

1.6 Sun's Position Relative to a Tilted Surface

To determine the position of the Sun relative to a tilted surface, the **slope** of the surface with respect to the horizontal plane and the **orientation** of the surface with respect to the local meridian must be specified.

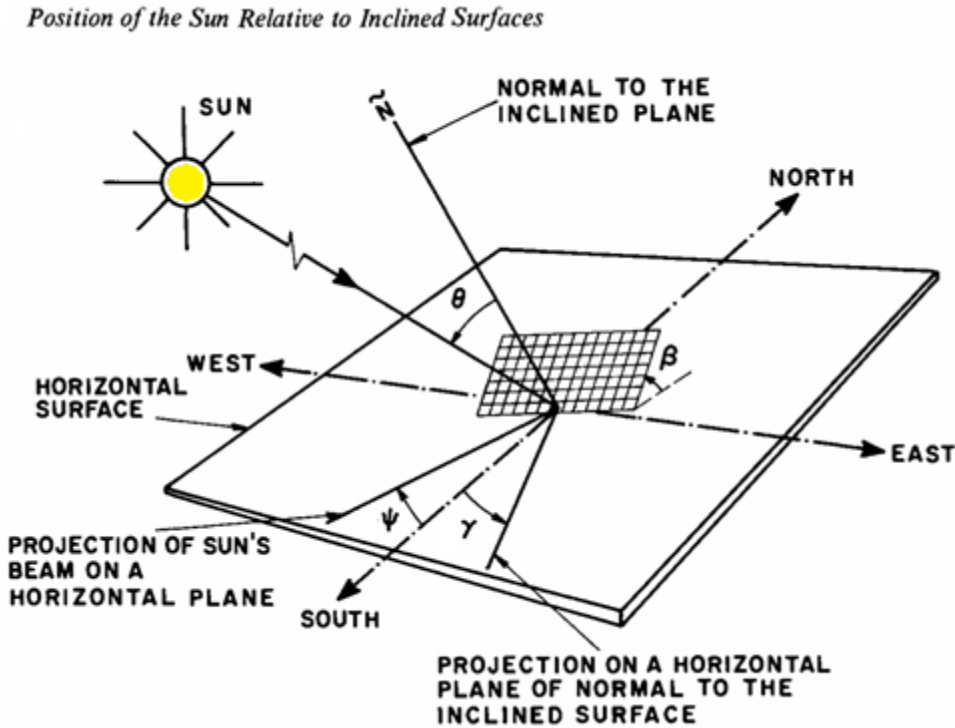


Figure 12. Position of the Sun relative to an inclined plane.

The angles defining the position of the collector surface are:

β is the slope (tilt) of the surface, i.e., its inclination with respect to the horizontal plane.

γ is the surface azimuth, i.e., the deviation of the surface normal from the local meridian (North–South direction).

θ is the angle of incidence of the solar rays on an arbitrarily oriented surface.

θ_z is the angle of incidence of the solar rays on a horizontal surface.

ψ solar azimuth is the angle between the North–South line and the horizontal projection of the Sun's direction.

1.6.1 Equator-facing tilted surface

Let θ_0 be the angle of incidence of the solar rays on an equator-facing tilted surface. We will derive an expression for $\cos\theta_0$. Figure 13 shows two surfaces located at latitudes ϕ and $\phi - \beta$. The

surface at latitude ϕ is tilted by an angle β with respect to the horizontal plane and faces the equator, while the surface at latitude $\phi - \beta$ is horizontal.

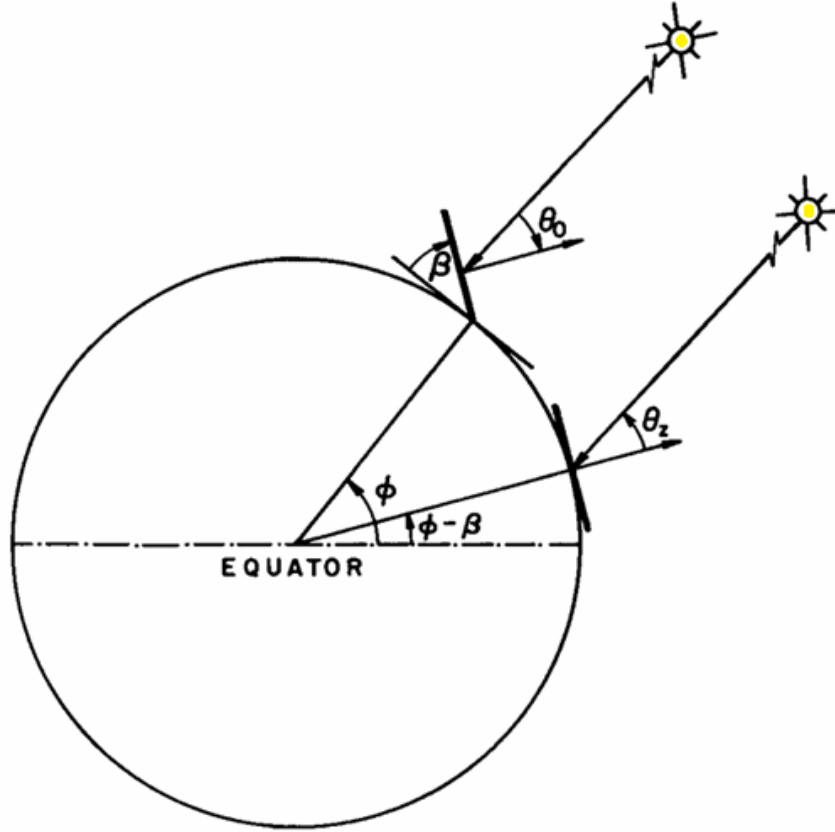


Figure 13. Diagram showing the equality of angles θ_0 and θ_z . (from Liu and Jordan)

From elementary geometry, it can be seen that the two collector surfaces are parallel. Therefore, the angle of incidence θ_0 at latitude ϕ is equal to the angle of incidence θ_z at latitude $\phi - \beta$. Therefore, by analogy with the previously established relation, the angle of incidence (θ_0) for an equator-facing tilted surface is given by:

$$\cos \theta_z = \sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega \quad (1)$$

$$\cos \theta_0 = \sin(\phi - \beta) \sin \delta + \cos(\phi - \beta) \cos \delta \cos \omega \quad (2)$$

Sunrise angle for a tilted surface is the hour angle at which direct solar radiation first strikes the surface in the morning.

On a tilted surface, sunrise or sunset occurs when the angle of incidence is 90° . Let ω'_s be the sunrise hour angle for an equator-facing tilted surface. Thus, at sunrise:

$$\begin{aligned} \theta_0 &= 90^\circ & \omega &= \omega'_s \\ 0 &= \sin(\phi - \beta) \sin \delta + \cos(\phi - \beta) \cos \delta \cos \omega'_s \end{aligned} \quad (3)$$

$$\cos \omega'_s = -\sin(\phi - \beta) \sin \delta / \cos(\phi - \beta) \cos \delta$$

$$\omega'_s = \arccos(-\tan \delta \tan(\phi - \beta)) \quad (4)$$

This relation can be used to calculate the sunrise and sunset hour angles. They differ only in sign.

Special cases:

- (a) At the equinox, $\delta = 0$ and relation (4) gives $\omega'_s = \pi/2$

The sunrise hour angle is independent of both the surface tilt and the latitude.

- (b) During summer in the Northern Hemisphere $\delta > 0$, $\phi > 0$ which leads to

$$\tan \delta \tan(\phi - \beta) < \tan \delta \tan \phi$$

$$-\tan \delta \tan(\phi - \beta) > -\tan \delta \tan \phi$$

$$\cos \omega'_s > \cos \omega_s$$

$$\omega_s > \omega'_s$$

This means that the Sun rises earlier on a horizontal surface than on a tilted surface.

- (c) During winter in the Northern Hemisphere, $\delta < 0$, $\phi > 0$ which leads to

$$\tan \delta \tan(\phi - \beta) > \tan \delta \tan \phi$$

$$-\tan \delta \tan(\phi - \beta) < -\tan \delta \tan \phi$$

$$\cos \omega'_s < \cos \omega_s$$

$$\omega_s < \omega'_s$$

Mathematically, this means that the Sun would rise earlier on a tilted surface than on a horizontal surface. Since this is not physically possible, the following expression is adopted for calculating the sunrise hour angle on a tilted surface:

$$\omega'_s = \min\{\arccos(-\tan \delta \tan \phi), \arccos(-\tan \delta \tan(\phi - \beta))\} \quad (5)$$

Example: Compute:

- (a) The sunrise hour angle for a flat collector surface when the surface tilt relative to the horizontal is (i) 30° (ii) 90° and it is oriented toward the equator.
(b) Calculate the angle of incidence at 11:00 true solar time for each tilt angle (30° , 90°) for a flat collector surface in London ($51^\circ 31' \text{ N}$), tilted toward the equator, on May 15.

$$J = 135 \quad \text{Declination angle: } \delta = 18.67^\circ$$

- (a) Sunrise hour angle on a horizontal surface

$$\omega_s = \arccos(-\tan 51.5 \tan 18.67) = 115.15^\circ$$

- (i) Sunrise hour angle on a tilted surface at 30°

$$\omega_s' = \arccos(-\tan 18.7 \tan(51.5 - 30)) = 97.65$$

(ii) Sunrise hour angle on a tilted surface at 90°

$$\omega_s' = \arccos(-\tan 18.77 \tan(51.5 - 90)) = 74.41$$

(b) Angle of incidence on the tilted surface

At AST = 11:00 $\omega = -15^\circ$

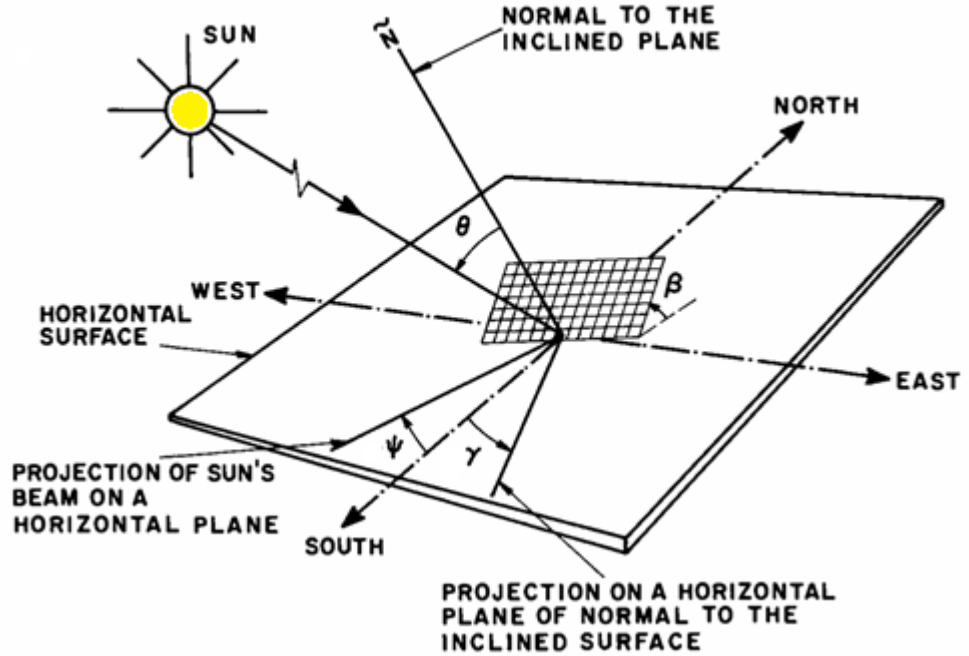
$$\cos \theta_0 = \sin(\phi - \beta) \sin \delta + \cos(\phi - \beta) \cos \delta \cos \omega$$

(i) $\theta_0 = 14.36^\circ$

(ii) $\theta_0 = 58.86^\circ$

1.6.2 Arbitrarily oriented surface

Position of the Sun Relative to Inclined Surfaces



For collector surfaces arbitrarily oriented with respect to the local meridian, the trigonometric relation for the angle of incidence of the solar rays is:

$$\begin{aligned} \cos \theta = & (\sin \phi \cos \beta - \cos \phi \sin \beta \cos \gamma) \sin \delta \\ & + (\cos \phi \cos \beta + \sin \phi \sin \beta \cos \gamma) \cos \delta \cos \omega \\ & + \cos \delta \sin \beta \sin \gamma \sin \omega \end{aligned} \quad (6)$$

Or:

$$\cos \theta = \cos \beta \cos \theta_z + \sin \beta \sin \theta_z \cos(\psi - \gamma) \quad (7)$$

However, Equation (6) is preferred because it does not require separate calculations of the solar azimuth and zenith angles.

For equator-facing tilted surfaces ($\gamma = 0$), it can be shown that Equation (6) reduces to Equation (2).

$$\begin{aligned} \cos\theta &= (\sin\phi\cos\beta - \cos\phi\sin\beta\cos 0)\sin\delta \\ &\quad + (\cos\phi\cos\beta + \sin\phi\sin\beta\cos 0)\cos\delta\cos\omega \\ &\quad + \cos\delta\sin\beta\sin 0\sin\omega \end{aligned}$$

$$\begin{aligned} \cos\theta_0 &= (\sin\phi\cos\beta - \cos\phi\sin\beta)\sin\delta \\ &\quad + (\cos\phi\cos\beta + \sin\phi\sin\beta)\cos\delta\cos\omega \end{aligned}$$

$$\cos\theta_0 = \sin(\phi - \beta)\sin\delta + \cos(\phi - \beta)\cos\delta\cos\omega$$

For vertical surfaces, ($\beta = 90^\circ$), Equation (6) gives:

$$\begin{aligned} \cos\theta &= (\sin\phi\cos 90^\circ - \cos\phi\sin 90^\circ\cos\gamma)\sin\delta \\ &\quad + (\cos\phi\cos 90^\circ + \sin\phi\sin 90^\circ\cos\gamma)\cos\delta\cos\omega \\ &\quad + \cos\delta\sin 90^\circ\sin\gamma\sin\omega \end{aligned}$$

$$\begin{aligned} \cos\theta &= -\cos\phi\cos\gamma\sin\delta + \sin\phi\cos\gamma\cos\delta\cos\omega \\ &\quad + \cos\delta\sin\gamma\sin\omega \end{aligned}$$

Example: Calculate the angle of incidence of direct solar radiation on a surface located in Madison, (latitude $43^\circ N$), at 10:30 (true solar time) on February 13, if the surface is tilted at 45° from the horizontal and oriented 15° west of south.

$$\begin{aligned} J &= 44 & \delta &= -13.62^\circ \cong -14^\circ & \omega &= -22.5^\circ \\ \phi &= 43^\circ & \beta &= 45^\circ \end{aligned}$$

$$\begin{aligned} \cos\theta &= (\sin\phi\cos\beta - \cos\phi\sin\beta\cos\gamma)\sin\delta \\ &\quad + (\cos\phi\cos\beta + \sin\phi\sin\beta\cos\gamma)\cos\delta\cos\omega \\ &\quad + \cos\delta\sin\beta\sin\gamma\sin\omega \end{aligned} \quad (6)$$

$$\cos\theta = 0.818 \quad \theta = 35.05^\circ$$

Chapter 2 THERMAL RADIATION

2.1 Thermal Radiation and the Electromagnetic Spectrum

Matter can emit electromagnetic radiation by molecular and atomic agitation. The spectrum of electromagnetic radiation encompasses γ rays, x rays, ultraviolet radiation, light, heat, radio waves, and radar waves.

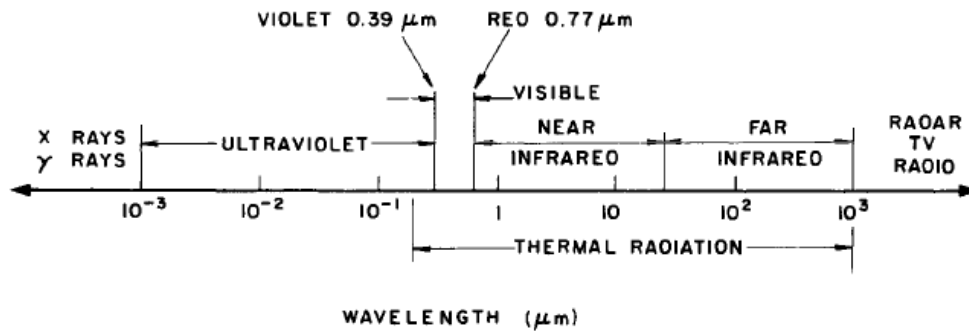


Figure 1 Spectrum of electromagnetic radiation

Our main focus is on the **thermal radiation** portion of the electromagnetic spectrum. Thermal radiation is emitted by matter as a result of the thermal motion of its particles and is associated with its temperature. The human eye is a highly sensitive detector of visible light, whereas our bodies are relatively poor detectors of thermal radiation. Most of the solar radiation reaching the Earth's surface lies within the **thermal radiation range**.

Electromagnetic radiation is generally classified by wavelength, though frequency and wave number are also used. **Frequency** has the advantage over wavelength of not changing when radiation passes from one medium to another. Frequency ν is defined as

$$\nu = \frac{c_0}{\lambda_{vac}} = \frac{c}{\lambda_{med}} \quad (1)$$

where c_0 and c are the speeds of propagation for electromagnetic radiation in a vacuum and in a medium, respectively; λ is wavelength.

In a vacuum $c_0 = 2.998 \times 10^8 \text{ m/s}$

The speed c in a medium is given in terms of the index of refraction n

$$n = \frac{c_0}{c} \quad (2)$$

For gases, n is very close to but greater than unity.

Thermal radiation encompasses the wavelength range $0.2 - 1000 \mu m$.

The visible spectrum may be considered within $0.39 - 0.77 \mu m$.

The ultraviolet (UV) spectrum may be divided into three bands:

near uv $0.3 - 0.4 \mu m$

far uv $0.2 - 0.3 \mu m$

maximum uv $0.001 - 0.2 \mu m$

Solar UV radiation is classified into three sub-bands:

UV-C (100–280 nm), UV-B (280–315 nm) and UV-A (315–400 nm).

The infrared (IR) portion of thermal radiation is generally divided into two parts:

near IR, $0.77 - 25 \mu m$, and far IR, $25 - 1000 \mu m$.

Another subdivision of thermal radiation is into **shortwave** and **longwave** radiation. The boundary between the two is somewhat arbitrary. In solar energy applications, most **solar radiation** is considered shortwave radiation, with the upper wavelength limit commonly taken between 3 and 4 μm . Radiation at wavelengths greater than 4 μm is generally referred to as **longwave radiation**. The longwave radiation emitted by the Earth and its atmosphere is commonly called **terrestrial radiation**.

2.2 Blackbody Radiation

A body (or surface) emits energy at all wavelengths of the electromagnetic spectrum. At a given temperature, a **blackbody** is an ideal surface that emits the maximum possible amount of energy at each wavelength and in all directions and absorbs all incident radiation at every wavelength and from every direction.

A blackbody is an idealized surface used as a reference for comparing the radiative properties of real surfaces.

The radiation emitted by the Sun can be approximated by the radiation from a blackbody at an equivalent temperature (5777 K Iqbal, 5760 K Nelson, 5793 K Mackay).

The emissive power of a blackbody at any wavelength and temperature, called its **spectral emissive power**, is given by Planck's law. For radiation into a vacuum or a medium of refractive index of unity, this law in a simple form can be written

$$G_b(\lambda) = \frac{C_1}{\lambda^5 \left(e^{\frac{C_2}{\lambda T}} - 1 \right)} \quad (3)$$

$G_b(\lambda)$ is the hemispherical spectral emissive power of a blackbody ($W m^{-2} \mu m^{-1}$)

$$C_1 = 2\pi h c^2 = 3.74 \times 10^{-16} W m^2$$

$C_1 = 2\pi hc^2 = 3.74 \times 10^8 \text{ W}\mu\text{m}^4\text{m}^{-2}$ first radiation constant

$$C_2 = \frac{hc}{k_B} = 0.0144 \text{ K m}$$

$$C_2 = \frac{hc}{k_B} = 1.44 \times 10^4 \mu\text{m K} \quad \text{second radiation constant}$$

λ the wavelength (μm)

T the blackbody temperature (K).

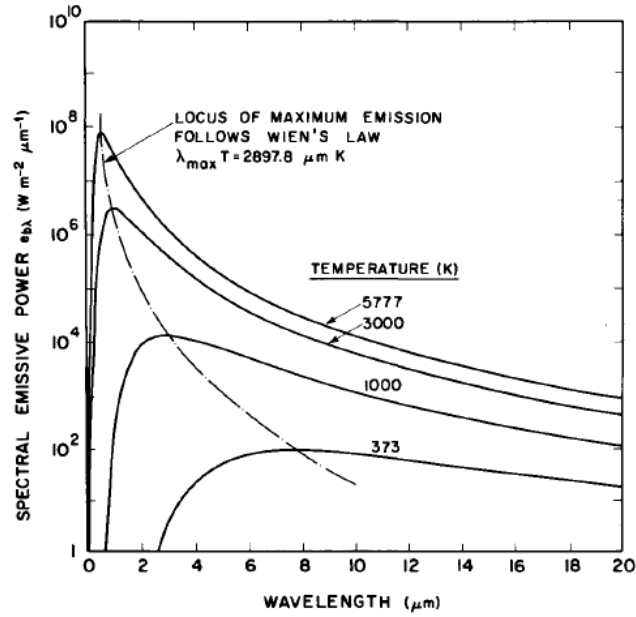
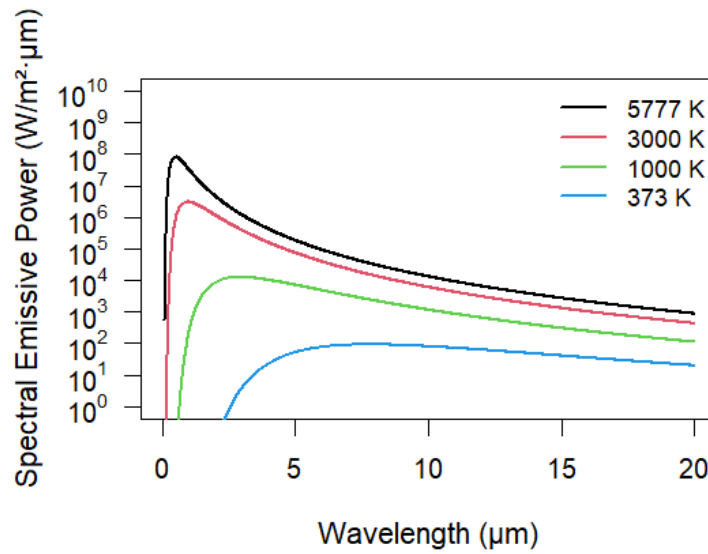


Figure 2. Spectral emissive power of a blackbody (Iqbal)



More energy is emitted at shorter wavelengths.

The position of maximum emissive power shifts toward shorter wavelengths.

The sun's equivalent surface temperature is 5777 K. Figure 2 shows that if the sun's surface were a blackbody, most of its energy would be in the short-wavelength range. Some flat-plate collectors are designed to operate at $\approx 100^\circ\text{C}$. From Fig. 2 it can be concluded that the energy emitted by such collectors is mostly in the longwave region.

Thus, the spectral emissive power of the Sun becomes:

$$G_b(\lambda) = \frac{2\pi hc^2}{\lambda^5} \frac{1}{\exp(hc/\lambda k_B T_S) - 1} \quad (4)$$

Stefan-Boltzmann Law

The emissive power of a blackbody within bandwidth $d\lambda$ is written $G_b(\lambda)d\lambda$. The radiation leaving a surface of unit area at all wavelengths is called the total emissive power G_b

$$G_b = \int_0^\infty G_b(\lambda)d\lambda = \int_0^\infty \frac{C_1}{\lambda^5 \left(e^{\frac{C_2}{\lambda T}} - 1 \right)} d\lambda$$

$$G_b = (C_1 \pi^4 / 15 C_2^4) T^4 = \sigma T^4 \quad (5)$$

σ = Stefan-Boltzmann constant

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

Wien's Displacement Law

$$\lambda_{max} T = 2897.8 \mu\text{m K} \quad (6)$$

Maximum emissive power per unit wavelength is at

$$\lambda_{max} = 2897.8 / T \mu\text{m} \quad (7)$$

Assuming that the Sun is a blackbody at 5777 K,

$$\lambda_{max} = \frac{2897.8}{5777} = 0.5016 \mu\text{m}$$

For radiation from a flat-plate collector at 373 K,

$$\lambda_{max} = \frac{2897.8}{373} \approx 8 \mu\text{m} \text{ which is near infrared.}$$

EXAMPLE 1. Determination of the surface temperature of a blackbody radiating with a total emissive power of $7.250 \times 10^4 \text{ W m}^{-2}$ and of the wavelength of maximum spectral emissive power.

$$G_b = \sigma T^4 \quad T = (G_b/\sigma)^{1/4} \quad \lambda_{max} = \frac{2897.8}{T} \mu m$$

R: 1063.4 K; 2.73 μm

EXAMPLE 2. Plotting the spectral irradiance on a surface normal to the rays placed at the mean sun-earth distance, assuming that the sun is a blackbody at an effective temperature of 5777 K.

Solution. The mean sun-earth distance $r_0 = 149\,597\,890$ km.

The mean radius of the solar disk $r_s = 6.9598 \times 10^5$ km .

$$G_b(\lambda) = \frac{2\pi hc^2}{\lambda^5} \frac{1}{\exp(hc/\lambda k_B T_S) - 1}$$

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

$$G_{0n\lambda} = G_{b\lambda} \left(\frac{r_s}{r_0} \right)^2 \quad (8)$$

The geometric factor $(r_s/r_0)^2$ accounts for the geometric spreading of solar radiation between the solar surface and the Earth's orbit.

$$G_{0n\lambda} = \frac{2\pi hc^2}{\lambda^5} \cdot \frac{1}{\exp\left(\frac{hc}{\lambda k_B T_S}\right) - 1} \cdot \left(\frac{r_s}{r_0} \right)^2 \quad (9)$$

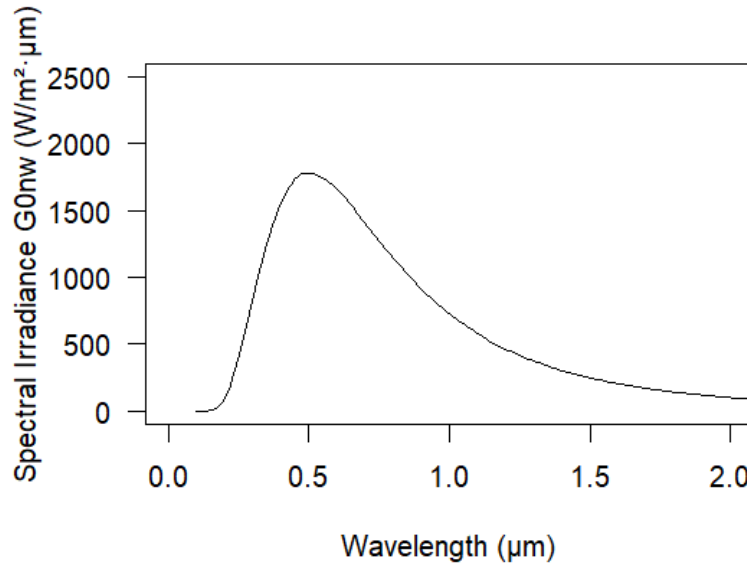


Figure 3 Extraterrestrial Spectral Irradiance with Planck law

2.3 Comparison with Michael Mackay and Jenny Nelson

The geometric factor $\left(\frac{r_s}{r_0}\right)^2$ can also be expressed using the apparent half-angle subtended by the Sun.

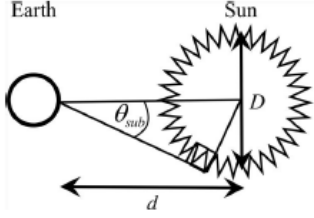


Figure 4. The apparent half-angle subtended by the Sun (from Mackay)

$$\sin^2 \theta_{sun} = \left(\frac{r_s}{r_0}\right)^2 \quad (10)$$

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

$$G_{0n\lambda} = \frac{2\pi \sin^2 \theta_{sun} h c^2}{\lambda^5} \frac{1}{\exp(hc/\lambda k_B T_S) - 1} \quad (11)$$

$$G_{ext}(\lambda) = \frac{2\pi \sin^2 \theta_{sub} h c^2}{\lambda^5} \frac{1}{\exp(hc/\lambda k_B T_S) - 1}$$

A More Detailed Calculation of Extraterrestrial Spectral Irradiance

The angular photon flux density, n , is the number of photons of given energy passing through unit area in unit time, per unit solid angle. It is defined on an element of surface area, and its direction is defined by the angle to the surface normal, θ , and an azimuthal angle, ϕ , projected on the plane of the surface element.

$$n(E) = \frac{2}{h^3 c^2} \frac{E^2}{\exp(E/k_B T_S) - 1} \quad \left(\frac{\text{photons}}{\text{s sr J m}^2}\right) \quad (12)$$



Figure 5. Angular photon flux and along the normal to the surface.

In structures symmetry it is sufficient to know the photon flux density resolved along the normal to the surface, N_p . N_p is obtained by integrating the components of n normal to the surface over solid angle.

If we integrate only over the surface of the blackbody,

$$N_p(E) = \int_0^{2\pi} \int_0^{\pi/2} \frac{2}{h^3 c^2} \frac{E^2}{\exp(E/k_B T_S) - 1} \cos \theta \sin \theta d\theta d\phi$$

$$= \frac{2}{h^3 c^2} \frac{E^2}{\exp(E/k_B T_S) - 1} \pi$$
(13)

Away from the surface, the angular range is reduced and

$$N_p(E) = \int_0^{2\pi} \int_0^{\theta_{sub}} \frac{2}{h^3 c^2} \frac{E^2}{\exp(E/k_B T_S) - 1} \cos \theta \sin \theta d\theta d\phi$$

$$= \frac{2}{h^3 c^2} \frac{E^2}{\exp(E/k_B T_S) - 1} \pi \sin^2 \theta_{sub}$$
(14)

Where θ_{sub} is the half angle subtended by the radiating body to the point where the flux is measured. For the sun as seen from the earth, $\theta_{sub} = 0.265^\circ$.

$$N_p(E) = \frac{2\pi \sin^2 \theta_{sub}}{h^3 c^2} \frac{E^2}{\exp(E/k_B T_S) - 1} \quad \left(\frac{\text{photons}}{\text{s J m}^2} \right)$$

The extraterrestrial spectral irradiance (AM0) is obtained from the spectral photon flux by multiplying by the photon energy E and converting to wavelength representation.

$$E = \frac{hc}{\lambda}, \quad dE = -\frac{hc}{\lambda^2} d\lambda, \quad N_p(E) dE = G(\lambda) d\lambda$$
(15)

$$N_p(E) E dE = \frac{2\pi \sin^2 \theta_{sub}}{h^3 c^2} \frac{h^3 c^3}{\lambda^3} \frac{1}{\exp(hc/\lambda k_B T_S) - 1} \left(-\frac{hc}{\lambda^2} d\lambda \right)$$

So, the same equation (11) for the extraterrestrial spectral irradiance at the mean Sun–Earth distance.

$$G_{ext}(\lambda) = \frac{2\pi \sin^2 \theta_{sub} hc^2}{\lambda^5} \frac{1}{\exp(hc/\lambda k_B T_S) - 1}$$

References

- [1] Iqbal M (1983) An Introduction to Solar Radiation, ACADEMIC PRESS.
- [2] M.E. Mackay (2015) Solar Energy An introduction, Oxford University Press.
- [3] J. Nelson (2002) The Physics of Solar Cell, Imperial College Press.

Cod R:

```
J<-135
> Lat_deg <- 51
> Lat_min <- 31
> Lat <- Lat_deg + Lat_min/60
> Lat
[1] 51.51667
```

```

> AST<-11
> HourAngle<-function(x)
+   return((x-12)*2*pi/24)
> omega<-HourAngle(AST)
> omega
[1] -0.2617994
> omega*180/pi
[1] -15
> 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)
> AngleDeclin(J)
[1] 18.67362
> ## declination and latitude in rad
> delta<-AngleDeclin(J)*pi/180
> phi<-Lat*pi/180
> ###unghi orar de rasarit pe supraf orizontala
> Unghi_Orar_rasarit_S_oriz<-function(x,y)
+   return<-acos(-tan(x)*tan(y))
> Omega_s<-Unghi_Orar_rasarit_S_oriz(phi,delta)
> Omega_s
[1] 2.009911
> Omega_s*180/pi
[1] 115.1594
> ###unghi orar de rasarit pe supraf inclinata
> beta<-30
> beta<-90
> ###folosesc aceeasi functie de calcul pt supraf oriz in care modific Lat
cu Lat-beta
> Omega_s_tilt<-Unghi_Orar_rasarit_S_oriz(phi-beta*pi/180,delta)
> Omega_s_tilt
[1] 1.298783
> Omega_s_tilt*180/pi
[1] 74.41476

####unghi de incidenta pe suprafata inclinata
> ## verif beta
> beta
[1] 90
> AST<-11
> omega<-HourAngle(AST)
> omega
[1] -0.2617994
> omega*180/pi
[1] -15
> CosTeta0<-sin(phi-beta*pi/180)*sin(delta)+cos(phi-beta*pi/180)*cos(delta)
*cos(omega)
> CosTeta0
[1] 0.5170708
> Teta0<-acos(CosTeta0)
> Teta0
[1] 1.027371
> Teta0*180/pi
[1] 58.86403
> beta<-30
> CosTeta0<-sin(phi-beta*pi/180)*sin(delta)+cos(phi-beta*pi/180)*cos(delta)
*cos(omega)
> CosTeta0

```

```

[1] 0.9687383
> Teta0<-acos(CosTeta0)
> Teta0
[1] 0.2507028
> Teta0*180/pi
[1] 14.36421
> beta<-90
> CosTeta0<-sin(phi-beta*pi/180)*sin(delta)+cos(phi-beta*pi/180)*cos(delta)
*cos(omega)
> CosTeta0
[1] 0.5170708
> Teta0<-acos(CosTeta0)
> Teta0
[1] 1.027371
> Teta0*180/pi
[1] 58.86403

> #####unghi de incidenta pe suprafata orientata arbitrar
#####unghi de incidenta pe suprafata orientata arbitrar
> J<-44
> Lat<-43
> phi<-Lat*pi/180
> beta<-45      ###inclinare suprafata
> gama<-15      ##azimut suprafata
> AST<-10.5
> omega<-HourAngle(AST)
> omega
[1] -0.3926991
> omega*180/pi
[1] -22.5
> delta<-AngleDeclin(J)*pi/180
> delta
[1] -0.2378596
> delta*180/pi
[1] -13.62835
> CosTeta<-((sin(phi)*cos(beta*pi/180)-cos(phi)*sin(beta*pi/180)*cos(gama*pi/180))*sin(delta)
+ (cos(phi)*cos(beta*pi/180)+sin(phi)*sin(beta*pi/180)*cos(gama*pi/180))*cos(delta)*cos(omega)
+ cos(delta)*sin(beta*pi/180)*sin(gama*pi/180)*sin(omega))
> CosTeta
[1] 0.8185736
> Teta<-acos(CosTeta)
> Teta
[1] 0.6118731
> Teta*180/pi
[1] 35.05775

##### Blackbody Radiation
h<-6.625*10^(-34)  ##J s
> c<-3*10^8      ##m/s
> kB<-1.38*10^(-23)  ##J/K
> Const_1<-2*pi*h*c^2  ##W m2
> Const_1
[1] 3.746349e-16
> Const_1*10^24  ##W microm^4 /m2
[1] 374634924
> Const_2<-h*c/kB  ## K m
> Const_2
[1] 0.01440217
> Const_2*10^6  ##K micro m
[1] 14402.17
> LawPlanck <- function(lambda, T){
+   # lambda in micrometri, T in Kelvin

```

```

+   C1 <- 3.74e8 # w  $\mu\text{m}^4$  / m2
+   C2 <- 1.44e4 #  $\mu\text{m}\cdot\text{K}$ 
+   result <- C1 / (lambda^5 * (exp(C2 / (lambda * T)) - 1))
+   return(result)
+ }
> w <- seq(0.1, 20, 0.01)
> I1 <- LawPlanck(w, 5777)
> I2 <- LawPlanck(w, 3000)
> I3 <- LawPlanck(w, 1000)
> I4 <- LawPlanck(w, 373)
> plot(w, I1,
+       type = "l",
+       lwd = 2,
+       log = "y",
+       xlab = "Wavelength ( $\mu\text{m}$ )",
+       ylab = "Spectral Emissive Power ( $\text{W}/\text{m}^2\cdot\mu\text{m}$ )",
+       las = 1,
+       ylim = c(1, 10^10),
+       xlim = c(0, 20),
+       yaxt = "n",
+       cex.lab = 1.1,
+       cex.axis = 1.0)
> # Axa Y cu puteri ale lui 10
> yt <- 10^(0:10)
> axis(2, at = yt, labels = parse(text = paste0("10^", 0:10)), las = 1)
> lines(w, I2, lwd = 2, col = 2)
> lines(w, I3, lwd = 2, col = 3)
> lines(w, I4, lwd = 2, col = 4)
> legend("topright",
+       legend = c("5777 K", "3000 K", "1000 K", "373 K"),
+       col = 1:4,
+       lwd = 2,
+       bty = "n",
+       cex = 0.9)
> ## EXEMPLU1
> sigma<-5.6697e-8 ## const Boltzmann
> Gb<-7.25e4 ##W/m2
> T<-(Gb/sigma)^(1/4)
> T
[1] 1063.395
> landa_max<-2897.8/T
> landa_max
[1] 2.725047
> r0<-149597890e3
> rs<-6.9598e8
> G0nw <- LawPlanck(w, 5777)*(rs/r0)^2
> plot(w, G0nw, type = "l",
+       xlab = "Wavelength ( $\mu\text{m}$ )", ylab = "Spectral Irradiance G0nw ( $\text{W}/\text{m}^2\cdot\mu\text{m}$ )",
+       xlim = c(0,2),ylim = c(0,2500),las=1)

```