

# An Introduction to Atmospheric Radiation

K. N. LIOU



AP

INTERNATIONAL GEOPHYSICS SERIES, VOLUME 84



The annual global insolation is proportional to  $(1 + e^2/2)$ , but is independent of the declination of the sun  $\delta$  and the true anomaly  $\nu$ .

## 2.3 Solar Spectrum and Solar Constant Determination

### 2.3.1 Solar Spectrum

The solar spectrum covers wavelengths ranging from gamma rays to radio waves, as shown in Fig. 1.1. Because of the nonquantized electronic transitions, most solar energy is carried by the continuum, i.e., radiation is continuous rather than selective. The single most important contributor is hydrogen, both in its neutral state and as negative ions. A radiation transition from one level to another is characterized by an absorption or an emission line whose frequency is governed by Planck's relation. However, in the ionization process the atom (or molecules) may absorb more than the minimum energy required to remove the electron. This additional energy may be thought of as supplying kinetic energy to the freed electron and is not quantized. As a consequence, absorption is not selective but rather continuous. The ionization continuum occurs on the high-frequency (shorter wavelength) side of the ionization frequency. Neutral hydrogen has ionization continua associated with lines, some of which were defined in Fig. 1.9. Metallic atoms also contribute to the continuum in the ultraviolet spectrum. The continuum absorption in the visible and infrared spectrum, however, is produced by negative hydrogen ions.

Electromagnetic radiation emerging from within the sun is continuously emitted and absorbed by atoms. As shown in Fig. 2.2, the radiative temperature first drops off to a minimum value of about 4500 K just above the photosphere, and then levels off and slowly rises in the chromosphere, followed by a rapid rise in the transition region to several million degrees in the corona. At each temperature, probabilities of the electronic transition exist that any atom will achieve a particular excited state, leading to the formation of absorption lines at different levels in the solar atmosphere. The core of a line forms at the temperature where the maximum transition probabilities of an electron moving from one orbital level to another occur (see Fig. 1.8). The wings of a line form at different temperature levels because of the required transition probabilities. Each absorption line has a preferred formation region in the solar atmosphere. Those lines that absorb very little radiation are known as weak lines, which can form in narrow layers of the solar atmosphere. Some of the absorption lines in the solar atmosphere were displayed in Fig. 2.2.

In view of the preceding discussion, the solar spectrum consists of a continuous emission with a superimposed line structure. The visible and infrared spectrum of the photosphere shows absorption lines, known as the *Fraunhofer spectrum*. The strongest of these lines are produced by H, Mg, Fe, Ca, and Si, as well as singly ionized Ca and Mg. Most of the lines shorter than 1850 Å produced from the photosphere exhibit in emission. Light from the chromosphere and the corona has emission lines at all observed wavelengths.

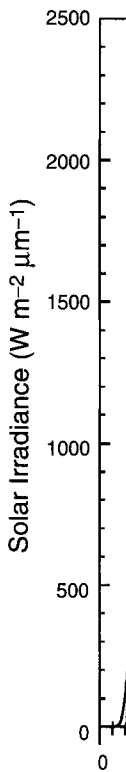
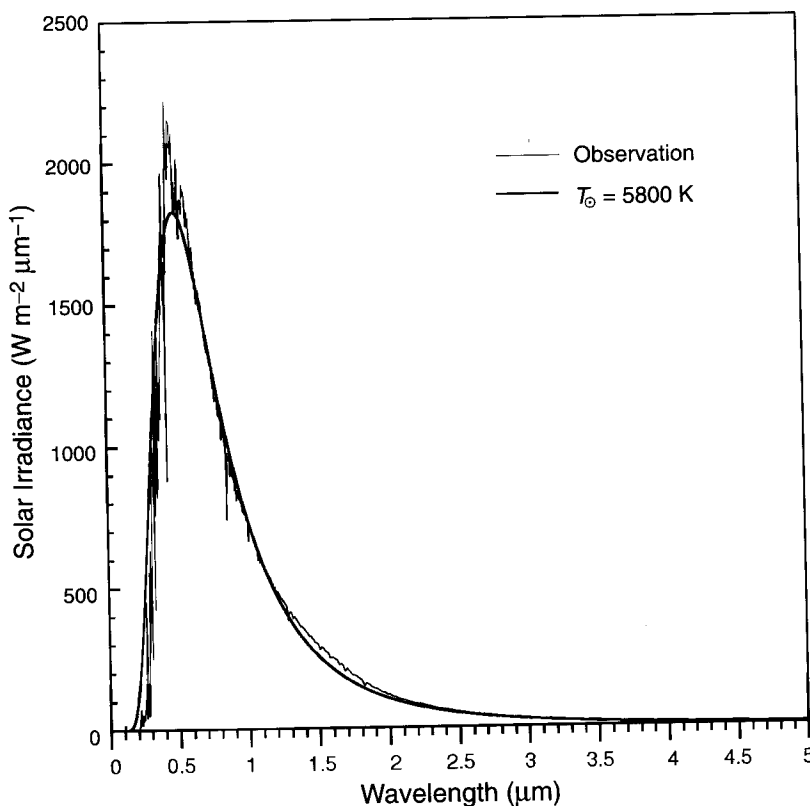


Figure 2.9 Solar Irradiance results presented in the text, based on a 5800 K accounting for

Figure 2.9 shows the solar spectrum averaged over a 5 μm band, based on the results of (Sato et al., 1995). Although the spectral solar constant is proposed as a 50 cm<sup>-1</sup> spectral irradiance, it is produced by the absorption of radiation. It can be seen, particularly in the visible spectrum of the sun and the earth, that the spectrum characterizes the solar radiation. In applications, it is used in radiative transfer



**Figure 2.9** Solar irradiance for a  $50 \text{ cm}^{-1}$  spectral interval at the top of the atmosphere based on the results presented in the MODTRAN 3.7 program. Also shown is the Planck flux with a temperature of 5800 K accounting for the mean distance between the earth and the sun.

Figure 2.9 shows the spectral solar irradiance observation at the top of the atmosphere averaged over a  $50 \text{ cm}^{-1}$  spectral interval as a function of wavelength up to  $5 \mu\text{m}$ , based on the results presented in the MODTRAN 3.7 program (Anderson *et al.*, 1995). Although the total solar irradiance derived from this program is  $1373 \text{ W m}^{-2}$ , the spectral solar irradiance curve presented here is scaled with respect to the recently proposed solar constant of  $1366 \text{ W m}^{-2}$  (see Section 2.3.3 for further discussion). A  $50 \text{ cm}^{-1}$  spectral average has been performed to smooth out the rapid fluctuations produced by the absorption/emission line structure. However, some variabilities can still be seen, particularly in the ultraviolet spectrum. Also shown is the Planck curve with an emitting temperature of 5800 K, taking into account the mean distance between the sun and the earth. This temperature appears to fit closely with the visible and infrared spectrum characteristic of radiation emitted from the photosphere. For atmospheric applications, it is critically important to have reliable spectral solar irradiances for use in radiative transfer models. Table 2.3 gives tabulated data from 0.2 to  $5 \mu\text{m}$  with

Table 2.3

Distribution of Solar Spectral Irradiance  $S_\lambda$  from 0.2 to 100  $\mu\text{m}$  in Terms of the Accumulated Energy and Percentage Based on the Values Listed in the MODTRAN 3.7 Program<sup>a</sup>

$\lambda$ ( $\mu\text{m}$ )	$S_\lambda$ ( $\text{W m}^{-2} \mu\text{m}^{-1}$ )	$S_{0-\lambda}$ ( $\text{W m}^{-2}$ )	$S_{0-\lambda}$ (%)	$\lambda$ ( $\mu\text{m}$ )	$S_\lambda$ ( $\text{W m}^{-2} \mu\text{m}^{-1}$ )	$S_{0-\lambda}$ ( $\text{W m}^{-2}$ )	$S_{0-\lambda}$ (%)
0.20	2.0832E+01	2.08317E+00	0.15250	3.8	1.0564E+01	1.35239E+03	99.00390
0.30	5.4765E+02	5.68479E+01	4.16163	3.9	9.6162E+00	1.35335E+03	99.07430
0.40	1.4042E+03	1.97272E+02	14.44155	4.0	8.6980E+00	1.35422E+03	99.13797
0.50	1.9619E+03	3.93464E+02	28.80410	4.1	7.9180E+00	1.35502E+03	99.19593
0.60	1.7632E+03	5.69780E+02	41.71153	4.2	7.2072E+00	1.35574E+03	99.24870
0.70	1.4300E+03	7.12778E+02	52.17994	4.3	6.5062E+00	1.35639E+03	99.29633
0.80	1.1257E+03	8.25347E+02	60.42075	4.4	5.7954E+00	1.35697E+03	99.33875
0.90	8.8835E+02	9.14182E+02	66.92404	4.5	5.2622E+00	1.35749E+03	99.37727
1.00	7.2943E+02	9.87125E+02	72.26392	4.6	4.8180E+00	1.35798E+03	99.41255
1.10	5.8743E+02	1.04587E+03	76.56425	4.7	4.4724E+00	1.35842E+03	99.44529
1.20	4.8921E+02	1.09479E+03	80.14558	4.8	4.1565E+00	1.35884E+03	99.47573
1.30	4.0851E+02	1.13564E+03	83.13614	4.9	3.8504E+00	1.35922E+03	99.50391
1.40	3.4450E+02	1.17009E+03	85.65813	5.0	3.5740E+00	1.35958E+03	99.53008
1.50	2.9066E+02	1.19916E+03	87.78592	6.0	1.8385E+00	1.36303E+03	99.78240
1.60	2.4644E+02	1.22380E+03	89.58999	7.0	1.0108E+00	1.36404E+03	99.85639
1.70	2.0453E+02	1.24425E+03	91.08726	8.0	5.9672E-01	1.36464E+03	99.90007
1.80	1.6829E+02	1.26108E+03	92.31927	9.0	3.7458E-01	1.36501E+03	99.92751
1.90	1.3725E+02	1.27481E+03	93.32404	10.0	2.4702E-01	1.36526E+03	99.94559
2.00	1.1624E+02	1.28643E+03	94.17501	11.0	1.6932E-01	1.36543E+03	99.95798
2.10	9.7416E+01	1.29617E+03	94.88816	12.0	1.2005E-01	1.36555E+03	99.96677
2.20	8.2132E+01	1.30439E+03	95.48942	13.0	8.7276E-02	1.36563E+03	99.97315
2.30	6.9594E+01	1.31134E+03	95.99889	14.0	6.5062E-02	1.36570E+03	99.97792
2.40	5.9198E+01	1.31726E+03	96.43226	15.0	4.9463E-02	1.36575E+03	99.98154
2.50	5.1023E+01	1.32237E+03	96.80577	16.0	3.8307E-02	1.36579E+03	99.98434
2.60	4.4280E+01	1.32679E+03	97.12994	17.0	3.0112E-02	1.36582E+03	99.98655
2.70	3.8672E+01	1.33066E+03	97.41305	18.0	2.3991E-02	1.36584E+03	99.98831
2.80	3.3815E+01	1.33404E+03	97.66058	19.0	1.9351E-02	1.36586E+03	99.98973
2.90	2.9589E+01	1.33700E+03	97.87720	20.0	1.5797E-02	1.36588E+03	99.99088
3.00	2.6133E+01	1.33962E+03	98.06850	30.0	3.4388E-03	1.36598E+03	99.99860
3.10	2.3093E+01	1.34193E+03	98.23756	40.0	1.0465E-03	1.36599E+03	99.99937
3.20	2.0476E+01	1.34397E+03	98.38746	50.0	4.2098E-04	1.36600E+03	99.99968
3.30	1.8186E+01	1.34579E+03	98.52059	60.0	2.0151E-04	1.36600E+03	99.99983
3.40	1.6191E+01	1.34741E+03	98.63913	70.0	1.0860E-04	1.36600E+03	99.99991
3.50	1.4562E+01	1.34887E+03	98.74574	80.0	6.3779E-05	1.36600E+03	99.99995
3.60	1.3032E+01	1.35017E+03	98.84114	90.0	3.9985E-05	1.36600E+03	99.99998
3.70	1.1670E+01	1.35134E+03	98.92657	100.0	2.6459E-05	1.36600E+03	100.0000

<sup>a</sup>The solar constant is taken to be  $1366 \text{ W m}^{-2}$ .

a  $0.1\text{-}\mu\text{m}$  spectral interval. From 5 to 100  $\mu\text{m}$ , solar irradiance accounts for about  $6 \text{ W m}^{-2}$ . Based on these values, about 50% of the total solar irradiance lies in wavelengths longer than the visible, about 40% in the visible region, and about 10% in wavelengths shorter than the visible. Note that from 3.5 to 5  $\mu\text{m}$ , the emitted thermal infrared radiation from the earth and the atmosphere system becomes significant.

According to solar flux observations, the ultraviolet region ( $<0.4 \mu\text{m}$ ) of the solar spectrum deviates greatly from the visible and infrared regions in terms of

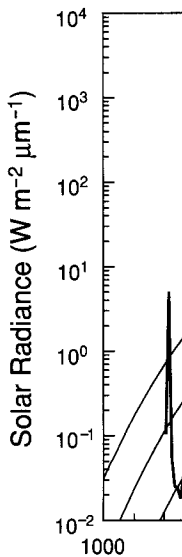


Figure 2.10 Observed solar spectrum from Brasseur and Simonovic, 1980, for temperatures of 4500 K to 6000 K.

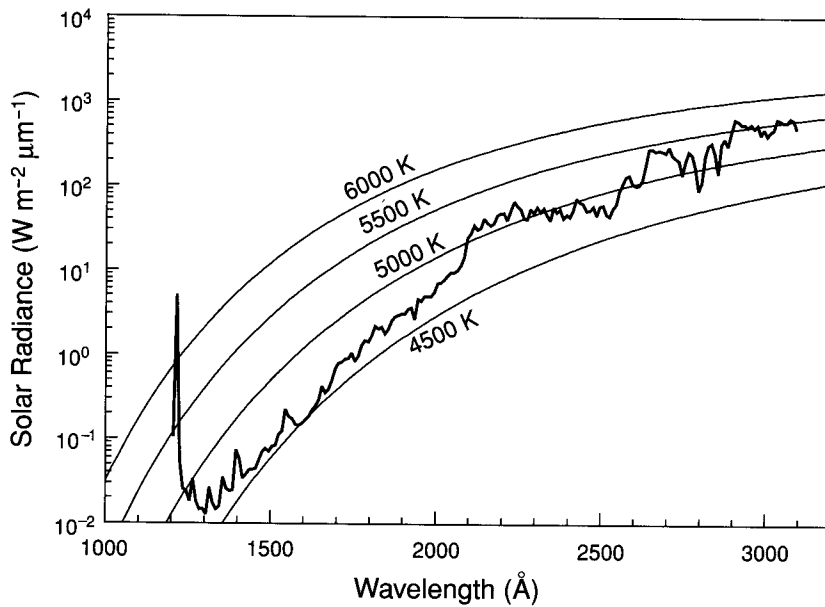
the equivalent blackbody temperature of the observed solar spectrum. The equivalent blackbody temperatures of 4500, 5000, and 6000 K correspond to a minimum level of solar radiance at various wavelengths, a large peak at approximately 1216 Å associated with hydrogen atoms. The small peak at approximately 8446 Å is due to atomic oxygen. The curve represents the prime

### 2.3.2 Determination of Solar Constant

For historical reasons, the determination of the solar constant has been the purpose of determining the solar constant. The instrument used is the *pyrheliometer*, which is used to measure the solar constant, utilizing a suitable instrument, measure

Terms of the Accumulated Energy and  
DTRAN 3.7 Program<sup>a</sup>

$\lambda$ ( $\mu\text{m}^{-1}$ )	$S_{0-\lambda}$ ( $\text{W m}^{-2}$ )	$S_{0-\lambda}$ (%)
0564E+01	1.35239E+03	99.00390
06162E+00	1.35335E+03	99.07430
06980E+00	1.35422E+03	99.13797
070180E+00	1.35502E+03	99.19593
072072E+00	1.35574E+03	99.24870
075062E+00	1.35639E+03	99.29633
07954E+00	1.35697E+03	99.33875
082622E+00	1.35749E+03	99.37727
08180E+00	1.35798E+03	99.41255
08724E+00	1.35842E+03	99.44529
08565E+00	1.35884E+03	99.47573
08504E+00	1.35922E+03	99.50391
08740E+00	1.35958E+03	99.53008
08385E+00	1.36303E+03	99.78240
09108E+00	1.36404E+03	99.85639
09672E-01	1.36464E+03	99.90007
097458E-01	1.36501E+03	99.92751
09702E-01	1.36526E+03	99.94559
09932E-01	1.36543E+03	99.95798
092005E-01	1.36555E+03	99.96677
09276E-02	1.36563E+03	99.97315
095062E-02	1.36570E+03	99.97792
09463E-02	1.36575E+03	99.98154
09307E-02	1.36579E+03	99.98434
09112E-02	1.36582E+03	99.98655
08991E-02	1.36584E+03	99.98831
089351E-02	1.36586E+03	99.98973
08797E-02	1.36588E+03	99.99088
08438E-03	1.36598E+03	99.99860
080465E-03	1.36599E+03	99.99937
072098E-04	1.36600E+03	99.99968
070151E-04	1.36600E+03	99.99983
06860E-04	1.36600E+03	99.99991
06779E-05	1.36600E+03	99.99995
069985E-05	1.36600E+03	99.99998
06459E-05	1.36600E+03	100.0000



**Figure 2.10** Observed irradiance outside the earth's atmosphere in the ultraviolet region (data taken from Brasseur and Simon, 1981) and comparison with the Planck curves for temperatures ranging from 4500 K to 6000 K.

the equivalent blackbody temperature of the sun. Figure 2.10 illustrates a detailed observed solar spectrum from about 1000 to 3000 Å, along with blackbody temperatures of 4500, 5000, 5500, and 6000 K. In the interval 2100–3000 Å, the equivalent blackbody temperature of the sun lies somewhat above 5000 K. It falls gradually to a minimum level of about 4700 K at about 1400 Å. From there toward shorter wavelengths, a larger amount of energy flux is observed at the Lyman  $\alpha$  emission line of 1216 Å associated with the transition of the first excited and ground states of hydrogen atoms. The ultraviolet portion of the solar spectrum below 3000 Å contains a relatively small amount of energy. However, because the ozone and the molecular and atomic oxygen and nitrogen in the upper atmosphere absorb all this energy, it represents the prime source of the energy in the atmosphere above 10 km.

### 2.3.2 Determination of the Solar Constant: Ground-Based Method

For historical reasons, we shall first introduce the ground-based method for the determination of the solar constant. Ground-based observations of solar irradiance for the purpose of determining the solar constant require three primary instruments. These are the *pyrheliometer*, the *pyranometer*, and the *spectrobolometer*. The pyrheliometer is used to measure the direct, plus some diffuse, solar radiation, while the pyranometer, utilizing a suitable shield to block the direct solar radiation from striking the instrument, measures only the diffuse solar radiation for arriving at a pyrheliometer

irradiance accounts for about  
total solar irradiance lies in wave-  
visible region, and about 10% in  
3.5 to 5  $\mu\text{m}$ , the emitted thermal  
system becomes significant.  
violet region ( $<0.4 \mu\text{m}$ ) of the  
and infrared regions in terms of

correction. The amount of direct sunlight can then be calculated by subtracting the flux density measured by the pyranometer from that measured by the pyrliometer. The spectrobolometer is a combination of a spectrograph and a coelostat. A coelostat is a mirror that follows the sun and focuses its rays continuously on the entrance slit of the spectrograph, which disperses the solar radiation into different wavelengths by means of a prism or diffraction grating. In the Smithsonian solar constant measurements, about 40 standard wavelengths between 0.34 and 2.5  $\mu\text{m}$  are measured nearly simultaneously from the record of the spectrograph. The instrument for these measurements is called a *bologram*. There are two techniques of measuring the solar constant from the ground-based radiometer, called the *long* and *short* methods of the Smithsonian Institution. The long method is more fundamental and establishes the basis for the short method. The long method uses the Beer–Bouguer–Lambert law and is introduced in the following.

Consider an atmosphere consisting of plane-parallel layers. At a given position of the sun, which is denoted by the solar zenith angle  $\theta_0$ , the effective path length of the air mass is  $u \sec \theta_0$ , where

$$u = \int_{z_1}^{z_\infty} \rho dz. \quad (2.3.1)$$

In this equation  $z_1$  is the height of the station and  $z_\infty$  denotes the top of the atmosphere. On the basis of the Beer–Bouguer–Lambert law, the irradiance  $F$  of the direct solar radiation of wavelength  $\lambda$  observed at the surface level is given by

$$F_\lambda = F_{\lambda 0} \exp(-k_\lambda u \sec \theta_0) = F_{\lambda 0} T_\lambda^m, \quad (2.3.2)$$

where  $F_{\lambda 0}$  is the monochromatic solar irradiance at the top of the atmosphere,  $k_\lambda$  denotes the monochromatic mass extinction cross section,  $T_\lambda$  is the monochromatic transmissivity defined in Eq. (1.4.10), and  $m (= \sec \theta_0)$  represents the ratio of the air mass between the sun and the observer to the air mass with respect to the local zenith distance. Upon taking the logarithm, we find

$$\ln F_\lambda = \ln F_{\lambda 0} + m \ln T_\lambda. \quad (2.3.3)$$

Observations of  $F_\lambda$  may be made for several zenith angles during a single day. If the atmospheric properties do not change during the observation period, then the transmissivity  $T_\lambda$  is constant. A plot of  $\ln F_\lambda$  versus  $m$  shown in Fig. 2.11 may be extrapolated to the zero point, which represents the top of the atmosphere ( $m = 0$ ). This is referred to as the *Langley plot*. If observations of the monochromatic irradiance are carried out for wavelengths covering the entire solar spectrum, then we have

$$F_\odot = \int_0^\infty F_{\lambda 0} d\lambda \approx \sum_{i=1}^N F_{\lambda_i 0} \Delta\lambda_i, \quad (2.3.4)$$

where  $N$  is the total number of the monochromatic irradiances measured. The irradiance  $F_\odot$  corresponds to the actual distance between the earth and the sun,  $r$ . By using

Figure 2.11  
path length from  
referred to as the

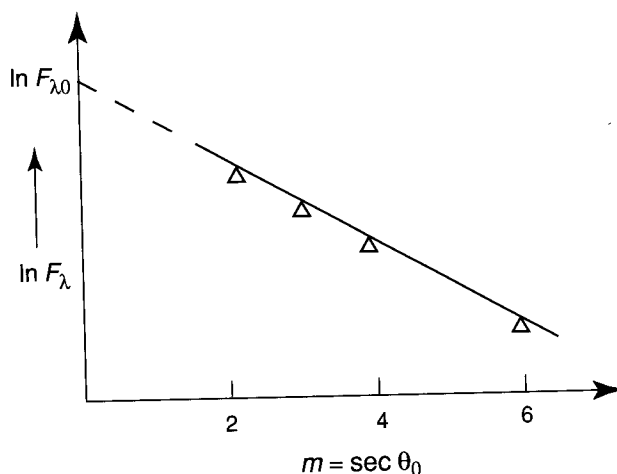
the mean dist

The forego  
for the determ  
opaque for w  
spectively. Co  
Therefore, en  
for about 8%

There are c  
(1) empirical  
of infrared by  
(2) an unknow  
instrument; (3)  
measurement  
and observati

Employing  
to 3 hours of  
In addition, t  
will remain u  
and the burde  
determine the

In the shor  
measured for



**Figure 2.11** Hypothetical observed monochromatic solar irradiances  $F_\lambda$  as a function of the effective path length from which the solar irradiance at the top of the atmosphere can be graphically determined, referred to as the Langley plot.

(2.3.1)

the mean distance  $r_0 = a$ , the solar constant is defined by

$$S = F_\odot (r/a)^2. \quad (2.3.5)$$

The foregoing outlines the theoretical procedures of the Smithsonian long method for the determination of the solar constant. However, the atmosphere is essentially opaque for wavelengths shorter and longer than about  $0.34 \mu\text{m}$  and  $2.5 \mu\text{m}$ , respectively. Consequently, flux density observations cannot be made in these regions. Therefore, empirical corrections are needed for the omitted ranges, which account for about 8% of the solar flux.

There are other sources of error inherent in the Smithsonian long method caused by (1) empirical corrections for the absorption of ultraviolet by ozone, and the absorption of infrared by water vapor and carbon dioxide in the wings of the solar spectrum; (2) an unknown amount of diffuse radiation entering the aperture of the observing instrument; (3) variations of  $k_\lambda$  and the possible effects of aerosols during a series of measurements; and (4) measurement errors. Therefore, in spite of careful evaluation and observation, a certain amount of error is inevitable.

Employing the Smithsonian long method, each determination requires about 2 to 3 hours of observation time, plus twice that much time for the data reduction. In addition, there is no assurance that atmospheric properties and solar conditions will remain unchanged during the observation period. Because of this uncertainty and the burdensome, time-consuming work involved, a short method was devised to determine the solar constant.

In the short method, the diffuse component of solar radiation (the sky brightness) is measured for a given locality over a long period of time, so that a mean diffuse intensity

(2.3.3)

(2.3.4)

