1 Direct Normal Radiation

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1.1 Concepts and Definitions

The harvesting and conversion of solar radiation by concentrating photovoltaic (CPV) technologies depends explicitly on the quality and quantity of the solar resource that is available, as well as the optical and electrical properties of the photovoltaic technology. This chapter will address the quantitative and qualitative aspects of the solar resource, the direct solar radiation, and briefly, more qualitative discussions of the interaction of the resource with the photovoltaic technologies and system design issues. More quantitative discussion of the latter will be addressed in detail in subsequent chapters.

1.1.1 Orbital and Geometrical Considerations

The Earth orbits a typical star, the sun, which provides energy in the form of optical and thermal radiation that enables and supports life on our planet. A reference for most of the numerical data presented in this section is Allen’s Astrophysical Quantities [1].

The sun has a diameter ($d_s$) of 1,390,000 km (840,000 miles). At the surface of the sun (at radius $R_s = 695,000$ km from the center) the power flux density emitted is about $6.33 \times 10^7$ Wm$^{-2}$. The Earth’s orbit about the sun is an ellipse with an eccentricity of 0.0167. Closest approach of the Earth to the sun (perihelion) occurs on about January 2 or 3, and the furthest distance (aphelion) occurs on about July 4 or 5. The Earth’s perihelion, $R_p$, and aphelion, $R_a$, distances are about 147.5 million km and 152.6 million km, respectively. That is, the Earth-Sun distance varies from $-1.4\%$ to $+2.0\%$ of the average Earth-Sun distance, or a range of $3.4\%$ during the year. The average distance ($R_o$) between the sun and Earth is 1 Astronomical Unit (AU) of 149,597,870.7 km (92,955,807.273 miles).

Using simple geometry, the apparent angular diameter of the solar disk in degrees at 1 AU is $\arctan (d_s/R_o) = \arctan (1.390/149.59787) = 0.532^\circ$ or 9.28 mrad. The apparent diameter of the solar disk changes by 3.4% as the sun moves from aphelion ($\arctan (d_s/R_a) = 0.521 = \ldots$
0.91 mrad) to perihelion (arctan \(\frac{d_s}{R_p}\) = 0.539° = 0.94 mrad). In the absence of an atmosphere, because the solar disk subtends a solid angle of about 0.5°, an observer on the Earth’s surface will observe that the rays of sunlight falling on a plane surface with the surface normal (perpendicular) pointed at the center of the solar disk fill a solid angle of the same dimensions. The solar radiation filling the 0.5° cone of rays falling on a surface which is normal (i.e., perpendicular) to the axis of the cone constitute the direct normal radiation, or direct beam irradiance, also called direct normal irradiance, or DNI. Note than in the presence a clear, cloudless atmosphere, the actual solid angle of the DNI over short periods of time will vary slightly, both in time and physical extent. These tiny variations are due to the effects of turbulence and variations in density of the atmosphere as the direct beam radiation propagates through the atmosphere. The magnitude of these effects is demonstrated by the ‘twinkling’ of starlight from much more distant and more truly point-source-like stars.

As the sun moves in elevation from the horizon at sunrise, to higher in the sky at noon, to the horizon at sunset, the elevation angle, \(e\), of the solar disk, or angle from the horizon to the center of the disk, is constantly changing. Thus the path length through the atmosphere for the photons (defined as the air mass, \(m\)) also changes from long to shorter to longer as the sun moves from sunrise to noon to sunset. The geometrical air mass, \(m\), is defined as approximately \(m = \frac{1}{\sin(e)}\). The complement of the solar elevation angle is the solar zenith angle, \(z\), the angle between the local vertical and the center of the solar disk, thus \(m\) is also defined approximately as \(m = \frac{1}{\cos(z)}\).

For a surface or collector to capture the DNI, the normal or perpendicular to the surface must point to the center of the solar disk throughout the day. This will keep the incidence angle (the angle between the DNI beam and the surface normal, \(\theta\)) of the DNI beam near zero, and requires a mechanism to track the elevation and azimuth of the sun throughout the day. The accuracy of the mechanical system in performing the tracking function is an important aspect of the design of systems for intercepting and concentrating, or focusing the direct beam radiation.

For a stationary horizontal surface the incident angle of the direct beam will vary from 90° at sunrise to the (less than 90°, depending on the latitude of the site) solar elevation angle at noon to 90° at sunset. Because the projected area of the direct beam radiation will vary as the cosine of the incidence angle (known as Lambert’s law), the flux density per unit area (\(I\)) on an arbitrary surface will decrease at high incidence angles (near sunrise and sunset) and be a maximum at solar noon. That is:

\[ I = DNI \cos(\theta), \]

where \(\theta\) is the incidence angle of the DNI beam to the surface (in other texts DNI is denoted as \(B\)). For a horizontal surface, the normal to the surface points to the zenith, or elevation angle of 90°. For this surface, the incidence angle for a DNI beam, \((I_n)\), from the disk at solar elevation \(e\) is the zenith angle, \(z\), as defined above (i.e. 90°–\(e\), or the complement of the elevation). The DNI beam flux on a horizontal surface \((I_{bh})\) is then:

\[ I_{bh} = I_n \cos(z), \]

1.1.2 The Solar Constant

The term ‘solar constant’ was coined when it was assumed that the solar output and thus the intensity of solar extraterrestrial radiation (ETR) at the top of the atmosphere (denoted by \(I_o\))
was indeed constant over time. In the middle of the 19th century, irregular, periodic variations in the appearance and density of sunspots, with a period on the order of 11 years were discovered. This is the so-called 11 year ‘sunspot cycle’ or ‘solar activity cycle’. It has since been determined that irradiance variations on the order of peak-to-peak magnitude of ±0.1% in the ETR are associated with the solar activity cycle [2,3]. Here, the term solar constant continues to be used to denote the average ETR irradiance over several solar cycles, and is denoted by $I_o$.

Despite the fact that the sun subtends a rather large angle of 0.5° in the sky, it is often treated as a point source of radiation, subject to the inverse square law. The inverse square law states that the flux density of radiation decreases (increases) by the factor $1/r^2$ as the distance $r$ between the source and a detector increases (decreases). If we assume that solar radiation originates at a ‘point source’ at the center of the Sun, when the optical flux emitted at the surface of the sun quoted above reaches the Earth as the ETR direct beam radiation at 1 AU ($I_o$), it has been attenuated by a factor of:

$$\left(\frac{R_s}{R_o}\right)^2 = (695 \times 10^3 / 149.5 \times 10^6)^2 = 2.16 \times 10^{-5},$$  \hspace{1cm} (1.3)

where $R_s$ and $R_o$ were defined above in section 1.1.1. The resulting ETR power flux density at the top of the Earth’s atmosphere (the solar constant) at the average Earth-Sun distance of $R_o$ is then approximately:

$$I_o = (2.16 \times 10^{-5}) \cdot (6.33 \times 10^7) \text{ Wm}^{-2} = 1.368 \text{ Wm}^{-2} \text{ at 1 AU}$$  \hspace{1cm} (1.4)

### 1.1.3 Temporal Variations in Extraterrestrial Radiation (ETR)

Because the Earth-Sun distance varies as described in section 1.1.1, the $1/r^2$ variation in the ETR becomes ±3.3%, theoretically ranging from 1320 Wm$^{-2}$ to 1415 Wm$^{-2}$. Since 1978, multiple Earth orbiting satellite based broadband radiometers (absolute cavity radiometers) have measured the total solar irradiance with an accuracy of about ±0.5%, or ±7 Wm$^{-2}$, when corrected to a distance of 1 AU. The actual variations of ±3% in the ETR magnitude to the variations in orbital distance, as well as the approximately 11 year sunspot cycle related variations of ±0.1%, along with very short term solar activity (flares, solar storms, influence of bright faculae, etc.) have been detected by these orbiting sensors. The presently accepted ETR solar constant value based on the 37 year period of record from 1978–2015 is $I_o = 1366.1$ Wm$^{-2}$ ± 0.6 Wm$^{-2}$ (or ±0.04%) [4]. All uncertainty values quoted for measured data represent one standard deviation about the mean value, unless otherwise noted.

Different satellite sensors have exhibited differences or offsets (biases) between the set of measured data [2,3,5–11]. These differences apparently are dependent upon differing instrument designs. These differences have been analyzed and corrected using various schemes to arrive at a ‘composite’ standard solar constant value of $I_o = 1366.1$ Wm$^{-2}$ ± 0.04% [4].

As of 2013, the most recent total (solar) irradiance monitor data is that from the US National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) Solar Radiation and Climate Experiment (SORCE) satellite [9–11]. Analysis by Kopp and Lean [12] claim an ETR value at solar minimum of 1,360.8 ± 0.5 Wm$^{-2}$, 0.4% lower than the solar minimum of 1,365.4 ± 1.5 Wm$^{-2}$ derived from the earlier 1978–2010 observations. The difference, and
better accuracy (smaller uncertainty), of the SORCE measurement is attributed to an instrument design that reduces stray light reflected from view limiting apertures and baffles, on-orbit calibrations, and detailed laboratory characterization of the SORCE radiometer. If this lower solar minimum SORCE value is used to correct the accepted 1 AU value of average ETR, the result would be \( I_o = 1,361.5 \pm 0.5 \text{ Wm}^{-2} \). That is, a 1AU ETR that is 0.34\% (4.5 Wm\(^{-2}\)) lower than the 1978 to 2010 published values. The investigation of the accuracy of these new measurements are under way as of this writing (2015). The accuracy of the theoretical estimate of \( I_o \) from Eq. (1.4) is dependent upon the accuracy of the estimated (theoretically calculated) flux density at the surface of the sun.

Spencer [13] developed a Fourier series expansion for the Earth-Sun distance correction factor \( R_c \) as a function of the day of the year, \( d_n \) (for Jan 1, \( d_n = 1 \)), using \( R_o \) is the mean distance, \( R \) is the actual distance, and \( d = \) ‘day angle’ computed from:

\[
D = 2\pi(d_n - 1)/365, \tag{1.5}
\]

\[
R_c = (R_o/R)^2 = 1.000110 + 0.034221 \cos(d) + 0.001280 \sin(d) + 0.000719 \cos(2d) + 0.000077 \sin(2d), \tag{1.6}
\]

Multiplying the solar constant \( I_o \) by \( R_c \) produces the solar extraterrestrial irradiance at the top of the Earth’s atmosphere for the day of the year \( d_n \).

Figure 1.1 is a composite time series of corrected and adjusted broadband ETR intensity measurements from space for the period 1975–2008. Descriptions of the history and issues associated with ETR data collection and analysis are provided in references [14–23].

### 1.1.4 Extraterrestrial Radiation Spectral Power Distribution

Above we discussed the total, or integrated broadband direct beam ETR. This total integrated irradiance is comprised of photons of electromagnetic radiation (as well as energetic atomic particles, such as electrons, protons, neutrinos, etc.). The photons and elementary particles generated by the nuclear reactions deep within the sun eventually propagate outward and escape from the solar surface. The photons (or ‘optical radiation’) generated range from extremely energetic gamma rays, to X-rays, ultraviolet, visible, infrared, radio and microwave radiation. The distribution of power in the solar emissions with respect to wavelength (or frequency) of the radiation is the solar spectral power distribution. Spectral power distributions are important, in that various photovoltaic technologies respond to or utilize different portions of the solar spectrum to greater or lesser degrees, as will be extensively discussed in Chapter 2 for CPV solar cells.

The presently accepted international standard for a composite solar spectral power distribution, or standard reference solar spectrum, as well as value of \( I_o \), is published by the American Society for Testing and Materials (ASTM) International as ASTM E490-10 [4]. This standard is important to the aerospace community in evaluating the performance of spectrally sensitive components such as materials degradation, detectors and solar cells for satellite remote sensing and power generation applications. Figure 1.2 shows a plot of the 200 nm to 2000 nm spectral region of the extraterrestrial solar spectrum tabulated in ASTM E490. See Chapter 2 for detailed discussion on the influence of terrestrial SPD with respect to CPV solar cell technologies.
Figure 1.1: Solar constant temporal variations. Source: http://www.acrim.com/RESULTS/TSIS/Earth_2000Observatory/earth_obs_ACRIM_Composite.pdf.
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1.1.5 The Atmospheric Filter

So far, we have discussed the ETR, or direct beam radiation, or direct normal irradiance (DNI) at the top of the Earth atmosphere. Section 1.1.1 described general considerations regarding solar geometry. This section will discuss the impact of the atmosphere and its effect upon the DNI beam radiation as it traverses this highly variable medium. In essence, we could think of the atmosphere as an optical filter that transforms the spectrum and intensity of the ETR. Thereby, the atmosphere attenuates the solar radiation and suppresses some bands as result of the selective absorption of some of its constituents. Even more, such transformation is dynamically influenced by a number of factors that evolve over time – length traversed by the light beam, amount of trace gases, particulate, etc. – and therefore the atmospheric filter changes along the day, from season to season, with altitude, latitude and location. In the next paragraphs, we summarize most of the physical processes that modify the direct normal irradiance as it propagates through the atmosphere.

The gases and particulates present in the atmosphere (or any medium) traversed by the direct beam reflect, absorb, and scatter differing spectral regions and proportions of the direct beam, and thus act as a continuously variable filter. As the narrow cone of DNI beam encounters the atmosphere, some photons are reflected by the atmosphere back into space. Some of the remaining photons are selectively absorbed by atmospheric gas molecules, liquid droplets, or particles suspended in the atmosphere [24]. The energy from these photons is either converted to heat (longer wavelength infrared radiation) or re-radiated and ‘lost’ back to space. Photons with wavelengths approximating the dimensions of atmospheric gas molecules, liquid droplets, or suspended solid particles are preferentially scattered out of the beam and into a broader random radiation field, the diffuse sky radiation. Photons that are not scattered out of the DNI...
beam radiation propagate parallel to the direction of the beam, and are responsible, for instance, for the casting of shadows.

Two different scattering processes based on elastic collision and electromagnetic interactions between photons and atmospheric constituents affect the DNI. Rayleigh scattering (named for Lord Rayleigh, who first mathematically described the process) is caused by atmospheric gas molecules or particles smaller than a photon wavelength. Lord Rayleigh derived the strong wavelength dependence of the scattering process named after him, namely that the intensity of the scattered radiation is proportional to the reciprocal of the fourth power of the wavelength ($\lambda^{-4}$) and the sixth power of the scattering particle diameter ($d^6$). Since physical dimensions of atmospheric gas molecules are generally much less (5 Angstroms or $5 \times 10^{-10}$ m, or the order of hundreds of picometers (pm), or $10^{-12}$ m), only shorter wavelengths on the order of 300 nm (or $10^{-9}$ m) to 400 nm or ‘blue’ photons are scattered the most efficiently and rather uniformly in random directions by the Rayleigh process, hence the apparent blue color of the clear sky.

Mie scattering was described by Danish physicist Gustav Mie by explicitly solving James Clerk Maxwell’s equations for the interaction of electromagnetic waves (photons) and particles or molecules larger than the photon wavelengths. Mie scattering is only very weakly dependent on wavelength, but preferentially redirects photons forward, in the direction of the initial path of propagation. Thus, when particles larger than about 500 nm (0.5 μm), are suspended in the atmosphere, a white haze, more extensive and intense as the size and number density of the particles increases, is seen around the solar disk. This Mie scattered radiation is the circumsolar radiation (CSR) or solar aureole. Note that while the CSR is scattered generally along the direction of propagation, the photons are scattered into a much larger solid angle, up to several tens of degrees, or a much larger solid angle than the 0.5° of the DNI beam. See van de Hulst [24] for detailed technical information on scattering in the atmosphere. CSR will be discussed in more detail in section 1.6.2.

At the Earth surface, where a photovoltaic collector may be located, the combined direct beam radiation (direct normal irradiance, DNI) and diffuse sky radiation (diffuse horizontal irradiance, DHI) represent the total hemispherical solar radiation on a horizontal surface, usually referred to as the global horizontal irradiance, GHI. Thus the relationship of DNI, DHI, and GHI is:

$$GHI = DNI \cdot \cos(z) + DHI,$$

(1.7)

It is important to note that diffuse sky radiation photons generally propagate in random, uncorrelated directions because of multiple scattering events and interactions in the atmosphere.

In addition, to the radiation components of Eq. (1.7) there is a fourth one, namely, the albedo or reflected component, which accounts for radiation that reaches the target surface after reflection from the ground, buildings, snowy hills or any other reflecting surface.

A general procedure to model DNI will be given in section 1.3.1. However, it is also valuable to introduce at this point a few concepts and parameters that are useful in modeling solar radiation and its components. These include the following:

- As has been mentioned in section 1.1.1, the air mass (AM or $m$) measures path length through the atmosphere for the photons in the solar radiation. More formally, AM is defined as the ratio of the length of the beam irradiance path through the atmosphere to the vertical length of the atmosphere. Accordingly, in PV terminology AM0 refers to the extraterrestrial irradiance; AM1.5 to an irradiance traversing an atmosphere length 1.5 times its vertical length.
The key functions to characterize the atmospheric filter are the \( T(x) \) as function of constituent \( x \). In essence, \( T(x) \) is the ratio of transmitted direct normal irradiance to that at the top of the atmosphere, as a function of the concentration or intensity of the constituent \( x \); with \( x \) being aerosols, uniformly mixed gases, ozone, water vapor, or the effects of Rayleigh scattering.

A parameter frequently used to quantify how hazy an atmosphere is the so called Linke Turbidity, \( T_L \), which represents the number of clean (aerosol free), dry (free of water vapor) atmospheres necessary to produce an observed attenuation of the extraterrestrial direct normal insolation. Accordingly, \( T_L \) is always greater than 1; has a value around 2 for very clean and cold air; and may reach 6 or more for polluted areas.

Aerosols (small particles of dust, smoke and other materials suspended in the atmosphere) have a deep impact on atmospheric transmissivity. This impact is quantified by means of the aerosol optical depth, AOD, usually also denoted as \( \tau \) or \( \tau(\lambda) \), which is calculated as the dimensionless attenuation of incident radiation, \( I_o \), as a function of unit path length through a distance \( d \) (usually air mass, \( m \)) of absorbing aerosol. That is, \( AOD = \tau = -\ln (I/I_o) \) per unit \( m \). In fact, \( AOD \) varies by wavelength, but is often represented by the AOD at a specific wavelength of 1.0 \( \mu \)m (1,000 nm) or 500 nm. Angstrom’s equation for \( AOD(\lambda) = \tau(\lambda) = \beta \lambda^{-\alpha} \), where \( \alpha \) is the Angstrom exponent, depending on the size distribution of particles, and \( \beta \) is the AOD at the reference wavelength of 1 \( \mu \)m (1000 nm). See the section 1.3.1 below on modeling DNI.

Finally, in the clearness index includes a set of parameters, frequently used to correlate the different components of irradiance. For instance, the direct normal clearness index, \( K_n = DNI/(R_c I_o) \), is the ratio of the terrestrial DNI to the ETR DNI (\( I_o \), corrected for the Earth-Sun distance for the day of the year). Similarly, the total hemispherical clearness index, \( K_t = GHI/(R_c I_o \cos(z)) \) is the analogous ratio for global horizontal irradiance.

All these concepts and parameters will be presented in more detail in section 1.3.1 for the modeling of DNI.

1.2 Measuring Broadband Direct Solar Radiation

Historically, a device to measure solar radiation in general has been called a pyrheliometer, from pyre (heat, fire), helios (the sun) and meter, or measurement. However, as the total hemispherical solar radiation, diffuse hemispherical radiation, and direct normal (beam) incident radiation components came to be identified and separated, the term pyrheliometer became associated with the DNI beam radiation measurement, as the intensity of the beam radiation from the solar disk was the target measurement. Instruments for the measurement of the hemispherical diffuse and total radiation are now termed pyranometer, or simply ‘heat meters’ for measuring the combined sky and DNI beam radiation, or total hemispherical sky radiation. See Iqbal [25], Coulson [26], Vignola et al. [27] or Stoffel et al. [28] for details of solar radiation instrumentation and measurements.

1.2.1 Pyrheliometers

In section 1.1, we described the DNI beam radiation as radiation incident perpendicular to a plane that tracks the position of the solar disk as it moves in azimuth and elevation throughout the day. To obtain only the DNI beam radiation component, one must exclude the sky diffuse hemispherical radiation from intercepting the tracking plane. This is accomplished by aligning
a cylindrical tube parallel to the perpendicular to the plane, or along the normal to the plane. Since the normal to the plane is tracking the sun, the tube will be pointed at the sun as well. By situating an opening aperture, a field of view limiting aperture, and light baffles within the tube, a well-defined field of view solid angle can be established (see Figure 1.3). The Russian scientist Alexander Gershun [29] describes such a device in his study of the spatial distribution of sunlight, thusly these view limiting devices are called Gershun tubes.

The construction of a pyrheliometer consists of such a view limiting tube, with a black coating on the internal components, sealed for all weather operation with a detector at the bottom of the tube, and a high transmittance protective window at the end of the tube pointing at the sun. Baffles within the tube limit internal reflections that would generate erroneous (higher) input at the detector. The physical dimensions of the detector, tube, and apertures determine the solid angle field of view at the detector. Figure 1.3 is a sketch of construction of such a device. Figure 1.4 is a photograph of several models of pyrheliometer mounted on a device for pointing the pyrheliometers at the sun, a solar tracker.

The detector is generally a thermopile, comprised of a collection of thermocouples. Thermocouples consist of dissimilar conducting metals in contact with each other at a thermojunction. This junction generates an electrical potential (voltage) dependent on temperature differences between the junction and a similar junction located to sense a reference temperature. Individual thermocouples generate low levels of voltage (microvolts per degree C). Assembling many in series into a ‘thermopile’, the electrical signal is increased as the individual signals add together. In solar radiometer design, the most common and accurate detectors used are thermopiles in thermal contact with substrate materials coated with black absorbing paints or layers that absorb the photons across the solar spectrum and heat up, transferring thermal energy to the thermopiles. The radiometer output signal is proportional to the difference in temperature between the thermojunctions under the illuminated black absorber and the non-illuminated reference thermojunctions.

A common thermocouple material pair is the type-T thermocouple made from copper bonded to constantan (a nickel–copper alloy). A single type-T thermocouple generates 40 microvolts per degree Celsius ($\mu$V/°C) for temperatures between $-50^\circ$C and $+150^\circ$C. Thus if
50 thermojunctions are assembled into a thermopile and put in contact with a black absorber that heats up 5°C, and a similar 50 junction thermopile is at ambient temperature, a signal of $40\mu V \times 50 \times 5 = 10000\mu V$, or 10.0 mV is generated. This is a reasonable signal for modern voltage measurement equipment.

Construction of the Gershun tube for early pyrheliometers was based on a simple ratio of the diameter of the front view limiting aperture and the distance between the limiting aperture and the detector of one to ten (1/10). The opening angle, seen from the center of the detector to the edge of the limiting aperture is then the radius of the limiting aperture to the distance from detector to aperture, or 1/20. This simplified manufacturing dimensions, and provided for a relatively large field of view (half opening angle) of arctan (0.1) = 2.86° and a total field of view of 5.7°. Since the pyrheliometer must track the sun throughout the day, and early solar tracking mechanisms were electro-mechanical or clock driven, and not very accurate, the large opening angle permitted some tracking error on the order of $\pm 2^\circ$ or so, without loss of detector illumination.

Since 1978, the World Meteorological Organization (WMO) Commission on Instrumentation, Measurements and Observations (CIMO) has recommended a half-opening angle of 2.5° for primary reference absolute cavity pyrheliometers (see next section) and newer pyrheliometer designs [30]. The resulting total field of view of such a pyrheliometer is then 5.0°, or about 10 times the apparent diameter of the solar disk seen from Earth.

There are two other view angles described in the WMO/CIMO chapter 7 [30] on radiation measurement. These are the slope angle, defined as arctan $(R - r)/L$ where $R$ is the radius of the open aperture at distance $L$ from the detector of radius $r$, and the limit angle equal to arctan $(R + r)/L$. The former defines the maximum angle at which the edge of the solar disk (accounting for the radius of the solar disk of 0.5°) is just tangent to the field of view opening angle cone. The radiation from the entire solar beam then reaches the detector. The slope angle is considered the useful field of view of the pyrheliometer. The slope angle is generally smaller than the opening angle or nominal field of view. The slope angle for several commercial and primary reference pyrheliometer designs ranges from 20% to 65% of the opening angle. If the center of the solar disk is at an angle greater than the slope angle, a portion of the solar disk is
cut off from the point of view of the detector. Thus it is the slope angle of the pyrheliometer that
determines the needed tracking, or pointing accuracy of the solar tracking mechanism (see
Figure 1.4) required to keep the solar disk (and all direct beam radiation) within the field of
view of the pyrheliometer.

All commercial pyrheliometers are provided with an alignment target to indicate the
accuracy of the solar alignment. Generally, these consist of a pinhole aperture that produces
an image of the solar disk on a target. Target rings are designed to show the approximate
angular alignment or misalignment of the pyrheliometer axis with the center of the solar disk.
When choosing solar trackers, the tracker accuracy, in terms of angular deviation from perfect
alignment with the sun, should be examined to make sure the tracking accuracy is at least as
good (comparable to or less than) the slope angle of the pyrheliometer.

The limit angle is the angle beyond which no radiation at all from the solar disk reaches
the edge of the detector. There are no internationally accepted standards for the definition of
pyrheliometer design other than these WMO CIMO recommendations.

1.2.2 Rotating Shadow Band Radiometers

In section 1.1 we mentioned that the total hemispherical radiation on a horizontal surface or
global horizontal irradiance (GHI) results from a combination of the projected DNI beam on the
surface, plus the total hemispherical diffuse sky radiation on a horizontal surface (DHI). For a
given solar zenith angle \( z \), DNI can be calculated using Eq. (1.7):

\[
DNI = (GHI - DHI) / \cos(z),
\]

(1.8)

One may use this relationship to derive DNI measurement from the combination of a GHI
measurement and a DHI measurement. These measurements are accomplished using a
pyranometer, a radiometer with a 180° field of view and a horizontal detector. DHI is measured
by blocking the solar disk with an opaque band, ball or disk on a tracking mechanism to track
the sun and block the solar disk. These shading devices are designed to subtend the same solid
angle (as seen from the pyranometer detector) as the opening angle prescribed for a
pyrheliometer.

This method requires two (GHI and DHI) hemispherical irradiance measurements, and a
calculated value of the zenith angle. Generally, pyranometer measurements have greater
uncertainty than pyrheliometer measurements, and the calculation of \( z \) is dependent on accurate
time keeping and site longitude and latitude coordinates, as well as an accurate solar position
calculation algorithm. Uncertainty in estimating DNI using two independent pyranometers for
the GHI and DHI measurements requires combining the uncertainties in the calibration and
field performance of each radiometer, increasing the uncertainty in the resulting DNI [28].

It is possible to use only a single pyranometer, alternately unshaded for the GHI measure-
ment, then shaded with an appropriate diameter blocking disk or ball at an appropriate distance
from the detector for the DHI measurement. The uncertainty in the computed DNI is now
dependent on the uncertainty in the one pyranometer, but that uncertainty may be different in
each circumstance.

A popular pyranometer design implementing this shade/unshade strategy uses a silicon
photodiode detector, which has a spectral response over the limited spectral range of 300 nm to
1100 nm. These radiometers are used in rotating shadow band radiometers (RSR) because their
response time is very short, and the shade/unshade cycle can automated with a rotating band to shade the radiometer during the DHI measurement [31]. Figure 1.5 is a photograph of a typical RSR in the field.

The short wavelength (less than 400 nm) response of these devices is very low, 10% or less of the response in middle of the visible spectrum (550 nm). When shaded, such a pyranometer is receiving radiation from only the shortwave (blue) sky. The detector response of a silicon detector pyranometer is much lower than a pyranometer with a constant responsivity over all wavelengths (such as thermopile in contact with a black absorber). Using a single calibration factor for a silicon photodiode detector, based on the radiation over the entire available spectral response region, to measure both the diffuse sky and total hemispherical (global) radiation will lead to considerable (approaching 50%) errors in the measurement of diffuse radiation. These errors are then carried over into the computation of the DNI. Because the spectral power distribution of the total hemispherical will change throughout the day, the error in computing total hemispherical radiation using a single calibration factor will also vary throughout the day.

There have been efforts to develop correction algorithms to account for spectral, temperature, and cosine response variations for silicon radiometers [32–35], but in general these empirical correlations themselves contain considerable (up to 0.5% or more) scatter. This means that as each correction is applied; an additional ±0.5% random uncertainty is to be combined with the calibration and measurement sources of uncertainty. If we combine three corrections with 0.5% random scatter in each, using the typical root sum of squares approach, an additional 0.87% uncertainty must be combined with calibration and field measurement data uncertainty for the derived DNI [35]. As we will see below, the additional uncertainty due to such corrections approaches the uncertainty in a well calibrated pyrheliometer measurement alone.
In short, as will be shown in the next section, the most accurate measurements of DNI beam (±2%) are accomplished with pyrheliometers using thermopile detectors for direct measurement of the solar DNI. Lower accuracy (±5%) DNI data is generally collected by the RSR radiometers or DNI computed from total hemispherical and diffuse sky radiation measurements. The trade-off between accuracy and cost in terms of equipment and maintenance resources should be evaluated against the impact on the end use or goal of the measurements.

1.2.3 Reference Standards, the World Radiometric Reference (WRR)

Since the design and performance of commercially available pyrheliometers may vary considerably, there is the need for an internationally accepted reference for the calibration of pyrheliometers for measuring DNI beam irradiance. The responsibility for the international reference for the calibration of radiometric instruments rests with the World Meteorological Organization Physical Meteorological Observatory World Radiation Centre (WRC) at Davos, Switzerland [30]. This laboratory maintains a group of highly characterized Absolute Cavity Pyrheliometers (ACP) called the World Standard Group (WSG) that use electrical substitution to calibrate their response. Figure 1.6 is a photograph of the group of reference ACPs in operation at the WRC. These primary reference standard pyrheliometers are absolute in that their response to solar energy is directly traceable to absolute physical and electrical quantities [36–39]. The directly measured dimensions of aperture area, and physical and electrical quantities used to calibrate the response of ACPs, are applied based on the following principles.

![Figure 1.6](image)
The ACP consists of a photon trap (cavity) detector, covered with a black absorbing paint or coating, at the bottom of a Gershun tube with no window, with total opening angles of 5.0°, and typical (total) slope angles of 1.5° to 1.75°. Cavity shapes such as cylinders with opening apertures beveled or slanted inward, and pyramidal or inverted cone shapes at the bottom of the cavity are commonly used to enhance the trapping of photons. This trap detector is in thermal contact with thermocouples to measure the temperature rise of the detector when exposed to DNI sunlight.

When the DNI beam is blocked, an electrical current can be supplied to heat the cavity to produce the same temperature rise as that caused by the sunlight. The electrical power required to heat the detector is derived by accurately measuring the electrical current, voltage, and electrical resistance in the circuit that produces the equivalent heating. This electrical power is almost (but not identically) equivalent to the solar DNI beam power that produced the equivalent temperature rise. Slight differences (non-equivalence) in the heat transfer due to the radiative (solar) heating and electrical heating (generally supplied through a different physical pathway and subject to some tiny losses) must be characterized for each individual primary reference ACP design [36–41].

Careful, accurate measurements of the limiting aperture area, efficiency of the trap detector design (absorptivity and reflectivity of coatings, thermal conductivity of the cavity material and coating, etc.), precise properties of the thermocouple junction performance, ohmic losses in conductors, radiative losses during the electrical calibration phase, the above mentioned non-equivalence of electrical and solar heat transfer, and other sources of error in the measurement of electrical current and voltages are required to obtain the highest accuracy ACP radiometric measurements. The process of obtaining the detailed information for the reference ACPs is called characterization, and results in individual correction factors for each individual reference ACP to obtain DNI beam irradiance. Characterization and correction magnitudes generally range from 1 to several hundred part per million (1 ppm to 200 ppm), or 0.001% to 0.020%, depending on the parameter. Table 1.1 shows elements of characterization and the magnitudes involved, from [37]. Figure 1.7 shows sources of uncertainty accounted for in some of the characterization processes.

The WSG instruments are used to establish the World Radiometric Reference (WRR) scale [30]. It is important to note that all the members of the World Standard Group have

Table 1.1  Elements of cavity radiometer comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Correction factor</th>
<th>3σ uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity absorptance</td>
<td>1.00115</td>
<td>0.00150</td>
</tr>
<tr>
<td>Electrical measurements</td>
<td>1.00000</td>
<td>0.00150</td>
</tr>
<tr>
<td>Aperture areas</td>
<td>0.99853</td>
<td>0.00040</td>
</tr>
<tr>
<td>Radiative loses</td>
<td>1.00029</td>
<td>0.00300</td>
</tr>
<tr>
<td>Coating thermal resistance</td>
<td>1.00007</td>
<td>1.00015</td>
</tr>
<tr>
<td>Electrical vs. radiation equivalence</td>
<td>1.00000</td>
<td>1.00015</td>
</tr>
<tr>
<td>Conduction from heated aperture</td>
<td>0.99990</td>
<td>0.00015</td>
</tr>
<tr>
<td>Internal reflected radiation</td>
<td>0.99991</td>
<td>0.00009</td>
</tr>
<tr>
<td>Nonequivalent heat path radiation vs. electrical heat</td>
<td>0.99996</td>
<td>0.00009</td>
</tr>
<tr>
<td>Overall correction factor</td>
<td>0.99981</td>
<td>0.00220</td>
</tr>
</tbody>
</table>
undergone very detailed, individual characterization as described above. They each have individually characterized total field of view opening angles of $5.0^\circ \pm 0.2^\circ$, and slope angles from $1.5^\circ$ to $1.75^\circ$ ($\pm 0.2^\circ$) as recommended by the World Meteorological Organization Commission on Instrumentation Measurements and Observations. The World Radiation Center at Davos, Switzerland is recognized as a National Metrology Institution, and the World Radiation Reference (WRR) scale is recognized by the International Bureau of Weights and Measures (French acronym BIPM), as the international reference standard for solar radiation measurements [41].

Historically, several radiation reference radiometers or scales have been used in meteorology, namely the Angstrom scale of 1905, the Smithsonian scale of 1913, and the international pyrheliometric scale of 1956 (IPS 1956) [30]. Since 1970, the developments in absolute radiometry have very much reduced the uncertainty of radiation measurements. With results of many comparisons of 15 individual absolute pyrheliometers of 10 different types, the WRR was defined in 1975. The old scales can be transferred into the WRR using the following factors:

- $WRR = 1.026$ Ångström scale 1905, from 1905 to 1913;
- $WRR = 0.977$ Smithsonian scale 1913, from 1913 to 1956;
- $WRR = 1.026$ International Pyrheliometric Scale (IPS) 1956, from 1956 to 1975.

During international pyrheliometer comparisons (IPC), organized every five years since 1975, the measuring standards (usually commercially procured ACP or conventional pyrheliometers) of national meteorological centers and laboratories are compared with the World Standard Group, outdoors, over several days. The participating standard pyrheliometer’s calibration factors (provided by ACP manufacturers) are used to derive a WRR correction.
factor to make the test radiometer agree with the WRR. The WRR factor is derived from the statistical analysis of a series of individual ratios of the irradiance from the test standard pyrheliometer to the World Standard Group irradiance over the series of clear days. A very detailed step-by-step measurement and computational procedure for accomplishing the transfer of WRR to institutional working standards is available on-line from the National Renewable Energy Laboratory (NREL) publications database. For further details on this process, see Reda [42].

In turn, the participating standard reference pyrheliometers are used to transfer the WRR scale to network pyrheliometers for use in the field via standard calibration procedures [43–46]. The WRR is accepted as representing the physical units of total irradiance within 0.3% (99.5% confidence interval, or 3 standard deviation uncertainty). A very important point is that since the quoted accuracy of the WRR scale itself is 0.3%, it is impossible to transfer the WRR to a reference standard pyrheliometer with uncertainty smaller than 0.3%. A pyrheliometer calibrated by any additional transfer of the WRR between a working reference ACP or working standard pyrheliometer and a field pyranometer must have an even larger uncertainty as described in the next section. Note that the WRR is based on measurement of electrical units, and not direct measurement of irradiance. The International System (SI) base unit of luminous intensity is the candela.

Recent comparisons in the laboratory between a World Standard Group radiometer and extremely high accuracy (and complex) cryogenic absolute cavity radiometers, used to define the SI laboratory irradiance scale (based upon the candela base unit) show agreement to better than 0.1% between the SI scale and WRR scale at a great many amplitude stabilized laser wavelengths [47]. The World Radiation Center is working to develop a cryogenic version of the Absolute Cavity Pyrheliometer suitable for solar DNI beam measurements. The goal is for uncertainty in the WRR to be lowered to the order of 0.05% and later on to 0.01% if possible; however this is still a work in progress.

1.2.4 Calibration of Pyrheliometers

Periodic comparisons between the World Radiation Center maintained World Standard Group established WRR and national and institutional standard reference ACP and pyrheliometers are performed to transfer the WRR scale to working standards. Similar procedures are used to transfer the WRR from working standard ACP or standard pyrheliometers to field instruments. There are several international consensus standards describing calibrations of field or test pyrheliometer based upon a standard pyrheliometer [43–46]. This transfer process implements the concept of calibration which is defined in the International Vocabulary of Metrology (or VIM for short) [48] as a process that ‘. . . establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties . . . and uses this information to establish a relation for obtaining a measurement result from an indication.’

The concept of traceability to the WRR scale and reference standard refers to a chain of measurements or comparisons from the standard World Standard Group reference and WRR to the final calibration value. The VIM [27] referred to above states that traceability (pg. 29, definition 2.41) is the ‘property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.’ Note that traceability requires a knowledge of the measurement
uncertainty (discussed below) and known sequence of relationships between reference standards and the instruments being calibrated.

The ISO and ASTM consensus standard on calibration procedures [43–46] require sequences of simultaneous measurements of a reference direct beam irradiance, $I_{ref}$, and signals from the test instruments, usually in voltages, $V_{test}$, over a period of at least one, and sometimes several days. Each individual ratio of $V_{test}/I_{ref}$ results in a responsivity, $R_s$, (usually $\mu V/Wm^{-2}$). The collection of all $R_s$ is examined using statistics and graphs of $R_s$ with respect to time and zenith (or elevation) angles to characterize the variability and possible dependence of $R_s$ on time of day or zenith angle, and estimate the uncertainty in the results.

An important note is that all commercially available ACP radiometers used as standard reference radiometers with WRR traceability are designed with the World Meteorological Organization recommended 5.0° full field of view. Commercially available pyrheliometers have different fields of view, ranging from the historical 5.7° full field of view to a 5.0° field of view nominally matching the ACP field of view. Also, the World Standard Group ACP reference pyrheliometers are always operated without a window in place. Reference ACPs compared to the WRR in international and regional comparison experiments generally do not use a window either. It is possible to compare an ACP with a window (say, for all weather operation) with an unwindowed (open aperture) reference ACP to obtain a WRR calibration factor for the windowed unit. However, it has been shown that the addition of the window produces increased random variation in the WRR correction factor due to spectral transmittance and cleanliness issues with the windows.

The final point is that whether fitted with a window or not, and whether the field of view of the test radiometer matches the ACP field of view or not, the correction factors derived for the test pyrheliometer are all relative to the un-windowed, 5° field of view reference ACP radiometer. That is, the field of view differences and window effects are all relative to the ACP standard configuration and are included in the derived WRR calibration factor.

Since the un-windowed ACP generally collects, and responds to, a spectral range beyond several tens of micrometers, a pyrheliometer with a window with limited spectral transmittance range is effectively ‘corrected’ for the presence of the window, and for the difference in field of view, by comparison with the ACP. The derived WRR calibration factor represents the performance of the pyrheliometer and reference ACP under the prevailing conditions at the time of the calibration. Under different conditions than those prevailing at the time the calibrations were conducted, there are additional sources of uncertainty contributing to the uncertainty of pyrheliometers deployed in the field and operating.

### 1.2.5 Accuracy and Uncertainty

Accuracy is generally defined as the difference between a measurement (which is never perfect), and the value of a ‘perfect, zero error’ measurement. A series of repeated measurements will always show some natural variation in the measured values. This variation is described as precision, or the distribution of measured values. Uncertainty in a measurement is conceptually a combination of the accuracy (difference from zero error measurement) and precision (scatter in the measurements). Up to this point we have discussed or mentioned several concepts and values related to the accuracy and uncertainty issues applicable to the measurement of DNI beam radiation. Examples are the total uncertainty in the WRR ($\pm 0.3\%$), variation in angular field of view ($\pm 0.2\$), variation in the diameter of the solar disk ($\pm 3.0\$)
and statistical variation represented by 1-sigma, (σ) and 2σ standard deviations of data distributions. Over the long period of technology development, a wide variety of methods for assessing and (sometimes) reporting accuracy, precision, and uncertainty in measured data have been developed and used. The lack of a standardized methodology often created confusion and even led to engineering errors in many technical fields. Recognizing these problems, during the early 1990s an international community effort produced an international, standardized consensus methodology for expressing uncertainty in measurements.

Since 1995 there has been a formal and explicit recommended standard method for quantifying the uncertainty of measurements in general. This is the Evaluation of Measurement Data-Guide to the Expression of Uncertainty in Measurements (JCGM 100:2008), referred to as the GUM [49]. The GUM was developed and published by the Joint Committee for Guides in Metrology (JCGM) of the International Bureau of Weights and Measurements (BIPM). The BIPM, with 54 member countries, headquartered in Sèvres, near Paris, France, was created in 1875 by the International Treaty on the Convention of the Meter, and is the internationally recognized authority for world metrology (the science of measurement). The GUM is also a joint BIPM International Standards Organization (ISO) and International Electrotechnical Commission (IEC) consensus standard, ISO/IEC Guide 98-2008 Guide to the expression of uncertainty in measurement (GUM) [50]. A basic summary of the GUM methodology and application to the measurement of direct beam radiation is presented in the following section.

1.2.6 Summary of Guide to Uncertainty in Measurement (GUM) Approach

Basic concepts of the GUM approach are a) the measurement process can be expressed mathematically in a measurement equation dependent on variables leading to the measurement result, an b) there are two fundamental types of sources of uncertainty; Type A, based on statistical analysis of data, and Type B arising from results that are not amenable to statistical analysis, but ‘other means’. The latter are represented by things such as a single quoted uncertainty in a standard value or reference, offsets quoted in specifications of measurement equipment (such as ±X μV + 2.5 μV), or differences between reported values from different sources, etc.

Because statistical processes, such as identifying the standard deviation in a series of measurements have been in use for so long, the term ‘standard uncertainty’ is used to denote a value that is considered to represent the standard deviation associated with the presumed distribution of errors, or differences between the actual value measured without error and the inevitable spread or distribution of value resulting from many repeated measurements. The steps to be followed for evaluating and expressing the uncertainty of the result of a measurement as presented in the GUM may be summarized as follows:

1. Write down the measurement equation, the mathematical relationship between the measurand Y and the input quantities X_i on which Y depends: $Y = f(X_1, X_2, \ldots, X_N)$. The function f should contain every quantity, including all corrections and correction factors that can contribute a significant component of uncertainty to the result of the measurement.
2. Determine $x_i$, the estimated value of input quantity $X_i$, either on the basis of the statistical analysis of series of observations (Type A) or by other means (Type B).
3. Evaluate the standard uncertainty $u(x_i)$ of each input estimate $x_i$. For an input estimate obtained from the statistical analysis of a series of observations, use the standard deviation
(Type A evaluation of standard uncertainty). For an input estimate obtained by other means, (Type B evaluation of standard uncertainty) $u(x_i)$ is stated, estimated, or evaluated (with an explanation of the derivation).

4. Evaluate the covariances associated with any input estimates that are correlated. This entails computing the sensitivity coefficients for each variable in the function $f$, defined as the partial derivative of the function with respect to each variable $\partial f/\partial x_i$. The product of the square of the sensitivity coefficient and the square of the estimated standard uncertainty for variable $x_i$ is computed and combined using root sum of squares for all of the products. Variables $X_i$ which are correlated inflate the uncertainty estimates proportional to the cross correlation coefficients.

5. Calculate the result of the measurement, that is, the estimate $y$ of the measurand $Y$ from the functional relationship $f$ using for the input quantities $X_i$ the estimates $x_i$ obtained in step 2.

6. Compute the combined standard uncertainty $u_c(y)$ of the measurement result $y$ from the standard uncertainties (step 3) and covariances (step 4) associated with the input estimates.

7. Compute an expanded uncertainty $U$, whose purpose is to provide an interval $y - U$ to $y + U$ that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand $Y$. Multiply the combined standard uncertainty $u_c(y)$ (step 6) by a coverage factor $k$, typically in the range 2 to 3, to obtain $U = k \cdot u_c(y)$.

8. Select $k$ on the basis of the level of confidence required of the interval.

9. Report the result of the measurement $y$ together with its combined standard uncertainty $u_c(y)$ or expanded uncertainty $U$. Describe how $y$ and $u_c(y)$ or $U$ were obtained.

The implementation of the GUM approach to estimating the uncertainty in a pyrheliometer measurement in the field will be the result of several successive stages of analysis [51,52]. These stages are summarized in Table 1.2 (with some typical magnitudes indicated):

Finally, the uncertainty estimates for the field data derived from the uncertainties associated with the data collection system component specifications or performance, influence of environmental conditions, specifications and uncertainty in the derived calibration factor for the field pyrheliometer (equipment dependent; ranging from $\pm1.0\%$ to $\pm2.0\%$). See for example the Concentrating Solar Power Best Practices Handbook for the Collection and Use of Solar Resource Data [28].

If summed, assuming a well maintained, regularly cleaned, near perfect tracking mechanism, and no degradation over time, the total accumulated uncertainty in a field measurement of DNI beam radiation is 2.2%. Root sum squaring the uncertainties, we obtain 1.8% for typical

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Typical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncertainty in the characterization of the WSG reference pyrheliometers</td>
<td>$\pm 0.1%$</td>
</tr>
<tr>
<td>Uncertainty in the definition of the WRR derived from the WSG reference pyrheliometers</td>
<td>$\pm 0.3%$</td>
</tr>
<tr>
<td>Uncertainty in the determination of the WRR factor for a standard ACP pyrheliometer during an international or regional comparison</td>
<td>$\pm 0.15%$</td>
</tr>
<tr>
<td>Uncertainty in the derivation of the calibration factor from a standard reference ACP (or secondary reference pyrheliometer) to the field instruments</td>
<td>$\pm 0.75%$</td>
</tr>
</tbody>
</table>
uncertainties. A year-long comparison of several models and designs of pyrheliometers to evaluate performance in the field reported uncertainties on this order of magnitude [53].

### 1.2.7 Measurement Data Quality

The quality of measured DNI data is established at the time the data is recorded. Tracking accuracy, window cleanliness, departure of the measurement environment from the environment of the calibration transfer, data recording equipment performance and stability of the radiometer and its components all affect the quality of DNI data. Data quality assessment depends on the amount of effort and resources devoted to examining and understanding the data. Resources can be expended on redundant measurements, such as duplicate instruments, on independent trackers, daily or event driven site visits for cleaning, tracker alignment, visual inspections, and so on [54]. Ancillary data, such as attendant GHI and DHI measurements (so a calculated DNI can be compared with the measured DNI) or environmental data (temperatures below freezing and precipitation leading to icing, for instance) can be leveraged to decide if problems arise.

Given that the basic uncertainty expected in pyranometer measurements is on the order of ±3% to ±5%, the combined uncertainty of GHI and DHI measurements used in the computation of DNI results in an uncertainty of ±3% to ±5%, or two to five times the uncertainty in the DNI data from a pyrheliometer alone. However, one may detect changes greater than the combined uncertainty of 3% to 5% in computed DNI values with respect to measured DNI data. Differences greater than expected measurement uncertainty should be cause for investigating the condition of the pyrheliometer and the tracker used (or the GHI and DHI instruments!)

Other methods of detecting possible problems with the DNI pyrheliometer data is to compare clear sky data with historical clear sky data for similar atmospheric conditions, such as relative humidity, temperature, dew points, etc.; or comparison with mathematically modeled clear sky data. Modeling of clear sky DNI radiation is discussed in the next section. Historical DNI data for periods of clear sky from nearly identical time periods within the year can be compared. Historical, archived clear sky data can be normalized to a selected reference clear sky day, or even the ETR DNI. Comparing similarly normalized measured data with normalized historical data may help identify serious problems with current measurements.

Normalizing measured DNI to the ETR DNI ($I_o$, corrected for the Earth-Sun distance for the day of the year) is called the *clearness index* ($K_n$) for the atmosphere [55]:

$$K_n = \frac{DNI}{(R_e \cdot I_o)}, \quad (1.9)$$

Depending on the natural variation in the atmospheric conditions, weather, or climate, the performance of a pyrheliometer may be compared with these reference conditions, and significant deviations (greater than 3%) can alert the operator to investigate the cause of the deviation (poor tracking, contamination, degradation of calibration, etc.).

When DNI measurements are being conducted along with completed and installed concentrating PV (CPV) systems, constant comparison of the DNI data with the system performance data may be used to identify problems with either one or both of the systems [56–58]. The ratio of electrical power out to incident DNI power in (a sort of efficiency only considering DNI) is often used as a performance index for the CPV system [56]. Changes in this ratio greater than
the combined uncertainty in the ratio (the measurements of CPV system electrical parameters have their own uncertainty) may be used to alert operators of problems needing attention with either or both systems.

1.3 Modeling Broadband Direct Solar Radiation

Knowledge of the available broadband DNI beam radiation resource data is essential in designing a CPV system. Spectral variations in the DNI beam radiation may affect the performance of a CPV system depending on the solar cell technology used. Because of the expense of measuring equipment, neither of these types of data, and especially spectral data, are generally available. The designer or planner must then resort to surrogate data produced by mathematical models.

There are a relatively few models that have been developed since the 1970s that are in common use at this time (2013) [59–63]. Most are developed from and validated by comparison with measured data, and rely on empirical correlations [64,65]. Typical figures of merit for model performance are mean bias error (MBE, the average of differences between measured, preferably from an independent data set, and modeled results), and root mean square error (RMSE, the square root of the average of the sum of squares of differences computed in the MBE). That is:

\[ MBE = \frac{1}{n} \sum (y_i - Y_i), \]
\[ RMSE = \left( \frac{1}{n} \sum (y_i - Y_i)^2 \right)^{1/2}, \]

where \( Y_i \) are estimated from the model, and \( y_i \) are measured data, and \( n \) is the number of data points compared.

Theoretical physics is sometimes combined with empirical data correlations to produce semi-empirical models. The user of these models must be aware that often the data used to develop the model is used to verify or report the model performance. Verification of the model against independent data sets not used in the model development provides a more accurate estimate of model performance.

Users should keep in mind that it is impossible for empirical models to be more accurate than the measured data used to produce the models. This generally means that claimed model accuracy of better than 5% or so is probably unrealistic [64,65]. Also, measured data inevitably have scatter – represented by the Root Mean Square Error of Eq. (1.11) – about the correlation equations for the model data, which must be combined with the measurement uncertainties to assess the model performance.

1.3.1 Models for Direct Beam Irradiance

Empirical models are based on correlations, functions derived through linear or multi-linear regression analysis (curve fitting). It is assumed that measured solar radiation data can be described as a function of some other independently measured or available variables or parameters. These independent variables can range from simple, single variables such as temperature, to more complex combinations of temperature, relative humidity, day length, cloud cover, sunshine duration in hours, and so on [59–64].
A simple approach is to lump all of the effects of atmospheric transmittance into the one parameter of air mass \((m)\), or path length through the atmosphere, and a ‘bulk’ attenuation factor [66]. Such a model for computing the direct beam irradiance (DNI) at the surface on a clear day was presented by Meinel and Meinel in 1976 [67]. That model requires only the calculation of the extraterrestrial direct beam radiation, 1366.1 Wm\(^{-2}\), corrected for the Earth-Sun distance; a factor for average clear sky transmittance at air mass \(m = 1.0\), equal to 0.7; and an average (exponential) extinction coefficient (0.678) per unit air mass \(m\) (at sea level):

\[
DNI = 0.7 \times R_{c} I_{o}^{(0.678 m)},
\]

(1.12)

If one begins to consider site specific issues, or atmospheric conditions, additional functional terms are needed. In 1970, Laue derived a model involving the altitude, \(h\), in kilometers [68]:

\[
DNI = R_{c} I_{o} [0.7(1.0 - 0.14 h)R_{c} I_{o}^{(0.678 m)} + 0.14 h],
\]

(1.13)

These extremely simple models provide only a back-of-the-envelope estimate of clear sky DNI throughout the day, as the air mass decreases and increases.

### 1.3.2 Atmospheric Component Transmittance

#### 1.3.2.1 Linke’s Model

A popular method of estimating the bulk transmittance of the atmosphere is the Linke Turbidity Factor \((T_{L})\) proposed by Linke in 1922 [66]. Linke’s proposal is based on air mass \(m\), the optical thickness, \(\tau_{D}\), of clean (aerosol free), dry (no water vapor) atmosphere. The transmitted DNI irradiance is expressed as:

\[
DNI = R_{c} I_{o} \exp(-\tau_{D} T_{L} m),
\]

(1.14)

or, solving for \(T_{L}\):

\[
T_{L} = \ln(DNI/(R_{c} I_{o})))/(-\tau_{D} m),
\]

(1.15)

with the clean dry atmosphere optical thickness being calculated as:

\[
\tau_{D} = 0.128 - 0.054 \log(m),
\]

(1.16)

Thus \(T_{L}\) represents the number of clean dry atmospheres necessary to produce the observed attenuation. Databases of Linke turbidity are available online through the European Solar Energy for Professionals website [69].

A 2012 technical report by Reno, Hansen, and Stein [70] reports the accuracy of these simple clear sky models, when compared with measured DNI at several different sites to be on the order of 10%, at best.

#### 1.3.2.2 Comprehensive Transmittance Models

Somewhat better results can be achieved by considering the atmosphere in somewhat more detail. The individual constituent mixed gases (nitrogen, oxygen, carbon dioxide, etc.) water
vapor, stratospheric ozone, and aerosols, or small scattering centers suspended in the atmosphere can be considered to have a transmittance (ratio of what impinges at the top of the atmosphere to what remains at the ground level). Each transmittance can be parameterized in terms of the air mass and concentration or amount of a constituent present in the atmosphere. This is the basis of models developed by Bird and Hulstrom [61,62], and earlier work by Watt et al. [59], and Atwater and Ball [60]. More recently Gueymard [63] and many others have developed models using a similar approach. The total transmittance of the atmosphere, $T$, is then calculated as the product of the terms:

- $T_r$: transmittance due to Rayleigh scattering;
- $T_a$: transmittance due to aerosol properties;
- $T_g$: transmittance due to optical properties of gases;
- $T_o$: transmittance due to ozone (in the stratosphere);
- $T_w$: transmittance of water vapor.

Therefore, the DNI can be written as:

$$DNI = I_o R_c T_r T_a T_g T_o T_w,$$

(1.17)

where $I_o$ is the extraterrestrial direct beam irradiance calculated using Eq. (1.4) and $R_c$ is the Earth-Sun distance correction factor calculated using Eq. (1.6).

The equations defining the above transmittance parameters for the direct beam model of Bird and Hulstrom [61,62] are discussed in the next paragraphs. Note that many of these expressions depend on the air mass ($m$) which essentially equals $1/\cos(z)$, $z$ being the solar zenith or altitude angle ($\zeta$). The computation of solar zenith including effects of atmospheric refraction is based on site location (latitude, longitude) and accurate knowledge of local time. Example algorithms are reported in Iqbal [25], Michalsky [71] and Reda [72].

The expression for the Rayleigh transmittance ($T_r$) is:

$$T_r = \exp(1.0 + M_p - M_p^{1.01})(-0.0903 M_p^{0.84}),$$

(1.18)

where $M_p$ is the air mass corrected for station pressure or altitude: $M_p = m$ (station pressure)/ (sea level pressure).

The expression for the mixed gas transmittance ($T_g$) can be also calculated as a function of $M_p$:

$$T_g = \exp(-0.0127 M_p^{0.26}),$$

(1.19)

The total column ozone amount $O_z$ in atmospheric-cm is the total equivalent depth in cm of all ozone in a vertical column of air, condensed from the atmosphere: $O_m = m O_z$. From this magnitude the ozone transmittance ($T_o$) can be calculated as:

$$T_o = 1 - 0.1611 O_m(1.0 + 139.48 O_m)^{-0.3035} - (0.002715 O_m)/(1 + 0.044 O_m + 0.0003 O_m^2),$$

(1.20)

Historical total ozone estimates are available from the NASA Ozone and Air Quality website [73].
There is a frequently cited model due to Heuklon \[74\] to estimate ozone. This model estimates total column ozone based on the day of the year and the latitude and longitude of the site. Since the ozone absorbs strongly in the ultraviolet, and only weakly in the visible part of the spectrum, the impact of \(T_o\) on the transmittance of total DNI through the atmosphere is nearly negligible. The difference in total DNI beam irradiance resulting from a low ozone amount of 0.25 atm-cm and a higher amount of 0.35 atm-cm for a mid-latitude continental site, averaged over a year of 4400 daylight hours, is \(5 \pm 1.5 \text{ Wm}^{-2}\) out of an average DNI of 760 \text{ Wm}^{-2}, or less than 0.75%.

Water vapor transmittance \((T_w)\) for precipitable water vapor amount \(PW\) atm-cm, using:

\[
W = m \ PW
\]

\[
T_w = 1 - 2.4959 \frac{W}{[(1 + 79.034 W)^{0.6828} + 6.385 W]}, \tag{1.21}
\]

The aerosol transmittance \((T_a)\) is:

\[
T_a = \exp\{(-T_{a3}^{0.873})(1.0 + T_{a5} - (T_{a5}^{0.7088}))m^{0.9108}\}, \tag{1.22}
\]

where

\[
T_{a3} = 0.2758 T_{a3} + 0.35 T_{a5}, \tag{1.23}
\]

and \(T_{a3}\) is the aerosol optical depth at 380 nm, and \(T_{a5}\) is the aerosol optical depth at 500 nm. Here, optical depth \((OD)\) is the dimensionless attenuation of incident radiation, \(I\), as a function of unit path length through a distance \(d\) of absorbing material: \(I_{out} = I \exp(-OD \ d)\). That is, \(OD = -\ln(I_{out}/I)\) per unit \(d\). Sometimes \(OD\) is expressed without units, or as attenuation per unit of measure, as in \(\text{cm}^{-1}\), \(\text{m}^{-1}\), \(\text{km}^{-1}\), etc. In our case, the unit of measure for path length is the dimensionless air mass, \(m\).

Here, \(T_{a3}\) was based on a rural aerosol distribution of Shettle and Fenn \[75\], which could be approximated from routine measurements from the National Oceanic and Atmospheric Administration (NOAA) at the time of the model development (1982). Measured aerosol optical depth data is available from the National Aeronautics and Space Administration (NASA) AERONET network described below.

So called broadband aerosol optical depth or BAOD may be derived from the attenuation of the DNI beam, \(I/(R_c I_o) = \exp(-BAOD \ m)\) once the attenuation due to ozone and water vapor is accounted for. Molineaux and Ineichen \[76\] have shown that BAOD is equivalent to the spectral aerosol optical depth at a specific wavelength, namely 700 nm. Because optical depth is a decreasing function of increasing wavelength, multiplying a BAOD by \(~1.5\) would be equivalent to spectral optical depth at 500 nm, and \(1.8\)-BAOD is approximately the spectral AOD at 380 nm.

Total precipitable water (the equivalent depth of water in centimeters if condensed out of the entire atmosphere above a location) may be estimated from relative humidity as described by Garrison and Adler \[77\] using the following sequence:

1. The saturated vapor pressure \((E_s)\) of water vapor, in mbar, can be calculated from temperature, \(T\), in K, using:

\[
\log_{10}(E_s) = -8.430 - 1827.178/T - 71208.271/T^2, \tag{1.24}
\]
2. The pressure corrected water vapor pressure \((E)\), in mbar, can be calculated from relative humidity \((RH)\) and station pressure \((P)\) with respect to sea level atmospheric pressure of 1013.25 mBar:

\[
E = RH \cdot E_s(P/1013.25),
\]

(1.25)

3. Finally, the estimated water vapor amount, \(W\), in atmosphere-millimeters (atm-mm) is:

\[
W = 1.45E + 1.5,
\]

(1.26)

Aerosol and water vapor data needed for these equations is available from the National Aeronautics and Space Administration AERONET network [78].

### 1.3.3 Estimating Direct Beam Radiation from Hemispherical Data

**Total hemispherical irradiance**, GHI, is the most common solar radiation measurement available, because it uses the most simple measurement equipment, a pyranometer on a horizontal surface. Measurements of DNI and GHI have been used to develop correlations between the two measured quantities by many authors. Below we discuss an extremely simple model and a relatively complex model. Both are based on the idea of clearness index, or bulk transmittance of the atmosphere for one or the other or both of the components.

#### 1.3.3.1 Boes Simple Correlation

Boes et al. [79] used one year of data from three United States stations with measured DNI and GHI data. Their correlation produces DNI (in Wm\(^{-2}\)) as a function of global horizontal clearness index \(K_t = (GHI)/(I_o \cos(z))\) and solar zenith angle, \(z\):

\[
\begin{align*}
DNI &= 400 \text{ Wm}^{-2} \text{ for } z = 80^\circ \text{ and } K_t > 0.5 \\
&= -520 + 1.8K_t \text{ Wm}^{-2} \text{ for } 0.3 \leq K_t \leq 0.85, \\
&= 1000 \text{ Wm}^{-2} \text{ for } K_t > 0.85
\end{align*}
\]

(1.27.a) (1.27.b) (1.27.c)

The original work only utilized \(K_t\) values between 0.3 and 0.85; and reported monthly values of clear sky DNI \((K_t > 0.85)\) ranging from 950 Wm\(^{-2}\) to 1,050 Wm\(^{-2}\). They used the value of 1000 Wm\(^{-2}\) (a value that certainly can occasionally be exceeded, as a reasonable maximum to simplify the model. Reno, Hansen, and Stein [70] report in a 2012 publication an accuracy of only about ±20% for this model.

#### 1.3.3.2 The Maxwell Direct Insolation Simulation Code (DISC) Model

Maxwell [80] at NREL developed his *direct insolation simulation code* (DISC) model using \(K_n\), the direct clearness index \((DNI/(R_x, I_o))\), rather than the \(DNI/GHI\) ratio for the dependent variable. He developed the model using one year of measured data for Atlanta, Georgia, USA. Three United States sites with measured DNI and GHI were used to validate the model. The sites have diverse climates: Brownsville, Texas; Albuquerque, New Mexico; and Bismarck, North Dakota.
Maxwell used parameterizations of $K_n$ with respect to $K_t$ and $K_n$ bins of width 0.05 and air mass, $m$. He derives a general formulation of $K_n$ versus $K_t$ (from measured GHI data). The model equation produces the change or deviation $\Delta K_n$ from clear sky transmittance, denoted by $K_{nc}$. Modeled DNI is computed as $DNI = I_o K_n$, where:

$$K_n = K_{nc} - \Delta K_n,$$

(1.28.a)

$$\Delta K_n = a + b \exp(c \cdot m),$$

(1.28.b)

The clear sky limit $K_{nc}$ is computed from a polynomial in air mass, $m$:

$$K_{nc} = 0.866 - 0.122 m + 0.0121 m^2 - 0.000653 m^3 + 0.000014 m^4,$$

(1.29)

To determine the coefficients $a$, $b$, and $c$, the $K_t$ space was partitioned into two parts, $K_t \leq 0.6$ and $K_t > 0.6$.

For $K_t \leq 0.60$:

$$a = 0.512 - 1.56 K_t + 2.286 K_t^2 - 2.222 K_t^3,$$

(1.30.a)

$$b = 0.370 + 0.962 K_t^3,$$

(1.30.b)

$$c = -0.280 + 0.932 K_t - 2.048 K_t^2,$$

(1.30.c)

For $K_t > 0.60$:

$$a = -5.743 + 21.77 K_t - 27.49 K_t^2 + 11.56 K_t^3,$$

(1.31.a)

$$b = 41.4 - 118.5 K_t + 66.05 K_t^2 + 31.90 K_t^3,$$

(1.31.b)

$$c = -47.01 + 184.2 K_t - 222.0 K_t^2 + 73.81 K_t^3.$$  

(1.31.c)

The DISC model has bias (mean of differences between measured and model data) errors of about $\pm 50 \text{Wm}^{-2}$ and random (RMSE) errors of about $\pm 150 \text{Wm}^{-2}$ depending on the site. There are caveats about the DISC code. One is that the range of zenith angles and air masses for the model development and validation are only for United States continental sites with latitude ranging from $28^\circ$N to $45^\circ$N.

Perez et al. [81] attempted to improve the DISC model by application of corrections based on water vapor and aerosol estimates, however the improvements were so slight that measured data uncertainty are larger than the reported magnitude of the updated model. Secondly, the model was derived based on hourly average GHI and DNI data. There is no guarantee that the model equations apply equally to data measured at different (higher) time resolution. There is still a need for a more accurate, universal model for converting more widely available GHI data to DNI data for CPV applications [82,83].

### 1.4 Modeling Spectral Distributions

In sections 1.1.4 and 1.1.5 there was cursory mention of the extraterrestrial solar spectral distribution, the effect of the atmospheric filter, and the issues with spectral sensitivities of PV
and optical component materials in CPV applications. Many spectrally dependent parameters for materials can be measured in the laboratory. These laboratory measurements must be combined with solar spectral distributions to compute either detailed or overall CPV system performance. Terrestrial DNI solar spectral power distribution data are very rare, so one must resort to models for generating realistic estimates of CPV performance. As with broadband DNI models, the properties of atmospheric constituents, this time with spectral dependence included, are used to modify an ETR spectral power distribution\(^1\). We briefly describe here two popular and easy to use spectral models; the simple Spectral 2 (SPCTRL2) model of Bird [84,85], and the moderately complex *simple model of the atmospheric radiative transfer of sunshine* (SMARTS) of Gueymard [86]. The following chapters will discuss the impact of spectral irradiance distribution on concentrating system performance.

### 1.4.1 Bird Simple Spectral Model (SPCTRL2)

The Bird Simple Spectral Model, SPCTRL2, developed by Bird and Riordan [84,85], at NREL, computes clear sky spectral direct beam, hemispherical diffuse, and hemispherical total irradiances on a prescribed receiver plane – tilted or horizontal – at a single point in time. This model was used as the basis for early (1995 and earlier) and now inactive versions of reference solar spectra standards for PV applications such as ASTM E891/E892 and G159 (see the section on Consensus Standards).

For tilted planes, the user specifies the incidence angle of the direct beam (FORTRAN version) or the tilt and azimuth of the plane (Excel\(^\circ\) and C versions). The wavelength spacing is irregular, covering 122 wavelengths from 305 nm to 4000 nm. Aerosol optical depth, total precipitable water vapor (cm), and equivalent ozone depth (cm) must be specified by the user. No variations in atmospheric constituents or structure are available. There is no separate computation of circumsolar radiation. The direct beam spectral irradiance is assumed to contain the circumsolar radiation within a 5° solid angle.

The equations for the broadband Bird clear sky DNI model are re-written in terms of functions of wavelength [84], to generate the spectral DNI, \(I_b(\lambda)\):

\[
I_b(\lambda) = R_c I_o(\lambda)T_r(\lambda)T_a(\lambda)T_g(\lambda)T_o(\lambda)T_w(\lambda),
\]

where \(I_o(\lambda)\) is the air mass zero (AM0) or extraterrestrial spectrum; \(T_r\), \(T_a\), \(T_g\), \(T_o\), and \(T_w\) are wavelength dependent transmittance functions for Rayleigh scattering, aerosols, uniformly mixed atmospheric gases, ozone, and water vapor, respectively; \(R_c\) is the Earth-Sun radius vector correction. Bird used the 1985 Wehrli AM0 spectrum [87] as the starting point for his model. Only 122 irregularly spaced wavelengths at approximately 10 nm intervals from 305 nm to 4000 nm were selected to simplify the spectral calculations. Many absorption features are captured using only three or four wavelengths to identify the shoulders and greatest absorption of the features. The model is easily implemented in about 50 lines of computer programming code and is estimated to be accurate to about 5% to 10% when compared with measured spectra. Source code in FORTRAN, C, and Microsoft Excel\(^\circ\) versions and the ancillary data files (absorption coefficients and ETR spectrum) are available from the NREL Renewable Resource Data Center [88].

---

\(^1\) An extensive catalog of many atmospheric radiative transfer model codes, some very complex and requiring highly esoteric and difficult to locate input parameters, is available at [http://en.wikipedia.org/wiki/Atmospheric_radiative_transfer_codes](http://en.wikipedia.org/wiki/Atmospheric_radiative_transfer_codes)
1.4.2 Simple Model for Atmospheric Transmission of Sunshine (SMARTS)

Gueymard [86] developed a simple model for atmospheric transmission of sunshine, SMARTS, to improve upon the performance of SPCTRL2, improve the existing PV reference standard spectral distribution, and provide more flexible options for solar engineering applications involving solar spectral power distributions. Version 2.9.2 of SMARTS is the basis for the present ASTM and IEC reference spectra ASTM G-173 and ASTM G-177, IEC 60904 [89–91] used for photovoltaic performance testing and materials degradation studies. The model source code is comprised of about 5000 lines of FORTRAN code and is supplied with about 50 ancillary data files for various atmospheric profiles, spectral ground reflectance (albedo), and atmospheric gas absorption. SMARTS computes clear sky spectral irradiances (direct beam, circumsolar, hemispherical diffuse, and total on a tilted or horizontal receiver plane) for specified atmospheric conditions. Users choose one of 10 standard atmospheres or can build their own atmosphere profile. Output for one or many points in time or solar geometries (tilted surfaces, etc.) may be selected.

The algorithms used by SMARTS were developed to match within ±2% the output from the very general MODTRAN complex band models developed by the US Air Force Geophysical Laboratory [92,93]. The algorithms are implemented in compiled FORTRAN code for Macintosh and PC platforms. Source code is included within the model package. The algorithms are used in conjunction with files for atmospheric absorption of atmospheric components and spectral albedo functions. The spectral resolution is 0.5 nm for 280–400 nm, 1 nm for 400–1750 nm, and 10 nm for 1750–4000 nm.

SMARTS users construct text files of 20–30 lines of simple text and numbers to specify input conditions and up to 28 spectral output parameters. Users can specify field-of-view angles for direct-beam computations and a separate computation for the circumsolar component. Gaussian or triangular smoothing functions with user-defined bandwidth can also be specified to compare model results with measurements made with the specified passband. Users can specify only ultraviolet (280–400 nm) computations for erythemal dose, UV index, and similar measurements. Photometric (luminous flux) computations, weighted by a selected photonic response curve, can also be specified. Model output consists of spreadsheet-compatible text files with header information and a record of the prescribed conditions.

Both SPCTRL2 and SMARTS have been validated in many comparisons with measured spectral data [94–100] and generally shown to be within the spectral measurement uncertainty limits, which range from 10% in the ultraviolet to 2%-3% in the visible, and 5% in the infrared, greater than 1200 nm. While more complex, SMARTS is much more flexible than SPCTRL2 and can provide much more detailed information. Given the same atmospheric conditions, however, the two models produce about the same amplitudes of modeled data.

1.4.3 Spectral Distributions from Broadband Data

The SPCTRL2 and SMARTS models both compute clear sky solar spectral power distributions. It is natural to deploy CPV systems in places where the skies are most likely to be clear, to optimize the conversion of DNI beam radiation into energy. At times, clouds of various types and density may intervene and affect both the intensity and spectral content of the direct beam. Should the designer wish to consider these effects upon the CPV system design there very few examples of measured spectral data publically available. One such set is the NREL Spectral Solar Radiation Database [101–103]. The database of over 3000 measured spectra under
various conditions at three sites is available online [104]. The database documentation, including uncertainties associated with the data, is available in Riordan et al. [101,102], and Myers [103].

In the absence of measured data, there are published spectra and spectral models for estimating spectral distributions affected by clouds. In 1990, the Commission Internationale de l’Éclairage (CIE), or International Commission on Illumination, published a collection of solar spectra [105] based on the SPCTRL2 model and a model by Justus [106] to account for cloud effects. Since then two models based on the SPCTRL2 model and addressing cloud effects have been published. These are the SEDES (Solar Energy Data Acquisition System, Erwerb in German) of the Center for Solar and Hydrogen Science Center (ZSW) in Stuttgart, Germany [107]; and the TMYSPEC model modified version of SEDES developed at NREL [108]. The original SEDES model converts hourly measured broadband GHI data to spectral data on a prescribed tilted surface. The TMYSPEC model converts typical meteorological year (TMY) or measured GHI data to both GHI and DNI spectral data on a surface of prescribed tilt. The concept of TMY is discussed in more detail in section 1.5.2.

Both SEDES and TMYSPEC models modify the computed clear sky SPCTRL2 model with the ratio of measured broadband data to theoretical clear sky broadband data and empirically derived cloud cover modifiers which are spectrally dependent. The theoretical clear sky broadband data is computed by integrating the modeled clear sky spectral data. For SEDES the resulting modeled spectral power distributions have a spectral range of 300 nm to 1400 nm, and for TMYSPEC the spectral range is 300 nm to 1800 nm. The SPCTRL2 computed spectra are interpolated to 10 nm wavelength intervals. TMYSPEC also generates DNI beam spectra, while the SEDES model only produces the total hemispherical spectra on a prescribed tilted surface. The modeled spectra compare with measured spectra to an uncertainty of about ±15% for the total hemispherical spectra, and ±20% for the direct beam spectra.

### 1.5 Resources for Broadband Estimates of CPV Performance

The first choice and best quality data for estimating the performance of a CPV system at a certain location is that measured in place for a long period of record at relatively high temporal resolution, such as hourly average data. For environments with high variability in solar radiation and weather data, higher time resolution data, such as data sampled at 1 minute, 5 minute, or 10 minute intervals is desirable. This permits the study of the impact of input transients on the CPV system. The ASTM 2527 consensus standard [109] was mentioned above describing a methodology for estimating the performance of CPV system after it has been deployed in the field. However, these types of measurements can only be used to validate or evaluate the accuracy of the original design of the system. System design usually includes some modeling of system performance based on broadband DNI beam data, sources of which are described in the next section.

#### 1.5.1 Broadband Direct Beam Radiation Data Resources

The only archive of worldwide measured solar radiation data is maintained at the WMO World Radiation Center (WRC) at St. Petersburg, Russia [110]. Member nations contribute measured data in various formats which are quality assessed and archived at the center. DNI beam radiation is sometimes included from some sites, however only rarely. The units of the archived data are in energy, Joules (or megaJoules, MJ) rather than power. The data is available on
Data from a station may consist of only a few months of data to many years, depending on the support and operation of the stations by the member nation.

Unfortunately, long periods of recorded solar radiation data, and especially DNI beam radiation, are generally very rare. This means that broadband data for most locations must be modeled. Several sources of data have been assembled slowly over the past 40 years at various national and international levels. In the United States, the National Climatic Data Center (NCDC) in conjunction with Sandia National Laboratory first developed a Solar and Meteorological (SOLMET) database of hourly average measured data for 23 National Weather Service (NWS) solar and meteorological measurement stations [112]. Empirical models were then developed (using the measured data) to produce SOLMET type data for an additional 200 NWS sites where only meteorological data were available. The modeled data were called SOLMET ERSATZ (German for ‘substitute’) sites [113]. SOLMET/ERSATZ data covered the period from 1952 to 1970. Various original NWS monitoring sites were closed down and either eliminated or re-instrumented between 1975 and 1985. In 1995 the United States solar monitoring network was shut down, and replaced with a ‘research’ network of only seven stations. See Renné et al. [114] for the status of United States measurement networks as of 1999.

In 1990, NREL began developing the first version of the National Solar Radiation Data Base (NSRDB) [115,116]. The NSRDB consists of (95% modeled) solar hourly data for DNI, GHI, DHI, total precipitable water, and broadband aerosol optical depths, along with NCDC reported meteorological data and conditions. NREL developed the Meteorological and Statistical (METSTAT) model to produce the estimated parameters, and algorithms to construct serially complete hourly data files for 239 stations for the period from 1960 to 1990 [117]. The METSTAT model was also modified to produce the Climatological Solar Radiation (CSR) model [118], to produce monthly mean solar radiation data for various renewable energy projects under United Nations Solar and Wind Energy Resource Assessment (SWERA) program\(^2\) and for the King Abdul Aziz City for Science and Technology (KACST) to produce a solar radiation atlas for Saudi Arabia [119].

In 2001, and again in 2012, the NSRDB was updated and expanded [120]. The updates included extending the period of record first from 1990 to 2000, and again from 2000 to 2010. The expansion included the estimation of solar radiation components on a 10 kilometer (approximately) spatial resolution, using Earth orbiting meteorological satellite data (From US GOES, or European METEOSAT platforms) in conjunction with solar radiation estimation models [121]. The quality of meteorological satellite data needed becomes widely available in 1995. The updated NSRDB for 1995 to 2010 now contains approximately 100,000 grid cells, 10 km on a side, with DNI, GHI, and DHI solar radiation estimates representing 1 hour average values. The United States and other nations’ satellite conversion models are now used to estimate broadband solar radiation in many countries.

Maps of monthly and annual average solar radiation values for many countries have been developed using these techniques. A few examples are shown in section 1.7 on Direct Solar Radiation Climates. The underlying hourly data for a specific cell may be available from several sources. For the US, NREL provides access through the Solar Prospector website [122], and PVWatts PV system simulator (for flat plate collectors, but includes solar 2-axis and 1-axis tracking flat plates) [123]. Commercial firms are now providing near real-time (up to

\(^2\) (see [http://en.openei.org/apps/SWERA/](http://en.openei.org/apps/SWERA/))
‘yesterday’) estimates of solar radiation resources for specific locations for a fee. These are based on publicly available weather satellite data and their own proprietary satellite conversion algorithms [124,125].

NASA has also prepared long term (22-year) yearly and average satellite based estimates of solar radiation and meteorological data and made it available through the Surface Meteorology and Solar Energy (SSE) website [126]3. Meteorology and solar radiation for SSE Release 6.0 were obtained from the NASA Science Mission Directorate’s satellite and re-analysis research programs [127].

Parameters based upon the solar and/or meteorology data were derived and validated based on recommendations from partners in the energy industry. The 2013 release 6.0 extends the temporal coverage of the solar and meteorological data from July 1983 through June 2010. Most of the data is available as monthly averaged data, but individual daily total radiation are available for each year. The underlying (hourly or sub-daily total) data are not available. The SSE data is based on one degree by one degree cells and is available for single cell, or regions bounded by coordinates provided by the user.

The European Union website PVGIS [128], provides a catalog of, and links to available solar radiation datasets. There is also an online publication containing an inventory of solar databases. Examples of several solar radiation data bases are the Solar Energy Services for Professionals (SODA) website where various forms of modeled and measured data are available online [129]. In addition, there is also a European Solar Radiation Atlas produced by the École des Mines de Paris [130,131].

A comprehensive world-wide set of combined measured and modeled solar radiation data, including the ability to ‘downscale’ to higher time resolution (1 minute) from hourly average data is the Swiss METEONORM data set, available from MeteoTest (where some on-line computations are available) [132].

It is important to note that the uncertainty of DNI beam data in any of the models of this type has been shown to be on the order of ±20% for most continental, seasonally variable climate sites, such as Europe, or mid-continent United States. The uncertainty may be expected to be lower for sites suitable for CPV deployment, where consistent clear sky conditions are preferred. The only way to verify this hypothesis is to conduct at least some measurements at a proposed site and evaluate the correlation of the measured and satellite (or other model) derived data sets. This approach is currently described as a ‘measure, correlate, predict’ (MCP) or ‘measure, correlate, evaluate’ (MCE) program. See for example Thuman, Schnitzer, and Johnson [133].

1.5.2 Typical Meteorological Year Data for CPV Performance Estimates

The concept of Typical Meteorological Year or TMY was developed by the North Atlantic Treaty Organization (NATO) for heating and cooling applications in 1977 [106]. Data sets for the United States and many international sites have been developed over the years [107–109].

These data are used extensively in the modeling of building heating and cooling loads and building energy performance models. TMY broadband solar and meteorological data have also become popular as input to solar energy conversion system modeling software because of the wide availability of the data.

3 http://eosweb.larc.nasa.gov/sse/
TMY data are serially complete, 8760 hourly records of solar GHI, DNI, and DHI data in conjunction with meteorological parameters such as wind speed, ambient and dew point temperatures, water vapor and broadband aerosol optical depth. The TMY hourly data are selected from a long time series (many years) of hourly data based using a specific statistical analysis and parameter weighting scheme methodology.

For a given month, the methodology is structured so as to find the closest match to an ‘average’ cumulative frequency distribution of parameters from the collection of all cumulative frequency distributions for the particular month. The single month of hourly values selected from the collection of available months (filtered to remove extreme events such as volcanic events, etc.) is considered ‘typical’ for the site. The concatenation of the typical months (probably selected from different years) into a typical year is considered ‘typical’, and somewhere between extremes, for the site in question.

It is wise to remember that since the T in TMY represents ‘typical’ and that weather and solar conditions vary considerably from typical most of the time, that TMY based energy conversion performance predictions may have a great deal of uncertainty, dependent on the inter-annual (and intra-annual) variability of the weather at particular site.

 Nonetheless, TMY data sets are very popular input data for modeling PV conversion technology performance for a ‘typical’ or ‘average’ year. Many system modeling software packages include these data sets as a library of sites to select from. Such packages also permit ‘TMY format’ data from other sources to be used as input. The term ‘TMY’ has become rather generic, but various versions are available, so the user must be knowledgeable of the time frame and formats used. The original TMY [134] was developed from the 1952–1975 SOLMET/ERSATZ [112,113] data, and based on true solar time, not local standard time at the sites. The format of the earliest TMY data consisted of concatenated (with no spaces), variable length data fields in American Standard Code for Information Interchange (ASCII) text that required parsing or filtering to select the correct values.

The TMY2 [135] developed from the 1960–1990 US NSRDB used the same concatenated variable field length format, but was constructed with slightly different data fields. Local standard time for the site is used. Weighting factors for the solar radiation data, and units for some variables are different and are described in documentation for the TMY2. For a full description, see [136].

The US TMY developed from 1960 to 2010 NSRDB data are denoted as TMY3 files [137], and are available as comma separated variable (CSV) format suitable for spreadsheet import, and are not necessarily compatible with all PV performance models unless they are reformatted. For a full description, see [138].

Because the initial primary application of ‘typical year’ weather data was the design of buildings to meet indoor environmental needs with respect to the outdoor environment, many international versions of the TMY data are available. The US Department of Energy maintains a library of these (and similar) data sets (‘weather year for energy calculation’) [139].

The interpretation of results using typical year input data as opposed to multi-year simulation runs may be misleading, especially in highly variable climates. Extreme weather and man-made events such as volcanic eruptions, biomass burning, el-Niño and la-Niña events, etc. may strongly attenuate DNI, and are excluded from typical weather year data. Multi-year simulations of performance may provide a much better picture of year to year performance variations that the system may be sensitive to [127]. See section 1.7.3 for a discussion of intra- and inter-annual variability of resources.
1.5.3 CPV Spectral Performance Issues

Because terrestrial solar spectral DNI data is even more complex and sparse than broadband data, model calculations are the tools of choice in studying the sensitivity of a CPV system performance to spectral variations. A very few studies have been made that demonstrate the relative importance of spectral variation in this regard [133,140,141]. This means that the computation of the product of optical properties, PV material spectral response, and spectra under different conditions are required. The spectral distribution of the DNI beam radiation is a strong function of the air mass (as well as atmospheric condition), so correlations of spectral effects with air mass are often used as surrogate for the above complete spectral computations.

Several authors have shown that this approach can lead to erroneous and misleading results [142]. Best practice for evaluation of CPV sites and system design is to collect and process as much information as possible on the parameters that affect spectrally significant performance parameters. Even if there is no desire to perform spectral modeling, at least an estimate of the variation in performance can be obtained from knowledge of the variability of parameters that affect the DNI spectral power distribution.

The most important examples are: variability of the aerosol optical depth, including that of (possibly polluted) upwind sites for the prevailing wind patterns, sand particle size and transport, terrain type (vegetated or not, hard pan desert, such as the American southwest, or loose, fine grained desert surface, such as the Gobi or sub-Saharan deserts), nearby biomass burning, and frequency and type of clouds. If there is concern that these parameters are indeed highly variable, modeling of effects using spectral models for extreme conditions is recommended. See Gueymard [143].

1.6 Sunshape

Recall that section 1.1.1 discussed the geometrical relationship between the Earth and Sun that result in the $0.52^\circ$ to $0.54^\circ$ solid angle (cone) of slightly divergent, quasi-parallel bundle of optical rays in the direct solar beam at the top of the atmosphere. Section 1.1.5 on the atmospheric filter described scattering and absorption processes in the atmosphere that attenuate and redistribute the energy in the DNI beam passing through the atmosphere. These effects result in what the CPV community has come to describe as the ‘sunshape’ as projected on the sky dome, or the conversion device in the CPV system. The desire to optimize the capture of photons in a CPV system in combination with the optical properties of the system design have lead designers to study the field of view and tracking accuracy of CPV systems that depend on sunshape in detail.

1.6.1 The Solar Disk

The sun is essentially a large sphere of extremely high temperature gases whose size is determined by the outward pressure of radiation and opposing gravitational force of the mass of the solar constituents. As seen from Earth above the atmosphere, the solar disk, or photosphere of the sun, appears to have a somewhat ill-defined edge with diminishing brightness. The disk is surrounded by a faint ‘corona’ or ‘solar atmosphere’ of ejected, high energy ionized atoms emitting some visible, X-ray, and radio wave energy over a wide spectral range. The photograph of the transit of Venus on June 6, 2012 (Figure 1.8) illustrates the ill-defined edge seen in optical (‘white-light’) or other spectral ranges. This decrease of intensity in the
image of the sun as one moves from the center of the image to the edge is the so-called limb darkening.

Limb darkening results from the combination of the depth dependence of temperature (through the near surface solar atmosphere, and surface layer of the photosphere itself) and the decreasing optical depth of the path length as one measures the intensity from the center of the disk to the solar limb. Eddington derived the relationship between optical depth, source function temperature and integrated intensity [144]. A closed form representation of limb darkening as a function of the angle \( \theta \) from the center of the sun, \( (\theta = 0^\circ) \) to the limb \( (\theta = 90^\circ) \), using \( \mu = \cos(\theta) \) is:

\[
I(\mu) = I(0)(3/5)(\mu + 2/3),
\]

(1.33)

Table 1.3 shows the diminution of the intensity of the radiation as one moves from the center to the limb as computed with the Eddington approximation – using Eq. (1.33) – and the

<table>
<thead>
<tr>
<th>( \theta ) (°)</th>
<th>( \mu = \cos(\theta) )</th>
<th>Eddington</th>
<th>Measured at 500 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.0</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>37</td>
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measured intensity in the visible, at 500 nm. Figure 1.9 is a plot of a polynomial fit to the measured data in Table 1.3.

Figure 1.10 is a plot of relative intensity as a function of central angle $\theta$ for various wavelengths in $\mu$m, illustrating that limb darkening is a function of the wavelength of emitted light in the solar spectrum [145]. The shorter the wavelength, the stronger the reduction in intensity as one moves away from the disk center. As soon as the observer line of site moves off
the edge of the photosphere, the emitted optical radiation from the corona falls by more than three or four orders of magnitude (or a factor of 0.001 to 0.0001).

1.6.2 Circumsolar Radiation

As the direct beam at the top of the atmosphere, which includes the limb darkened radiation at the periphery of the beam, propagates through the atmosphere and the scattering processes described in section 1.1.5 occur, especially the Mie scattering from large particles, a circumsolar component of the beam radiation is created. Mie scattering preferentially re-directs photons in the direction of the propagation of the beam, however into a much larger solid angle than the beam and large angles from the axis of the center of the beam. Mie scattering around the solar disk in the clear sky is also independent of wavelength, so produces an appearance of ‘white’ light surrounding the disk. This circumsolar radiation is also often referred to as the solar aureole.

The radiation from the limb darkened solar disk irradiance is also attenuated by the atmospheric absorption processes. From a site at the surface, if a very narrow field of view instrument (say 0.05°, or 1/10 of the solar disk diameter) is scanned from the center of the solar disk to a few degrees beyond the limit of the solar disk a profile of the intensity of the radiation can be established. Several approaches of experimentally accomplishing this measurement of sunshape under various atmospheric conditions have been developed since the early 1970s.

1.6.2.1 The Lawrence Berkeley Circumsolar Telescope Data

The Lawrence Berkeley Laboratory (LBL) at the University of California in Berkeley, developed a circumsolar telescope with a field of view of 0.025° or 1/20 of the solar diameter [146,147]. A photograph of one of the telescopes rehabilitated by NREL to acquire spectral data is shown in Figure 1.11.

![Figure 1.11 LBL Circumsolar Telescope (without data acquisition system). Source: © David Myers](image-url)
Four copies of the original LBL instrument were deployed at eleven different sites in the United States. The telescopes were configured to automatically perform scans over 6° of arc, with the solar disk at the center, at approximately 10 minute intervals. The scan data was acquired in steps of 1.5 arc seconds (0.0004°). A broadband pyroelectric detector (electrical signal generated proportional to heating by absorption of optical radiation) was exposed to the radiation within the field of view of the telescope. Across the much brighter solar disk, an aperture field of view of 1.5 arc seconds (0.0004°) was used. To account for the large decrease in intensity in the circumsolar region, an aperture with a 4.5 arc second (0.00125°) field of view is used. A reduced version (only a half of the scan data, from 0° to 3.2° away from the disk center, and only about 10% of all the data actually collected) is available online [48].

Table 1.4 is an image of the data format in the reduced data set to illustrate the structure of the data files and assist in their interpretation. The data fields are the site number; telescope number; date; solar time; local time; 2 digit flag status (1 = no errors, 0 = rain flap open); 2 digit line identifier (01 to 07 for broadband data; 21 to 24 for solar disk data; 41 to 47 for circumsolar data). Data lines 01 to 07 contain fields for altitude and azimuth of the sun; Earth-Sun Distance (ESD) in A.U.; flag fields (for instrument problem identification); total hemispherical pyranometer irradiance data for unfiltered and filtered pyranometers on the tracker, normal to the sun, and in horizontal positions; pyrheliometer readings using a filter wheel with clear aperture, filters with wavelength passbands of 0.38–0.46 μm, 0.46–0.54 μm, 0.54–0.62 μm, 0.62–0.72 μm, 0.72–0.85 μm, 0.85–1.05 μm, 1.05–1.25 μm, and >1.25 μm, and a blank or ‘dark’ reading; the solar radiation from the disk alone (SolRad); the total radiation within the circumsolar region from 0.30° to 3.2° from the center (Circum); the circumsolar (C) to total solar plus circumsolar (C+S) ratio or $CSR = C/(C+S)$; ACR signal (a Willson type active cavity radiometer [37]); pyrheliometer fractional error; and a correction factor for converting pyroelectric readings for Wm$^{-2}$sr$^{-1}$. Data fields 21 to 24 contain intensity data in steps of 1.5

**Table 1.4** Sample image of data for one NREL LBL circumsolar database scan

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arc seconds (reading from left to right and down) from the solar disk center to the limb with a field of view of 1.5 arc seconds. Thus the central intensity is $1.486 \times 10^7$ in relative intensity, and after 10 steps toward the limb (15 arc sec) has fallen to $1.684 \times 10^6$, or 46%. Data lines 41 to 48 contain circumsolar radiation intensity data using a 4.5 arc second field of view. Data line identifier 99 indicates the end of the scan data. Figure 1.12 is a sample of the data from two sites (Albuquerque NM and Fort Hood, TX) with various levels of general atmospheric transparency and atmospheric conditions from reference [147].

The LBL circumsolar data set is the only easily accessible no-cost data available for the investigation of the relationship between circumsolar radiation and broadband radiometric measurements. Figure 1.13 graphically illustrates the relationship between the ratio of DNI beam to GHI and circumsolar radiation. The figure shows the limits of a 5° and 5.7° field of view pyrheliometers, illustrating the difficulty of even measuring quantitatively the impact of circumsolar radiation using broadband pyrheliometers or absolute cavity pyrheliometers.

Recall that pyrheliometer and pyranometer accuracy is at best about 0.5%, or 5 parts out of 1000. Figure 1.13 shows that even if 24% of the disk radiation is scattered into the circumsolar region, (not a likely candidate for site for CPV!). The intensity of the circumsolar radiation at the limits of a 5° field of view cavity pyrheliometer and a 5.7° field of view pyrheliometer is less than a few parts out of 1000, or probably close to the random noise level in such measurements. Under clearer conditions the difference falls to a few parts out of 10 000. This is 100 times the uncertainty in either instrument.

It is also clear that if a CPV system has an acceptance angle or field of view smaller than, or less than the field of view of a pyrheliometer, the pyrheliometer will provide a relative overestimate of the radiation available to the CPV system, represented at most (but less than, as only a small fraction of the circumsolar aureole photons are scattered parallel to the direct beam) by the integrated circumsolar radiation between the limit of the CPV system acceptance and the limit of the pyrheliometer field of view.
The spectrally filtered LBL pyrheliometer data itself contains valuable information about how atmospheric conditions affect the spectral power distribution of DNI beam radiation. Some of this data is discussed in Buie, Monger and Dey [149] mentioned in the next section. Despite the coarse spectral resolution of this data, it should be possible to correlate the LBL spectral DNI data with clear sky modeled spectra to produce scaling factors to match higher resolution spectral model results with data from spectral regions in the filtered LBL pyrheliometer data set.

1.6.3 Recent Circumsolar Radiation Research

Recent publications on newer instrumentation and results investigating circumsolar radiation have occurred because of the recent current revival of interest in concentrating solar technology and CPV in particular. Using the LBL circumsolar data base, Rabl and Bendl [150] developed a modeled ‘standard solar sunshape profile’ (figure 7 of [150]) for use in conjunction with optical performance models for concentrating systems. They mention, but do not discuss in detail, the effects of imperfect optical components, scattering of photons off component surfaces, etc., which ‘smeared out’ the image of the sunshape on the conversion device. The profile they selected resembles the 4th curve from the bottom of the Ft. Hood example data plot in Figure 1.12; dropping three orders of magnitude from the central disk intensity at the solar limb, and dropping to 0.0001 of that intensity at 50 mrad from the disk center.

Buie, Monger and Dey [149] and Buie and Monger [151] summarized the LBL circumsolar data set (including some analysis of spectral scan data) and the Rabl and Bendl work mentioned above. They developed their own simulations of the convolution of LBL sunshapes and various concentrating system acceptance angles. They show that as the circumsolar ratio, CSR, [ratio of solar disk/(disk + circumsolar) intensity] decreases or increases that smaller or larger acceptance angles, respectively, are adequate to intercept more beam plus circumsolar energy.
The results of Buie and Monger [151] show that for an acceptance angle (total field of view) of 1 degree, even with a CSR of 0.8 (circumsolar = 80% of the total disk plus circumsolar intensity!) that 94% of the energy in the sunshape is intercepted. As the CSR is reduced to 0.1, 0.05, and 0.02, a 1° concentrating system acceptance angle intercepts from 96% to 97% to 99.0%, respectively, of the total DNI plus circumsolar radiation. Of course, larger acceptance angles intercept larger portions of the sunshape energy no matter what the CSR. Note we use the term **intercept the sunshape profile** as opposed to **collect the energy in the sunshape profile**. The reason for this distinction is that not every photon observed in the sunshape profile will propagate to the system conversion device, due to imperfections in the optical system and smearing of the sunshape profiles mentioned above.

Buie, Monger and Dey [149] also summarized sunshape measurements by Neumann and Witzker [152,153] of the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, DLR) based on modern charge couple device (CCD) camera system and 12-bit digital resolution. Such devices have a (grayscale) intensity resolution of 0.02% (1 out of 4096 grayscale bins) and dynamic range of about 30,000 to 1; or just over 4 orders of magnitude. They discuss differences between the sunshapes observed with this modern instrumentation and the older LBL circumsolar data sets. They also present a new model, similar to Eq. (1.33), for computing sunshape relative intensity $\phi$ as a function of $\theta$, in mrad, from the center of the solar disk:

$$\phi(\theta) = \cos(0.326 \theta) / \cos(0.308 \theta) \quad \text{for } \theta \leq 4.65 \text{ mrad}(0.265^\circ),$$

$$\phi(\theta) = \exp(k \theta^y) \quad \text{for } \theta > 4.65 \text{ mrad},$$

where $k$ and $y$ are derived from the circumsolar ratio (CSR), designated by them as $\chi$:

$$k = 0.9 \ln(13.5 \chi) \chi^{-0.3},$$

$$y = 2.2 \ln(0.52 \chi) \chi^{0.43} - 1,$$

The concepts regarding sunshapes described in this section are not definitive, and research in this area continues. However these issues must be taken into consideration in conjunction with a detailed knowledge of limitations or uncertainties associated with the mechanical and optical design of any solar concentrating system.

### 1.7 Direct Solar Radiation Climates

The discussion of atmospheric parameters affecting DNI beam resources leads one to consider if these parameters produce what might be characterized as direct solar radiation climates. That is, are there large regions where DNI beam resources may be deemed as exceptional, above average, average, below average, or poor for CPV applications? Qualitative adjectives such as ‘above average’ are only moderately informative. Quantitative values or ranges of values for DNI beam resources provide more information. However, consideration of quantity or magnitude of resources alone may not be sufficient. The quality of the resources, based on parameters such as clearness index for DNI beam ($K_a$), seasonal patterns for clouds or storms, or ratios such as DNI/GHI or DHI/GHI (if DNI data is not available) provide even more information and should be considered by CPV system designers.
1.7.1 Measurement Networks and Data

Measurement networks and model and measured DNI resources were covered in section 1.5.1 above. We mentioned that the WMO World Radiation Center (WRC) at St. Petersburg, Russia [110] contains measured DNI data when available, however this parameter is rare in that data set. The WMO also archives research data from a volunteer Baseline Surface Radiation Network (BSRN) [154,155]. All sites were last accessed in April, 2015.

The paper by Renné et al. [114] describes the sparse and intermittent sets of US solar measurement $n$, which consists mostly of sites oriented toward scientific research and not routine monitoring. A summary list of these networks is shown in Table 1.5. The University of Oregon has operated various stations in the northwest United States since 1978 [156].

The most popular way of presenting solar radiation and DNI beam data is in the graphical form of maps. Figure 1.14 to Figure 1.18 represent example maps of DNI resources derived from either meteorological satellite conversion models such as [121,124], or climatological solar radiation models based on cloud cover and atmospheric parameters such as described in [117,118].

1.7.2 Concentrating Solar Power Site Selection

Selection of a site to optimize the harvesting of direct beam radiation requires knowledge of the solar DNI resources. Many other factors regarding concentrating solar power system design come into play, such as system component design, land availability, terrain types and accessibility, financial resources, etc.; but solar resource information is important for sizing and initial system configurations. Many of these other considerations are addressed in greater detail in the following chapters. Here, we address some approaches and caveats regarding resource evaluation or assessment.

Measured data DNI is a rare, premium product, as previously described. Electronic data files of modeled data available through databases such as the US NSRDB, or the European SODA

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<tr>
<td>NOAA ISIS</td>
<td>NOAA CMDL</td>
<td><a href="http://www.esrl.noaa.gov/gmd/grad/isis/">http://www.esrl.noaa.gov/gmd/grad/isis/</a></td>
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<td>NOAA CMDL</td>
<td><a href="http://www.esrl.noaa.gov/gmd/grad/surfrad/index.html">http://www.esrl.noaa.gov/gmd/grad/surfrad/index.html</a></td>
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<td>ARM SGP (30)</td>
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<td>U of O Northwest (34)</td>
<td>Univ. Oregon</td>
<td><a href="http://solardat.uoregon.edu/">http://solardat.uoregon.edu/</a></td>
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Figure 1.14 Map of worldwide solar radiation. Direct normal irradiance annual average sum, kWh m$^{-2}$ based on NASA SSE model. Source: http://www.dlr.de/tt/Portaldata/41/Resources/dokumente/institut/system/projects/reaccess/ssedni60.jpg. Reproduced with permission of NASA
or European Solar Atlas, worldwide NASA Surface Solar Radiation and WRDC world radiation databases, their availability and limitations, have been described above. Another data source is data manuals summarizing the resources available to various solar collectors, including concentrating PV collectors and solar tracking flat plate PV collectors. One example is the NREL Data Manual for Flat Plate and Concentrating Collectors [157]. This manual presents monthly average radiation resources for direct beam and hemispherical radiation computed from the US NSRDB for various collector configurations using the Perez anisotropic diffuse model [158]. However, the most popular starting point for site selection is an examination of regional, national, continental, or worldwide maps based on combinations of modeled and measured data. Examples, with some caveats, are described in the next section.

1.7.3 Concentrating Solar Power Resource Map Examples

Figure 1.14 presents one version of worldwide CPV resources. The map shows relative yearly average sum, or annual total DNI radiation in kWh/m$^2$. The data are based on NASA SSE 22 year model calculations [127]. CPV ‘hot spots’ are represented by areas exceeding 2400 kWh/m$^2$ per year total DNI, in lightest tones. This represents about 200 kWh/m$^2$ total DNI per month per year in these areas. A month of 30 days therefore averages about 6.7 kWh/m$^2$/day for total DNI. For an average 12 hour day this means that the average hourly DNI value exceeds 555 W/m$^2$. These numbers provide a feel for what the lower end of the best (highest) levels of resources are on hourly, daily, monthly and annual DNI time scales.

Often only maps of total horizontal irradiance or hemispherical irradiance on tilted surfaces such as PV panels are available. A rule of thumb for converting hemispherical (for PV panels) to DNI resources can be derived for the sites with the highest resources; namely DNI CPV resources are approximately 1.25 to 1.4 times the hemispherical solar radiation resources for flat plate PV. Similar results can obtained from some of the tabular data base summaries, such as found in NASA SSE monthly result files or the NREL flat plate and concentrating collector data manual [157].

Moving to national and regional scales, Figure 1.15 is a grayscale version of the high resolution color map of annual average DNI resources per day produced by NREL for the Indian Solar Energy Center. The modeled data is produced from seven years of hourly satellite imagery and meteorological input data (estimated aerosol optical depth, water vapor, and ozone) using the satellite base model described of Perez [121] and averaged over the period. The frequency of the DNI resource above 5000 Wh/m$^2$/day or 5 kWh/m$^2$/day or 1800 kWh/year total indicates that significant DNI resources for CPV systems are widely available.

These annual summary maps give an indication of the relative magnitude of average resources on an annual basis, but do not help when it comes to evaluating the variability of the solar resource. Variation from month to month and year to year is dependent on regional and national weather and climate patterns can be portrayed in maps covering monthly or seasonal time frames.

An analysis of solar resource variability for both hemispherical and direct normal resources for the United States has been performed by Wilcox and Gueymard [159] and is available online on the NREL Renewable Resource Data Center [160]. These maps show that long term interannual variability in United States DNI resources, computed from the coefficient of variation, or standard deviation divided by the mean (over many years of data) is generally less than 10% for the continental United States, and can be less than 2% for desert regions.

However, even as for inter-annual variability, there is variability from year to year for each month. Figure 1.16, from [159], shows the coefficient of variation of DNI resources for the
Figure 1.15 Annual average direct normal irradiance derived from meteorological satellite data conversion to solar irradiance. This is a grayscale version of the color original map, available at the NREL database. This figure is included as an example and not for actual use since some artifacts have appeared as a result of the grayscale conversion. Source: http://en.openei.org/w/index.php?title=File:NREL-DNI-Annual.jpg. Reproduced with permission of the US Department of Energy
Figure 1.16 Monthly coefficient of variation as percent in DNI resources for the United States from 1998 to 2005. This is a grayscale version of the color original figure from reference [159]. This figure is included as an example only and not for actual use since some artifacts have appeared as a result of the grayscale conversion. Source: Wilcox and Gueymard, 2010 [159]. Reproduced with permission of the US Department of Energy.
United States for each of the twelve months of the year, based on eight years of 1998 to 2005. Note how the intra-annual monthly variability decreases greatly in the summer months and increases in the winter months for the mid-continent sites. These considerations should be addressed in the design goals for CPV systems, such as targeting specific seasonal (heating, air conditioning) or long term (refrigeration, lighting) loads and the consistency of the solar resource.

Figure 1.17 illustrates the challenge of spatial resolution in developing national resource maps for very large areas or countries, such as China. The western segment of the map was generated using the Perez [121] meteorological satellite conversion model at 10 km resolution. The eastern segment is derived from the NREL 40 km gridded CSR [118] modeled data. Insufficient satellite data or ground based meteorological data may be the cause of the discontinuity in coverage. The discontinuity in magnitudes at about 95° east longitude is probably due to variations in model input data and the factor of 16 in the size of the spatial averages (10 km by 10 m versus 40 km by 40 km) represented.

Whatever the performance of models used to generate such maps, consistent application of the model techniques can be used to establish some indication of the resources for large regions relative to each other.

Figure 1.17 Annual average DNI beam for China from meteorological satellite conversion model (Western segment) and 40 km gridded CSR modeled data (eastern segment). This is a grayscale version of the color original map, available at the NREL database. Source: http://en.openei.org/w/index.php?title=File:NREL-China-Solar-CSP-01.jpg. Reproduced with permission of the US Department of Energy
This assumption depends on the premise that the input data for the model algorithms is of uniform quality as well. This assumption is usually a weak one, as it is very difficult to obtain some of the required meteorological parameters (especially aerosol data) on a sufficient scale or consistent spatial resolution. Medium, or mesoscale (approximately 100 km to 1000 km per side grid square) and microscale (less than 100 km per side grid square) meteorological parameters are almost impossible to obtain from ground measurements. Satellite based estimates of such input data are dependent on retrieval algorithms, satellite sensor calibration, resolution, quality, and satellite navigational and positional drift issues. Figure 1.18 for the United States are based on satellite imagery and reanalysis meteorological data over 8 years, and 10 km spatial resolution modeling using the model of Perez [121].

1.7.4 Solar Resource Maps and Data Internet Resources

Searching the internet for maps, data, and information pertaining to any subject can be daunting, even with tools such as Google, Ask, or Bing. Even navigating a single website dedicated to renewable, solar, concentrating and photovoltaic power, such as that of the National Renewable Energy Laboratory, can be somewhat frustrating. Listed in Table 1.6 are a few website URLs that have great potential for addressing typical user needs. All sites were last accessed in April, 2015.
1.8 Consensus Standards for Direct Solar Radiation Applications

This final section of the chapter provides references to existing (as of March, 2013) national and international consensus standards applicable to CPV applications. As a former participant in consensus standards activities, the author highly recommends the active participation, whenever possible, of industry, academic, and government parties in standards development to help foster the deployment of safe, reliable, efficient, and durable solar energy conversion systems. Note that numerous other consensus standards related to PV performance and characterization in general are in force, but not listed here. Those standards relate to PV reference cell construction, calibration, etc., as well as PV cell and module electrical performance and characterization (spectral response, spectral mismatch calculations, resistance to hail impact, qualification testing, mechanical load testing, etc.). It is highly recommended that engineers and designers become familiar with the widest range of applicable standards relating to general solar radiation applications.

1.8.1 World Radiometric Reference

The internationally accepted WRR reference is defined in the WMO CIMO Guide, Publication No. 8, and recognized by the International Bureau of Weights and Measures as described in section 1.2.3 above; see references [30,41,42]. Some of these standards are cited in the references, however this is a complete compilation as of this writing (2013).

1.8.2 Solar Radiometric Instrumentation Calibration

In the following lists, ISO is the International Organization for Standardization, IEC is the International Electro-Technical Commission, IEEE is the Institute of Electrical and Electronic
Engineers, and ASTM is the American Society for Testing and Materials, now called ASTM International:

- ISO 9846 Solar energy – Calibration of a pyranometer using a pyrheliometer.
- ISO 9847 Solar energy – Calibration of field pyranometers by comparison to a reference pyranometer.
- ISO 9059 Solar energy – Calibration of field pyrheliometers by comparison to a reference pyrheliometer.

1.8.3 Spectral Calibration Standards

These standards are used to calibrate instrumentation for measuring spectral distributions or the spectral regions such as the ultraviolet, and optical properties of materials used in solar conversion systems:


1.8.4 Standard and Reference Spectral Distributions

These standards specify reference solar spectral distributions for comparing the performance of PV materials in terrestrial and extraterrestrial standard reporting conditions:

• ISO 9845-1 Solar energy – Reference solar spectral irradiance at the ground at different receiving conditions, Part 1: Direct normal and hemispherical solar irradiance for air mass 1.5.
• IEC 60904-03 Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data.

The author hopes these resources provide a foundation for the chapters that follow, which delve into greater detail on many subjects simply mentioned in passing here. The CPV and solar energy conversion industry in general are at a frontier similar to that of the carbon based fossil fuel and electrical generation industry 100 years ago. We hope progress toward a more sustainable and less stressful energy infrastructure will accelerate due to the work of engineers and scientists in pushing this new energy frontier forward.

Glossary

List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ACP</td>
<td>Absolute cavity pyrheliometers</td>
</tr>
<tr>
<td>AM</td>
<td>Air mass</td>
</tr>
<tr>
<td>AM0</td>
<td>Air mass zero</td>
</tr>
<tr>
<td>AOD</td>
<td>Aerosol optical depth</td>
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<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>AU</td>
<td>Astronomical Unit</td>
</tr>
<tr>
<td>BAOD</td>
<td>Broadband aerosol optical depth</td>
</tr>
<tr>
<td>BIPM</td>
<td>(French acronym) International Bureau of Weights and Measures</td>
</tr>
<tr>
<td>BSRN</td>
<td>Baseline Surface Radiation Network</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge couple device</td>
</tr>
<tr>
<td>CFD</td>
<td>Cumulative frequency distribution</td>
</tr>
<tr>
<td>CIE</td>
<td>Commission Internationale de l’Eclairage</td>
</tr>
<tr>
<td>CIMO</td>
<td>Commission on Instrumentation, Measurements and Observations</td>
</tr>
<tr>
<td>CSR</td>
<td>Circumsolar radiation, circumsolar ratio, or climatological solar radiation (model)</td>
</tr>
<tr>
<td>DHI</td>
<td>Diffuse horizontal irradiance</td>
</tr>
<tr>
<td>DISC</td>
<td>Direct insolation simulation code</td>
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<tr>
<td>DLR</td>
<td>German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt)</td>
</tr>
<tr>
<td>DNI</td>
<td>Direct normal irradiance</td>
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<tr>
<td>DOE</td>
<td>Department of Energy</td>
</tr>
<tr>
<td>EOS</td>
<td>Earth observing system</td>
</tr>
<tr>
<td>ESD</td>
<td>Earth-Sun distance</td>
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<tr>
<td>ETR</td>
<td>Extraterrestrial radiation</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographical information systems</td>
</tr>
<tr>
<td>GHI</td>
<td>Global horizontal irradiance</td>
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<tr>
<td>GOES</td>
<td>Geostationary operational environmental satellites</td>
</tr>
<tr>
<td>GUM</td>
<td>Guide to the expression of uncertainty in measurement</td>
</tr>
<tr>
<td>IEC</td>
<td>International Electrotechnical Commission</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronic Engineers</td>
</tr>
<tr>
<td>IPC</td>
<td>International pyrheliometer comparisons</td>
</tr>
<tr>
<td>ISO</td>
<td>International Standards Organization</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>JCGM</td>
<td>Joint Committee for Guides in Metrology</td>
</tr>
<tr>
<td>KACST</td>
<td>King Abdul Aziz City for Science and Technology</td>
</tr>
<tr>
<td>LBL</td>
<td>Lawrence Berkeley Laboratory</td>
</tr>
<tr>
<td>MBE</td>
<td>Mean bias error</td>
</tr>
<tr>
<td>RMSE</td>
<td>Root mean square error</td>
</tr>
<tr>
<td>MCE</td>
<td>Measure, correlate, evaluate</td>
</tr>
<tr>
<td>METSTAT</td>
<td>Meteorological and statistical</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<tr>
<td>NATO</td>
<td>North Atlantic Treaty Organization</td>
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<tr>
<td>NCDC</td>
<td>National Climatic Data Center</td>
</tr>
<tr>
<td>NMI</td>
<td>National Metrology Institution</td>
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<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
</tr>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
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<tr>
<td>NSRDB</td>
<td>National Solar Radiation Data Base</td>
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<tr>
<td>NWS</td>
<td>National Weather Service</td>
</tr>
<tr>
<td>PMOD</td>
<td>Physical Meteorological Observatory, Davos</td>
</tr>
<tr>
<td>PVUSA</td>
<td>Photovoltaics for utility scale applications</td>
</tr>
<tr>
<td>PW</td>
<td>Precipitable water</td>
</tr>
<tr>
<td>RMSE</td>
<td>root mean square error</td>
</tr>
<tr>
<td>RredC</td>
<td>Renewable Resource Data Center</td>
</tr>
<tr>
<td>RSR</td>
<td>Rotating shadow band radiometers</td>
</tr>
<tr>
<td>SODA</td>
<td>Solar Energy Services for Professionals</td>
</tr>
<tr>
<td>SOLMET</td>
<td>(ERSATZ, German for substitute) solar and meteorological</td>
</tr>
<tr>
<td>SORCE</td>
<td>Solar Radiation and Climate Experiment</td>
</tr>
<tr>
<td>SPD</td>
<td>(Solar) spectral power distribution</td>
</tr>
<tr>
<td>SSE</td>
<td>Surface Meteorology and Solar Energy (NASA data website)</td>
</tr>
<tr>
<td>SWERA</td>
<td>Solar and wind energy resource assessment</td>
</tr>
<tr>
<td>TMY</td>
<td>Typical meteorological year</td>
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<tr>
<td>VIM</td>
<td>International Vocabulary of Metrology</td>
</tr>
<tr>
<td>WMO</td>
<td>World Meteorological Organization</td>
</tr>
<tr>
<td>WRC</td>
<td>World Radiation Centre</td>
</tr>
<tr>
<td>WRR</td>
<td>World Radiometric Reference</td>
</tr>
<tr>
<td>WSG</td>
<td>World Standard Group</td>
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</tbody>
</table>

**List of Symbols**

Typical units given in square brackets. If no units are given, variable is dimensionless.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description [Units]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$</td>
<td>Day angle [rad]</td>
</tr>
<tr>
<td>$DHI$</td>
<td>Diffuse horizontal irradiance [Wm$^{-2}$]</td>
</tr>
<tr>
<td>$d_n$</td>
<td>Day of the year (for Jan 1, $d_n = 1$)</td>
</tr>
<tr>
<td>$DNI$</td>
<td>Direct Normal Irradiance [Wm$^{-2}$]</td>
</tr>
<tr>
<td>$d_s$</td>
<td>Sun diameter (1 390 000 km) [km]</td>
</tr>
<tr>
<td>$e$</td>
<td>Elevation angle of the solar disk or solar elevation angle [rad]</td>
</tr>
<tr>
<td>$GHI$</td>
<td>Global horizontal irradiance [Wm$^{-2}$]</td>
</tr>
</tbody>
</table>

(continued)
Symbol | Description [Units]
---|---
h | Altitude [km]
$I(\theta)$ | Direct irradiance component on an arbitrary surface oriented an angle $\theta$ to the DNI beam; (sometimes denoted as $B$) [Wm\(^{-2}\)]
$I_{bh}$ | DNI beam flux on a horizontal surface [Wm\(^{-2}\)]
$I_n$ | DNI or $I(\theta=0)$ [Wm\(^{-2}\)]
$I_o$ | Solar constant or intensity of solar extraterrestrial radiation (ETR) at the top of the atmosphere ($I_o = 1366.1$ W/m\(^2\) at 1 AU) [Wm\(^{-2}\)]
k | Coverage factor for the calculation of the expanded uncertainty
$K_d$ | Diffuse hemispherical clearness index
$K_n$ | Direct normal clearness index
$K_t$ | Total hemispherical clearness index
$m$ | Geometrical air mass or path length through the atmosphere for photons ($m = 1/\sin(e) = 1/\cos(z)$)
$MBE$ | Mean bias error
$M_p$ | Pressure corrected air mass
$M_R$ | Refraction corrected air mass
$O_z$ | Total column ozone amount [atmospheric-cm]
$P_o$ | Sea level pressure (1013.25 mbar) [mbar]
$P_s$ | Site pressure [mbar]
$PW$ | Precipitable water [atmospheric-cm]
$R_a$ | Earth’s aphelion distance (152.6×10\(^6\) km) [km]
$R_c$ | Earth-Sun distance correction factor
$RMSE$ | Root mean square error
$R_o$ | Average distance between the Sun and Earth (1 AU or 149 597 870.7 km) [km]
$R_p$ | Earth’s perihelion distance (147.5×10\(^6\) km) [km]
$R_s$ | Sun radius (695 000 km) [km]
$T(x)$ | Atmospheric transmittance
$T_{a3}$ | Aerosol optical depth at 380 nm
$T_{a5}$ | Aerosol optical depth at 500 nm.
$T_a$ | Transmittance due to aerosol properties
$T_g$ | Transmittance due to optical properties of gases
$T_L$ | Linke turbidity
$T_o$ | Transmittance due to ozone (in the stratosphere)
$T_r$ | Transmittance due to Rayleigh scattering
$T_w$ | Transmittance of water vapor
$U$ | Expanded uncertainty
$u(x_i)$ | Standard uncertainty of each input estimate $x_i$
$u_c(y)$ | Combined standard uncertainty of the measurement result $y$
$z$ | Angle between the local vertical and the center of the solar disk; complement of the solar elevation angle ($z = 90 – e$) [rad]
$\chi$ | Circumsolar ratio or CSR
$\phi(\theta)$ | Sunshape relative intensity $\phi$ as a function of $\theta$, angle from the center of the sun, ($\theta = 0^\circ$) to the limb ($\theta = 90^\circ$)
$\theta$ | Angle between the DNI beam and the surface normal [rad]
$\tau(\lambda)$ | Aerosol optical depth or AOD
$\tau_D$ | Optical thickness of clean (aerosol free) and dry (no water vapor) atmosphere
References


121. Perez, R., Kmiecik, M., Moore, K. et al. (2004) Status of high resolution solar irradiance mapping from satellite data, presented at the 33rd ASES Annual Conference (SOLAR 2004), Portland, OR.


