ECE 333 – Green Electric Energy

13. Solar Insolation Components and Measurement

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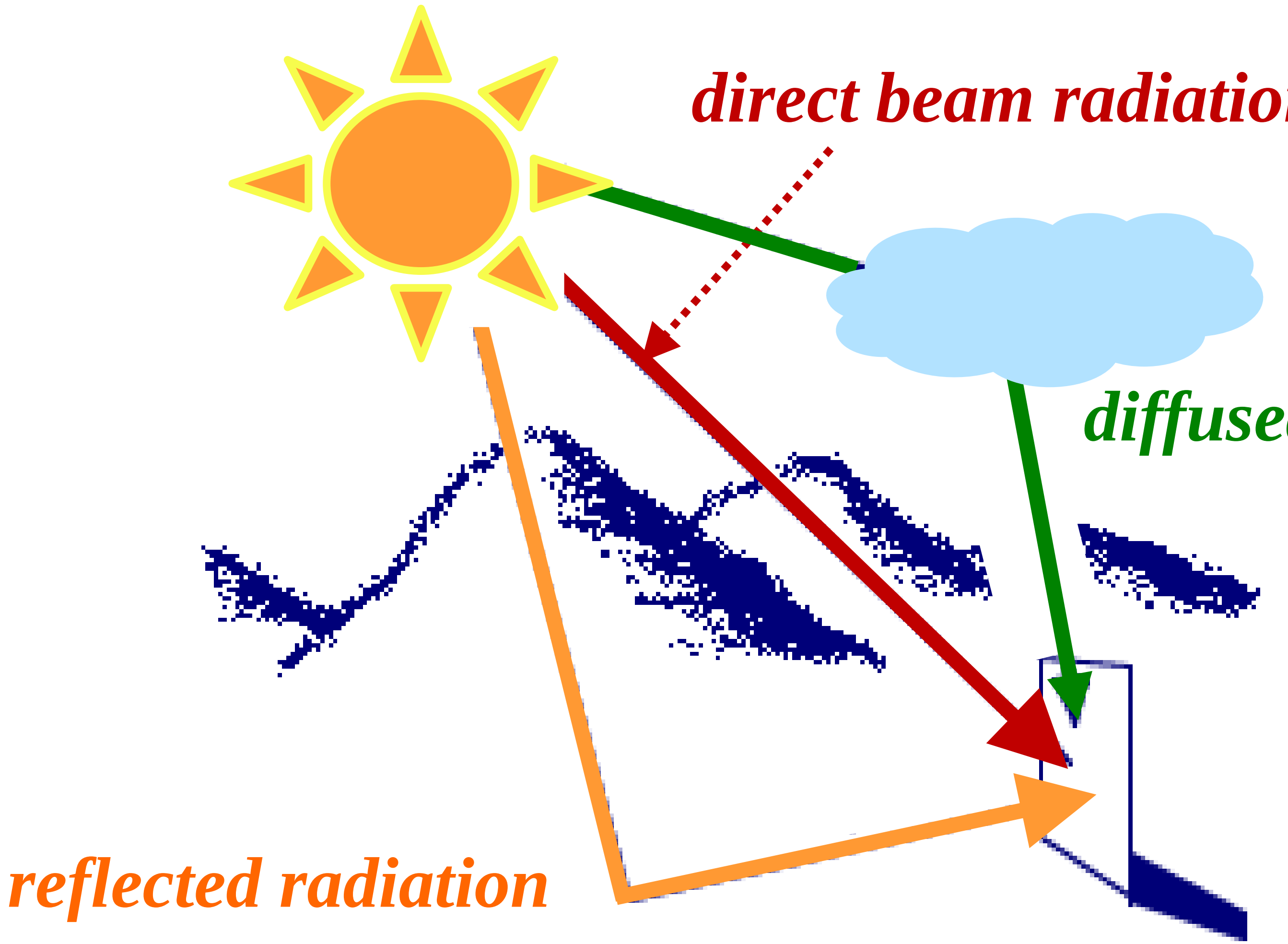
THE IMPACTS OF THE ATMOSPHERE ON SOLAR IRRADIATION

- The incidence angle of the sun rays and the length of their 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 portion 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:
  - ***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 important since its rays arrive from a consistent direction
- Over a year's time, less than half of the extrater-restrial 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 an approximation of ***the clear-sky direct beam radiation*** on earth's surface to provide practical means to predict the radiation on solar panels
- The approximation of ***the clear-sky direct beam radiation*** explicitly accounts for the time-varying intensity of the sun and the distance between the earth and the sun

CLEAR – SKY DIRECT BEAM RADIATION APPROXIMATION

- Since the extraterrestrial irradiation undergoes attenuation 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 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

$$k\big|_d = 0.174 + 0.035\,sin\left(\frac{2\pi}{365}\left(d - 81\right)\right)$$

CLEAR – SKY DIRECT BEAM RADIATION APPROXIMATION

- The *air mass ratio* $r(h)\big|_d$ accounts for the time-varying sun ray path length through atmosphere and the spheric 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, whose 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 AT CHICAGO

- The solar declination angle is

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

- The altitude angle at solar noon is given by

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

- Now, we have data to compute the air mass ratio

EXAMPLE: DIRECT BEAM IRRADIATION AT CHICAGO

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

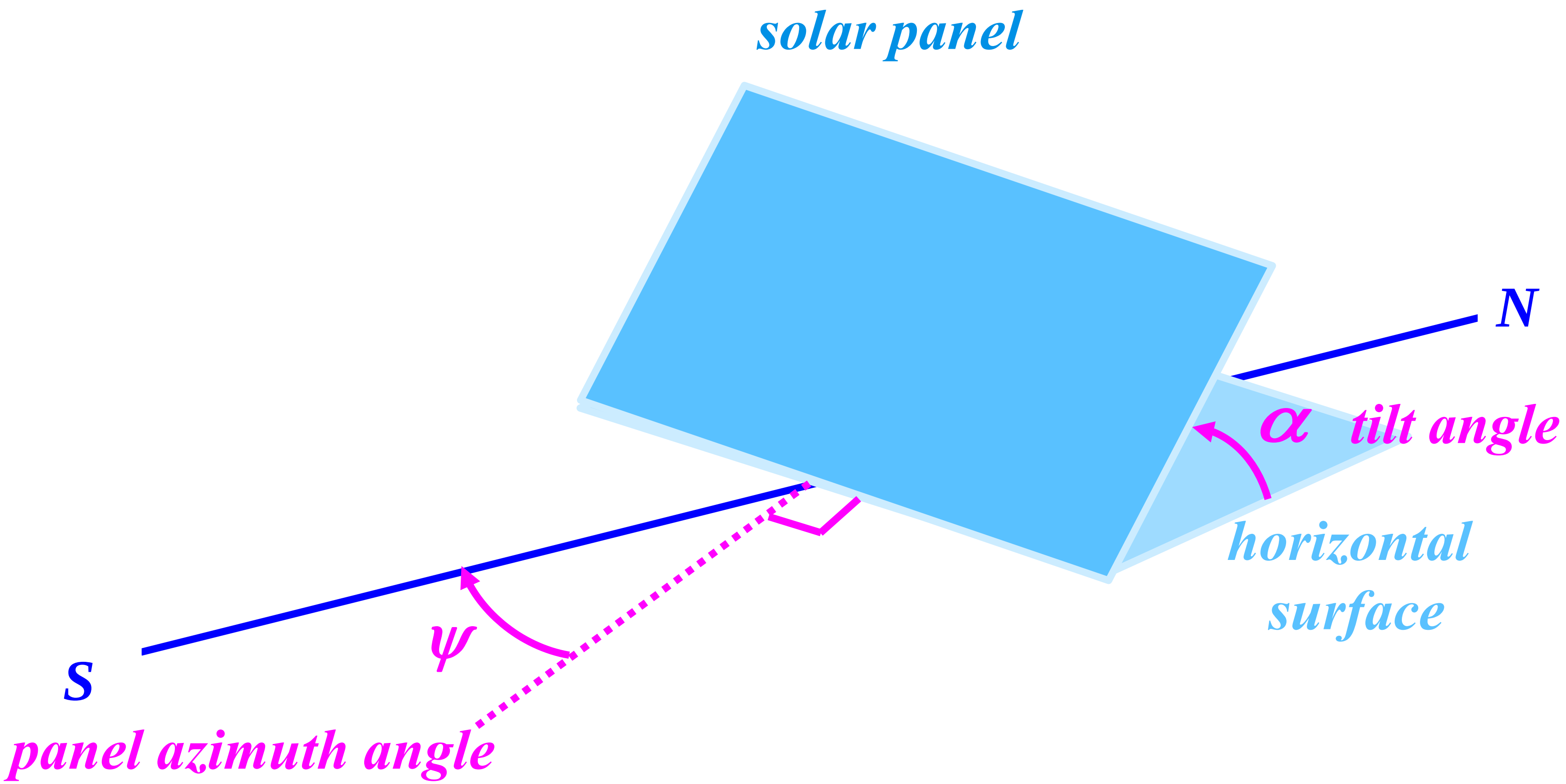
- The optical depth is given by

$$k\Big|_{141} = 0.174 + 0.035\,sin\left(\frac{2\pi}{365}(141 - 81)\right) = 0.197$$

- Therefore, the clear-sky direct beam radiation is

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

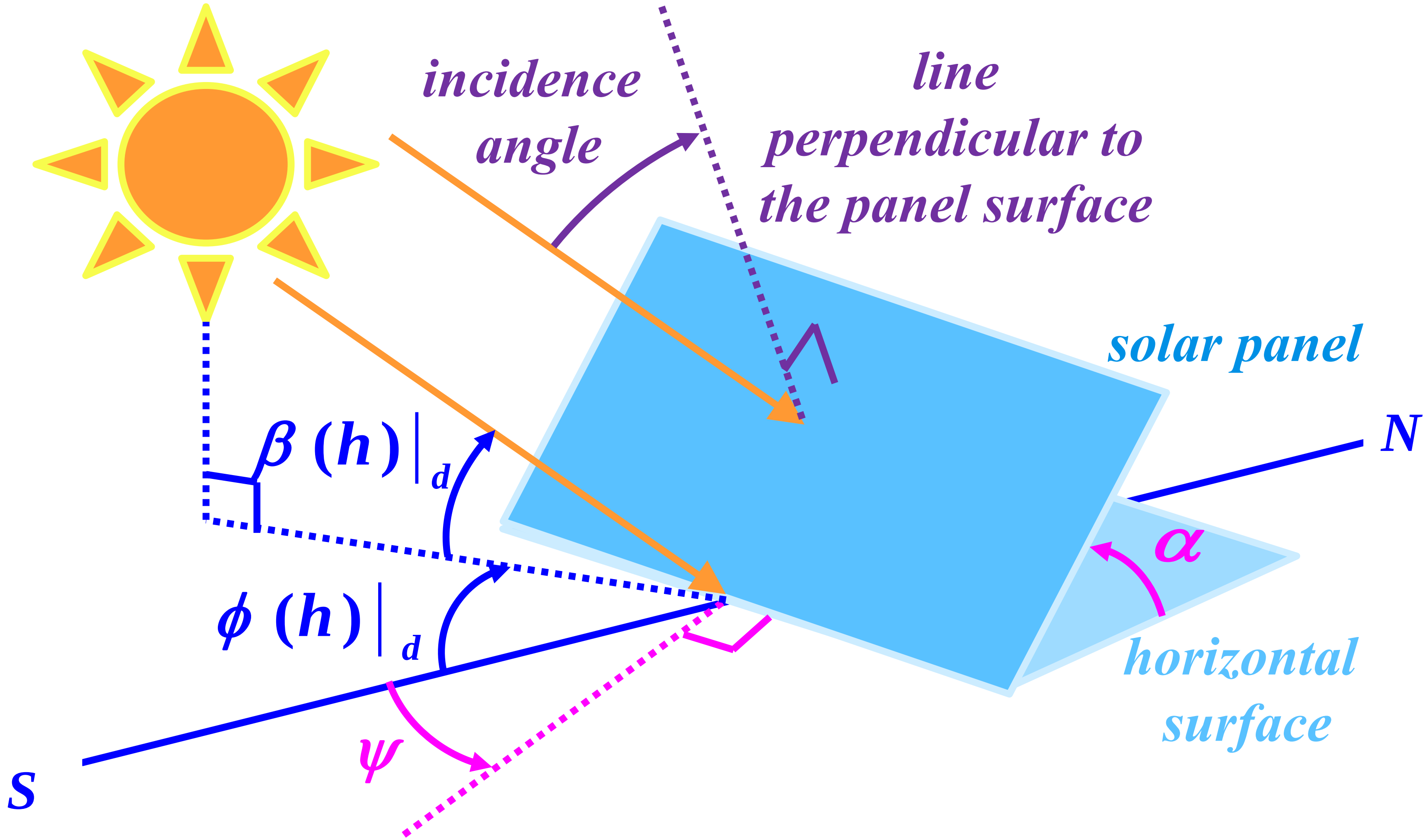
SOLAR PANEL POSITION/ORIENTATION



SOLAR PANEL POSITION

- **Solar panel position is expressed in terms of**
  - ***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 to face due South**
- **We use the convention that** ψ **is** ***positive*** **(*negative*)** ***for*** **the panel facing 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*** is the basis to estimate each component of the solar insolation that strikes a solar panel on the earth's surface
- Given the panel's tilt angle α and the azimuth angle ψ, we determine the ***angle of incidence*** $\varepsilon(h)\big|_d$

DIRECT BEAM RADIATION ON THE SOLAR PANEL

between a line drawn perpendicular to the solar

panel surface and the sun’s rays using

$$cos\left(\varepsilon(h)\big|_{d}\right) = cos\left(\beta(h)\big|_{d}\right)cos\left(\phi(h)\big|_{d} - \psi\right)sin(\alpha) +$$

$$cos\left(\beta(h)\big|_{d}\right)cos(\alpha)$$

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

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

EXAMPLE: DIRECT BEAM RADIATION ON THE PANEL

- **In the example, at solar noon on May 21 in Chicago at $\ell = 0.731$ *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

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

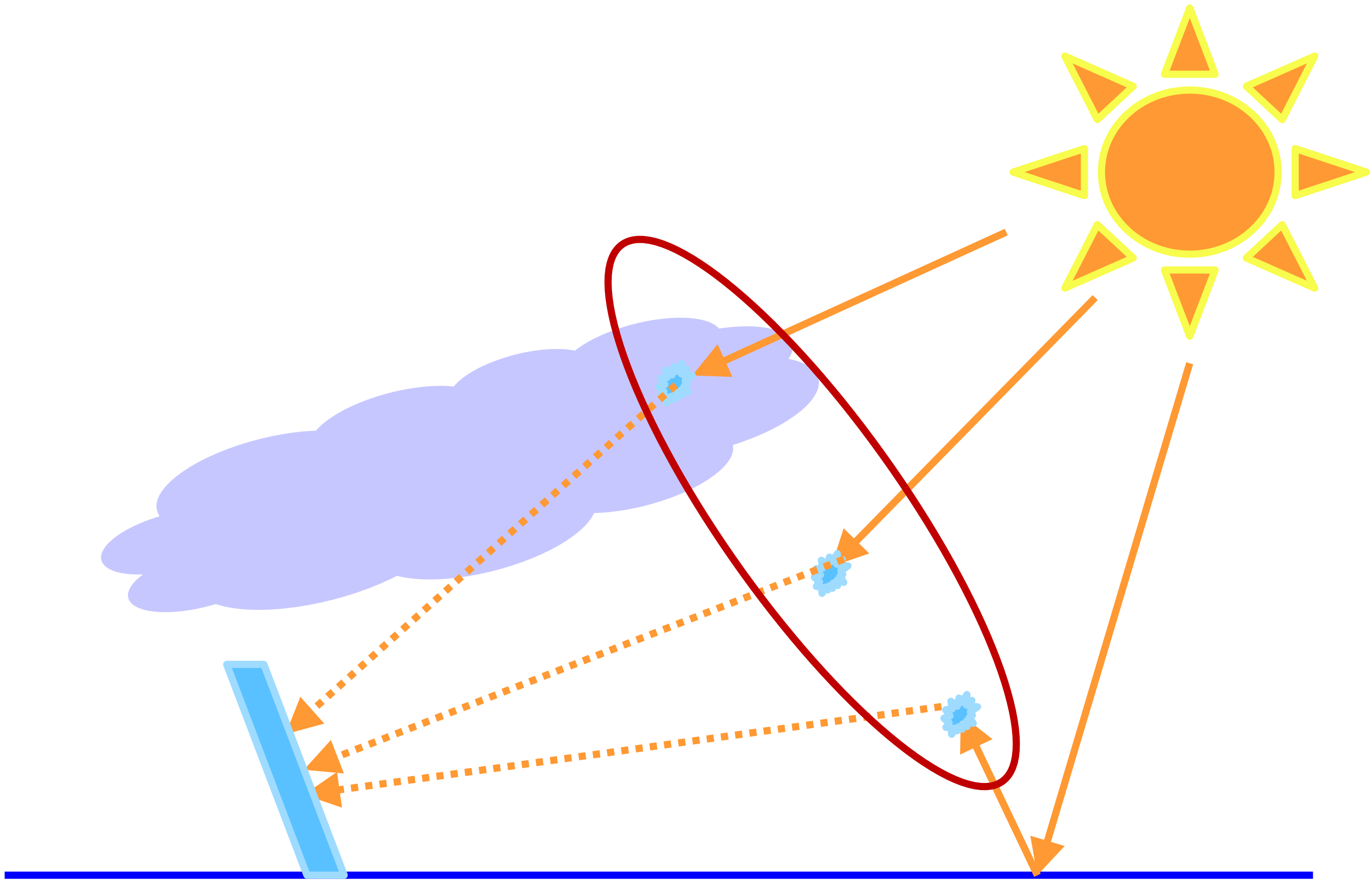
$$+\,sin\left(1.221\right)cos\left(0.907\right)$$

$$=\;0.833$$

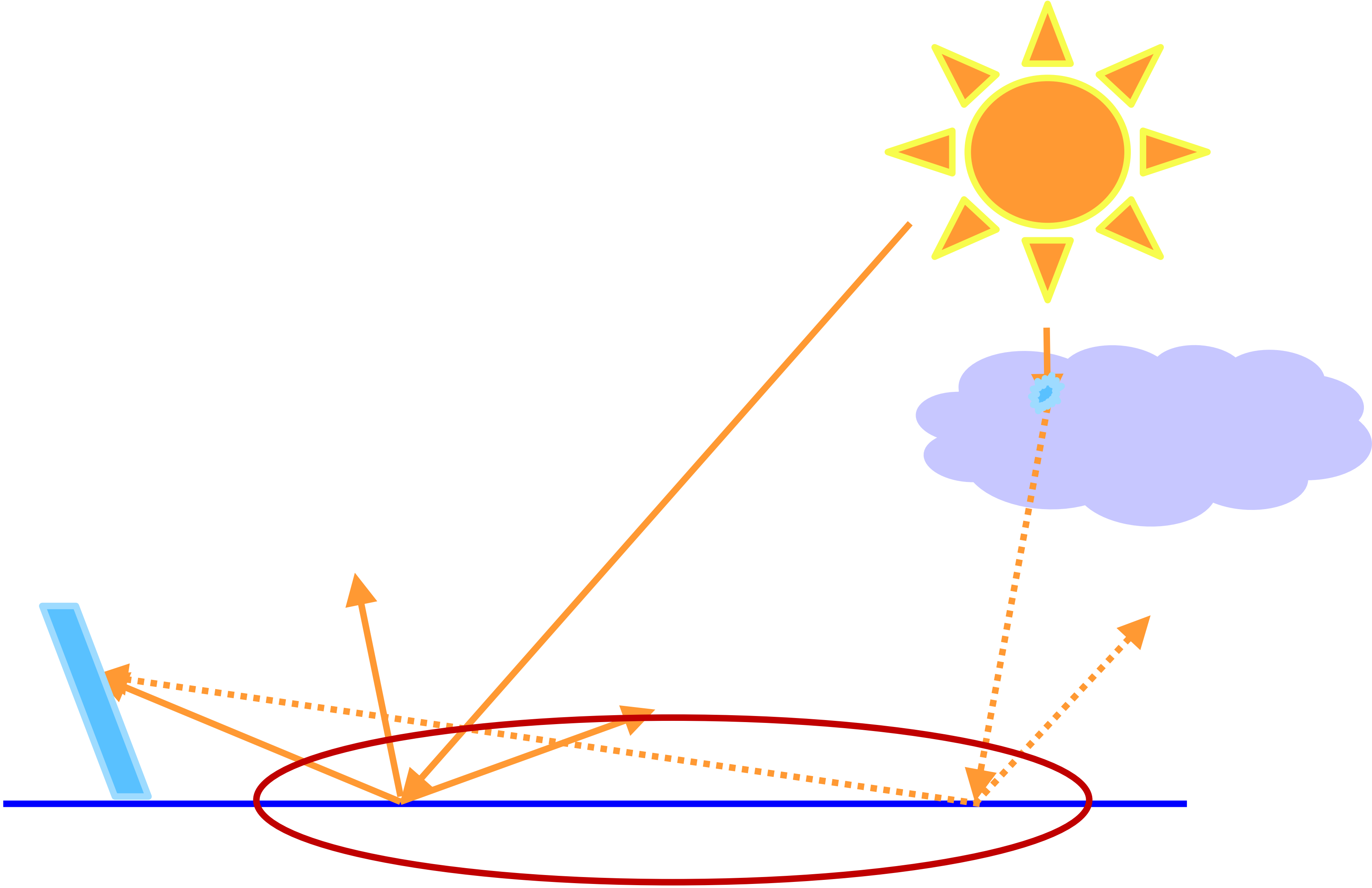
- Thus, the beam radiation on the panel is

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

DIFFUSED RADIATION



RELECTED RADIATION



DIFFUSED AND REFLECTED RADIATION ON THE SOLAR PANEL

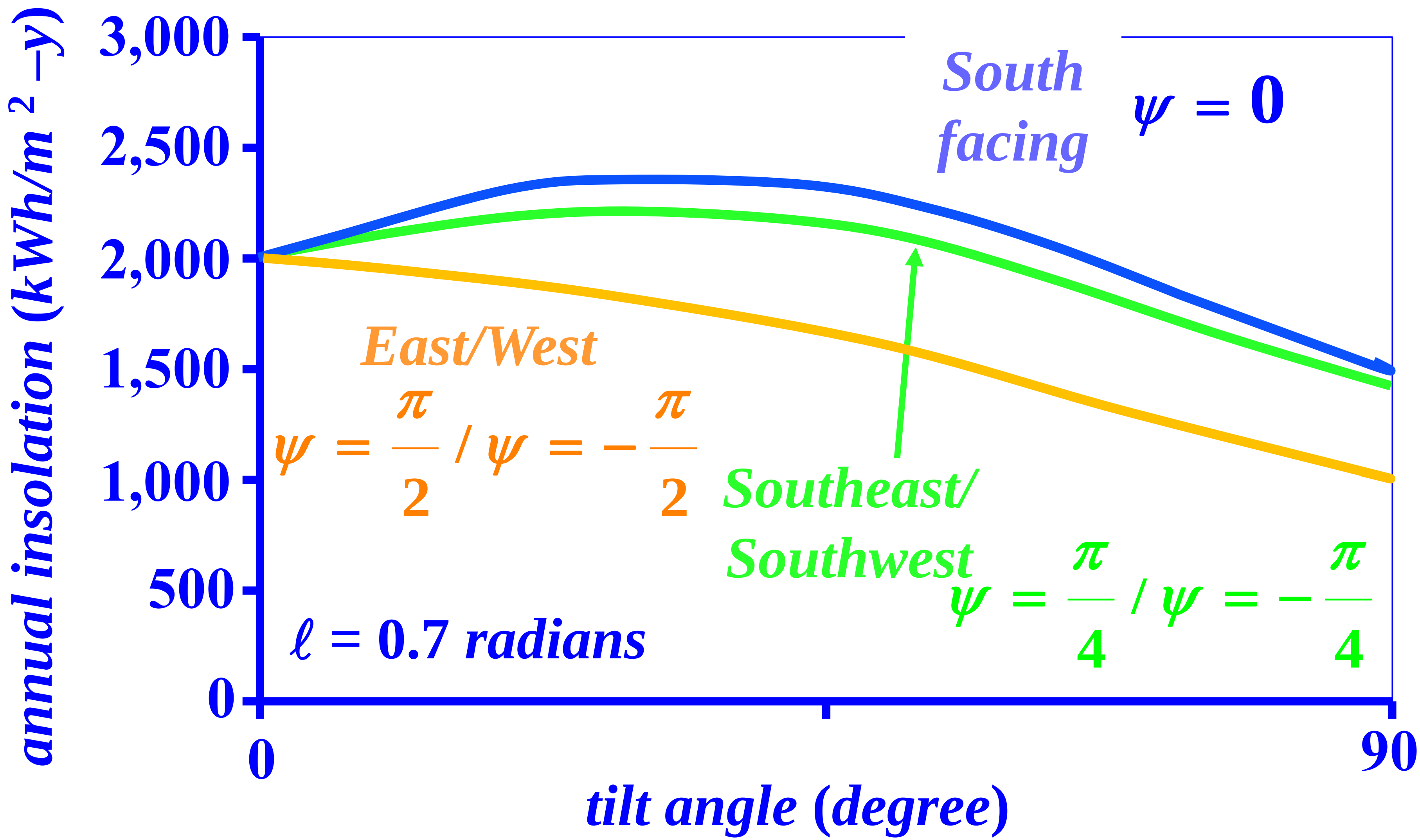
- The indirect radiation components are subject to
  - the uncertain impacts of particles and molecules in the atmosphere
  - the irregularities of the terrain of the earth surface for the reflected radiation

  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 utilize the different components of the insolation in various ways and so approximation methods are used to evaluate the performance of the solar plants
- The clear-sky radiation approximation can be tabulated into *hourly, daily, monthly* and *annual* values to provide the basis to determine the position/orientation of each panel

ANNUAL CLEAR-SKY INSOLATION VARIATION BY TILT ANGLE



APPLICATION OF CLEAR-SKY RADIATION APPROXIMATION

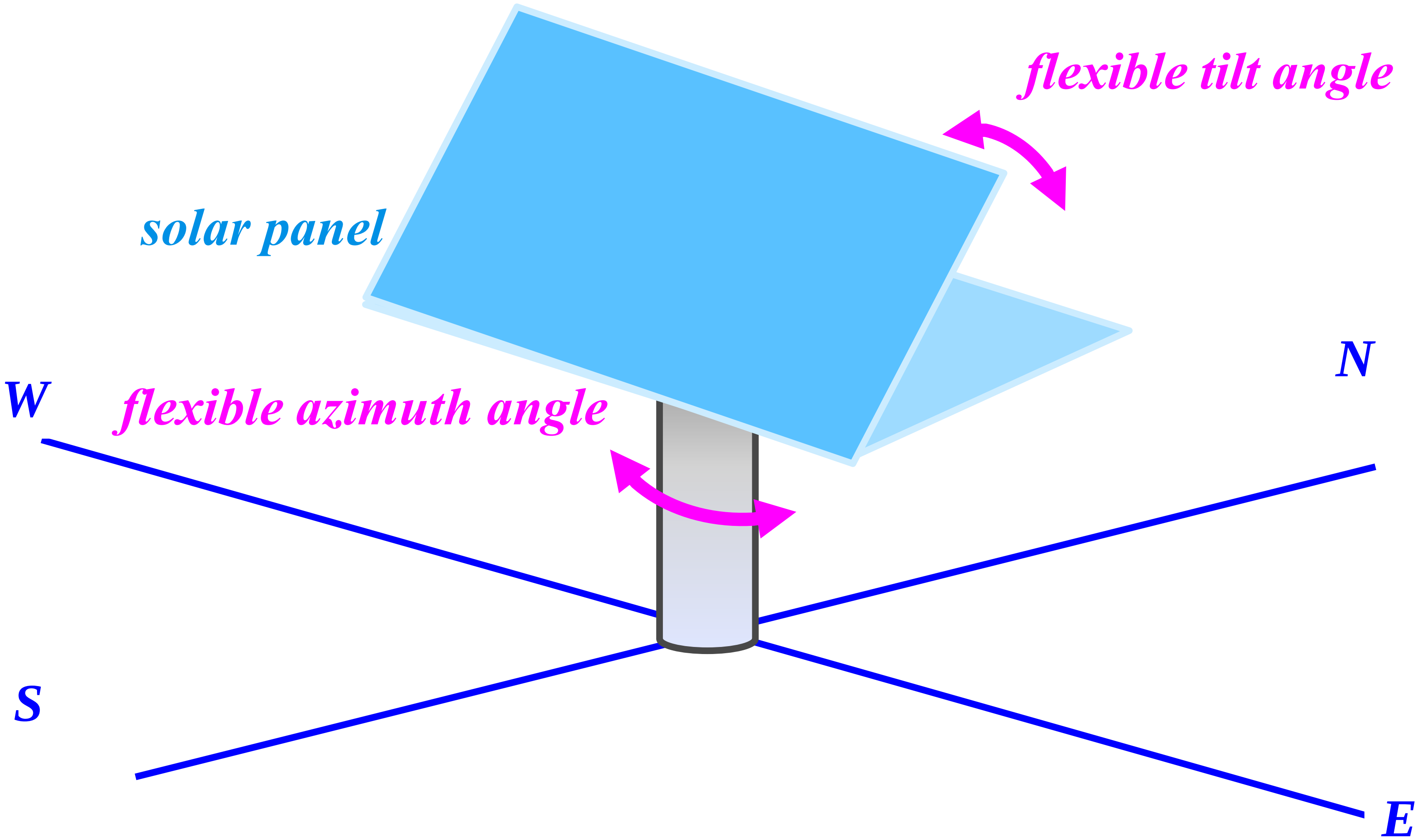
- **We can observe that the solar panel position has significant impacts on the insolation received by the solar panels**
- **Thus, in many circumstances, the solar panels are equipped with *tracking systems*, which allows the panels to track the movement of the sun across the sky and change panel positions to better utilize the insolation the panels receive**

TRACKING SYSTEMS

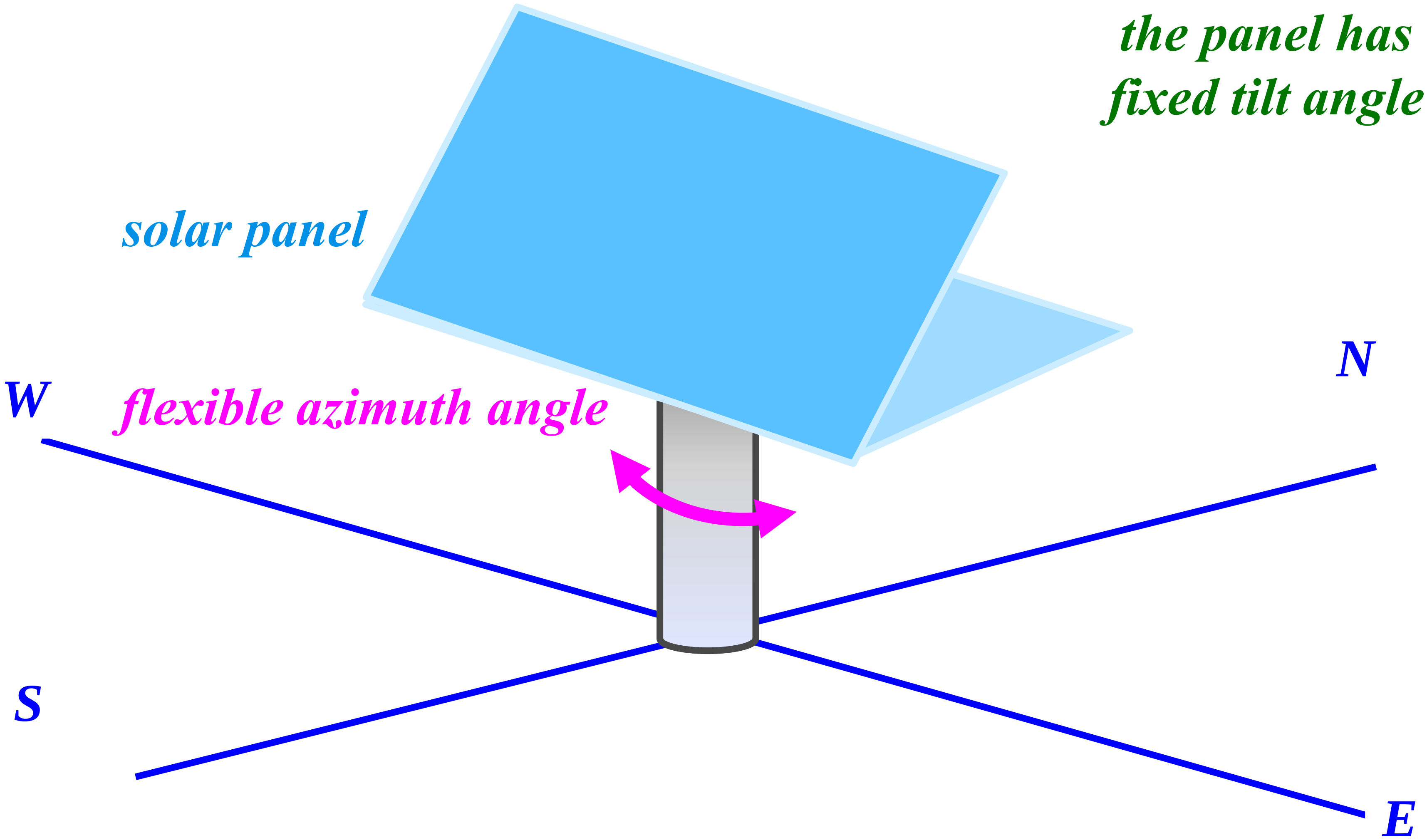
Tracking systems are categorized as

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

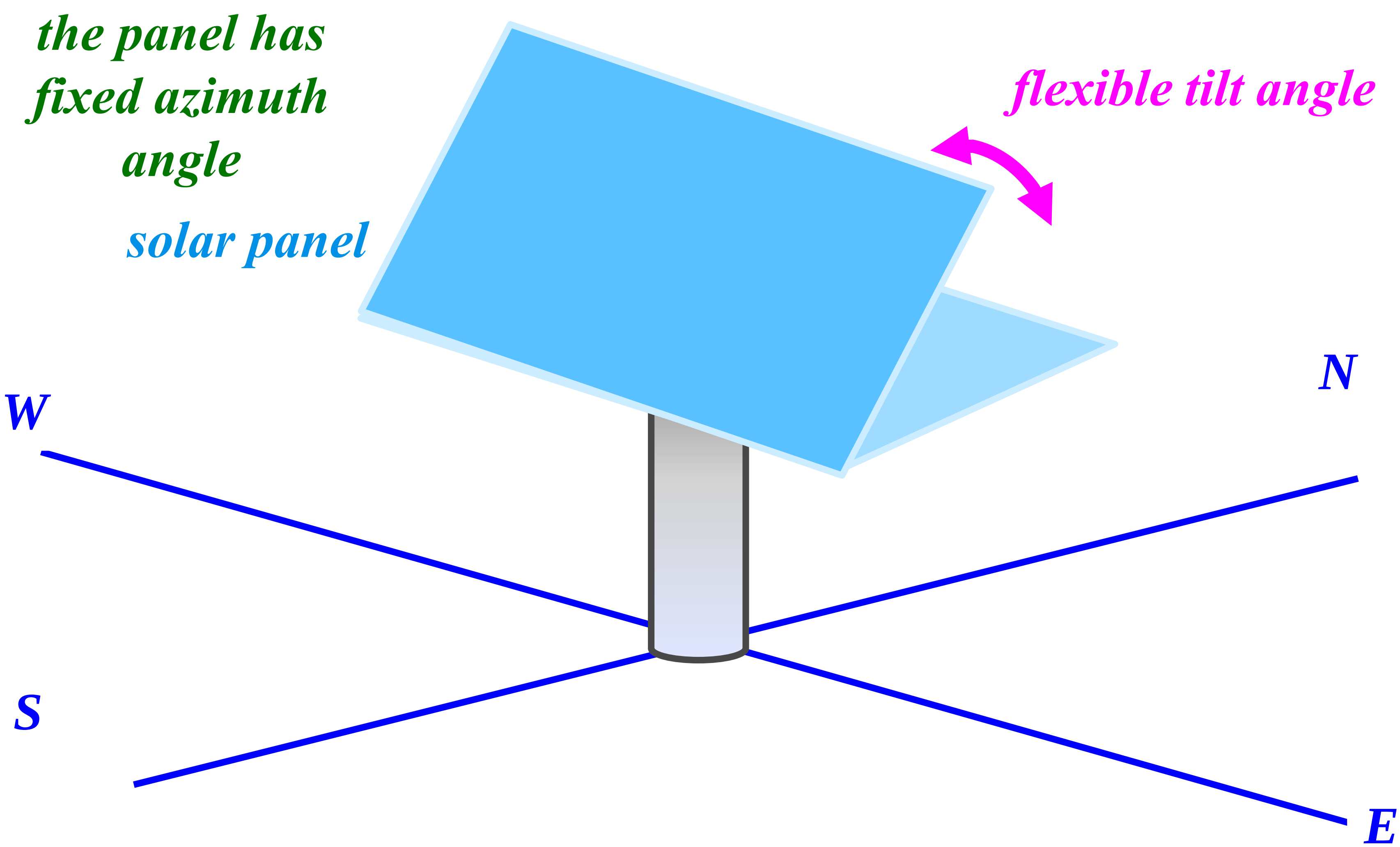
TWO-AXIS TRACKERS



SINGLE-AXIS TRACKERS



SINGLE-AXIS TRACKERS

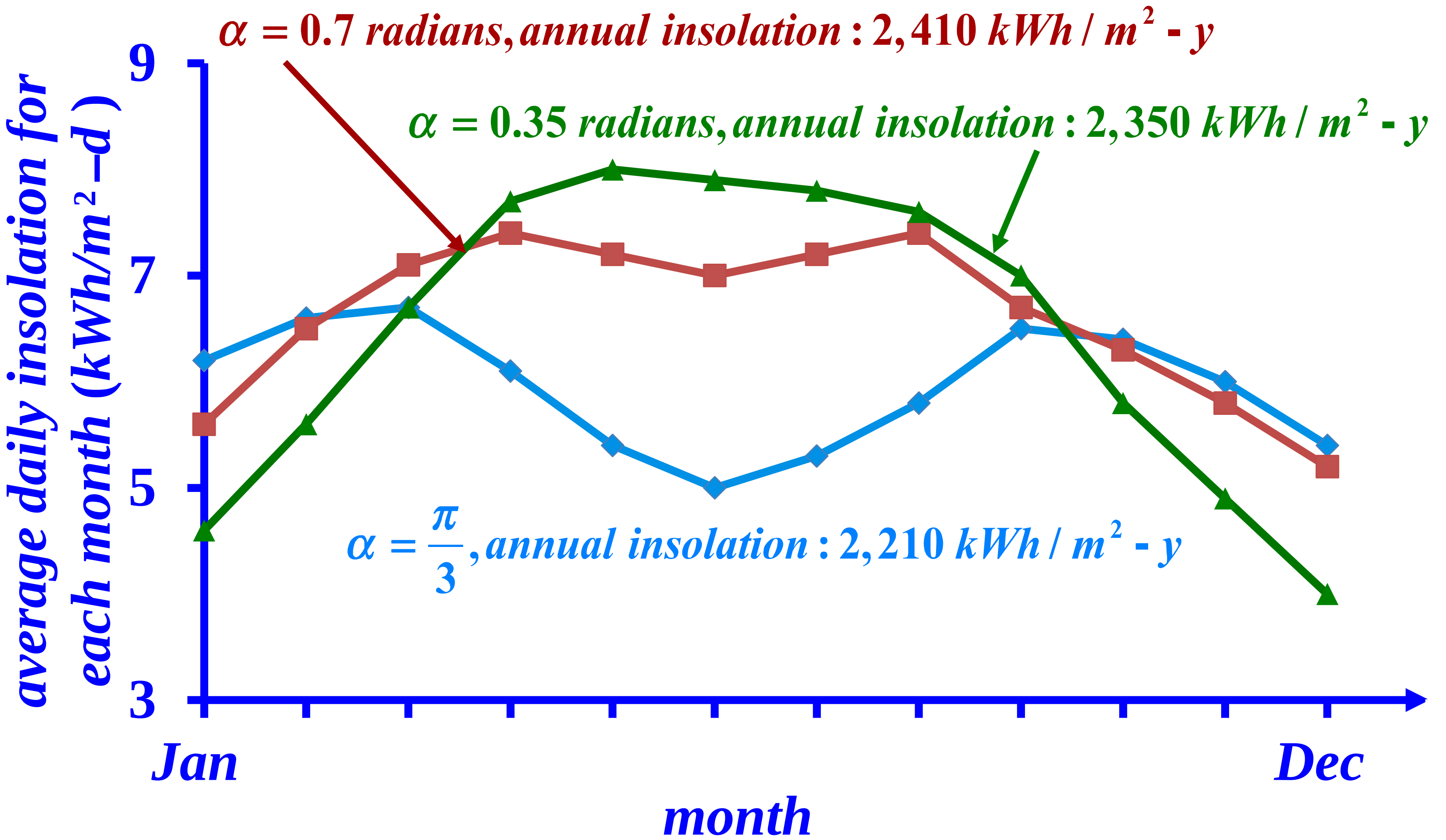


SINGLE-AXIS TRACKERS

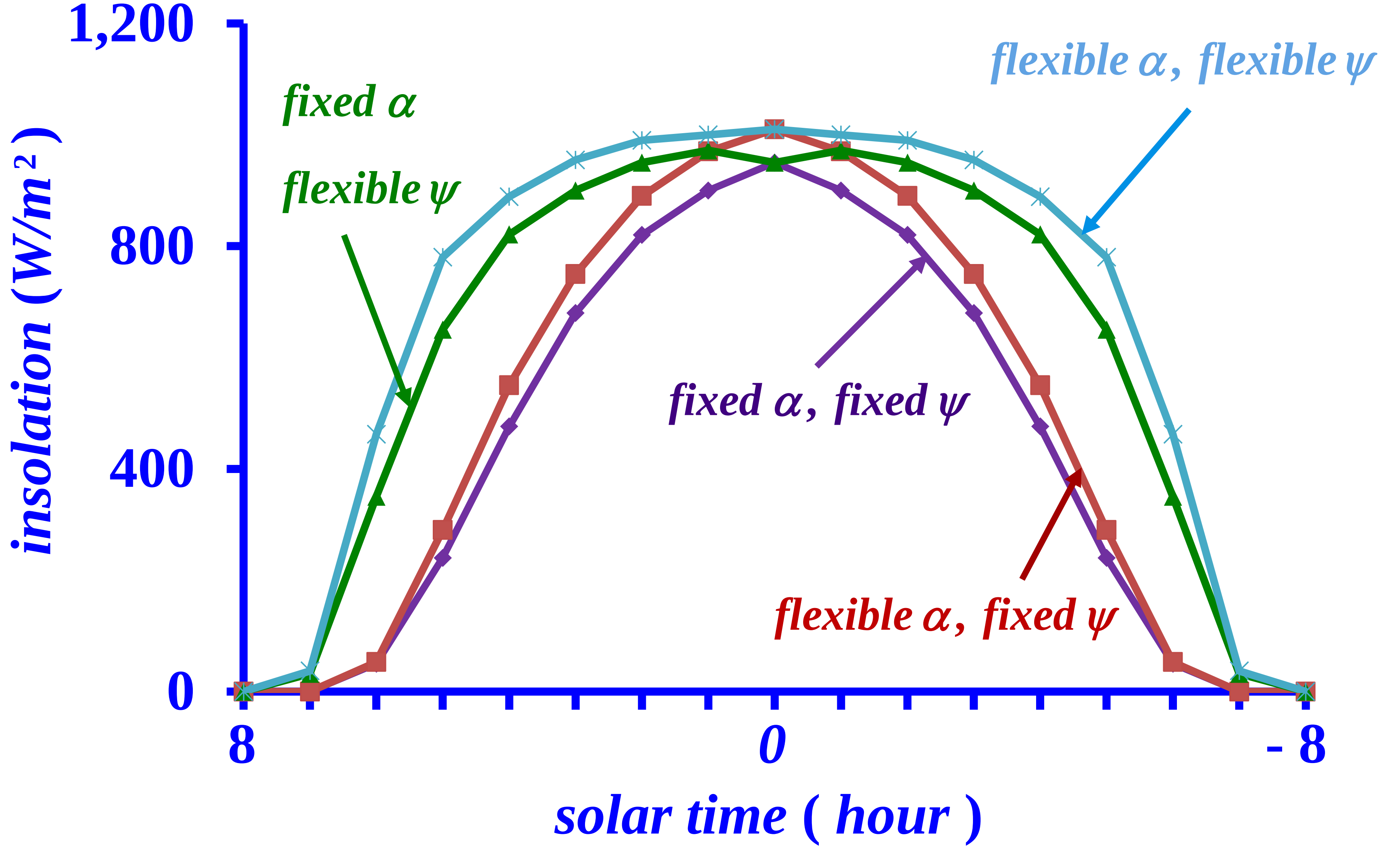
TRACKER

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 is not always satisfied and the insolation is very uncertain and may be intermittent
- Thus, we need specific devices to measure the actual insolation for performing the analysis

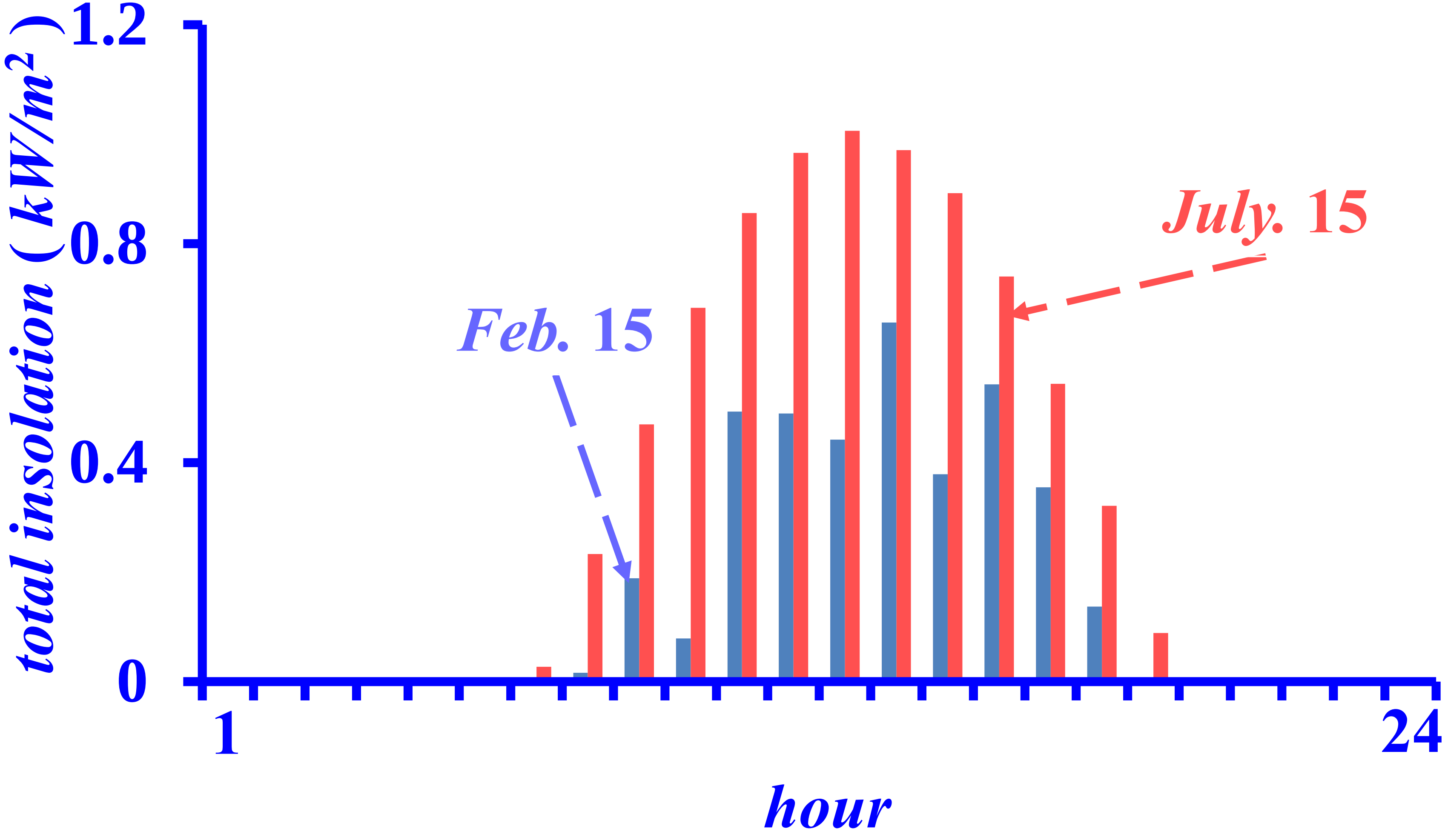
INSOLATION MEASUREMENT DEVICES

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

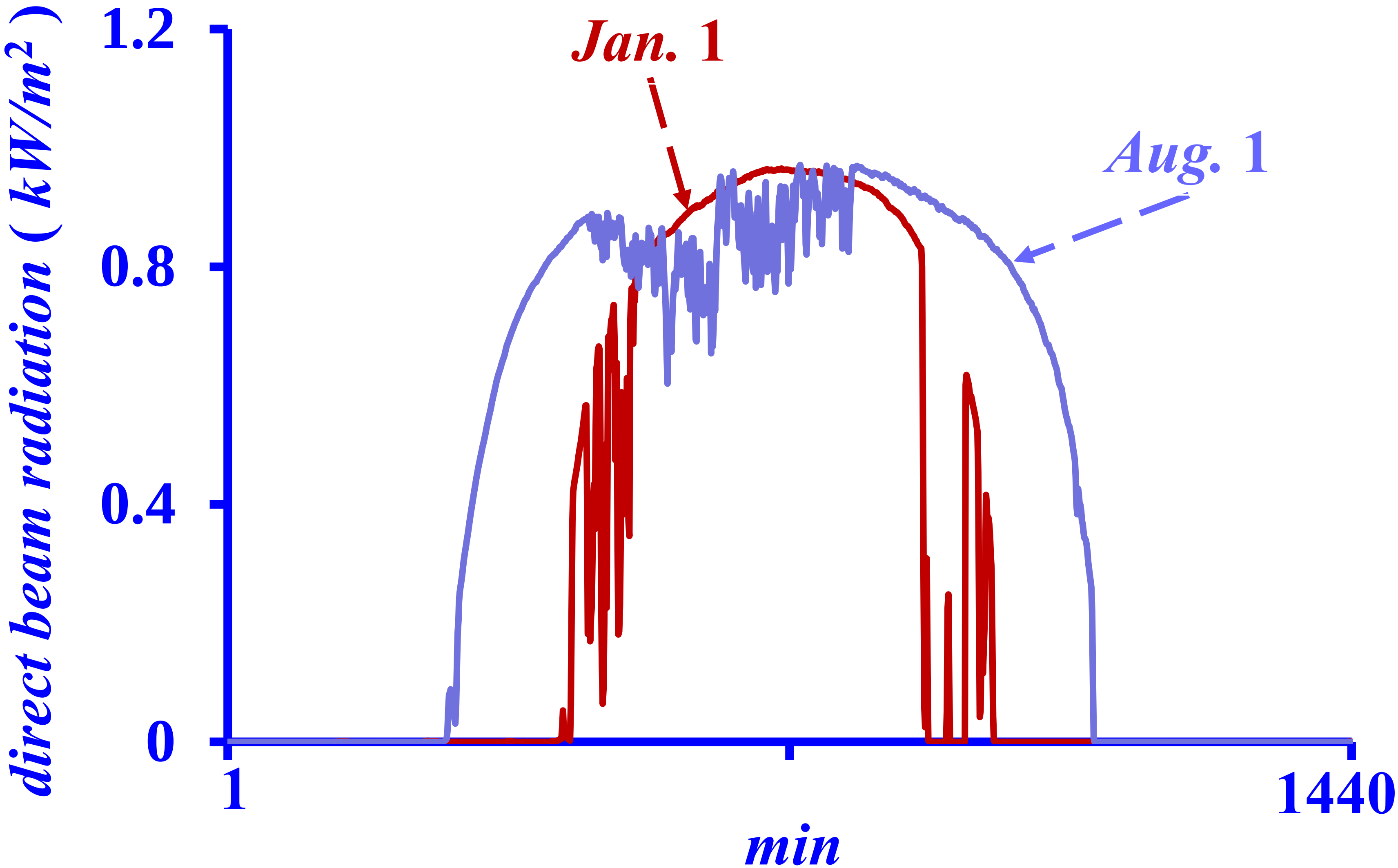
  - ***pyranometer*** **which measures the total insolation of all the three components**

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

PYRANOMETER HOURLY INSOLATION MEASUREMENTS IN ABILINE, TX



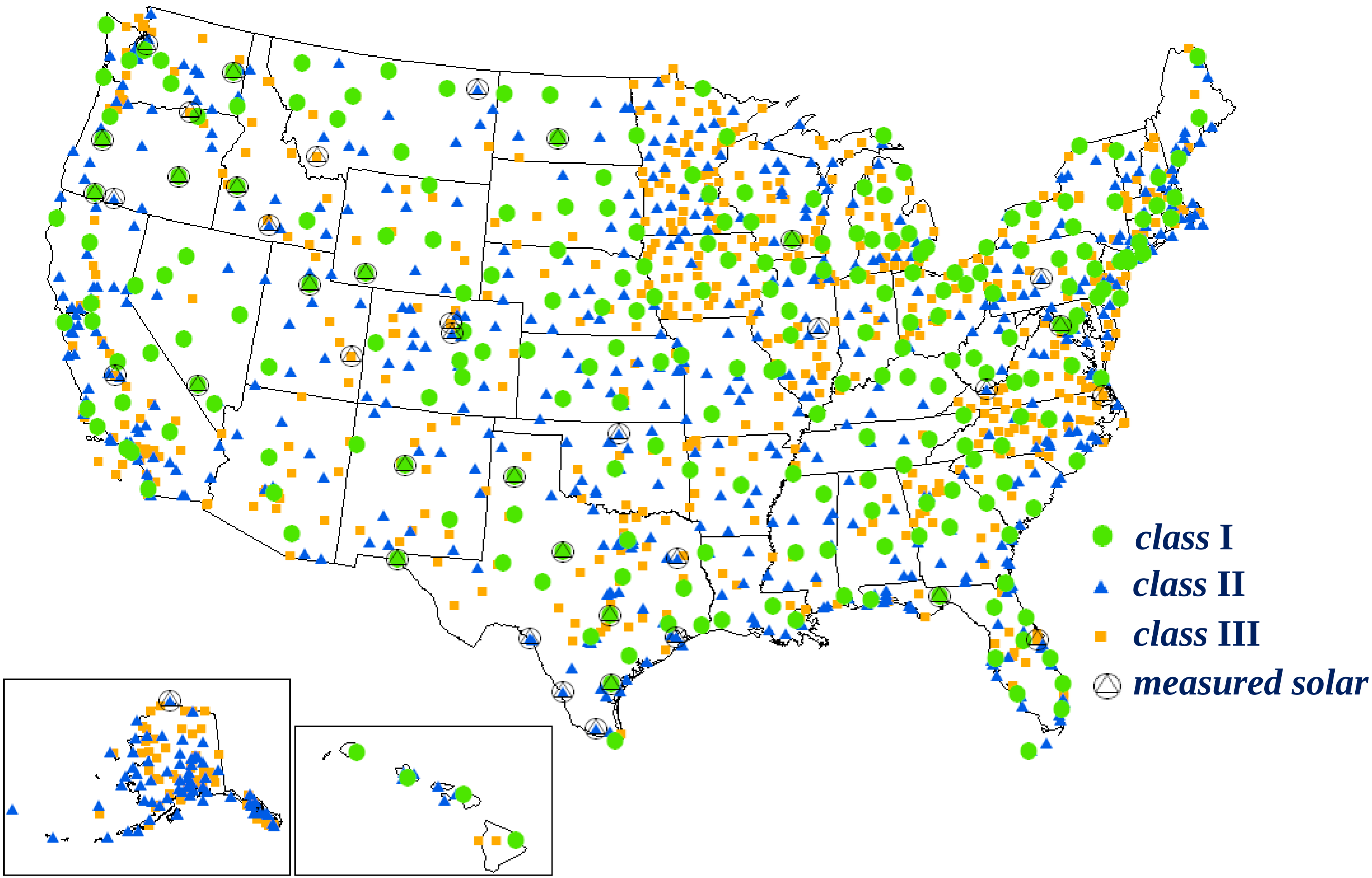
1-*MIN* DIRECT BEAM PYRHELIOMETER MEASUREMENTS: LAS VEGAS



SOLAR IRRADIATION DATA BASES

- *National Oceanic and Atmospheric Administration* (*NOAA*) **constructed the first solar data base of** *U.S.* **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: http://rredc.nrel.gov/solar/old_data/nsrdb/

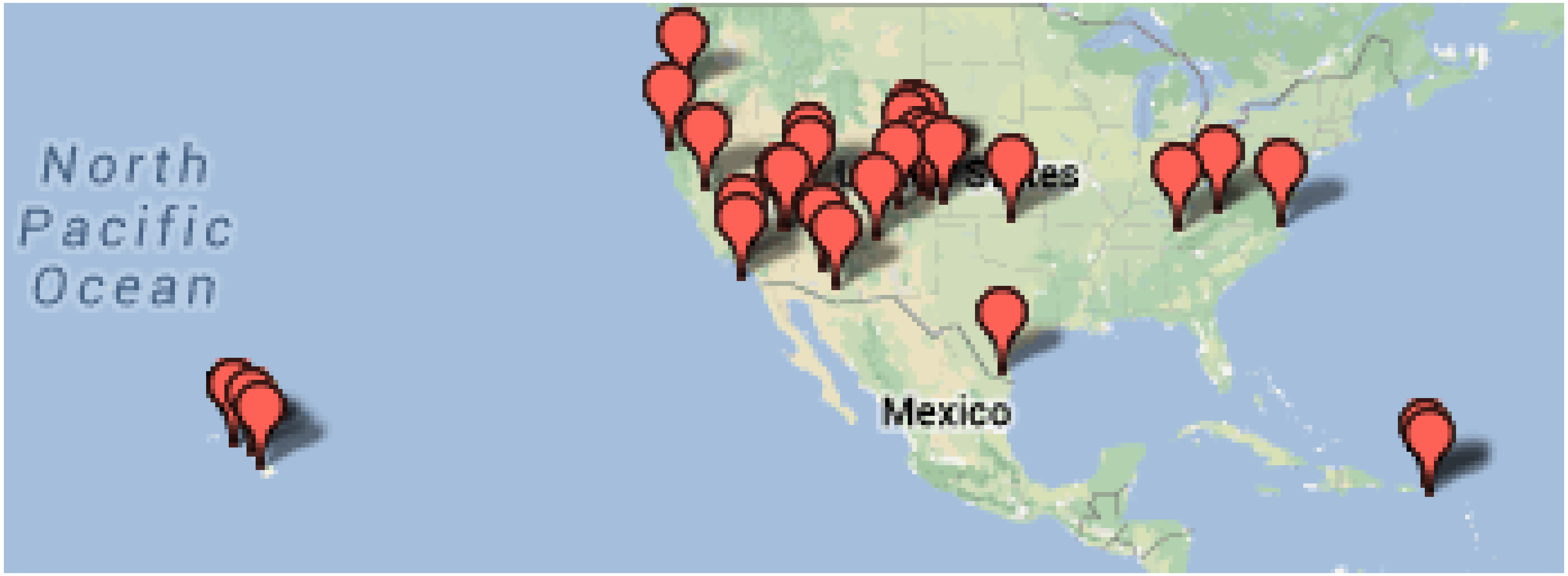
NSRDB STATIONS

- The 221 *Class* I stations have a complete hourly data set
- The 637 *Class* II stations have a complete hourly data set, but assembled from lower-quality input data
- The 596 *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 *U.S.* sites shown below at *http://www.nrel.gov/midc/*



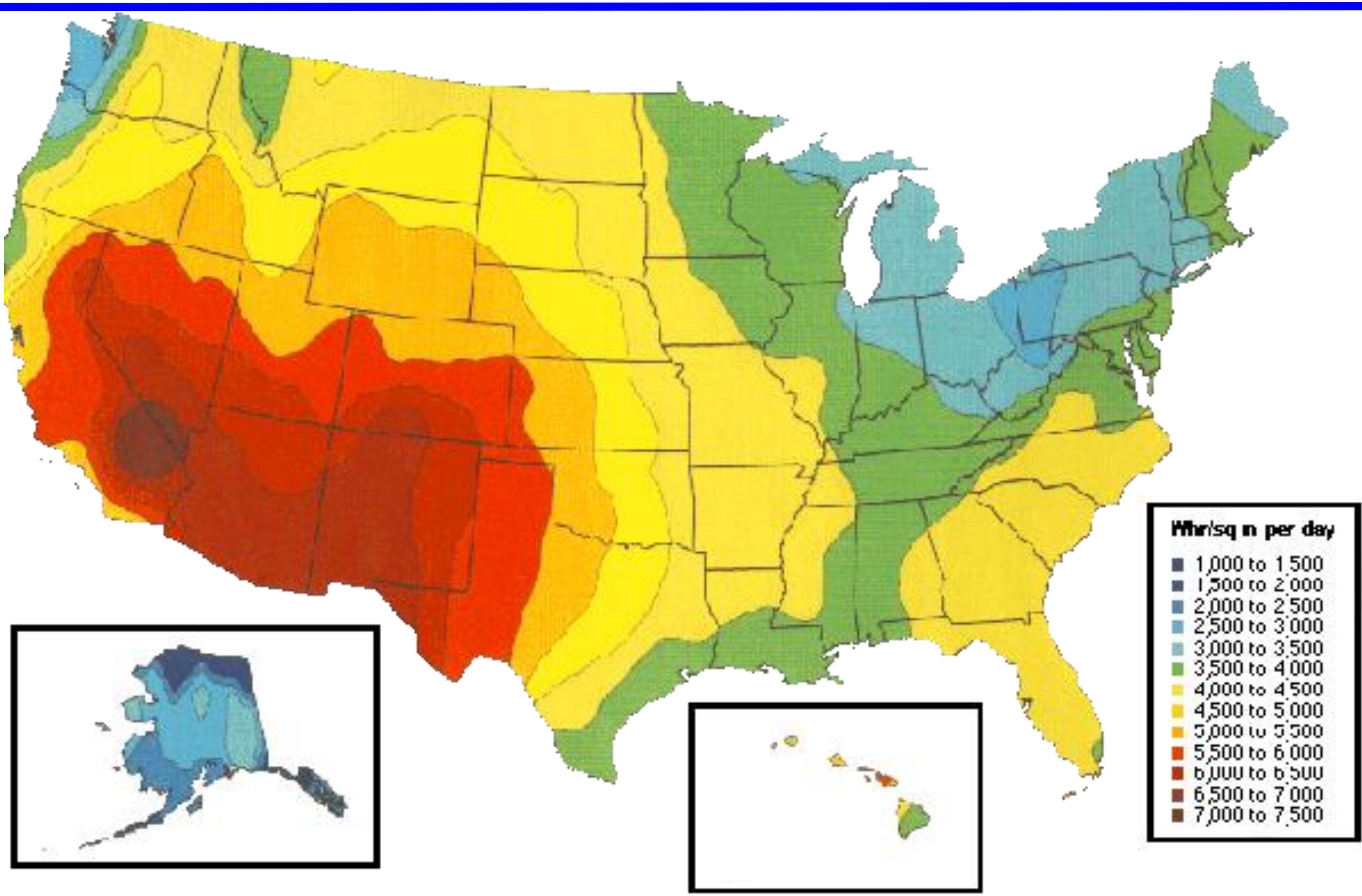
MIDC TYPICAL 1-*MINUTE* SOLAR DATA FILE

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/***

U.S. SOLAR INSOLATION MAP



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

WORLD INSOLATION MAP