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Lecture 7

7.1 INTRODUCTION

In Modules 4, 5, and 6, extraterrestrial and terrestrial solar radiation components and the terminology have been explained. For various applications, knowledge of solar radiation, ambient temperature and with a few other meteorological parameters (wind velocity, relative humidity etc.) are required. The information may be needed in the design of equipment, or in running or in controlling them. In this Module, measurement methods and the instruments required for measuring solar radiation are described. Ambient temperature measurement is relatively straightforward, though the importance on performance of the solar energy thermal systems is not to be underestimated. Subsequently, in order to facilitate design and performance calculations when data are not available, estimation methods have been dealt with. It is to be understood that "nonavailability" of data is of two kinds: 1) does not exist, i.e., no measurements good enough to obtain statistical averages have been made in the past and 2) not available at the moment and or is not suitable for simple calculations. The second category of the limitation becomes clearer when design methods (essentially simplified methods that can be adapted by non-experts) and philosophy is dealt with. Lastly, several isolated correlations to estimate solar radiation and ambient temperature developed at different points of time by scientists pooled together forms, now, what is commonly being referred to as Synthetic Data Generation. Data so generated essentially mimics the actual data, at east in so far as yielding dependable long term performance estimates of environmentally driven systems in general and solar energy systems in particular. Use of synthetic data further has the advantage of easy implementation on a computer.
7.2 SOLAR RADIATION MEASURING INSTRUMENTS

There are two types of infrared detectors for solar radiation measurement. The difference is in the detectors, thermal detectors and photon detectors. Heating effect of incident radiation causing a change in some physical property of the detector is the principle underlying the thermal detectors. The time constant of the detectors should be small for responding to quick changes in the incident radiation. However, a quick response requires a long time constant and a low heat capacity. Fortunately, time constant of several seconds can be accepted in solar radiation measurements, since the systems in general massive and have long time constants. Photon detectors convert some of the incident radiation directly into electricity, which is proportional to the incident radiation. The detecting capability, in general, of photon detectors is one or two orders of magnitude greater. However, the penalty associated with photon detectors is that their spectral response is non-uniform.

Alternately, instruments to measure solar radiation broadly fall into two three categories. Those, 1) measure global radiation 2) diffuse radiation and 3) direct radiation. It is easy to envisage that, it is best to measure normal incident direct radiation and in order to do this, the instrument sensor needs to face the sun always. This calls for a tracking instrument with consequent inconvenience and additional equipment to follow the sun. Most often, global and diffuse components of radiation are measured and direct radiation measurements be used in checking the other two measurements. The instruments used to measure global radiation are referred to as, Pyranometers, and those used to measure diffuse radiation are referred to as pyranometers with shading ring which cuts off the direct radiation. The instruments that measure direct radiation are called pyrheliometers.

Pyranometers

Eppley pyranometer designed by Kimball and Hobbs [3], of US Weather Bureau has become the most widely used working pyranometer. The Eppley Pyranometer's detector or the working surface consists of two concentric silver rings. The inner ring is coated with Parsons optical black lacquer and the outer one is coated with white magnesium oxide. The temperature difference between the two is an indication of the incident solar radiation and is measured by a thermopile. The sensor is placed inside a hermetically sealed spherical lamp bulb filled with dry air. The detector is best when used to measure horizontal radiation. A reduction of 5% output is caused when the instrument is mounted vertically due to convective currents in the glass enclosure.

The new Eppley pyranometer equipped with a thermister compensated electrical circuit reduced the temperature dependence and improved the cosine response.
Moll - Gorczynski Pyranometer ( Kipp Solarimeter )

The Moll - Gorczynski pyranometer is a thermopile instrument, in which the receiving surface is covered by two concentric ground and polished glass hemispherical domes of 2-mm thickness. The thermopile surface is rectangular and is orientation sensitive.

Other Pyranometers

Dirmhirn - Sauberer Pyranometer also called Star Pyranometer, Volochine Pyranometer, and Yanishevsky Thermoelectric Pyranometer are the other pyranometers with some variation in the detector or the sensor arrangement.

Bimetallic Actinographs

Bimetallic actinographs are self contained recorders. The temperature difference between a black coated bimetallic strip exposed to solar radiation and two similar bimetallic strips either painted white or shielded from solar radiation is recorded through a mechanical linkage. The relatively large mass of the bimetallic strips makes the instrument slow in response and mechanical linkage is an additional source of error, even though some improvements have been incorporated.

Diffuse Pyranometers

Pyranometers described measure the global solar radiation, i.e.; they receive both direct and diffuse components of radiation. The same instrument can be used to measure diffuse radiation by shielding the sensor element from direct radiation. The shielding of direct radiation is accomplished by fitting a shading ring of predesigned width the shadow of which just shields the sensor of the pyranometer. The ring needs an adjustment once a day, such that the path of the sun from sunrise to sunset is included in the plane formed by the shading ring and its base diameter.

Though, all the pyranometers described produce an electric output, which can be read out by a millivoltmeter or a microvoltmeter, continuous recording for subsequent integration ( to obtain, hourly, or daily totals ) need recorders and or integrators that need uninterrupted power supply. In the absence of which power failures, not only disrupt the recording, may also cause initialization problems and the readings become suspect.
Sunshine Recorder

The sunshine recorders essentially static, do not require power supply and alleviate the difficulties faced by the recorders where uninterrupted power supply is not available. They are essentially, spherical lenses, which blacken a sensitive strip. The length of the charred portion of the strip is related to the solar radiation with the help of measurements made by alternate instruments. The empirical constants derived in the relations are expected to be valid for the type of climate for which they are derived. Though these recorders are only approximate, they are simple to use. Indeed, significant numbers of studies have been made in deriving reliable constants and examining their applicability for different climates.

*Campbell-Stokes* Recorder focuses solar radiation to burn a trace in a chart.

*Jordan* Recorder focuses sunlight on to photographic paper.

*Marvin* Recorder makes use of a thermoelectric switch to actuate a chronograph to trace the sunshine hours.

The daily global solar radiation on a horizontal radiation $H$ is related to the number of hours of bright sunshine (directly related to the length of the blackened portion of strip) according to Page [4], (originally Angstrom expressed in terms of clear sky radiation, see, Duffie and Beckman [1]) relation,

$$\frac{H}{H_o} = a + b \left( \frac{N_b}{N_s} \right)$$  \hspace{1cm} (7.1)

In Eq.(7.1), $H_o$ is the daily extraterrestrial horizontal radiation, $N_b$ is the number of hours bright sunshine and $N_s$ is the number of sunshine hours for the day. Eq.(7.1), performs satisfactorily for the climate type for which the constants $a$ and $b$ have been derived, particularly for the monthly average daily values, i.e., the relation given by Eq.(7.1) may be rewritten as,

$$\frac{\bar{H}}{\bar{H}_o} = a + b\left( \frac{\bar{N}_b}{\bar{N}_s} \right)$$  \hspace{1cm} (7.2)

In Eq.(7.2), $\bar{N}_b$ and $\bar{N}_s$ are the monthly average (or even total) bright sunshine hours and possible sunshine hours.

Pyrheliometers

*Angstrom Compensation Pyrheliometer* is one of the most commonly used pyrheliometer.

The other pyrheliometers include *Abbot Silver-Disk Pyrheliometer, Michelson Bimetallic pyrheliometer* and *Linke-Feussner Pyrheliometer*. *Michelson Bimetallic pyrheliometer* and *Linke-Feussner Pyrheliometer* are also called *Actinometers*.
Eppley (Normal Incidence) Pyrheliometer is another popular pyrheliometer. Moll-Gorczynski Pyrheliometer comes in two models, short tube and long tube. The difference is in including or otherwise of circumsolar radiation.

Yanishevsky Thermoelectric Pyrheliometer incorporates a symmetrical star shaped thermal battery and has an angular aperture of $10^\circ$, which is twice the diameter of the sensor. Battery sensitivity is about $7 \text{ mV} / [\text{cal} / (\text{cm}^2 \text{ min})]$. The 99% response is about 30 sec.

Photovoltaic Silicon Pyrheliometer, makes use of the silicon solar cell property that the short-circuit current is proportional to the radiation intensity at normal incidence.

Active Cavity Radiometer is the newest (Wilson, [5]) instrument developed at the Jet Propulsion Laboratory, Pasadena, CA, USA for accurate measurement of irradiance in absolute units. It is a reference standard pyrheliometer.

7.3 ESTIMATION OF SOLAR RADIATION OR DETAILS AND INTERRELATIONS

In this section most commonly employed correlations and the latest relations available for estimating the solar radiation or details of solar radiation are presented. Later, the available information (in the literature) is shown as a flow chart, which forms the basis of synthetic data generation. Also identified are certain missing links, when developed complete the synthetic data scheme.

Diffuse Fraction correlations

The correlation due to Orgil and Hollands [6], relates the hourly diffuse fraction to the hourly clearness index $k_T = (I / I_o)$ according to,

$$
\frac{I_d}{I} = \begin{cases} 
1.0 - 0.249k_T & \text{for} \quad k_T < 0.35 \\
1.557 - 1.84k_T & \text{for} \quad 0.35 < k_T < 0.75 \\
0.177 & \text{for} \quad k_T > 0.75 
\end{cases}
$$

(7.3)

The daily diffuse fraction is related to the daily clearness index ($K_T = H/H_o$) by Collares-Pereira and Rabl [7], according to,
\[
H_d/H = \begin{cases} 
0.99 & \text{for } K_T \leq 0.17 \\
1.188 - 2.272 K_T + 9.473 K_T^2 - 21.865 K_T^3 + 14.648 K_T^4 & \text{for } 0.17 < K_T < 0.75 \\
-0.54 K_T + 0.632 & \text{for } 0.75 < K_T < 0.80 \\
0.2 & \text{for } K_T \geq 0.80 
\end{cases}
\]

(7.4)

The monthly average daily diffuse fraction has been related by Collares-Pereira and Rabl [7] to the monthly average daily clearness index \((\overline{K}_T = \overline{H}/\overline{H}^*_d)\) and the sunset hour angle, \(\omega_s\), according to,

\[
\frac{H_d}{H} = 0.775 + 0.00653(\omega_s - 90) - [0.505 + 0.00455(\omega_s - 90)]\cos[15\overline{K}_T - 103]
\]

(7.5)

Liu and Jordan [8] correlated the ratio of hourly diffuse radiation on a horizontal surface to the daily diffuse radiation on a horizontal surface, \(r_d = I_d/H_d\) as,

\[
r_d = \frac{\pi}{24} \frac{\cos \omega - \cos \omega_s}{\sin \omega_s - (2\pi \omega_s/360)\cos \omega_s}
\]

(7.6)

Collares-Pereira and Rabl [7] correlated the ratio of hourly global radiation on a horizontal surface to the daily global radiation on a horizontal surface, \(r_t = I/H\) as,

\[
r_t = \frac{\pi}{24} (a + b \cos \omega) \frac{\cos \omega - \cos \omega_s}{\sin \omega_s - (2\pi \omega_s/360)\cos \omega_s}
\]

(7.7)

Where,

\[
\begin{align*}
a &= 0.409 + 0.5016 \sin(\omega_s - 60) \\
b &= 0.6609 - 0.4767 \sin(\omega_s - 60)
\end{align*}
\]

(7.8)

It may be noted that in Eqs.(7.6) and (7.7), \(\omega_s\) is in degrees. Also, it is left as an exercise to the reader to recognize that, \(r_d\) given by Eq.(7.6) also equals to the ratio of hourly extraterrestrial radiation on a horizontal surface to the daily extraterrestrial radiation on a horizontal surface, i.e., \(I_o/H_o\). This feature is specially mentioned in order to emphasize, that \(r_d\) as correlated by Liu and Jordan [8], given by Eq.(7.6) is purely geometric relation and hence can not take care of climatic or location dependence. This lacunae as well as accounting for asymmetry have been taken into account by Satyamurty and Lahiri [9].
Distribution of Clearness Indices

Liu and Jordan [8], studied the distribution of hourly clearness index distributions based on the data of north American locations and developed cumulative frequency, \( f \), distribution curves. Cumulative frequency, is the fraction of the time that occurs below a certain specified clearness index. For example, For a fixed monthly average daily clearness index, \( \bar{K}_T \), 30 or 31 daily clearness indices, \( K_T \)'s are associated. If, 17 daily clearness index values in the month are less than, say, a value of \( K_T = 0.62 \), the cumulative frequency, \( f = 17/30 = 0.6 \). Thus, if a generalized distribution of \( K_T \) vs. \( f \) for a fixed \( \bar{K}_T \) becomes available, from a known monthly average daily clearness index, the 30 or 31 daily clearness index values can be generated. Thus, in terms of dimensional quantities, if the monthly average daily global radiation on a horizontal surface is known, the thirty (or 31) daily values can be generated. The original Liu and Jordan [8] are shown in Fig. 7.1.

![Fig. 7.1 Liu and Jordan distribution of clearness indices](image)

Liu and Jordan [8] have shown that these distribution curves can be applied for the hourly distribution of clearness index. If \( \bar{k}_r \) \{see, Eqs.(6.4) and (6.5)\} is the monthly average hourly clearness index for a particular hour in the month of 30 or 31 hourly clearness index values and hence the hourly global radiation on a horizontal surface values can be obtained from the curves shown in Fig.7.1.

7.4 SUMMARY

- Principles of operation of different solar radiation measuring instruments have been described.
- Some of them measure the global radiation, some the diffuse radiation and the others the direct radiation.
• Direct radiation measurements are usually made to check the measurements of global and diffuse radiation.

• Sunshine recorder is a convenient (though approximate) solar radiation measuring instrument, since it does not require power supply. However, needs to be calibrated (to determine the location dependent constants) against measurements made by pyranometers etc. The location dependent constants, thus determined are applicable for locations of similar climate.

• Several empirical relations have been presented; relating diffuse radiation to global radiation on different time scales, relating hourly (global as well as diffuse) values to the daily values.

• Cumulative frequency distribution of clearness indices enables one to determine the daily or hourly (for a desired hour, say, 8-9 AM) clearness indices when the monthly average clearness index (on the time scale hourly or daily) is known.