SOLAR ENERGY MONITOR
IN SPACE (SEMIS)

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MARCH 1974

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND
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by

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Greenbelt, Maryland 20771

ABSTRACT

Measurements made at high altitudes from aircraft have resulted in the establishment of standard values of the solar constant and extraterrestrial solar spectral irradiance. They have been adopted as the engineering standard by the American Association of Testing and Materials (ASTM) and as design values for the NASA Space Vehicles Design Criteria. These standard values and other solar spectral curves which were derived from these for practical applications are described. The problem of possible variations of the solar constant and solar spectrum and their influence on the Earth–atmosphere system and weather related phenomena is examined. It is shown that the solar energy input parameters should be determined with considerably greater accuracy and precision than has been hitherto possible. A measurement program which is currently being planned for this purpose and the instrumentation which is being developed will be described. The instrument package is designed as a compact, low weight solar energy monitor in space (SEMIS). Preliminary measurements will be made at 20 km altitude from the U-2 aircraft. More advanced versions of the SEMIS will be flight-tested on balloons and aircraft for installation eventually in the Space Shuttle.

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1. THE SOLAR CONSTANT AND THE SOLAR SPECTRUM

We shall present first the data on the solar constant and solar spectrum which have been developed in recent years in the United States. This will show the inadequacy of available data and the need for a program such as the SEMIS.

Since the advent of satellites and high altitudes research aircraft several attempts were made to measure the solar constant from above all or almost all of the Earth's atmosphere. An ad hoc committee on Solar Electromagnetic Radiation was appointed by the NASA Space Vehicles Design Criteria Office and by the Institute of Environmental Sciences to study this question. The Committee made a detailed survey of all available information and recommended standard values for the solar constant and the extraterrestrial solar spectrum. The solar constant was evaluated from nine series of measurements, all made from high altitude platforms, namely, Convair 990 and B-57B jet aircraft, X-15 rocket aircraft, balloons and Mariner Mars probe.

These nine values are shown in Table I. Each one of these is the result of many series of measurements. The uncertainties claimed by the authors are shown in the last column. The values are referenced to three different radiation scales: the International Pyrheliometric Scale of 1956 (IPS 56), the Absolute Electrical Units Scale (AEUS) and the Thermodynamic Kelvin Temperature Scale (TKTS). The differences in values may be due to basic differences in radiation scales, calibration errors of each instrument, errors in extrapolation to air mass zero, window transmittance, scattered light and other causes. The
Table I
High Altitude Determinations of the Solar Constant

<table>
<thead>
<tr>
<th>Platform</th>
<th>Detector</th>
<th>Reference Scale of Radiometry</th>
<th>Solar Constant Wm(^{-2})</th>
<th>Estimated Error ±Wm(^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balloon(^{(1)}) U. of Denver Expt.</td>
<td>Normal incidence</td>
<td>IPS 56</td>
<td>1338</td>
<td>6</td>
</tr>
<tr>
<td>CV 990(^{(2)}) GSFC Expt.</td>
<td>Ångström 6618</td>
<td>IPS 56</td>
<td>1343</td>
<td>26</td>
</tr>
<tr>
<td>CV 990(^{(2)}) GSFC Expt.</td>
<td>Ångström 7635</td>
<td>IPS 56</td>
<td>1349</td>
<td>40</td>
</tr>
<tr>
<td>CV 990(^{(2)}) GSFC Expt.</td>
<td>Hycal</td>
<td>TKTS</td>
<td>1352</td>
<td>22</td>
</tr>
<tr>
<td>Mariner 6 and 7 Spacecraft, JPL(^{(3)})</td>
<td>Cavity radiometer</td>
<td>AEUS</td>
<td>1353</td>
<td>10</td>
</tr>
<tr>
<td>Balloon, U. of Leningrad Expt.(^{(4)})</td>
<td>U. of Leningrad actinometer</td>
<td>IPS 56</td>
<td>1353</td>
<td>14</td>
</tr>
<tr>
<td>CV 990(^{(2)}) GSFC Expt.</td>
<td>Cone radiometer</td>
<td>AEUS</td>
<td>1358</td>
<td>24</td>
</tr>
<tr>
<td>CV 990, B-57B, X-15 Eppley-JPL Expt.(^{(5,6,7)})</td>
<td>Eppley pyrheliometer</td>
<td>IPS 56</td>
<td>1360</td>
<td>13</td>
</tr>
<tr>
<td>Balloon, JPL Expt.(^{(8)})</td>
<td>Active Cavity radiometer</td>
<td>AEUS</td>
<td>1368</td>
<td>7</td>
</tr>
<tr>
<td>Standard Value</td>
<td></td>
<td></td>
<td>1353</td>
<td>21</td>
</tr>
</tbody>
</table>
Goddard experimenters had also another value obtained by integrating the value under the spectral curve, 1352 W m\(^{-2}\). That this was so close to the average was assumed to be fortuitous rather than warranted by the accuracy of the spectral data. So this value was not included in the list selected for averaging. The detectors included Ångström pyrheliometers, cavity radiometers, and normal incidence pyrheliometers of different types and manufacturers. The value of the solar constant derived from these measurements was 1353 W m\(^{-2}\) or 1.940 cal cm\(^{-2}\) min\(^{-1}\).

The solar spectral irradiance was obtained mainly from measurements made by NASA GSFC experimenters at an altitude of 11.6 km from a Convair 990 jet aircraft.\(^{(2)}\) In Table II are listed the spectroradiometric instruments used on the CV 990. Along with each instrument is shown the disperser, the aircraft window material, the energy detector, and the wavelength range. The main standard of calibration was a set of five 1000 W quartz iodine lamps calibrated at the National Bureau of Standards or the Eppley Laboratory. These were supplemented in the long wavelength range by two blackbody sources operating at 1200 K and 3000 K. As shown in Table II, there were two large prism monochromators, a filter radiometer (33 filters, each 100 A bandwidth) and two interferometers. The spectral irradiance curve obtained from these detailed measurements was modified slightly in the visible range with the aid of data from the multi-channel filter radiometers flown by the Eppley-JPL Team under the direction of A. J. Drummond.\(^{(5,6,7)}\) The GSFC results cover the spectral range
## Table II

Spectral Irradiance Instruments on board CV 990 NASA 711 Aircraft

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Spectral Dispersion by</th>
<th>Aircraft Window Material</th>
<th>Energy Detector</th>
<th>Wavelength Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perkin-Elmer monochromator</td>
<td>Lithium fluoride prism</td>
<td>Sapphire</td>
<td>1 P 28 Phototube Thermocouple</td>
<td>0.3 - 0.7 μm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.7 - 4.0 μm</td>
</tr>
<tr>
<td>Leiss double prism monochromator</td>
<td>Two quartz prisms</td>
<td>Dynasil quartz</td>
<td>EMI 9558 QA Tube PbS tube</td>
<td>0.3 - 0.7 μm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.7 - 1.6 μm</td>
</tr>
<tr>
<td>Filter radiometer</td>
<td>33 Dielectric thin film filters</td>
<td>Dynasil quartz</td>
<td>RLA type 917 phototube (S-1)</td>
<td>0.3 - 1.2 μm</td>
</tr>
<tr>
<td>P-4 polarization type interferometer</td>
<td>Soleil prism</td>
<td>InfraSil quartz</td>
<td>1 P 28 or R136 Tube PbS tube</td>
<td>0.3 - 0.7 μm</td>
</tr>
<tr>
<td>I-4 moving mirror type interferometer</td>
<td>Michelson mirror</td>
<td>Intran 4</td>
<td>Thermistor bolometer</td>
<td>2.6 - 15.0 μm</td>
</tr>
</tbody>
</table>
0.3 to 15 \mu m which contains nearly 99 percent of the Sun's energy. Data from other sources were added for the two extreme ends of the spectrum, from Heath\(^{(9)}\) and Hinteregger\(^{(10)}\) for the UV and from Shimabukoro and Stacey\(^{(11)}\) for the IR beyond 15 \mu m.

The spectral curve which was derived from the GSFC data and the Eppley-JPL data is shown in Figure 1. The wavelength range is 0.2 to 2.6 \mu m. The solar spectral irradiance values for the wavelength range 0.115 to 1000 \mu m is given in Table III. The columns are wavelength, spectral irradiance \(E_\lambda\), area under the curve 0 to \(\lambda\) and \% area. The values of \(E_\lambda\) are averages over 100 \(\AA\) for most of the range.

![Figure 1. The NASA/ASTM standard curve of extraterrestrial solar spectral irradiance, 0.2 to 2.6 \(\mu m\).](image-url)
### Table III. Solar Spectral Irradiance – Standard Curve

<table>
<thead>
<tr>
<th>( \lambda )</th>
<th>( E_\lambda )</th>
<th>( E_{\Delta \lambda} )</th>
<th>( D_{\Delta \lambda} )</th>
<th>( \lambda )</th>
<th>( E_\lambda )</th>
<th>( E_{\Delta \lambda} )</th>
<th>( D_{\Delta \lambda} )</th>
<th>( \lambda )</th>
<th>( E_\lambda )</th>
<th>( E_{\Delta \lambda} )</th>
<th>( D_{\Delta \lambda} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.15</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
<td>2.37</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
<td>2.37</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
</tr>
<tr>
<td>1.20</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
<td>2.37</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
<td>2.37</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
</tr>
<tr>
<td>1.25</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
<td>2.37</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
<td>2.37</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
</tr>
<tr>
<td>1.30</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
<td>2.37</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
<td>2.37</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
</tr>
<tr>
<td>1.35</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
<td>2.37</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
<td>2.37</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
</tr>
<tr>
<td>1.40</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
<td>2.37</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
<td>2.37</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
</tr>
<tr>
<td>1.45</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
<td>2.37</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
<td>2.37</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
</tr>
<tr>
<td>1.50</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
<td>2.37</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
<td>2.37</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
</tr>
<tr>
<td>1.55</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
<td>2.37</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
<td>2.37</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
</tr>
<tr>
<td>1.60</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
<td>2.37</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
<td>2.37</td>
<td>0.001</td>
<td>0.0000001</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

*Note: lines indicate change in wavelength interval of integration.*

**Solar constant** - 1353 W m\(^{-2}\)

---

**Notes:**
- \( \lambda \) - Wavelength in micrometers
- \( E_\lambda \) - Solar spectral irradiation averaged over small bandwidth centered at \( \lambda \), in W m\(^{-2} \) \( \mu \)m\(^{-1} \)
- \( D_{\Delta \lambda} \) - Integrated solar irradiance in the wavelength range \( \alpha \) to \( \lambda \), in W m\(^{-2} \)
- \( D_{\Delta \lambda} \) - Percentage of solar constant associated with wavelengths shorter than \( \lambda \)

---

Percentage of solar constant associated with wavelengths shorter than \( \lambda \) is calculated as:

\[
\frac{D_{\Delta \lambda}}{1353} \times 100\%
\]

Where \( D_{\Delta \lambda} \) is the integrated solar irradiance in the wavelength range \( \alpha \) to \( \lambda \), and 1353 W m\(^{-2}\) is the solar constant.

---

**Change in wavelength interval:**

The change in wavelength interval is indicated by line breaks in the table. Each line represents a change in the integration interval for the solar spectral irradiance. The wavelengths \( \alpha \) and \( \lambda \) at the beginning and end of each interval are specified.

---

**Emission and Absorption:**

The table also includes data on the emission and absorption of radiation at various wavelengths. The values are given in units of W m\(^{-2} \) and represent the intensity of radiation at the solar constant level. The range is from 1000 to 3000 Å (Angstrom units), indicating the spectrum's distribution across the electromagnetic spectrum.
The whole of the solar electromagnetic spectrum from 10 A to 10 m is shown in Figure 2. There are 10 decades on the wavelength scale. The irradiance scale changes 3 times in the IR each time by $10^6$. The Sun is a variable star in the radio range near 1 m and in the UV. The dashed lines show Planckian curves at equivalent blackbody temperature, which is 5762 K over most of the range but goes to higher values at the two extremes.

Following the recommendation of the Committee on Solar Electromagnetic Radiation, these values have received a wide circulation and have been extensively used as a standard of reference. A monograph published in the NASA Space Vehicles Design Criteria series recommends these values as criteria for design and testing of spacecraft systems. These values have been adopted by the Solar Simulation Committee of the Institute of Environmental Sciences and have been developed by the American Society for Testing and Materials (ASTM) into an "Engineering Standard for the Solar Constant and Solar Spectrum." A practical application which incidentally gave the first impetus to the GSFC Convair 990 project is the design of solar simulators and pre-launch testing of satellites and spacecraft components. In the laboratories of NASA, ESRO and their contractors the new values have replaced the older Johnson values. One of the major suppliers of solar simulators, Spectrolab, Inc. of Sylmar, California, has issued for the convenience of users a wallet size card presenting the data. The standard solar spectral irradiance table is available in the current edition of the American Institute of Physics Handbook and in the forthcoming Van Nostrand-Reinhold Encyclopedia of Physics. The chapter on Solar Radiation in
Figure 2. The extraterrestrial solar spectrum from X-rays to radio waves.
the AFCRL Handbook of Geophysics and Space Environments is in process of revision to incorporate these data. Typical of the new curves to be published in the AFCRL Handbook is Figure 3 which gives irradiance also at ground level of air mass 1, 4, 7 and 10; i.e., for solar zenith angles 0, 75°, 82° and 84°. These curves are for US standard atmosphere, ozone = 3.4 mm, precipitable water
vapor = 20 mm, relatively clear air with turbidity coefficients, \( \alpha = 1.3, \beta = 0.02 \).

Elterman's values are assumed for extinction optical thickness due to Rayleigh scattering and ozone absorption\(^{(16)}\). For aerosol scattering (turbidity) the optical thickness is assumed to be of the form \( \tau = \frac{\beta}{\lambda^\alpha} \). For absorption due to water vapor and other molecules the coefficients derived by Gates and Harrop\(^{(17)}\) have been used. The program for computing these values for irradiance at ground level and for punching the cards was developed by D. Hoyt of NOAA, Boulder, Colorado.

Solar spectral irradiance values in Table III are listed at intervals of 50 A for the visible and near UV, and are averages over 100 A bandwidth centered at the given wavelength. This method of listing was chosen so as not to make the table too long and to give a spectrum independent of the Fraunhofer absorption which different instruments portray differently according to their resolution. For many applications like atmospheric modelling, pollution studies, transmittance computations of interference filters, studies of absorptive processes in the atmosphere, etc., a more detailed knowledge of the extraterrestrial solar spectrum was found to be necessary. In response to inquiries from users a project was undertaken recently to meet this need. For the wavelength range 3000 to 6100 A tables and charts are now available which give the spectrum at intervals of 1 A.

One of the curves for the range 3000 to 4000 A is shown in Figure 4. It is based on the data of the Perkin-Elmer monochromator on board the CV 990 aircraft. The spectral curve was read at 1 A intervals and cards were punched by
Figure 4. Solar spectrum obtained with a Perkin-Elmer monochromator, air mass zero, 3000 - 4000 A.

J. DeLuisi of NCAR. We developed a normalization program so that in each 50 A range the integral under this curve is equal to the values of the standard spectrum (Table III). The dashed line shows the standard curve. The curve for the range 3600 to 6100 is shown in Figure 5. The well known solar absorption Ca\(^+\) H and K lines at 3969 A and 3934 A respectively, the H\(_\alpha\) line at 4861 A, the Fe G line at 4308, etc., are readily recognizable on this curve.
Figure 5. Solar spectrum obtained with a Perkin-Elmer monochromator, air mass zero, 3600 - 6100 Å.

Punched cards giving solar spectral irradiance data ($\lambda$ and $E_\lambda$) are available for the tables and figures discussed earlier, the standard table (Table III), spectral curves at ground level for several sets of atmospheric parameters and the extraterrestrial solar spectrum, 3000 to 6100 Å, at one Å intervals. User organizations which have need of such data for computer aided applications may obtain them by writing to the National Space Science Data Center, Code 601, NASA/GSFC, Greenbelt, Maryland 20771.
2. UNCERTAINTIES IN CURRENTLY AVAILABLE DATA

In many applications of solar irradiance data, solar and spectral, there are two questions of major importance, the absolute accuracy and the variability of these values.

As for the absolute accuracy of the solar constant there are several major problems. The values given in Table I based on high altitude measurements vary between a maximum of 1338 W m\(^{-2}\) and 1368 W m\(^{-2}\). The two extreme values are those which claim the least estimated error. The standard value adopted by NASA and ASTM is 1353 W m\(^{-2}\) with an estimated uncertainty of ±21 W m\(^{-2}\). For applications in meteorology, atmospheric physics, solar physics, etc., an absolute accuracy of the order of 0.1% or ±1.4 W m\(^{-2}\) is desirable and many authors believe that it is possible within the state-of-the-art of radiometric measurements. Variations in the solar constant with sporadic or cyclic variations of the Sun itself cannot be detected unless the precision, if not the absolute accuracy, of the solar constant is 0.1% or better.

The values of the solar constant derived from ground-based measurements are significantly higher than 1353 W m\(^{-2}\). F. S. Johnson's\(^{(14)}\) value which was published in 1954 and had long been accepted as a standard in the U.S. was 1395 W m\(^{-2}\) or 3.1% higher. Nicolet's value\(^{(18)}\) was close to this, 1380 W m\(^{-2}\). Still higher are the values derived by Stair and Johnston\(^{(19)}\), 1428 W m\(^{-2}\), and by Makarova and Kharitonov\(^{(20)}\), 1418 W m\(^{-2}\). In a recent monograph, "Distribution of Energy in the Solar Spectrum and the Solar Constant" published in Moscow\(^{(21)}\),
Makarova and Kharitonov have proposed a value $1360 \text{ W m}^{-2}$; this is a weighted average of all the earlier measurements by many different authors. In 1968 Labs and Neckel\textsuperscript{(22)} derived the value $1366 \text{ W m}^{-2}$ based on measurements they made from Jungfraujoch in the wavelength range 0.33 to 1.25 $\mu$m and data from other authors for the region outside their range. In 1970\textsuperscript{(23)} they revised their earlier value downwards to $1358 \text{ W m}^{-2}$. The measurements made from mountain tops by C. G. Abbot and his co-workers at the Smithsonian Institution are by far the most detailed and extensive for the solar constant and the solar spectrum. They cover a period of nearly half a century. The Smithsonian value, $1352 \text{ W m}^{-2}$\textsuperscript{(24)}, is very close to the NASA and ASTM standard.

The uncertainties in the distribution of the solar energy as a function of wavelength are considerably greater than in the solar constant itself. The four different instruments used by the GSFC experimenters on board CV 990 for the same wavelength range did not yield identical curves; there was a certain amount of scatter between them, though the variations were within the estimated error limits of the instruments. There were greater differences between the GSFC curve (weighted average of the four instruments) and the Eppley-JPL filter data\textsuperscript{(25)}.

The differences between the NASA/ASTM standard (based on GSFC and Eppley-JPL data) and the solar spectral curves obtained from earlier ground based measurements are considerably greater. Three of these curves and the standard are shown in Figure 6. The most significant variations are in the
spectral range near 0.55 \mu m. This mode of comparison fails to show the spectral differences as distinct from those in the solar constant; and in the wavelength range of low irradiance the curves seem to be identical, though they are far from being so.

![Graph showing solar spectral irradiance](image)

Figure 6. The NASA/ASTM standard curve compared with the curves derived by Makarova and Kharitonov, Labs and Neckel, and Nicolet.
A clearer and more meaningful comparison of the standard curve with that of Labs and Neckel is shown in Figure 7. The Y-axis is the ratio $R = k \cdot \frac{P_A}{P_A'}$, where $P_A$ is the irradiance as given in the standard table (Table 3) and $P_A'$ is the irradiance at the same wavelength from Labs and Neckel. $k$ is a normalizing constant which makes the area under the Labs and Neckel curve equal to the standard solar constant, 1353 Wm$^{-2}$. The excursions of the ratio curve above and below the 1.0 line show to what extent the Labs and Neckel distribution differs from that of the standard curve.

Similar comparisons with three other spectral curves, those published by F. S. Johnson, Nicolet and Stair and Ellis$^{(26)}$ are shown in Figures 8, 9 and 10 respectively. A comparison of Figures 7, 8 and 9 shows that in the range

Figure 7. Comparison of NASA/ASTM spectrum with Labs and Neckel spectrum. (Curve gives the ratio of normalized Labs and Neckel values to those of Table III.)
Figure 8. Comparison of NASA/ASTM spectrum to Johnson spectrum. (Curve gives ratio of normalized Johnson values to those of Table III.)

Figure 9. Comparison of NASA/ASTM spectrum to Nicolet spectrum. (Curve gives the ratio of normalized Nicolet values to those of Table III.)
Figure 10. Comparison of NASA/ASTM spectrum to Stair and Ellis spectrum. (Curve gives the ratio of normalized Stair and Ellis values to those of Table III.)

0.25 to 0.45 μm, the Johnson values are higher and those of Labs and Neckel and Nicolet are lower than the standard. It will be recalled that Johnson had scaled Dunkelman and Scolnik's values (27) upward by 8.8%. The values of Labs and Neckel and of Nicolet are low probably because of the difficulty of estimating the solar continuum in a wavelength range which is so rich in Fraunhofer lines. Both Nicolet and Labs and Neckel show a sharp change in the ratio near the Balmer discontinuity, which is not seen in Figures 8 and 10 where the data are based on irradiance of the whole disc rather than on radiance at the center of the disc. The Stair and Ellis curve is of special significance. Two instruments were used, a Leiss monochromator and a filter radiometer. The wavelength range was limited by the photo-multiplier detector to 0.3 to 0.53 μm. The excursions of the ratio line above and below the ratio line are more or less evenly balanced.
A wavelength range which has given rise to a certain amount of controversy is from 0.5 to 0.7 μm. In this range the values of Labs and Neckel, Johnson and Nicolet are all higher than the standard values, as shown by Figures 7, 8 and 9. But this is a spectral range where the different instruments of the GSFC CV 990 experiment were in rather close agreement. Confirmation of the standard values was obtained recently from independent sources. Michael Kuhn (28) made measurements at Plateau Station in the Antarctic with differential broadband filters and a pyrheliometer and extrapolated the values to zero air mass. The zero air mass solar irradiance values were respectively 178.9 W m\(^{-2}\) and 116.5 W m\(^{-2}\) for the wavelength ranges 0.525 to 0.63 μm and 0.63 to 0.71 μm. The corresponding values of the standard table are 178.7 W m\(^{-2}\) and 116.5 W m\(^{-2}\), as may be seen by taking the differences of the column \(E_{0-\lambda}\) of Table III. Since Table III claims an accuracy of ±5%, this agreement should be considered rather fortuitous. R. Hulstrom (Martin Marietta, Boulder, Colorado) (29) made during 1973 a series of measurements over the range 0.4 to 1.35 μm. His values extrapolated to zero air mass show close agreement with the standard curve over the whole range. The agreement over the range 0.5 to 0.7 μm is particularly striking. Another valuable confirmation is from A. Ångström (30). His detailed analysis of atmospheric turbidity (\(\beta\) coefficient) covers a period of many years and ground based data of several observers including those of himself and A. Drummond from Mauna Loa. He concludes that the extraterrestrial solar spectrum in the range 0.3 to 0.7 as given in Table III is essentially correct.
3. POSSIBLE VARIATIONS IN SOLAR IRRADIANCE AND THEIR EFFECTS

Next question is the variability of the solar energy output. Does the energy output, total and spectral, change with all the other features of the Sun which are known to change? Among the cyclic changes of the Sun the best known is the 11 year sunspot cycle. Figure 11 shows the annual average sunspot numbers from 1760 to 1960. In addition to the 11 year cycle there is the 22 year cycle of solar magnetic field and probably a 90 year cycle of sunspots. There are several intriguing meteorological phenomena which seem to follow the changes in the Sun. J. M. Mitchell(31) presented a very detailed study of this topic at an

![Graph showing annual average sunspot number over the period 1750 to 1960.](image)

Figure 11. Annual average sunspot number (Zurich number or Wolf number of sunspots) over the period 1750 to 1960.
NCAR symposium in 1965. Among these variations are Etesian winds, wintriness index of the northern hemisphere sea level pattern, the annual march of temperature in different cities of Europe, changes in meridional sea level pressure, growth rings of trees, ozone density, geomagnetism, glacier movement. Add to these, the recurrence of drought in North America every 22 years (solar magnetic cycle) as was pointed out by C. G. Abbot in 1938 and the 11 year pattern in the movement of high pressure systems in Australia as pointed out by E. G. Bowen(32).

Let us look at some of these in more detail. Figure 12 shows the number of days per year when Etesian winds blow over Athens. The annual frequency of Etesian winds from 1893 to 1961 follows the same trends of maxima and minima as the sunspot numbers. That the Earth-atmosphere system reacts to changes in the input energy of the Sun is a well established fact. The density of the ozone layer changes from day to night. The changes in the ionization layers of the upper atmosphere and their dependence on solar phenomena have been studied in great detail because of their direct effects on radio communication. The geomagnetic disturbances have a periodicity of 27 days superposed on an 11-year period, in agreement with the rotational and Wolf number cycles of the Sun(33). The 11-year cycle of magnetic μ figure is clearly shown on Figure 13. In Figure 14 the charts of magnetic character figure C1 over a period of nine solar rotation cycles are shown one below the other. Long period correlation with sunspot cycles has been observed in such weather related phenomena as
Figure 12. Correlation between annual average of sunspot numbers and the number of days per year of Etesian winds.

Figure 13. Correlation between geomagnetic disturbance and the 11 year sunspot activity. Upper curve shows the magnetic $\mu$ figure and the lower curve shows the annual mean sunspot number.
Figure 14. Correlation of geomagnetic disturbance and solar rotation. Curve shows the magnetic character figure $C_1$ as a function of days 1 through 27 over nine solar rotations.
the water level in rivers and lakes, annual growth rings of petrified and living
trees, and the advance and retreat of glaciers. Solar events such as flares
cause corpuscular emission of which the effects are observed in aurorae, geo­
magnetic disturbances, changes in cosmic ray flux; increase in ionization of
the D layer, possibly localized heating of the atmosphere. Changes in photon
flux, though small, apparently act as a trigger mechanism which upsets a deli­
cate energy balance and causes large scale meteorological changes.

Several attempts have been made to determine the variations in solar con­
stant. The most extensive data are those of the Smithsonian Institution.
Kondratyev and his co-workers\(^{(4)}\) conclude from their balloon data over a six­
year period that the maximum value of the solar constant occurs for sunspot
numbers between 80 and 100 and that the solar constant decreases by 2 to 2.5
percent during sunspot maximum and minimum. The Lowell Observatory pro­
gram on the Sun as a variable star\(^{(34)}\) shows a gradual increase of the solar
constant by 1.4 percent as the sunspot number increases from 2 to 200.
Bossolasco and his group\(^{(35)}\) analyzed data from four widely separated stations
and concluded that the maximum value of the solar constant occurs for Wolf
number \(N\) about 160, and that the solar constant is significantly lower for
\(N < 160\) and \(N > 160\); the minimum at \(270 < N < 330\) is about 15 percent lower.
But this conclusion has been disputed by Kondratyev who ascribes the low value
to increased atmospheric turbidity caused by nuclear tests. C. G. Abbot and
his co-workers of the Smithsonian Institution\(^{(36)}\) present a large mass of
evidence for variations in the solar constant, for example, a drop of 4 percent when a large sunspot crosses the disc, a similar decrease accompanied by magnetic storms and West Indian hurricanes, periodicities related to 273 months (period of the solar magnetic cycle) and related weather phenomena.

While there is a great deal of literature about changes in the solar constant and their effects on weather, there is hardly any mention of changes in spectral distribution in the visible and near IR where the energy output is the greatest. The reason is not that changes do not exist, but they are totally unknown and unexplored. Almost all solar energy effects on the atmosphere and the Earth are wavelength dependent. Localized radiation balance and transport of large masses of air, increase of pollution and changes in sink mechanisms, the making of weather and climate and the modelling required for prediction of 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 an achromatic absorber. The Earth albedo spectrum is different from the solar spectrum. Ozone production is due to solar UV. Photosynthesis essential for all life support is due to wavelength bands centered round 0.44 and 0.75 \( \mu m \). Other resonance phenomena are photomorphogenic responses like seed and flower development, shape and size of leaves, plant height, leaf movements as in mimosa; the associated wavelengths are 0.66 and 0.73 \( \mu m \). Absorption by water vapor with all its major effects on the making of weather is
in narrow wavelength bands, all beyond 0.7 \( \mu \text{m} \), as shown on Figure 3. This is the more poorly known part of the solar spectrum.

4. A MEASUREMENT PROGRAM FOR SOLAR ENERGY IN SPACE

An obvious conclusion from these discussions of the state of our knowledge on the solar constant and solar spectrum and the relative lack of knowledge about the variations of these parameters is that a strong effort should be made for the measurement of solar irradiance, both total and spectral, with considerably greater accuracy and precision and that such measurements should be made on a continuing basis. During the first decade of the space age it has been possible to measure solar irradiance from above all or almost all of the atmosphere. Except for the Mars Mariner, the observing platforms were spacecraft and balloons. Satellites were not used for this purpose since the degree of accuracy aimed at is such that the experimental package should be retrieved after the flight for recalibration and for checking possible degradation of the optical components and detectors.

A project is now being developed for more precise and accurate determination of solar irradiance on a continuing basis. The objective is to monitor the solar constant with an accuracy of better than one percent and the solar spectral irradiance with an accuracy better than three percent. The variations of these parameters will be determined with a precision considerably greater than the absolute accuracy. The instrument package will be mounted in a U-2 aircraft which has a cruising altitude of 20 km. Observing time per flight will be about
six hours. The instrument package will consist of a medium resolution prism monochromator for the spectrum and a thermopile detector for the total energy.

A schematic of the instrument package is given in Figure 15. Sun's light enters an integrating sphere A through an aperture on its top B. The total irradiance is measured by a thermopile detector C and the spectral irradiance by a monochromator D. The mirror E focuses the light to the entrance slit F. It is chopped by a tuning fork chopper G, collimated by the mirror H, and spectrally dispersed by the prism I. The Littrow mirror J returns the light to the prism for doubling the dispersion. The concave mirror H focuses the light to the exit slit K, from which it falls on another focusing mirror L. The beam splitter M transmits the light to the two detectors, a photodiode N for the wavelength range 0.25 to 1.1 \( \mu m \) and a lead sulfide tube or a thermopile for the wavelength range \( \lambda > 0.7 \mu m \).

The instrument package will be provided with a tracking mechanism so that it will view constantly the Sun and a small portion of the circumsolar sky. It will be mounted in the Q-bay of the U-2 aircraft where a pressure of 350 millibars and a temperature range of 5°C to 25°C will be maintained. The residual atmosphere above the aircraft at 20 km is about 5% of what it is at sea level and the water vapor above the aircraft is 0.05% of the average amount of precipitable water in the atmosphere. About 50% or more of the ozone is above the aircraft so that the lower limit of the observable spectrum is 0.27 \( \mu m \). The upper limit is 2.6 \( \mu m \) with quartz optics and 4.0 \( \mu m \) with sapphire optics. Since
Figure 15. Optical schematic of Solar Energy Monitor in Space (SEMIS). Sunlight is received by an integrating sphere. Total energy is measured by a detector C and the spectrum is scanned by a prism monochromator D.
there is a certain amount of residual atmosphere above the aircraft, extrapolation to zero air mass will be made by measuring the solar energy at zenith angles varying between 15° and 60°. The instrument will be sufficiently light weight and compact so that it can be flown "piggy-back" on all routine missions of the U-2 aircraft.

The U-2 measurements will permit the development of a more reliable and rugged instrument for deployment on the Space Shuttle which will be in operation in the 80's. A floating laboratory above the ozonosphere and all other atmospheric absorbents, with manned instruments and on-board calibration, with few constraints as to weight, size and power, with long observation periods, total and spectral irradiance of the Sun can be determined with sufficient accuracy and resolution. This will provide an answer to many questions about the Sun's energy output which have often been raised but never adequately answered.

5. ACKNOWLEDGMENTS

The author wishes to acknowledge the help received from the late Dr. A. J. Drummond in the derivation of the standard values, from D. Hoyt of NOAA, Boulder, Colorado, for the computations of the solar spectrum on the ground, from J. DeLuisi of the National Center of Atmospheric Research, Boulder, Colorado, for the spectrum at one Ångström intervals and from R. Mitchell of NASA/GSFC for computer programs at different stages of this work.
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FIGURE CAPTIONS

Fig. 1. The NASA/ASTM standard curve of extraterrestrial solar spectral irradiance, 0.2 to 2.6 μm.

Fig. 2. The extraterrestrial solar spectrum from X-rays to radio waves.

Fig. 3. Solar irradiance spectra at ground level for air mass 1, 4, 7 and 10, compared to the standard curve - computed values.

Fig. 4. Solar spectrum obtained with a Perkin-Elmer monochromator, air mass zero, 3000 - 4000 A.

Fig. 5. Solar spectrum obtained with a Perkin-Elmer monochromator, air mass zero, 3600 - 6100 A.

Fig. 6. The NASA/ASTM standard curve compared with the curves derived by Makarova and Kharitonov, Labs and Neckel, and Nicolet.

Fig. 7. Comparison of NASA/ASTM spectrum with Labs and Neckel spectrum. (Curve gives the ratio of normalized Labs and Neckel values to those of Table III.)

Fig. 8. Comparison of NASA/ASTM spectrum to Johnson spectrum. (Curve gives ratio of normalized Johnson values to those of Table III.)

Fig. 9. Comparison of NASA/ASTM spectrum to Nicolet spectrum. (Curve gives the ratio of normalized Nicolet values to those of Table III.)

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