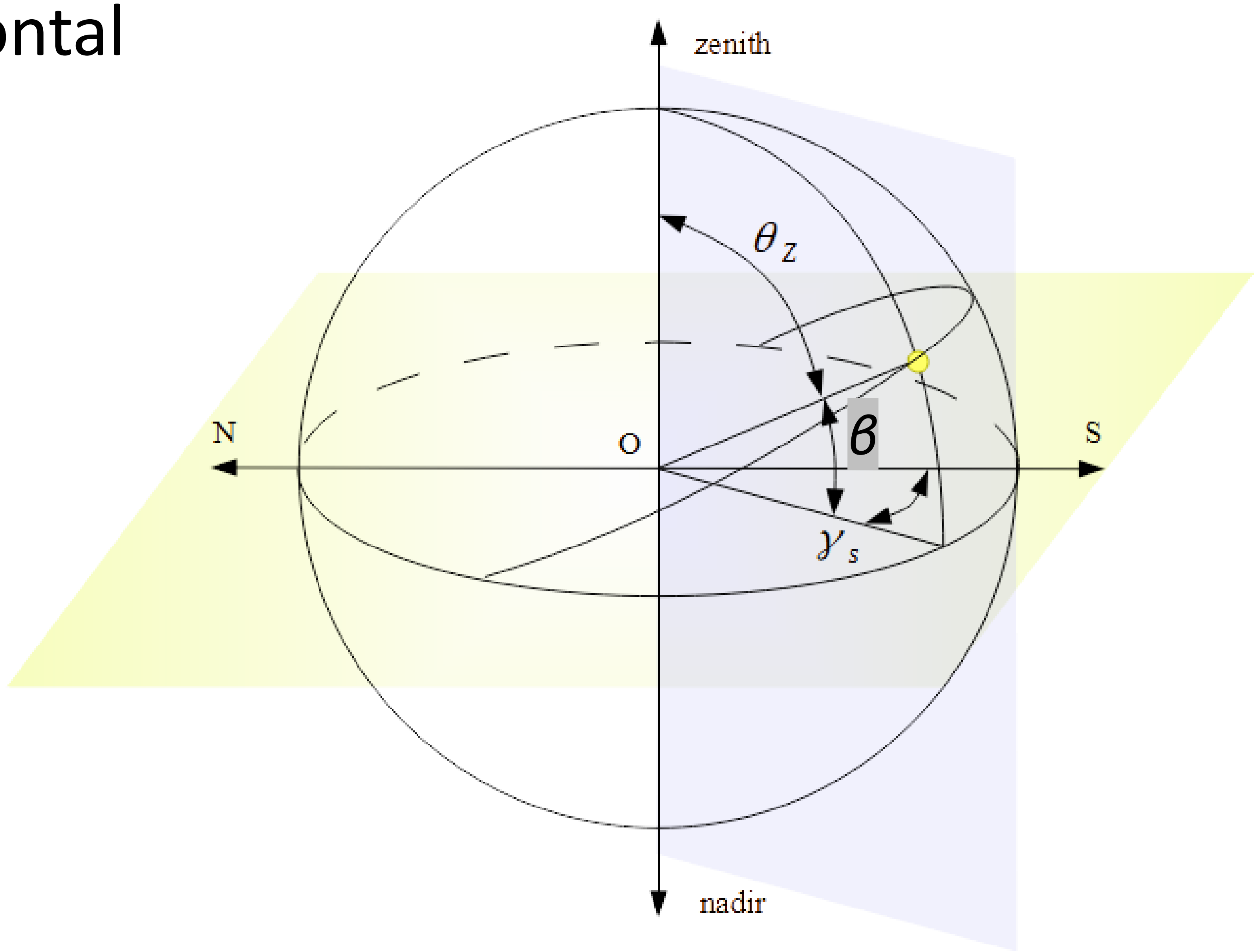
BUILDINGS HVAC SYSTEM
Solar Angles

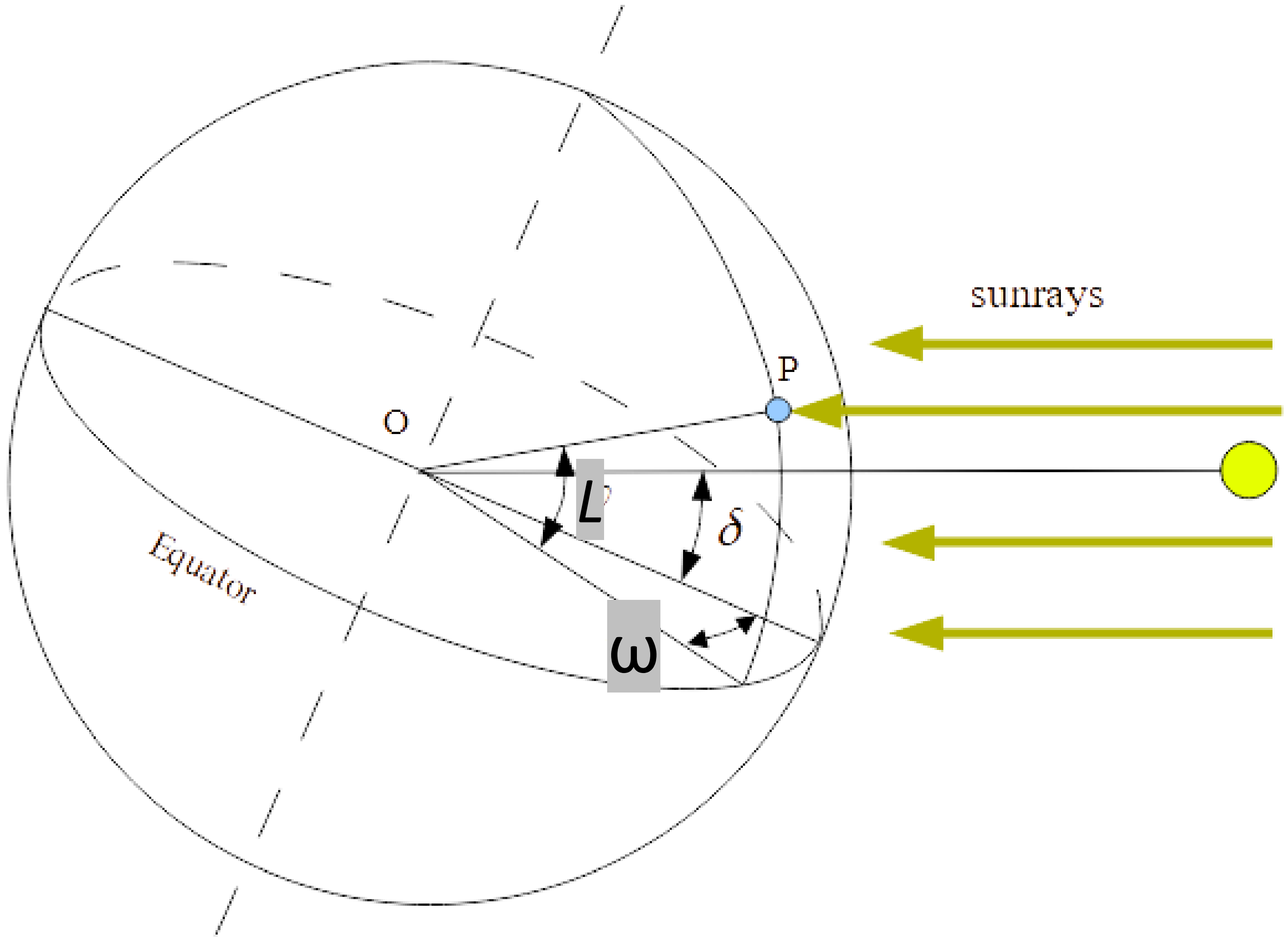
Solar angles, horizontal coordinates

- The reference is the observation horizontal plan
- We identify the solar angles
- θ_z : zenith angle
- α : solar height
- γ_s : solar azimuth

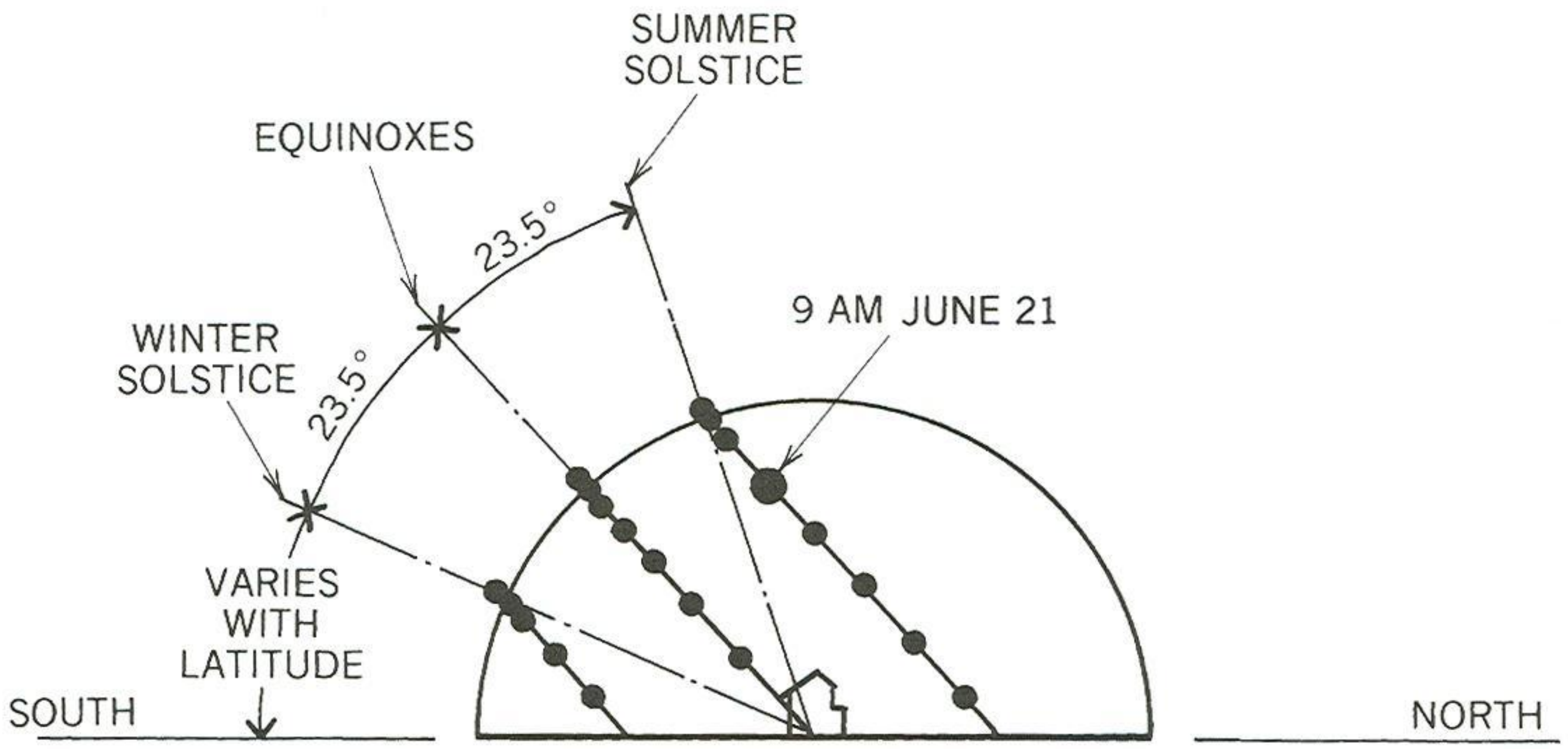


Geographic coordinates

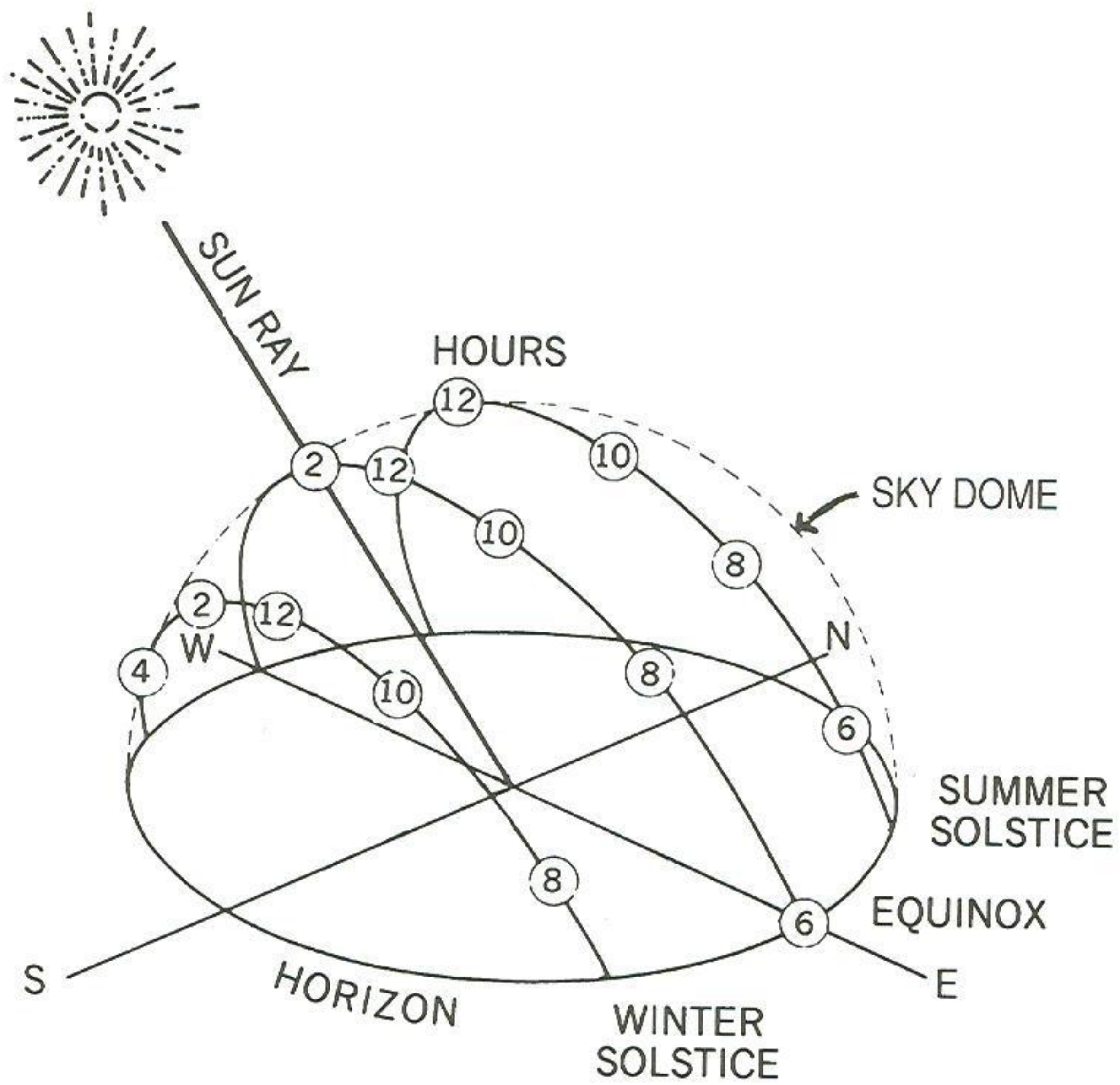
- φ : latitude
- δ: declination
- ω : hour angle
- n : day of the year

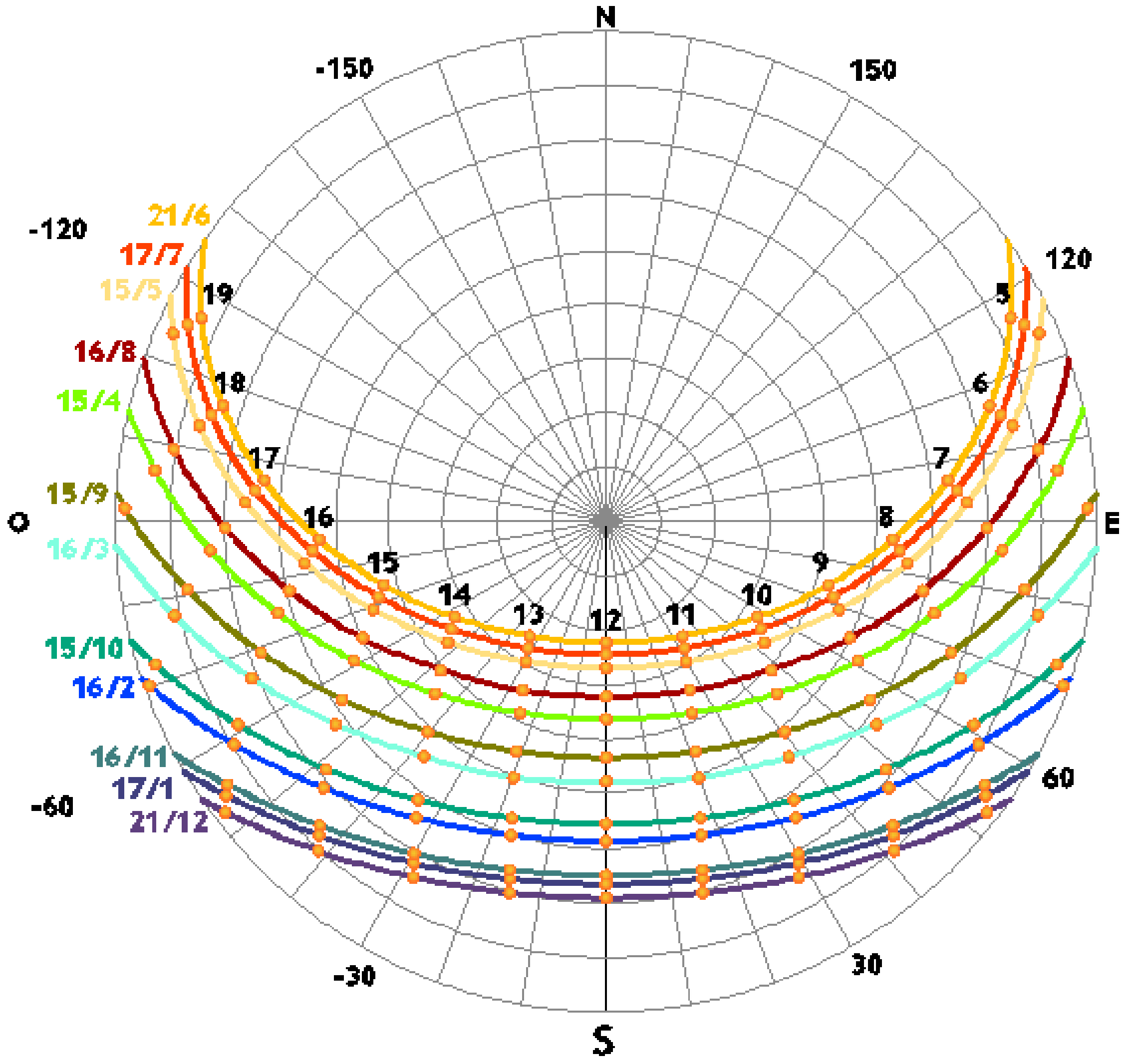


Sun and seasons



Solar path


SUN RAY
HOURS
12
2
12
10
10
8
SKY DOME
2
12
4
W
10
8
N
6
SUMMER
SOLSTICE
8
6
EQUINOX
S
HORIZON
WINTER
SOLSTICE
E


N
-150
150
-120
120
21/6
17/7
15/5
16/8
15/4
15/9
O
16/3
15/10
16/2
16/11
17/1
21/12
-60
60
E
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
-30
30
S

Solar time

- When computing solar position and solar related quantities all must be referenced using the true solar time
- But solar time differs from the one measured by a clock
- Solar time must be recovered in function of the solar angles and the coordinates of the location
- The difference between true solar time and local time is defined as "Equation of time"
- We define the orbit angle Ω

$$\Omega = 2 \cdot \pi \cdot \frac{n-1}{365}$$

Solar time and equation of time

- The difference between true solar time and local time is defined as "Equation of time"

$$\frac{Et}{hour} = \left(\frac{24}{2\,\pi}\right) \times [a_1 + a_2 \cdot \cos(\Omega) + a_3 \times \sin(\Omega) + a_4 \times \cos(2\Omega) + a_5 \times \sin(2\Omega)]$$

a_1=	0,0000075	a_4=	-0,014615
a_2=	0,001868	a_5=	-0,040849
a_3=	-0,032077		

- For Italy (hour defined with reference at the meridian at east of Greenwich

- $t_{sa} = t_{is} + Et + \frac{\psi - 15°}{15°} + DST$

ψ longitude in degree, positive east

t_{is} local standard time

Position of sun

- Hour angle
  - Positive in the afternoon
  - Negative in the morning

$$\omega = 15° \times \left(\frac{t_{sa}}{hour} - 12\right)$$

- Height of the sun

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

- Maximum height at solar noon *ω=0*

$$\alpha_{max} = 90° - |\varphi - \delta|$$

- Azimuth angle $\sin \gamma_s = \sin \omega \cdot \cos \delta \cdot \cos \beta$

$$\cos \gamma_s = (\cos \omega \cdot \cos \delta \cdot \sin \psi - \sin \delta \cdot \cos \psi) \cdot \frac{1}{\cos \beta}$$

Earth orbit deviation and declination

- the hearth orbit is inclined therefore the declination changes during the year

$$\delta = \frac{360°}{2\pi} \times \left[a_0 + a_1 \times \cos(\Omega) + a_2 \times \sin(\Omega) + a_3 \times \cos(2\Omega) + a_4 \times \sin(2\Omega) + a_5 \times \cos(3\Omega) + a_6 \times \sin(3\Omega)\right]$$

$a_0 = 0{,}006918$

$a_1 = -0{,}399912$

$a_2 = 0{,}070257$

$a_3 = -0{,}006758$

$a_4 = 0{,}000907$

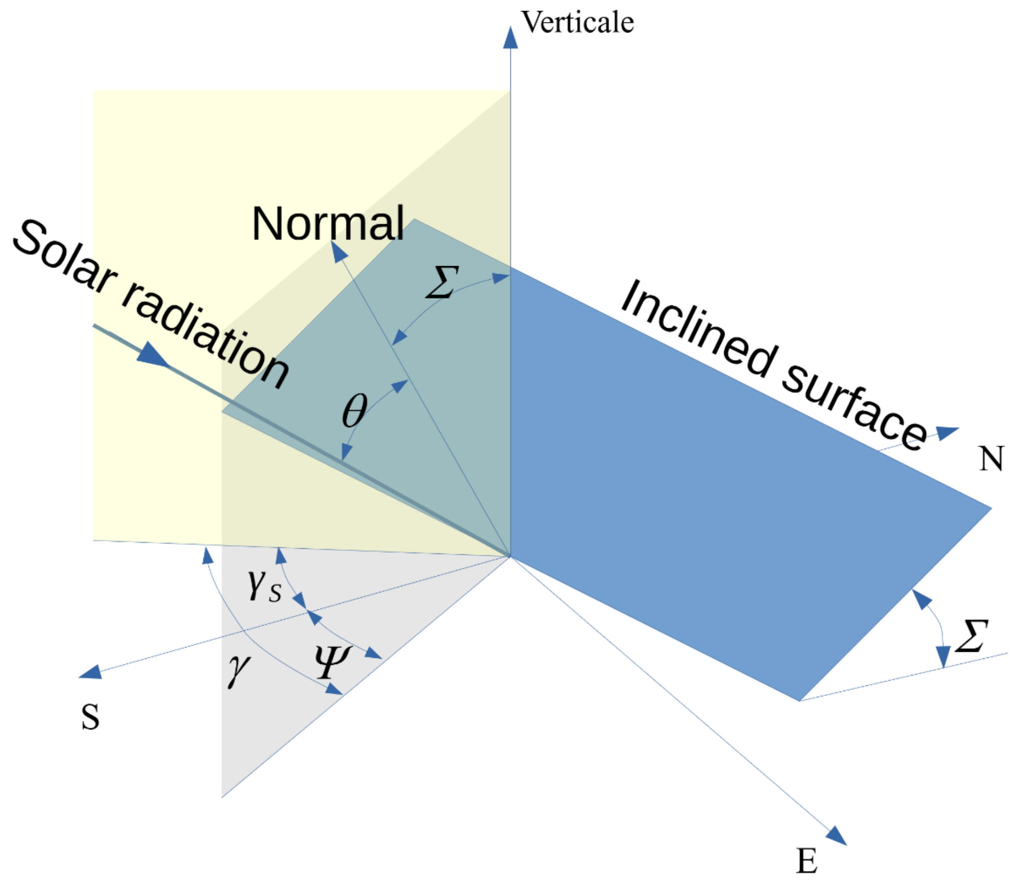
$a_5 = -0{,}002697$

$a_6 = 0{,}00148$

- Simple relation $\delta = 23.45 \cdot \sin\left(360° \cdot \frac{n + 284}{365}\right)$

Surface and solar radiation

- Tilt angle is the angle between the surface and the horizontal plane. Its value lies between 0 and 180°.
- The surface azimuth ψ is defined as the displacement from south of the projection, on the horizontal plane, of the normal to the surface.
- The surface-solar azimuth angle γ is defined as the angular difference between the solar azimuth γ_s and the surface azimuth ψ
- Values of γgreater than 90° or less than –90° indicate that the surface is in the shade.

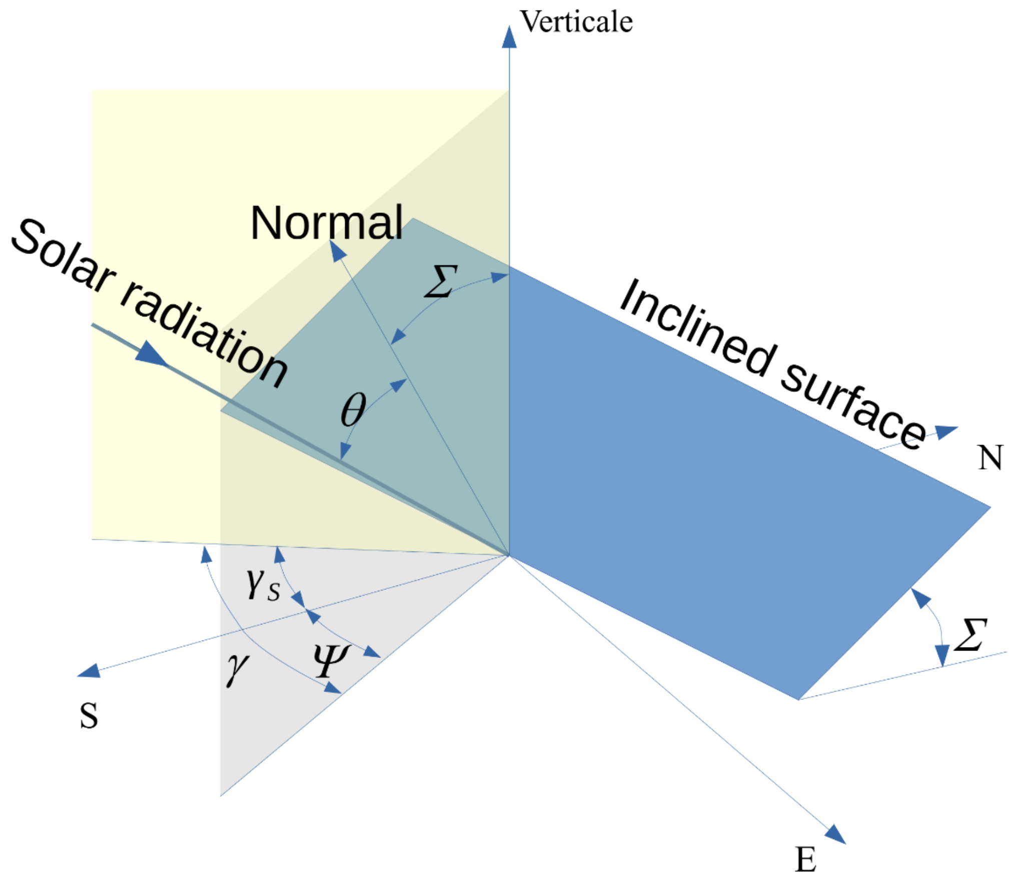


$$\gamma = \gamma_s - \psi$$

Angle of incidence

- angle between the line normal to the irradiated surface and the earth-sun line

$$\cos\theta = \cos\ \beta \cdot \cos\gamma \cdot \sin\Sigma + \sin\beta \cdot \cos\Sigma$$



- For vertical surfaces

$$\cos\theta = \cos\beta \cdot \cos\gamma$$

- Horizontal

$$\theta = 90\ - \beta$$

Exernal solar radiation

- External normal solar G_0 radiation can be computed as:

$$G_0 = G \times [a_0 + a_1 \times \cos(\Omega) + a_2 \times \sin(\Omega) + a_3 \times \cos(2\Omega) + a_4 \times \sin(2\Omega)]$$

$$a_0 = 1{,}000110$$
$$a_1 = 0{,}034221$$
$$a_2 = 0{,}001280$$
$$a_3 = 0{,}000719$$
$$a_4 = 0{,}000077$$

- External global radiation on a plane parallel to the horizontal is computed as

$$I_{\mathrm{ho}} = G_0 \times \sin(\beta)$$

Solar radiation

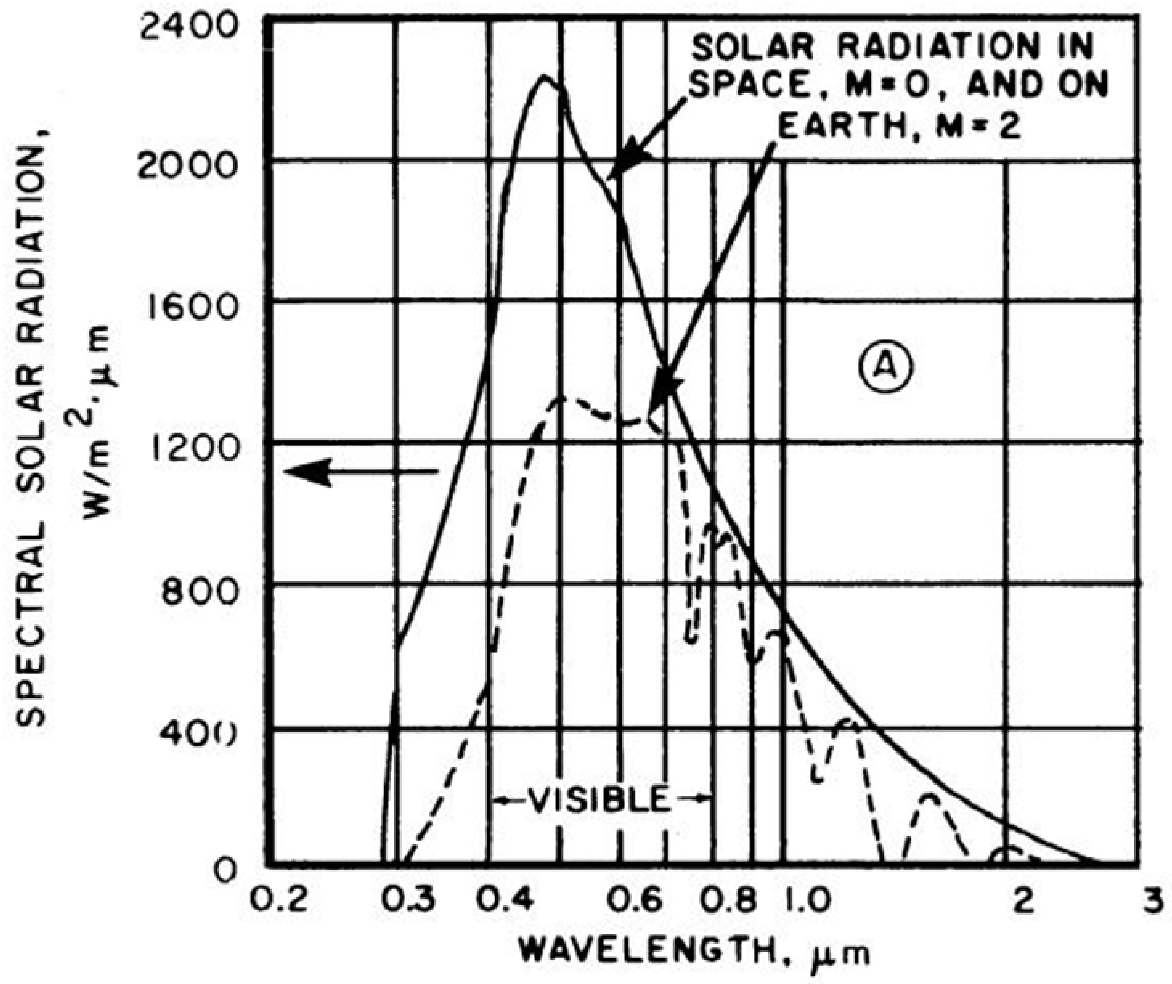


Fig. 7 Terrestrial and Extraterrestrial Solar Spectral Irradiances

- Solar radiation is absorbed
- The spectrum changes
- Solar radiation reaches the ground with two components
- Direct component
- Diffuse component

Air Mass

- The relative air mass *m* is the ratio of the mass of atmosphere in the actual earth/sun path to the mass that would exist if the sun were directly overhead. Air mass is solely a function of solar altitude and is obtained from

$$m = \frac{1}{[\sin\beta + 0.50572 \cdot (6.07995 + \beta)^{-1.6364}}$$

β in degrees

Clear-Sky Solar Radiation

- Solar radiation on a clear day is defined with direct (beam) and diffuse components
- $E_b = E_0 \cdot \exp(-\tau_b \cdot m^{ab})$
- $E_d = E_0 \cdot \exp(-\tau_d \cdot m^{ab})$
- E_b normal irradiance measured in the direction of sun rays
- E_d diffuse radiation on a horizontal plane
- m air mass
- τ_b *and* τ_d beam and diffuse optical depth

Air mass exponents

$$ab = 1.219 - 0.043 \cdot \tau_b - 0.151 \cdot \tau_d - 0.204 \cdot \tau_b \cdot \tau_d$$

$$ad = 0.202 - 0.852 \cdot \tau_b - 0.007 \cdot \tau_d - 0.357 \cdot \tau_b \cdot \tau_d$$

Fenestration

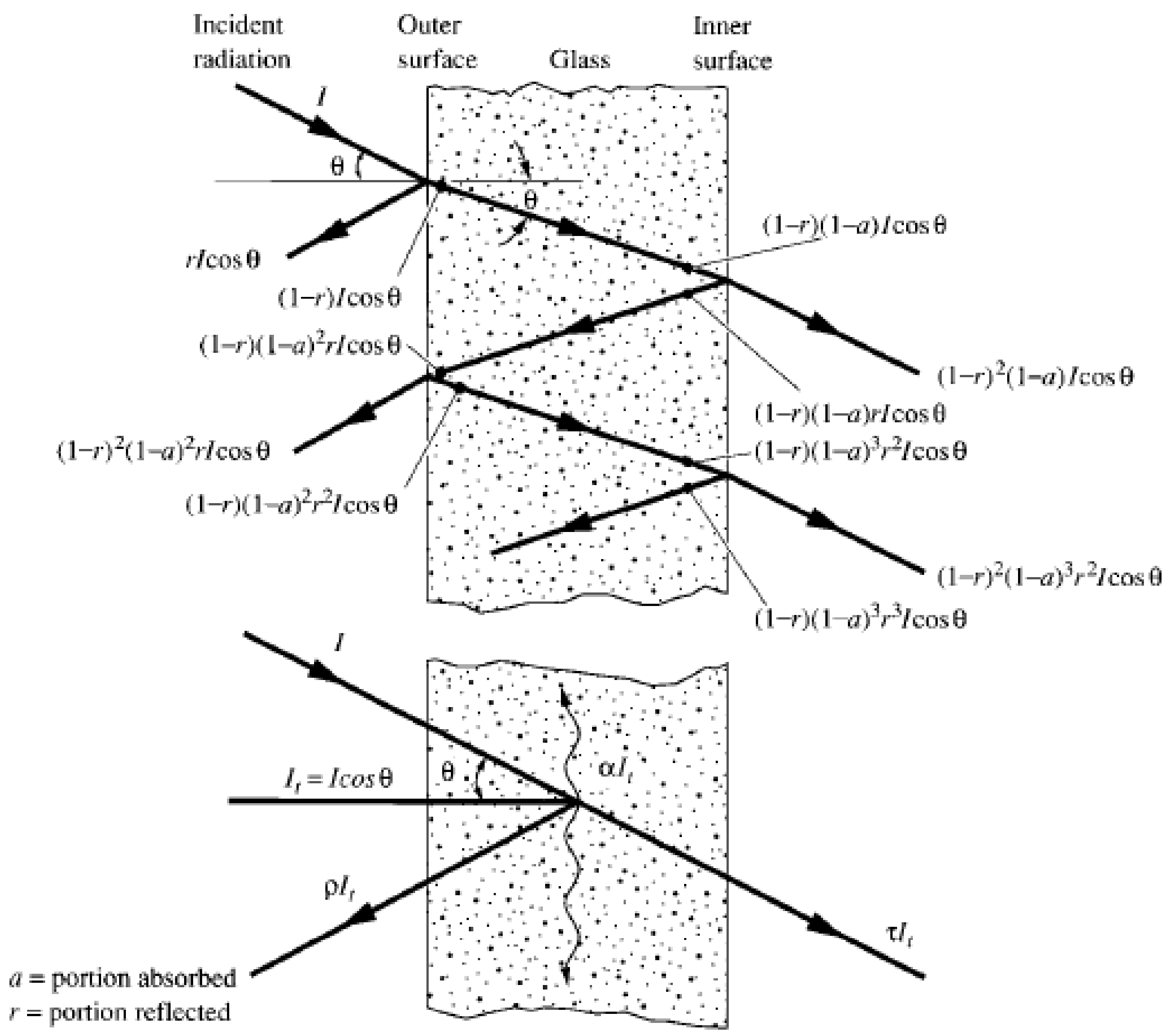
- *Clear plate or sheet glass or plastic*. Clear plate glass permits good visibility and transmits more solar radiation than other types.
- *Tinted heat-absorbing glass*. Tinted heat-absorbing glass is fabricated by adding small amounts of selenium, nickel, iron, or tin oxides. These produce colors from pink to green, including gray or bluish green, all of which absorb infrared solar heat and release a portion of this to the outside atmosphere through outer surface convection and radiation. Heat-absorbing glass also reduces visible light transmission.
- *Insulating glass*. Insulating glass consists of two panes—an outer plate and a inner plate—or three panes separated by metal, foam, or rubber spacers around the edges and hermetically sealed in a stainless-steel or aluminum-alloy structure. The dehydrated space between the glass panes usually has a thickness of 0.125 to 0.75 in. (3.2–19 mm) and is filled with air, argon, or other inert gas. Air- or gas-filled space increases the thermal resistance of the fenestration.
- *Reflective coated glass*. Reflective glass has a microscopically thin layer of metallic or ceramic coating on one surface of the glass, usually the inner surface of a single-pane glazing or the outer surface of the inner plate for an insulating glass. For a single pane, the coating is often protected by a layer of transparent polyester. The chromium and other metallic coatings give excellent reflectivity in the infrared regions but reduced transmission of visible light compared to clear plate and heat-absorbing glass. Reflections from buildings with highly reflective glass may blind drivers, or even kill grass in neighboring yards.
- *Low-emissivity (low-E) glass coatings*. Glazing coated with low-emissivity, or low-*E*, films has been in use since 1978. It is widely used in retrofit applications. A low-emissivity film is usually a vacuum-deposited metallic coating, usually aluminum, on a polyester film, at a thickness of about 4 107 in. (0.01 m).

Optical properties

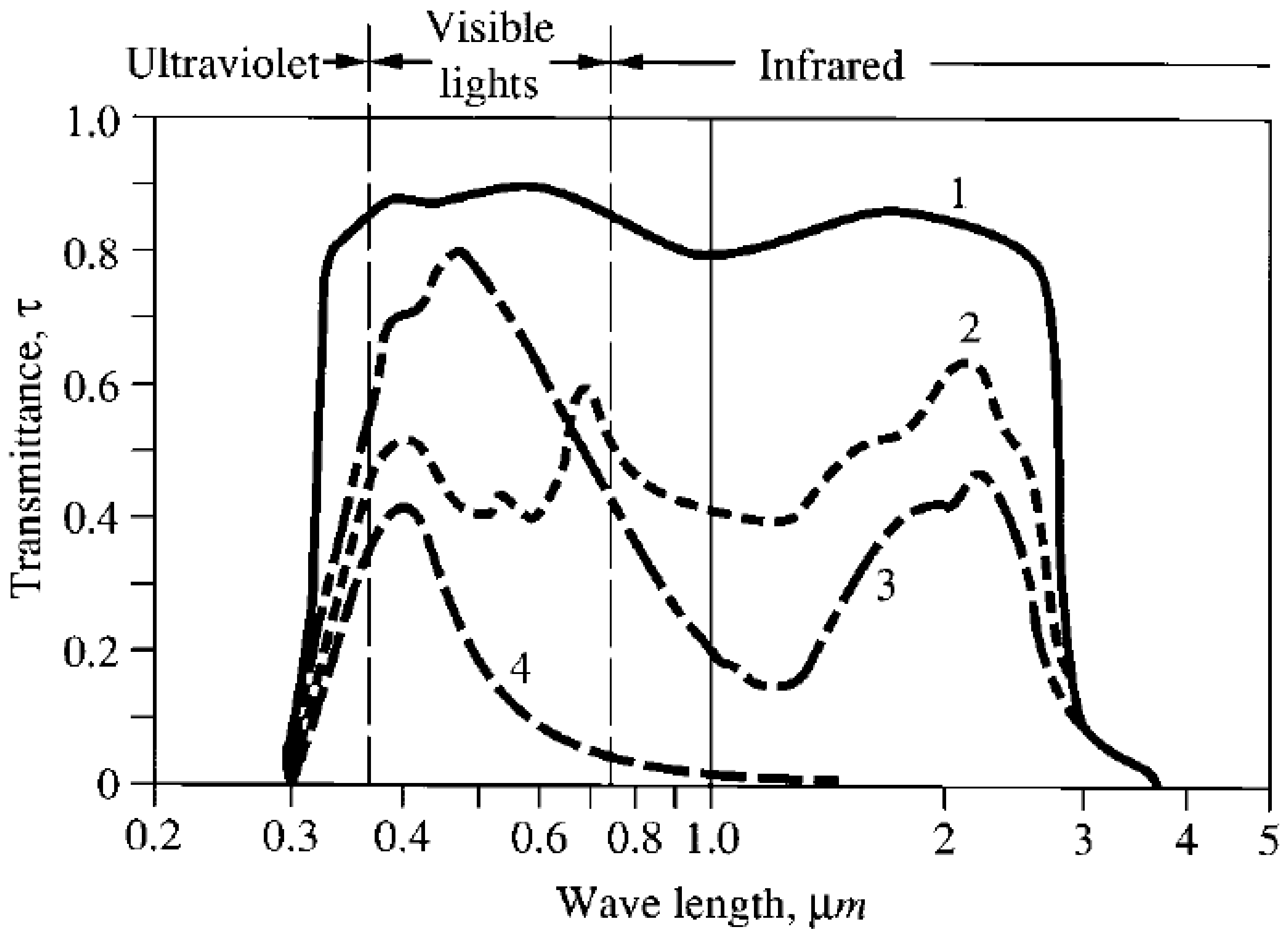
- Solar radiation is
  - Transmitted
  - Reflected
  - Absorbed

$$\tau + \alpha + \rho = 1$$

$$I \cdot \tau + I \cdot \alpha + I \cdot \rho = I$$



Spectral transmittance of window glasses



1 Clear plate
2 Gray heat absorbing
3 Bluish-green heat absorbing
4 Reflective coating

- Different glasses perform in different way
- Each glass has a spectral transmittance
- Spectral transmittance can be modified also using films

Heat trough windows

- $Heat\ gain\ through\ window = \ solar\ radiation\ transmitted\ + \ inward\ heat\ flow\ from\ glass\ inner\ surface$

$$\frac{Q_{wi}}{A_s} = \frac{\tau \cdot I_t + Q_{RCi}}{A_s}$$

- Q_{RCi} inward heat flow from inner surface

Single glazing

- $Q_{RCi} = U \cdot A_s \cdot \left(\frac{\alpha \cdot I_t}{h_o} + T_o - T_i\right)$
- $\frac{Q_{wi}}{A_s} = \tau I_t + U \cdot \left(\frac{\alpha \cdot I_t}{h_o} + T_o - T_i\right)$
- Solar heat gain coefficient (SHGC) ratio of solar heat gain entering the space to the incident solar radiation
- $SHGC = \frac{Q_{ws}}{\{I_t A_s\}} = \tau + \frac{U \cdot \alpha}{h_o}$