ECE 333 – Green Electric Energy

13. Solar Insolation Components and Measurement

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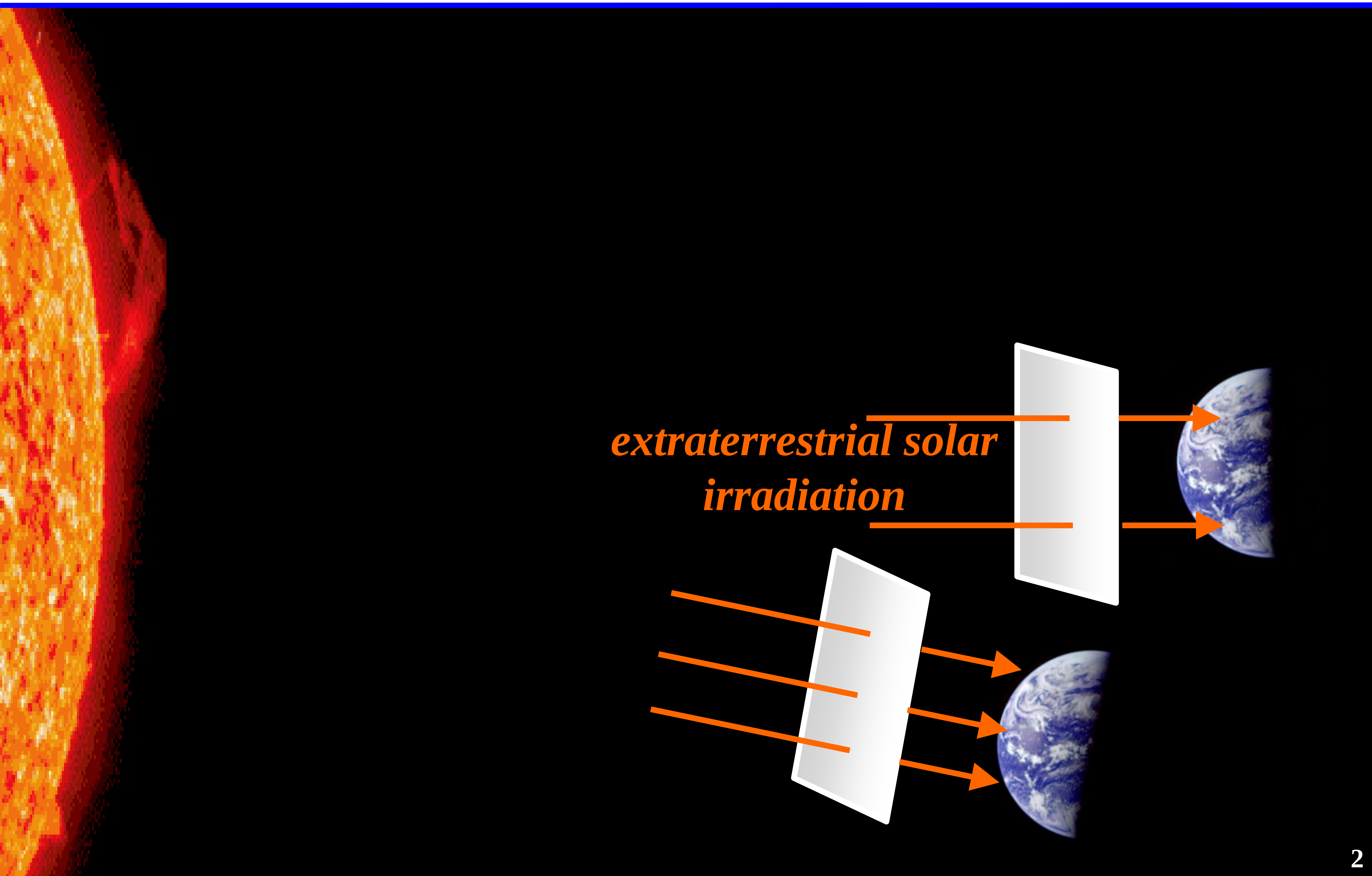
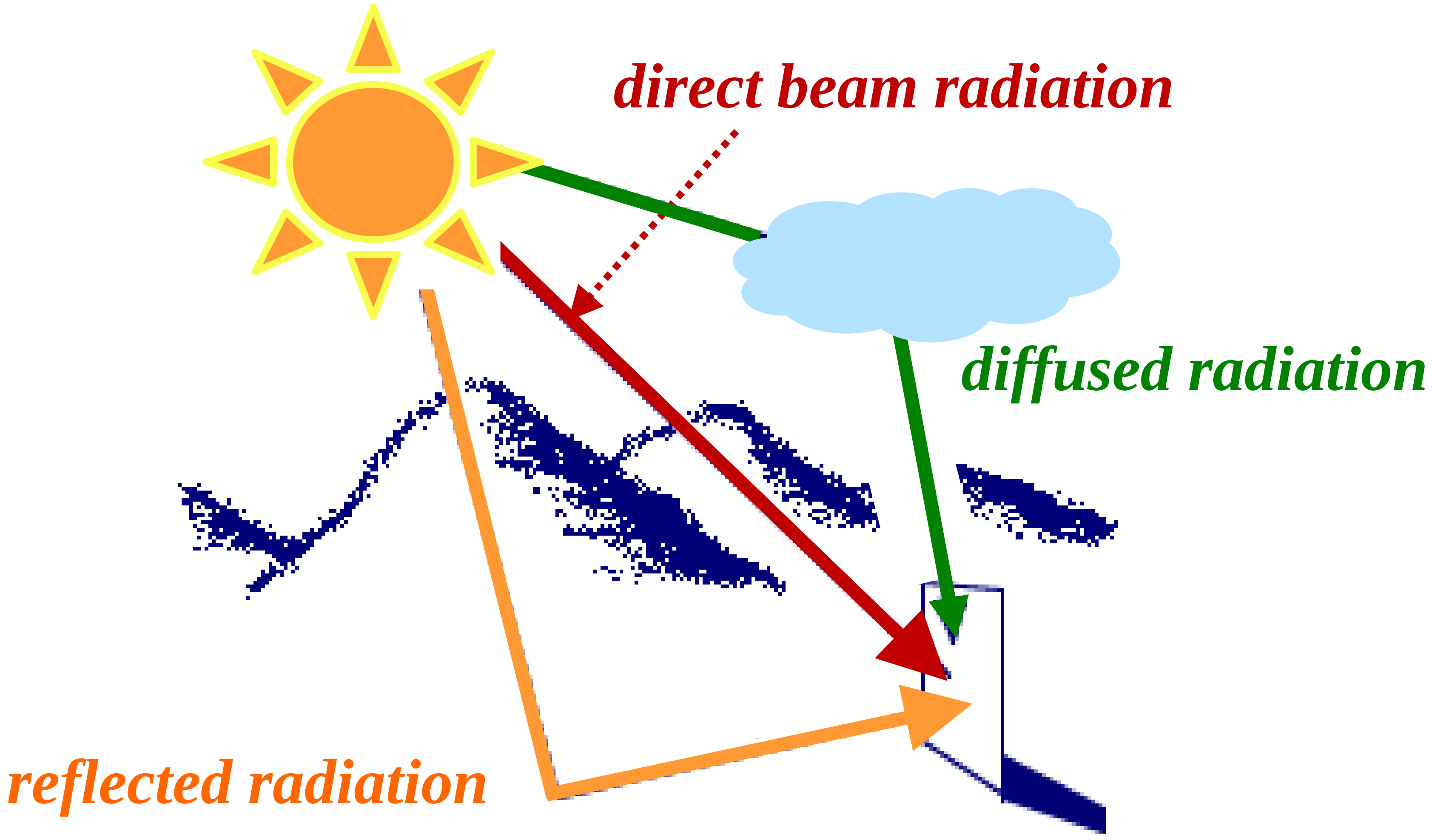
EXTRATERRESTRIAL SOLAR IRRADIATION



INSOLATION COMPONENTS ON A SOLAR PANEL



Source: http://www.inforse.org/europe/dieret/Solar/solar.html

THE IMPACTS OF THE ATMOSPHERE ON SOLAR IRRADIATION

- **The incidence angle of the solar rays and the path length of each ray through the atmosphere vary with, to a great extent, the *sun's position in the sky***
- **As each beam passes through the atmosphere, the atmospheric gases absorb a fraction of its radiation and air molecules, or particulate matter or aerosols scatter some other fraction**
- **Yet another fraction of insolation is reflected by surfaces in front of the solar panel**

INSOLATION COMPONENTS AT THE EARTH'S SURFACE

- **Insolation received at a solar panel is the combi–nation of three distinct components:**
  - ***direct beam radiation*** **that passes in a straight path through the atmosphere**
  - ***diffused radiation*** **that is scattered by the molecules and aerosols in the atmosphere**
  - ***reflected radiation*** **that the grounds/other sur–faces in front of the solar panel bounce off**

INSOLATION COMPONENTS AT THE EARTH'S SURFACE

- The *direct beam* portion of the insolation is, by far, the most significant and impactful since its rays arrive along a consistent direction
- Over a year duration, *less than half of the extraterres– trial solar irradiation that hits the top of the atmosphere* reaches the earth's surface as *direct beam radiation*
- On a clear day, however, direct beam radiation on the earth's surface can exceed 70 % of the extra– terrestrial solar irradiation

CLEAR – SKY DIRECT BEAM RADIATION

- **As weather conditions are uncertain, we need to approximate *the clear–sky direct beam radiation* on the earth's surface to provide practical means to predict the radiation on solar panels**
- **In the approximation of *the clear–sky direct beam radiation*, we explicitly account for the time–varying intensity of the sun and the distance between the earth and the sun**

CLEAR – SKY DIRECT BEAM RADIATION APPROXIMATION

- As the extraterrestrial irradiation is attenuated as a function of the distance that the beam travels through the atmosphere, an approximation of the *clear–sky direct beam radiation* $i_b(h)\Big|_d$ on the earth's surface is given by the expression

$$i_b(h)\Big|_d = a\Big|_d \, e^{-k|_d \, r(h)|_d} \quad \frac{W}{m^2}$$

CLEAR – SKY DIRECT BEAM RADIATION APPROXIMATION

- $a\big|_d$ is the approximation of the "apparent" solar irradiation on day d expressed in W/m^2

$$a\big|_d = 1{,}160 + 75\,sin\left(\frac{2\pi}{365}(d - 275)\right)$$

- The dimensionless factor *optical depth* $k\big|_d$ is

$$k\big|_d = 0.174 + 0.035\,sin\left(\frac{2\pi}{365}(d - 100)\right)$$

CLEAR – SKY DIRECT BEAM RADIATION APPROXIMATION

- The *air mass ratio* $r(h)\big|_d$ accounts for the time–varying *sun ray path length* through the atmosphere and the spherical nature of the atmosphere

$$r(h)\big|_d = \sqrt{\left[708\,sin\left(\beta(h)\big|_d\right)\right]^2 + 1{,}417} - 708\,sin\left(\beta(h)\big|_d\right)$$

EXAMPLE: DIRECT BEAM RADIATION IN CHICAGO

- **We approximate the total direct beam radiation at the solar noon on a clear May 21 in Chicago with latitude $\ell = 0.731$ *radians***
- **For May 21, $d = 141$, the "apparent" solar irradiation is**

$$a\Big|_{141} = 1{,}160 + 75\, sin\left(\frac{2\pi}{365}\left(141 - 275\right)\right) = 1{,}104\ \frac{W}{m^2}$$

EXAMPLE: DIRECT BEAM RADIATION IN CHICAGO

- The *solar declination* angle is given by

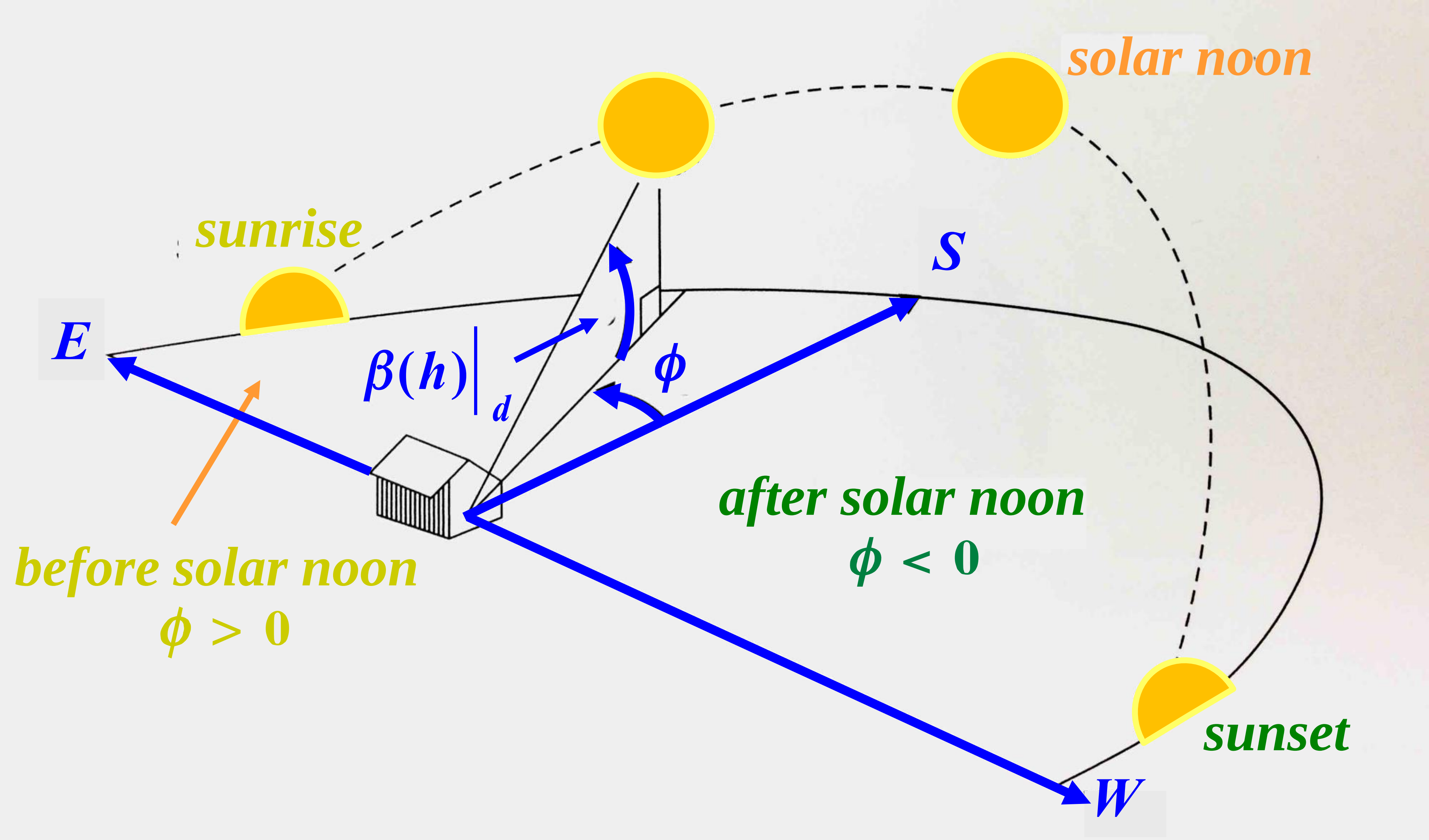
$$\delta \,|_{141} = 0.41 \, sin\left(\frac{2\pi}{365} (141 - 81) \right) = 0.351 \, radians$$

- The *solar altitude angle* at solar noon is given by

$$\beta(0)\Big|_{141} = \frac{\pi}{2} - 0.731 + 0.351 = 1.19 \, radians$$

- Now, the *air mass ratio* at solar noon on day 141 is

THE SOLAR AZIMUTH ANGLE



EXAMPLE: DIRECT BEAM RADIATION IN CHICAGO

$$r(0)\Big|_{141} = \sqrt{(708 \bullet 0.933)^2 + 1417} - (708)(0.933) = 1.064$$

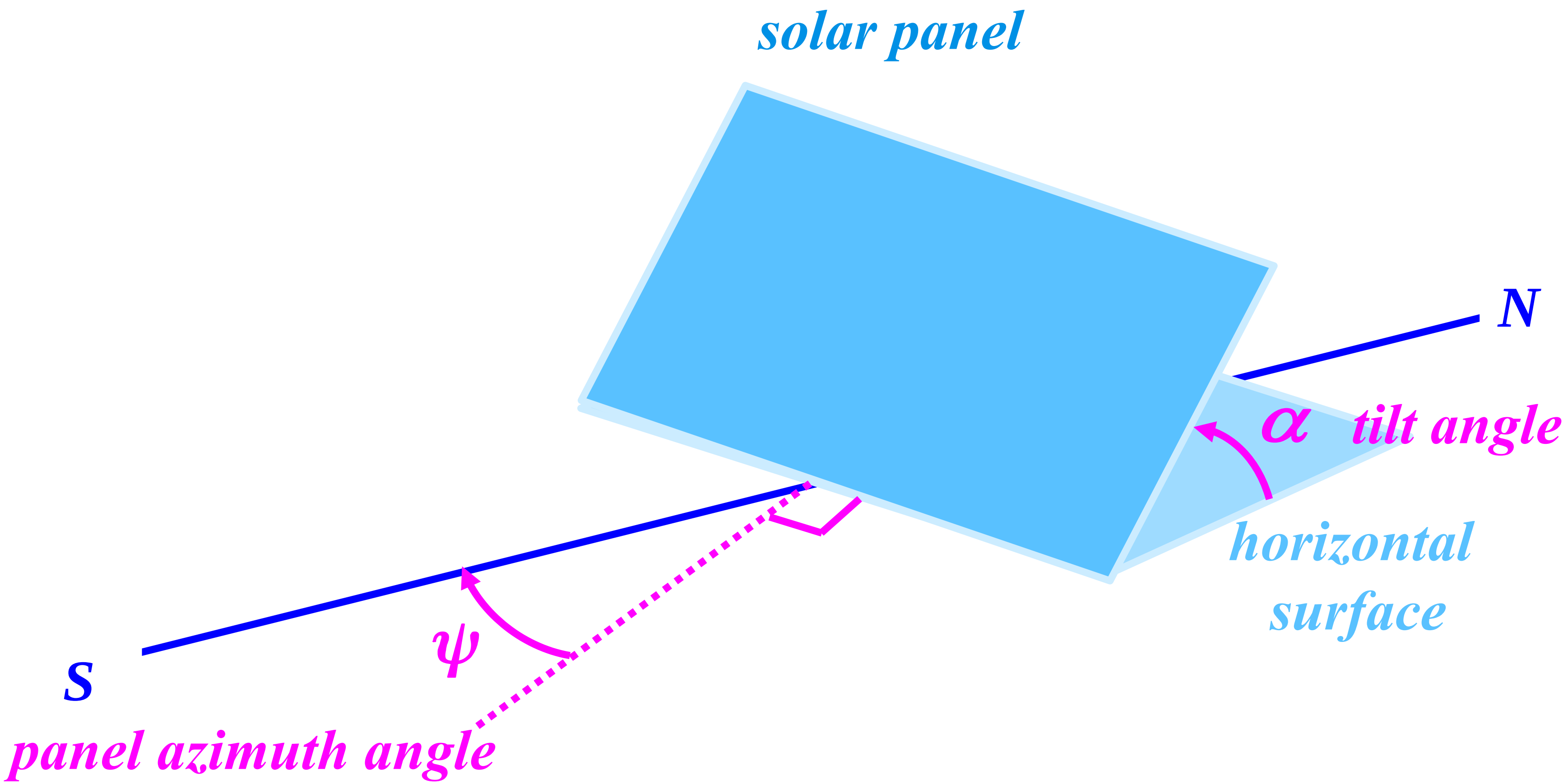
- The optical depth is given by

$$k\Big|_{141} = 0.174 + 0.035\, sin\left(\frac{2\pi}{365}(141 - 100)\right) = 0.197$$

- Therefore, the clear-sky direct beam radiation is

$$i_b(0)\Big|_{141} = 1{,}104\, e^{(-0.197)(1.064)} = 895\, \frac{W}{m^2}$$

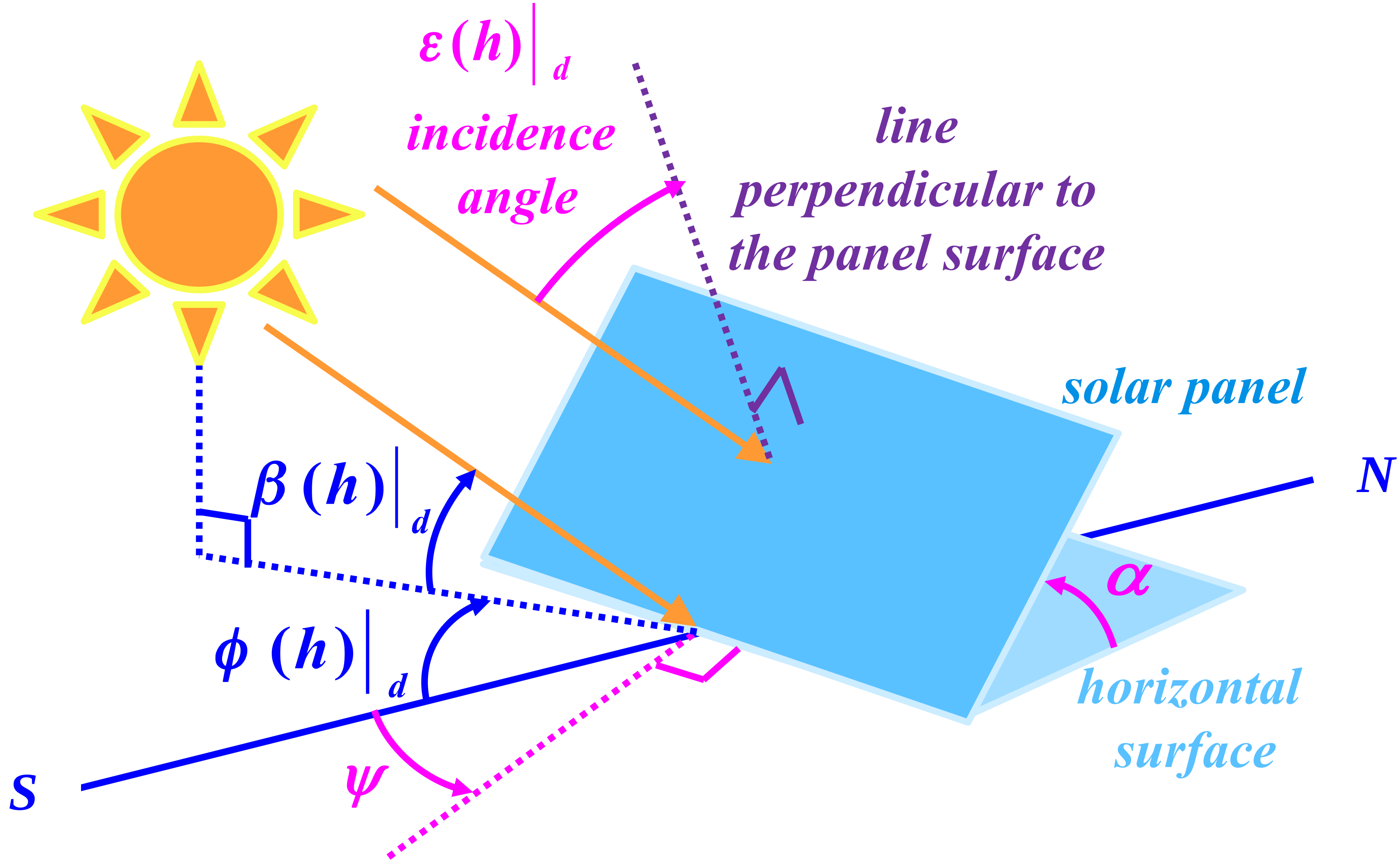
SOLAR PANEL POSITION/ORIENTATION



SOLAR PANEL POSITION

- **Solar panel position is expressed in terms of the**
  - ***tilt angle*** $\boldsymbol{\alpha}$ **, defined as the angle between the panel and a horizontal surface**
  - ***panel azimuth angle*** $\boldsymbol{\psi}$ **, defined as the angular displacement, through which the panel needs to rotate in order to face due South**
- **The convention is:** $\boldsymbol{\psi}$ **is *positive* (*negative*) *for* the panel facing away from *South* to the *East* (*West*)**

RADIATION ON THE SOLAR PANEL



DIRECT BEAM RADIATION ON THE SOLAR PANEL

- The approximation of *the clear–sky direct beam radiation* becomes the basis to estimate each component of the solar insolation that strikes a solar panel on the earth's surface

- Given the *panel tilt angle* α and the *azimuth angle* ψ , we determine the *incidence angle* $\varepsilon(h)\big|_{d}$ between a

DIRECT BEAM RADIATION ON THE SOLAR PANEL

line drawn perpendicular to the solar panel

surface and the sun's rays in terms of

$$\cos\left(\varepsilon(h)\big|_d\right) = \cos\left(\beta(h)\big|_d\right)\cos\left(\phi\,(h)\big|_d - \psi\right)\sin\left(\alpha\right) +$$

$$\sin\left(\beta(h)\big|_d\right)\cos\left(\alpha\right)$$

and thus, the direct beam radiation received at

the solar panel is its projection on the panel

DIRECT BEAM RADIATION ON THE SOLAR PANEL

- The projection of the clear–sky direct beam radiation $i_b(h)\big|_d$ to direct beam radiation, under a clear sky, that strikes the panel surface, denoted by $i_{bp}(h)\big|_d$, is given by

$$i_{bp}(h)\Big|_d = i_b(h)\Big|_d \cos\left(\varepsilon(h)\big|_d\right) \quad \frac{W}{m^2}$$

EXAMPLE: DIRECT BEAM RADIATION ON THE PANEL

- In the example, at solar noon on *May* 21 in *Chicago* with $\ell = 0.731$ *radians*, the altitude angle of the sun is 1.221 *radians* and the clear–sky direct beam irradiation is 895 W/m^2
- We consider a solar panel with 0.907–*radian tilt angle* and 0.348–*radian azimuth angle*

EXAMPLE: DIRECT BEAM RADIATION ON THE PANEL

- The incidence angle satisfies the relationship

$$cos\left(\varepsilon(0)\big|_{141}\right) = cos\left(1.221\right)cos\left(0-0.348\right)sin\left(0.907\right)$$

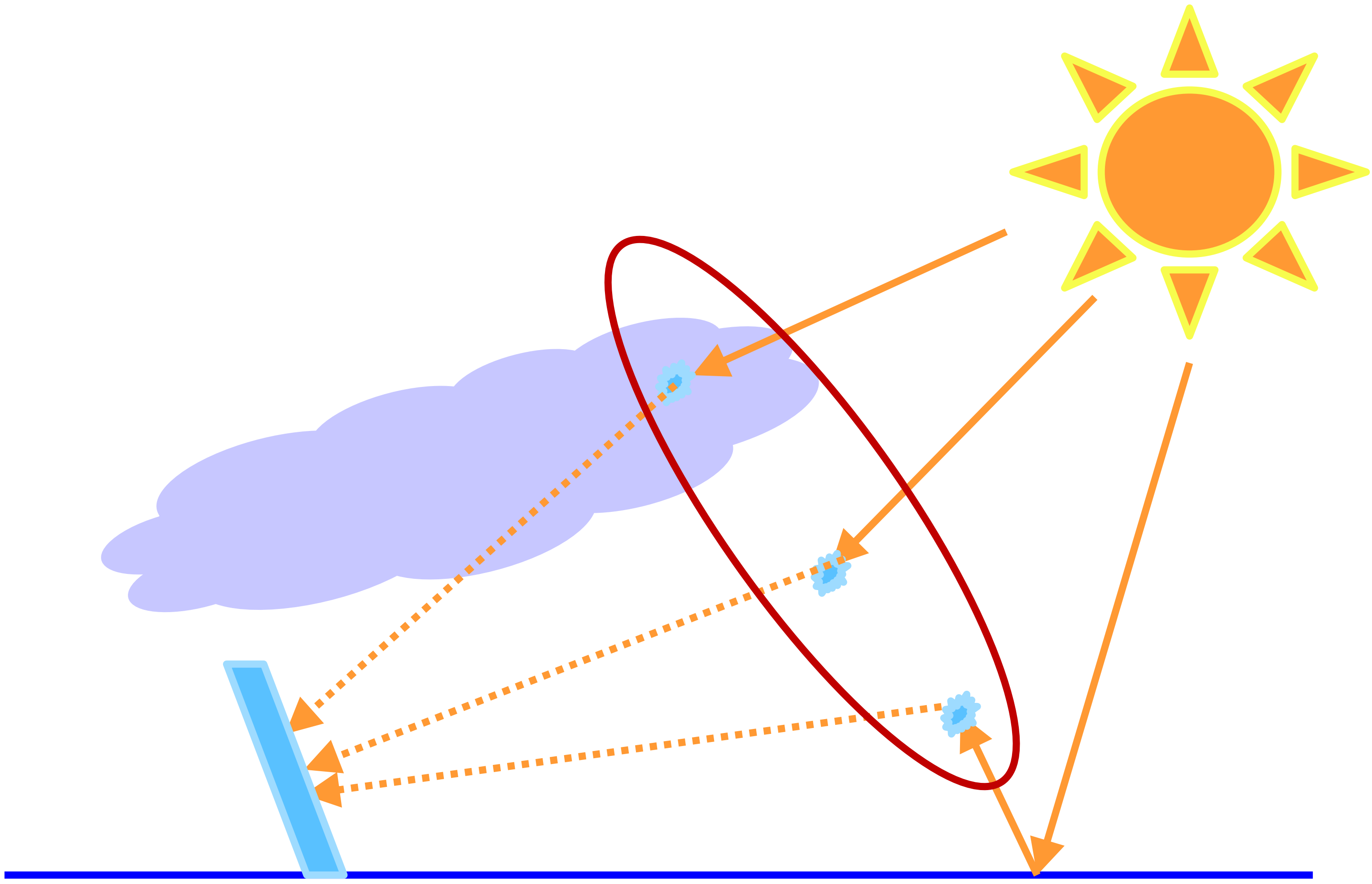
$$+\,sin\left(1.221\right)cos\left(0.907\right)$$

$$= 0.833$$

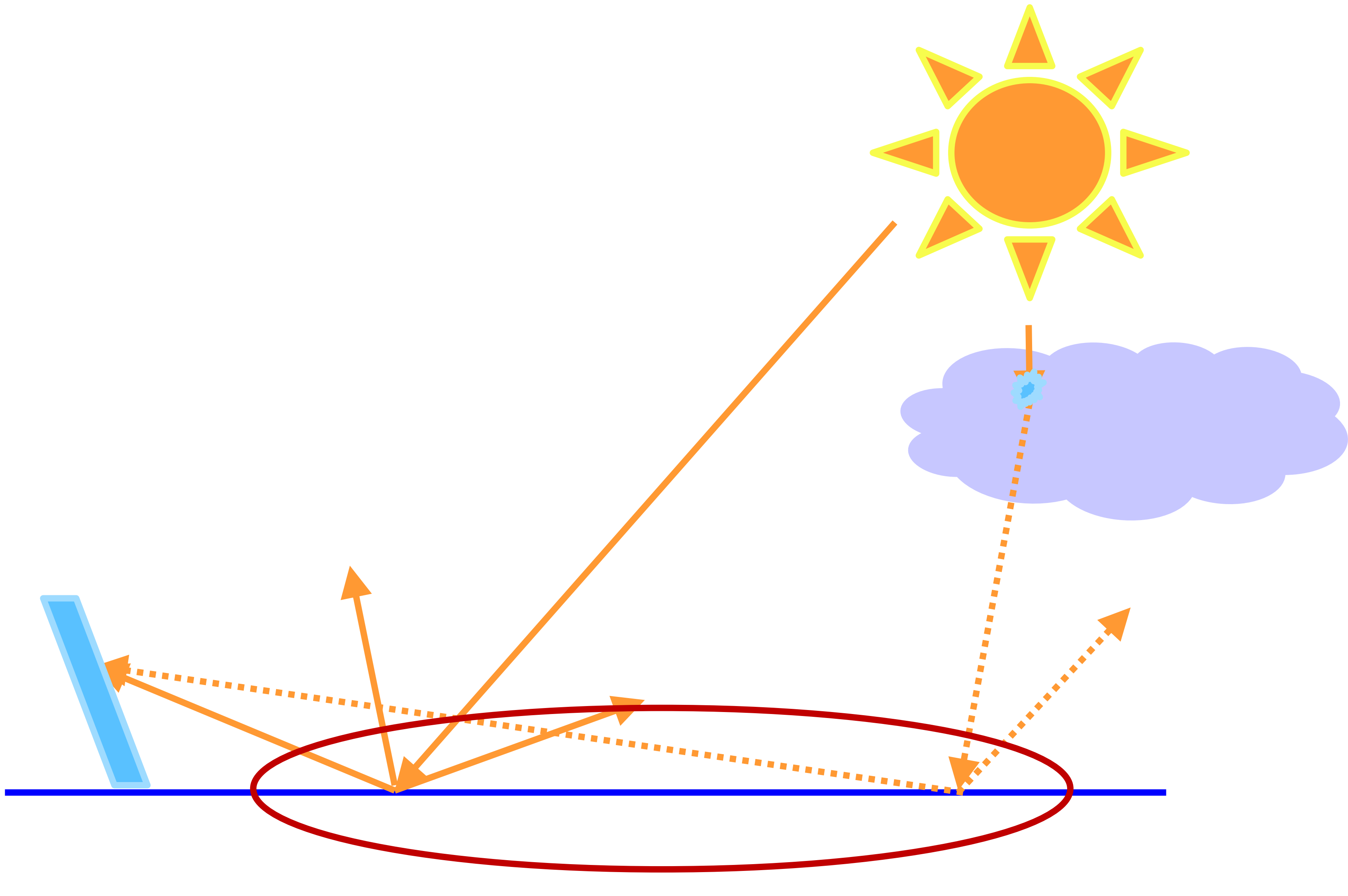
- Thus, the beam radiation on the panel is

$$i_{b\,p}(0)\Big|_{141} = \left(895\right)\left(0.833\right) = 745 \quad \frac{W}{m^2}$$

DIFFUSED RADIATION



RELECTED RADIATION



DIFFUSED AND REFLECTED RADIATION ON THE SOLAR PANEL

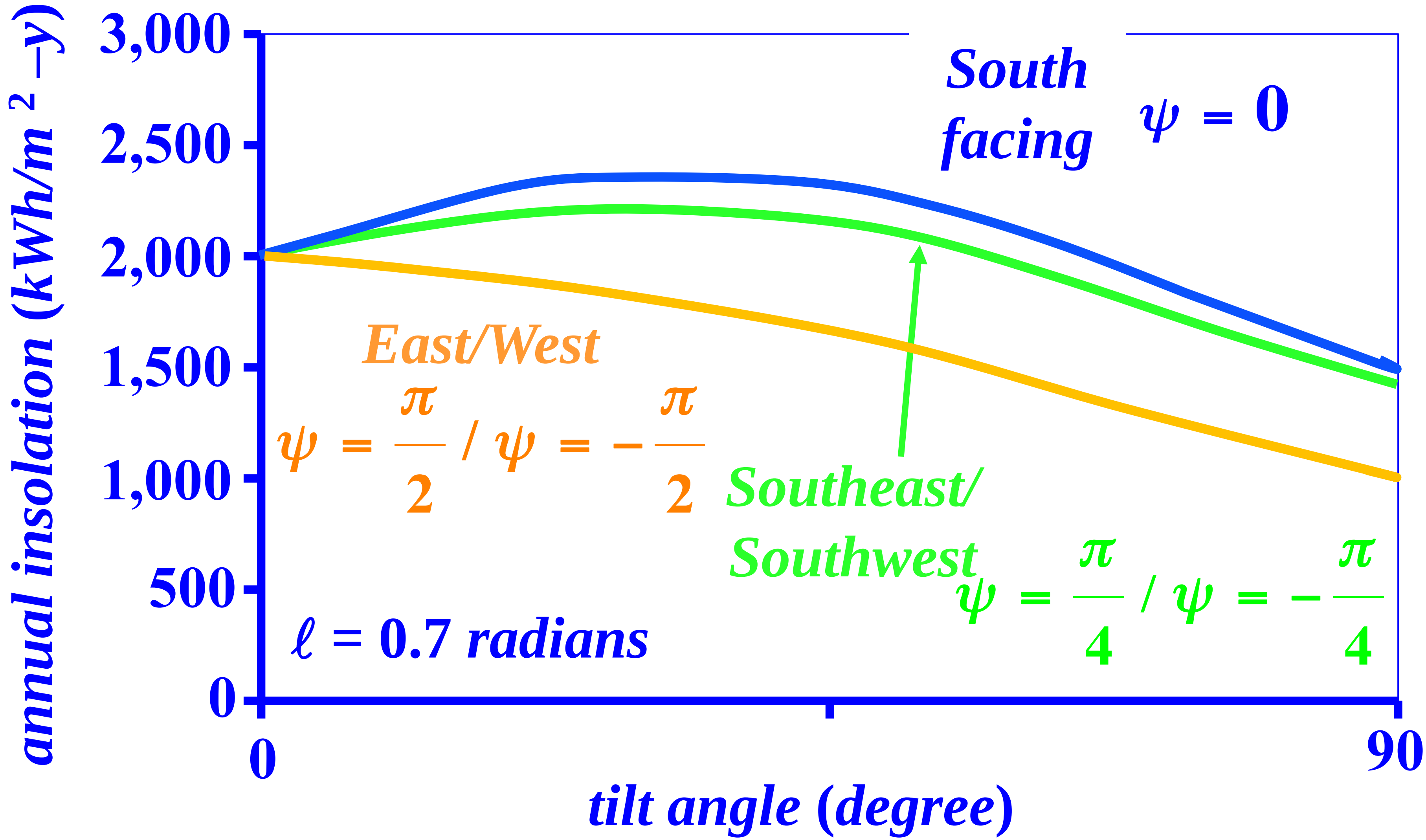
- The indirect radiation components are subject to
  - the uncertain impacts of particles and molecules in the atmosphere
  - the irregularities of the terrain of the earth surface for the reflected radiation

  and the approximation of the diffused and reflec– ted radiation components is rather complicated
- The approximation of the diffused and reflected radiation is beyond the scope of the course

APPLICATION OF CLEAR – SKY RADIATION APPROXIMATION

- Various solar technologies use these 2 insolation components in specific ways and so approximation methods are used to assess the performance of the solar panels
- The clear–sky radiation approximation may be tabulated into *hourly*, *daily*, *monthly* and *annual* values to provide the basis for the determination of the position/orientation of each panel

ANNUAL CLEAR – SKY INSOLATION VARIATION BY TILT ANGLE



APPLICATION OF CLEAR – SKY RADIATION APPROXIMATION

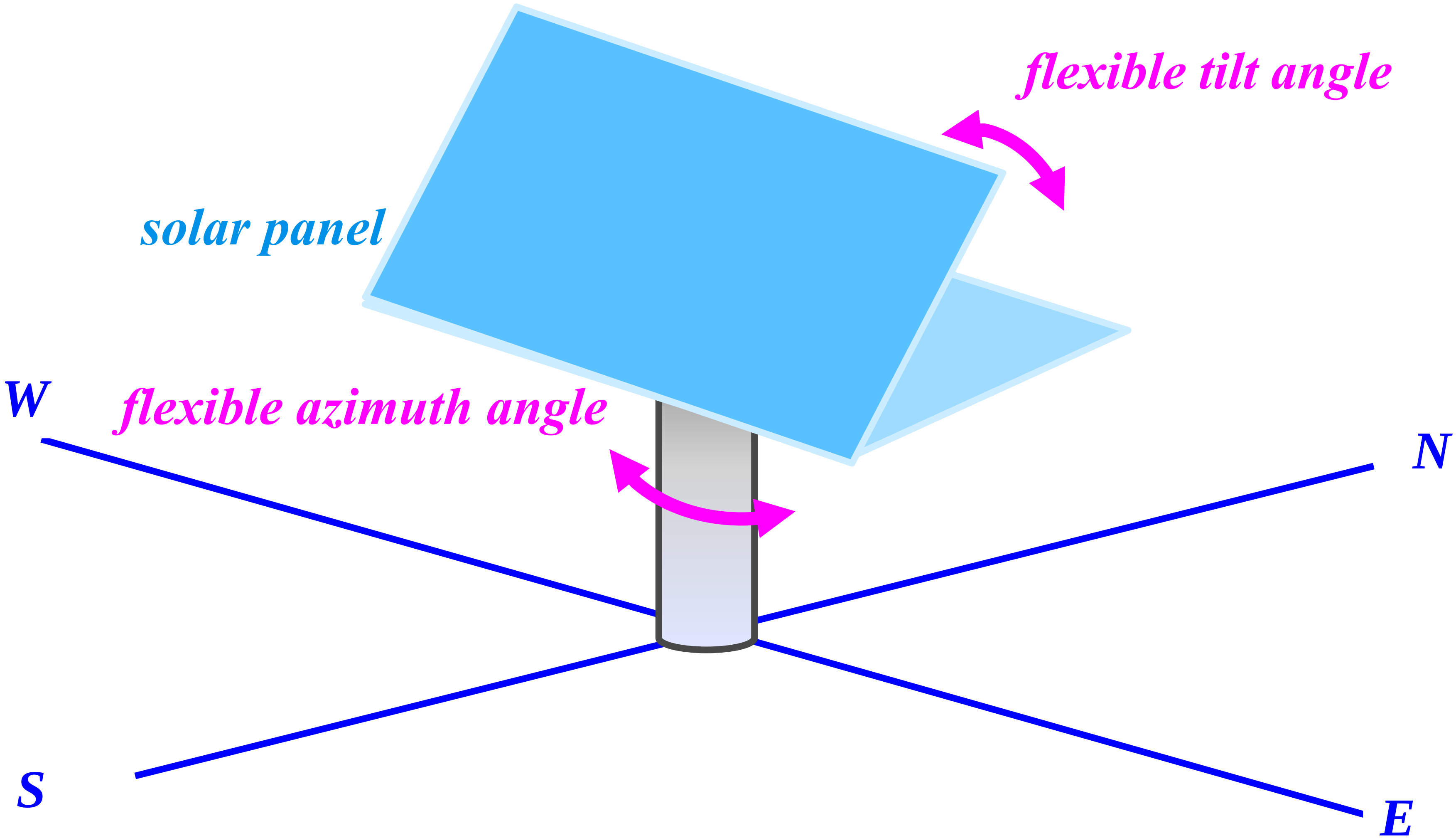
- We note that the solar panel position impacts significantly the *insolation* the solar panels receive
- As such, in many implementations, the solar panels are equipped with *tracking systems* to allow the panels to track the *movement of the sun across the sky* during the sunrise-to-sunset period and to continually change panel positions to harness more fully the insolation the panels receive

TRACKING SYSTEMS

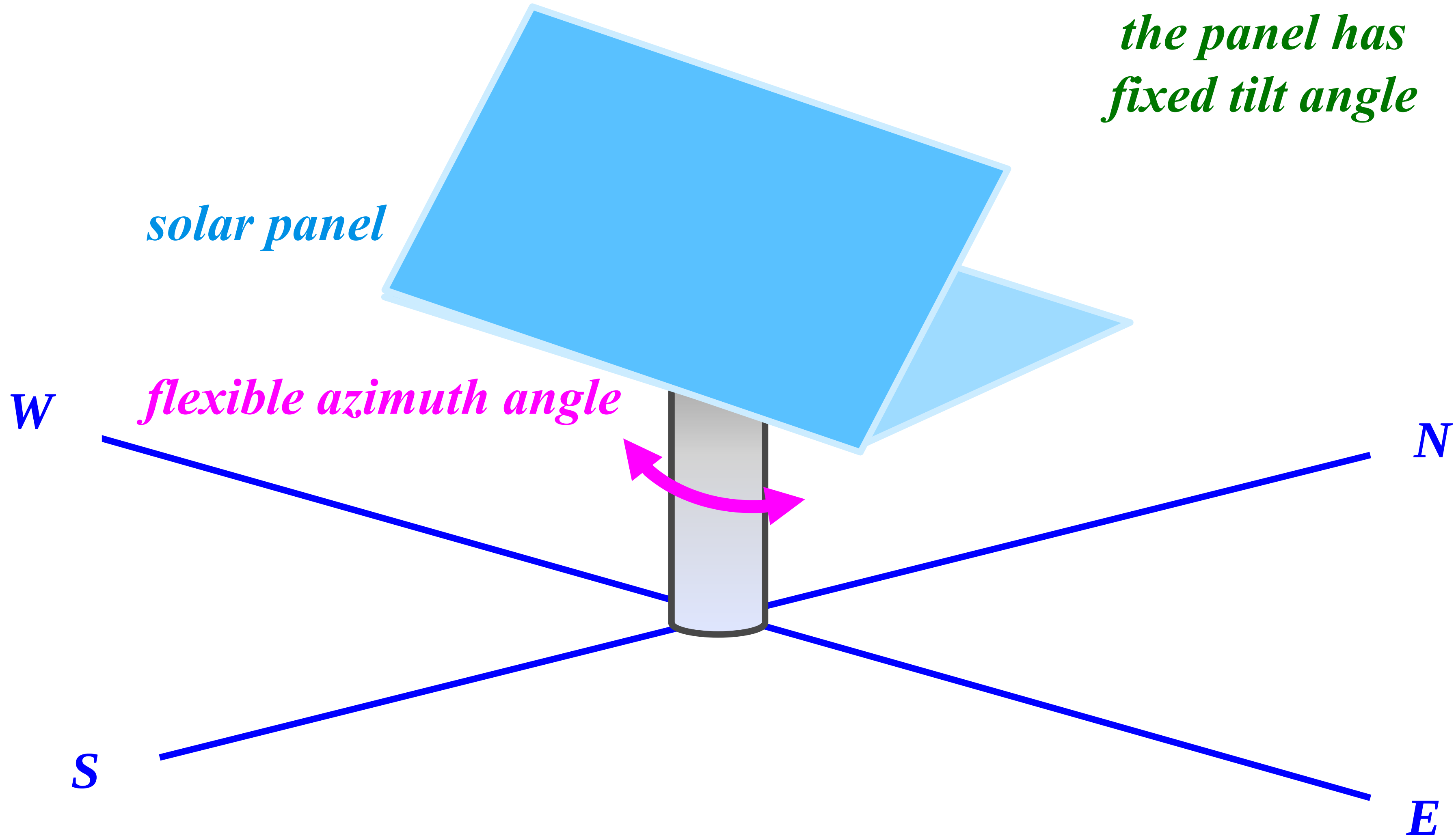
The 2 *classes* of tracking systems are:

- ***two–axis trackers*, which can adjust the two panel angles – tilt and azimuth – to orient the panels to lie perpendicularly to the sun rays**
- ***single–axis trackers*, which can change *only one* of the solar panel angles – either tilt or azimuth – but not both**

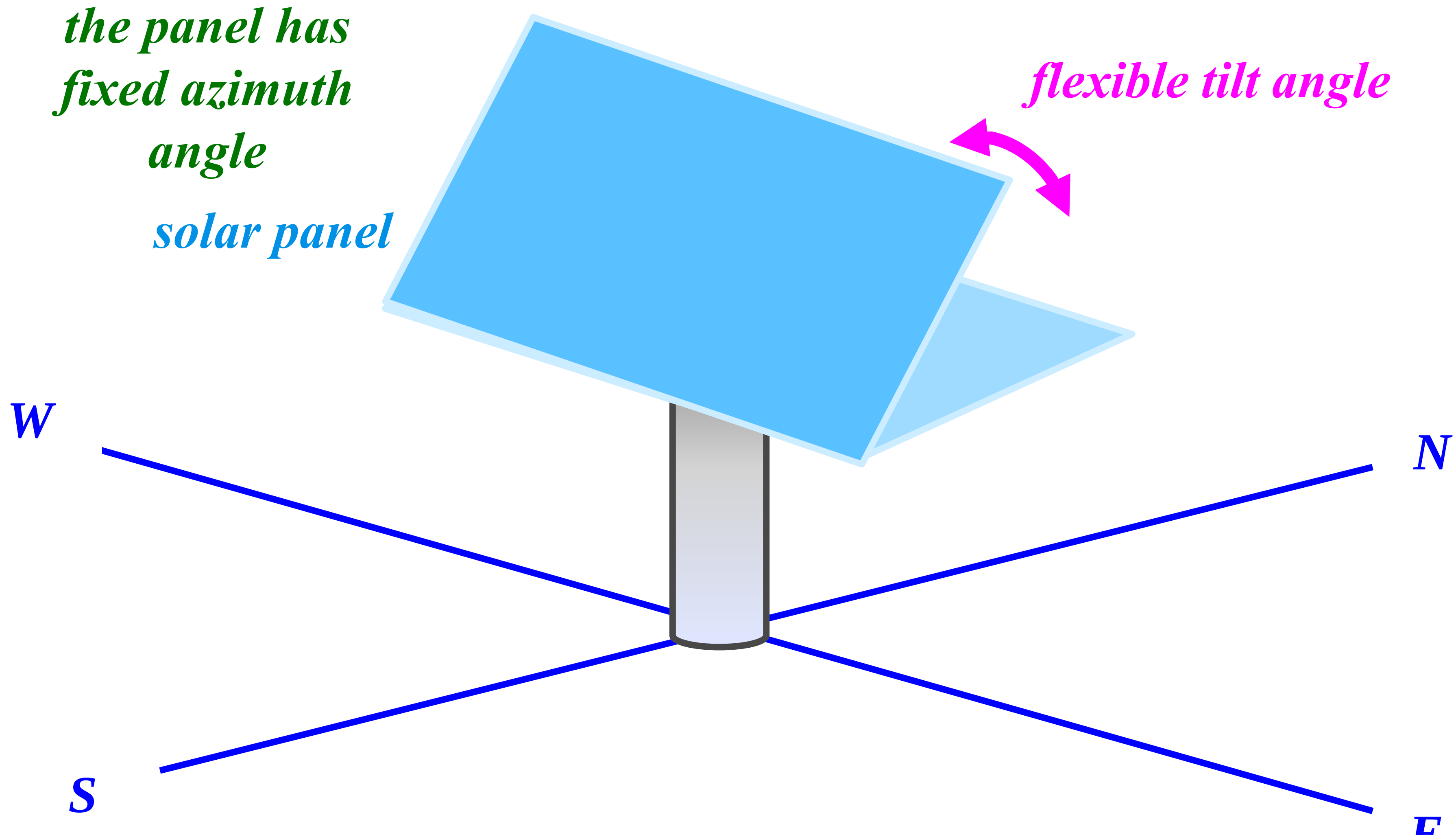
TWO – AXIS TRACKERS



SINGLE – AXIS TRACKERS



SINGLE – AXIS TRACKERS

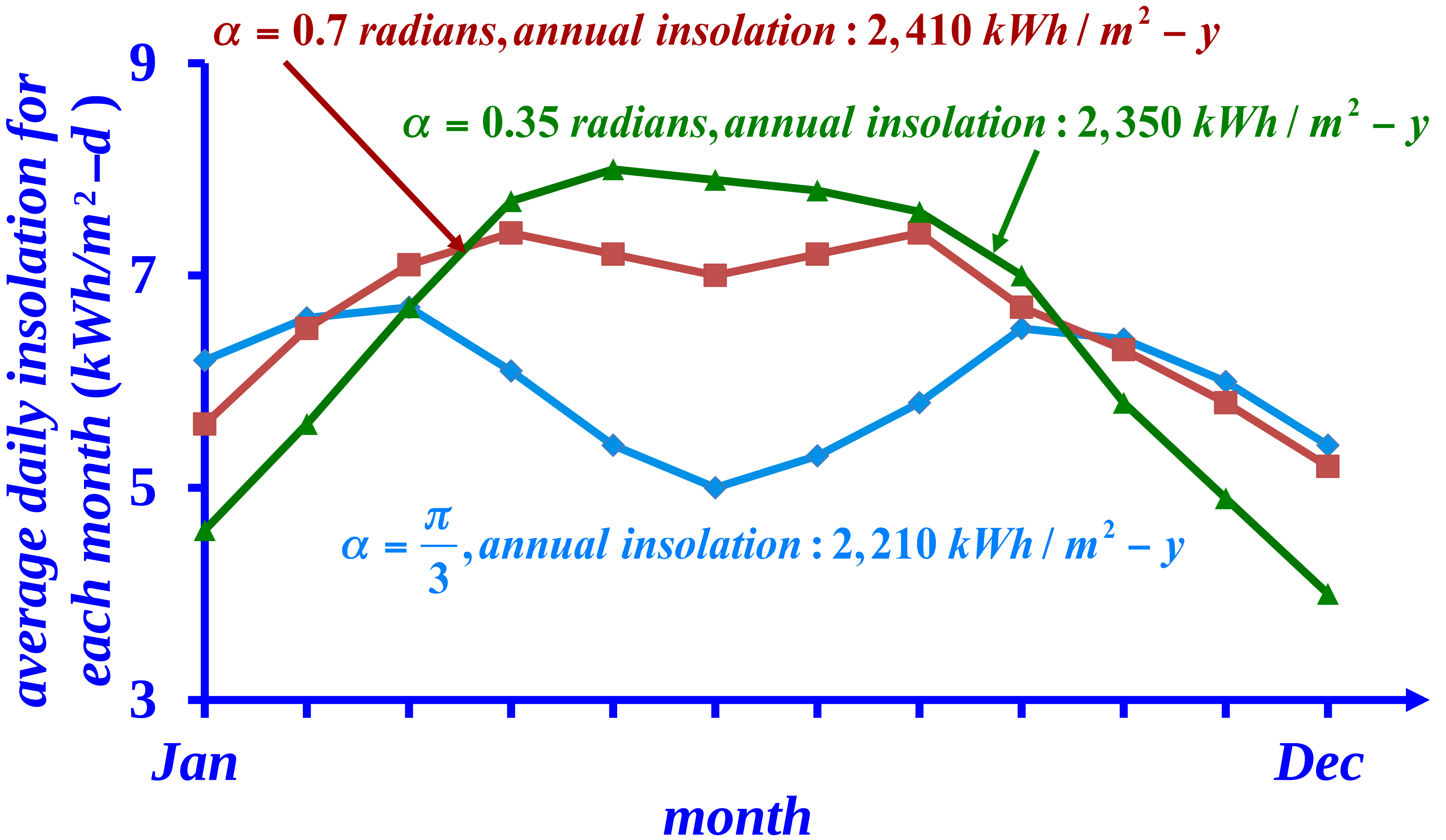


SINGLE – AXIS TRACKERS

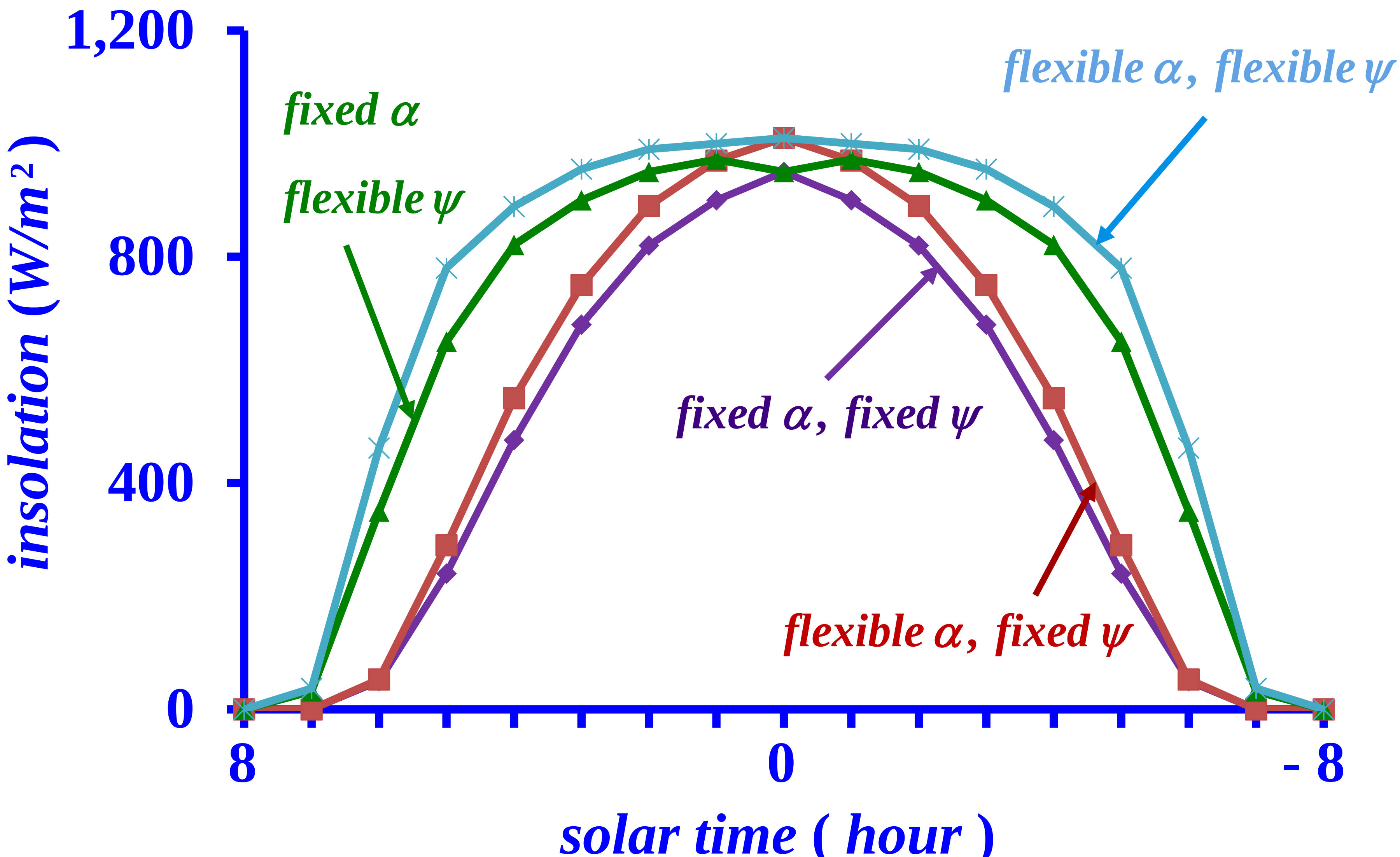
TRACKER

http://www.solarpanel-manufacturer.com/solar-tracking-system.html

CLEAR – SKY INSOLATION ON SOUTH–FACING PANELS



CLEAR – SKY INSOLATION WITH VARYING PANEL POSITIONING



INSOLATION UNDER NORMAL SKY

- **However, since the weather conditions are highly uncertain, the assumption that the sky is clear need not always be satisfied and the insolation is *uncertain* and may, in addition, be *intermittent***
- **As such, we need specific devices to measure the actual insolation to perform the analysis**

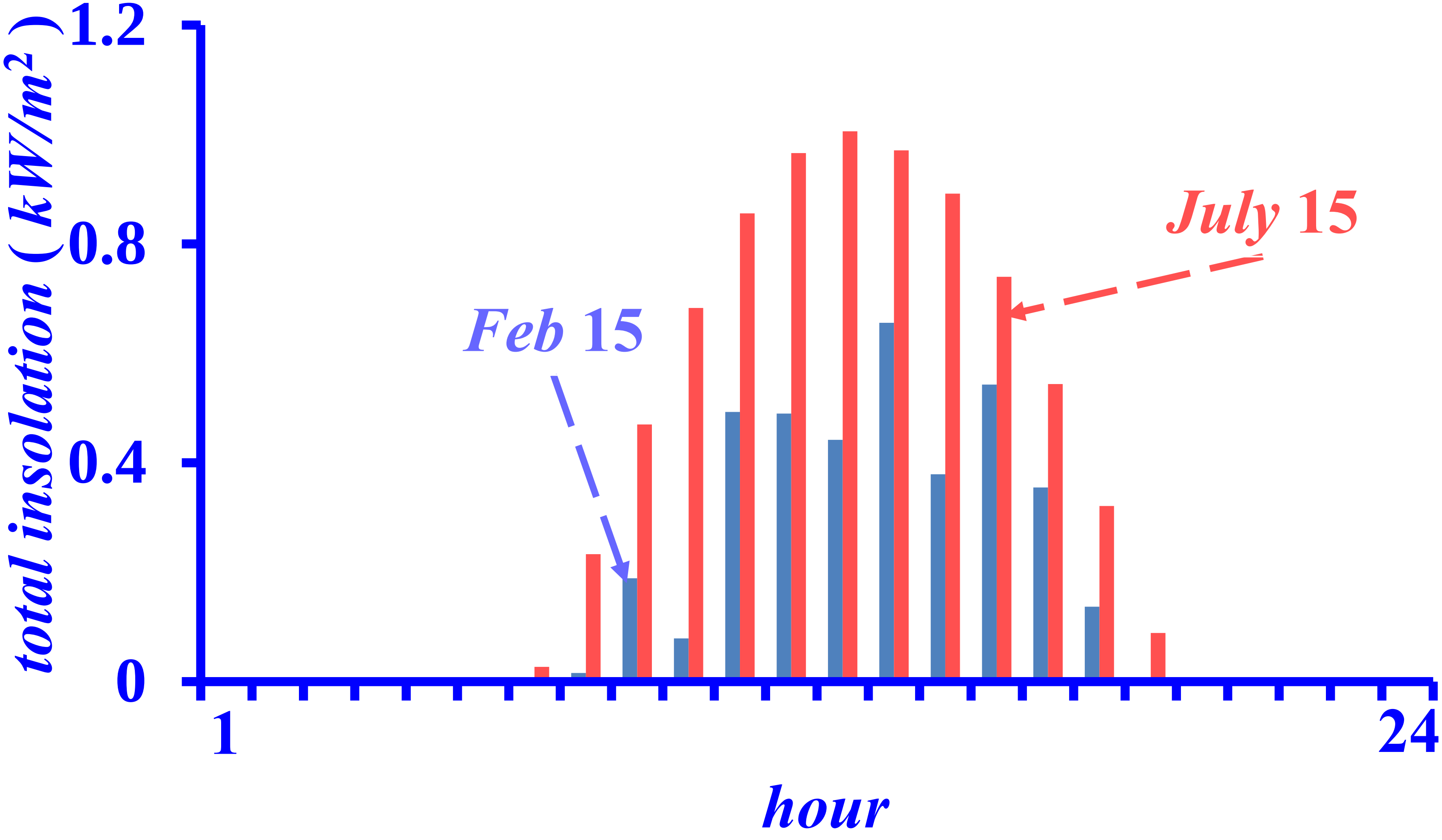
INSOLATION MEASUREMENT DEVICES

There are two major types of devices used to measure the insolation on the earth's surface

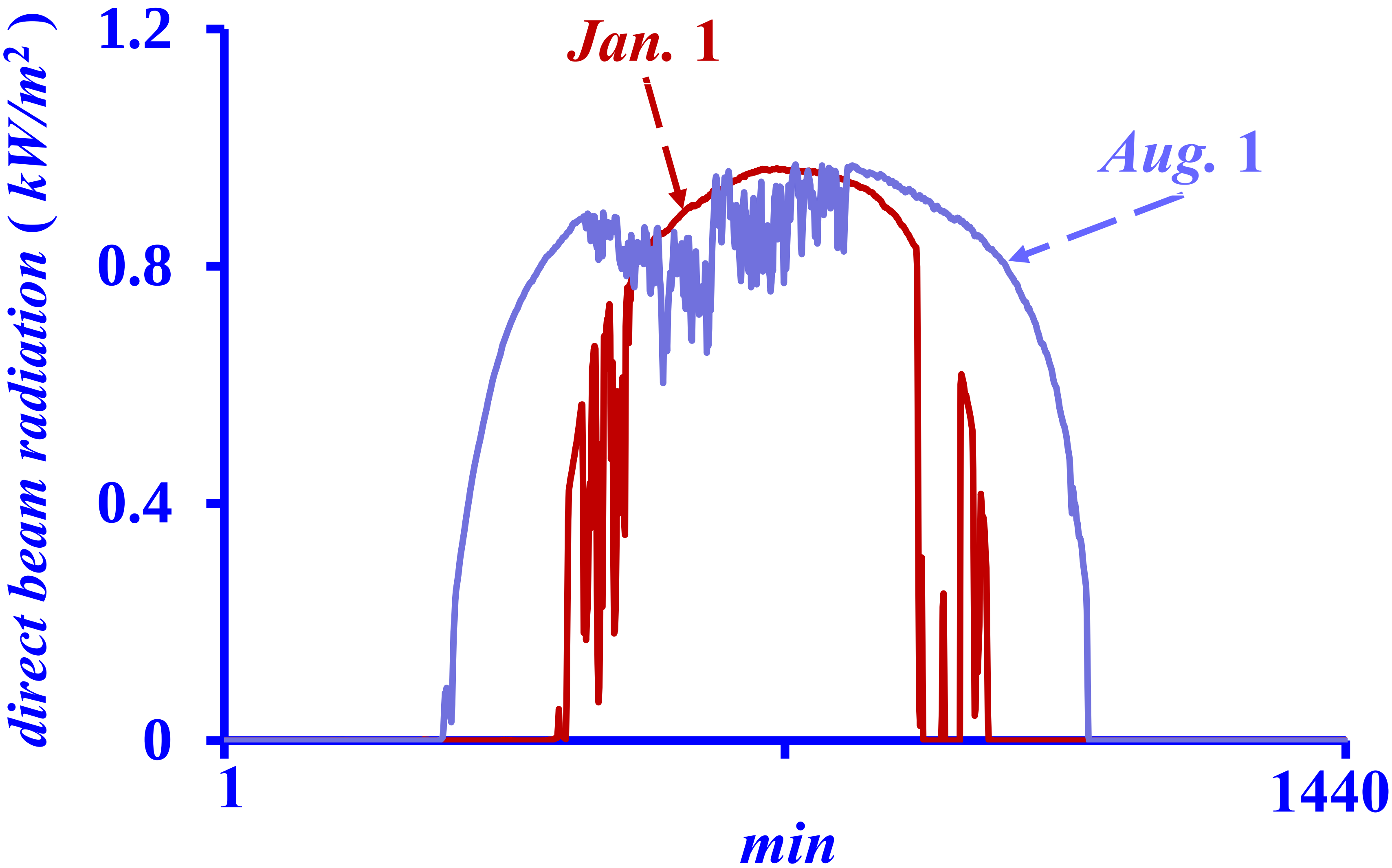
pyranometer **which measures the total insolation of all the three components**

pyrheliometer **which measures only the direct beam radiation**

PYRANOMETER HOURLY INSOLATION MEASUREMENTS IN ABILENE, TX



1 – *m* DIRECT BEAM PYRHELIOMETER MEASUREMENTS: LAS VEGAS



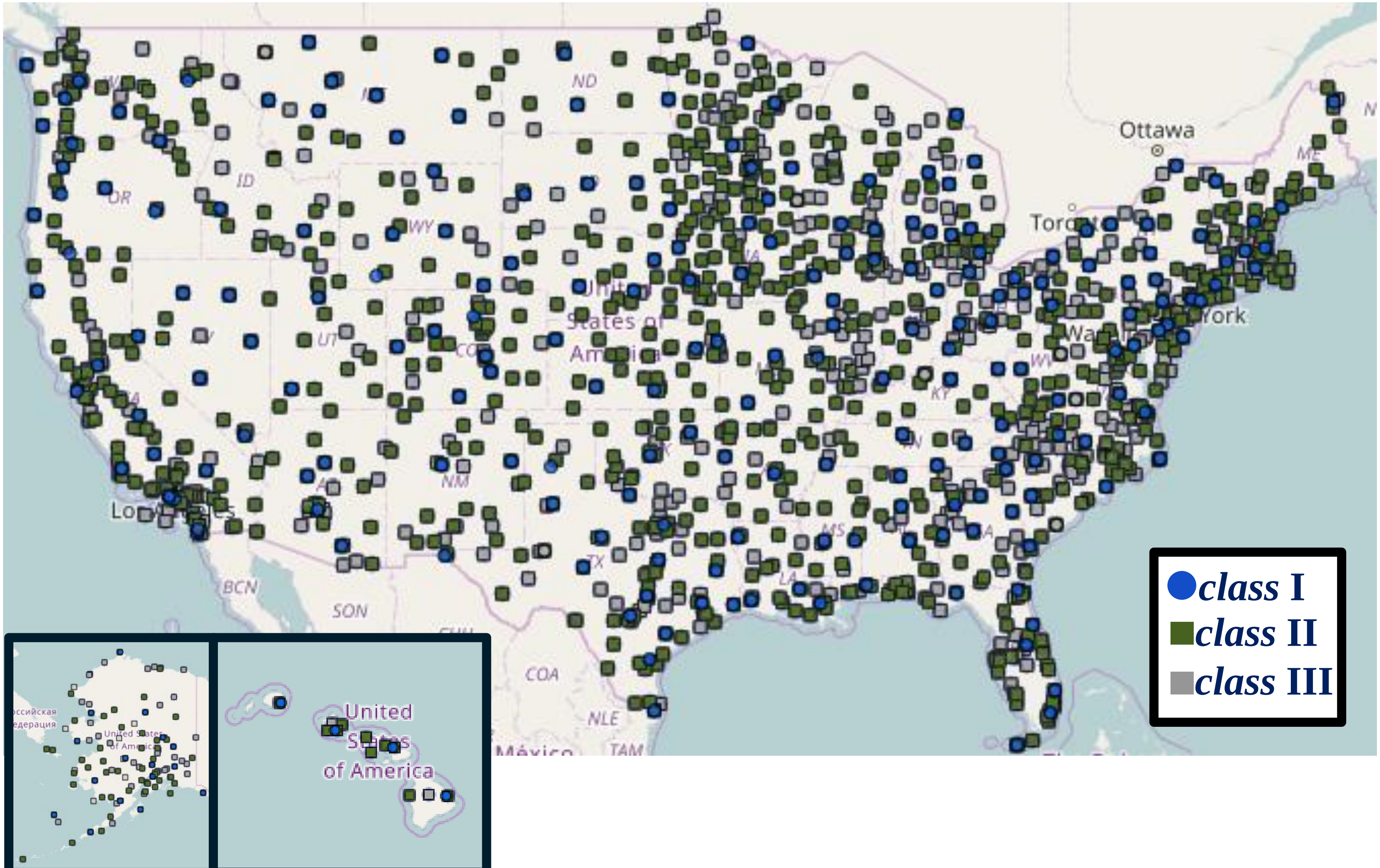
SOLAR IRRADIATION DATA BASES

- *National Oceanic and Atmospheric Administration* (*NOAA*) **constructed the first *US* solar data base in the 1970s, primarily for weather forecasting**

  http://www.swpc.noaa.gov/Data/

- **In 1995,** ***National Renewable Energy Laboratory*** **(*NREL*) established the** ***National Solar Radiation Data Base*** **(*NSRDB*) with the** ***typical meteorological year*** **(*TMY*) data of** ***hourly*** **solar measurements from over 1,000 stations;** ***http://rredc.nrel.gov/solar***

NSRDB STATIONS



Source: https://maps.nrel.gov/nsrdb-viewer/

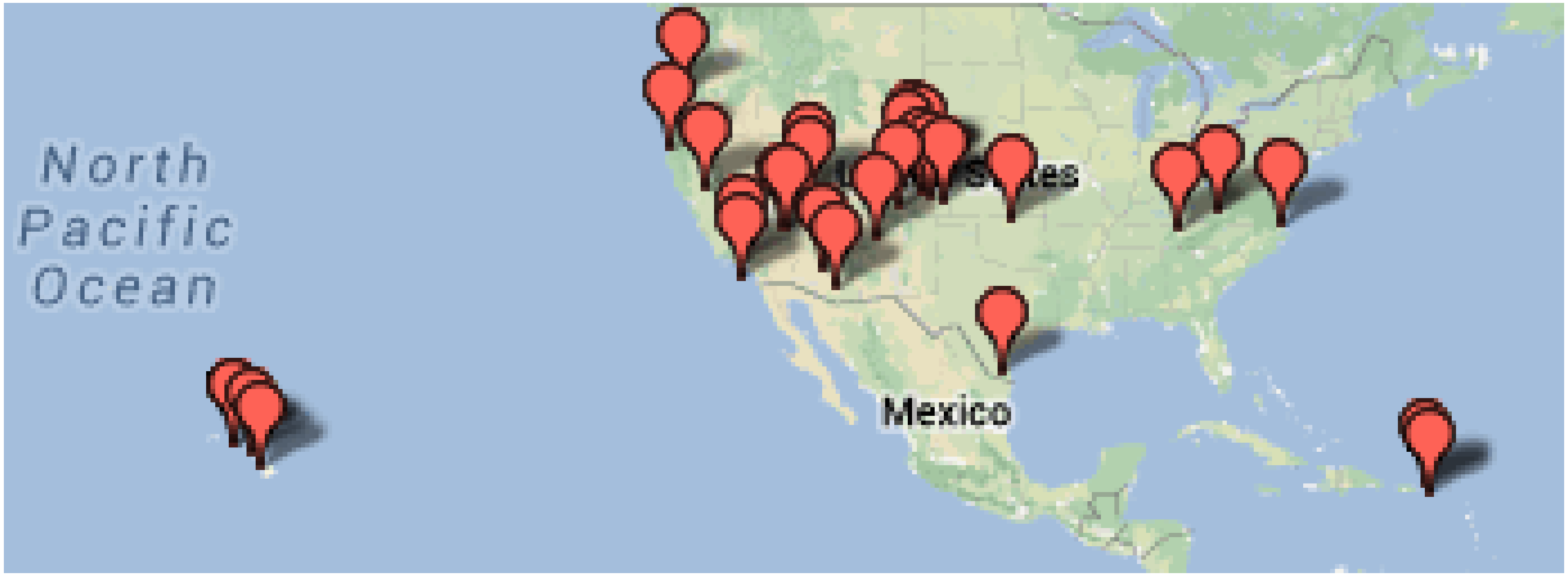
NSRDB STATIONS

- The 239 *Class* I stations have a complete hourly data set
- The 1462 *Class* II stations have a complete hourly data set, but assembled from lower–quality input data
- The 1454 *Class* III stations contain gaps in the records but have data for at least 3–*year* period
- The 40 stations in the updated *NSRDB* include *measured solar data* supplied by non–*NREL* groups

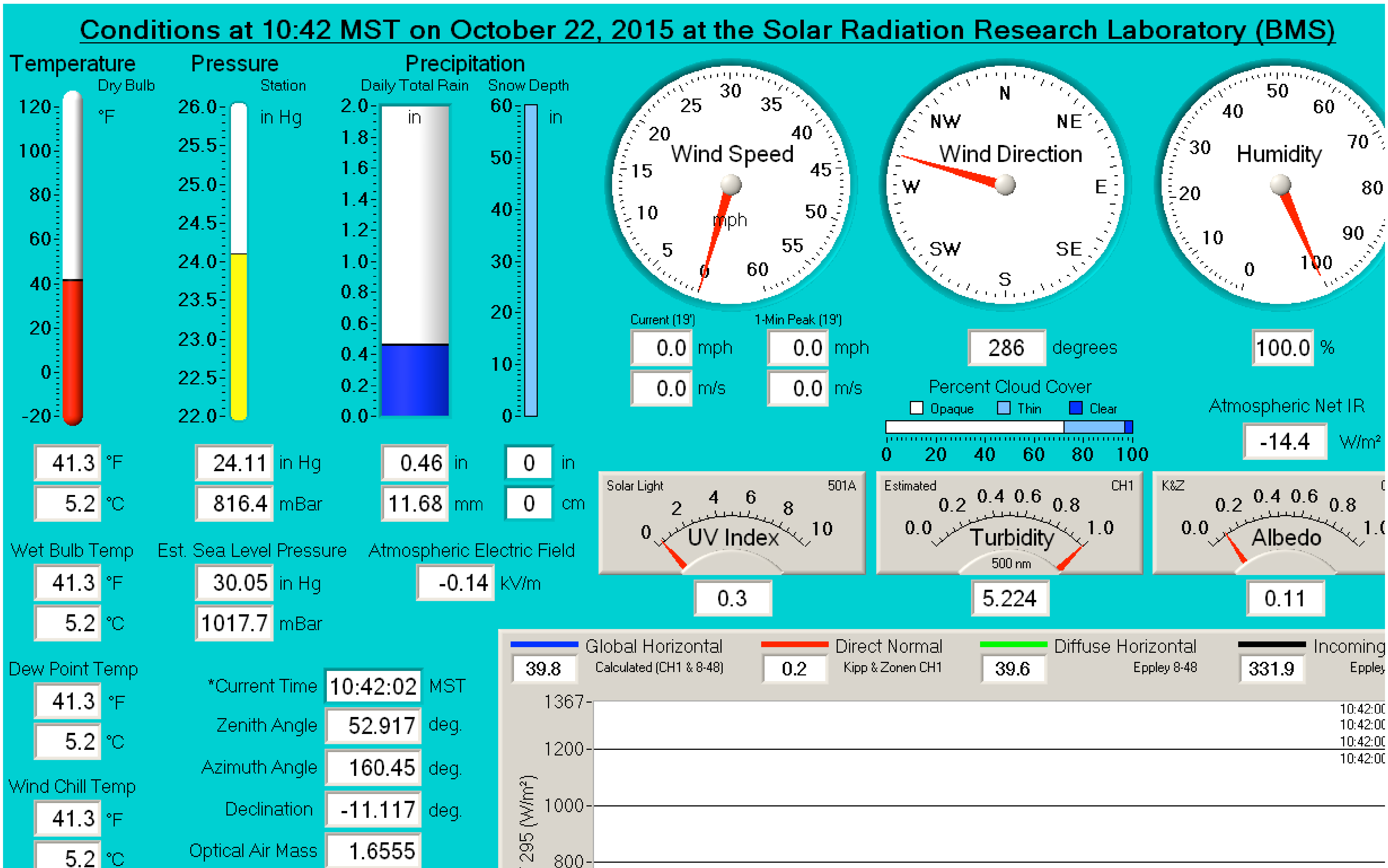
Measurement and Instrumentation Data Center **(*MIDC*)**

provides *1–minute* solar and wind data base for the

_US_ sites shown below at *http://www.nrel.gov/midc/*



LIVE GRAPHICAL DISPLAY OF SOLAR MEASUREMENTS

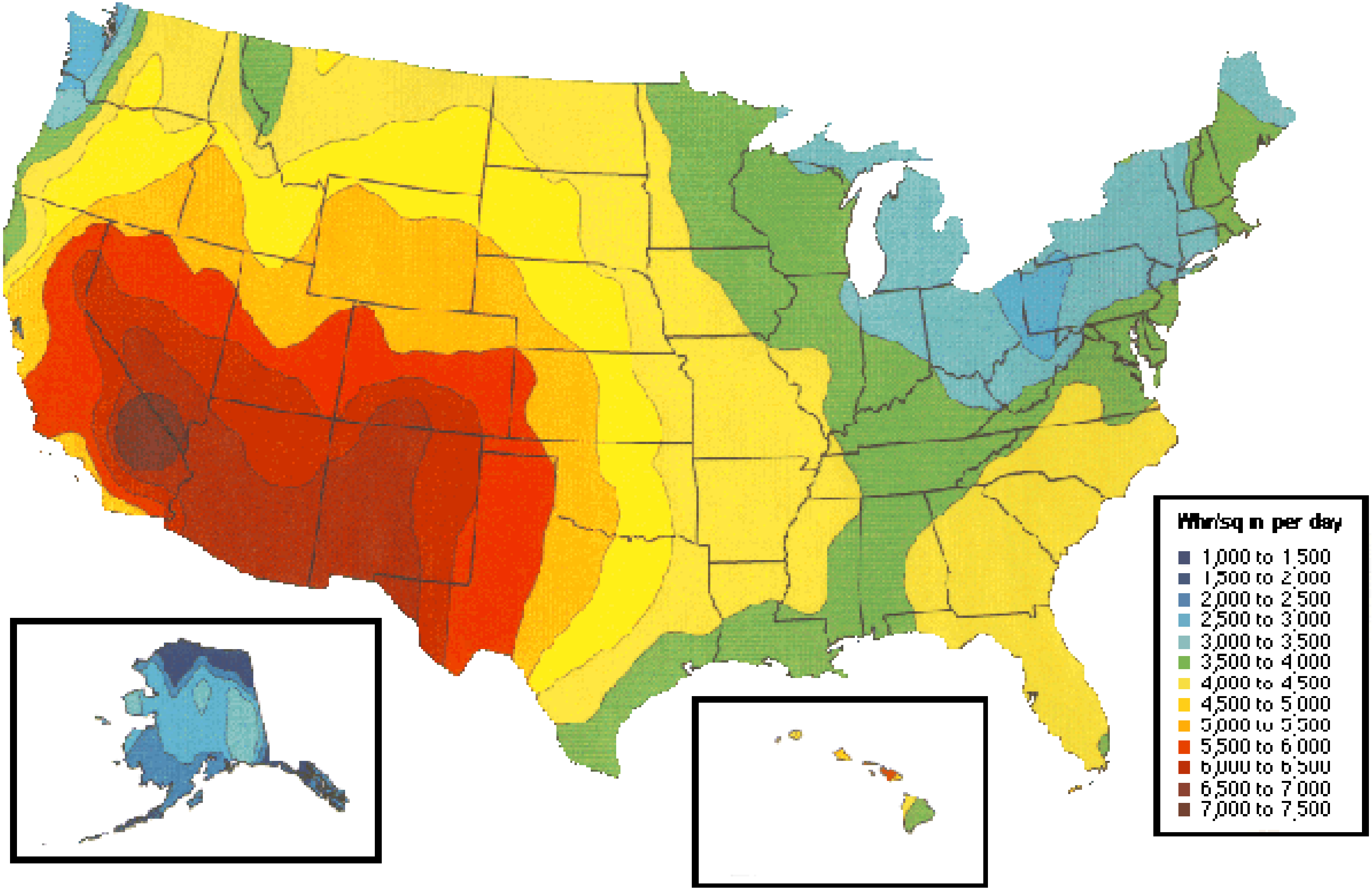


Source: http://www.nrel.gov/midc/srrl_bms/display/

SOLAR IRRADIATION DATA BASES

- *National Climatic Data Center* (*NCDC*) **maintains the** **world's largest climate data archive and provides climatological services and data, ranging from centuries–old data to data less than an hour old**
- **The Center's mission is to collect, store and provide access to these data to the public, business, industry, government, and researchers at** ***http://www.ncdc.noaa.gov/***

US SOLAR INSOLATION MAP



Source: http://www.aesystems.com/solarmap.gif/

WORLD INSOLATION MAP