

# What is a pyrheliometer?

A quick introduction to pyrheliometer basics

This note provides readers with a basic technical background and an introduction to pyrheliometers and the measurement of direct irradiance.

## Introduction

A pyrheliometer is a device that measures solar irradiance coming directly from the sun. The SI units of irradiance are watts per square meter ( $W/m^2$ ). Traditionally, pyrheliometers were mainly used for climatological research and weather monitoring; however, recent worldwide interest in solar energy has led to an increased interest in pyrheliometers.

In this article, we will explore the basic aspects of a pyrheliometer: what does it measure, what is it useful for, and how does it work?



Figure 1 A pyrheliometer is pointed at the sun to measure the solar irradiance coming directly from the sun.

A pyrheliometer must be mounted on a solar tracker: a device that points the instrument at the sun throughout the day. See Box 1.

This direct radiation  $E$ , together with diffuse radiation  $E_d$ , gives the total available amount of solar energy on the Earth's surface, the global irradiance  $E_{g\downarrow}$ :

$$E_{g\downarrow} = E \cos(\theta) + E_d$$

where  $\theta$  is the angle between the surface normal and the position of the sun in the sky.

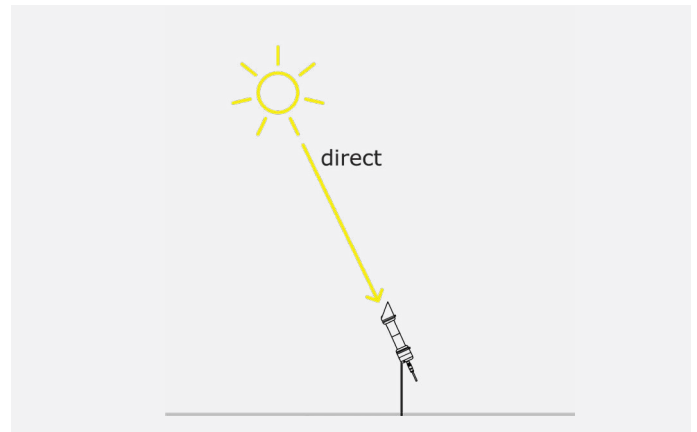


Figure 2 Pyrheliometers measure direct solar radiation.

## Pyrheliometer: a solar irradiance sensor

Pyrheliometers measure "direct solar radiation"  $E$ : the amount of solar energy per unit area per unit time incident on a plane normal to the position of the sun in the sky, coming directly from the sun itself. This is also called "direct normal irradiance", often abbreviated to DNI.

### Solar trackers

To point a pyrheliometer at the sun, a solar tracker rotates around 2 axes, varying the zenith angle moving up and down and the azimuth angle in the horizontal plane (north, east, south to west).

The required pointing is calculated from GPS coordinates, date and time, using a solar position algorithm. Some trackers integrate extra devices ("sun sensors") to fine-tune the pointing once the sun is visible, achieving pointing accuracies better than 0.1°.

It is important that the tracker remains stable and level for long periods of time, in all weather conditions.

Solar trackers are available in many different shapes and sizes.

Per WMO (World Meteorological Organization) convention, all modern pyrheliometers use the same field of view, characterized by an opening half-angle of 2.5°. This means that the measurement of direct solar radiation includes some "circumsolar" radiation.

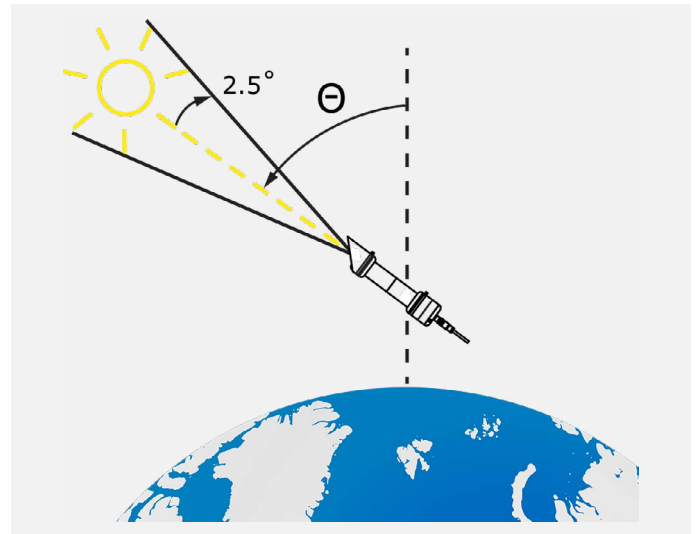


Figure 4 Pyrheliometers measure only the sunlight from a small area around the sun, characterized by an opening half-angle of 2.5°.

Direct solar radiation varies greatly depending on the height of the sun in the sky (and thus location on the Earth, time of day, and day of year), and on meteorological and environmental factors such as clouds, aerosols, smog, fog, precipitation, and others. Typical values for the direct solar irradiance are in the range from 0 to the theoretical maximum of the solar constant, about 1361 W/m<sup>2</sup>.

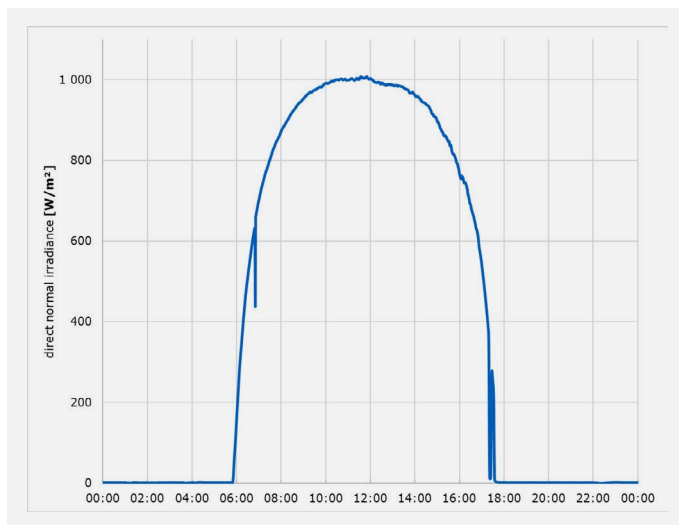


Figure 3 Direct normal irradiance, as measured by a DR30 pyrheliometer. Data taken 25 September 2019, during the NREL National Pyrheliometer Comparison.

To measure only the radiation coming directly from the sun, it is necessary to limit the field of view of the instrument. From outside the Earth's atmosphere, the sun is seen as a disk with an field of view angle of about 0.27°. At ground level, the sun looks a lot bigger. Its visual size depends on the atmosphere: the hazier the sky, the larger the sun appears.

### Pyrheliometer angles

Due to the physical size of the detector, the **opening half-angle** alone does not fully define the field of view of a pyrheliometer.

Pyrheliometers integrate all radiation with a geometrical function called the "acceptance function."

This function equals one from normal to the **slope angle**, then decreases slowly until it reaches a value of zero at the **limit angle**.

This means that a beam of radiation within an angle of  $1^\circ$  of the center of the pyrheliometer is always counted in the final signal. The slope angle of  $1^\circ$  allows for a small misalignment before it impacts the measurement.

### Standard pyrheliometer angles

slope angle	$1^\circ$
opening half-angle	$2.5^\circ$
limit angle	$4^\circ$
viewing angle	$6 \times 10^{-3}$ sr

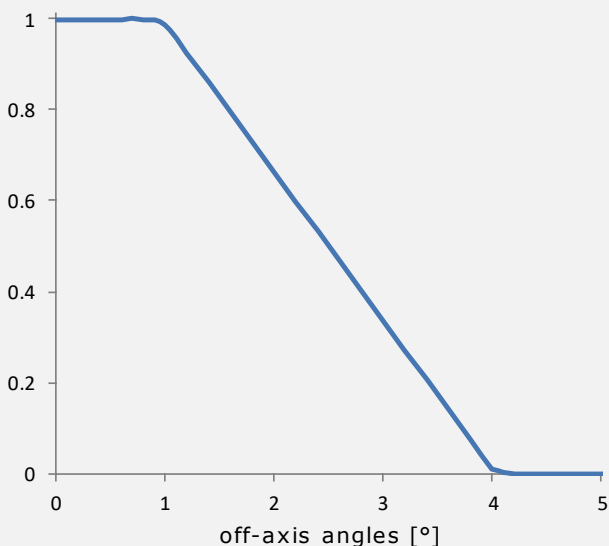


Figure 5 The acceptance function of a pyrheliometer with a standard geometry.

For more detail, see reference [1].



## What are pyrheliometers used for?

The sun is Earth's main source of extra-terrestrial energy. This has important implications in two areas: 1) weather and climate, and 2) energy production by harvesting solar energy.

Solar radiation is one of the driving forces behind the Earth's weather patterns and is thus an important factor in weather and climate studies. In these studies, pyrheliometers are often combined with pyranometers to measure all components of the solar radiation: direct, global, and diffuse.

Traditionally, large zero offsets and directional errors in pyranometers meant that the measurement of Global Horizontal Irradiance using combined pyrheliometer + diffuse radiation measurement was much more accurate than a measurement using a single pyranometer. However, in the past few years, pyranometers have become much more accurate. Modern pyranometers, such as models **SR300**, have very low zero offsets and near-perfect directional responses. Nevertheless, a separate measurement of direct and diffuse radiation (instead of only global radiation) is still the standard in high-accuracy installations, such as in the Baseline Surface Radiation Network (BSRN).

In particular, when adding a separate pyranometer for an independent measurement of GHI and measuring all three components allows users to check for internal consistency by comparing the global radiation to the "back-calculated" global radiation derived from direct and diffuse radiation.

In the solar energy industry measurements with pyrheliometers, combined with those with pyranometers, are used to monitor the performance of photovoltaic (PV) power plants. By comparing the actual power output from the PV power plant to the expected output based on solar radiation data, the efficiency of the PV power plant can be determined. Pyrheliometers can also be used to determine the suitability of potential sites for PV power plants. In this case, pyrheliometers are used to estimate the expected yield of a PV installation.

For PV installations that use concentrated sunlight, monitoring the direct solar radiation is necessary to ensure proper operation of the plant.



Finally, a pyrheliometer provides the most accurate method of measuring sunshine duration. The WMO defines sunshine hours as “the sum of the time intervals (in hours) during which the direct normal solar irradiance exceeds a threshold of 120 W/m<sup>2</sup>.”

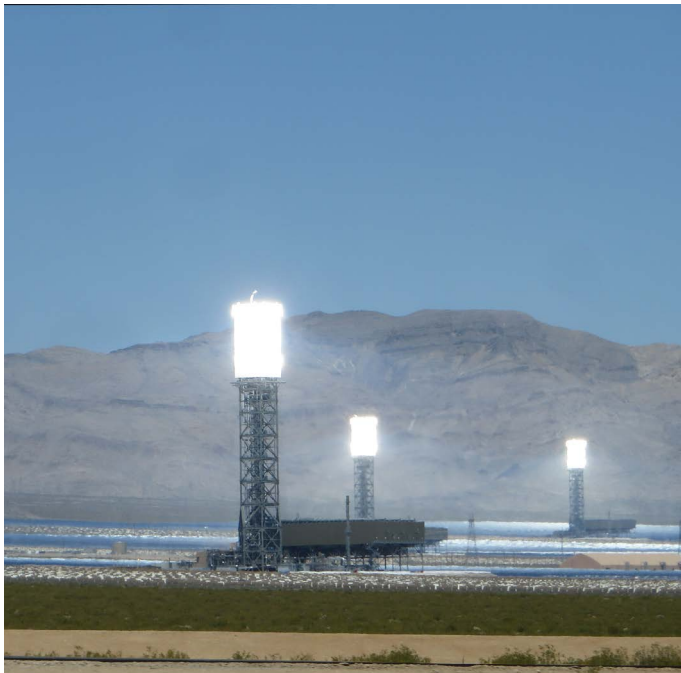


Figure 7 In concentrated solar PV, pyrheliometer measurements are necessary to operate the plant. Image of Ivanpah plant by Ken Lund, CC BY-SA 2.0.

Box 3

**Pyrheliometers in space: the solar constant**

The solar radiation that reaches Earth at the top of our atmosphere is, on average, 1361 W/m<sup>2</sup>.

This quantity has been monitored in space since the late 1970s by a special type of high-accuracy pyrheliometers, referred to as “absolute radiometers” or “cavity radiometers.”

The sun’s energy output is not constant; it varies by about 0.1% during the 11-year solar cycle. Therefore, the term “solar constant” is officially no longer in use. Scientists refer to the “total solar irradiance” (TSI) instead.

**How does a pyrheliometer work?**

Pyrheliometers are irradiance sensors that incorporate thermopiles: sensors based on the Seebeck, or thermoelectric, effect. The main components of a pyrheliometer are a quartz window, a black absorber, a thermopile, the pyrheliometer tube (which together with the apertures at the sensor and the quartz window defines the acceptance function), and, in some cases, additional electronics. Sights are included to enable the instrument to be pointed correctly.

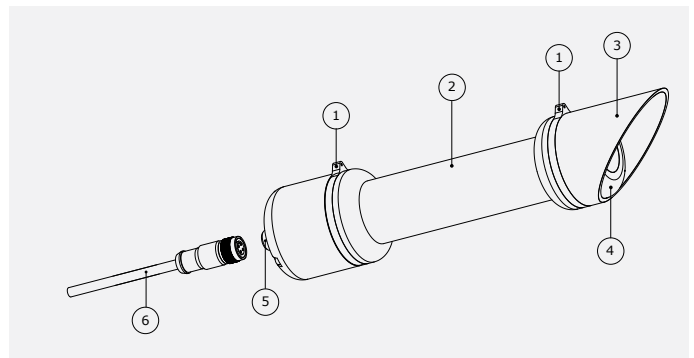


Figure 8 The main components of a pyrheliometer are a quartz window (4), a sensor with a black absorber (not pictured), and the pyrheliometer tube (2). Sights (1) allow the instrument to be pointed to the sun with a solar tracker.

The window on a pyrheliometer acts as a filter that transmits solar radiation with wavelengths from roughly 200 nm to about 4000 nm (this contains the near-infrared, visible UV-A and part of the UV-B radiation, see Figure 3), but blocks thermal radiation with wavelengths longer than 4 μm.

The window and sensor housing serve to protect the black absorber and the thermopile from the elements (i.e., rain, snow, etc.).

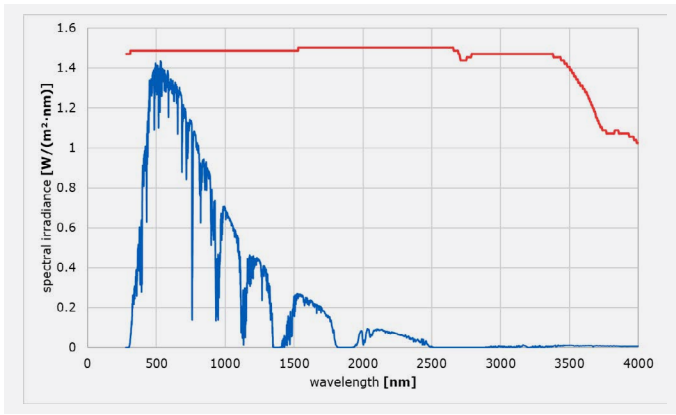


Figure 9 An example of the spectral distribution of direct normal irradiance (DNI). Data from the ASTM G173-03 Reference Spectra. A typical spectral response curve of quartz is shown as a red line.

The window on a pyrheliometer acts as a filter that transmits solar radiation with wavelengths from roughly 200 nm to about 4000 nm (this contains the near-infrared, visible UV-A and part of the UV-B radiation, see Figure 3), but blocks thermal radiation with wavelengths longer than 4  $\mu\text{m}$ .

The radiation passing the window is absorbed by the black surface of the pyrheliometer sensor and converted into heat. If the transmission through the window is  $\tau$ , the area of the black surface is  $A$ , and the absorption coefficient of the black surface is  $\alpha$ , then the heat absorption can be calculated as follows:

$$P_{\text{absorption}} = \alpha \cdot \tau \cdot A \cdot E \quad (2)$$

This creates a temperature gradient from the black surface through the thermopile to the pyrheliometer body, which acts as a heatsink. The temperature difference is given by:

$$\Delta T = R_{\text{thermal}} \cdot P_{\text{absorption}} \quad (3)$$

where  $R_{\text{thermal}}$  is the thermal resistance of the thermopile sensor. This thermal resistance depends on the specific composition and geometry of the thermopile sensor.

A thermopile consists of a number of thermocouples connected in series. Each thermocouple will generate a voltage proportional to the temperature difference between the black surface and the body:

$$u = \zeta \cdot \Delta T \quad (4)$$

where  $\zeta$  is the Seebeck coefficient. For example, the Seebeck coefficient of a copper-constantan thermocouple is 41  $\mu\text{V/K}$ .

The voltage  $U$  across the thermopile leads is simply the sum of the voltages  $u_i$  from the individual thermocouples. If the thermopile consists of  $N$  identical thermocouples, the voltage across the thermopile leads is:

$$U = \sum_{i=0}^N u_i = N \cdot \zeta \cdot \Delta T \quad (5)$$

Connecting thermocouples in series allows the user to detect very small temperature differences. The overall sensitivity of the pyrheliometer is:

$$S = \frac{U}{E} = \alpha \cdot \tau \cdot A \cdot N \cdot \zeta \cdot R_{\text{thermal}} \quad (6)$$

And the measured direct normal irradiance is then:

$$E = \frac{U}{S} \quad (7)$$

In practice, the sensitivity is determined by calibrating against a reference pyrheliometer rather than by calculation from the separate coefficients.

The output signal from the pyrheliometer can either be the output voltage from the thermopile of the pyrheliometer, or can be generated by electronics that convert the signal from the thermopile to a more convenient output signal. Typical outputs include amplified voltage outputs and digital output like Modbus RTU over RS-485.

Depending on the pyrheliometer specifications (such as the response time, thermal offsets, non-stability, non-linearity, directional response, spectral response, temperature response and tilt response), a pyrheliometer may be classified either as a Class A, Class B or Class C in accordance with the ISO 9060 standard [2].

A more in-depth discussion on how pyrheliometers work can be found in the book by Vignola et al. [3].

## Pyrheliometers in the field

Performing reliable pyrheliometer measurements in the field involves many practical aspects, such as the pyrheliometer alignment, limitations on data availability due to precipitation, and pyrheliometer maintenance and calibration.

Pyrheliometers are mounted on solar trackers that point the instrument to the sun throughout the day. Many pyrheliometers have standardized tube diameters of  $38 \times 10^{-3}$  m (1.5 inch). Contact the factory for tracker compatibility.

When taking measurements, it is important to make sure that the pyrheliometer has a clear window. Snow, frost, rain, dew, or dust collecting on the window can absorb, scatter, or focus radiation, leading to erroneous measurements (see Figure 9).

Modern pyrheliometers, such as DR30, DR20, and DR15, are equipped with powerful window heaters to deal with snow, frost, and dew, and thereby increase the data availability. These heaters are especially designed to minimize any adverse effects on the radiation measurements.

Pyrheliometer model DR30 also has many on-board diagnostic features;

- a tilt sensor, with which the zenith angle of the sensor can be monitored.
- Humidity, temperature and pressure sensors so that leakage can be detected

To avoid dust from collecting on the window, frequent (daily) window cleaning is recommended.



Figure 10 Pyrheliometers with window heating (right) are effective to mitigate snow, frost, and dew deposition on the window, providing the user with more valid data points.

For more information on how to measure solar radiation, we recommend reading references [4-6].

## Literature

1. Blanc et al. (2014), [Direct normal irradiance related definitions and applications; the circumsolar issue](#), Solar Energy, Volume December 2014, pp. 561-577
2. ISO (1990) [ISO 9060:1990: Solar energy – Specification and classification of instruments for measuring hemispherical solar and direct solar radiation](#).
3. Frank Vignola, Joseph Michalsky, Thomas Stoffel (2019); [Solar and infrared radiation Measurements](#); CRC Press
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5. M. Sengupta, A. Habte, S. Kurtz, A. Dobos, S. Wilbert, E. Lorenz, S. Wilcox, P. Blanc and R. Perez (2015) [Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications](#).
6. McArthur L.J.B. (2005) WMO/TD-No. 1274 [Baseline Surface Radiation Network \(BSRN\). Operations Manual. Version 2.1](#)

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