



USER MANUAL **SR15-A1**

Analogue first class pyranometer
with millivolt output and heater



Warning statements



Putting more than 12 Volt across the sensor wiring can lead to permanent damage to the sensor.



Do not use "open circuit detection" when measuring the sensor output.



For proper instrument grounding: use SR15-A1 with its original factory-made cable.



Disconnect power while performing service or maintenance.

Contents

Warning statements	2
Contents	3
List of symbols	4
Introduction	5
1 Ordering and checking at delivery	9
1.1 Ordering SR15-A1	9
1.2 Included items	10
1.3 Quick instrument check	10
2 Instrument principle and theory	11
3 Specifications of SR15-A1	14
3.1 Specifications of SR15-A1	14
3.2 Dimensions of SR15-A1	18
4 Standards and recommended practices for use	19
4.1 Classification standard	19
4.2 General use for solar radiation measurement	19
4.3 General use for sunshine duration measurement	19
4.4 Specific use for outdoor PV system performance testing	20
4.5 Specific use in meteorology and climatology	21
5 Installation of SR15-A1	22
5.1 Site selection and installation	22
5.2 Installation of the sun screen	23
5.3 Installation of optional mounts	24
5.4 Installation of optional extension cable of 20 m	27
5.5 Electrical connection of SR15-A1: wiring diagram	28
5.6 Grounding and use of the shield	29
5.7 Requirements for data acquisition / amplification	29
6 Making a dependable measurement	30
6.1 The concept of dependability	30
6.2 Reliability of the measurement	31
6.3 Repair and maintenance	32
6.4 Uncertainty evaluation	32
7 Maintenance and trouble shooting	35
7.1 Recommended maintenance and quality assurance	35
7.2 Trouble shooting	36
7.3 Calibration and checks in the field	37
7.4 Data quality assurance	38
8 Appendices	39
8.1 Appendix on cable extension / replacement	39
8.2 Appendix on tools for SR15-A1	40
8.3 Appendix on spare parts for SR15-A1	40
8.4 Appendix on standards for classification and calibration	41
8.5 Appendix on calibration hierarchy	42
8.6 Appendix on meteorological radiation quantities	43
8.7 Appendix on ISO and WMO classification tables	44
8.8 Appendix on definition of pyranometer specifications	45
8.9 Appendix on terminology / glossary	46
8.10 EU declaration of conformity	47

List of symbols

Quantities

	Symbol	Unit
Voltage output	U	V
Sensitivity	S	V/(W/m ²)
Sensitivity at reference conditions	S ₀	V/(W/m ²)
Temperature	T	°C
Electrical resistance	R _e	Ω
Global horizontal solar irradiance	E, GHI	W/m ²
In-plane solar irradiance	G _i	W/m ²
Solar radiant exposure	H	W·h/m ²
Time in hours	h	h

(see also appendix 8.6 on meteorological quantities)

Subscripts

Not applicable

Introduction

SR15-A1 is a high-accuracy solar radiation sensor. It is “first class” according to the WMO guide and ISO 9060:1990 standard and “Spectrally Flat Class B” in the 2018 revision. With its on-board heater, it is compliant in its standard configuration with the requirements for “Class B” PV monitoring systems of the new IEC 61724-1:2017 standard.

SR15-A1 is a solar radiation sensor that is applied in general high accuracy observations. It measures the solar radiation received by a plane surface from a 180 ° field of view angle. This quantity, expressed in W/m^2 , is called “hemispherical” solar radiation. SR15-A1 pyranometer can be employed outdoors under the sun, as well as indoors with lamp-based solar simulators. Its orientation depends on the application and may be horizontal, tilted (for plane of array radiation) or inverted (for reflected radiation).

This user manual covers use of the analogue sensor in the SR15 series range: SR15-A1. Specifications of this version differs from those of the digital versions of model SR15: SR15-D1 and SR15-D2A2, offering various digital and analogue outputs. For SR15-D1 and SR15-D2A2 use, consult the separate SR15 digital series user manual.

Using SR15-A1 is easy. It can be connected directly to commonly used data logging systems. The irradiance, E , in W/m^2 is calculated by dividing the SR15-A1 output, a small voltage U , by the sensitivity S . The sensitivity is provided with SR15-A1 on its calibration certificate.

The central equation governing SR15-A1 is: $E = U/S$ (Formula 0.1)

The incorporated heater reduces measurement errors caused by early-morning dew deposition. The instrument should be used in accordance with the recommended practices of ISO, IEC, WMO and ASTM.



Figure 0.1 SR15-A1 first class pyranometer with and without its sun screen

SR15 design

SR15-A1 analogue first class pyranometer employs a thermal sensor with black coating, two glass domes and an anodised aluminium body.

Suggested use for SR15-A1:

- PV system performance monitoring
- general solar resource monitoring
- indoor simulated solar testing
- meteorological networks

PV system performance monitoring: compliant with IEC class B

IEC 61724-1: Photovoltaic System Performance Monitoring - Guidelines for Measurement, Data Exchange and Analysis - requires heating for Class B monitoring. SR15-A1 offers heating, without the need for additional accessories. WMO, the World Meteorological Organization, recommends use of first class pyranometers such as SR15-A1 for network operation.

Improved measurement accuracy

Calibration of SR15 pyranometer has been improved; our latest calibration method results in an uncertainty of the sensitivity of 1.8 %, compared to typical uncertainties of higher than 2.8 % for this pyranometer class. SR15 response time is 10 s: a significant improvement relative to earlier sensors.

Your benefits:

- best measurement accuracy in first class
- improved response time
- with onboard heater: compliant with IEC 61724-1 Class B in its standard configuration

The ASTM E2848 “Standard Test Method for Reporting Photovoltaic Non-Concentrator System Performance” (issued end 2011) confirms that a pyranometer is the preferred instrument for PV system performance monitoring. SR15-A1 pyranometer complies with the requirements of this standard. For more information see our [pyranometer selection guide](#).

WMO has approved the “pyranometric method” to calculate sunshine duration from pyranometer measurements in WMO-No. 8, Guide to Meteorological Instruments and Methods of Observation. This implies that SR15-A1 may be used, in combination with appropriate software, to estimate sunshine duration. This is much more cost-effective than using a dedicated sunshine duration sensor. Ask for our application note.

Options for mounting and levelling

There are two mounting options available for SR15-A1: a levelling mount and a tube levelling mount. They allow for simplified mounting, levelling and instrument exchange on either a flat surface or a tube.



Figure 0.2 *Optional levelling mount (picture on the left); a practical spring-loaded mount for easy mounting, levelling and instrument exchange on flat surfaces, and the optional tube mount (picture on the right) including spring-loaded levelling upper clamp, lower clamp for tube mounting and two sets of bolts.*

Spring-loaded levelling

When opting for one of the levelling mounts, SR15-A1 is easily mounted and levelled using the mount's spring-loaded centre bolt and SR15-A1's adjustable levelling feet.



Figure 0.3 *Optional levelling mount allows spring-loaded levelling*

Cabling

The standard cable length is 5 m. Optionally cables of 10 and 20 m are supplied. Extension to longer cable lengths is achieved by adding extension cables of 20 m with 2 connectors.



Figure 0.4 On the left the SR15-A1 cable with M12-A female connector on sensor end, stripped over 0.15 m and conductors with ferrules. Its length is 5 metres standard and available in 10 and 20 metres too. On the right the optional Hukseflux extension cable with connector pairs, with male and female M12-A connectors, available in 20 metres



Figure 0.5 SR15 pyranometer mounted on a mast in POA (Plane Of Array) for PV system performance monitoring

1 Ordering and checking at delivery

1.1 Ordering SR15-A1

The standard configuration of SR15-A1 is with 5 metres cable.

Common options are:

- longer cable; 10 and 20 metres
- levelling mount. Specify accessory LM01
- tube levelling mount with set of bolts. Includes LM01. Specify accessory TLM01
- 20 metres extension cable with 2 connectors. Specify article number C07E-20

Table 1.1.1 Ordering codes for SR15

VERSIONS OF SR15-A1 (part numbers)	
SR15-A1	analogue first class pyranometer with millivolt output and heater
SR15-A1-LM01	analogue first class pyranometer with millivolt output and heater, with levelling mount, for spring-loaded levelling and mounting SR15-A1 on a surface
SR15-A1-TLM01	analogue first class pyranometer with millivolt output and heater, with tube levelling mount, for spring-loaded levelling and mounting SR15-A1 on a tube
ADAPTED SENSITIVITY RANGE	
SR15-A1-S7-8.5	analogue first class pyranometer with millivolt output and heater, with adapted sensitivity range between 7 and 8.5 x 10 ⁻⁶ V/(W/m ²)
	the sensitivity range can be adapted to customer requirements between 7 x 10 ⁻⁶ and 10 x 10 ⁻⁶ V/(W/m ²)
	option code = S"lower end of the allowed range" - "higher end of the allowed range" (range in 10 ⁻⁶ V/(W/m ²))
CABLE FOR SR15-A1, with female M12-A connector at sensor end, stripped over 0.15 m and conductors with ferrules	
'-05' after SR15-A1 part number	standard cable length: 5 m
'-10' after SR15-A1 part number	cable length: 10 m
'-20' after SR15-A1 part number	cable length: 20 m
CABLE EXTENSION FOR SR15-A1, with male and female M12-A connectors	
C07E-20	cable length: 20 m

An extension cable (with connector pair) can be used in combination with a regular cable (with one connector at sensor end) to make alternative SR15-A1 cable lengths possible.

1.2 Included items

Arriving at the customer, the delivery should include:

- pyranometer SR15-A1
- sun screen
- cable of the length as ordered
 - product certificate matching the instrument serial number, including:
 - calibration certificate
- any other options as ordered

For SR15-A1-LM01, also

- spring-loaded levelling mount

For SR15-A1-TLM01, also

- spring-loaded levelling mount
- lower clamp to mount SR15 to a tube or mounting rod
- 2 sets of bolts for different tube diameters

Please store the certificates in a safe place.

1.3 Quick instrument check

A quick test of the instrument can be done by using a simple hand held multimeter and a lamp.

1. Check the electrical resistance of the sensor between the grey (-) and white (+) wire. Use a multimeter at the 1000 Ω range. Measure the sensor resistance first with one polarity, than reverse the polarity. Take the average value. The typical resistance of the cable is 0.1 Ω /m. Typical resistance should be the typical sensor resistance of 50 to 150 Ω plus 1.5 Ω for the total resistance of two wires (back and forth). Infinite resistance indicates a broken circuit; zero or a low resistance indicates a short circuit.
2. Check if the sensor reacts to light: put the multimeter at its most sensitive range of DC voltage measurement, typically the 100 x 10⁻³ VDC range or lower. Expose the sensor to a strong light source, for instance a 100 W light bulb at 0.1 m distance. The signal should read > 2 x 10⁻³ V now. Darken the sensor either by putting something over it or switching off the light. The instrument voltage output should go down and within one minute approach 0 V.
3. Remove the sun screen, (see chapter on installation of the sun screen). Inspect the bubble level.
4. Inspect the instrument for any damage.

2 Instrument principle and theory

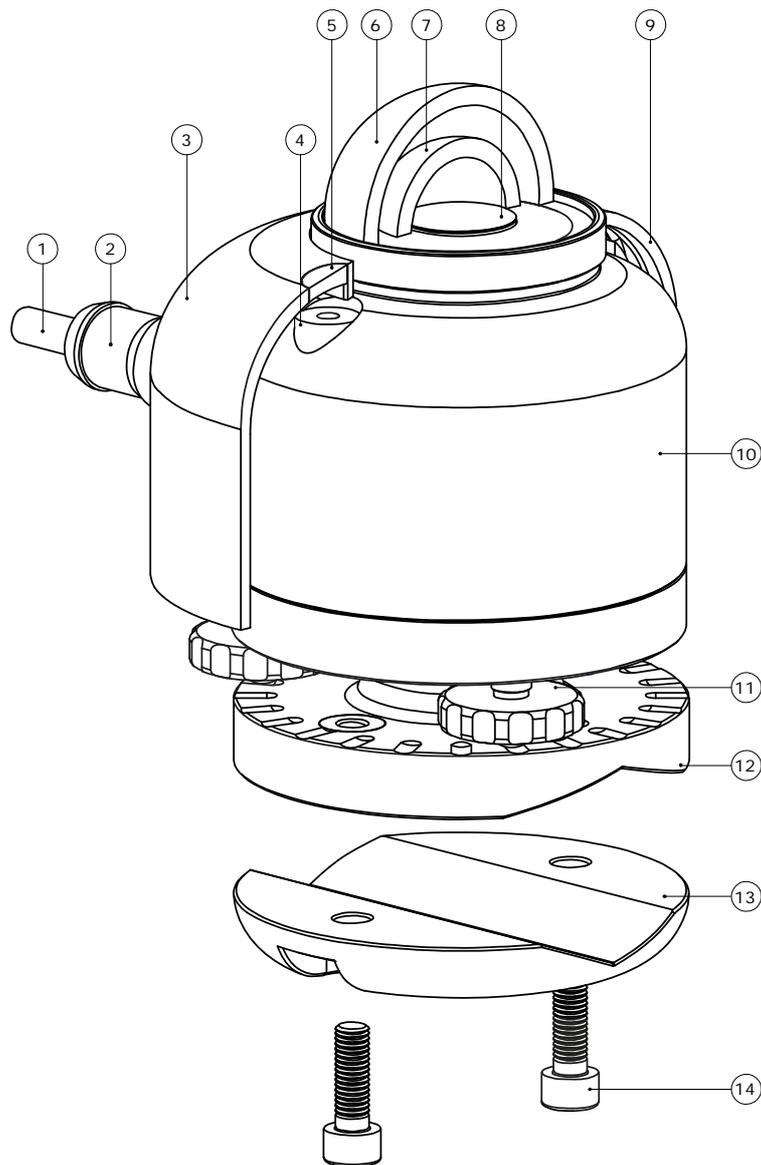


Figure 2.1 Overview of SR15-A1:

- (1) cable (standard length 5 metres, optional longer cable)
- (2) connector
- (3) sun screen
- (4) bubble level
- (5) bubble level window
- (6) outer dome
- (7) inner dome
- (8) thermal sensor with black coating
- (9) quick release system of sun screen
- (10) instrument body
- (11) levelling feet
- (12) optional spring-loaded levelling mount
- (13) optional tube mount
- (14) screws included with tube mount

SR15-A1's scientific name is pyranometer. A pyranometer measures the solar radiation received by a plane surface from a 180° field of view angle. This quantity, expressed in W/m^2 , is called "hemispherical" solar radiation. The solar radiation spectrum extends roughly from 285 to 3000×10^{-9} m. By definition a pyranometer should cover that spectral range with a spectral selectivity that is as "flat" as possible.

In an irradiance measurement by definition the response to "beam" radiation varies with the cosine of the angle of incidence; i.e. it should have full response when the solar radiation hits the sensor perpendicularly (normal to the surface, sun at zenith, 0° angle of incidence), zero response when the sun is at the horizon (90° angle of incidence, 90° zenith angle), and 50 % of full response at 60° angle of incidence.

A pyranometer should have a so-called "directional response" (older documents mention "cosine response") that is as close as possible to the ideal cosine characteristic.

In order to attain the proper directional and spectral characteristics, a pyranometer's main components are:

- a thermal sensor with black coating. It has a flat spectrum covering the 200 to 50000×10^{-9} m range, and has a near-perfect directional response. The coating absorbs all solar radiation and, at the moment of absorption, converts it to heat. The heat flows through the sensor to the sensor body. The thermopile sensor generates a voltage output signal that is proportional to the solar irradiance.
- a glass dome. This dome limits the spectral range from 285 to 3000×10^{-9} m (cutting off the part above 3000×10^{-9} m), while preserving the 180° field of view angle. Another function of the dome is that it shields the thermopile sensor from the environment (convection, rain).
- a second (inner) glass dome: for a first class pyranometer, two domes are used, and not one single dome. This construction provides an additional "radiation shield", resulting in a better thermal equilibrium between the sensor and inner dome, compared to using a single dome. The effect of having a second dome is a strong reduction of instrument offsets.

Pyranometers can be manufactured to different specifications and with different levels of verification and characterisation during production. The ISO 9060 - 1990 standard, "Solar energy - specification and classification of instruments for measuring hemispherical solar and direct solar radiation", distinguishes between 3 classes; secondary standard (highest accuracy), first class (second highest accuracy) and second class (third highest accuracy).

From second class to first class and from first class to secondary standard, the achievable accuracy improves by a factor 2.

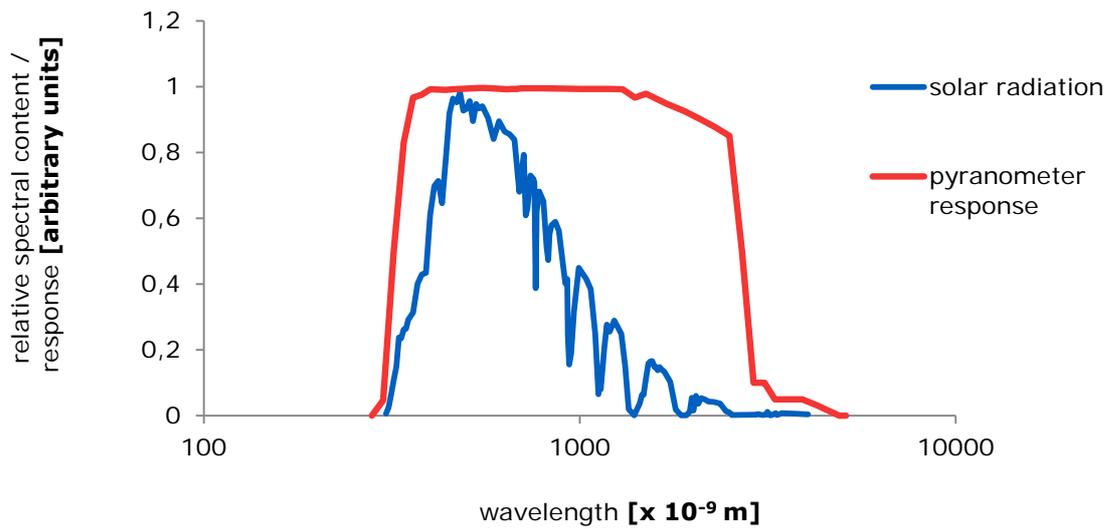


Figure 2.2 Spectral response of the pyranometer compared to the solar spectrum. The pyranometer only cuts off a negligible part of the total solar spectrum.

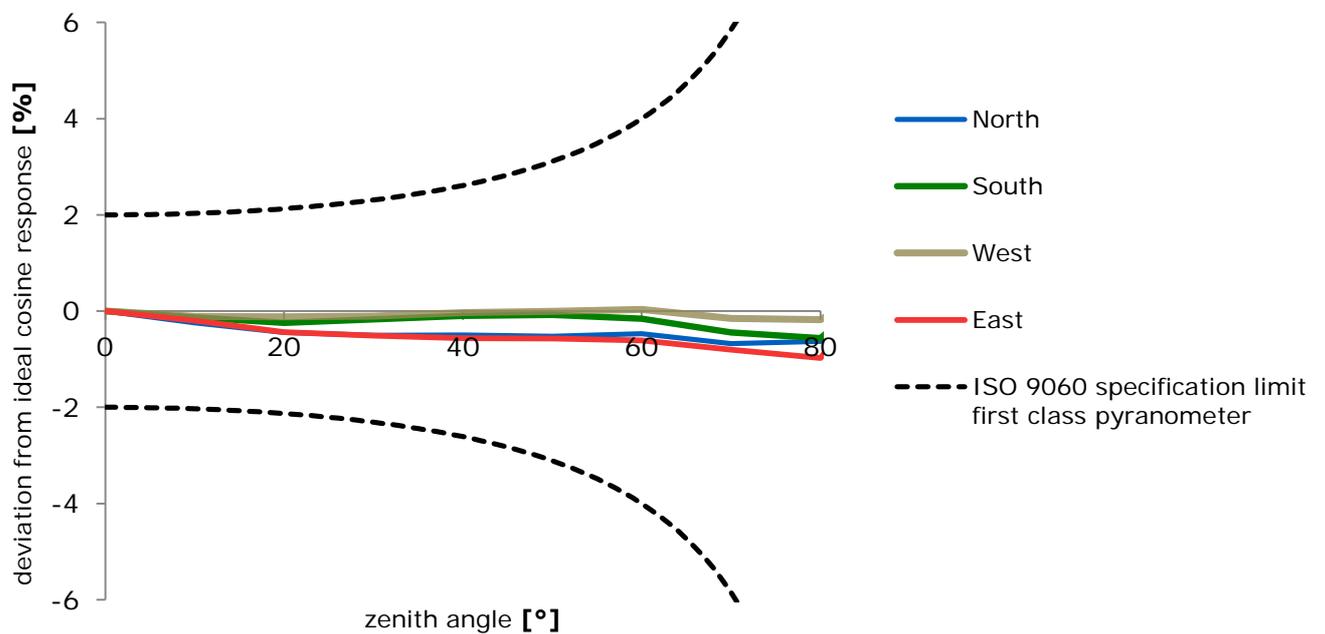


Figure 2.3 Directional response of a SR15-A1 pyranometer of 4 azimuth angles, compared to first class standard limits

3 Specifications of SR15-A1

3.1 Specifications of SR15-A1

SR15-A1 is a “first class” pyranometer according to the WMO guide and ISO 9060:1990 standard. It measures the solar radiation received by a plane surface from a 180 ° field of view angle. This quantity, expressed in W/m^2 , is called “hemispherical” solar radiation. Working completely passive, using a thermopile sensor, SR15-A1 generates a small output voltage proportional to this flux and can be heated to improve data availability. It can only be used in combination with a suitable measurement system.

This user manual covers use of the analogue sensor in the SR15 series range: SR15-A1. Specifications of this version differs from those of the digital versions of model SR15: SR15-D1 and SR15-D2A2, offering various digital and analogue outputs. For SR15-D1 and SR15-D2A2 use, consult the separate SR15 digital series user manual.

SR15-A1 has an onboard heater. Heating the sensor contributes to the dependability and accuracy of the measurement, helping to prevent dew and frost deposition. Therefore the heater is typically switched on at night-time only. During daytime it is recommended to switch off the heater. Note that using the heater without any additional ventilation may cause zero offsets.

The instrument should be used in accordance with the recommended practices of ISO, IEC, WMO and ASTM.

Table 3.1.1 Specifications of SR15-A1 (continued on next pages)

SR15-A1 MEASUREMENT SPECIFICATIONS: LIST OF CLASSIFICATION CRITERIA OF ISO 9060*	
ISO classification (ISO 9060: 1990)	first class pyranometer
WMO performance level (WMO-No. 8, seventh edition 2008)	good quality pyranometer
Response time (95 %)	< 10 s
Zero offset a (response to 200 W/m^2 net thermal radiation)	5 W/m^2 unventilated
Zero offset b (response to 5 K/h change in ambient temperature)	< $\pm 4 W/m^2$
Non-stability	< ± 1 % change per year
Non-linearity	< ± 1 % (100 to 1000 W/m^2)
Directional response	< $\pm 20 W/m^2$
Spectral selectivity	< ± 3 % (0.35 to 1.5×10^{-6} m)
Temperature response	< ± 2 % (-10 to +40 °C)
Tilt response	< ± 2 % (0 to 90 ° at 1000 W/m^2)
IEC 61724-1:2017 COMPLIANCE	
IEC 61724-1:2017 compliance	SR15-A1 meets Class B PV monitoring system requirements

*For the exact definition of pyranometer ISO 9060 specifications see the appendix.

Table 3.1.1 *Specifications of SR15-A1 (continued)*

SR15-A1 ADDITIONAL SPECIFICATIONS	
Measurand	hemispherical solar radiation
Measurand in SI radiometry units	irradiance in W/m^2
Optional measurand	sunshine duration
Field of view angle	180 °
Measurement range	0 to 3000 W/m^2
Sensitivity range	7 to 15 x 10 ⁻⁶ V/(W/m^2)
Sensitivity (nominal)	10 x 10 ⁻⁶ V/(W/m^2)
Expected voltage output	application under natural solar radiation: -0.1 to +30 x 10 ⁻³ V
Measurement function / required programming	$E = U/S$
Measurement function / optional programming for sunshine duration	programming according to WMO guide paragraph 8.2.2
Required readout	1 differential voltage channel or 1 single ended voltage channel, input resistance > 10 ⁶ Ω
Rated operating temperature range	-40 to +80 °C
Sensor resistance range	50 to 150 Ω
Required sensor power	zero (unheated)
Spectral range (20 % transmission points)	285 to 3000 x 10 ⁻⁹ m
Standards governing use of the instrument	ISO/TR 9901:1990 Solar energy -- Field pyranometers -- Recommended practice for use ASTM G183 - 05 Standard Practice for Field Use of Pyranometers, Pyrheliometers and UV Radiometers IEC 61724-1 Photovoltaic System Performance Monitoring- Guidelines for Measurement, Data Exchange and Analysis
Standard cable length (see options)	5 m
Cable diameter	4.8 x 10 ⁻³ m
Cable conductor cross-section	0.25 x 10 ⁻³ m (24 AWG)
Chassis connector	M12-A straight male connector, male thread, 5-pole
Cable connector	M12-A straight female connector, female thread, 5-pole
Connector protection class	IP67
Cable replacement	replacement cables with connector can be ordered separately from Hukseflux
Mounting	2 x M5 bolt at 46 x 10 ⁻³ m centre-to-centre distance on north-south axis, or 1 x M6 bolt at the centre of the instrument, connection from below under the bottom plate of the instrument
Levelling	bubble level and adjustable levelling feet are included
Levelling accuracy	< 0.1 ° bubble entirely in ring
Desiccant	two bags of silica gel, 1 g, (45 x 25) x 10 ⁻³ m, Tyvek bag
Desiccant replacement	> 5 year interval, typically replaced during calibration, ask the manufacturer for instructions
IP protection class	IP67

Table 3.1.1 Specifications of SR15-A1 (started on previous pages)

Gross weight including 5 m cable	0.89 kg
Net weight including 5 m cable	0.65 kg
Packaging	box of 182 x 140 x 156 mm
HEATING	
Heater operation	the heater is not necessarily switched on; recommended operation is to activate the heater when the sun is below the horizon
Required heater power	1.5 W at 12 VDC (the heater is not necessarily active)
Heater resistance	95 Ω
Steady state zero offset caused by heating	0 to -8 W/m ²
CALIBRATION	
Calibration traceability	to WRR
Calibration hierarchy	from WRR through ISO 9846 and ISO 9847, applying a correction to reference conditions
Calibration method	indoor calibration according to ISO 9847, Type IIc
Calibration uncertainty	< 1.8 % (k = 2)
Recommended recalibration interval	2 years
Reference conditions	20 °C, normal incidence solar radiation, horizontal mounting, irradiance level 1000 W/m ²
Validity of calibration	based on experience the instrument sensitivity will not change during storage. During use under exposure to solar radiation the instrument "non-stability" specification is applicable.
MEASUREMENT ACCURACY	
Uncertainty of the measurement	statements about the overall measurement uncertainty can only be made on an individual basis. See the chapter on uncertainty evaluation
WMO estimate on achievable accuracy for daily sums (see appendix for a definition of the measurement conditions)	± 5 % (WMO-No. 8, seventh edition 2008)
WMO estimate on achievable accuracy for hourly sums (see appendix for a definition of the measurement conditions)	± 8 % (WMO-No. 8, seventh edition 2008)
OPTIONS	
Adapted sensitivity range	the sensitivity range can be adapted to customer requirements between 7×10^{-6} and 10×10^{-6} V/(W/m ²) option code = S"lower end of the allowed range"- "higher end of the allowed range" (range in 10^{-6} V/(W/m ²))
Longer cable: 10 or 20 metre length Cable with M12-A female connector on sensor end, stripped (stripped over 0.15 m and conductors with ferrules) on other end	option code = total cable length
Extension cable with connector pair, 20 m length Cable with male and female M12-A connectors	option code = C07E-20 for 20 metres

Table 3.1.1 *Specifications of SR15-A1 (started on previous pages)*

ACCESSORIES	
Levelling mount, for spring-loaded levelling and mounting SR15-A1 on a surface	mountable on flat surface allowing tilt adjustment to 3.4 ° requires 4 mm hex key or 10 mm spanner for connecting to SR15-A1 requires two M5 bolts and hex key for mounting to a surface (not included) 2 x M5 at 46×10^{-3} m centre to centre distance option code = LM01
Tube levelling mount, for spring-loaded levelling and mounting SR15-A1 on a tube	mountable on tubes \varnothing 25 to \varnothing 40 mm one spring-loaded levelling mount, one clamp for tube mounting and two sets of bolts (two M5x30 and two M5x45) included allowing tilt adjustment to 3.4 ° requires 4 mm hex key for mounting and 4 mm hex key or 10 mm spanner for connecting to SR15-A1 option code = TLM01
Alternative pyranometer mounting fixture	for mounting any Hukseflux pyranometer on horizontal and vertical tubes, on platforms, both horizontal and in Plane of Array order code = PMF01

3.2 Dimensions of SR15-A1

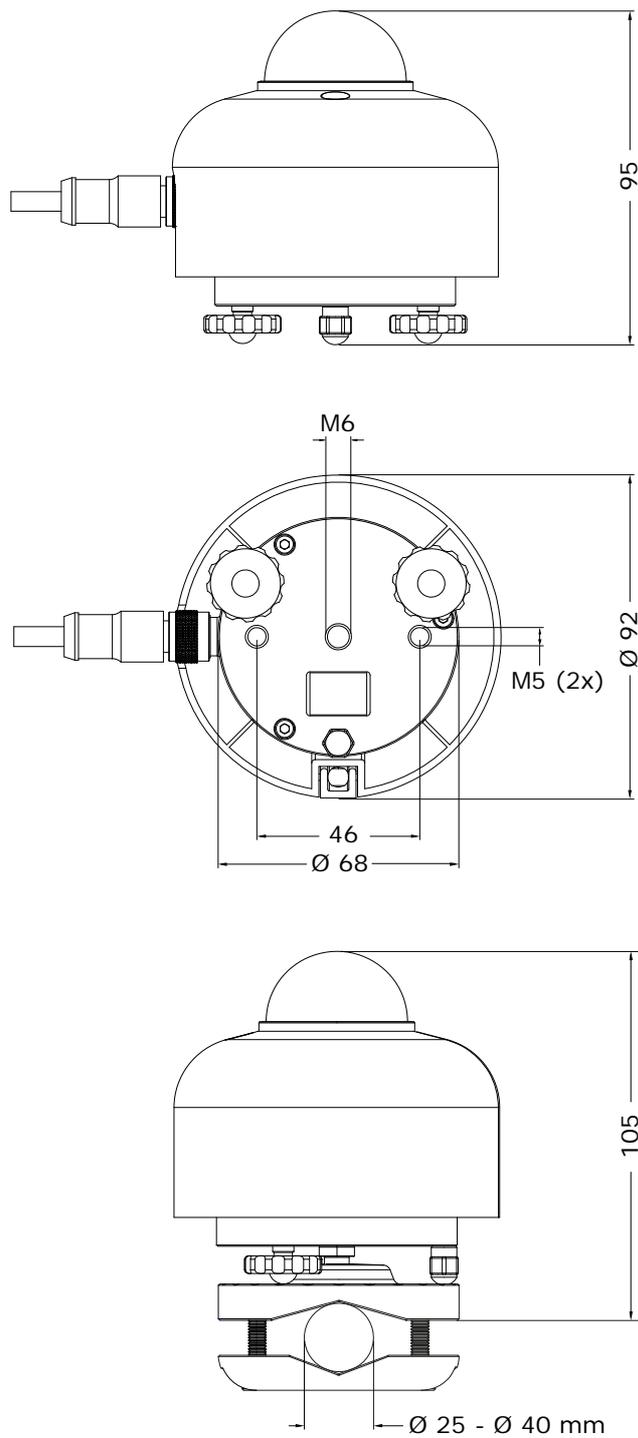


Figure 3.2.1 Dimensions of SR15-A1 in $\times 10^{-3}$ m. Mounts are optional

4 Standards and recommended practices for use

Pyranometers are classified according to the ISO 9060 standard and the WMO-No. 8 Guide. In any application the instrument should be used in accordance with the recommended practices of ISO, IEC, WMO and / or ASTM.

4.1 Classification standard

Table 4.1.1 Standards for pyranometer classification. See the appendix for definitions of pyranometer specifications, and a table listing the specification limits.

STANDARDS FOR INSTRUMENT CLASSIFICATION		
ISO STANDARD	EQUIVALENT ASTM STANDARD	WMO
ISO 9060:1990 Solar energy -- specification and classification of instruments for measuring hemispherical solar and direct solar radiation	Not available	WMO-No. 8; Guide to Meteorological Instruments and Methods of Observation, chapter 7, measurement of radiation, 7.3 measurement of global and diffuse solar radiation

4.2 General use for solar radiation measurement

Table 4.2.1 Standards with recommendations for instrument use in solar radiation measurement

STANDARDS FOR INSTRUMENT USE FOR HEMISPHERICAL SOLAR RADIATION		
ISO STANDARD	EQUIVALENT ASTM STANDARD	WMO
ISO/TR 9901:1990 Solar energy -- Field pyranometers -- Recommended practice for use	ASTM G183 - 05 Standard Practice for Field Use of Pyranometers, Pyrhemimeters and UV Radiometers	WMO-No. 8; Guide to Meteorological Instruments and Methods of Observation, chapter 7, measurement of radiation, 7.3 measurement of global and diffuse solar radiation

4.3 General use for sunshine duration measurement

According to the World Meteorological Organization (WMO, 2003), sunshine duration during a given period is defined as the sum of that sub-period for which the direct solar irradiance exceeds 120 W/m².

WMO has approved the “pyranometric method” to estimate sunshine duration from pyranometer measurements (Chapter 8 of the WMO Guide to Instruments and Observation, 2008). This implies that a pyranometer may be used, in combination with appropriate software, to estimate sunshine duration. Ask for our application note.

Table 4.3.1 *Standards with recommendations for instrument use in sunshine duration measurement*

STANDARDS FOR INSTRUMENT USE FOR SUNSHINE DURATION

WMO

WMO-No. 8; Guide to Meteorological Instruments and Methods of Observation, chapter 8, measurement of sunshine duration, 8.2.2 Pyranometric Method

4.4 Specific use for outdoor PV system performance testing

Pyranometers are used for monitoring PV power plant efficiency, in order to measure incoming solar radiation independently from the PV system. Pyranometers can be placed in two positions:

- plane of array (POA), parallel to the PV panels, for measurement of the in-plane irradiance (also noted as G_i in IEC 61724-1)
- horizontally, for measurement of the global horizontal irradiance (E , also noted as G_{HI} in IEC 61724-1)

SR15-A1 is very well applicable in outdoor PV system performance testing. See also model **SR30** “next level digital secondary standard pyranometer”.

Table 4.4.1 *Standards with recommendations for instrument use in PV system performance testing*

STANDARDS ON PV SYSTEM PERFORMANCE TESTING

IEC / ISO STANDARD	EQUIVALENT ASTM STANDARD
IEC 61724; Photovoltaic system performance monitoring – guidelines for measurement, data exchange and analysis SR15-A1 complies, in its standard configuration, with the IEC 61724-1:2017 requirements of Class B PV monitoring systems COMMENT: Allows pyranometers or reference cells according to IEC 60904-2 and -6. Pyranometer reading required accuracy better than 5% of reading (Par 4.1) COMMENT: equals JISC 8906 (Japanese Industrial Standards Committee)	ASTM 2848-11; Standard Test Method for Reporting Photovoltaic Non-Concentrator System Performance COMMENT: confirms that a pyranometer is the preferred instrument for outdoor PV testing. Specifically recommends a “first class” pyranometer (paragraph A 1.2.1.)

4.5 Specific use in meteorology and climatology

The World Meteorological Organization (WMO) is a specialised agency of the United Nations. It is the UN system's authoritative voice on the state and behaviour of the earth's atmosphere and climate. WMO publishes WMO-No. 8; Guide to Meteorological Instruments and Methods of Observation, in which a table is included on "level of performance" of pyranometers. Nowadays WMO conforms itself to the ISO classification system.

5 Installation of SR15-A1

5.1 Site selection and installation

Table 5.1.1 *Recommendations for installation of pyranometers*

Location	the situation that shadows are cast on the instruments is usually not desirable. The horizon should be as free from obstacles as possible. Ideally there should be no objects between the course of the sun and the instrument.
Mechanical mounting / thermal insulation	preferably, use the optional spring-loaded levelling mount for mounting to a flat surface, or use the optional tube mount. If not, use connection by bolts to the bottom plate of the instrument. A pyranometer is sensitive to thermal shocks. Do not mount the instrument with the body in direct thermal contact to the mounting plate (so always use the levelling feet also if the mounting is not horizontal), do not mount the instrument on objects that become very hot (black coated metal plates).
Instrument mounting with 2 bolts (without optional levelling mount)	2 x M5 bolt at 46×10^{-3} m centre to centre distance on north-south axis, connection from below under the bottom plate of the instrument.
Instrument mounting with one bolt (without optional levelling mount)	1 x M6 bolt at the centre of the instrument, connection from below under the bottom plate of the instrument.
Performing a representative measurement	the pyranometer measures the solar radiation in the plane of the sensor. This may require installation in a tilted or inverted position. The black sensor surface (sensor bottom plate) should be mounted parallel to the plane of interest. In case a pyranometer is not mounted horizontally or in case the horizon is obstructed, the representativeness of the location becomes an important element of the measurement. See the chapter on uncertainty evaluation.
Levelling	in case of horizontal mounting, use the bubble level and levelling feet.
Instrument orientation	by convention: with the cable exit pointing to the nearest pole, so the cable exit should point north in the northern hemisphere, south in the southern hemisphere.
Installation height	in case of inverted installation, WMO recommends a distance of 1.5 m between soil surface and sensor (reducing the effect of shadows and in order to obtain good spatial averaging).

5.2 Installation of the sun screen

SR15-A1's bubble level can be inspected at all times, even with the sun screen installed: a small window allows to see the bubble level. The quick release system of SR15-A1's sun screen allows for easy and secure mounting of the sun screen on the sensor. Installation and removal of the the connector can be done after removal of the sun screen.

The quick release system consists of a spring-loaded lever opposite the bubble level window of the SR15 sun screen. The bottom of the handle can be pulled out gently. Once the handle is pulled out and fully released, as shown in the figure below, the sun screen can be lifted off manually for removal. Installing the sun screen is easy too: pull out the bottom of the quick release system handle so it is fully released, place the screen on SR15-A1 and, once it is positioned properly, press the handle of the quick release system until it is locked.



Figure 5.2.1 *SR15-A1's sun screen with its quick release system and bubble level window*



Figure 5.2.2 *Installation of SR15-A1's sun screen*

5.3 Installation of optional mounts

5.3.1 Levelling mount

The optional levelling mount, for simplified mounting and levelling of SR15-A1 on a flat surface such as a platform or bracket, is easy to use. It can be fitted to SR15-A1 using the mount's spring-loaded centre bolt and a 4 mm hex key or a 10 mm spanner. It can be mounted on a flat surface by inserting two M5 bolts (not included) in the designated holes.



Figure 5.3.1.1 *Optional spring-loaded levelling mount for SR15-A1*

The preferred way to connect the mount to SR15-A1 and lock its connection, is by using a 4 mm hex key via the bottom part of the levelling mount (see Figure 5.3.1.2). If the bottom part is not accessible, the connection between SR15-A1 and the mount can be made by using a 10 mm spanner (see Figure 5.3.1.3). The spanner may be used as well to lock, or unlock, when SR15-A1 is already fitted to the mount (See Figure 5.3.1.4). In all cases, ensure the legs of SR15-A1 fit into one of the small ledges of the levelling mount. Locking is in place, when the nut of the spring-loaded centre bolt is turned all the way towards SR15-A1's bottom panel.

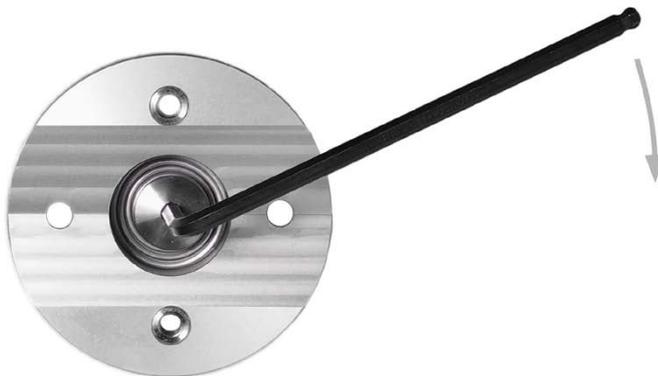


Figure 5.3.1.2 *bottom of SR15-A1 levelling mount. Preferred (un)locking with 4 mm hex key*



Figure 5.3.1.3 SR15-A1 levelling mount seen from above: (un)locking with a 10 mm spanner



Figure 5.3.1.4 SR15-A1 levelling mount seen from the side: (un)locking with a 10 mm spanner

The levelling mount is spring-loaded. Once SR15-A1 is connected and locked to the levelling mount, SR15-A1 can be levelled by the user, judging the bubble level. Levelling is done by fastening or loosening SR15-A1's two adjustable levelling feet by hand. SR15-A1's static foot remains fixed. Fasten or loosen both legs so that the instrument is level, judging by the bubble level.



Figure 5.3.1.5 SR15-A1 locked on its optional levelling mount: by fastening (on the left) or loosening (on the right) SR15-A1's two adjustable feet, SR15-A1 can be levelled, judging by the bubble level. SR15-A1's static foot remains fixed. In all cases, ensure the legs of SR15-A1 fit into one of the small ledges of the levelling mount. Locking is in place, when the nut is turned all the way against the bottom plate of SR15-A1.

5.3.2 Tube levelling mount

SR15-A1 may also be mounted on a tube or a mounting rod using SR15-A1's optional tube mount.



Figure 5.3.2.1 SR15-A1 mounted with its optional tube levelling mount on a tube

The tube mount option includes the levelling mount, described in the previous paragraph, a lower clamp for tube mounting and two sets of bolts for tube diameters 25 to 40 mm (tube not included). Installation requires a 4 mm hex key.



Figure 5.3.2.2 *Optional tube levelling mount; installation requires a 4 mm hex key*

5.4 Installation of optional extension cable of 20 m



Figure 5.4.1 *Optional extension cable of 20 metres with 2 connectors*

Extension to longer cable lengths is achieved by adding extension cables of 20 m with 2 connectors, male and female M12-A.

5.5 Electrical connection of SR15-A1: wiring diagram

In order to operate, a pyranometer should be connected to a measurement system, typically a datalogger. SR15-A1 is a passive sensor that does not need any power. Cables generally act as a source of distortion, by picking up capacitive noise. We recommend keeping the distance between a datalogger or amplifier and the sensor as short as possible. For cable extension, see the appendix on this subject.

Table 5.5.1 Wiring diagram of SR15-A1 including the pin numbering of the connector

PIN	WIRE	SR15-A1
1	Brown	heater ¹
4	Black	heater ¹
3	Blue	not connected
2	White	signal [+]
5	Grey	signal [-]
-	Yellow	cable shield/housing ²

Note 1: the heater is a resistive heater element

Note 2: at the connector-end of the cable, the shield is connected to the connector chassis and thereby to the sensor housing

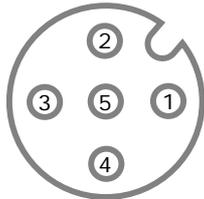


Figure 5.5.1.1 Chassis connector layout of SR15-A1, indicating PIN numbers (viewed from cable side)

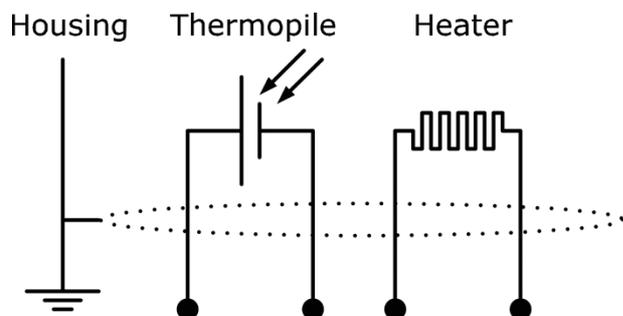


Figure 5.5.1.2 Electrical diagram of the internal wiring of SR15-A1. The shield is connected to the sensor body.

5.6 Grounding and use of the shield

Grounding and shield use are the responsibility of the user. The cable shield is connected to the aluminium instrument body via the connector. In most situations, the instrument will be screwed on a mounting platform that is locally grounded. In these cases the shield at the cable end should not be connected at all. When a ground connection is not obtained through the instrument body, for instance in laboratory experiments, the shield should be connected to the local ground at the cable end. This is typically the ground or low voltage of the power supply or the common of the network. Avoid creating a ground loop by grounding the instrument body and connecting the cable shield to ground, at the same time. This may cause permanent damage the instrument or the data logging equipment.

5.7 Requirements for data acquisition / amplification

The selection and programming of dataloggers is the responsibility of the user. Please contact the supplier of the data acquisition and amplification equipment to see if directions for use with the SR15-A1 are available.

In case programming for similar instruments is available, this can typically also be used. SR15-A1 can usually be treated in the same way as other thermopile pyranometers. Pyranometers usually have the same programming as heat flux sensors.

Table 5.7.1 *Requirements for data acquisition and amplification equipment for SR15-A1 in the standard configuration*

Capability to measure small voltage signals	preferably: 5×10^{-6} V uncertainty minimum requirement: 20×10^{-6} V uncertainty (valid for the entire expected temperature range of the acquisition / amplification equipment)
Capability for the data logger or the software	to store data, and to perform division by the sensitivity to calculate the solar irradiance. $E = U/S$ (Formula 0.1)
Data acquisition input resistance	$> 1 \times 10^6 \Omega$
Open circuit detection (WARNING)	open-circuit detection should not be used, unless this is done separately from the normal measurement by more than 5 times the sensor response time and with a small current only. Thermopile sensors are sensitive to the current that is used during open circuit detection. The current will generate heat, which is measured and will appear as an offset.

6 Making a dependable measurement

6.1 The concept of dependability

A measurement with a pyranometer is called “dependable” if it is reliable, i.e. measuring within required uncertainty limits, for most of the time and if problems, once they occur, can be solved quickly.

The requirements for a measurement with a pyranometer may be expressed by the user as:

- required uncertainty of the measurement (see following paragraphs)
- requirements for maintenance and repairs (possibilities for maintenance and repair including effort to be made and processing time)
- a requirement to the expected instrument lifetime (until it is no longer feasible to repair)

It is important to realise that the uncertainty of the measurement is not only determined by the instrument but also by the way it is used.

See also ISO 9060 note 5. In case of pyranometers, the measurement uncertainty as obtained during outdoor measurements is a function of:

- the instrument class
- the calibration procedure / uncertainty
- the duration of instrument employment under natural sunlight (involving the instrument stability specification)
- the measurement conditions (such as tilting, ventilation, shading, instrument temperature)
- maintenance (mainly fouling)
- the environmental conditions*

Therefore, ISO 9060 says, “statements about the overall measurement uncertainty under outdoor conditions can only be made on an individual basis, taking all these factors into account”.

* defined at Hukseflux as all factors outside the instrument that are relevant to the measurement such as the cloud cover (presence or absence of direct radiation), sun position, the local horizon (which may be obstructed) or condition of the ground (when tilted). The environmental conditions also involve the question whether or not the measurement at the location of measurement is representative of the quantity that should be measured.

6.2 Reliability of the measurement

A measurement is reliable if it measures within required uncertainty limits for most of the time. We distinguish between two causes of unreliability of the measurement:

- related to the reliability of the pyranometer and its design, manufacturing, calibration (hardware reliability).
- related to the reliability of the measurement uncertainty (measurement reliability), which involves hardware reliability as well as condition of use.

Most of the hardware reliability is the responsibility of the instrument manufacturer. The reliability of the measurement however is a joint responsibility of instrument manufacturer and user. As a function of user requirements, taking into account measurement conditions and environmental conditions, the user will select an instrument of a certain class, and define maintenance support procedures.

In many situations there is a limit to a realistically attainable accuracy level. This is due to conditions that are beyond control once the measurement system is in place. Typical limiting conditions are:

- the measurement conditions, for instance when working at extreme temperatures when the instrument temperature is at the extreme limits of the rated temperature range.
- the environmental conditions, for instance when installed at a sub-optimal measurement location with obstacles in the path of the sun.
- other environmental conditions, for instance when assessing PV system performance and the system contains panels at different tilt angles, the pyranometer measurement may not be representative of irradiance received by the entire PV system.

The measurement reliability can be improved by maintenance support. Important aspects are:

- dome fouling by deposition of dust, dew, rain or snow. Fouling results in undefined measurement uncertainty (sensitivity and directional error are no longer defined). This should be solved by regular inspection and cleaning.
- sensor instability. Maximum expected sensor aging is specified per instrument as its non-stability in [% change / year]. In case the sensor is not recalibrated, the uncertainty of the sensitivity gradually will increase. This is solved by regular recalibration.
- moisture condensing under pyranometer domes can result in a change of sensitivity (within specifications). This is solved by regular replacement of desiccant or by maintenance (drying the entire sensor) in case the sensor allows this. Please refer to [7.1 Recommended maintenance and quality assurance](#) for the maintenance schedule.

Another way to improve measurement reliability is to introduce redundant sensors.

- the use of redundant instruments allows remote checks of one instrument using the other as a reference, which leads to a higher measurement reliability.
- in PV system performance monitoring, in addition to instruments measuring in the plane of array, horizontally placed instruments are used for the measurement of global radiation. Global irradiance data enable the user to compare the local climate and system efficiency between different sites. These data can also be compared to measurements by local meteorological stations.

6.3 Repair and maintenance

Dependability is not only a matter of reliability but also involves the reaction to problems; if the processing time of service and repairs is short, this contributes to the dependability.

Hukseflux pyranometers are designed to allow easy maintenance and repair. The main maintenance actions are:

- cleaning of dome
- replacement of desiccant
- replacement of cabling

For optimisation of dependability a user should:

- design a schedule of regular maintenance
- design a schedule of repair or replacement in case of defects

When operating multiple instruments in a network Hukseflux recommends keeping procedures simple and having a few spare instruments to act as replacements during service, recalibrations and repair.

6.4 Uncertainty evaluation

The uncertainty of a measurement under outdoor or indoor conditions depends on many factors, see paragraph 1 of this chapter. It is not possible to give one figure for pyranometer measurement uncertainty. Several research groups around the world are actively working on the development of a concise method for uncertainty evaluation and are participating in the standardisation of this method. The effort aims to work according to the guidelines for uncertainty evaluation (according to the "Guide to Expression of Uncertainty in Measurement" or GUM).

6.4.1 Evaluation of measurement uncertainty under outdoor conditions

Hukseflux actively participates in the discussions about pyranometer measurement uncertainty; we also provide spreadsheets, reflecting the latest state of the art, to assist our users in making their own evaluation. The input to the assessment is summarised:

- 1) The formal evaluation of uncertainty should be performed in accordance with ISO 98-3 Guide to the Expression of Uncertainty in Measurement, GUM.
- 2) The specifications of the instrument according to the list of ISO 9060 classification of pyranometers and pyrhemometers are entered as limiting values of possible errors, to be analysed as type B evaluation of standard uncertainty per paragraph 4.3.7. of GUM. A priori distributions are chosen as rectangular.
- 3) A separate estimate has to be entered to allow for estimated uncertainty due to the instrument maintenance level.
- 4) The calibration uncertainty has to be entered. Please note that Hukseflux calibration uncertainties are lower than those of alternative equipment. These uncertainties are entered in measurement equation (equation is usually Formula 0.1: $E = U/S$), either as an uncertainty in E (zero offsets, directional response) in U (voltage readout errors) or in S (tilt error, temperature dependence, calibration uncertainty).
- 5) In uncertainty analysis for pyranometers, the location and date of interest is entered. The course of the sun is then calculated, and the direct and diffuse components are estimated, based on a model; the angle of incidence of direct radiation is a major factor in the uncertainty.
- 6) In uncertainty analysis for modern pyrhemometers: tilt dependence often is so low that one single typical observation may be sufficient.
- 7) In case of special measurement conditions, typical specification values are chosen. These should for instance account for the measurement conditions (shaded / unshaded, ventilated/ unventilated, horizontal / tilted) and environmental conditions (clear sky / cloudy, working temperature range).
- 8) Among the various sources of uncertainty, some are "correlated"; i.e. present during the entire measurement process, and not cancelling or converging to zero when averaged over time; the off-diagonal elements of the covariance matrix are not zero. Paragraph 5.2 of GUM.
- 9) Among the various sources of uncertainty, some are "uncorrelated"; cancelling or converging to zero when averaged over time; the off-diagonal elements of the covariance matrix are zero. Paragraph 5.1 of GUM.
- 10) Among the various sources of uncertainty, some are "not included in analysis"; this applies for instance to non-linearity for pyranometers, because it is already included in the directional error, and the spectral response for pyranometers and pyrhemometers because it is already taken into account in the calibration process.

Table 6.4.1.1 Preliminary estimates of achievable uncertainties of measurements with Hukseflux pyranometers. The estimates are based on typical pyranometer properties and calibration uncertainty, for sunny, clear sky days and well maintained stations, without uncertainty loss due to lack of maintenance and due to instrument fouling. The table specifies expanded uncertainties with a coverage factor of 2 and confidence level of 95 %. Estimates are based on 1 s sampling. **IMPORTANT NOTE:** there is no international consensus on uncertainty evaluation of pyranometer measurements, so this table should not be used as a formal reference.

Pyranometer class (ISO 9060)	season	latitude	uncertainty minute totals at solar noon	uncertainty hourly totals at solar noon	uncertainty daily totals
secondary standard	summer	mid-latitude	2.7 %	2.0 %	1.9 %
		equator	2.6 %	1.9 %	1.7 %
		pole	7.9 %	5.6 %	4.5 %
	winter	mid-latitude	3.4 %	2.5 %	2.7 %
first class (SR15-A1)	summer	mid-latitude	4.7 %	3.3 %	3.4 %
		equator	4.4 %	3.1 %	2.9 %
		pole	16.1%	11.4 %	9.2 %
	winter	mid-latitude	6.5 %	4.5 %	5.2 %
second class	summer	mid-latitude	8.4 %	5.9 %	6.2 %
		equator	7.8 %	5.5 %	5.3 %
		pole	29.5 %	21.6 %	18.0 %
	winter	mid-latitude	11.4 %	8.1 %	9.9 %

6.4.2 Calibration uncertainty

New calibration procedures were developed in close cooperation with PMOD World Radiation Center in Davos, Switzerland. The latest calibration method results in an uncertainty of the sensitivity of less than 1.8 %, compared to typical uncertainties of higher than 3 % for this pyranometer class. See the appendix for detailed information on calibration hierarchy.

7 Maintenance and trouble shooting

7.1 Recommended maintenance and quality assurance

SR15-A1 can measure reliably at a low level of maintenance in most locations. Usually unreliable measurements will be detected as unreasonably large or small measured values. As a general rule this means that regular visual inspection combined with a critical review of the measured data, preferably checking against other measurements, is the preferred way to obtain a reliable measurement.

Table 7.1.1 *Recommended maintenance of SR15-A1. If possible the data analysis and cleaning (1 and 2) should be done on a daily basis.*

MINIMUM RECOMMENDED PYRANOMETER MAINTENANCE			
	INTERVAL	SUBJECT	ACTION
1	1 week	data analysis	compare measured data to maximum possible / maximum expected irradiance and to other measurements nearby (redundant instruments). Also historical seasonal records can be used as a source for expected values. Analyse night-time signals. These signals may be negative (down to - 5 W/m ² on clear windless nights), due to zero offset a. In case of use with PV systems, compare daytime measurements to PV system output. Look for any patterns and events that deviate from what is normal or expected. check tilt, internal humidity, internal pressure, according to the recommendations in the chapter about remote diagnostics
2	2 weeks	cleaning	use a soft cloth to clean the dome of the instrument, persistent stains can be treated with soapy water or alcohol
3	6 months	inspection	inspect cable quality, inspect connectors, inspect mounting position, inspect cable, clean instrument, clean cable, inspect levelling, change instrument tilt angle in case this is out of specification, inspect mounting connection, inspect interior of dome for condensation
5	2 years	recalibration	recalibration by side-by-side comparison to a higher standard instrument in the field according to ISO 9847. Typically during calibration desiccant is replaced.
6		lifetime assessment	judge if the instrument should be reliable for another 2 years, or if it should be replaced

MINIMUM RECOMMENDED PYRANOMETER MAINTENANCE (continued)

INTERVAL	SUBJECT	ACTION
7 > 5 years	desiccant replacement	desiccant replacement. Typically during calibration desiccant is replaced. Ask the manufacturer for directions.
8	parts replacement	if applicable / necessary, replace the parts that are most exposed to ageing and weathering; cable, sun screen. NOTE: use Hukseflux approved parts only.

7.2 Trouble shooting

Table 7.2.1 *Trouble shooting for SR15-A1*

The sensor does not give any signal	<p>Check the electrical resistance of the sensor between the grey (-) and white (+) wire. Use a multimeter at the 1000 Ω range. Measure the sensor resistance first with one polarity, than reverse the polarity. Take the average value. The typical resistance of the wiring is 0.1 Ω/m. Typical resistance should be the typical sensor resistance of 50 to 150 Ω plus 1.5 Ω for the total resistance of two wires (back and forth) length of the used cable. Infinite resistance indicates a broken circuit; zero or a low resistance indicates a short circuit.</p> <p>Check if the sensor reacts to light: put the multimeter at its most sensitive range of DC voltage measurement, typically the 100 x 10⁻³ VDC range or lower. Expose the sensor to strong light source, for instance a 100 W light bulb at 1 x 10⁻¹ m distance. The signal should read > 2 x 10⁻³ V now. Darken the sensor either by putting something over it or switching off the light. The instrument voltage output should go down and within one minute approach 0 V. Check the data acquisition by applying a 1 x 10⁻⁶ V source to it in the 1 x 10⁻⁶ V range. Check the condition of the connectors (on chassis as well as the cable).</p>
The sensor signal is unrealistically high or low.	<p>Note that night-time signals may be negative due to zero offset a and heating offsets when the heater is used. The contribution from zero offset a can be down to -5 W/m², offset due to heating can be -8 W/m².</p> <p>Check if the pyranometer has clean domes.</p> <p>Check the location of the pyranometer; are there any obstructions that could explain the measurement result.</p> <p>Check the orientation / levelling of the pyranometer.</p> <p>Check if the right calibration factor is entered into the algorithm. Please note that each sensor has its own individual calibration factor, as documented in its calibration certificate.</p> <p>Check if the voltage reading is divided by the calibration factor in review of the algorithm. Check the condition of the wiring at the logger.</p> <p>Check the cable condition looking for cable breaks. Check the condition of the connectors (on chassis as well as the cable). Check the range of the data logger; signal can be negative (this could be out of range) or the amplitude could be out of range. Check the data acquisition by applying a 1 x 10⁻⁶ V source to it in the 1 x 10⁻⁶ V range. Look at the output. Check if the output is as expected.</p> <p>Check the data acquisition by short circuiting the data acquisition input with a 100 Ω resistor. Look at the output. Check if the output is close to 0 W/m².</p>
The sensor signal shows	<p>Check the presence of strong sources of electromagnetic radiation (radar, radio)</p> <p>Check the condition of the shielding.</p>

unexpected variations	<p>Check the condition of the sensor cable.</p> <p>Check if the cable is not moving during the measurement</p> <p>Check the condition of the connectors (on chassis as well as the cable)</p>
The outer dome shows internal condensation.	<p>In case there is a minor layer of moisture that is hardly visible: replace the desiccant and wait a few days to see if the situation improves.</p> <p>In case of condensation of droplets: disassemble the instrument and dry out the parts.</p>
The inner dome shows internal condensation	<p>Arrange to send the sensor back to Hukseflux for diagnosis.</p>

7.3 Calibration and checks in the field

Recalibration of field pyranometers is typically done by comparison in the field to a reference pyranometer. The applicable standard is ISO 9847 "International Standard-Solar Energy- calibration of field pyranometers by comparison to a reference pyranometer". At Hukseflux an indoor calibration according to the same standard is used.

Hukseflux recommendation for re-calibration: if possible, perform calibration indoor by comparison to an identical reference instrument, under normal incidence conditions.

In case of field comparison; ISO recommends field calibration to a higher class pyranometer. Hukseflux suggests also allowing use of sensors of the same model and class, because intercomparisons of similar instruments have the advantage that they suffer from the same offsets. It is therefore just as good to compare to pyranometers of the same brand and type as to compare to an instrument of a higher class. ISO recommends to perform field calibration during several days; 2 to 3 days under cloudless conditions, 10 days under cloudy conditions. In general this is not achievable. In order to shorten the calibration process Hukseflux suggests to allow calibration at normal incidence, using hourly totals near solar noon.

Hukseflux main recommendations for field intercomparisons are:

- 1) to take normal incidence as a reference and not the entire day.
- 2) to take a reference of the same brand and type as the field pyranometer or a pyranometer of a higher class, and
- 3) to connect both to the same electronics, so that electronics errors (also offsets) are eliminated.
- 4) to mount all instruments on the same platform, so that they have the same body temperature.
- 5) assuming that the electronics are independently calibrated, to analyse radiation values at normal incidence radiation (possibly tilting the radiometers to approximately normal incidence), if this is not possible to compare 1 hour totals around solar noon for horizontally mounted instruments.

6) for second class radiometers, to correct deviations of more than $\pm 10\%$. Lower deviations should be interpreted as acceptable and should not lead to a revised sensitivity.

7) for first class pyranometers, to correct deviations of more than $\pm 5\%$. Lower deviations should be interpreted as acceptable and should not lead to a revised sensitivity.

8) for secondary standard instruments, to correct deviations of more than $\pm 3\%$. Lower deviations should be interpreted as acceptable and should not lead to a revised sensitivity.

7.4 Data quality assurance

Quality assurance can be done by:

- analysing trends in solar irradiance signal
- plotting the measured irradiance against mathematically generated expected values
- comparing irradiance measurements between sites
- analysis of night-time signals

The main idea is that one should look out for any unrealistic values. There are programs on the market that can semi-automatically perform data screening. See for more information on such a program <http://www.dqms.com>.

8 Appendices

8.1 Appendix on cable extension / replacement

The sensor cable of SR15-A1 is equipped with a M12-A straight connector. In case of cable replacement, it is recommended to purchase a new cable with connector at Hukseflux.

In case of cable extension, it is recommended to purchase an extension cable with connector pair at Hukseflux. Please note that Hukseflux does not provide support for Do-It-Yourself connector- and cable assembly.

SR15-A1 is equipped with one cable. Maximum length of the sensor cable is recommended to be 100 meter. It is good practice to keep the length of the instrument as short as possible to avoid inference of the signal and keep noise at acceptable levels.

Connector, cable and cable connection specifications are summarised on the next page.

Table 8.1.1 Preferred specifications for SR15-A cable replacement and extension

General replacement	please order a new cable with connector at Hukseflux
General cable extension	please order an extension cable with connector pair at Hukseflux
Connectors used	chassis: M12-A straight male connector, male thread, 5-pole manufacturer: Binder cable: M12-A straight female connector, female thread, 5-pole manufacturer: Binder the shield is electrically connected to the connector housing
Cable	5-wire, shielded manufacturer: Binder
Length	cables should be kept as short as possible, in any case the total cable length should be less than 100 m
Outer jacket	with specifications for outdoor use (for good stability in outdoor applications)

8.2 Appendix on tools for SR15-A1

Table 8.2.1 *Specifications of tools for SR15-A1*

tooling required for sun screen fixation and removal	by hand
tooling required for opening of the sensor bottom	T10 torx key
tooling required for mounting and levelling SR15 with the optional (tube) levelling mount	4 mm hex key and (alternatively) 10 mm spanner

8.3 Appendix on spare parts for SR15-A1

- levelling feet (set of 2)
- static foot
- sun screen for SR15. Specify SCR05.
- cable for SR15, with female M12-A connector at sensor end, stripped over 0.15 m and conductors with ferrules (5, 10 , 20 m). Specify cable length
- cable extension for SR15, 20 m length, with male and female M12-A connectors (order number C07E-20)
- levelling mount for SR15-A1, for spring-loaded levelling and mounting SR15-A1 on a surface (order number LM01)
- tube levelling mount for SR15, for spring-loaded levelling and mounting SR15-A1 on a tube (order number TLM01)
- lower clamp for tube mount
- pair of M5x30 bolts for tube mount
- pair of M5x45 bolts for tube mount

NOTE: Outer dome, bubble level, thermopile sensor and internal sensors of SR15-A1 cannot be supplied as spare parts. In case of damage to the SR15-A1, after repair the instrument must be tested to verify performance within specification limits. This is required by ISO 9060. Testing involves verification of the directional response after dome, thermal sensor and level replacement and verification of the temperature response after thermal sensor replacement.

8.4 Appendix on standards for classification and calibration

Both ISO and ASTM have standards on instrument classification and methods of calibration. The World Meteorological Organisation (WMO) has largely adopted the ISO classification system.

Table 8.4.1 *Pyranometer standardisation in ISO and ASTM.*

STANDARDS ON INSTRUMENT CLASSIFICATION AND CALIBRATION	
ISO STANDARD	EQUIVALENT ASTM STANDARD
ISO 9060:1990 Solar energy -- Specification and classification of instruments for measuring hemispherical solar and direct solar radiation	not available Comment: work is in progress on a new ASTM equivalent standard
Comment: a standard "Solar energy --Methods for testing pyranometer and pyrhelimeter characteristics" has been announced in ISO 9060 but is not yet implemented.	not available
ISO 9846:1993 Solar energy -- Calibration of a pyranometer using a pyrhelimeter	ASTM G167 - 05 Standard Test Method for Calibration of a Pyranometer Using a Pyrhelimeter
ISO 9847:1992 Solar energy -- Calibration of field pyranometers by comparison to a reference pyranometer	ASTM E 824 -10 Standard Test Method for Transfer of Calibration from Reference to Field Radiometers ASTM G207 - 11 Standard Test Method for Indoor Transfer of Calibration from Reference to Field Pyranometers
ISO 9059:1990 Solar energy -- Calibration of field pyrhelimeters by comparison to a reference pyrhelimeter	ASTM E 816 Standard Test Method for Calibration of Pyrhelimeters by Comparison to Reference Pyrhelimeters

8.5 Appendix on calibration hierarchy

The World Radiometric Reference (WRR) is the measurement standard representing the SI unit of irradiance. It was introduced in order to ensure world-wide homogeneity of solar radiation measurements and is in use since 1980. The WRR was determined from the weighted mean of the measurements of a group of 15 absolute cavity radiometers which were fully characterised. It has an estimated accuracy of 0.3 %. The WMO introduced its mandatory use in its status in 1979.

The world-wide homogeneity of the meteorological radiation measurements is guaranteed by the World Radiation Center in Davos Switzerland, by maintaining the World Standard Group (WSG) which materialises the World Radiometric Reference.

See <http://www.pmodwrc.ch>

The Hukseflux standard is traceable to an outdoor WRR calibration. Some small corrections are made to transfer this calibration to the Hukseflux standard conditions: sun at zenith and 1000 W/m² irradiance level. During the outdoor calibration the sun is typically at 20 to 40° zenith angle, and the total irradiance at a 700 W/m² level.

Table 8.5.1 Calibration hierarchy for pyranometers

WORKING STANDARD CALIBRATION AT PMOD / WRC DAVOS

Calibration of working standard pyranometers:

Method: ISO 9846, type 1 outdoor. This working standard has an uncertainty "uncertainty of standard". The working standard has been calibrated under certain "test conditions of the standard". The working standard has traceability to WRR world radiometric reference.

CORRECTION OF (WORKING) STANDARD CALIBRATION TO STANDARDISED REFERENCE CONDITIONS

Correction from "test conditions of the standard" to "reference conditions" i.e. to normal incidence and 20 °C:

Using known (working) standard pyranometer properties: directional, non linearity, offsets, temperature dependence). This correction has an uncertainty; "uncertainty of correction". At Hukseflux we also call the working standard pyranometer "standard".

INDOOR PRODUCT CALIBRATION

Calibration of products, i.e. pyranometers:

Method: according to ISO 9847, Type IIc, which is an indoor calibration.

This calibration has an uncertainty associated with the method.

(In some cases like the BSRN network the product calibration is with a different method; for example again type 1 outdoor)

CALIBRATION UNCERTAINTY CALCULATION

ISO 98-3 Guide to the Expression of Uncertainty in Measurement, GUM Determination of combined expanded uncertainty of calibration of the product, including uncertainty of the working standard, uncertainty of correction, uncertainty of the method (transfer error). The coverage factor must be determined; at Hukseflux we work with a coverage factor $k = 2$.

8.6 Appendix on meteorological radiation quantities

A pyranometer measures irradiance. The time integrated total is called radiant exposure. In solar energy radiant exposure is often given in $W \cdot h/m^2$.

Table 8.6.1 Meteorological radiation quantities as recommended by WMO (additional symbols by Hukseflux Thermal Sensor). POA stands for Plane of Array irradiance. The term originates from ASTM and IEC standards.

SYMBOL	DESCRIPTION	CALCULATION	UNITS	ALTERNATIVE EXPRESSION	
E_{\downarrow}	downward irradiance	$E_{\downarrow} = E_{g\downarrow} + E_{l\downarrow}$	W/m^2		
H_{\downarrow}	downward radiant exposure for a specified time interval	$H_{\downarrow} = H_{g\downarrow} + H_{l\downarrow}$	J/m^2		
E_{\uparrow}	upward irradiance	$E_{\uparrow} = E_{g\uparrow} + E_{l\uparrow}$	W/m^2		
H_{\uparrow}	upward radiant exposure for a specified time interval	$H_{\uparrow} = H_{g\uparrow} + H_{l\uparrow}$	J/m^2	$W \cdot h/m^2$	Change of units
E	direct solar irradiance normal to the apparent solar zenith angle		W/m^2	DNI	Direct Normal Irradiance
E_0	solar constant		W/m^2		
$E_{g\downarrow h}$	global irradiance; hemispherical irradiance on a specified, in this case horizontal surface.*	$E_{g\downarrow} = E \cos \theta_h + E_{d\downarrow}$	W/m^2	GHI	Global Horizontal Irradiance
$E_{g\downarrow t}$	global irradiance; hemispherical irradiance on a specified, in this case tilted surface.*	$E_{g\downarrow} = E \cdot \cos \theta_t + E_{d\downarrow t} + E_{r\uparrow t}$ ***	W/m^2	POA	Plane of Array
$E_{d\downarrow}$	downward diffuse solar radiation		W/m^2	DHI	Diffuse Horizontal Irradiance
$E_{l\uparrow}, E_{l\downarrow}$	upward / downward long-wave irradiance		W/m^2		
$E_{r\uparrow}$	reflected solar irradiance		W/m^2		
E^*	net irradiance	$E^* = E_{\downarrow} - E_{\uparrow}$	W/m^2		
T_{\downarrow}	apparent surface temperature**		$^{\circ}C$ or K		
T_{\uparrow}	apparent sky temperature**		$^{\circ}C$ or K		
SD	sunshine duration		h		

θ is the apparent solar zenith angle θ_h relative to horizontal, θ_t relative to a tilted surface
 g = global, l = long wave, t = tilted *, h = horizontal*

* distinction horizontal and tilted from Hukseflux,

** T symbols introduced by Hukseflux,

*** contributions of $E_{d\downarrow t}$ and $E_{r\uparrow t}$ are $E_{d\downarrow}$ and $E_{r\uparrow}$ both corrected for the tilt angle of the surface

8.7 Appendix on ISO and WMO classification tables

Table 8.7.1 Classification table for pyranometers per ISO 9060 and WMO.

NOTE: WMO specification of spectral selectivity is different from that of ISO. Hukseflux conforms to the ISO limits. WMO also specifies expected accuracies. ISO finds this not to be a part of the classification system because it also involves calibration. Please note that WMO achievable accuracies are for clear days at mid latitudes and that the uncertainty estimate does not include uncertainty due to calibration*.

ISO CLASSIFICATION** TABLE			
ISO CLASS	SECONDARY STANDARD	FIRST CLASS	SECOND CLASS
Specification limit			
Response time (95 %)	15 s	30 s	60 s
Zero offset a (response to 200 W/m ² net thermal radiation)	+ 7 W/m ²	+ 15 W/m ²	+ 30 W/m ²
Zero offset b (response to 5 K/h in ambient temperature)	± 2 W/m ²	± 4 W/m ²	± 8 W/m ²
Non-stability (change per year)	± 0.8 %	± 1.5 %	± 3 %
Non-linearity (100 to 1000 W/m ²)	± 0.5 %	± 1 %	± 3 %
Directional response	± 10 W/m ²	± 20 W/m ²	± 30 W/m ²
Spectral selectivity (350 to 1500 x 10 ⁻⁹ m)	± 3 %	± 5 %	± 10 %
Temperature response (interval of 50 K)*	2 %	4 %	8 %
Tilt response (0 to 90 ° at 1000 W/m ²)	± 0.5 %	± 2 %	± 5 %
ADDITIONAL WMO SPECIFICATIONS			
WMO CLASS	HIGH QUALITY	GOOD QUALITY	MODERATE QUALITY
WMO: achievable accuracy for daily sums*	2 %	5 %	10 %
WMO: achievable accuracy for hourly sums*	3 %	8 %	20 %
WMO: achievable accuracy for minute sums*	not specified	not specified	not specified
WMO: resolution (smallest detectable change)	1 W/m ²	5 W/m ²	10 W/m ²
WMO: spectral selectivity (300 to 3000 x 10 ⁻⁹ m)	± 2 %	± 5 %	± 10 %
CONFORMITY TESTING***			
ISO 9060	individual instrument only: all specs must comply	group compliance	group compliance

* WMO 7.2.1: The estimated uncertainties are based on the following assumptions: (a) instruments are well-maintained, correctly aligned and clean; (b) 1 min and 1 h figures are for clear-sky irradiances at solar noon; (c) daily exposure values are for clear days at mid-latitudes. WMO 7.3.2.5: Table 7.5 lists the expected maximum deviation from the true value, excluding calibration errors.

** At Hukseflux the expression ± 1 % is used instead of a range of 2 %.

*** an instrument is subject to conformity testing of its specifications. Depending on the classification, conformity compliance can be proven either by group- or individual compliance. A specification is fulfilled if the mean value of the respective test result does not exceed the corresponding limiting value of the specification for the specific category of instrument.

8.8 Appendix on definition of pyranometer specifications

Table 8.8.1 *Definition of pyranometer specifications*

SPECIFICATION	DEFINITION	SOURCE
Response time (95 %)	time for 95 % response. The time interval between the instant when a stimulus is subjected to a specified abrupt change and the instant when the response reaches and remains within specified limits around its final steady value. The response time is a measure of the thermal inertia inherent in the stabilization period for a final reading.	ISO 9060-1990 WMO 1.6.3
Zero offset a: (200 W/m ² net thermal radiation)	response to 200 W/m ² net thermal radiation (ventilated). Hukseflux assumes that unventilated instruments have to specify the zero-offset in unventilated – worst case – conditions. Zero offsets are a measure of the stability of the zero-point. Zero offset a is visible at night as a negative offset, the instrument dome irradiates in the far infra red to the relatively cold sky. This causes the dome to cool down. The pyranometer sensor irradiates to the relatively cool dome, causing a negative offset. Zero offset a is also assumed to be present during daytime.	ISO 9060-1990
Zero offset b: (5 K/h in ambient temperature)	response to 5 K/h change in ambient temperature. Zero offsets are a measure of the stability of the zero-point.	ISO 9060-1990
Non-stability (change per year)	percentage change in sensitivity per year. The dependence of sensitivity resulting from ageing effects which is a measure of the long-term stability.	ISO 9060-1990
Non-linearity (100 to 1000 W/m ²)	percentage deviation from the sensitivity at 500 W/m ² due to the change in irradiance within the range of 100 W/m ² to 1000 W/m ² . Non-linearity has an overlap with directional response, and therefore should be handled with care in uncertainty evaluation.	ISO 9060-1990
Directional response	the range of errors caused by assuming that the normal incidence sensitivity is valid for all directions when measuring from any direction a beam radiation whose normal incidence irradiance is 1000 W/m ² . Directional response is a measure of the deviations from the ideal “cosine behaviour” and its azimuthal variation.	ISO 9060-1990
Spectral selectivity (350 to 1500 x 10 ⁻⁹ m) (WMO 300 to 3000 x 10 ⁻⁹ m)	percentage deviation of the product of spectral absorptance and spectral transmittance from the corresponding mean within 350 x 10 ⁻⁹ m to 1500 x 10 ⁻⁹ m. Spectral selectivity is a measure of the spectral selectivity of the sensitivity.	ISO 9060-1990
Temperature response (interval of 50 K)	percentage deviation of the sensitivity due to change in ambient temperature within an interval of 50 K the temperature of the pyranometer body.	ISO 9060-1990
Tilt response (0° to 90° at 1000 W/m ²)	percentage deviation from the sensitivity at 0° tilt (horizontal) due to change in tilt from 0° to 90° at 1000 W/m ² irradiance. Tilt response describes changes of the sensitivity due to changes of the tilt angle of the receiving surface.	ISO 9060-1990
Sensitivity	the change in the response of a measuring instrument divided by the corresponding change in the stimulus.	WMO 1.6.3
Spectral range	the spectral range of radiation to which the instrument is sensitive. For a normal pyranometer this should be in the 0.3 to 3 x 10 ⁻⁶ m range. Some pyranometers with coloured glass domes have a limited spectral range.	Hukseflux

8.9 Appendix on terminology / glossary

Table 8.9.1 *Definitions and references of used terms*

TERM	DEFINITION (REFERENCE)
Solar energy or solar radiation	solar energy is the electromagnetic energy emitted by the sun. Solar energy is also called solar radiation and shortwave radiation. The solar radiation incident on the top of the terrestrial atmosphere is called extra-terrestrial solar radiation; 97 % of which is confined to the spectral range of 290 to $3\,000 \times 10^{-9}$ m. Part of the extra-terrestrial solar radiation penetrates the atmosphere and directly reaches the earth's surface, while part of it is scattered and / or absorbed by the gas molecules, aerosol particles, cloud droplets and cloud crystals in the atmosphere. The former is the direct component, the latter is the diffuse component of the solar radiation. (ref: WMO, Hukseflux)
Hemispherical solar radiation	solar radiation received by a plane surface from a 180° field of view angle (solid angle of 2π sr). (ref: ISO 9060)
Global solar radiation	the solar radiation received from a 180° field of view angle on a horizontal surface is referred to as global radiation. Also called GHI. This includes radiation received directly from the solid angle of the sun's disc, as well as diffuse sky radiation that has been scattered in traversing the atmosphere. (ref: WMO) Hemispherical solar radiation received by a horizontal plane surface. (ref: ISO 9060)
Plane-of-array irradiance	also POA: hemispherical solar irradiance in the plane of a PV array. (ref: ASTM E2848-11 / IEC 61724)
Direct solar radiation	radiation received from a small solid angle centred on the sun's disc, on a given plane. (ref: ISO 9060)
Terrestrial or Longwave radiation	radiation not of solar origin but of terrestrial and atmospheric origin and having longer wavelengths ($3\,000$ to $100\,000 \times 10^{-9}$ m). In case of downwelling $E_i \downarrow$ also the background radiation from the universe is involved, passing through the "atmospheric window". In case of upwelling $E_i \uparrow$, composed of long-wave electromagnetic energy emitted by the earth's surface and by the gases, aerosols and clouds of the atmosphere; it is also partly absorbed within the atmosphere. For a temperature of 300 K, 99.99 % of the power of the terrestrial radiation has a wavelength longer than $3\,000 \times 10^{-9}$ m and about 99 per cent longer than $5\,000 \times 10^{-9}$ m. For lower temperatures, the spectrum shifts to longer wavelengths. (ref: WMO)
World Radiometric Reference (WRR)	measurement standard representing the SI unit of irradiance with an uncertainty of less than ± 0.3 % (see the WMO Guide to Meteorological Instruments and Methods of Observation, 1983, subclause 9.1.3). The reference was adopted by the World Meteorological Organization (WMO) and has been in effect since 1 July 1980. (ref: ISO 9060)
Albedo	ratio of reflected and incoming solar radiation. Dimensionless number that varies between 0 and 1. Typical albedo values are: < 0.1 for water, from 0.1 for wet soils to 0.5 for dry sand, from 0.1 to 0.4 for vegetation, up to 0.9 for fresh snow.
Angle of incidence	angle of radiation relative to the sensor measured from normal incidence (varies from 0° to 90°).
Zenith angle	angle of incidence of radiation, relative to zenith. Equals angle of incidence for horizontally mounted instruments
Azimuth angle	angle of incidence of radiation, projected in the plane of the sensor surface. Varies from 0° to 360° . 0 is by definition the cable exit direction, also called north, east is $+90^\circ$. (ASTM G113-09)
Sunshine duration	sunshine duration during a given period is defined as the sum of that sub-period for which the direct solar irradiance exceeds 120 W/m^2 . (ref: WMO)

8.10 EU declaration of conformity



We, Hukseflux Thermal Sensors B.V.
Delftechpark 31
2628 XJ Delft
The Netherlands

in accordance with the requirements of the following directives:

2011/65/EU The Restriction of Hazardous Substances Directive
2014/30/EU The Electromagnetic Compatibility Directive

hereby declare under our sole responsibility that:

Product model: SR15-A1
Product type: Pyranometer

has been designed to comply and is in conformity with the relevant sections and applicable requirements of the following standards:

Emission: EN 61326-1 (2006)
Immunity: EN 61326-1 (2006)
Emission: EN 61000-3-2 (2006)
Emission: EN 61000-3-3 (1995) + A1 (2001) + A2 (2005).
Report: 08C01340RPT01, 06 January 2009

A handwritten signature in blue ink, appearing to be 'Eric Hoeksema', written over a light blue grid background.

Eric HOEKSEMA
Director
Delft
26 April, 2018

