X-912-75-155
PREPRINT

NASA TM X- 70944

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(NASA-TM-X-70944) THE TOTAL AND SPECTRAL SOLAR IRRADIANCE AND ITS POSSIBLE VARIATIONS (NASA) 33 p HC $3.75 CSCL 03B

N75-30988

Unclas

G3/92 34751

JUNE 1975

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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ABSTRACT

The present status of our knowledge of the total and spectral irradiance of the Sun is briefly reviewed. The currently accepted NASA/ASTM standard values of the solar constant and the extraterrestrial solar spectral irradiance are presented along with a discussion of how they were derived. The uncertainties in these values are relatively high. Data on the variability of the solar constant are conflicting and inconclusive. The variability of solar spectral irradiance is almost totally unknown and unexplored. Some of the alleged Sun-weather relationships are cited in support of the need of knowing more precisely the variations in total and spectral solar irradiance. An overview of the solar monitoring program of NASA is presented, with special emphasis on the Solar Energy Monitor in Space (SEMIS) experiment which has been proposed for several of the spacecraft missions. It is a combination of a solar constant detector and a prism monochromator. Measurements from outside the atmosphere are essential for determining the absolute values and the possible variations of the total and spectral solar irradiance.

*Based on a presentation at the Solar Constant Workshop, Big Bear Lake Observatory, Ca, May 19-21, 1975

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1. INTRODUCTION

This gathering is entitled a solar constant workshop, but from the titles of the papers and from this morning's discussion one would think it should rather be entitled a workshop on the solar inconstant. All who have tried to measure it have come up with different values. At the turn of the century, Hann's Handbook of Meteorology published without preference three values of the solar constant, Pouillet's 1230 Wm^{-2}, Ångström's 2717 Wm^{-2} and Langley's 2051 Wm^{-2}. That was indeed a very wide spread of values. The long series of measurements made by C. G. Abbot resulted in values close to 1350 Wm^{-2}. Subsequent to Abott's work and prior to the more recent measurements made from high altitude platforms, two values which were widely accepted were Johnson's 1396 Wm^{-2} and Nicolet's 1380 Wm^{-2}.

2. THE NASA/ASTM STANDARD OF TOTAL AND SPECTRAL SOLAR IRRADIANCE

A listing of the values proposed as a result of measurements made from research aircraft, balloons and spacecraft is given in figure 1. They are grouped according to the three radiation scales to which they are referred, the International Pyrheliometric Scale of 1956, the Absolute Electrical Units Scale and the Thermodynamic Kelvin Temperature Scale. Each of these values is the result of a long series of measurements. The horizontal lines indicate the degree of uncertainty claimed by each author. The principal authors are Kondratyev, Murcray and Drummond for the first three entries, the NASA/GSFC team of the Convair 990 flights for the values from the two Ångström pyrheliometers, the GSFC cone and the Hy-Cal, Plamondon for the JPL Temperature Controlled Flux Monitor (TCFM) and Willson for the JPL Active Cavity Radiometer. Most of these measurements were made from aircraft and balloons. Only one, the JPL, TCFM, was from spacecraft, the Mars Mariner 6 and 7. It would seem that the energy from the Sun has all along been a low priority item for the scientific community and hence for NASA. The late Dr. Abbot used to protest this quite strongly, but his was a lone and weak voice; he was in his nineties when spacecraft technology was sufficiently advanced to make solar irradiance measurements from entirely outside the Earth's atmosphere. The highly absorbent and variable atmosphere had been all along a large source of uncertainty for ground based measurements.

Out of these measurements from high altitude platforms resulted a revised value of the solar constant, 1353 Wm^{-2}. This has been accepted as the design criteria for NASA space vehicles[1] and as the engineering standard of the American Society of Testing and Materials (ASTM).[2] The NASA/ASTM standard includes also values of solar spectral irradiance, which are shown in tabular form in Table I and as a graph in Figure 2. This is based mainly on measurements made by the GSFC CV 990 team who used five large spectral irradiance instruments of different types. Table II gives a listing of the instruments along with the detectors, aircraft window material and wavelength range of each. The spectral curve obtained from the GSFC data was modified slightly in the range 0.3 to 0.7 μm with the aid of the filter radiometer data obtained by the Eppley-JPL team and thus was defined the NASA/ASTM standard. The GSFC measurements covered the spectral range 0.295 to 15.0 μm. For the two extremes in the UV below 0.295 μm which contains one percent of the energy and in the IR above 15 μm which contains 0.02 percent of the energy, other sources of data from Hinteregger,[3] Heath,[4] Parkinson and Reeves,[5] and Shimabukoro and Stacey[6] were used.

Before going on to the inadequacies of the NASA/ASTM standard, a brief mention might be made of some other derived tables which were developed in response to user requests. One of these is the solar spectral irradiance at 1 A intervals for the range 3000 to 6100 A. This is based on the measurements made by the Perkin-Elmer monochromator but normalized to the standard curve.[7] The values in the standard table for this range are at wavelengths 50 A apart, and are averages over 100 A bandwidth centered at those wavelengths. There are also available[8] several tables and graphs for solar irradiance at ground level. Four of these graphs are shown in Figure 3 for air mass 1, 4, 7 and 10. The atmospheric parameters are 20 mm of precipitable water vapor, 3.4 mm of ozone and a rather high value of turbidity. Turbidity or aerosol scattering is expressed by the two Ångström coefficients α and β. The total irradiance when the Sun is at the zenith, air mass one, is 800 Wm^{-2}; the values are naturally lower for greater solar zenith angles. Most of the absorption bands in the infrared are due to water vapor. This is a range where extrapolation to zero air mass from ground based measurements is highly uncertain partly because the water vapor content is variable and partly because the absorbance is not governed by the exponential law. Even at the altitude of CV990 flights where the water vapor in the line of sight is one thousandth of that from the ground, the H_2O bands were found to be a serious correction factor.

Solar spectral irradiance tables and total solar irradiance have been computed for a large variety of parameters of H_2O, O_3, turbidity, altitude above sea level and air mass. The NASA/ASTM standard table and most of the derived tables are available as punched card decks. User organizations can obtain them from the National Space Science Data Center at GSFC.

3. UNCERTAINTIES IN CURRENTLY ACCEPTED VALUES

A closer look at the currently accepted values of the total and spectral irradiance of the Sun outside the atmosphere shows that these values are by no means final and considerably more work needs to be done especially through measurements from spacecraft. The NASA Space Vehicles Design Criteria are reissued periodically; the current edition of Solar Electromagnetic Spectrum first printed in 1971 and since then reprinted twice is a revision of an older monograph of the same title which had presented the Johnson curve. The ASTM Book of Standards is reprinted annually and corrections are introduced as needed. The value 1353 Wm^{-2} is significantly lower than those of Johnson and Nicolet, but rather close to those proposed more recently by Labs and Neckel,[9] Makarova and Kharitonov[10] and Stair and Ellis.[11] And it is close to the earlier Smithsonian value of Abbot. But one observes that it is based on nine values which range between 1338 Wm^{-2} and 1368 Wm^{-2}, and the two extreme values are those which according to the respective authors claim least uncertainty.

The NASA/ASTM value of the solar constant has a stated uncertainty of ±21 Wm^{-2} or ±1.5 percent, which is rather large for an important constant of geophysics and astronomy, when we consider that most other constants like the velocity of light, Planck's constant or electron charge are quoted to an accuracy of a few parts in a million. The uncertainty in the spectral irradiance is considerably greater than in the solar constant itself and varies with the wavelength range. In the visible and near IR the GSFC experimenters used four instruments which did not yield identical spectral curves, though all four instruments used the NBS standards of spectral irradiance for calibration.

There were greater differences between the GSFC data and the Eppley-JPL filter data as shown in Figure 4. Each horizontal line refers to one of the filter channels, the length of the line shows the width of the pass band and the displacement along the y-axis shows the ratio of the irradiance as measured by Eppley-JPL to the energy derived by integrating the earlier GSFC curve[12] over the same pass band. Thus, for example, the filter with low wavelength cut-off at 0.295 μ m gave a value 11% higher than that measured by the GSFC team. The wide scatter of these lines above and below the 1.00 ratio line is rather surprising, especially since both sets of data were based on long series of measurements. The reference radiation scale for Eppley-JPL was the IPS 56 and hence ultimately the AEUS; that for GSFC was the NBS irradiance lamps (1964 scale) which through Planck's equation are traceable to the TKTS. In 1973 the NBS introduced a new scale of spectral irradiance for the wavelength range 0.25 to 1.6 μ m. Comparisons between the two scales show that over most of the range significant downward corrections have to be applied to the 1964 scale especially in the UV and IR. If those corrections are proved genuine and are applied, the scatter of the lines in Figure 4 would be greater, not less. The continuous curve shown close to the 1.00 line gives the ratio by which the GSFC spectral irradiance values were multiplied to derive the NASA ASTM values.

Equally disturbing, if not more so, are the differences between the NASA/ASTM curve and those published earlier. In Figure 5 is shown a comparison with two of the earlier widely used curves, those of F. S. Johnson (upper curve) and of Labs and Neckel (lower curve). The wavelength range is 0.25 to 2.5 μ m. The y-axis gives the ratio of spectral irradiance as a function of wavelength. A normalizing factor has been applied to equalize the area under the curves being compared, so as to show the difference in spectral irradiance independently of that in the solar constant. In the visible range the Johnson values are about 5 percent higher and the Labs and Neckel values are about 10 percent lower than that given by the NASA/ASTM curve. There are larger differences in the IR and UV.

4. SOLAR VARIABILITY, INCONCLUSIVE EVIDENCE

One conclusion that emerges strongly from these different proposed values of the total and spectral irradiance of the Sun is that the accuracy of the measurements is significantly poorer than what should be required for so important a parameter of the physical world and can be expected from state-of-the-art in radiometry. In many of the applications of the solar irradiance values, both total and spectral, a question of major concern is the variability of these values. The changes in the solar irradiance in the UV below 0.3 μm and in the microwave range between 2 cm and 10 m have been well established. As for the solar constant itself the variability is over a smaller range, probably one or two percent, or perhaps less; but the data available in literature do not permit any firm conclusions. A precision considerably better than what is possible for absolute accuracy is required to determine the variability of the total and spectral irradiance of the Sun. Measurements made from sea level and even from mountain tops and research aircraft do not have the required accuracy and precision because of the highly variable atmospheric attenuation and the errors inherent in extrapolation to zero air mass.

The most extensive data on the solar constant are those collected by C. G. Abbot and his coworkers at the Smithsonian Institution. They cover a period of over 50 years. There have been numerous attempts at an analysis of these data to determine whether the solar constant varies with the sunspot number, the magnetic field or any of the other observable features of the Sun. The sunspots have the well known 11 year cycle. In addition there are several other cycles, those of solar rotation, the solar magnetic field, the magnetic sector boundaries, the longer periodicities of 90 years and more. There are also the sporadic and unpredictable events which last for periods from a few minutes to several days.

A few of the major contributions to the analysis of the Smithsonian data for correlation between the sunspot number, N, and the solar constant, E, are given in Table III. The Table lists the authors, the period of the Smithsonian data which they considered, the year of publication, the serial number of the publication in the list of references at the end of this paper and the main conclusions which the authors have derived. This summary statement of the main conclusions does not do full justice to the wealth of information contained in the respective publications. It is obvious that different authors examining the same data come to entirely different conclusions. Reference 20, one of the latest in Abbot's monumental work, is of special interest because it cites a number of observations which at best are puzzling, and gives a complete list of 10 day averages of the solar constant from August 1, 1920 to December 31, 1950.

Three studies which are independent of the Smithsonian data should also be cited. Bossolasco et al[23] made an analysis of ground based measurements at four stations, Uccle (Belgium), Jerusalem (Israel) Krippenstein and Sonnblick (Austria) over the period 1956 to '60 and concluded that E has a pronounced maximum for $N \simeq 160$ and that it decreases by 15 to 17% as N increases to 250 or 300. The decrease of E for low values of N is less clear. Kondratyev[22] attributes this finding to increased atmospheric absorption; there is a close correlation between the nine dates of observations of Bossolasco et al with $N > 250$ and the dates of the U. S. nuclear tests of the 1956-58 period. From the Leningrad balloon data Kondratyev and Nikolsky[22] conclude that E is maximum for $80 < N < 100$ and that there is a decrease of N of 2 to 2.5% for higher and lower N values. They also find that Ångström's analysis made in 1922 had yielded a curve of E versus N of much the same shape and Thekaekara's value of the solar constant based on measurements made in August 1967 when N was 96 is in general agreement with the Leningrad data. The TCFM of JPL[24] was flown on two Mars Mariner Missions in 1969. Data were available on a period of 200 days, but the signals normalized to one astronomical unit showed a steady downward slope, decreasing from 1352.5 Wm^{-2} at launch to 1288 Wm^{-2} at encounter with Mars. The probable cause was instrument drift which could be corrected by making a pitch turn of 100° after encounter and determining the shift in the zero of the instrument. Major conclusions from the TCFM were that there are variations in E of the order of tenths of 1% which are random, that the largest observed variation was 0.4%, and that long term cyclic variations of several percent were not observed.

In 1952 Aldrich and Hoover[16] concluded their paper "The Solar Constant" with the following remark: "There is currently much interest in travel beyond the stratosphere. When this is accomplished, direct measurements of the solar constant, unhampered by an ever-changing and complex atmosphere will follow." Travel beyond the stratosphere is a reality. Apart from the TCFM no attempt has been made from spacecraft to determine whether the solar irradiance, total and spectral, is changing along with all the other observable features of the Sun which are known to be changing. The question is not a new one. The opening paragraph of a paper published in 1966 by C. G. Abbot, Solar Variation, a

Weather Element,[25] is well worth quoting: "The eminent astronomer Dr. Samuel Pierpoint Langley, third secretary of the Smithsonian Institution, at Dr. George E. Hale's invitation, sent me to Mt. Wilson Observatory in 1905 to observe the radiation of the Sun. Langley suspected that this might be variable, and that its variation might be a cause of weather changes. If the suspected solar variations proved periodic, they might lead to long-range weather forecasts of great value to agriculture and water supply."

While there a great deal in literature about changes in the solar constant and their effects on weather, a great deal that is conflicting and inconclusive, there is hardly any mention of changes in the spectral distribution in the visible and near IR where the energy output of the Sun is the greatest. The reason is not that changes do not exist, but that they are totally unknown and unexplored. Almost all solar energy effects on the atmosphere and the Earth are wavelength dependent. Localized radiation balance and the transport of large masses of air, increase of atmospheric pollution and its sink mechanisms, the making of weather and climate and the numerical modelling required for predicting weather, changes in ozone and their erythemal effects on humans, all depend on some limited portions of the solar spectrum more than on others. The atmosphere is far from being a neutral density filter, nor is the land and ocean surface of the Earth a grey absorber. The Earth albedo spectrum is very different from the solar spectrum. Ozone production is due to solar UV. Chlorophyll photosynthesis essential for all life support is due to wavelength bands centered around 450 and 650 nm, with half-intensity bandwidths of about 30 nm. Other resonance phenomena are photomorphogenic responses like seed and flower development, shape and size of leaves, plant height, leaf movements as in mimosa, phototropism; the associated wavelengths are nearly the same, but with slightly greater bandwidths. Absorption by water vapor with all its major effects on the making of weather is in narrow-wavelength bands, all beyond 700 nm which is the more poorly known part of the spectrum. If the solar constant is shown to be changing, we would want to know what spectral ranges are causing this change. Nor there is any reason to assume that the changes in solar spectral irradiance over limited wavelength bands are as small as in the solar constant itself.

5. RELATION TO TERRESTRIAL PHENOMENA

If it is known with sufficiently high precision what are the changes in solar radiant flux, in what wavelength ranges and with what periodicities, that would provide a solution to many intriguing correlations which have been observed between solar activity and terrestrial phenomena. Among such phenomena are wintriness index of northern hemisphere sea level pressure, the annual march of temperature of different cities of Europe, the changes in meridional sea level pressure, the annual frequency of Etesian winds over Greece. Thus, for example, the number of days per year when Etesian winds, winds from the NE and NNE as opposed to sea breeze, blew over Athens in the period 1893 to 1961 followed the same trends of maxima and minima as the annual mean sunspot numbers. The geomagnetic disturbances have a periodicity of 27 days superposed on an 11-year period. Long period correlations have been observed in such weather related phenomena as the water level in rivers and lakes, annual growth rings of petrified and living trees, the advance and retreat of glaciers, the frequency of lightning strikes on the electrical power grid, the annual rainfall in different locations. In 1953 Brooks and Carruthers observed: "There is a correlation coefficient of +0.88 between the number of thunderstorms recorded in Siberia and the annual mean sunspot relative number. Since it is inconceivable that thunderstorms in Siberia cause sunspots, it is reasonable to assume that sunspots or some other solar phenomenon associated with sunspots cause thunderstorms." The literature on this subject is voluminous and it must also be stated that there are serious investigators who fail to see the correlations or their significance. In a recent review article J. W. King [26] has brought together a large mass of data on Sun-weather relationships. He says: "Even the most sceptical scientist who investigates the literature thoroughly will be forced to concede that important aspects of lower atmosphere behavior are associated with solar phenomena ranging from short-lived events such as solar flares, through 27-day solar rotations to the 11-year, 22-year, and even longer solar cycles. The complicated pattern of Sun-weather relationships undoubtedly needs much further clarification, but progress in this field will be hindered if the view prevails that such relationships should not be taken seriously simply because the mechanisms involved in explaining them are not yet identified." If these Sun-weather relationships are proved to be genuine, an essential factor in finding the mechanisms involved is the precise determination of the variations, if any, in total and spectral solar irradiance.

6. PROPOSED MEASUREMENTS FROM SPACECRAFT, SEMIS

In view of the above discussion it would seem to be of the utmost importance to measure the total and spectral irradiance of the Sun from outside the atmosphere. What is needed is an instrument or a complex of instruments on a satellite to monitor the solar flux almost continuously and over a long period of time with sufficiently high accuracy and precision and adequate spectral resolution. Several instruments are being developed or are in the planning stage in the NASA program; they are mainly for the solar constant. Table IV gives an overview of the NASA solar monitoring program; it was prepared by the Meteorology Program Office of NASA/GSFC. Some of the instruments listed here have been documented extensively. The first on the list is the Earth Radiation Budget (ERB) experiment of NIMBUS-F, a spacecraft which was launched on June 12, 1975. It has 10 solar viewing channels. The spacecraft has a Sun-synchronous, high noon, near polar track (81° inclination) orbit. The ERB experiment views the Sun when the spacecraft is over the South Pole, just before it starts the northward trip on the daylight side of the Earth. The spectrum is measured mainly by five interference filter channels in the wavelength ranges (units in nm) of 250-300, 280-350, 300-400, 350-450 and 400 to 500. The experiment has just been turned on as this is being written.

Two other instruments, the ESP and the SCSD, also plan to use interference filters with wide-band resolution similar to that of ERB.

We shall discuss here in little more detail an instrument, the Solar Energy Monitor In Space, SEMIS, with which our group at GSFC is more directly concerned.

It is a combination of a total irradiance detector and a prism monochromator. This is the only proposed experiment with adequate spectral resolution over the entire wavelength range. An optical schematic of the SEMIS is shown in Figure 6. The total irradiance detector is either a thermopile of the type used in ERB or an absolute radiometer, the GSFC cone radiometer, similar in principle to the ACR and PACRAD. The SEMIS is designed to be a compact, light-weight, low data rate instrument which can be readily accommodated on a large variety of spacecraft missions. One model of the instrument has been built and been used extensively for monitoring the solar simulation in space environment simulators at GSFC. Another model has been built for aircraft use; it will be flying piggyback on all routine missions of the NASA-U-2 aircraft at an altitude of 20 km. It will start gathering solar data in the fall of 1975. The wavelength range of the spacecraft model is from less than 0.2 μm to over 40 μm for the total irradiance detector and from 0.25 μm to 2.6 μm for the prism monochromator. Over 99.99 percent of the Sun's energy is contained in the wavelength rage of the total irradiance detector. The monochromator has quartz optics so that 0.2% of the energy in the UV and 3.3% of the energy in the IR will not be spectrally scanned. An added reason for limiting the spectral range is that spectral irradiance standards of sufficient accuracy are not available outside this range. The bandwidth or spectral resolution varies with the spectral range and slitwidth. Representative values for a slitwidth of 0.1 mm are 0.0012 μm at 0.25 μm, 0.01 μm at 0.6 μm and 0.05 μm at 2.6 μm. The value of $\lambda/\Delta\lambda$ varies between 200 and 50. The wavelength resolution is not as high as can be obtained with a large monochromator with double prism or grating as the dispersing element, but is adequate for monitoring solar spectral variability. Larger instruments can be located on the ground or on aircraft and their absolute spectral irradiance levels can be determined from the spacecraft instrument. For studying the variability of solar flux it is essential that identical instruments be flown on several missions spanning a complete solar cycle of 11 or 22 years. Hence the SEMIS has been designed to be small in size and weight; it can fly on a non-interfering basis on most spacecraft missions. The experiment has been proposed for Landsat, Solar Maximum Mission, Applications Explorer Mission and the Space Shuttle. The Space Shuttle provides the advantage of retrieving the package for recalibration after flight. The Solar Maximum Mission provides a spacecraft which unlike those of applications area is pointed towards the Sun. The accuracy goal for the solar constant detector is between 0.5 and 0.1%. For spectral irradiance the accuracy will be close to that of the NBS standards of spectral irradiance, that is, between 2 and 5 percent, depending on the wavelength range. The precision or repeatability will be considerably better than the absolute accuracy. Precision rather than absolute accuracy is what is required for monitoring solar variability. There are a few internal and external checks for the degradation, if any, of the spacecraft instrument. The solar constant monitor and the prism monochromator provide a mutual check, since the integral of the spectral curve is the solar constant. There is also the well-known variation of ±3.5% with the ellipticity of the Earth's orbit. An external check is provided by the SEMIS on U-2 which during flight is above 95% of the Earth's atmosphere and above nearly half of the ozone and which can be recalibrated periodically on the ground.

7. CONCLUSION

There is a renewed interest in the measurement of solar radiant flux, both total and spectral. The current energy crisis and the possibility of direct conversion of solar energy for man's use is one of the reasons. Another is a new awareness that solar variability may be one of the most important parameters for prediction of weather and climate. Nor can it be ignored that solar energy is part of solar physics. Modelling of the Sun's atmosphere and the Sun's interior, determining whether the Sun is a variable star, explaining the departure at certain wavelengths of the solar spectrum from that of an equivalent blackbody, the dependence of the energy output or the lack of it on variable solar phenomena like sunspots and faculae and the many known solar periodicities, all these can benefit from an accurate knowledge of the total and spectral solar irradiance. The Sun is the nearest star, the only one about which detailed direct measurements are possible at present. Ground based measurements of solar flux are necessary and will continue to be made. Though they yield more information about the Earth's atmosphere than about the Sun itself, they are an essential complement to the data from spacecraft instruments which at present are necessarily much simpler than those on the ground. A great deal more can be expected from the Space Shuttle which will be operational in the 80's. With few constraints on weight, size and power, with man in the loop, with long observing periods, a considerably greater accuracy and precision can be expected in the measurement of the total and spectral irradiance of the Sun.

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SOLAR CONSTANT ON DIFFERENT RADIATION SCALES

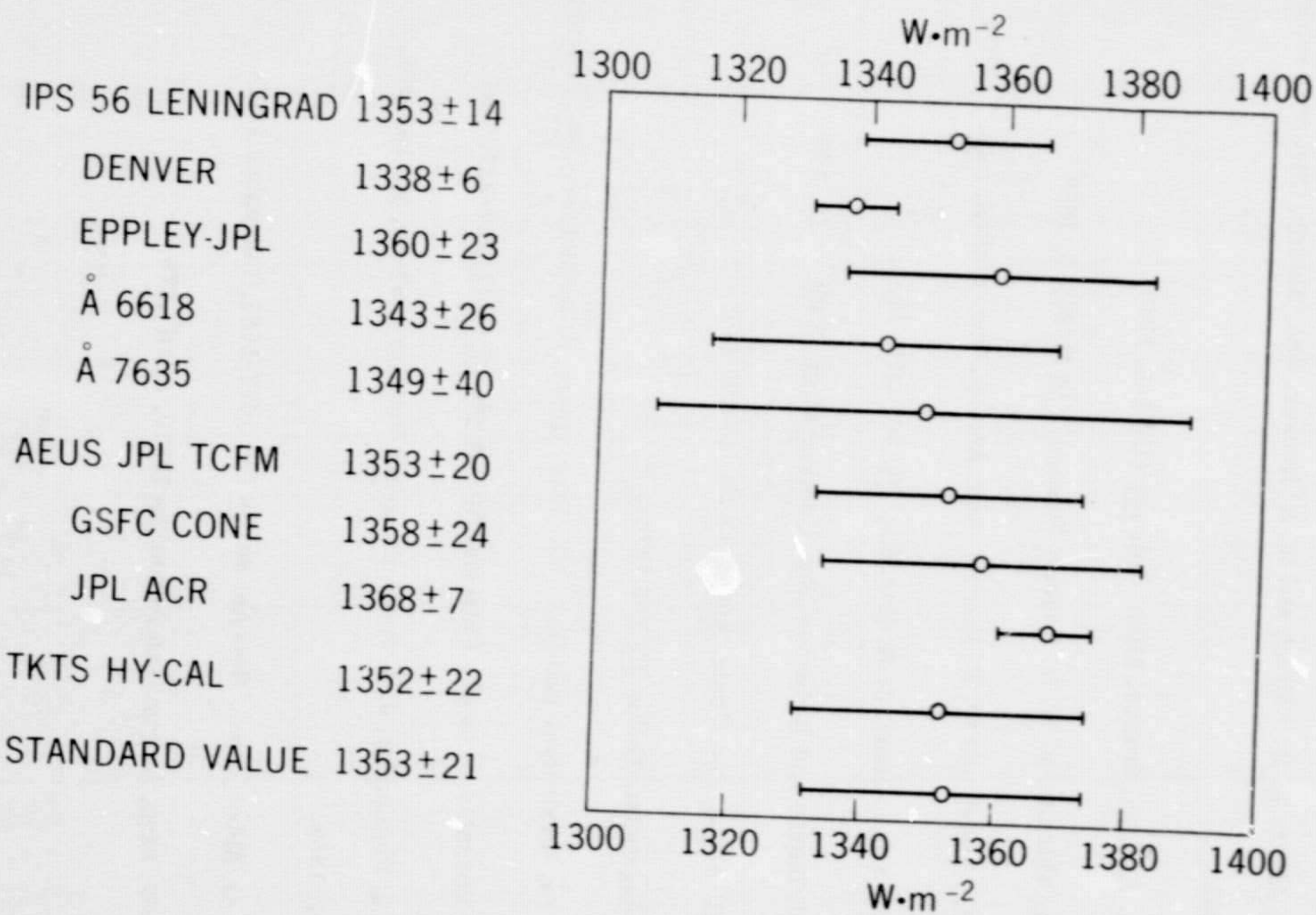

Figure 1. Values of solar constant derived from high altitude measurements

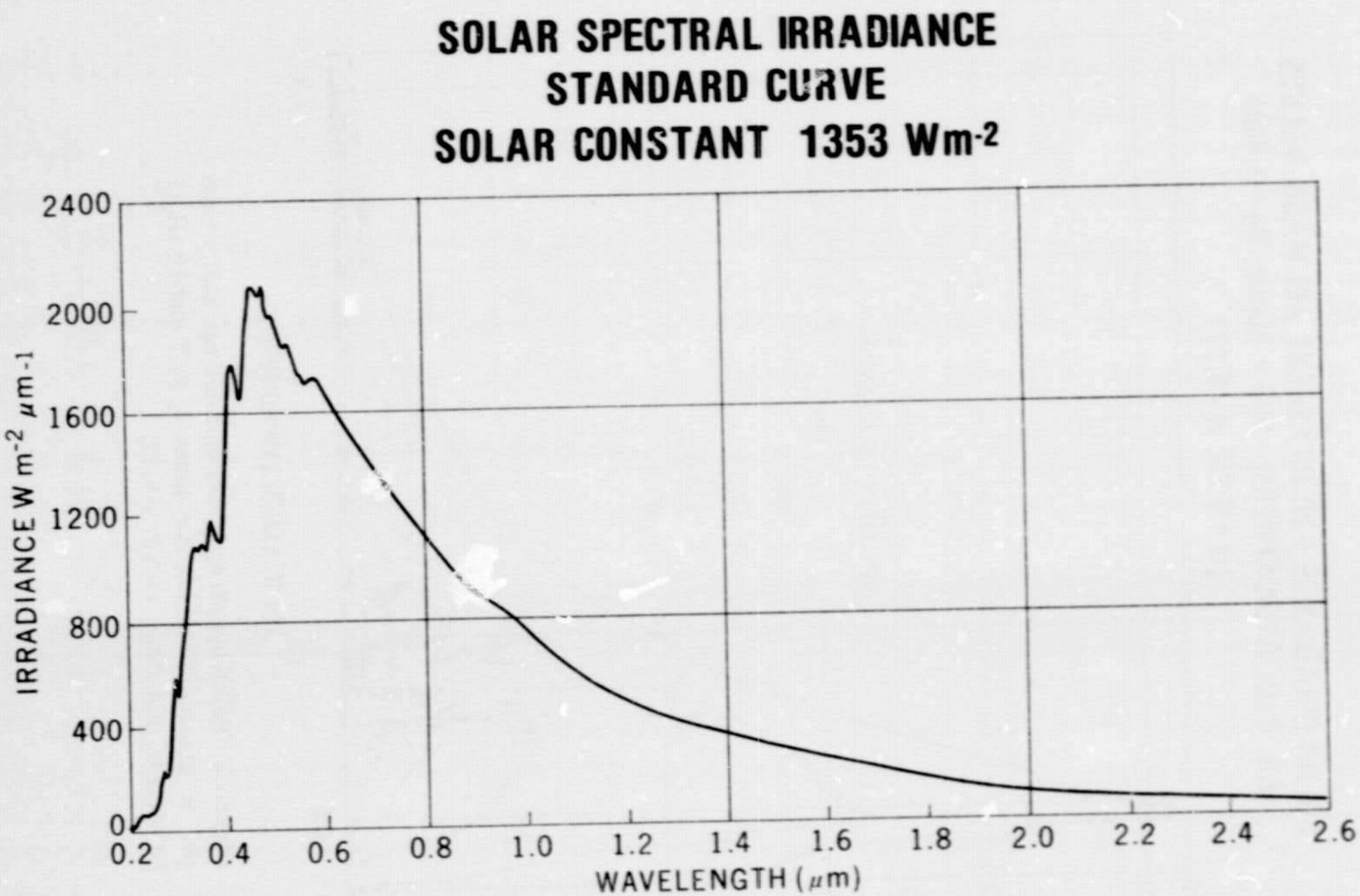

Figure 2. The NASA/ASTM standard curve of extraterrestrial solar spectral irradiance

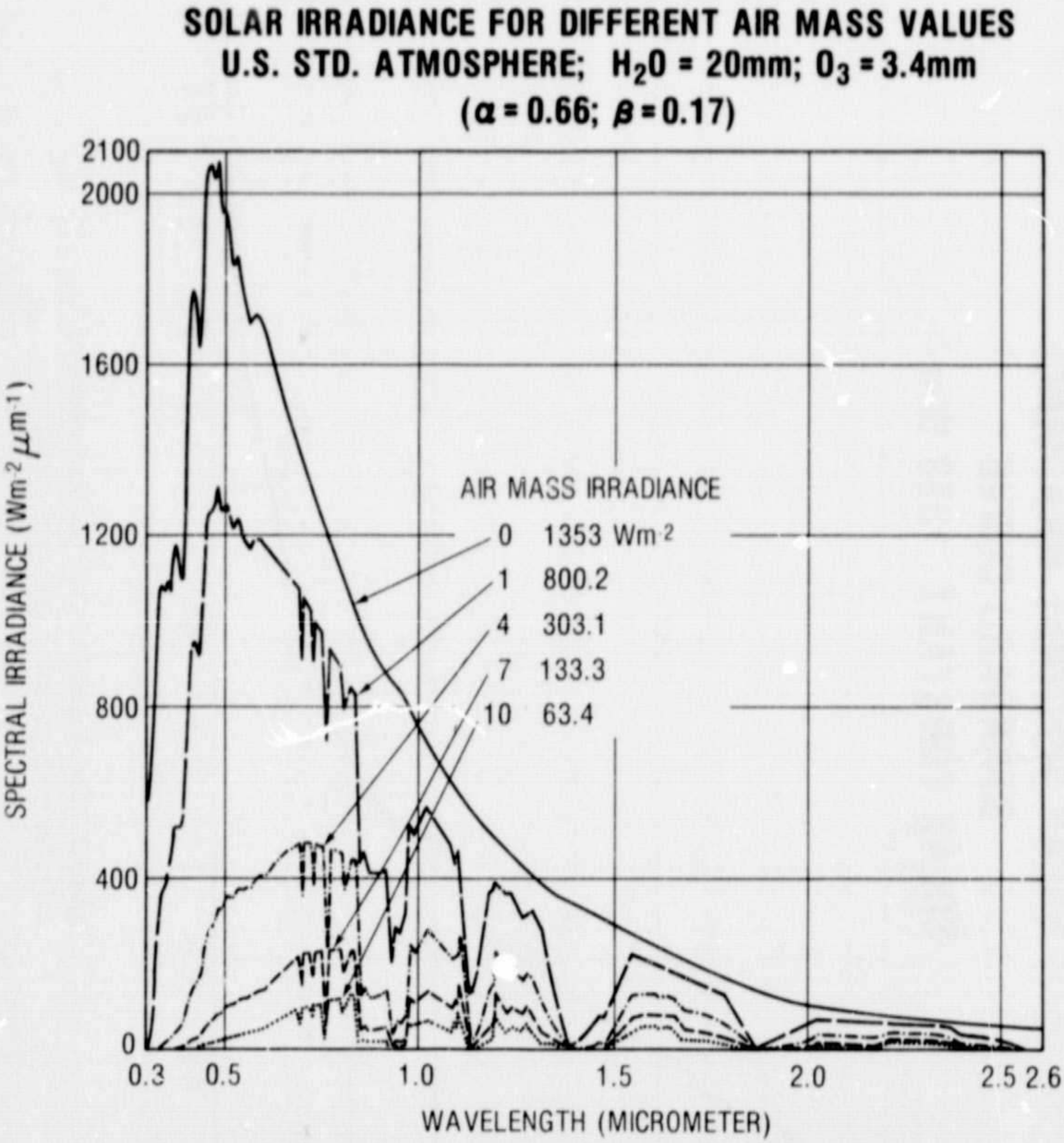

Figure 3. Solar spectral irradiance for air mass zero and at ground level for air mass 1, 4, 7 and 10 (H_2O 20 mm; O_3 3.4 mm; α 0.66; β 0.17)

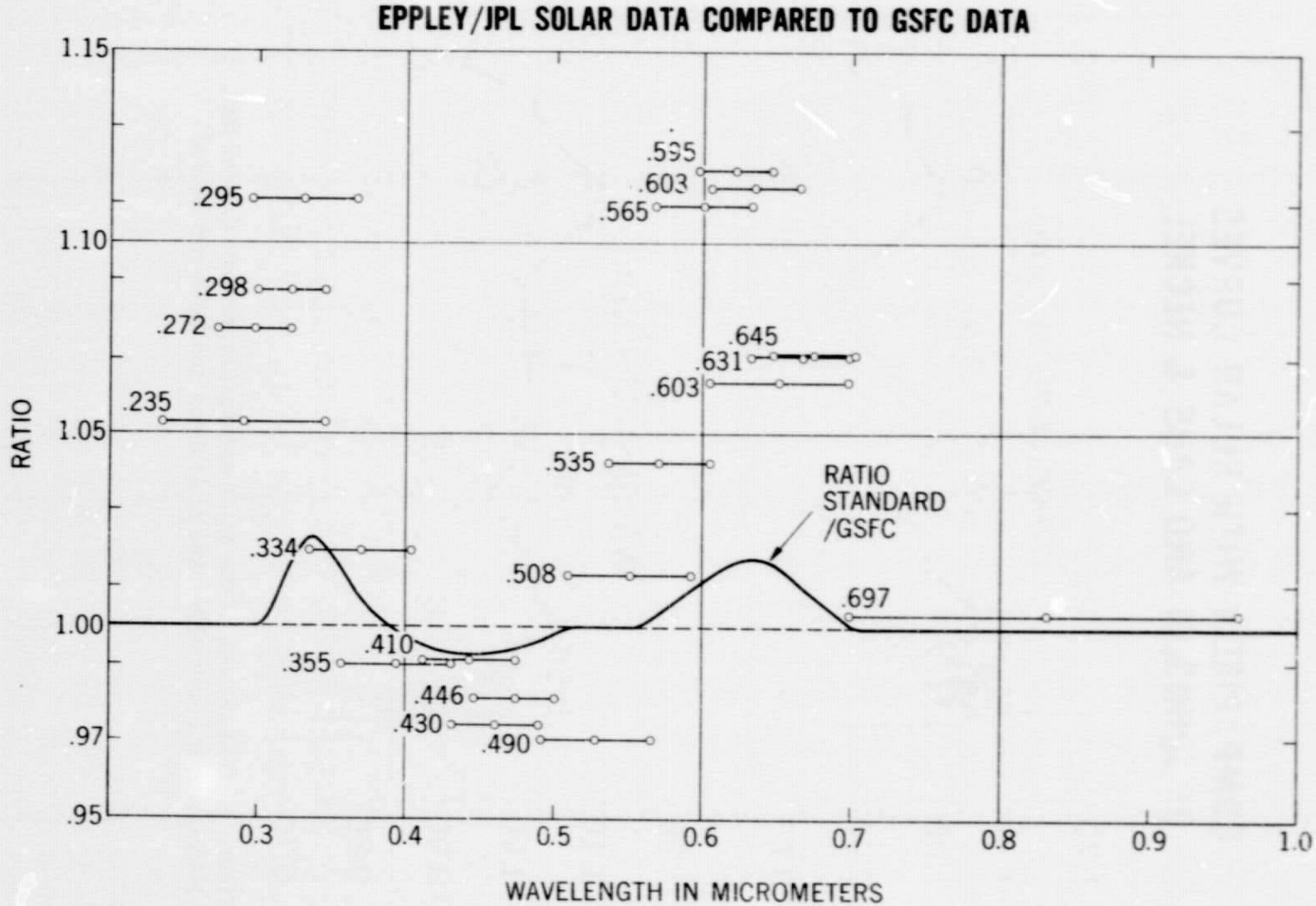

Figure 4. Comparison of Eppley JPL solar irradiance filter data with the GSFC CV990 monochromator spectral data

COMPARISON WITH SOLAR CURVES OF JOHNSON AND LABS & NECKEL

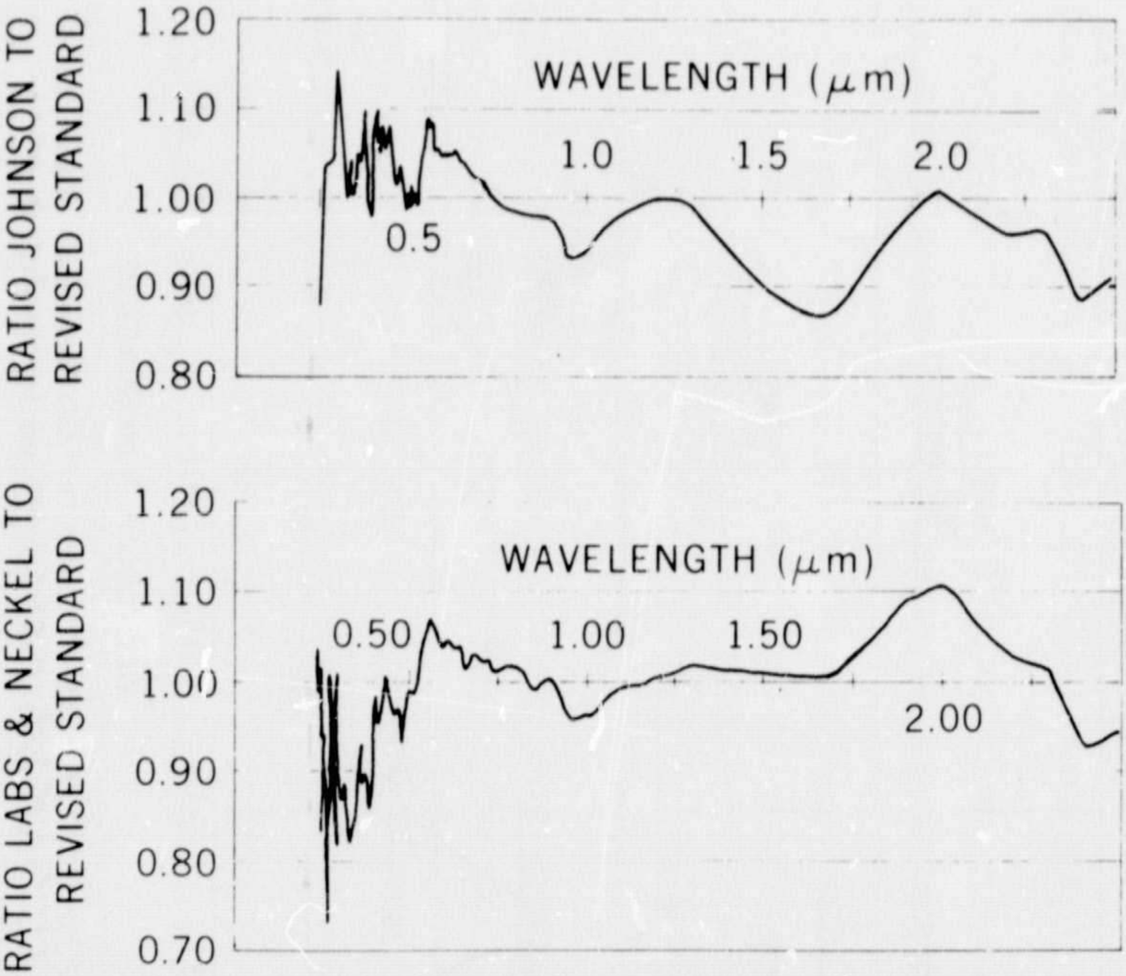

Figure 5. Comparison of the solar spectral irradiance data of the NASA/ASTM curve with those of Johnson and Labs and Neckel

SEMIS

OPTICAL SCHEMATIC OF THE INSTRUMENT

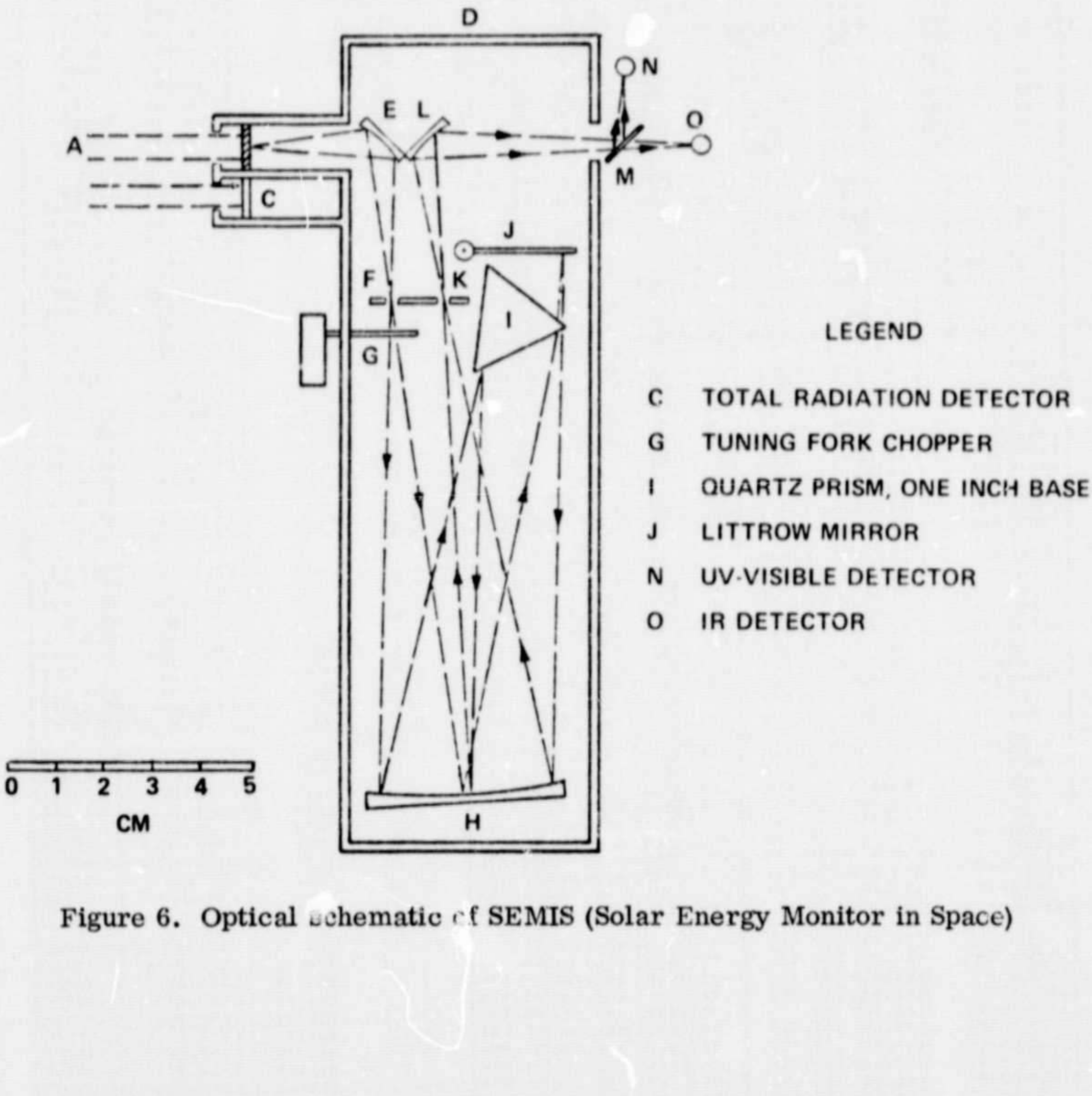

Figure 6. Optical schematic of SEMIS (Solar Energy Monitor in Space)

Table I
Solar Spectral Irradiance – Standard Curve

λ – Wavelength in micrometers

E_λ – Solar spectral irradiance averaged over small bandwidth centered at λ, in W m^{-2} μm^{-1}

$E_{o-\lambda}$ – Integrated solar irradiance in the wavelength range o to λ, in W m^{-2}

$D_{o-\lambda}$ – Percentage of solar constant associated with wavelengths shorter than λ

Solar constant = 1353 W m^{-2}

Note: lines indicate change in wavelength interval of integration

λ	E_λ	$E_{o-\lambda}$	$D_{o-\lambda}$	λ	E_λ	$E_{o-\lambda}$	$D_{o-\lambda}$	λ	E_λ	$E_{o-\lambda}$	$D_{o-\lambda}$
.115	.007	.0025	.0001	.510	1882	324.926	24.015	1.55	267	1186.109	87.665
.120	.900	.0048	.0003	.515	1823	334.214	24.701	1.60	245	1198.909	88.611
.125	.007	.0070	.0005	.520	1833	343.379	25.379	1.65	223	1210.609	89.475
.130	.007	.0071	.0005	.525	1852	352.591	26.059	1.70	202	1221.234	90.261
.140	.030	.0073	.0005	.530	1842	361.826	26.742	1.75	180	1230.784	90.967
.150	.070	.0078	.0005	.535	1818	370.976	27.418	1.80	159	1239.259	91.593
.160	.230	.0093	.0006	.540	1783	379.979	28.084	1.85	142	1246.784	92.149
.170	.630	.0136	.0010	.545	1754	388.821	28.737	1.90	126	1253.484	92.644
.180	1.250	.0230	.0016	.550	1725	397.519	29.380	1.95	114	1259.484	93.088
.190	2.710	.0428	.0031	.555	1720	406.131	30.017	2.00	103	1264.909	93.489
.200	10.7	.1098	.0081	.560	1695	414.669	30.648	2.1	90	1274.559	94.2024
.210	22.9	.2778	.0205	.565	1705	423.169	31.276	2.2	79	1283.009	94.8269
.220	57.5	.6798	.0502	.570	1712	431.711	31.907	2.3	69	1290.409	95.3739
.225	64.9	.9858	.0728	.575	1719	440.289	32.541	2.4	62	1296.959	95.8580
.230	66.7	1.3148	.0971	.580	1715	448.874	33.176	2.5	55	1302.809	96.2903
.235	59.3	1.6298	.1204	.585	1712	457.441	33.809	2.6	48	1307.959	96.6710
.240	63.0	1.9356	.1430	.590	1700	465.971	34.439	2.7	43	1312.509	97.0073
.245	72.3	2.2738	.1680	.595	1682	474.426	35.064	2.8	39	1316.609	97.3103
.250	70.4	2.6306	.1944	.600	1666	482.796	35.683	2.9	35	1320.309	97.5838
.255	104.0	3.0666	.2266	.605	1647	491.079	36.295	3.0	31	1323.609	97.8277
.260	130	3.6516	.269	.61	1625	499.284	36.902	3.1	26.0	1326.459	98.0383
.265	185	4.4391	.328	.62	1602	515.469	38.098	3.2	22.6	1328.889	98.2179
.270	232	5.4816	.405	.63	1570	[illegible]	39.270	3.3	19.2	1330.979	98.3724
.275	204	6.5716	.485	.64	1544	546.899	40.421	3.4	16.6	1332.769	98.5047
.280	222	7.6366	.564	.65	1511	562.174	41.550	3.5	14.6	1334.329	98.6200
.285	315	8.9791	.663	.66	1486	577.159	42.657	3.6	13.5	1335.734	98.7238
.290	482	10.9716	.810	.67	1456	591.869	43.744	3.7	12.3	1337.024	98.8192
.295	584	13.6366	1.007	.68	1427	606.284	44.810	3.8	11.1	1338.194	98.9056
.300	514	16.3816	1.210	.69	1402	620.429	45.855	3.9	10.3	1339.264	98.9847
.305	603	19.1741	1.417	.70	1369	634.284	46.879	4.0	9.5	1340.254	99.0579
.310	689	22.4041	1.655	.71	1344	647.849	47.882	4.1	8.70	1341.1641	99.12521
.315	764	26.0366	1.924	.72	1314	661.139	48.864	4.2	7.80	1341.9891	99.18618
.320	830	30.0216	2.218	.73	1290	674.159	49.826	4.3	7.10	1342.7341	99.24124
.325	975	34.5341	2.552	.74	1260	686.909	50.769	4.4	6.50	1343.4141	99.29150
.330	1059	39.6191	2.928	.75	1235	699.384	51.691	4.5	5.92	1344.0351	99.33740
.335	1081	44.9691	3.323	.76	1211	711.614	52.595	4.6	5.35	1344.5986	99.37905
.340	1074	50.3566	3.721	.77	1185	723.594	53.480	4.7	4.86	1345.1091	99.41678
.345	1069	55.7141	4.117	.78	1159	735.314	54.346	4.8	4.47	1345.5757	99.45127
.350	1093	61.1191	4.517	.79	1134	746.779	55.194	4.9	4.11	1346.0049	99.48299
.355	1083	66.5591	4.919	.80	1109	757.994	56.023	5.0	3.79	1346.3999	99.51219
.360	1068	71.9366	5.316	.81	1085	768.966	56.834	6	1.8200	1349.2049	99.71950
.365	1132	77.4366	5.723	.82	1060	779.694	57.627	7	.9900	1350.6099	99.82335
.370	1181	83.2191	6.150	.83	1036	790.174	58.401	8	.5850	1351.3974	99.88155
.375	1157	89.0641	6.582	.84	1013	800.419	59.158	9	.3670	1351.8734	99.91673
.380	1120	94.7566	7.003	.85	990	810.434	59.899	10	.2410	1352.1774	99.93920
.385	1098	100.3016	7.413	.86	968	820.224	60.622	11	.1650	1352.3804	99.95420
.390	1098	105.7916	7.819	.87	947	829.799	61.330	12	.1170	1352.5214	99.96462
.395	1189	111.5091	8.241	.88	926	839.164	62.027	13	.0851	1352.6224	99.97209
.400	1429	118.0541	8.725	.89	908	848.334	62.700	14	.0634	1352.6967	99.97758
.405	1644	125.7366	9.293	.90	891	857.329	63.365	15	.0481	1352.7524	99.98170
.410	1751	134.224	9.920	.91	880	866.184	64.019	16	.037100	1352.7950	99.98485
.415	1774	143.036	10.571	.92	869	874.929	64.665	17	.029100	1352.8281	99.98730
.420	1747	151.839	11.222	.93	858	883.564	65.304	18	.023100	1352.8542	99.98923
.425	1693	160.439	11.858	.94	847	892.089	65.934	19	.018600	1352.8751	99.99077
.430	1639	168.769	12.473	.95	837	900.509	66.556	20	.015200	1352.8920	99.99202
.435	1663	177.024	13.083	.96	820	908.794	67.168	25	.006170	1352.9454	99.99596
.440	1810	185.706	13.725	.97	803	916.909	67.768	30	.002970	1352.9683	99.99765
.445	1922	195.036	14.415	.98	785	924.849	68.355	35	.001600	1352.9797	99.99850
.450	2006	204.856	15.140	.99	767	932.609	68.928	40	.000942	1352.9860	99.99897
.455	2057	215.014	15.891	1.00	748	940.184	69.488	50	.000391	1352.9927	99.99946
.460	2066	225.321	16.653	1.05	668	975.584	72.105	60	.00019000	1352.9956	99.99967
.465	2048	235.606	17.413	1.10	593	1007.109	74.435	80	.00006160	1352.9981	99.99986
.470	2033	245.809	18.167	1.15	535	1035.309	76.519	100	.00002570	1352.9990	99.99992
.475	2044	256.001	18.921	1.20	485	1060.809	78.404	120	.00001260	1352.9994	99.99995
.480	2074	266.296	19.681	1.25	438	1083.884	80.109	150	.00000523	1352.9997	99.99997
.485	1976	276.421	20.430	1.30	397	1104.759	81.652	200	.00000169	1352.9998	99.99999
.490	1950	286.236	21.155	1.35	358	1123.634	83.047	250	.00000070	1352.9999	99.99999
.495	1960	296.011	21.878	1.40	337	1141.009	84.331	300	.00000034	1352.9999	99.99999
.500	1942	305.766	22.599	1.45	312	1157.234	85.530	400	.00000011	1352.9999	99.99999
.505	1920	315.421	23.312	1.50	288	1172.234	86.639	1000	.00000000	1353.0000	100.00000

Table II
Spectral Irradiance Instruments Aboard the NASA 711 Aircraft
(GSFC Convair 990 Measurements)

Instrument	Energy Detector	Type of Instrument	Aircraft Window Material	Wavelength Range (μ m)
Perkin-Elmer Monochromator	1P28 Tube Thermocouple	LiF Prism	Sapphire	0.3-0.7 0.7-4
Leiss Monochromator	EMI 9558 QA PbS Tube	Quartz Double Prism	Dynasil	0.3-0.7 0.7-1.6
Filter Radiometer	Phototube	Dielectric Thin Films	Dynasil	0.3-1.2
P-4 Interferometer	1P28 or R136 PbS Tube	Soleil Prism	Infrasil	0.3-0.7 0.7-2.5
I-4 Interferometer	Thermistor Bolometer	Michelson Mirror	Irtran 4	2.6-15

Table III

Major Contributions to Analysis of Smithsonian Data for Correlation between Solar Constant, E, and Sunspot Number, N

	Data Period	Year	Reference	Main Conclusions of the Authors
Angstrom	1915-17	1922	13	E is max. for 100 < N < 160. E increases by 2.4% for N 0 to 80.
Abbot, Aldrich and Hoover	1920-39	1942	14	E does not vary with N. E varies by 1% with faculae area.
Aldrich	1923-44	1945	15	E is maximum for N near 20. Greatest variation of E was 0.4% in 1923-33.
Aldrich and Hoover	1922-52	1952	16	E has small irregular variations, less than 2%. Largest increase during 1946-50 when N was high.
Aldrich and Hoover	1944-52	1954	17	E increases by 0.8% as N increases from 0 to 175.
Allen	1915-52	1958	18	Variations in E do not exceed 0.1%.
Sterne and Dieter	1923-58	1958	19	There are no periodicities in N common to data from two stations, Table Mountain and Montezuema.
Abbot	1923-58	1958	20	N has many periodicities with submultiples of 273 months. N changes up to 4% with large sunspots and magnetic storms.
Angstrom	1923-55	1970	21	Variations in N are less than 0.2%.
Kondratyev and Nikolsky	1928-32 1943-52	1970	22	There is indubitable correlation between N and faculae area. There are synchronous variations up to 0.8% at three stations.

Table IV

Experiments Proposed for the NASA Program of Measuring the Total and Spectral Irradiance of the Sun from Spacecraft

Instrument	Proposed Flight System	Measurement Totl	Measurement Spect	Accuracy (Goal)	Instrument Status*	Proposing and/or Cognizant Organization(s)
Earth Radiation Budget (ERB)	Nimbus-F/G	X	X	$<1\%$	A-Nimbus	NOAA/NASA
Solar and Earth Radiation Monitor (RCR/SERM)	Tiros-N	X	—	$\sim 1\%$	P-OSIP	NOAA/CSU/ NASA
Active Cavity Radiometer (ACR)	ERBOS	X	–	0.2–0.5%	F-SR&T	Univ. of Wis./ NASA
Primary Active Cavity Radiometer (PACRAD)	LZEEBE/ CLIMSAT	X	–	0.2–0.5%	A	JPL/NASA
Eclectic Satellite Pyrheliometer (ESP)	AEM/Shuttle	X	X	0.2%	F-AAFE	NASA
Solar Energy Monitor in Space (SEMIS)	LANDSAT/ Solar Max. Mission/ AEM/Shuttle	X	X	$0.5 \rightarrow 0.1\%$	P	NASA
Total Solar Irradiance Measurements (TSIM)	Tiros-N	X	–	0.1%	P	NOAA-ARL
Solar Constant and Spectral Distribution (SCSD)	TBD	X	X	0.5%	P	Faraday Labs
Solar Irradiance Cavity Radiometer (SCIR)	CLIMSAT/ Shuttle	X		0.2%	P	NASA/NBS

*A – Available, F – Funded Study, P – Proposed Study