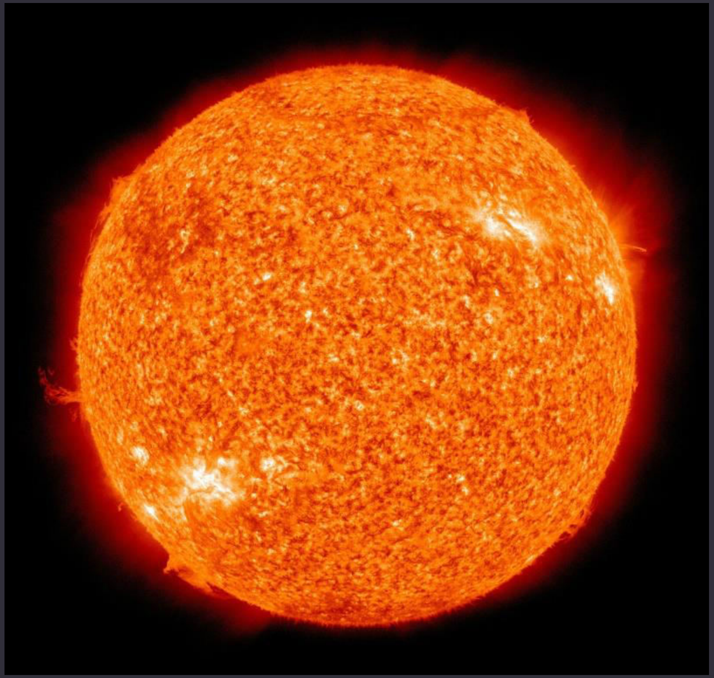
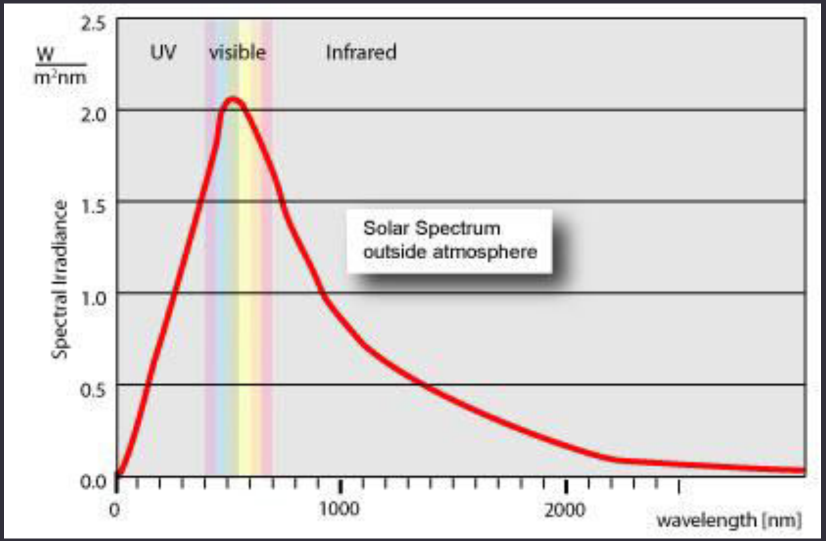
SOLAR RADIATION

THE SUN

The sun is a big fusion reactor that transform hidrogen in helium with rate of 4 Mt/s, in a temperature of 6000ºC

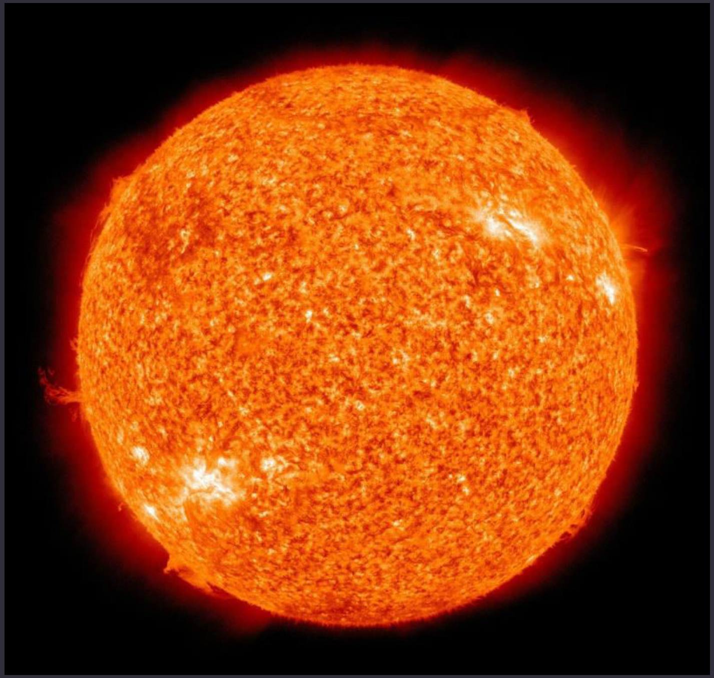


Source: https://pixabay.com/es/sun-bola-de-fuego-llamarada-solar-11582/



Source: http://www.greenrhinoenergy.com/solar/radiation/characteristics.php

THE SUN



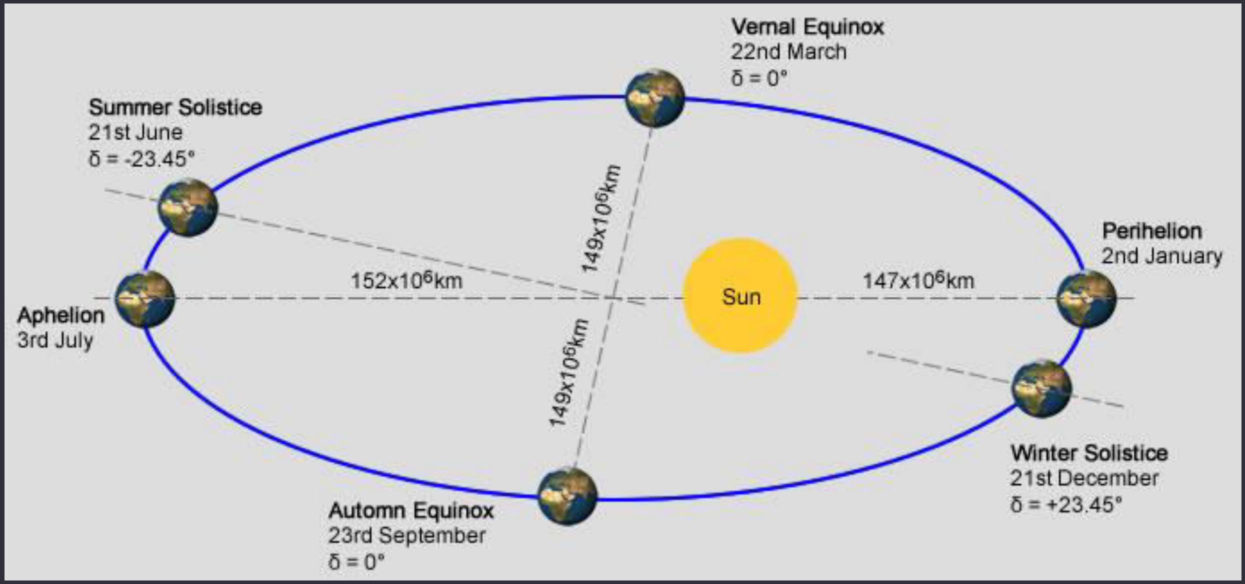
Source: https://pixabay.com/es/sun-bola-de-fuego-llamarada-solar-11582/

The Solar Radiation that arrive to Earth surface is due to two factors:

- Astronomical factors: distance Sun-Earth, Earth position, angle of incidence, etc.
- Climatic factors: clouds, water vapor, ozone, etc.

THE SUN

Source: http://www.greenrhinoenergy.com/solar/radiation/characteristics.php



Average distance from Sun to Earth: $R=149.6\ 10^6$ Km (AU: astronomical unit)

Inclination of the Earth axis: 23.45º

Distance from Sun to Earth : $R[1+0.033\cos(360d_n/365)]$

d_n = 1,2,..., 365 (day of the year)

THE SUN

Solar Irradiance: Power of solar radiation that crosses a surface per 1 m^2 .

$$G_n = G\,(1+0.033\cos(360 d_n/365))$$

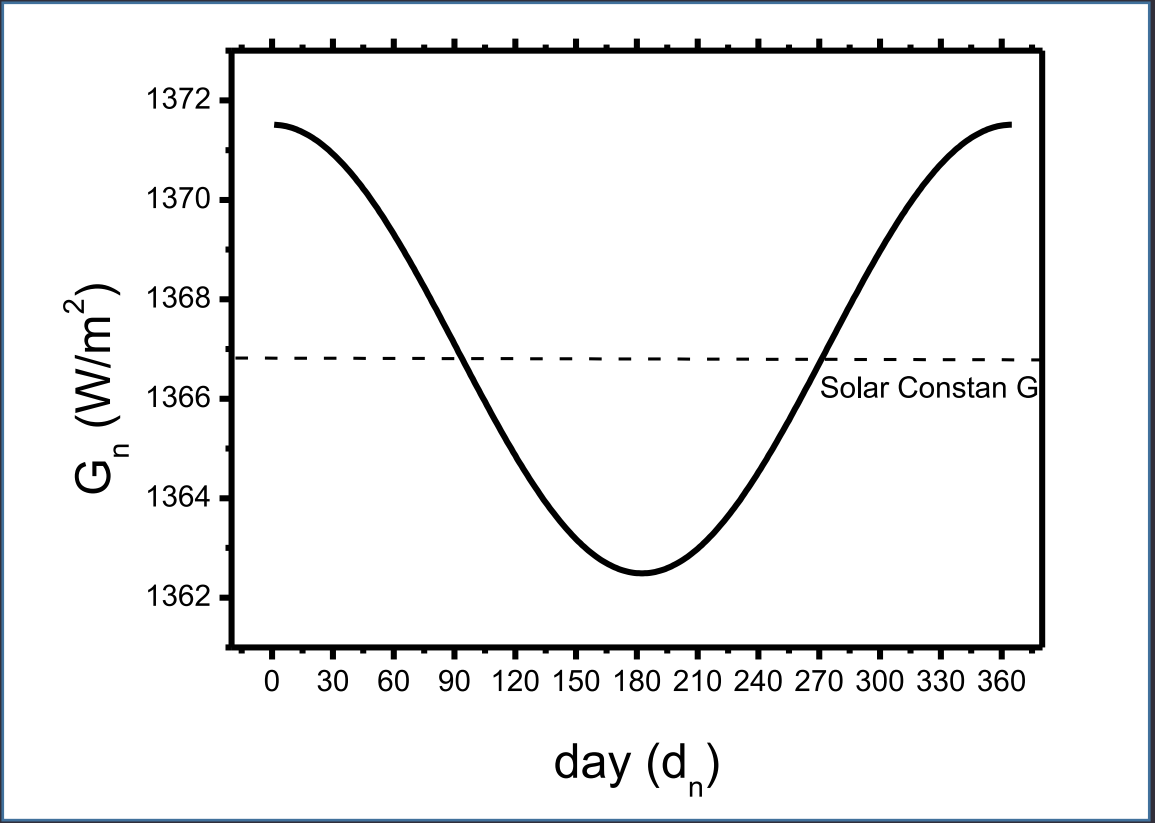
Units: W/m^2

G= Solar constant, the solar irradiance that would be incident on a plane perpendicular to the rays, at a distance of one astronomical unit (AU) .

$$G = 1367\ W/m^2$$

THE SUN

Variation of Solar Irradiance along the year

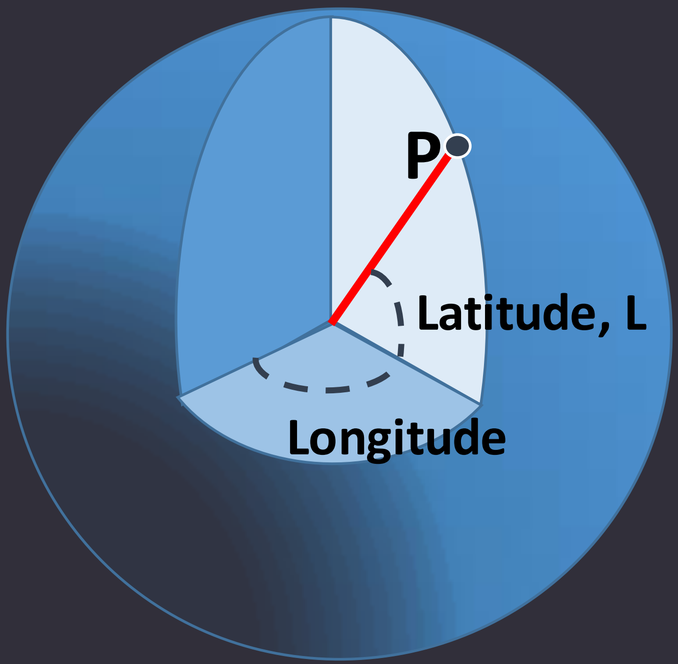


GEOGRAPHIC COORDINATES

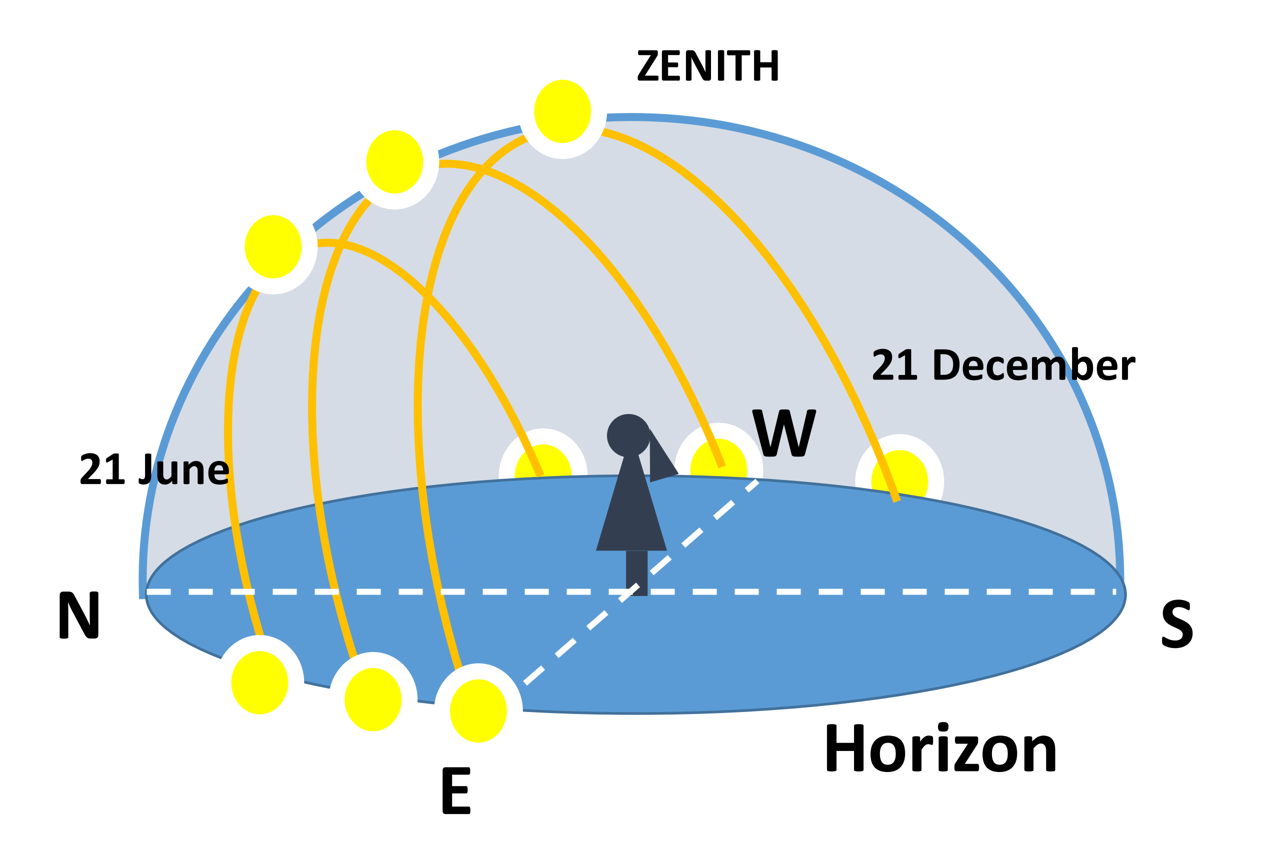
Allows to determinate positions of points on Earth.

- **Latitude, L:** angle between the equatorial plane and the straight line that passes through that point and through the center of the Earth

- **Longitude:** angle east or west of a reference meridian to another meridian that passes through that point



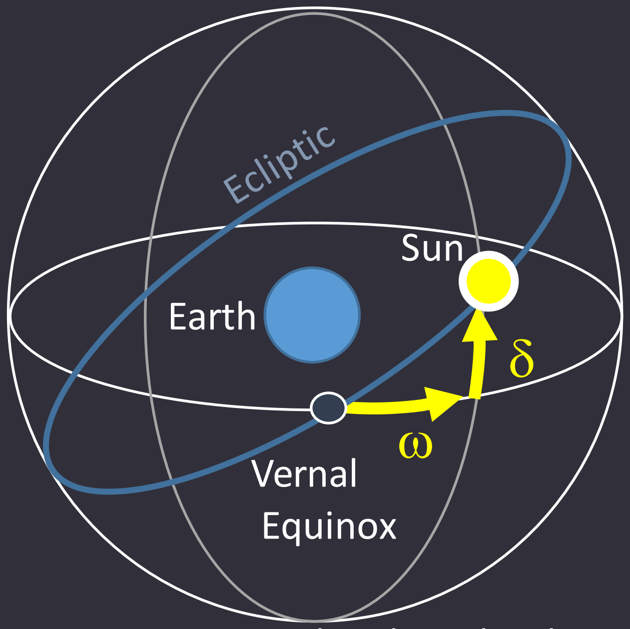
SUN POSITION



Perceived Sun movement

SUN POSITION

Equatorial coordinates system



Easy for calculation with day and hour:

δ: declination

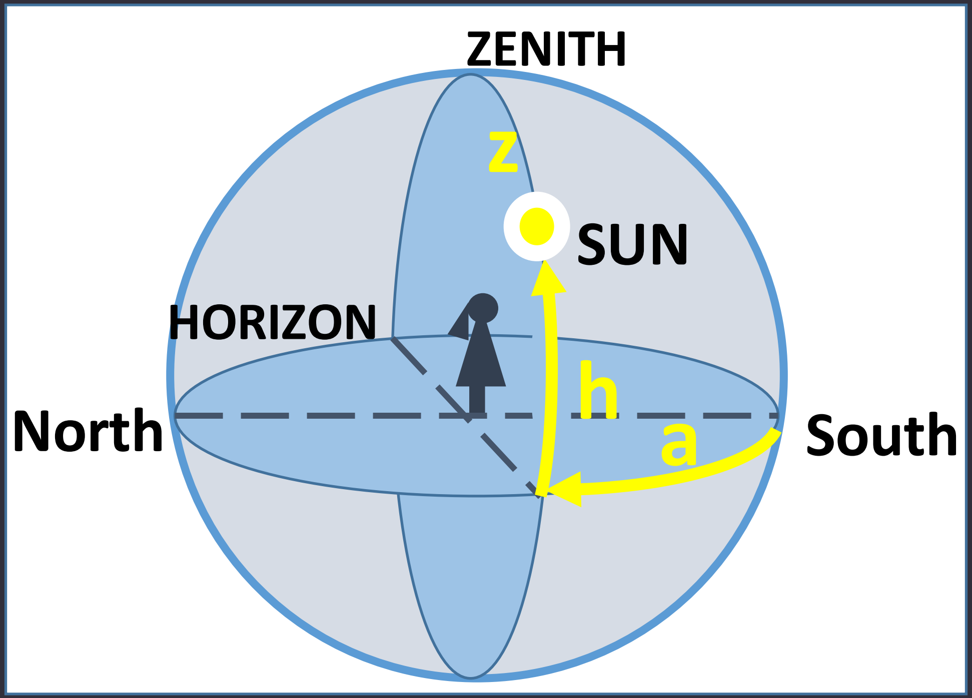
$$\delta = 23.45 \sin[(284+d_n)360/365]$$

ω: Right ascension or hour angle

$$\omega = (\text{hora solar}-12h)/15º$$

SUN POSITION

Horizontal coordinates system



Intitutive for observer:

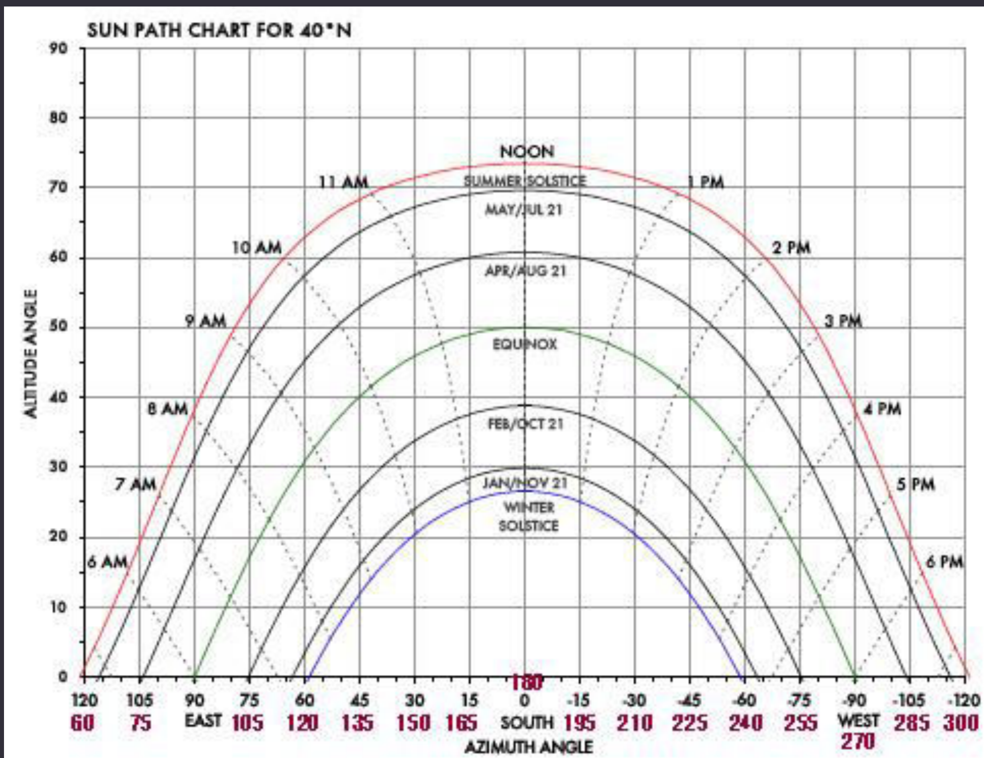
- a: azimuth
- h: altitude
- z: Zenith (90º-h)

SUN POSITION

Coordinates transformations:

$$\sin(h) = \sin(L)\sin(\delta)+\cos(L)\cos(\delta)\cos(\omega)$$
$$\sin(h)\cos(a)=\sin(L)\cos(\delta)\cos(\omega)-\cos(L)\sin(\delta)$$
$$\cos(h)\sin(a) = \cos(L)\sin(\omega)$$

SUN PATH DIAGRAMAN (cartesian)



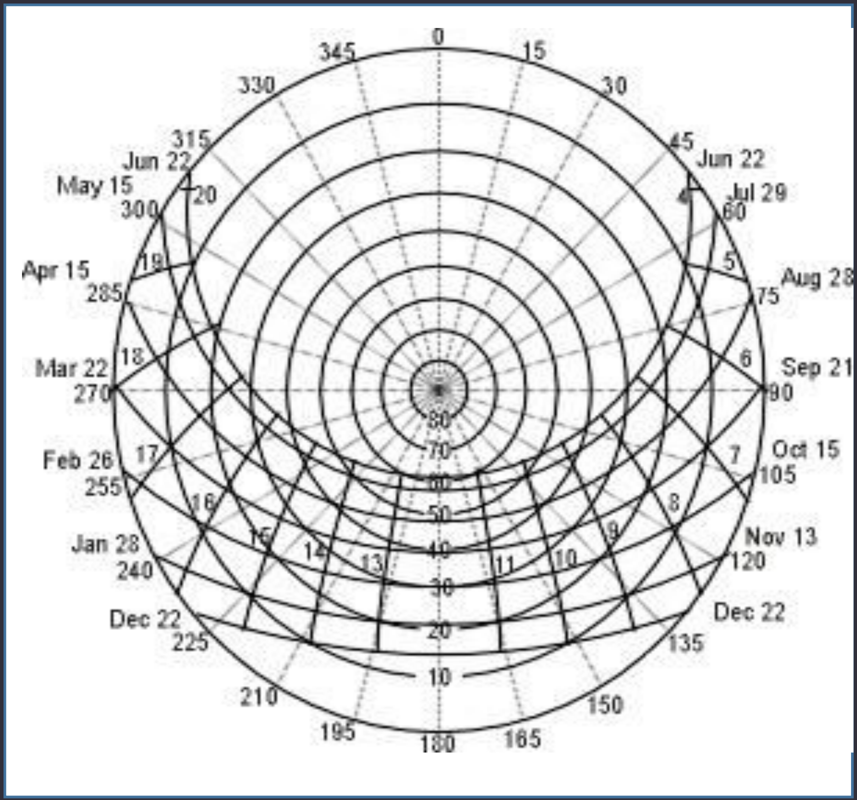
Source: http://www.thesolarplanner.com/array_placement3.html

Hour angle in the sunset:

In the sunset, the altitude is h=0

$$\omega_p = \arccos(-tg\ L\ tg\delta)$$

SUN PATH DIAGRAMAN (polar)



Source: http://www.l-e-s-s.co.uk/Guides/Physics/SolarGeometry.htm

MAXIMUM INSOLATION

Time between sunrise and sunset

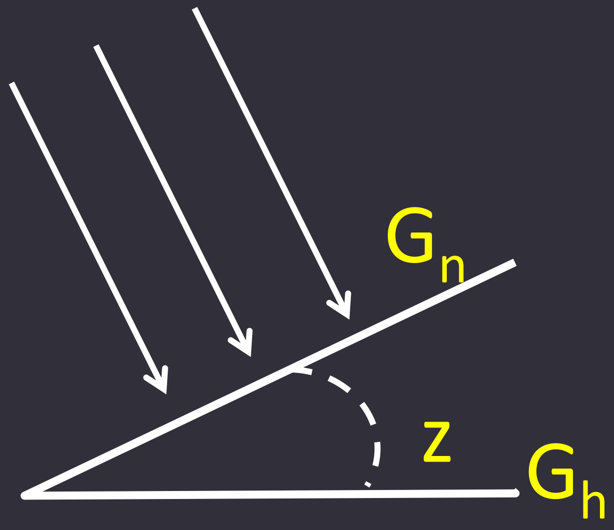
$$N_{hours} = \frac{2\omega_p}{15º}$$

Hour angle in the sunset

$$N_{horas} = \frac{2 \arccos(-tg\, L\, tg\delta)}{15º}$$

HORIZONTAL EXTRATERRESTRIAL IRRADIANCE

Irradiance through a surface parallel to Earth suface located out atmosphere



$$G_h = G_n \cos z = G_n \text{sen } h$$

$$G_h = G_n\,(\sin\delta\,\sin L + \cos\delta\,\cos L\,\cos\omega)$$

HORIZONTAL EXTRATERRESTRIAL IRRADIATION

Irradiation: Integral of the irradiance over a range of time.

$$H = \int G_h dt = 12/\pi \int G_h d\omega$$

Units: J/m^2

HORIZONTAL EXTRATERRESTRIAL IRRADIATION

Daily Irradiation: Integrate over a whole day.

$$H_d = \int_0^{24h} G_h dt = 12/\pi \int_{-\omega_p}^{\omega_p} G_h d\omega$$

For the extraterrestrial irradiation:

$$H_0 = 24/\pi\ G_n\ (\omega_p \sin\delta \sin L + \cos\delta \cos L \sin\omega_p)$$

There are also irradiation by hour, month, etc.

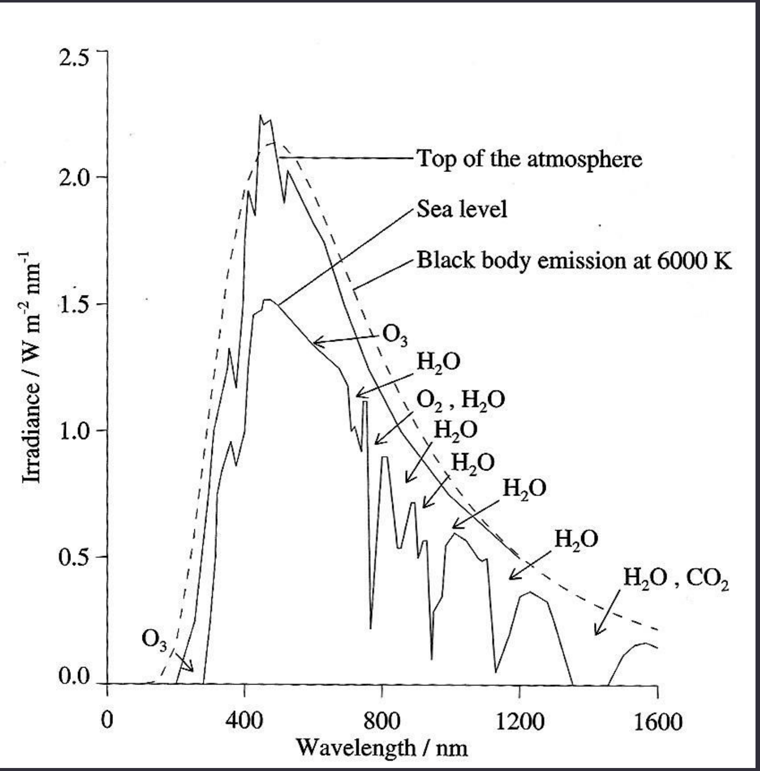
HORIZONTAL EXTRATERRESTRIAL IRRADIATION

Daily Irradiation: Integrate over a whole day.

It is possible to show that the monthly average of this daily irradiation coincides numerically with the daily irradiation corresponding to the representatives days.

	Jan	Feb	Mar	Abr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dic
d_n	17	45	74	105	135	161	199	230	261	292	322	347

IRRADIATION ON EARTH'S SURFACE



atmospheric absorption spectrum

Source: http://lasp.colorado.edu/~bagenal/3720/CLASS5/5Spectroscopy.html

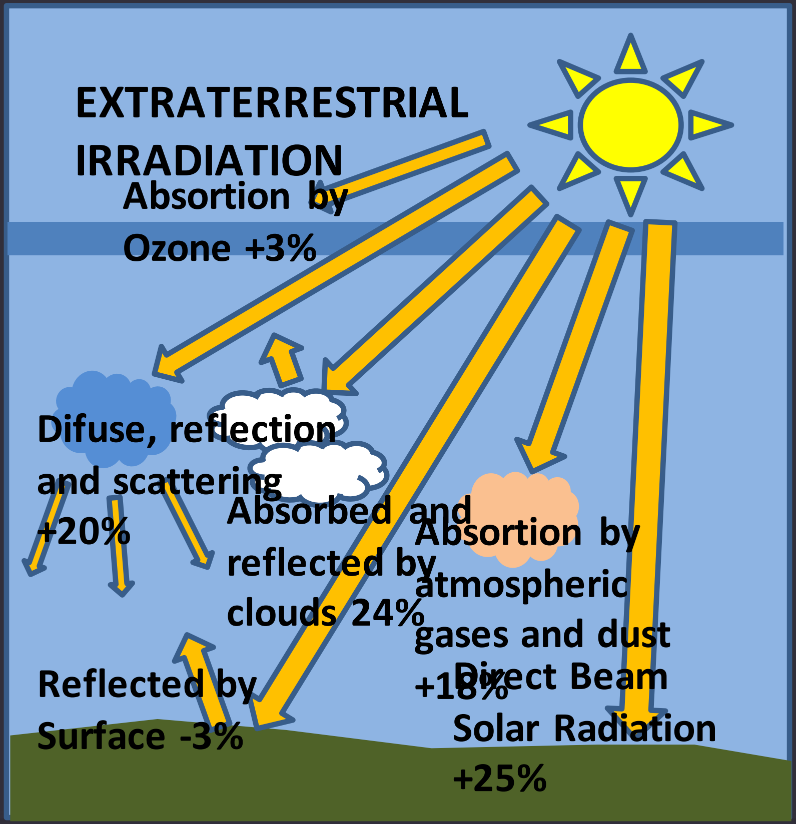
IRRADIATION ON EARTH'S SURFACE

Irradiation that arrives to a horizontal plane on earth's surface can be:

- Direct: solar radiation traveling on a straight line from the sun down to the surface of the earth.
- Diffused: sunlight that has been scattered by molecules and particles in the atmosphere.
- Reflected: Reflected on the ground and nearby objects.

Global: $H = H_{dir} + H_{dif} + H_{ref}$

IRRADIATION ON EARTH'S SURFACE



IRRADIATION ON EARTH'S SURFACE

Mesurements of Direct Radiation:

Pyrheliometers

Source: https://upload.wikimedia.org/wikipedia/commons/4/4b/Hukseflux_solarradiation_dr01_photo.jpg

IRRADIATION ON EARTH'S SURFACE

Mesurements of Global and Diffused Radiation:

Pyranometers

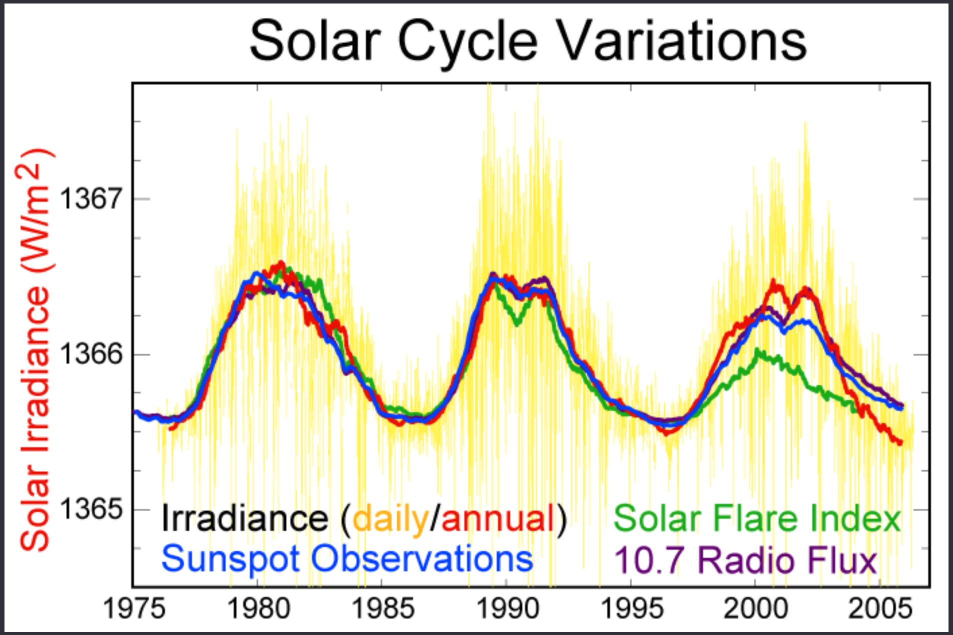
Source: https://commons.wikimedia.org/wiki/File:Hukseflux_radiometer_sr11_photo.jpg

IRRADIATION ON EARTH'S SURFACE

Mesurements of Global and Diffuse Radiation:

Global radiation evolution during time.

Large dispersion, statistical methods should be used.



Source: https://commons.wikimedia.org/wiki/File:Solar-cycle-data.png

IRRADIATION ON EARTH’S SURFACE

Clearness Index:

Ratio of the monthly average daily irradiation reaching a horizontal plane at the location on the Earth’s surface and the extraterrestrial irradiation.

Thus K_T is an indication of how much of the Sun’s radiation is lost to scattering and absorption in the atmosphere.

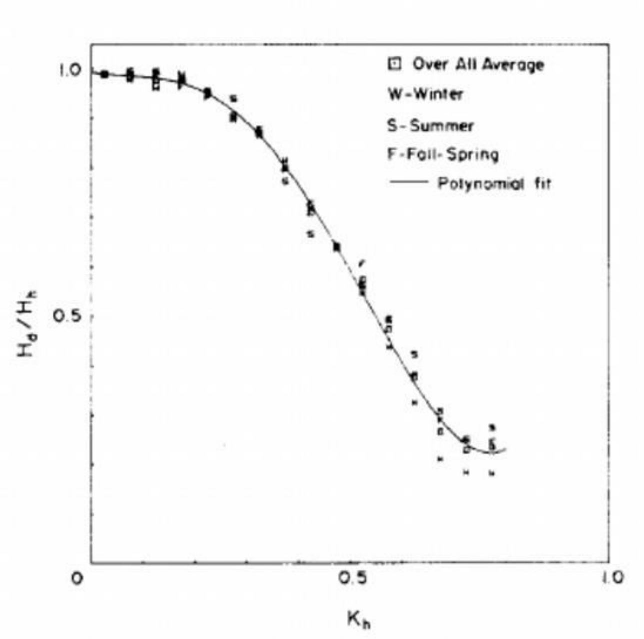
$$K_T = \frac{\overline{H_d}}{H_0}$$

IRRADIATION ON EARTH’S SURFACE

Models of diffused radiation:

The ratio of diffused radiation and global radiation have to depend on the clearness of atmosphere .

$$\frac{\overline{H_{dif}}}{H} = f(K_T)$$



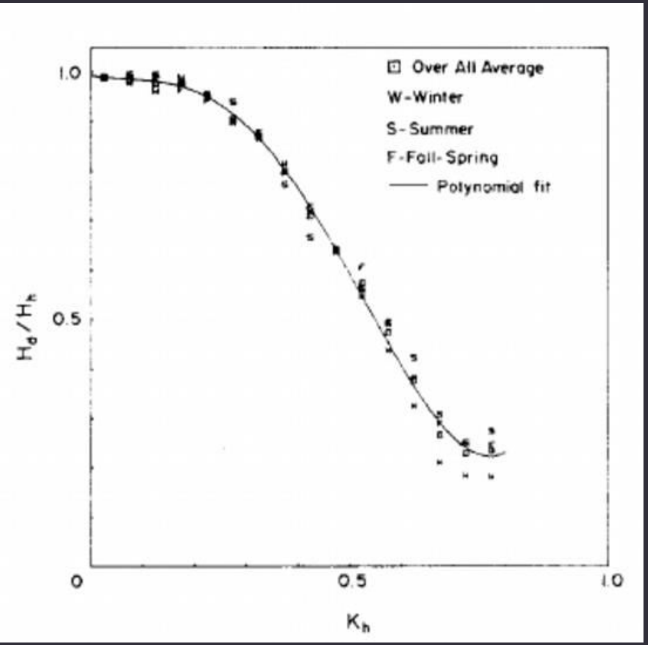
Source:M. Collares-Pereira, A. Raabl Solar Energy 22, 155-164 (1979)

IRRADIATION ON EARTH'S SURFACE

Models of diffused radiation:

The ratio of diffused radiation and global radiation have to depend on the clearness of atmosphere .

$$\frac{\overline{H}_{dif}}{H} = 1\text{-}1.13\ K_T$$



Page Equation ($0.3 \leq K_T \leq 0.8$ still applies)

Source:M. Collares-Pereira, A. Raabl Solar Energy 22, 155-164 (1979)

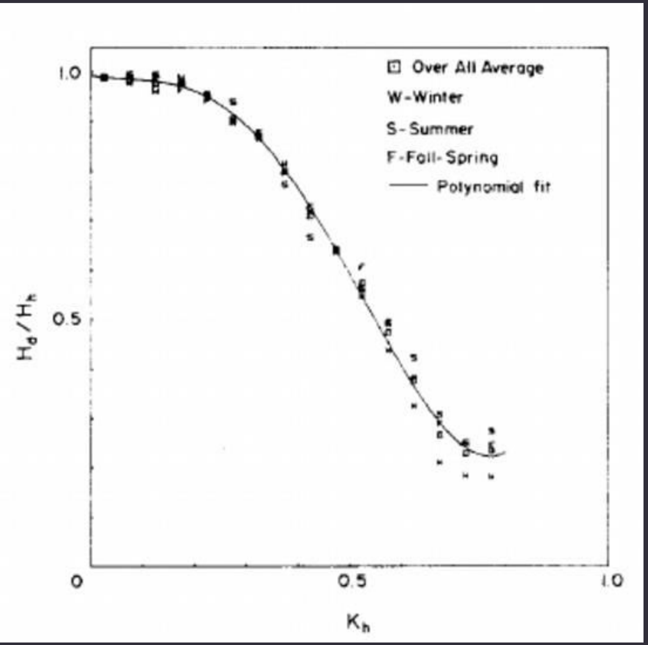
IRRADIATION ON EARTH'S SURFACE

Models of diffused radiation:

The ratio of diffused radiation and global radiation have to depend on the clearness of atmosphere .

$$\frac{\overline{H_{dif}}}{H} = 1.39 - 4.03\,K_T + 5.53\,K_T^{2} - 3.11\,K_T^{\ 3}$$

Liu & Jordan (1960)



Source:M. Collares-Pereira, A. Raabl Solar Energy 22, 155-164 (1979)

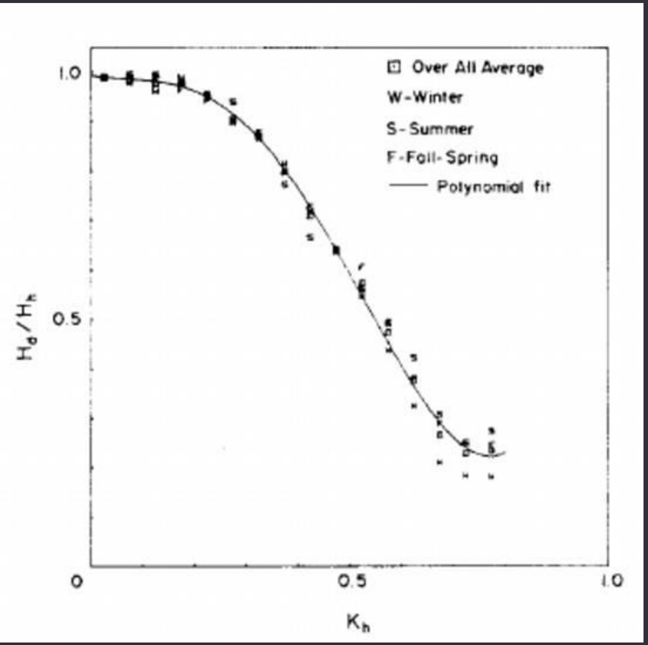
IRRADIATION ON EARTH'S SURFACE

Source:M. Collares-Pereira, A. Raabl Solar Energy 22, 155-164 (1979)

Models of diffused radiation:

The ratio of diffused radiation and global radiation have to depend on the clearness of atmosphere .

Collares-Pereira & Rabl (1979)



$$\frac{\overline{H_{dif}}}{\overline{H}} = 0.775+0.0065(\omega_p-90) - [0.505+0.0261(\omega_p-90)]\cos(115K_T-103)$$

IRRADIATION ON EARTH'S SURFACE

Terrestrial Albedo:

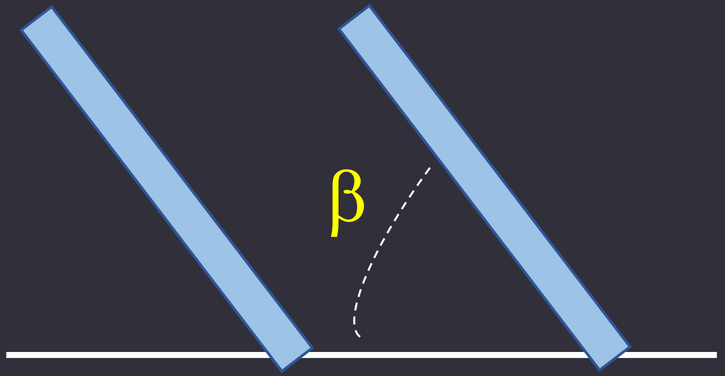
Albedo or reflectivity of the surrounding ground is the ratio of reflected radiation to global radiation

$$\rho = \frac{\overline{H}_{ref}}{H}$$

Ground cover	Albedo	Ground cover	Albedo
Dry bare ground	0.2	Pale soil	0.3
Dry grassland	0.3	Dark soil	0.1
Desert sand	0.4	Water	0.1
Snow	0.5-0.8	Vegetation	0.2

IRRADIATION ON A TILTED SURFACE

Diffused radiation on a Tilted Surface:

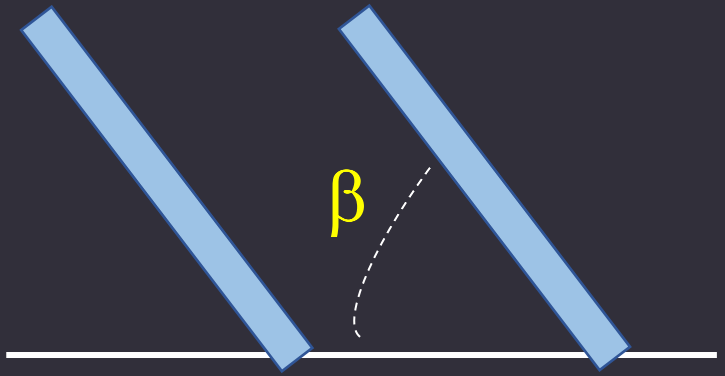


$$\overline{H}_{dif}(\beta) = 0.5\,\overline{H}_{dif}\,(1+\cos\beta)$$

Model of Liu & Jordan for isotropic radiation

IRRADIATION ON A TILTED SURFACE

Reflected radiation
on a Tilted Surface:

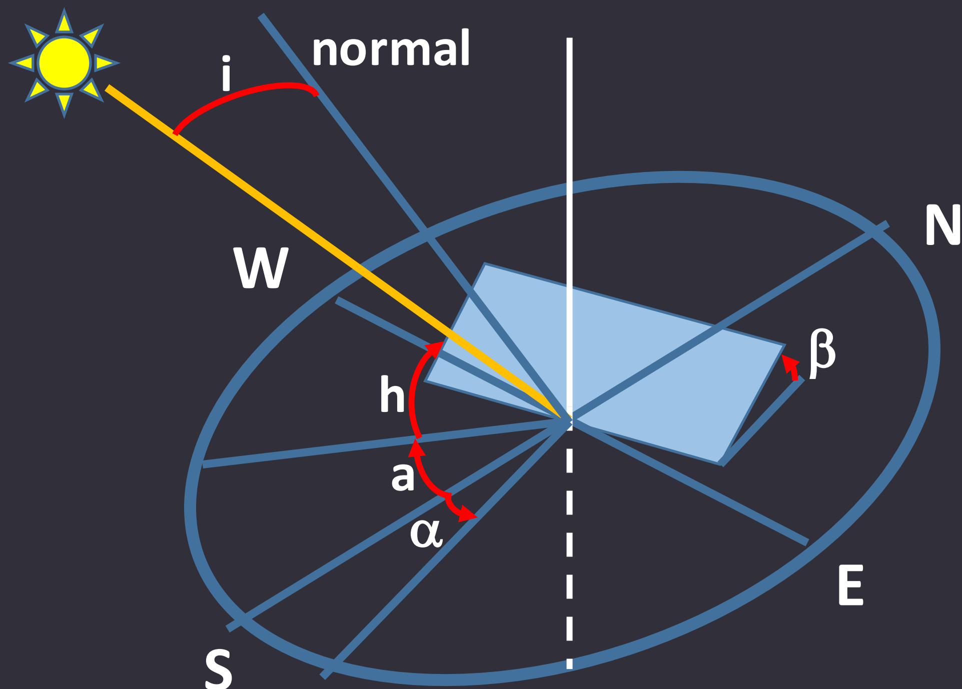


$$\overline{H}_{ref}(\beta) = 0.5\,\rho\overline{H}\,(1-\cos\beta)$$

Model of Liu & Jordan
for isotropic radiation

IRRADIATION ON A TILTED SURFACE

Direct radiation on a Tilted Surface:



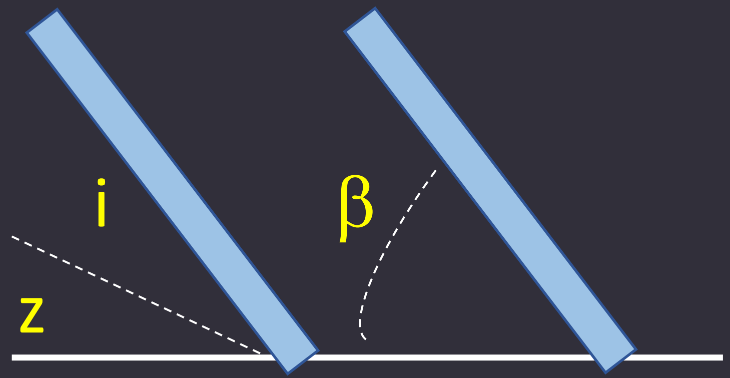
- β: Inclination angle
- α: Orientatation angle
- i: Angle of Incidence

IRRADIATION ON A TILTED SURFACE

Direct radiation on a Tilted Surface:

$$\bar{H}_{dir}(\beta) = R_{cor}\,\bar{H}_{dir}$$

$$H \sim (H_{dir} + H_{dif})$$ Horizontal surface



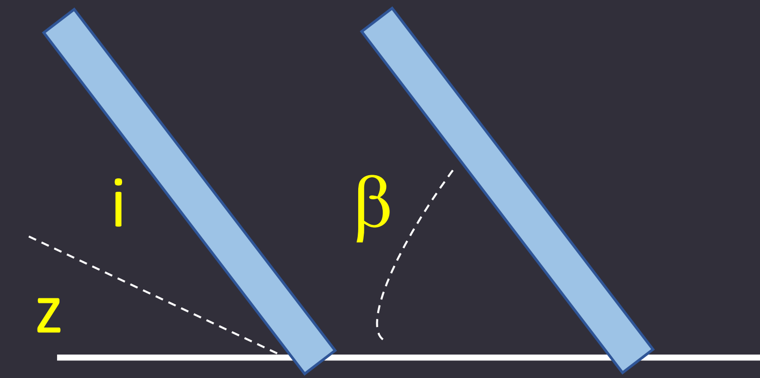
$$R_{cor} = \frac{\cos i}{\cos z}$$

Complex geometric expression

IRRADIATION ON A TILTED SURFACE

Direct radiation on a Tilted Surface:

$$\overline{H}_{dir}(\beta) = R_{cor}\,(H - \overline{H}_{dif})$$



For $\alpha = 0$ (South orientation):

$$R_{cor} = \frac{\cos(L-\beta)\,\cos\delta\,\sin\omega_p + \omega_p \mathrm{sen}(L-\beta)\,\sin\delta}{\cos L\,\cos\delta\,\sin\omega_p + \omega_p \mathrm{sen}\,L\,\sin\delta}$$

IRRADIATION ON A TILTED SURFACE

Global radiation on a Tilted Surface:

$$H(\beta)= H_{dir}(\beta) + H_{dif}(\beta) + H_{ref}(\beta)$$

IRRADIATION ON A TILTED SURFACE

Factor correction for orientation:

$$H(\alpha) = K_{or}\, H(\alpha=0)$$

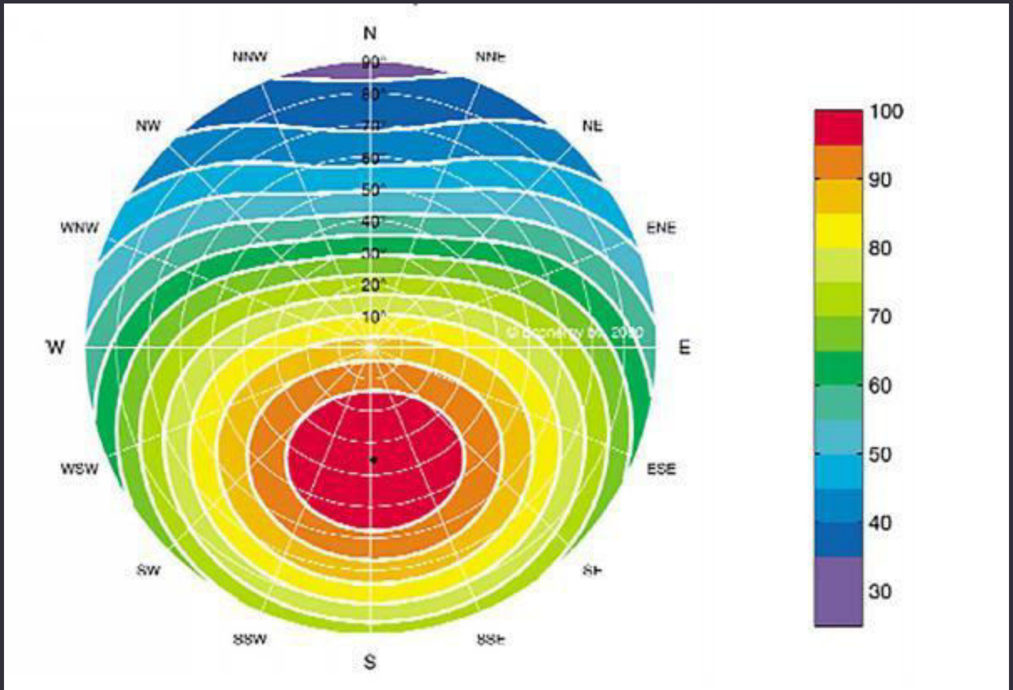
Approximate expression:

$$K_{or} \sim (1 - 3.5\ 10^{-5}\ \alpha^2)$$

IRRADIATION LOSSES

Loss by Orientation-Inclination:

Solar radiation loss chart



IRRADIATION LOSSES

Loss by Orientation-Inclination:

Approximate expression:

$$\text{Power loss}(\%) = 100[1.2\ 10^{-4}(\beta-\beta_{opt})^2 + 3.5\ \ 10^{-5}\ \alpha^2]$$

Optimum angles:

- Optimum orientation angle: α=0, South
- Optimum inclination angle : β=L - δ, depends on day

IRRADIATION LOSSES

Loss by Orientation-Inclination:

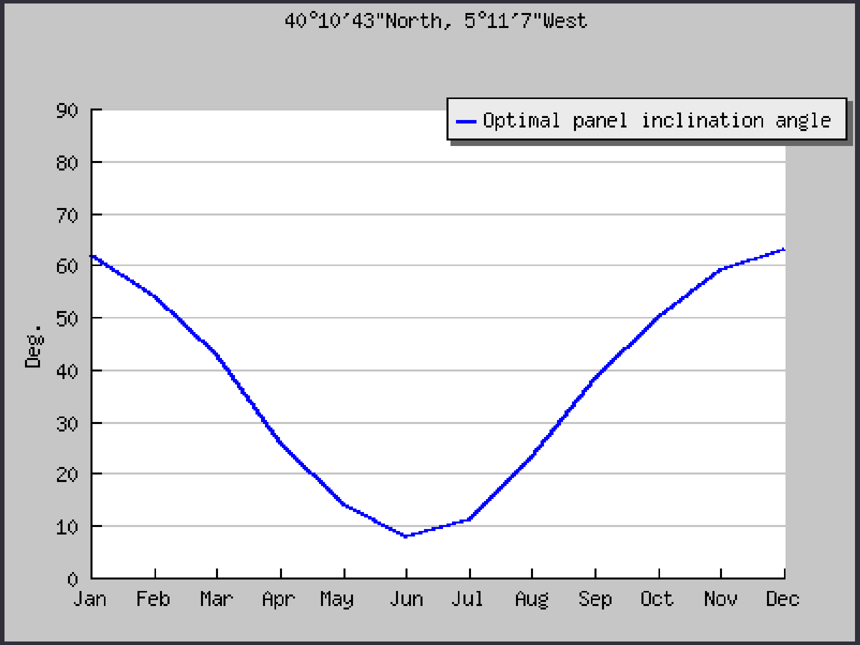
Design angles:

- Orientation angle: α=0, South
- Inclination angle :

  β=L (General case)

  β=L+10 (Design for winter)

  β=L-10 (Design for summer)



IRRADIATION LOSSES

Loss by Orientation-Inclination:

Spanish CTE Regulation:

Maximum allowed losses:

	Orientation-Inclination	Shadow	Total
General	10%	10%	15%
Collector overlap	20%	15%	30%
Architectural integration	40%	20%	50%

IRRADIATION LOSSES

Loss by Orientation-Inclination:

Spanish CTE Regulation:

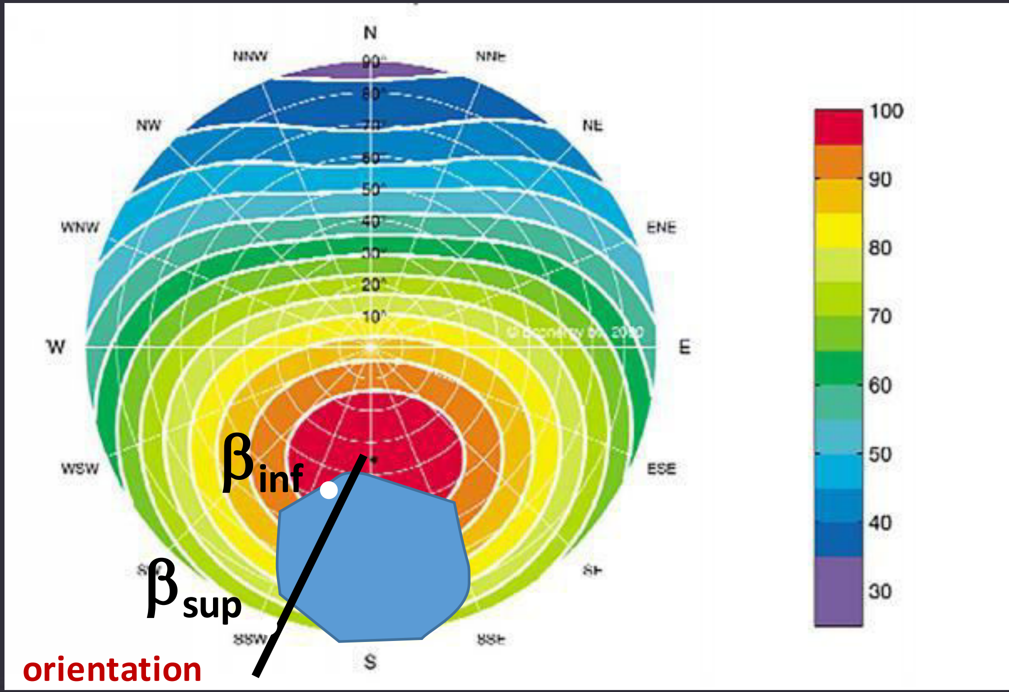
Method of Calculation using Solar radiation loss chart:

1. In the loss chart corresponding to L=41º, the orientation azimuth line is drawn.
2. The intersection points with curve correspondint to allowed loss (10%, 20% or 40%) are obtained.
3. These limit inclinations are corrected to right latitude.

IRRADIATION LOSSES

Loss by Orientation-Inclination:

Spanish CTE Regulation:



β_{inf}: Minimum inclination

β_{sup}: Maximum inclination

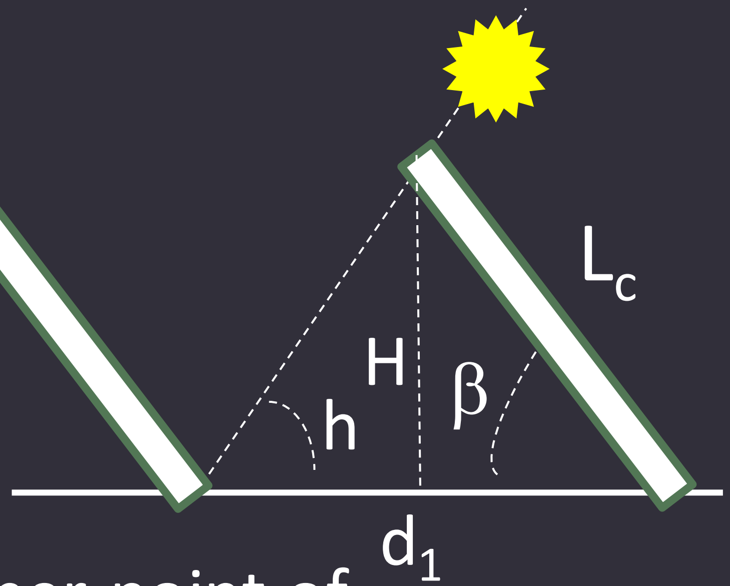
Latitude correction:

$$\beta(L) = \beta(41º)-(41º-L)$$

IRRADIATION LOSSES

Loss by shadow:

Shadow between adjacent collectors (minimum separation):



Relation between the height of upper point of collector, H, and lenght of shadow, d1:

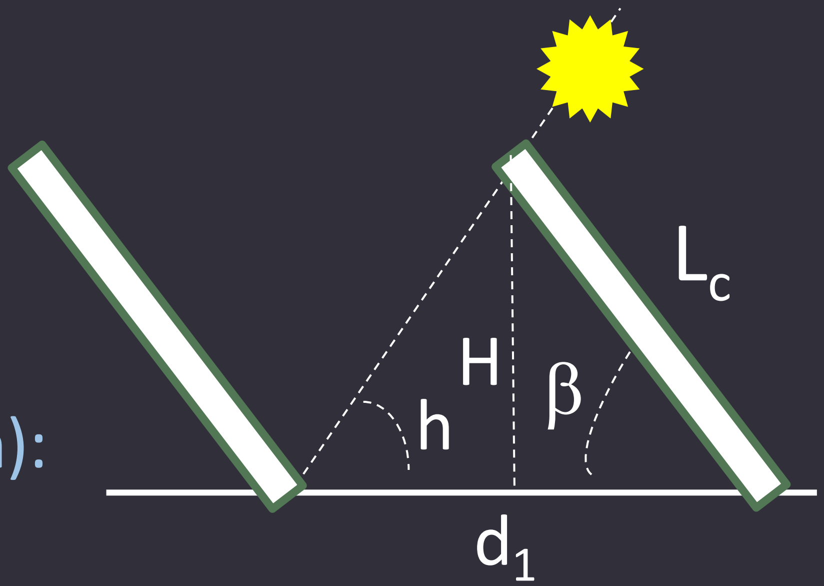
$$tg\ h = \frac{H}{d_1}$$

$$d_1 = H/tgh$$

IRRADIATION LOSSES

Loss by shadow:

Shadow between adjacent collectors (minimum separation):



$$H = L_C \text{ sen } \beta$$

Minimum separation between collectors:

$$d_{min} = d_1 + d_2 = L_c[\text{sen}\beta/\text{tg}h + \cos\beta]$$

In design, it is calculated for the worst condition: day 21/12 at 12:00h

IRRADIATION LOSSES

Loss by shadow:

Shadow of adjacent obstacles (method of calculation):

1. Determination of obstacle profile: Values of elevation and azimuth of the object.
2. Transfer of the profile to the chart of the Sun trajectories divided into zones.
3. Determination of the shaded areas and search in the corresponding table closest to the collector conditions.

IRRADIATION LOSSES

Loss by shadow:

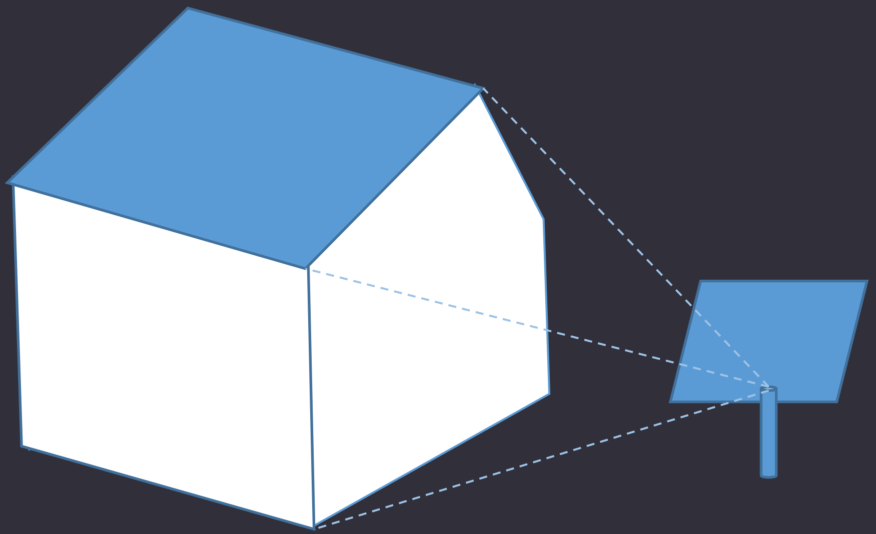
Shadow of adjacent obstacles (method of calculation):

4. Quantification of losses by adding the contribution of each zone weighted by a factor of 0.25, 0.5, 0.75 and 1 according to the degree of shadow.

IRRADIATION LOSSES

Loss by shadow:

Shadow of adjacent obstacles (method of calculation):



h_1, a_1

h_2, a_2

h_3, a_3

.

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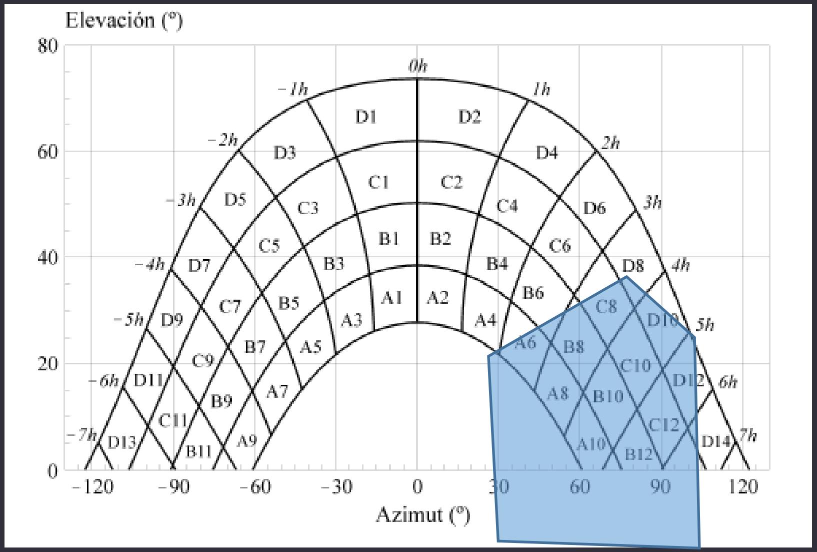
IRRADIATION LOSSES

Loss by shadow:

Shadow of adjacent obstacles (method of calculation):



A_1 B_2

A_2 B_4

A_4 B_6

A_6

Source: Pliego de las Condiciones Técnicas del IDAE

Tabla 5-A

β = 35° α = 0°	A	B	C	D
13	0,00	0,00	0,00	0,03
11	0,00	0,01	0,12	0,44
9	0,13	0,41	0,62	1,49
7	1,00	0,95	1,27	2,76
5	1,84	1,50	1,83	3,87
3	2,70	1,88	2,21	4,67
1	3,15	2,12	2,43	5,04
2	3,17	2,12	2,33	4,99
4	2,70	1,89	2,01	4,46
6	1,79	1,51	1,65	3,63
8	0,98	0,99	1,08	2,55
10	0,11	0,42	0,52	1,33
12	0,00	0,02	0,10	0,40
14	0,00	0,00	0,00	0,02

Tabla 5-B

β = 0° α = 0°	A	B	C	D
13	0,00	0,00	0,00	0,18
11	0,00	0,01	0,18	1,05
9	0,05	0,32	0,70	2,23
7	0,52	0,77	1,32	3,56
5	1,11	1,26	1,85	4,66
3	1,75	1,60	2,20	5,44
1	2,10	1,81	2,40	5,78
2	2,11	1,80	2,30	5,73
4	1,75	1,61	2,00	5,19
6	1,09	1,26	1,65	4,37
8	0,51	0,82	1,11	3,28
10	0,05	0,33	0,57	1,98
12	0,00	0,02	0,15	0,96
14	0,00	0,00	0,00	0,17

Tabla 5-C

β = 90° α = 0°	A	B	C	D
13	0,00	0,00	0,00	0,15
11	0,00	0,01	0,02	0,15
9	0,23	0,50	0,37	0,10
7	1,66	1,06	0,93	0,78
5	2,76	1,62	1,43	1,68
3	3,83	2,00	1,77	2,36
1	4,36	2,23	1,98	2,69
2	4,40	2,23	1,91	2,66
4	3,82	2,01	1,62	2,26
6	2,68	1,62	1,30	1,58
8	1,62	1,09	0,79	0,74
10	0,19	0,49	0,32	0,10

Tabla 5-D

β = 35° α = 30°	A	B	C	D
13	0,00	0,00	0,00	0,10
11	0,00	0,00	0,03	0,06
9	0,02	0,10	0,19	0,56
7	0,54	0,55	0,78	1,80
5	1,32	1,12	1,40	3,06
3	2,24	1,60	1,92	4,14
1	2,89	1,98	2,31	4,87
2	3,16	2,15	2,40	5,20
4	2,93	2,08	2,23	5,02
6	2,14	1,82	2,00	4,46
8	1,33	1,36	1,48	3,54
10	0,18	0,71	0,88	2,26

Shadow of adjacent obstacles (method of calculation):

A_1 B_2

A_2 B_4

A_4 B_6

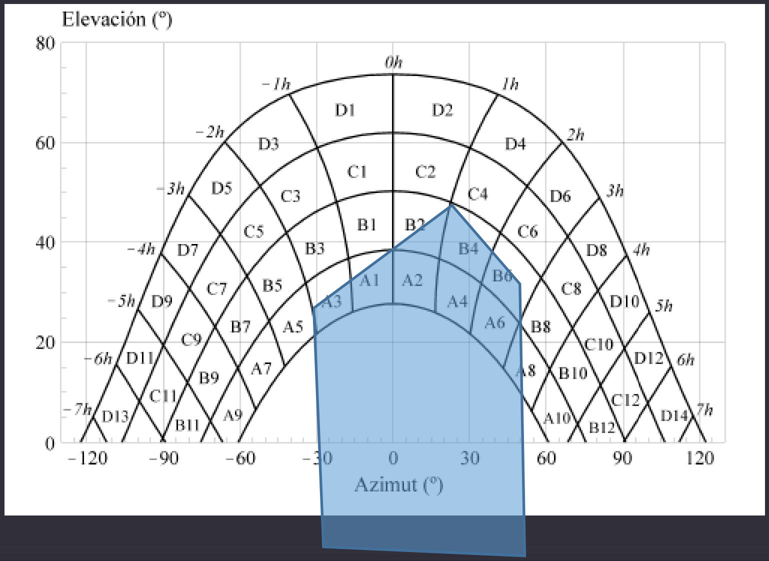
A_6

Source: Pliego de las Condiciones Técnicas del IDAE

IRRADIATION LOSSES

Loss by shadow:

Shadow of adjacent obstacles (method of calculation):



A_1: 0.75 B_2 : 0.5

A_2 : 1 B_4: 0.75

A_4 : 1 B_6 : 0.25

A_6 : 0.75

$$P_T = \sum C_i P_i$$

Source: Pliego de las Condiciones Técnicas del IDAE

- slide 23

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