Solar irradiance: total and spectral and its possible variations

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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. 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 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.

I. Introduction

The solar constant and the solar spectral distribution have been the topic of extensive investigations for a long period of time, and many different values have been proposed. 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 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 that were widely accepted were Johnson's 1396 Wm^{-2} and Nicolet's 1380 Wm^{-2}.

II. 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 Fig. 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.

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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 a solar spectral irradiance curve which is shown in Fig. 2. The table of spectral irradiance values is given in Ref. 3. This is based mainly on measurements made by the GSFC CV 990 team who used five large spectral irradiance instruments of different types.[4] The spectral curve obtained from the GSFC data was modified slightly in the 0.3–0.7-μm range with the aid of the filter radiometer data obtained by the Eppley-JPL team and thus was defined the NASA/ASTM spectral irradiance standard.

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. 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,[5] Makarova and Kharitonov,[6] and Stair and Ellis.[7] And it is also 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 that, 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 $\pm 1.5\%$, which is rather large for an important constant of geophysics and astronomy, when we consider that most other

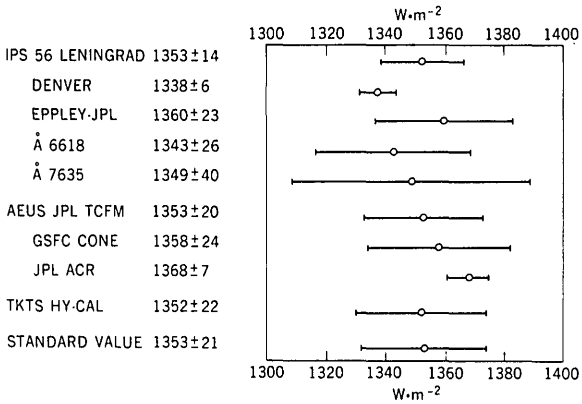

Fig. 1. Values of solar constant derived from high altitude measurements.

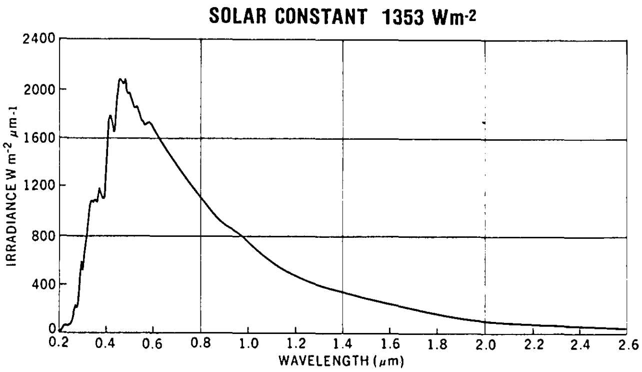

Fig. 2. The NASA/ASTM standard curve of extraterrestrial solar spectral irradiance.

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 different instruments which did not yield identical spectral curves. There were greater differences between the GSFC data and the Eppley-JPL filter data. Equally disturbing, if not more so, are the differences between the NASA/ASTM CURVE curve and those published earlier, those of F. S. Johnson, Labs, Neckel, and others.

III. Solar Variability and its Effects: Inconclusive Evidence

In many 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 1% or 2% 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 Abbot and his co-workers at the Smithsonian Institution. They cover a period of over 50 yr. There have been numerous attempts at an

Table I. 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
Ångström	1915–17	1922	8	E is max. for $100 < N < 160$. E increases by 2.4% for N 0–80.
Abbot, *et al.*	1920–39	1942	9	E does not vary with N. E varies by 1% with faculae area.
Aldrich	1923–44	1945	10	E is maximum for N near 20. Greatest variation of E was 0.4% in 1923–33.
Aldrich and Hoover	1922–52	1952	11	E has small irregular variations, less than 2%. Largest increase during 1946–50 when N was high.
Aldrich and Hoover	1944–52	1954	12	E increases by 0.8% as N increases from 0 to 175.
Allen	1915–52	1958	13	Variations in E do not exceed 0.1%.
Sterne and Dieter	1923–58	1958	14	There are no periodicities in N common to data from two stations: Table Mountain and Montezuema.
Abbot	1923–58	1958	15	N has many periodicities with submultiples of 273 months. N changes up to 4% with large sunspots and magnetic storms.
Ångström	1923–55	1970	16	Variations in N are less than 0.2%.
Kondratyev and Nikolsky	1928–32 1943–52	1970	17	There is indubitable correlation between N and faculae area. There are synchronous variations up to 0.8% at three stations.

analysis of these data to determine whether the solar constant varies with the sunspot number, the magnetic field, or any other observable feature of the sun. The sunspots have the well known 11-yr 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 yr and more. There are also the sporadic and unpredictable events that last for periods from a few minutes to several days.

A few 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 I. The Table lists the authors, the period of the Smithsonian data that 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 that 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.

Three studies that are independent of the Smithsonian data should also be cited. Bossolasco *et al.*[18] made an analysis of ground based measurements at four stations, Uccle (Belgium), Jerusalem (Israel), Krippenstein, and Sonnblick (Austria), over the 1956–1960 period and concluded that E has a pronounced maximum for $N \simeq 160$ and that it decreases by 15–17% as N increases to 250 or 300. This is an upper extreme for suggested variations in the solar constant. Kondratyev attributes this finding to increased atmospheric absorption;[17] 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 1956–1958 period. From the Leningrad balloon data Kondratyev and Nikolsky[17] conclude that E is maximum for $80 < N < 100$ and that there is a decrease of N of 2–2.5% for higher and lower N values. They also find that Ångström's analysis made in 1922 had yielded a curve of E vs 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 Temperature Control Flux Monitor (TCFM) of JPL was flown on two Mars Mariner Missions in 1969.[19] 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% that 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[11] 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 and the more recent Earth Radiation Budget(ERB) experiment 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 new. The opening paragraph of a paper published in 1966 by Abbot, "Solar Variation, a Weather Element,"[20] 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 modeling 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, or is the land and ocean surface of the earth a gray 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 nm 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-wavelengths 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 is there any reason to assume that the changes in solar spectral irradiance over limited wavelength bands are as small as in the solar constant itself.

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 1893–1961 period 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-yr 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. 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.

IV. 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 II gives an overview of the NASA solar monitoring program. Some instruments listed here have been documented extensively. The first on the list is the Earth Radiation Budget (ERB) experiment of NIMBUS-F, a spacecraft that was launched in June 1975. 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 with approximate wavelength ranges (units in nm) of 250–300, 280–350, 300–400, 350–450, and 400–500. Considerable data are available and will be published in due course by the ERB experimental team. Two other instruments, the ESP and the SCSD, also plan to use interference filters with wideband 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 NASA/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 op-

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

Instrument	Proposed flight system	Measurement total spect.	Accuracy (goal)	Instrument status[a]	Proposing and/or cognizant organization(s)
Earth Radiation Budget (ERB)	Nimbus-F/G	*XX*	<1%	*A*—Nimbus	NOAA/NASA
Solar and Earth Radiation Monitor (RCR/SERM)	Tiros-N	*X*—	~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	*XX*	0.2%	*F*—AAFE	NASA
Solar Energy Monitor in Space (SEMIS)	LANDSAT/Solar Max. Mission/AEM/Shuttle	*XX*	0.5 → 0.1%	*P*	NASA
Total Solar Irradiance Measurements (TSIM)	Tiros-N	*X*—	0.1%	*P*	NOAA-ARL
Solar Constant and Spectral Distribution (SCSD)	TBD	*XX*	0.5%	*P*	Faraday Labs
Solar Irradiance Cavity Radiometer (SCIR)	CLIMSAT/Shuttle	*X*	0.2%	*P*	NASA/NBS

[a] *A*—available, *F*—funded study, *P*—proposed study.

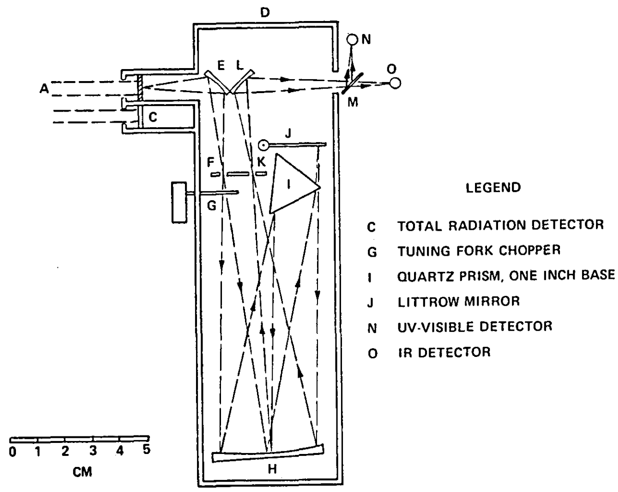

Fig. 3. Optical schematic of SEMIS (Solar Energy Monitor in Space).

tical schematic of the SEMIS is shown in Fig. 3. The total irradiance detector is either a thermopile of the type used in ERB or an absolute radiometer, for example, the GSFC cone radiometer,[4] similar in principle to the ACR and PACRAD. The SEMIS is designed to be a compact, lightweight, low data rate instrument that can be readily accommodated on a large variety of spacecraft missions. One model of the instrument has been built and 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. 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. 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. The bandwidth or spectral resolution varies with the spectral range and slitwidth. For a slitwidth of 0.1 mm the value of $\lambda/\Delta\lambda$ varies between 200 and 50. This wavelength resolution is adequate for monitoring solar spectral variability. For studying the long term variability of solar flux it is essential that identical instruments be flown on several missions spanning a complete solar cycle of 11 yr or 22 yr. Hence the SEMIS has been designed to be small in size and weight; it can fly on a noninterfering 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 toward 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%, depending on the wavelength range. The precision or repeatability will be considerably better than the absolute accuracy. Precision rather than absolute accuracy is required for monitoring solar variability.

V. 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 reason. 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. Modeling 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 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. Although 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 1980'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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The New York Section of the Society for Applied Spectroscopy has presented its 1975 Medal to George H. Morrison of Cornell University. The medal was presented to Dr. Morrison at the Eastern Analytical Symposium in New York City on 21 November 1975. Dr. Morrison was cited for his contributions to atomic absorption and emission spectroscopy, spark source mass spectrometry, and for his recent work on the use of vidicon tubes in flame spectrometers for simultaneous multielement analysis. Dr. Morrison received the 1971 ACS award in Analytical Chemistry, and was a Guggenheim Fellow at Université de Paris (Orsay) in 1974–75.