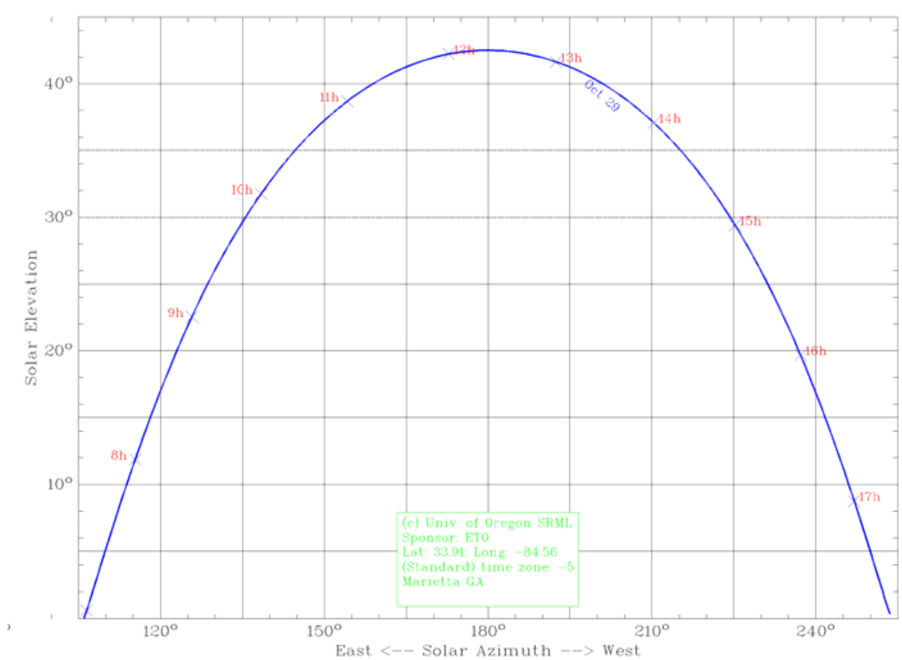
## Data

The electric power produced by the Q-building solar array was monitored for several hours on October 29th, the results of which are shown in Table 3.1.

The system's solar array contains 4 solar panels, each of which is composed of 11 solar modules. Each solar module has a surface area of 1.6m$^2$.

Additionally, the panels are tilted at an angle of 15° such that they are aligned east-west and facing the south.

The position of the Sun in the sky on that day is shown in the following plot:




| 29-Oct | |
|---|---|
| **time** | **$P_{electric}$ (W)** |
| 8:00 | 1930 |
| 8:40 | 3340 |
| 9:20 | 4545 |
| 9:40 | 5135 |
| 10:00 | 5660 |
| 10:20 | 6055 |
| 10:40 | 6390 |
| 11:00 | 6675 |
| 11:20 | 6845 |
| 11:40 | 7050 |
| 12:00 | 7130 |
| 12:20 | 7170 |
| 12:40 | 7130 |
| 13:00 | 7000 |
| 13:20 | 6840 |
| 13:40 | 6600 |

**Note that the times in the table have been adjusted to "Standard Time"**

## Procedure

1. Using the **AM1.5G** total global irradiance $I_{T(G)}$ value of **1000 W/m$^2$** for when the Sun was at its peak elevation angle (which occurs ~12:20pm) and the total surface area $A_{array}$ of the solar array, **calculate**:

   **a)** The total amount of **solar power**, $P_{solar}$, that was incident upon the array, and

   **b)** The overall **efficiency** of the photovoltaic system. ($\eta = P_{electric} / P_{solar}$)

   Note, that the AM1.5G value assumes that the array was aligned such that the surface of the panels was orthogonal to the direct-path of the solar energy. Although the array was pointing to the south, be sure to account for the actual tilt angle of the panels (**$\tau$ = 15°**) when calculating the actual global **surface irradiance $I_{surface}$** that will be incident upon the surface of the solar array.

2. Based on the information provided by the solar position plot, **determine** the **elevation angle** ($\alpha_e$) for the Sun at each time for which the solar array's electric power was recorded. Add the results to the data table in a new column labeled $\alpha_e$.

**3.** Based on the information provided by the solar position plot, **determine** the **azimuth angle** ($\alpha_a$) for the Sun at each time for which the solar array's electric power was recorded. Add the results to the data table in a new column labeled $\alpha_a$.

**4.** Based on the elevation angles, **determine** the **air mass** (***AM***) through which the solar energy must travel to reach the solar array at each time for which the solar array's electric power was recorded. Add the results to the data table in a new column labeled ***AM***.

**5.** Based on the air mass values, **determine** the **total global irradiance** $I_{T(G)}$ that would be incident upon the solar array at each time for which the solar array's electric power was recorded. Add the results to the data table in a new column labeled $I_{T(G)}$.

**6.** Based on the total global irradiance, elevation angle, and azimuth angle values along with the tilt angle of the array, **determine** the global **surface irradiance** $I_{surface}$ that will actually be incident upon the surface of the solar array at each time for which the solar array's electric power was recorded. Add the results to the data table in a new column labeled $I_{surface}$.

**7.** Based on the surface irradiance values along with the total surface area of the array, **determine** the actual **rate** at which **solar energy**, $P_{solar}$, is incident upon the array at each time for which the solar array's electric power was recorded. Add the results to the data table in a new column labeled $P_{solar}$.

**8.** Assuming that the array will operate at a constant efficiency, utilize the solar power values along with the array efficiency value calculated in step 2b to **determine** the theoretical electric power $P_{elec(theory)}$ that the array should produce at each time for which the solar array's electric power was recorded. Add the results to the data table in a new column labeled $P_{elec(theory)}$.

**9.** Using Excel, **plot** both the **measured electric power** and the **theoretical electric power** vs. **time** for the Q-building's solar array (on the same graph) and determine the 2$^{nd}$-order, polynomial, **best-fit curves** that represent each data set.

**10. Compare** the **theoretical electric power** $P_{elec(theory)}$ values to the **measured electric power** $P_{electic}$ values at each time for which the solar array's electric power was recorded by means of a relative difference calculation. Add the results to the data table in a new column labeled ***RD%***.

**11.** Based on the relative difference results, **discuss** the accuracy of the method utilized to predict the theoretical electric power that would be produced by the solar array at the different times of day.

## Report Guide

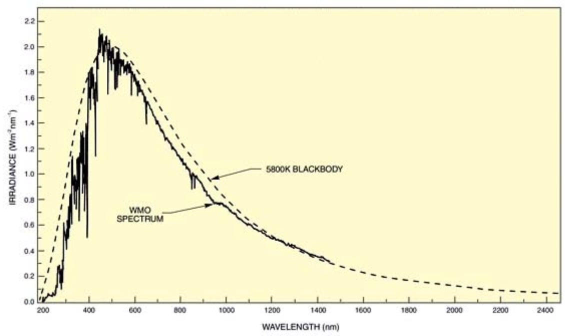
You must submit an electronically-generated, memo-style report that introduces this experiment and presents all of the required results of this experiment.

Note that the submission requirements are stated in the REET 2020 – Course Introduction handout that is available on the course webpage.

## Theory

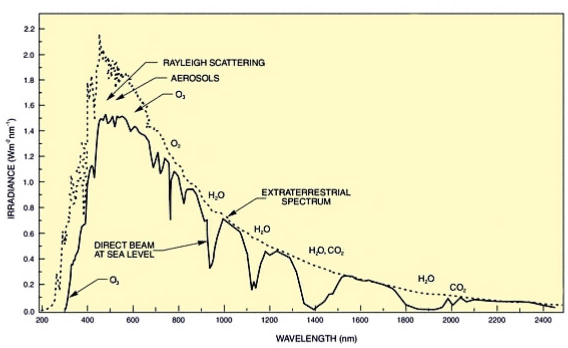
The Sun continuously emits energy in the form of electromagnetic radiation, a tiny portion of which reaches the Earth. Solar **irradiance** is the rate at which the Sun's energy reaches a unit-sized area, and is typically defined in terms of watts (joules/second) per meter$^2$ area.

Currently accepted values for solar irradiance at the outer edge of the Earth's atmosphere are around **1360 W/m²**. These values were obtained by utilizing solar spectral irradiance measurement data from a variety of sources including satellites and space shuttle missions. Although the actual irradiance value fluctuates throughout the year due to both the variation in the earth/sun distance resulting from the Earth's elliptical orbit and the fluctuating solar activity, it provides a good starting point for the analysis or characterization of a solar-based renewable energy systems.



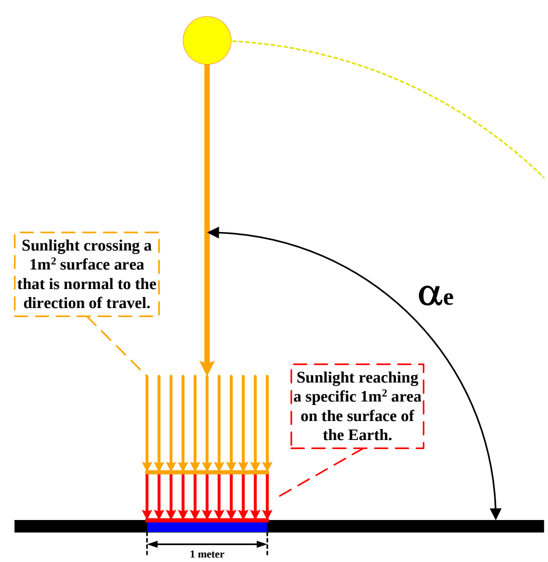

As the energy that reaches the Earth begins to penetrate the atmosphere, several things can happen:

- some of the energy will continue to travel along a direct path,
- some of the energy will be absorbed by the air molecules or atmospheric pollutants, and
- some of the energy will be reflected or scattered by the air molecules or atmospheric pollutants, thus changing the energy's direction of travel.



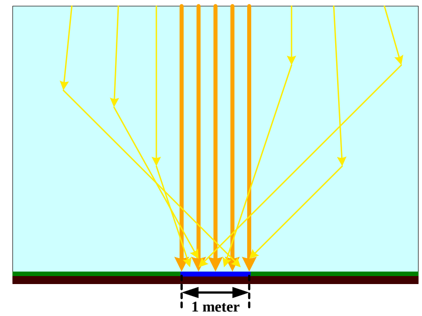

The amount of both absorption and scattering is affected by a variety of factors including the % air composition ($O_2$, $CO_2$, $H_2O$, $N_2$, etc.), the amount and type of atmospheric pollutants, and the distance that the energy travels through the atmosphere. Furthermore, the atmosphere does not affect the solar energy uniformly. For example, water vapor absorbs light at 1400nm but not at 1600nm. Thus, determining the actual amount of energy that reaches the Earth's surface can be problematic.

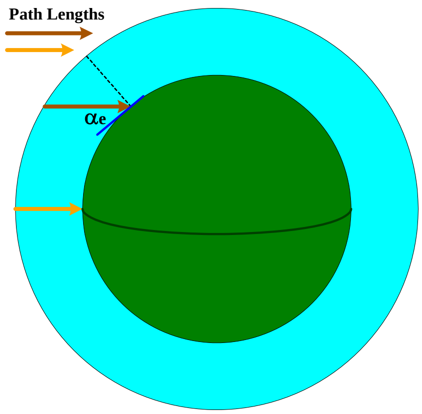
On a clear day, when the Sun is directly overhead with an elevation angle **$\alpha_e$ = 90°**, the solar irradiance at the surface of the earth (at sea-level) is around **1050 W/m²**. This value is assigned to the Air Mass coefficient **AM1.0D**, because the sunlight has traveled along a direct (**D**) optical path through the atmosphere for a distance that is 1.0x the thickness of the atmosphere defined along a path that is normal (⊥) to the Earth's surface.




The direct path value is important when characterizing the operation of Concentrating Solar Power (CSP) systems that only focus direct-path light onto their receivers. But, the AM1.0D coefficient is really only useful for systems that are operating near the equator because at the higher latitudes, the elevation angle of the Sun is typically much lower than 90°, especially during the winter months.

On the other hand, Photovoltaic (PV) Systems convert solar energy into electricity regardless of the angle at which the light is incident upon the PV cells. For this reason, there is also a global (**G**) coefficient that takes into account both the direct-path energy and the energy that reaches the Earth's surface after being scattered or reflected. Global values are typically around 10% larger than their associated direct coefficient values. The **AM1.0G** coefficient value is often assumed to be around **1120 W/m²**.

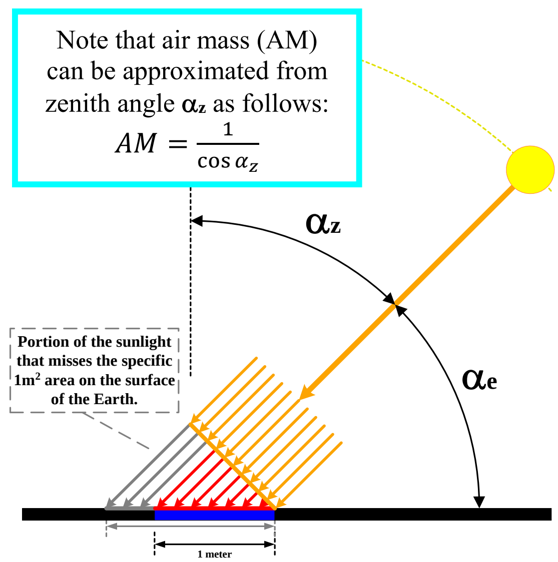


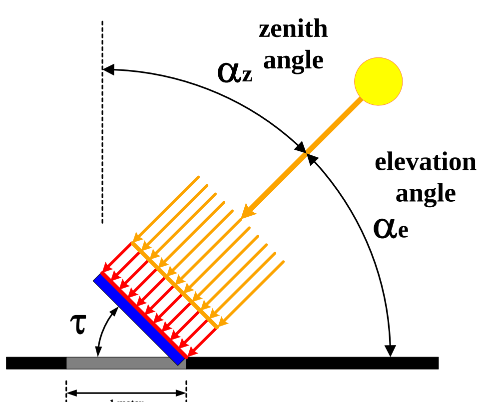

When the Sun is lower in the sky with an elevation angle $\alpha_e$ **< 90°**, which will be the case at higher latitudes, there are two primary mechanisms that affect the amount of energy that reaches a specific 1m² surface area on the Earth's surface:

1) Since the light is entering the atmosphere at an angle, it must travel a greater distance along a direct path to reach the surface of the Earth. The increased distance results in a larger air mass through which the light must travel, in-turn increasing the amount of atmospheric absorption and scattering. Once again, varying atmospheric conditions and pollution levels can make it very difficult when trying to account for the increased air mass.

2) Due to the smaller angle of elevation $\alpha_e$, the light will reach the ground after traveling along a path that is not normal (⊥) to the Earth's surface. Because of this, the energy will be spread out across a greater area along the Earth's surface, resulting in less energy actually reaching a specific 1m² surface area.




Although there is no way to compensate for the effects of the increased air mass that occurs at the higher latitudes, the energy spreading effect that occurs due to the lower angle of incidence upon the target surface area can be compensated for by tilting the surface at an angle $\tau$, where $\tau$ **= 90° –** $\alpha_e$ **=** $\alpha_z$, in order to form an inclined surface that is normal (⊥) to the direction of energy travel.




All of this is further complicated by the fact that the Sun's position in the sky varies by latitude, day of the year, and time of the day. Solar tracking systems that keep the receiving surface oriented towards the Sun, in-turn keeping the angle of incidence at 90° even as the Sun's position varies by time and day of the year, can help simplify matters, but many solar energy conversion systems do not utilize solar trackers. When trackers are not used, then the basic algebraic relationships relating to right triangles can be employed in order to determine the percentage of the direct energy that will actually be incident upon the target surface. Either way, the varying air mass effects will still exist.

In terms of the effect of air mass on the **Direct Solar Irradiance** $I_{T(D)}$, the following relationship can be utilized to approximate the irradiance at the Earth's surface as a function of air mass:

$$I_{T(D)} = I_o \cdot 0.74^{AM^{0.678}} \quad \text{(W/m}^2\text{)}$$

where: $I_o = 1353$ W/m$^2$ (the solar irradiance at the outer edge of the atmosphere), and *AM* is the air mass through which the direct-path light must travel.

If the **Global Solar Irradiance** $I_{T(G)}$, is desired, then the direct approximation is increased by 10%:

$$I_{T(G)} = 1.1 \cdot I_o \cdot 0.74^{AM^{0.678}} \quad \text{(W/m}^2\text{)}$$

Note that the original approximations shown above were based on an empirical fit to experimentally observed data while taking into account the non-uniformities in the atmospheric layers. They were then further modified such that they would return a global irradiance value of 1000 W/m$^2$.

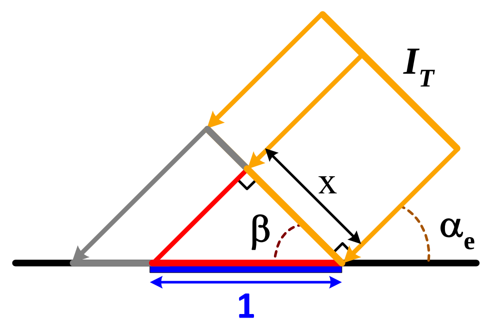
Once the effect of air mass on solar irradiance is determined, the spreading effect due to the angle of the Sun's position can then be determined for non-tracking systems as described below.

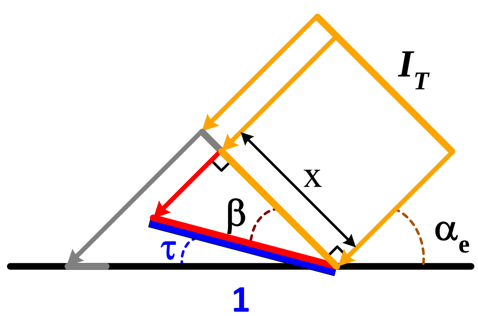
Given a **1m²** surface that is parallel to the ground, if direct sunlight with a total irradiance $I_T$ hits the area while the Sun is at an **elevation angle** $\alpha_e$, then only a portion of the total irradiance, $x \cdot I_T$, will actually hit the 1m$^2$ surface.

The value of ***x*** can be determined utilizing the right-triangle relationship shown in the figure to the right:

$$x = 1 \cdot cos\beta \quad \text{where} \quad \beta = 90° - \alpha_e.$$

Thus: $$I_{surface} = I_T \cdot \cos(90° - \alpha_e)$$




If the **1m²** surface is not parallel with the ground, but instead is tilted at an angle τ, then the portion of the total irradiance, $x \cdot I_T$, that actually hits the 1m$^2$ surface can be determined utilizing the right-triangle relationship shown in the figure to the left:

$$x = 1 \cdot cos\beta \quad \text{where} \quad \beta = 90° - \tau - \alpha_e.$$

Thus: $$I_{surface} = I_T \cdot \cos(90° - \tau - \alpha_e)$$

The above procedure accounts for any variation in the Sun's angle of elevation. A similar procedure can be applied to changes in the Sun's **azimuth angle** $\alpha_a$ as it travels across the sky from east to west throughout the day. Since most solar arrays are oriented towards the south (**$\alpha_a$ = 180°**), the additional effect of energy spreading due to varying azimuth angle can be accounted for by including an additional scale factor as follows:

$$I_{surface} = I_T \cdot \cos(90° - \tau - \alpha_e) \cdot \cos(180° - \alpha_a)$$

Note that both the elevation ($\alpha_e$) and azimuth ($\alpha_a$) angles of the Sun can be obtained as a function of time, date and geographic location by utilizing the **Sun Chart Program** developed by the University of Oregon and found at:

***http://solardat.uoregon.edu/SunChartProgram.html***

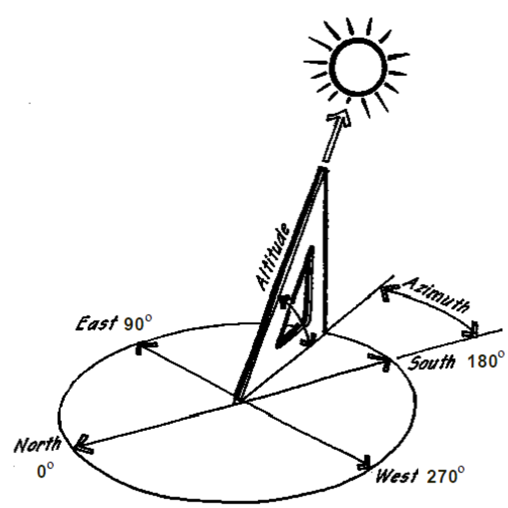



Illustration from *Environmental Control Systems* by Fuller Moore, McGraw-Hill, Inc., 1993, p. 76.

### Characterizing the Total Global Irradiance Incident Upon the Q-Building's Solar Array

In order to characterize the performance of photovoltaic systems, the global (**G**) air mass coefficients are utilized because PV cells accept the solar energy at any angle of incidence. Within the continental United States, the **AM1.5G** standard is typically utilized as the base value for solar irradiance because the conditions upon which the standard is based are representative of those often seen in that area.

The **AM1.5G** standard specifies a solar irradiance of **1000 W/m²** incident upon an inclined planar surface having a tilt angle of **$\tau$ = 37°**, the normal of which points (south) toward the Sun that while it's positioned in the sky with an elevation angle of **$\alpha_e$ = 42°** or a zenith angle of **$\alpha_z$ = 48°**.

> If 1000 W/m² hits the $\tau$ = 37° tilted surface, then the total irradiance would be:
>
> $$I_T = \frac{I_{surface}}{\cos(90° - 37° - 42°)} = 1019 \text{ W/m}^2$$
>
> Since $I_T \approx I_{surface}$, the value **$I_T$ = 1000 W/m²** will be utilized for simplicity.

It turns out that, on the day the data was recorded for this experiment (**Oct. 29, 2018**), the peak elevation angle of the Sun was roughly **$\alpha_e$ = 43°**. This is negligibly different from the elevation angle used for the AM1.5G standard. On the other hand, the tilt angle of the Q-building solar array is **$\tau$ = 15°**, which is notably different from the 37° angle used for the standard. Thus, only a portion of the standard 1000 W/m² will be incident upon the solar array when the Sun is at its peak elevation.

Additionally, the Q-building system has a static array that does not track the Sun as it travels across the sky, instead it always points due south and an incline of 15°. But, as the Sun travels across the sky from sunrise to sunset, both the elevation angle and the azimuth angle of the Sun will vary.

Thus, the following procedure can be applied in order to predict the solar irradiance that will be incident upon the Q-building solar array as the angle and direction of the Sun varies during the day:

**1)** Utilize the Sun Chart Program to **obtain** a **plot*** of the both the **elevation angle $\alpha_e$** and the **azimuth angle $\alpha_a$** of the Sun throughout the day on the date of interest.

* – The plot required for this lab is already provided on the last page of this handout.

**2) Estimate** the values of both the **elevation angle $\alpha_e$** and the **azimuth angle $\alpha_a$** at the times of interest from the solar position plot.

**3)** Utilize the elevation angles **$\alpha_e$** to **determine** the zenith angle of **$\alpha_z$** and then the **air mass *AM*** through which the solar energy must travel at the times of interest. **($\alpha_z$ = 90° – $\alpha_e$)**

$$AM = \frac{1}{\cos \alpha_z}$$

**4)** Then utilize the air mass values to **determine** the **total global irradiance $I_{T(G)}$** that would be incident upon the solar array at the times of interest if its panels were perfectly aligned such that their surfaces were normal (⊥) to the direct-path of energy travel.

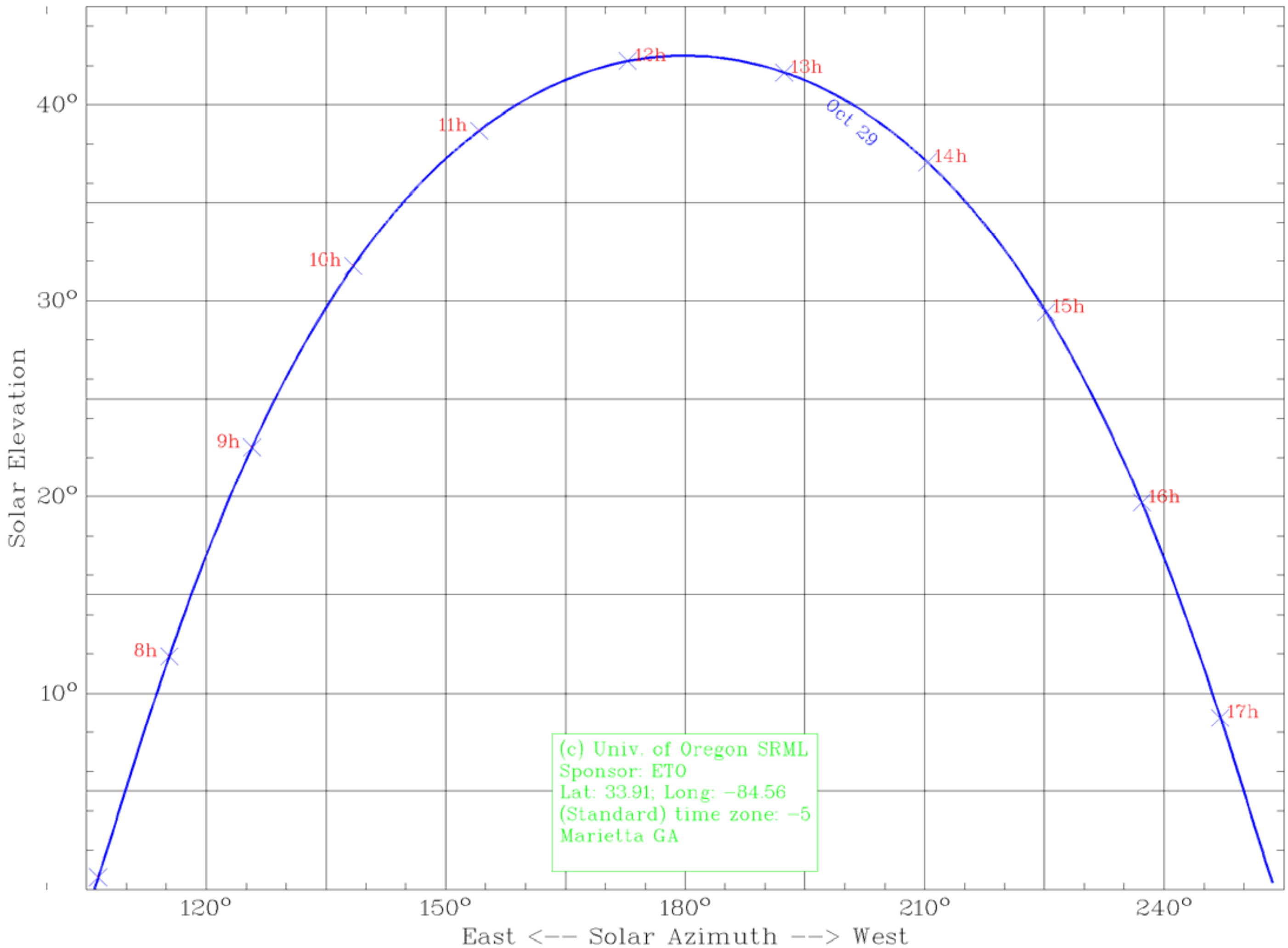
$$I_{T(G)} = 1.1 \cdot I_o \cdot 0.74^{AM^{0.678}} \quad (\text{W/m}^2)$$

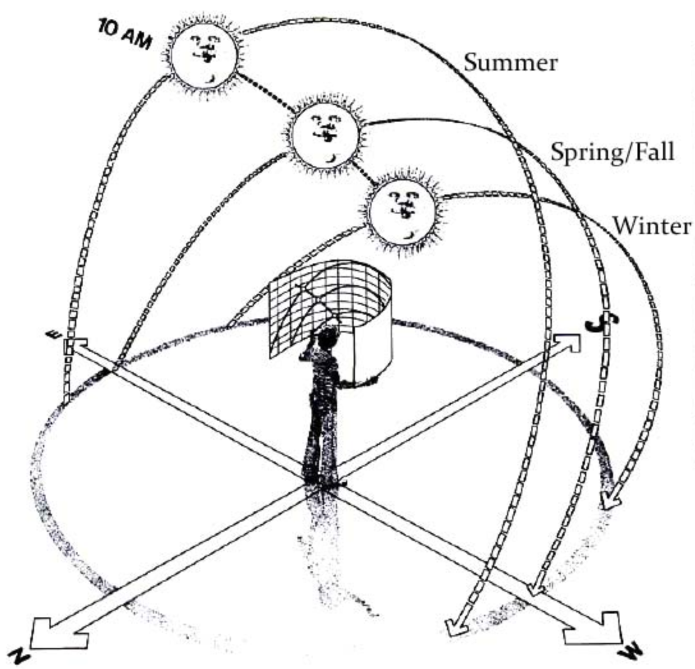
**5)** Finally, utilize the total global irradiance values along with the elevation, azimuth, and tilt angles ($\alpha_e$, $\alpha_a$, and $\tau$) to **determine** the global **surface irradiance $I_{surface}$** that will actually be incident upon the surface of the solar array.

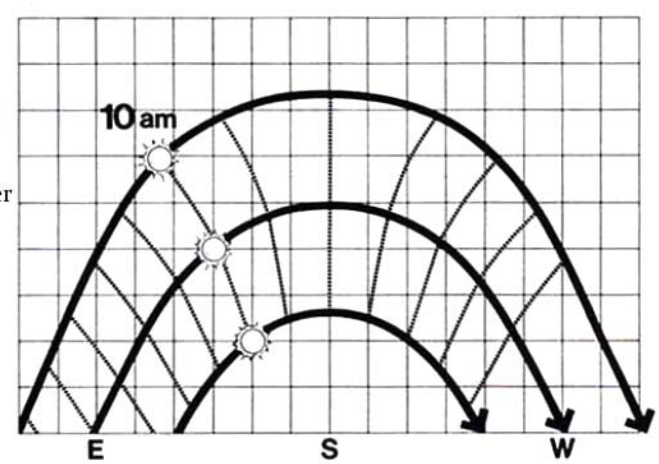
$$I_{surface} = I_T \cdot \cos(90° - \tau - \alpha_e) \cdot \cos(180° - \alpha_a)$$

**6)** The **solar power** or the **rate** at which **solar energy**, **$P_{solar}$**, is incident upon the solar array can be determined by utilizing the surface irradiance values and the total surface area of the array:

$$P_{solar} = I_{surface} \cdot A_{array}$$




Edward Mazria. Passive Solar Energy Book, Expanded Professional Edition
Rodale Press, 1979, Pg. 311