NASA SP-74

SURVEY of the LITERATURE on the SOLAR CONSTANT and the SPECTRAL DISTRIBUTION of SOLAR RADIANT FLUX

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

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Data currently available on the solar constant and the spectral distribution of the solar radiant flux are surveyed. The relevant theoretical considerations concerning radiation, solar physics, scales of radiometry and the thermal balance of spacecraft have been discussed briefly. A detailed review has been attempted of the data taken by the Smithsonian Institution, the National Bureau of Standards, and the Naval Research Laboratory, of the methods of data analysis, and the many revisions of the results. The survey shows that the results from different sources have wide discrepancies, that no new experimental data have been taken in recent years, and that the conventional technique of extrapolation to zero air mass leaves large uncertainties. The feasibility of further measurements and of a new method of approach has been discussed in the light of the results of this survey.

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INTRODUCTION

The solar constant and the spectral distribution of the solar radiant flux are of considerable importance in many areas of physics and engineering. In geophysics and meteorology, in studies of the upper atmosphere and of the thermal balance of the earth, in the investigation of solar phenomena and in many areas of illuminating engineering, the radiant energy received from the sun is a significant parameter. In recent years the topic has received a great deal of attention because of its bearing on the thermal balance of satellites and space probes.

In spite of the widespread interest in the subject and its importance in many areas of scientific research, no new experimental data have been collected in recent years. It is generally assumed that the best value of the solar constant available at present is 2.00 cal/cm^2-min. This value was deduced by Francis S. Johnson at the Naval Research Laboratory, Washington, D. C. in 1954 (Reference 1) from revisions of data which had been collected for over 30 years by the Smithsonian Institution, later data collected by Dunkelman and Scolnik (Reference 2) in 1951 and a re-evaluation of the correction factors for the infrared and ultraviolet regions of the spectrum.

It is interesting to observe that the solar constant has frequently been revised and each new revision has increased its value. Parry Moon (Reference 3), in 1940 published a detailed analysis of the data of the Smithsonian Institution, and arrived at the value 1.896 cal/cm^2-min. A revision in 1952 by Aldrich and Hoover (Reference 4) raised the value to 1.934 cal/cm^2-min. Francis S. Johnson's value of 1954 as quoted above was 2.00 $\pm$ .004 cal/cm^2-min. C.W. Allen (Reference 5) in 1955 gave a value, 1.97 $\pm$ .01 cal/cm^2-min. An independent set of measurements was made by Ralph Stair and Russell G. Johnston (Reference 6) at an altitude of 9200 feet; they published in 1956 a still higher value, 2.05 cal/cm^2-min.

The discrepancies between different investigators are even greater for the published data on the spectral distribution of the radiant flux. Extensive tables and charts of solar spectral radiant flux have been published by Moon, Johnson, Stair, and others. Some of the more significant available data were collated and published by Gast (Reference 7) in the *Handbook of Geophysics*.

The present report will attempt to collect the available information about the solar constant and about the solar spectral radiant flux, and to describe the methods used in gathering such information. The feasibility of further measurements will be studied in the light of existing data.

THEORETICAL CONSIDERATIONS

Terminology

The topic of primary interest is the solar constant, which is the radiant flux received from the sun at the average distance of the earth from the sun — but in the absence of the earth's atmosphere. The physical quantity which has been measured in most cases is the radiant flux at some particular distance depending on the time of the year and after transmission through the atmosphere. Both these quantities are related to the radiant flux received from a hypothetical blackbody at the location of the sun, having the same size and average temperature as the sun. It is convenient to discuss the terminology and the laws of radiation in terms of a blackbody.

There is no uniformity in the literature concerning the terms and symbols used for the physical quantities involved in the statement of radiation laws. In recent years many authors have shown a preference for *The American Standards Nomenclature for Radiometry and Photometry* ASA, Z 58.1.1 — 1953 (Reference 8), which was proposed by the American Standards Association Sectional Committee, Z-58. This committee had been sponsored by the Optical Society of America and the proposed nomenclature was approved on February 27, 1953.

Radiant energy density or radiant density u at a given point in space is the energy per unit volume in the vicinity of that point. The *radiant flux* P through a given surface is the radiant energy which crosses unit area in unit time. The *radiant emittance* (or flux density) W of a radiating surface at a given point is the radiant energy emitted per unit area in the vicinity of that point, per unit time. The *radiant intensity* J of a point source in a given direction is the radiant energy emitted by the source per unit solid angle in that direction, in unit time. The *radiance* N of a radiating surface at a given point in a given direction is the radiant energy emitted per unit time, per unit solid angle in that direction from unit projected area in the vicinity of the point. *Radiant reflectance* ρ of a surface is the ratio of energy reflected both specularly and diffusely by the surface to the energy incident on the surface. *Radiant transmittance* of a given medium τ is the ratio of energy transmitted per unit thickness by a small thickness dx of the medium to the energy incident on the medium.

The above quantities refer to the energy radiated in all frequencies or in the entire wavelength range 0 to ∞. The notation for wavelength and related quantities are: wavelength λ, wave number $n = 1/\lambda$; frequency $\nu = c/\lambda$.

The spectral quantities corresponding to u, P, W, J, N, ρ, and τ, are denoted by a subscript λ, n or ν added to the respective symbol. The spectral radiant flux P_λ is defined as follows: If $P_{\lambda,\lambda+d\lambda}$ is the part of the total energy density due to radiation in the wavelength range λ to $\lambda + d\lambda$, the spectral radiant flux in terms of wavelength is

$$P_\lambda = \frac{P_{\lambda,\lambda+d\lambda}}{d\lambda} ; \qquad P = \int_0^\infty P_\lambda \, d\lambda . \tag{1}$$

Let Figure 1 represent the variation of radiant flux with wavelength in an arbitrary case. The shaded area represents $P_{\lambda,\lambda+d\lambda}$; the ordinate of the curve represents P_λ; and the area enclosed between the curve and x-axis represents P. Similiar definitions may be derived for the other spectral quantities.

The physical quantities we are interested in are radiant flux P and spectral radiant flux P_λ. These quantities are referred to in earlier literature by symbols such as E, I, N or H, and by terms such as intensity, energy, irradiance, with or without the adjective monochromatic, or spectral.

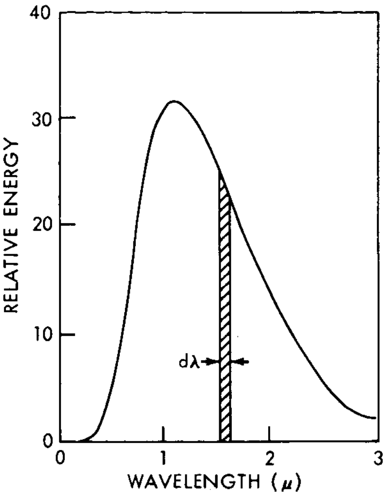


Figure 1—Distribution of spectral radiant flux for an arbitrary source (a tungsten lamp).

Laws of Radiation

Certain simple relations hold between P, W, u, and N if the radiating surface obeys Lambert's law, that is, if it is a surface having constant radiance in all directions. Such a surface is called a perfectly diffuse surface (References 9 and 10). The radiant emittance W from a surface, that is, the energy emitted into a solid angle 2π from a unit surface, is related to the radiance N, energy emitted in a given direction per unit solid angle per unit projected area, by the equation

$$W = \pi \Omega_0 N , \tag{2}$$

where Ω_0 is 1 ster.

In the vicinity of a point in vacuum the energy density u which is due to radiation streaming in all directions is related to N (the radiance of the source) by the equation

$$u = \frac{4\pi \Omega_0 N}{c} , \tag{3}$$

where c is the velocity of light in vacuum.

From Equations 2 and 3, we have

$$W = \frac{c}{4} u ; \tag{4}$$

Further, for collimated radiation,

$$P = c u . \tag{5}$$

The three important laws of blackbody radiation are the Stefan-Boltzmann law, the Wien displacement law, and the Planck radiation law. Planck's theory of radiation assumes that there exists a state of energy equilibrium between the heated walls of an enclosure and the stationary electromagnetic waves of radiation within the enclosure. In other words, the average energy per degree of freedom in matter and radiation is the same. Planck also introduced a new concept that energy transfer can occur only in integral multiples of a fundamental unit, the frequency ν times a constant h. Hence we obtain the average energy per degree of freedom for all stationary waves of wavelength λ; and multiplying it with the number of degrees of freedom per unit volume in the wavelength range λ to $\lambda + d\lambda$, we obtain the spectral energy density:

$$u_\lambda = \frac{8\pi hc}{\lambda^5 \left(e^{hc/(\lambda kT)} - 1\right)} , \tag{6}$$

where k is Boltzmann's constant.

By combining Equations 3, 4 and 6, Planck's equations for W and N are obtained:

$$N_\lambda = \frac{2hc^2}{\lambda^5 \left(e^{hc/(\lambda kT)} - 1\right)} .$$

The above equation is often written in the form

$$N_\lambda = \frac{c_1}{\lambda^5 \left[e^{c_2/(\lambda T)} - 1\right]} , \tag{7}$$

where c_1 and c_2 are known as the first and second Planck's constants, respectively:

$$c_1 = \frac{2hc^2}{\Omega_0} , \text{ and } c_2 = \frac{hc}{k} . \tag{8}$$

The Stefan-Boltzmann law and the Wien displacement law may be derived from Planck's law or from thermodynamical considerations independent of the quantum theory.

Differentiating Equation 6 with respect to λ and equating du_λ $d\lambda$ to zero, we obtain,

$$e^{hc/\lambda kT} \left(1 - \frac{hc}{5\lambda kT}\right) = 1 . \tag{9}$$

The above result shows that $\lambda_{max} T = 0.289776$ cm°K, a constant. This is the Wien displacement law.

The Stefan-Boltzmann law states that the radiant emittance of a blackbody surface is proportional to the fourth power of the absolute temperature:

$$W = \sigma T^4 , \tag{10}$$

where σ is called the Stefan-Boltzmann constant.

The value of σ in terms of the fundamental physical constants can be derived by rewriting Equation 6 in terms of ν rather than λ and integrating the right hand side with respect to ν:

$$u = \int_0^\infty u_\nu \, d\nu = \int_0^\infty \frac{8\pi h\nu^3}{c^3 \left(e^{h\nu/kT} - 1\right)} \, d\nu$$

$$= \frac{8}{15} \frac{\pi^5 k^4}{c^3 h^3} T^4 .$$

By substituting for u (from Equation 5),

$$W = \frac{2}{15} \frac{\pi^5 k^4}{c^2 h^3} T^4 ,$$

and hence

$$\sigma = \frac{2}{15} \frac{\pi^5 k^4}{c^2 h^3} . \qquad (11)$$

Solar Radiant Flux

The three important Equations 6, 9, and 10, of blackbody radiation are applicable to solar radiant flux, though only to a first degree of approximation. If the effective temperature of the sun's radiating surface, the area of the radiating surface and the time average of the distance of the earth from the sun are known, both the solar constant and the solar spectral radiant flux can be determined from a purely theoretical standpoint. However, a few basic considerations of the physics of the sun show that the effective temperature and radiating area of the sun do not permit a precise definition nor can they be determined experimentally with a sufficient degree of accuracy.

The different parts of the sun which are responsible for the energy received by the earth are the photosphere, the reversing layer, the chromosphere, and the corona.

The photosphere is the sun's surface directly visible in a telescope or a darkened glass. The opacity of the gases in this layer increases rapidly with depth and hence prevents us from seeing farther into the sun. Even with the best telescopes the edge of the photosphere at the circumference of the solar disc appears very sharp, which shows that the rapid transition in brightness from the photosphere to the surrounding layers takes place within a depth of about 50 km. This explains the close similarity of the solar spectrum to that of blackbody radiation.

The reversing layer and the chromosphere together form the atmosphere of the sun. They consist of luminous but very transparent gases. The reversing layer extends to a height of a few hundred miles, and the chromosphere to a height of several hundred miles. The chromosphere, consisting mainly of helium and hydrogen, is a partial absorber of solar radiation, but its effect

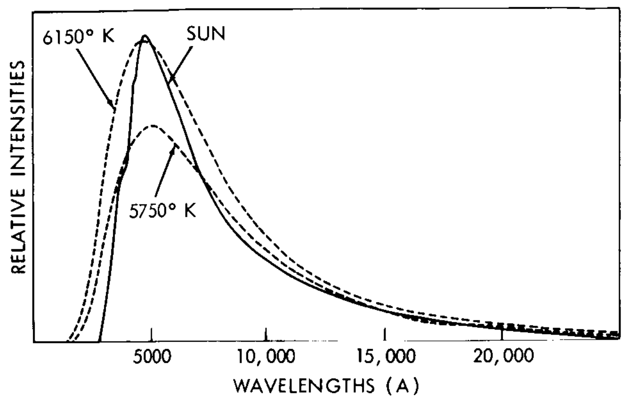


Figure 2—Distribution of solar spectral radiant flux compared to blackbody distribution (Reference 11).

is small compared to the more dense reversing layer. The reversing layer, containing vapors of almost all the familiar elements of the earth's crust, is responsible for the numerous dark lines seen in a spectrum of the sun under high despersion. The gaseous atoms in the reversing layer partially absorb the energy emitted by the photosphere, and are thereby raised from the ground level to excited levels. These atoms emit in their turn light of longer wavelength or of the same wavelength by returning to a lower excited state or to the initial state. The reversing layer is mainly responsible for the departure of the spectral energy distribution of the solar spectrum from that of a blackbody. Figure 2, reproduced here from a classical textbook of astronomy, gives the spectral energy distribution of the sun along with blackbody energy distribution curves at two temperatures, 6150°K and 5750°K. The solar energy curve is based on earlier data of the Smithsonian Institution and does not show many of the finer details. These finer details will be given in later figures and tables. Below 4700A and above 5700A the departure from the blackbody distribution is very pronounced (Reference 11).

The corona may be considered the extreme fringes of the solar atmosphere. The luminous part of the corona seen during a total eclipse of the sun extends to a height of several solar radii. But recent experiments with space probes have shown that the corona has no distinct outer boundary and that even the earth's orbit is enclosed within a tenuous coronal region. Hence the attenuation of energy in the sun-earth distance is greater than in the more rarified regions of interstellar or intergalactic space.

There are several other factors which affect the total energy and the spectral energy distribution of the sun. Among these are the sunspots which have a periodicity of eleven years, and the faculae and the prominences which are relatively unpredictable, and the more permanent inhomogeneities of the photosphere.

Hence we conclude that though the energy emitted from the photosphere may be very close to that of blackbody radiation, the radiative processes of absorption and emission in the solar atmosphere cause the energy received at the mean distance of the earth to be significantly different.

Solar Simulation and Thermal Balance of Spacecraft

In the area of solar simulation and thermal balance of spacecraft, the above theoretical considerations of blackbody radiation laws and solar radiant flux are of great importance. A question of special significance is the degree of error and inaccuracy in the predicted equilibrium temperatures of satellites, caused by errors in the assumed values of the solar constant and the solar spectral radiant flux. A complete discussion of this problem in any actual case involves many, highly complex and variable parameters. Among these parameters are the planet radiation of the earth, the reflected solar radiation from the earth, cloud cover and meteorological conditions, relative duration of the satellite inside and outside the earth's shadow, the ellipticity of the satellite orbit round the earth, the ellipticity of the earth's orbit round the sun, the external geometry of the satellite, the internal transfer of heat between satellite components, and the properties of the exposed surface of the satellite as regards absorption of radiation and its re-emission.

In the present discussion of the problem we shall ignore the radiation from the earth. It will also be permissible to treat many of the other parameters as a constant, independent of the solar radiant flux. For the sake of mathematical simplicity we shall consider first the case of a flat disc, then that of a sphere; we shall extend the conclusions to a few other more general cases.

Let A be the surface area of the disc, and let the thickness of the disc be negligibly small compared to A. Let the disc be coated with an ideal black paint. Hence the surface is a perfect absorber and emitter, so that the radiant emittance is given by the Stefan-Boltzmann law (Equation 10), and all the solar energy incident on the surface is absorbed by it. If the exposed area is normal to the solar radiant flux, the energy abosrbed is PA, where P is the solar radiant flux. The energy radiated by the body is

$$2A\sigma\left(T^4 - T'^4\right) ,$$

where T is the temperature of disc and T' is the ambient temperature. Since T and T' are of the order of 300°K and 4°K, respectively, T'^4 is about 10^{-7} times T^4, and is negligible in comparison to T^4. Let T be the equilibrium temperature. Since the heat absorbed is equal to the heat radiated, $2A\sigma T^4 = PA$, i.e.,

$$T^4 = \frac{1}{2\sigma} P . \tag{12}$$

Differentiating both sides, we have

$$4T^3\,dT = \frac{1}{2\sigma}\,dP . \tag{13}$$

By dividing Equation 13 by Equation 12,

$$\frac{dT}{T} = \frac{1}{4}\frac{dP}{P} . \tag{14}$$

Hence for a perfectly flat disc, the percentage error in the predicted value of equilibrium temperature, on the Kelvin scale, is one-fourth the percentage error in the assumed value of the solar constant.

It may readily be shown that Equation 14 is independent of the geometrical shape of the body, and holds true for all cases of a perfectly black surface, with no internal heat sources or heat sinks.

If the body is spherical of radius R, the effective absorbing area is the area of cross-section πR^2, and is one-fourth the total emitting area. Hence Equation 12 should be changed to $T^4 = (1/4\sigma)P$, and Equation 14 is unchanged. For a cube having one of its six surfaces normal to the solar radiation, the equation of thermal balance corresponding to Equation 12 is $T^4 = (1/6\sigma)P$. For a spinning body of arbitrary shape, the only term that needs modification is the area of the absorbing surface, which is the time average of the area of a cross section normal to incident radiation.

The above results may be illustrated by a few numerical examples. The Stefan-Boltzmann constant σ is 5.6693×10^{-5} erg/cm^2-sec-(°K)^4, the solar constant P is assumed to be 0.1395×10^7 erg/cm^2-sec. Substitution of these values in Equation 12 gives the equilibrium temperature of a disc to be 331.1°K or 60.1°C. An increase of ten percent in the assumed value of the solar constant would increase the predicted equilibrium temperature to 68.1°C, and decrease of ten percent would lower the predicted value to 51.4°C.

For a spherical body, the ratio of the absorbing area to the emitting area is half that of a flat disc, and the equilibrium temperatures are lower. The predicted values are 7°C, 13.4°C and -0.2°C respectively for assumed solar constant 0.1395, 0.1535 and 0.1256 watts/cm^2.

Actually the surfaces of satellites are not perfect absorbers or emitters, and hence it is necessary to introduce the expressions for absorptance and emissivity into the equations of thermal equilibrium. The absorptance α is the ratio of the energy absorbed to the energy incident; this definition is essentially similar to those of reflectance and transmittance given earlier. The emissivity, ϵ of a surface is the ratio of the radiant emittance of the surface to that of a blackbody surface at the same temperature. Both absorptance and emissivity are to be distinguished as total and monochromatic. The relations between the different quantities can be best expressed by the following equations.

If $P_\lambda' \, d\lambda$ is the energy incident in the wavelength range λ to $\lambda + d\lambda$, the energy absorbed in the same range is $P_\lambda' \alpha_\lambda \, d\lambda$. (The prime indicates that the radiant flux has a spectral distribution different from that of a blackbody.) The total energy absorbed is $\int_0^\infty P_\lambda' \alpha_\lambda \, d\lambda$, and the total incident energy is $\int_0^\infty P_\lambda' \, d\lambda$. The ratio of the two integrals is the total absorptance α. The definition of the absorptance of a surface is thus necessarily with reference to a specific spectral distribution of the incident radiant flux. In particular, solar absorptance values differ according to whether the absorptance at sea level or for zero air mass is considered and according to which of the accepted solar spectral radiation functions is used for performing the integration. Solar absorptance is determined either by exposing specimens to sunlight and measuring the energy absorbed or by calculating the value from known functions of α_λ and P_λ'.

The radiant emittance from a non-blackbody surface is given in terms of that from a blackbody surface at the same temperature by the equation

$$W' = \int_0^\infty W_\lambda' \, d\lambda = \int_0^\infty \epsilon_\lambda W_\lambda \, d\lambda = \epsilon \int_0^\infty W_\lambda \, d\lambda = \epsilon W . \tag{15}$$

ϵ and ϵ_λ are respectively the total emissivity and the spectral emissivity.

The equation for temperature equilibrium for a body which is not a perfect absorber or emitter is

$$\epsilon A_\epsilon \sigma T^4 = \alpha A_\alpha P' . \qquad (16)$$

A_ϵ and A_α are respectively the areas of the emitting surface and the absorbing surface.

The equilibrium temperature depends not only on the ratio A_α/A_ϵ as discussed earlier, but also on the ratio α/ϵ. For numerical examples, we might consider two extreme cases of α/ϵ equal 16 or 1/16. These numbers are respectively 2^4 and 2^{-4}. The corresponding equilibrium temperatures of a flat disc are respectively 666.2°K and 166.6°K. In actual cases α/ϵ does not vary over such wide ranges. For white paint representative values are $\alpha = 0.22$; $\epsilon = 0.88$; for evaporated gold, $\alpha = 0.07$; $\epsilon = 0.02$. It is important to note that the temperatures with reference to which the two ratios α and ϵ are measured are very different. The emissivity refers to the actual temperature of the satellite. The definition of α assumes the spectral energy distribution of a body at a relatively high temperature, 6000 °K.

Insofar as the calculation of α is dependent on the assumptions regarding the solar constant and the solar spectral radiant flux, the degree of error in these values causes a corresponding error in the predicted values of the equilibrium temperature. However, this is a second order effect since α is the ratio of two integrals, $\int_0^\infty P_\lambda' \alpha_\lambda \, d\lambda$ and $\int_0^\infty P_\lambda' \, d\lambda$. This becomes significant in cases where α_λ is very highly wavelength dependent, as may well happen with specially prepared surfaces of very thin multilayer coatings. Reference may be made in this connection to the extensive studies made by the Armour Research Foundation (Reference 12) on solar absorptances at sea level and for zero air mass of a large number of standard aircraft materials. These data have been cited in a review of literature entitled "Thermal Radiation Properties Survey," published in 1960 by Honeywell Research Center, (Reference 13). Over 70 different types of surfaces have been examined, mostly metal surfaces with different grades of polishing, and a few surfaces of graphite and plastic laminate. The difference between α at sea level and α above the atmosphere is of the order of one or two percent for surfaces having α greater than 0.4. Large percentage differences of 5 to 35 percent occur in cases where α is small, as for example copper, aluminum and magnesium alloys. For copper and magnesium alloys the absorptance at sea-level is lower than that above the atmosphere, and for aluminum it is higher. The uncertainties in our current knowledge of the solar spectral radiant flux are the greatest in the wavelength range below 3600 A, and unfortunately this is also the range where the spectral absorptance of most satellite coatings are highly wavelength dependent. As stated earlier, the percentage error in the predicted temperature (°K) is 1/4 the corresponding percentage error in the assumed values of α or P. These errors are cumulative.

Given the large variety of the external shape and the surface coatings of spacecraft, it is not possible to draw any more specific conclusions about the degree of error in predicted equilibrium temperatures. Those engaged in prelaunch testing in solar simulators and in theoretical computations of predicted temperatures should have at hand the values as accurate as possible, of the solar constant and the solar spectral radiant flux. And more importantly they should have an estimate of the possible errors in the accepted values of these quantities.

Standard Scales of Radiation Measurement

One of the major problems in all measurements of energy is the standard scale with reference to which the energy measurements are reported. Internationally accepted standards exist for fundamental units like length and mass and for many of the derived units like ampere and volt. For total radiant flux and spectral radiant flux, however, different countries use different standards, and intercomparisons between them show that they differ among each other by one or two percent.

For the sake of clarity the question of a standard may be put thus: when can one say that a certain length is one meter, that a certain current is one ampere or that a certain radiant flux is one watt/cm^2? The answer about the meter and the ampere are given unambiguously, with a high degree of accuracy, and is accepted by international commissions. The meter is defined in terms of a spectral line of krypton, and the ampere in terms of the amount of silver deposited by a standard cell. There is no such internationally accepted standard for energy.

A secondary standard of spectral radiant energy most widely used in the US is the tungsten ribbon lamp operated at a specified current. The calibration table supplied along with the lamp gives the spectral radiance of the incandescent ribbon at a large number of wavelengths. The physical quantity which is measured in the process of calibration is the color temperature of the ribbon at one or more wavelengths. The color temperature is determined with reference to a blackbody of known temperature. From known values of the emissivity of tungsten, the transmission coefficient of the envelope of the lamp and blackbody radiation functions, it is possible to calculate the spectral radiance from the color temperature. Relatively large errors may be introduced into the calculations because of the poor accuracy with which the emissivity of tungsten and the color temperature are determined. The calibration tables of the tungsten standard ribbon lamps do not have an accuracy better than 5 percent. Perhaps this may be a conservative estimate. No attempt has been made to establish an international standard for spectral radiance.

The situation is slightly better for total radiant flux. The standard in this case is not a source of radiant flux but an instrument for measuring radiant flux. In other words a standard scale of radiant flux is established giving the incident energy (in watts/cm^2) in terms of a more readily measurable physical quantity — the temperature (in °C) or current (in amperes) generated in a given instrument. Most of this work of standardization has been done in connection with the measurement of solar energy with the instrument being a phyrheliometer.

In meteorological institutes measurements of total radiant flux are usually standardized with reference to one or the other of two standard scales. For the sake of brevity we shall refer to them as the Smithsonian scale and the Ångström scale. Both scales have been revised periodically and considerable work has been done in comparing them with one another and with other independent radiation scales. A brief description of the instruments and the standardization procedures will help clarify some of the confusion concerning radiation measurements and will show the degree of error in such measurement.

The Smithsonian scale is defined with the aid of the Abbot silver disc pyrheliometer (Reference 14). A silver disc is exposed to solar radiation and the rise in temperature of the disc is measured. To convert the temperature rise in °C to energy in watts/cm^2, a calorimeter is exposed to the same solar radiation and the heat absorbed by the calorimeter is determined. The Ångström scale is defined with the aid of the Ångström compensated strip pyrheliometer. One of two similar metallic strips is exposed to solar radiation and the other is heated by an electric current; the value of the current is adjusted until both the strips are at the same temperature. From known values of the resistance of the strip and the absorptance of its surface it is possible to establish a standard scale of radiant flux in watts/cm^2 in terms of the current in amperes.

In 1932, the Smithsonian Institution introduced an improved form of calorimeter, and re-examined the accuracy of the scale which had been in use since 1913. The result of this study was that the Smithsonian announced that the measurements made on the 1913 scale had been 2.5% too high. This finding was confirmed by later measurements made in 1934, 1947 and 1952. However, the Smithsonian continued to standardize instruments in terms of the 1913 scale so as to preserve continuity.

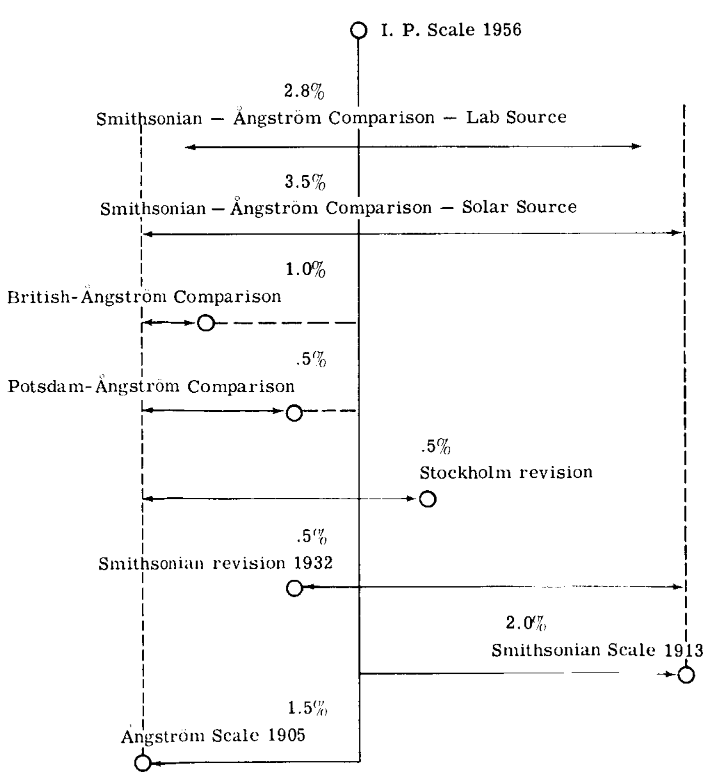
The Ångström scale, originally established in 1905 (Reference 15), is based on two main types of instruments. For one type of instruments the original calibrations were made at Uppsala, Sweden, and now they are being made at Stockholm, Sweden; the source of energy is the sun and the conversion from current in amperes to energy in watts/cm^2 is made from the known parameters of the instrument. For the other type of instruments the calibration is made at the Smithsonian Institution, with the sun as source and the standard calorimeter as the reference, in the same manner as for the Abbot silver disc pyrheliometer. We shall refer to the absolute scale established by the Uppsala-Stockholm group as the Ångström scale. The original scale established in 1905, was later found to be in error due to several causes, in particular, due to the edges of the exposed strip receiving no radiation, referred to as "the edge effect." Extensive studies made at Stockholm in 1956 and preceding years showed that the measurements made on the Ångström 1905 scale were 2% too low.

Thus a reading on the Smithsonian 1913 scale is to be lowered by 2.5%, and that on the Ångström 1905 scale is to be raised by 2% to give the correct value of radiant flux. If the experiments on which these results are based are accurate, then we would expect that a substandard instrument calibrated on both the Smithsonian 1913 scale and the Ångström 1905 scale should give different readings according to which scale is used; the reading on the Smithsonian scale should be 4.5% higher than the reading on the Ångström scale. Several such comparisons of the two scales have been made using sub-standard instruments with the sun as source. The differences are not constant, but show a large scatter; and the mean of the differences is 3.5% and not 4.5% as expected. One explanation for this may be that different instruments when directed at the sun do not always view the same fraction of the circum-solar atmosphere. Laboratory sources should be free from this source of error. A few measurements have been reported using a laboratory source instead of the sun as the source of radiant flux. The average of the differences between the two scales is even lower, namely 2.8 percent. This has been explained as probably due to another source of error, introduced by the relatively weak laboratory source; the area of the Abbot silver disc of the Smithsonian instrument is too large and does not receive a uniform distribution of energy when exposed to a laboratory source.

Comparisons have been made also between the Ångström 1905 scale and two other independent, so-called standard scales, one British and the other East German, both of which are claimed to be absolute, that is, to give radiant flux in watts/cm^2. A laboratory comparison between the British standard scale maintained at the National Physical Laboratory and a sub-standard representing the Ångström 1905 scale showed that the latter is lower by 0.5 percent. A series of intercomparisons, using the sun as source, were made in 1934 at Davos, Switzerland, between the absolute pyrheliometer (a calorimeter) maintained at Potsdam, Germany, and a sub-standard representing the Ångström 1905 scale. These studies showed that the Ångström 1905 scale was too low by 1 percent. Neither of these differences comes up to the 2 percent which according to the Stockholm Institute is the correction to be applied to the Ångström 1905 scale.

The International Radiation Conference held in 1956 at Davos, Switzerland, recommended the adoption of a new scale of radiation to replace the Smithsonian 1913 scale and the Ångström 1905 scale. This scale was adopted by the World Meteorological Organization, to be effective from January 1, 1957, and is known as the International Pyrheliometric Scale 1956, which we shall write as I. P. Scale 1956. By definition, to express pyrheliometric measurements on the I. P. Scale 1956, the measurements on the Ångström 1905 scale should be increased by 1.5 percent and the measurements on the Smithsonian 1913 scale should be decreased by 2.0 percent.

The relation between the I. P. Scale 1956 and the other scales is shown in the diagram below. Each circle represents a scale of radiation, and its relative distance to the right or to the left of the vertical line shows by what percentage the readings on that scale are higher or lower than the readings on the International Pyrheliometric (I. P.) Scale 1956. By definition of the I. P. Scale 1956, the Ångström 1905 scale is low by 1.5%, and the Smithsonian 1913 scale is high by 2.0%. The Smithsonian revision of 1932 makes the Smithsonian 1932 scale 0.5% lower than the I. P. Scale 1956. The Stockholm revision makes the corrected Ångström scale 0.5% higher than the I. P. Scale 1956. Both the British and German scales are lower than the I. P. Scale 1956.



These relatively large differences between the different scales should be borne in mind when comparing the values of the solar constant given by different authors.

As a question of special interest, on what scale is based the Johnson value, 2.00 cal/cm^2-min of the solar constant? What Johnson attempted was a revision of the Smithsonian data. According to the Smithsonian, the solar constant, on the scale of 1913 is 1.981 cal/cm^2-min. But readings on this scale are too high. Aldrich and Hoover (Reference 4) stated in a paper in 1952 by how much the value should be lowered; the amount is 2.37 percent, which is slightly less than the 2.5 percent of the 1932 revision. It is this correction that Johnson accepted as a starting point: 1.981 (1 - 0.0237) = 1.934. Thus the Johnson value is based on a scale 0.37 percent lower than the International Pyrheliometric Scale 1956.

ABSORPTION OF SOLAR RADIATION BY THE EARTH'S ATMOSPHERE

Most of the data for our present knowledge of solar radiation is based on measurements made from the surface of the earth. Hence it is important to know what fraction of the energy is abosrbed by the earth's atmosphere and in what wavelength ranges.

The section on "Solar Radiation" by Gast in the *Handbook of Geophysics* (Reference 7) presents the main results in several graphs and tables, from which Figure 3 and Table 1 are reproduced below. In Figure 3 are given four curves which are related to solar radiation. The lowest curve having a large number of sharp dips in the infrared is the spectral radiant flux as observed by an earth-based instrument when viewing solar radiation through "air mass one." "Air mass one" is the optical path equivalent to the earth's atmosphere at pressure of 760 mm, when the light penetrates the atmosphere in a direction normal to the earth's surface. A more general definition is: air mass m is the ratio of the optical path through the atmosphere of sunlight viewed at any given zenith angle to the optical path for normal incidence, or zenith angle zero; for zenith angles less than 75°, this ratio is nearly equal to the secant of the zenith angle.

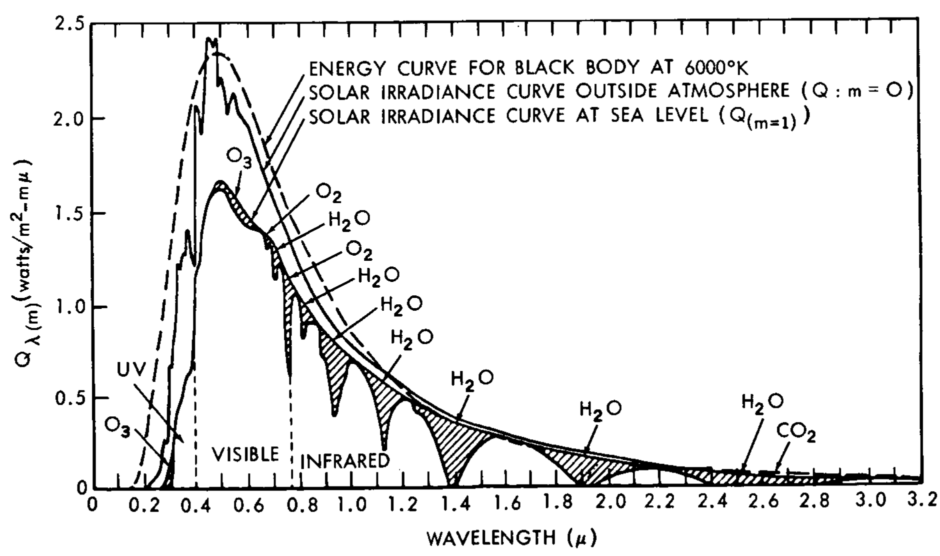


Figure 3—Curves of spectral radiant flux related to solar energy.

Table 1

Attenuation of Solar Radiation by the Earth's Atmosphere (Reference 7).

Pressure (mbar)	Altitude: Miles	Altitude: Thousand Feet	Altitude: Kilometers	Wavelength Regions: 0.12 to 0.20	0.20 to 0.29	0.29 to 0.32	0.32 to 0.35	0.35 to 0.55	0.55 to 0.9	0.9 to 2.5	2.5 to 7	7 to 20	Altitude	IUGG
0.2	37	200	60	O_2 Absorbs almost completely	Solar irradiation intensity approximates extra atmospheric. Attenuation by scattering increases markedly toward shorter wavelengths.								Above 60 km	110 km
7.5	20	108	33		(0.20 to 0.21 Absorption by O_2) Absorption by O_3 appreciable	O_3 absorption not important					Energy small	Energy very small	60 km to 33 km	CHEMO-SPHERE
227	6.8	36	11		No radiation penetrates below about 11 km	O_3 absorption attenuates more than loss by scattering.	O_3 absorption significantly attenuates radiation	Irradiation diminished mostly by scattering by permanent gases in atmosphere	H_2O responsible for major absorption; CO_2 absorbs slightly at 2. Water vapor (or ice crystals) is found up to about 70,000 feet.			Strong O_3 absorption at 9.6. Strong CO_2 absorption 12-17.	33 km to 11 km	20 km STRATO-SPHERE
795	1.2	6.6	2				Highly variable Dust, Haze (H_2O) (and Smoke) responsible for attenuation in regions 0.32 to 0.7.		Energy transmitted with small loss down to 2 km.	Energy penetrates to sea level only through "windows" at approximately 1.2, 1.6 and 2.2.	No significant penetration below 2 km except in "windows" at approximately 3.8 and 4.9.	Energy transmitted with moderate loss Many absorption bands due to atmospheric gases	11 km to 2 km	11 km TROPO-SPHERE
1013						Appreciable penetration through "clear" atmosphere to sea level: About 7% / About 30%	Penetration through "clear" atmosphere to sea level about 40%	Dust may rise to more than 4 km					2 km to sea level	0 km

Sea level

In Figure 3 the smoother curve shown above the experimentally observed curve is what the spectral distribution would be in the absence of the major absorption peaks of O_2, O_3, H_2O and CO_2. The third curve is the solar spectral radiant flux for air mass zero, based on Johnson's computation. A fourth curve, the blackbody radiation curve for 6000°K, is shown for purposes of comparison.

In Table 1 a detailed description is given of the attenuation of solar radiant flux due to the atmosphere at different altitudes and pressures, and for the major wavelength ranges of the spectrum. We observe that in the wavelength range above 0.29μ the solar flux at a height of 33 km is practically the same as that in the absence of all atmosphere. Nearly 99% of the mass of the total atmosphere is below this altitude. The factors which contribute to the absorption of energy are seen to vary considerably with wavelength and with altitude. In the visible range the energy losses due to ozone and the permanent gases in the atmosphere are small. From 11 down to 2 km, dust, haze, and smoke are the main causes of attenuation. Ozone and molecular oxygen absorb solar radiant flux of wavelengths less than 0.29μ in the altitude range 33 to 110 km.

More detailed information on the absorption of solar energy as viewed at different zenith angles is given in Figure 4 and Table 2. They give the results for different zenith angles in terms

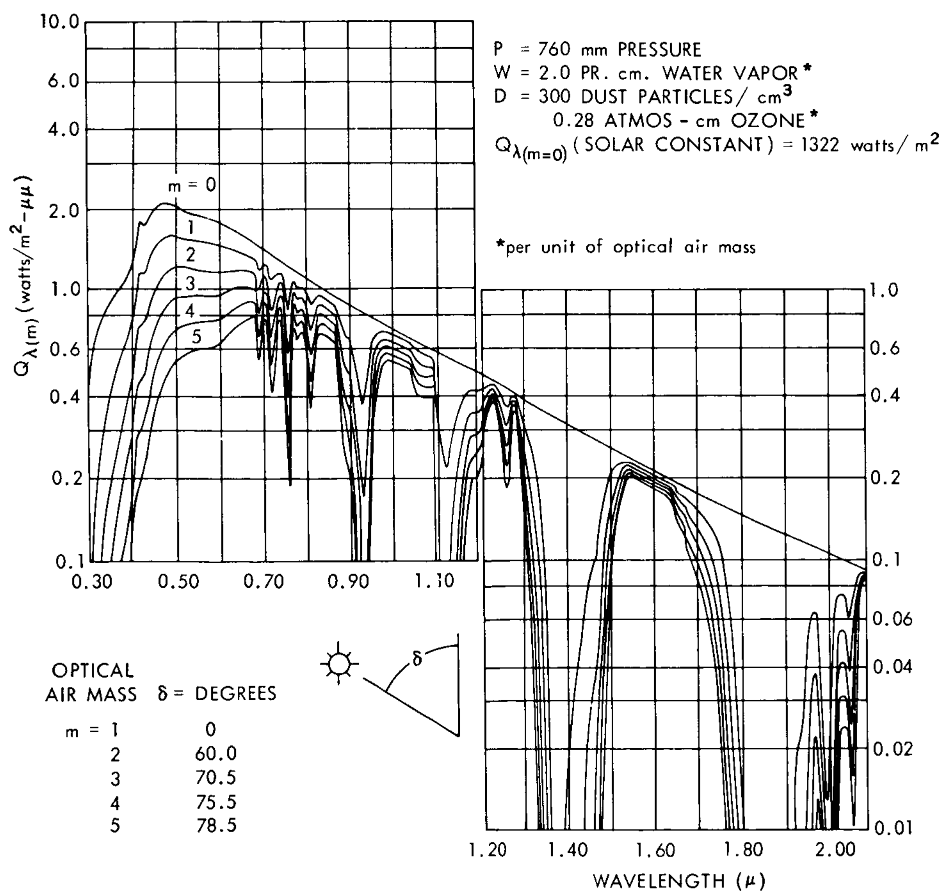


Figure 4—Solar spectral radiant flux at different zenith angles. (Energy on a logarithmic scale).

Table 2

Solar Radiant Flux in Spectral Bands Outside the Earth's Atmosphere, and at Sea Level, Calculated for Different Air Masses (Reference 7).

Bandwidth (μ)	Solar Radiant Flux (w/m^2)					
	0	1	2	3	4	5
0.29 - 0.40	94.6	40.1	19.8	10.0	5.4	2.7
0.40 - 0.70	540.0	419.7	327.8	258.6	205.8	163.7
0.70 - 1.1	365.4	309.2	267.5	233.4	205.1	181.5
1.1 - 1.5	162.5	95.3	70.7	57.0	48.1	40.7
1.5 - 1.9	72.8	50.8	45.1	41.0	38.0	35.2
1.9 - ∞	86.8	12.8	9.2	7.5	6.5	5.8
Total	1322.1	927.9	739.8	607.5	508.9	429.6

Table 3

Comparison of Calculated and Observed Solar Radiant Flux at Sea Level for Different Air Masses (Reference 7).

Bandwidth (μ)	$\frac{\text{calculated}}{\text{observed}}$ (percent)					
	0	1	2	3	4	5
0.29 - 0.40	102	83	83	83	86	100
0.40 - 0.77	97	97	95	93	91	89
0.77 - ∞	103	103	101	101	100	98
0.29 - ∞	100	96	97	96	94	93

of the optical air mass equal to 1, 2, 3, etc. These results are also based on the calculations of Moon as quoted by Gast.

It should be emphasized that there is a considerable amount of uncertainty in these calculations. In the intervening years since Moon's original work, more precise experimental data have been gathered for absorption due to each atmospheric constituent. But apparently very little work has been done for relating these findings to the solar spectral radiant flux and the solar constant.

The degree of error in the calculations is shown in Table 3 (which is also from Gast). The table gives the ratio of the calculated values to the observed values of the solar radiant flux at sea level in different wavelength ranges and for varying values of air mass. These ratios are not all equal to unity and hence it would seem there are large uncertainties in any attempt to extrapolate to zero air mass from ground-based observations made at different zenith agnles. Haze due to water molecules, dust, and carbon dioxide are factors depending on varying geographical locations, altitudes, time of the day, season of the year, etc. The attenuation of the energy due to the Rayleigh scattering in an inhomogeneous medium cannot be determined with a sufficient degree of accuracy. The law of Rayleigh scattering is in itself an approximation. The density, size, and scattering coefficients of the particles which interact with the radiation are too poorly known and too highly variable. Multiple scattering in a three dimensional volume presents a mathematical problem of great complexity. Hence arise the many sources of error.

SMITHSONIAN INSTITUTION, PARRY MOON

A contribution of major importance in our current knowledge of solar energy and its spectral distribution was made by Moon in 1940 (Reference 3). Moon's main purpose was to propose standard solar radiation curves for engineering use. He attempted to collate and compare available data on questions such as variation of solar illumination with seasons of the year, hours of the day, latitude of the location, height above sea level, etc. In doing so, Moon made a systematic study of the absorption effect of the atmosphere and the spectral distribution of radiant flux outside the atmosphere.

By far the greatest amount of work on solar spectral radiant flux had been done by the Smithsonian Institution of Washington. The work was extended over a period of several years. Smithsonain's best result was believed to be the weighted mean of the 1920 and 1922 measurements. Figure 5, reproduced from Moon, indicates the Smithsonian data of 1920-22 by circles and the dotted curve. Three other sets of Smithsonian data shown in the figure are from earlier periods — 1903 to 1918. Moon compares these values with those from three independent sources, Wilsing's measurements made at Potsdam (Reference 16), Pettit's measurements (Reference 17), and those of Fabry and Buisson (Reference 18). The data of Figure 5 are in arbitrary units on a log-log

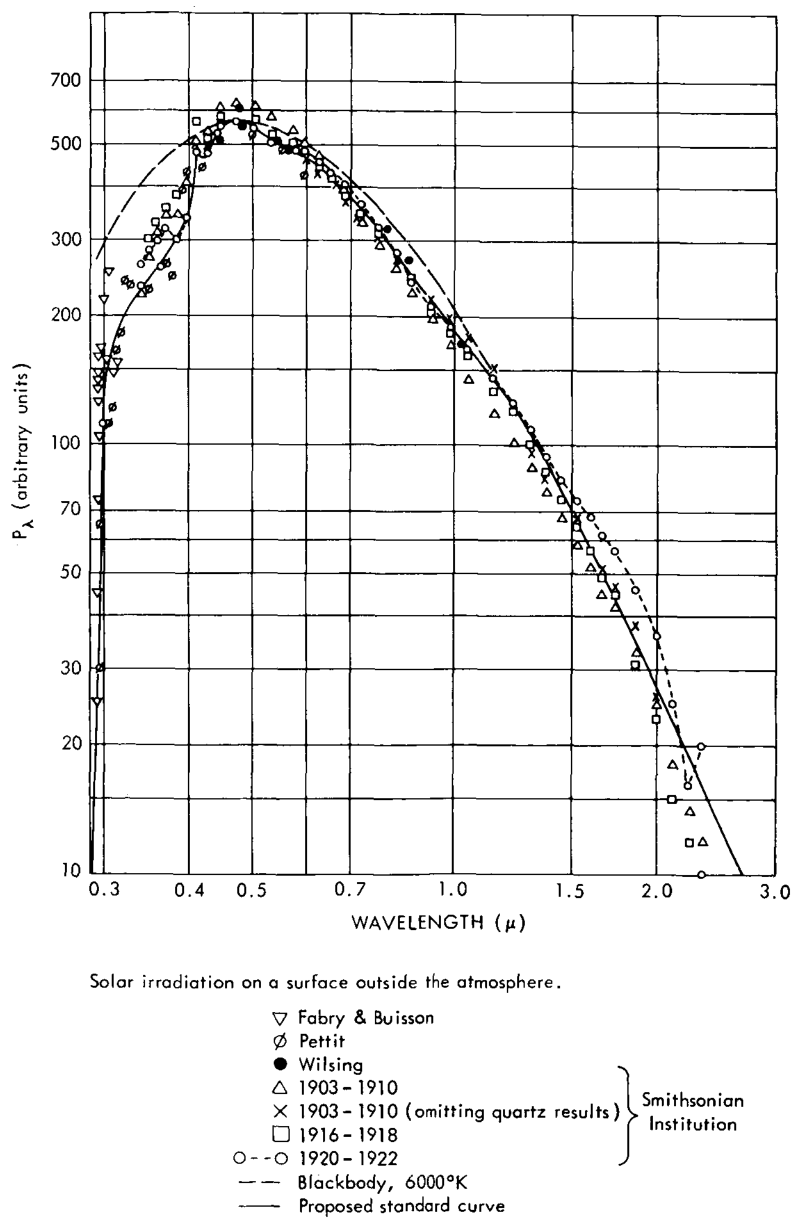


Figure 5—Parry Moon's curve of solar spectral radiant flux for air mass zero — Comparison of Smithsonian data with other data.

Table 4
Solar Spectral Radiant Flux for Air Mass Zero
(Parry Moon's data) Solar constant = 1322 w/m^2.

λ (μ)	P_λ (watt/m^2 μ)	λ (μ)	P_λ (watt/m^2 μ)	λ (μ)	P_λ (watt/m^2 μ)
0.290	0	0.400	1304	1.0	706
0.291	190	0.405	1427	1.1	590
0.292	250	0.410	1728	1.2	488
0.293	289	0.413	1803	1.3	395
0.294	318	0.420	1766	1.4	319
		0.424	1742		
0.295	345	0.430	1788	1.5	260
0.296	368	0.440	1939	1.6	214
0.297	389			1.7	177
0.298	410	0.45	2036	1.8	148
0.299	430	0.46	2096	1.9	124
		0.47	2119		
0.300	450	0.48	2127	2.0	105
0.301	470	0.49	2103	2.1	89.3
0.302	489			2.2	76.4
0.303	507	0.50	2061	2.3	65.8
0.304	524	0.51	2000	2.4	56.9
		0.52	1954		
0.305	540	0.53	1912	2.5	49.5
0.306	556	0.54	1894	2.6	43.2
0.307	571			2.7	37.9
0.308	586	0.55	1878	2.8	33.4
0.309	601	0.56	1861	2.9	29.5
		0.57	1841		
0.310	616	0.58	1819	3.0	26.1
0.311	628	0.59	1795	3.1	23.3
0.312	640			3.2	20.8
0.313	652	0.60	1762	3.3	18.6
0.314	664	0.61	1727	3.4	16.6
		0.62	1690		
0.315	676	0.63	1653	3.5	14.9
0.316	686	0.64	1616	3.6	13.5
0.317	696			3.7	12.2
0.318	706	0.65	1579	3.8	11.1
0.319	716	0.66	1543	3.9	10.1
		0.67	1508		
0.320	726	0.68	1473	4.0	9.20
0.325	762	0.69	1439	4.1	8.44
0.330	796			4.2	7.75
0.335	826	0.70	1405	4.3	7.10
0.340	856	0.71	1371	4.4	6.50
0.345	886	0.72	1337		
		0.73	1304	4.5	5.93
0.350	916	0.74	1270	4.6	5.44
0.360	976			4.7	4.99
0.370	1046	0.75	1236	4.8	4.62
0.380	1121	0.80	1097	4.9	4.32
0.390	1202	0.85	976		
		0.90	871	5.0	4.06
		0.95	781		

graph, and thus we may shift the sets of points up or down to secure maximum agreement among all the different measurements. The blackbody curve shown in the graph is for 6000°K. This temperature was chosen because the maximum of the 6000°K blackbody curve is at about the same wavelength as that of the curve of the Smithsonian data of 1920-22.

All the data presented in Figure 5 agree in showing a narrow peak at 0.48μ and a depression at 0.55μ. However, in the region from 0.60 to 0.75μ the Smithsonian 1920-22 curve is higher than all the other curves, and in the region from 0.85 to 1.0μ it is lower. Hence Moon's proposed standard curve agrees with the Smithsonian 1920-22 curve in the shorter wavelength range from 0.40 to 0.55μ, but departs slightly from it at longer wavelengths. At wavelengths shorter than 0.40μ, Moon preferred the values of Pettit for the range 0.32 to 0.40μ, and those of Fabry and Buisson for the range below 0.32μ. The Smithsonian values in this low wavelength range are apparently too high due to scattered radiation in the monochromator.

Table 4 gives Moon's values for spectral radiant flux of the sun at the earth's average distance for zero air mass. The wavelengths are in microns; the radiant-flux P_λ is in watts/meter^2μ. The total area under the $P_\lambda - \lambda$ curve is 1322 watts/m^2 which was Moon's revised estimate of the solar constant. For a comparison of Moon's results of Table 4 and Figure 5 with the recent results of F. Johnson all values of P_λ given by Moon should be multiplied by 1.026, which is the ratio of the Johnson's and Moon's values of the solar radiant flux in the wavelength range of Moon's table.

In the wavelength range 0.50 to 1.0μ, the depression of the solar curve seemed so well established that Moon felt there was no justification for following the Planckian curve in this range. In the range beyond 1.25, the blackbody curve at 6000°K seemed sufficiently close to all available experimental data other than the Smithsonian 1920-22 data; and hence the P_λ values in Moon's table for wavelengths greater than 1.25μ are those of 6000°K blackbody radiation. In the range beyond 2.5μ experimental data were scarce. Water vapor and carbon dioxide have strong absorption bands in this range so that the extrapolation of ground-based measurements to zero air mass is subject to large errors. Abbot, Aldrich and Fowle (Reference 19) had estimated that the radiant-flux in the wavelength range 2.5μ to infinity is only about 2 percent of the total. Moon concluded 2 percent is too low a value to affect the final results, and hence suggested a Planckian curve of 6000°K as the best fit for the solar radiant flux in the range beyond 2.5μ .

NATIONAL BUREAU OF STANDARDS, STAIR AND JOHNSTON

Ralph Stair and Russell G. Johnston made in 1955 (Reference 6) and earlier years a series of extensive measurements of the spectral radiant flux of the sun. They attempted to eliminate some of the major sources of error of the Smithsonian data. The authors observe that in the Smithsonain work the solar beam was reflected into a spectrobolometer by a metal-coated mirror whose reflectivity was subject to change with age. The light is incident on the mirror at different angles, which introduces another factor of uncertainty in the reflection coefficient of the mirror. The solar image is focused on the slit of the spectrograph, and hence the spectrograph views only a very small portion of the solar disc at a given time. Large and rather uncertain correction factors are invloved in calculating the energy of whole solar disc from such measurements.

Another source of error in the Smithsonian data is that a pyrheliometer is used to integrate the energy of the entire spectrum and to obtain the result in absolute units. This involves several assumptions based on inadequate observational data concerning the absorption of energy by the atmosphere and the spectral limit of the pyrheliometer.

Stair and Johnston adopted an experimental arrangement which automatically eliminated several of these sources of error. The apparatus was set up at a location where the effects of the atmospheric absorption were considerably less than at sea level in a densely populated city. The location chosen was Sunspot, New Mexico, at an altitude of 9200 feet. The spectrum was scanned by a Leiss double quartz prism spectrograph. It was mounted on the polar axis and driven across the sky. Hence the corrections for oblique incidence of light on heliostat mirrors could be eliminated. A specially designed amplifier circuit ensured a high degree of linearity of response. Tungsten ribbon standard lamps calibrated at the National Bureau of Standards were used to reduce the readings to absolute intensity values.

Measurements were made on four days, June 3, 4, 6, and 7, 1955, in the spectral range 0.3 to 0.54μ . On four other days, June 16, 17, 18, and 19, measurements were made in the range 0.32 to 2.6μ . The effect of atmospheric attenuation was determined by the conventional method of assuming that the pathlength through the atmosphere is proportional to the secant of the zenith angle. A complete discussion of the methods of data reduction are given in various publications of Stair and his coworkers (References 6, 20-22).

Table 5

Stair and Johnston's Data for Solar Spectral Radiant Flux for Air Mass One and Air Mass Zero; λ in millimicrons or nanometers; Spectral Radiant Flux in μw/cm^2 per 10 millimicrons.

1	2	3	4	5	6	7	8
Wave-length (mμ)	June 3 Air mass 1.00	June 4 Air mass 1.00	June 6 Air mass 1.00	June 7 Air mass 1.00	Mean Air mass 1.00	M_0 factor	I_0 Air mass 0
299.5	--------	--------	--------	--------	5.3	45	241
300.7	--------	--------	--------	--------	11.1	34	377
302.5	16.3	--------	--------	16.7	16.5	18.5	306
304	40.0	36.5	42.9	43.2	40.6	11.6	472
305.5	--------	--------	--------	--------	64.3	9.00	579
306	60.0	56.2	62.7	65.6	61.1	8.20	501
309.2	--------	--------	--------	--------	112	5.39	602
310	101	98	108	105	103	4.97	514
311.3	--------	--------	--------	--------	194	4.40	852
312	180	177	190	183	182	4.13	752
314	--------	--------	--------	--------	233	3.62	843
314.9	--------	--------	--------	--------	225	3.43	772
315.8	--------	--------	--------	--------	245	3.22	789
316.5	209	213	214	208	211	3.11	658
317.9	--------	--------	--------	--------	319	2.88	920
318.5	275	272	284	274	276	2.78	769
319.8	--------	--------	--------	--------	303	2.60	788
321.1	--------	--------	--------	--------	374	2.46	921
321.7	--------	--------	--------	--------	342	2.40	821
322.8	--------	--------	--------	--------	351	2.31	811
323.5	320	320	328	321	322	2.25	725
325.5	--------	--------	--------	--------	404	2.15	867
327.5	--------	--------	--------	--------	548	2.08	1,141
328.5	524	520	526	517	522	2.06	1,075
330.3	--------	--------	--------	--------	640	2.00	1,278
331.5	588	584	579	572	581	1.96	1,139
332.9	--------	--------	--------	--------	585	1.93	1,129
333.6	--------	--------	--------	--------	573	1.91	1,094
335.3	--------	--------	--------	--------	612	1.88	1,151
337	544	543	543	534	541	1.85	1,001
340.8	--------	--------	--------	--------	686	1.78	1,220
341.7	--------	--------	--------	--------	653	1.77	1,156
343.5	--------	--------	--------	--------	696	1.745	1,214
344.1	587	586	585	577	584	1.73	1,010
348.5	--------	--------	--------	--------	666	1.69	1,125
351.5	--------	--------	--------	--------	760	1.66	1,261
352.6	--------	--------	--------	--------	710	1.65	1,171
355.1	--------	--------	--------	--------	845	1.625	1,373
358.1	597	600	608	590	599	1.60	958
360	--------	--------	--------	--------	801	1.585	1,269

Table 5 (Continued)

1	2	3	4	5	6	7	8
Wave-length ($m\mu$)	June 3 Air mass 1.00	June 4 Air mass 1.00	June 6 Air mass 1.00	June 7 Air mass 1.00	Mean Air mass 1.00	M_0 factor	I_0 Air mass 0
360.9	739	696	751	734	730	1.575	1,150
363.6	--------	--------	--------	--------	814	1.555	1,265
366.4	--------	--------	--------	--------	987	1.53	1,509
367.8	--------	--------	--------	--------	928	1.52	1,411
370	--------	--------	--------	--------	974	1.51	1,471
373.5	769	774	778	758	770	1.48	1,139
378.2	--------	--------	--------	--------	1,085	1.46	1,583
380	--------	--------	--------	--------	968	1.45	1,403
382.3	--------	--------	--------	--------	966	1.44	1,392
381	--------	--------	--------	--------	653	1.43	932
387	--------	--------	--------	--------	846	1.42	1,202
391	--------	--------	--------	--------	1,086	1.40	1,521
393.4	683	689	688	680	685	1.39	952
396	--------	--------	--------	--------	955	1.375	1,314
396.9	--------	--------	--------	--------	805	1.37	1,103
403.5	--------	--------	--------	--------	1,514	1.34	2,029
406.4	1,414	1,434	1,424	1,395	1,417	1.33	1,884
410.2	--------	--------	--------	--------	1,426	1.31	1,868
416.7	--------	--------	--------	--------	1,495	1.295	1,937
420.7	--------	--------	--------	--------	1,500	1.28	1,920
423.5	--------	--------	--------	--------	1,429	1.27	1,815
427.2	1,182	1,201	1,196	1,177	1,189	1.26	1,498
432.5	--------	--------	--------	--------	1,361	1.25	1,701
438.3	1,454	1,454	1,448	1,431	1,447	1.24	1,794
440.5	--------	--------	--------	--------	1,610	1.23	1,980
450.8	1,732	1,743	1,732	1,711	1,730	1.22	2,110
455.6	--------	--------	--------	--------	1,732	1.205	2,087
465	1,725	1,740	1,709	1,694	1,717	1.19	2,043
482	--------	--------	--------	--------	1,843	1.18	2,175
487	1,702	1,711	1,694	1,675	1,695	1.175	1,992
497	--------	--------	--------	--------	1,871	1.17	2,188
500	1,851	1,856	1,843	1,813	1,841	1.17	2,154
509	--------	--------	--------	--------	1,900	1.16	2,204
518	1,778	1,781	1,778	1,742	1,770	1.155	2,044
527	--------	--------	--------	--------	1,892	1.15	2,175
530	1,932	1,959	1,950	1,913	1,938	1.15	2,229
535	--------	--------	--------	--------	1,865	1.15	2,145

In Table 5 the results of the four days of observations of the solar spectral radiant flux in the range 0.3 to 0.54μ are given. The M_0 factor in column 7 is the ratio of the flux for air mass zero to the flux for unit air mass. The values of columns 6 and 8 are shown graphically in Figure 6.

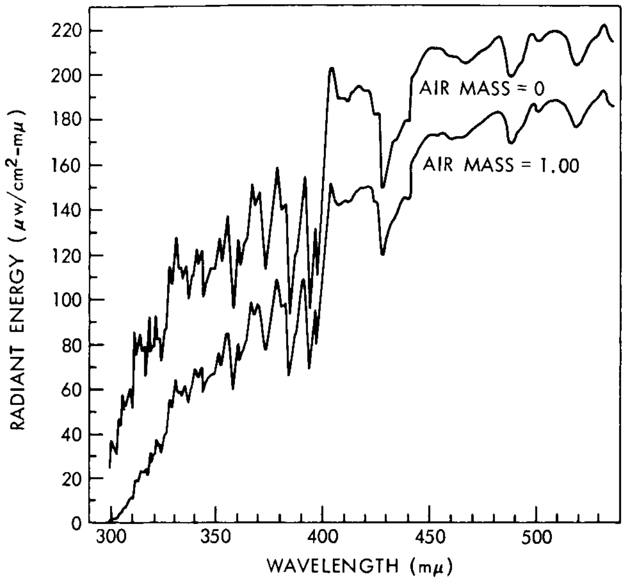


Figure 6—Solar spectral radiant flux for air mass zero and air mass one (Stair and Johnston).

The solar constant is calculated from the area under the spectral radiant flux curve for zero air mass. The experimental curve is for the actual sun-earth distance at the time of the measurement. No data for the spectral radiant flux are experimentally available for the ultraviolet range below 0.3μ or for the infrared range above 2.6μ. For the ultraviolet, the curve is arbitrarily assumed to drop down to zero at about 0.2 or 0.22μ. A correction factor of 0.06 calories per/cm^2-min is assumed to be the probable solar energy of wavelength beyond 2.5μ, based on a blackbody curve at the solar temperature. With the addition of these correction factors, the value of the solar constant is 2.05 cal/cm^2-min.

According to the authors this value is probably correct to within 5 percent, and "is in general agreement with recent estimates, being a little higher than those usually reported by the Smithsonian Institution." Johnson's value is 2.00 cal/cm^2-min which is only 2.5 percent less than Stair's value, and hence well within the percentage accuracy claimed by Stair. The infrared correction of 0.06 cal/cm^2-min assumed by Stair is 2.93 percent of the total, and is slightly below Johnson's estimate for this range, which is .065 cal/cm^2-min or 3.27 percent of the total.

In their discussion of the data, Stair and Johnston stress the complicated nature of the steps involved in gathering and evaluating the measurements. There are numerous sources of uncertainty and error. Hence the accuracy cannot be better than plus or minus a few percent. They also observe that the results they obtained at Sunspot were slightly different from those they had reported earlier from their measurements at Climax (Reference 21) and at Sacramento Peak (Reference 22). This should probably be attributed to improvements in experimental technique, or may also be due to solar changes within the interval. Another important source of uncertainty which the authors have stressed is the radiometric standard. The values currently adopted for the spectral emissivity of tungsten are subject to revision, and such revision, if later found necessary, will alter the values of the solar constant and the solar spectral radiant flux.

Stair and Johnston's final results for the integrated spectral radiant flux are given in Table 6. These results were reached in two steps. First the area under the spectral energy distribution curve for zero air mass is integrated for small finite wavelength regions. Next a correction is made by multiplying the values by 1.0294 to give the energy at the earth's mean distance from the sun. These integrated values are based on the data for four days for the range 0.3 to 0.54μ, and the data for four other days for the range 0.32 to 2.60.

Table 6

Stair and Johnston's Data for Solar Spectral Radiant Flux for Air Mass Zero, Integrated over Finite Wavelength Ranges; Wavelength in millimicrons gives the Center of the Range of Integration; Radiant Energy is in μw/cm^2.

Center of wavelength interval (mμ)	Radiant energy (μw/cm^2)	Center of wavelength interval (mμ)	Radiant energy (μw/cm^2)	Center of wavelength interval (mμ)	Radiant energy (μw/cm^2)
300	1,857	497.5	1,089	865	1,005
302.5	200	502.5	1,084	875	985
307.5	279	507.5	1,100	885	968
312.5	378	512.5	1,096	895	948
317.5	388	517.5	1,043	905	930
322.5	410	522.5	1,050	915	911
327.5	521	527.5	1,097	925	894
332.5	578	535	2,113	935	876
337.5	548	545	2,138	945	859
342.5	586	555	2,113	955	842
347.5	551	565	2,086	965	826
352.5	621	575	2,053	975	809
357.5	585	585	2,018	985	793
362.5	613	595	1,982	995	778
367.5	624	605	1,944	1,005	762
372.5	665	615	1,906	1,015	746
377.5	691	625	1,868	1,025	732
382.5	666	635	1,829	1,035	718
387.5	592	645	1,790	1,045	703
392.5	623	655	1,754	1,055	689
397.5	696	665	1,707	1,065	675
402.5	1,009	675	1,662	1,075	661
407.5	940	685	1,614	1,085	646
412.5	947	695	1,564	1,095	632
417.5	972	705	1,513	1,150	5,707
422.5	929	715	1,463	1,250	4,715
427.5	818	725	1,415	1,350	3,916
432.5	869	735	1,367	1,450	3,194
437.5	923	745	1,321	1,550	2,541
442.5	1,021	755	1,278	1,650	1,951
447.5	1,058	765	1,242	1,750	1,446
452.5	1,054	775	1,213	1,850	1,102
457.5	1,049	785	1,187	1,950	947
462.5	1,050	795	1,164	2,050	830
467.5	1,027	805	1,139	2,150	711
472.5	1,035	815	1,115	2,250	653
477.5	1,061	825	1,093	2,350	593
482.5	1,072	835	1,069	2,450	558
487.5	1,000	845	1,047		
492.5	1,055	855	1,025		

Total μw/cm^2 for wavelengths shorter than 2,500 mμ = 139,164
Total gram-calories/cm^2 min for wavelengths shorter than 2,500 mμ = 1.99
Correction for wavelengths longer than 2,500 mμ = 0.06
Total value of solar constant, Q = 2.05

NAVAL RESEARCH LABORATORY, DUNKELMAN AND SCOLNIK, AND FRANCIS JOHNSON

Another set of measurements which should be reviewed in some detail were made by Dunkelman and Scolnik. The measurements were made in 1951 but were not reported in detail until eight years later in 1959 (Reference 2). The conventional method used by Stair, Moon, and earlier workers was adopted to extrapolate from ground-based measurements to zero air mass. The observation station was situated on the top of a flat rock, at an elevation of 8025 feet, on Mount Lemmon, near Tucson, Arizona. But it was a real disappointment to the observers that the sky above Mount Lemmon was overcast with clouds during most of the period (September 20 to October 17, 1951) which they spent on the mountaintop. Usable data were obtained only on one day, October 4. On that day a total of 25 spectral scans were made at different times from early morning through late in the evening.

The spectrum was produced and the energy scanned by a Leiss quartz double monochromator, detected by a 1P21 photomultiplier, amplified and presented on a strip chart recorder. The wavelength range covered was from 0.303μ to 0.700μ, the only range where the 1P21 detector is sufficiently sensitive. The measurements were restricted to this small range of about 0.4μ, partly because this range contains 48% of the total solar energy, though on the wavelength scale, it is only 8 percent of the solar spectral range (zero to 5μ). The major purpose of the observers was not to chart the entire spectrum or to evaluate the solar constant, but to provide a calibration standard whereby the relative measurements of the rocket data collected by the Naval Research Laboratory in the little known ultraviolet range could be reduced to absolute values of radiant energy.

The equipment was calibrated frequently by recording the spectrum of the tungsten lamp. The tungsten lamp which operated at a temperature of 2800°K had previously been calibrated at the National Bureau of Standards with reference to a blackbody, in accordance with the Bureau's well established procedure. There is no reason to doubt the NBS calibration technique and it was decidedly the best available at that time. However, it should be noted that the NBS did not claim an accuracy better than 5% for its calibration table. The method which was used in 1951 involved a series of difficult calculations from the color temperature to the true temperature, and thence through blackbody radiation functions and spectral emmissivity curves of tungsten to the spectral radiance of the tungsten ribbon as viewed through a quartz window. The method has since been replaced; and the calibration tables now being supplied give the spectral radiance at selected wavelengths.

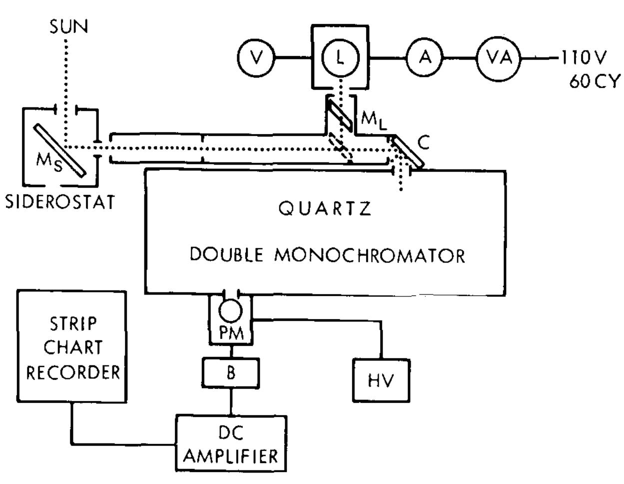


Figure 7—Block diagram of the apparatus (Dunkelman and Scolnik).

A block diagram of the apparatus used by Dunkelman and Scolnik is given in Figure 7.

Light from the sun or from the standard source is introduced into the Leiss double monochromator from the magnesium carbonate block C. The lamp current and voltage are monitored continuously by means of a voltmeter V and ammeter A, and adjusted when necessary by a variac VA. The mirror M_L is interposed in the path of the beam from the siderostat when a calibration run is to be made. The signals are recorded by a strip chart recorder through a photomultiplier and a DC amplifier. A bucking box B serves to subtract the dark current.

The final results of Dunkelman and Scolnik are presented in Tables 7 and 8.

In both these tables the wavelength is in angstroms, and the energy is in microwatts/cm^2-A, for zero air mass and for the average distance of the earth from the sun. The wavelengths in Table 7 were selected in order to present all the identifiable features of the solar energy distribution, and in particular, the Fraunhofer absorption lines. These data are too detailed for many purposes, and do not permit a ready comparison of the results with those of other observers. Hence, values of integrated solar spectral radiant flux were obtained by averaging the detailed curve over 100A intervals, taking points separated by 10A. These values are presented in Table 8.

A major contribution of Dunkelman and Scolnik was the detailed comparative study they made of the data obtained by different observers. The results of this study are given in Figures 8, 9, and 10.

In Figure 8 the better known measurements from the entire solar disk made prior to 1949 are given. The Smithsonian data (References 14 and 23) are usually shown in relative units only, though they are basically absolute. Pettit (Reference 20) normalized his spectral solar irradiance data to agree with those of the Smithsonian at 0.45μ . In Figure 8, both the Smithsonian and Pettit's

Table 7

Dunkelman and Scolnik's Data on Solar Spectral Radiant Flux (denoted by H_λ) for Air Mass Zero.

λ	H_λ	λ	H_λ	λ	H_λ	λ	H_λ	λ	H_λ	λ	H_λ
3032	7.3	3221	8.1	3456	11.2	3807	13.5	4380	20.1	5380	19.7
3052	7.7	3225	7.5	3470	11.3	3830	9.2	4390	19.4	5450	20.0
3056	7.1	3242	8.9	3508	12.7	3848	12.1	4439	22.0	5525	19.4
3078	6.9	3255	12.7	3522	11.3	3870	10.4	4546	22.0	5604	19.0
3086	7.3	3279	11.1	3550	13.1	3908	13.4	4640	21.4	5700	18.8
3088	6.5	3301	13.2	3585	9.2	3933	8.6	4720	21.9	5758	18.7
3116	8.4	3308	11.5	3600	13.0	3950	12.2	4808	21.5	5800	18.7
3118	7.9	3322	11.3	3610	11.0	3968	10.1	4850	20.3	5842	18.4
3141	8.3	3330	11.3	3637	12.0	4019	19.4	4948	20.7	5980	18.2
3152	8.3	3335	11.2	3668	14.4	4062	18.5	5002	19.5	6021	18.0
3158	6.8	3368	10.4	3683	13.9	4094	20.0	5088	20.0	6122	17.1
3168	9.7	3380	11.3	3698	13.0	4140	19.6	5174	18.7	6280	16.6
3182	7.5	3410	12.3	3716	13.5	4190	18.2	5230	19.4	6500	15.9
3192	8.1	3414	11.7	3740	10.9	4220	20.2	5260	19.1		
3204	9.4	3430	11.9	3752	11.5	4272	19.0	5312	19.5		
3212	7.2	3442	10.3	3780	14.5	4300	16.1				

Table 8

Dunkelman and Scolnik's Data on Integrated Solar Spectral Radiant Flux (denoted by H_λ) for Air Mass Zero. λ in A; H_λ in microwatts/cm^{-2} A.

λ	H_λ	λ	H_λ	λ	H_λ	λ	H_λ	λ	H_λ	λ	H_λ
3080	7.4	3310	11.5	3540	11.6	3770	12.8	4000	15.4	4230	19.2
3090	7.5	3320	11.3	3550	11.7	3780	12.5	4010	16.0	4240	19.0
3100	7.6	3330	11.2	3560	11.6	3790	12.3	4020	16.7	4250	18.9
3110	7.6	3340	11.2	3570	11.5	3800	12.4	4030	17.5	4260	18.7
3120	7.8	3350	11.2	3580	11.5	3810	12.4	4040	18.2	4270	18.4
3130	8.0	3360	11.1	3590	11.5	3820	12.2	4050	18.8	4280	18.2
3140	8.0	3370	11.2	3600	11.6	3830	12.0	4060	19.1	4290	17.9
3150	8.2	3380	11.2	3610	11.7	3840	11.7	4070	19.3	4300	17.8
3160	8.3	3390	11.2	3620	11.9	3850	11.6	4080	19.3	4310	17.7
3170	8.3	3400	11.1	3630	12.2	3860	11.6	4090	19.3	4320	17.8
3180	8.2	3410	11.1	3640	12.6	3870	11.4	4100	19.4	4330	17.8
3190	8.3	3420	11.3	3650	13.0	3880	11.2	4110	19.4	4340	17.9
3200	8.5	3430	11.5	3660	13.1	3890	11.2	4120	19.4	4350	18.2
3210	8.9	3440	11.6	3670	13.3	3900	11.4	4130	19.4	4360	18.6
3220	9.2	3450	11.6	3680	13.4	3910	11.3	4140	19.3	4370	19.0
3230	9.4	3460	11.7	3690	13.3	3920	11.2	4150	19.2	4380	19.4
3240	9.8	3470	11.6	3700	13.3	3930	11.4	4160	19.1	4390	19.9
3250	10.3	3480	11.6	3710	13.2	3940	11.6	4170	19.2	4400	20.2
3260	10.5	3490	11.6	3720	13.2	3950	11.9	4180	19.2	4410	20.6
3270	10.8	3500	11.8	3730	13.2	3960	12.4	4190	19.2	4420	20.9
3280	11.1	3510	12.0	3740	13.2	3970	13.0	4200	19.2	4430	21.1
3290	11.4	3520	12.0	3750	13.2	3980	13.7	4210	19.2	4440	21.3
3300	11.6	3530	11.8	3760	13.1	3990	14.7	4220	19.2	4450	21.5

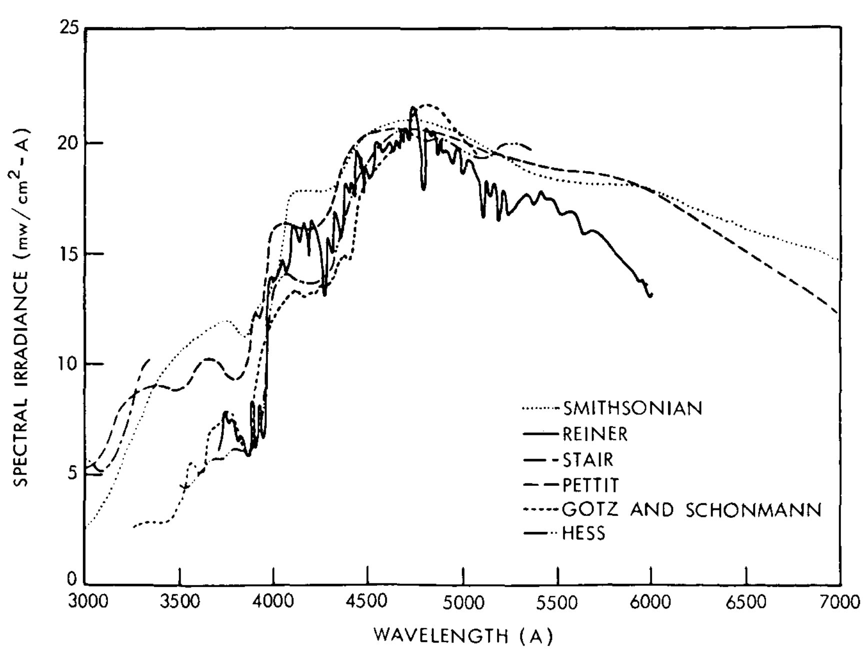


Figure 8—Data on solar spectral radiant flux prior to 1949 (Dunkelman and Scolnik).

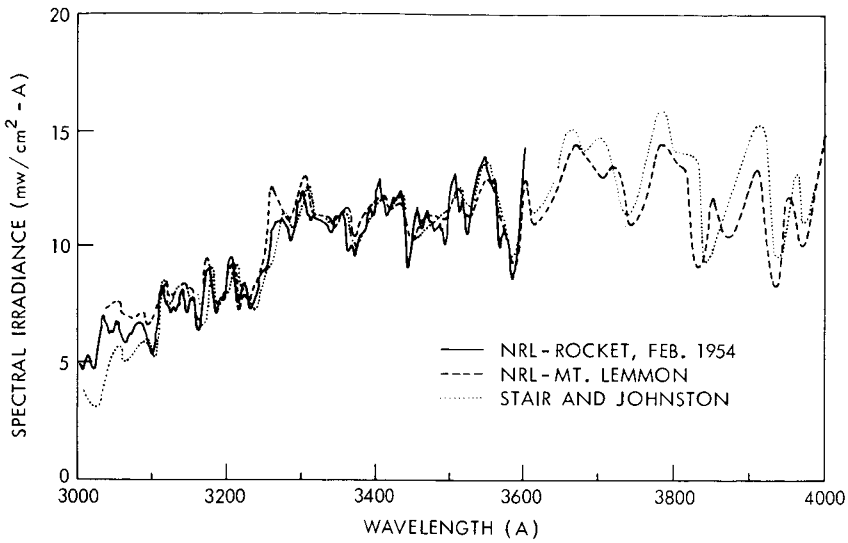


Figure 9—Comparison of NRL data with those of Stair, and Johnston in the range 3000 to 4000A (Dunkelman and Scolnik).

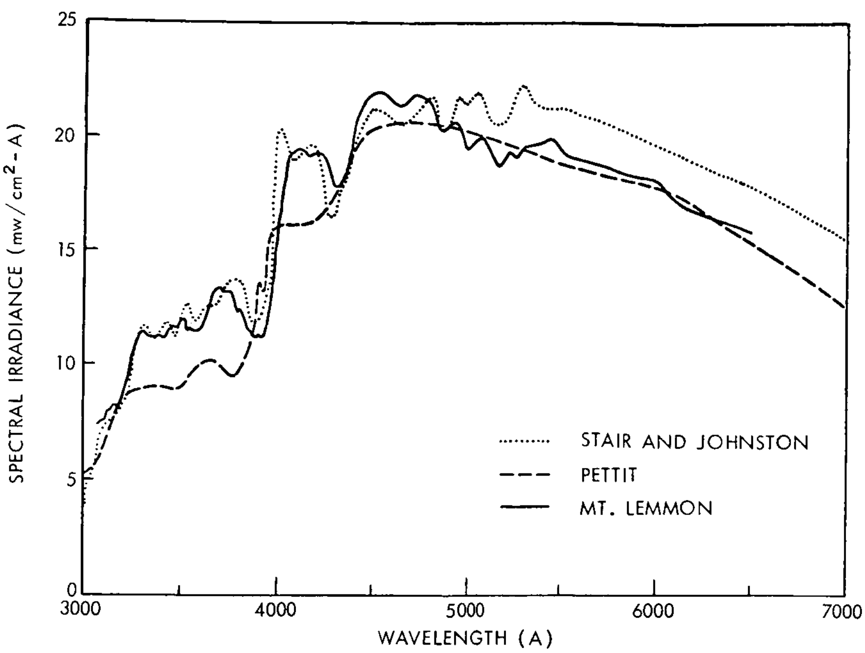


Figure 10—Comparison of the data of NRL, Pettit, and Stair and Johnston in the range 3000 to 7000A — Integrated values for the range below 4500A (Dunkelman and Scolnik).

curves have been readjusted downward to make them conform to the new absolute energy values for the solar spectrum given in the Ninth Revised Edition of the Smithsonian Physical Tables (Reference 25). The short curve for the range 0.3 to 0.33 μ is based on Stair's absolute measurements of 1947 (Reference 26). The data of Hess (Reference 27), Reiner (Reference 28), and Gotz and Schonmann (Reference 29) were published only as curves of relative intensity distribution.

Dunkelman and Scolnik normalized these curves against Pettit's at 0.4725μ in order to make a meaningful comparison. The large differences in the wavelength range below 0.4μ are probably due to stray light in the spectrograph, uncertainties in the calibration of the tungsten standard, and errors in the extrapolation to zero air mass in a wavelength range of high absorption.

In Figure 9 the data from the measurements of Dunkelman and Scolnik in the range 0.3 to 0.4μ are compared with those from two other sets of measurements made in more recent years. Dunkelman and Scolnik's data are referred to in Figure 9 as NRL-Mt. Lemmon. The continuous curve, referred to as NRL-Rocket, February 1954, is based on data obtained by Purcell and Tousey from the analysis of a solar spectrum photographed from a rocket at 104 km altitude on February 22, 1954. These measurements are relative and were normalized against the NRL-Mt. Lemmon curve at 0.36μ. The dotted curve is based on the 1955 measurements of Stair and Johnston (Reference 6) which were described earlier; it is in fact the upper curve of Figure 6 on an expanded wavelength scale.

A comparison of Dunkelman and Scolnik's measurements over the whole wavelength range of their data (0.3 to 0.7μ) with those of Pettit and of Stair and Johnston is made in Figure 10. The curves are based on integrated energy values and hence do not show the finer details which may be seen in Figures 6 and 9. The energy values were averaged over 100A intervals, taking points separated in wavelength by 10A. As may be seen readily from Figure 10, Stair and Johnston's curve agrees closely with that of Dunkelman and Scolnik in the wavelength range below 0.5μ, whereas Pettit's values are lower by about 25%. In the range above 0.5μ, the results of Stair and Johnston are high, whereas those of Dunkelman and Scolnik and of Pettit are in fairly close agreement. According to Stair and Johnston's data given in Table 6, P_λ at 0.6μ is 1.963 μw/cm^2-A, and according to Dunkelman and Scolnik's data given in Table 7, P_λ at 0.6μ is 1.81 μw/cm^2-A. The difference is approximately 12% and this large difference occurs in a wavelength range which might be considered the most favorable for accurate solar energy measurement. This is a range where solar energy is high, atmospheric absorption is low, detectors are highly sensitive and the tungsten standard is sufficiently strong. Concerning this difference, however, Dunkelman and Scolnik (Reference 2) made the following observation: "The results of Stair between 5000 and 7000A are high, and are not in agreement with any previous work, including his own earlier measurements. Furthermore, they lead to a value of the extra-terrestrial illuminance that is higher than the recent measurement of Karandikar [Reference 30] and most previous solar illuminance measurements."

Francis S. Johnson and his coworkers at the Naval Research Laboratory undertook a major revision of the solar constant and of the solar spectral radiant flux. This work was stimulated by the new measurements (in the range 0.22 to 0.34μ) made by rocket-borne spectrographs (References 31 and 32) and by the Mt. Lemmon data of Dunkelman and Scolnik (Reference 2). Johnson's discussion of this revision was reported in 1954 in the *Journal of Meteorology* (Reference 1). In 1957 an abridged report was published by R. Tousey in *Nuovo Cimento* (Reference 33). Johnson used as a starting point the measurements which had been made for nearly half a century by the Smithsonian Institution and which had served as the basis for Moon's earlier investigation. A number of corrections are involved in deriving the solar constant from the Smithsonian data, and

Johnson attempted to re-evaluate these corrections with the aid of the more recent NRL data.

In Figure 11 a block diagram is given which shows the major steps in the Smithsonain procedure. There are two independent measuring instruments, one a pyrheliometer which measures the total energy without any spectral resolution, and the other a spectrobolometer which measures on a relative scale the solar spectral radiant flux.

The pyrheliometer reading is used for converting the relative values of the spectrobolometer to an absolute scale.

But the two instruments do not have an identical wavelength range. The spectrobolometer is limited to the range 0.346 to 2.4μ, whereas the pyrheliometer registers the entire spectrum insofar as it is not absorbed by the atmosphere. Hence in order to compare the reading of the pyrheliometer to the intergrated area under the curve given by the spectrobolometer, a correction factor must be added to the integrated area. This correction factor, referred to by NRL as the spectrobologram correction, is the integrated area for the range below 0.346μ and for the range above 2.4μ under a spectral distribution curve which might have been obtained if the spectrobolometer could review the entire wavelength range of the pyrheliometer.

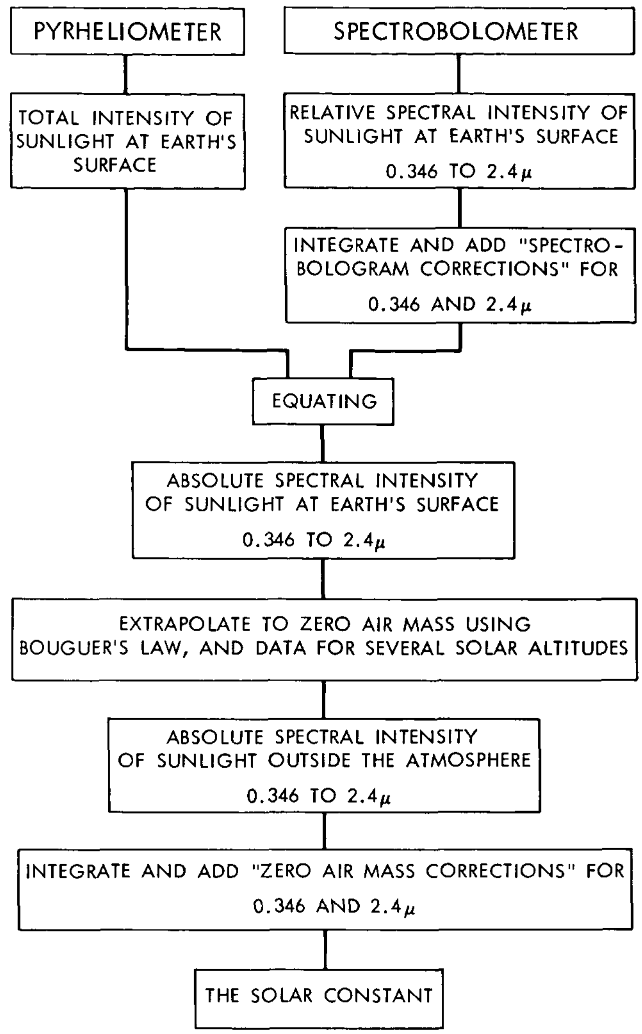


Figure 11—Flow chart of the procedure of the Smithsonian Institution for evaluating the solar constant (Johnson and Tousey).

By equating the two values, the factor for converting the spectrobolometer readings to an absolute scale is obtained. Thus the solar spectral radiant-flux is determined in absolute units at the earth's surface in the range 0.346 to 2.4 μ. The table of values thus obtained for different wavelengths are next extrapolated to zero air mass by comparing the data for different zenith angles. For large zenith angles the assumption that the optical air mass m is equal to the secant of the zenith angle does not hold, and Bemporad's modifications (Reference 34) correcting for the curvature of the atmosphere and refraction are applied.

The extrapolation to zero air mass gives the curve for spectral radiant flux in the range 0.346 to 2.4μ outside the earth's atmosphere. It is necessary to add to this the areas under the ultraviolet below 0.346μ and under the infrared beyond $2.4\ \mu$. These areas are referred to by NRL as the zero air mass corrections.

In addition to the difficulty of determining these corrections, there was also a certain amount of confusion over the scale used by the Smithsonian in reporting the data. This confusion was cleared up by Aldrich and Hoover in 1952 (Reference 4). Three different scales had been used over the years. The "true" scale, according to the Smithsonian, is the scale of 1932, and on that scale the solar constant is 1.934 cal/cm^2-min. This is the value which the NRL accepted as the starting point for its revision of the solar constant. Subtracting from this the Smithsonian zero air mass correction of 0.061 in the UV below 0.346μ and 0.038 in the IR region above 2.4μ, Johnson obtained 1.835 cal/cm^2-min as the radiant flux for zero air mass in the range 0.346 to $2.4\ \mu$. To this value Johnson added three correction factors: 0.006, an increase due to the revised UV spectrobolometer correction based on the Mt. Lemmon data of Dunkelman and Scolnik; 0.085, the revised UV zero air mass correction based on the NRL rocket data and the Mount Lemmon data; and 0.076, the revised IR zero air mass correction based on the assumption that in the IR from 2.4 to at least $14\ \mu$, the solar spectral radiant flux for zero air mass is that of a 6000°K blackbody. This assumption had been made earlier by Moon, and was apparently justified by the work of Adel (Reference 35 and 36) and Peyturaux (Reference 37). These three corrections, when added to 1.835 yield the final value of the solar constant; 2.002 cal/cm^2-min. Tousey (Reference 32) observes: "We perfer to call it 2.00 since we feel that the probable error may be of the order of ±2 percent." Thus we have the value most frequently cited in literature, 2.00 cal/cm^2-min, and referred to as the NRL value or the Johnson value.

Johnson's revision of the Smithsonian data also yielded a new table for the spectral solar radiant flux. For this, the starting point is a curve of the spectral radiant flux on a relative scale — the same as for the revision of the solar constant. This curve is based on three sources which Johnson considered most reliable, the NRL rocket data for wavelengths shorter than $0.318\ \mu$, the Mount Lemmon data for the range 0.318 to $0.60\ \mu$, and Parry Moon's results for the wavelength range beyond $0.60\ \mu$. The normalization procedure for converting the relative scale to an absolute scale is based on the re-evaluation of the spectrobologram corrections and the zero air mass corrections. Johnson (Reference 1) has discussed in detail the steps involved in the procedure. The final results of Johnson's revision are presented in Table 9 and Figure 12.

CONCLUSION

In view of the discussions in the previous sections, it would seem highly desirable that a new attempt be made to obtain morc accurate and complete experimental data on the solar constant and the spectral distribution of the solar radiant flux. Johnson's work was mainly one of revision, and the experimental data for the revision had been obtained many years earlier by the Smithsonian Institution. The observations of Dunkelman and Scolnik were made on one single day, and were limited to the visible portion of the spectrum. The data of Stair and Johnston were averaged over eight days, but the authors themselves emphasize the large uncertainties inherent in the method. Gast (Reference 7) made the following observation: "As an example of a more important uncertainty,

Table 9

Johnson's Data on Solar Spectral Radiant Flux (denoted by H_λ) for Air Mass Zero.

λ (μ)	H_λ (w/cm$^2\mu$)	P_λ (percent)	λ (μ)	H_λ (w/cm$^2\mu$)	P_λ (percent)	λ (μ)	H_λ (w/cm$^2\mu$)	P_λ (percent)	λ (μ)	H_λ (w/cm$^2\mu$)	P_λ (percent)
0.22	0.0030	0.02	0.395	0.120	3.54	0.57	0.187	33.2	1.9	0.01274	93.02
0.225	0.0042	0.03	0.40	0.154	9.03	0.575	0.187	33.9	2.0	0.01079	93.87
0.23	0.0052	0.05	0.405	0.188	9.65	0.58	0.187	34.5	2.1	0.00917	94.58
0.235	0.0054	0.07	0.41	0.194	10.3	0.585	0.185	35.2	2.2	0.00785	95.20
0.24	0.0058	0.09	0.415	0.192	11.0	0.59	0.184	35.9	2.3	0.00676	95.71
0.245	0.0064	0.11	0.42	0.192	11.7	0.595	0.183	36.5	2.4	0.00585	96.18
0.25	0.0064	0.13	0.425	0.189	12.4	0.60	0.181	37.2	2.5	0.00509	96.57
0.255	0.010	0.16	0.43	0.178	13.0	0.61	0.177	38.4	2.6	0.00445	96.90
0.26	0.013	0.20	0.435	0.182	13.7	0.62	0.174	39.7	2.7	0.00390	97.21
0.265	0.020	0.27	0.44	0.203	14.4	0.63	0.170	40.9	2.8	0.00343	97.47
0.27	0.025	0.34	0.445	0.215	15.1	0.64	0.166	42.1	2.9	0.00303	97.72
0.275	0.022	0.43	0.45	0.220	15.9	0.65	0.162	43.3	3.0	0.00268	97.90
0.28	0.024	0.51	0.455	0.219	16.7	0.66	0.159	44.5	3.1	0.00230	98.08
0.285	0.034	0.62	0.46	0.216	17.5	0.67	0.155	45.6	3.2	0.00214	98.24
0.29	0.052	0.77	0.465	0.215	18.2	0.68	0.151	46.7	3.3	0.00191	98.39
0.295	0.063	0.98	0.47	0.217	19.0	0.69	0.148	47.8	3.4	0.00171	98.52
0.30	0.061	1.23	0.475	0.220	19.8	0.70	0.144	48.8	3.5	0.00153	98.63
0.305	0.067	1.43	0.48	0.216	20.6	0.71	0.141	49.8	3.6	0.00139	98.74
0.31	0.076	1.69	0.485	0.203	21.3	0.72	0.137	50.8	3.7	0.00125	98.83
0.315	0.082	1.97	0.49	0.199	22.0	0.73	0.134	51.8	3.8	0.00114	98.91
0.32	0.085	2.26	0.495	0.204	22.8	0.74	0.130	52.7	3.9	0.00103	98.99
0.325	0.102	2.60	0.50	0.198	23.5	0.75	0.127	53.7	4.0	0.00095	99.05
0.33	0.115	3.02	0.505	0.197	24.2	0.80	0.1127	57.9	4.1	0.00087	99.13
0.335	0.111	3.40	0.51	0.196	24.9	0.85	0.1003	61.7	4.2	0.00080	99.18
0.34	0.111	3.80	0.515	0.189	25.6	0.90	0.0895	65.1	4.3	0.00073	99.23
0.345	0.117	4.21	0.52	0.187	26.3	0.95	0.0803	68.1	4.4	0.00067	99.29
0.35	0.118	4.63	0.525	0.192	26.9	1.0	0.0725	70.9	4.5	0.00061	99.33
0.355	0.116	5.04	0.53	0.195	27.6	1.1	0.0606	75.7	4.6	0.00056	99.38
0.36	0.116	5.47	0.535	0.197	28.3	1.2	0.0501	79.6	4.7	0.00051	99.41
0.365	0.129	5.89	0.54	0.198	29.0	1.3	0.0406	82.9	4.8	0.00048	99.45
0.37	0.133	6.36	0.545	0.198	29.8	1.4	0.0328	85.5	4.9	0.00044	99.48
0.375	0.132	6.84	0.55	0.195	30.5	1.5	0.0267	87.6	5.0	0.00042	99.51
0.38	0.123	7.29	0.555	0.192	31.2	1.6	0.0220	89.4	6.0	0.00021	99.74
0.385	0.115	7.72	0.56	0.190	31.8	1.7	0.0182	90.83	7.0	0.00012	99.86
0.39	0.112	8.13	0.565	0.189	32.5	1.8	0.0152	92.03			

in the ultraviolet region (300 - 359mμ), the discrepancy between various observations is about 10 per cent, and there have been reported [Reference 22] variant observations as large as 40 per cent, which can be neither ignored nor explained."

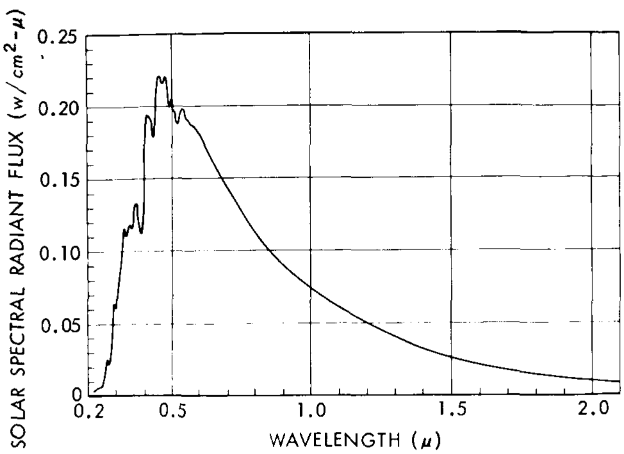


Figure 12—Solar Spectral Radiant Flux for Air Mass Zero.

The uncertainty in the solar constant and the solar spectral radiant flux has serious consequences for solar simulation and the thermal balance of spacecraft. This aspect of the question has a special interest for those engaged in building and testing satellites, since one of the more accurate methods of improving upon current data is to make measurements from above the atmosphere by satellite-borne instruments. Earlier we discussed to what extent errors in the solar constant and the solar spectral radiant flux would affect the equilibrium temperature of spacecraft. A vast effort is now being made in building and maintaining solar simulators for prelaunch testing of satellites and space probes. The operational assumption in such testing is that if the satellite fails to maintain the required thermal balance under the simulated conditions, it will also fail to do so under the actual conditions. High energy radiant sources, as for example, the carbon arc or the mercury-xenon arc, illuminate the test floor with energy which matches — as far as practicable — the energy of the sun both in spectral distribution and in total energy. It is obviously impossible to simulate accurately something unknown or uncertain. However, it should be pointed out that at the present time the degree of error in our knowledge of the solar energy is not the only obstacle or the major obstacle for adequate solar simulation. The margin of tolerance permitted or realistically attainable with high energy solar simulator sources is larger than the assumed margin of error in the published values of the solar constant and the spectral distribution of solar radiant flux. However, as efforts are being made to improve the energy output and the spectral characteristics of solar simulators, a parallel effort should be made to ascertain more accurately that which we are trying to simulate. The large uncertainties (referred to by Gast) in the ultraviolet region may also have unpredictable effects on the rapid deterioration of certain surface materials.

Tousey (Reference 33) concluded his discussion of the NRL revision of the solar constant with this remark: "I feel that new work on the solar constant is in order, but it will not be easy to improve on the accuracy attained by the Smithsonian. Attempts to make measurements directly from rockets have been made, but not yet with completely satisfactory results. The values obtained were of the order of 2.0 however. Measurements from the ground could now be made with increased accuracy due to the present day availability of many new radiation measuring techniques. To do this will require a long series of painstaking measurements, preferably, from two independent stations located at widely separated points on the earth."

Tousey's observations were made in 1957 at the threshold of the satellite age. The intervening years have witnessed a rapid progress in satellite technology. Satellites of the near future give promise of larger and bolder experiments. The severe limitations which existed in earlier years on the size and mass of the experimental package and on the available supply of power are now being removed. The obvious advantage of a satellite experiment to measure the solar spectral radiant flux is that the spectrograph is outside the earth's atmosphere and that the difficult and highly dubious corrections for atmospheric absorption are unnecessary. Measurements can be made over a prolonged period of time, and many repeated values can be taken so as to average out all random experimental errors.

However, every precaution should be taken to forestall systematic errors which might wholly vitiate the results. The measurements of the Smithsonian, NBS, and NRL were made by experienced observers who always had ready access to their apparatus and could make readjustments whenever necessary. A completely automated experimental package presents problems of a different order of magnitude. But the solutions to these problems are within reach for present day satellite technology.

A quartz double prism monochromator might well be the main unit in the experimental package. More than one energy sensing device will be needed to cover completely all ranges of wavelength. Some form of on-board calibration — as for example, with a secondary standard of spectral radiance — will be necessary. Adequate shielding should be provided for stray radiation from the earth or from the body of the satellite itself; or these will have to be corrected for. The satellite should have the attitude control for pointing constantly to the sun, and the optical system should be such as to view the whole solar disc.

A total energy sensor might well be needed as an auxiliary piece of apparatus. R. Hanel (Reference 38) and his coworkers have suggested a compact unit of this type, and the original design is now being improved upon. Readings of the total energy sensor would provide an additional means of calibration, in the same manner as the Smithsonian pyrheliometer was used to convert the relative scale of the spectrobolometer to an absolute scale.

Due attention will have to be paid also to small percentage of energy in the ultraviolet and the infrared wavelength ranges where the quartz prism is an effective absorber. The NRL rocket-borne spectrographs and the albedo measuring devices of the Tiros satellites provide many helpful suggestions for mapping accurately these relatively inaccessible regions of the spectrum.

The prism spectrograph with the auxiliary units for calibration provides one method of approach and perhaps the best. A slightly different method is to employ a series of narrow-band-pass filters, of which many different types are commercially available. The relative ruggedness and simplicity of an experimental package with a series of filters and a thermopile might more than compensate for the lack of detailed spectral resolution. But considerable research still needs to be done on the stability of the transmission characteristics of the filters and on the method for obtaining a curve for the spectral radiant flux from the energy transmitted by the filters.

Tousey (Reference 33) justly pointed out the desirability of more ground-based measurements, since new radiation measuring techniques are now available. He also said that measurements should preferably be made from widely separated points on the earth. More ground-based measurements would undoubtedly be of great value. The best Smithsonian observations are for the period 1920-22; these form the basis of the later data analysis by Moon and Johnson. As stated earlier, Dunkelman and Scolnik had only one day of observations in 1951. Stair and Johnston made their measurements on eight days in 1955. The sum total of accurate data is thus small. One objection to ground-based measurements is that they would tell us more about the characteristics of the atmosphere than about the solar radiant flux. Abundant data about the upper atmosphere and about the earth albedo are now available from satellite experiments. These data might well serve for a more reliable extrapolation to zero air mass than was previously possible. The problem of extrapolation can be considerably reduced if the measurements are made not from a mountaintop but from a high flying aircraft such as the X-15, A-11, U-2, or from a balloon. These provide alternate approaches to the satellite experiment.

A major problem in all absolute measurement of energy is the standard of spectral radiance. Data of any degree of accuracy which are cited in literature, whether of Smithsonian, NRL, or NBS, refer ultimately to the spectral radiance standards of the NBS or the Smithsonian pyrheliometer. There is no complete agreement between different countries and different national laboratories concerning the standard of energy. If a determined and massive effort is made to re-evaluate the solar constant and the solar spectral radiant flux, an essential part of the effort will be to resolve the discrepancies between different standard scales.

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