Cursul 3 **Blackbody Radiation**

The emissive power of a blackbody at any wavelength and temperature, called its spectral emissive power, is given by Planck's law.

$$G_{b\lambda} = \frac{C_1}{\lambda^5\left(e^{\frac{C_2}{\lambda T}}-1\right)} \quad (1)$$

$G_{b\lambda}$ the spectral emissive power of a blackbody ($Wm^{-2}\mu m^{-1}$)

$C_1 = 2\pi hc^2 = 3.7427 \times 10^8 W\mu m^4 m^{-2}$ the first radiation constant

$C_2 = \frac{hc}{k_B} = 1.4388 \times 10^4\ \mu m\ K$ the second radiation constant

λ the wavelength (μm)

T the blackbody temperature (K).

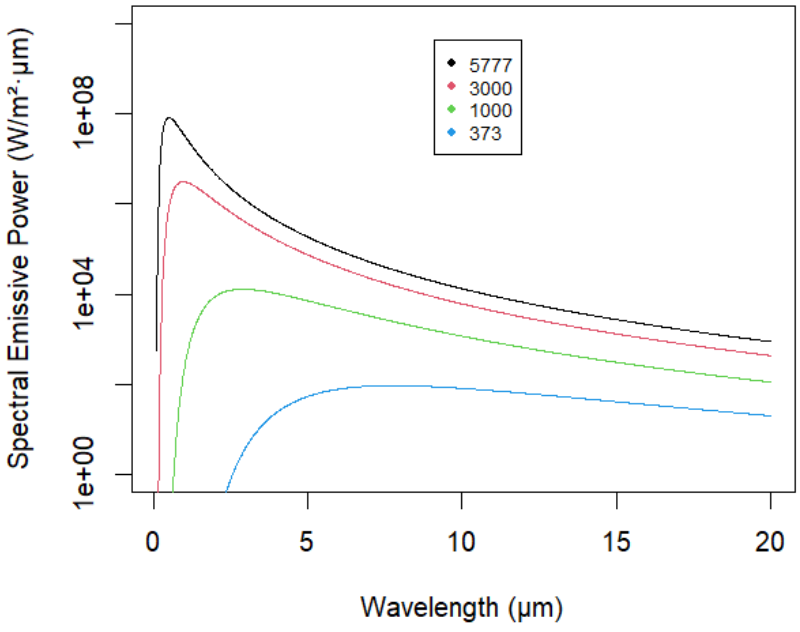

Figure 1. Spectral emissive power of a blackbody

The mean Sun-Earth distance $r_0 = 149\ 597\ 890$ km.

The mean radius of the solar disk $r_s = 695\ 980$ km.

The geometric spreading of solar radiation between the solar surface and the Earth's orbit, gives

$$G_{b\lambda}\, 4\pi {r_s}^2 = G_{0n\lambda}\, 4\pi {r_0}^2 \tag{2}$$

$$G_{0n\lambda} = G_{b\lambda} \left(\frac{r_s}{r_0}\right)^2 \tag{3}$$

$$G_{0n\lambda} = \frac{2\pi hc^2}{\lambda^5} \cdot \frac{1}{\exp\left(\frac{hc}{\lambda k_B T_S}\right) - 1} \cdot \left(\frac{r_s}{r_0}\right)^2 \tag{4}$$

Or, using the apparent half-angle subtended by the Sun

$$G_{0n\lambda} = \frac{2\pi\, sin^2\theta_{sun}\, hc^2}{\lambda^5} \frac{1}{\exp(hc/\lambda k_B T_S) - 1} \tag{5}$$

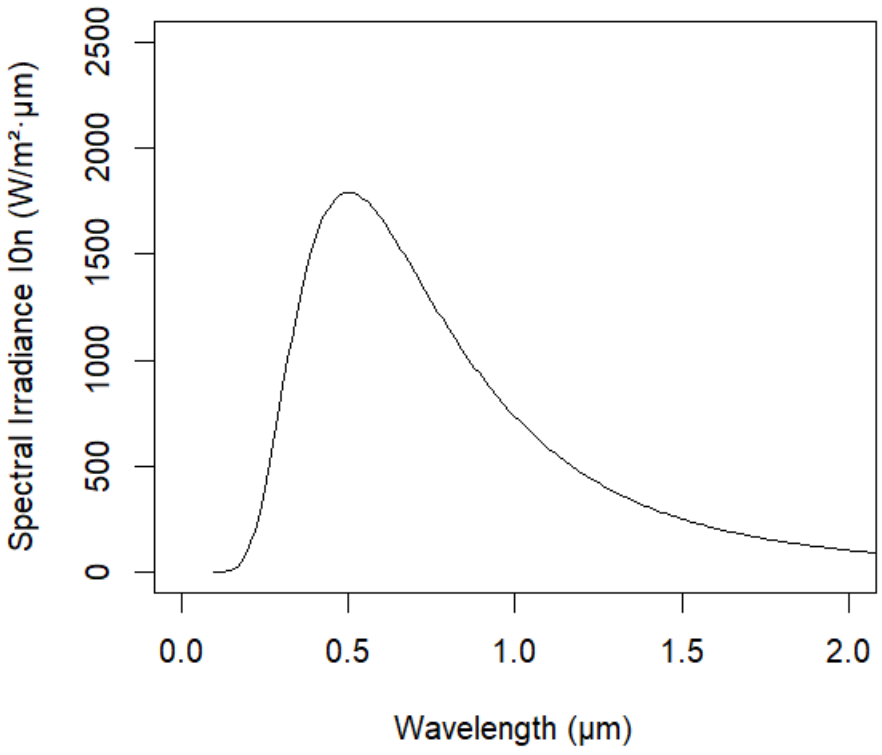

Figure 2. Spectral irradiance from the sun as a blackbody, at 1AU.

Some Definitions

The main subject of these chapters is solar radiation, with particular emphasis on its spectral distribution and the energy received by a surface on Earth.

Several radiometric terms are used to describe radiant energy and its transfer. Although some are occasionally used interchangeably in the literature, they represent different physical quantities.

A fundamental distinction is between the **amount of radiant energy received over a period of time** and the **rate at which radiant energy is received**.

Solar irradiance is the radiant power incident on a surface per unit area. It describes the instantaneous rate of energy received per unit area.

Unit: Wm^{-2}

Solar Irradiation is the radiant energy incident on a surface per unit area over a specified time interval. It is obtained by integrating irradiance over time.

Units: $kJ\ m^{-2}\ h^{-1}$ or $MJ\ m^{-2}\ day^{-1}$

Intensity will mean irradiance from a particular direction and contained within a unit solid angle.

Unit: $Wm^{-2}sr^{-1}$

These quantities are essential for describing solar radiation, from its spectral distribution outside the Earth's atmosphere to the irradiance incident on terrestrial surfaces.

Chapter 3 THE SOLAR CONSTANT AND ITS SPECTRAL DISTRIBUTION

This chapter discusses the physics of the sun, the nature of the radiant energy emanating from its surface, spectral distribution, and the total quantity of this energy arriving just outside the earth's atmosphere.

3.1 The Sun: Structure and Radiation

The Sun is the star closest to the Earth and the primary source of energy driving the atmospheric processes and influencing Earth's climate. It is a sphere of hot gaseous matter with a diameter of approximately 1.39×10^9 m, located at an average distance of 1.5×10^{11} m from Earth.

Solar energy is generated in the Sun's core through nuclear fusion, in which hydrogen nuclei combine to form helium, releasing energy as a result of the mass difference between the reactants and products. This energy is transported outward through the solar interior and ultimately emitted into space as electromagnetic radiation.

The Sun has an effective temperature of approximately 5777 K. Its main structural layers are the core, the radiative zone, the convective zone, the photosphere, the chromosphere, and the corona. The photosphere is the visible surface of the Sun and the main source of solar radiation received by Earth. Above it, the chromosphere and corona form the outer solar atmosphere.

Although the Sun's effective temperature is close to that of an ideal blackbody at 5777 K, the Sun does not emit radiation as a perfect blackbody. Its spectral distribution results from the emission and absorption of radiation at different wavelengths in layers with different temperatures and physical properties.

The **extraterrestrial solar spectrum** describes the spectral distribution of solar irradiance before it enters Earth's atmosphere. It has been determined through **various measurements** and is represented by **several reference spectra**, discussed in the following sections.

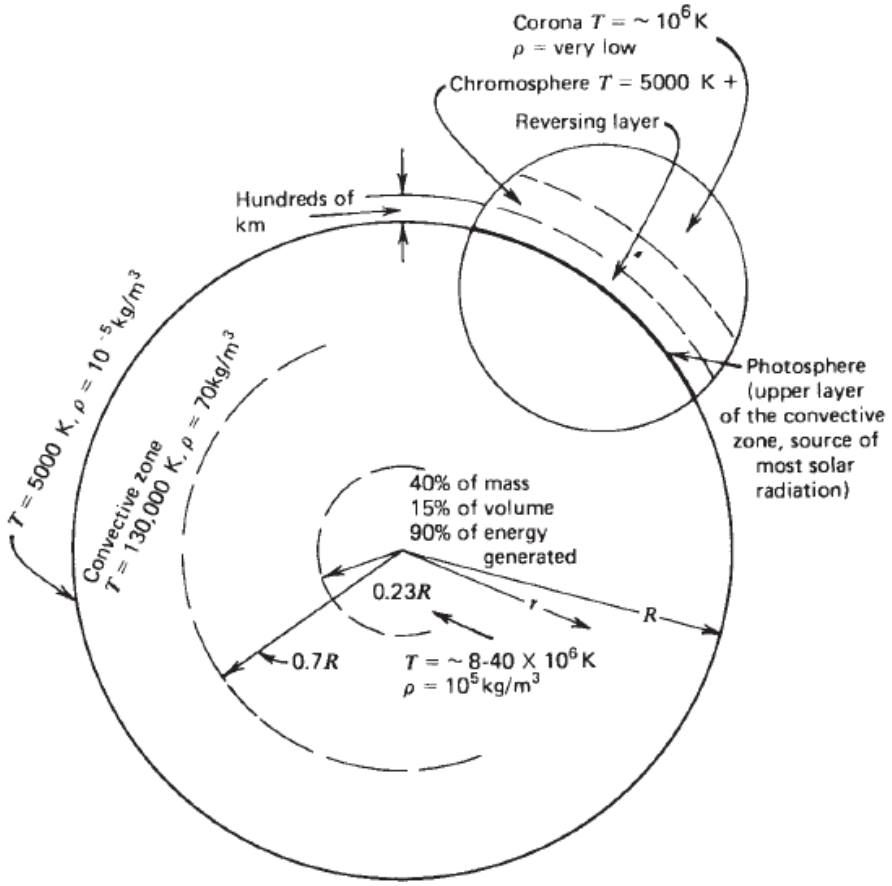

Figure 1. Structure of the Sun (Solar Engineering of Thermal Processes, Photovoltaics and Wind,

Author(s): John A. Duffie, William A. Beckman, Nathan Blair

First published:25 February 2020)

3.2 Extraterrestrial Solar Spectral Irradiance

Solar radiation outside the Earth's atmosphere varies with wavelength. Understanding its spectral distribution is essential for studying solar energy conversion and evaluating the performance of photovoltaic systems.

The spectral distribution of radiation arriving on the surface of the earth is a function of its extraterrestrial distribution and the atmospheric constituents.

Ground-based measurements of solar spectral irradiance began around the beginning of the last century, and from these measurements the extraterrestrial distribution was obtained by extrapolation.

Between 1966 and 1971, NASA conducted a series of measurements of extraterrestrial solar spectral irradiance using the NASA 711 Galileo research aircraft. There were eleven instruments, five for total and six for spectral irradiance. A total of six flights were made, and during each flight the instruments were pointed at the Sun for about two and a half hours.

The flights were made in August 1967.

After a critical evaluation of all high-altitude data on the solar constant, the Committee on Solar Electromagnetic Radiation proposed unanimously that the revised value of the solar constant should be 135.3 mW cm^{-2}. This value was first announced at the 1970 International Solar Energy Society Conference in Melbourne, Australia. It is the average of the nine high altitude values.

The results were reported in several publications, including the paper by Thekaekara (1973), "Solar Energy Outside the Earth's Atmosphere" (*Solar Energy*, 14(2), 109–127).

The resulting spectral irradiance data were subsequently adopted by the American Society for Testing and Materials (ASTM) and became widely known as **the NASA/ASTM standard extraterrestrial solar spectrum**, or simply the NASA standard. This reference spectrum was widely used for nearly a decade.

The World Radiation Center (WRC) Solar Spectrum (1981)

In 1981, C. Fröhlich and his colleagues at the World Radiation Center (WRC) in Davos, Switzerland, proposed a revised spectral distribution of solar irradiance. The main references are:

- C. Frohlich and R. W. Brusa, Solar radiation and its variation in time. *Sol. Phys.* 74, 209-215(1981).
- C. Frohlich and C. Wehrli, Spectral distribution of solar irradiance from 25000 nm to 250 nm. World Radiation Center, Davos, Switzerland, private communication (1981).

The spectral irradiance values were adjusted slightly and uniformly so that their integration over the full spectrum yielded a solar constant of 1367 W m^{-2}.

In October 1981, at its Eighth Session, the Commission for Instruments and Methods of Observation (CIMO) of the World Meteorological Organization (WMO) adopted the spectral distribution recommended by Fröhlich. This reference spectrum is commonly referred to as the **WRC spectrum**.

The WRC spectral data are presented in a table in Iqbal's book. The first column lists the wavelength, (λ), in micrometres. The second gives the spectral irradiance in $\frac{W}{m^2 \mu m}$ at each wavelength, while the third presents the integrated irradiance over the corresponding wavelength intervals. The cumulative irradiance reaches 1367 W m^{-2}, the adopted value of the solar constant.

The fourth column gives the percentage of the solar constant contributed by wavelengths shorter than the specified wavelength.

The table shows that approximately 99% of the solar energy lies within the wavelength range from 0.25 to 4.0 μm.

Figure 2 compares the NASA/ASTM and WRC reference spectra. Noticeable differences can be seen between the two distributions, particularly in the ultraviolet and visible regions of the spectrum.

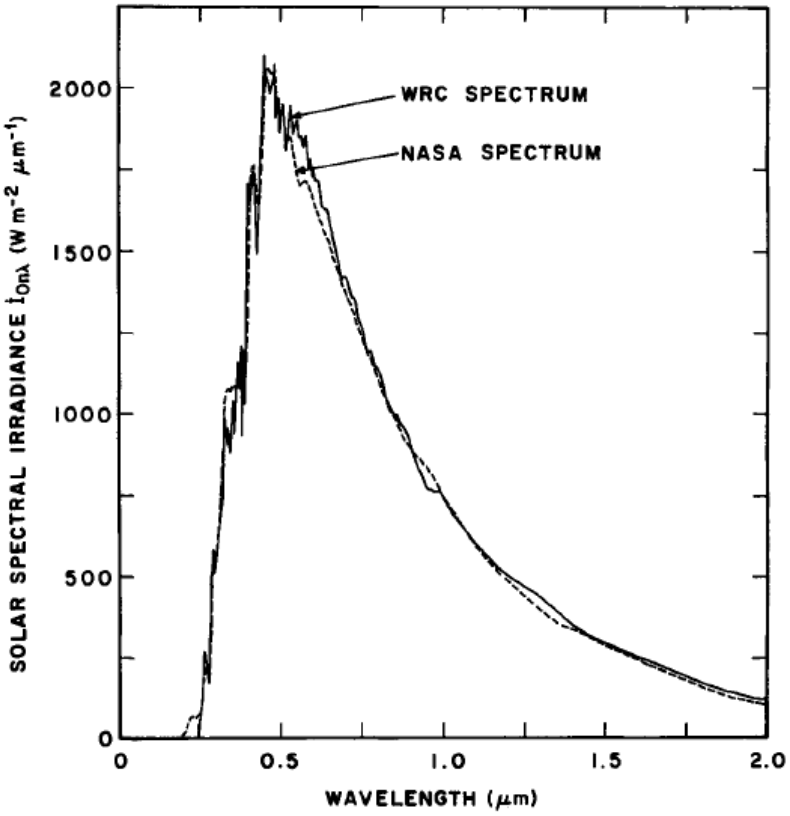

Figure 2. WRC and NASA spectrum (from Iqbal)

Note: There is and WRC85 extraterrestrial solar spectrum, published by Wehrli in 1985.

The SMARTS2 Solar Spectrum (1995)

In 1995, Christian A. Gueymard introduced an upgraded spectral radiation model called SMARTS2 (*Simple Model of the Atmospheric Radiative Transfer of Sunshine*). The model

incorporated an improved extraterrestrial solar spectrum, together with updated spectral transmittance functions for the main atmospheric extinction processes.

The extraterrestrial spectrum provides the reference to solar irradiance before the radiation enters the Earth's atmosphere. SMARTS2 calculates how this radiation is modified under clear-sky conditions by Rayleigh scattering, aerosol extinction, and absorption by atmospheric constituents, including ozone, water vapor, nitrogen dioxide, and uniformly mixed gases.

An important improvement was the use of an enhanced extraterrestrial spectrum with a finer spectral resolution, including 1 nm intervals below 1700 nm. This made it possible to represent spectral variations more accurately and to improve calculations of solar irradiance in the ultraviolet, visible, and near-infrared regions.

Figure 3 compares the four representations of extraterrestrial solar spectral irradiance: the NASA spectrum (1973), the WRC spectrum (1981), the spectrum used in SMARTS2 (1995), and the theoretical spectrum calculated using Planck's law for a blackbody at a temperature of 5777 K.

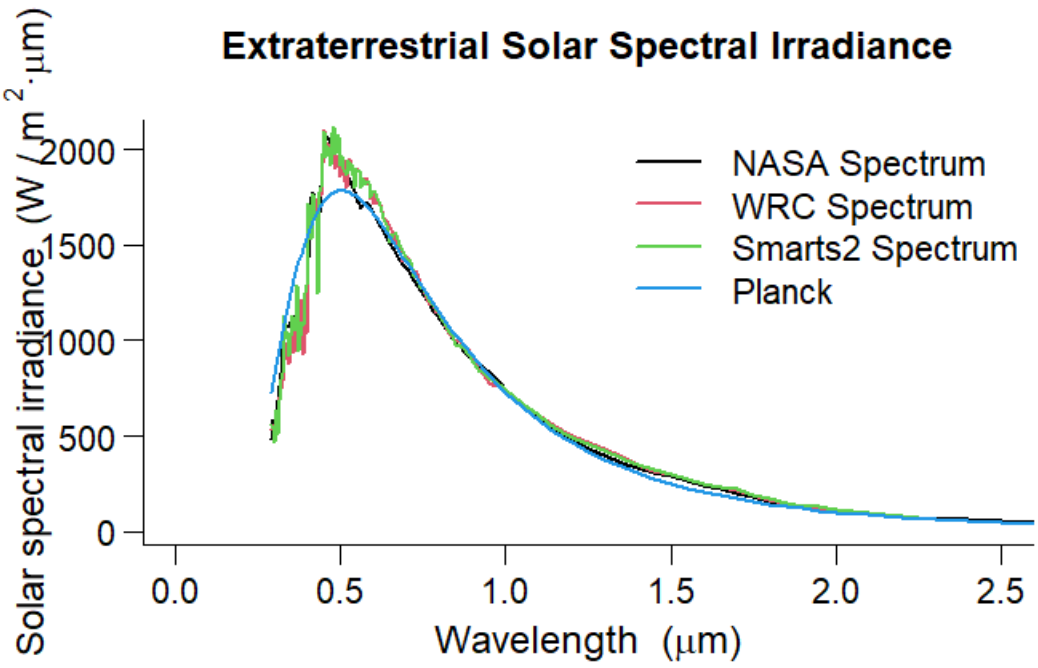

Figure 3. Comparison of extraterrestrial solar spectral irradiance according to the NASA/ASTM (1973), WRC (1981), and SMARTS2 (1995) reference spectra and Planck's blackbody radiation law for (T=5777 K).

The NASA, WRC, and SMARTS2 spectra represent reference descriptions of extraterrestrial solar irradiance, whereas the Planck curve provides an idealized approximation of the solar spectrum. Although all four curves show the characteristic distribution of solar energy across wavelength, differences can be observed in their spectral profiles. These differences reflect the distinction between an ideal blackbody spectrum and reference spectra that account for the Sun's actual spectral characteristics.

This comparison illustrates why reference extraterrestrial solar spectra are preferred in quantitative solar radiation calculations, while Planck's law remains useful for understanding the general shape of the solar spectrum.

Next Table [1] demonstrates the distribution of extraterrestrial energy within different color bands. About half the solar energy lies in the visible region and almost the same amount in the infrared: little energy is found in the ultraviolet. Approximately 95% of the sun's energy lies within 0.3-2.4 μm, and approximately one percent lies in wavelengths longer than 4.0 μm.

Approximate Division of Solar Spectrum in Various Color Bands and Energy Regions[a]

Color	λ (μm)	Band irradiance (W m^{-2})	Percentage of I_{sc}
Violet	0.390–0.455	108.85	7.96
Blue	0.455–0.492	73.63	5.39
Green	0.492–0.577	160.00	11.70
Yellow	0.577–0.597	35.97	2.63
Orange	0.597–0.622	43.14	3.16
Red	0.622–0.770	212.82	15.57
Broader color divisions			
Ultraviolet	<0.4	109.81	8.03
Visible	0.390–0.770	634.40	46.41
Infrared	>0.77	634.40	46.40
Sun's energy (%)			
95	0.3–2.4		
1.2	<0.3		
3.6	>2.4		

[a] Solar constant I_{sc} = 1367 W m^{-2} (values obtained from Table 3.3.2).

The Solar Constant

Thekaekara: Solar constant is the amount of total solar energy of all wavelengths received per unit time per unit area exposed normally to the sun's rays at the average distance of the earth and in the absence of the Earth's atmosphere.

It is not a true constant but seems to fluctuate slightly, a few tenths of a percent over periods of years.

The Revised Solar Constant

The solar constant has been reevaluated as a result of improvements in spaceborne measurements of total solar irradiance (TSI). In 2018, Gueymard analyzed a 42-year record of satellite observations covering the period 1976–2017 and reconciled measurements from several radiometers using a proxy model of solar activity.

The study proposed a revised long-term mean solar irradiance of 1361.1 ± 0.5 W m^{-2} at the mean Earth–Sun distance of 1 astronomical unit (AU). This value is approximately 5 W m^{-2} lower than the values previously used in ASTM and ISO standards. The revision reflects improvements in the absolute calibration of spaceborne radiometers and in the reconciliation of measurements from different instruments.

Although commonly called the solar constant, total solar irradiance varies slightly with solar activity. The revised value therefore represents a long-term mean rather than an invariant quantity[2].

Gueymard, C. A. (2018). “A reevaluation of the solar constant based on a 42-year total solar irradiance time series and a reconciliation of spaceborne observations.” Solar Energy, 168, 2–9.

$$\int_0^\infty G_{0n\lambda} d\lambda = G_{SC}$$

$G_{SC} = 1329.278\ \mathrm{W}/m^2$ NASA **Thekaekara**

$G_{SC} = 1346.535\ \mathrm{W}/m^2$ WRC **Frohlich**

$G_{SC} = 1352.649\ \mathrm{W}/m^2$ Smarts2 **Guyemard**

Blackbody Temperature of the Sun

The temperature of the Sun is calculated from the two types of information we have: the solar constant and its spectral distribution. Using the solar constant in conjunction with the Stefan-Boltzmann equation:

$$G_{0n\lambda} = G_{b\lambda}\left(\frac{r_s}{r_0}\right)^2$$

$$\int_0^\infty G_{0n\lambda} d\lambda = G_{SC} = \left(\frac{r_s}{r_0}\right)^2 \sigma T^4$$

$$T = \left(\frac{G_{SC} r_0^2}{\sigma r_s^2}\right)^{1/4} = 5777\ K$$

The mean sun-earth distance r_0 = 149 597 890 km.

The mean radius of the solar disk r_s = 695980 km.

$$\sigma = 5.6697 \times 10^{-8}\ W m^{-2} K^{-4}$$

$$G_{SC} = 1367\ W\ m^{-2}$$

Chapter 4 ***EXTRATERRESTRIAL SOLAR IRRADIATION***

The integrated extraterrestrial solar radiation across all wavelengths is analyzed, and mathematical formulations are developed to determine irradiation for various surface orientations and time periods.

Extraterrestrial Irradiation on a Horizontal Surface

Different time periods: an hour, a day, a month, and so forth.

A. *Hourly Radiation on a Horizontal Surface*

On a given day, let G_{0n} be the extraterrestrial irradiance on a surface normal to the rays from the sun,

$$G_{0n} = G_{SC}\left(\frac{r_0}{r}\right)^2 = G_{SC}\,\varepsilon_j \tag{1}$$

$r_0 = D_{SE} = 1\,AU = 1.496 \cdot 10^8 km$

ε_j the *eccentricity correction factor* of the earth's orbit,

$\varepsilon = (r_0/r)^2 = 1.00011 + 0.034221\,cos\,\theta_j + 0.00128\,sin\,\theta_j + 0.000719\,cos\,2\,\theta_j + 0.000077\,sin\,2\,\theta_j$

$\theta_j = 2\pi\,(j-1)/365$ is the day angle

and j is the day number of the year (Julian day).

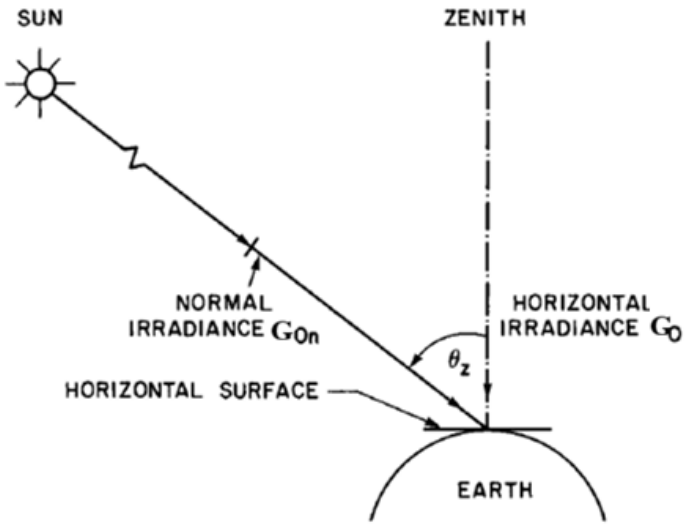

Figure 1. Relationship between the direct normal and the horizontal irradiance (Iqbal).

The ***irradiance*** on a horizontal surface can be written

$$G_0 = G_{0n}\cos\theta_z \tag{2}$$

$$G_0 = G_{SC}\varepsilon_j(sin\,\phi\,sin\,\delta + cos\,\phi\,cos\,\delta\,cos\,\omega) \tag{3}$$

The units are W/m^2.

The ***irradiation*** *(amount* of energy) dH_0 during a short period of time *dt* will *be*

$$dH_0 = G_{SC}\varepsilon_j \cos\theta_z \, dt \tag{4}$$

The time dt is in hours, and $\cos\theta_z$ contains the solar hour angle ω in degrees or radians. The time in hours can be converted to the hour angle as follows:

Ω = rotational speed of the earth around its polar axis

$$\Omega = \frac{2\pi \, rad}{24 \, h} = \frac{d\omega}{dt}$$

$$dt = \frac{12}{\pi} \, d\omega \tag{5}$$

$$dH_0 = \frac{12}{\pi} G_{SC}\varepsilon_j \, (sin\,\phi \, sin\,\delta + cos\,\phi \, cos\,\delta \, cos\,\omega) \; d\omega \tag{6}$$

One can now readily obtain H_0, the radiation over a period of $1\ h$. Let us consider the *i*-th hour from solar noon, and ω_i (the hour angle at the middle of this hour. The radiation over a period of $1\ h$ will be

$$H_{0,h} = \frac{12}{\pi} G_{SC}\varepsilon_j \int_{\omega_i-\pi/24}^{\omega_i+\pi/24} (sin\,\phi \, sin\,\delta + cos\,\phi \, cos\,\delta \, cos\,\omega) \; d\omega \tag{7}$$

$$H_{0,h} = \frac{12}{\pi} G_{SC}\varepsilon_j \left(sin\,\phi \, sin\,\delta \;\; \omega|_{\omega_i-\pi/24}^{\omega_i+\pi/24} + \; cos\,\phi \, cos\,\delta \;\; \sin\omega|_{\omega_i-\pi/24}^{\omega_i+\pi/24} \right)$$

$$H_{0,h} = G_{SC}\varepsilon_j \left(sin\,\phi \, sin\,\delta \; + \frac{12}{\pi} cos\,\phi \, cos\,\delta \cdot 2\cos\omega_i \sin\frac{\pi}{24} \right)$$

$$H_{0,h} = G_{SC}\varepsilon_j \left(sin\,\phi \, sin\,\delta \; + \frac{24}{\pi} \sin\frac{\pi}{24} \; cos\,\phi \, cos\,\delta \cos\omega_i \right) \tag{8}$$

Coef<- (24/pi)*sin(pi/24)

> Coef

[1] 0.9971467

$$H_{0,h} \; \cong G_{SC}\varepsilon_j \, (sin\,\phi \, sin\,\delta \; + \; cos\,\phi \, cos\,\delta \cos\omega_i) \tag{9}$$

The above yields ***extraterrestrial irradiation***, on a horizontal surface, for 1 h centered around the hour angle ω_i.

Example 1: Calculation of the extraterrestrial hourly solar irradiation on a horizontal surface over Vancouver (49° 11' N) for the hour ending at 11:00 (LAT) on 16 October.

16 october $j = 289 \quad \phi = 49.18°$

Solar constant $G_{SC} = 1367\ W/m^2 \quad \times 3.6 \quad \rightarrow \quad G_{SC} = 4921\ kJ/m^2h$

$$\varepsilon_j = 1.0065$$

$$\delta_j = -8.589°$$

At the midhour between 10:00 and 11:00 , $\omega_i = -22.5°$

$$H_{0,h} = G_{SC}\varepsilon_j \left(sin\,\phi\ sin\,\delta\ + \frac{24}{\pi}\sin\frac{\pi}{24}\ cos\,\phi\ cos\,\delta\cos\omega_i\right)$$

$$G_{sc} = 1367\frac{W}{m^2} = 1367\frac{J}{sm^2} = 1367 \times 3.6\frac{kJ}{m^2h} = 4921\frac{kJ}{m^2h}$$

$$H_{0,h} = 4921 \cdot 1.0065 \left(sin\,49.18°\,sin(-8.589°) + \frac{24}{\pi}\sin\frac{\pi}{24}\ cos\,49.18°\cos(-8.589°)\cos(-22.5°)\right)$$

$H_{0,h}$ =2389.253 kJ/m^2 h kJ/m^2 intr-o ora 10:00-11:00 AST 0.663681 kWh/m^2

References

[1] Iqbal M (1983) An Introduction to Solar Radiation, ACADEMIC PRESS.

[2] Gueymard, C. A. A reevaluation of the solar constant based on a 42-year total solar irradiance time series and a reconciliation of spaceborne observations. Solar Energy, 2018, 168, 2–9.

Cod R:

```
tabel_ETR_Coef_Leckner_Davos_Smart2<- read.table("ETR_CoefAbs_Leckner_Davos_S
mart2.txt",header = TRUE)
>   head(tabel_ETR_Coef_Leckner_Davos_Smart2, 3)
   wave Gextw Ko Kw Kg Gext_D Gext_S2
1 0.290  48.2 38  0  0  53.50   55.96
```

```
2 0.295  58.4 20  0  0  56.00   54.53
3 0.300  51.4 10  0  0  52.75   47.00
>   N<-nrow(tabel_ETR_Coef_Leckner_Davos_Smart2)
>   N
[1] 144
>   par(mar = c(5, 7, 4, 2))  # (jos, stânga, sus, dreapta)
>   plot(
+     tabel_ETR_Coef_Leckner_Davos_Smart2$wave, tabel_ETR_Coef_Leckner_Davos_
Smart2$Gextw,
+     type = "l",                      # linie continuă
+     lwd = 2,                         # grosimea liniei
+     col = "darkorange3",             # culoare caldă, solară
+     xlab = expression("Wavelength ("*mu*"m)"),   # axa X: lungimea de undă
în micrometri
+     ylab = expression("Solar spectral irradiance  (mW / cm"^2*"·"*mu*"m)"),
# axa Y
+     main = "Extraterrestrial Solar Spectral Irradiance",  # titlu
+     cex.lab = 1.2,    # dimensiune etichete axe
+     cex.main = 1.3, # dimensiune titlu
+     cex.axis = 1.1,  # dimensiune marcaje
+     las = 1,         # cifrele pe axa Y orizontale
+     bty = "l"         # ramă tip L (stânga și jos)
+   )
>   plot(
+     tabel_ETR_Coef_Leckner$wave, tabel_ETR_Coef_Leckner$Gextw*10,
+     type = "l",                      # linie continuă
+     lwd = 2,                         # grosimea liniei
+     col = 1,            # culoare caldă, solară
+     xlab = expression("Wavelength  ("*mu*"m)"),     # axa X: lungimea de un
dă în micrometri
+     ylab = expression("Solar spectral irradiance  (W / m"^2*"·"*mu*"m)"),
# axa Y
+     main = "Extraterrestrial Solar Spectral Irradiance",  # titlu
+     cex.lab = 1.2,                   # dimensiune etichete axe
+     cex.main = 1.3,                  # dimensiune titlu
+     cex.axis = 1.1,                  # dimensiune marcaje
+     las = 1,                         # cifrele pe axa Y orizontale
+     bty = "l"                        # ramă tip L (stânga și jos)
+   )
>   lines(tabel_ETR_Coef_Leckner_Davos_Smart2$wave,tabel_ETR_Coef_Leckner$Gex
t_D*10,col = 2, lwd = 2)
>   lines(tabel_ETR_Coef_Leckner$wave,tabel_ETR_Coef_Leckner$Gext_S2*10,col =
3, lwd = 2)
>   LawPlanck <- function(lambda, T){
+     # lambda in micrometri, T in Kelvin
+     C1 <- 3.7427e8  # W μm^4 / m²
+     C2 <- 1.4388e4  # μm·K
+     result <- C1 / (lambda^5 * (exp(C2 / (lambda * T)) - 1))
+     return(result)
+   }
>   r0<-149597890e3
>   rs<-6.9598e8
>   Gext_P <- LawPlanck(tabel_ETR_Coef_Leckner_Davos_Smart2$wave, 5777)*(rs/r
0)^2
>   summary(Gext_P)
    Min.  1st Qu.   Median     Mean  3rd Qu.     Max.
   9.158  455.172 1175.340 1049.825 1658.732 1792.222
>   lines(tabel_ETR_Coef_Leckner_Davos_Smart2$wave, Gext_P, type = "l",lwd =
2,col=4)
>   legend("topright",
+          legend = c("NASA Spectrum", "WRC Spectrum", "Smarts2 Spectrum", "P
lanck"),
+          col = c(1,2,3,4),
+          lwd = 2,
```

```
+          bty = "n",           # fără chenar
+          cex = 1.1,
+          text.col = "black")


>   ##Constanta Solara
>   head(tabel_ETR_Coef_Leckner_Davos_Smart2)
   wave Gextw    Ko Kw Kg Gext_D Gext_S2
1 0.290  48.2 38.00  0  0 53.500   55.96
2 0.295  58.4 20.00  0  0 56.000   54.53
3 0.300  51.4 10.00  0  0 52.750   47.00
4 0.305  60.3  4.80  0  0 55.750   63.73
5 0.310  68.9  2.70  0  0 60.251   50.55
6 0.315  76.4  1.35  0  0 70.500   68.68
>   s<- 0
>   for(i in 2:N){
+
+     s<- s+(tabel_ETR_Coef_Leckner_Davos_Smart2$Gextw[i]+tabel_ETR_Coef_Leck
ner_Davos_Smart2$Gextw[i-1])*(tabel_ETR_Coef_Leckner_Davos_Smart2$wave[i]-tab
el_ETR_Coef_Leckner_Davos_Smart2$wave[i-1])/2
+
+   }
>   G_SC<- s
>   G_SC   ## mW/cm2
[1] 132.9278
>   G_SC*10  ##  W/m2
[1] 1329.278
>   s<- 0
>   for(i in 2:N){
+
+     s<- s+(tabel_ETR_Coef_Leckner_Davos_Smart2$Gext_D[i]+tabel_ETR_Coef_Lec
kner_Davos_Smart2$Gext_D[i-1])*(tabel_ETR_Coef_Leckner_Davos_Smart2$wave[i]-t
abel_ETR_Coef_Leckner_Davos_Smart2$wave[i-1])/2
+
+   }
>   G_SC<- s
>   G_SC   ## mW/cm2
[1] 134.6535
>   G_SC*10  ##  W/m2
[1] 1346.535
>   s<- 0
>   for(i in 2:N){
+
+     s<- s+(tabel_ETR_Coef_Leckner_Davos_Smart2$Gext_S2[i]+tabel_ETR_Coef_Le
ckner_Davos_Smart2$Gext_S2[i-1])*(tabel_ETR_Coef_Leckner_Davos_Smart2$wave[i]
-tabel_ETR_Coef_Leckner_Davos_Smart2$wave[i-1])/2
+
+   }
>   G_SC<- s
>   G_SC   ## mW/cm2
[1] 135.2649
>   G_SC*10  ##  W/m2
[1] 1352.649
>   ###Solar Temperature
>   G_SC<-1361.1  #W/m2
>   r0<-149.59789e9  ##m
>   rs<-0.69598e9  ##m
>   sigma<-5.6697e-8  ##W m-2  K-4
>   Ts<-(G_SC*(r0/rs)^2/sigma)^(1/4)
>   Ts
[1] 5770.944
>   Coef<- (24/pi)*sin(pi/24)
>   Coef
[1] 0.9971467
```

```
>   # Example 1
>   J<-289   ##16 october
>   # Spencer correction factor for orbital eccentricity
>   correction_spencer <- function(J) {
+     1.00011 +
+       0.034221 * cos(2*pi*(J-1)/365) +
+       0.00128  * sin(2*pi*(J-1)/365) +
+       0.000719 * cos(4*pi*(J-1)/365) +
+       0.000077 * sin(4*pi*(J-1)/365)
+   }
>   eccentricity<-correction_spencer(J)
>   eccentricity
[1] 1.006508
>   Lat_deg <- 49  ##Vancouver
>   Lat_min <- 11
>   Lat <- Lat_deg + Lat_min/60
>   Lat
[1] 49.18333
>   AngleDeclin <- function(x)
+     return((0.006918 -
+               0.399912*cos(2*pi*(x-1)/365) +
+               0.070257*sin(2*pi*(x-1)/365) -
+               0.006758*cos(4*pi*(x-1)/365) +
+               0.000907*sin(4*pi*(x-1)/365) +
+               0.00148*sin(6*pi*(x-1)/365) -
+               0.002697*cos(6*pi*(x-1)/365))*180/pi)
>   delta<-AngleDeclin(J)*pi/180
>   delta
[1] -0.1499134
>   delta*180/pi
[1] -8.589403
>   G_SC<-4921  ##in kJ/m2 h
>   omega<- -22.5   ## omega i
>   H0<-G_SC*eccentricity*(sin(delta)*sin(Lat*pi/180)+(24/pi)*sin(pi/24)*cos(
delta)*cos(Lat*pi/180)*cos(omega*pi/180))
>   H0  ##in kJ/m2       h
[1] 2389.23
>   H0/3600  ## in kWh/m2 intr-o ora
[1] 0.6636751
```