are a powerful short-range weather forecasting tool.

The measurement of microwave attenuation and scattering due to water droplets is a field in which much investigation and basic research may be done. Such an investigation will employ instruments for observing rainfall rates, water droplet sizes, and the liquid water content of clouds. Some of the meteorological equipment now used or being developed is described below.

B. Rainfall Measuring Devices.

(1) The Ferguson-type Weighing Rain Gauge (53) is an instrument for measuring rate and amount of rainfall. It functions equally well for liquid or solid forms of precipitation. A collecting ring receives the falling precipitation and guides it into a bucket. Here it is weighed by a special scale which translates weight directly into equivalent units of rainfall. A stylus pen operated by the weighing mechanism moves across a chart on a clock-driven drum to provide a continuous record of the rate and quantity of rainfall. The rate of rainfall is indicated by the slope of the line. The first 6 inches of rainfall are recorded by an upward motion of the pen over the record sheet and the second 6 inches of

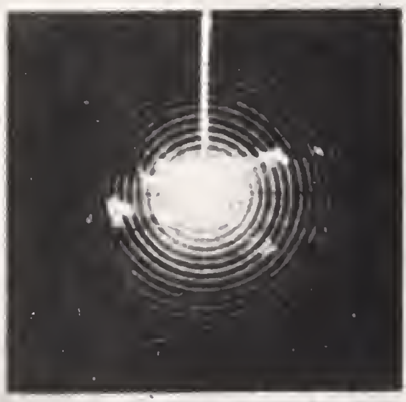
1235 EST

1245 EST

1300 EST

1315 EST

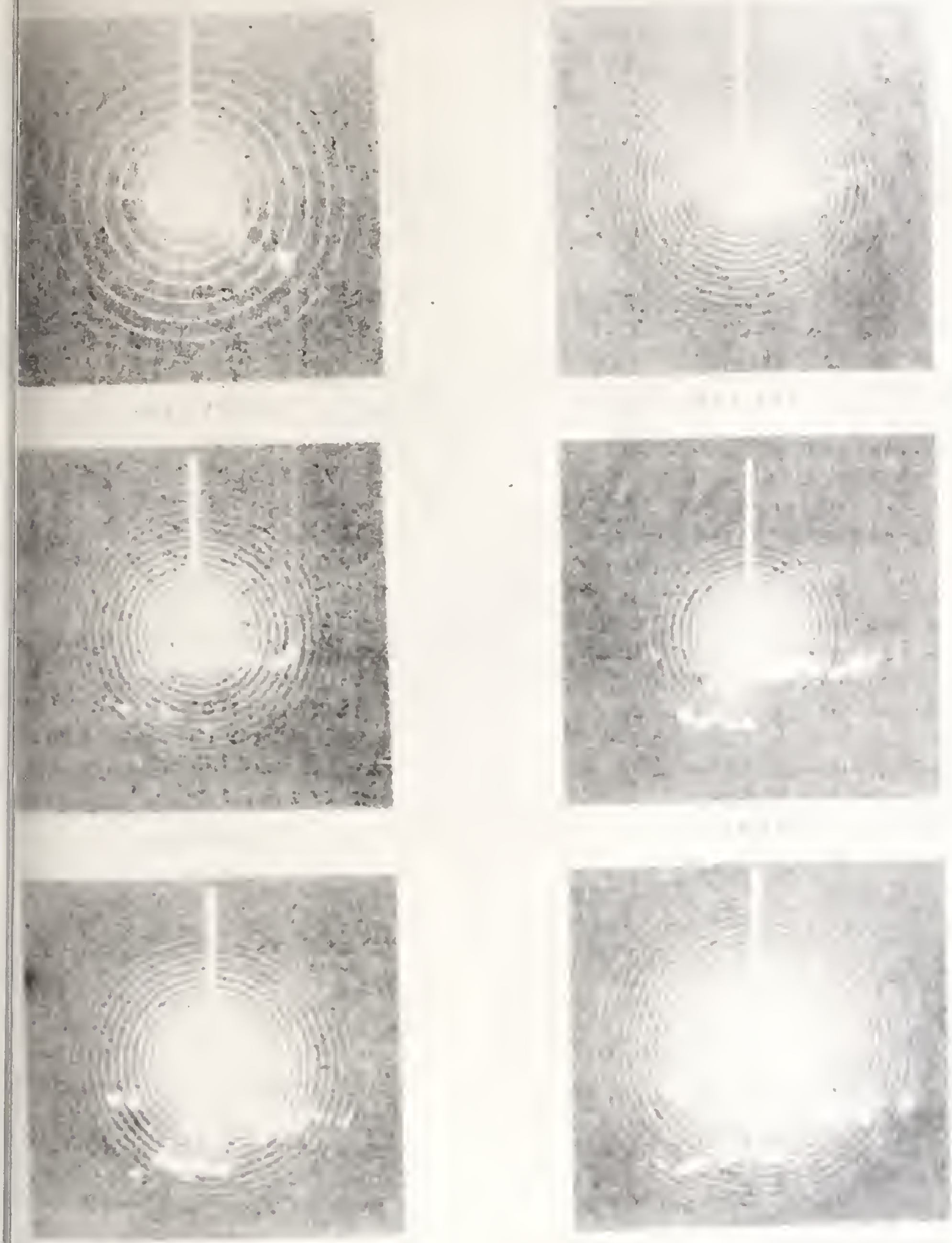
1338 EST



1353 EST

Fig 32 APPROACH OF COLD FRONT TOWARD BELMAR, N. J., 18 JUNE 1946

WHITE LINE TO TOP IS TRUE NORTH
CIRCULAR MARKERS ARE AT FIVE NAUTICAL MILE INTERVALS
ANGLE OF ELEVATION OF ANTENNA IS 2°



[illegible] PROGRESS OF COLD FRONT [illegible] 8 JUNE 194[illegible]

rainfall are indicated by a downward motion of the pen. The record sheet is 9 inches wide. The turning rate of the clock-driven drum may be changed to give one revolution every 6, 12, 24, 48, 96 or 192 hours. An oil immersed piston plunger attached to the shaft of the stylus pen damps out shock oscillations of the pen.

The weighing and recording mechanism is attached to a metal base plate. A housing fastened to the base, covers the instrument and supports the cylindrical collecting ring. Covers protect the scale and clock against moisture and dust. In its present form this gauge cannot be used for remote recording.

(2) The Tipping Bucket Rain Gauge (4) can easily be adap to remote recording. The rain is collected in a funnel and is directed to a U-shaped trough. This trough, the tipping bucket, til about a pin passing through the center along its narrow dimension. In the center of the U-trough a partition parallel to the tilting axis divides the trough into two equal sections. The center of gr ity is situated so that the trough is in a stable equilibrium when tilted on either side. When 0.01 inch of rainfall from the funnel collects in one side of the bucket the additional weight tilts the trough, automatically emptying out the water and bringing the empty section of the trough to the filling position. An electric switch is operated each time the bucket tilts. The amount and rate of rainfall (in units of 0.01") corresponding to the number and time of tilts can be recorded electrically on a clock-driven drum in so place remote from the tipping bucket. A linear error up to 10% at rate of fall of 18 inches per hour, and negligible at small rates c rainfall is introduced by the tilting time of the bucket. Rates of rainfall in excess of five inches per hour can scarcely be evaluate because of the slow turning rate of the recorder now used by the Weather Bureau.

(3) A Rate-of-Rainfall Indicator (54) has recently been developed at the National Bureau of Standards and is still in the experimental stage. The rain collects in a funnel, flows into a cylindrical receiver of about one inch diameter, and leaves through either an orifice or capillary tubes. The head of water above the outlet is a measure of the rate of rainfall. If capillary tubes are used as an outlet, the pressure head is directly proportional to the rate of rainfall. If the outlet is an orifice, the pressure head is approximately proportional to the square of the rainfall rate. However, the flow in capillary tubes is a function of temperature and consequently, the temperature of the water must be known and corrections made.

The experimental model of this instrument uses 3 capillary tubes in parallel and is designed to measure instantaneou rates of rainfall up to 10 inches per hour. Larger rates of rainfa may be measured by adding more capillary tubes in parallel. The otal time lag of the instrument is the time required for he receiver tube to drain and is of the order of 17 seconds. mall rates of rainfall may be measured by using only one capillary tube for an outlet. At present no provision is made or remote reading of the pressure head in the receiver cylinder.

C. Water Droplet-size Measuring Instruments.

The instruments which have been discussed measure ainfall rates. In addition, for attenuation computation we eed information about the drop size distribution. Laws and arsons made a study (57) relating drop size distribution empirically to rainfall rate. A summary of their investigations s shown in Table 6, and in the paragraph below an explanation s given:

Laboratory measurements were first made relating the ize of a known water droplet to the size and mass of a pellet t would form in falling into a tray of finely sifted well erated flour. After an empirical relationship was established, ampling measurements of rain drop sizes at different rainfall ates were made. For exposure to rainfall, flour trays 10 inches n diameter and 1 inch deep were used. Samples were made for ifferent lengths of time depending upon the rate of rainfall. fter exposure of a sample to rain at a known rainfall rate, the lour was dried carefully, and the hardened flour pellets were ifted through sieves of different sized meshes. The average mass f the pellets collected on each screen was computed by taking the otal weight of the pellets and dividing by their number. The ize of the water droplet corresponding to this average pellet ass was worked out for each of the collecting screens, and a able constructed relating the number of drops in different drop ize intervals to the rates of rainfall. The data in the accompanying table are taken from many such samplings and are an abreviation of the original Laws and Parsons Table.

Some other methods for measuring drop sizes have been sed (60):

1. Soot-coated slides (13). Exposures made with coated slides are easily damaged unless they are given a protective coat of lacquer.

2. Water sensitive dye-coated surfaces. These are found to be less easily damaged. A special 1/8 inch dye-coated moveable tape recorder has been perfected for exposure on an airplane, but in use the tape becomes waterlogged due to leaky exposing shutters.

3. Vaseline-coated surfaces. A small slide or rod,

(Continued on Page 73)

Table 6

Percentage of Total Precipitation on a Horizontal Surface Contributed by Drops of Various Sizes. Precipitation Rate, p, is in mm/hr, and Drop Diameter, D, is in cm.

Percentage of Total Volume

D (cm) \ P	0.25 mm/hr	1.25 mm/hr	2.5 mm/hr	12.5 mm/hr	25 mm/hr	50 mm/hr	100 mm/hr	150 mm/h
0.05	28.0	10.9	7.3	2.6	1.7	1.2	1.0	1.0
0.10	50.1	37.1	27.8	11.5	7.6	5.4	4.6	4.1
0.15	18.2	31.3	32.8	24.5	18.4	12.5	8.8	7.6
0.20	3.0	13.5	19.0	25.4	23.9	19.9	13.9	11.7
0.25	0.7	4.9	7.9	17.3	19.9	20.9	17.1	13.9
0.30		1.5	3.3	10.1	12.8	15.6	18.4	17.7
0.35		0.6	1.1	4.3	8.2	10.9	15.0	16.1
0.40		0.2	0.6	2.3	3.5	6.7	9.0	11.9
0.45			0.2	1.2	2.1	3.3	5.8	7.7
0.50				0.6	1.1	1.8	3.0	3.6
0.55				0.2	0.5	1.1	1.7	2.2
0.60					0.3	0.5	1.0	1.2
0.65						0.2	0.7	1.0
0.70								0.3

The above is taken from the 3rd report of Ryde and Ryde entitled: "Attenuation of Centimeter and Millimeter Waves by Rain, Hail, Fog and Clouds." (58)

This table is an abbreviation of the original table of J. O. Laws and D. A. Parsons as presented in their article: "The Relation of Drop Siz to Intensity of Rainfall." (57)

coated with molten vaseline just before exposure gives an excellent means for direct observation of actual particles. The droplets penetrate the molten surface and are imbedded as the vaseline solidifies. The droplets are then preserved in a spherical shape for measurement. Exposures have been taken with this system at wind speeds as great as 180 miles per hour.

4. Optical scattering device. A collimated light beam is directed through air containing droplets. The scattering by the droplets is a function of the diameter and number of the water particles. A light sensitive cell indicates the amount of scattering in a direction normal to the collimated beam. A trap eliminates the direct light illuminating the droplets. This system is especially applicable to the study of cloud particles. Attempts have been made to relate the amount of light scattered to the liquid water content of the clouds.

5. Photographic method. Westinghouse Research Laboratories (65) developed a method of measuring water droplet diameters in connection with a study of sprays from various types of nozzles. A beam of light from a spark gap source is focused by a condenser lens across an opening in a water droplet channel on to the lens of a camera. This camera lens is adjusted so that the droplets confined in the narrow focal plane of the channel are shown in clear relief against the light source on the photographic plate. The overall magnification obtained on the plate is 32 diameters. The exposure time of each photograph is about 10^{-5} seconds.

The Westinghouse Research Laboratories suggest several improvements in their equipment. These are:

a. A camera using a narrow depth focus, short focal length lens, a long extension bellows and a 5" x 7" (or larger) photographic plate. The magnification on the plate should be about 5x.

b. A fine-grained emulsion photographic plate similar to the micro-film type in texture.

c. A projector with a high resolution lens, giving a magnification of about 50x. This combined with the 5x magnification on the plate would give an overall magnification of 250 diameters.

d. A high speed motion picture camera, synchronized with the spark gap light source for study of droplet motions in the channel.

D. Liquid Water Content Measuring Instruments.

(1) The General Electric Cloud Meter (61).

Whereas the above described methods give indications of rain or cloud droplet size, an instrument has been developed which measures water content of a column of rain or cloud droplets. The measuring element (a), or collector (Figure 34), is a porous metallic plug, 0.5 cm in diameter, mounted in a streamlined holder and directed into the wind by a vane. A small vertical capillary tube is connected to the head. This tube is filled with water before exposure and an 18 cm head of water applies a suction to the collecting porous surface exposed to the passing droplets. Water drops blown on to the plug surface are immediately drawn into the tube. This increases the water content of the capillary tube and causes a water droplet to form at the tube base (b). Here the droplet grows to a given size, and then contacts an insulated capillary receiving slot designed to take the droplet away from the end of the collector tube. In passing from the collector to the receiving slot the droplet momentarily closes an electric counting circuit. The capillary size is usually adjusted so that the amount of water necessary to produce this operation is about 0.001 gram. Greater sensitivity can be obtained by reducing the distance between the collector tube base (b) and the capillary slot in the top of the receiving tube at (c).

The number of drops is counted as they collect on the end of the capillary tube and complete a counter circuit by touching the slot strips across the receiver tube. A recording microammeter is placed in the circuit to count the number of drops which pass from the capillary tube. These droplets accumulate in the receiving tube until they form a large droplet which falls by its own weight from the bottom of the receiver tube at (d) into a container. A mark is also made on the microammeter recorder roll each time a large drop falls.

Calibration of the unit is accomplished by determining the weight of the large droplets. Since the number of small droplets contained in a large drop is indicated, the exact weight of each small droplet can also be computed. Knowing the air velocity at the collecting head, the number of small and large droplets counted per unit time and the absorption efficiency of the collector, the liquid water density of the column of air striking the collecting head may be computed. Several determinations may lead to a representative value for the liquid water density. The unit is provided with an electric heating attachment for measurements at temperatures below freezing. The cloud meter may be used on the ground or in an airplane.

(2) <u>The M.I.T. Capillary Collector</u> (79).

The M.I.T. Department of Meteorology, De-Icing Research Laboratory has used a capillary collector which is in some respects similar to the G. E. Cloud Meter. The collector unit consists of a cup-shaped porous plug (1/2 in. in diameter) made of porex, which is sealed in a streamlined holder, a measuring unit and a capillary tube connecting the collecting head to the measuring unit.

Airborne water droplets strike the porous plug and are drawn into the capillary tube. At the same time an equal amount of water is emitted at the end of the measuring tube. The rate of collection of liquid water is measured by noting the rate of flow of a given point in the water column along a fine bore capillary tube having a volume of 0.01 cc/cm length. A measuring scale is mounted behind this capillary tube so that water column flow can be read with respect to time. Stopcocks are provided for filling and draining the system. An air-flow pressure differential system is provided to keep the wind stream which strikes the porous collecting head from forcing air into the capillary collecting system along with the water droplets.

(3) <u>Liquid Water Collecting Cylinders.</u>

Solid cylinders of metal or porous material have been used for collecting airborne water droplets, and thus giving an indication of liquid water content of air in clouds and rain.

Solid rotating cylinders of 6", 2", 1" and 1/8" diameter have been exposed from an airplane at below freezing temperatures in clouds or rain by the M.I.T. De-Icing Project (79). The smaller droplets are deflected around the curved edges of a relatively large cylinder, whereas larger droplets, on account of their greater inertia, strike the cylinder surface and form an ice deposit. Owing to the selective properties of a given diameter cylinder for collecting drops of a given size or larger, an estimate of the distribution of drop size in a given rain or cloud area can be made.

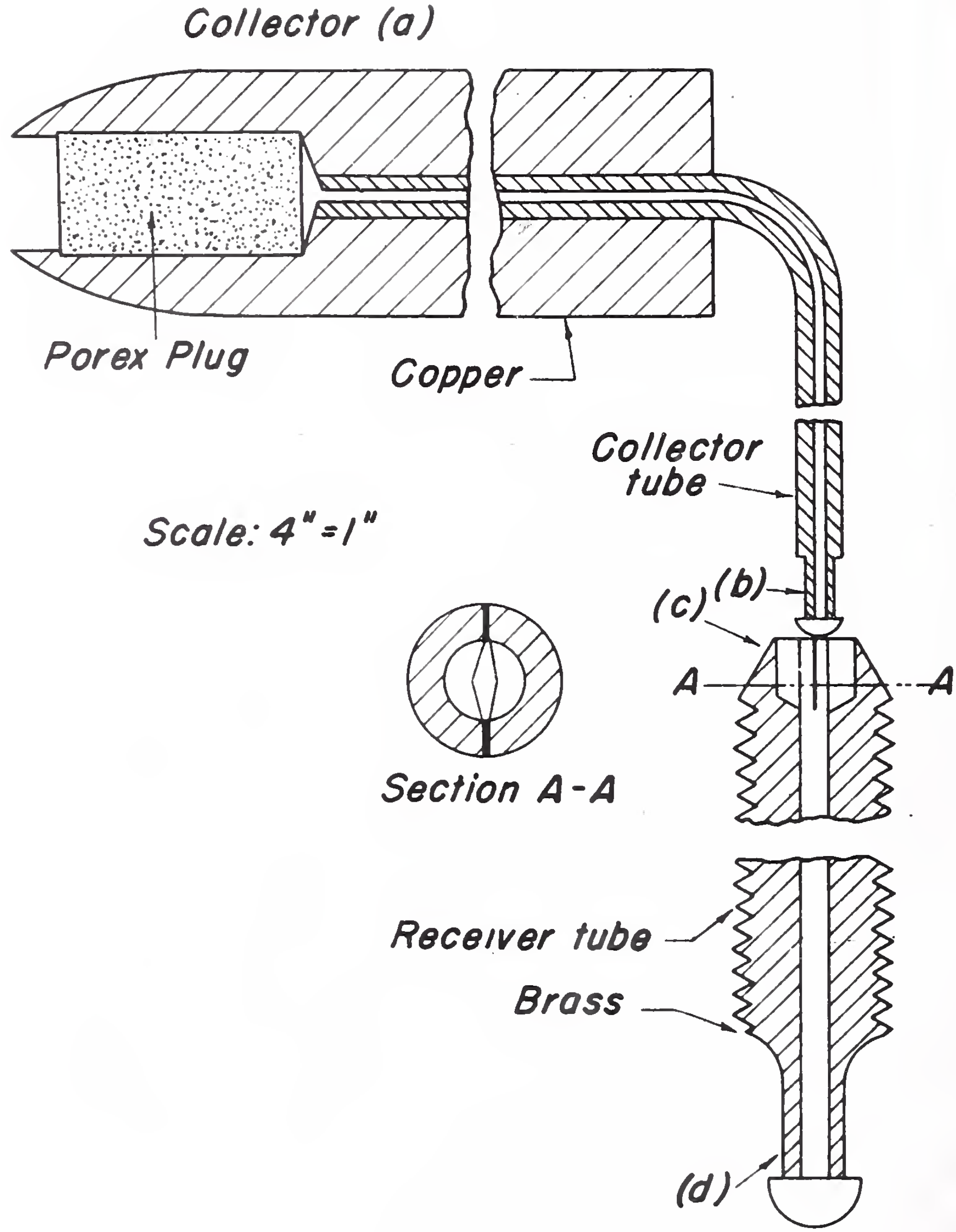


FIG. 34. SKETCH OF COLLECTOR AND COUNTING UNIT OF G. E. CLOUD METER.

The General Electric Research Laboratory has used units of porous cylinders of different diameters, exposing them from the ground. The windborne water droplets strike the porous cylinders and are absorbed in the material. The amount of water collected during an exposure is obtained by observing the increase in weight of the cylinders. Drop size distributions can also be estimated with this system.

(/) The General Electric Cloud Analyzer (60).

Another liquid water measuring device for radiosonde use, being developed at General Electric Laboratories, is described below:

It consists of a one megohm chemically treated wire acting as a sensing element in the radiosonde circuit. The salt impregnated wire acts as a collector of water as the balloon borne radiosonde slowly rises through clouds or rain droplets. The reaction of the salt and water on the wire varies the electrical resistance of the conductor as a function of the liquid water content of the adjacent air. The radiosonde constantly transmits this information to the ground receiving station. If this element is successful, it is planned to construct an airborne instrument consisting of two such elements, one in free air and the other at the stagnant point of a small cylinder. The ratio of the amount of water particles collected by each of the two elements can be used to determine an effective particle size.

VIII. Methods of Exposing Instruments.

Various types of instruments and circuits have been descri- but little has been said about methods for lifting and exposing measuring elements.

At first the regular radiosonde instruments were attached t a free balloon weighted down with sand or water ballast. The balloon was given a slow ascensional rate at low levels by allow ing the ballast to escape slowly. Later captive balloon was use Continuous meteorological soundings for the lowest few hundred f are obtained by mounting meteorological instruments on a mast or tower and automatically recording the data at the ground.

A. Captive Balloons and Kites.

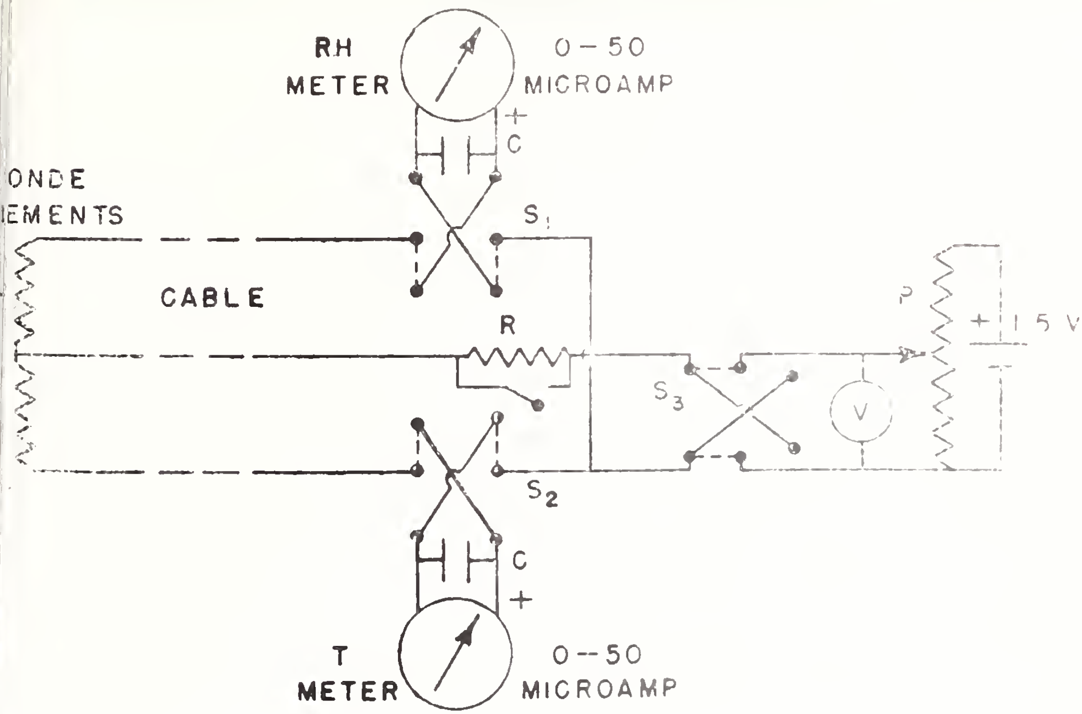
1. Radiosonde Method. In the regular radiosonde, the baroswitch allows reports of temperature or humidity data only a fixed 5 mb pressure intervals (about 150 feet height intervals n sea level). The baroswitch is not sensitive enough to small cha in pressure at low levels. This is a very important defect becau upon it depends:

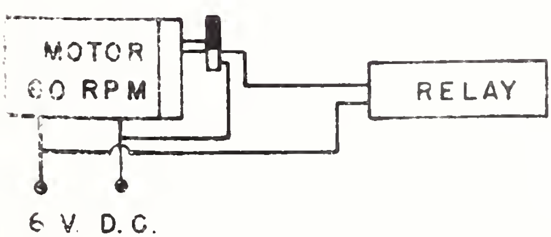
1. Calculations of height.
2. Accurate measurements of pressure.
3. Frequent reports of temperature [illegible]

It was decided to replace the baroswitch with a clock driven armature (22) to get more frequent [illegible] ature and humidity. Heights were to be estimated from the length of cord and angle of elevation of the balloon. Pressures could be calculated from the hypsometric equation from known values of height, temperature, humidity and surface pressure. Usually the procedure was to let the balloon ascend to its maximum altitude rather rapidly, and then to make detailed readings of the [illegible] where marked moisture gradients or temperature inversions were shown. The results obtained with this method were quite satisfac tory and the technique was found useful for locations equipped [illegible] the standard radiosonde recorder. However, it was found that the radiosonde recorder was too cumbersome and delicate for field use Furthermore, for military purposes, where radio silence was neces sary, the system could not be used.

2. Wiresonde Method. To overcome this difficulty, Washington State College (1 and 74) developed a system which was much lighter and more adaptable to general field use. The temper ature and humidity elements were carried aloft by the balloon, and the measurements transmitted electrically through wires. The difficulty of the extra weight of a cable connecting the exposed elements in the balloon with a recording device on the ground was solved by using a strength member of light, strong material. The

conductors of #30 copper wire were spiraled around the strength member with a pitch of 4-6 feet. The cable was coated with airplane dope to cement it together and to make it waterproof. The weight of the cable was approximately one pound per thousand feet, and it had a tensile strength of 64 pounds. A reel was used to control the length of cable, and slip-ring contacts maintained electrical connections between the measuring elements in the balloon and the ground meters.





"The potentiometer P applies a constant voltage (0.36 volts at low relative humidity and [illegible] volts at high relative humidity) to both of the independent circuits of the sonde proper. The currents, determined by the resistances of the relative humidity and temperature elements respectively are read on the 'RH meter' and 'T meter'. S_3 commutes these currents at half-second intervals. S_1 and S_2 actuated simultaneously with S_3, maintain constant polarity at the meters. The 1,000 microfarad condensers C & C smooth the currents through the meters. S_1, S_2, S_3 are contained in the pile-up of a single relay which is actuated by a miniature worm-geared motor. The 10,000 ohm protective resistance R is shorted out during the measurement. All components, except the sonde cable and 6 volt storage battery, are housed in a single case 20" x 9" x 7". "The Captive Radiosonde and Wiredsonde Techniques for Detailed Low Level Meteorological Soundings"

a Washington State College System used alternating current for the relative humidity and temperature elements. This prevented polarization errors and thus gave more accurate humidity readings than were possible with direct current. The alternating current was introduced by commutating the direct current by means of a direct current motor driven switch pile (see Figure 25).

When the Washington State College wiredsonde system was first originated the sort of difficulties found were:

1. Winds over 12 m.p.h. forced the lifting balloon down, with the result that if the sounding was to be continued a kite had to be substituted. The turbulence and gustiness of a strong wind caused the kite to lift irregularly and sometimes these jerks broke the connecting cable.

2. Temperature and humidity readings were not accurate because air was not circulated around the measuring elements.

3. Insulation of the conductor cable became electrically leaky if it got wet. With constant usage the insulation flaked off of the cable.

4. The winding reel was difficult to control as it was not provided with a brake for unreeling cable, and with only a crank for reeling in the cable.

5. The reel was too light for the work it was required to do.

6. The reel [illegible] surface [illegible] of [illegible] is rather [illegible]. This irregular surface [illegible] cable [illegible]

7. The slip ring contacts on the reel were not [illegible]tected and got dirty quickly.

8. The indicating meters were not shock-mount[illegible]

For improved means of lifting the instruments, the Bureau of Ships, U. S. Navy, has developed the kytoon. The kytoon (76) (see Figure 36), is an aerodynamic combination of balloon and kite. In calm air, it is buoyed up and supports the instruments the same as any balloon, but in strong wind, it lifts like a kite and is never driven down. It is so arranged that its lift remains practically constant regardless of the wind speed. The kytoon was first developed to support radio antennas over aviators' life rafts. Its present state of development is not entirely satisfactory for wiredsonde work, but research is being done, and an improved kytoon is expected.

b. The Navy Radio and Sound Laboratory (81) at San Diego, California, has developed a very satisfactory low level sounding system. It consists of a balloon-borne temperature-humidity unit, a cable reel, and a ground indicator box. The system is battery operated and may be transported by two men.

The construction features of this system are:

1. A 600 cubic foot Seyfang balloon carries the temperature-humidity measuring unit. The shape of the balloon is similar to that of the kytoon. It is 20 feet long, and has a maximum diameter of 7 feet at the middle. The free lift of the Seyfang balloon in calm air is 7 pounds. This lift increases to 18 pounds in an 11 mph wind. The helium leakage is about 20 cubic feet (or [illegible]) per day. In an 11 mph wind the balloon holds an angle of better than 70° with the horizontal. The balloon does not lose its shape with repeated use.

2. The air-borne temperature-humidity unit is contained in a double walled aluminum shield. An electric blower powered with a 6 volt battery draws a 3 mph air current past the temperature and humidity elements. The total weight of this air-borne unit, including batteries, is 1 lb 6 oz.

3. A three conductor cable connects the air-borne elements to the ground indicator box. The length of cable is controlled by a crank operated reel. The reel is 10 feet in circumference and the winding surface of the reel is 18 in. wide. The cable is

wound on 10 metal rods spaced at equal distances around the circumference of the reel. The length of cable unreeled is measured directly by a counter. For both lightness and strength of construction the reel is made out of Duralumin.

4. The ground indicator box houses the measuring circuit. A switch is provided for changing the cable connections to the temperature or humidity element. The measurements of temperature or humidity are made by a comparison method. A voltage divider is used as a current source for the circuit. First, a standard resistance is placed in series with the meter and the current source. Then the voltage of the divider is varied until a given current flows through the fixed resistor. The standard resistor is then replaced by the temperature or humidity element. In order to bring the reading at zero temperature to a convenient place on the meter scale a large adjustable resistance is placed in parallel with the temperature element. Similarly a series resist nce is used for the humidity element.

A bucking circuit is shunted across the meter to obtain greater range. This consists of another voltage divider which impresses an opposing voltage across the meter in opposition to that impressed upon it by the measuring circuit. This is used to expand the range of values over which readings may be taken. The temperature range of the measuring circuit is from 0° to 44° C. The humidity range is from 10% to 100% relative humidi A motor commutates the current flowing through the humidity element at the rate of 50 cycles per minute.

The performance of this equipment has been tested quite extensively. Three independent sounding stations were set up within 400 feet of each other and simultaneous soundings were made by all three stations. Observations were made simultaneously at the three stations and at 30 different levels between 0 and 1,000 feet. The average deviations of observed temperature and humidity at the 30 levels was found to be within ±0.1° C and ±0.5% relative humidity, respectivel

These deviations were found to be about the same as the differences for two different observers reading the same meter.

c. An improved wiredsonde system has been developed for the Bureau of Ships, Navy Department (80) by the Friez Instrument Division of Bendix Aviation Corporation. This system employs the conventional type radiosonde ceramic thermometer and strip hygrometer (see Pages 5 and 20). These measuring elements are mounted in a motor-ventilated, balloon-borne shield. The visual indicating panel on the ground is connected to the air-borne unit by a three conductor cable and a special cable reel. (See Figure 37, Page 87).

Some of the improved construction features of this system are:

1. The air-borne unit is housed in a double walled, spun aluminum can, which shields it from rain and solar radiation. The unit is ventilated by a centrifugal blower, driven at 1,500 rpm by an electric motor. The motor power is supplied by a 6 volt silver chloride-magnesium battery, activated with water. The battery weighs only 24 grams and supplies adequate power for 60 minutes. The motor, by means of a cam, actuates two double-pole, double-throw switches, which reverse the current through the hygrometer elements. The entire weight of the air-borne unit is 500 grams.

2. The three conductor cable used with this equipment is covered with a highly moisture impervious plastic. The cable has a tensile strength of 100 lbs. and weighs about 3 lbs. per 1,000 feet. The leakage resistance between cable conductors is 100 megohms per 1,000 feet.

3. The cable reel is mounted on a steel stand at a convenient height for cranking. The crank may be used either with direct drive or 1/3 speed. The reel is about 12 inches in diameter and 15 inches long. A counter indicates the number of feet of cable played out and is used with the elevation angle to compute the height of the balloon. Brakes are provided for maintaining a constant cable length, and for locking the azimuth position of the reel.

4. The dual bridge circuit panel on the ground is provided with two meters. Temperature and humidity values are obtained by referring the meter deflection to temperature and humidity calibration curves. It is necessary to throw a toggle switch to the temperature or humidity position to read the meter deflections.

5. A preflight calibration of the temperature and humidity elements is obtained by enclosing the air-borne unit in a calibration chamber with a saturated solution of sodium chloride which maintains a fixed humidity in the chamber. Wet- and dry-bulb thermometers, visible through a port in the top of the chamber are used to compute the relative humidity of the air in the chamber. Ventilation is provided by the motor driven blower of the enclosed air-borne unit.

The accuracy of this system is very good. Within the temperature range from $+7$ to $+44^\circ$ C, over the humidity rang from 20% to 95% the humidity may be measured within an accuracy c ± 2 relative humidity units. The temperature may be measured to $\pm\frac{1}{2}^\circ$ C over the range from -7 to $+44^\circ$ C. The accuracy of the t perature and humidity measurements made with this system is very good because of the forced ventilation provided by the motor in t air-borne unit. The use of alternating current through the hygro meter element extends to 60 minutes or more the period during whi the element will measure within ± 2 relative humidity units.

d. Another system (80 and 77) under development at the Bureau of Standards, for the Navy, is quite different in design i the following respects (see Figures 37a, 38, 39 and 40):

1. Heights of the instruments above the ground ar determined by a pressure cell carried aloft wi the temperature and humidity elements. In oth wiredsonde systems, heights are determined by the length of the cord used and the elevation angle of the balloon, or by some other triangulation system.

2. Ventilation of the temperature and humidity ele ments is accomplished by a gravity driven motor Other systems have an electric ventilating moto or depend upon the ascensional rate of the balloon for circulation of the air around the temperature and humidity elements.

3. The gravity driven motor is also used to regula the number of readings taken each second instea of a clock or pressure interval.

4. The system is completely energized from 60 cps commercial power.

The pressure capsule, temperature and humidity elements of the regular radiosonde are used in this new type wiredsonde gear.

The slightest expansion of the pressure cell with in creasing altitude changes the reluctance of a high permeability ir

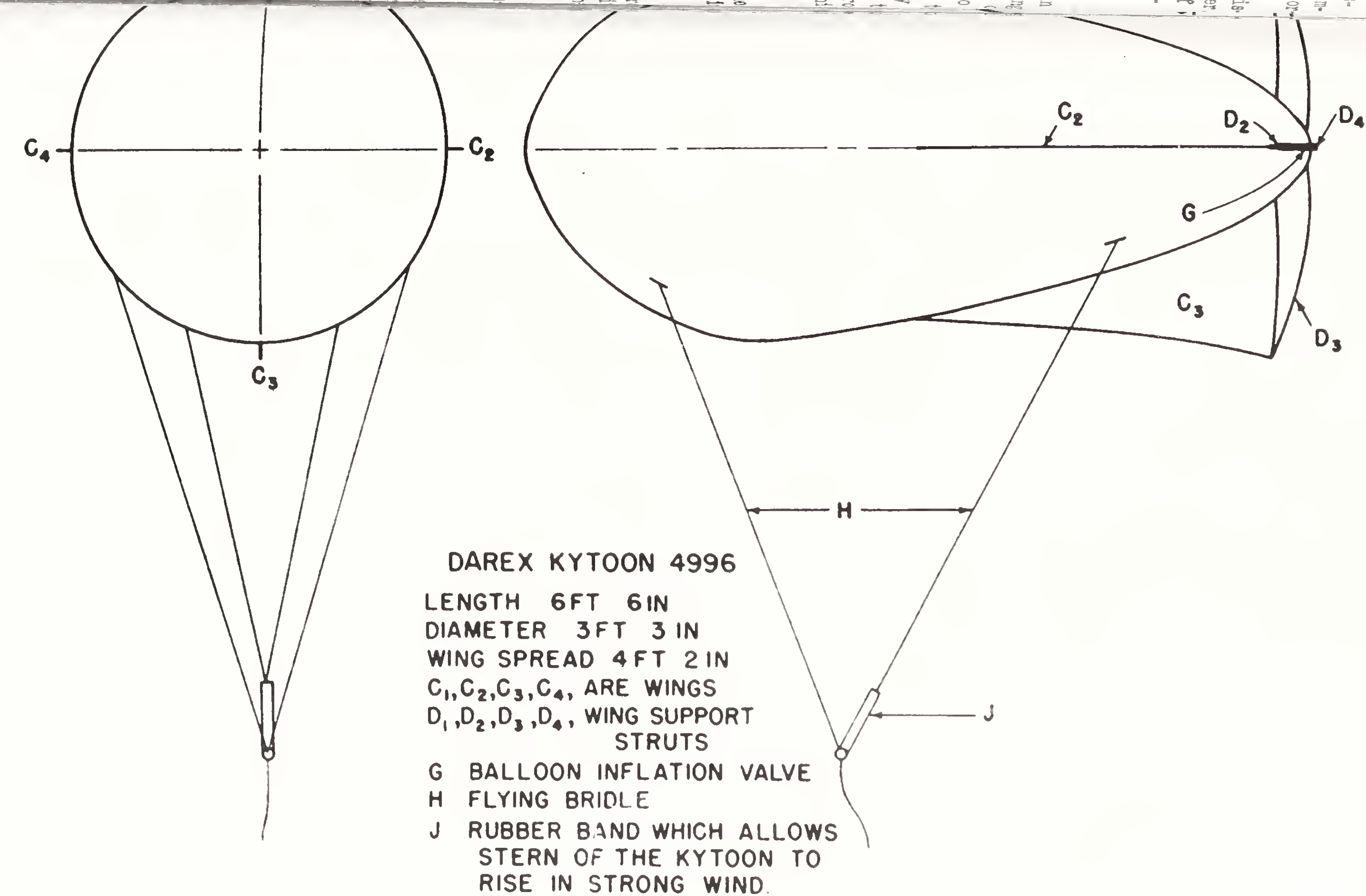


Fig. 36. THE KYTOON

circuit, by increasing the air gap over part of the circuit path. Magnetic flux through the high permeability iron and variable air gap circuit is induced by a coil of wire energized by 60 cps alternating current. Thus the pressure cell, through the variable air gap in the magnetic circuit, controls the number of lines of magnetic intensity passing through the core of the coil and hence the inductance impedance of the coil, as a function of altitude. The alternating current is switched through a reference impedance, the pressure controlled impedance, the ceramic resistor and the strip hygrometer in turn, and a record is made of the respective voltages.

Ventilation is provided for the humidity and temperature elements by a gravity driven fan. For this, the equipment is connected to the balloon by means of a cord which is wrapped around a drum and then attached directly to the balloon. The fan is geared to a drum which is driven by the unwinding of a cord around it, due to the weight of the equipment and the lift of the balloon or kite. A governor is used to control the speed of unwinding and hence the speed of ventilation. A reel unwinds at 2 rpm while the fan turns at 1500 rpm. A circular commutator, attached to one end of the gravity motor reel, switches the reference impedance, the pressure impedance, the temperature element and the humidity element into the ground recording circuit twice each minute.

The cord which mechanically secures the balloon-or kite borne instruments to the ground reel and at the same time electrically connects the pressure, temperature and humidity sensitive elements to the ground recorder is a three conductor cable. A 1/4 hp direct current reversible motor regulated by a rheostat operates the reel. The reducing gear train between the motor and the reel provides ample mechanical advantage to control any reel torque due to varying cable tension. The cable is wound on the reel by an automatic spacing mechanism (level winder) which distributes it in even layers. Electrical contact between the balloon cable and the ground indicating equipment is made by means of slip ring contacts attached to the cable wires through the axle of the reel. The slip rings are enclosed in a dust-proof box. Two of the conductors in the three conductor cable are used to connect the instrument to the ground recorder, while the third is used as a ground for draining off vertical potential gradient charges. This prevents spurious currents from deflecting the microammeter in the ground recording circuit.

In Figure 40 it is seen that a tapped transformer is used to feed current to the wiredsonde elements and to the plate circuit of a 6SJ7 containing the microammeter. The plate voltage and grid voltage are thus out of phase and cause a constant average plate current to flow for any values of wiredsonde measuring element impedance in the grid circuit. This obviates the necessity of using

FIGURE 37

COMPLETE EQUIPMENT (OPERATIVE)

Fig 37a LOW LEVEL WIRE [illegible]

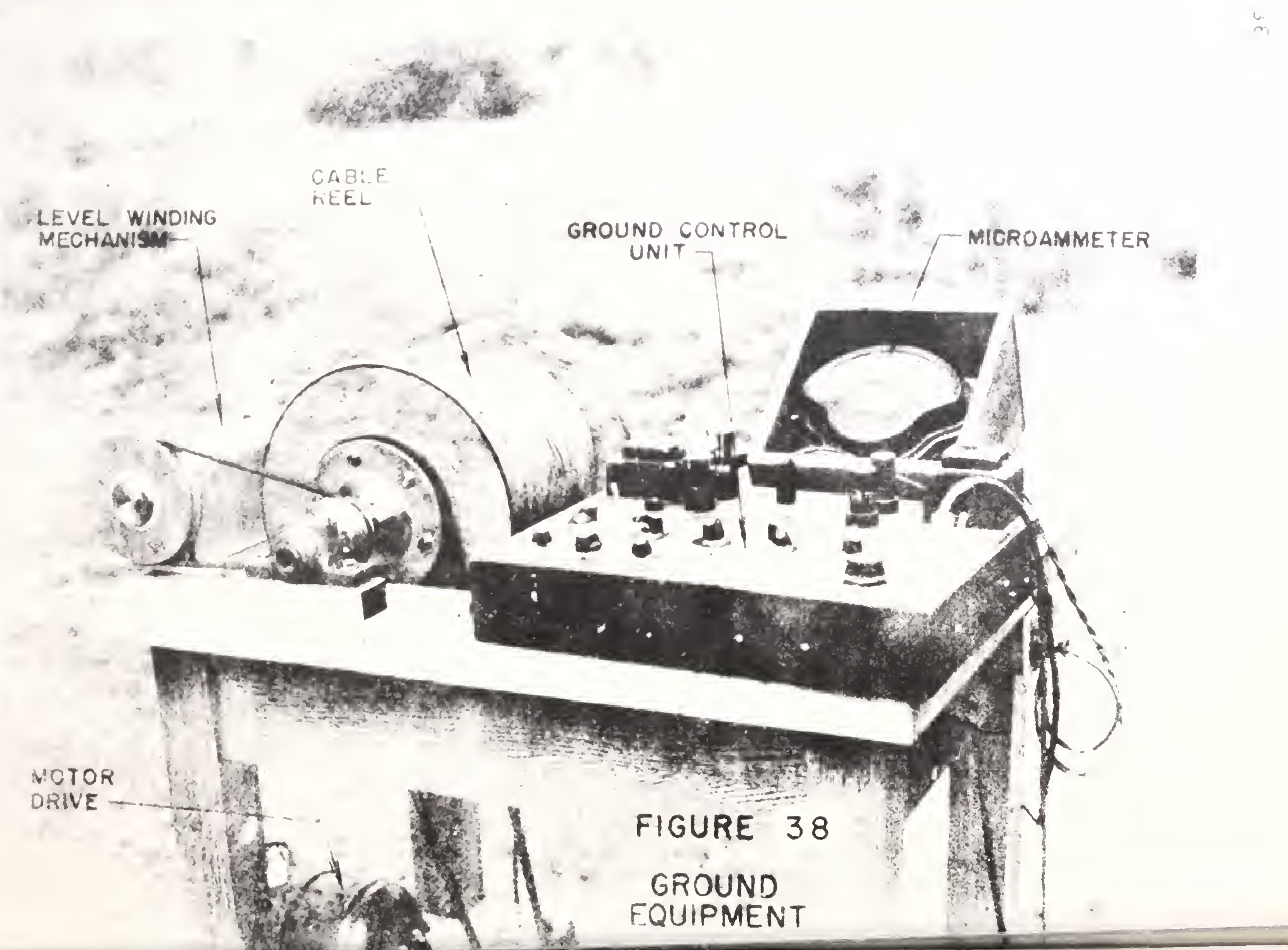


FIGURE 38

GROUND EQUIPMENT

ALT - ALTITUDE
R = REFERENCE

FIGURE 39

RECORDER AND TRACE

Fig. 39 N. B. S. LOW LEVEL WIREDSONDE RECORD.

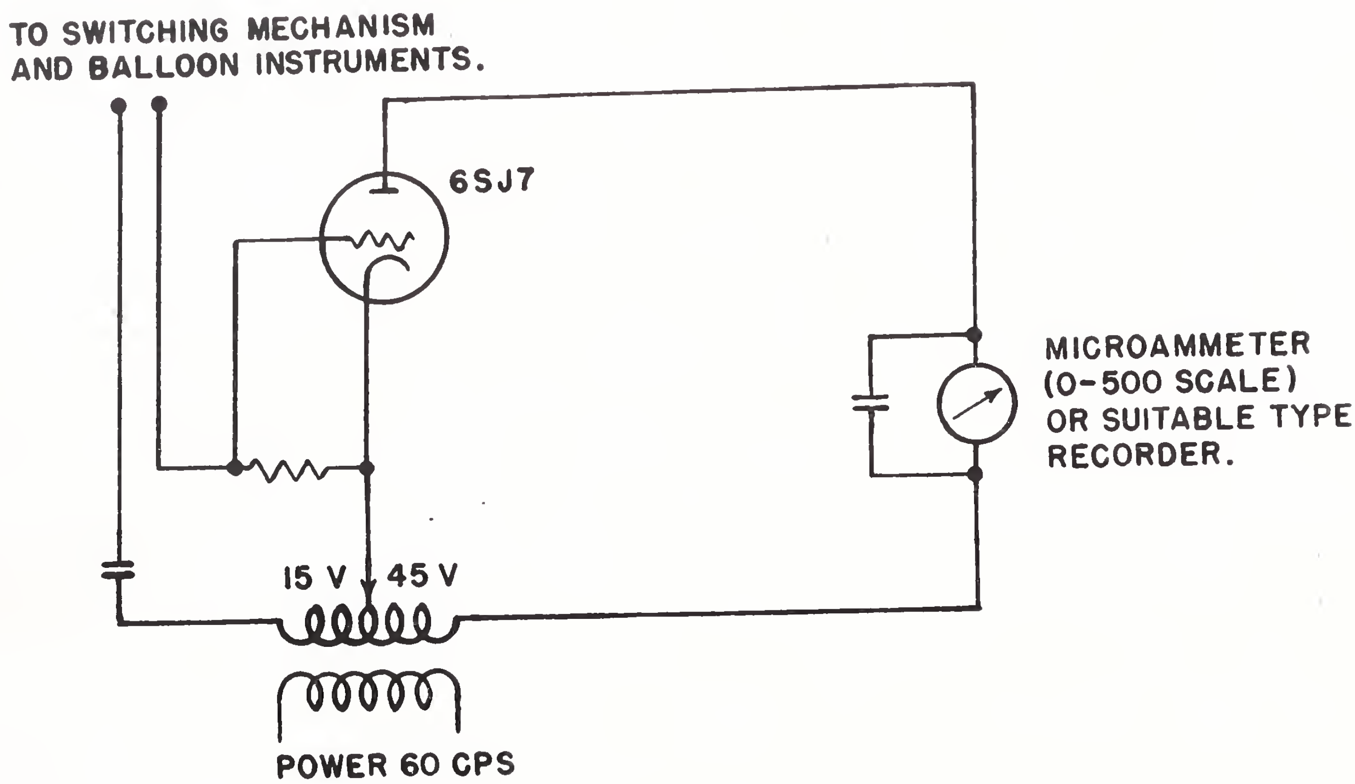


Fig. 40 SIMPLIFIED CIRCUIT DIAGRAM OF N.B.S. LOW LEVEL WIREDSONDE SYSTEM.

direct current plate supply which entails the use of batteries or a rectifying circuit. The plate current flows only when the plate is on a positive half cycle of an alternation. But this occurs 60 times a second compared with the time of record of each measuring element of $7\frac{1}{2}$ seconds so that an average plate current representative of the measuring element impedance may be measured. There is a filter in the recorder circuit smoothing out plate current ripple.

The normal frequency or voltage variations in the power supply have little effect on the operation of the wiredsonde and ground recording circuits. The power supply voltage, even with frequency variation in the line voltage of as much as 10 cps for a line voltage range between 95 and 130 volts is controlled to within 0.2% by a combination of two voltage regulators. Changes in line voltage over this range will not be serious because the wiredsonde switching mechanism gives a reference impedance for each set of altitude (pressure), temperature and humidity readings.

The pressure, temperature and humidities measured by the balloon borne elements can be observed very accurately. Using the Friez radiosonde recorder the following accuracies are observed.

1. The temperature can be read to 0.3° F by reading to $\frac{1}{4}$ division on the recorder dial. The temperature scale may be read from 110° F to 30° F, or from 30° F to -50° F, depending upon the resistance range of the temperature element used in the instrument.

2. The relative humidity range from 10% to 100% is covered by 93 divisions of the recorder. Between 90% and 100% a quarter division corresponds to a change of 1% relative humidity. Between 20% and 90% a quarter division corresponds to an average change of 0.2% relative humidity. Between 10% and 20% a quarter division corresponds to a change of 0.7% relative humidity made at 72° F.

3. The altitude range of the instrument is from 0 to 2000 feet. Each division of the recorder scale corresponds to an average change in balloon height of 32 feet (at sea level).

To secure accuracy throughout a sounding, the temperature, humidity and altitude are checked immediately before the observation. The wiredsonde elements are placed in an instrument shelter, and after the instrument has reached the temperature of the shelter the deflection of the recorder is compared with the mercurial thermometer

reading of the instrument shelter. The humidity element deflection is checked by placing the tube of the wiredsonde unit which contains the humidity element into a special ground calibration chamber containing an atmosphere of known relative humidity. The tube of the wiredsonde unit just fits into the chamber and the air of known relative humidity is circulated around the element. The altitude indication is set for zero at station pressure before the sounding is started.

B. <u>Location for Wiredsonde Exposures</u>.

Wiredsonde gear may be used for observations over water as well as over land (75 and 1). If turbulence is to be kept at a minimum a land observation point should not be near a sharp ridge or hill. It is better to locate the instruments on the windward side if a ridge cannot be avoided. In this way, the sounding will be more representative of the large scale atmospheric conditions and processes. Also, any chances of damage due to pitching and jerking of the sonde balloon or kite may thus be lessened. Favorable locations for exposures along a shoreline are a pier or small peninsula. The site should be protected from surf spray which will cause equipment corrosion. At sea, the balloon, kite, or kytoon may be let up from a small power boat and very satisfactory results obtained. From the deck of a steamer, difficulties are experienced in keeping the balloon out of the pillar of smoke from the stacks.

Various methods of exposing the wiredsonde system are shown in Figure 41. Methods a and d are the most commonly used.

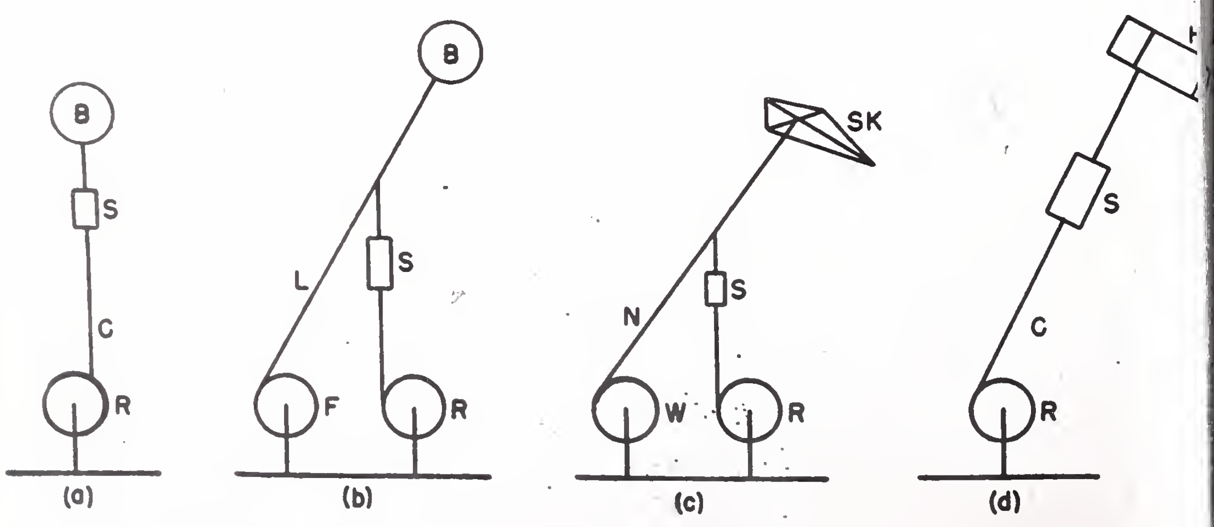


Fig. 41. SYSTEMS OF EXPOSING WIREDSONDES (1)

(a) Temperature and humidity elements mounted within the radiation shield S are connected through the 3-conductor cable C with slip rings on the cable reel R.

(b) 300 gram neoprene balloon ... light fish line, F, fish line reel.

(c) SK, Seyfang 7 ft. kite. N, nylon kite line W, Kite winch.

(d) NK, Hoffman single cell box kite. Arrangement (d) is suitable for soundings from moving ships. Its ceiling is limited to about 400 feet by the small lift of the kite. "Meteorological Equipment for Short Wave Propagation Studies" (1)

G. Airplane or Autogyro. An airplane or autogyro equipped as a flying meteorological laboratory is a more flexible means of making atmospheric soundings. Accurate measuring and recording equipment may be installed almost regardless of weight. Additional significant data may also be entered by an observer alongside the record. Furthermore, the cables from the wired balloon or kite type of exposure is a hazard to aircraft if used near an airport.

The aeropsychrograph (11). (12), and (22), using the ceramic resistor temperature elements has been used for flights made in aircraft. The complete instrument was placed in the plane, and the thermometers exposed from a tube mounted on a wing strut. The temperatures were recorded automatically.

To obtain accurate values of temperature heating effects due to the speed of the plane had to be considered. The method used to calibrate airplane thermometers is to fly at various speeds under isothermal conditions. Corrections are then applied for the increase in the indicated temperature with increased speed. The corrections for the ceramic wet- and dry-bulb thermometers, with the air striking the dry-bulb first, were found to be small, ranging from -0.3° C at 80 miles per hour to -0.7° C at 130 miles per hour.

Airplane soundings with an instrument of this type have several advantages. In practice the flight can be started at low levels and the rate of ascent maintained at about 100 feet/minute. If sudden variations are noticed in the rate of change of temperature or moisture with height the layer can be explored very carefully. Readings of pressure and wet- and dry-bulb temperature can be recorded while the plane is in flight and related to the elevation and thickness of cloud layers and the degree of turbulence experienced.

There is also a disadvantage to the use of airplanes for carrying meteorological instruments aloft. It is hazardous to take observations at low levels in poor visibility. It is suggested that autogyros or helicopters, due to their ability to ascend vertically and to hover in space, are more readily adaptable for low level soundings than airplanes.

D. Tower Installations. Tower installations are used for permanent land stations away from airways where a continuous surface layer sounding is desired (2).

1. The Tower at Rye.

The British Government operates tower stations at Porton and Rye. The 360 ft. tower at Rye is located on a grassy plain. It is constructed of steel lattice work. The effect of the tower on the meteorological elements is considered to be negligible. The instrument shelter, or screen, containing a thermometer and hygrometer are mounted on the WSW side of the tower at heights of 50, 155, and 350 feet. Each shelter rides on a track which extends out into space, about 8 feet away from the tower. When measurements are made the shelter is secured at the end of the track away from the tower, but when the instruments are serviced, the shelter is drawn in over a platform for convenient attention. Another instrument shelter is erected on a concrete bed at a height of 4 feet above the ground at about 10 yards from the base of the tower on the south side.

The air temperature[1] at 4 feet, and the difference in temperature between 50 feet and 4 feet, 50 feet and 155 feet and 50 feet and 350 feet are recorded. For differential measurement an out-of-balance Wheatstone bridge circuit is used, two of the bridge arms are resistance thermometers. The resistance thermometer at the 50 foot level is in the circuit constantly, while the ground level, 155 foot level and 350 foot level are switched alternately into the circuit by a three point recorder. The difference between the temperatures at 50 feet, and the other three heights are traced on a Negretti & Zambra electrical thermometer type recorder. The position of the sensitive galvanometer pointer, which indicates the difference in temperature potential between the 50 foot level and some other level switched into the circuit, is printed through different colored ribbons in accordance with the level switched into the circuit every 30 seconds. All connections to the electrical resistance temperature elements are made through temperature compensated leads. The ground level temperature, measured by a separate Wheatstone bridge circuit, is recorded on a separate instrument. The ground temperature may be estimated to $\frac{1}{4}^{\circ}$ F, over a range from 0° to 100° F, while the differential temperatures may be estimated to 0.1° F.

The relative humidities[2] at 4 feet, 50 feet,

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1. See electrical resistance thermometers, "Temperature Measuring Devices," Page 10.
2. See Gregory Humidiometers, "Humidity Measuring Devices," Page 21.

155 feet, and 350 feet are printed by a 4 point recorder. An independent additional recording of the humidity at 4 feet is made with another instrument.

The temperature of the recording room is thermostatically controlled at 60° to 62° F. A recording voltmeter is used to keep a check on the voltage variation and failure of the power supply to the meteorological instruments.

The circuit diagrams (Figures 42, 43, 44, and 45) give further information about the equipment.

2. The Oakhurst 400 Foot Meteorological and Radar Tower.

In this country the Army Signal Corps uses a 400 foot tower at Oakhurst, New Jersey, (Figure 47), for continuous low level soundings. The tower is constructed on a hill about 133 feet above sea level. An elevator runs to the top of the structure from a small house at the base. The meteorological recording equipment is located in one room of the house.

a. Temperature Measurements.

Dry- and wet-bulb thermometers are located in ten instrument shelters placed at various levels. The elevations of the ten temperature recording stations in feet above mean sea level are 133 (ground level), 186, 234, 277, 306, 354, 393, 426, 474 and 501. Five alternate stations report on one ten-element L. & N. Micromax Recorder; while the other five stations report on a second recorder. The stations are easily identified on the recorder sheet because the Micromax records each element by printing a corresponding number with a position dot. Dry-bulb temperature for station number one is identified as 1., wet-bulb temperature for station number one as 2., dry-bulb temperature for station number 3., etc. The even numbered stations are recorded in a similar fashion except that the first even number is 0.. Approximately three minutes are required to record the temperatures for the ten stations. From the dry- and wet-bulb data relative humidity and dew points are computed for each of the 10 temperature levels. A Micromax Recorder is shown in Figure 46.

The instrument shelters used at the 10 temperature stations are especially designed for tower use. Ground and tower radiation is a source of temperature error. This radiation is screened out by the special type metal shelter (see Figure 48). It consists of an outer jacket made of a steel metal cylinder about 3 feet long and 1 foot in diameter. A small cylinder of about 10 inches in diameter forms the second enclosure. Two water tanks are located on opposite sides of the inner enclosure. When these are filled they maintain water at a fixed level in a trough in the center of the inner jacket. Two 100 ohm copper resistance thermometers (L. & N. Thermohm Thermometer) are mounted in the center of the inner

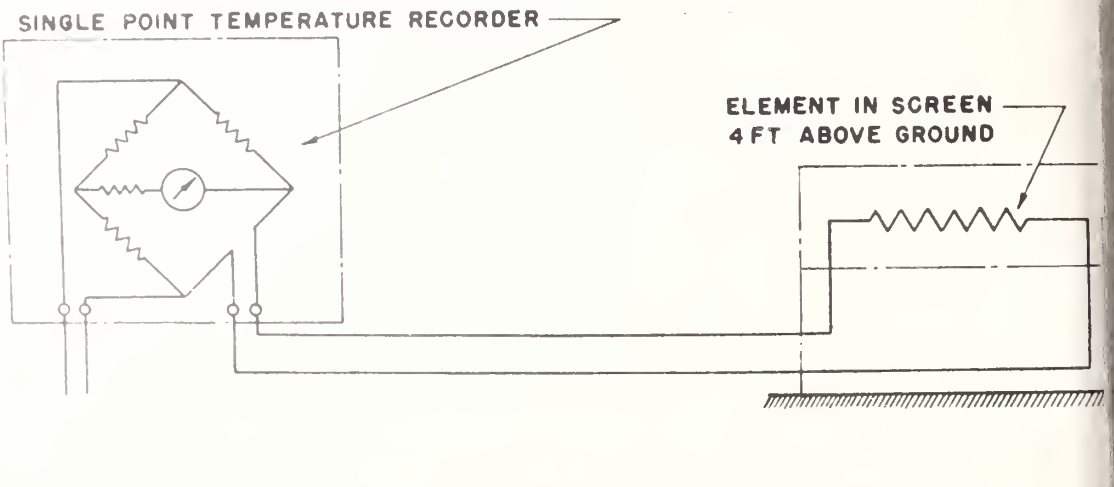


Fig. 42 CIRCUIT FOR MEASUREMENT OF ACTUAL TEMPERATURE AT

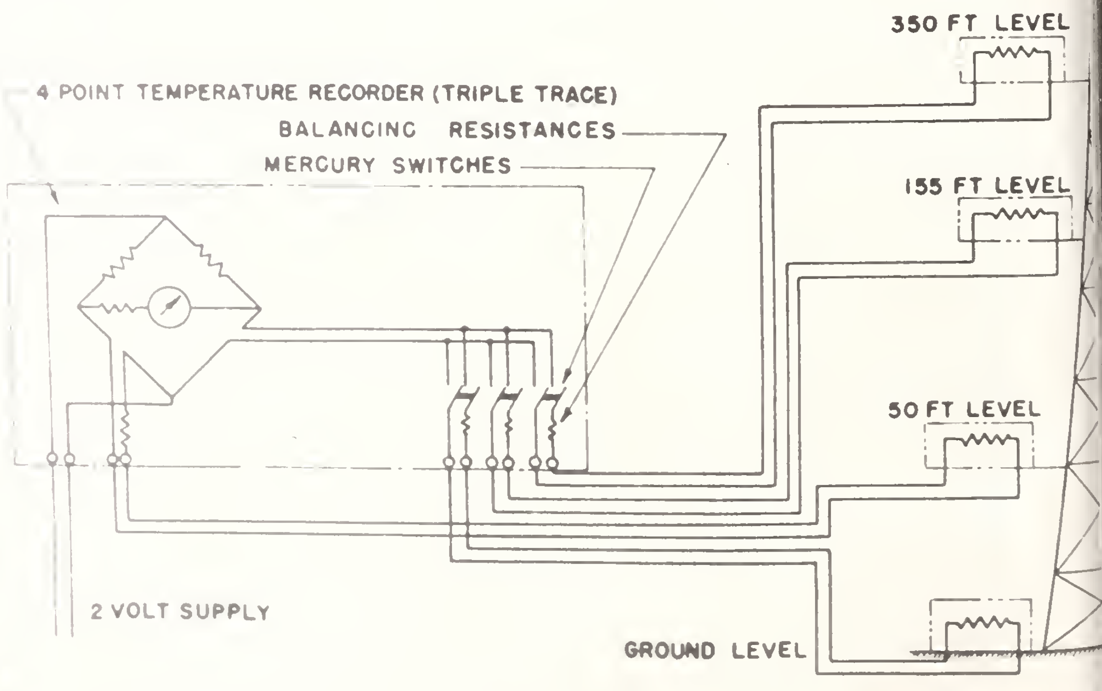


Fig 43. CIRCUIT FOR MEASUREMENT OF DIFFERENTIAL TEMPERATU

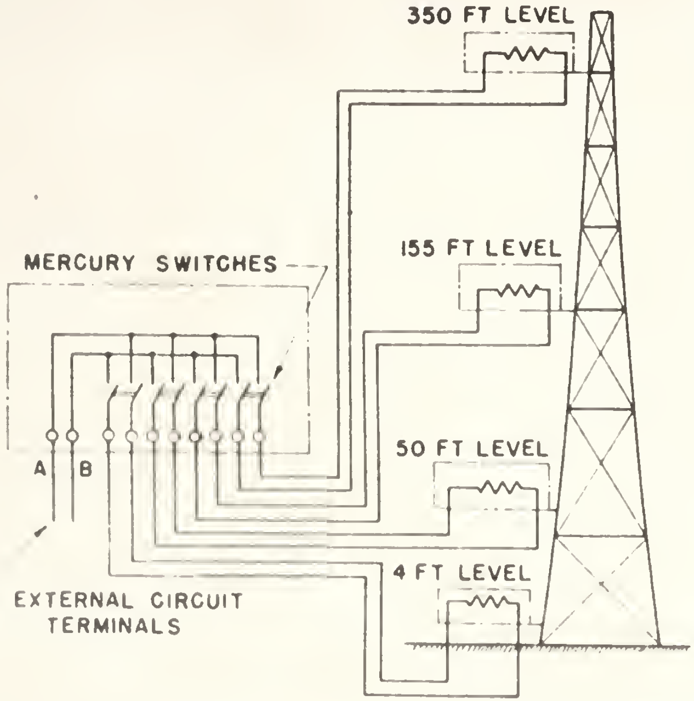
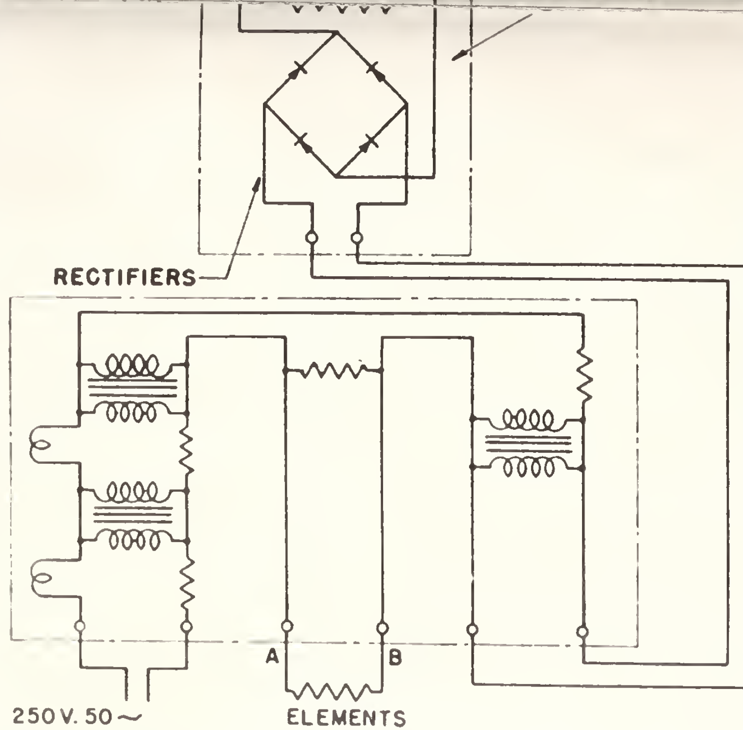


Fig. 44 EXTERNAL CIRCUIT FOR 4 POINT HUMIDITY RECORDER. (2)



THE ABOVE CIRCUIT IS FOR THE SINGLE POINT HUMIDITY RECORDER. FOR THE 4 POINT INSTRUMENT THE ONLY DIFFERENCE IS THAT AB, THE TERMINALS TO THE EXTERNAL CIRCUIT, ARE CONNECTED VIA MERCURY SWITCHES TO SEPARATE ELEMENTS AS SHOWN IN FIG. 44.

Fig. 45. CIRCUIT FOR MEASUREMENT OF RELATIVE HUMIDITY. (2)

cylinder. The wet-bulb thermometer is mounted about 6 inches above the dry-bulb thermometer and about 1 inch above the water trough. A thin muslin wick keeps the wet-bulb moist. Sliding doors are provided in the sides of the cylinders to make the thermometers easily accessible. The ends are covered with louvred vents, and good circulation is provided by an electric fan mounted in the top of the shelter.

b. Wind Measurements.

There are three wind measuring instruments the tower, and one on the ground. They are spaced at 120 foot intervals, the first tower station being 120 feet above the gro The wind speed and direction is measured on the tower by standa Signal Corps equipment (AN/GMQ-1) consisting of an electrical r sistance type windvane and a three-cup electrical generator typ anemometer. A visual meter is provided for indicating the wind speed and direction at any level, a variable contact switch bei used to connect the wind instruments to the indicator. Three Esterline-Angus recorders are used to record the wind speed. G wind speed and direction data are measured from a 20 foot mast cated near the tower. A Friez bridled anemometer unit measures wind speed and the direction is measured by the usual wind vane A permanent record of the ground wind data is made by a Friez S recorder, while visual meters are used to observe the instantan values.

Figure 46. The Leeds and Northrup Ten-point Micromax Recor

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1. See sections on "Recording Instruments" and "Temperature Measuring Devices,"

Fig. 47. THE 400 FOOT OAKHURST TOWER.

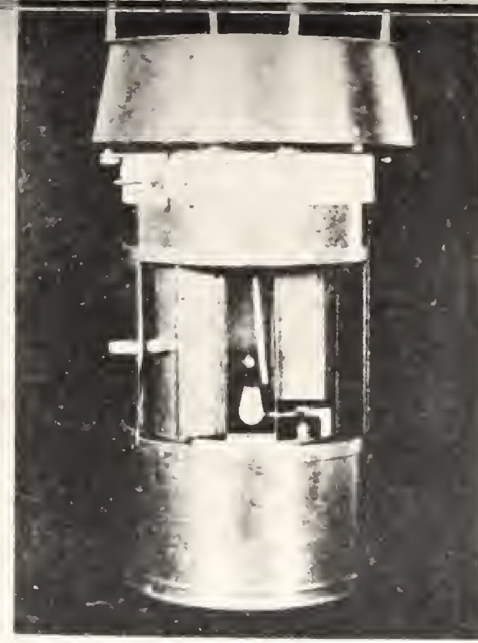


Fig. 48 THE TOWER THERMOMETER SHELTER. THE WET-BULB THERMOMETER WITH ITS ASSOCIATED WATER RESERVOIR TROUGH ARE SHOWN. THE DRY-BULB THERMOMETER IS MOUNTED BELOW THE TROUGH.

IX. Recording Instruments.

Recording microammeters and milliammeters are used for making records of radiosonde and wiredsonde flight data. There are several commercial recorders which can be used for this purpose.

A. The Friez Recorder (66)

This instrument is designed for use with the Diamond-Hinman radiosonde. The recorder receives the resistance controlled frequency modulated signals from the balloon transmitter and converts them to a direct current proportional to the controlling resistances. These controlling resistances measure the pressure, temperature and humidity. Two identical reading microammeters (0-500 μa full scale deflection) measure this current. One microammeter is read visually and the other is recorded automatically. The position of the pointer in the recording meter is printed every 2 seconds on a strip of paper ten inches wide. This is accomplished by means of a photoelectric cell and a light source revolving about the axis of the pointer. When the beam of light is interrupted by the pointer a relay is thrown forcing a tapper bar to print on paper against a narrow raised spiral edge wound around the roller. The printed dots are proportional to meter deflections because the revolving photoelectric cell and light source are geared to the spiral edged roller. The paper is fed at a fixed rate of speed between the tapper bar and roller. The resultant record shows a value of pressure, temperature, humidity or an instrument reference point every two seconds as the balloon ascends. As a result these are not printed in a regular sequence, because the radiosonde changes the reported element in fixed intervals of pressure, which bear no relation to the two second printing interval of the recorder.

The Friez Recorder may also be adapted to wiredsonde instruments, if the direct current from the balloon measuring elements is fed directly to the microammeters.

B. Leeds and Northrup, High Speed Potentiometer Recorder (Speedomax) (68, 69, 73).

Current from the radiosonde receiver frequency meter or from the measuring elements of the wiredsonde gear may be measured by the Speedomax recorder by shunting it through a drop resistor. The instrument operates on the null-type potentiometer principle, i.e., an unknown e.m.f. of the drop resistor is balanced against a slide wire potentiometer which delivers a known e.m.f. at every point on the recorder scale. The range of the instrument is 0-5 millivolts, but when the direct current is measured across a drop resistor of 10 ohms a range of 0-500 microamperes is obtained.

The unbalanced direct current in the potentiometer circuit is converted into pulsating direct current by an a.c. magnetically driven carbon microphone. The primary of a transformer is connected in series with the microphone and detects changes in current.

These current changes are then amplified and applied to a phasing circuit which determines the direction of rotation of a reversible direct current motor. The potentiometer slide wire contact to which the pen is attached is driven by the motor. Two separate field windings are provided in the motor for making it reversible. The direction of current flow due to the unbalanced voltage will cause one or the other of two thyratrons to conduct. The direction of rotation of the motor depends on which thyratron is conducting. The slide wire contact is mechanically coupled to the motor so that it always seeks the balance position.

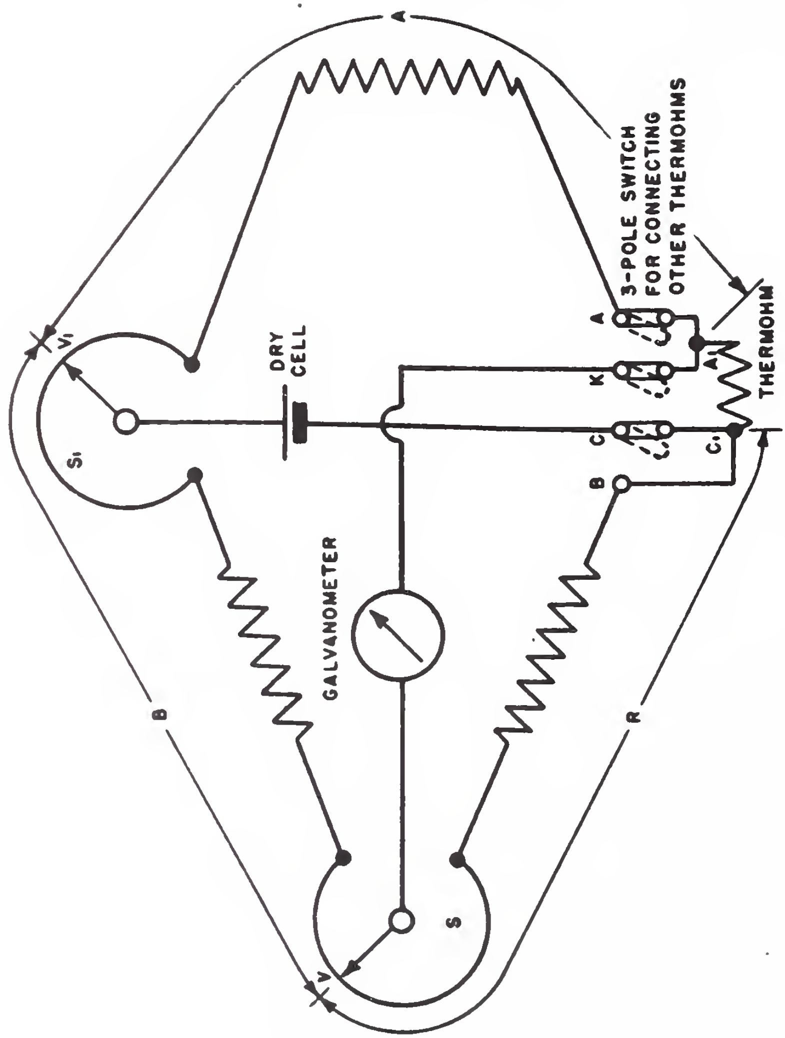
The instrument is prevented from overshooting the balance point by a direct current tachometer generator driven mechanically by the motor.

A continuous record is traced on a moving sheet of paper by the potentiometer pen. The time of response to full scale changes is less than one second. The accuracy of the instrument is 0.5% (full scale deflection 10"). This instrument, because of its accuracy and quick response is well adapted for radiosonde recording.

C. <u>Leeds and Northrup Micromax Recorder</u> (69, 73).

A very popular form of recorder is the Leeds and Northrup Micromax. This instrument employs a Wheatstone bridge circuit (see Figure 49) with the special Thermohm copper resistance thermometer forming the variable resistance arm. The other three known resistance arms of the bridge, two of which are relatively high in comparison to the third known resistance (and the Thermohm), are alternately joined by slide wire coaxially mounted discs S and S_1.

A dry cell battery circuit is connected from the variable contact of the slide wire disc between the two known high resistances to the junction of the low resistance arm and the Thermohm. The galvanometer circuit is connected from the variable contact of the slide wire between the known high resistance and the low known resistance to the junction of the Thermohm and the other known high resistance. The slide wire contacts are so arranged that the ratio of the voltage drops over the two high resistance arms is 1 when no current flows through the galvanometer circuit. The wires connecting the Thermohm to the recorder are included in the low resistance arms of the bridge so that resistance in the Thermohm winding is measured independent of length and temperature of the leadwire.


3-POLE SWITCH
FOR CONNECTING
OTHER THERMOHMS
THERMOHM
DRY
CELL
GALVANOMETER
A
B
R
S
A
K
C
B

The bridge circuit is balanced mechanically. The pointer of the sensitive galvanometer swings freely along a slot, between two fingers, one at each end of the slot. At two second intervals, a mechanism driven by a synchronous motor closes the fingers on the galvanometer indicator. If the galvanometer pointer is off the center position, indicating a current flow, then the fingers close in the off center position and engage a friction clutch mounted on the same shaft as the two slide wire contact discs. A pair of cams, also having a two second revolution period, then return the clutch to its normal horizontal position which balances the Wheatstone Bridge circuit by means of the attached slide wire discs. The galvanometer pointer then comes to its position of zero current flow. About 20 seconds is required for full scale deflection. The instrument may be read to an accuracy of about 1/16 inch in a total paper width of 9 7/8 inches or about 0.6% accuracy. Several temperature ranges are provided for the scale depending upon the particular type Thermohm. Chart speeds are adjustable from 1 to 12 inches per hour. If desired, point number printing may be employed and individual values may be recorded for 2, 3, 4, 6, 8, 10, 12 or 16 elements.

The Micromax Recorder is reliable and will operate accurately over long periods of time. It is best adapted in meteorology to recording of temperatures where the mean state of the atmosphere with height is desired.

D. The Brown Instrument Company -- D. C. Potentiometer Recorder (Electronik) (76)

The "Electronik" is another well known electrical recorder. The direct current unbalanced voltage of the potentiometer circuit is converted into an alternating voltage by an electrically driven vibrating reed. The primary of a transformer is connected in series in the circuit. The voltage is further increased with an electronic amplifier. This alternating current voltage which is proportional to the original unbalanced direct current is fed to a two phase induction motor. One set of control windings on the motor is connected to the output of the amplifier. If the control winding current leads the power current by 90° the motor runs one way. If it lags by 90° the motor runs the opposite way. A capacitor is connected with the control winding current to shift the phase 90° with respect to the power supply. The phase of the amplifier shifts 180° when the current in the unbalanced potentiometer circuit changes direction of flow. The response of the motor varies directly as the out of balance e.m.f.; this prevents overshooting.

The sensitivity of the instrument depends upon the voltage output of the amplifier. The slide wire contact carries a recording pen or printing carriage and is connected mechanically to the balancing

motor through a cable system. The accuracy of this instrument is 0.5% of full scale deflection. It is provided with contacts so that 2, 3, 4, 6, 8, 12 and 16 elements may be recorded. In the printing multicircuit types, a balance must be established before the element will print. One contact is made per second, but the time of response for the full scale 11 inch deflection is $4\frac{1}{2}$ seconds.

E. <u>The General Electric High Speed Photoelectric Recorder</u> (71)

The High Speed Photoelectric Recorder is suitable for wiredsonde or radiosonde recording. There are several models of the instrument which make it adaptable for many purposes. It is possible to select a wide range of sensitivity and response characteristics by choosing different basic elements. Sensitivities can be obtained as low as 1/10 microampere full-scale deflection. Response periods can be as fast as 1/5 second* The instrument is small and light, weighing only 42 pounds, and its dimensions are $9\frac{1}{2}$" x 13" x $1\frac{1}{2}$". The chart size is about 3 3/4". Four different motor arrangements provide chart speeds ranging from $\frac{1}{2}$ inch per hour to 72 inches per minute.

The instrument uses an optical balancing system for its basic operation. The input current from the meteorological measuring instrument deflects a very sensitive galvanometer. Connected to the armature of the galvanometer is a mirror, which reflects a light beam on to a spherical mirror surface. From the spherical mirror surface, the <u>beam</u> is incident upon another mirror which is connected to the armature of a very sturdy recording meter (slave meter), and then is reflected to a light-dividing mirror. The dividing mirror separates the beam equally on to the surfaces of two photoelectric cells when the photoelectric-recording element circuit is in balance. If the beam does not fall equally upon the surfaces of the two photoelectric cells an unbalance current flows from the photoelectric cell amplifier to the recording element controlled by the slave meter. This rotates the slave meter mirror until the beam is again equally divided on to the two photoelectric cells.

A pen is attached to the recording element which traces the movement of the slave meter mirror on a moving sheet of paper, as it continually balances the light beam which the input signal unbalances. Errors are reduced to negligible amounts, because the function of the optical-balancing system depends upon division of the light beam, and not upon the absolute value of the light intensity. An unbalance of 0.1 μa causes the amplifier unit to give full output. All the tube characteristics can change widely without affecting the final result.

The General Electric Company is adapting this meter for general radiosonde recording. The paper record is to be ten inches wide and a "spark" is to be used for marking the paper. The paper is perforated only when the instrument is in balance. This instrument

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* The fast response time and sensitivity do not apply to the same instrument model.

is usable for present radiosonde recording and for projected rapid sequence sondes.

F. Esterline-Angus Recorder (72).

All of the meters described above are designed for stationary operation and require an external supply of current. The Esterline-Angus Company makes a portable type of recorder which can be operated without a power supply. This meter is small, light and sturdy. It functions well out-of-doors in extremes of weather. It is a recording milliameter which operates on currents varying from 0-1 milliampere to 0-500 milliamperes. There are several choices in the speed of the paper drive ranging from 3/4" per hour to 3" per second. This model has an accuracy of 1% for full scale deflection ($4\frac{1}{2}$"), with a response of 2 seconds for full scale deflection. The recorder operates best when making a continuous record of one element. Additional instruments can be added for the recording of more than one element. A special chronograph pen may be attached to the instrument for indicating some other element which may be a function of the quantities measured. For example, in a wiredsonde flight this may be length of cable.

G. Tagliabue Celectray (formerly Fairchild) (67) recorder employs the conventional potentiometer circuit to measure temperature by the e.m.f. of a thermocouple. The balancing slide wire contact of the potentiometer is carried on a recording pen carriage which is connected mechanically to a balancing two phase drive motor. Potentiometer unbalance is detected and amplified by a combination of a mirror galvanometer, photoelectric cell and amplifier tube. Two relays whose armatures are connected in series in the plate circuit of the amplifier tube reverse the phase of current flow through the motor windings and hence bring the potentiometer to balance by moving the slide wire contact carriage to a new balance position.

Depending upon the thermocouple measuring element employed, a great choice of temperature ranges can be obtained. Over a range from -50 to 100° F the temperature may be read to 0.5° F. The chart on which temperatures are printed is $9\frac{1}{4}$ inches wide. Chart speeds can be adjusted from 2 to 12 inches per minute in steps of 2 inches per minute. Some models of the Celectray recorder print readings every 7 or 8 seconds. The recording carriage can traverse the chart in approximately 22 seconds and records approximately 4 seconds after the balance point is reached. Machines, using either colored dots or numbered dots may record temperatures from 1, 2, 3, 4, 6, 8 or 12 reporting stations.

H. Recorder Comparisons.

It should be pointed out that the present Friez re-order prints only at intervals and does not necessarily record he equilibrium position of the meter pointer. This makes it nsatisfactory for rapid sequence recording. The Speedomax ecorder depends upon a standard cell for voltage reference, nd cannot be used in an ambient temperature below 0° C or bove 40° C. Since it traces a continuous line and cannot reach quilibrium in less than a second it is not quite satisfactory or the recording of proposed rapid sequence radiosondes. However, t is well adapted to the present radiosonde technique. The pres-nt Electronik, Micromax and Celectray recorders are perhaps best dapted to fixed recording as may be used in tower installations. he present General Electric recorder has too narrow a chart for ccurate scaling of meteorological data, but the larger "Stratometer" ecorder under development appears to be satisfactory. At present he Esterline-Angus recorder chart is very narrow for recording oundings, but it is a valuable instrument for many kinds of ex-perimental work.

There are other electrical measuring instruments which ay be used for wiredsonde and radiosonde recording such as multi-element oscilloscopes, but it is believed that the meteorologist can meet most of his requirements with the instruments already mentioned.

X. Conclusion.

With the more detailed studies of microwave radio propagation, it is necessary that the best methods and instruments be used in determining the meteorological factors. The instruments described in the above survey are the best of those in use at present (March 1947). However, other developments are in progress and will be included in future additions to this survey as they are announced.

The question naturally arises as to which type of instrument is best. Since there are so many different needs it is evident that a different system may be suitable for each application. The relative availability of equipment is many times a deciding factor.

While most recent low level sounding equipment has been developed as an aid to microwave propagation, it also has many uses in the field of weather forecasting. This equipment could well be employed in fruit districts for forecasting the minimum temperatures and temperature inversion heights used in determining the amount of fuel required to keep the orchard temperatures above freezing. Cities which are frequently bound with radiation fog could profitably use this equipment to forecast the beginning and duration of the fog. Furthermore, fire weather forecasting in forest areas could greatly be improved if equipment were available to make "on the spot" soundings of the general atmospheric moisture structure to predict thunderstorms.

An interesting result of research in the field of ultrasonics propagation have been the studies in micro-meteorology (82). Micrometeorological instruments show that the turbulence near the ground, especially within 10 feet of sunlit ground surface, may produce fluctuations in air temperature of as much as 10° C in the time interval of a second or two. The relationship of this phenomenon to the fluctuations in intensity of a microwave beam over a path near the ground has not been fully investigated.

The development and perfection of new systems and instruments for measuring water droplet sizes and water content of clouds is of increasing importance not only in microwave radio propagation, but also in meteorology, hydrology and aeronautics. The degree of aircraft icing is dependent upon the cloud water content and particle size. Fog dissipation systems for airports are vitally concerned with liquid water content of clouds. Rate and amount of precipitation is a function of cloud water content

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