REVIEW OF GROUND-BASED MEASUREMENTS

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ABSTRACT

Early measurements of the solar constant made from the ground are described and discussed with particular emphasis on the Smithsonian program. A brief description is given of the monitoring program now operating at San Diego State.

HISTORICAL PROGRAMS

The solar constant is, of course, the solar irradiance at one astronomical unit integrated over all wavelengths. It is commonly expressed for example as 1368 watts/square meter, 136.8 milliwatts/square centimeter, or 1.961 calories/square centimeter/minute.

Historically the measurement of the solar constant begins in 1837 (see ref. 1). Pouillet constructed a pyrheliometer consisting of a blackened copper container, filled with water, into which a thermometer was inserted. After first determining the temperature in the shade, he placed his instrument in the sun and obtained the rate of change of temperature per minute due to the incident solar energy. Remembering that the solar constant is cal.-cm^{-2}-min^{-1}, from the known heat capacity of the water and copper he got the cal.-min^{-1}, and from the cross-sectional area of the container he got the number of cm^2, and hence the solar constant - well, almost. He had to make a correction of 2.5% for the estimated radiation lost to reflection, and he had to make a correction for the radiation lost due to scattering and absorption by the earth's atmosphere. Bouguer in 1760 had shown that for a plane parallel atmosphere the logrithm of the observed intensity is linearly related to the secant of the zenith distance (what today, allowing for curvature of the atmosphere, we call airmass). Pouillet then corrected his data for atmospheric attenuation using a linear Bouguer plot. This is not quite correct because the Bouguer plot is linear only for monochromatic radiation. Nevertheless, the value he obtained was 1.76 cal-cm^{-2}-min^{-1}, which is rather remarkable for such a simple device.

Thirty years later the famous solar astronomer, Father Secchi, built a cylindrical device with two thermometers - one exposed to the sun and one not. He used his device to determine the temperature of the sun's surface - unsuccessfully, since he arrived at a value of over five million degrees.

I mention these historical devices because (1) they illustrate the basic principles of determining the solar constant and they are remarkably like, in principle, the devices used today, and (2) the problems of determining the amount of radiation lost to scattering from the cavity and correcting for the radiation lost due to the earth's atmosphere are still the main problems of ground-based solar constant measurement.

The next major advance was the work of Langley and Abbot at the Smithsonian building upon earlier instrumental work by Langley at Allegany Observatory (Langley built the bolometer there) and Tyndall's silver disc pyrheliometer. Parallel to the Smithsonian work was the development by Angstrom in 1896 of the compensating pyrheliometer. Angstrom's device consisted of two small, thin, blackened plates of manganin (an alloy of copper, manganese, and nickel). The temperature of each plate was measured with a thermocouple, and each plate could be heated by passing a known amount of current through it. When one plate was heated by the sun, the other was heated electrically to the same temperature. The radiant power from the sun (watts) was then equal to the measured electrical power (volts times amps). You would switch the plates and take an average. The ease of operation of this device led the Smithsonian to adopt it for field work in the mid-1930's.

The bolometer, developed by Langley, consisted of two blackened strips of platinum that formed two arms of a Wheatstone bridge. When one of the platinum strips, later inclosed in a vacuum, was exposed to solar radiation its resistance changed producing a proportional change in the measured current through the bridge. On July 7, 1881 Langley's expedition with 5000 lbs of equipment (including the bolometer) left Pennsylvania by train for San Francisco (it took them 15 days), and thence with soldiers, wagons, and mules to the summit of Mt. Whitney (14,495 ft). He derived a value of the solar constant at around 3.0 cal-cm^{-2}-min^{-1} with a range of 2.63 to 3.5 (ref. 2). Abbot later reanalyzed this data set and got 2.14, which did not agree well with Angstrom's turn-of-the-century value of 1.763. Here in this difference the Smithsonian's solar constant monitoring program began.

There have been a number of published reviews of solar constant measurements: Labs at the Workshop at Big Bear Observatory (ref. 3); Thekaekara in NASA Special Publications (ref. 4 and 5); Labs and Neckel (ref. 6), and Frohlich and Brusa at the Big Bear Workshop (ref. 7) have reviewed relatively recent measurements, most of which have not been ground-based. The scales have been reviewed by Latimer (ref. 8) and Frohlich (ref. 9) among others. The two basic devices (the Angstrom and Abbot's water flow) differed by approximately 5% with the Smithsonian scale higher. Today's "absolute scale" lies just about half way between the Angstrom and Smithsonian. Abbot's improved water flow pyrheliometer with a compensating cavity (circa (1932) led to a later refinement (in 1952), which brought the Smithsonian scale very close to today's absolute scale. Thekaekara (ref. 10) lists twelve ground-based solar constant determinations from 1940 to 1969. The range from highest to lowest is 5% of the mean, which is worse than the earlier work.

There are two basic methods employed in measuring the solar constant. One is a total measurement from exposing a blackened cavity to the sun's total energy reaching the ground. Two is a measurement of the sun's spectral irradiance, which is then integrated with respect to wavelength. There is not time to discuss all the measurements and intercomparisons in the U.S., Davos, and elsewhere, so I shall select a few to serve as examples.

In the category of "total measurement" the Smithsonian data of over 50 years (1902 - 1960) is the most extensive. Data covering a period of over a decade was obtained by Rimmer and Allen in Australia (ref. 11) using both an Angstrom and a silver disc. They reported detecting no variations in the solar constant greater than 0.1% for the period 1927 to 1939.

Sitnik (ref. 12), Stair and Ellis (ref. 13), and Labs and Neckel (ref. 14) have all determined the solar constant from spectral irradiance measurements made from mountain top sites. In all cases comparison was made to tungsten lamps and ultimately to blackbody radiation sources. Bouguer's method was used to extrapolate out to zero airmass. Labs and Neckel used a Czerny-Turner double monochrometer on a small telescope that looked at the center of the sun and then at a standard lamp, which was at the focus of a collimating mirror. Accurate knowledge of solar limb darkening was used to transfer from the sun's center to the whole solar disc. Rocket data from Tousey (ref. 15) supplied the UV shortward of 0.33 microns and model solar atmospheres supplied the data longward of 1.25 microns. They obtained a value of 1358 watts/m^2.

SMITHSONIAN PROGRAM

I will now turn to the Smithsonian program both as an example of a "total measurement" method and as an example of a solar constant monitoring program. My colleague R. Roosen and I have spent some years analyzing this data. General information concerning the Smithsonian sites is given in Figure 1. The measurements span a period of time from 1902 to 1960. The last two columns refer only to the published data. We have retrieved much unpublished data from the Smithsonian Archives for the two primary sites Mt. Montezuma, Chile and Table Mt., California. In particular the unpublished data fills in the gap from 1930 to 1940.

Figures 2 and 3 show the observing tunnels at Mt. Montezuma and Table Mt. respectively. One can see the coelostat reflecting the sunlight into the observing tunnel, which contains the spectrobolometer. One can also see two silver discs for measuring the solar irradiance and pyranometer for measuring the solar aureole brightness.

The silver disc, shown in Figure 4, was the "field instrument". A thermometer, parallel to the viewing axis, makes a right-angle bend and protrudes radially into a blackened silver disc. One then reads the rate of change in temperature upon exposure to the sun. The silver disc had to be calibrated against an absolute detector, and so Abbot built the Water Flow Pyrheliometer, which is shown in Figure 5. The incoming water flowed across a platinum strip, whose change in resistance allowed them to calculate the starting temperature, then it flowed around a blackened cone and receiver, and finally it flowed out across another platinum strip to measure the temperature change due to the incident sunlight. They also measured the grams per minute of water flowing through the device. The Water Flow and Water Stir pyreheliometers set the "Smithsonian Revised Scale of 1913".

The Smithsonian used the spectrobolometer, shown in Figure 6, to determine the amount of atmospheric attenuation. A prism spectrograph dispersed the solar spectrum onto a bolometer. The bolometer output was measured with a Boys galvanometer, which consisted of a mirror on a quartz fiber reflecting a light beam back and forth in proportion to the signal from the bolometer. The light beam exposed a line on a moving photographic plate, which became in essence a strip chart recorder.

They typically recorded five tracings of the solar spectral irradiance on one spectrobologram, each tracing at a different airmass. The height of each tracing was measured at 34 wavelengths, and the spectrobolometer curves were numerically integrated and corrected for instrumental transmission and UV and IR losses. Since the spectrobolometer was not an absolute device, this integrated area was normalized to the total surface irradiance measured by the silver disc (later they used a Compensating Angstrom detector). Then point by point, using Bouguer's law, they extrapolated the normalized curve to zero airmass, integrated it again, added zero-airmass UV and IR corrections, and obtained the solar constant. Further discussion can be found in ref. 16.

A ground-based determination of the solar constant is only as good as the correction for the atmospheric effects on the measurement. These atmospheric effects, derived from the Smithsonian data, are shown in the following three figures. Figure 7 shows the optical depth at 4 of 34 wavelengths for Mt. Montezuma (ref. 17). One can clearly see the seasonal variation and the eruption of Mt. Quizopu, Chile in 1932. The total ozone can be determined from the Chappuis band (ref. 18), and Figure 8 shows the result for Table Mt. in the form of monthly means. Absorption by water vapor is one of the largest effects and its changes are shown in Figure 9 for both Table Mt. and Mt. Montezuma (ref. 19). They determined it from the depths of three water vapor bands, calibrated by Fowle, and developed a scheme for calculating the band areas from these depts. From these figures one can clearly see that these atmospheric effects are both large and variable and must be accurately determined on each day of measurement. Rayleigh and aerosol scattering remove at one airmass typically 10 to 15% of the direct solar beam, ozone 4 to 5%, and water vapor 10 to 20%. In spite of all this, it is possible to make accurate atmospheric corrections, and the Smithsonian was successful in doing so.

Our on-going analysis of the Smithsonian data (ref. 16), funded by NSF, shows that they made the atmospheric corrections quite well. The main question is whether they detected variations in the solar constant. This has been much discussed in the past, but perhaps Figure 10 will allow the reader to make his own judgement. In this figure, which is a preliminary plot from our analysis, Roosen and I present the raw, daily solar constant values for both Table Mt. and Mt. Montezuma; there are several thousand data points. The values range from about 1.92 to 1.96 cal-cm^{-2}min^{-1} on the scale of 1913. If it is the case that the variations are due to the sun, then one should see the same variations, in phase, at both sites. A preliminary cross correlation analysis shows no solar variations greater than 0.3%.

MODERN PROGRAM

There are five ways in which we can now improve on ground-based solar constant measurements since the time of C. G. Abbot and the Smithsonian program. First, instrumentation has advanced giving us the absolute cavities of Willson, Kendall, PMO, and the ERB experiment to replace the silver disc. We have temperature-controlled silicon photodiodes to replace the vacuum bolometer. Second, we have microprocessors and automation. This allows one to obtain more than ten times the number of daily measurements on the earth's atmospheric effects than in the Smithsonian program, and a consequent increase in the accuracy of this correction. Third, there has been an increase in knowledge. We know more about these atmospheric effects, we can better measure them, and we can better correct for them. We know more about the UV and IR corrections and have more accurate solar spectra. Fourth, modern data can be reduced and analyzed with electronic computers allowing both more sophisticated and more accurate determinations of the solar constant. Fifth, we have now the ultimate calibration of ground-based measurements through intercomparison with the space measurements.

With these improvements in mind, we have begun at San Diego State's Mt. Laguna Observatory (6100 ft altitude) a long-term monitoring program on the solar constant. We intend to continue our program through at least one solar magnetic cycle. A flow diagram of our method is shown in Figure

11. The basic instruments consist of three absolute cavities (a Kendall Mk VI, a Willson ACR III, and a Willson ACR IV) and a filter wheel radiometer with a temperature-controlled (± 0.1 °C) silicon photodiode. The eleven narrow-band filters (FWHM 75 Angstroms) cover the range 3840 to 10100 Angstroms. They were carefully selected to cover the Chappuis band for ozone determination, the 9350 water vapor band, and part of the spectrum relatively free of telluric features for determining the amount of dust. For the purpose of calibration we have intercompared our instrument with both a Dobson and Glenn Shaw's instrument at Mauna Loa Observatory. The absolute cavities will be intercompared at Table Mt. with other cavities. In 94 intercomparisons between the Kendall Mk VI and the Willson ACR III, under various atmospheric conditions, the ACR III reads higher by about 4 percent, but this systematic difference is stable to 0.15 percent standard deviation.

With cavities in space, why measure the solar constant from the ground? First, the space experiments (such as SMM) may not run continuously for the next several decades. The ground-based measurements, carefully calibrated against the space measurements, can then fill in the periods of time when there are no space experiments. Second, even if the space experiments are continuous, and even if the sun should turn out to be essentially constant, then the ground-based measurements will still provide a valuable record of atmospheric aerosols, ozone, and water vapor.

REFERENCES

1. Abetti, G.: The Sun, MacMillan Co., New York, 1957.

2. Abbot, C. G., Fowle, F. E., and Aldrich, L. B.: Annals of the Astrophysical Observatory of the Smithsonian Institution, Vol. 3, 1913.

3. Labs, D.: in Proceedings of the Workshop: The Solar constant and the Earth's Atmosphere, Big Bear Obs., No. 0149, H. Zirin and J. Walter, eds., p. 157, May, 1975.

4. Thekaekara, M. P.: Survey of the Literature on the Solar Constant, NASA SP-74, 1965.

5. Thekaekara, M. P.: The Solar Constant and the Solar Spectrum Measured from a Research Aircraft, NASA TR R-351, 1970.

6. Labs, D. and Neckel, H.: Solar Physics, Vol. 19, pp. 3-15, 1971.

7. Frohlich, C. and Brusa, R. W.: Proceedings of the Workshop: The Solar Constant and the Earth's Atmosphere, Big Bear Solar Obs., No. 0149, H. Zirin and J. Walter, eds., p. 111, May, 1975.

8. Latimer, J. R.: Tellus, Vol. 25, pp. 586-592, 1973.

9. Frohlich, C.: in Total Solar Irradiance Monitoring Plan, NASA/GSFC, C. R. Laughlin and C. H. Duncan, eds., June, 1977.

10. Thekaekara, M. P.: Solar Electromagnetic Radiation, NASA SP-8005, 1971.

11. Rimmer, W. B. and Allen, C. W.: Mem. Commonwealth Obs. Mt. Stromlo, No. 11, October, 1950.

12. Sitnik, G. F.: Astr. Cirk. Izdav. Bjuro Astr. Soobsh. Kazan, No. 444, 1967.

13. Stair, R. and Ellis, H. T.: J. Appl. Meteor., Vol. 7, p. 635, 1968.

14. Labs, D. and Neckel, H.: Z. fur Astrophysik, Vol. 69, pp. 1-73, 1968.

15. Tousey, R.: Space Sci. Rev., Vol. 2, p. 3, 1963.

16. Roosen, R. G., Angione, R. J., and Klemcke, C. H.: Bull. Amer. Met. Soc., Vol. 54, p. 307, 1973. Hoyt, D. V.: Rev. Geophys. and Space Phys., Vol. 17, p. 427, 1979.

17. Roosen, R. G. and Angione, R. J.: preprint, 1981

18. Angione, R. J., Medeiros, E. J., and Roosen, R. G.: Nature, Vol. 261, p. 289, 1976.

19. Roosen, R. G. and Angione, R. J.: Pub. Ast. Soc. Pac., Vol. 89, p. 814, 1977.

SITE	LAT.	LONG.	ALT. METERS	PERIOD OF OBSERV.	DAYS OBS.
MT. MONTEZUMA, CHILE	22° 40'S	68° 56'W	2711	1920 - 1930	518
				1940 - 1948	46
TABLE MTN., CALIFORNIA	34° 22'N	117° 41'W	2286	1925 - 1930	445
				1940 - 1950	39
CALAMA, CHILE	22° 28'S	68° 56'W	2250	1918 - 1920	577
MT. WILSON, CALIFORNIA	34° 13'N	118° 4'W	1737	1905 - 1906	121
				1908 - 1920	1124
MT. HARQUA HALA, ARIZONA	33° 48'N	113° 20'W	1721	1920 - 1925	225
MT. BRUKKAROS, S.W. AFRICA	25° 52'S	17° 48'E	1586	1926 - 1930	203
HUMP MTN., N. CAROLINA	36° 8'N	82° 0'W	1500	1917 - 1918	58
WASHINGTON, D.C.	38° 53'N	77° 2'W	10	1902 - 1907	44
MT. ST. CATHERINE, EGYPT	28° 31'N	33° 56'E	2591	1934 - 1937	40
BURRO MTN., NEW MEXICO	32° 40'N	108° 33'W	2440	1940 - 1945	30
MIAMI, FLORIDA	25° N	80° W	10	1948	10

Figure 1. Basic data for the sites used in the Smithsonian solar constant program.

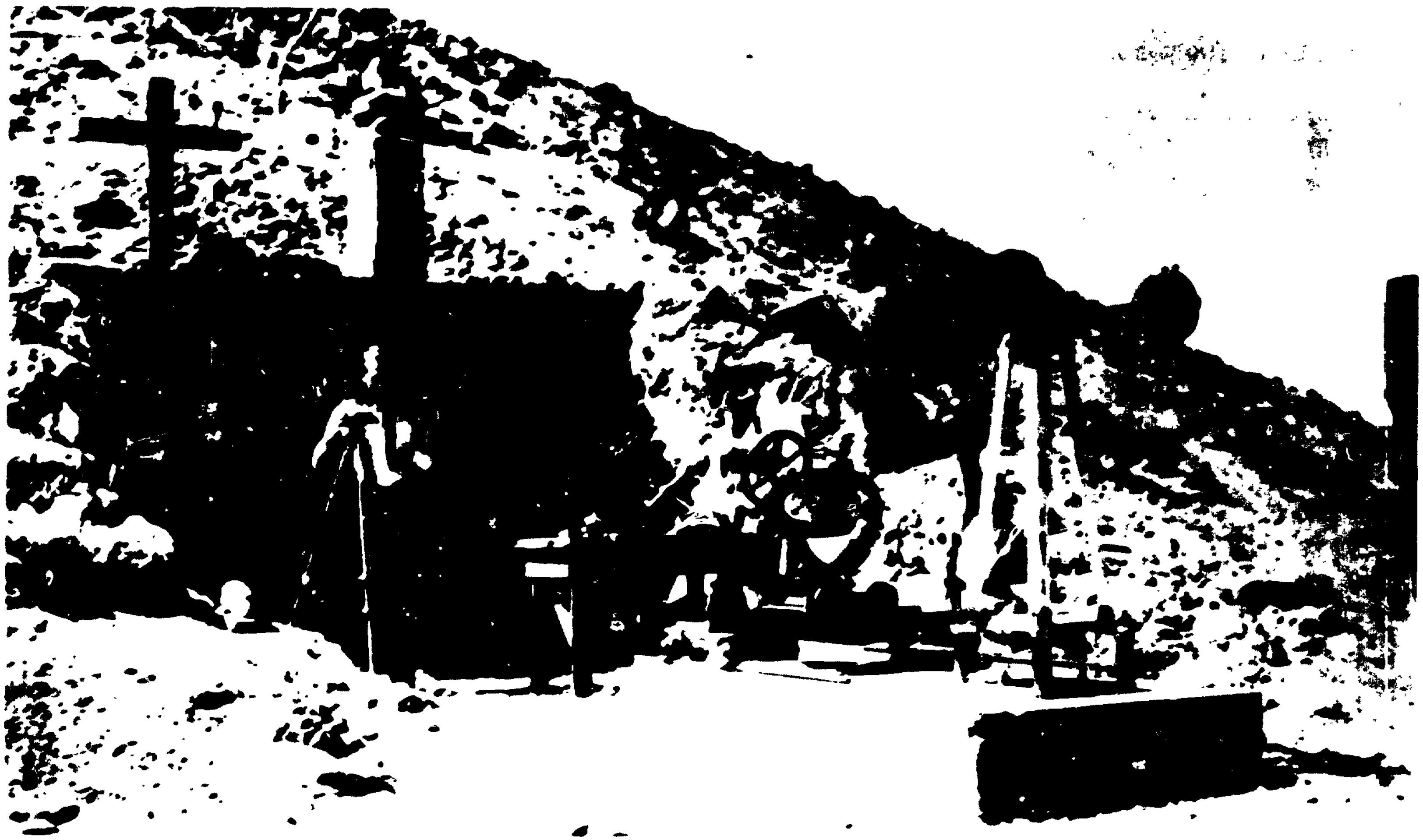


Figure 2. The observing site at Mt. Montezuma Chile. One can see the celeostat reflecting sunlight into the observing tunnel, two silver discs, and a theodolite for obtaining the solar altitude. Courtesy of the Smithsonian Archives.

Figure 3. Celeostat and observing tunnel at Table Mountain. Courtesy of the Smithsonian Archives.

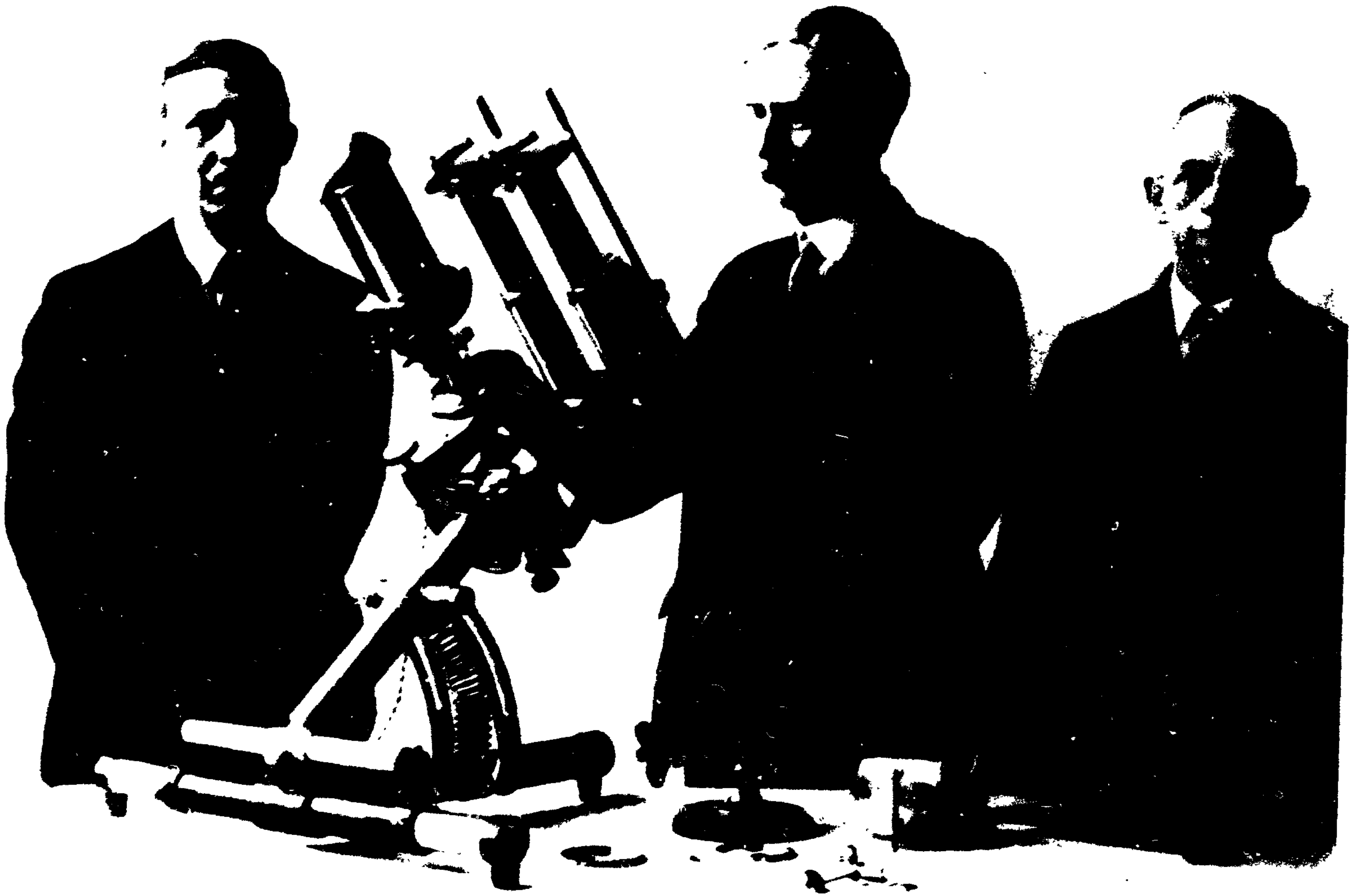


Figure 4. From left to right, L. B. Aldrich, C. G. Abbot, and A. Cramer. Abbot is demonstrating two silver discs and a pyranometer. Courtesy of the Smithsonian Archives.

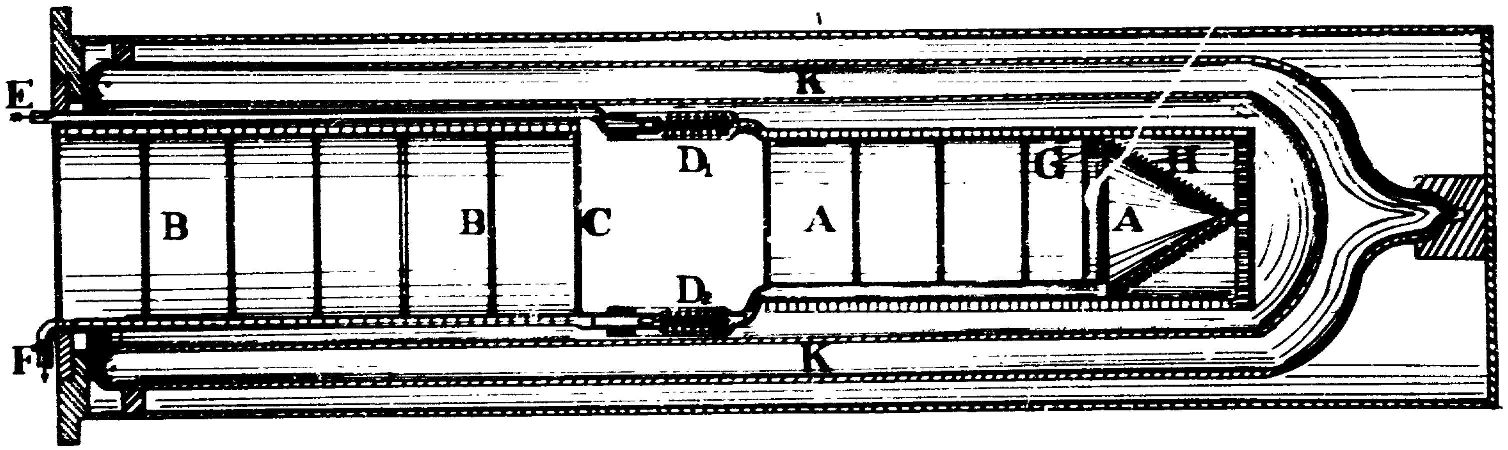
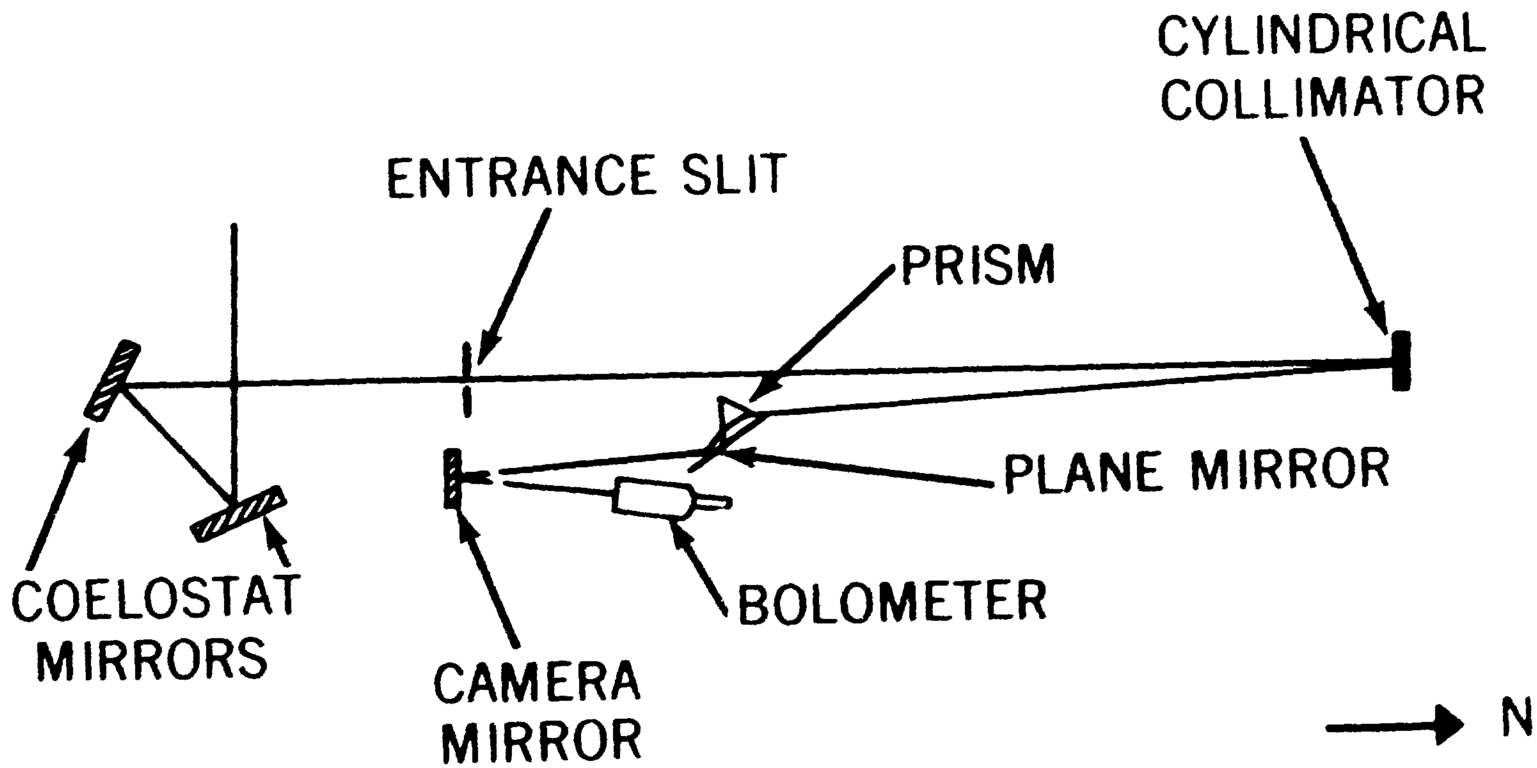


Figure 5. Schematic diagram of the Water Flow Pyrheliometer. Water enters at E and flows out at F. D_1 and D_2 are the platinum strips. Courtesy of the Smithsonian Archives.



SOLAR CONSTANT OBSERVING APPARATUS

Figure 6. Diagram of the spectrobolometer, which was used for determining the atmospheric corrections to the total solar irradiance.

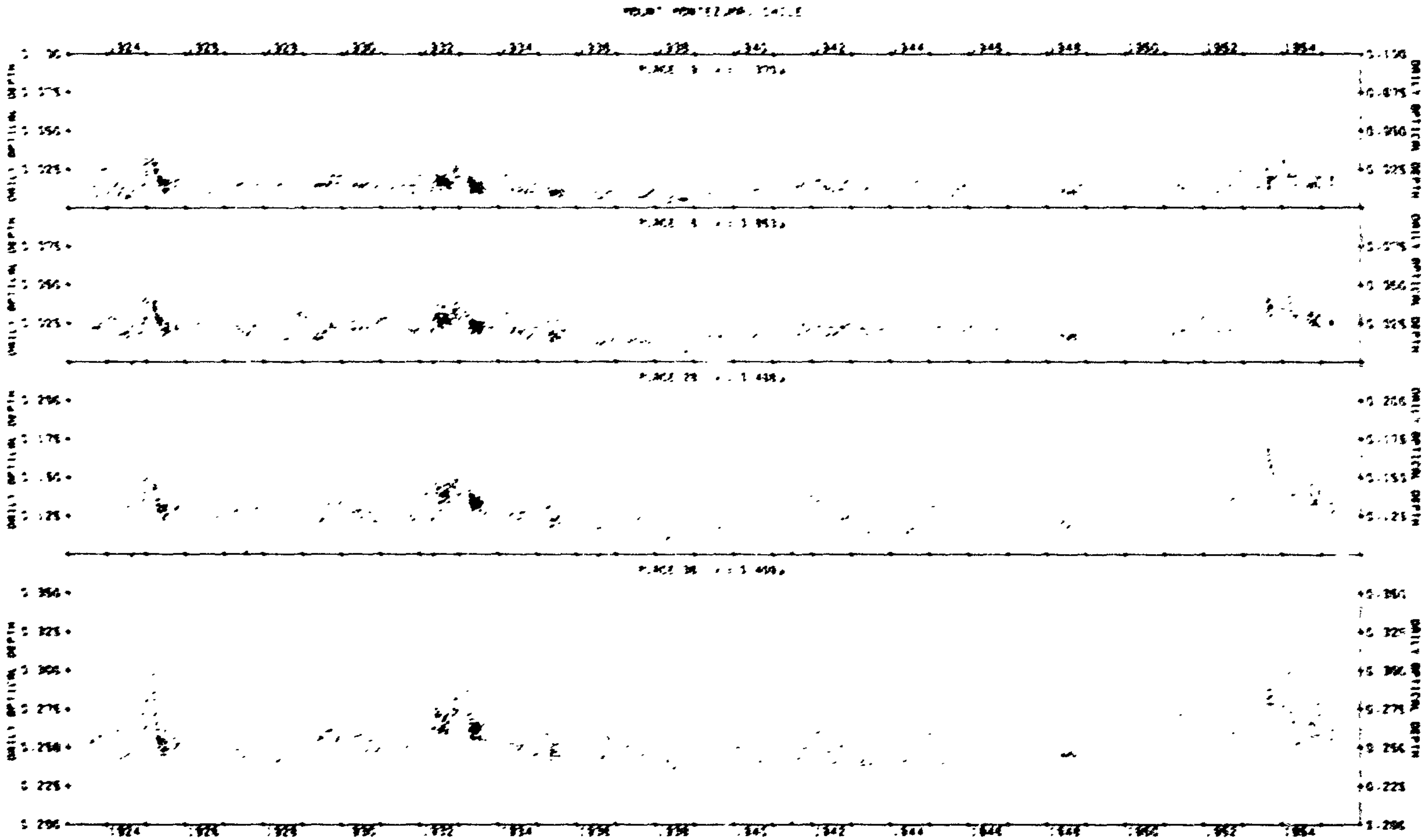


Figure 7. The optical depth at 4 of 34 wavelengths determined by the Smithsonian program at Mt. Montezuma.

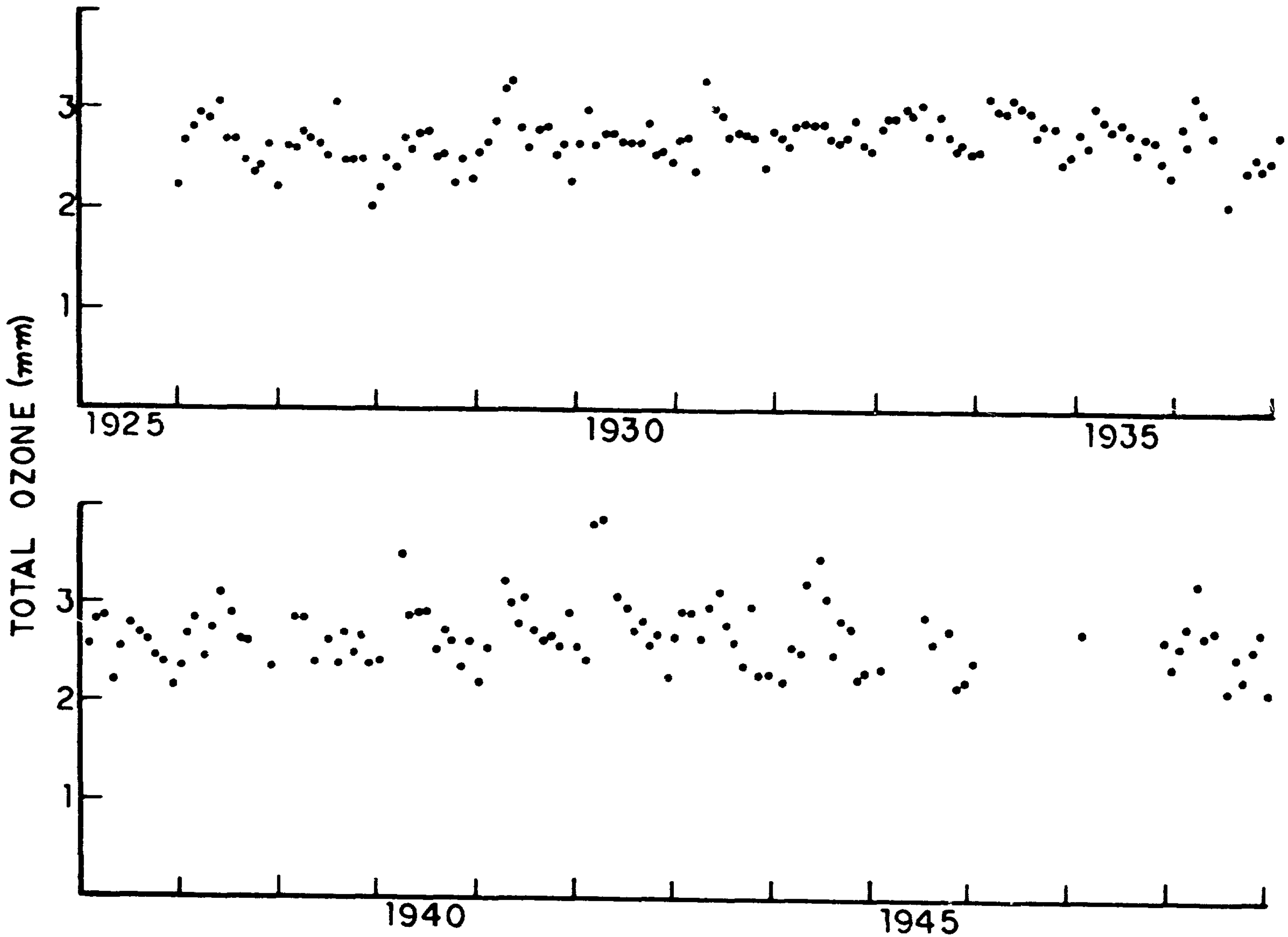


Figure 8. The monthly mean total ozone obtained from the Smithsonian data for Table Mountain. The method uses the absorption by the Chappuis band.

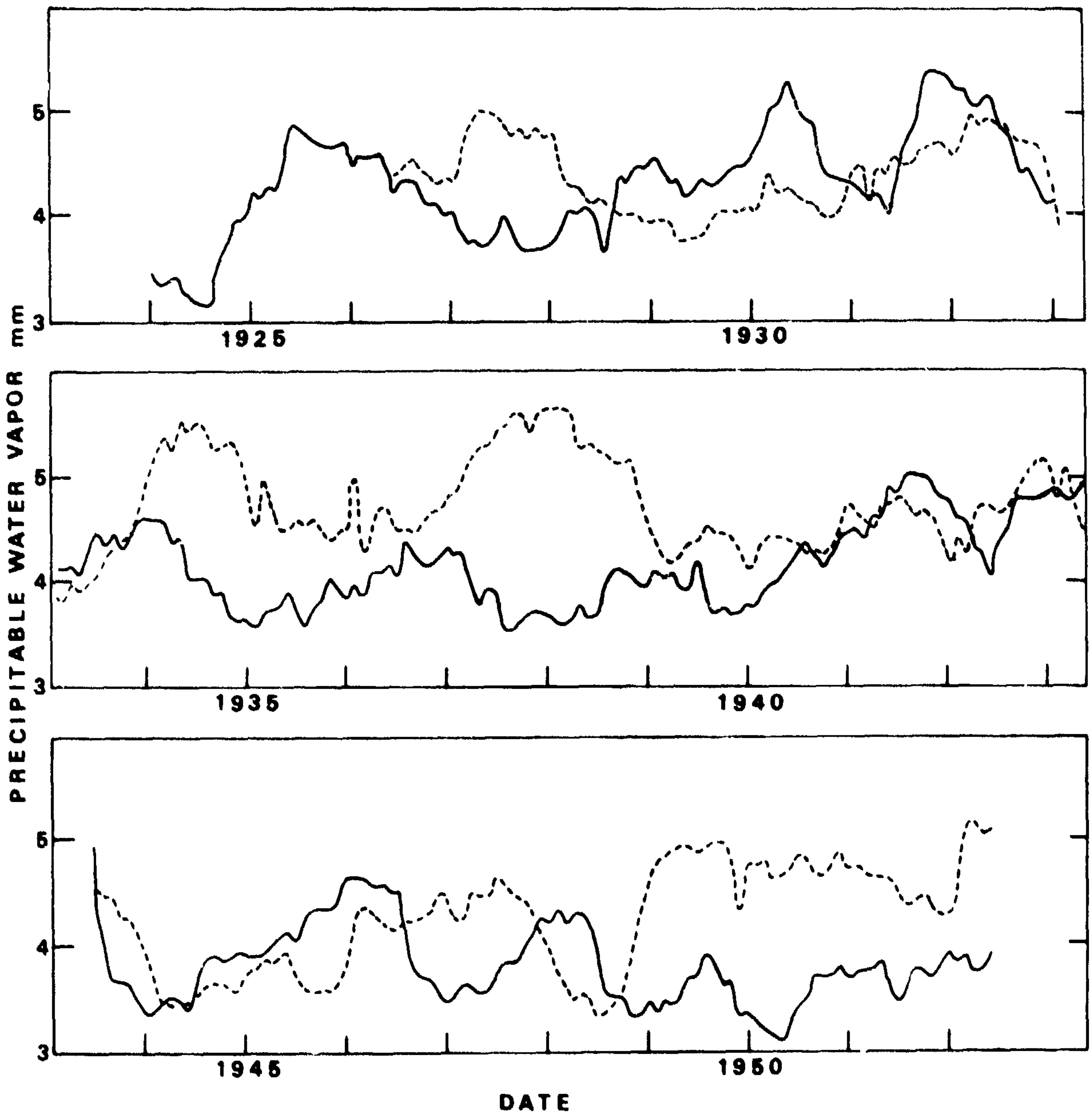


Figure 9. Twelve-month running means of precipitable water vapor at both Mt. Montezuma (solid line) and Table Mountain (dashed line).

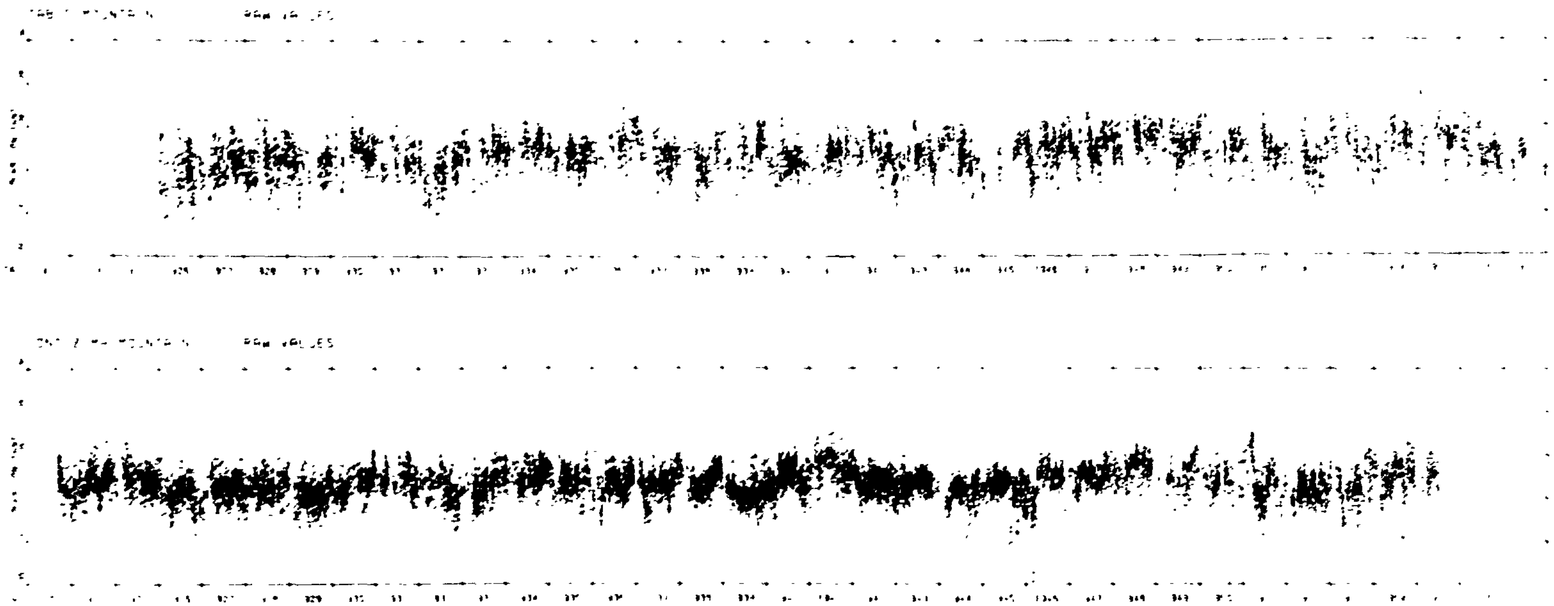


Figure 10. The raw, daily values of the solar constant determined by the Smithsonian program at the two primary sites.

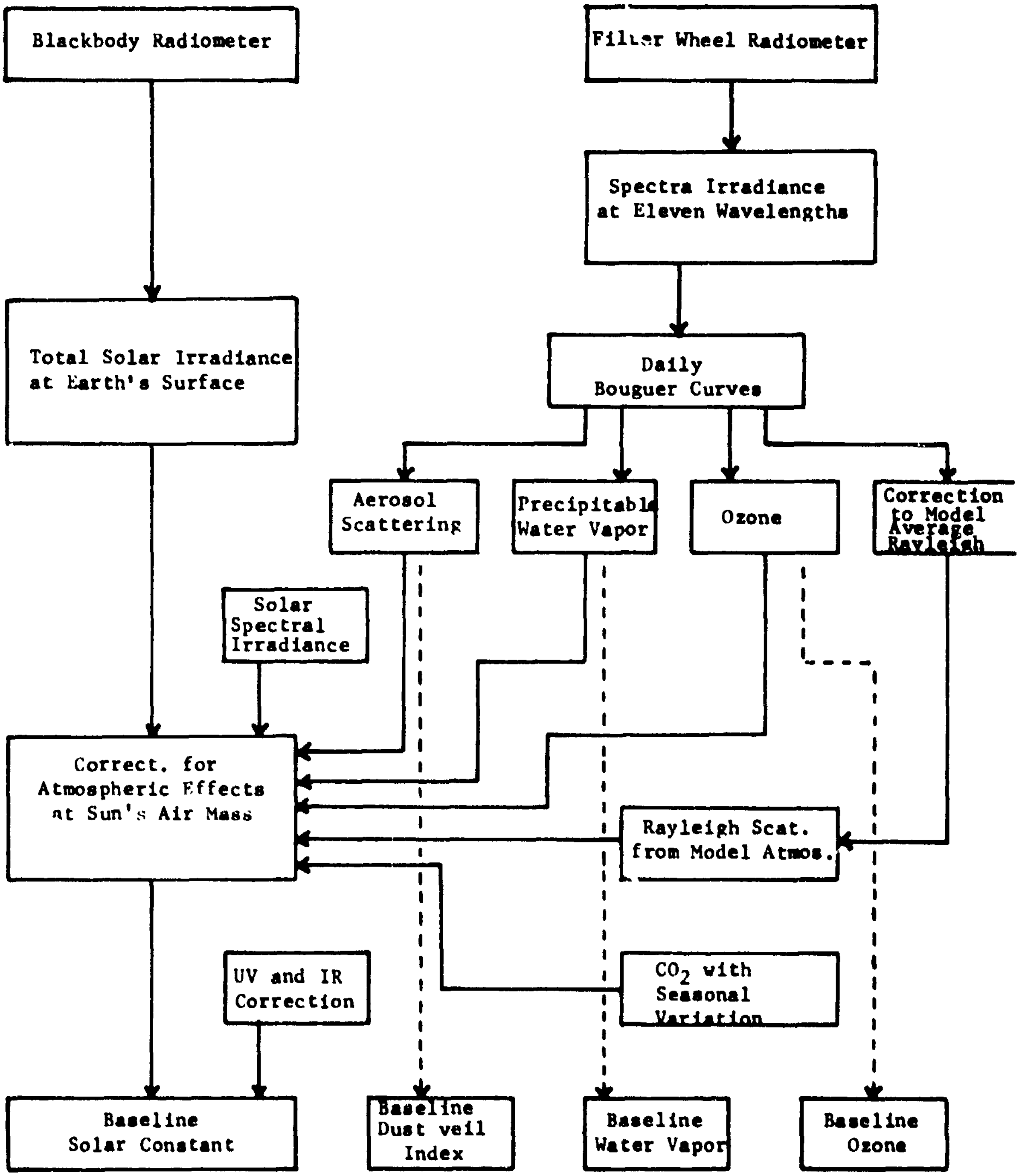


Figure 11. Flow diagram of the solar constant measurement scheme at San Diego State's Mt. Laguna Observatory.