ECE 333 – Green Electric Energy

13. Solar Insolation Components and Measurement

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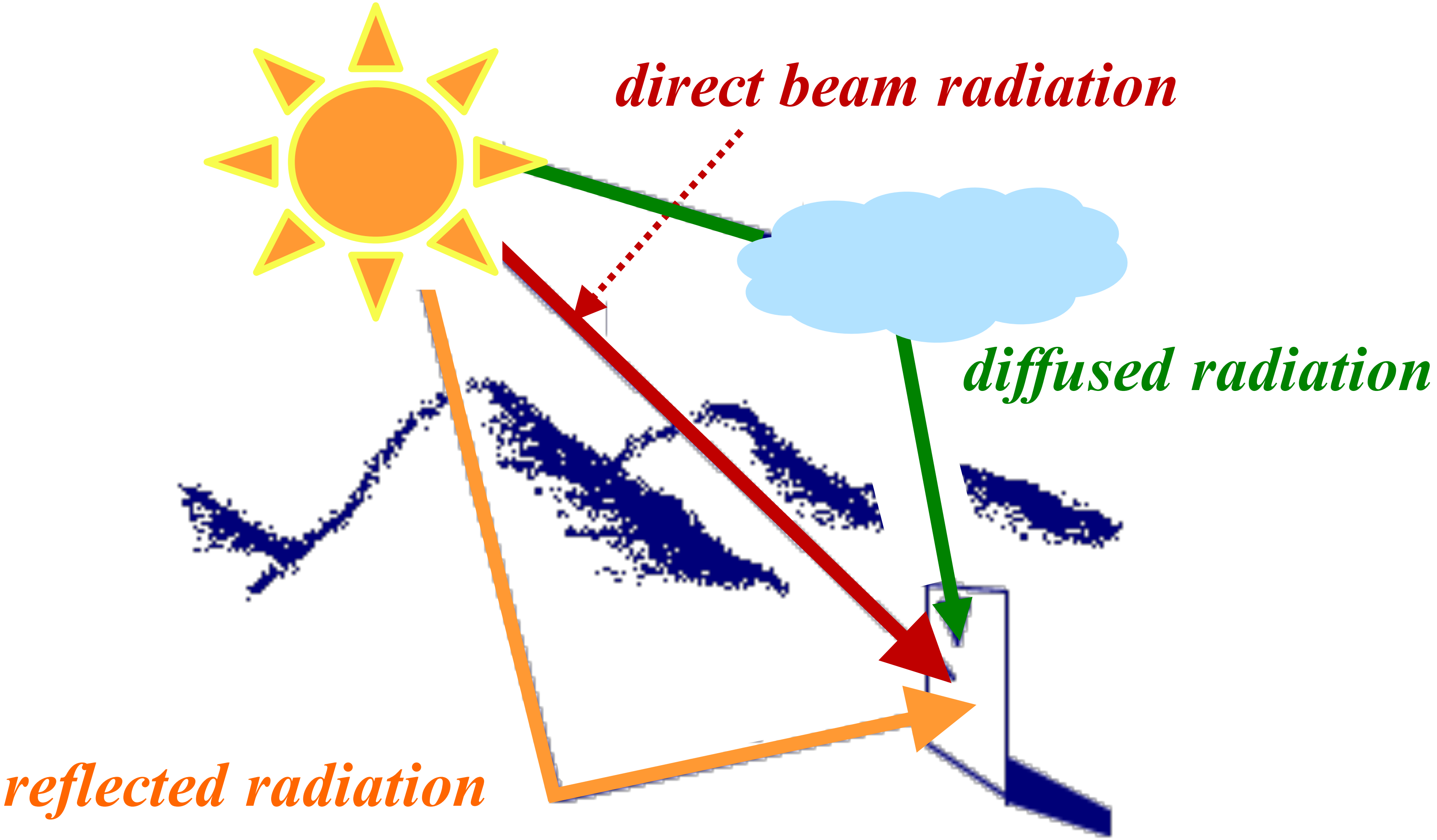
THE IMPACTS OF THE ATMOSPHERE ON SOLAR IRRADIATION

- ☐ The incidence angle of the solar rays and the length of each ray's path through the atmosphere depend on the *sun's position in the sky*
- ☐ As each beam passes through the atmosphere, a fraction is absorbed by atmospheric gases or scattered by air molecules or particulate matter
- ☐ Another fraction of insolation is reflected by surfaces in front of the solar panel

INSOLATION COMPONENTS ON A SOLAR PANEL



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

INSOLATION COMPONENTS AT THE EARTH'S SURFACE

- Insolation received at a solar panel is a combination of three distinct components:
  - *direct beam radiation* that passes in a straight line through the atmosphere
  - *diffused radiation* that has been scattered by molecules and aerosols in the atmosphere
  - *reflected radiation* that is bounced off the ground or other surfaces in front of the solar panel

INSOLATION COMPONENTS AT THE EARTH’S SURFACE

- ☐ The direct beam portion of the insolation is, typically, the most significant since its rays arrive along a consistent direction
- ☐ Over a year’s time, less than half of the extraterrestrial 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 extraterrestrial solar irradiation

CLEAR – SKY DIRECT BEAM RADIATION

- ☐ Since 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
- ☐ The approximation used for *the clear–sky direct beam radiation* explicitly accounts for the time-varying intensity of the sun and 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

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

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

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

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

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

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 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 at latitude l $= 0.731$ *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 AT CHICAGO

- ☐ The *solar declination* angle is

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

- ☐ 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 is

EXAMPLE: DIRECT BEAM IRRADIATION AT CHICAGO

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

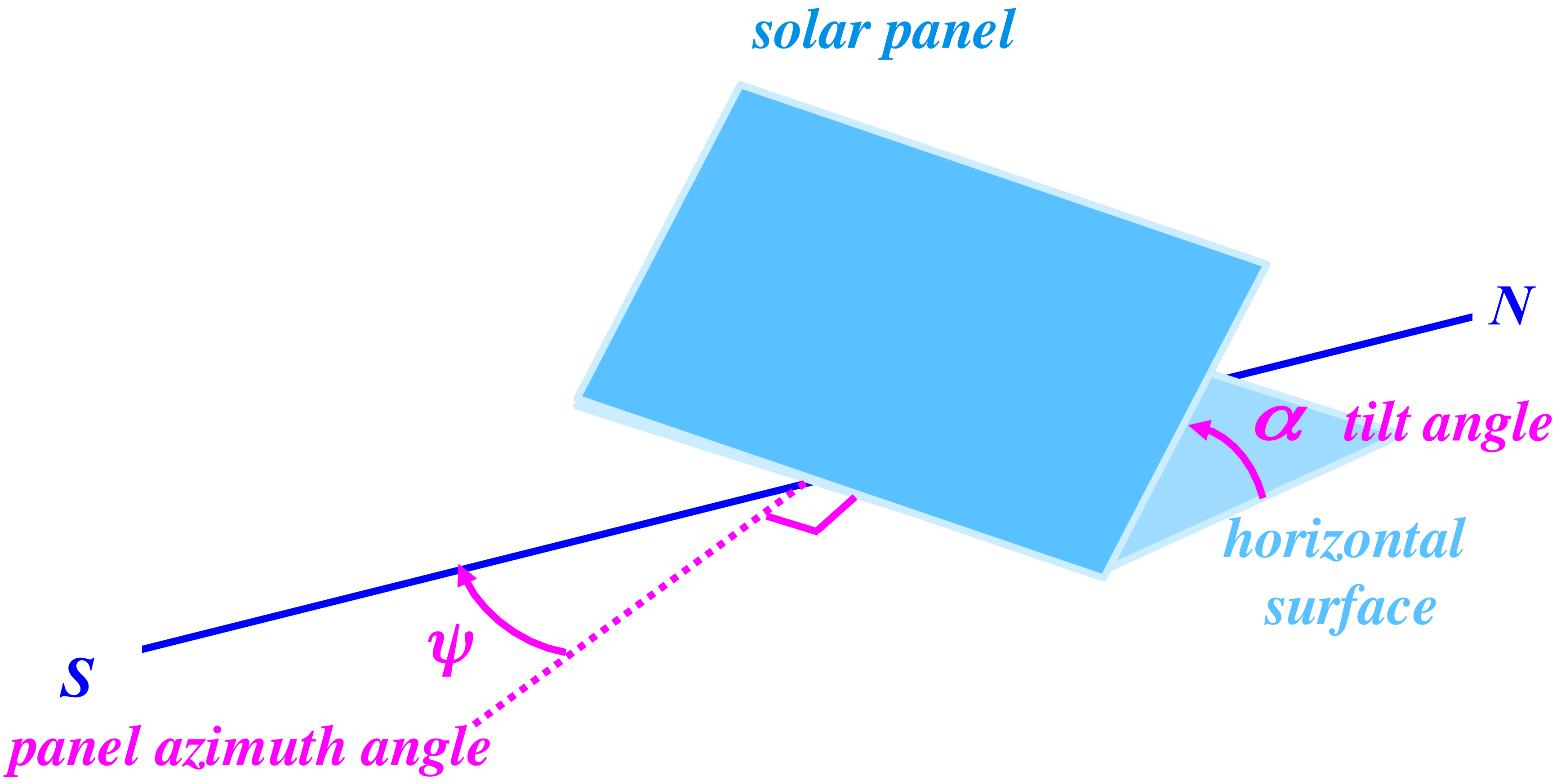
- ☐ The optical depth is given by

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

- ☐ Therefore, the clear-sky direct beam radiation is

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

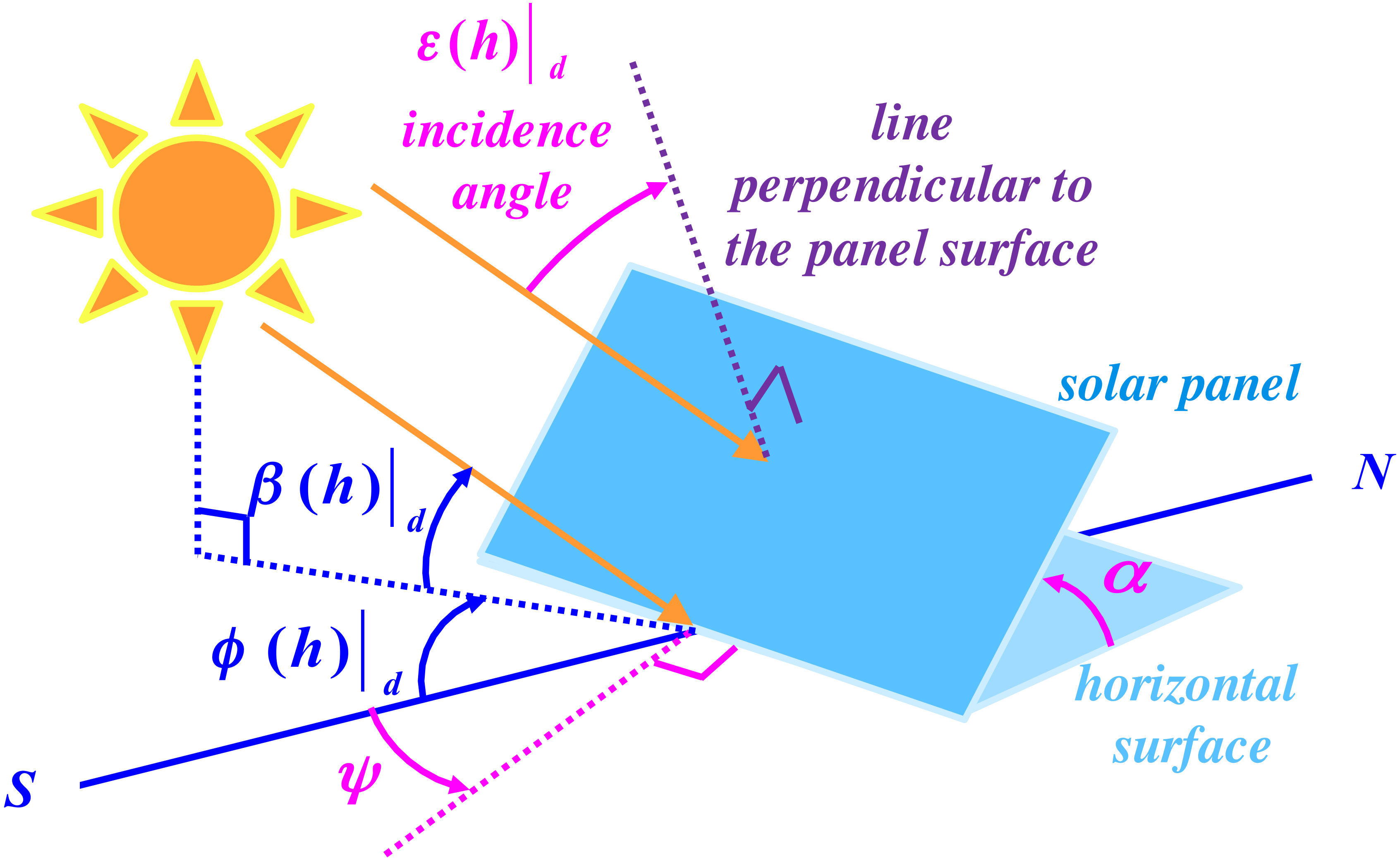
SOLAR PANEL POSITION/ORIENTATION



SOLAR PANEL POSITION

- ☐ Solar panel position is expressed in terms of the
  - ○ *tilt angle* α , defined as the angle between the panel and a horizontal surface
  - ○ *panel azimuth angle* ψ , defined as the angular displacement, through which the panel needs to rotate in order to face due South
- ☐ The convention is that ψ 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* provides 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 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 so 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

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

EXAMPLE: DIRECT BEAM RADIATION ON THE PANEL

- In the example, at solar noon on *May* 21 in *Chicago* at l = 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

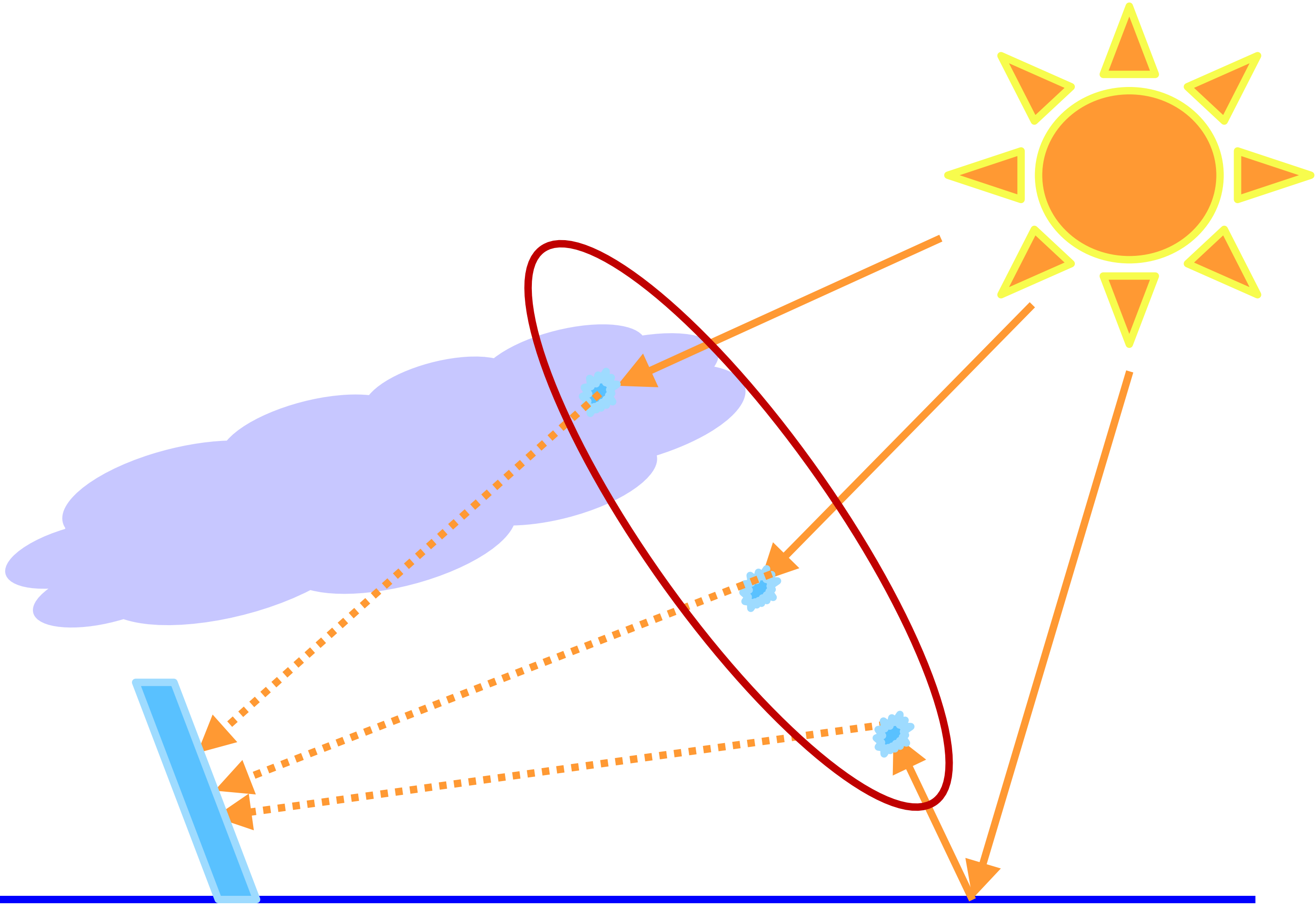
- ☐ The incidence angle satisfies

$$\cos\left(\varepsilon(0)\Big|_{141}\right) = \cos(1.221)\cos(0-0.348)\sin(0.907) + \sin(1.221)\cos(0.907) = 0.833$$

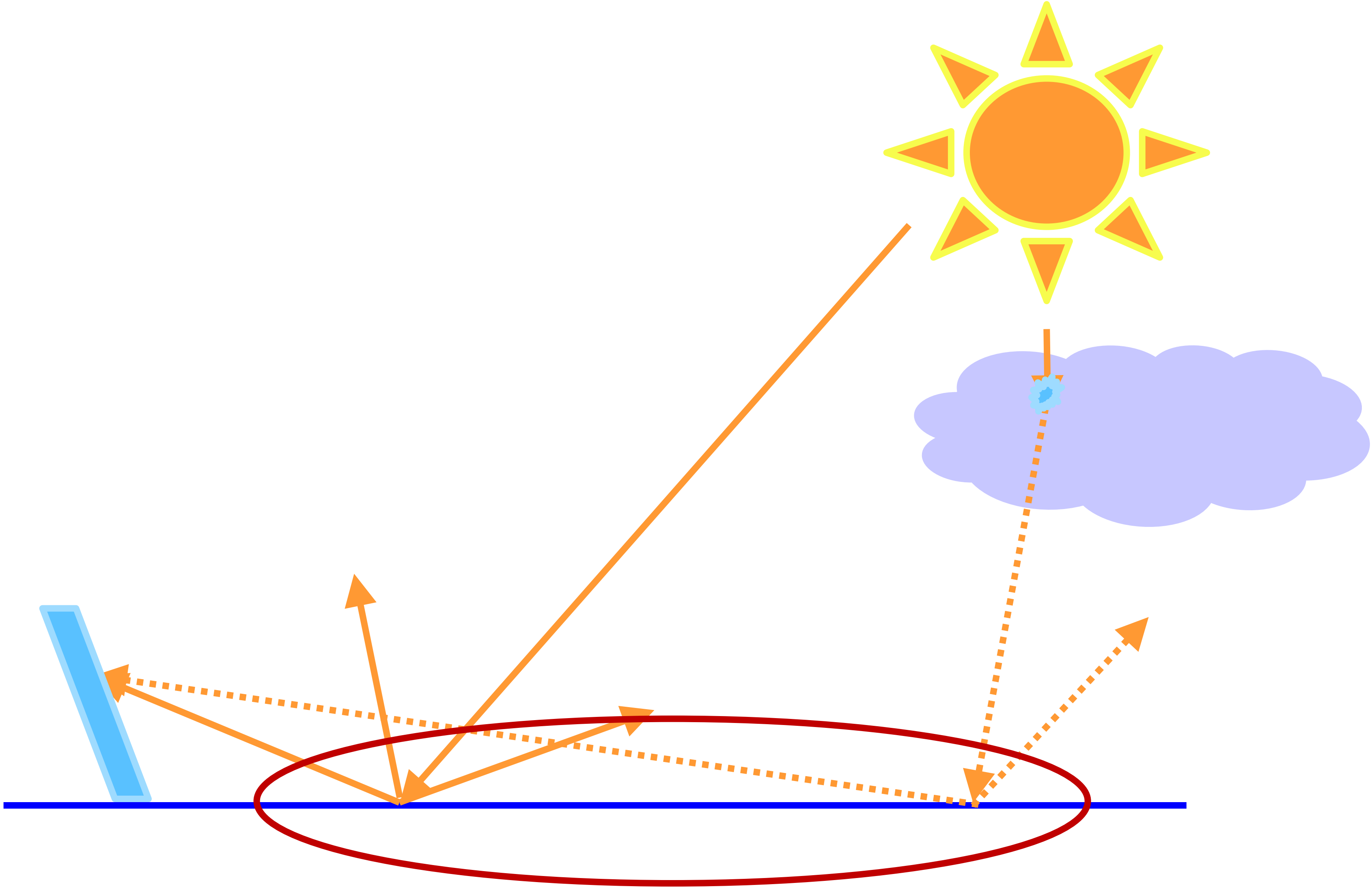
- ☐ Thus, the beam radiation on the panel is

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

DIFFUSED RADIATION



RELECTED RADIATION



DIFFUSED AND REFLECTED RADIATION ON THE SOLAR PANEL

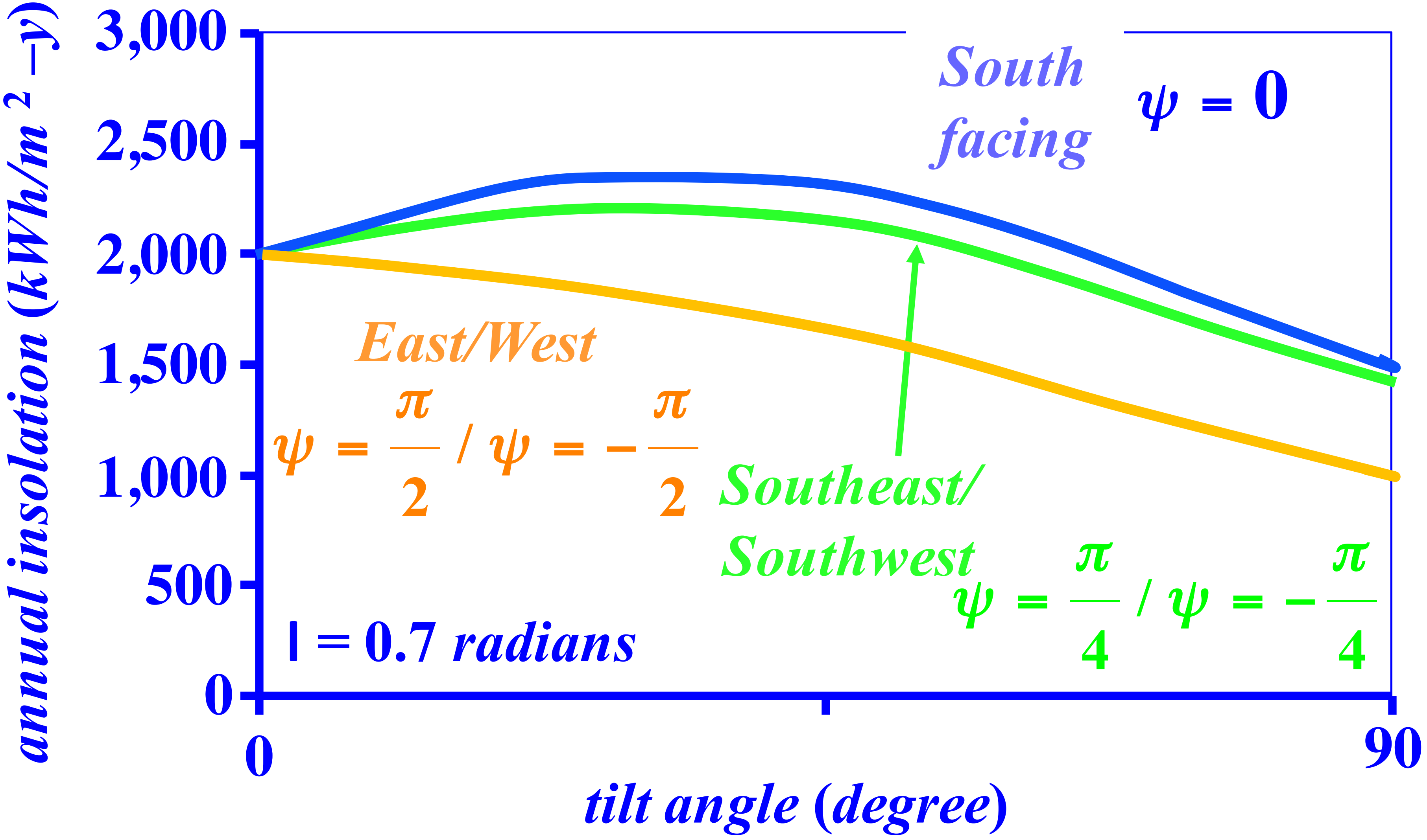
- The indirect radiation components are subject to
  - the uncertain impacts of particles and molecules in the atmosphere
  - the irregularities of the terrain of the earth surface for the reflected radiation

  and so the approximation of the diffused and reflected radiation components is complicated
- The approximation of the diffused and reflected radiation is outside 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 can observe that the solar panel position has significant impacts on the insolation received by the solar panels

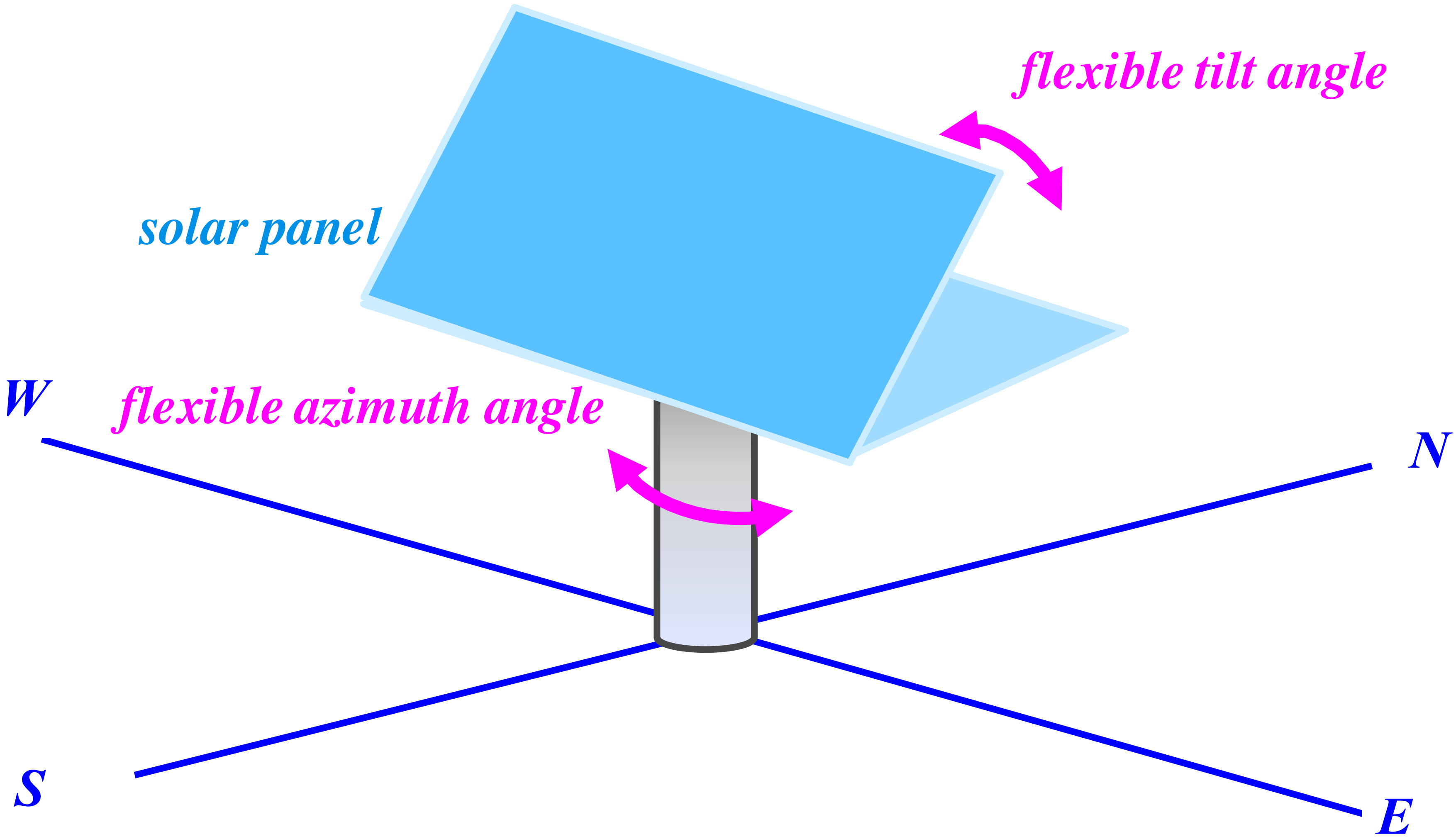
☐ As such, in many implementations, the solar panels are equipped with *tracking systems* to allow the panels to track the movement of the sun across the sky and change panel positions to better use the insolation the panels receive

TRACKING SYSTEMS

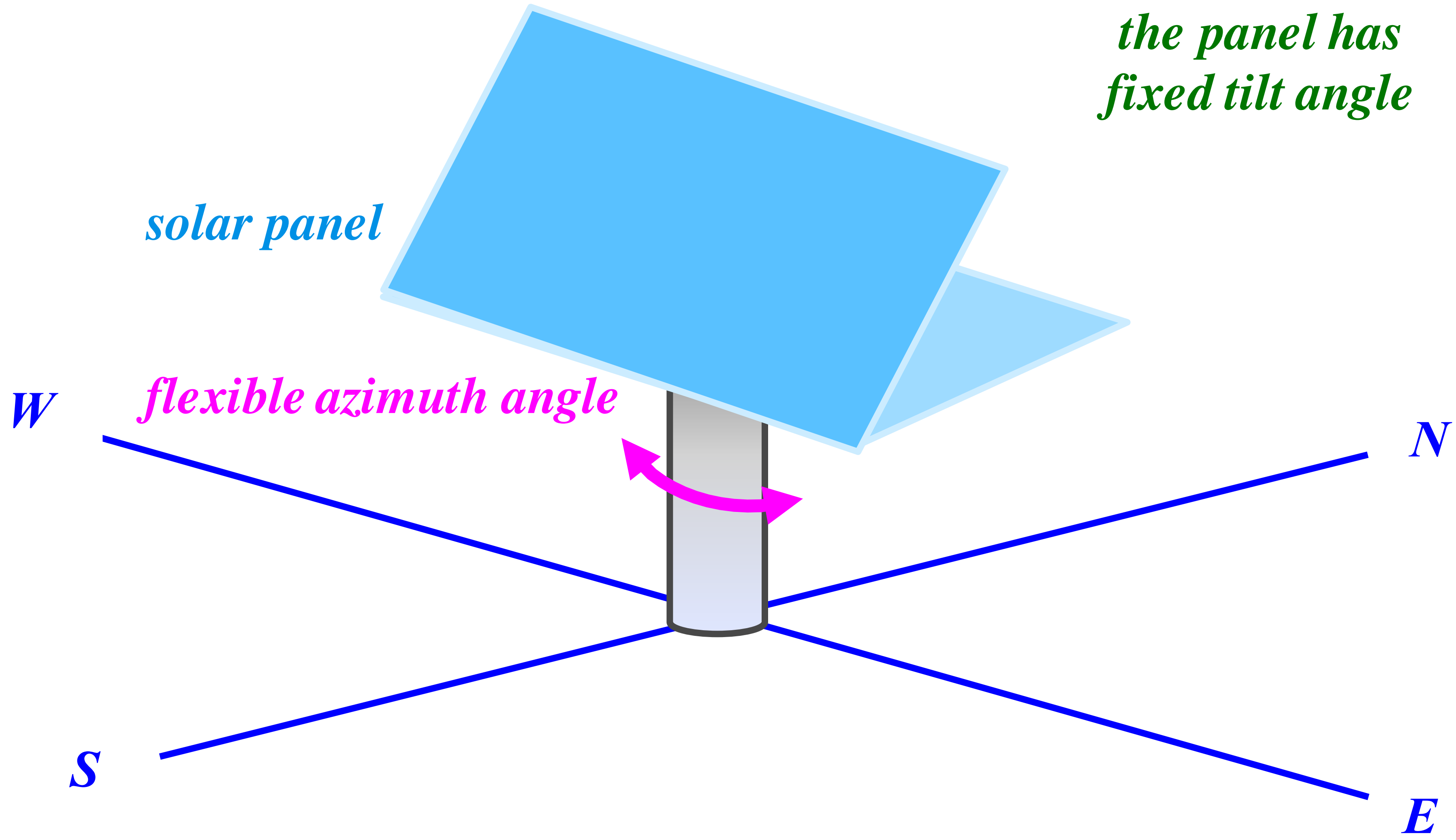
Tracking systems are categorized as

- *two–axis trackers*, which can adjust the two panel angles – tilt and azimuth – to orient the panels to be perpendicular to the sun rays
- *single–axis trackers*, which can change only one of the solar panel angles – either tilt or azimuth

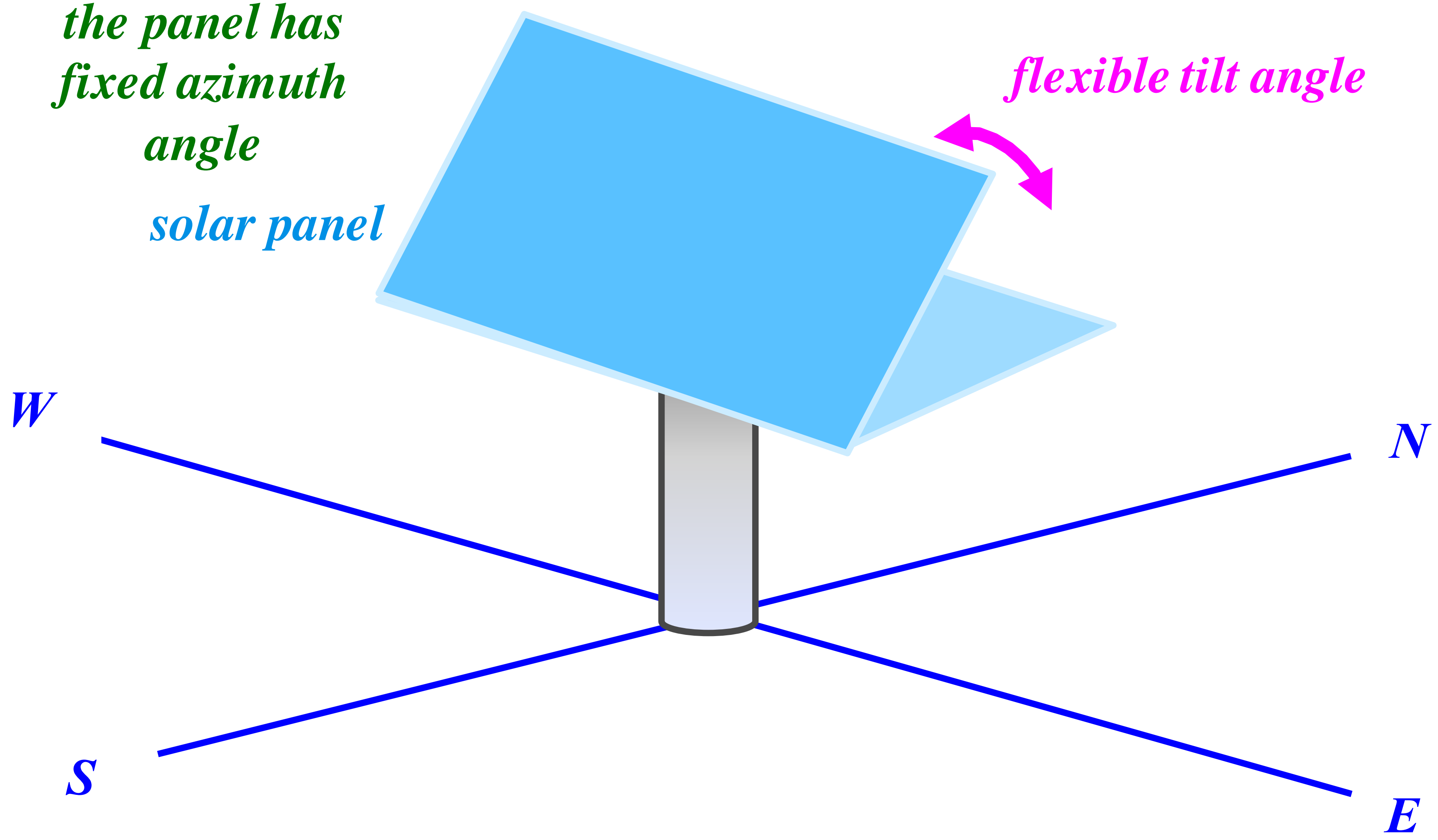
TWO – AXIS TRACKERS



SINGLE – AXIS TRACKERS



SINGLE – AXIS TRACKERS

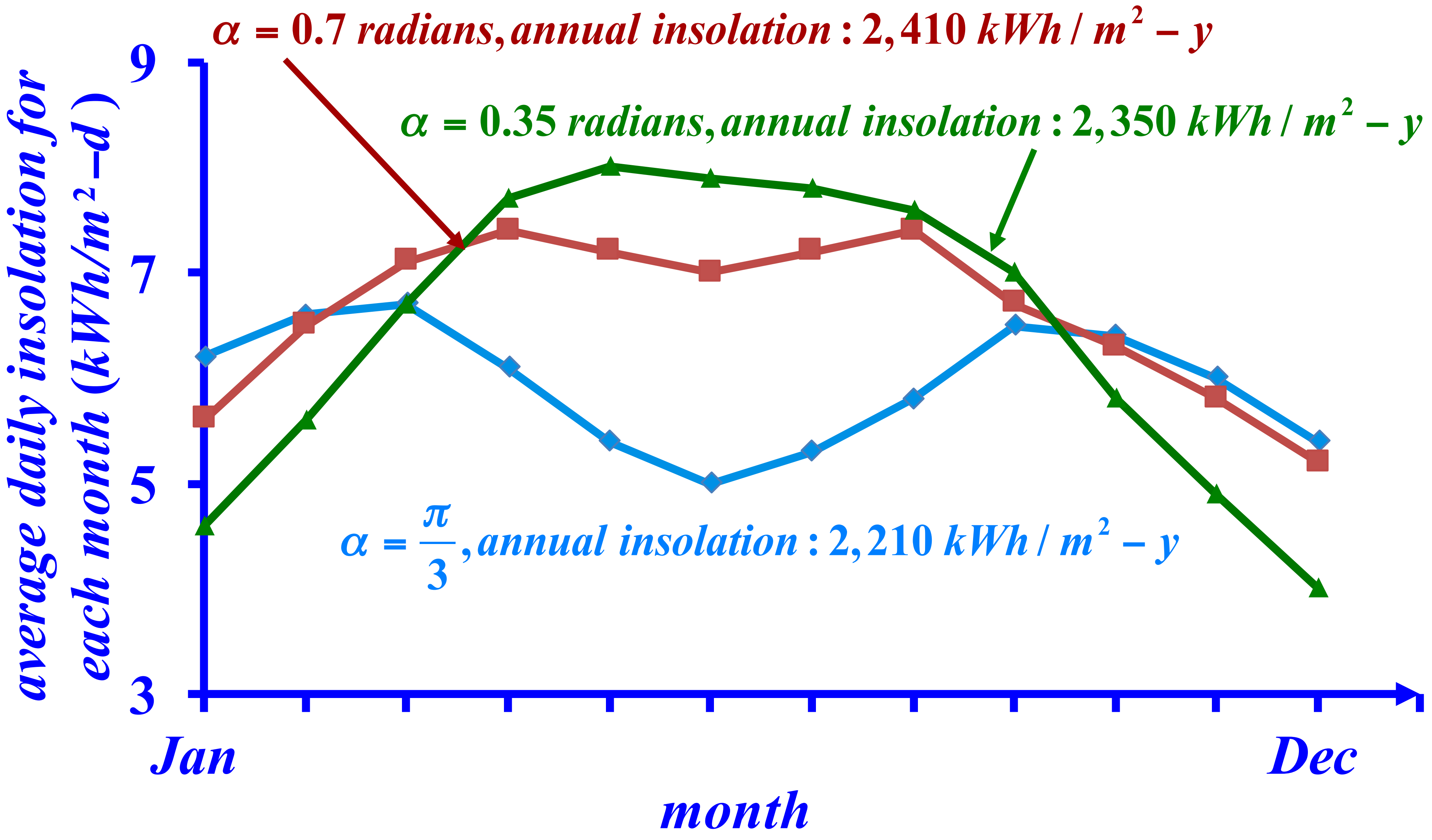


SINGLE – AXIS TRACKERS

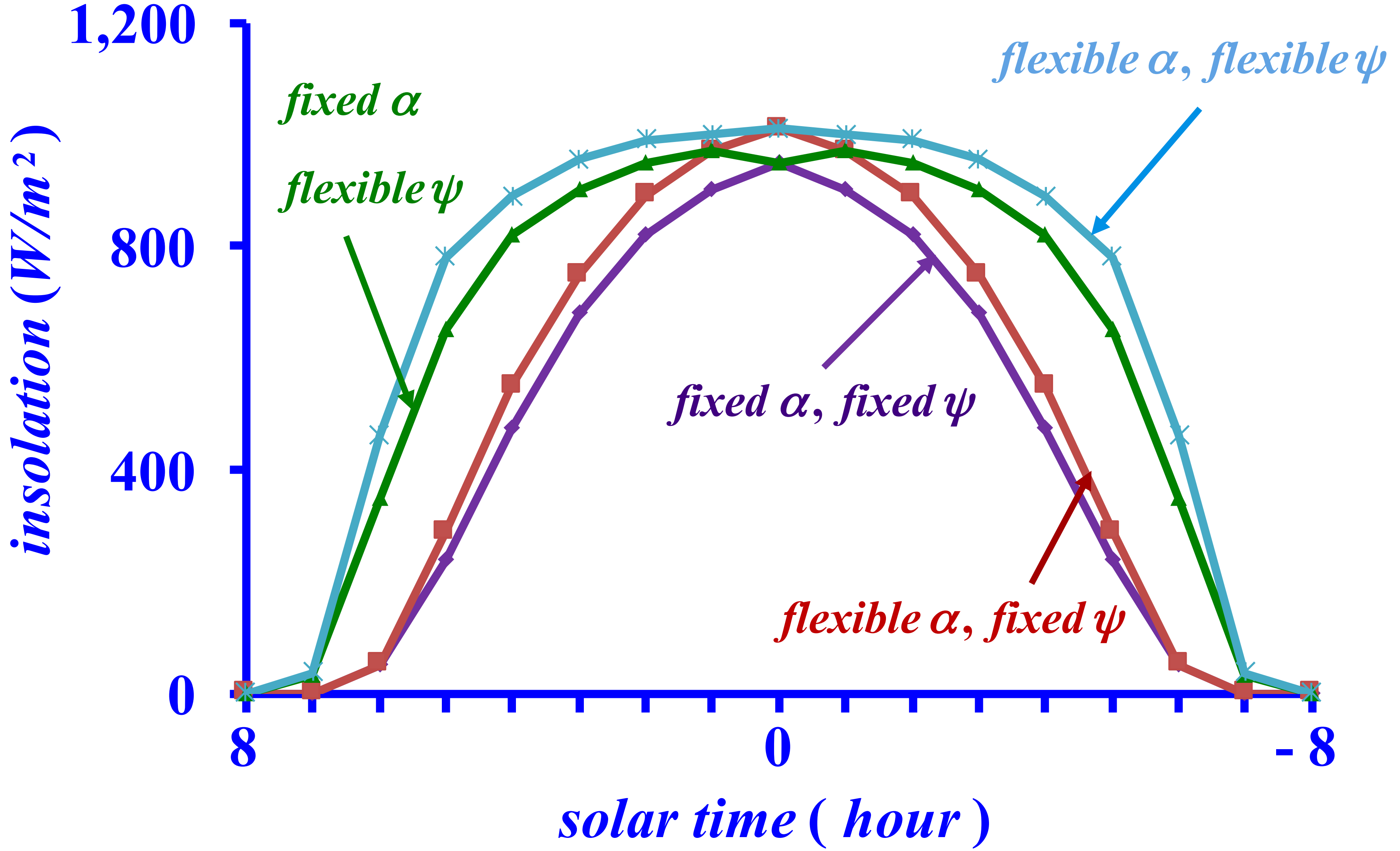
TRACKER

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 be *intermittent*
- ☐ As such, we need specific devices to measure the actual insolation to perform the analysis

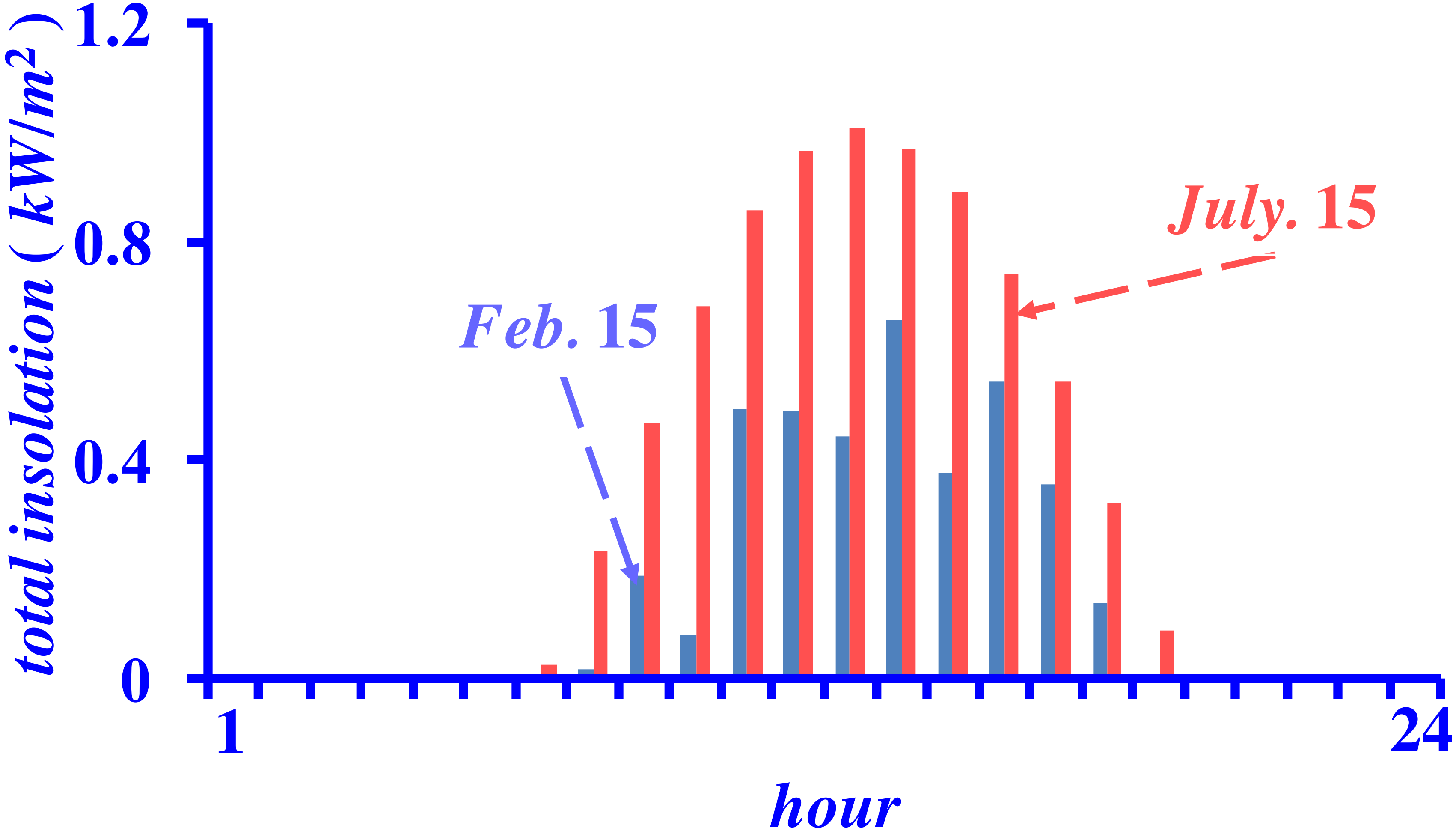
INSOLATION MEASUREMENT DEVICES

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

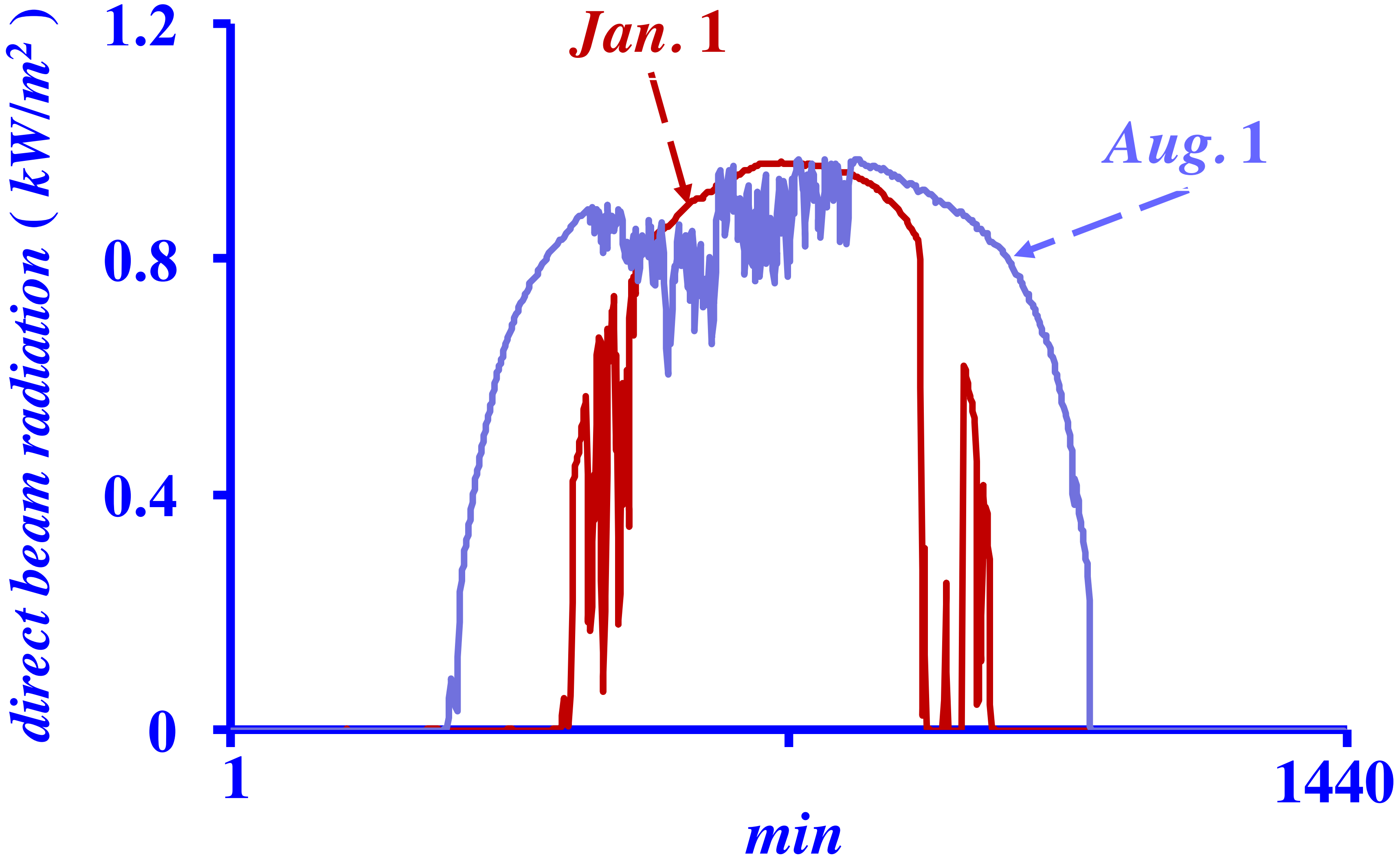
- ***pyranometer*** **which measures the total insolation of all the three components**

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

PYRANOMETER HOURLY INSOLATION MEASUREMENTS IN ABILENE, TX



$1-m$ DIRECT BEAM PYRHELIOMETER MEASUREMENTS: LAS VEGAS



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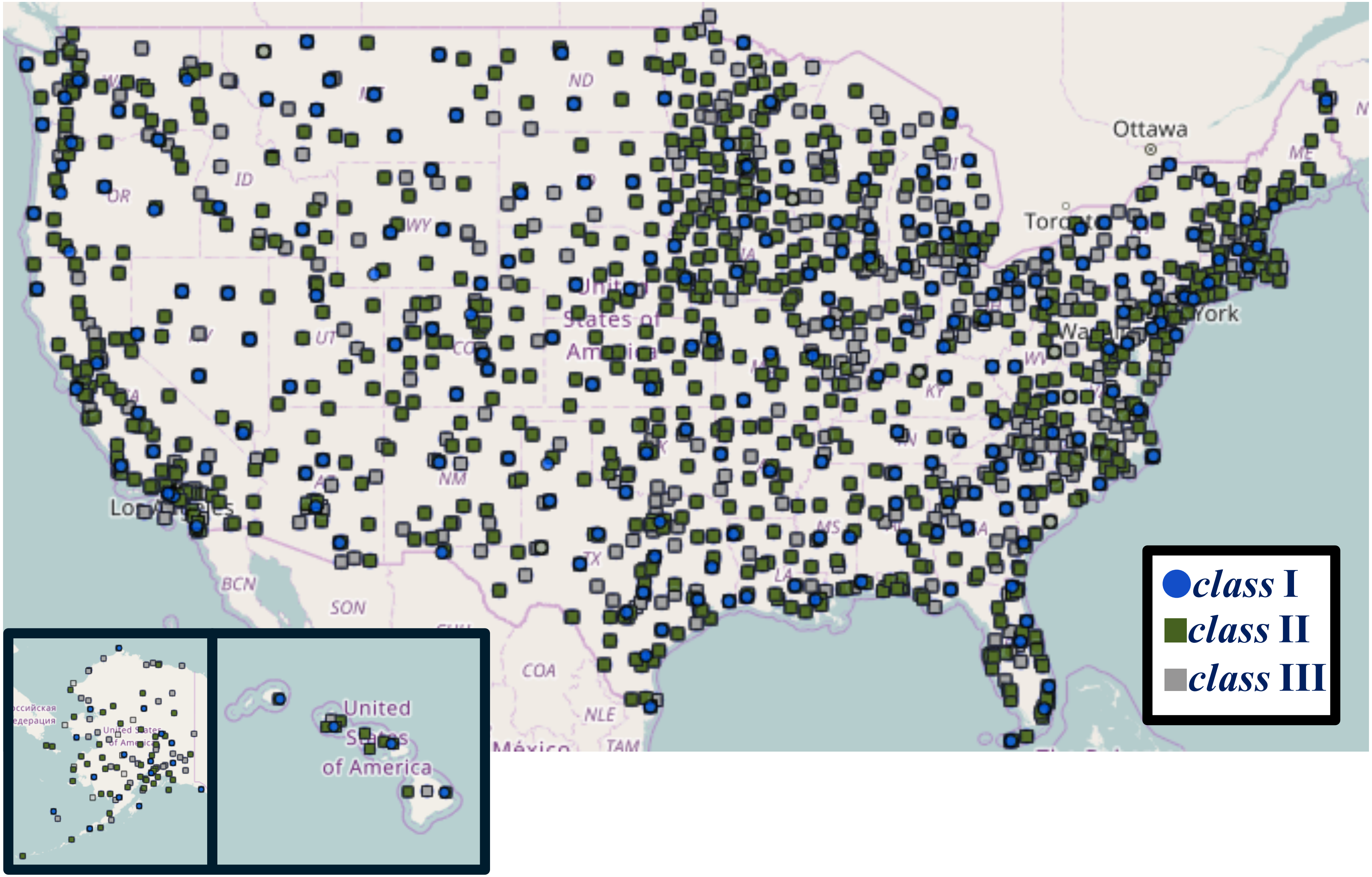
SOLAR IRRADIATION DATA BASES

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

  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 at over 1,000 stations; *http://rredc.nrel.gov/solar*

NSRDB STATIONS



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

NSRDB STATIONS

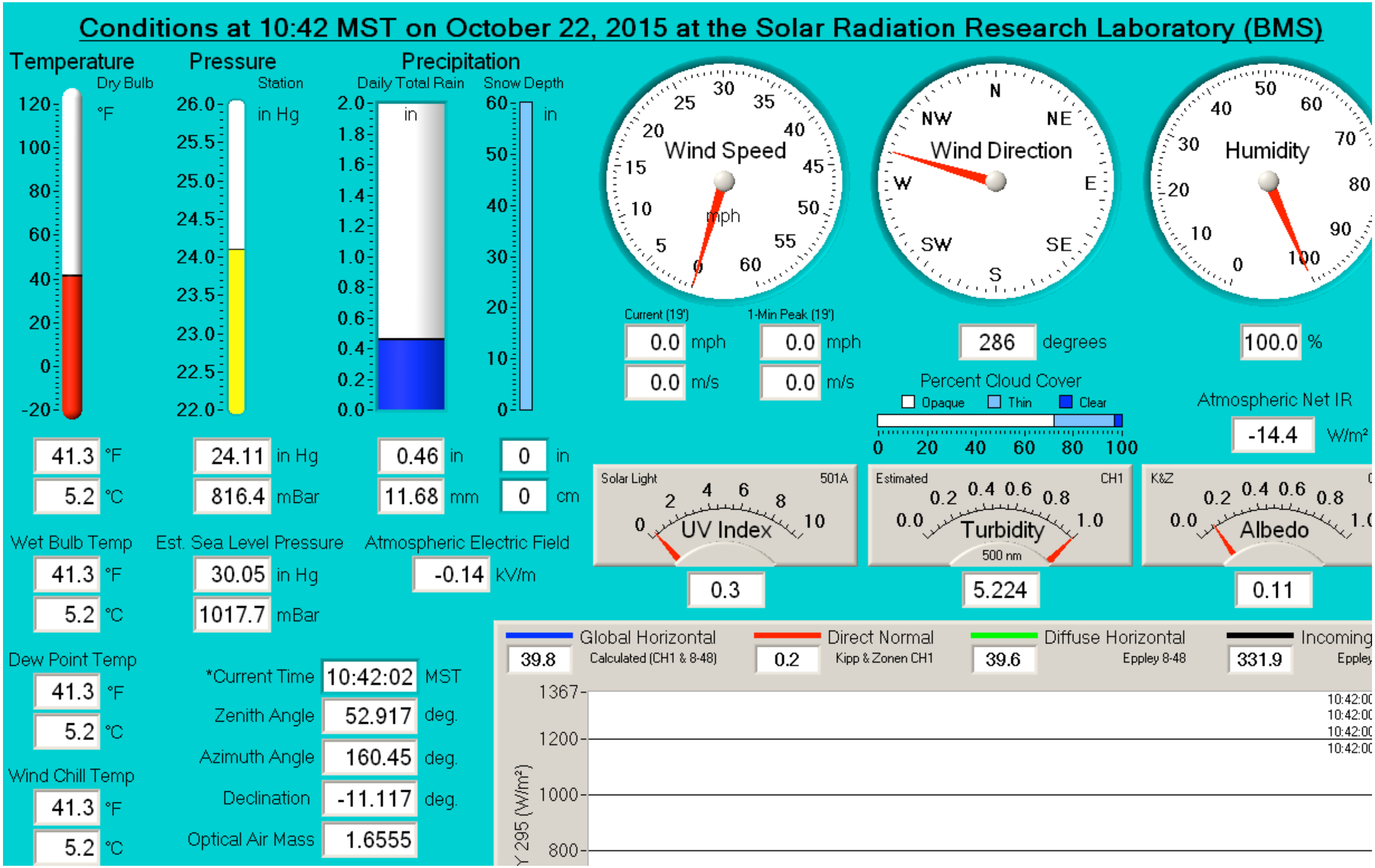
- The 239 *Class* I stations have a complete hourly data set
- The 1462 *Class* II stations have a complete hourly data set, but assembled from lower–quality input data
- The 1454 *Class* III stations contain gaps in the records but have data for at least 3–*year* period
- The 40 stations in the updated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

MEASUREMENT & INSTRUMENTATION DATA CENTER

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



Conditions at 10:42 MST on October 22, 2015 at the Solar Radiation Research Laboratory (BMS)

Temperature – Dry Bulb: 41.3 °F, 5.2 °C

Pressure – Station: 24.11 in Hg, 816.4 mBar

Precipitation – Daily Total Rain: 0.46 in, 11.68 mm; Snow Depth: 0 in, 0 cm

Wet Bulb Temp: 41.3 °F, 5.2 °C

Est. Sea Level Pressure: 30.05 in Hg, 1017.7 mBar

Atmospheric Electric Field: -0.14 kV/m

Dew Point Temp: 41.3 °F, 5.2 °C

Wind Chill Temp: 41.3 °F, 5.2 °C

*Current Time: 10:42:02 MST

Zenith Angle: 52.917 deg.

Azimuth Angle: 160.45 deg.

Declination: -11.117 deg.

Optical Air Mass: 1.6555

Wind Speed – Current (19'): 0.0 mph, 0.0 m/s; 1-Min Peak (19'): 0.0 mph, 0.0 m/s

Wind Direction: 286 degrees

Humidity: 100.0 %

Percent Cloud Cover: ☐ Opaque ☐ Thin ☐ Clear

Atmospheric Net IR: -14.4 W/m²

UV Index (Solar Light 501A): 0.3

Turbidity (Estimated CH1, 500 nm): 5.224

Albedo (K&Z): 0.11

Global Horizontal – Calculated (CH1 & 8-48): 39.8

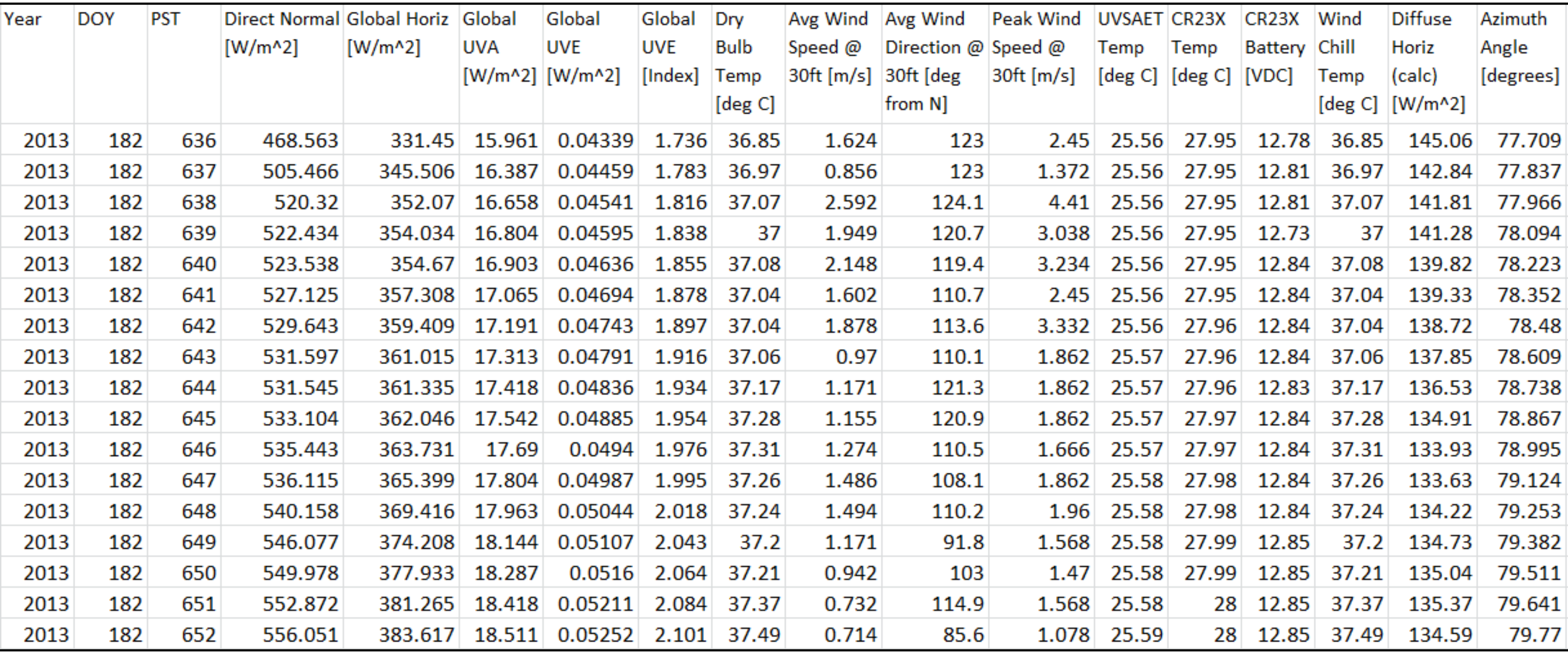
Direct Normal – Kipp & Zonen CH1: 0.2

Diffuse Horizontal – Eppley 8-48: 39.6

Incoming – Eppley: 331.9

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

MIDC TYPICAL 1–*MINUTE* SOLAR DATA FILE

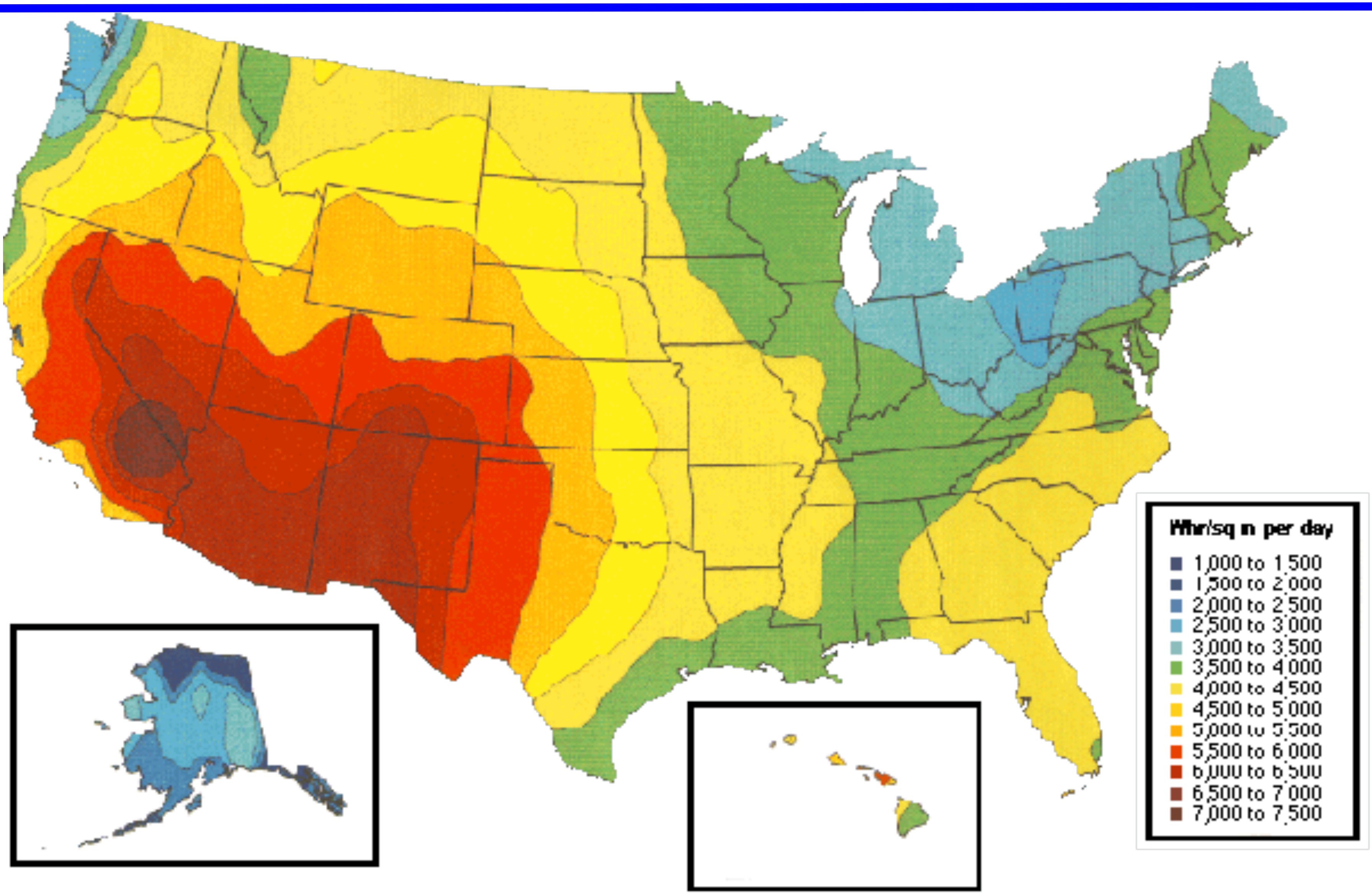


Year	DOY	PST	Direct Normal [W/m^2]	Global Horiz [W/m^2]	Global UVA [W/m^2]	Global UVE [W/m^2]	Global UVE [Index]	Dry Bulb Temp [deg C]	Avg Wind Speed @ 30ft [m/s]	Avg Wind Direction @ 30ft [deg from N]	Peak Wind Speed @ 30ft [m/s]	UVSAET Temp [deg C]	CR23X Temp [deg C]	CR23X Battery [VDC]	Wind Chill Temp [deg C]	Diffuse Horiz (calc) [W/m^2]	Azimuth Angle [degrees]
2013	182	636	468.563	331.45	15.961	0.04339	1.736	36.85	1.624	123	2.45	25.56	27.95	12.78	36.85	145.06	77.709
2013	182	637	505.466	345.506	16.387	0.04459	1.783	36.97	0.856	123	1.372	25.56	27.95	12.81	36.97	142.84	77.837
2013	182	638	520.32	352.07	16.658	0.04541	1.816	37.07	2.592	124.1	4.41	25.56	27.95	12.81	37.07	141.81	77.966
2013	182	639	522.434	354.034	16.804	0.04595	1.838	37	1.949	120.7	3.038	25.56	27.95	12.73	37	141.28	78.094
2013	182	640	523.538	354.67	16.903	0.04636	1.855	37.08	2.148	119.4	3.234	25.56	27.95	12.84	37.08	139.82	78.223
2013	182	641	527.125	357.308	17.065	0.04694	1.878	37.04	1.602	110.7	2.45	25.56	27.95	12.84	37.04	139.33	78.352
2013	182	642	529.643	359.409	17.191	0.04743	1.897	37.04	1.878	113.6	3.332	25.56	27.96	12.84	37.04	138.72	78.48
2013	182	643	531.597	361.015	17.313	0.04791	1.916	37.06	0.97	110.1	1.862	25.57	27.96	12.84	37.06	137.85	78.609
2013	182	644	531.545	361.335	17.418	0.04836	1.934	37.17	1.171	121.3	1.862	25.57	27.96	12.83	37.17	136.53	78.738
2013	182	645	533.104	362.046	17.542	0.04885	1.954	37.28	1.155	120.9	1.862	25.57	27.97	12.84	37.28	134.91	78.867
2013	182	646	535.443	363.731	17.69	0.0494	1.976	37.31	1.274	110.5	1.666	25.57	27.97	12.84	37.31	133.93	78.995
2013	182	647	536.115	365.399	17.804	0.04987	1.995	37.26	1.486	108.1	1.862	25.58	27.98	12.84	37.26	133.63	79.124
2013	182	648	540.158	369.416	17.963	0.05044	2.018	37.24	1.494	110.2	1.96	25.58	27.98	12.84	37.24	134.22	79.253
2013	182	649	546.077	374.208	18.144	0.05107	2.043	37.2	1.171	91.8	1.568	25.58	27.99	12.85	37.2	134.73	79.382
2013	182	650	549.978	377.933	18.287	0.0516	2.064	37.21	0.942	103	1.47	25.58	27.99	12.85	37.21	135.04	79.511
2013	182	651	552.872	381.265	18.418	0.05211	2.084	37.37	0.732	114.9	1.568	25.58	28	12.85	37.37	135.37	79.641
2013	182	652	556.051	383.617	18.511	0.05252	2.101	37.49	0.714	85.6	1.078	25.59	28	12.85	37.49	134.59	79.77

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