NATIONAL BUREAU OF STANDARDS REPORT

#9300

A New Photoelectric Filter Spectroradiometer
and its use in Spectral Solar Irradiance
Measurements at Table Mountain

by
Ralph Stair and William R. Waters
Metrology Division
National Bureau of Standards
Washington, D.C.

Supported by
National Aeronautics and Space Administration
ORDER R-116

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

THE NATIONAL BUREAU OF STANDARDS

The National Bureau of Standards is a principal focal point in the Federal Government for assuring maximum application of the physical and engineering sciences to the advancement of technology in industry and commerce. Its responsibilities include development and maintenance of the national standards of measurement, and the provisions of means for making measurements consistent with those standards; determination of physical constants and properties of materials; development of methods for testing materials, mechanisms, and structures, and making such tests as may be necessary, particularly for government agencies; cooperation in the establishment of standard practices for incorporation in codes and specifications; advisory service to government agencies on scientific and technical problems; invention and development of devices to serve special needs of the Government; assistance to industry, business, and consumers in the development and acceptance of commercial standards and simplified trade practice recommendations; administration of programs in cooperation with United States business groups and standards organizations for the development of international standards of practice; and maintenance of a clearinghouse for the collection and dissemination of scientific, technical, and engineering information. The scope of the Bureau's activities is suggested in the following listing of its three Institutes and their organizational units.

Institute for Basic Standards. Applied Mathematics. Electricity. Metrology. Mechanics. Heat. Atomic Physics. Physical Chemistry. Laboratory Astrophysics.* Radiation Physics. Radio Standards Laboratory:* Radio Standards Physics; Radio Standards Engineering. Office of Standard Reference Data.

Institute for Materials Research. Analytical Chemistry. Polymers. Metallurgy. Inorganic Materials. Reactor Radiations. Cryogenics.* Materials Evaluation Laboratory. Office of Standard Reference Materials.

Institute for Applied Technology. Building Research. Information Technology. Performance Test Development. Electronic Instrumentation. Textile and Apparel Technology Center. Technical Analysis. Office of Weights and Measures. Office of Engineering Standards. Office of Invention and Innovation. Office of Technical Resources. Clearinghouse for Federal Scientific and Technical Information.**

---

*Located at Boulder, Colorado, 80301.
**Located at 5285 Port Royal Road, Springfield, Virginia, 22171.

NATIONAL BUREAU OF STANDARDS REPORT

NBS PROJECT | **NBS REPORT**

2120419 | #9300

A New Photoelectric Filter Spectroradiometer
and its use in Spectral Solar Irradiance
Measurements at Table Mountain

by
Ralph Stair and William R. Waters
Metrology Division
National Bureau of Standards
Washington, D. C.

Supported by
National Aeronautics and Space Administration
ORDER R-116

NBS

U. S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

A New Photoelectric Filter Spectroradiometer
and its use in Spectral Solar Irradiance
Measurements at Table Mountain

by

Ralph Stair and William R. Waters

I. Introduction.

During the past fifty years a considerable amount of data have been obtained on the spectral irradiance from the sun penetrating the earth's atmosphere. The measurements made by Pettit[1/], Abbot[2/] and others [3/] prior to 1940 were carefully summarized by P. Moon [4/] for use by engineers. More recently the published data on solar irradiance was analyzed by F. S. Johnson [5/]. The Moon summary contained no information on solar irradiance for wavelengths shorter than about 3000A (300 nm). The Johnson summary included rocket and balloon data covering the shorter wavelengths as well as furnishing a more detailed survey of the longer wavelengths. Other surveys[6/] and measurements [7/] not included in the Johnson report furnish additional information and a greater detailed analysis of the solar spectral energy distribution. Needless to say the different reports are not in complete agreement and there still remain uncertainties in the solar data as regards both spectral composition and total irradiance. The greatest uncertainty is in the ultraviolet spectral region.

The recent development of new narrow-band ultraviolet interference filters [8/] of high quality has made possible a new approach toward the accurate measurement of the spectral solar irradiance. Previously, the use of filters has been inconvenient because only wide-band filters or filters having multiple transmission bands were available. Now, through efficient blocking, high transmission filters having narrow-band characteristics set at specified wavelengths are readily available commercially. These do not give the high dispersion possible with a grating, nor even that possible with a good prism instrument but since the solar data are for practical purposes usually smoothed in terms of 100A (10 nm) intervals, the available filters are completely satisfactory in this respect.

II. Instruments and Methods.

The instrument employed in this work was originally set up in its general form for use in solar simulator spectral irradiance measurements [9/]. A modified form of the instrument was automated and set up to cover the ultraviolet spectral region only, through the use of ten filters (nine narrow-band and one wide-band) for use in a study of solar and sky irradiance at two locations in the Los Angeles area (one in downtown Los Angeles and a second station on Mt. Wilson) as a part of an air pollution study carried on under the auspices of the U.S.P.H.S., to determine the available solar ultraviolet irradiance in a smog area relative to that present just outside (and above) the smog. In this work the measurements were made in terms of the irradiances at different wavelengths incident on a horizontal surface. For the Table Mountain work described in the present report the Los Angeles instrumentation was modified to permit measurement of the direct solar irradiance incident on a plane normal to the solar rays.

In Figure 1 is shown a layout diagram of the photoelectric spectroradiometer and auxiliary equipment as employed at Table Mountain October 28 to November 1, 1965. The solar direct irradiance was collected in the integrating sphere which was coated with a thick layer of $BaSO_4$. The entrance and exit ports were each 1/2 inch in diameter, the sphere diameter being 4 inches. The entrance port was shielded by a tube and defining aperture at a distance of about 10 inches to limit the angular aperture to a small conical angle surrounding the sun. The exit opening was covered by a shield and Corning filter 9863 having high opacity within the visible spectrum to eliminate any possible irradiance within this region of the spectrum that might be transmitted by any one of the ultraviolet filters.

A filter wheel carrying one wide-band and 9 narrow-band interference filters and 2 blanks (zero transmittance) was set at about 6 inches from the sphere exit port so that a narrow beam of ultraviolet flux passed (nearly perpendicularly) through each of the filters onto an RCA-935 photoelectric cell as the filter-wheel was step-rotated by a synchronous motor and geneva-drive mechanism. In this manner each filter and each blank (zero transmittance) was set in position for a period of about 10 seconds (sufficient time for the pico-ammeter and recorder to register on a strip chart a definite value). Thus the measurement of each solar spectral irradiance was registered once each revolution of the filter wheel (25 times per hour). The complete optical and photoelectric setup as well as the motor drive were enclosed in a light-tight box which was painted white outside and black inside and mounted on a polar axis to follow the sun.

For purposes of calibration at intervals during each day a 1000-watt quartz iodine lamp standard of spectral irradiance 10/ was placed above the integrating sphere (at a measured distance) and the output through the 10 filters was recorded over a period of several minutes (during 2 to 3 rotations of the filter disk).

The spectral transmittance of each of the 9 narrow-band interference filters employed at Table Mountain is depicted in Figure 2. Each filter has a half-band width of approximately 10 nm, and its centroid is situated near even 10-nm intervals from 310 nm to 390 nm.

In Table I are tabulated (in column 2) the relative response of the RCA type 935 phototube (#5) when irradiated by a 1000-watt quartz-iodine lamp standard of spectral irradiance #131 through Corning filter 9863 and each interference filter in turn, (in column 3) the wavelength centroid under these same conditions, and (in column 4), as an example, the correction that should be applied when the spectral energy distribution of the irradiating source is that of the sun (calculated for even 10 nm intervals) as determined at Sacramento Peak, New Mexico 7/, for air mass 1.0 rather than that of lamp standard #131. The spectral data on these sources, this detector, and Corning filter 9863 are also included in Figure 2.

The instrumentation required but little attention in its use since all operations, except for setting up and operating the standard lamp for calibration, were automated. The usual service consisted in keeping the quartz hemisphere cover clean, the recorder pen cleaned and filled, an occasional adjustment of the instrument for correct azimuth and declination; and the marking of time, air mass, and other pertinent weather and air pollution information on the recorder strip chart or associated notebook.

An examination of column 2 of Table I discloses that there is a factor of more than 10 between the highest and lowest integrated instrumental readings for one source. A further variation of about 10 occurred between the early morning (or late afternoon) readings and those obtained near the noon hour. Since it is impractical to change instrumental sensitivity either between the interposition of filters or during the day, another method was employed to keep all data on a reasonable chart scale. This consisted of placing (permanently) perforated metal screens (of various transmittances) over most of the filters so that in all cases the short-wave spectral regions produced readable deflections while the other spectral regions produced deflections not exceeding the chart limits or the fatigue level for the phototube. The transmittance values for these screens were not required and have not been obtained for use in the reduction of the data since their effect cancels out in the mathematical handling of the data. Figure 3 shows a short section of the recorder chart covering an interval of about twelve minutes in mid-morning and illustrates the nature of the recorded data. The time delay for the recorder pen to reach a constant value is inherent in the recorder since both the photoelectric tube and the pico-ammeter have very short time constants. In reducing the data the value reached near the end of the exposure interval was employed in each case.

The photoelectric output was fed into a Keithley Model 417 dc pico-ammeter although this resulted in a small zero upscale deflection at all times it was relatively constant and usually only a few divisions on the recorder chart. A special voltage divider reduced the pico-ammeter output to less than 10 millivolts and provided for intermediate steps in the recorder response not available through the use of the normal sensitivity steps of the pico-ammeter.

Determinations of the air mass over the Table Mountain station were obtained from measurements of the solar altitude at intervals each day. This was accomplished by observing the length of shadow formed by a vertical rod set on a horizontal metal table. Ordinarily, however, a more elegant method [11/], making use of the current issue of the American Ephemeris and Nautical Almanac [12/], would be employed in this determination.

III. Results.

The equipment was set up on Table Mountain, California (Lat. 34.382 deg. N., Long. 117.681 deg. W.) at an elevation of 7,225 feet, and operated during 5 days from October 28 to November 1, 1965. During this time a heavy smog condition existed in the Los Angeles basin and usually some smog spread up to or over the Table Mountain area each afternoon (sometimes during the morning). Most mornings, however, were relatively clear and some very good data were obtained. Unfortunately, due to the lateness of the season the solar elevation never reached altitudes corresponding to air masses less than 1.5. Hence extrapolation to zero air mass contains greater uncertainties than is the case when air masses near 1.0 are reached at noon.

In the reduction of the data the observed recorder deflections were plotted for each filter as a function of the time of day. Figure 4 illustrates such a plot for the 350 nm filter as observed on October 30. Similar plots were made for the other 8 narrow-band filters. (The data for the wide-band filter was not employed in this work. It could possibly be used as a check on overall ultraviolet irradiances). The mean values for the recorder deflections were read from the resulting 45 curves at selected times corresponding to air masses 3.6, 3.4, ..., and 1.5 and are plotted in log form in Figure 5. Mean values for morning and afternoon were employed. Hence, each curve in this figure represents the average of 10 sets of data covering the 5 days during which the measurements were in progress. The values obtained in the afternoon for equal air masses were lower than the morning values due to an increase in air pollution (smog, water vapor, etc.) during the day. On some days the decrease was greater, and while the rate of decrease may not have been precisely constant, the mean curves shown in this figure (No. 5) do not show any radical departure from a straight line. The intercept at $M = 0$ is not (as noted above) the solar irradiance outside the atmosphere but simply represents a recorder deflection corresponding to that at zero air mass. (In fact the curves for the 370, 380, and 390 nm bands have been arbitrarily adjusted up or down scale by the amounts indicated on the chart in order to lessen confusion on the plot in the vicinity of the logarithm 2.0). This procedure was followed in order to reduce greatly the mathematical calculations involved. Thus, the factors for the standard lamp irradiances and adjustments for centroid position for the various filters were applied only once for the data obtained with each filter instead of being employed for the 24 positions entering into the final results for each of the five days.

An alternate method for the data reduction would have been the determination of the solar curve at the wavelengths corresponding to the centroid positions. While this would have resulted in considerable simplicity and possibly higher accuracy the resulting data would have had overlapping and missing bands resulting in complications in the integration of the total solar curve.

In Table II we have tabulated a number of quantities entering into or having a direct relationship to the data reduction process. These include the standard lamp data at the even wavelength position and at the centroid position; the Sacramento Peak 7/ evaluation of the solar curve for both the even wavelength and for the centroid position; the required percent correction to the computed data to shift from the centroid to the nominal even values; the solar irradiance for air mass = 0, determined at Table Mountain during the period of October 28 to November 1, 1965; and finally the corrected value of the spectral solar irradiance for the mean solar distance. The latter correction amounted to -1.41 percent and was applied to the final data as listed in column 8.

The data tabulated in column 4 of Table II and illustrated in Figure 6 for the spectral distribution of the irradiance from the sun as determined at Sacramento Peak, New Mexico, have been reduced from that reported in the original publication 7/ by approximately 4.5 percent representing the probable error in the early type of tungsten-in-quartz lamp standard of spectral irradiance employed in the New Mexico work. Also in Figure 6 and shown by the circles are the results obtained in the present investigation. The close agreement in the two sets of data for most regions of the ultraviolet spectrum is gratifying.

Supplementary to the measurement of the direct ultraviolet spectral solar radiation on November 1 some data were obtained on the amount of atmospheric scattering at different wavelengths in the ultraviolet in various areas of the sky. Between about 9:30 and 10:30 a.m. (P.S.T.) the filter spectroradiometer was pointed at elevations centered on even 9 degree intervals from the eastern horizon to the western horizon and the data in Figure 7 were obtained. The data at wavelengths 360, 370, 380, and 390 nm so nearly coincided with those at 330, 340, 350, and 360 nm that, to avoid complete confusion on the chart, they were omitted from this illustration. It is noted that at all wavelengths higher values were obtained in the western sky; also that higher values were obtained near the horizon. In all cases the angular aperture of the filter radiometer was constant at about 20 degrees -- the value employed in all the observations on the direct solar radiation. There appears to be little or no selective wavelength effect present in these data. The drop near the horizon probably resulted primarily because trees and other objects obstructed a clear view of the sky at the lower angles. Other irregularities in the data were caused by clouds and other air pollutions.

In Figure 8, data similar to that of Figure 7 are summarized for sky scans from northwest to southeast (data taken between about 11:00 a.m. and 1:00 p.m.) and from northeast to southeast (data taken between 2:00 and 4:00 p.m.). At near 27 degrees above the southwest horizon the radiometer intercepted the sun. The high irradiances above and below the solar position indicate the magnitude of ultraviolet scattering in the sky area surrounding the sun. Cloudiness below the sun probably reduced the lower values somewhat since the radiometer viewed the clouds on their lower darker side. The relatively high values of the atmospheric scattering, especially for a low sun, add much to the uncertainty in the data obtained at this station. Hence, the great importance of extending work in this area at a high altitude station such as is available on Mauna Loa where but little water vapor or other air pollutants are present and where an air mass of 1.0 may be obtained in May and July each summer. Considerable improvement can and will be obtained through reducing the angular aperture of the radiometer. Present plans are under development for making such measurements during July-August 1966.

The authors acknowledge with appreciation the assistance afforded them by John K. Jackson in obtaining the measurements and by Roger E. Brown in the reduction of the data.

REFERENCES

1. Edison Pettit, Measurements of ultraviolet solar radiation, Astrophys. J. 75, 185 (1932).

   Edison Pettit, Spectral energy-curve of the sun in the ultraviolet, Astrophys. J. 91, 159 (1940), (Not used by P. Moon).

2. C. G. Abbot, F. E. Fowle, and L. B. Aldrich, The distribution of energy in the spectra of the sun and stars, Smithon. Misc. Coll., 74, No. 7, 15 (1923).

3. I. Wilsing, über die Helligkeitsverteilung im Sonnenspektrum nach bolometrischen Messungen, Astrophys. Obs. Potsdam, Publikationen, 32, No. 72, 91 (1917).

   Fabry and Buisson, A study of the ultraviolet end of the solar spectrum, Astrophys. J., 54, 297 (1921).

4. Parry Moon, Proposed standard solar-radiation curves for engineering use, J. Franklin Inst., 230, 583 (1940).

5. F. S. Johnson, The solar constant, J. Meteorol. 11, 431 (1954).

6. A. J. Drummond and E. Lane, The extra-terrestrial solar spectrum, Proceedings of joint symposium on solar radiation, Los Angeles, Calif. 18-20 January 1965.

   NASA, Solar electromagnetic radiation, Environment, Part B, 1 (1965).

7. Ralph Stair, and Russell G. Johnston, Preliminary spectroradiometric Measurements of the solar constant, J. Res. NBS, 57, 205 (1956).

8. Thin Film Products, Inc., 169 Bridge Street, Cambridge, Mass.

9. Ralph Stair, William E. Schneider, William R. Waters, John K. Jackson, and Roger E. Brown, Some developments in improved methods for the measurement of the spectral irradiances of solar simulators, NASA Report CR-201, Washington, D. C. 1965.

10. Ralph Stair, William E. Schneider, and John K. Jackson, A new standard of spectral irradiance, Appl. Opt. 2, 1151 (1963).

11. Ralph Stair, Measurement of ozone over the Organ Mountains, New Mexico, J. Res. NBS, 40, 9 (1948).

12. The American ephermeris and nautical almanac (Nautical Almanac Office, U. S. Navy Dept., Washington, D. C.)

Table I

Interference Filter nm	Filter τ x Lamp energy x phototube Resp x Corning 9863 τ	Wavelength centroid nm	Percent correction when measuring solar irradiance (Air Mass; M = 1.0
310	1172	309.42	+ 2.9
320	3345	322.29	- 3.0
330	4663	331.58	+ 1.4
340	5145	340.65	+ 0.8
350	9759	352.70	+ 3.2
360	12500	360.22	+ 0.2
370	10539	371.80	+ 2.5
380	8805	381.33	+ 1.9
390	7609	392.10	- 2.7

Table II

Interference Filter nm	Lamp Irradiance $\mu W/(cm^2-10nm)$	Lamp Irradiance at centroid $\mu W/(cm^2-10nm)$	Sun Irradiance M = 0 Sac. Peak $\mu W/(cm^2-10nm)$	Sun Irradiance M = 0 Sac. Peak at centroid $\mu W/(cm^2-10 nm)$	Percent correction when measuring solar irradiance (Air Mass, M=1.0)	Sun Irradiance (observed for Table Mt.) M = 0 $\mu W/(cm^2-10nm)$	Sun Irradian[ce] (Mean Solar Distance) M = 0 $\mu W/(cm^2-10[nm])$
300			394				
310	2.81	2.74	594	583	+ 2.9	621	612
320	4.055	4.429	811	850	- 3.0	808	797
330	5.69	5.97	982	998	+ 1.4	1212	1195
340	7.47	7.59	1081	1083	+ 0.8	1175	1158
350	9.26	9.84	1119	1132	+ 3.2	1127	1111
360	11.4	11.46	1167	1168	+ 0.2	1105	1089
370	14.2	14.79	1238	1256	+ 2.5	1224	1207
380	17.5	17.98	1248	1247	+ 1.9	1165	1149
390	21.1	21.88	1231	1300	- 2.7	1140	1124
400	24.8						

Legends to Illustrations

Figure 1. Block diagram showing the instrumental layout. All optical components were placed inside a light-tight box, painted white on the outside and black inside. The phototube and 45-volt battery source were connected through a special shielded coaxial cable to the pico-ammeter whose output was fed through a special voltage divider for proper match at selected voltage steps with a standard 10-millivolt strip-chart recorder. The box containing the optics was mounted on a motor-driven polar axis.

Figure 2. Spectral characteristics of the filters, phototube, 1000-watt quartz-iodine lamp standard of spectral irradiance, and the sun. The ordinates are exact for the nine interference filters, divided by 5 for Corning glass No. 9863, and relative only for the phototube, standard lamp and the sun.

Figure 3. Short section of recorder chart covering 5 rotations of the filter wheel (about 12 minutes) during mid morning. This shows the constancy of the zero deflection and the gradual increase in solar irradiance during this 12 minute period.

Figure 4. Recorded values of solar irradiance through the 350-nm filter as observed on October 30, 1965. This chart is representative as regards scatter of the data obtained with the other filters; also similar to those obtained on other days.

Figure 5. Determination of deflection representing solar irradiance outside the atmosphere through graphing the logarithm of the observed data as a function of the solar angle (air mass). Mean of data for five days (October 28 to November 1, 1965).

Figure 6. Spectral distribution of the irradiance from the sun (after Stair and Johnston, Ref. 7) with ordinate reduced approximately 4.5 percent to correct to new standard of spectral irradiance. Circles indicate solar intensities from Table Mountain filter measurements of 1965.

Figure 7. Atmospheric scattering as a function of elevation above horizon, east to zenith to west, for a conical angle of approximately 20 degrees for five of the nine 10-nm spectral bands during the morning on November 1, 1965 at Table Mountain.

Figure 8. Mean atmospheric scattering for 10-nm bands for all wavelengths between 330 and 390 nm, northwest to zenith to southeast with data taken near the noon hour; and similar data taken in mid-afternoon from northeast to zenith to southwest.

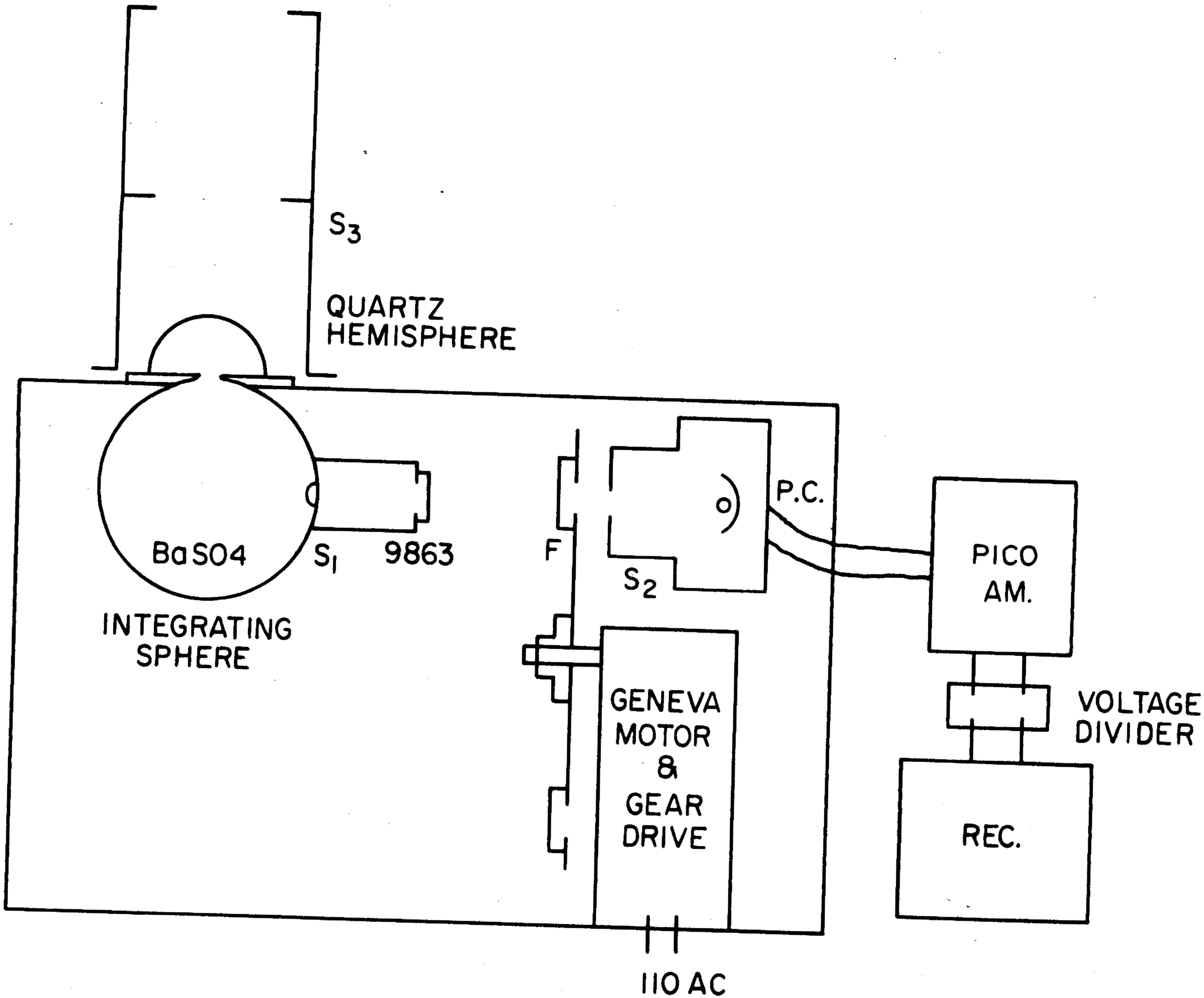

S3
QUARTZ
HEMISPHERE
BaSO4
S1
9863
INTEGRATING
SPHERE
F
S2
P.C.
PICO
AM.
GENEVA
MOTOR
&
GEAR
DRIVE
VOLTAGE
DIVIDER
REC.
110 AC

Figure 1.

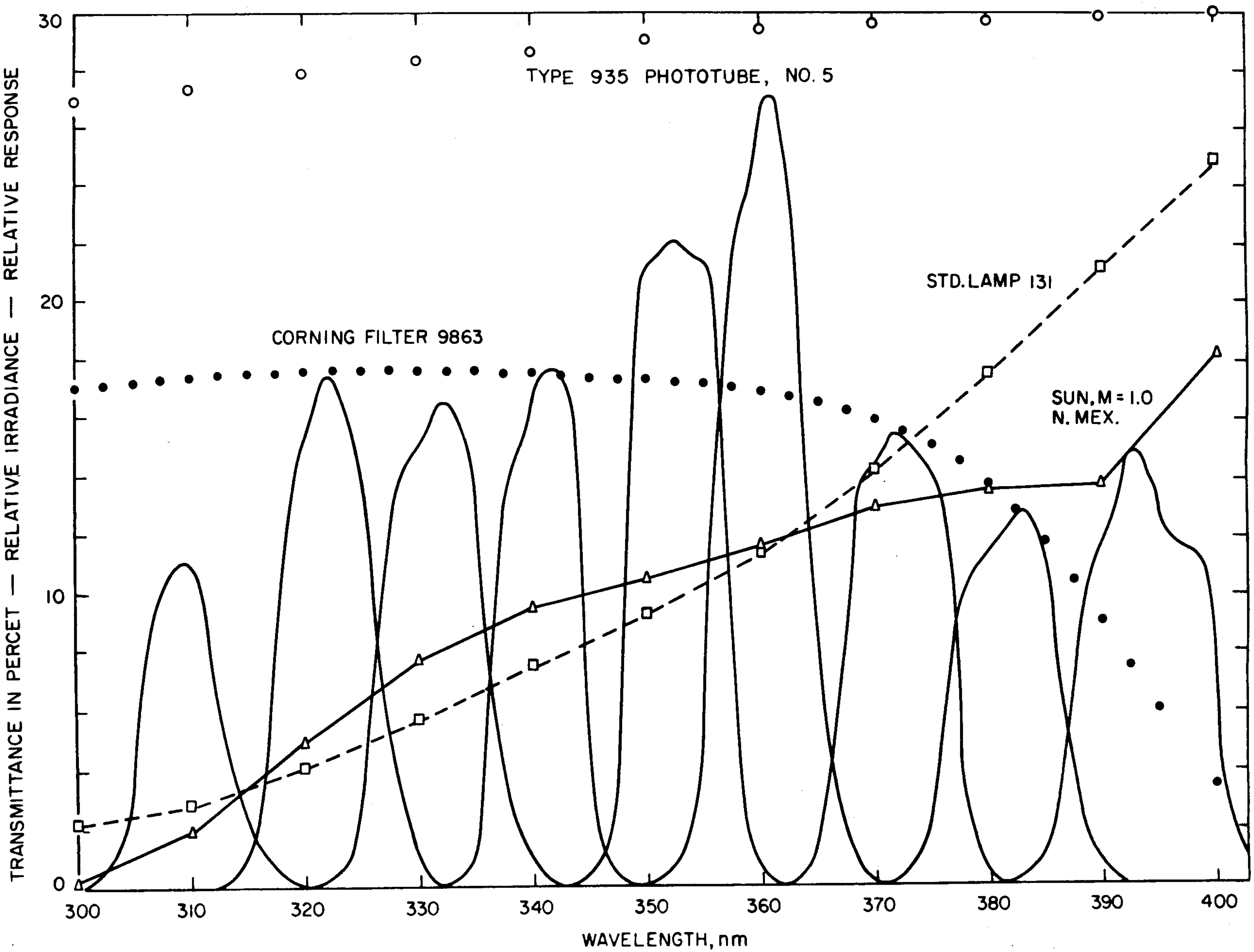

TYPE 935 PHOTOTUBE, NO. 5
STD. LAMP 131
CORNING FILTER 9863
SUN, M = 1.0
N. MEX.
TRANSMITTANCE IN PERCET — RELATIVE IRRADIANCE — RELATIVE RESPONSE
WAVELENGTH, nm
0
10
20
30
300
310
320
330
340
350
360
370
380
390
400

Figure 2.

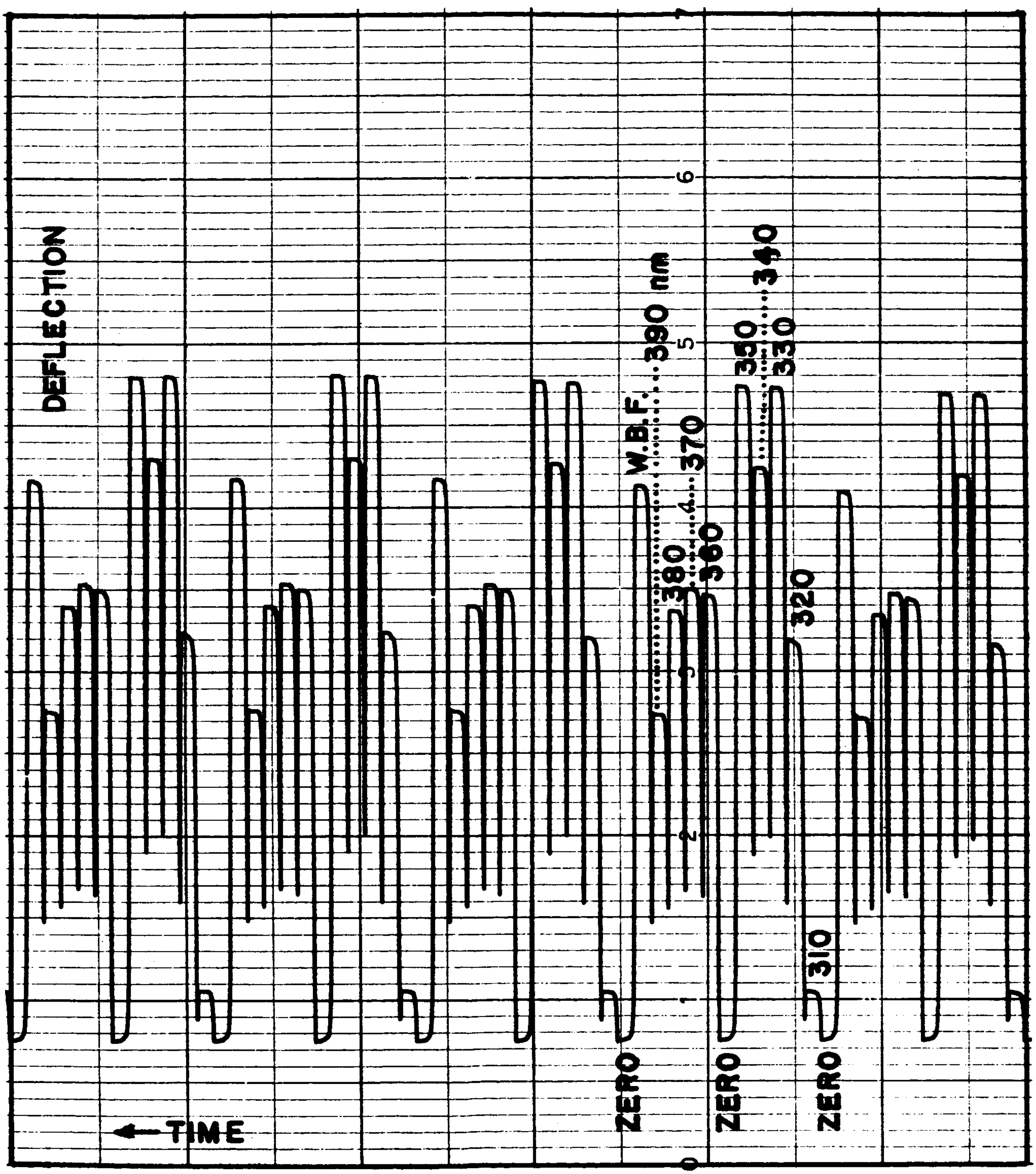

DEFLECTION
TIME
ZERO
ZERO
ZERO
W.B.F.
390 nm
380
370
360
350
340
330
320
310
0
1
2
3
4
5
6

Figure 3.

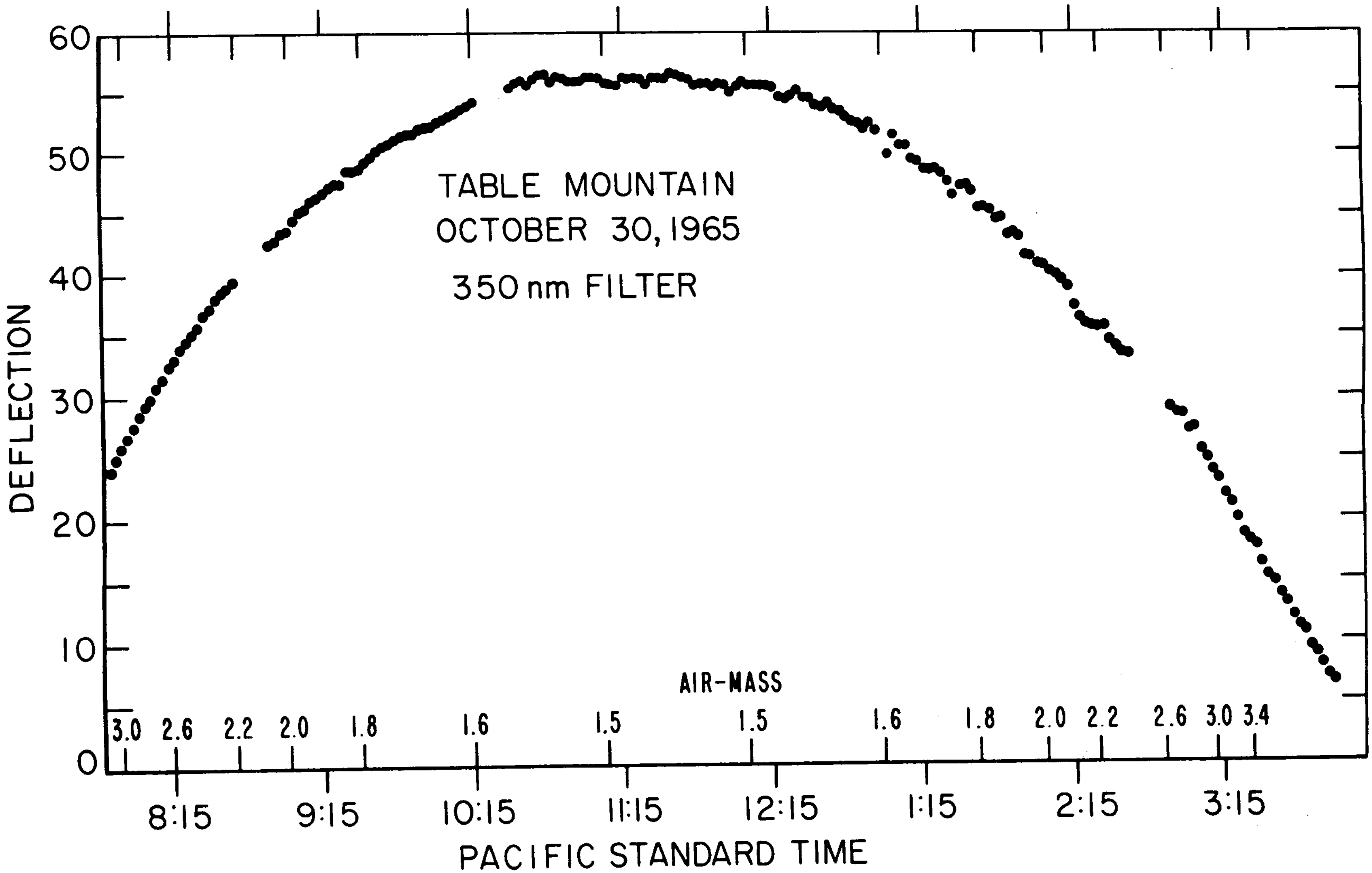
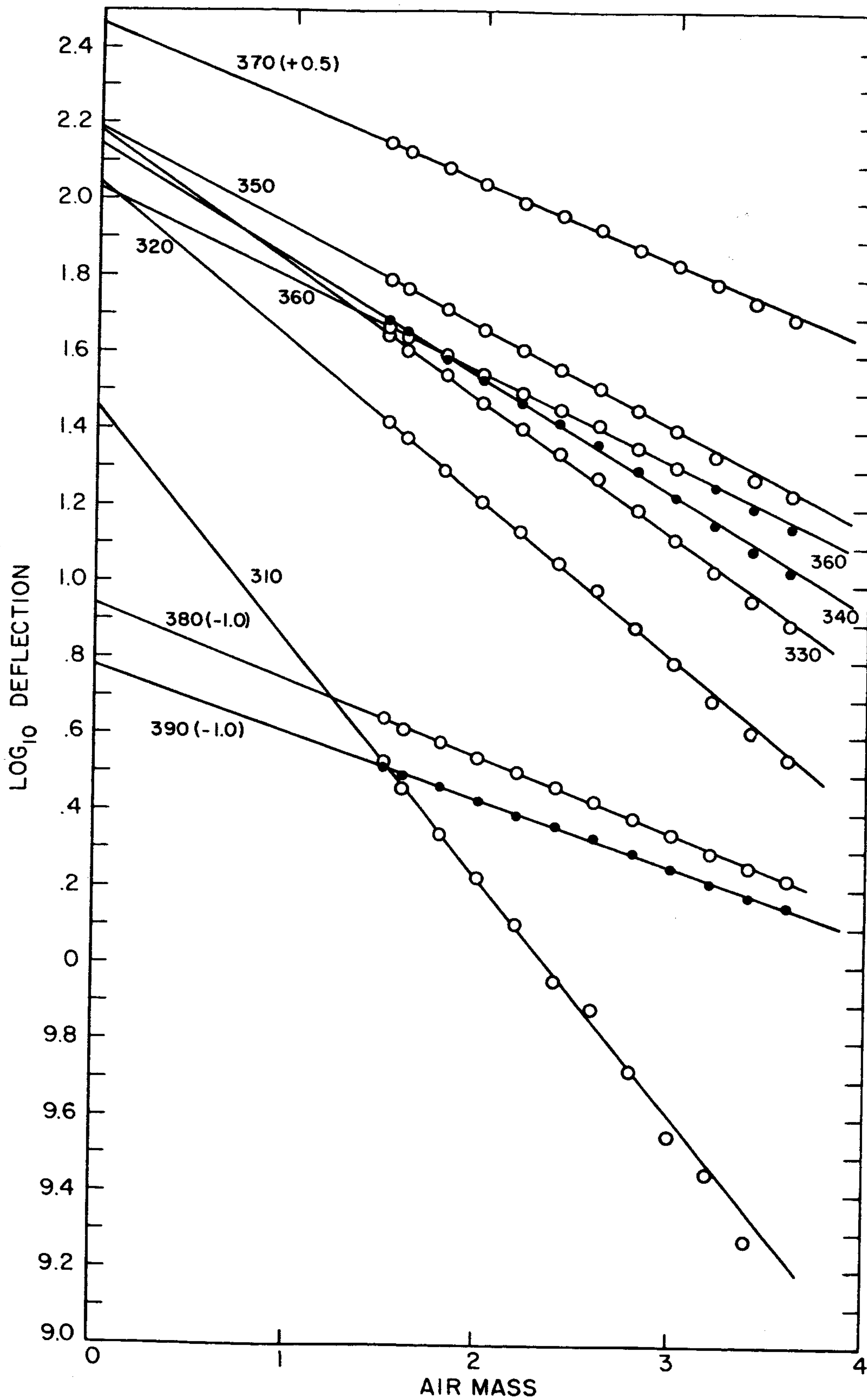


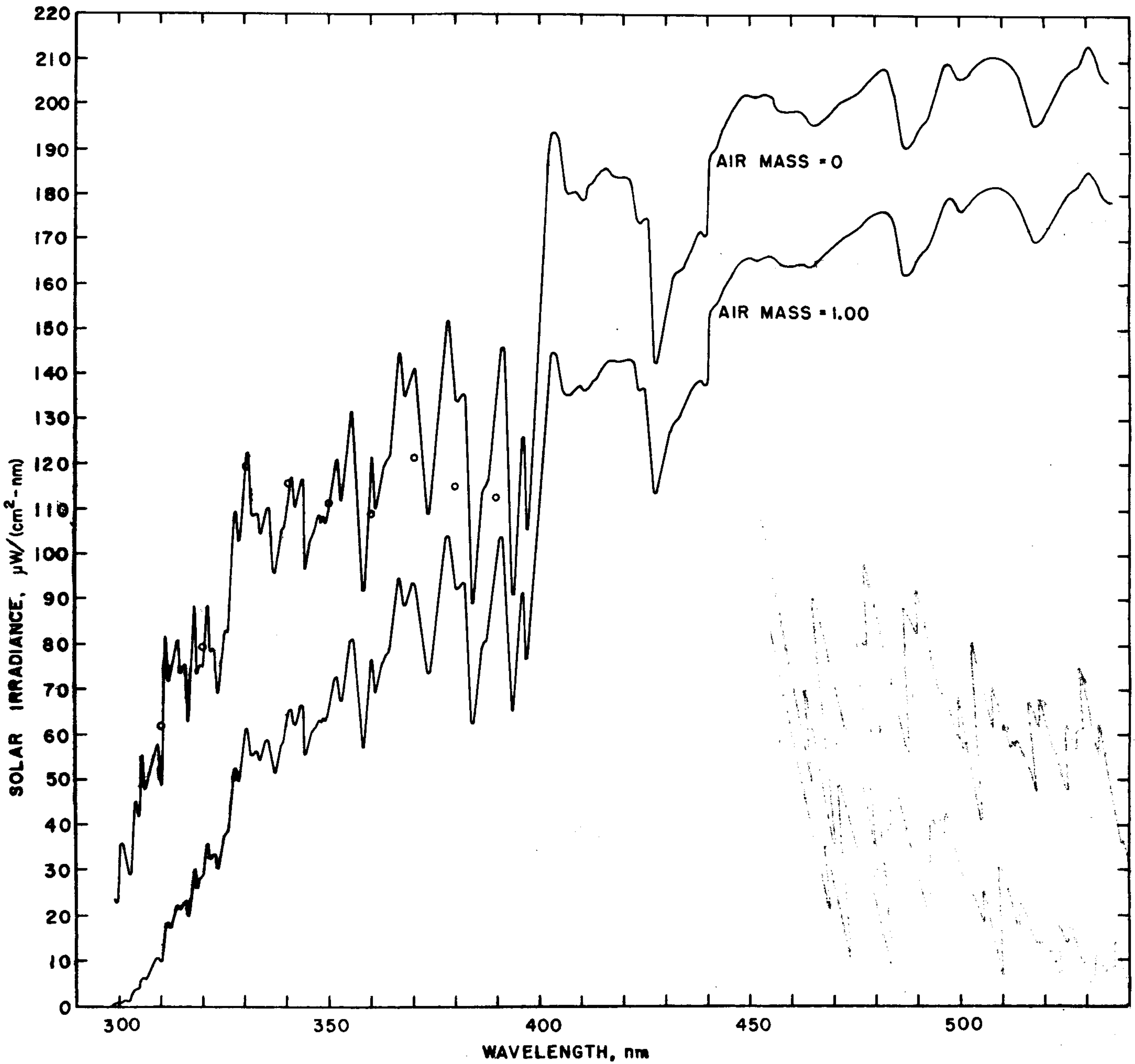
TABLE MOUNTAIN
OCTOBER 30, 1965
350 nm FILTER
DEFLECTION
60
50
40
30
20
10
0
AIR-MASS
3.0 2.6 2.2 2.0 1.8 1.6 1.5 1.5 1.6 1.8 2.0 2.2 2.6 3.0 3.4
8:15 9:15 10:15 11:15 12:15 1:15 2:15 3:15
PACIFIC STANDARD TIME

Figure 4.



370 (+0.5)
350
320
360
310
380(-1.0)
390(-1.0)
360
340
330
LOG10 DEFLECTION
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
9.8
9.6
9.4
9.2
9.0
0
1
2
3
4
AIR MASS

Figure 5.



AIR MASS = 0
AIR MASS = 1.00
SOLAR IRRADIANCE, μW/(cm²-nm)
WAVELENGTH, nm
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
300
350
400
450
500

Figure 6.

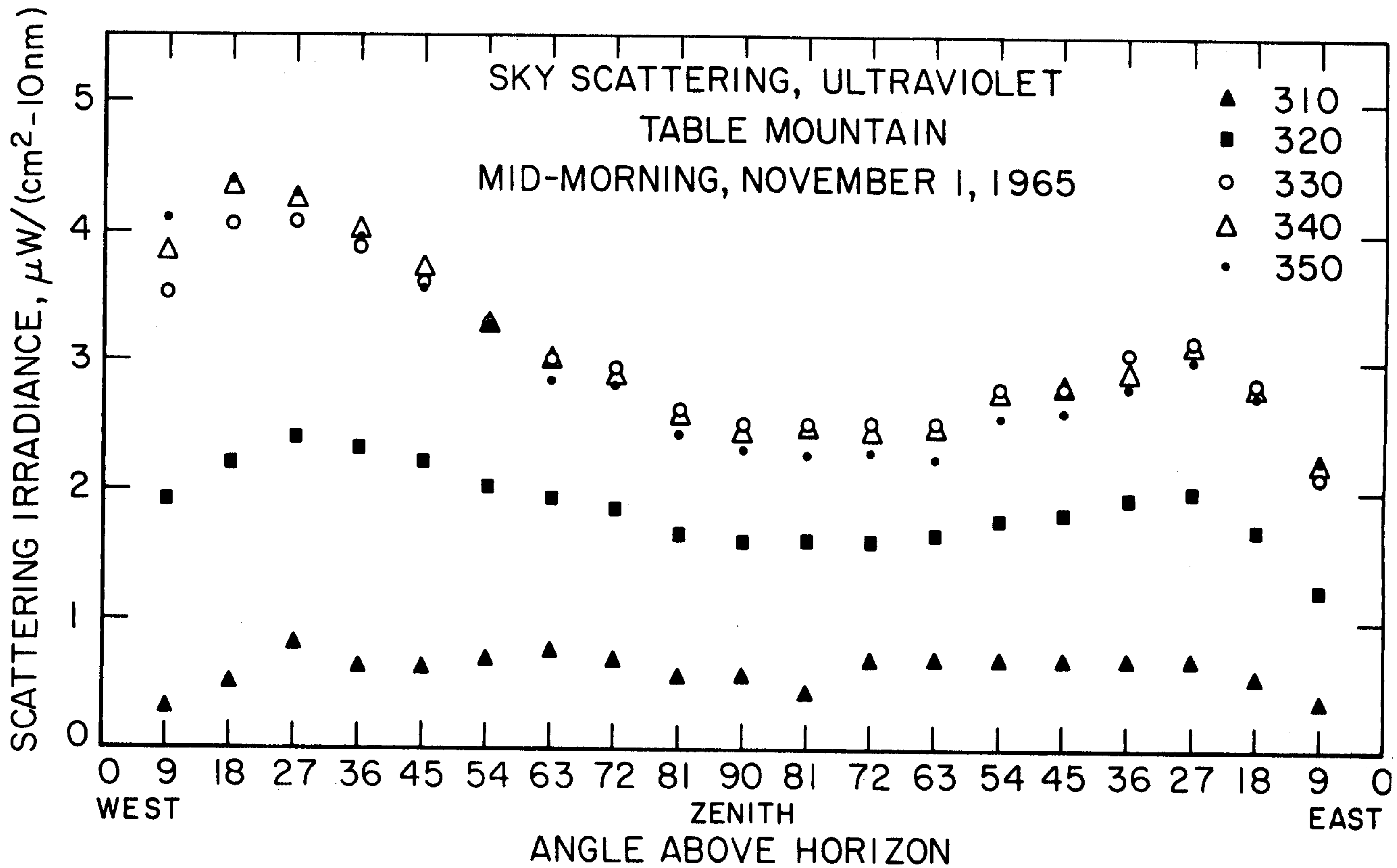

SKY SCATTERING, ULTRAVIOLET
TABLE MOUNTAIN
MID-MORNING, NOVEMBER 1, 1965
310
320
330
340
350
SCATTERING IRRADIANCE, μW/(cm2-10nm)
0
1
2
3
4
5
0 9 18 27 36 45 54 63 72 81 90 81 72 63 54 45 36 27 18 9 0
WEST
ZENITH
EAST
ANGLE ABOVE HORIZON

Figure 7.

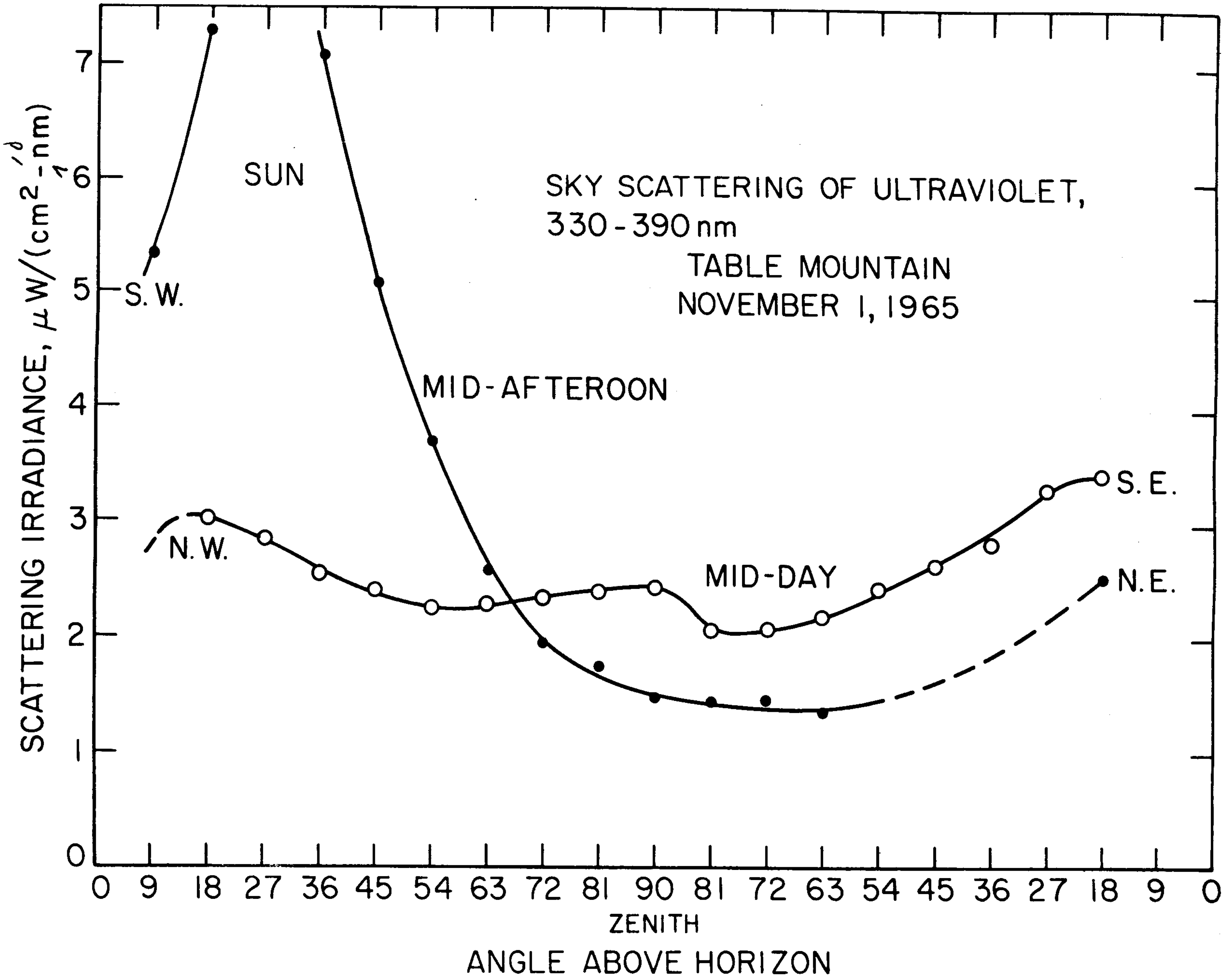

SKY SCATTERING OF ULTRAVIOLET,
330-390 nm
TABLE MOUNTAIN
NOVEMBER 1, 1965
SUN
MID-AFTEROON
MID-DAY
S.W.
N.W.
S.E.
N.E.
SCATTERING IRRADIANCE, μW/(cm²-nm)
0 9 18 27 36 45 54 63 72 81 90 81 72 63 54 45 36 27 18 9 0
ZENITH
ANGLE ABOVE HORIZON
0
1
2
3
4
5
6
7

Figure 8.