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EFFECTIVE CLEAR SKY TEMPERATURES IN THE 8- TO 14-MICRON BAND

BY

ALBERT R. TEBO

MAY 1965

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UNITED STATES ARMY ELECTRONICS COMMAND · FORT MONMOUTH, N.J.

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EW/Meteorological Department

May 1965

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U. S. ARMY ELECTRONICS LABORATORIES
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ABSTRACT

Apparent sky temperatures were measured on clear days and nights during a period in July and August of 1964 at Flagstaff, Arizona. A portable radiometer, with a two-degree field of view, sensing in the wavelength band 8 to 14 microns, was used to read sky temperatures at 5-degree intervals of zenith distances (angles) from the zenith to the horizon. These values were converted to radiances and summed over the whole sky, to arrive at effective whole-sky temperatures.

The apparent sky temperature at any zenith distance is not dependent on azimuth, but does vary with the time of day. The elevation scan of temperatures at a given time is duplicated by that of an equally clear sky at a different time if the zenith temperatures are the same. The effective whole-sky temperature is consistently the same value as the apparent sky temperature at a zenith distance of 54 degrees. Mathematical equations were developed empirically to express the dependence of radiance or apparent sky temperature on zenith distance.

Graphs of the spectral radiance of the clear zenith sky, obtained from a report by Ohio State University Research Foundation, were integrated over the band 8 to 14 microns to arrive at apparent zenith temperatures for locations at altitudes from sea level to 14,000 feet. These ranged from -21°C to -82°C.

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EFFECTIVE CLEAR SKY TEMPERATURES IN THE 8- TO 14-MICRON BAND

INTRODUCTION

As part of a study of environmental processes in the atmosphere, techniques and equipment are being developed to measure the surface temperature of the earth, using infrared radiometers. The accuracy of these measurements is dependent on a knowledge of the emissivity of the soil examined, within the wavelength band of the instrument (8 to 14 microns). A technique of measuring this emissivity has been devised that involves a measurement of the effective sky temperature, using the same radiometer. It was a study of this measurement that led to the work reported here.

Studies have been reported in the literature on infrared radiances of the sky and on transmission of radiation through the atmosphere, but none present the information needed here. Specifically, what was desired was a knowledge of the effective whole-sky infrared temperature, in order to determine the radiation in the 8 to 14 micron wavelength band that reaches the earth's surface.

Only clear skies were studied in order to simplify the handling of the data. The plan was to take measurements at different elevation and azimuth angles, and at different times of day and night, in order to examine these variables:

(a) dependence of apparent infrared sky temperature on elevation angle (or its complement, zenith distance),

(b) dependence on azimuth,

(c) dependence on time of day,

(d) consistency, that is, repeatability, from one day to another.

The ultimate aim was to arrive at a technique of measuring quickly the effective whole-sky temperature in the infrared, so that subsequent measurements of infrared emissivity of soils could be accomplished rapidly. The work on emissivity will be reported on separately.

DISCUSSION

Instrumentation and Techniques of Measurement

The instrument used for measuring sky temperature was the portable radiation thermometer, PRT-4, made by Barnes Engineering Company. It was used because it had been chosen for the technique of infrared emissivity measurements, and compatability of data was desired to simplify the handling of computations. This instrument also happens to be convenient in that it has a light-weight sensing head (three pounds), which can be easily mounted on a tripod. It has a field of view of two degrees diameter, and it senses in the wavelength band of 3 to 14 microns. The response time is listed as 150 milliseconds, as adapted for recorder use, and the accuracy as ±1°F, or ±0.05 microwatt/cm^2 irradiance.

The normal range of the instrument is 10°F to 110°F, which is equivalent to an irradiance range of 3.4 to 8.4 microwatts/cm^2. This range was modified internally by the user to accommodate the low temperatures expected from the sky. This modification was effective, even though the linearity was distorted. The modified instrument was calibrated by using it to read the surface temperatures of a well-stirred liquid bath of a mixture of chloroform and carbon tetrachloride, cooled with dry ice. By observing the readings of this bath and of water at the same temperature above the ice point, it was found that the mixture had just about the same emissivity as water. From this fact, plus the fact that a normal reference point is the temperature of melting ice, a reliable calibration was made possible.

The portable radiation thermometer is calibrated by the manufacturer with its meter marked in degrees of temperature, on the assumption that all targets are black bodies. Since the sky is very much a non-black body, the term "apparent" sky temperature for the measurements is used in this report.

The nature of the variation of sky temperature with elevation angle, or with its complement, zenith distance, was not known, so it was decided to take readings at five-degree intervals from the zenith to the horizon. It was also decided to repeat these measurements at the four azimuth quadrants to get a picture of the variation of sky temperature with azimuth. For this purpose a precision tripod, designed as a mount for a telephotometer, was used. Angles were marked off in degrees, and easily estimable to 0.2 degree.

Measurements were made at the airport in Flagstaff, Arizona, on 27 and 28 July and 4 to 9 August 1964, during both day and night. Only clear skies were measured, except that at night it was sometimes difficult to discern high haze and very light clouds. It is possible that several anomalous readings are attributable to these factors. The tripod was located in a clear area, so that the field of view in the NE, SE, SW, and NW directions was free from obstruction except at the horizon. The altitude of the airport is officially 7012 feet.

Analysis of Data

The data obtained from these measurements are presented in Figs. 1 through 23 as plots of apparent sky temperature versus zenith distance. As often as possible, a complete run of measurements was made at each of the four azimuth directions. The duplication of temperature values at different azimuths is indicated by circled dots on the graphs. On 9 August the sky was clear in patches, so the measurements were made at various azimuth directions from north to east instead of separate runs at each azimuth. Temperature values on all runs were recorded and plotted to the nearest $\frac{1}{2}$°C, since the accuracy of the instrument was no better than that.

The general weather pattern at Flagstaff in July and August is a tendency for the sky to become completely clear by late evening, to remain clear through the night, to begin cloudiness in midmorning, and to become overcast by noon. This routine prevented the taking of data on most afternoons and many mornings. A continuous sampling throughout a whole 24-hour period would be interesting, but would be difficult to obtain.

The data showed many slight variations in sky temperature values at the different azimuths, but no consistent pattern could be detected. So it is concluded that clear sky temperature in the infrared wavelengths is not dependent on azimuth.

The time required for an elevation run at one azimuth was 8 to 10 minutes, thereby requiring about one-half hour for a complete run at all four azimuths. The assumption that sky temperatures did not change appreciably during this time was validated in general by the data.

Curves were drawn through the smoothed averages of the data of all four azimuth runs. Deviations from true averages were made in order to obtain uniform, smooth curves.

These plots show clearly a consistent shape of curve, and a repeatability of value. Different plots having the same zenith temperature have almost identical curves, even if on different days. For example, the curves at 0256 and 0428 MST on 6 August, both having a zenith sky temperature of -55°C, are almost identical. The curves of 0640 on 28 July and 0845 on 5 August, both having a zenith sky temperature of -51°C, are almost identical, although separated in time by a week. Similarly, 0845 on 27 July and 1106 on 7 August, more than a week apart, are almost identical, with a zenith temperature of -45°C. This points out clearly that the thermal structure of the sky repeats itself from time to time, at least insofar as its infrared emission is concerned.

Table 1 lists the dates and times of all the measurements, as well as the zenith temperatures in each case. Other data in this table will be discussed later. The lowest zenith temperature was -62½°C at 0600 MST on 5 August, and the highest was -34°C at 1127 on 9 August.

Figure 24 is a plot of these zenith temperatures by days and hours. It shows the warming trend during the day and the cooling trend at night, and also shows a general warming trend over the period 7 to 9 August.

Some data from reports by Ohio State University Research Foundation[1,2,3] on work performed during 1955 to 1957 have provided the means of making comparisons of the clear zenith sky temperatures at other locations. The data were obtained by a Farrand spectrometer in the form of spectral radiance and were plotted as graphs over the wavelength band 2 to 20 microns. By integrating over the band 8 to 14 microns with a planimeter, then dividing by the fraction of total black body radiance emitted within this band, and finally converting this equivalent black-body radiance to temperature, the equivalent apparent zenith sky temperature was obtained.

Table 2 is a compilation of these results, giving sky temperatures in New Mexico, Colorado, and Florida, at altitudes from sea level to 14,000 feet. The coldest zenith temperature calculated was -82°C on Pike's Peak, Colorado, on 11 September 1956, at 0650. The warmest calculated was -21°C at Cocoa

Table 1. Effective Whole-Sky Temperatures and Apparent Zenith Temperatures of Clear Skies in the 8 to 14 micron band, Flagstaff, Arizona

Date (1964)	Time (MST)	Zenith Temperature T_o (°C)	Effective Whole-Sky Temperature T_{eff} (°C)	Zenith Distance for Sky with Same Temperature as T_{eff} ∅ (degrees)
July				
27	0845-0908	-45	-31	53½
28	0640	-51	-36½	54
August				
4	0630-0735	-56½	-40½	54
4	0915-0935	-47½	-33½	54
4	1040-1108	-47½	-34	53½
5	0550-0615	-62½	-45	54
5	0845-0910	-51	-37	54
5	1037-1058	-47	-33	54
5	1210-1230	-44	-31	53½
6	0040-0111	-52½	-37	54
6	0256-0323	-55	-39	54
6	0428-0450	-55	-40	54
6	0604-0613	-53½	-38½	54
6-7	2346-0005	-48	-33½	54
7	1106-1133	-45	-31	54
7	1408-1416	-45½	-32	54
7	1523	-50½	-37	54
7	1946-1954	-46½	-32	55
7-8	2348-0011	-47	-31	53
8	0237-0259	-47½	-30½	55½
8	0435-0447	-45½	-30	54
8	0918-0935	-41	-27	53½
8	1052-1112	-37½	-24	52½
9	1127	-34	-21½	52½

Table 2. Clear Zenith Sky Temperatures, Integrated from 8 to 14 Micron Spectral Curves

Reference	Location	Date	Local Time	Altitude (Feet)	Temperature (°C)
1	White Sands, N. M.	13 Aug 55	1730	4,300	-25
1	Sacramento Peak, N. M.	21 Aug 55	0040	9,000	-47
1	Climax, Colo.	30 Aug 55	1720	11,200	-69
1	Denver, Colo.	5 Sep 55	1205	5,300	-51
2	Pike's Peak, Colo.	10 Sep 56	1552	14,110	-77
2	" " "	11 Sep 56	0650	"	-82
2	" " "	12 Sep 56	1440	"	-59
2	" " "	14 Sep 56	1040	"	-50
2	" " "	14 Sep 56	2153	"	-55
2	" " "	15 Sep 56	0210	"	-57
2	" " "	15 Sep 56	0650	"	-62
2	Elk Park, Colo.	17 Sep 56	1305	11,750	-48
2	" " "	19 Sep 56	1430	"	-54
2	" " "	19 Sep 56	2058	"	-60
2	" " "	20 Sep 56	0705	"	-56
2	Fort Carson, Colo.	24 Sep 56	1338	5,960	-40
2	Peterson Field, Colo.	26 Sep 56	2210	6,130	-44
3	Cocoa Beach, Florida	13 Jun 57	0923 to 2310	0	-21

Beach, Florida, 13 June 1957, between 0923 and 2310 (an average of three sets of readings). Times listed are local.

These values agree well with the range of values obtained at Flagstaff. It is noted that the temperatures and radiances decrease with increasing altitude. This is expected, since the total mass of air available for radiating is less at the higher altitudes, and at the lower altitudes the warmer surface layer of the atmosphere predominates in determining the sky radiance.

Figures 25 through 33 are radiance plots of clear zenith skies, in the 8 to 14 micron band, copied from the Ohio State University reports. They were selected from the group listed in Table 2 to illustrate the form of the curve and to emphasize the non-blackbodyness of the sky radiation. Two features are of note. One is the ozone band that causes a hump in the curves at 9.6 microns. It is present in all the curves, to different degrees of intensity, although almost masked in the Cocoa Beach plot by the warm surface layer of the atmosphere. The other feature is the existence of sharp wings in the curves at 8 and 14 microns. This is interesting because it means that, for a sky of low radiance, most of the energy lies in these wings. If a detecting instrument were used with sensitivity in the 9 to 13 micron band instead of 8 to 14 microns, the apparent sky temperatures would be considerably lower than those recorded here. The temperatures computed from the curves depend critically on the actual pass band of the instrument.

Another aspect of this extreme non-blackbodiness is the error invited in calculations when blackbody values are used. In emissivity calculations, a factor enters to take into account the fraction of the total radiance or radiant emittance that falls within the spectral band seen by the instrument. If this fraction is taken from the Planck distribution of a blackbody radiator, it will be quite different from that taken from a distribution exemplified in these curves of Figs. 25 through 33, for the Planck distribution is convex upward at these temperatures, whereas these curves are concave.

This error is further compounded by the possible uncertainty of the actual pass band of the instrument. It is customary for manufacturers to specify the limits of a pass band at the half-power points. Unfortunately, with the Barnes portable radiation thermometer, which has a pass band of 8 to 14 microns, the response of the instrument reduces rapidly at the wings of the band at the same wavelengths that the energy from the sky rapidly increases. This makes for difficult calculations and uncertain results.

In the spectral studies of the clear sky made by Ohio State University Research Foundation, measurements were made over the spectral band 2 to 20 microns, at various zenith distances from the zenith to the horizon. It was found that the response gradually changed from a concave curve upward, taken at the zenith, to a convex curve upward approximating a blackbody at the temperature of the atmosphere near the ground, taken at the horizon. At low-altitude locations, this approximation to a blackbody curve was better than at higher altitudes. This is to be expected, because at sea level the spectrometer looks through a large air mass on the horizon which contains a relatively high density of solid aerosol particles whose emission is essentially blackbody radiation. These effects are shown in Figs. 34 and 35.3

The spectral radiance on the horizon at Cocoa Beach is very close to that of a blackbody at the temperature of the atmosphere near the ground, and the envelope of the curves at Elk Park, Colorado, again approximates that of a blackbody. This feature was used by Ohio State University to make an analysis of a mathematical approximation to the spectral curves at different zenith distances, and will be discussed later. It is significant that not until the zenith distance approaches very near the horizon does the curve approximate closely that of a blackbody. Even at a zenith distance of 88.2 degrees, which is 1.8 degrees above the horizon, the dimple in the spectral curve is appreciable at sea level and is quite large at 11,000 feet altitude. The air mass at this angle is about 20 air mass units at sea level, and is much less at 11,000 feet. It is evident that a very large air mass is necessary for the atmosphere to approximate a blackbody.

Of interest here, it is also significant that within the spectral band 2 to 20 microns it is the central portion between 8 and 14 microns that changes so radically with viewing angle.

These above-described factors lead to the conclusions that the sky temperatures "seen" by the Barnes portable radiation thermometer are never equivalent to the true blackbody temperatures except on the horizon at sea level, and the deviation from blackbody values is dependent on both altitude of site and viewing angle. Hence, all measured temperatures are called "apparent" temperatures.

Development of a Mathematical Approximation

The aim of the measurements at Flagstaff was to develop a method of obtaining, by simple means, an effective integrated value of temperature, representative of the whole sky in the 8 to 14 micron wavelength band. The approach taken was to develop a mathematical expression for the radiance of the sky, or for the radiant emittance, as a function of zenith distance, and integrate it from the zenith to the horizon.

Fortunately, the radiance of the sky in this wavelength band seems to be independent of azimuth, within the error of measurement. This is borne out by the plots of Figs. 1 through 23. The data on these plots include measurements at four different azimuths, and although there were differences in readings from one azimuth to another, no consistent pattern of variation showed up, and the variations were generally small enough to be considered as within experimental error. This conclusion was basically the same as that reached by Ohio State University Research Foundation in their measurements at various altitudes. The independence of radiance with azimuth simplifies the derivation of a mathematical relationship.

Our first attempt to find a mathematical expression for the dependence of sky radiance on zenith distance was the use of an equation for atmospheric transmission developed by R. M. Goody[4] and adapted by Ohio State University. Goody's law describes the average transmission of infrared radiation through the atmosphere.

$$\bar{\tau} = \exp\left[-\frac{w\,\sigma\,\alpha}{\delta(\alpha^2 + w\,\sigma\,\alpha/\pi)^{\frac{1}{2}}}\right],$$

where α is the half-width of the Lorentzian-shaped absorption lines, σ is the mean line strength, δ is the mean line spacing, and w is the mass of the absorber per unit cross-sectional area of the path.

It is known that transmission of sunlight through the atmosphere follows a dependence on the mass of air through which the radiation passes. It would be expected that the variation of radiant emittance, or the variation of radiance, would also follow such a dependence. The standard values for air mass are very closely approximated by the simple expression $w = \sec\varphi$, where w is the air mass and φ is the zenith distance. This approximation is good to 0.4 percent for zenith distances up to 65 degrees and falls off to 3 percent at 80 degrees.[5]

E. E. Bell of Ohio State[6] simplified Goody's law by assuming a stratified atmosphere, for which w is proportional to $\sec\varphi$, and assuming that the other quantities are constants. Then the absorptivity, or emissivity, is given by

$$a = \epsilon = 1 - \bar{\tau} = 1 - \exp\left[-\frac{\sec\varphi}{(A+B\sec\varphi)^{\frac{1}{2}}}\right],$$

where A and B are lumped constants. Bell found, for the Ohio State data in the infrared region, that $B >> A$, and the equation reduced to

$$\epsilon = 1 - \exp\left[-C(\sec \varphi)^{\frac{1}{2}}\right],$$

where C is another lumped constant. Bell considered that the sky radiance at zenith distance φ is

$$N = \epsilon N_0 = N_0 \left[1 - e^{-C(\sec\varphi)^{\frac{1}{2}}}\right]$$

where N_0 is the blackbody radiance at atmospheric temperature. Bell found that N_0 was satisfactorily approximated by the sky radiance at the horizon, where $\varphi = 90$ degrees.

A test of fit of the Ohio State data in the wavelength region 2 to 20 microns showed good agreement when the constant C was approximately 0.4. For one set of data at 4.6 microns, C was 0.44; for another set at 9.3 microns, C was 0.40. The equation fits the data well except at the horizon.

A test was made of the fit of this equation to the data of this report by converting the radiances N and N_0 to equivalent apparent sky temperatures, T and T_H, respectively, where T_H is the apparent sky temperature on the horizon.

$$N = \frac{\sigma T^4}{\pi} = \frac{\sigma T_H^4}{\pi}\left[1 - e^{-C(\sec \varphi)^{\frac{1}{2}}}\right] \text{ for a diffuse sky.}$$

$$T^4 = T_H^4 \left[1 - e^{-C(\sec \varphi)^{\frac{1}{2}}}\right].$$

Here, σT^4 is the Stephan-Boltzmann expression for blackbody radiant emittance.

The equation did not fit the data well using either value of C--0.44 or 0.40. Deviations were in excess of 3°C over much of the range of zenith distances, and it appeared that choosing a different value for the constant C would only shift the position of the deviations on the curve, and not eliminate them. So this approach was abandoned.

The next approach was to look for an empirical relationship that would fit the data over part of the range of zenith distances and, if necessary, another to fit the remaining part. It was hoped that such expressions could be integrated to calculate the effective whole-sky temperatures, thus avoiding the tedious work of summing all the radiance values (or radiant emittance values) calculated at each zenith distance. However, it turned out that the work of calculating the constants of the empirical equations for each set of data, plus the work of calculating the resultant integral, was more tedious than a summation process. Hence the integral form was used only to verify the accuracy of the summation process. The development of these mathematical relations is given next.

The fundamental physical quantity of a radiating body is radiant emittance, expressed by the Stephan-Boltzmann relation

$$W = \sigma T^4,$$

where W is the rate of energy emitted per unit time from a unit surface area of the source into the whole hemisphere to which it is exposed, T is absolute temperature, and σ is the Stephan-Boltzmann constant. Hence, a fourth-power relationship between sky temperature and zenith distance is sought.

The smoothed data from the temperature curves of Figs. 1 through 23 show that the fourth power of temperature fitted closely a linear relationship with the secant of the zenith distance, which was chosen because of its representation of the air mass.

$$T^4 \times 10^{-9} = \sec \varphi + A, \tag{1}$$

where A is an arbitrary constant.

The radiation seen by the portable radiation thermometer is only that within the spectral band 8 to 14 microns, but the instrument registers the temperature as though it were seeing a blackbody with spectral emittance represented by this amount of energy. Hence we are justified in using, in this analysis, this temperature in its relation to the total radiant emittance.

The constant A can be evaluated by inserting the value of T at the zenith distance 0°, T_0. Then,

$$A = T_0^{\,4} \times 10^{-9} - 1.$$

The total radiant emittance of a sky with an apparent temperature T is

$$W = \sigma T^4 = \sigma\left[T_0^{\,4} + 10^9 (\sec \varphi - 1)\right]. \tag{2}$$

The constant A is obviously different for each sky scan having a different apparent zenith temperature.

Equation (2) fits the data of almost all elevation scans of temperature with an accuracy of $\pm\frac{1}{2}$°C through zenith distances 0° through 60°. There are a few exceptions, but they are small enough to be included in the errors of measurement. For smooth data, this accuracy is correct. The relation deviates rapidly from this accuracy at zenith distances greater than 60 degrees, partly because the expression sec φ no longer holds accurately for the value of air mass.

In an attempt to find a relation to express the radiant emittance at zenith distances greater than 60 degrees, an exponential form was used. A three-constant equation was found to be necessary to meet the requirements.

$$T^4 = a\, e^{b\varphi} + c, \tag{3}$$

where T is absolute temperature, φ is zenith distance in radians, and a, b, and c are constants.

This equation fits the data of two of the smooth-valued test runs in the zenith distance range 60 to 90 degrees, with an accuracy of $\pm\frac{1}{2}$°C. The tediousness of calculating temperatures with this equation discouraged our using it for more than two sets of data. But it was decided that if the equation fit the data closely enough, and if the integration of radiances with this equation agreed with the summation technique closely enough, then the summation technique would be considered valid and would be used for all other data.

The irradiance of energy from the whole sky on a horizontal surface of the earth is sought. Consider an element of area dA_s of the sky, taken normal to the direction of the earth, radiating as a Lambertian radiator, i.e., a diffuse source, for which the cosine law holds. In Fig. 36 the energy from this source strikes an element of area dA_e of the earth's surface that is exposed to the whole hemisphere of the sky. R is the distance between the source and receiver elements. φ is the zenith distance, the angle between the direction of R and the normal to the receiver element.

The radiance from dA_s, considering it as a blackbody, is N_s watt cm^{-2} ster^{-1}, and the radiant intensity J_s is $N_s dA_s$ watt ster^{-1}. The radiant power striking dA_e is

$$P_{Ae} = N_s \, dA_s \times \left(\frac{dA_e}{R^2} \cos \varphi\right),$$

where the expression in parentheses is the solid angle subtended by dA_e from dA_s.

For this Lambertian source, the relation between radiance and radiant emittance is

$$N_s = \frac{1}{\pi} W_s,$$

where W_s is the total radiation power emitted from a unit area of the source into the whole hemisphere. The factor π enters here rather than 2π because the radiance is defined in terms of radiation in a direction normal to the emitting surface. If the radiance multiplied by the cosine of the angle to the normal is integrated over the whole hemisphere, the resultant quantity, the radiant emittance, is equal to π times the radiance. Then,

$$P_{Ae} = \frac{1}{\pi R^2} W_s \, dA_s \, dA_e \cos \varphi.$$

The infrared energy rate received by the portable radiation thermometer from the clear sky was found to be independent of azimuth. Since the instrument records the radiation as though the source were a blackbody, the analysis is carried out in blackbody fashion with this assumption of azimuth independence.

The radiation power from a spherical band, described by the element dA_s, at the radius R, is

$$P_{Be} = \int_{Band} \frac{1}{\pi R^2} W_s \, d A_s \, d A_e \cos \varphi$$

$$= \frac{\cos \varphi}{\pi R^2} W_s \, dA_e \int_{Band} dA_s$$

$$= \frac{1}{\pi R^2} W_s \, dA_e \cos \varphi \, (2\pi \times R d\varphi)$$

$$= W_s \, dA_e \sin 2\varphi \, d\varphi.$$

The irradiance from the band on dA_e is

$$H_B = \frac{P_{B_e}}{d A_e} = W_s \sin 2\varphi \, d\varphi = \sigma T_S^4 \sin 2\varphi \, d\varphi \text{ watt cm}^{-2}.$$

The irradiance from the total hemisphere of the sky is

$$H = \int_0^{\pi/2} \sigma T_S^4 \sin 2\varphi \, d\varphi \text{ watt cm}^{-2}.$$

Since the aim is to determine the "effective" temperature of the whole sky as the instrument sees it, "effective" is defined. It is the temperature that the instrument would see if the energy were distributed uniformly throughout the hemisphere.

If T_S is uniform, then the irradiance is

$$H_u = \sigma T_S^4 \int_0^{\pi/2} \sin 2\varphi \, d\varphi.$$

$$H_u = \sigma T_S^4 = W_S, \tag{5}$$

where the subscript u refers to a uniform sky. This states that the irradiance on a small surface element enclosed in a hemispherical blackbody radiating uniformly is the same as the radiant emittance of the blackbody. Hence, using this one-to-one relationship between irradiance on the receiver and effective radiant emittance of the sky, it can be said that the effective radiant emittance for any kind of sky is

$$\text{eff } W_s = H = \int_0^{\pi/2} \sigma T_S^4 \sin 2\varphi \, d\varphi = \sigma T_S{}^4_{\text{eff}}. \tag{6}$$

The effective sky temperature is then

$$\text{eff } T_S = \left(\frac{1}{\sigma} \text{ eff } W_s\right)^{1/4}. \tag{7}$$

To obtain the total irradiance from the whole hemisphere, Eq. 6 is integrated in two parts, one covering zenith distances 0 to 60 degrees, the other covering zenith distances 60 to 90 degrees. Equations (2) and (3) are used, inserted into equation (6).

$$\text{eff } W_s = H = \int_0^{\pi/3} \left[\sigma T_o^{\,4} + 10^9 \sigma (\sec \varphi - 1)\right] \sin 2\varphi \, d\varphi$$

$$+ \int_{\pi/3}^{\pi/2} \sigma (ae^{b\varphi} + c) \sin 2\varphi \, d\varphi. \qquad (8)$$

This can be integrated, and reduces to

$$\text{eff } W_s = \frac{3}{4} \sigma T_o^{\,4} + \frac{1}{4} \sigma \times 10^9 +$$

$$\frac{\sigma a}{b^2 + 4} \left[2e^{b\pi/2} - e^{b\pi/3}\left(\frac{b\sqrt{3}}{2} + 1\right)\right] + \frac{1}{4} \sigma c. \qquad (9)$$

Here, σ is the Stefan-Boltzmann constant, T_o is the apparent sky temperature at 0-degree zenith distance, and a, b, and c are constants determined from the data of a set of measurements.

This equation was used to calculate the effective radiant emittance of the sky and the effective whole-sky temperature, $T_{eff} = (\frac{1}{\sigma} \text{ eff } W_s)^{1/4}$, for the data of 27 and 28 July 1964.

A summation process was also made of the same data, using 18 equally spaced segments of zenith distance (from 0 to 90 degrees) to obtain the same effective radiant emittances and effective whole-sky temperatures. From the geometry of Fig. 36, the solid angle of the spherical band as seen by the element of earth's surface dA_e is

$$\Omega_{Band} = 2\pi (\cos \varphi_1 - \cos \varphi_2),$$

where φ_1 and φ_2 are the zenith distances of the edges of the band. If we let $\varphi_A = \frac{\varphi_1 + \varphi_2}{2}$ and $\Delta\varphi = \varphi_2 - \varphi_1$, this converts to

$\Omega_{Band} = A_\pi \sin \varphi_A \sin \frac{\Delta\varphi}{2}$. If $\Delta\varphi < 8$ degrees, we can approximate

$\sin \frac{\Delta\varphi}{2} = \frac{\Delta\varphi}{2}$ with an error of less than 0.1 percent. Since these data were taken in steps of 5-degree intervals of zenith distance, we can use the approximation. Then,

$$\Omega_{Band} = 2\pi \sin \varphi_A \, \Delta\varphi.$$

In a manner analogous to the development of the integral expression, it can be stated that the irradiance on the elemental surface of the earth dA_e from the spherical band is

$$H_{Band} = N_{Band} \, \Omega_{Band} \cos \varphi_A,$$

where N_{Band} = average radiance across the band $= \frac{W_A}{\pi} = \frac{1}{\pi} \sigma T_A^4$, $\cos \varphi_A$ is the factor due to Lambert's law, and T_A is the average temperature across the band.

$$H_{Band} = \frac{W_A}{\pi} 2\pi \sin \varphi_A \cos \varphi_A \Delta\varphi$$
$$= 2 \sigma T_A^4 \sin \varphi_A \cos \varphi_A \Delta\varphi.$$

Since T and cos φ are both nonlinear functions, the question arises as to the proper values to choose for the respective "average" values, T_A and $\cos \varphi_A$. However, for simplicity it is assumed that the band interval $\Delta\varphi$ is small enough so that the midpoints of these variables may be used. Then $\cos \varphi_A$ and $\sin \varphi_A$ refer to the same angle. Then

$$H_{Band} = \sigma T_A^4 \sin 2\varphi_A \Delta\varphi. \tag{10}$$

Summing this over all values of zenith distances gives, in exact analogy to the integral expression of equation (6),

$$\text{eff } W_s = H = \Sigma_0^{\pi/2} \sigma T_A^4 \sin 2\varphi_A \Delta\varphi. \tag{11}$$

This equation was used on the data of 27 and 28 July 1964 to determine $T_{eff} = (\frac{1}{\sigma} \text{ eff } W_s)^{1/4}$. The results agreed with those of the integral equation to better than $\frac{1}{2}$°C. With this verification, the summation equation (11) was assumed valid, and it was used on the rest of the data.

Effective Whole-Sky Temperatures

The results of the calculations on effective whole-sky temperatures are given in Table 1. The last column gives the zenith distance at which the apparent sky temperature is the same value as the effective whole-sky temperature. The values in this last column are surprisingly constant at 54 degrees zenith distance, which attests to the consistency of the form of the curve over all times of day and night. This fact enables the evolvement of a much simpler method of obtaining reliable measurements of effective whole-sky temperature. A single measurement of apparent sky temperature at a zenith distance of 54 degrees is all that is needed, at least hypothetically. The reliability of such a technique should be held with reservations, especially when the measurements are extrapolated to all seasons of the year and other locations at different altitudes. But if high accuracy is not required, the gain in speed and simplicity makes this technique worth while.

By the same token, a linear relationship between effective whole-sky temperature and apparent sky temperature would be expected at the zenith. Such a relationship does exist in our data, as shown in the plot of Fig. 37, but it is not as definite a relationship as might be desired.

The calculations of effective whole-sky temperatures revealed the fact that the energy coming from the extremes of zenith distances--that is, at the zenith and at the horizon--contribute almost negligibly to the whole-sky temperature. At the zenith it is because of the cold temperature and rarefied atmosphere. At the horizon it is because of the cosine factor of Lambert's law.

SUMMARY

A portable radiation thermometer, made by Barnes Engineering Company, was used to measure apparent sky temperatures during July and August 1964 at Flagstaff, Arizona, at an altitude of 7000 feet. The two-degree field of view permitted point measurements at selected zenith distances from the zenith to the horizon, which were then used in a summation equation to obtain effective whole-sky temperatures.

The sensitivity of the instrument is in the 8- to 14-micron band, so the temperatures measured were not blackbody temperatures, nor even "true" sky temperatures. This was seen clearly in the spectral curves of sky radiance obtained by Ohio State University Research Foundation in measurements made over a period of time at different locations and at altitudes from sea level to 14,000 feet. These spectral curves show sharp "wings" in each case at about 8 and 14 microns, featuring very rapid changes of response at these points. Because of this the apparent sky temperature indicated by the Barnes instrument is critically dependent on the pass band of its filters. This is not a criticism of the instrument, since it was designed to measure temperatures of warmer surfaces such as the earth and bodies of water, which approximate blackbodies. But it does indicate precautions in using the instrument for this purpose.

All the measurements indicate that the apparent sky temperature at any zenith distance is not dependent on azimuth, but does vary with time of day. In general it follows the warming of the atmosphere by the sun. The plots of apparent sky temperature as a function of zenith distance were quite smooth and consistent, and it was found that the sky repeats itself thermally to such an extent that a plot of temperatures is duplicated reliably by any plot at another time or another day if the zenith temperature is the same.

Apparent zenith temperatures of clear skies were obtained for altitudes from sea level to 14,000 feet by integration of the Ohio State University curves. These temperatures ranged from -21°C to -82°C, and are generally consistent with the temperatures found at Flagstaff, which ranged from -34°C to -62½°C.

The summation equation used to compute the effective whole-sky temperatures was found, by comparison with an integral equation, to fit the data from Flagstaff to within ½°C. Being much simpler and faster to use, it was used in preference to the integral equation.

It was found that the effective whole-sky temperature was consistently the same value as the apparent sky temperature at a zenith distance of 54 degrees. This fact can simplify data-taking considerably.

The program of sky-temperature measurements was part of a program of measuring the emissivity of soil surfaces, for which the sky temperature is needed. The program of measuring the emissivity of soil surfaces will be covered in a separate report.

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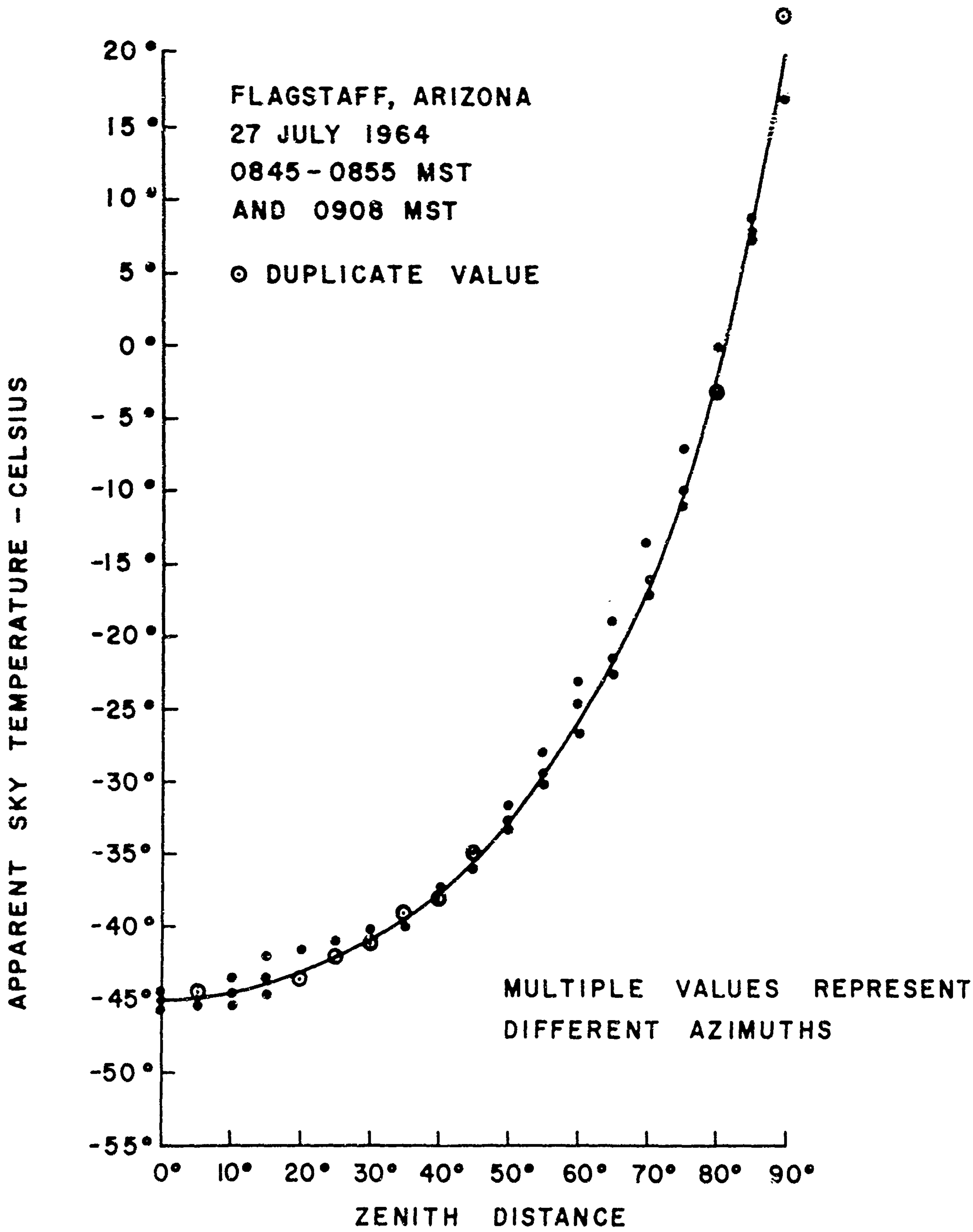

FIG. I APPARENT SKY TEMPERATURE WITH INFRARED THERMOMETER

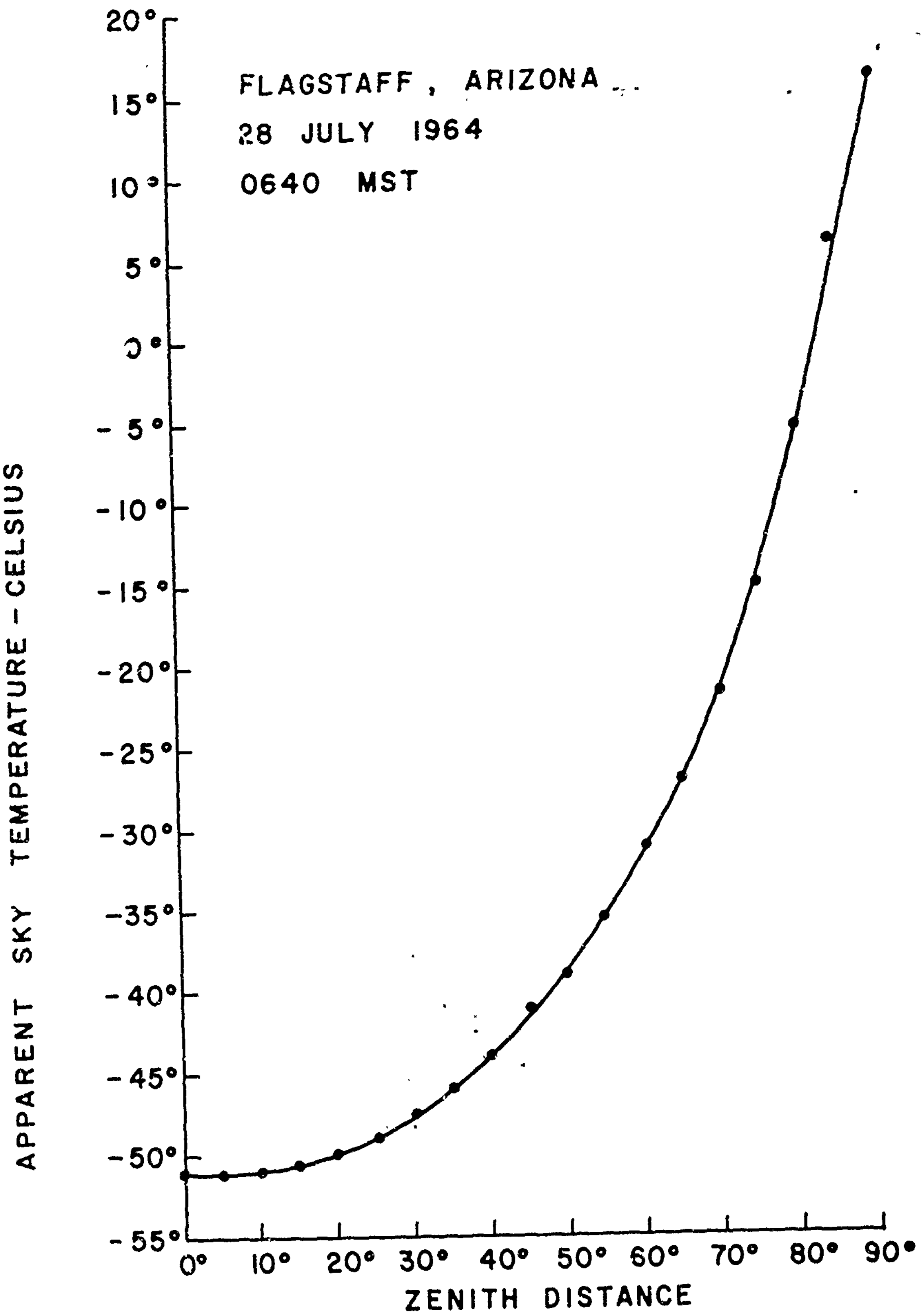

FIG. 2 APPARENT SKY TEMPERATURE WITH INFRARED THERMOMETER

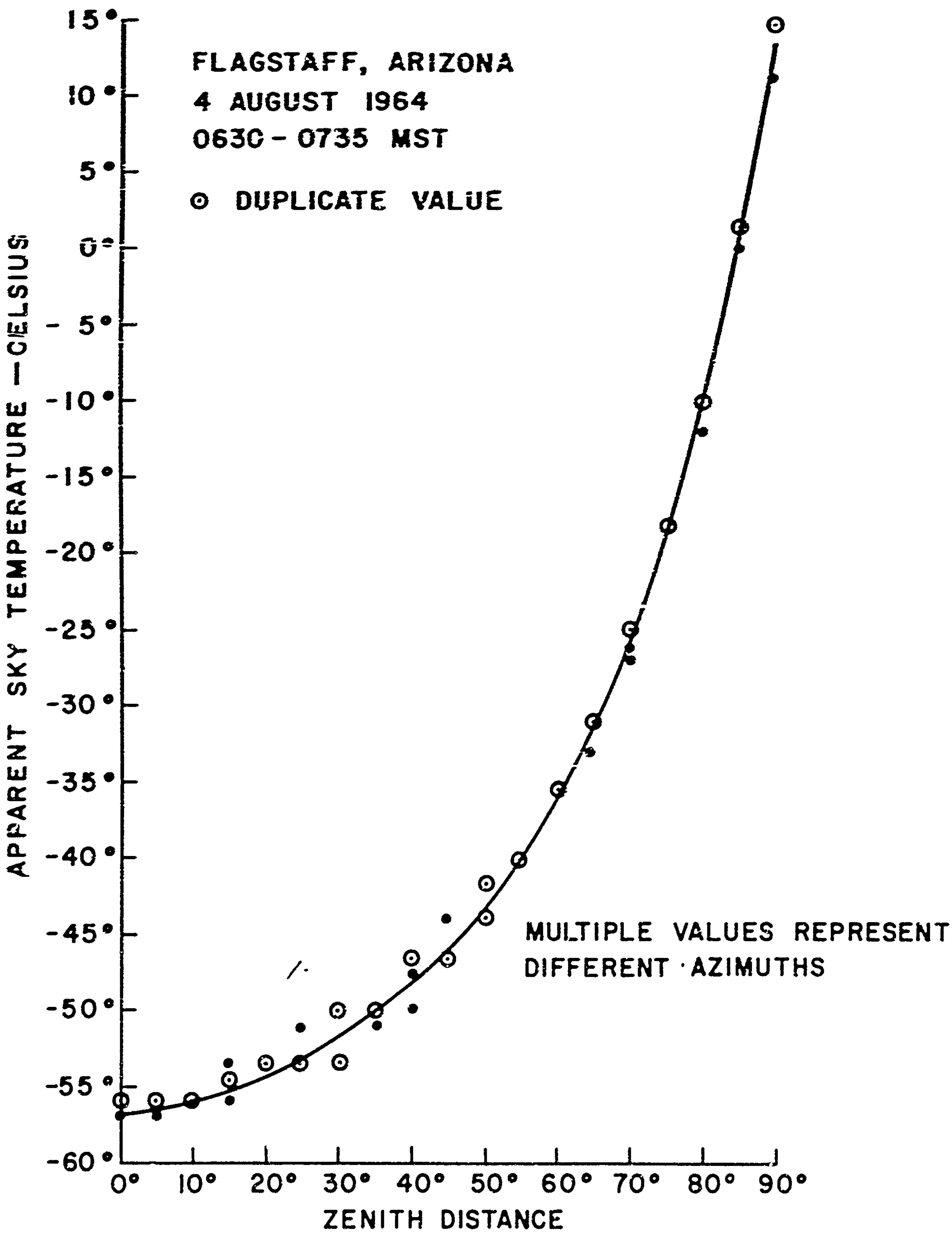

FIG 3 APPARENT SKY TEMPERATURE WITH INFRARED THERMOMETER

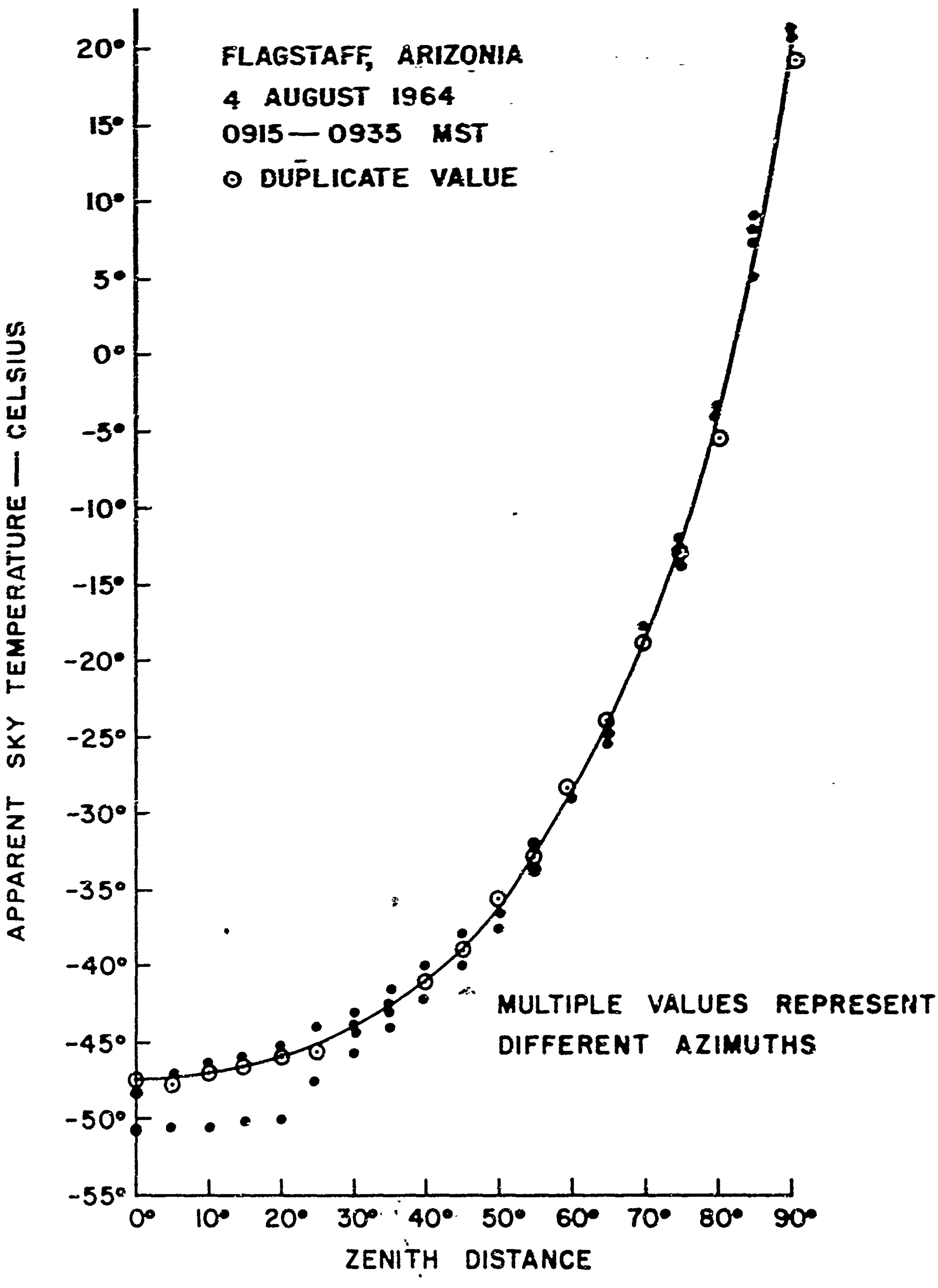

FIG. 4 APPARENT SKY TEMPERATURE WITH INFRARED THERMOMETER

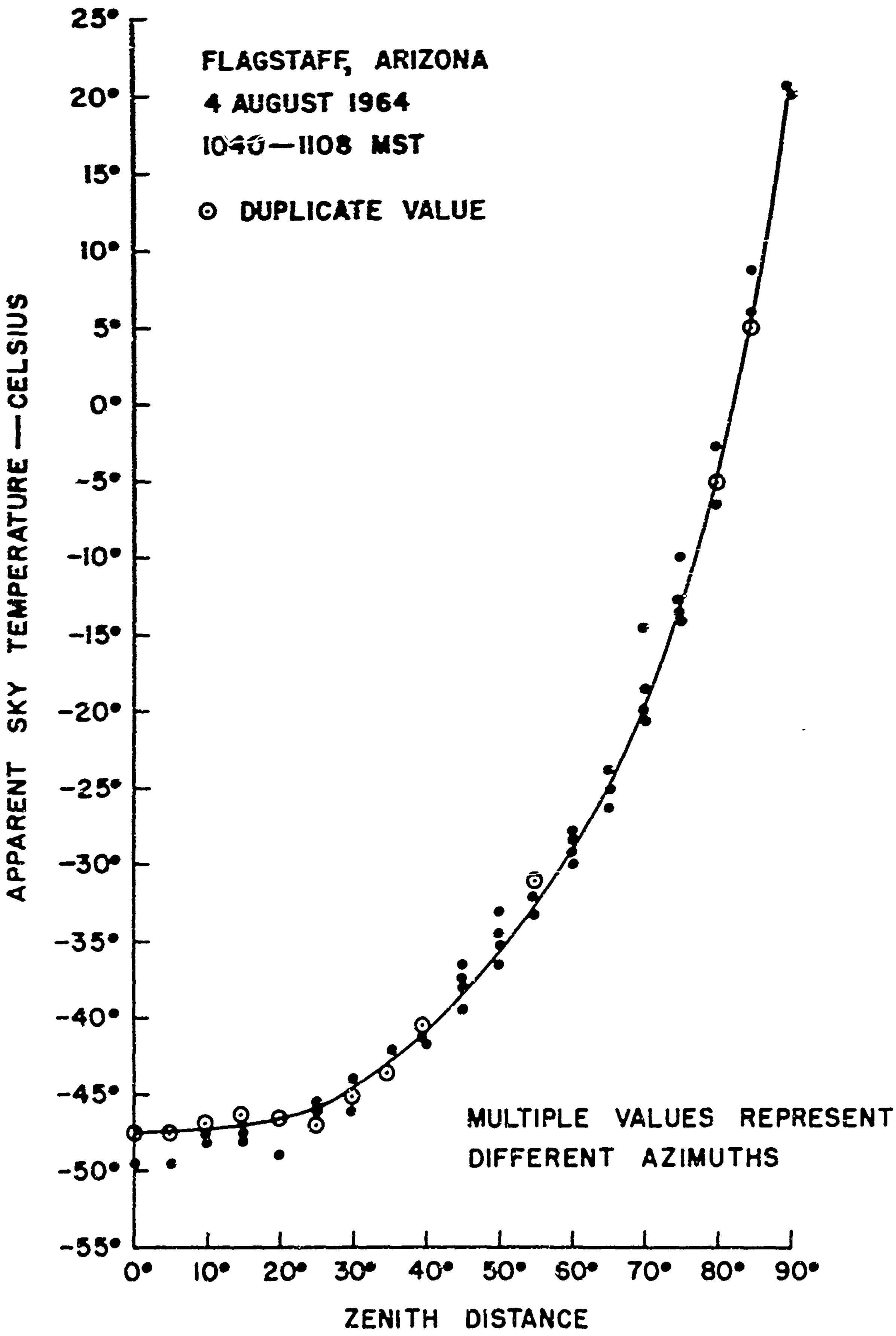

FIG. 5 APPARENT SKY TEMPERATURE WITH INFRARED THERMOMETER

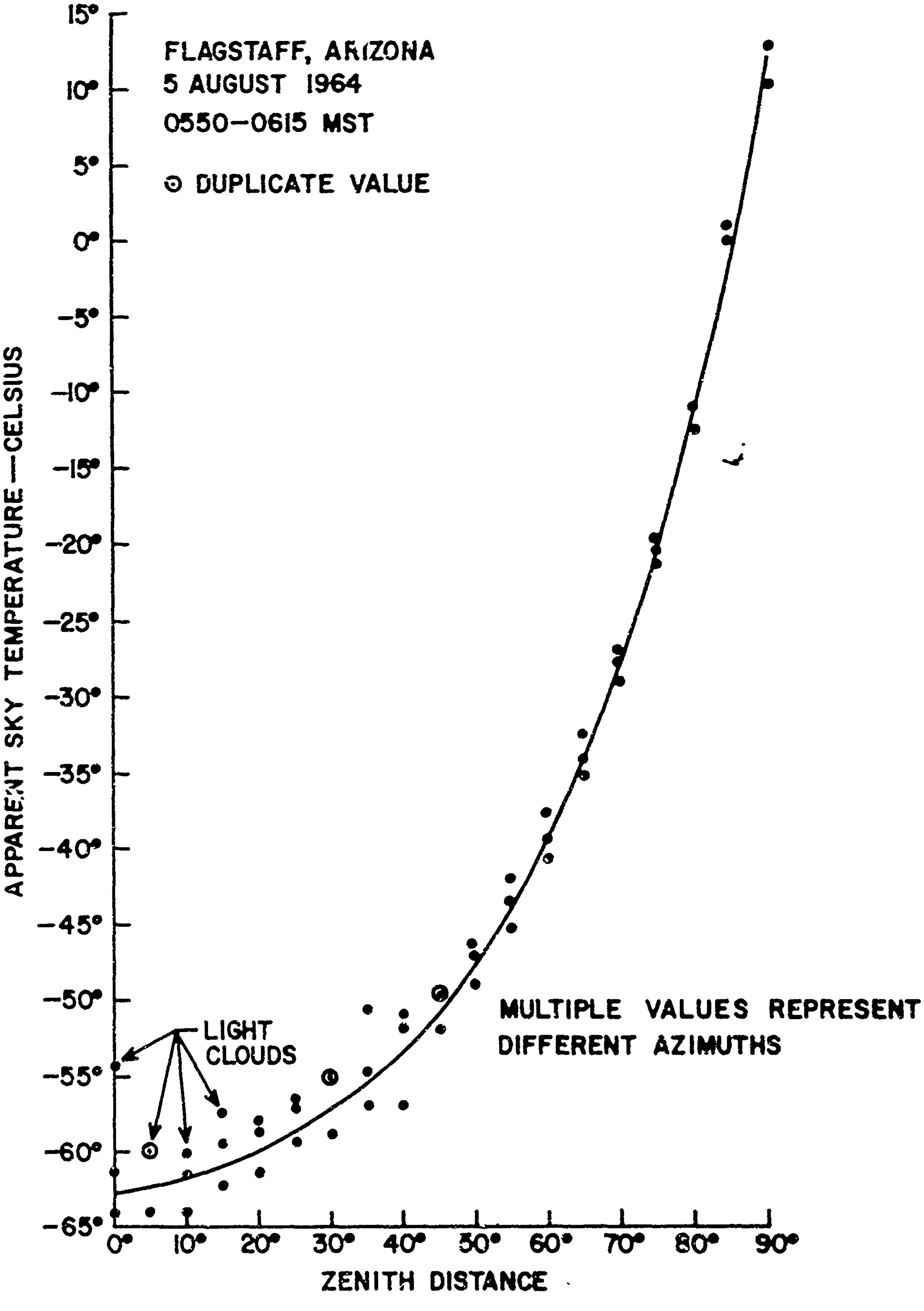

FIG 6 APPARENT SKY TEMPERATURE WITH INFRARED THERMOMETER

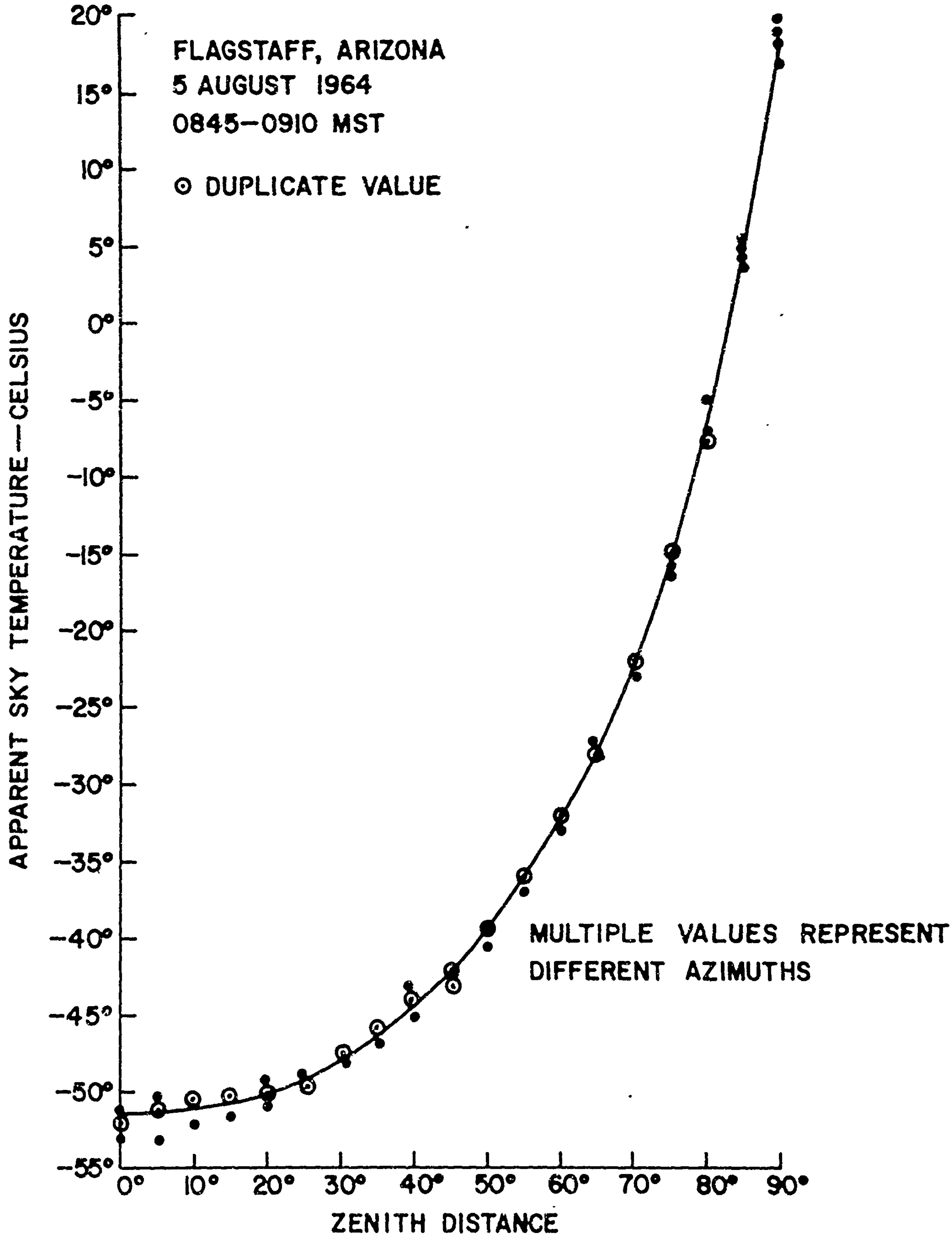

FIG 7 APPARENT SKY TEMPERATURE WITH INFRARED THERMOMETER

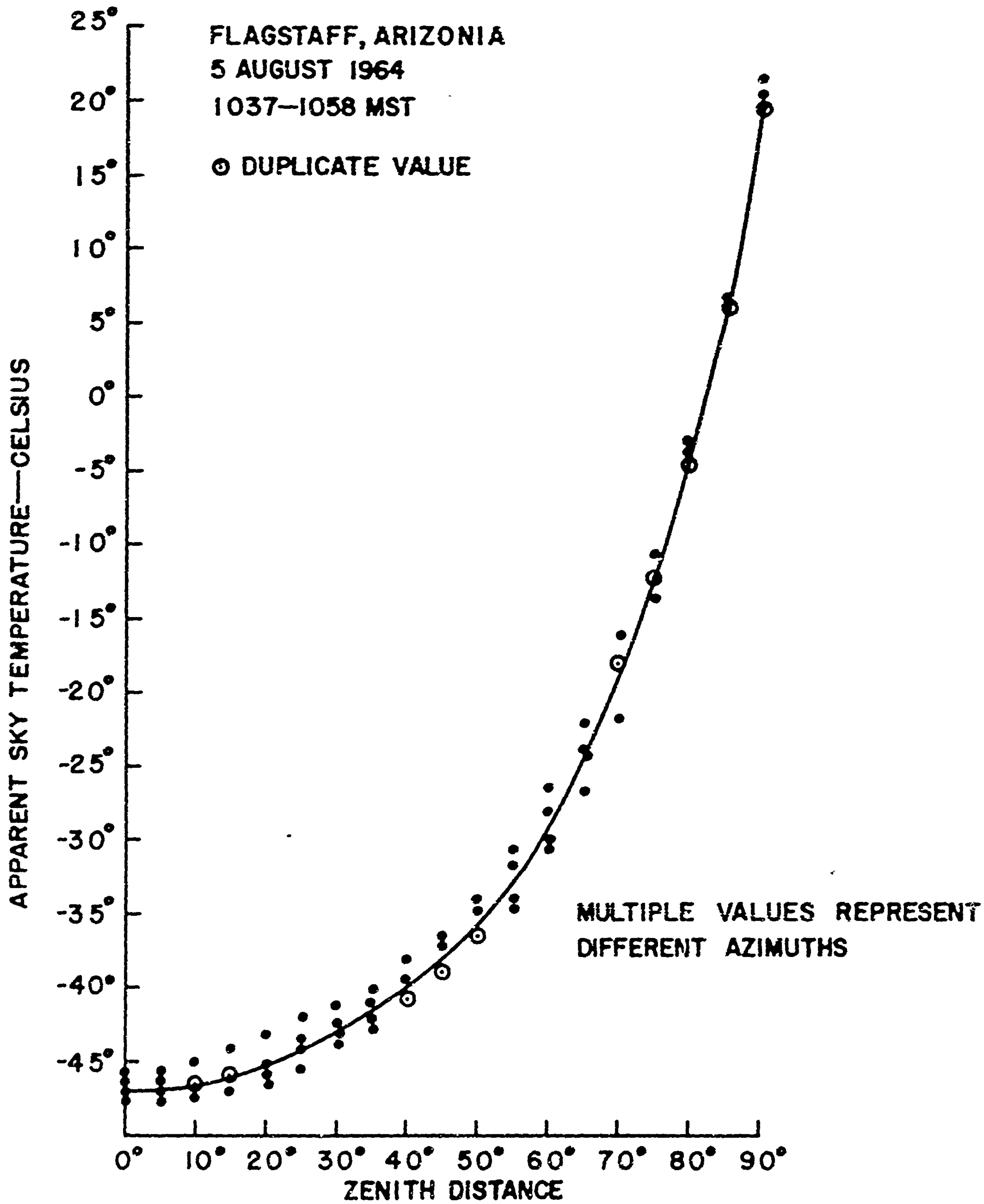

FIG 8 APPARENT SKY TEMPERATURE WITH INFRARED THERMOMETER

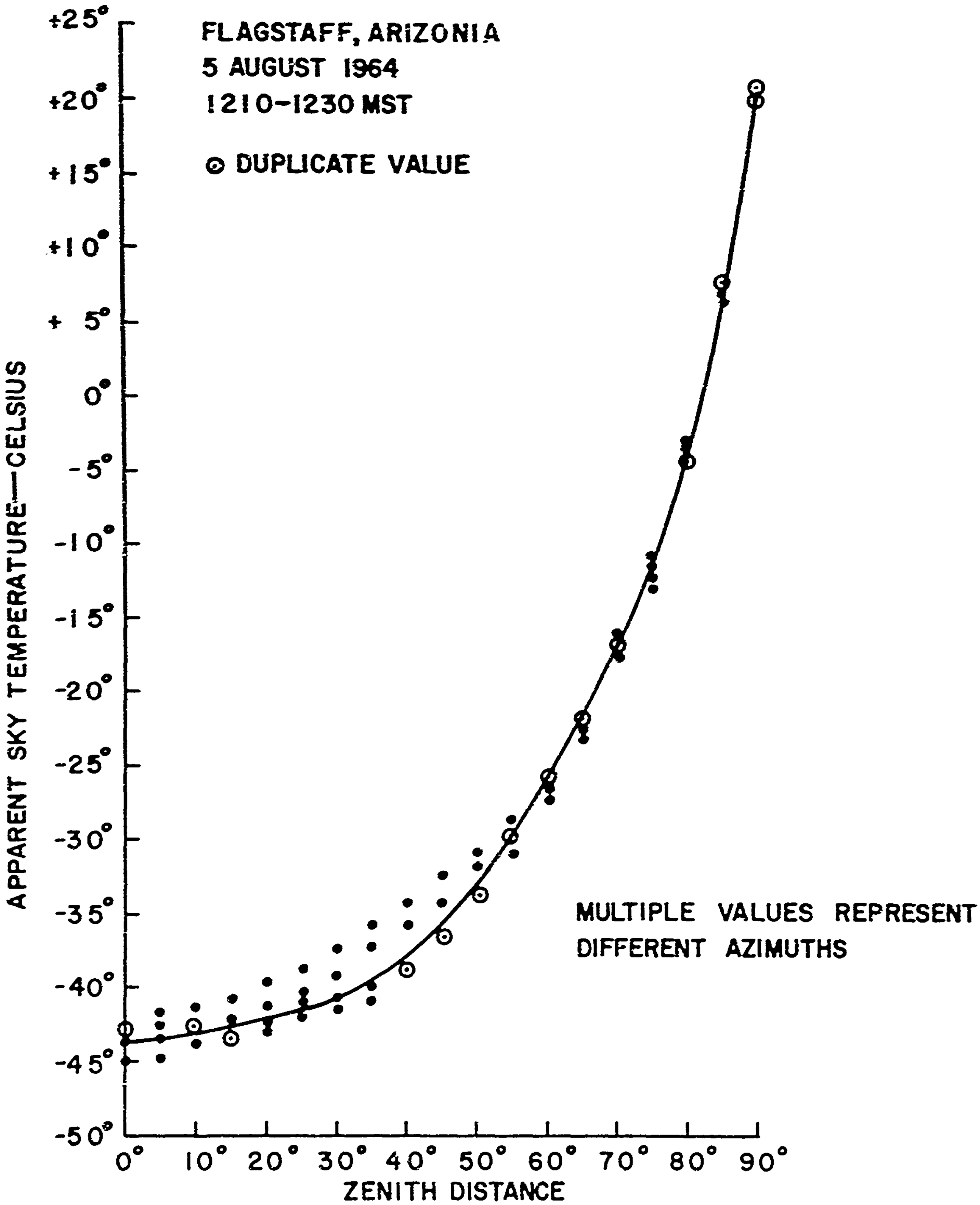

FIG 9 APPARENT SKY TEMPERATURE WITH INFRARED THERMOMETER

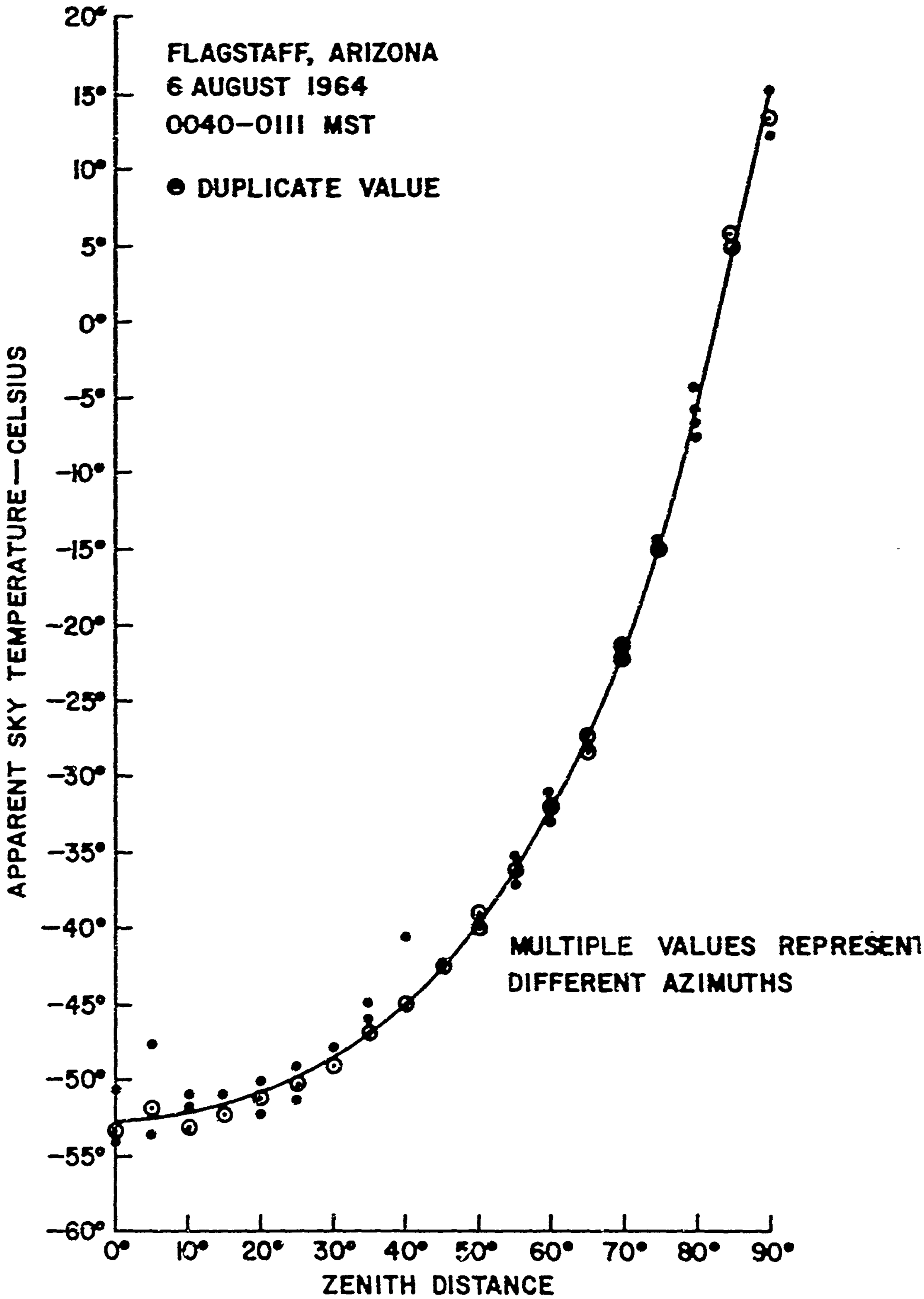

FIG 10 APPARENT SKY TEMPERATURE WITH INFRARED THERMOMETER

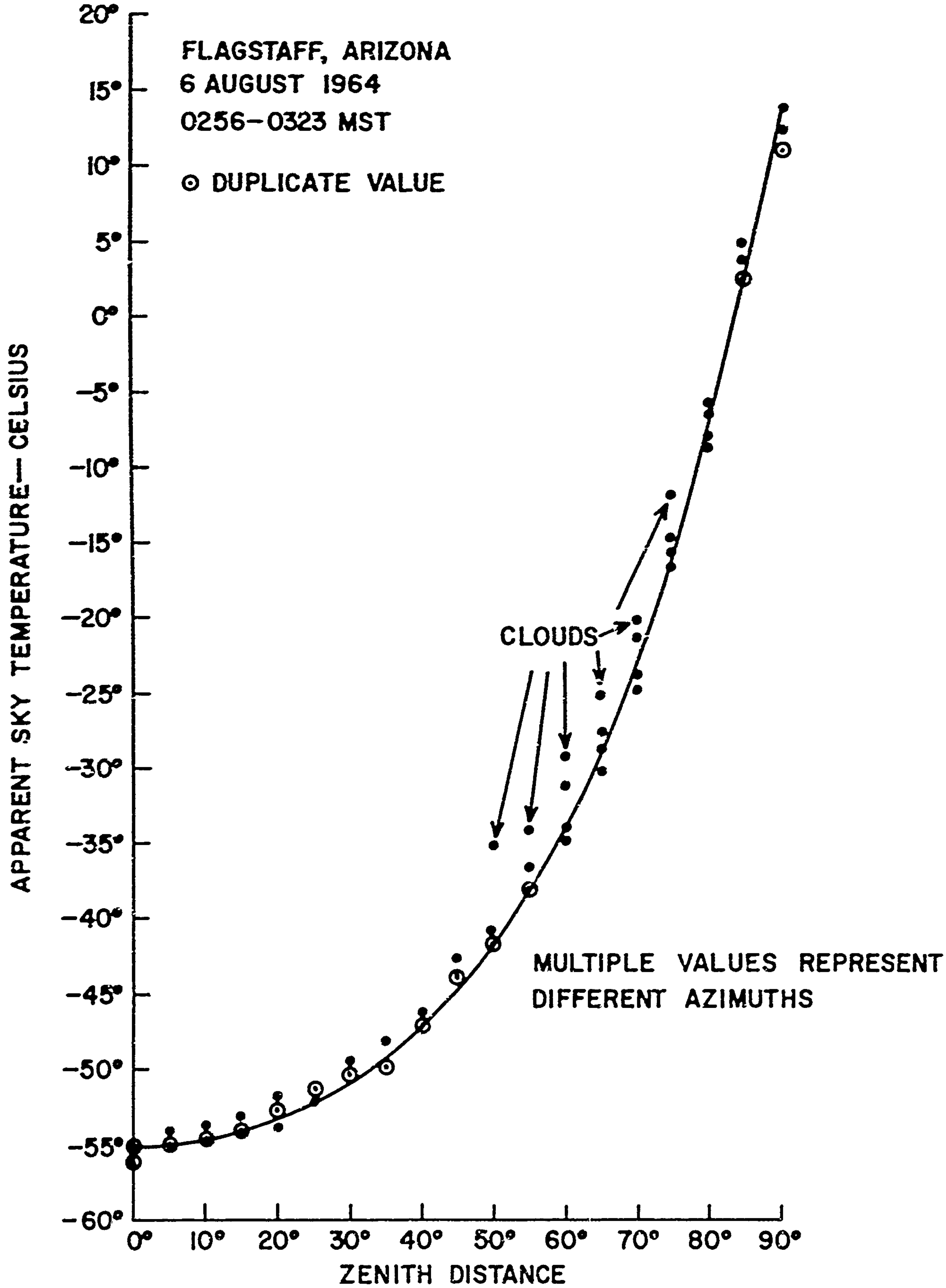

FIG 11 APPARENT SKY TEMPERATURE WITH INFRARED THERMOMETER

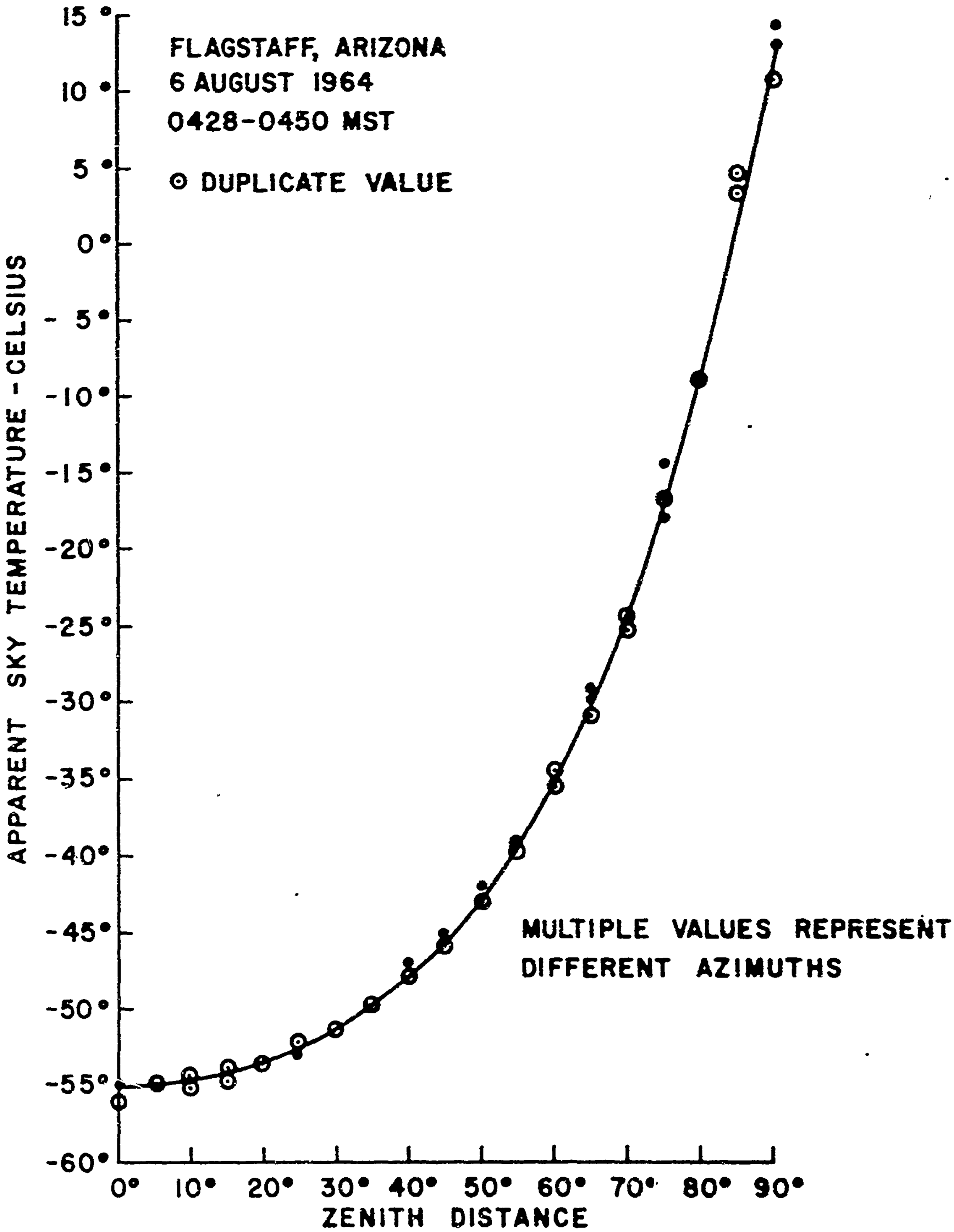

FIG. 12 APPARENT SKY TEMPERATURE WITH INFRARED THERMOMETER

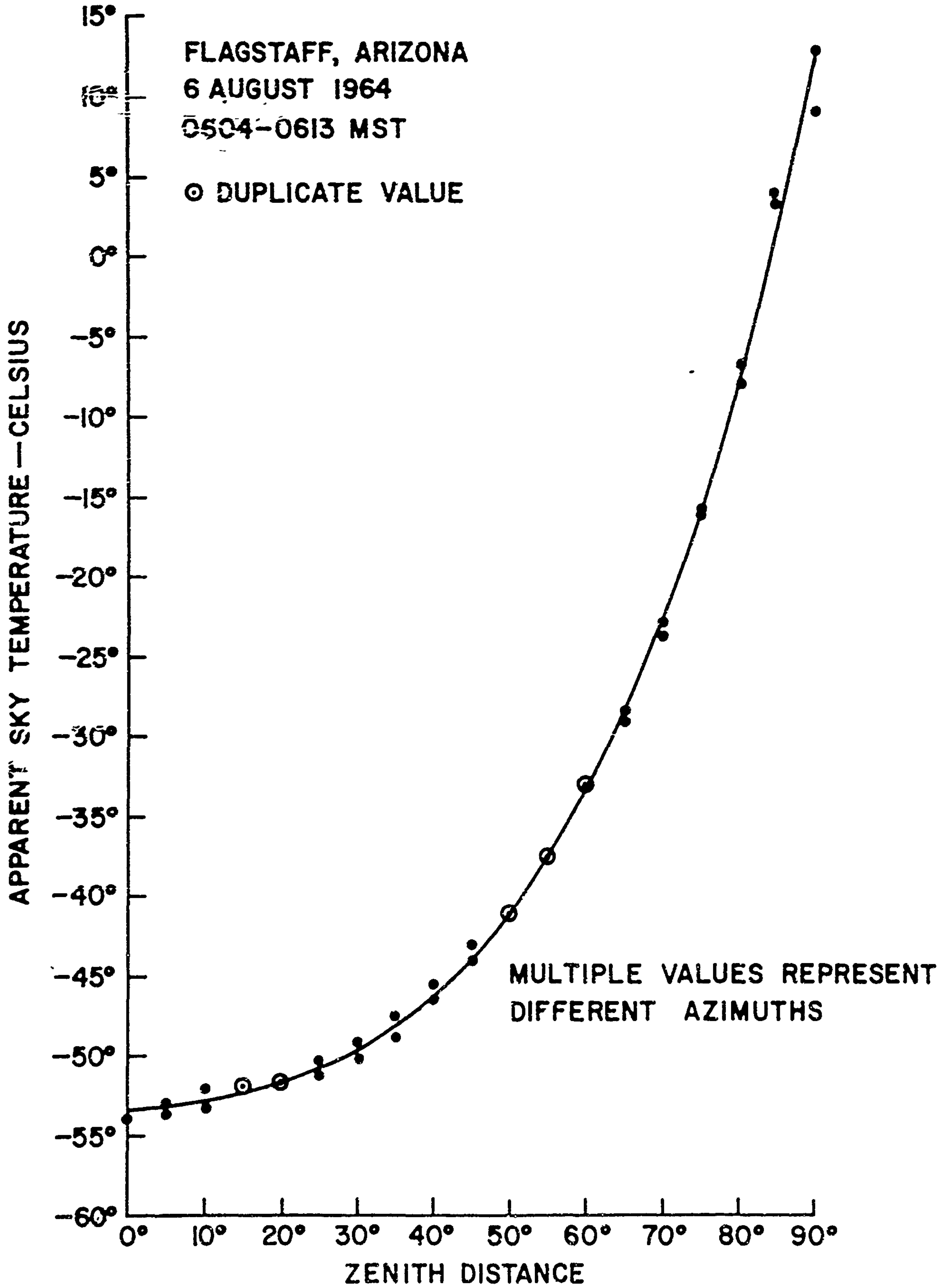

FIG 13 APPARENT SKY TEMPERATURE WITH INFRARED THERMOMETER

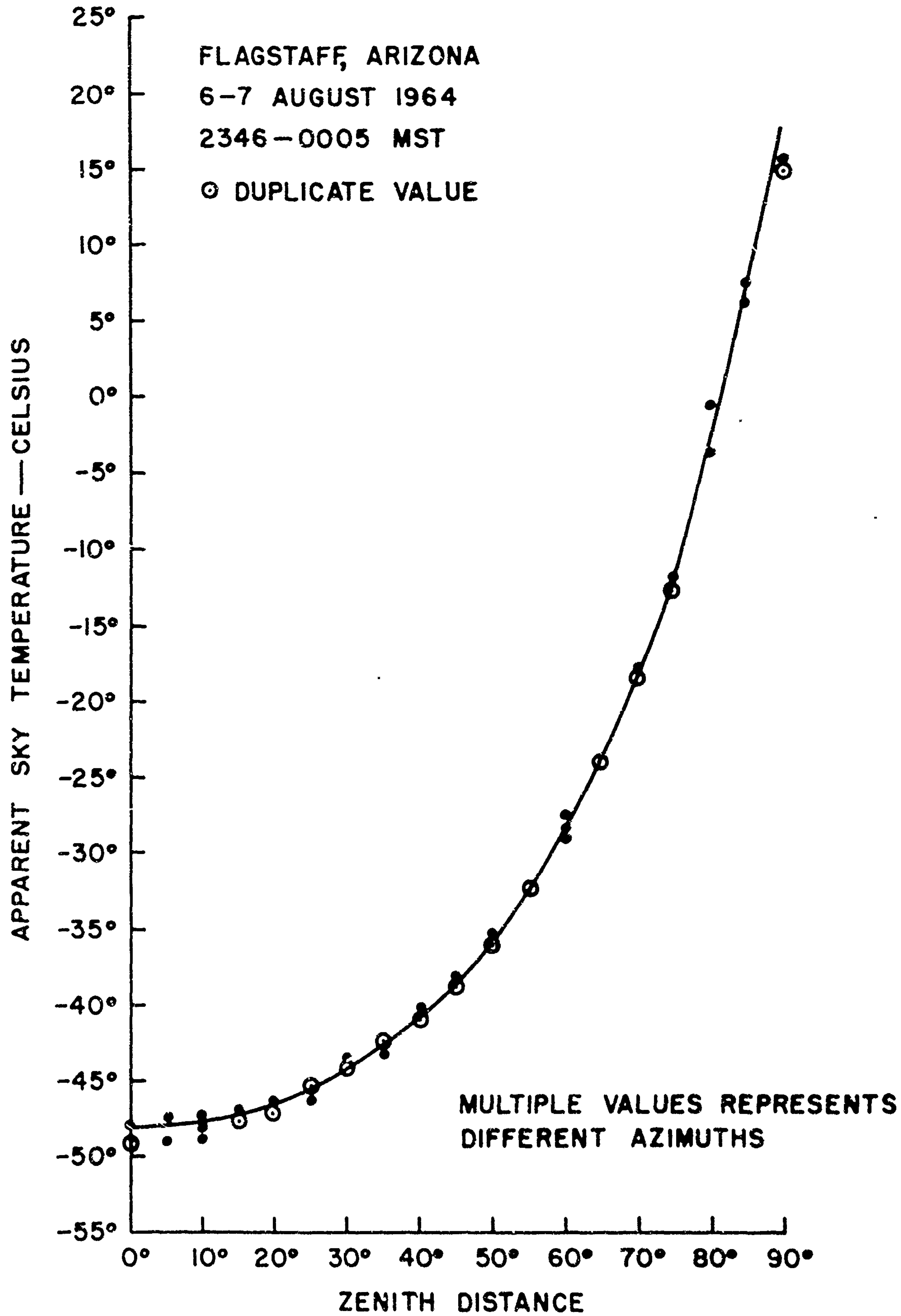

FIG. 14 APPARENT SKY TEMPERATURE WITH INFRARED THERMOMETER

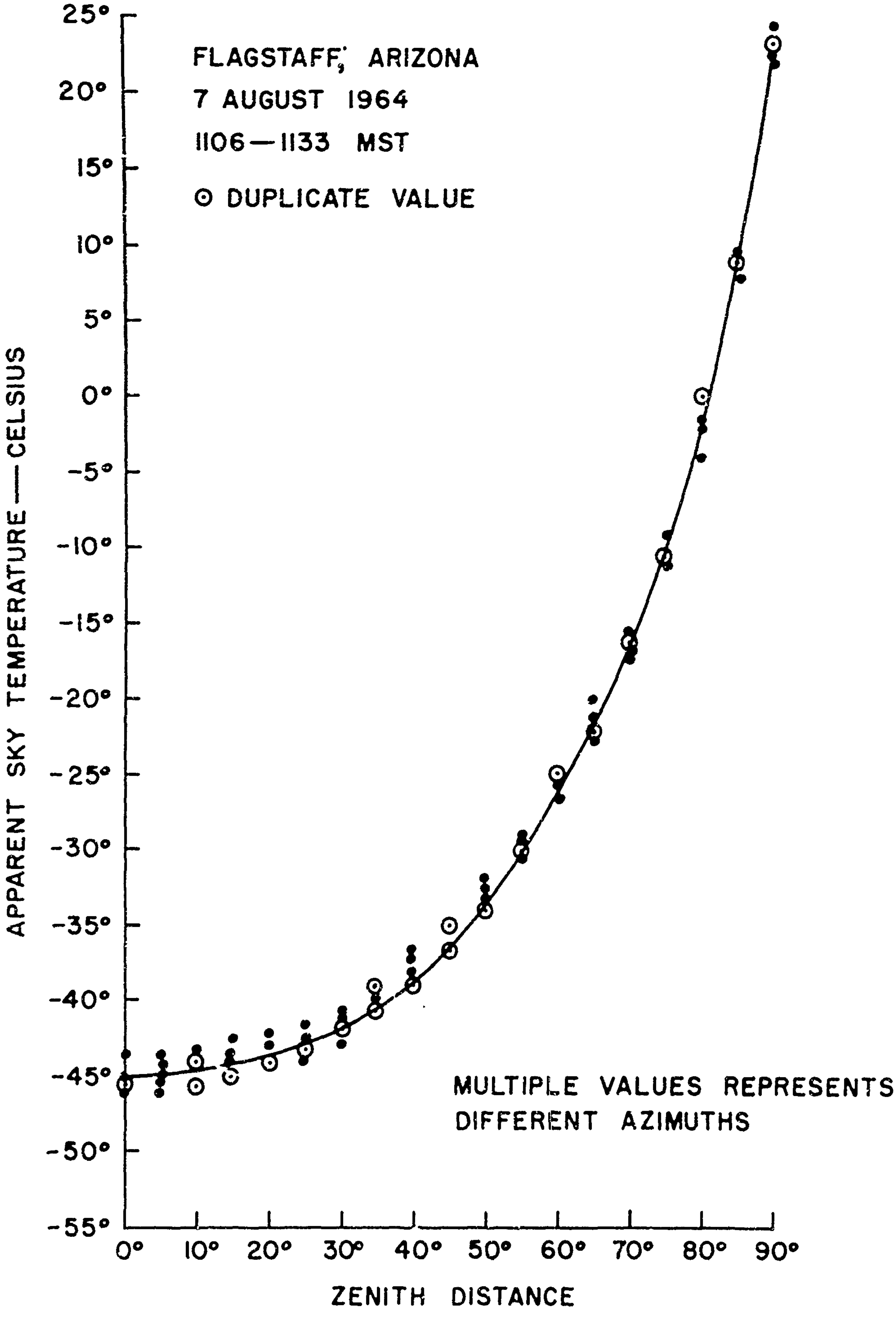

FIG. 15 APPARENT SKY TEMPERATURE WITH INFRARED THERMOMETER

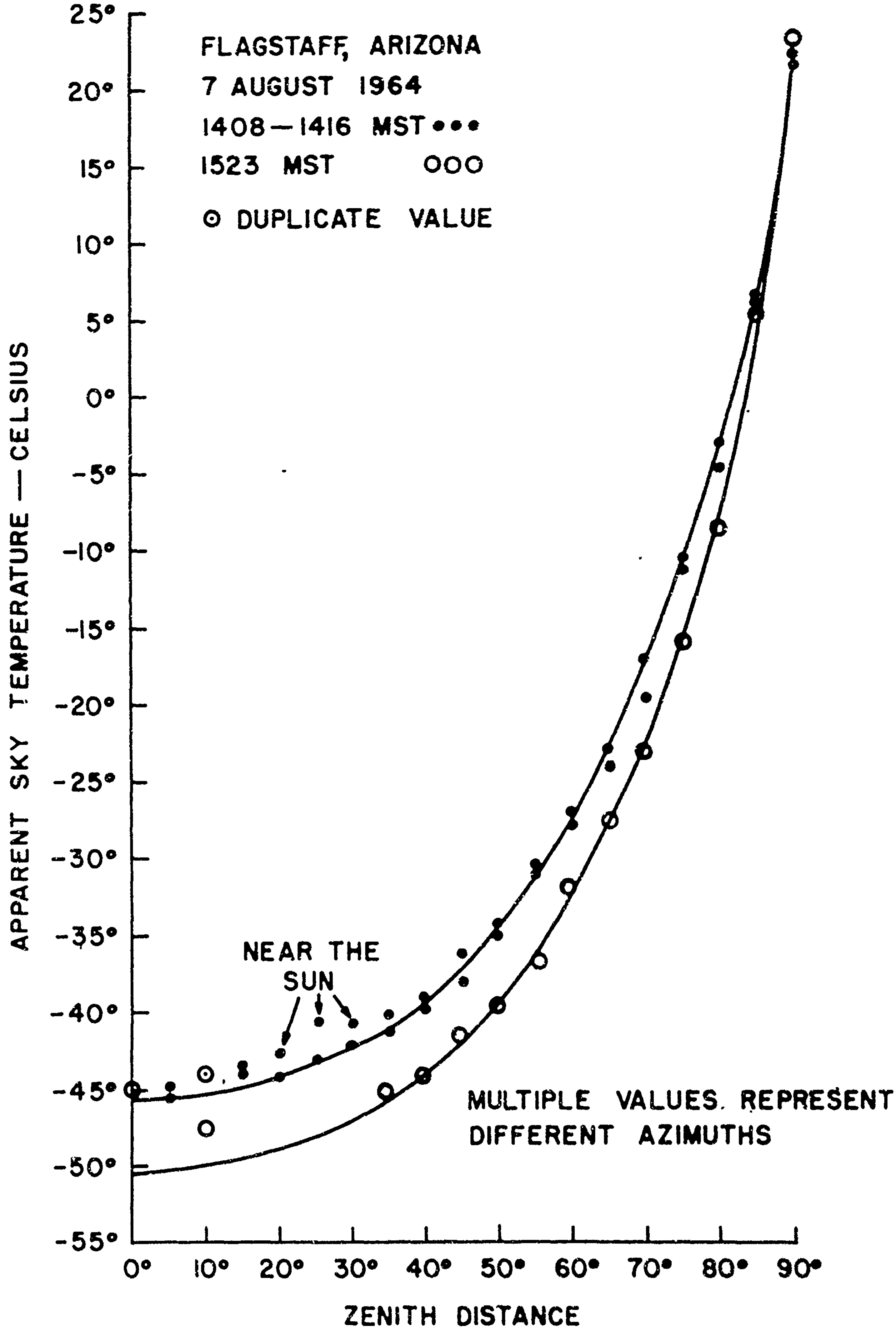

FIG. 16 APPARENT SKY TEMPERATURE WITH INFRARED THERMOMETER

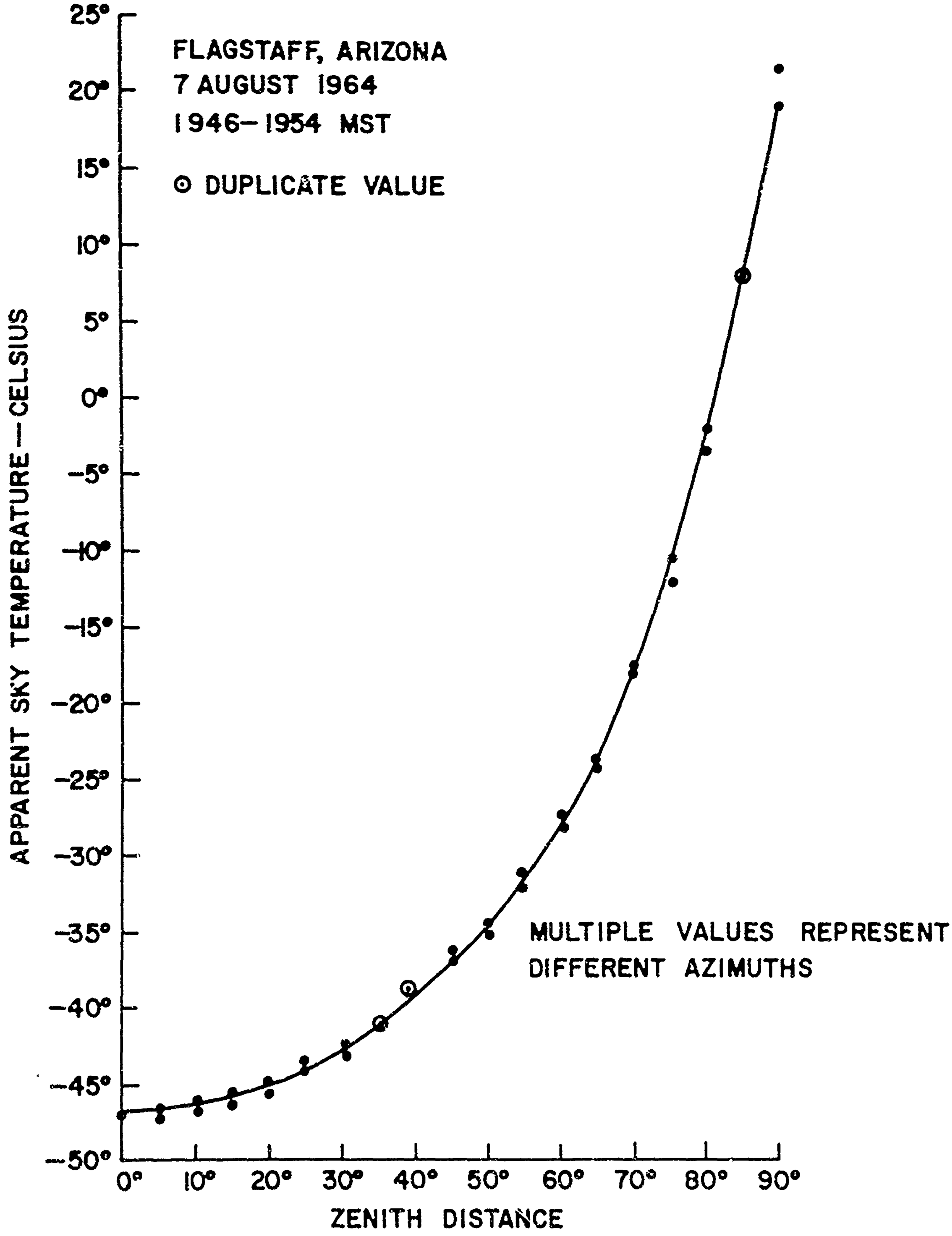

FIG 17 APPARENT SKY TEMPERATURE WITH INFRARED THERMOMETER

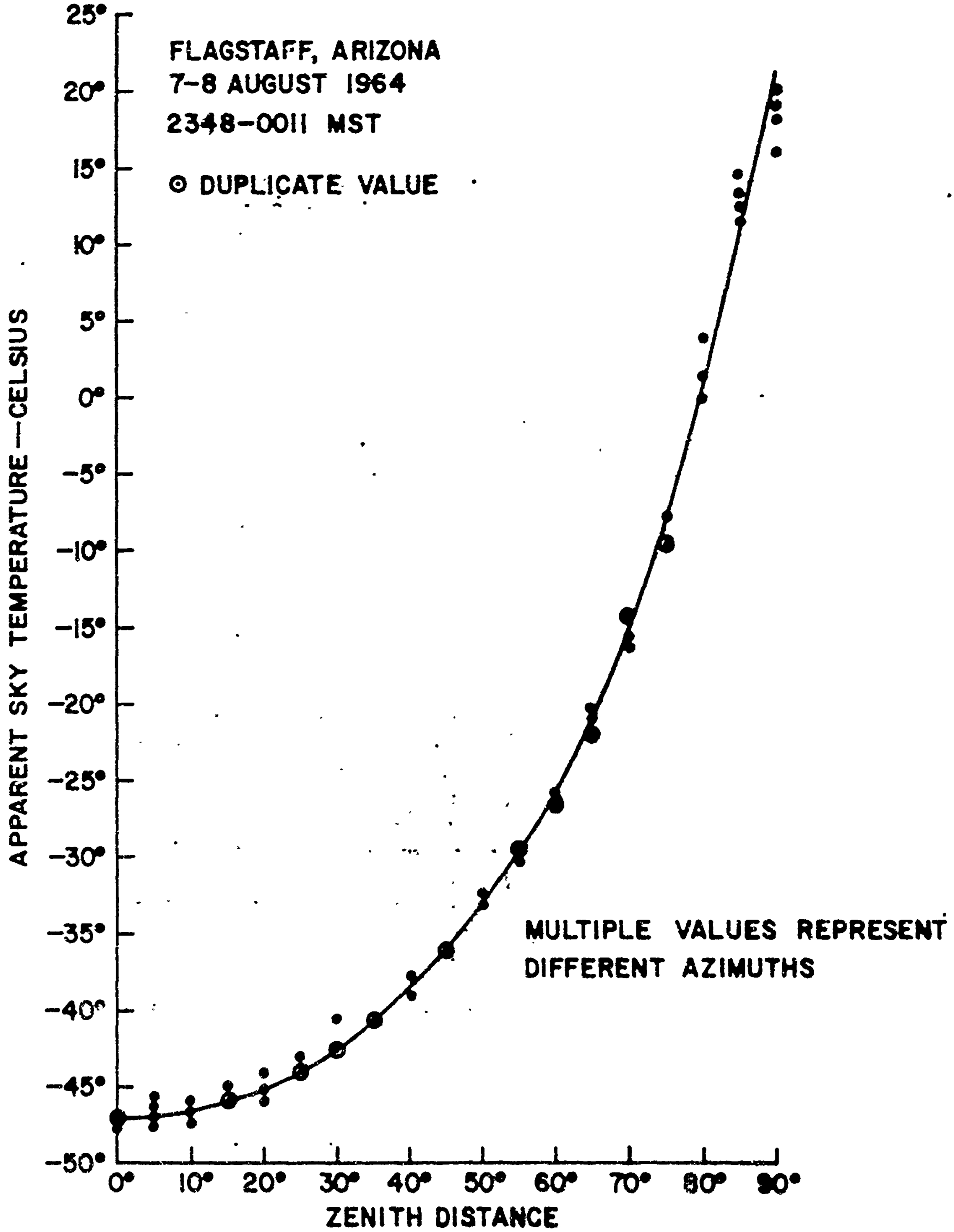

FIG 18 APPARENT SKY TEMPERATURE WITH INFRARED THERMOMETER

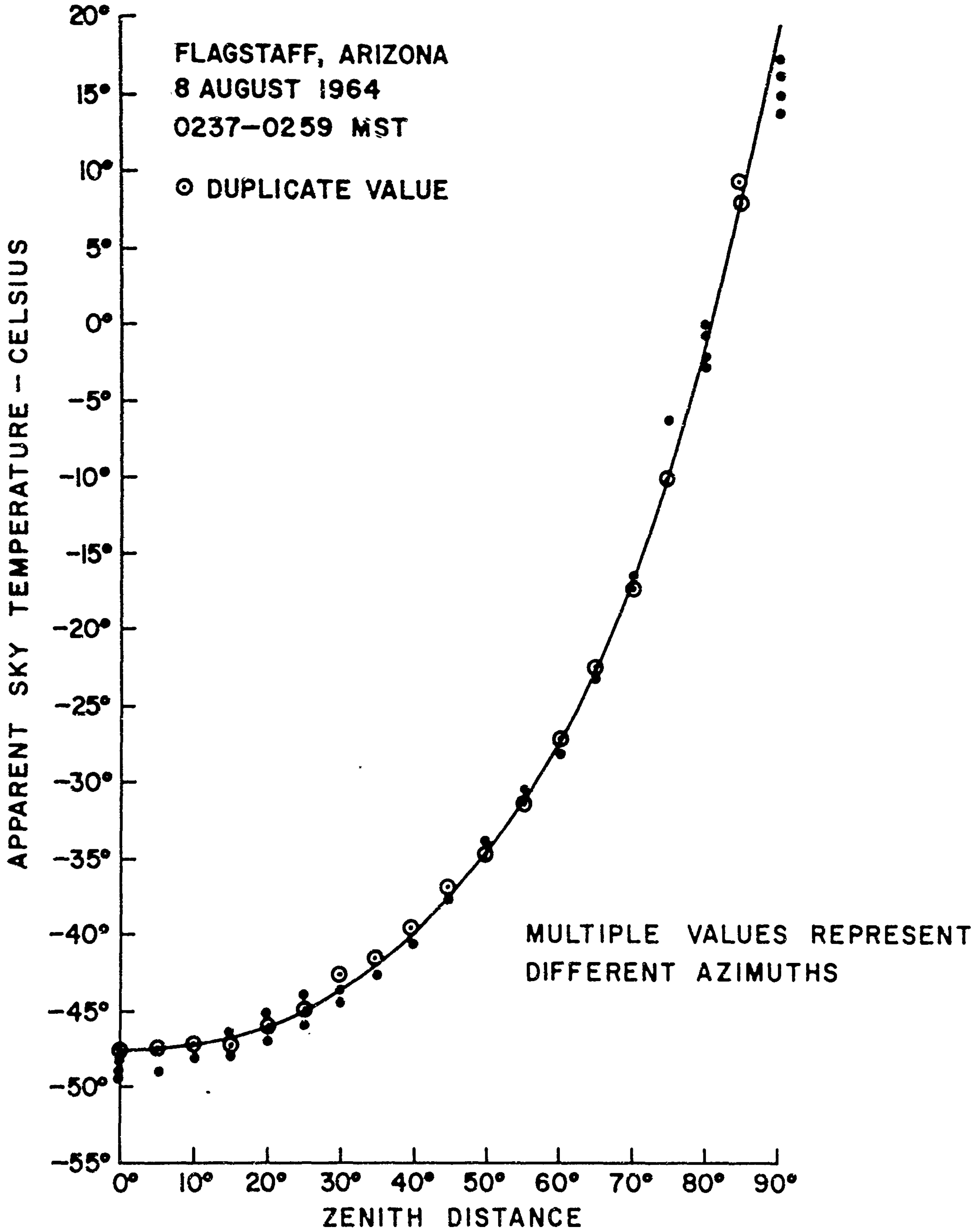

FIG. 19 APPARENT SKY TEMPERATURE WITH INFRARED THERMOMETER

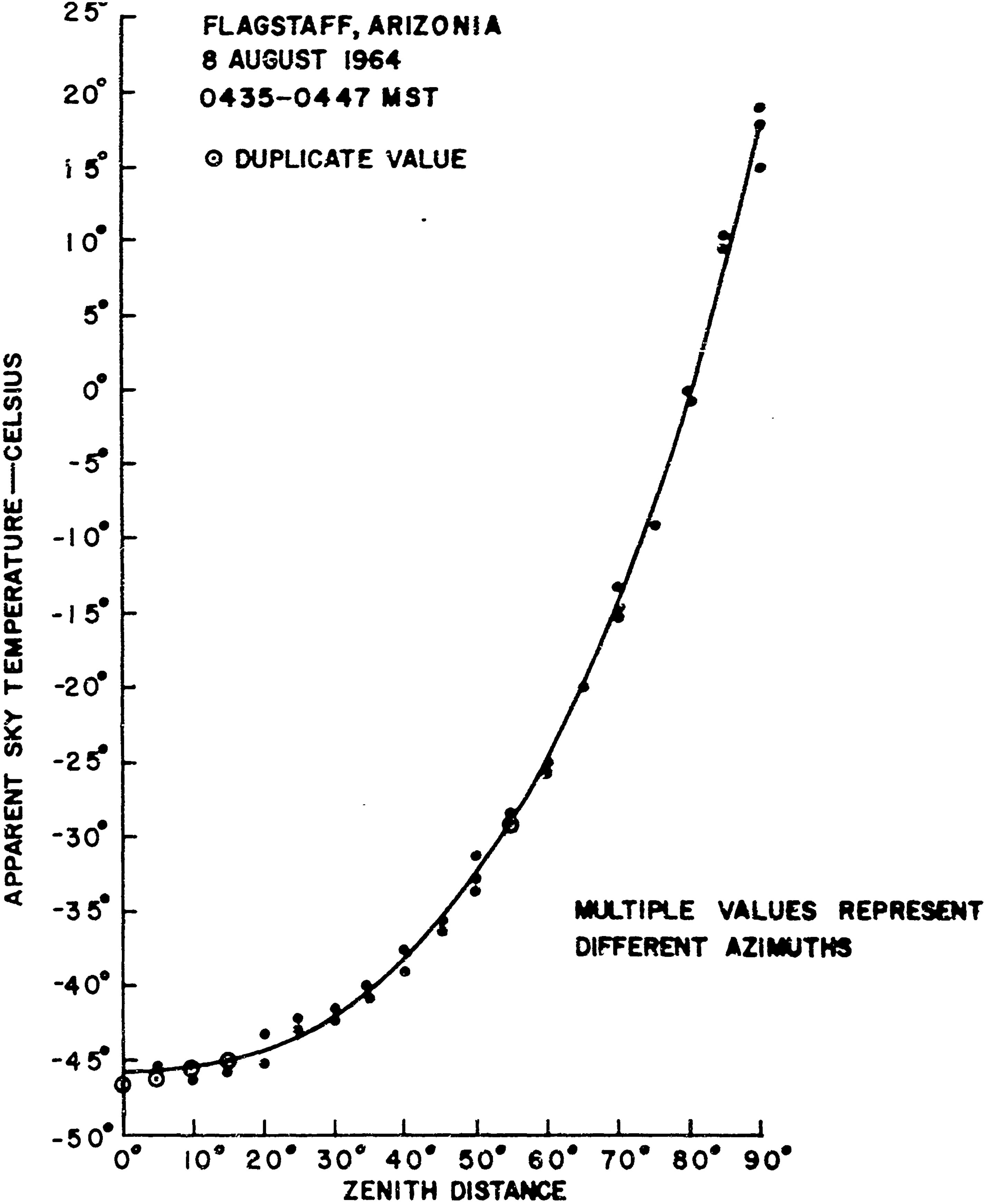

FIG 20 APPARENT SKY TEMPERATURE WITH INFRARED THERMOMETER

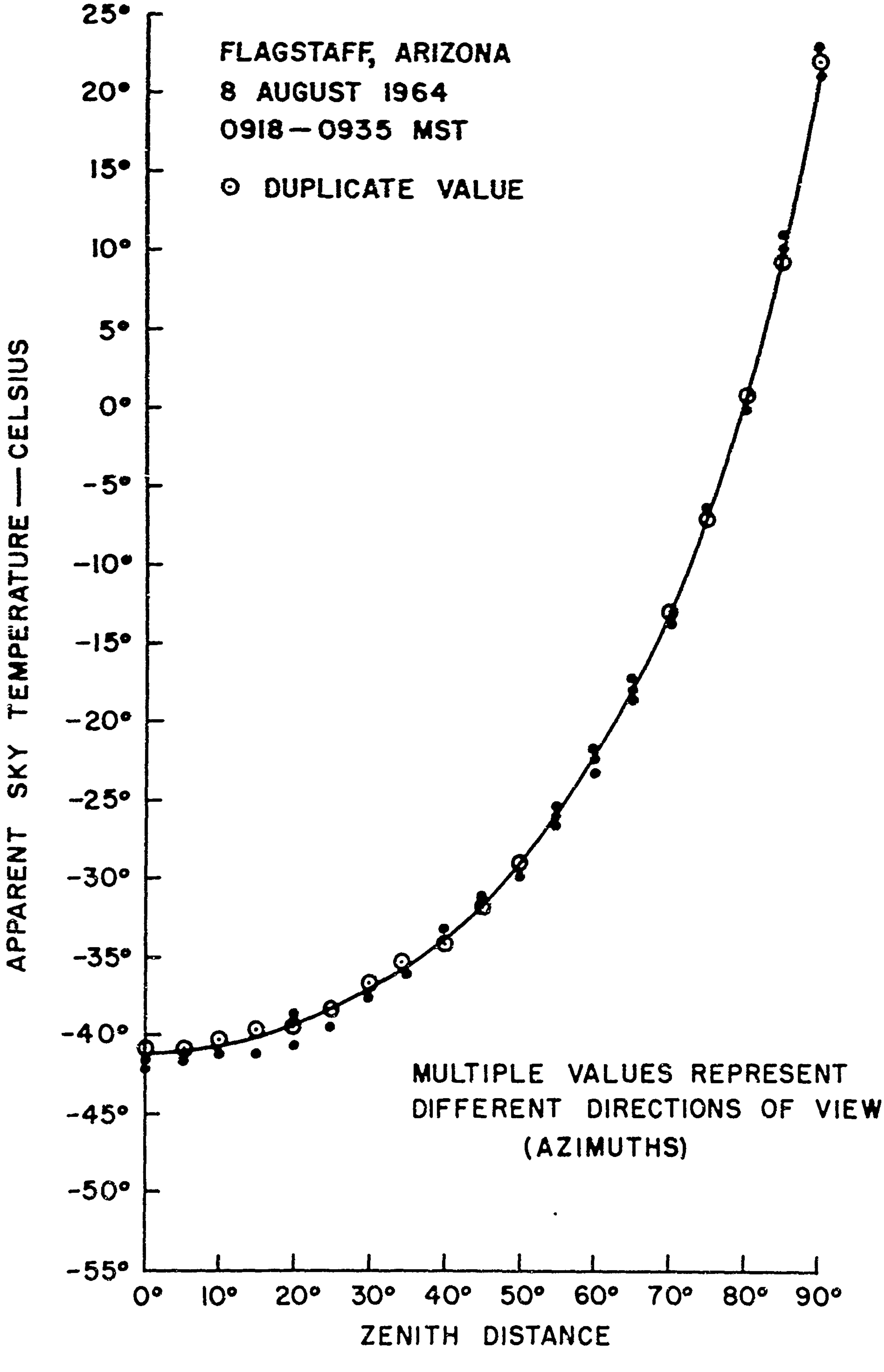

FIG. 21 APPARENT SKY TEMPERATURE WITH INFRARED THERMOMETER

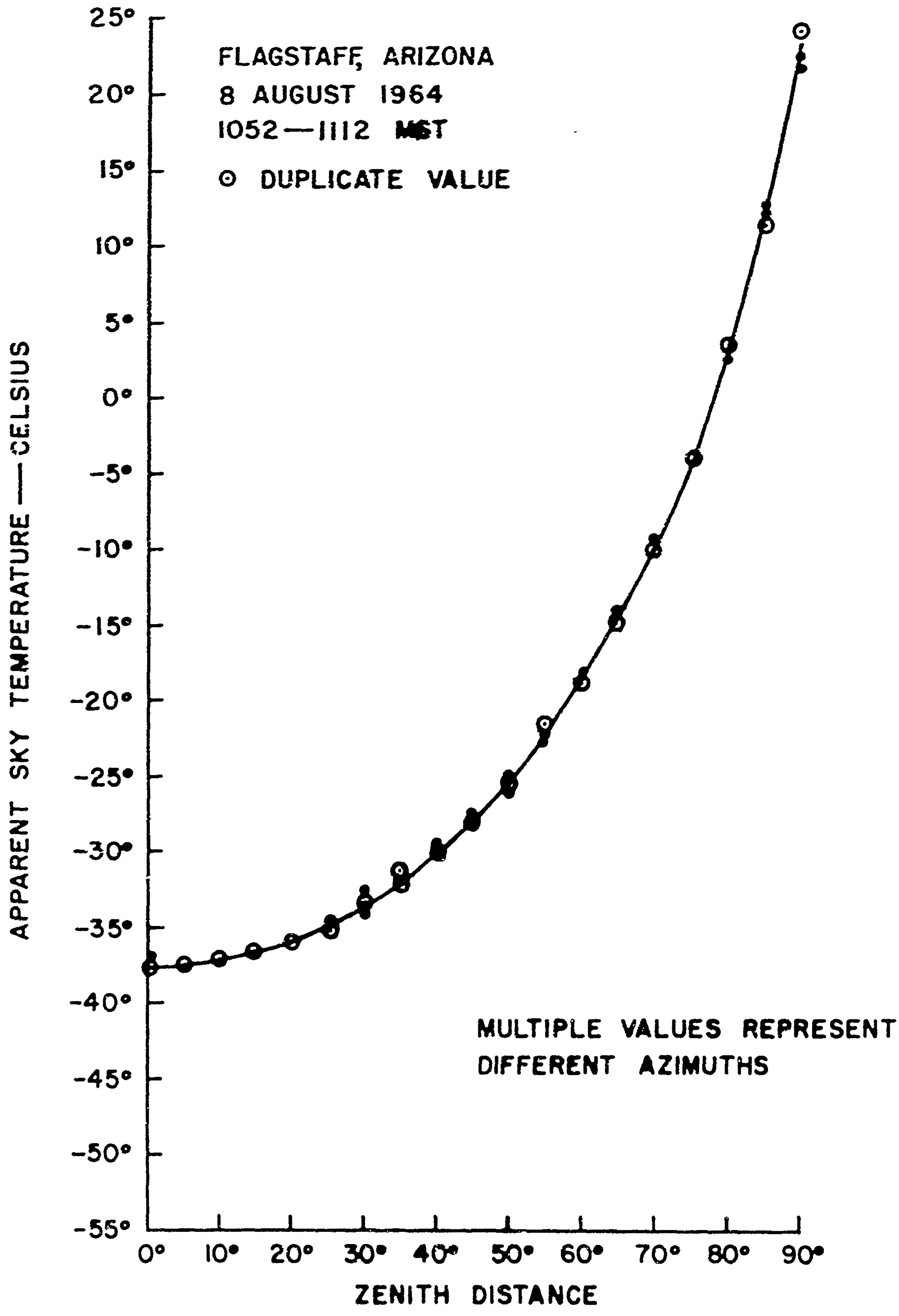

FIG. 22 APPARENT SKY TEMPERATURE WITH INFRARED THERMOMETER

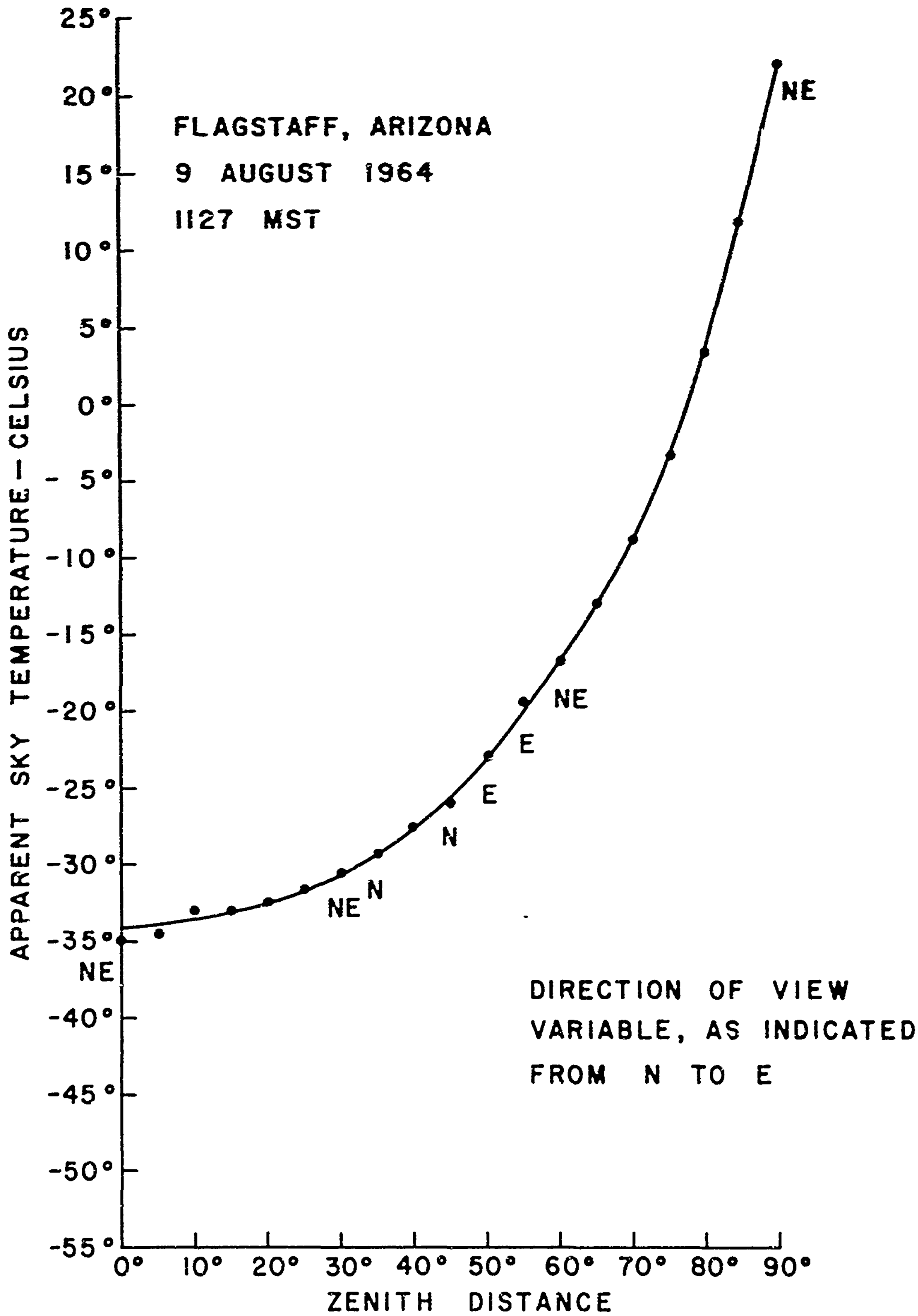

FIG. 23 APPARENT SKY TEMPERATURE WITH INFRARED THERMOMETER

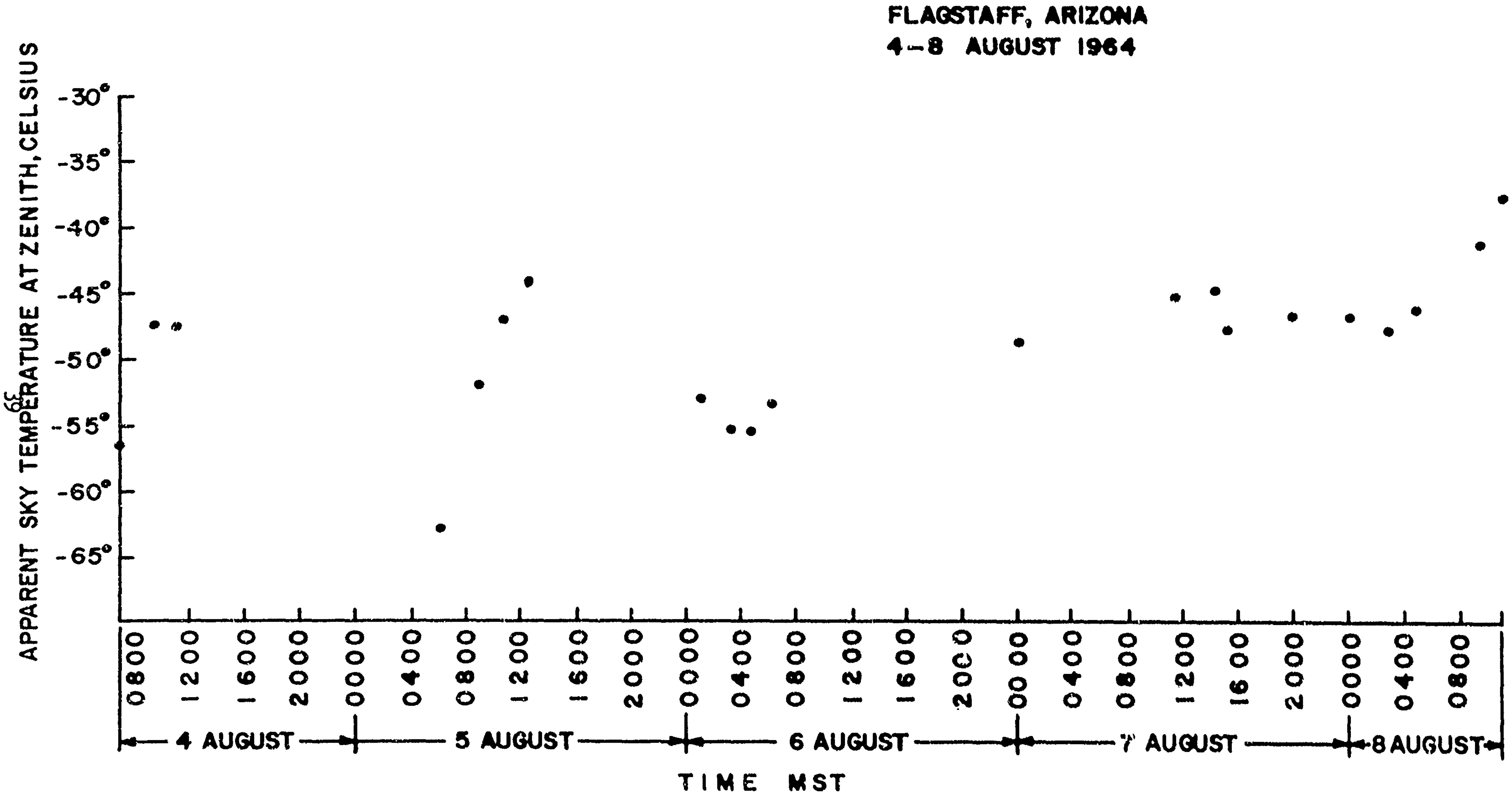

FIG 24 APPARENT SKY TEMPERATURE AT ZENITH
WITH INFRARED THERMOMETER

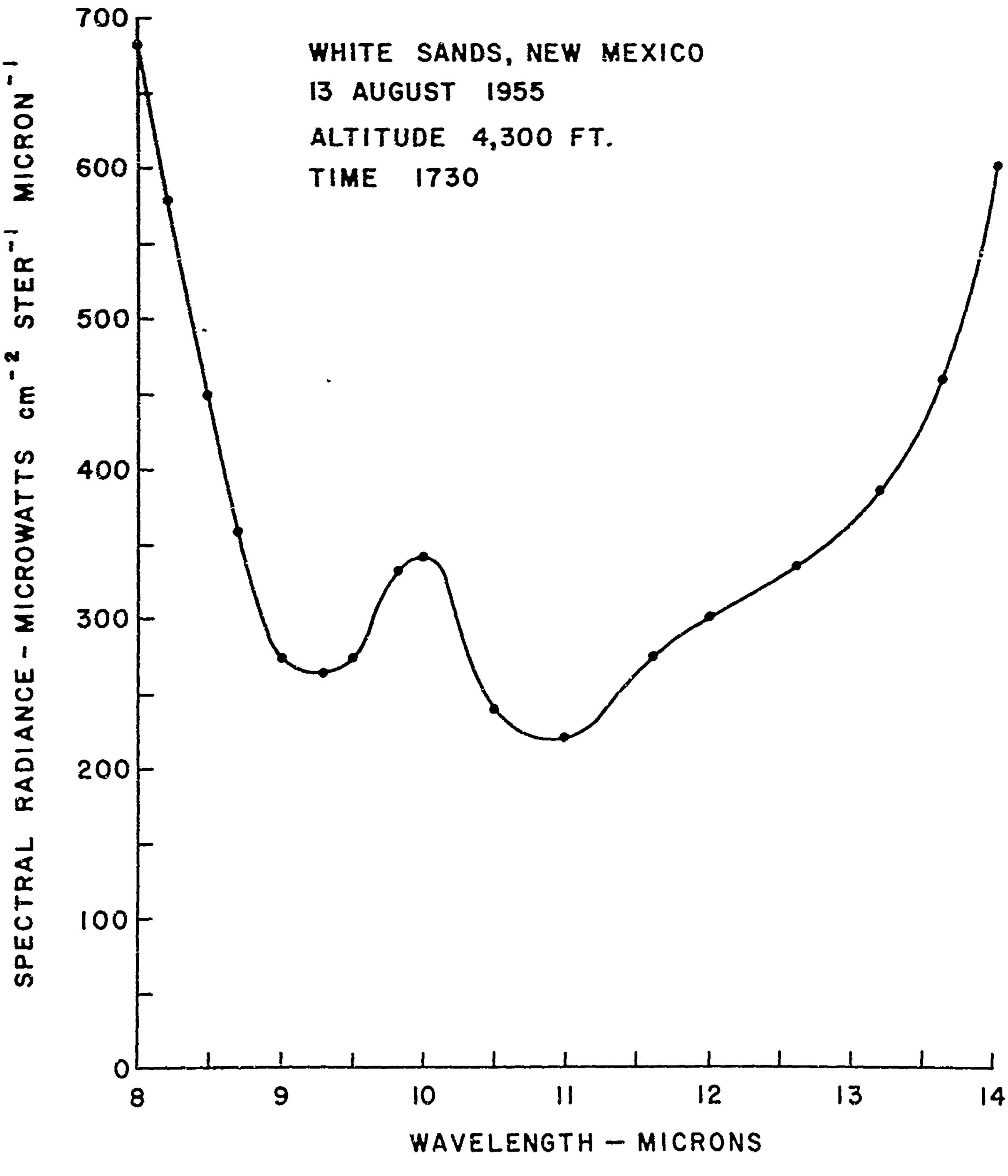

FIG. 25 CLEAR ZENITH SKY SPECTRAL RADIANCE

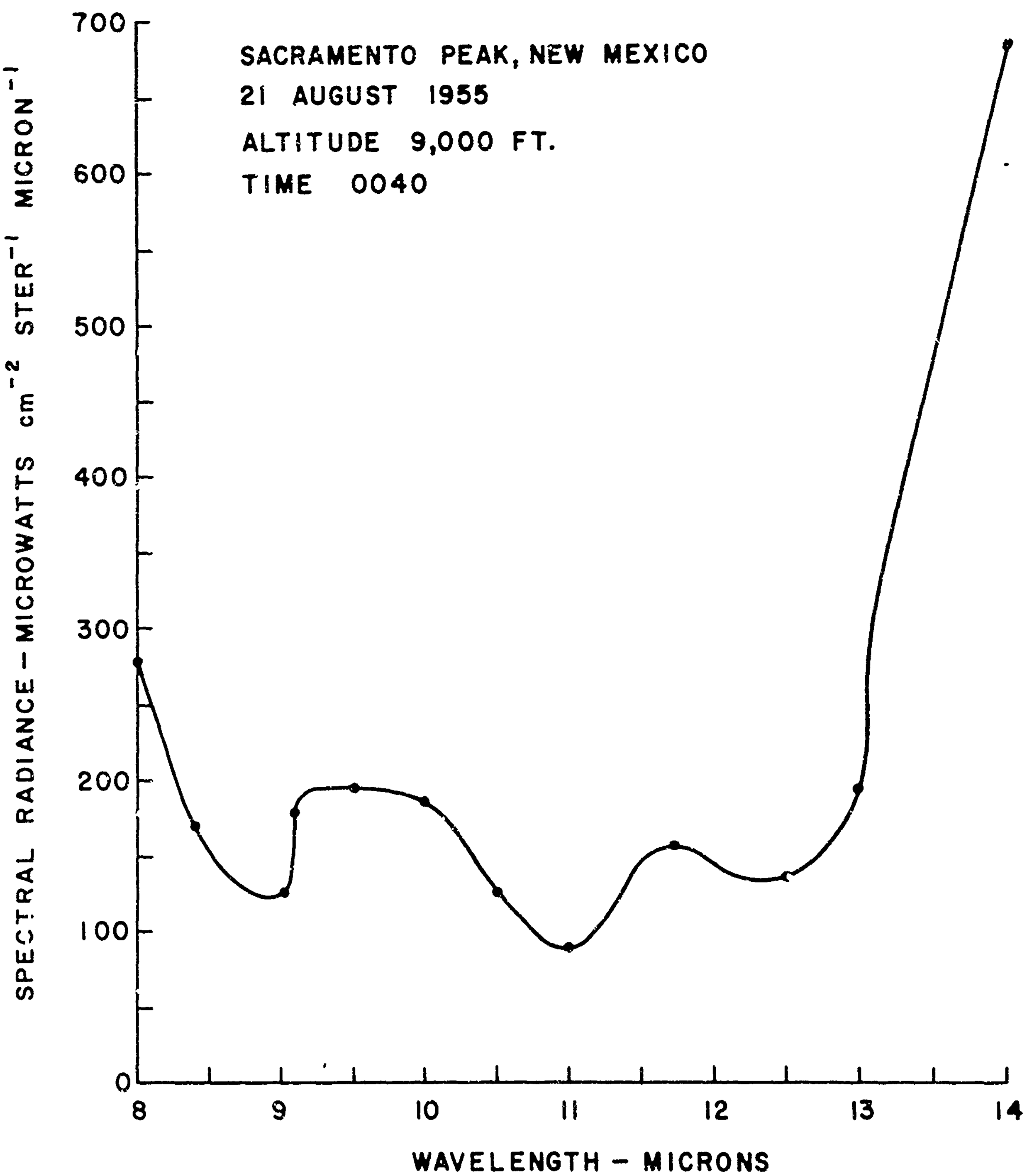

FIG. 26 CLEAR ZENITH SKY SPECTRAL RADIANCE

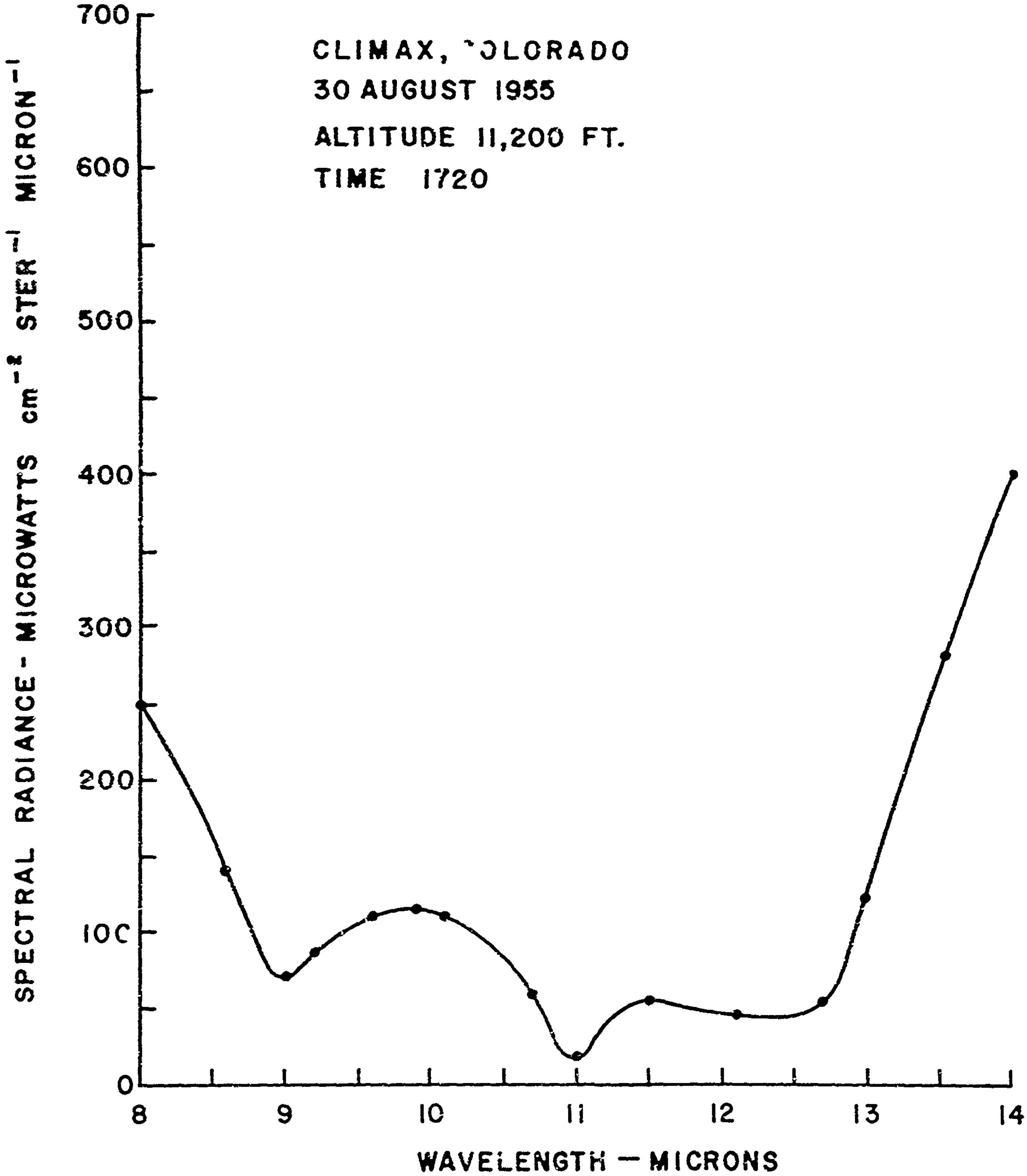

FIG. 27 CLEAR ZENITH SKY SPECTRAL RADIANCE

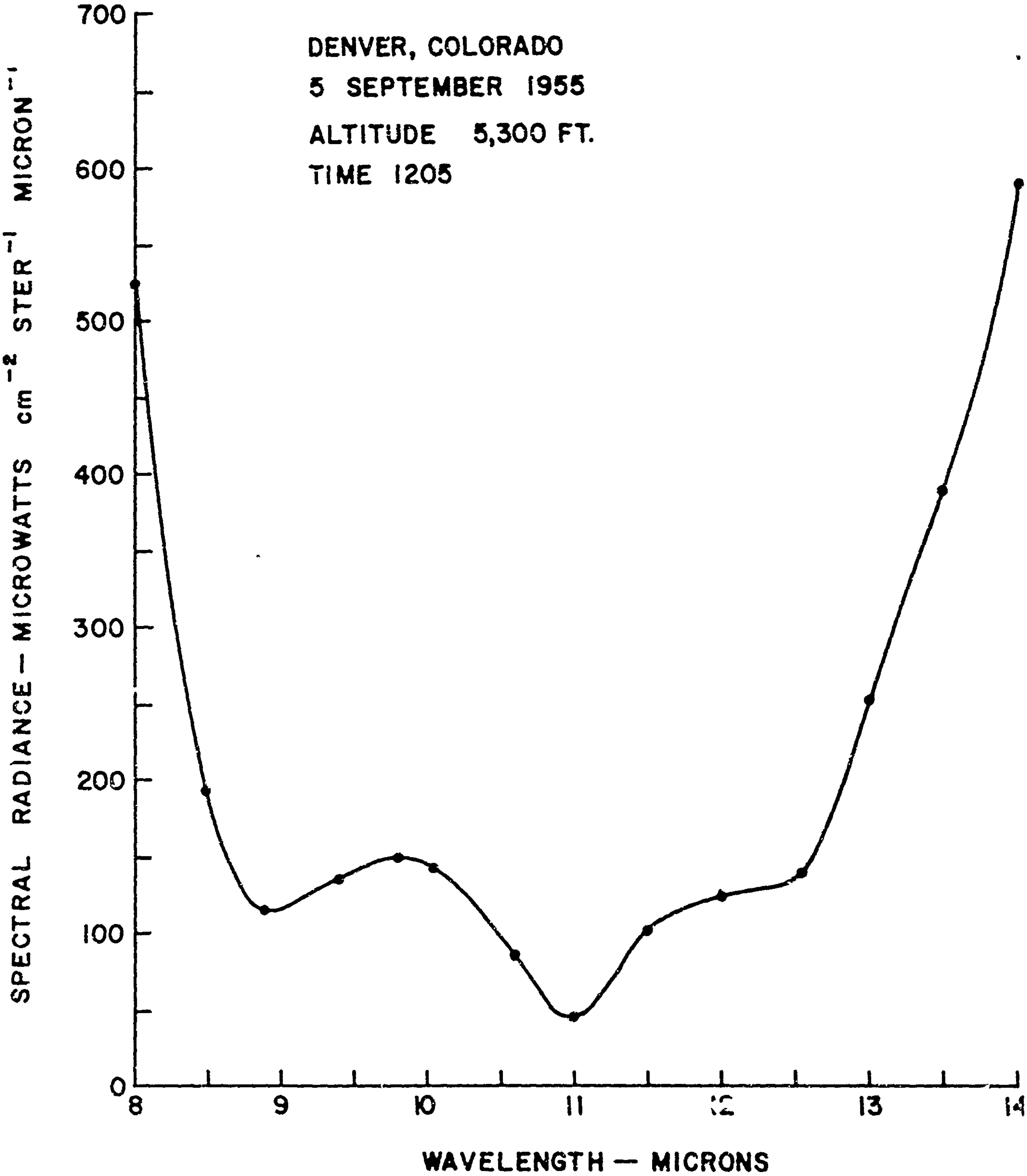

FIG 28 CLEAR ZENITH SKY SPECTRAL RADIANCE

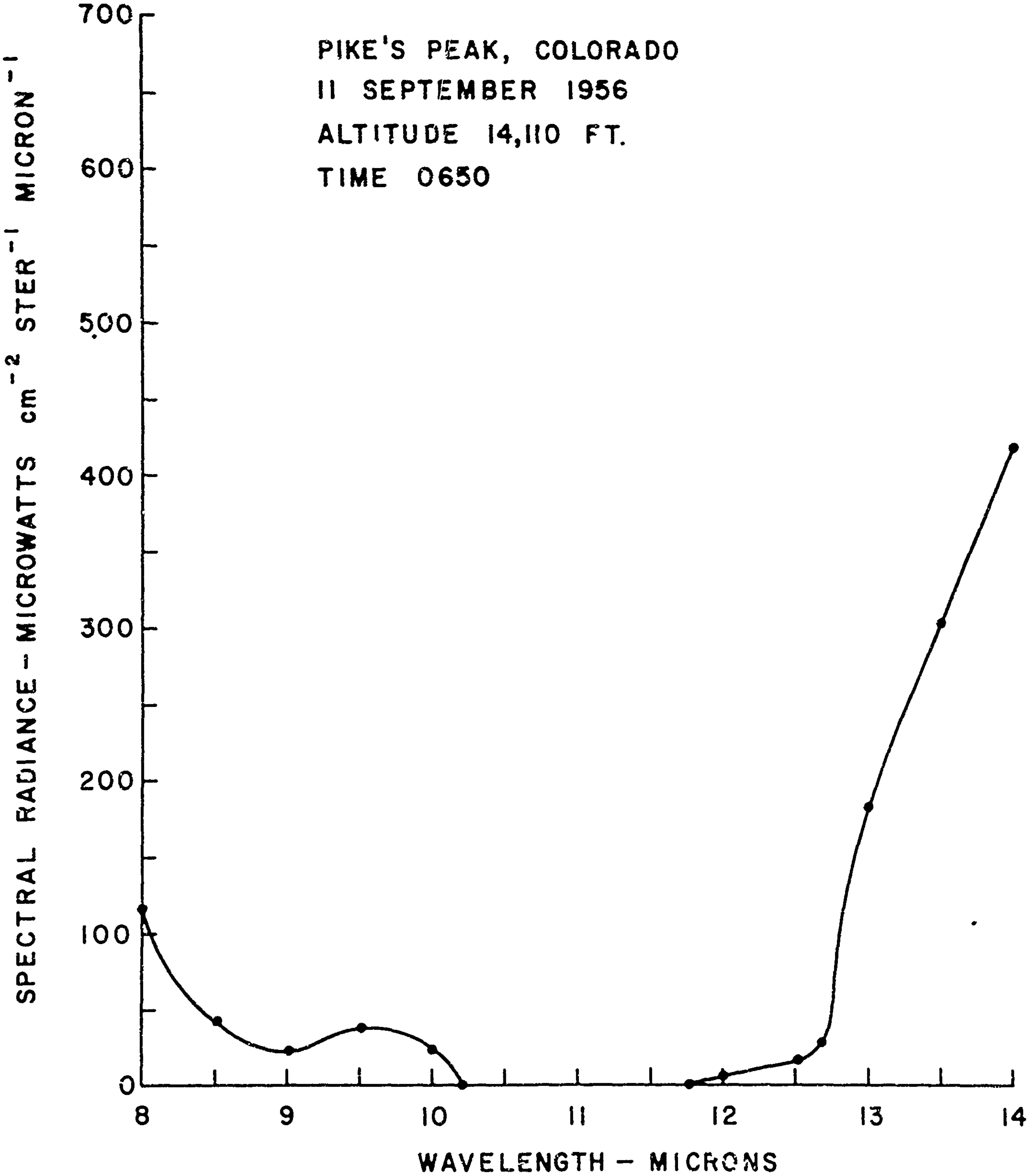

FIG. 29 CLEAR ZENITH SKY SPECTRAL RADIANCE

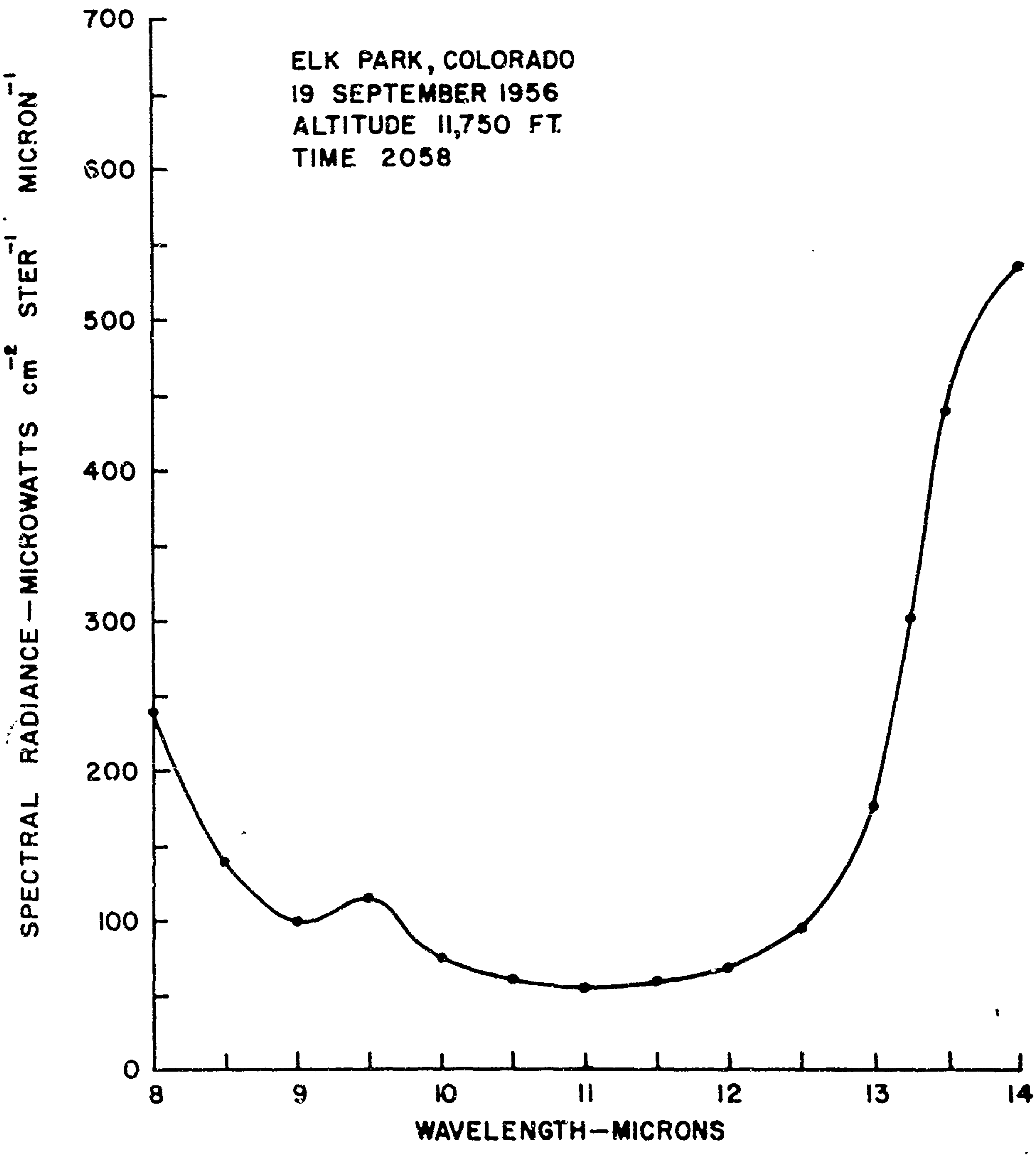

FIG. 30 CLEAR ZENITH SKY SPECTRAL RADIANCE

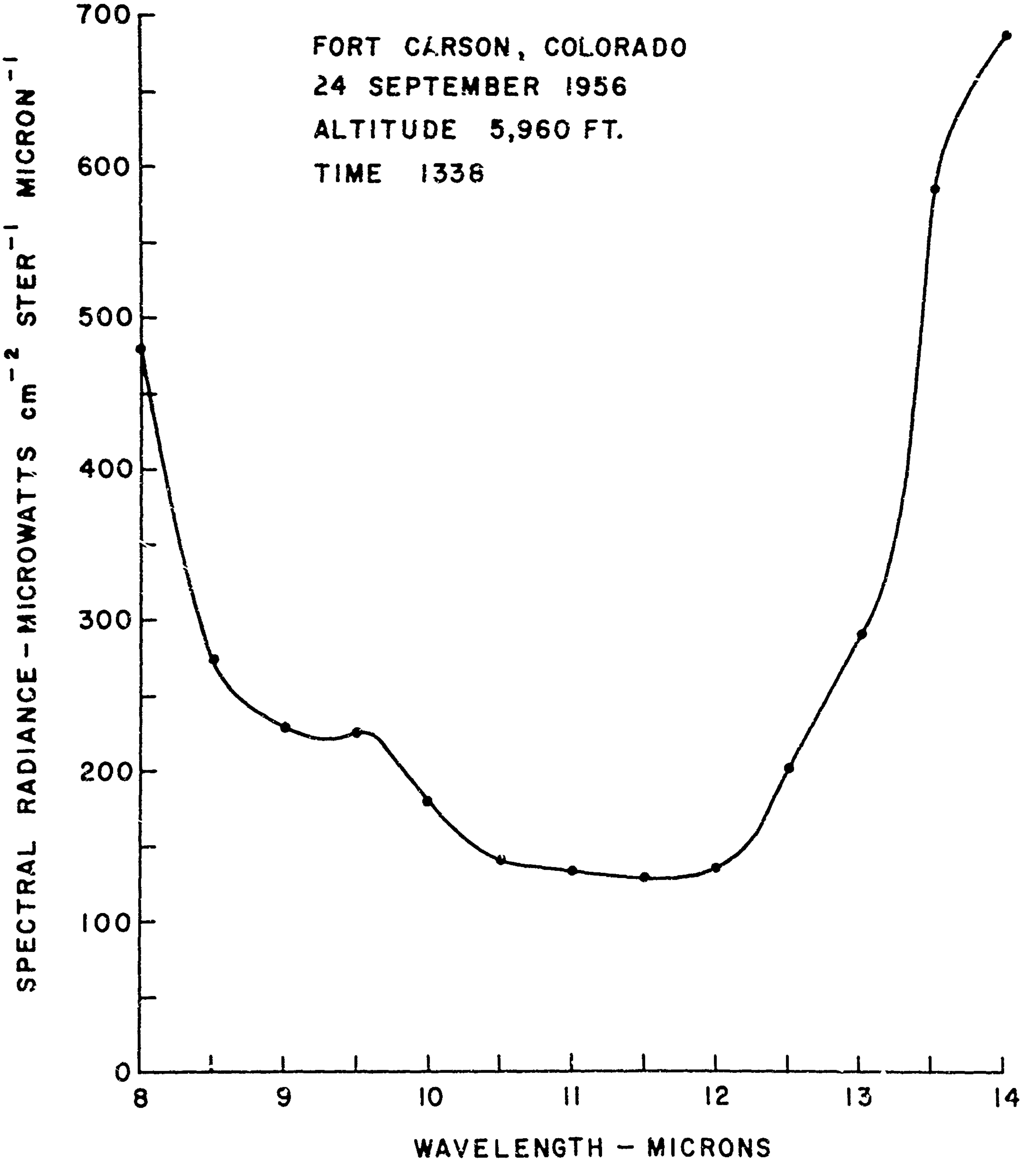

FIG. 31 CLEAR ZENITH SKY SPECTRAL RADIANCE

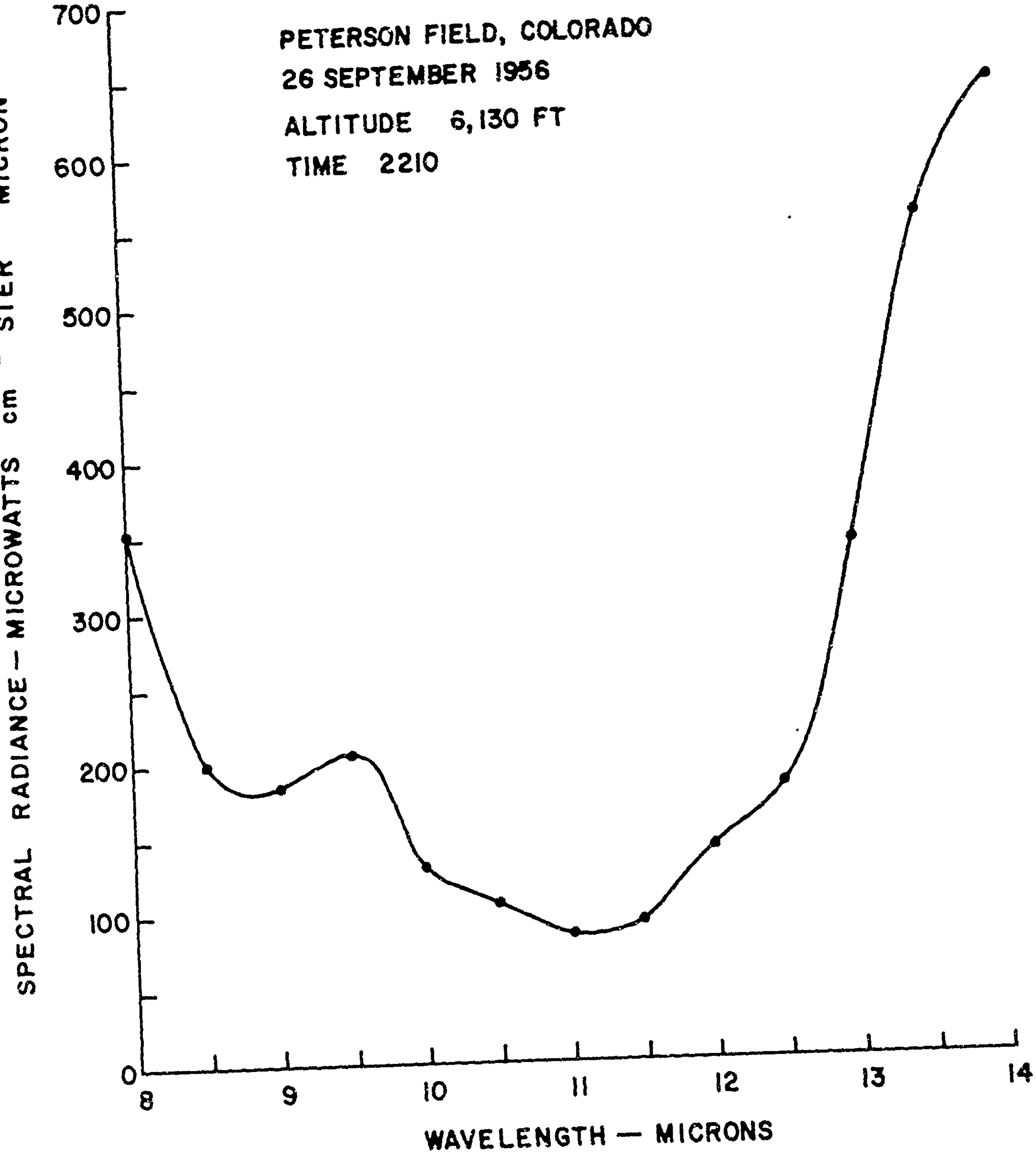

FIG 32 CLEAR ZENITH SKY SPECTRAL RADIANCE

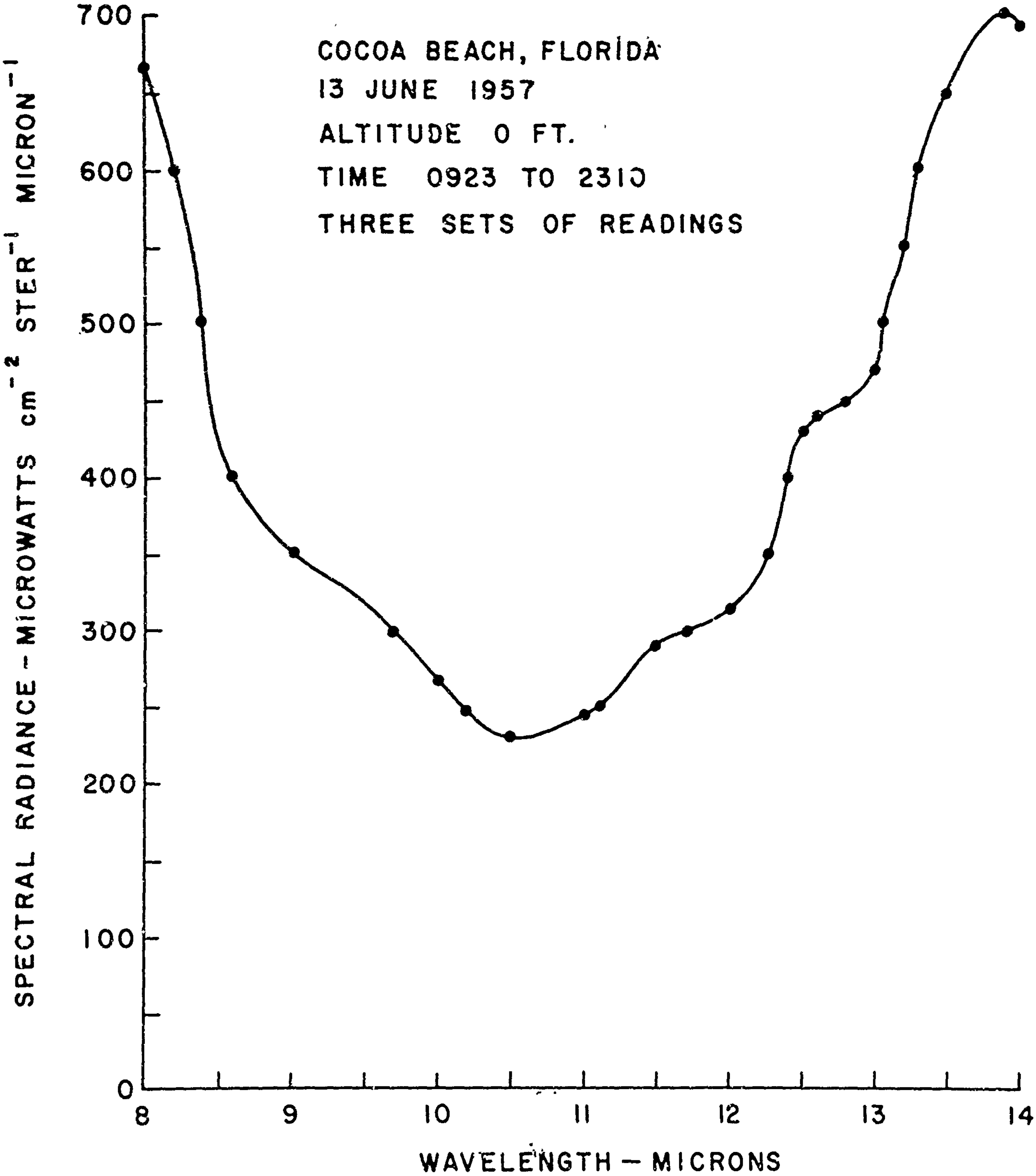

FIG. 33 CLEAR ZENITH SKY SPECTRAL RADIANCE

ELK PARK, COLORADO: SEPT. 1956, AT NIGHT
ZENITH DISTANCES: 0°, 88.2°, 90°
ELEVATION: 11,750 FT. AIR TEMP: 8°C

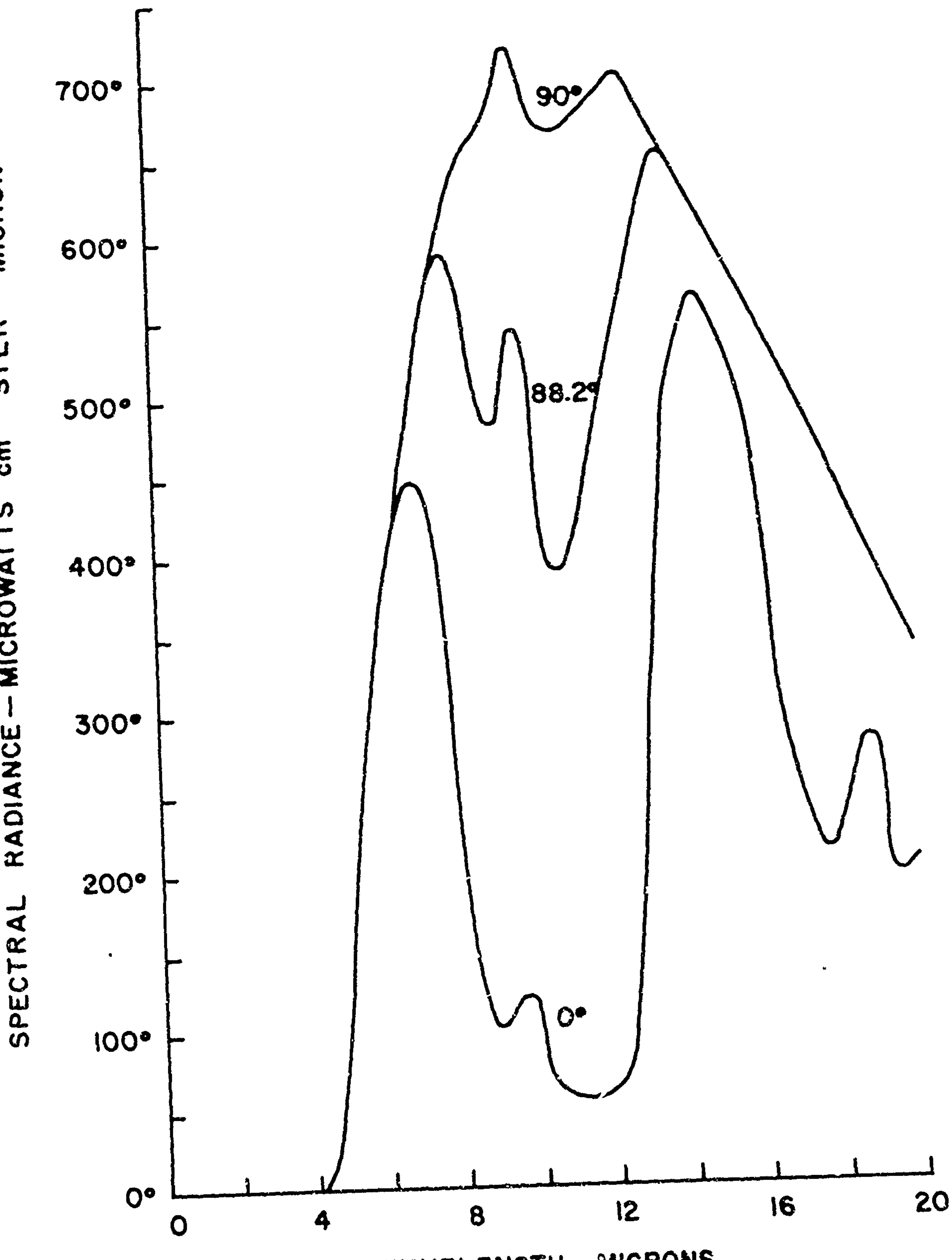

FIG. 34 SPECTRAL RADIANCE OF CLEAR SKY

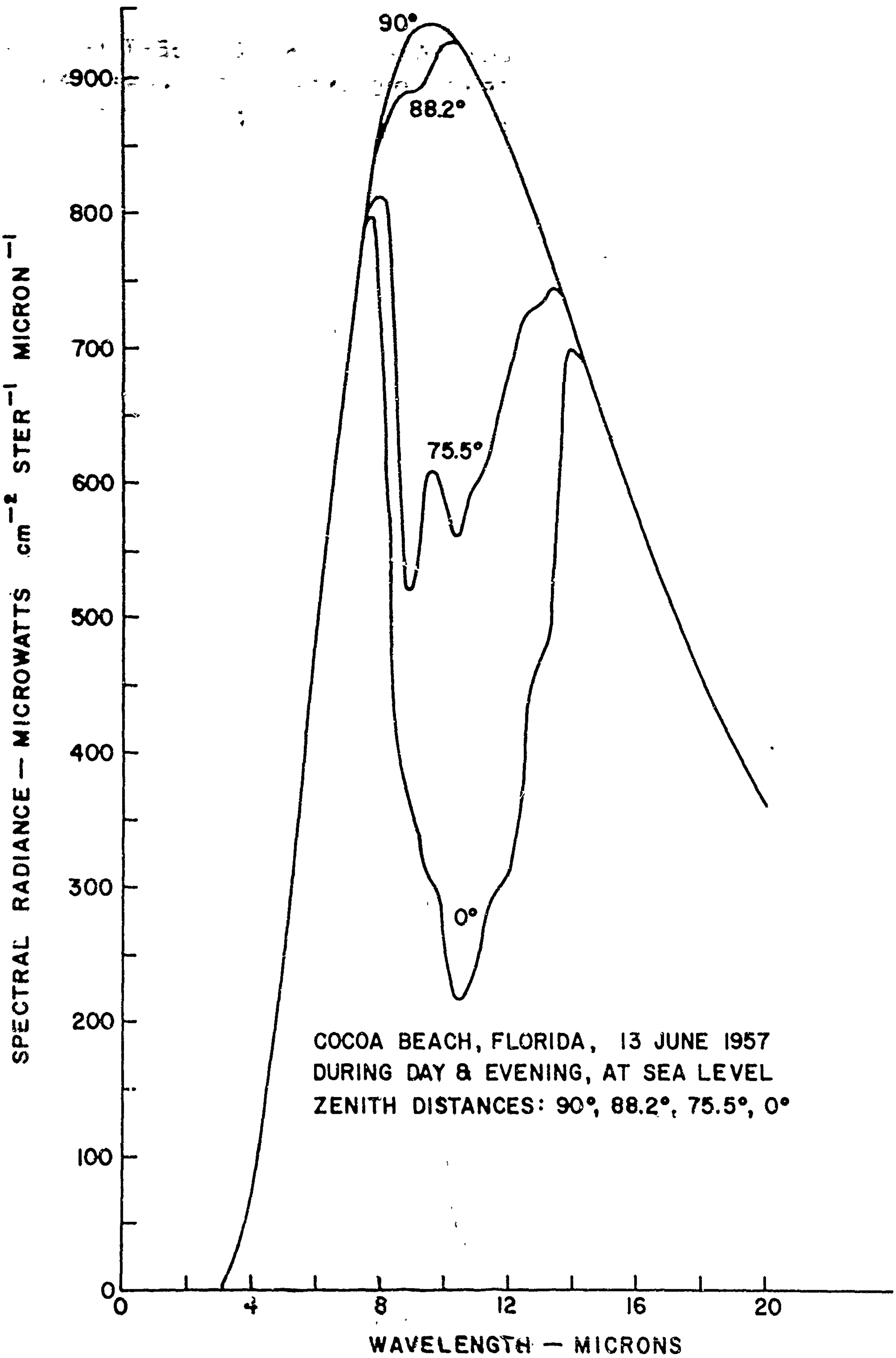

FIG 35 SPECTRAL RADIANCE OF CLEAR SKY

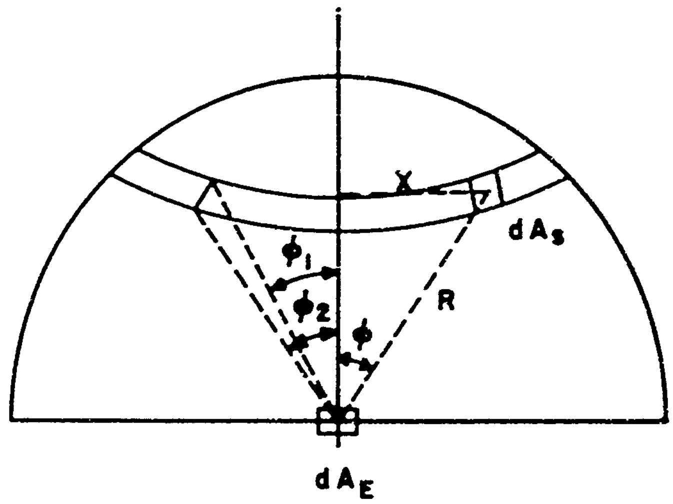

FIG. 36 GEOMETRY FOR DETERMINING RADIATION FROM THE SKY THAT REACHES AN ELEMENT OF THE EARTH'S SURFACE.

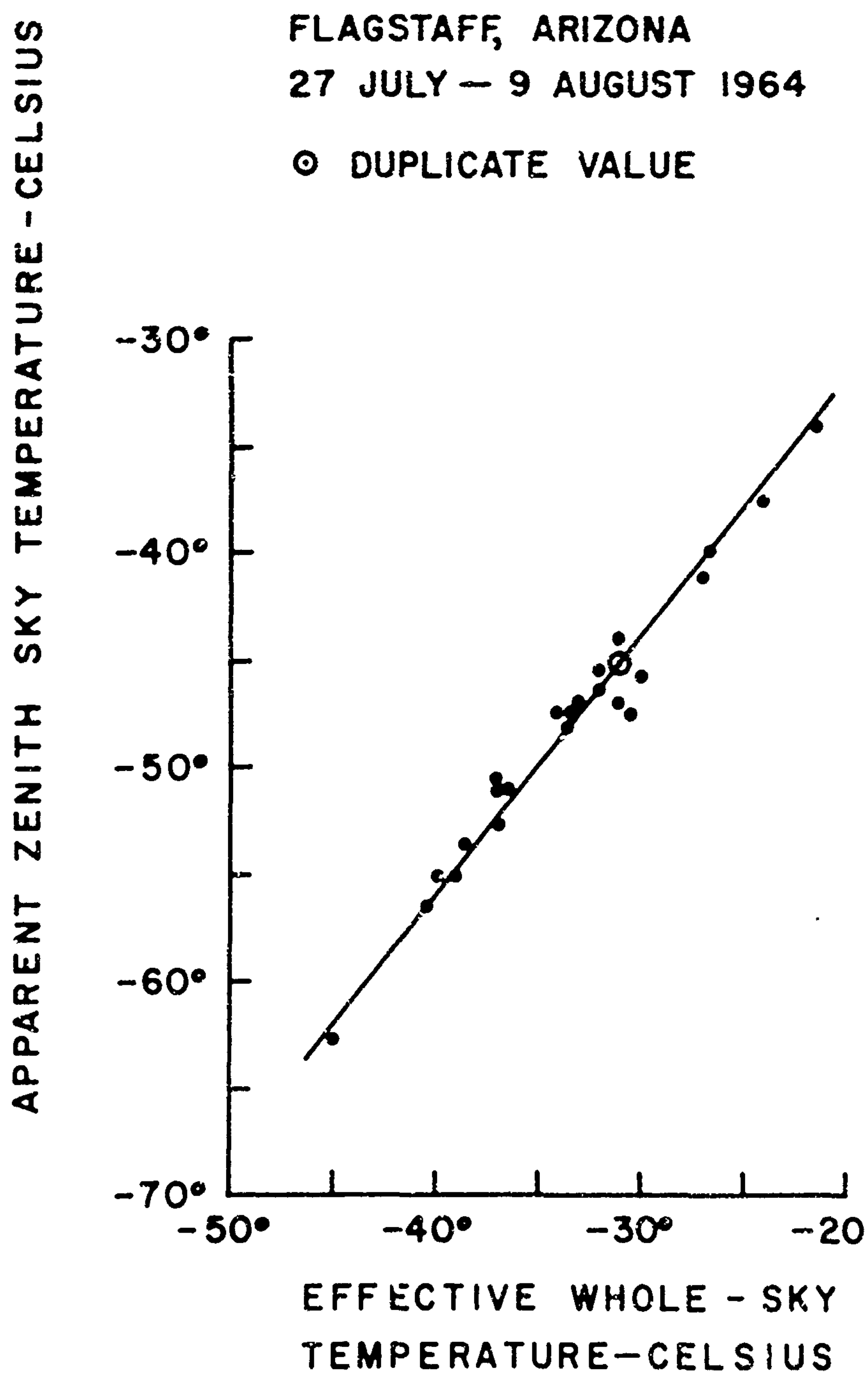

FIG. 37 EFFECTIVE WHOLE-SKY TEMPERATURE WITH INFRARED THERMOMETER

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13. ABSTRACT

Apparent sky temperatures were measured on clear days and nights during a period in July and August of 1964 at Flagstaff, Arizona. A portable radiometer, with a two-degree field of view, sensing in the wavelength band 8 to 14 microns, was used to read sky temperatures at 5-degree intervals of zenith distances (angles) from the zenith to the horizon. These values were converted to radiances and summed over the whole sky, to arrive at effective whole-sky temperatures.

The apparent sky temperature at any zenith distance is not dependent on azimuth, but does vary with the time of day. The elevation scan of temperatures at a given time is duplicated by that of an equally clear sky at a different time if the zenith temperatures are the same. The effective whole-sky temperature is consistently the same value as the apparent sky temperature at a zenith distance of 54 degrees. Mathematical equations were developed empirically to express the dependence of radiance or apparent sky temperature on zenith distance.

Graphs of the spectral radiance of the clear zenith sky, obtained from a report by Ohio State University Research Foundation, were integrated over the band 8 to 14 microns to arrive at apparent zenith temperatures for locations at altitudes from sea level to 14,000 feet. These ranged from -21°C to -82°C.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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Atmospheric temperature						
Infrared						
Radiometry						
Sky radiance						

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It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS), (S), (C), or (U)*.

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