NATIONAL BUREAU OF STANDARDS REPORT

9542

The Solar Constant Based on New Spectral Irradiance
Data from 3100 to 5300 Angstroms

by

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NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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ABSTRACT

Measurements made at an altitude of 11,150 feet on Mauna Loa in Hawaii with instrumentations recently developed at the National Bureau of Standards have yielded new solar spectral irradiance values (outside the atmosphere) within the region of 3100 to 5300 Angstroms. With two independent polar-axis-mounted instruments, a double-quartz-prism spectroradiometer, and a photoelectric-filter radiometer, each incorporating integrating spheres, closely agreeing spectral data were obtained on several days during August, 1966. A short-wavelength solar curve thus obtained agrees closely with the Johnson curve* near 5250 Å, but averages approximately 10 percent lower than the Johnson curve at shorter wavelengths. With the use of a new solar curve embodying the Smithsonian data without change as tabulated by Johnson at wavelengths above 5250 Å and our data at wavelengths up to 5250 Å, integration of the area under this curve results in a value of the solar constant of 0.136 watt per cm^2, or 1.95 calories per cm^2 per minute.

*F. S. Johnson, J. Meteorol. 11, 431 (1954).

I. Introduction

The solar constant is the solor irradiance on a unit surface perpendicular to the solar rays at the earth's mean distance from the sun. This power has been measured by various observers with results ranging from about 1.89 to 2.05 calories per square centimeter per minute. Measurements of the total and spectral solar irradiance made by Abbot and others[1] of the Smithsonian Institution established the solar spectral irradiance to a relatively high degree of accuracy from the visible through the infrared. However, most of these data as well as those obtained by Pettit and others[2] did not extend far into the ultraviolet region of the spectrum. These early data were summarized by Moon[3] in 1940. A later summary by Johnson[4] in 1954 included Naval Research Laboratory Rocket data[5] for the short wavelength ultraviolet spectral region based upon carbon-arc-lamp calibrations[6] (of questionable accuracy but best available at the time) and measurements by Dunkelman and Scolnik[7] in the longer-wavelength ultraviolet and visible retions of the spectrum from about 300 to 680 nm based upon an early NBS standard of spectral irradiance[8]. More recent summaries and discussions[9] relating to the solar constant and the solar spectral irradiance have emphasized the lack of close agreement among the various investigators and the urgent need of more accurate spectral solar irradiance data, especially in the ultraviolet and visible regions of the spectrum.

Most of the early measurements by Stair et al[10] at various locations have unfortunately served more to map the general shape of the ultraviolet solar irradiance curve than to give absolute spectral values. This resulted in large part because of an unnoticed difficulty in the performance of the conventional spectroradiometer; namely, the problem of correcting for, or eliminating, errors introduced into the measurements by variations in the sensitivity of detectors[11] over their surfaces. Nor was this problem recognized or solved in the measurements by most other workers in this field. In the development of new instrumentation and methods for the measurement of solar simulator sources[12] it was found that the use of a diffusing or integrating sphere at the entrance slit of a spectroradiometer eliminates the errors introduced into the measurements by variations in the sensitivity of detectors over their surfaces and of transmittances of spectrometers over their apertures. Only in the measurements by Dunkelman and Scolnik was a relatively satisfactory diffusing surface employed in the form of a flat $MgCO_3$ block set at an angle of 45 degrees.

The availability of new highly sensitive equipment with efficient integrating spheres together with the urgent need for more accurate spectral solar data in space work thus prompted a new investigation in this area.

II. Instrumentations and Methods

In this investigation two instrumentations were employed, each mounted on a polar axis to automatically follow the sun so that the recorded deflection was a measure of the solar irradiance on a surface normal to the rays of the sun.

The instrumentations were located at the Mauna Loa Observatory which is situated on the north slope of Mauna Loa, Hawaii (North Lat. 19° 32' 22". 152, West Long. 155° 34' 42".528) at an altitude of 11,150 feet. This location provides a station having uniquely clean atmosphere with an extremely low water vapor content (except when atmospheric flow is up-mountain). Information on the establishment of, and other details regarding this station, may be found elsewhere[13].

A. The Conventional Double-Quartz-Prism Spectroradiometer

The double-quartz-prism spectroradiometer employed in this investigation consisted of a modification of the instrument previously used on Sacramento Peak[14] and elsewhere. Solar irradiances as obtained with the un-modified instrument for air masses of 0 (outside the atmosphere) and for air mass 1 at Sacramento Peak are shown in figure 1. A layout of this instrument as modified for use at the Mauna Loa Observatory is shown in figure 2. The solar beam passes through a diaphragmed tube which limits the sky irradiance to a small conical angle (defined by a tube 9 inches in length with apertures of 2 inches and 0.5 inch) surrounding the sun.

The solar irradiance is diffused over the inner surface of a 4-inch hollow sphere coated with $BaSO_4$ and MgO for high and uniformly diffuse reflection. Thus the spectrometer slit is exposed to a uniformly irradiated area which completely fills the instrument aperture with the solar source during measurement and with the standard source during calibration. As a result errors due to variations in spectrometer transmittance over the instrument aperture and to variations in sensitivity over the detector surface are eliminated[12]. Diffusing surfaces[15,16] and spheres[16] have been used by others, but unfortunately most solar measurements of spectral irradiance have been made with spectroradiometric equipment devoid of this important accessory and so are of questionable accuracy.

In the present measurements the irradiance is chopped at a frequency of 33.9 c/s before entering the spectrometer, and the modulated signal is picked up by a photomultiplier at the exit slit of the instrument. An RCS type 1P28 multiplier phototube was operated with an overall voltage of 500 volts. The phototube output was fed to a Brower model 129 lock-in amplifier[17] and thence to a strip chart recorder.

The spectrometer is housed in a heavy aluminum box with the temperature thermostatically controlled at the level normally reached near the middle of the day. To eliminate the use of extraneous mirrors, etc., the spectrometer, together with the integrating sphere and diaphragmed tube, the chopper, and photomultiplier detector are mounted on a motor-driven polar axis to automatically follow the sun from early morning to late afternoon. For other details of the setup reference should be made to an earlier report[14].

In operation, a manually-controlled three-speed motor wavelength drive permits forward or reverse rotation of the wavelength drum at any one of three speeds. In the present work a single speed was employed with operation in both directions, but with the reverse run used only as a check on the forward run (with increasing wavelength).

Wavelength calibrations were obtained through the use of a mercury arc lamp[18] (see figure 3) and by making use of the known Fraunhofer structure of the solar spectrum. At three arbitrary positions on the wavelength drum pins were placed in the wavelength drive to momentarily operate microswitches thereby superimposing pulses on the strip chart record (see the points marked C in figure 3). These index points permitted precise wavelength marking when the standard lamp was in place.

Spectral radiant energy calibration of the spectroradiometer was accomplished through the use of an NBS 1000-watt quartz iodine lamp standard of irradiance[12,19] (see figure 4). In order to permit rapid and precise setting of this standard in exact position it was rigidly mounted on a four-legged super structure which could within seconds be lifted and firmly clamped into place. This mounting contained blackened shielding to prevent direct or reflected sunlight from entering the spectrometer during calibration with the standard lamp.

B. The New Photoelectric Filter Radiometer

The photoelectric filter wheel spectroradiometer employed in this work was originally set up in its general form for use in solar simulator spectral irradiance measurements[12]. 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[20]. Following the Los Angeles measurements the instrument was modified by placing a diaphragmed tube over the sphere opening as shown in figure 5. It was mounted on a polar axis, and measurements of direct solar irradiance were made on Table Mtn. (in California) as a function of air mass on several relatively clear days from October 28 to November 1, 1965, before transporting it to Mauna Loa in August 1966. In figure 6 is shown a section of a strip chart illustrating the type of record obtained with this instrument.

In this filter radiometer the direct solar irradiance is collected in an integ4ating sphere coated with a thick layer of $BaSO_4$ dusted with MgO. The entrance and exit ports are each 1/2 inch in diameter; the sphere diameter is 4 inches. The entrance port is shielded with a tube and a 1 inch defining aperture at a distance of 9 inches to limit the angular aperture to a small conical angle surrounding the sun. The exit opening is covered by a shield and a Corning 9863 filter to eliminate any visible radiation that might be transmitted by the ultraviolet filters.

A filter wheel carrying the 10 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 type 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 positioned for a period of about 10 seconds sufficient time for the recorder to plot the phototube output on a chart (See figure 6). The optics, photoelectric detector and the motor drive were completely enclosed in a light-tight box painted white on the outside and black inside. This assembly was mounted on a polar axis to automatically follow the sun.

For purposes of calibration at intervals during each day an NBS 1000-watt quartz iodine lamp standard of spectral irradiance[12,19] was precisely positioned above the integrating sphere in a manner similar to that employed with the prism spectroradiometer. The response through the 10 filters was recorded for several rotations of the filter wheel. The spectral transmittances of a set of 9 narrow-band interference filters used for this type of filter radiometry are shown in figure 7. The filters actually used were from another set having nearly identical transmittances and provided with a quartz seal at the edge for increased stability. Each filter has a half-band width of approximately 10 nm and their centroids are situated near even 10 nm wavelengths from 310 nm to 390 nm. The centroid wavelengths of the two sets of filters are given in Table I, as are also (in column 2) the relative response of RCA type 935 phototube (#5) when irradiated by the NBS 1000-watt quartz iodine lamp standard of spectral irradiance #131 through Corning filter 9863 and each interference filter in turn.

An examination of column 2 of Table I discloses that there is a factor of more than 10 between the highest and lowest instrument readings with the standard lamp. To keep all data on a reasonable chart scale, perforated metal screens of appropriate transmittance were permanently placed over most of the filters so that in all cases the shortwave 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 of these screens, which ranged from a few to as high as 70 percent, were not measured as their effects cancel out in the calibration of the radiometer.

III. Spectral Solar Energy Distribution

The methods for reduction of the data obtained with the two instrumentations are similar, and most of the details are described in previous reports on the use of the double-prism type of instrumentation[10]. In each case the measured value of spectral solar irradiance at each wavelength defined by a narrow-band filter or by a Fraunhofer line is plotted as a function of standard time. Mean values are read from the resulting plots at selected air masses. The air mass has been computed from the cosecant of the solar zenith angle and applies distinctly to the altitude of the station at which the measurements are made. Air mass 1 is taken as the mass of air directly above the particular station. For use in the present work the air mass has been calculated through the use of the American Ephemeris and Nautical Almanac, Balls Altitude Tables, and published data of angular cosecants as described in previous reports[14,21] on solar measurements in various localities.

Figure 8 is a modified plot of the average data obtained for 3 clear days on Mauna Loa (Aug. 15, 18 and 19, 1966) when using the filter radiometer. The plotted data were adjusted so that the nine curves could be shown in ascending wavelength order with no cross over. The solar irradiances outside the atmosphere are obtained by extrapolating these data to air mass 0 and by applying calibration factors for instrumental sensitivity at the various wavelengths. A similar procedure was followed in the case of the prism spectroradiometer, except that solar irradiance was plotted directly as a function of air mass. The use of different stand lamps and other variations in instrumentation on the three days (Aug. 20, 21, and 23) on which these data were taken required conversion of the data to solar irradiance before plotting as a function of air mass.

The spectral solar irradiances for a mean solar distance (outside the terrestrial atmosphere) are plotted in figure 9 as obtained with each instrument for an average of 3 days (in each case) in August 1966 at the Mauna Loa Observatory.

The prism spectroradiometer data are shown by the solid circles connected with a solid line in the ultraviolet and by a dotted line from about 400 to 530 nanometers. The data shown in this curve were obtained with rather wide slits on the monochromator. These slit widths were chosen to give a band width of approximately 100 Angstroms in the mid-part of the spectrum for two reasons: first to provide data for a wide pass band similar to that established in the Johnson solar curve, but second and more important to increase the irradiance available at the detector. The latter was most important since the integrating sphere reduced the available flux at this position by a factor approximating 1000. As previously employed this spectroradiometer was usually set to give a spectral dispersion of the type shown in figure 1, taken with ordinate modification from reference 14.

The filter radiometer data are shown by the solid stepped line also in figure 9. These data are shown for and apply to a 10-nm band centered at the even wavelengths 310, 320 .... 390 nm, although as shown in table I the centroid for each filter is slightly different.* It is recognized that a small error, possibly not greater than from 1 to a few percent, results, but there is no easy way to calculate it or correct for it. The only approximate solutions are to use filters precisely centered or to plot the results at adjusted wavelengths. The complex structure of the Fraunhofer spectrum results in uncertainties in any procedure.

As a rough mean of the results by the two instrumentations a dotted curve has been drawn from the spectral region of 300 nm to join with the prism spectroradiometer curve at about 400 nm. This curve is presented as best representing the 1966 observations.

IV. Atmospheric Transmittance and Ozone

The atmospheric transmittance curve calculated on the basis of the solar data for the 6 days (Aug. 15,18,19,20,21 and 23, 1966) is given in figure 10. It is to be noted that this curve is slightly higher than a similar one obtained at Mauna Loa[13a] in 1957. It is believed that at least part of this difference lies in the technique of plotting the flat part of the curve. In both cases considerable difficulties were encountered in keeping the deisel electric generators operating at proper voltage and frequency so that all readings scattered over a much wider range than if commercial power had been available, even though a special crystal-controlled electronic power supply was used to operate the lock-in amplifier. It is presumed that the ozone concentration in the upper atmosphere was between 0.25 and 0.30 cm (based upon the Vigroux[22] transmission coefficients for ozone) or between 0.20 and 0.25 cm (NTP) if based upon the Fabry and Buisson[23] transmission coefficients. This conclusion is based not only upon our previous measurements[10c] but also on other work at this station* as the

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* Similar data obtained by using a different set of filters at Table Mountain, California in 1965 are shown by the circles superimposed upon figure 1. These data are slightly higher, especially in the spectral region of 320 to 360 nm. A larger diaphragmed opening (2 inches) was employed permitting a much larger conical angle of sky irradiance to enter the diffusing sphere and to reach the detector. For this reason these data are too high by several percent. Also smoggy conditions near the noon hour and in the afternoon render their usefulness questionable. They have therefore been neglected in setting up the mean curve of figure 9.

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* A summary report by Arlette Vassy[24] includes a curve for the seasonal variation of ozone at the Mauna Loa Station. This indicates a value of about 0.275 cm (NTP) for late August. Measurements with the same instrumentation by one of the authors (H.T.E.) and his staff on the six days covered in the present work ranged from 0.283 to 0.292 cm, the mean value being 0.288 cm (all measurements being based on the Vigroux coefficients).

present calculations are widely scattered. Thus (with reference to figures 9 and 10) it may be presumed that the prism spectroradiometric solar data at 312 nm are too high while the filter data at 310 are too low, and that the correct value lies somewhere in between. The mean curve in figure 9 has been so drawn.

V. The Solar Constant

The solar constant has been defined in an earlier section of this paper as the solar irradiance available upon a unit surface perpendicular to the solar rays at the earth's mean distance from the sun. Hence, when one knows the spectral irradiance at this position the total may be found by integration over the limits of the solar spectrum -- which for practical purposes is from about 100 nm to 10,000 nm. The spectral data reported in the present paper cover only a small part of this range. However, most of the remainder is either insignificant in total amount (only about 1 percent lies outside the range of 300 to 7,000 nm) or else has been measured to a relatively high degree of accuracy. The range from about 500 nm to 7,000 nm falls in the latter category. Hence, the present measurements cover that least known spectral region of 300 to 500 nm.

The tabular values representing the Johnson curve are also plotted in figure 9. As noted earlier the measurements by Dunkelman and Scolnik in the spectral region of 300 to 680 nm were incorporated in this curve. But this was after their first being increased by 6 percent[4] to match the Moon[3] (or Smithsonian scale) curve in the infrared, the match being made at 600 nm. An additional adjustment of the Moon curve of 2.8 percent upward (by Johnson) resulted in a total increase of the Dunkelman and Scolnik data by about 9 percent. Since the NBS standard of spectral irradiance[8] employed by Dunkelman and Scolnik had values that are about 4 1/2 percent[25] high compared to those of the recently developed quartz-iodine lamp standard of spectral irradiance, it appears that their data as used by Johnson might be about 13 percent high in the spectral region of 300 to 680 nm. The calibration of their standard[8] was based upon color temperature and published values of tungsten emissivity, but it was the best available from the National Bureau of Standards at that time. Since then the new quartz-iodine lamp standards[12,19,25] based upon the radiance of a blackbody at a known temperature have been developed. The latest of these standards is the 1000-watt lamp illustrated in figure 4.

In terms of the 1966 Mauna Loa spectral solar data we find the Johnson curve to be (on the average within the spectral range of 300 to 520 nm) about 10 percent high. Hence it is concluded that the original Dunkelman and Scolni data were probably closer to the true value than the resulting Johnson curve in this region.

In setting up Table II the incorporated data are given for the same wavelengths as used by Johnson[4]. Since, as indicated above, the spectral values for wavelengths within the spectral range of 220 to approximately 310 nm were arbitrarly matched to the Dunkelman and Scolnik data (which was raised about 9 percent and based upon a high standard) we have accordingly lowered these data[5] over this spectral range by 13 percent from the values originally published by Johnson[4]*. For the region of 310 to 525 nm the mean of the Mauna Loa data as shown in Figure 9 were used. For the region of 525 to 7,000 nm the Smithsonian data, as tabulated in the Johnson curve, were used without change.

An integration of the complete solar curve as tabulated in Table II results in a solar constant of 0.136 watt per cm^2, or 1.95 calories per cm^2 per minute. It is interesting that this value agrees closely with the mean of the data reported by the Smithsonian Institution through the years. Also of interest is a similar value recently obtained by Drummond[26] et. al. as a preliminary result of filter radiometric measurements on high flying aircraft. It is also interesting to note that when the Sacramento peak measurements by Stair and Johnson[14] are increased by 4 1/2 percent because the standard of spectral irradiance used at that time is now recognized as low by that amount, the resulting value for the solar constant is reduced from 2.05 to 1.96 calories per cm^2 per minute.

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* In a later publication[9b] Johnson has revised his curve for wavelengths shorter than 260 nm, based upon some new measurements by Detwiler[27], et al. These changes are small radiometrically and do not affect the value of the solar constant significantly.

REFERENCES

1. C. G. Abbot and F. E. Fowle, Annals of the Astrophysical Observatory of the Smithsonian Institution, Vol. 2 (1908); C. G. Abbot and L. B. Aldrich, Annals of the Astrophysical Observatory of the Smithsonian Institution, Vol. 3 (1913) and Vol. 4 (1922)1 C. G. Abbot, L. B. Aldrich, and F. E. Fowle, Annals of the Astrophysical Observatory of the Smithsonian Institution, Vol. 5 (1932); C. G. Abbot, L. B. Aldrich and W. H. Hoover, Annals of the Astrophysical Observatory of the Smithsonian Institution, Col. 6 (1942).

2. I. Wilsing, Astrop. Obs. Potsdam, Publikationen, 32, 91 (1917); C. G. Aldrich, Smithson, Misc. Coll. 74, No. 7 (1923); E. Pettit, Astrop. J. 75, 185 (1932); C. Fabry and H. Buisson, Astrophys. J. 54, 297 (1921).

3. P. Moon, J. Franklin Inst. 230, 583 (1940).

4. F. S. Johnson, J. Meterol. 11, 431 (1954).

5. F. S. Johnson, J. D. Purcell, R. Tousey, and N. Wilson, in Rocket Exploration of the Upper Atmosphere, Ed. Boyd and Seaton, Pergamon Press, London, p. 279 (1954).

6. D. M. Packer and C. Lock, J. Opt. Soc. Amer. 42, 879 (1952).

7. L. Dunkelman and R. Scolnik, J. Opt. Soc. Amer. 49, 356 (1959).

8. R. Stair and W. O. Smith, J. Res. NBS 30, 449 (1943); Ralph Stair, J. Res. NBS 46, 437 (1951).

9. P. R. Gast, Handbook of Geophysics and Space Environments, U. S. Air Force Cambridge Res. Lab., Bedford, Mass. Ch 16-1 (1966); F. S. Johnson, Satellite Environment Handbook, p. 96, Stanford University Press, Stanford, California (1965); N. Robinson, Solar Radiation, p. 1, Elsevier Pub. Co. (1966); A. J. Drummond, International Symposium on Solar Radiation Similation Proceedings, p. 55 (Jan 1965).

10. Ralph Stair, J. Res. NBS, 49, 227 (1952); Ralph Stair and Russell G. Johnston, J. Res. NBS, 57, 205 (1956) and 61, 419 (1958).

11. Ralph Stair, William E. Schneider, William R. Waters, and John K. Jackson, Appl. Opt. 4, 703 (1965).

12. Ralph Stair, William E. Schneider, William R. Waters, John K. Jackson and Roger E. Brown, NASA Report CR-201 (1965).

13. Ralph Stair and W. O. Smith, J. Res. NBS 30, 449 (1943); Ralph Stair, J. Res. NBS 61, 419 (1958); Roy L. Fox, Nature 178 1271 (1956).

14. Ralph Stair and Russell G. Johnston, J. Res. NBS 57, 205 (1956).

15. S. T. Henderson, and D. Hodgkiss, Brit. J. Appl. Phys. 14, 125 (1962); E. R. Cooper and M. C. Probine, J. Sci. Instr. 26, 348 (1949).

16. R. S. Adhav, J. Sci. Instrum. 40, 455 (1963); P. L. Tea and H. D. Baker, J. Opt. Soc. Amer. 46, 875 (1956); W. E. K. Middleton and C. L. Sanders, J. Opt. Soc. Amer. 41, 419 (1951); Von Kurt Larché und Reinhart Schulze, Zeitchhr. f. techn. physik. Nr. 4, 114 (1942); Harry K. Hammond III, Appl. Opt., 2, 1207 (1963).

17. Robert D. Moore, Electronics 35, No. 23, 40 (June 8, 1962); R. D. Moore and O. C. Chaykowsky, Tech. Bull. 109, Princeton Applied Res. Corp., Princeton, N. J., (1963).

18. Ralph Stair, J. Res. NBS 46, 437 (1951).

19. Ralph Stair, William E. Schneider, and John K. Jackson, Appl. Opt. 2, 1151 (1963).

20. Ralph Stair and John S. Nader, Pilot Study of U-V radiation in Los Angeles, Oct., 1965, U.S. P.H.S. Pub. No. 999-AP-34, Sect. 2, National Center for Air Pollution Control, Cincinnati, Ohio, 1967.

21. Ralph Stair, J. Res. NBS 40, 9 (1948).

22. E. Vigroux, Ann. Phys. 8, 709 (1953).

23. C. Fabry and H. Buisson, Compt. rend. 192, 457 (1931).

24. Arlette Vassy, Advances in Geophysics 11, 115 (1965).

25. Ralph Stair, Air and Wat. Pollut. Int. J. 10, 665 (1966).

26. A. J. Drummond, J. R. Hickey, and W. J. Scholes, AIAA 5th Aerospace Sciences Meeting, New York, Jan 23-26, 1967.

27. C. R. Detwiler, D. L. Garrett, J. D. Purcell, and R. Tousey, Ann. Geophy. 17, 263 (1961).

LEGENDS TO ILLUSTRATIONS

1. Spectral distribution of the irradiance from the sun (after Stair and Johnston, Ref. 14) 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.

2. Optical layout of Carl Leiss monochromator and block diagram of complete double quartz-prism spectroradiometer as employed in solar irradiance measurements. The polar axis is not shown and the sphere with the diaphragm is rotated 90° for purposes of illustration.

3. Section of strip chart record illustrating the performance of the double monochromator as set up for this work with a high pressure mercury arc as source. The sharp "dips" at C result from impressed wavelength signals. The dip at S results from an arbitrary sensitivity shift to keep the complete spectrum on the same scale.

4. The NBS 1000-watt standard of spectral irradiance.

5. Block diagram showing the instrumental setup of the spectral ultraviolet filter wheel spectroradiometer. The box containing the optics and motor drive was placed on a polar axis to automatically follow the sun.

6. Section of strip chart covering 5 rotations of the filter wheel during mid-morning. This shows the constancy of the zero deflection and the gradual increase in solar irradiance during this period of about 12 minutes.

7. Spectral characteristics of the optical components of the ultraviolet filter wheel spectroradiometer (as used at Table Mtn.). New (and similar) narrow-band filters were employed on Mauna Loa. The ordinates are exact for the nine filters, divided by 5 for Corning glass No. 9863, but relativ only for the phototube, standard lamp and for the smoothened solar curve.

8. Determination of the deflections representing the spectral solar irradianc outside the atmosphere. Mean of data for three days in August 1966.

9. Solar spectral irradiance curve outside the earth's atmosphere, corrected to mean solar distance. Open circles, Johnson data (from ref. 4). New data, mean for 3 days in August 1966 on Mauna Loa for each instrumentation

10. Atmospheric transmittance above Mauna Loa Observatory, altitude 11,150 feet. The ozone transmittance curves are based on the Fabry and Buisson transmission coefficients (ref. 23).

Table I. This table illustrates some of the factors which enter into the measurement of spectral irradiance with narrow-band filters. The centroids are calculated in terms of standard lamp irradiance with the estimated errors for solar irradiance based upon the smooth solar curve illustrated in figure 7.

terference Filter inal Wavelength nm	Filter τ x Lamp Energy x Phototube Resp. x Corning 9863 τ	Wavelength Centroid Table Mtn., 1965 nm	Estimated Percent Correction for Solar Irradiance, M=1.0	Wavelength Centroid Mauna Loa, 1966 nm	Estimated Percent Correction for Solar Irradiance, M=1.0
310	1172	309.42	+2.9	311.26	-6.3
320	3345	322.29	-3.0	321.54	-1.5
330	4663	331.58	+1.4	331.74	+1.6
340	5145	340.65	+0.8	343.39	+4.2
350	9759	352.70	+3.2	350.97	+1.2
360	12500	360.22	+0.2	360.85	+0.8
370	10539	371.80	+2.5	371.41	+2.0
380	8805	381.33	+1.9	379.61	-0.6
390	7609	392.10	-2.7	390.52	-0.7

Table II. Solar Spectral Irradiance Data

Wavelength λ is given in nanometers for the center of the spectral band, the mean zero air mass spectral-irradiance E_λ is in W $cm^{-2}\mu^{-1}$, $\Delta\lambda$ is the wavelength interval used in computing $\Sigma E_{0-\lambda}$ and $P_{0-\lambda}$, $\Sigma E_{0-\lambda}$ is the summation of the irradiance for the represented and shorter wavelength intervals in units of 200 times W cm^{-2}, and $P_{0-\lambda}$ is the percentage of the solar constant associated with wavelengths shorter than the long-wavelength limit of the represented wavelength interval.

Finally, E_s is the solar constant in W cm^{-2} and in cal cm^{-2} $min.^{-1}$.

λ, nm	E_λ	$\Delta\lambda$	$\Sigma E_{0-\lambda}$	$P_{0-\lambda}$
220	0.0026	5	0.0026	0.01
225	.0037	5	.0063	0.02
230	.0046	5	.0109	0.04
235	.0047	5	.0156	0.06
240	.0051	5	.0207	0.08
245	.0056	5	.0263	0.10
250	.0056	5	.0319	0.12
255	.0088	5	.0407	0.15
260	.0114	5	.0521	0.19
265	.0176	5	.0697	0.26
270	.022	5	.0917	0.34
275	.020	5	.1117	0.41
280	.021	5	.1327	0.49
285	.030	5	.1627	0.60
290	.046	5	.2087	0.77
295	.055	5	.2637	0.97
300	.054	5	.3177	1.17
305	.059	5	.3767	1.39
310	.067	5	.4437	1.63
315	.072	5	.5157	1.90

320	.075	5	.5907	2.18
325	.083	5	.6737	2.48
330	.093	5	..7667	2.82
335	.091	5	.8577	3.16
340	.092	5	.9497	3.50
345	.096	5	1.0457	3.85
350	.101	5	1.1467	4.22
355	.105	5	1.2517	4.61
360	.104	5	1.3557	4.99
365	.109	5	1.4647	5.39
370	.115	5	1.5797	5.82
375	.113	5	1.6927	6.23
380	.115	5	1.8077	6.66
385	.107	5	1.9147	7.05
390	.108	5	2.0227	7.45
395	.109	5	2.1317	7.85
400	.150	5	2.2817	8.40
405	.180	5	2.4617	9.06
410	.178	5	2.6397	9.72
415	.178	5	2.8177	10.4
420	.177	5	2.9947	11.0
425	.171	5	3.1657	11.7
430	.157	5	3.3227	12.2
435	.163	5	3.4857	12.8
440	.174	5	3.6597	13.5

445	.186	5	3.8457	14.2
450	.192	5	4.0377	14.9
455	.191	5	4.2287	15.6
460	.190	5	4.4187	16.3
465	.190	5	4.6087	17.0
470	.190	5	4.7987	17.7
475	.194	5	4.9927	18.4
480	.195	5	5.1877	19.1
485	.184	5	5.3717	19.8
490	.183	5	5.5547	20.5
495	.190	5	5.7447	21.2
500	.190	5	5.9347	21.9
505	.189	5	6.1237	22.5
510	.192	5	6.3157	23.3
515	.194	5	6.5097	24.0
520	.191	5	6.7007	24.7
525	.192	5	6.8927	25.4
530	.195	5	7.0877	26.1
535	.197	5	7.2847	26.8
540	.198	5	7.4827	27.6
545	.198	5	7.6807	28.3
550	.195	5	7.8757	29.0
555	.192	5	8.0677	29.7

560	.190	5	8.2577	30.4
565	.189	5	8.4467	31.1
570	.187	5	8.6337	31.8
575	.187	5	8.8207	32.5
580	.187	5	9.0077	33.2
585	.185	5	9.1927	33.8
590	.184	5	9.3767	34.5
595	.183	5	9.5597	35.2
600	.181	5	9.7407	35.9
603.75	.1795	2.5	9.8305	36.2
610	.177	10	10.1845	37.5
620	.174	10	10.5325	38.8
630	.170	10	10.8725	40.0
640	.166	10	11.2045	41.3
650	.162	10	11.5285	42.5
660	.159	10	11.8465	43.6
670	.155	10	12.1565	44.8
680	.151	10	12.4585	45.9
690	.148	10	12.7545	47.0
700	.144	10	13.0425	48.0
710	.141	10	13.3245	49.1
720	.137	10	13.5985	50.1
730	.134	10	13.8665	51.1

740	.130	10	14.1265	52.0
750	.127	10	14.3805	53.0
765	.1227	20	14.8713	54.8
800	.1127	50	15.9983	58.9
850	.1003	50	17.0013	62.6
900	.0895	50	17.8963	65.9
950	.0803	50	18.6993	68.9
1000	.0725	50	19.4243	71.5
1037.5	.0680	25	19.7643	72.8
1100	.0606	100	20.9763	77.2
1200	.0501	100	21.9783	80.9
1300	.0406	100	22.7903	83.9
1400	.0328	100	23.4463	86.3
1500	.0267	100	23.9803	88.3
1600	.0220	100	24.4203	89.9
1700	.0182	100	24.7843	91.26
1800	.0152	100	25.0883	92.38
1900	.01274	100	25.3431	93.32
2000	.01079	100	25.5589	94.11
2100	.00917	100	25.7423	94.79
2200	.00785	100	25.8993	95.37
2300	.00676	100	26.0345	95.87
2400	.00585	100	26.1515	96.30
2500	.00509	100	26.2533	96.67

2600	.00445	100	26.3423	97.00
2700	.00390	100	26.4203	97.29
2800	.00343	100	26.4889	97.54
2900	.00303	100	26.5495	97.76
3000	.00268	100	26.6031	97.96
3100	.00230	100	26.6491	98.13
3200	.00214	100	26.6919	98.29
3300	.00191	100	26.7301	98.43
3400	.00171	100	26.7643	98.55
3500	.00153	100	26.7949	98.67
3600	.00139	100	26.8227	98.77
3700	.00125	100	26.8477	98.86
3800	.00114	100	26.8705	98.94
3900	.00103	100	26.8911	99.02
4000	.00095	100	26.9101	99.09
4100	.00087	100	26.9275	99.15
4200	.00080	100	26.9435	99.21
4300	.00073	100	26.9581	99.27
4400	.00067	100	26.9715	99.32
4500	.00061	100	26.9837	99.36
4600	.00056	100	26.9949	99.40
4700	.00051	100	27.0102	99.46
4800	.00048	100	27.0147	99.47
4900	.00044	100	27.0235	99.51

5000	.00042	100	27.0319	99.54
5275	.00036	450	27.0643	99.66
6000	.00021	1000	27.1063	99.81
7000	.00012	1000	27.1303	99.90
<7500	.00014*	1000*	27.1574	100.00
Total			27.1754	

E_S= .1358 W/cm^2 or 1.947 cal/(cm^2- min)

*Effective Value

LEGENDS TO ILLUSTRATIONS

1. Spectral distribution of the irradiance from the sun (after Stair and Johnston, Ref. 14) 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.

2. Optical layout of Carl Leiss monochromator and block diagram of complete double quartz-prism spectroradiometer as employed in solar irradiance measurements. The polar axis is not shown and the sphere with the diaphragm is rotated 90° for purposes of illustration.

3. Section of strip chart record illustrating the performance of the double monochromator as set up for this work with a high pressure mercury arc as source. The sharp "dips" at C result from impressed wavelength signals. The dip at S results from an arbitrary sensitivity shift to keep the complete spectrum on the same scale.

4. The NBS 1000-watt standard of spectral irradiance.

5. Block diagram showing the instrumental setup of the spectral ultraviolet filter wheel spectroradiometer. The box containing the optics and motor drive was placed on a polar axis to automatically follow the sun.

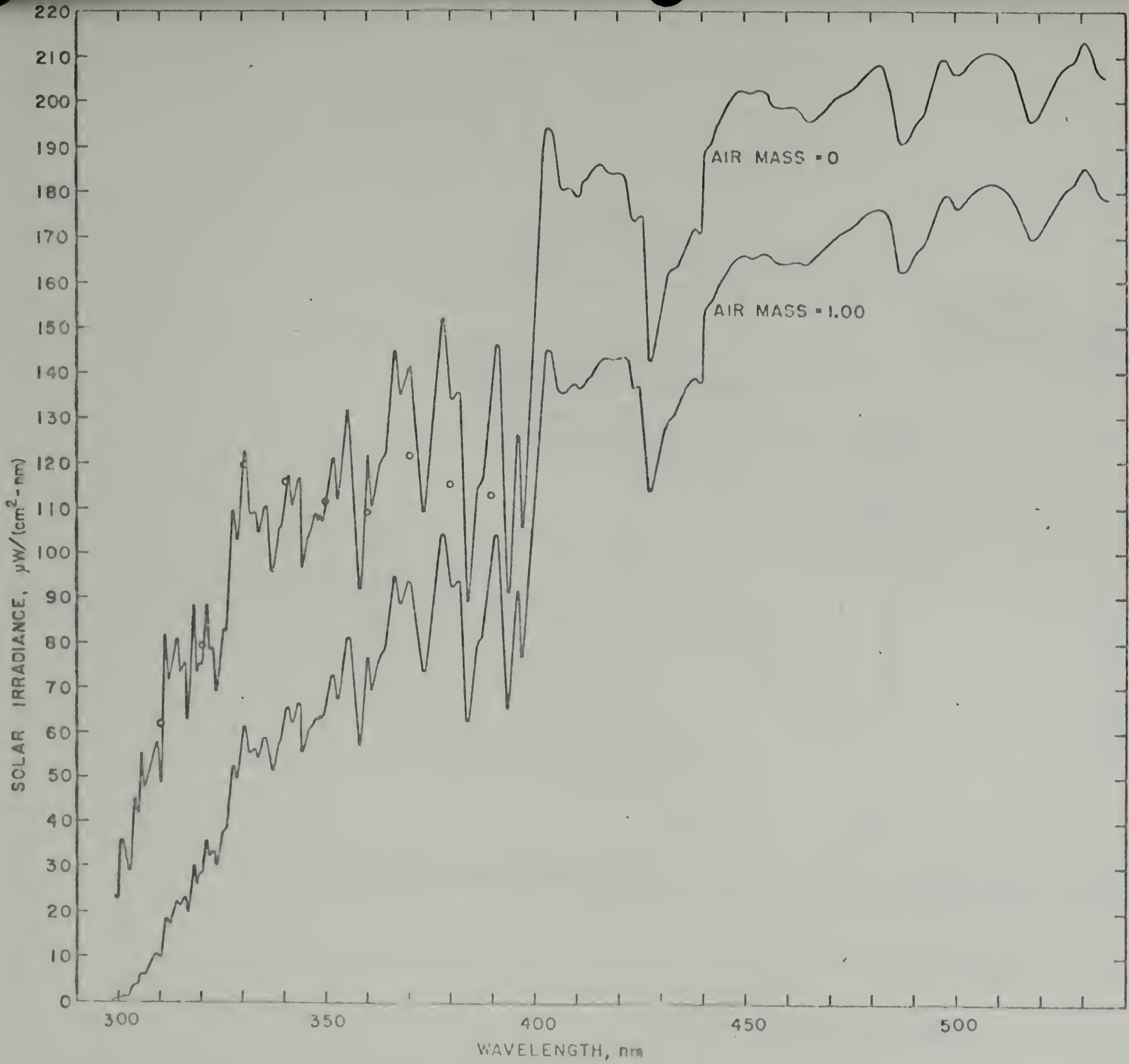
6. Section of strip chart covering 5 rotations of the filter wheel during mid-morning. This shows the constancy of the zero deflection and the gradual increase in solar irradiance during this period of about 12 minutes.

7. Spectral characteristics of the optical components of the ultraviolet filter wheel spectroradiometer (as used at Table Mtn.). New (and similar) narrow-band filters were employed on Mauna Loa. The ordinates are exact for the nine filters, divided by 5 for corning glass No. 9863, but relative only for the phototube, standard lamp and for the smoothened solar curve.

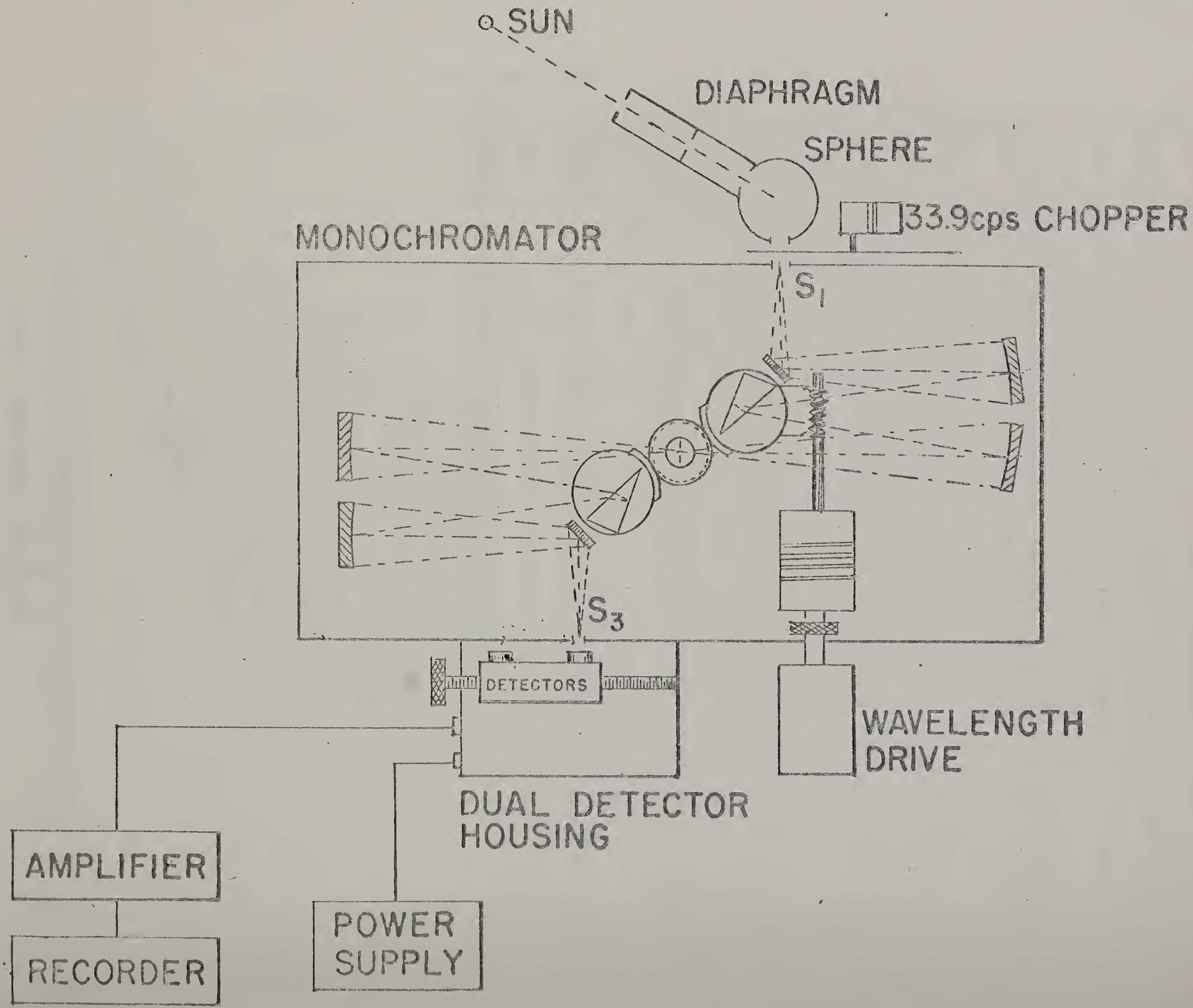
8. Determination of the deflections representing the spectral solar irradiance outside the atmosphere. Mean of data for three days in August 1966.

9. Solar spectral irradiance curve outside the earth's atmosphere, corrected to mean solar distance. Open circles, Johnson data (from ref. 4). New data, mean for 3 days in August 1966.on Mauna Loa for each instrumentation.

10. Atmospheric transmittance above Mauna Loa Observatory, altitude 11,150 feet. The ozone transmittance curves are based on the Fabry and Buisson transmission coefficients (ref. 23).



AIR MASS = 0
AIR MASS = 1.00
SOLAR IRRADIANCE, μW/(cm²-nm)
WAVELENGTH, nm


SUN
DIAPHRAGM
SPHERE
33.9cps CHOPPER
MONOCHROMATOR
S_1
S_3
DETECTORS
WAVELENGTH
DRIVE
DUAL DETECTOR
HOUSING
AMPLIFIER
RECORDER
POWER
SUPPLY

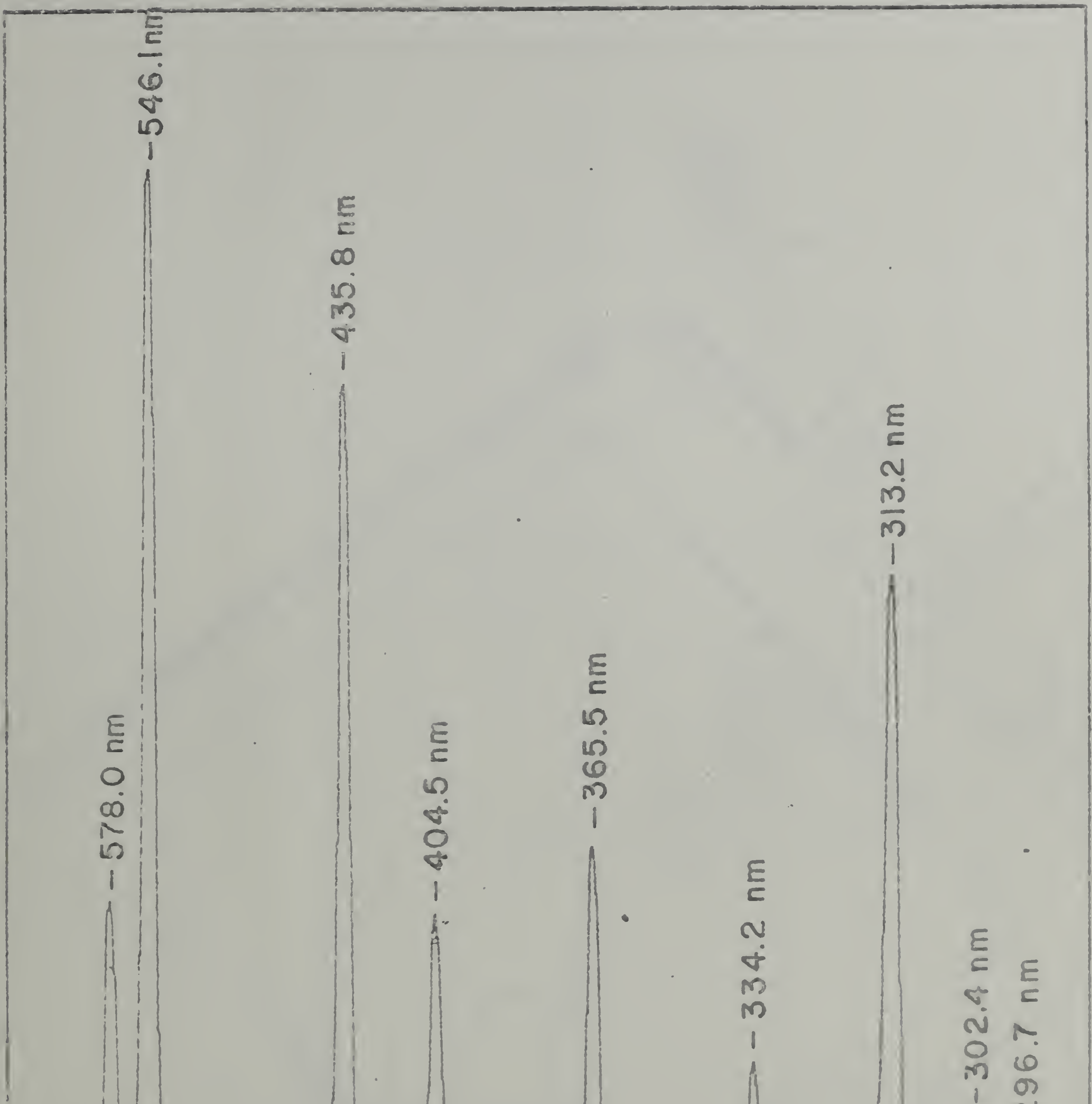
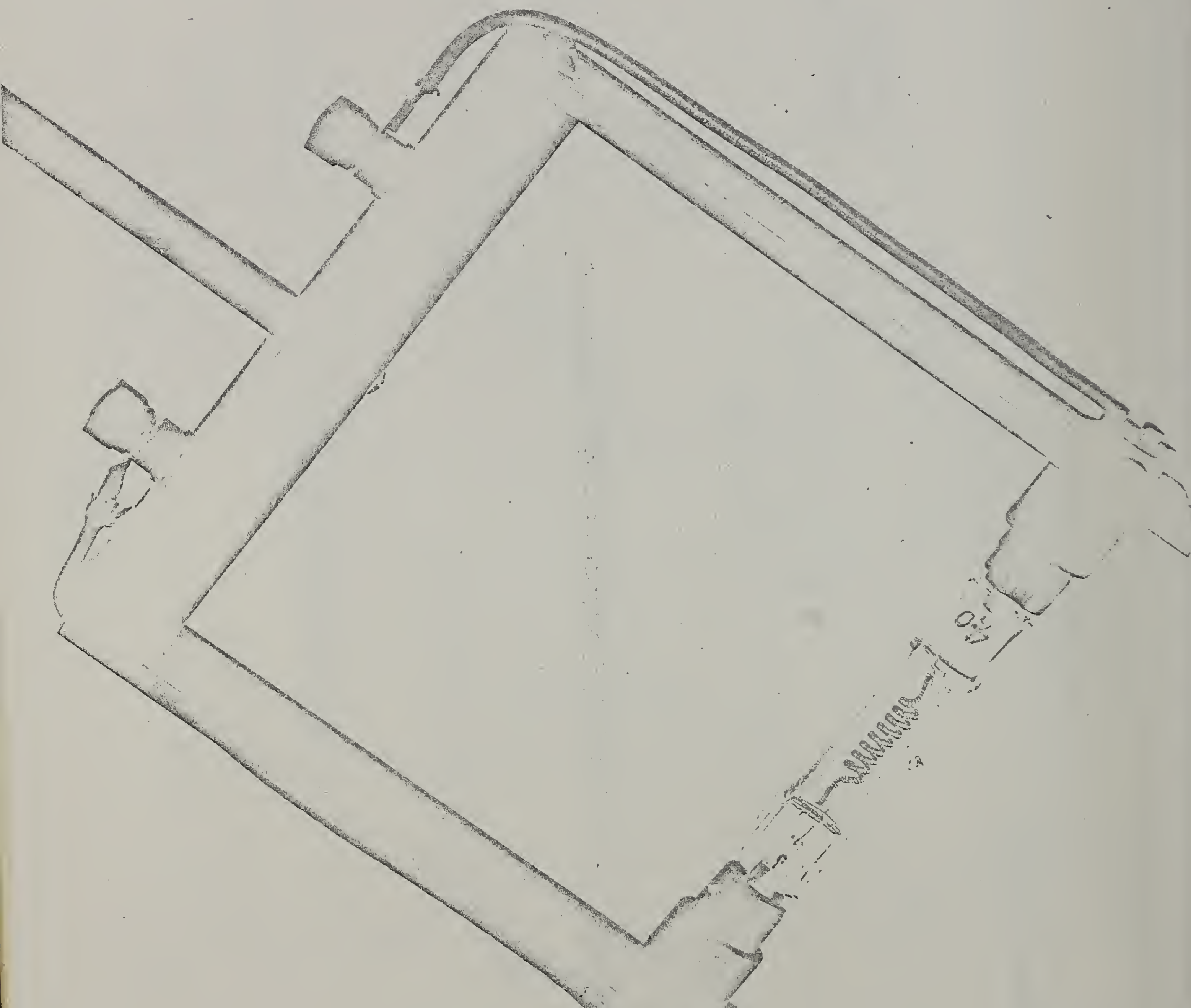

578.0 nm
546.1 nm
435.8 nm
404.5 nm
365.5 nm
334.2 nm
313.2 nm
302.4 nm
296.7 nm
C
C
C
C
S
C
C

Fig 9.



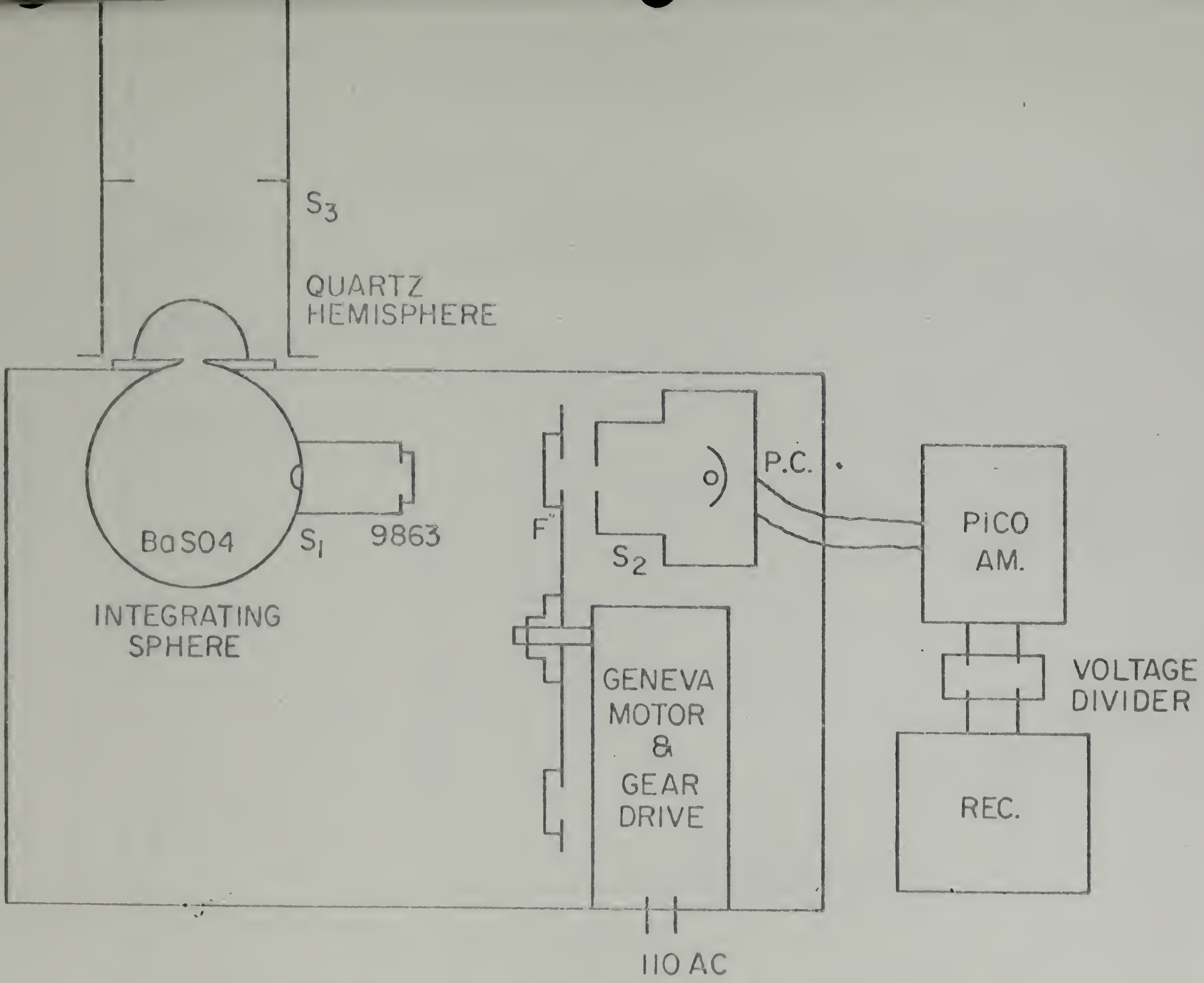
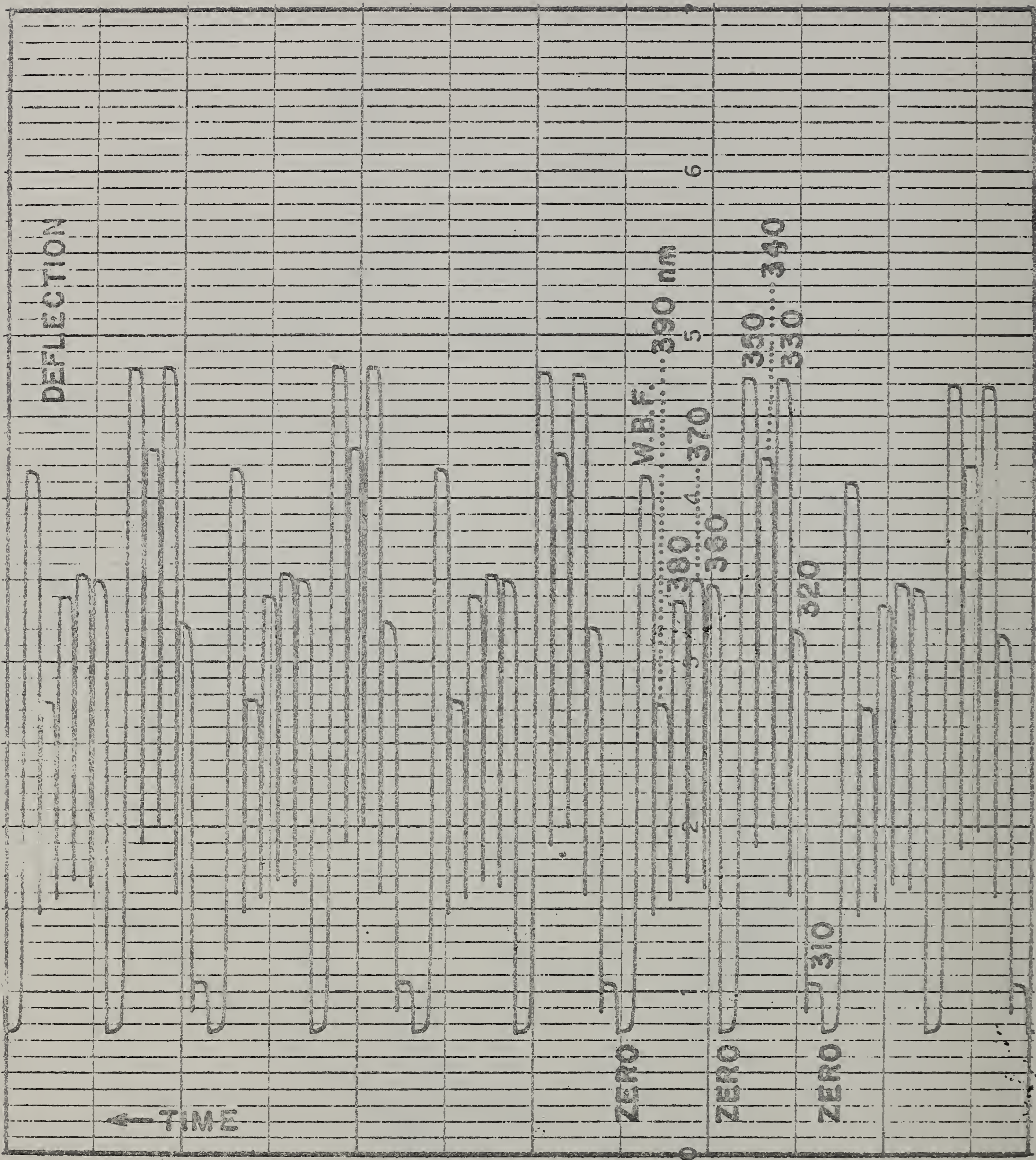

S3
QUARTZ
HEMISPHERE
Ba SO4
S1
9863
INTEGRATING
SPHERE
F
S2
P.C.
PICO
AM.
GENEVA
MOTOR
&
GEAR
DRIVE
VOLTAGE
DIVIDER
REC.
110 AC

Figure D. 5



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 6

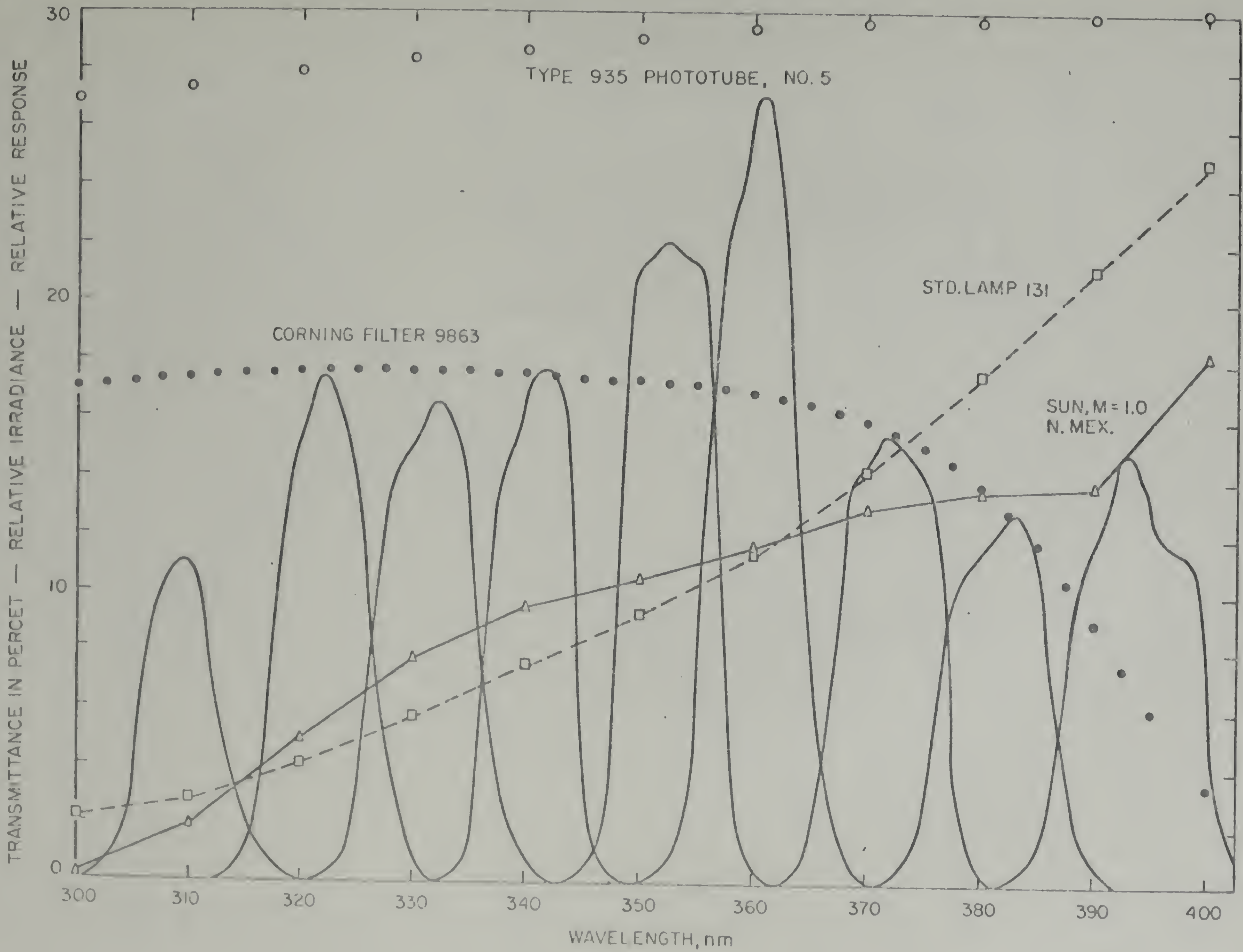
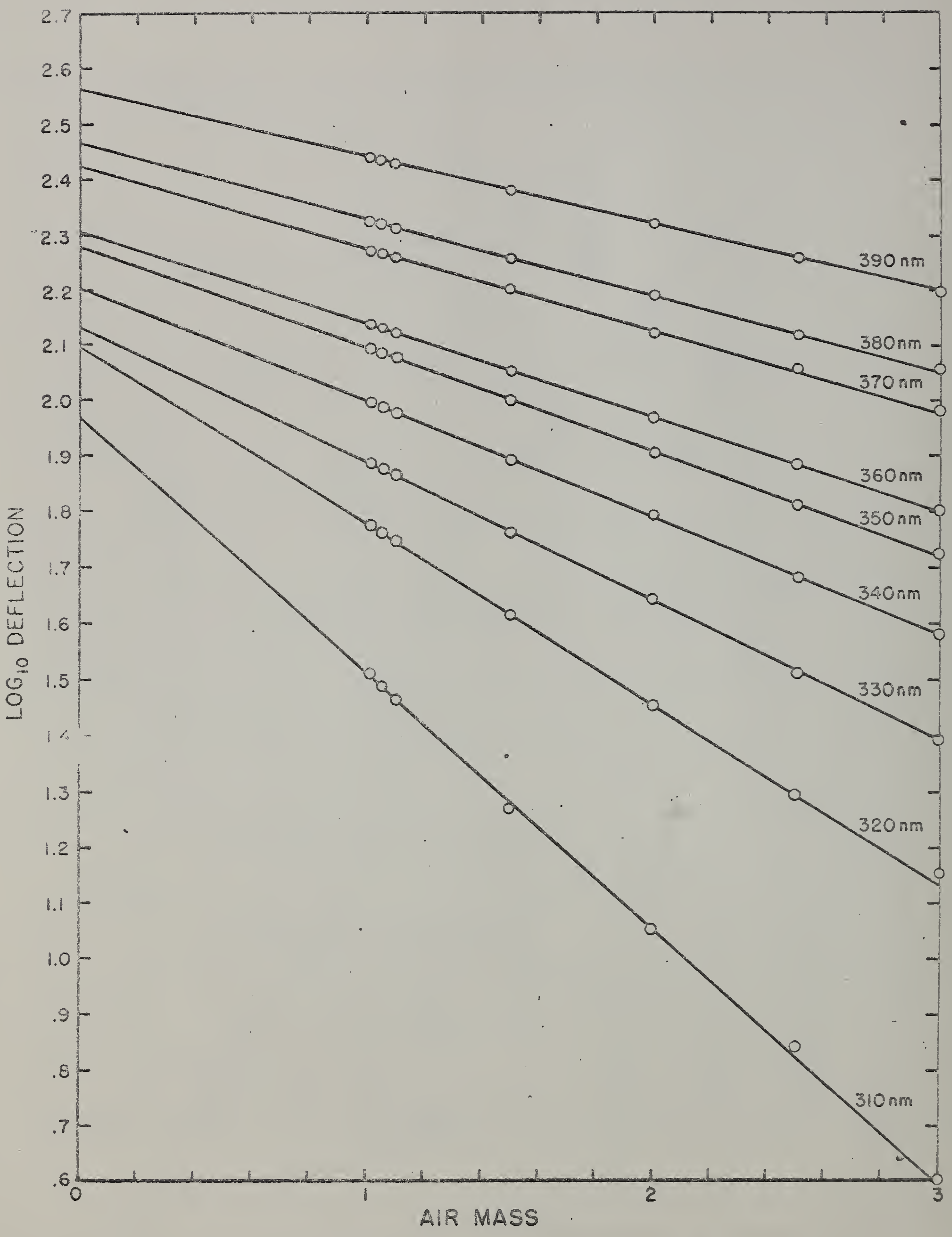

TYPE 935 PHOTOTUBE, NO. 5
CORNING FILTER 9863
STD. LAMP 131
SUN, M = 1.0
N. MEX.
TRANSMITTANCE IN PERCET — RELATIVE IRRADIANCE — RELATIVE RESPONSE
WAVELENGTH, nm
0
10
20
30
300
310
320
330
340
350
360
370
380
390
400

Fig. 1.



2.7
2.6
2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
LOG_{10} DEFLECTION
0
1
2
3
AIR MASS
390 nm
380 nm
370 nm
360 nm
350 nm
340 nm
330 nm
320 nm
310 nm

Fig

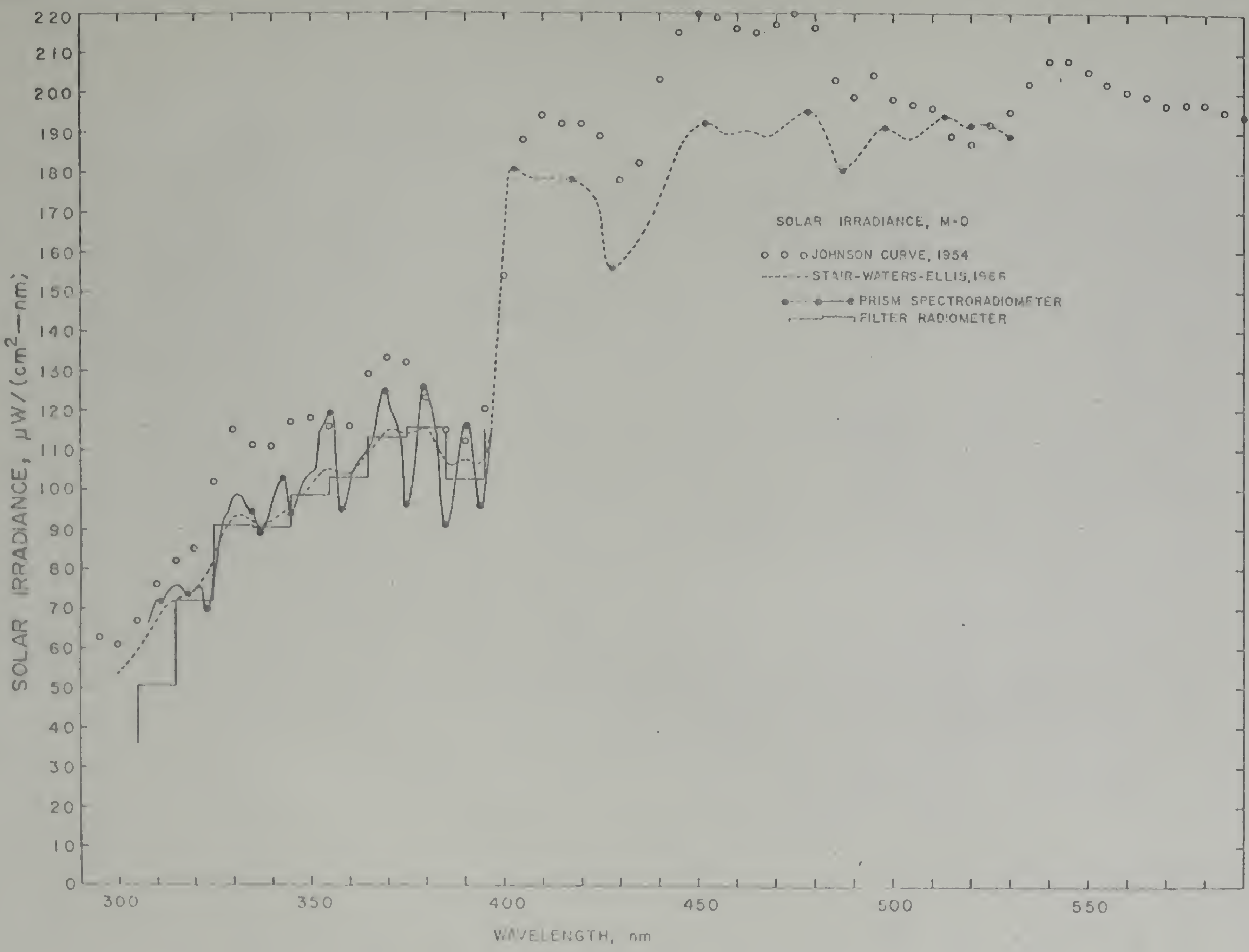
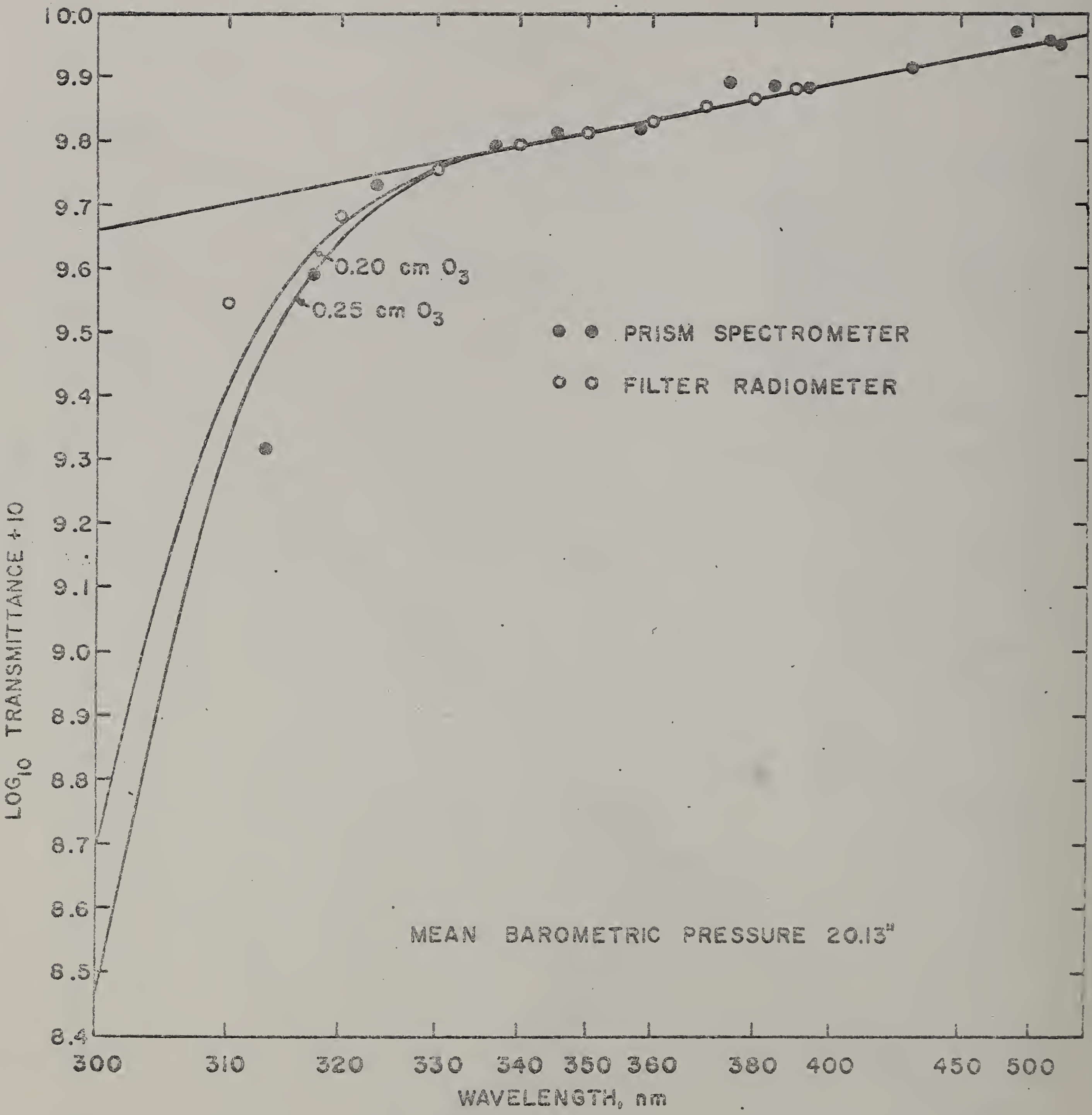

SOLAR IRRADIANCE, M=0
JOHNSON CURVE, 1954
STAIR-WATERS-ELLIS, 1966
PRISM SPECTRORADIOMETER
FILTER RADIOMETER
SOLAR IRRADIANCE, μW/(cm²—nm)
WAVELENGTH, nm
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
300
350
400
450
500
550

Fig 9


10.0
9.9
9.8
9.7
9.6
9.5
9.4
9.3
9.2
9.1
9.0
8.9
8.8
8.7
8.6
8.5
8.4
LOG10 TRANSMITTANCE + 10
0.20 cm O3
0.25 cm O3
PRISM SPECTROMETER
FILTER RADIOMETER
MEAN BAROMETRIC PRESSURE 20.13"
300
310
320
330
340
350
360
380
400
450
500
WAVELENGTH, nm

Fig

DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS