Hukseflux
Thermal Sensors

USER MANUAL **SR22**

Secondary standard pyranometer
with quartz domes – extended spectral range

Hukseflux
Thermal Sensors

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.

Contents

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
Solar irradiance	E	W/m^2
Solar radiant exposure	H	$W \cdot h/m^2$
Time in hours	h	h
Temperature coefficient	a	$1/°C^2$
Temperature coefficient	b	$1/°C$
Temperature coefficient	c	-
Resistance of Pt100	R_{Pt100}	Ω
Pt100 coefficient	A	
Pt100 coefficient	B	
Resistance of 10 kΩ thermistor	$R_{thermistor}$	Ω
Steinhart-Hart coefficient	α	
Steinhart-Hart coefficient	β	
Steinhart-Hart coefficient	γ	

(see also appendix 8.6 on meteorological quantities)

Introduction

SR22 is a solar radiation sensor of the highest category in the ISO 9060 classification system: secondary standard. On top of the features and benefits of the successful SR20 pyranometer, SR22 has domes made of high-quality quartz, resulting in an extended spectral range. Covering the full solar spectrum, SR22's extended spectral range potentially offers lower measurement- and calibration uncertainties compared to pyranometers with glass domes. SR22 is typically used in high-accuracy climatological networks.

It measures the solar radiation received by a plane surface, in W/m^2, from a $180°$ field of view angle. This ISO 9060 secondary standard pyranometer enables users to attain the highest measurement accuracy and offers the widest spectral range commercially available. SR22 has an onboard temperature sensor. When using SR22, additional ventilation is recommended. SR22 is typically combined with ventilation unit VU01.

SR22 has an inner and outer dome made of high-quality quartz. This results in SR22's spectral range of 190 to 4000×10^{-9} m. SR22 covers the full solar spectrum, including the part between 3000 to 4000×10^{-9} m, which is not measured by pyranometers with glass domes.

Using SR22 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 SR22 output, a small voltage U, by the sensitivity S. The sensitivity is provided with SR22 on its calibration certificate.

The central equation governing SR22 is: $E = U/S$ (Formula 0.1)

SR22's low temperature dependence makes it an ideal candidate for use under very cold and very hot conditions. The temperature dependence of every individual instrument is tested and supplied as a second degree polynomial. This information can be used for further reduction of temperature dependence during post-processing. In case the sensitivity is corrected for the instrument body temperature, the optional measurement equation becomes:

$E = U/(S_0 \cdot (a \cdot T^2 + b \cdot T + c))$ (Formula 0.2)

The temperature coefficients a, b, and c can be found on the calibration certificate of each instrument.

SR22 is equipped with an internal temperature sensor. This can be either a Pt100 (T1 version) or a 10 kΩ thermistor (T2 version), as ordered. To calculate temperature in degrees Celsius from resistance in Ohms, Formula 8.10.1 or 8.10.2 can be used. See the dedicated chapter in the appendix of this manual for these equations.

SR22 pyranometer uses a state of the art thermopile sensor with black coated surface, two quartz domes of the highest quality and an anodised aluminium body. The

connector, desiccant holder and sun screen fixation are very robust and designed for industrial use. All parts are specified for use across SR22's entire rated operating temperature range.

In order to improve overall measurement accuracy, Hukseflux effectively targeted two major sources of measurement uncertainty: calibration and "zero offset a".
The initial calibration uncertainty is less than 1.7 %. The "zero offset a" specification of SR22 is 5 W/m^2 unventilated. Ventilated (with VU01) it is just 2.5 W/m^2.

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

Suggested use for SR22:

- scientific climatological observations
- reference instrument for comparison
- extreme climates (tropical / polar)

Figure 0.1 *SR22 secondary standard pyranometer*

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. SR22 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 SR22 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.

1 Ordering and checking at delivery

1.1 Ordering SR22

The standard configuration of SR22 is with 5 metres cable.

Common options are:

- Longer cable (in multiples of 5 m). Specify total cable length.
- Internal temperature sensor. This can be either a Pt100 or a 10 kΩ thermistor. Specify respectively T1 or T2.
- Five silica gel bags in an air-thight bag for SR22 desiccant holder. Specify order number DC01.
- VU01 ventilation unit.

1.2 Included items

Arriving at the customer, the delivery should include:

- pyranometer SR22
- sun screen
- cable of the length as ordered
- calibration certificate matching the instrument serial number
- product certificate matching the instrument serial number (including temperature response and directional response test)
- any other options as ordered

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 green (-) 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 100 to 200 Ω plus 1.5 Ω for the total resistance of two wires (back and forth) of each 5 m. 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 100×10^{-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 $> 2 \times 10^{-3}$ 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.

5. Inspect if the humidity indicator is blue. Blue indicates dryness. The colour pink indicates it is humid: in the latter case replace the desiccant (see chapter on maintenance).

2 Instrument principle and theory
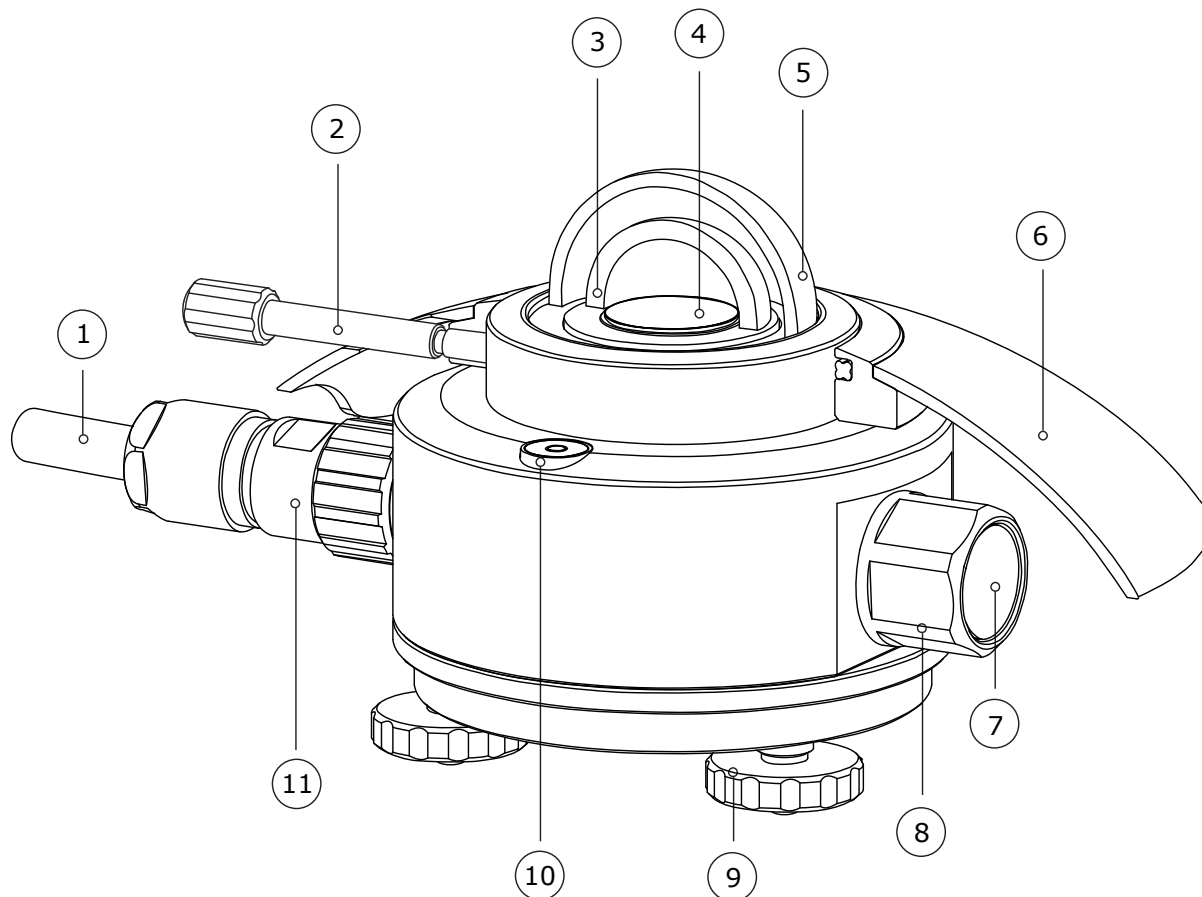

Figure 2.1 *Overview of SR22:*

(1)   cable (standard length 5 metres, optional longer cable)
(2)   fixation of sun screen (thumb screw)
(3)   inner quartz dome
(4)   thermal sensor with black coating
(5)   outer quartz dome
(6)   sun screen
(7)   humidity indicator
(8)   desiccant holder
(9)   levelling feet
(10)   bubble level
(11)   connector

SR22'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.

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.

SR22 is responsive to the total solar spectrum (190 to 4000 x 10^{-9} m). According to the ISO 9060 specification, a pyranometer should cover the spectral range from 350 to 1500 x 10^{-9} m with a spectral selectivity that is as "flat" as possible.

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 190 to 50000 x 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 quartz dome. This dome limits the spectral range from 190 to 4000 x 10^{-9} m (cutting off the part above 4000 x 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) quartz dome: For a secondary standard 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.

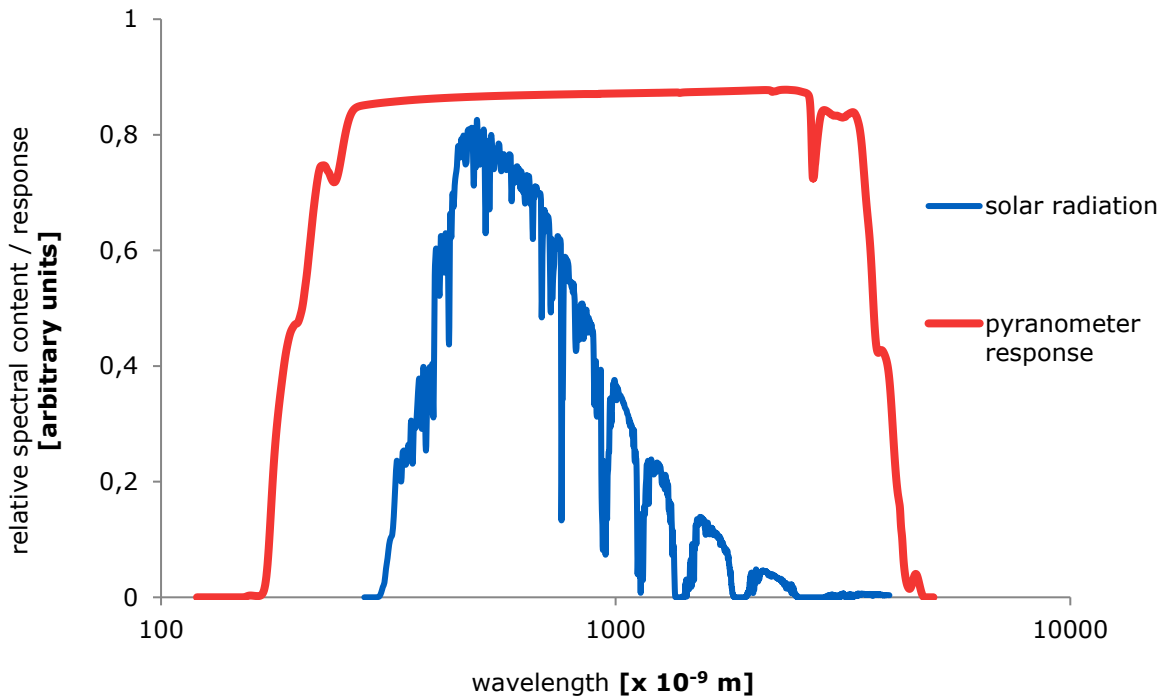**Figure 2.2** *Spectral response of the pyranometer compared to the solar spectrum. SR22 is responsive to the total solar spectrum.*
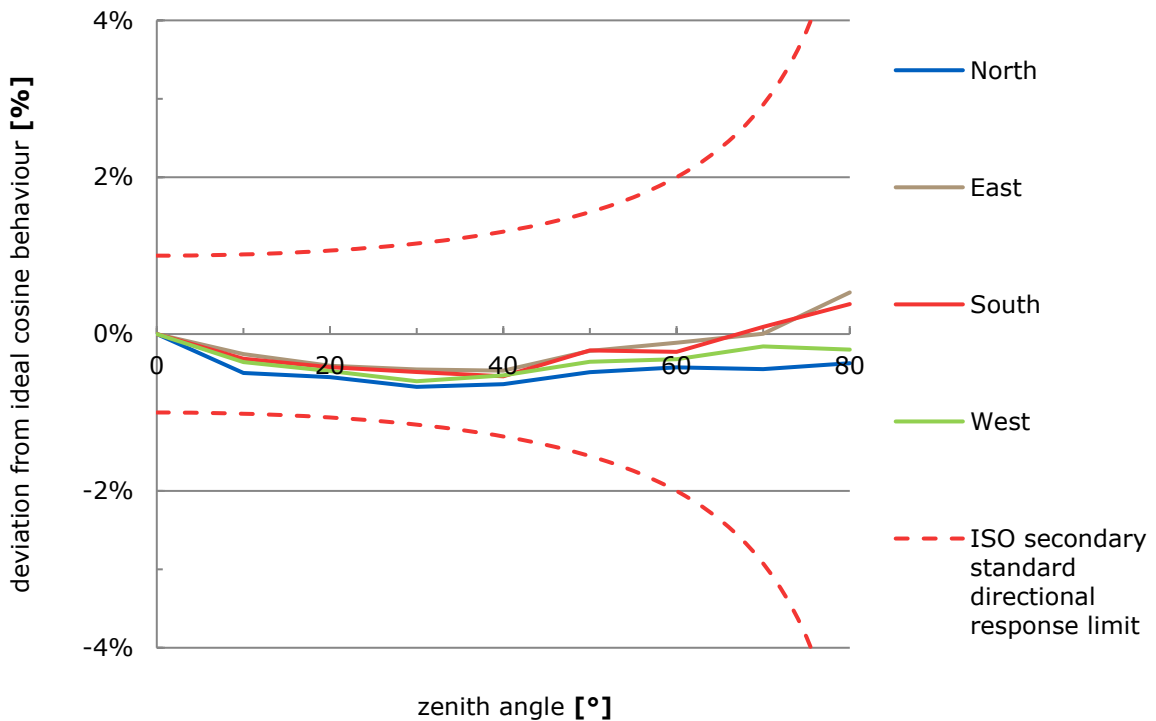

Figure 2.3 *Directional response of a SR22 pyranometer of 4 azimuth angles, compared to secondary standard limits.*

3 Specifications of SR22

3.1 Specifications of SR22

SR22 is a pyranometer of the highest category in the ISO 9060 classification system: secondary 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, SR22 generates a small output voltage proportional to this flux. It can only be used in combination with a suitable measurement system.

SR22 has an onboard heater and a temperature sensor. Heating the sensor, measuring the body temperature and using the correction of the temperature response, all contribute to the dependability and accuracy of the measurement. However, also when not using these features, SR22 still complies with the secondary standard requirements. The instrument should be used in accordance with the recommended practices of ISO, IEC, WMO and ASTM.

Table 3.1.1 *Specifications of SR22 (continued on next pages)*

SR22 MEASUREMENT SPECIFICATIONS: LIST OF CLASSIFICATION CRITERIA OF ISO 9060*	
ISO classification (ISO 9060: 1990)	secondary standard pyranometer
WMO performance level (WMO-No. 8, seventh edition 2008)	high quality pyranometer
Response time (95 %)	3 s
Zero offset a (response to 200 W/m^2 net thermal radiation)	5 W/m^2 unventilated 2.5 W/m^2 ventilated
Zero offset b (response to 5 K/h change in ambient temperature)	< ± 2 W/m^2
Non-stability	< ± 0.5 % change per year
Non-linearity	< ± 0.2 % (100 to 1000 W/m^2)
Directional response	< ± 10 W/m^2
Directional response test of individual instrument	report included
Spectral selectivity	< ± 2 % (0.35 to 1.5 x 10^{-6} m)
Temperature response	< ± 1 % (-10 to +40 °C) < ± 0.4 % (-30 to +50 °C) with correction in data-processing
Temperature response of individual instrument	report included
Tilt response	< ± 0.2 % (0 to 90 ° at 1000 W/m^2)

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

Table 3.1.1 *Specifications of SR22 (continued)*

SR22 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 4000 W/m^2
Sensitivity range	7 to 25 x 10^{-6} $V/(W/m^2)$
Sensitivity (nominal)	12 x 10^{-6} $V/(W/m^2)$
Expected voltage output	application under natural solar radiation: -0.1 to + 50 x 10^{-3} V
Measurement function / required programming	E = U/S
Optional measurement function / required programming for correction of sensitivity as a function of instrument body temperature	$E = U/(S_0 \cdot (a \cdot T^2 + b \cdot T + c))$
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
Internal temperature sensor	measuring the body temperature: version code = T1 for Pt100 DIN class A, version code = T2 for thermistor 10 kΩ at 25 °C
Optional readout	1 temperature channel in case the temperature sensor is used
Rated operating temperature range	-40 to +80 ˚C
Sensor resistance range	100 to 200 Ω
Required sensor power	zero (passive sensor)
Spectral range (20 % transmission points)	190 to 4000 x 10^{-9} m
Standard 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
Standard cable length (see options)	5 m
Cable diameter	5.3 x 10^{-3} m
Chassis connector	M16 panel connector, male thread, 10-pole
Chassis connector type	HUMMEL AG 7.840.200.000 panel connector, front mounting, short version
Cable connector	M16 straight connector, female thread, 10-pole
Cable connector type	HUMMEL AG 7.810.300.00M straight connector, female thread, for cable 3 to 6 x 10^{-3} m, special version
Connector protection class	IP 67 / IP 69 K per EN 60 529 (connected)
Cable replacement	replacement cables with connector can be ordered separately from Hukseflux
Mounting	2 x M5 bolt at 65 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, 0.5 g, 35 x 20 mm
Humidity indicator	blue when dry, pink when humid
IP protection class	IP 67

Table 3.1.1 *Specifications of SR22 (started on previous pages)*

|	
Gross weight	approx. 2 kg
Net weight	approx. 1 kg
Packaging	HPRC casing
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 -5 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	< 1.7 % (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)	2 %
WMO estimate on achievable accuracy for hourly sums (see appendix for a definition of the measurement conditions)	3 %
VERSIONS / OPTIONS	
Internal temperature sensor	measuring the body temperature: version code = T1 for Pt100 DIN class A, version code = T2 for thermistor 10 kΩ at 25 °C
Longer cable, in multiples of 5 m	option code = total cable length
ACCESSORIES	
Ventilation unit	VU01
Hand-held read-out unit	LI19
Bags of silica gel for desiccant	set of 5 bags in an air tight bag option code = DC01

3.2   Dimensions of SR22
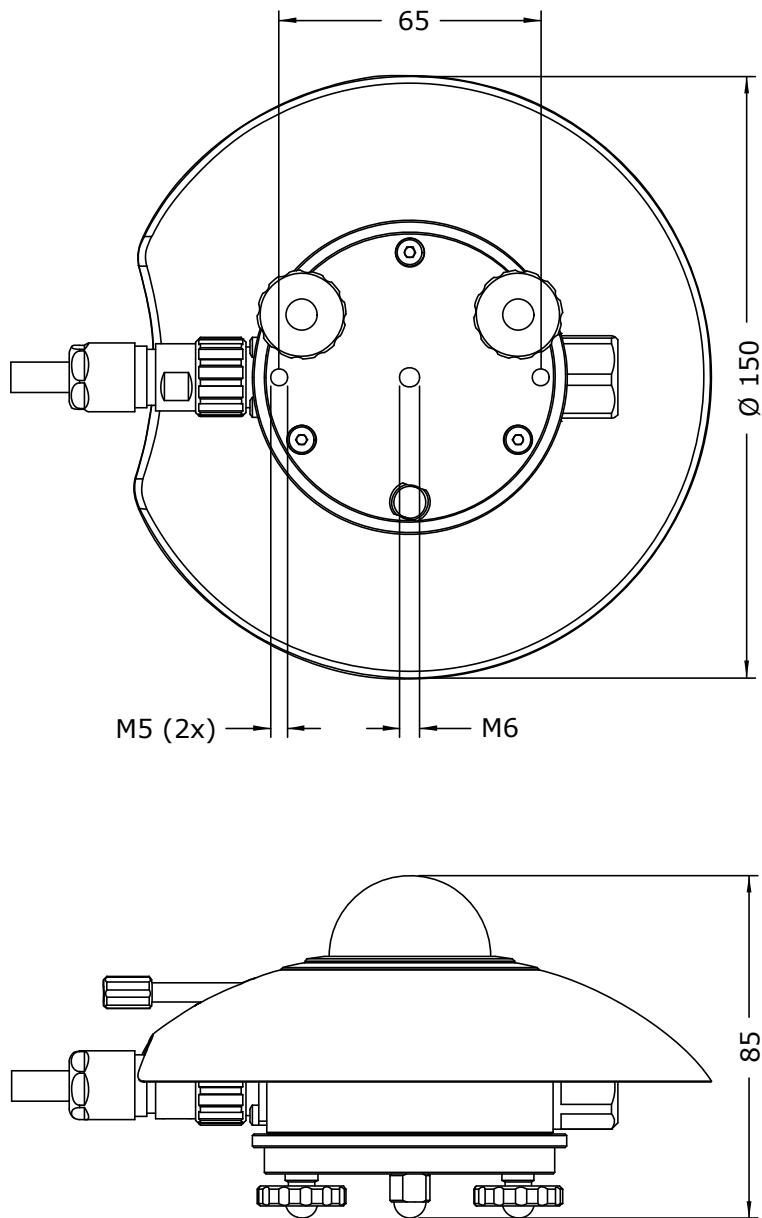
Figure 3.2.1 *Dimensions of SR22 in x 10⁻³ m.*

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, Pyrheliometers 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/m^2.

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

SR22 is very well applicable in outdoor PV system performance testing. See also Hukseflux model SR20-D2 "Digital secondary standard pyranometer with Modbus RTU and 4-20 mA output" and SR20 "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	ASTM 2848-11; Standard Test Method for Reporting Photovoltaic Non-Concentrator System Performance
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: confirms that a pyranometer is the preferred instrument for outdoor PV testing. Specifically recommends a "first class" pyranometer (paragraph A 1.2.1.)
COMMENT: equals JISC 8906 (Japanese Industrial Standards Committee)	

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 SR22

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 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	2 x M5 bolt at 65×10^{-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	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 only use the bubble level and levelling feet. For inspection of the bubble level the sun screen must be removed.
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

SR22's sun screen can be installed and removed by using the dedicated thumb screw. See item 2 of the drawing below. The thumb screw can be turned without tools for fixation or loosening of the sun screen, as visualised below. Once the thumb screw has turned the sun screen loose, the screen can be lifted off manually. After removal the user may inspect the bubble level, item 10 of the drawing, and remove the cable / connector, item 11.
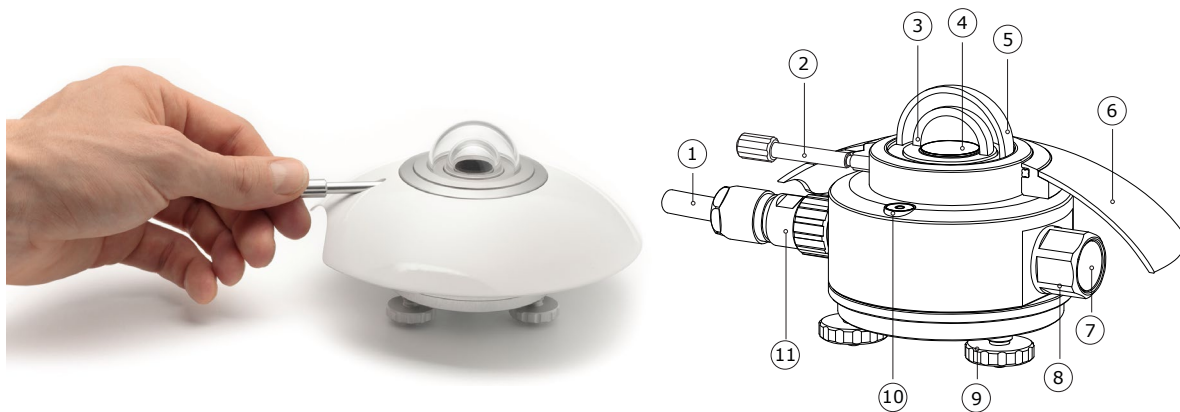

Figure 5.2.1 *Installation and removal of SR22's sun screen*

5.3 Electrical connection

In order to operate, a pyranometer should be connected to a measurement system, typically a so-called datalogger. SR22 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 5.3.1 *The electrical connection of SR22 versions T1 and T2. The heater is not necessarily used. The temperature sensor is not necessarily used.*

PIN	WIRE	SR22-T1	SR22-T2
2	Red	Pt100 [+]	10 kΩ thermistor [+]
3	Pink	Pt100 [+]	10 kΩ thermistor [+]
6	Blue	Pt100 [−]	10 kΩ thermistor [−]
8	Grey	Pt100 [−]	10 kΩ thermistor [−]
1	Brown	heater	heater
4	Yellow	heater	heater
9	Black	ground	ground
7	White	signal [+]	signal [+]
5	Green	signal [−]	signal [−]

Note 1: Pt100's of version T1 may be connected in a 3-wire of 4-wire configuration.
Note 2: 10k thermistors of version T2 are usually connected in a 2-wire configuration.
Note 3: the heater is not necessarily connected. In case it is connected, the polarity of the connection is not important.
Note 4: signal wires are insulated from ground wire and from the sensor body. Insulation resistance is tested during production and larger than 1×10^6 Ω.
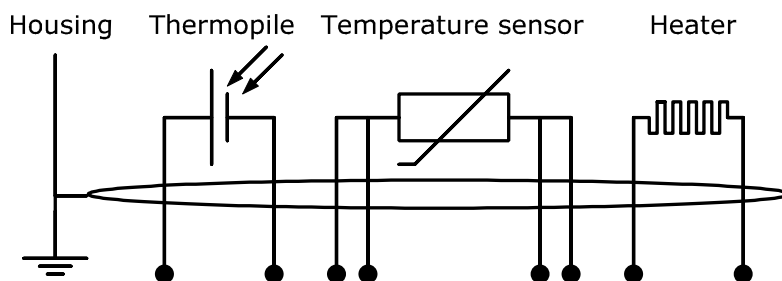Note 5: ground is connected to the connector, the sensor body and the shield of the wire.

Figure 5.3.1 *Electrical diagram of the internal wiring of SR22. The shield is connected to the sensor body.*

5.4 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 SR22 are available.
In case programming for similar instruments is available, this can typically also be used. SR22 can usually be treated in the same way as other thermopile pyranometers. Pyranometers usually have the same programming as heat flux sensors.

Table 5.4.1 *Requirements for data acquisition and amplification equipment for SR22 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	$> 1 \times 10^{6}$ Ω
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 resulting in a slow 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. For non-serviceable sensors like most second class pyranometers, this may slowly develop into a defect. For first class and secondary standard models (for instance model SR11 first class pyranometer and SR22 secondary standard pyranometer) extra desiccant (in a set of 5 bags in an air tight bag) is available.

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 Speed of 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:

- replacement of desiccant
- replacement of cabling

For optimisation of dependability a user should:

- estimate the expected lifetime of the instrument
- 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. The work on uncertainty evaluation is "in progress". There are several groups around the world participating in standardisation of the method of calculation. 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 pyrheliometers 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 pyrheliometers: 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 pyrheliometers 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 (SR22)	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	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 1.7 %, compared to typical uncertainties of higher than 1.7 % 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

SR22 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 SR22. 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.
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 in case this is out of specification, inspect mounting connection, inspect interior of dome for condensation
4		desiccant replacement	desiccant replacement (if applicable). Change in case the blue colour of the 40 % humidity indicator turns pink (indicating humidity), then replace desiccant. Coat the rubber of the cartridge with silicone grease or vaseline. Desiccant regeneration: heating in an oven at 70 °C for 1 to 2 hours. Humidity indicator regeneration: heating until blue at 70 °C
5	2 years	recalibration	recalibration by side-by-side comparison to a higher standard instrument in the field according to ISO 9847
6		lifetime assessment	judge if the instrument should be reliable for another 2 years, or if it should be replaced
7	6 years	parts replacement	if applicable / necessary replace the parts that are most exposed to weathering; cable, connector, desiccant holder, sun screen. NOTE: use Hukseflux approved parts only.
8		internal inspection	if applicable: open instrument and inspect / replace O-rings; dry internal cavity around the circuit board
9		recalibration	recalibration by side-by-side comparison to a higher standard instrument indoors according to ISO 9847 or outdoors according to ISO9846

7.2 Trouble shooting

Table 7.2.1 *Trouble shooting for SR22*

The sensor does not give any signal	Check the electrical resistance of the sensor between the green (-) 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 100 to 200 Ω plus 1.5 Ω for the total resistance of two wires (back and forth) of each 5 m. Infinite resistance indicates a broken circuit; zero or a low resistance indicates a short circuit. Check if the sensor reacts to light: put the multimeter at its most sensitive range of DC voltage measurement, typically the 100×10^{-3} VDC range or lower. Expose the sensor to strong light source, for instance a 100 W light bulb at 1×10^{-1} m distance. The signal should read $> 2 \times 10^{-3}$ 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 1×10^{-6} V source to it in the 1×10^{-6} V range. Check the condition of the connectors (on chassis as well as the cable).
The sensor signal is unrealistically high or low.	Note that night-time signals may be negative (down to -5 W/m^2 on clear windless nights), due to zero offset a. Check if the pyranometer has clean domes. Check the location of the pyranometer; are there any obstructions that could explain the measurement result. Check the orientation / levelling of the pyranometer. 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. 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. 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 1×10^{-6} V source to it in the 1×10^{-6} V range. Look at the output. Check if the output is as expected. 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/m^2.
The sensor signal shows unexpected variations	Check the presence of strong sources of electromagnetic radiation (radar, radio) Check the condition of the shielding. Check the condition of the sensor cable. Check if the cable is not moving during the measurement Check the condition of the connectors (on chassis as well as the cable)
The outer dome shows internal condensation.	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. In case of condensation of droplets: disassemble the instrument and dry out the parts.
The inner dome shows internal condensation	Arrange to send the sensor back to Hukseflux for diagnosis.

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 ± 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 ± 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 ± 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 SR22 is equipped with a M16 straight connector. In case of cable replacement, it is recommended to purchase a new cable with connector at Hukseflux. An alternative is to choose for a Do-it-yourself (DIY) approach; please ask for the DIY connector assembly guide. In case of cable extension, the user may choose purchasing a new cable with connector at Hukseflux or extending the existing cable himself. Please note that Hukseflux does not provide support for DIY connector- and cable assembly. SR22 is equipped with one cable. Keep the distance between data logger or amplifier and sensor as short as possible. Cables act as a source of distortion by picking up capacitive noise. In an electrically "quiet" environment the SR22 cable can be extended without problem to 100 metres. If done properly, the sensor signal, although small, will not significantly degrade because the sensor resistance is very low (so good immunity to external sources) and because there is no current flowing (so no resistive losses). Connector, cable and cable connection specifications are summarised below.

Table 8.1.1 *Preferred specifications for SR22 cable replacement and extension*

General replacement	please order a new cable with connector at Hukseflux or choose for a DIY approach. In case of DIY replacement by the user see connector specifications below and ask for the DIY connector assembly guide
General cable extension	please order a new cable with connector at Hukseflux or solder the new cable conductors and shield to the original sensor cable and make a connection, using adhesive-lined heat shrink tubing, with specifications for outdoor use. Always connect shield
Connectors used	chassis: M16 panel connector, male thread, 10-pole, HUMMEL AG 7.840.200.000 panel connector, front mounting, short version. cable: M16 straight connector, female thread, 10-pole. HUMMEL AG 7.810.300.00M straight connector, female thread, for cable 3 to 6 x 10^{-3} m, special version
Cable	8-wire, shielded, with copper conductors (at Hukseflux 8-wire shielded cable is used, of which 2 wires are used for signal transmission, 2 for heating and 2 to 4 for the temperature sensor)
Conductor resistance	< 0.1 Ω/m
Length	cables should be kept as short as possible, in any case the total cable length should be less than 100 m
Outer sheath	with specifications for outdoor use (for good stability in outdoor applications)

8.2 Appendix on tools for SR22

Table 8.2.1 *Specifications of tools for SR22*

tooling required for sun screen fixation and removal	by hand
tooling required for bottom plate fixation and removal	hex key 2.5 mm
tooling required for desiccant holder fixation and removal	spanner size 20 mm
tooling required for wire fixation and removal (internal wiring inside SR22 body)	screwdriver blade width 2 mm

8.3 Appendix on spare parts for SR22

- Desiccant holder (with glass window and rubber ring)
- Desiccant (set of 5 bags in air tight bag)
- Humidity indicator
- Levelling feet (set of 2)
- Static foot
- Sun screen with metal ring and thumb screw
- SR22 cable with connector (specify length in multiples of 5 m)
- O-ring SR22

NOTE: Outer dome, level and sensor of SR22 cannot be supplied as spare parts. In case of possible damage to the SR22, 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 pyrheliometer 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 pyrheliometer	ASTM G167 - 05 Standard Test Method for Calibration of a Pyranometer Using a Pyrheliometer
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 pyrheliometers by comparison to a reference pyrheliometer	ASTM E 816 Standard Test Method for Calibration of Pyrheliometers by Comparison to Reference Pyrheliometers

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/m^2 irradiance level. During the outdoor calibration the sun is typically at 20 to 40° zenith angle, and the total irradiance at a 700 W/m^2 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**		ºC or K		
$T{\uparrow}$	apparent sky temperature**		ºC 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 1 500 x 10^{-9} m) (WMO 300 to 3 000 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

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 and the spectral distribution of irradiance. 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 with glass dome(s) 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 x 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 2 π 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 x 10^{-9} m). In case of downwelling $E_l \downarrow$ also the background radiation from the universe is involved, passing through the "atmospheric window". In case of upwelling $E_l \uparrow$, 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 x 10^{-9} m and about 99 per cent longer than 5 000 x 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°. (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/m². (ref: WMO)

8.10 Appendix on converting resistance to temperature

SR22 is equipped with an internal temperature sensor. This can be either a Pt100 (SR22-T1 version) or a 10 kΩ thermistor (SR22-T2 version), as ordered.

Both versions require the user to measure the resistance of the temperature sensor and convert this value to temperature. Many dataloggers have built-in functions to perform such a conversion. In case the user wishes to calculate temperature (in degrees Celsius) from resistance (in Ohms) himself, there are two distinct procedures:

SR22-T1

T1 versions are equipped with a Pt100 platinum resistance thermometer. It is classified as class A according to DIN EN 60751. It has a resistance of 100 Ω at a temperature of 0 °C.

To convert resistance in Ω to temperature in °C, one can use the following equation:

$$T = \frac{-A + \sqrt{A^2 - 4B\left(1 - \frac{R_{Pt100}}{100}\right)}}{2B}$$ (Formula 8.10.1)

with R_{Pt100} the resistance in Ω, T the temperature in °C, A and B the Pt100 coefficients

A = 3.908 x 10^{-3}
B = -5.775 x 10^{-7}

SR22-T2

T2 versions are equipped with a 10 kΩ thermistor of type 44031RC. It has a resistance of 10000 Ω at a temperature of 25 °C.

To convert resistance in Ω to temperature in °C, one can use the Steinhart-Hart equation. Measure the resistance of the thermistor and then calculate the temperature from the resistance.

$$T = \frac{1}{\alpha + \beta \ln(R_{thermistor}) + \gamma \ln(R_{thermistor})^3} - 273.15$$ (Formula 8.10.2)

with $R_{thermistor}$ the thermistor resistance in Ω, T the temperature in °C, α, β and γ the Steinhart-Hart coefficients

α = 1.0295 x 10^{-3}
β = 2.391 x 10^{-4}
γ = 1.568 x 10^{-7}

Hukseflux
Thermal Sensors

8.11 EC declaration of conformity

CE

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

in accordance with the requirements of the following directive:

2004/108/EC The Electromagnetic Compatibility Directive

hereby declare under our sole responsibility that:

Product model: SR22
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).

Kees VAN DEN BOS
Director
Delft
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