What is a pyrheliometer?

A quick introduction to pyrheliometer basics

This article gives a reader with a basic level technical background 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 metre (W/m^2). Traditionally pyrheliometers were mainly used for climatological research and weather monitoring purposes, however recent worldwide interest in solar energy has also 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.*

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.

A pyrheliometer needs to 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 $E_{g\downarrow}$

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

where θ is the angle between the surface normal and the position of the sun in the sky.

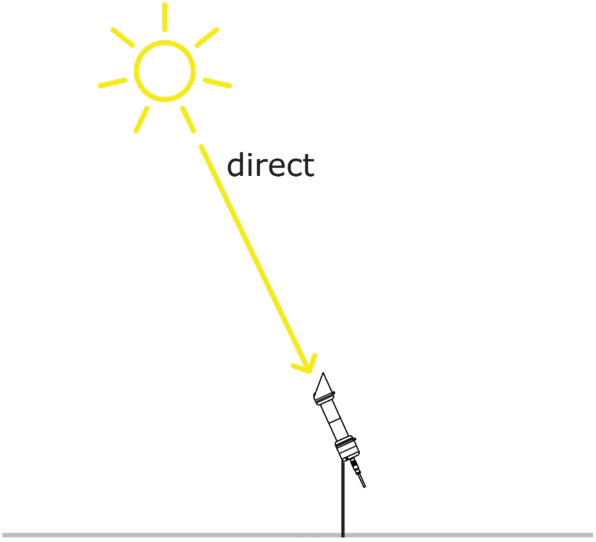

Figure 2 *Pyrheliometers measure direct solar radiation.*

BOX 1

SOLAR TRACKERS

To point a pyrheliometer at the sun, a solar tracker rotates around 2 axes: the zenith (up and down) and the azimuth (east to west) axis.

The required position is calculated from GPS coordinates and time, using a solar position algorithm. Some trackers integrate extra devices ('sun sensors') to fine-tune the position once the sun is visible and reach tracking accuracies of 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. Contact Hukseflux for suggestions.

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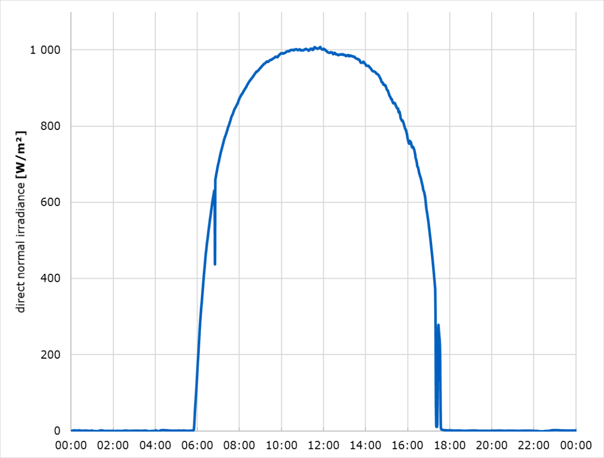

Figure 3 *Direct normal irradiance as measured by a DR30 pyrheliometer. Data taken 25 September 2019, during the NREL National Pyrheliometer Comparison.*

To limit the measurement to the radiation coming only directly from the sun, it is necessary to limit the field of view of the instrument. From outside the earth atmosphere, the sun is seen as a disk with an angular distance 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 bigger the sun in the sky.

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

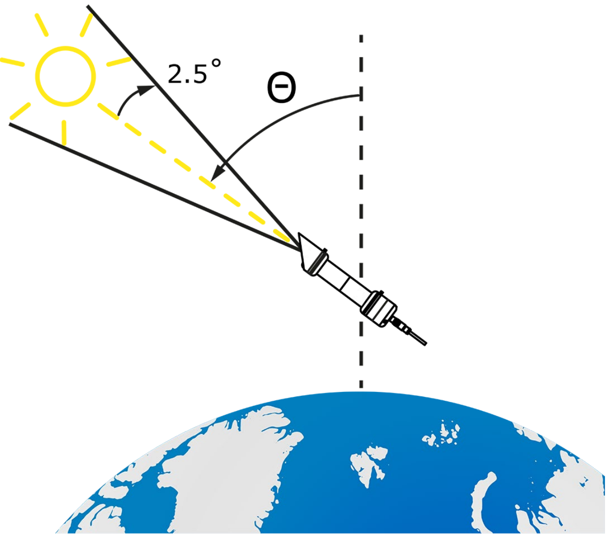

Figure 4 *Pyrheliometers measure only the sunlight from a small area around the sun, characterised by a opening half-angle of 2.5 °.*

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 time 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/m².

BOX 2

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 ° of the centre of the pyrheliometer is always counted in the final signal: the slope angle allows for a small misalignment before it impacts the measurement.

STANDARD PYRHELIOMETER ANGLES	
slope angle	1 °
opening half-angle	2.5 °
limit angle	4 °
viewing angle	6×10^{-3} sr

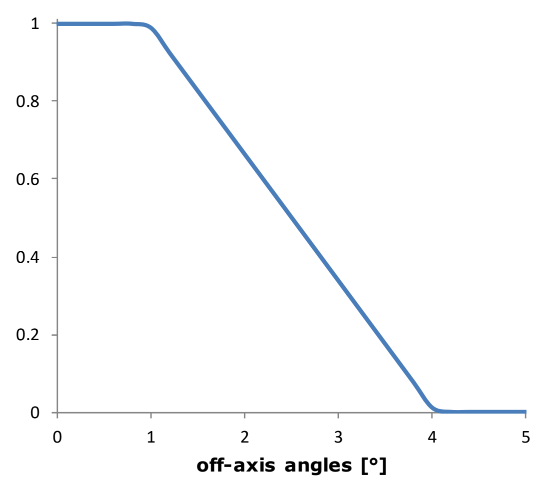

Figure 5 *The acceptance function of a pyrheliometer with a standard geometry.*

For more detail, see reference [1].

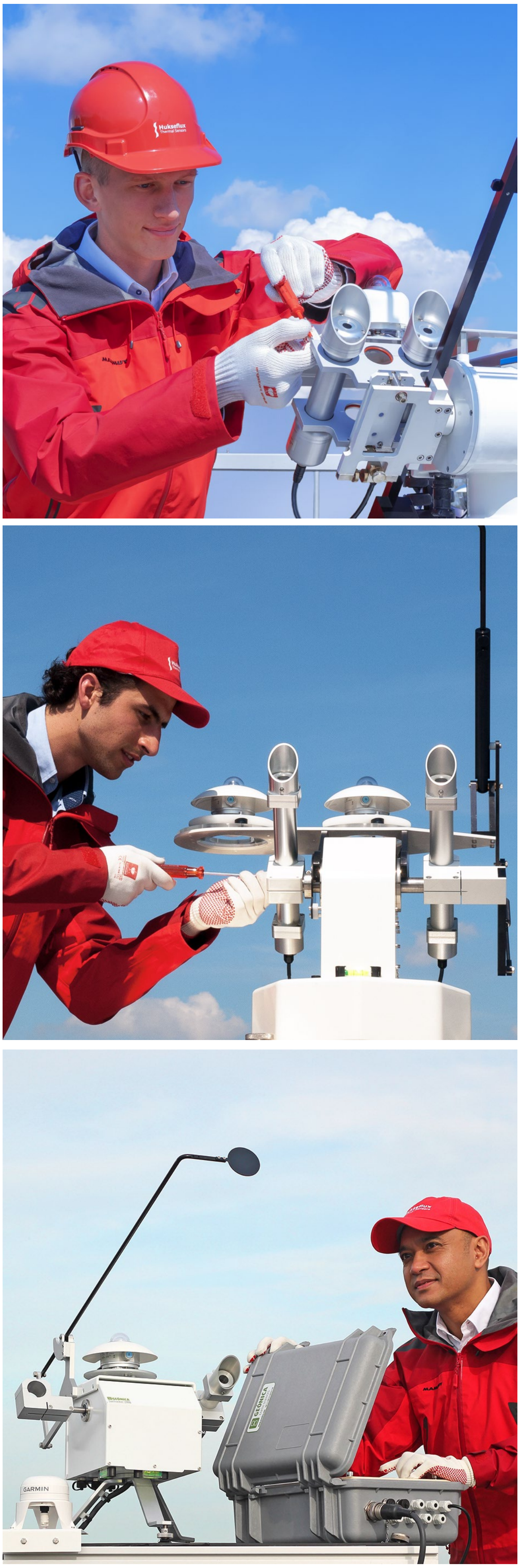

Figure 6 *Pyrheliometers mounted on solar trackers.*

What are pyrheliometers used for?

The sun is earth’s main source of extra-terrestrial energy. This has important implications in two areas: weather and climate on the one hand and energy production by harvesting solar energy on the other hand.

Solar radiation is one of the driving forces behind the earth’s weather patterns and thus an important factor in weather and climate studies. In such 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 SR25 and SR30, have very low zero offsets and near-perfect directional responses. However, 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 and independent measurement of global horizontal, and measuring all three components allows users to check for internal consistency by comparing the global radiation to the ‘back-calculated’ global radiation from direct and diffuse radiation.

In the solar energy industry pyrheliometers, again combined with pyranometer measurements, 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 determine the expected output 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.

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Finally, a pyrheliometer provides the most accurate method of measuring sunshine duration. The World Meteorological Organisation, 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^2”.

Figure 7 *In concentrated photovoltaics, 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 the earth at the top of our atmosphere, is on average 1361 W/m².

This quantity has been monitored in space since the late 1970’s 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 defines the field of view and in some cases additional electronics. Sights are included to enable the instrument to be pointed correctly.

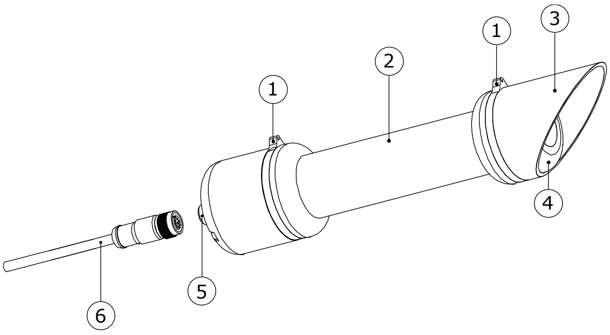

Figure 8 *The main components of a pyrheliometer are a quartz window (4), a sensor with a black absorber (not pictured) and the pyrheliometer tube (2) which defines the field of view. Sights (1) allow the instrument to be pointed to the sun with a solar tracker.*

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 transmission τ of solar radiation through a window is ideally close to 100 %, but is in practice closer to 95 %. The window also serves to protect the black absorber and the thermopile from the elements (rain, snow, etc.).

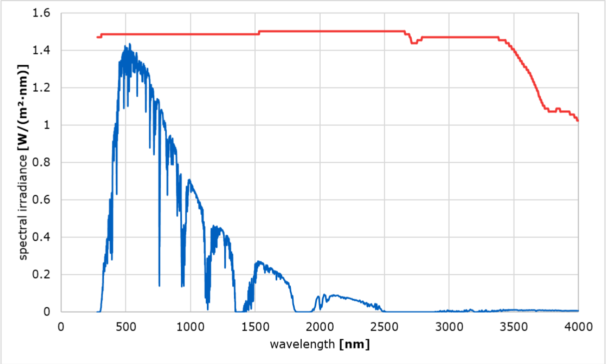

Figure 9 *An example of the spectral distribution of direct normal irradiance (DNI). Data from the ASTM G173-03 Reference Spectra. A typical spectral response curve of quartz is shown as a red line.*

The filtered radiation is absorbed by the black surface on the pyrheliometer and converted into heat. If the transmission through the window is τ, the area of the black surface is A and the

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absorption coefficient of the black surface is α then the heat absorption can be calculated as

follows:

$$P_{\text{absorption}} = \alpha \cdot \tau \cdot A \cdot E$$

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:

$$\Delta T = R_{\text{thermal}} \cdot P_{\text{absorption}}$$

Where R_{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:

$$u = \varsigma \cdot \Delta T$$

Where ς is the Seebeck coefficient. For example, the Seebeck coefficient of a copper-constantan thermocouple is 41 μV/K.

The voltage U accros 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:

$$U = \sum_{i=0}^{N} u_i = N \cdot \varsigma \cdot \Delta T$$

Putting thermocouples in series allows one to detect very small temperature differences. The overall sensitivity of the pyranometer is:

$$S \equiv \frac{U}{E} = \alpha \cdot \tau \cdot A \cdot N \cdot \varsigma \cdot R_{\text{thermal}}$$

And the measured direct normal irradiance is then:

$$E = \frac{U}{S}$$

In practice the sensitivity is determined by calibration 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 or the pyrheliometer can include 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 adds 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 x 10^{-3} m (1.5 inch). Contact the factory for tracker compatibility.

When taking measurements, one should make sure 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 effect on the radiation measurements.
To avoid dust from collecting on the window frequent cleaning of the window 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
4. WMO (2012) WMO-No.8 WMO Guide to Meteorological Instruments and Methods of Observations, Chapter 7
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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