Renewable Energy Systems

EE—325

Introduction

The utilization of photovoltaics depends on the availability of sunlight. For this reason we will devote this chapter to the characteristics and possibilities of solar radiation.

Properties of Solar Radiation

Solar radiation consists of electromagnetic radiations of different wavelengths.
The energy contained in a photon is related to the wavelength of the electromagnetic radiation and is given by (19.1):

$$E = \frac{hc}{\lambda} \tag{19.1}$$

where E is the energy of the photon (J), c is the speed of light (3×10^8 m/s), λ is the wavelength (m), and h is the Planck's constant (6.626×10^{-34} Js).

Example 19.1

Let 1.12 eV energy be needed to promote an electron to the conduction band. Calculate the minimum frequency of the photon required.

Solution

Band gap energy, $E_g = 1.12$ eV

1 eV = 1.6×10^{-19} J

So $E_g = 1.12 \text{ eV} = 1.12 \times 1.6 \times 10^{-19}\text{J} = 1.792 \times 10^{-19}$ J

The maximum wavelength (λ_{max}) that contains energy just equal to band gap energy is calculated as $E = \dfrac{hc}{\lambda_{max}} = E_g$

$$\text{Thus } \frac{6.626\times10^{-34}\text{ Js}\times 3\times10^{8}\text{ m/s}}{\lambda_{max}} = 1.792\times10^{-19}\text{ J}$$

or $\lambda_{max} = \dfrac{6.626\times10^{-34}\text{ Js}\times 3\times10^{8}\text{ m/s}}{1.792\times10^{-19}\text{ J}} = 1.109\times10^{-6}$ m and the corresponding frequency is

$$\upsilon_{min} = \frac{c}{\lambda_{max}} = \frac{3\times10^{8}\text{ m/s}}{1.109\times10^{-6}\text{ m}} = 2.705\times10^{14}\text{ Hz}.$$

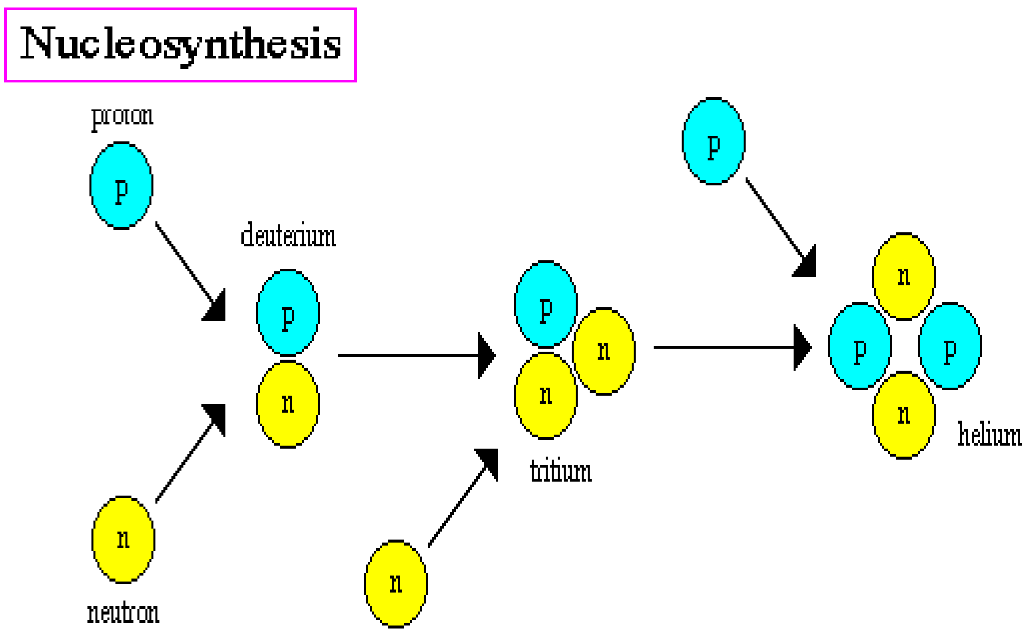
Properties of Solar Radiation

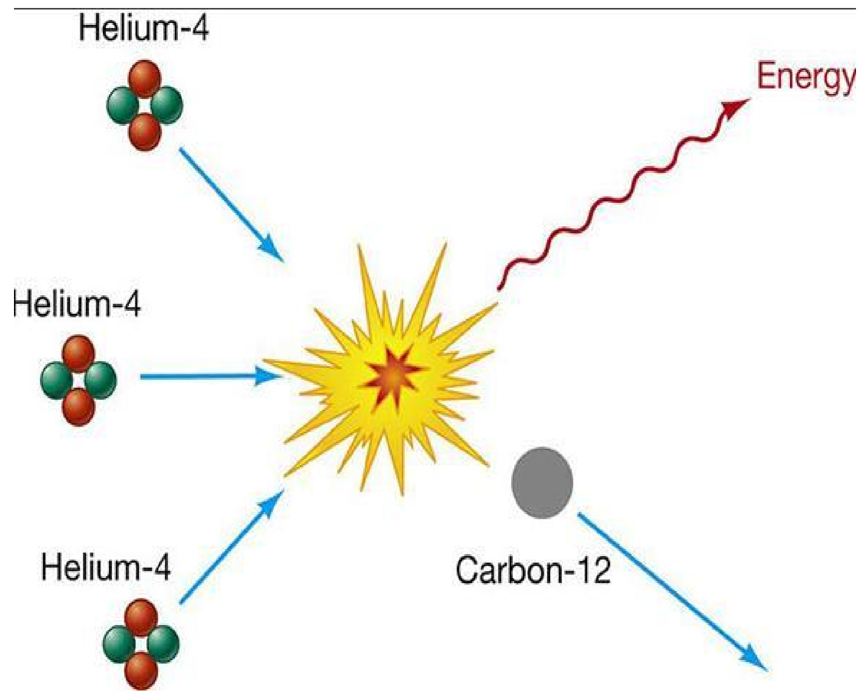
2.1.1 Solar Constant

The Sun, like other stars, is a natural **fusion reactor**, where stellar nucleosynthesis transforms lighter elements into heavier elements with the release of energy.

Stellar: relating to a star or stars.

Nucleosynthesis: is the process that creates new atomic nuclei from pre-existing nucleons (i.e., a proton or neutron.).





Properties of Solar Radiation

2.1.1 Solar Constant

The distance between the two space bodies is approximately 150 million km and other dimensions can be taken from Table 2.1.

The **Sun** continuously radiates an amount of P_{Sun}=**3.845×10²⁶W** in all directions of which the **Earth only receives a small fraction**.

Table 2.1 Characteristics of the Sun and the Earth

Properties	Sun	Earth
Diameter	$d_{\text{Sun}} = 1\,392\,520\,\text{km}$	$d_{\text{Earth}} = 12\,756\,\text{km}$
Surface temperature	$T_{\text{Sun}} = 5778\,\text{K}$	$T_{\text{Earth}} = 288\,\text{K}$
Temperature at center	15 000 000 K	6700 K
Radiated power	$P_{\text{Sun}} = 3.845 \cdot 10^{26}\,\text{W}$	–
Distance Sun–Earth	$r_{\text{SE}} = 149.6$ Mio. km	

Properties of Solar Radiation

2.1.1 Solar Constant

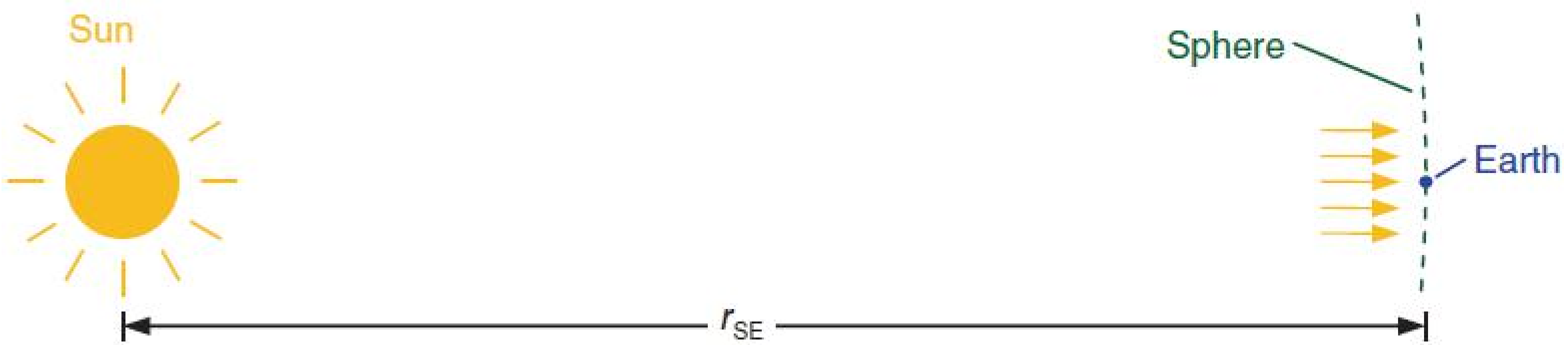


Figure 2.1 Determination of the solar constants

In order to calculate the solar power reaching the Earth, we assume there is a sphere around the Sun that has a radius of $r = r_{SE}$. At this distance the amount of radiation from the Sun has already spread over the whole area of the sphere. Thus at the position of the Earth we get the following power density or **irradiance**.

$$E_S = \frac{\text{Radiation power}}{\text{Area of sphere}} = \frac{P_{Sun}}{4 \cdot \pi \cdot r_{SE}^2} = \frac{3.845 \cdot 10^{26}\,\text{W}}{4 \cdot \pi \cdot (1.496 \cdot 10^{11}\,\text{m})^2} = 1367\ \text{W/m}^2 \qquad (2.1)$$

The result of $1367\,\text{W/m}^2$ is called the **solar constant**.

2.1.2 Spectrum of the Sun

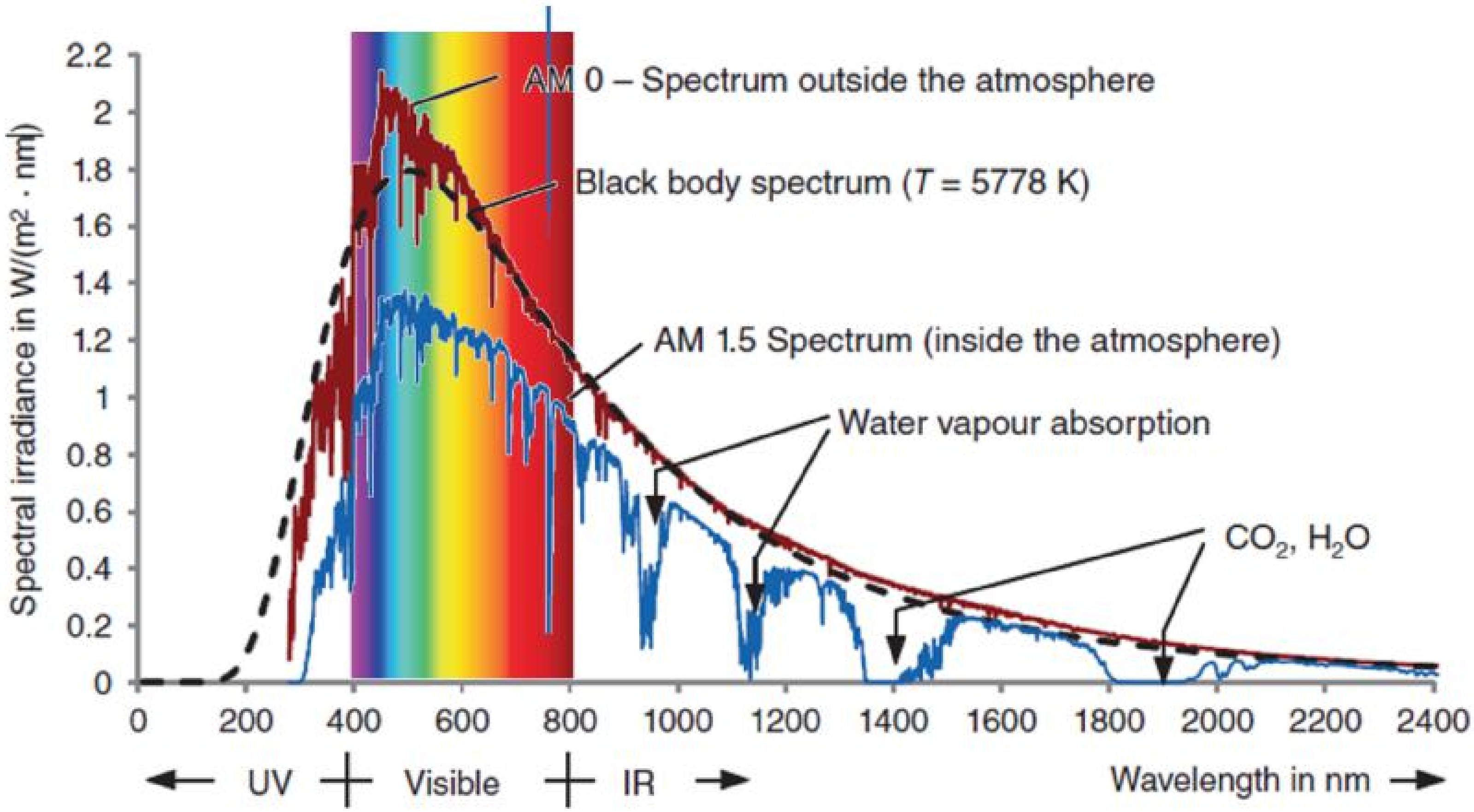


Figure 2.2 Spectrum outside and inside the atmosphere

2.1.2 Spectrum of the Sun

The spectrum changes when sunlight passes through the atmosphere. There are various reasons for this:

1. *Reflection of light*:
Sunlight is reflected in the atmosphere and this reduces the radiation reaching the Earth.

2. *Absorption of light*:
Molecules (O2, O3, H2O, CO2 . . .) are excited at certain wavelengths and absorb a part of the radiation causing “gaps” in the spectrum especially in the infrared region (see, for instance, Figure 2.2 at *l*=1400 nm).

3. *Rayleigh scattering*:
If light falls on particles that are smaller than the wavelength, then **Raleigh scattering** occurs. This is strongly dependent on wavelength (∼1/*l*4) so shorter wavelengths are scattered particularly strongly.

4. *Scattering of aerosols and dust particles*:
This concerns particles that are large compared to the wavelength of light. The strength of the scattering depends greatly on the location; it is greatest in industrial and densely populated areas.

2.2 Global Radiation

Direct radiation is defined as the **radiation** that has not experienced scattering in the atmosphere, so that it is directionally fixed, coming from the Sun.

Diffuse radiation is solar **radiation** reaching earth's surface after having been scattered from the direct solar beam by molecules or suspensoids in the atmosphere.

The sum of both types of radiation is called **global radiation**.

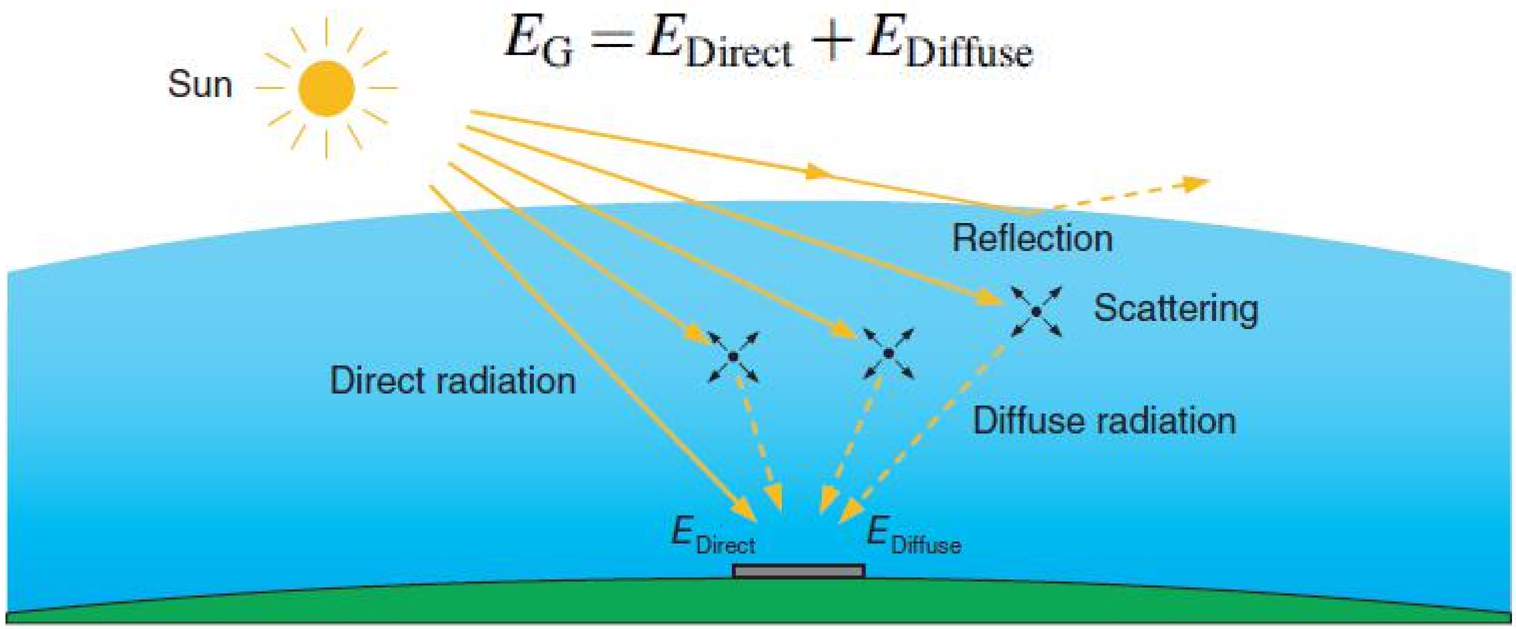
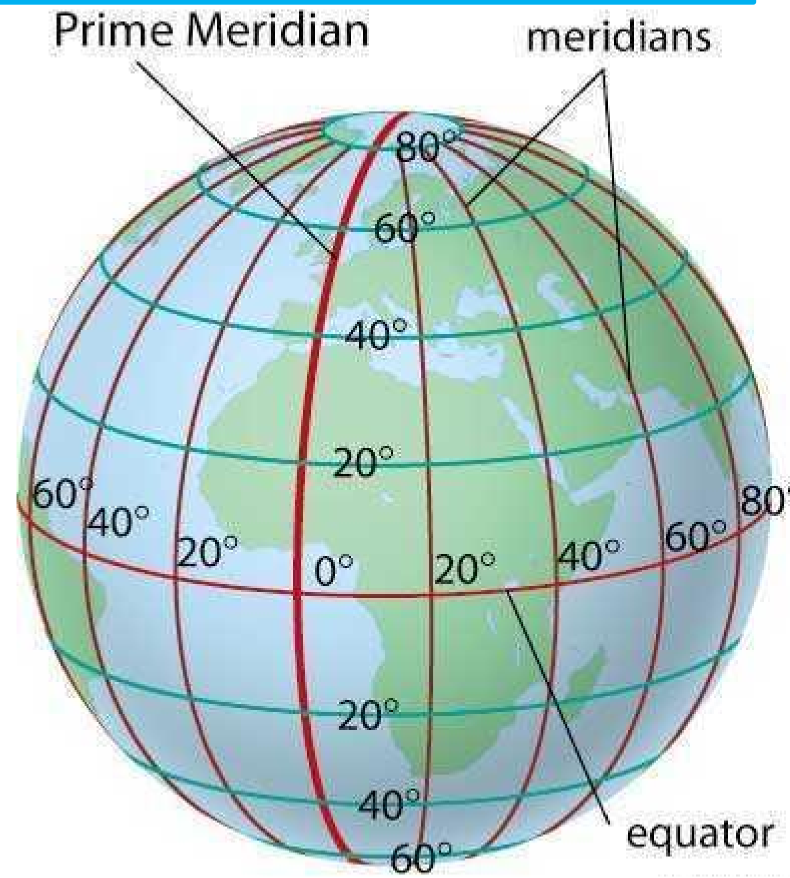


Figure 2.4 Origin of global radiation: It is the sum of the direct and diffuse radiation

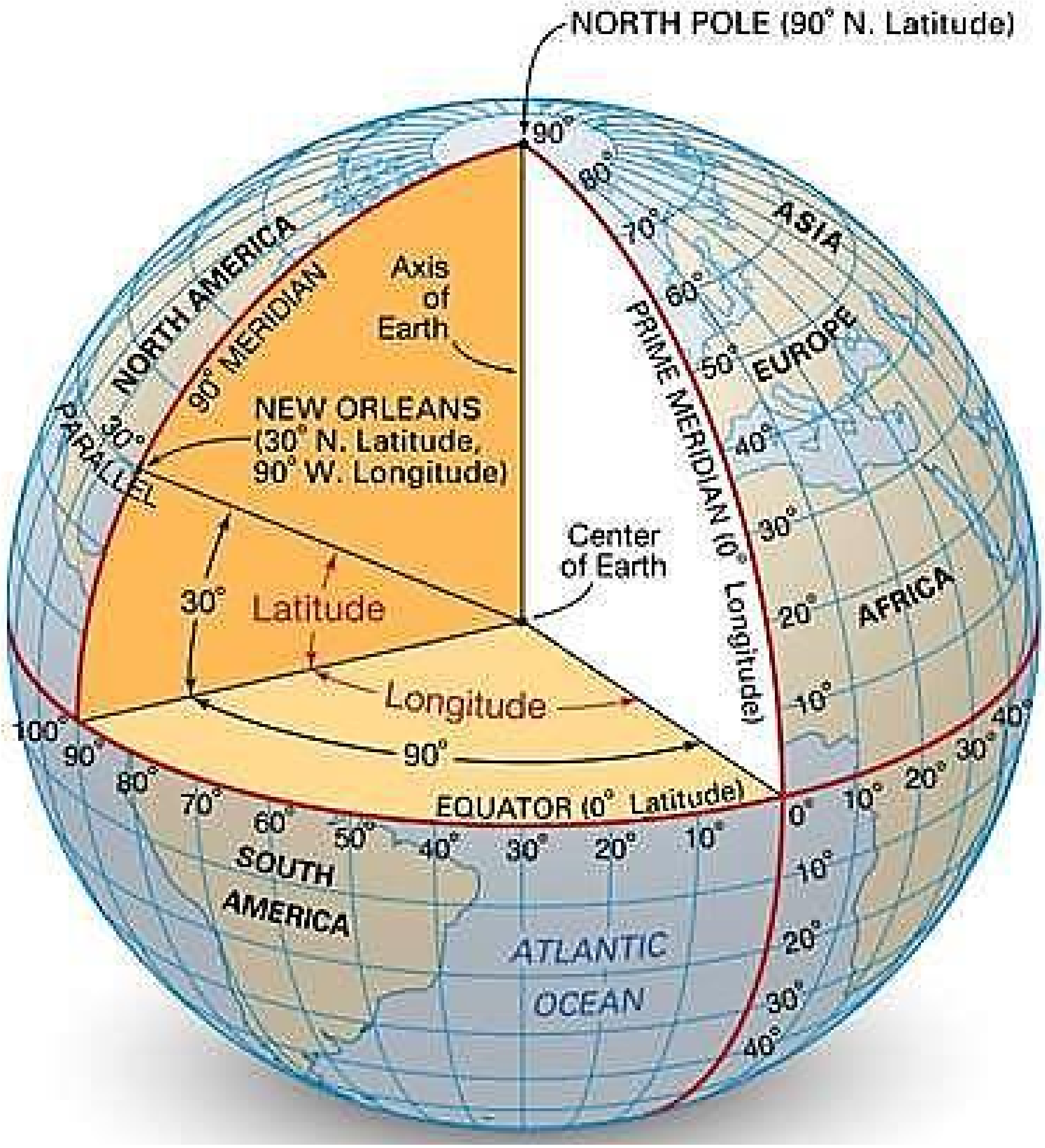
What is Latitude and Longitude

A **Prime Meridian** is a meridian (a line of longitude) in a geographic coordinate system at which longitude is defined to be 0°.

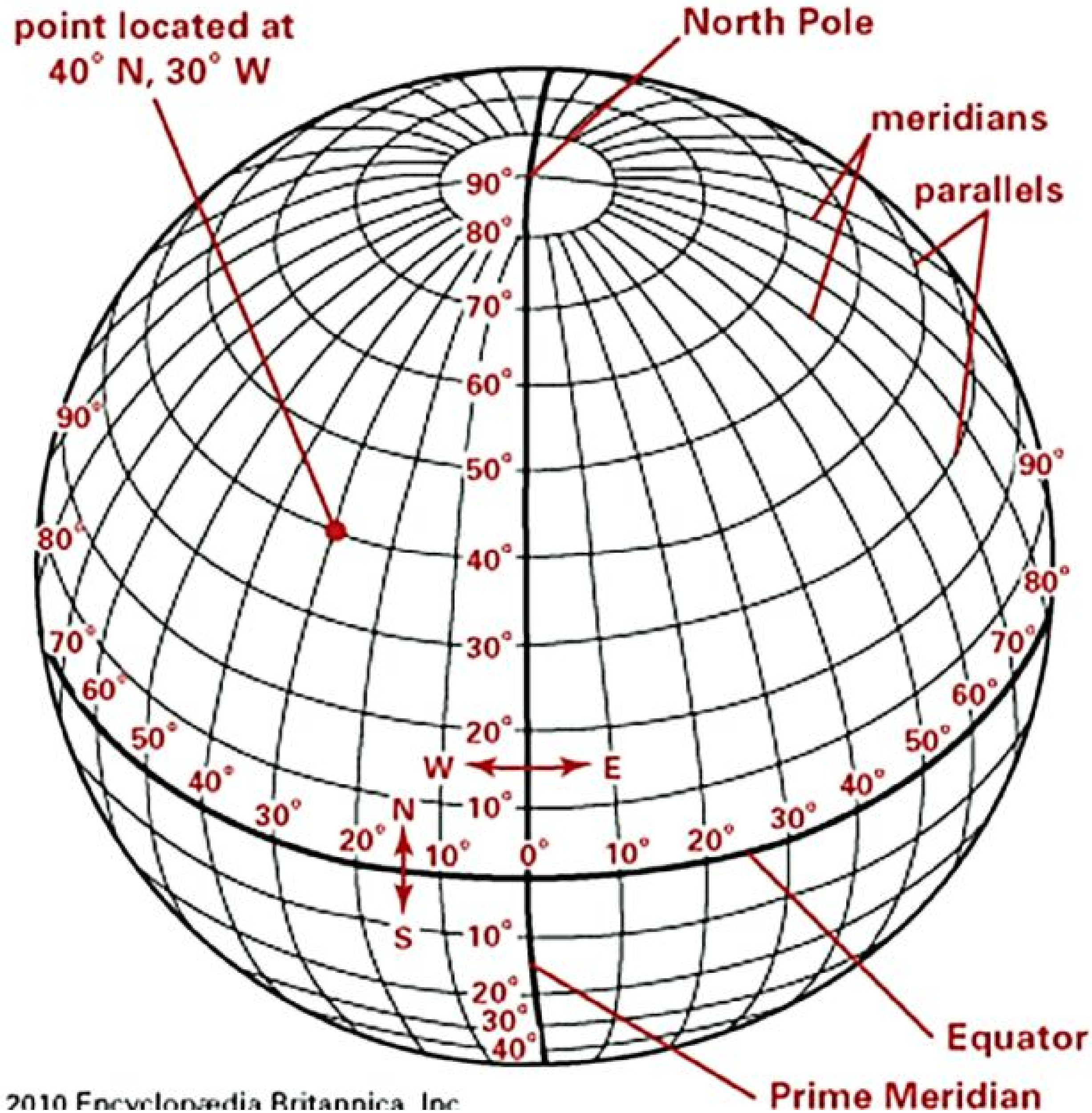


The **Equator** of a rotating spheroid is the parallel at which latitude is defined to be 0°. It is the imaginary line on the spheroid, equidistant from its poles, dividing it into northern and southern hemispheres

What is Latitude and Longitude



What is Latitude and Longitude

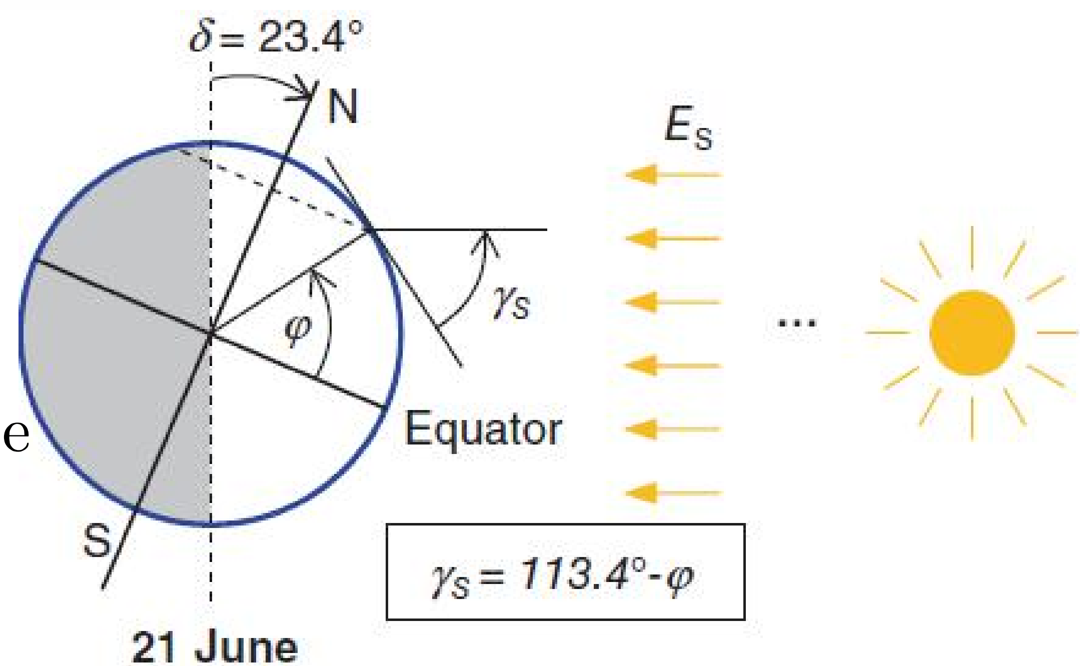


2.3 Calculation of the Position of the Sun

2.3.1 Declination of the Sun

Within a year the Earth travels around the Sun in an almost perfect circle. Because the axis of the Earth is tilted, the height of the Sun changes in the course of a year.

In **summer** the North Pole is tilted towards the Sun so that large angles of the sun (often also called the **solar altitude**) exist . The maximum solar altitude γ_{S_Max} (noon) can be determined with simple angle consideration:



$$\gamma_{S\_Max} = 113.4° - \varphi.$$

Sun height angle γ_S

ϕ is the latitude of the site being considered

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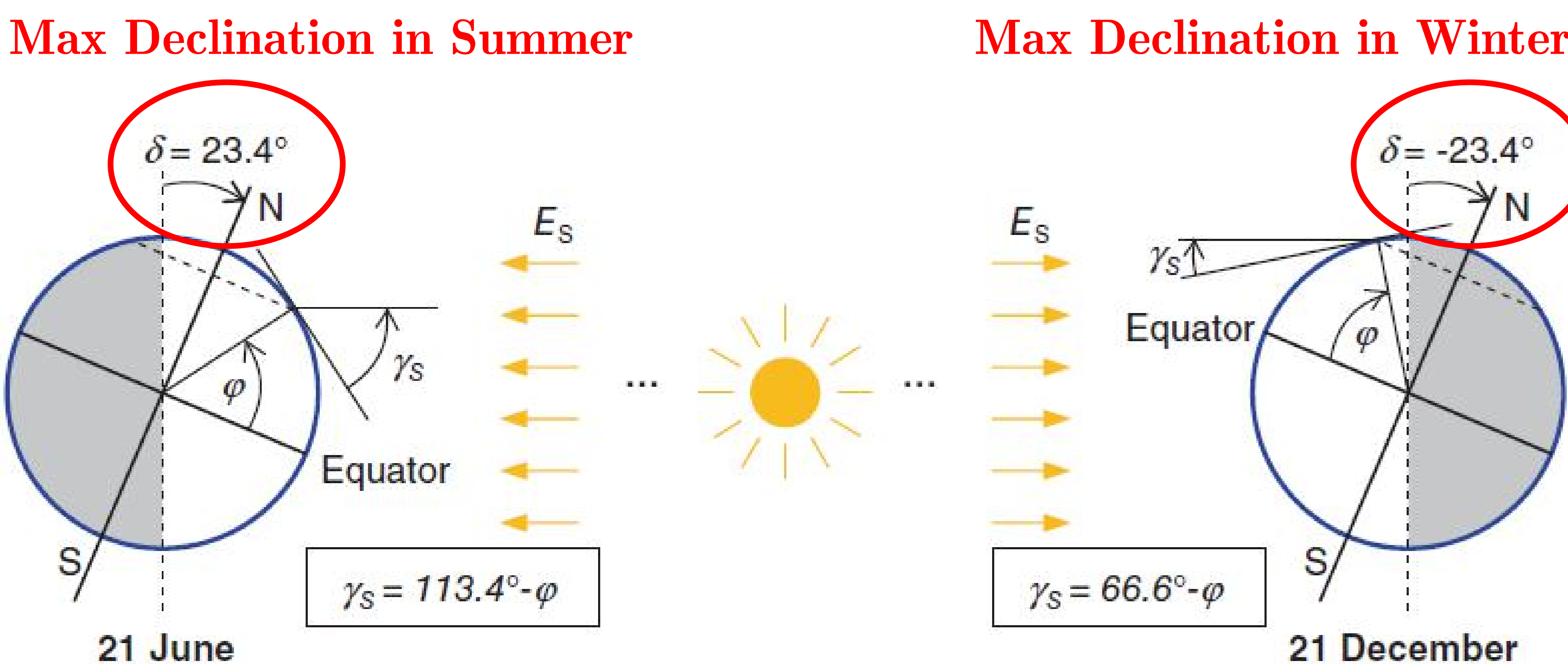
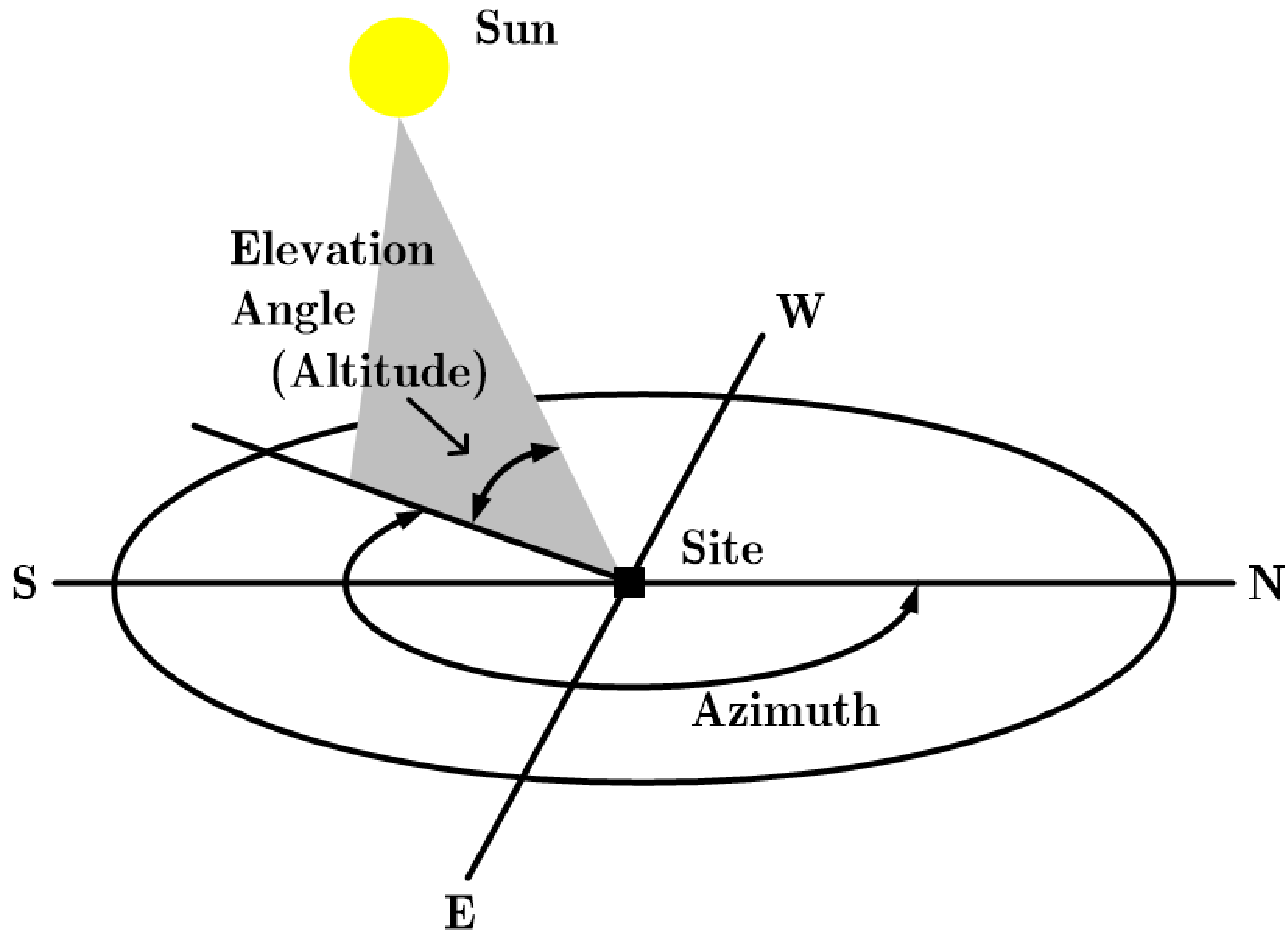


2.3.2 Calculating the Path of the Sun



2.3.2 Calculating the Path of the Sun

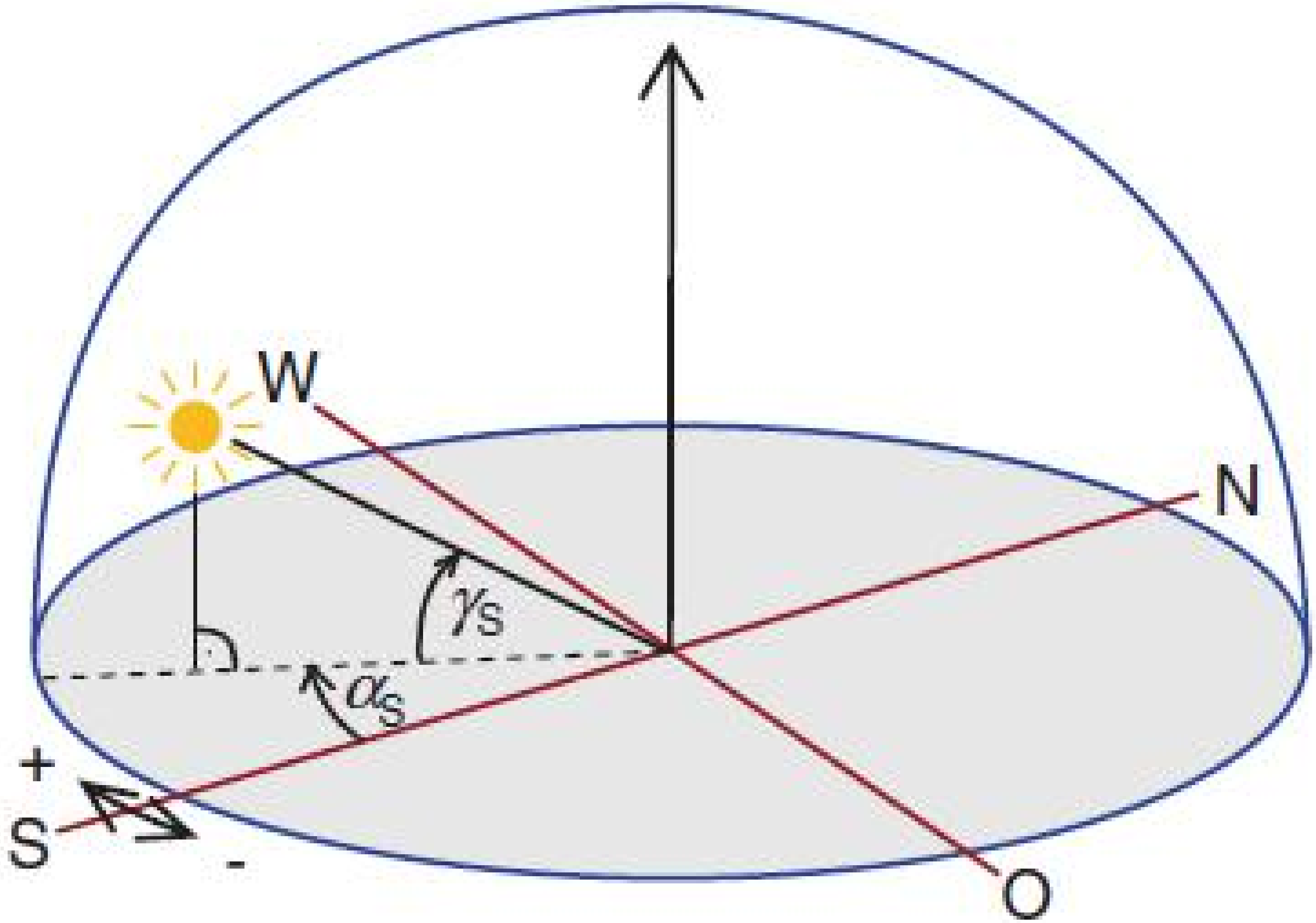
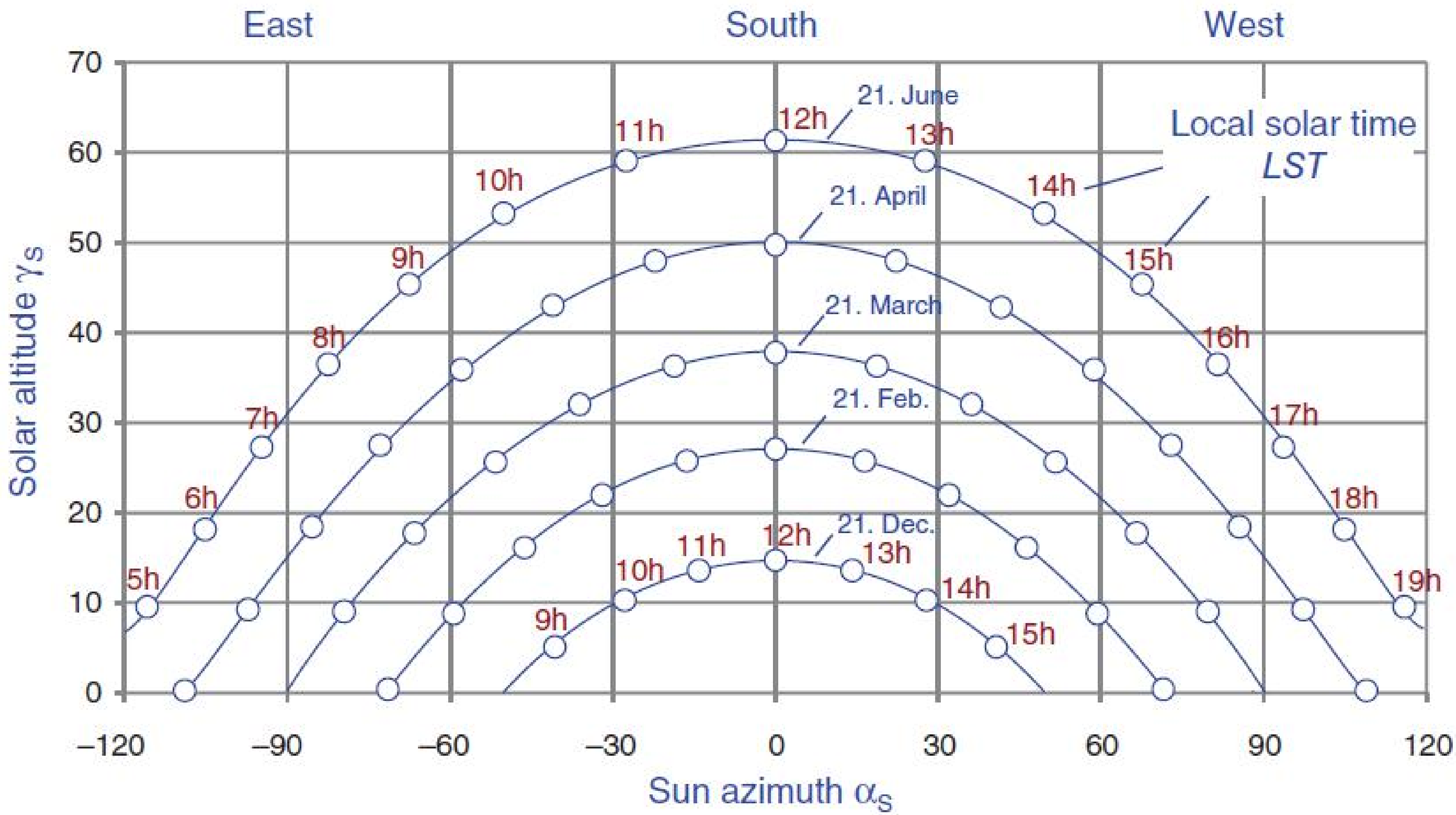
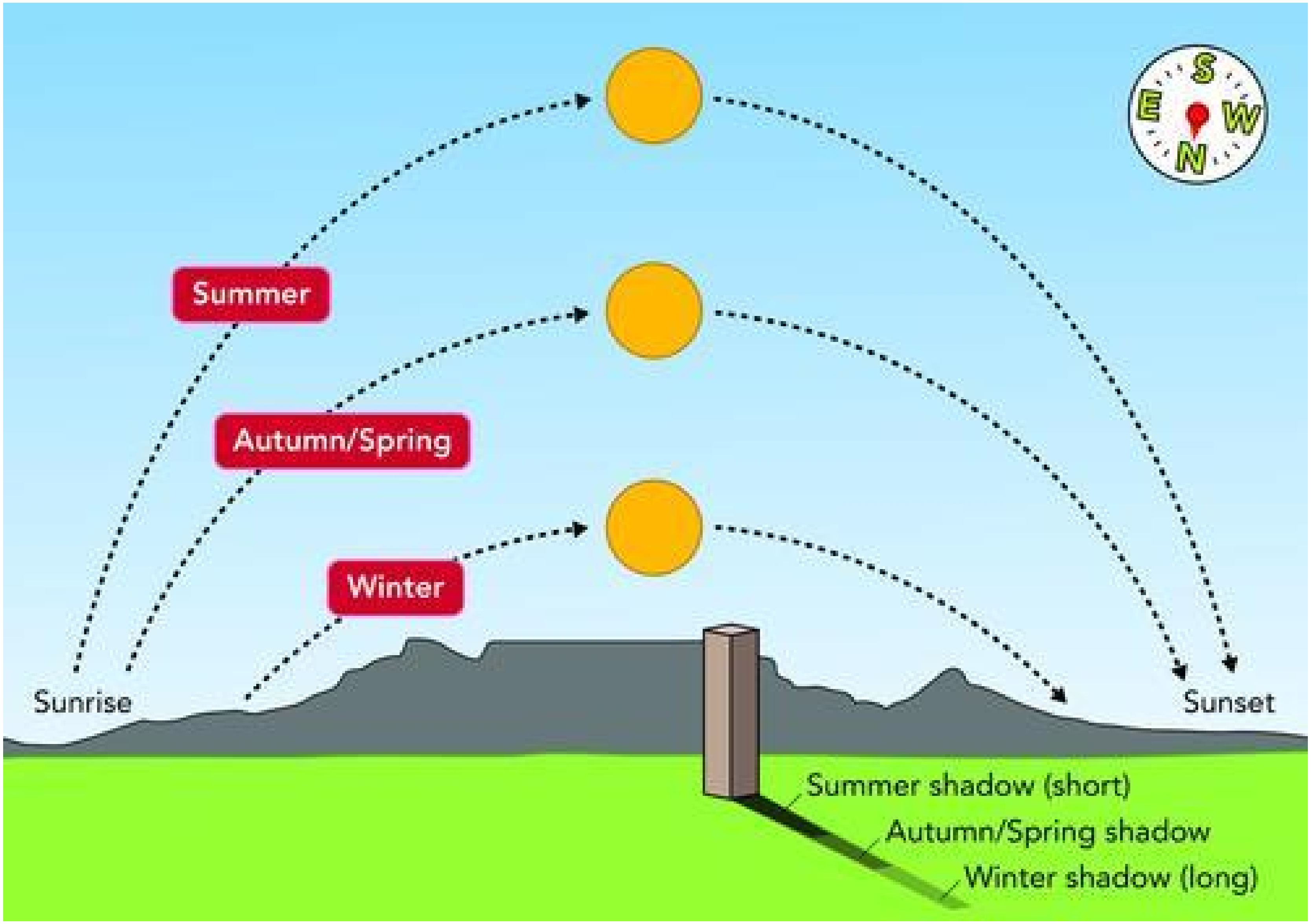


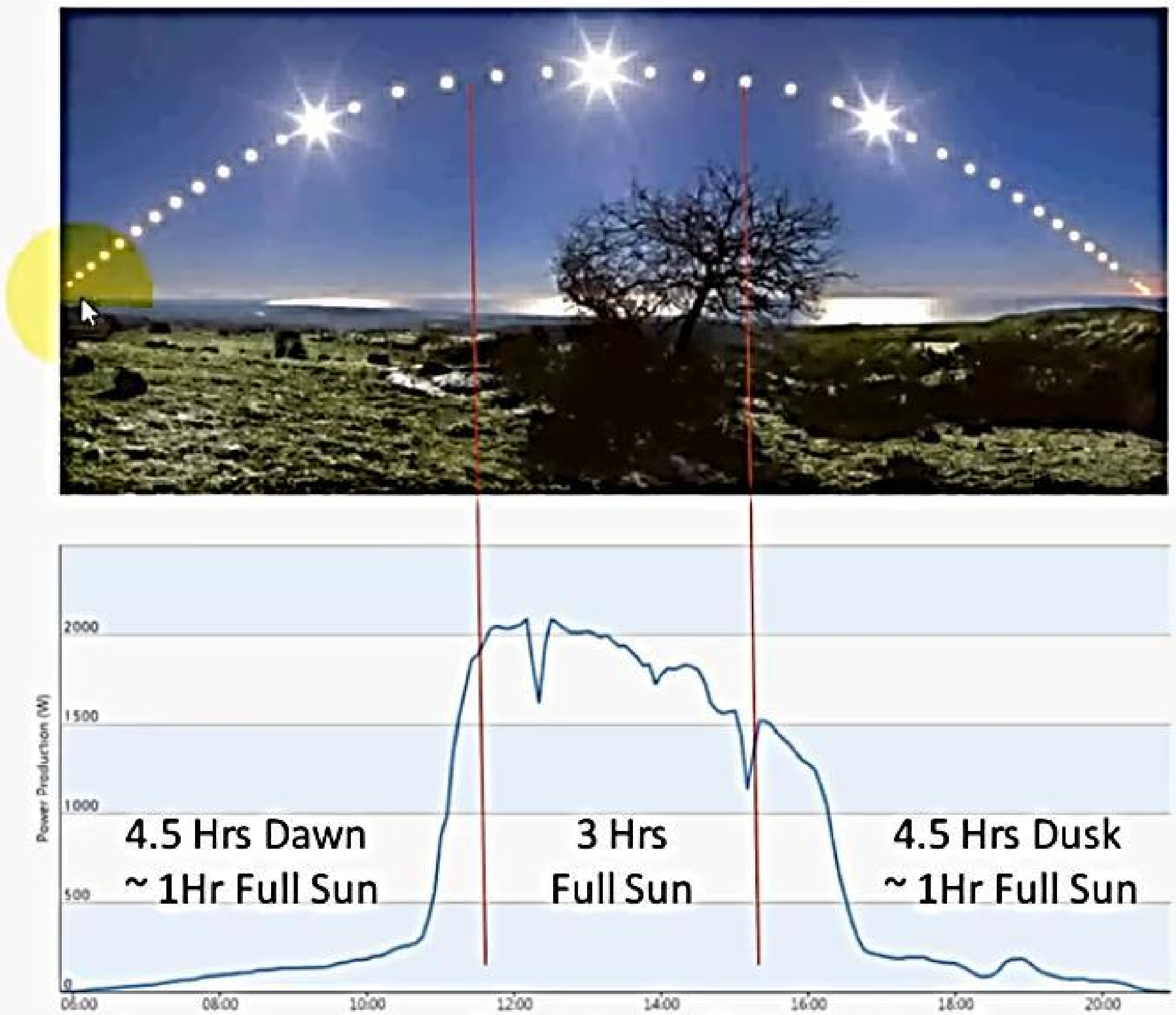
Figure 2.12 Calculation of the Sun's position with the dimension of solar altitude γ_S and Sun's azimuth α_S

2.3.2 Calculating the Path of the Sun



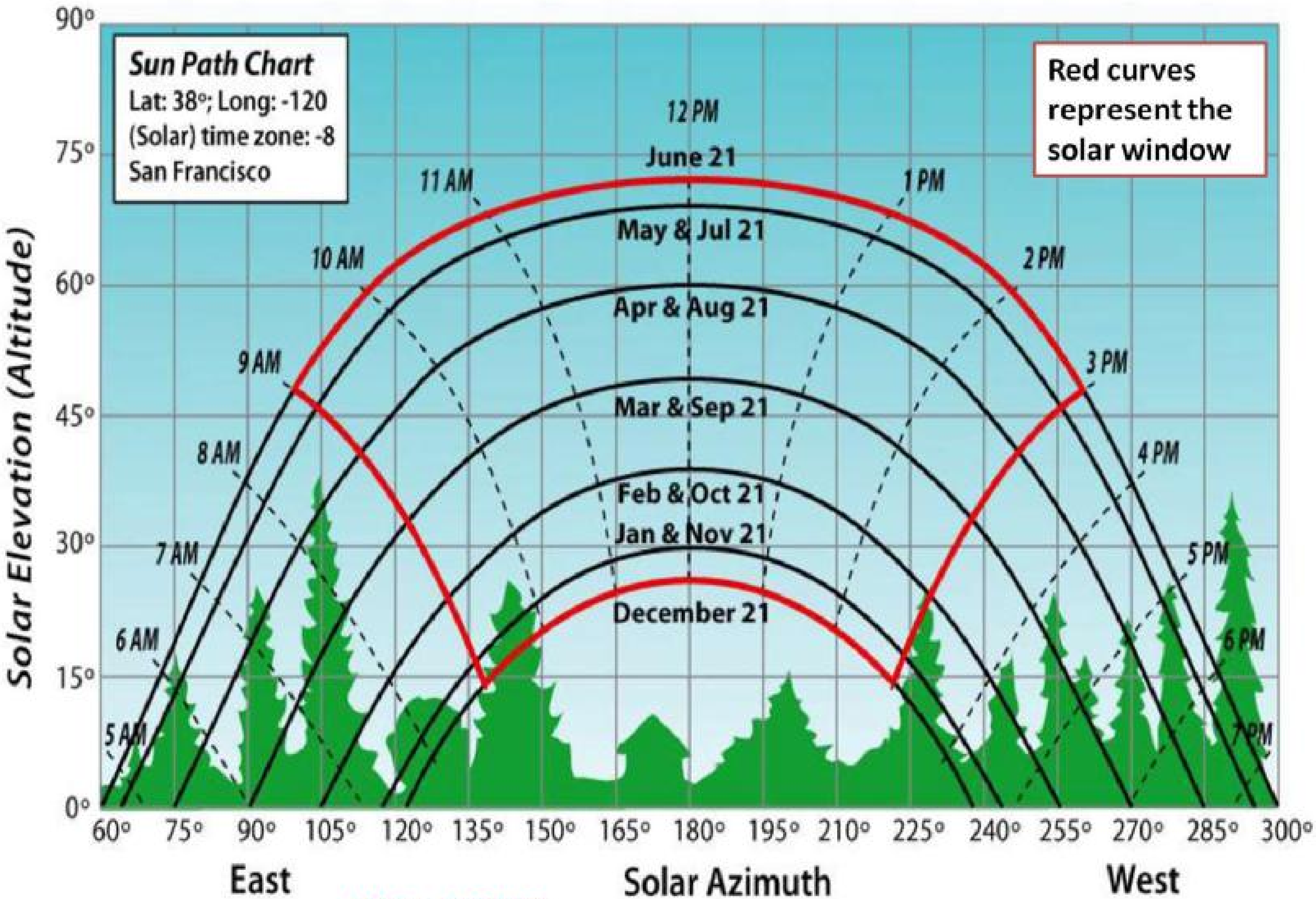

Summer
Autumn/Spring
Winter
S
E
W
N
Sunrise
Sunset
Summer shadow (short)
Autumn/Spring shadow
Winter shadow (long)

5 Hours of Full Operation per Day



Capacity Factor (5 Hrs / 24 Hrs) = 20% C.F.

https://www.youtube.com/watch?v=lB1fc_hVYwg



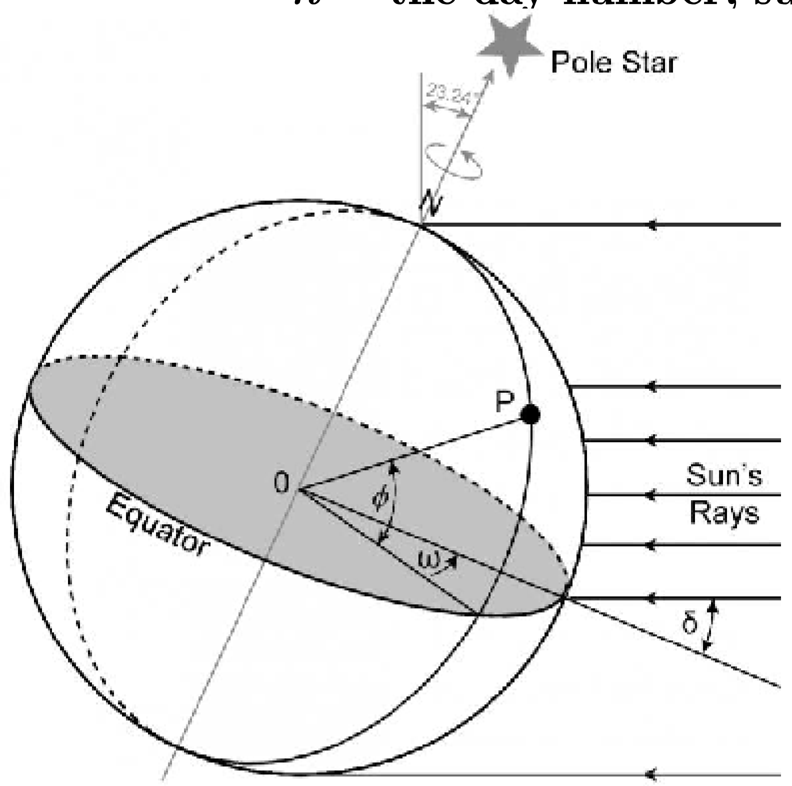
Sun Path Chart
Lat: 38°; Long: -120
(Solar) time zone: -8
San Francisco
Red curves represent the solar window
12 PM
June 21
May & Jul 21
Apr & Aug 21
Mar & Sep 21
Feb & Oct 21
Jan & Nov 21
December 21
5 AM
6 AM
7 AM
8 AM
9 AM
10 AM
11 AM
1 PM
2 PM
3 PM
4 PM
5 PM
6 PM
7 PM
Solar Elevation (Altitude)
90°
75°
60°
45°
30°
15°
0°
60° 75° 90° 105° 120° 135° 150° 165° 180° 195° 210° 225° 240° 255° 270° 285° 300°
East
Solar Azimuth
West

Declination Angle Calculation

The declination angle is described as :

$$\delta = 23.45\frac{\pi}{180}\sin\left[2\pi\left(\frac{284+n}{36.25}\right)\right]$$

Where: δ = declination angle (rads);
n = the day number, such that n = 1 on the 1st January.



The Hour Angle

The hour angle is described in figure below, is positive during the morning, reduces to zero at solar noon and becomes increasingly negative as the afternoon progresses. Two equations can be used to calculate the hour angle when various angles are known (note that δ changes from day to day and α and Az change with time throughout the day)

$$\sin\omega = -\frac{\cos\alpha \sin A_Z}{\cos\delta}$$

$$\sin\omega = \frac{\sin\alpha - \sin\delta\sin\phi}{\cos\delta\cos\phi}$$

Where:

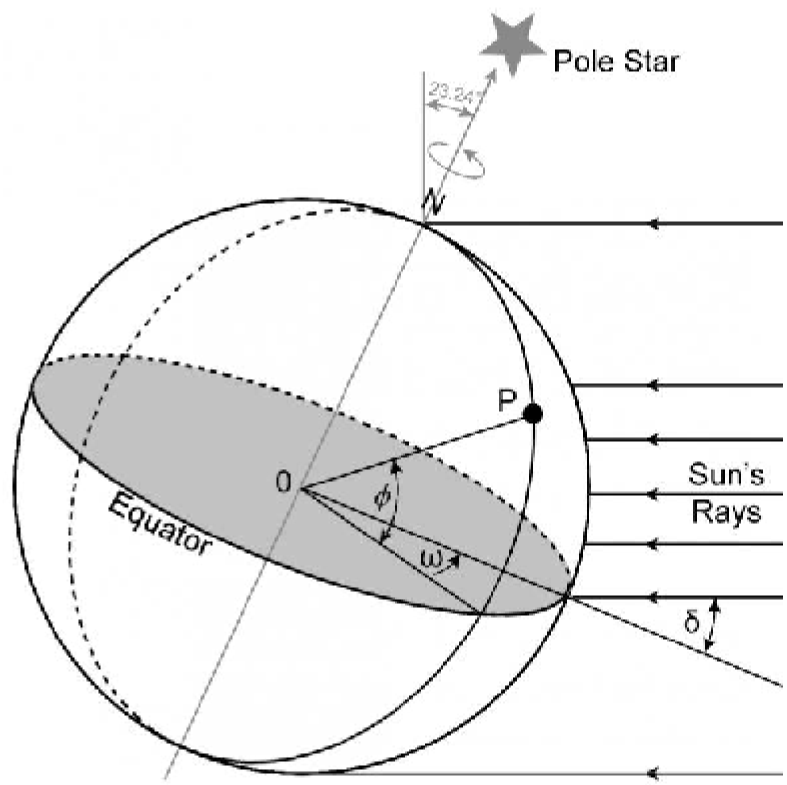
ω = the hour angle;

α = the altitude angle;

A_Z = the solar azimuth angle;

δ = the declination angle;

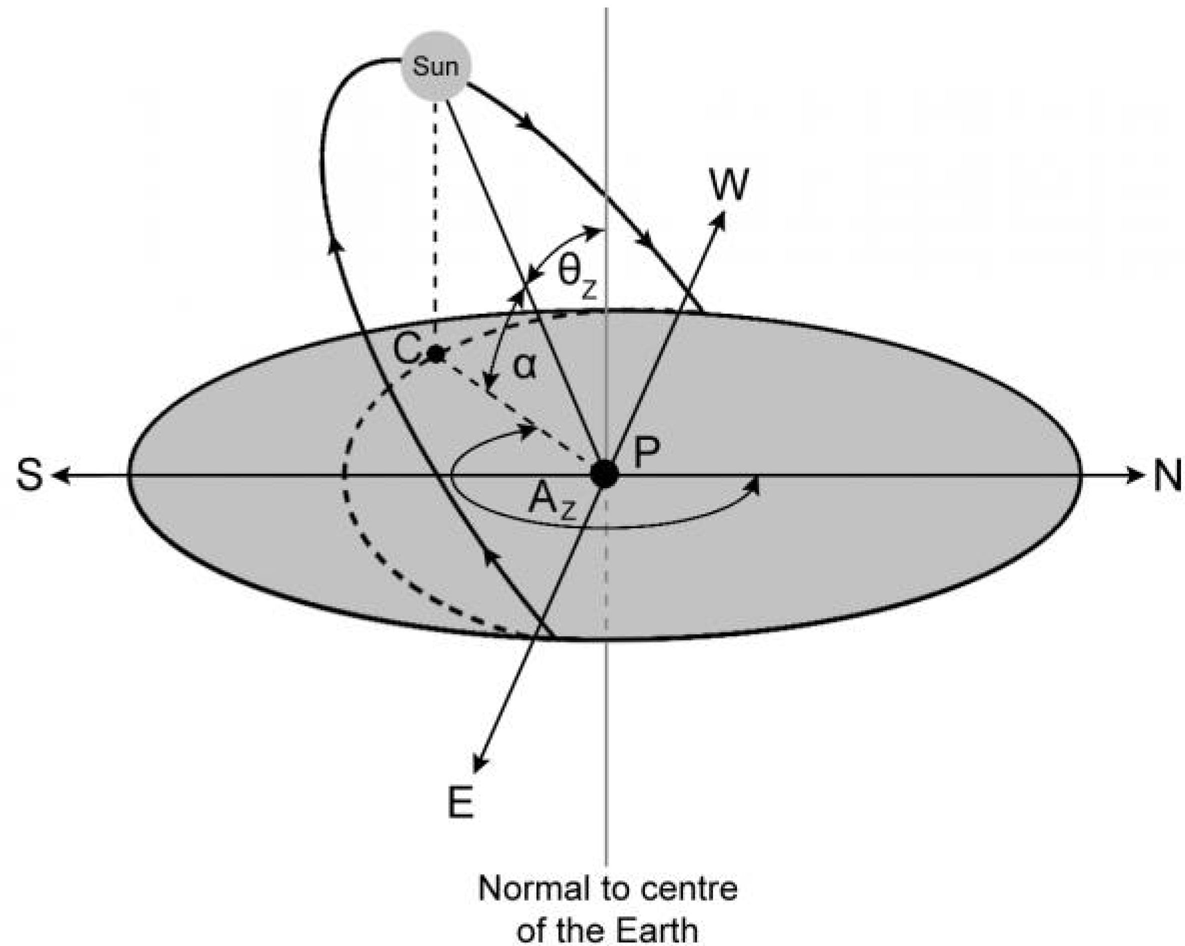
φ = observer's latitude. ϕ



The Altitude Angle

The altitude angle (α) as described in figure and can be calculated from:

$$\sin\alpha = \sin\delta\sin\phi + \cos\delta\cos\omega\cos\phi$$



The Azimuth Angle

The solar azimuth angle will be found rearranging the above equation for Az, i.e.,

$$\sin\omega = -\frac{\cos\alpha \sin A_Z}{\cos\delta}$$

Where:

ω = the hour angle;

α = the altitude angle;

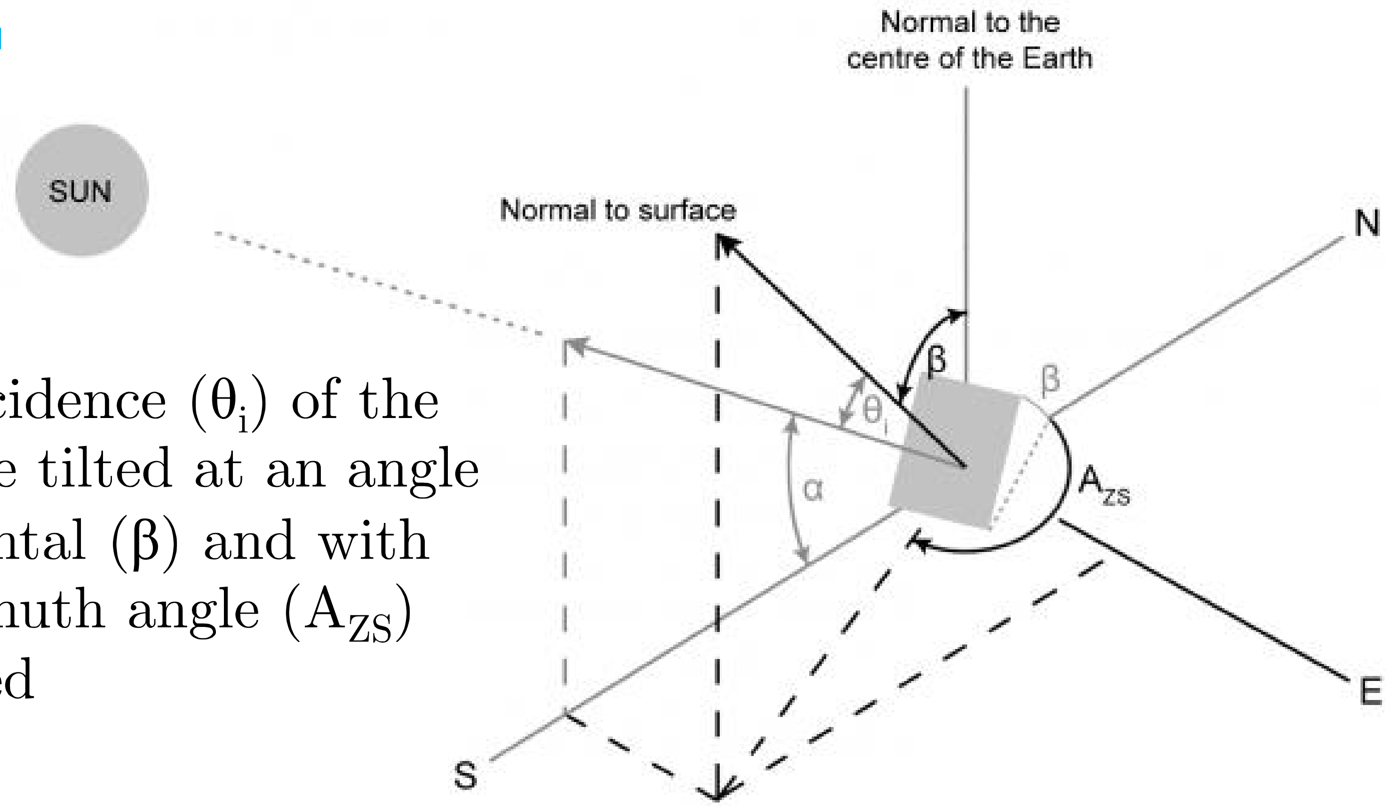
A_Z = the solar azimuth angle;

δ = the declination angle;

φ = observer's latitude.

https://www.itacanet.org/the-sun-as-a-source-of-energy/part-3-calculating-solar-angles/

Angle Of Incidence



The angle of incidence (θ_i) of the Sun on a surface tilted at an angle from the horizontal (β) and with any surface azimuth angle (A_{ZS}) can be calculated

$$\cos\theta_i = \cos\theta_Z = \cos\delta\cos\phi\cos\omega + \sin\delta\sin\phi$$

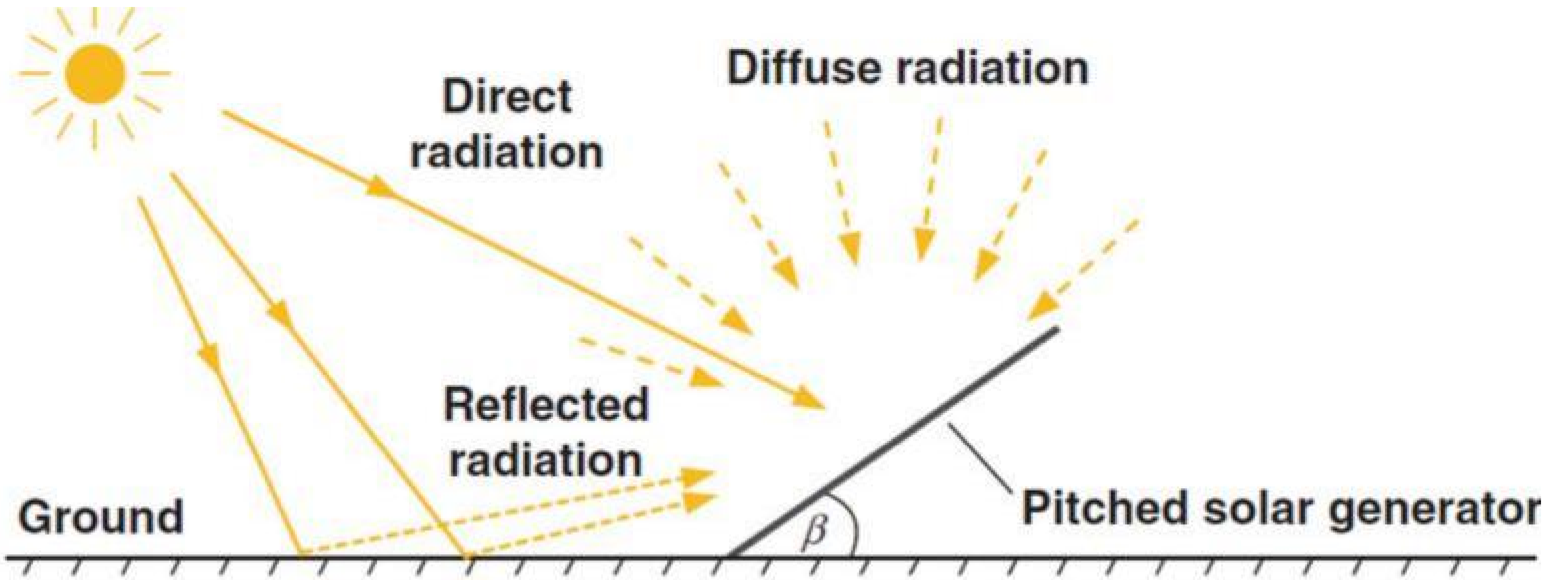
When the surface is tilted towards the equator (facing south in the northern hemisphere):

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

Note that if $\theta_i > 90°$ at any point the Sun is behind the surface and the surface will be shading itself.

2.4 Radiation on Tilted Surfaces

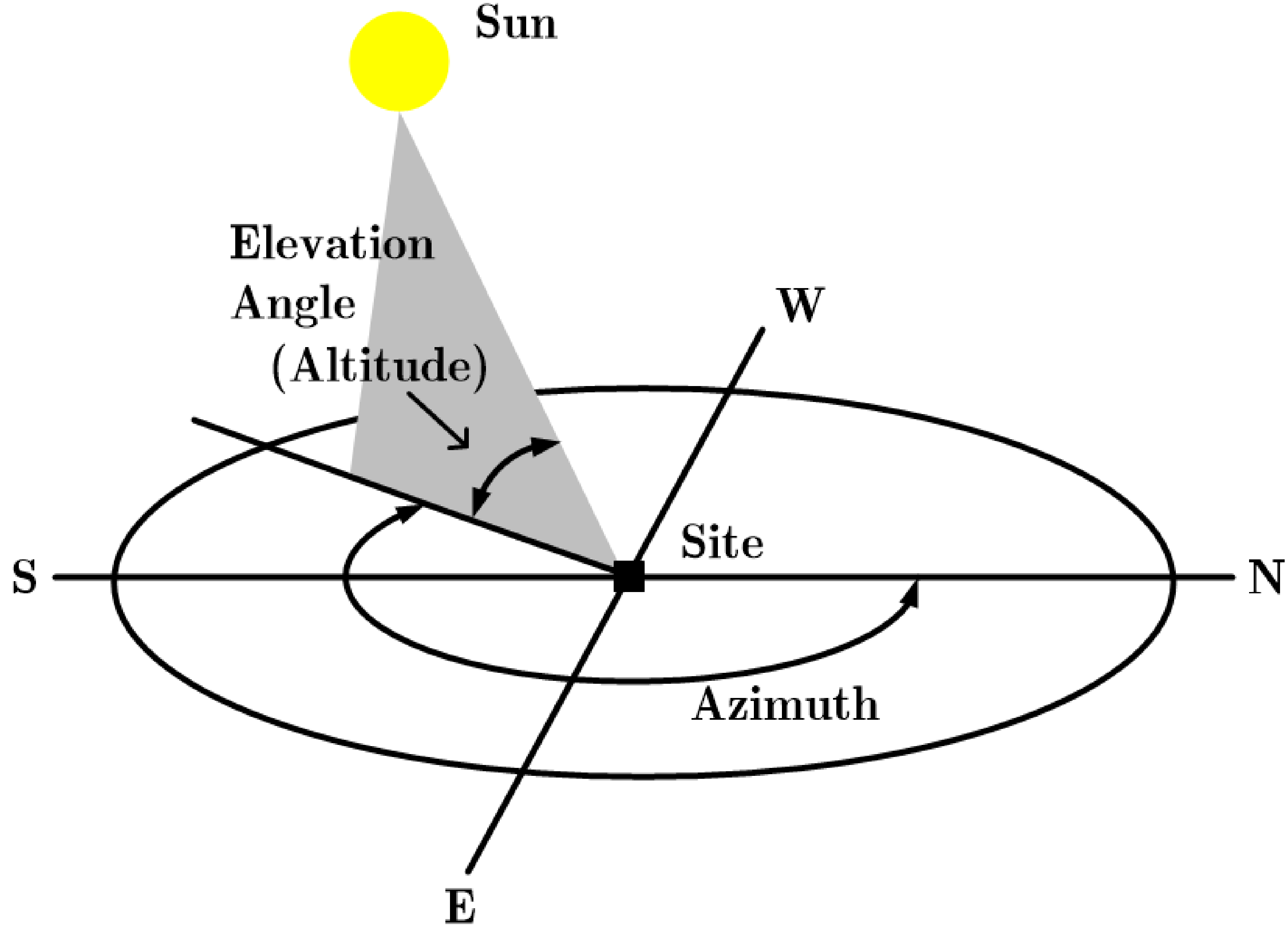
Photovoltaic plants are mostly installed on pitched roofs so that the module is at an angle of $\boldsymbol{\beta}$, as measured from the horizontal.



Besides the direct and diffuse radiation there is still a further radiation component: the radiation reflected from the ground. These add themselves to an overall radiation $\boldsymbol{E}_{\mathbf{Gen}}$ on the tilted generator.

$$E_{\text{Gen}} = E_{\text{Direct\_Gen}} + E_{\text{Diffuse\_Gen}} + E_{\text{Refl\_Gen}}$$

2.3.2 Calculating the Path of the Sun



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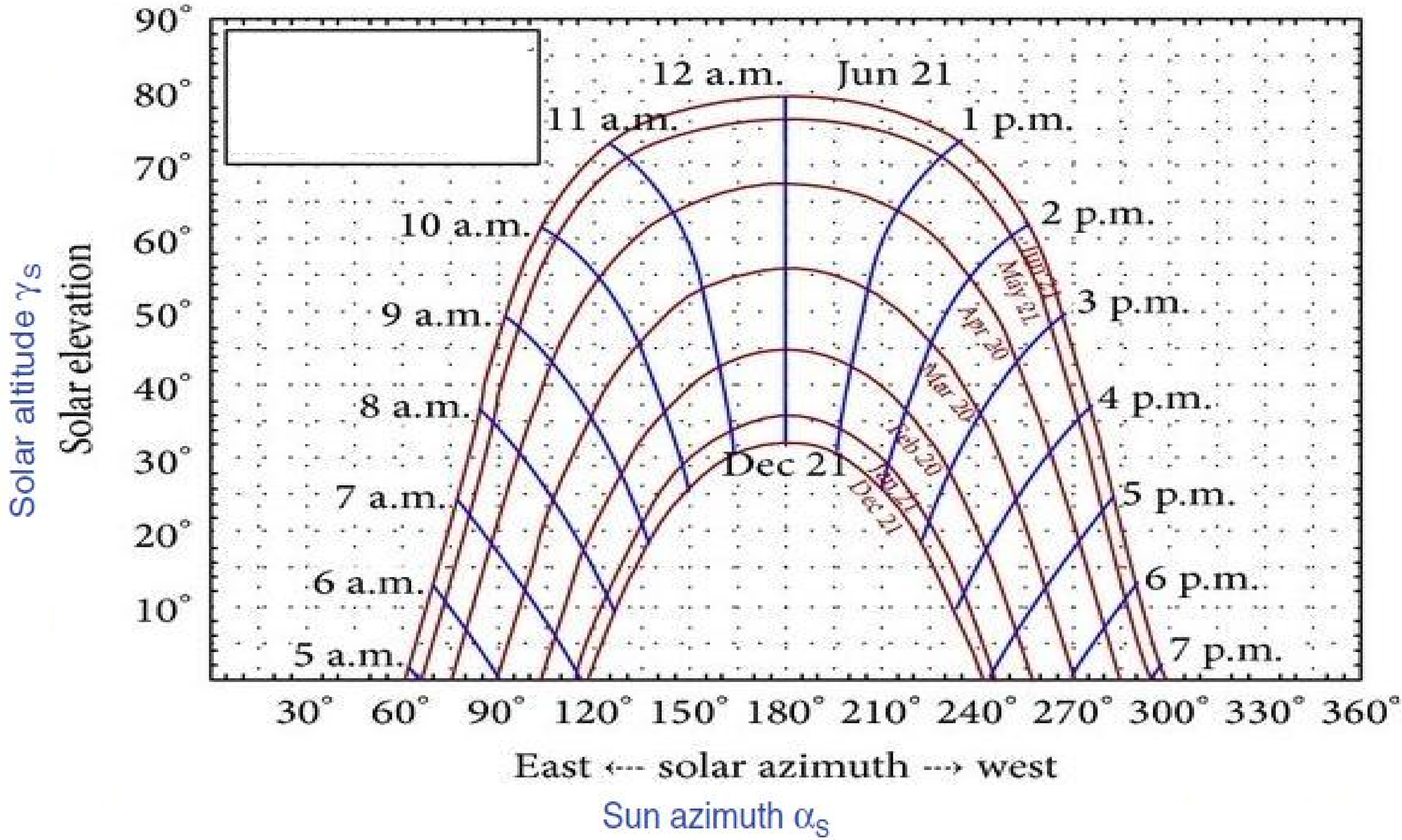
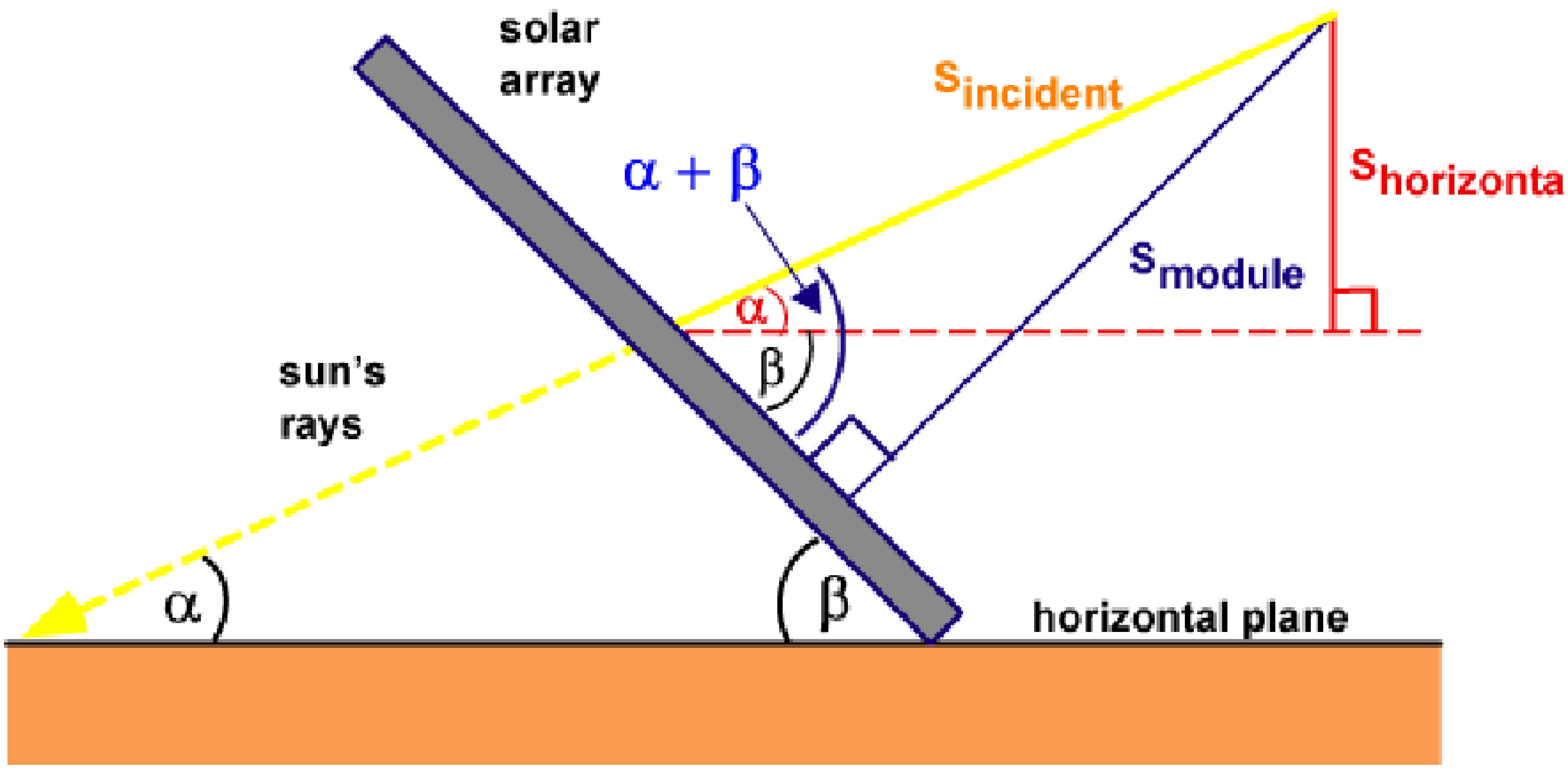


Angle Of Incidence



For optimal tilt angle of solar panel, following requirement should be met,

$$\alpha + \beta = 90°$$

2.4 Radiation on Tilted Surfaces

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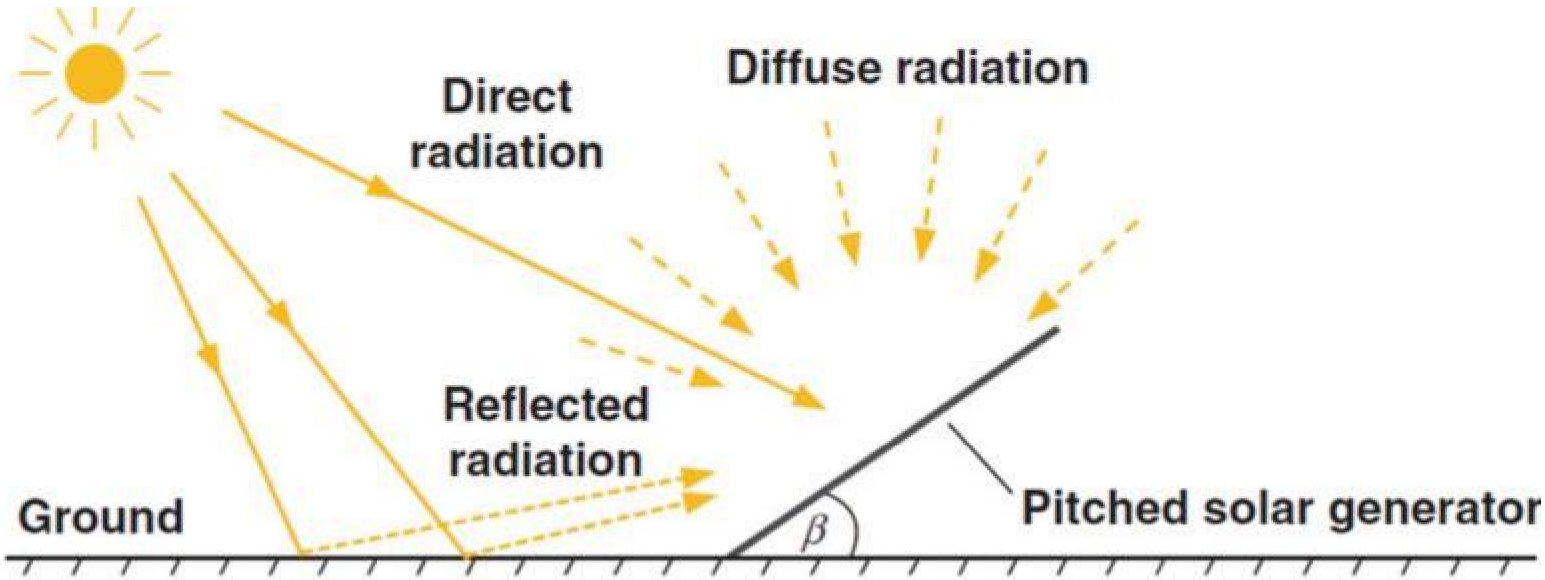


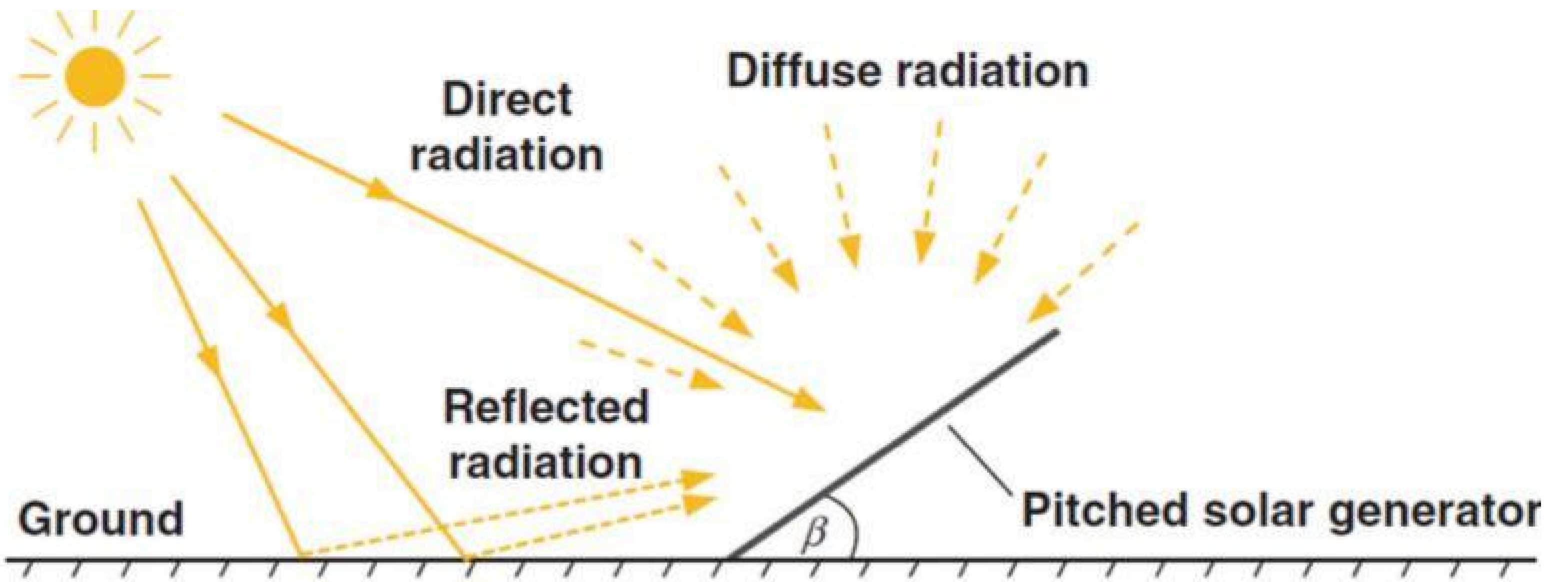
Besides the direct and diffuse radiation there is still a further radiation component: the radiation reflected from the ground. These add themselves to an overall radiation $\boldsymbol{E}_{\mathbf{Gen}}$ on the tilted generator.

$$E_{\mathrm{Gen}} = E_{\mathrm{Direct\_Gen}} + E_{\mathrm{Diffuse\_Gen}} + E_{\mathrm{Refl\_Gen}}$$

2.4.1 Radiation Calculation with the Three-Component Model

Besides the direct and diffuse radiation there is still a further radiation component: the radiation reflected from the ground. These add themselves to an overall radiation $\boldsymbol{E}_{\mathbf{Gen}}$ on the tilted generator.

$$E_{\text{Gen}} = E_{\text{Direct\_Gen}} + E_{\text{Diffuse\_Gen}} + E_{\text{Refl\_Gen}}$$



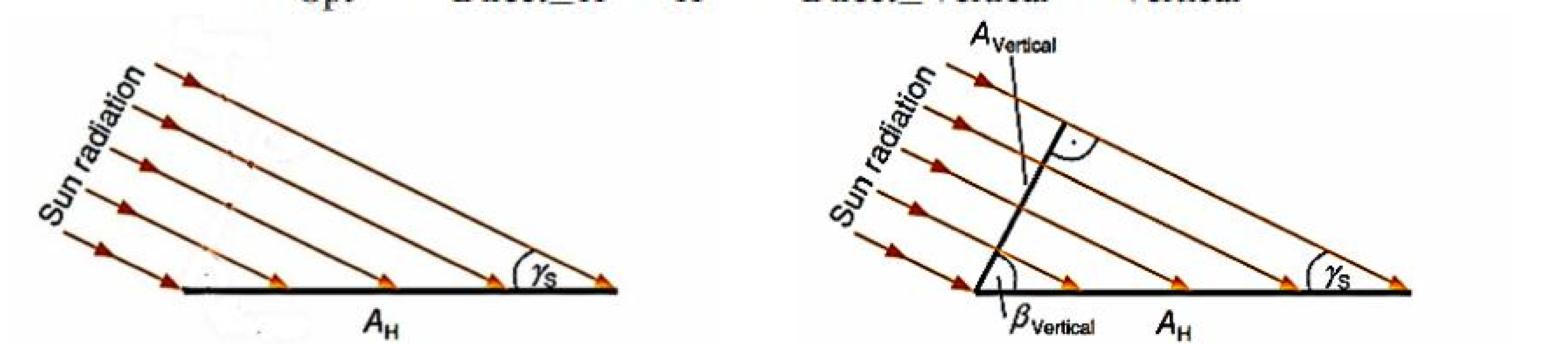
2.4.1.1 Direct Radiation

Let us consider the case that direct sunlight shines on a tilted solar module. For this case the left sketch of Figure 2.15 shows how solar radiation impinges on a horizontal surface $\boldsymbol{A_H}$. The optical power $\boldsymbol{P_{Opt}}$ of the impinging radiation is:

$$P_{Opt} = E_{Direct\_H} \cdot A_H$$

If a solar generator were arranged exactly vertically to the solar radiation, then it would be possible to take up the same power on a smaller surface $\boldsymbol{A_{Vertical}}$:

$$P_{Opt} = E_{Direct\_H} \cdot A_H = E_{Direct\_Vertical} \cdot A_{Vertical}$$



A_H:	Horizontal surface	γ_S :	Solar altitude angle
$A_{Vertical}$:	Surface vertical to the incidental direction	β :	Elevation angle of the solar generator
A_{Gen} :	Surface in generator level	χ :	Complementary angle

2.4.1.2 Diffuse Radiation

For calculation of the diffuse radiation of tilted surface, we make a simple assumption that the diffuse radiation from the whole sky is approximately of the same strength (the **isotropic assumption**: Figure 2.17, left). Thus the strength of radiation of a solar generator at an angle $\boldsymbol{\beta}$ is calculated as:

$$E_{\text{Diffus\_Gen}} = E_{\text{Diffus\_H}} \cdot \frac{1}{2} \cdot (1 + \cos\beta) \qquad (2.19)$$

Starting with a horizontal generator ($\beta = 0°$) the radiation is reduced until at ($\beta = 90°$) it is:

$$E_{\text{Diffus\_Gen}} = \frac{E_{\text{Diffus\_H}}}{2} \qquad (2.20)$$

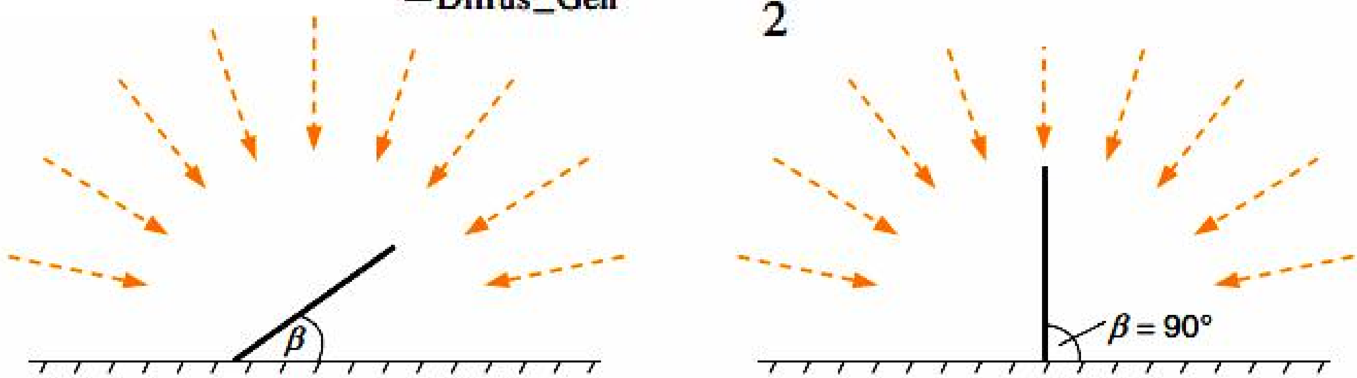
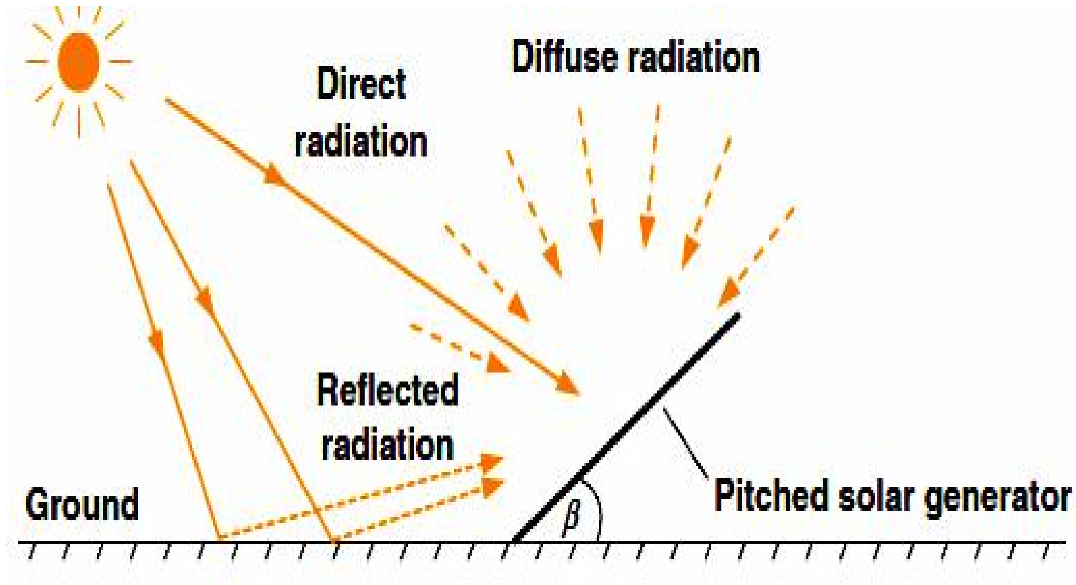


Figure 2.17 Isotropic assumption for diffuse radiation on a tilted surface. Only half the radiation can be used in the case of a vertically standing solar generator

In this case the solar generator is vertical so that only the left hand side of the sky can be used (Figure 2.17, right).

2.4.1.3 Reflected Radiation

As shown in figure a part of the global radiation is reflected from the ground and can act as an additional radiation contribution to the solar generator. In the calculation of this portion the main problem is that every ground material



reflects (or more exactly: scatters) differently. The so-called **albedo value (*ALB*)** describes the resulting reflection factor. Table 2.3 lists the albedo value of some types of ground.

2.4.1.3 Reflected Radiation

Table 2.3 Albedo value of different types of ground [21]

Material	Albedo (ALB)	Material	Albedo (ALB)
Grass (July, August)	0.25	Asphalt	0.15
Lawn	0.18 . . . 0.23	Concrete, clean	0.30
Unmown fields	0.26	Concrete, weathered	0.20
Woods	0.05 . . . 0.18	Snow cover, new	0.80 . . . 0.90
Heath surfaces	0.10 . . . 0.25	Snow cover, old	0.45 . . . 0.70

An isotropic assumption is again made for the calculation of the reflected radiation on the tilted generator.

$$E_{\mathrm{Refl\_Gen}} = E_{\mathrm{G}} \cdot \frac{1}{2} \cdot (1 - \cos\beta) \cdot ALB \qquad (2.21)$$