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LATEST DEVELOPMENTS IN SOLAR IRRADIANCE MEASUREMENT

(10th PVPMC Workshop 2018)

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Pyranometers in use

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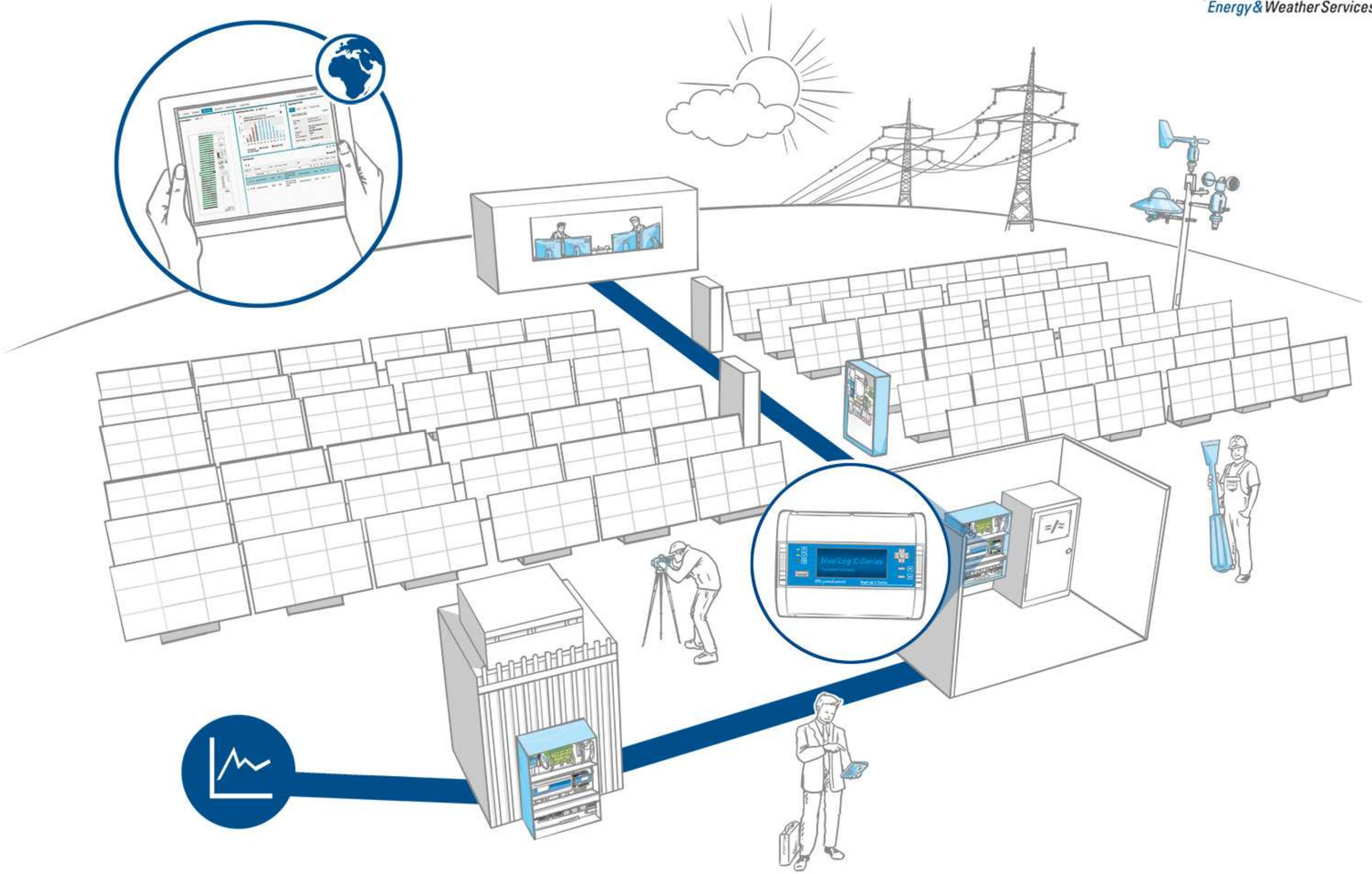
Example: monitoring services

meteo control
Energy & Weather Services



Improvements needed

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Subjects

- solar irradiance measurement

- improving measurement accuracy
- improving data availability

- IEC 61724-1: PV system performance monitoring
- ASTM G213: uncertainty evaluation of irradiance measurement

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Subjects

- ISO 9060 revision
- Good measurement practices

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PV system simplified

- A: Input: solar irradiance in W/m^2
- B: System: PV system in m^2
- C: Output: Electrical power in W

- D: System efficiency: $C/(A \cdot B)$
- Degradation: change of D versus time dD/dt

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Tool: pyranometer

- Measurement in POA
- A: Input: solar irradiance in W/m^2
- Maximum possible yield for a 100 % efficiency solar panel
- Independent of PV cell type
- Independent of PV cell Anti-reflection coating
- Independent of temperature

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NEW IEC 61724-1: 2017

IEC 61724-1

INTERNATIONAL STANDARD

Photovoltaic system performance –
Part 1: Monitoring

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Monitoring

- Measure – improve

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PV monitoring purposes

- Technical: Failure detection
- Technical: Creating a performance baseline

- Financial: Increase income
- Financial: Risk profile reduction
- Financial: Sale of the PV power plant

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PV Monitoring: service industry

Global Top 25 Players Map by Total Fleet and Growth in Megawatts, and Segment Mix

Source: SOLICHAMBA

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PV Monitoring

- Monitoring is an industry
- Utility scale PV plants hire independent monitoring companies

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IEC: 3 classes

NEW: IEC 61724-1: 2017 defines monitoring systems of 3 accuracy classes (A, B and C)

– 4 – IEC 61724-1 © IEC 2017

$\lambda = \frac{|P|}{S}$

NEW: IEC 61724-1: 2017 you must define if the system complies with class A, B or C

4 Monitoring system classification

The required accuracy and complexity of the monitoring system depends on the PV system size and user objectives. This standard defines three classifications of monitoring systems providing varying levels of accuracy, as listed in Table 1.

The monitoring system classification shall be stated in any conformity declarations to this standard. The monitoring system classification may be referenced either by its letter code (A, B, C) or its name (High accuracy, Medium accuracy, Basic accuracy) as indicated in Table 1. In this document, the letter codes are used for convenience.

Class A or Class B would be most appropriate for large PV systems, such as utility-scale and large commercial installations, while Class B or Class C would be most appropriate for small systems, such as smaller commercial and residential installations. However, users of the standard may specify any classification appropriate to their application, regardless of PV system size.

Throughout this standard, some requirements are designated as applying to a particular classification. Where no designation is given, the requirements apply to all classifications.

Table 1 – Monitoring system classifications and suggested applications

Typical applications	Class A High accuracy	Class B Medium accuracy	Class C Basic accuracy
Basic system performance assessment	X	X	X
Documentation of a performance guarantee	X	X	
System losses analysis	X	X	
Electricity network interaction assessment	X		
Fault localization	X		
PV technology assessment	X		
Precise PV system degradation measurement	X		

NEW: IEC 61724-1: 2017 see above: utility scale PV monitoring needs class A

5 General

NEW: IEC 61724-1:2017 requires use of 2 x pyranometers, horizontal and plane of array

Table 3 – Measured parameters and requirements for each monitoring system class

Parameter	Symbol	Units	Monitoring Purpose	Required?			Number of Sensors
				Class A High accuracy	Class B Medium accuracy	Class C Basic accuracy	
Irradiance (see section 7.2)							
In-plane irradiance (POA)	G_i	$W \cdot m^{-2}$	Solar resource	√	√ or E	√ or E	Table 4 column 1
Global horizontal irradiance	GHI	$W \cdot m^{-2}$	Solar resource, connection to historical and satellite data	√	√ or E		Table 4 column 1
Direct normal irradiance	DNI	$W \cdot m^{-2}$	Solar resource, concentrator	√ for CPV	√ or E for CPV		Table 4 column 1
Diffuse irradiance	G_d	$W \cdot m^{-2}$		√ for CPV with < 20× concentration	√ or E for CPV with < 20× concentration		Table 4 column 1
Circumsolar ratio	CSR						
Environmental factors (see section 7.3)							
PV module temperature	T_{mod}	°C	Determining temperature-related losses	√	√ or E		Table 4 column 2
Ambient air temperature	T_{amb}	°C	Connection to historical data, plus estimation of PV temperatures	√	√ or E	√ or E	Table 4 column 1
Wind speed		$m \cdot s^{-1}$	Estimation of PV temperatures	√	√ or E		Table 4 column 1
Wind direction		degrees		√			Table 4 column 1
Soiling ratio	SR		Determining soiling-related losses	√ if soiling losses expected to be >2 %			Table 4 column 1

IEC: Electrical

Table 11 – Inverter-level electrical measurement requirements

Parameter	Measurement Uncertainty		
	Class A High accuracy	Class B Medium accuracy	Class C Basic accuracy
Input voltage (DC)	±2,0 %	n/a	n/a
Input current (DC)	±2,0 %	n/a	n/a
Input power (DC)	±2,0 %	n/a	n/a
Output voltage (AC)	±2,0 %	±3,0 %	n/a
Output current (AC)	±2,0 %	±3,0 %	n/a
Output power (AC)	±2,0 %	±3,0 %	n/a

Table 12 lists the requirements for electrical measurements at the output of the power plant, i.e. the aggregate output produced by all inverters in the system.

For multi-phase systems, each phase shall be measured, or 2 of 3 phases shall be measured (two wattmeter method).

Table 12 – Plant-level AC electrical output measurement requirements

Parameter	Class A High accuracy	Class B Medium accuracy	Class C Basic accuracy
Active power and energy	Class 0,2 S as per IEC 62053-22	Class 0,5 S as per IEC 62053-22	Class 2 per IEC 62053-21
Power factor	Class 1 as per IEC 61557-12	Class 1 as per IEC 61557-12	n/a

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IEC: pyranometer class

NEW: IEC 61724-1:2017 requires use secondary standard pyranometers

Table 5 lists sensor choices and accuracy requirements for in-plane and global irradiance measurement, and Table 7 lists maintenance requirements for these sensors.

The sensor, signal-conditioning electronics, and data storage shall provide a range including at least 0 W·m^{-2} to 1 500 W·m^{-2} and a resolution of ≤ 1 W·m^{-2}.

NOTE Over-irradiance in the range 1 000 W·m^{-2} to 1 500 W·m^{-2} or higher can occur due to reflections from clouds under partly cloudy conditions.

Table 5 – Sensor choices and requirements for in-plane and global irradiance

Sensor Type	Class A High accuracy	Class B Medium accuracy	Class C Basic accuracy
Thermopile pyranometer	Secondary standard per ISO 9060 or High quality per WMO Guide (Uncertainty ≤ 3 % for hourly totals)	First class per ISO 9060 or Good quality per WMO Guide (Uncertainty ≤ 8 % for hourly totals)	Any
PV reference device	Uncertainty ≤ 3 % from 100 W·m^{-2} to 1 500 W·m^{-2}	Uncertainty ≤ 8 % from 100 W·m^{-2} to 1 500 W·m^{-2}	Any
Photodiode sensors	Not applicable	Not applicable	Any

Each irradiance sensor type has its benefits:

- Thermopile pyranometers are insensitive to typical spectral variations and therefore measure total solar irradiance. However, this can vary from the PV-usable irradiance by 1 % to 3% (monthly average) under typical conditions. In addition, thermopile pyranometers have long response times compared to PV devices and photodiodes.
- Matched PV reference devices measure the PV-usable portion of the solar irradiance

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IEC: calibration

7.2.1.7 **Sensor maintenance**

Irradiance sensor maintenance requirements are listed in Table 6.

Table 6 – Irradiance sensor maintenance requirements

Item	Class A High accuracy	Class B Medium accuracy	Class C Basic accuracy
Recalibration	Once per year	Once every 2 years	As per manufacturer's requirements
Cleaning	At least once per week	Optional	

NEW: IEC 61724-1:2017 once per year calibration is required for class A systems

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IEC: heating + ventilation

NEW: IEC 61724-1:2017 heating of pyranometers and PV reference cells is required in class A and B systems. Hukseflux models SR30, SR20 (not the digital version) and SR12 are heated. We do not know of heated PV reference cells.

Heating to prevent accumulation of condensation and/or frozen precipitation	Required in locations where condensation and/or frozen precipitation would affect measurements on more than 7 days per year	Required in locations where condensation and/or frozen precipitation would affect measurements on more than 14 days per year	
Ventilation (for thermopile pyranometers)	Required	Optional	
Desiccant inspection and replacement (for thermopile pyranometers)	As per manufacturer's requirements	As per manufacturer's requirements	As per manufacturer's requirements

NEW: IEC 61724-1:2017 ventilation of pyranometers is required in class A systems. Hukseflux model SR30 is ventilated

possible to minimize the time that sensors are offline. If sensors are to be sent off-site for laboratory recalibration, the site should be designed with redundant sensors or else backup sensors should be used to replace those taken offline, in order to prevent interruption of monitoring.

Cleaning of irradiance sensors without cleaning the modules can result in a lowering of the measured PV system performance ratio (defined in **Fout! Verwijzingsbron niet gevonden.**). In some cases contract requirements may specify that irradiance sensors are to be maintained in the same state of cleanliness as the modules.

Night-time data should be checked to ensure accurate zero-point calibration.

NOTE It is common for pyranometers to show a small negative signal, -1 $W \cdot m^{-2}$ to -3 $W \cdot m^{-2}$, at night time.

7.2.1.8 Additional measurements

7.2.1.8.1 Direct normal irradiance

Direct normal irradiance (*DNI*) is measured with a pyrheliometer on a two-axis tracking stage which automatically tracks the sun.

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Summary : IEC 61724-1

- measurement accuracy is important in PV monitoring
- IEC 61724-1 confirms pyranometers as “weakest link” in analysis,
- recommends the use of the best instruments
- Stresses maintenance & calibration

ASTM G213-17

INTERNATIONAL

Designation: G213 – 17

Standard Guide for Evaluating Uncertainty in Calibration and Field Measurements of Broadband Irradiance with Pyranometers and Pyrheliometers[1]

This standard is issued under the fixed designation G213; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide provides guidance and recommended practices for evaluating uncertainties when calibrating and performing outdoor measurements with pyranometers and pyrheliometers used to measure total hemispherical- and direct solar irradiance. The approach follows the ISO procedure for evaluating uncertainty, the Guide to the Expression of Uncertainty in Measurement (GUM) JCGM 100:2008 and that of the joint ISO/ASTM standard ISO/ASTM 51707 Standard Guide for Estimating Uncertainties in Dosimetry for Radiation Processing, but provides explicit examples of calculations. It is up to the user to modify the guide described here to their specific application, based on measurement equation and

mendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E772 Terminology of Solar Energy Conversion

G113 Terminology Relating to Natural and Artificial Weathering Tests of Nonmetallic Materials

G167 Test Method for Calibration of a Pyranometer Using a Pyrheliometer

Guide for Estimating Uncertainties in Dosimetry for Radiation Processing

2.2 *ASTM Adjunct:*[2]

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Uncertainty evaluation

- Methods based on GUM
- ISO/IEC Guide 98-3 *Guide to the expression of uncertainty in measurement*
- Type “B” evaluation

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Not easy

- Uncertainty depends on:

- Moving sun
- Variable environmental conditions
- Maintenance
- Data availability (dew, frost, snow)
- Horizon
- Reflections (tilted installation)

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Uncertainty evaluation

Follow BIPM's 'GUM'

1. Define the measurand → Global Horizontal Irradiance *E*

2. Write down the measurement equation → $E = \frac{U}{S}$

   - U: Your datalogger (voltmeter) specification
   - S: The calibration uncertainty on the product certificate

3. Assign uncertainties to input variables

4. Calculate

JCGM 100:2008 Evaluation of measurement data – Guide to the expression of uncertainty in measurement

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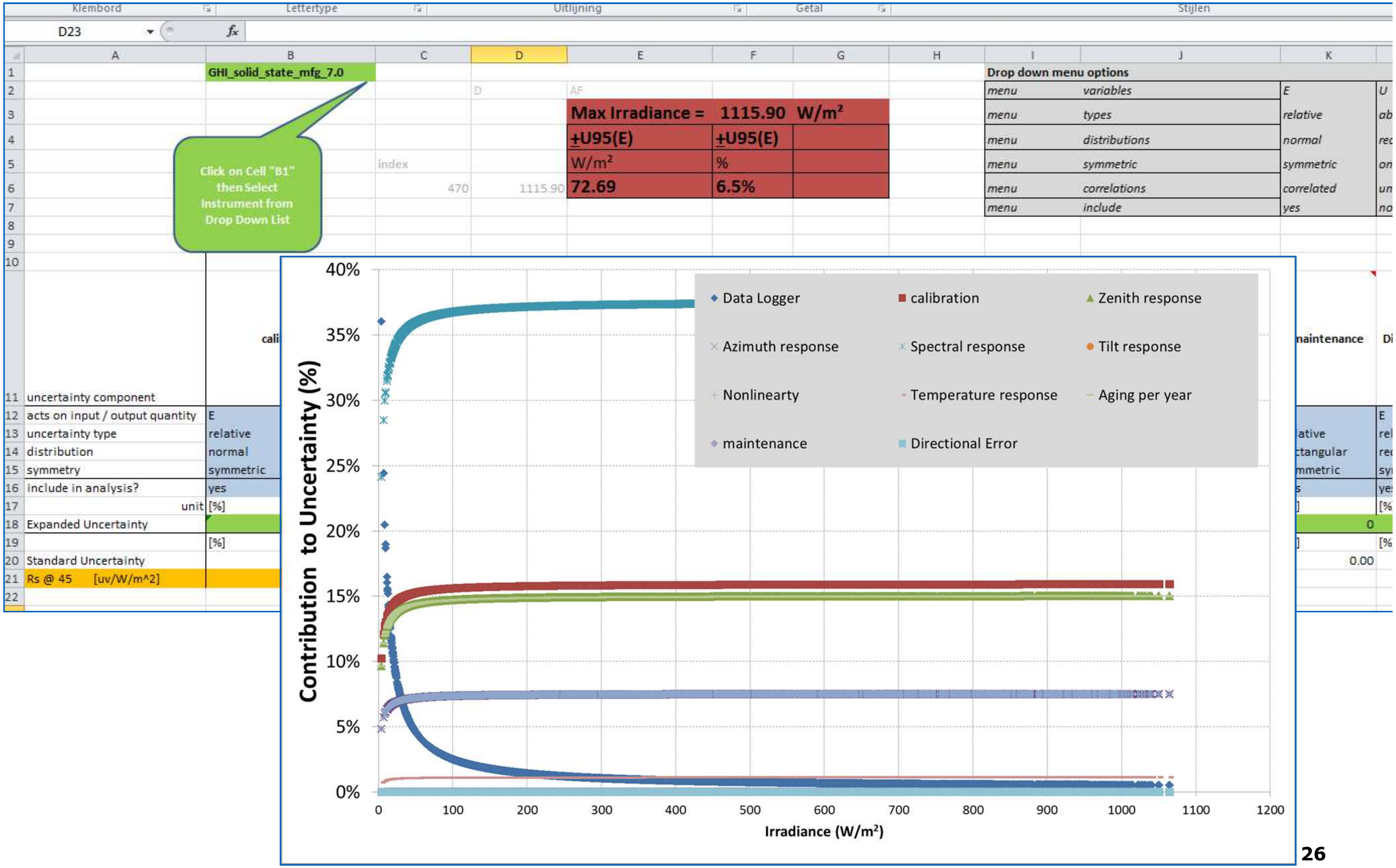
Spreadsheets (Excel)



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Typical uncertainty budget

- Calibration uncertainty
- Instrument specifications
  - known systematic errors may be corrected
- Datalogger accuracy
- Maintenance
- ...

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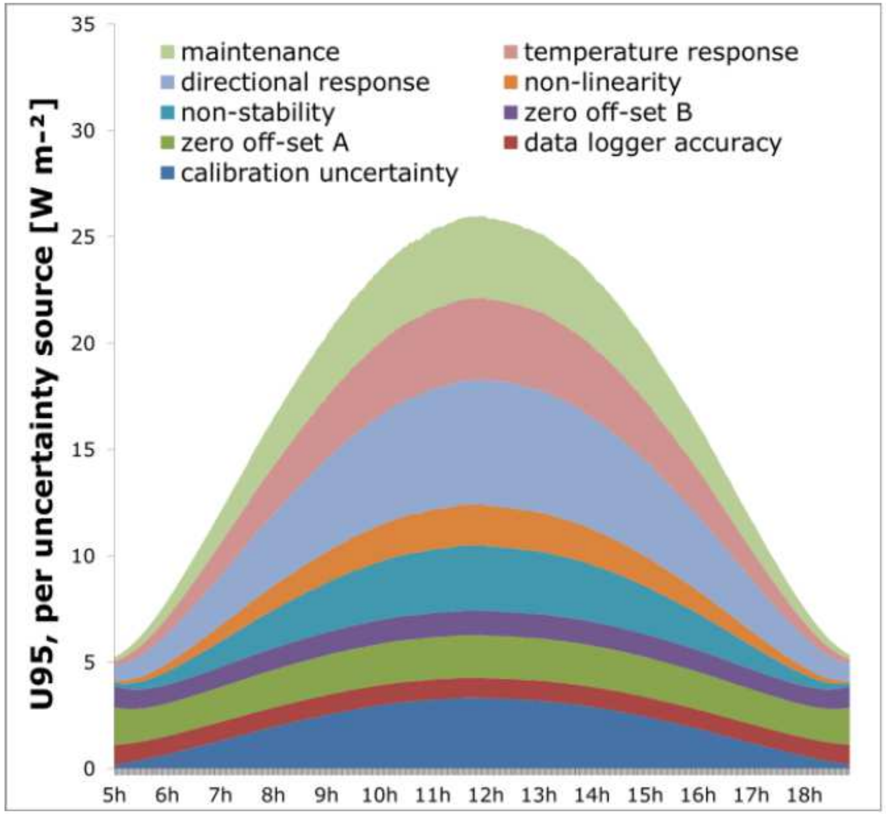
Result: sources of uncertainty



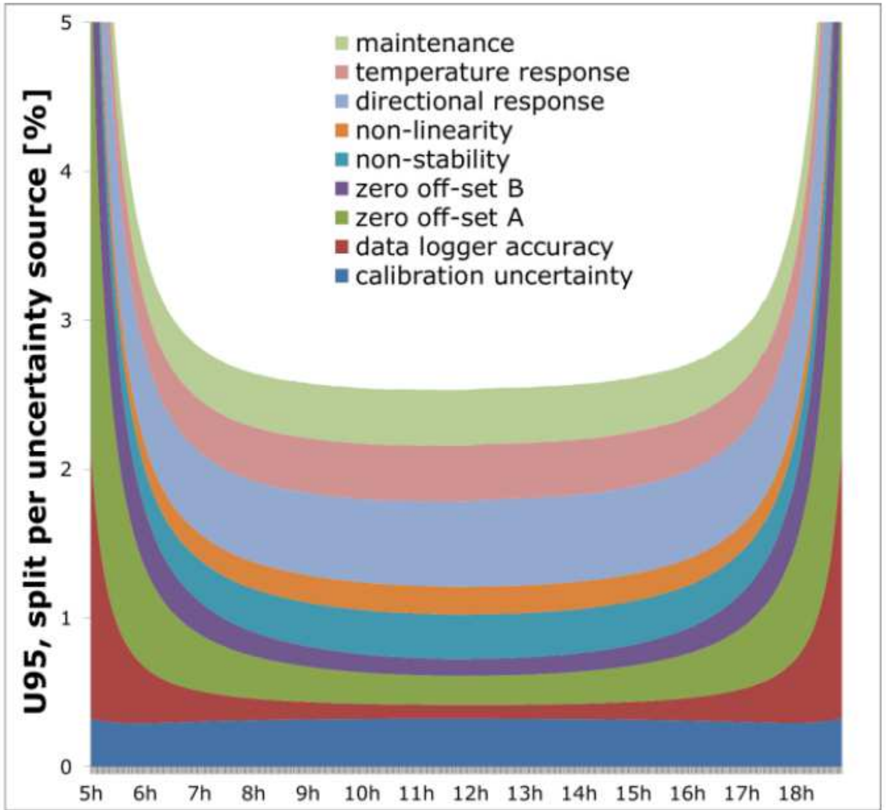
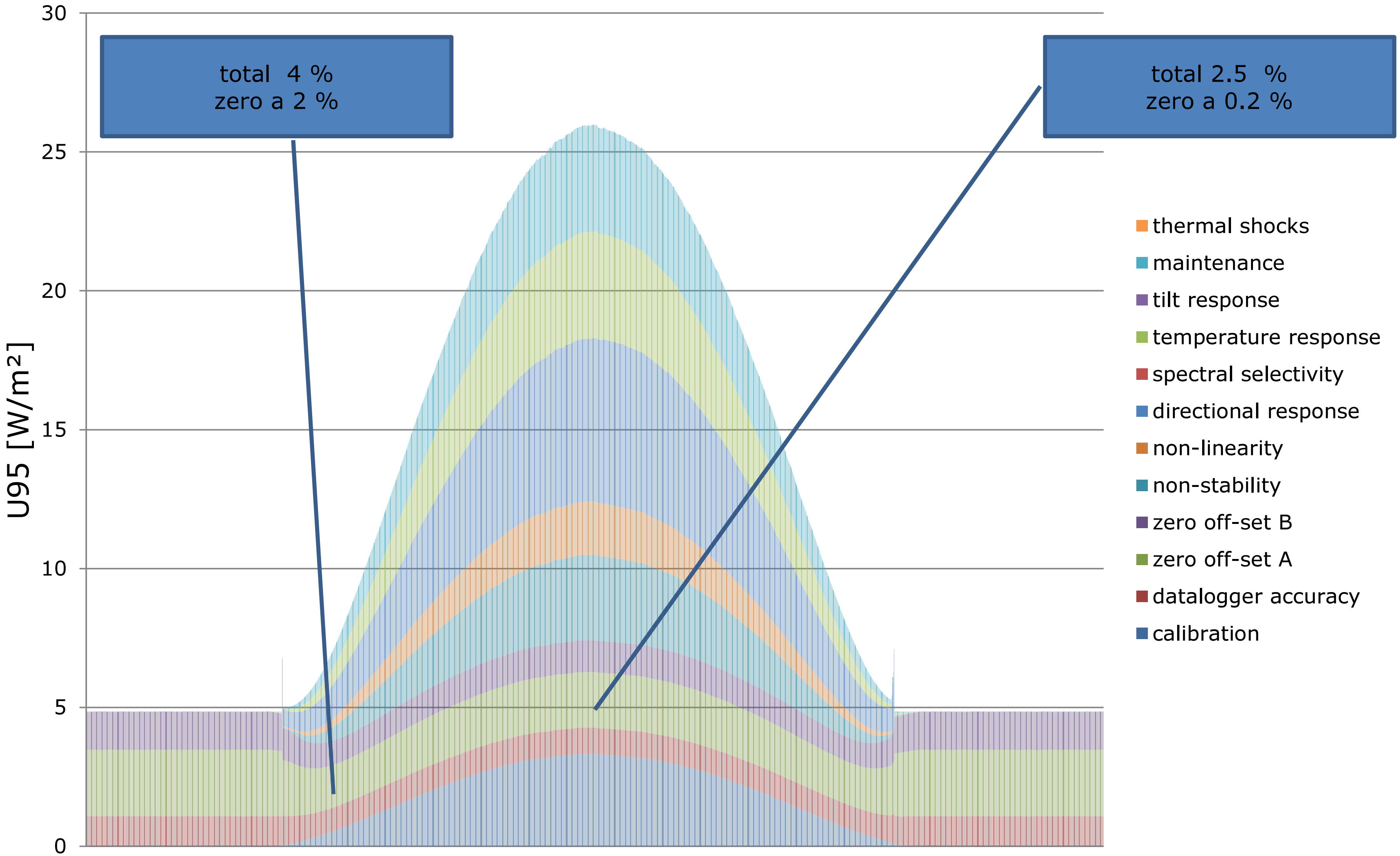


Fig. 2: Expanded uncertainty as function of time, split per uncertainty source.
The expanded uncertainty is expressed in a) absolute values in W m^{-2}, b) relative values in %.

example, offset a: 7 W/m^2



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2016 performance testing

- Anton Driesse, Willem Zaaiman, Daniel Riley, Nigel Taylor, Joshua S. Stein, *Investigation of Pyranometer and Photodiode Calibrations under Different Conditions*, conference paper presented at IEEE PVSC 2016, published on internet, accessed 10-Oct-2016.

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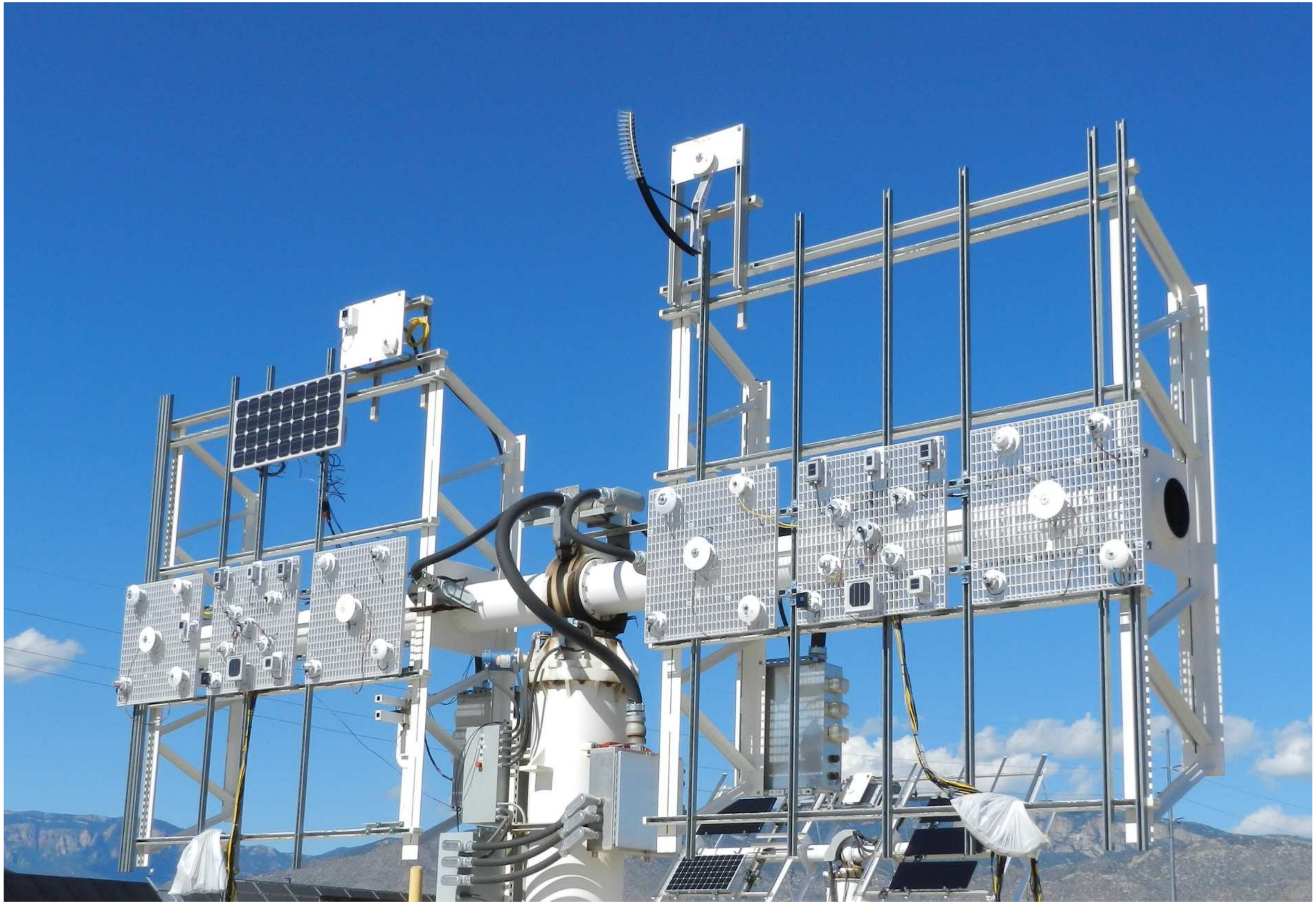
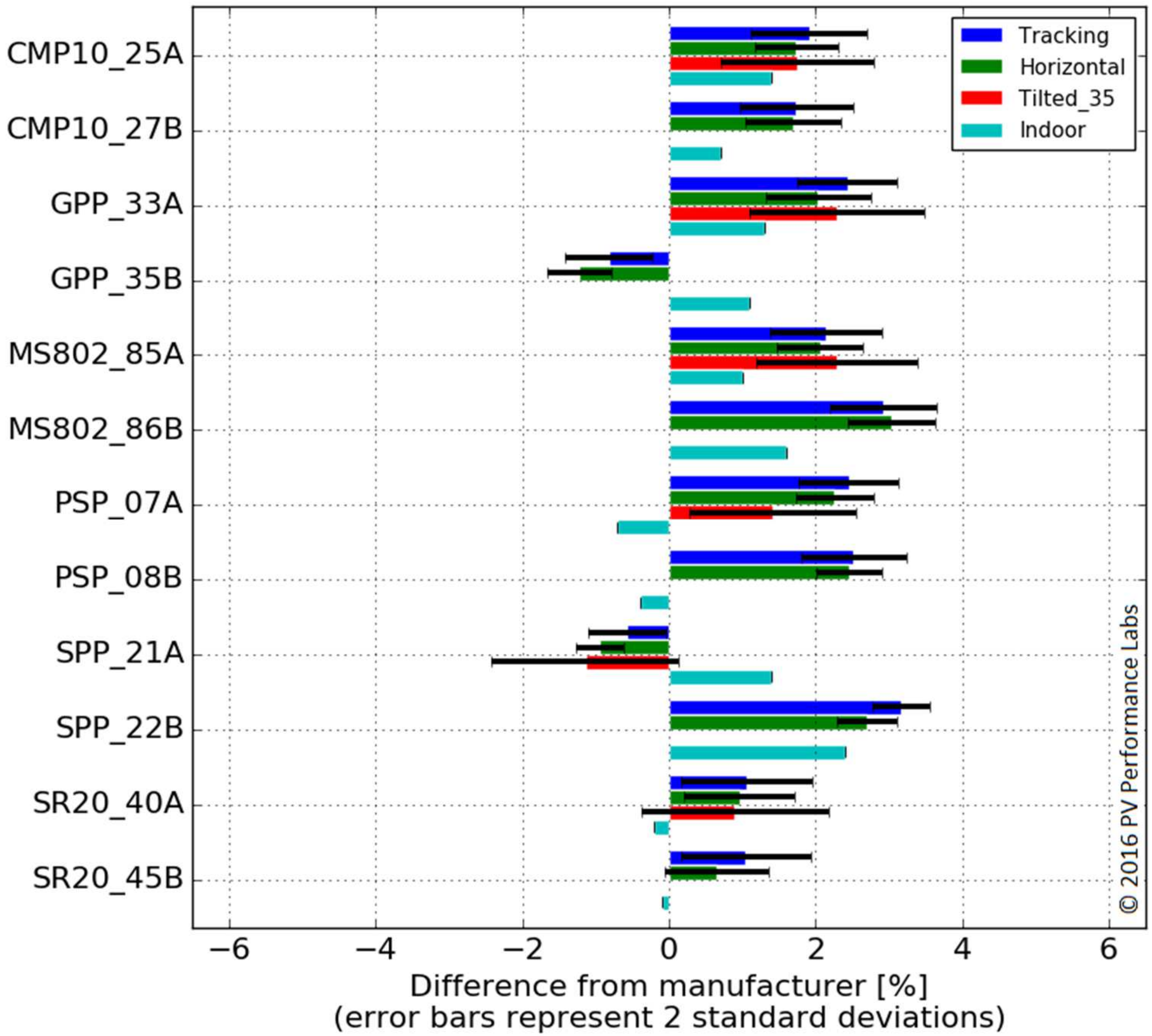
JRC Ispra / Sandia



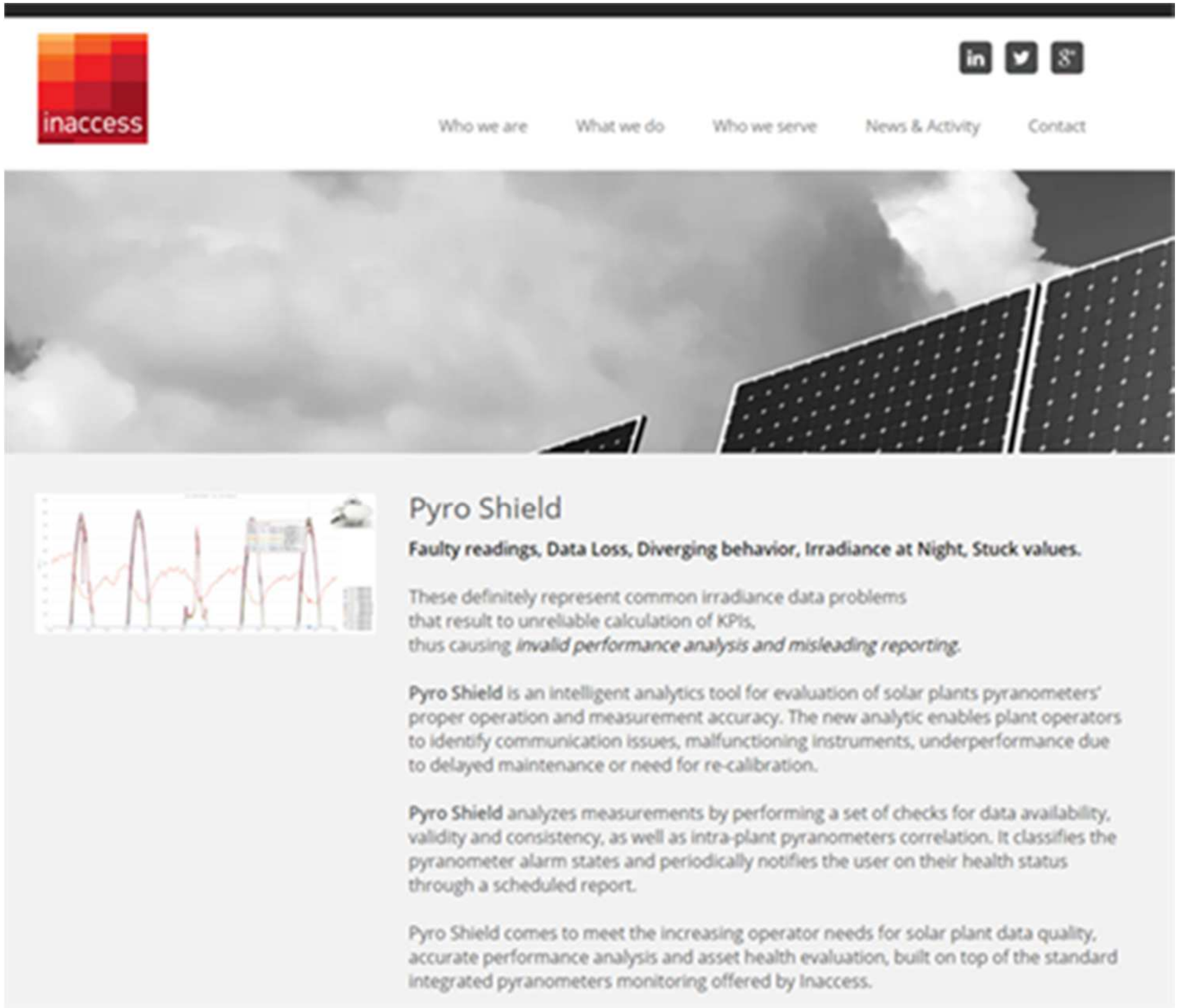
Errors in the 1 to 3 % range



Good practices

- Quality assurance software for PV power plants

Example software: “pyro shield”



inaccess

Who we are | What we do | Who we serve | News & Activity | Contact

Pyro Shield

Faulty readings, Data Loss, Diverging behavior, Irradiance at Night, Stuck values.

These definitely represent common irradiance data problems
that result to unreliable calculation of KPIs,
thus causing *invalid performance analysis and misleading reporting.*

Pyro Shield is an intelligent analytics tool for evaluation of solar plants pyranometers' proper operation and measurement accuracy. The new analytic enables plant operators to identify communication issues, malfunctioning instruments, underperformance due to delayed maintenance or need for re-calibration.

Pyro Shield analyzes measurements by performing a set of checks for data availability, validity and consistency, as well as intra-plant pyranometers correlation. It classifies the pyranometer alarm states and periodically notifies the user on their health status through a scheduled report.

Pyro Shield comes to meet the increasing operator needs for solar plant data quality, accurate performance analysis and asset health evaluation, built on top of the standard integrated pyranometers monitoring offered by Inaccess.

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Good practices

- Calibration companies for pyranometers

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Example: calibration companies

新气象
NEWSKY

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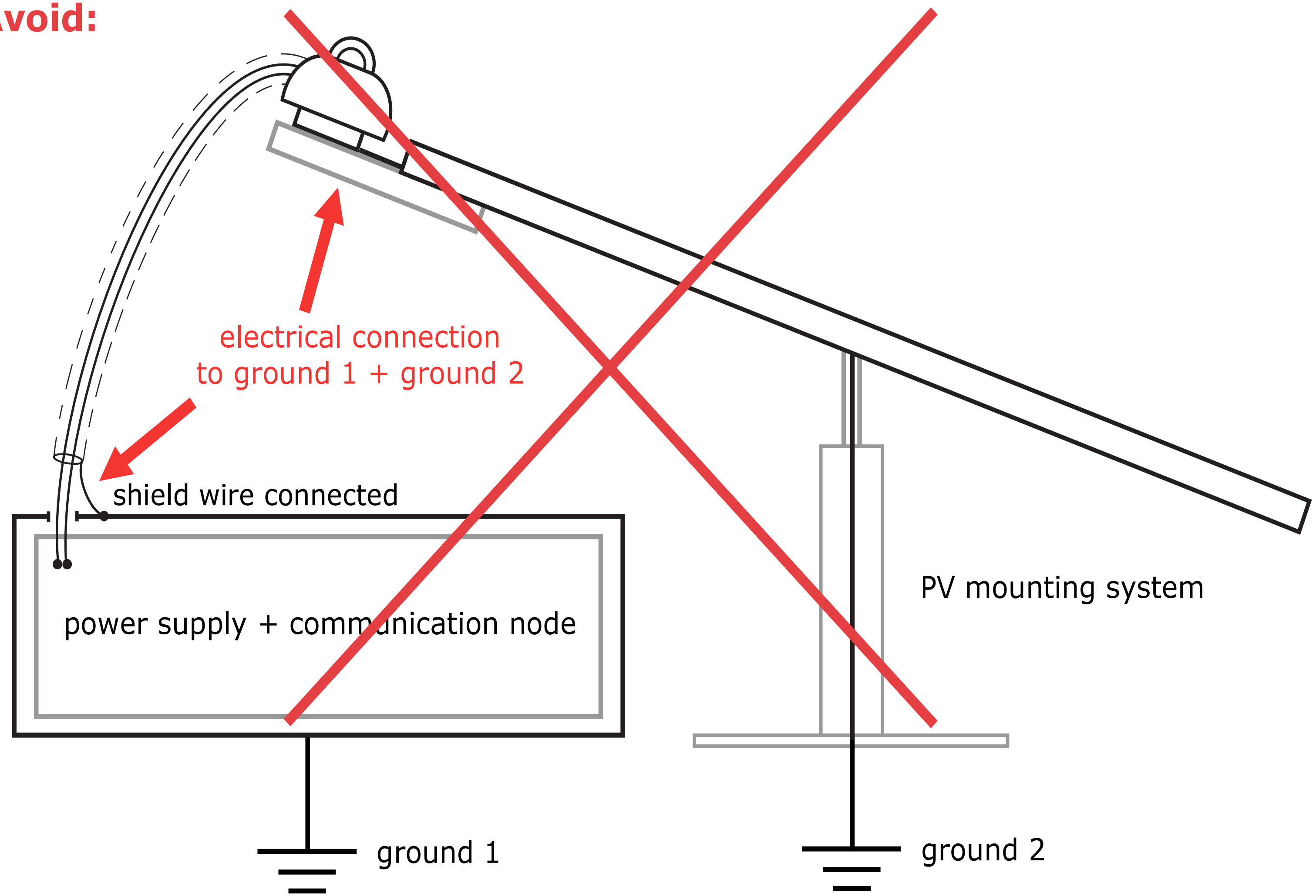
Good pracices / safety

Avoid:



evolution

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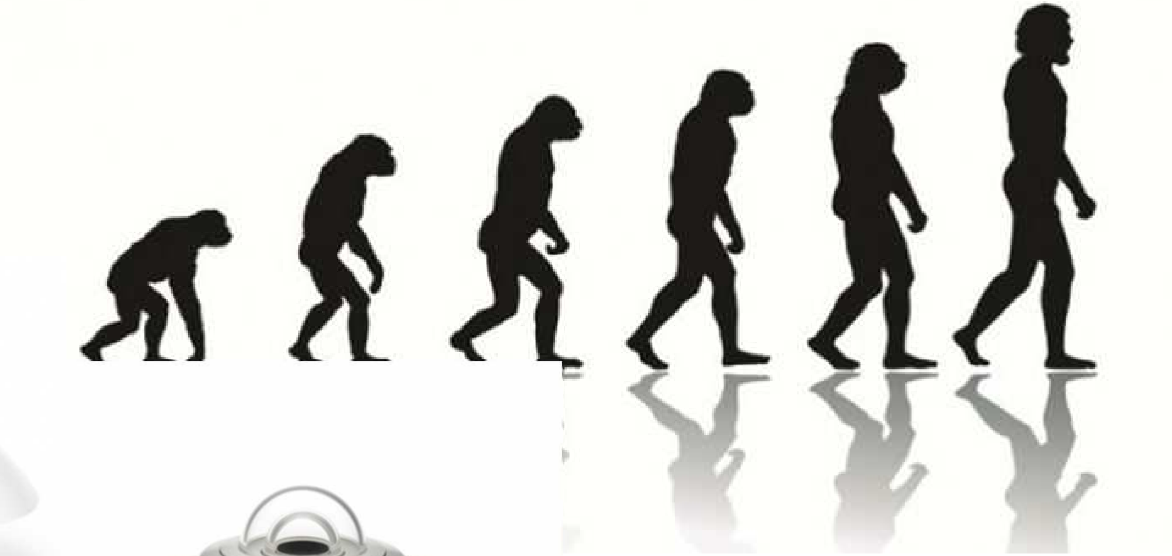
evolution



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Data availability

- We spent several years of R & D in reduction of dew and frost
- Our opinion: Dew and frost are # 1 in creating unreliable data
- We talk about “data availablility”
- IF (dew or frost)

  THEN (data availability = FALSE)

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data availability = FALSE

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The new SR30 pyranometer

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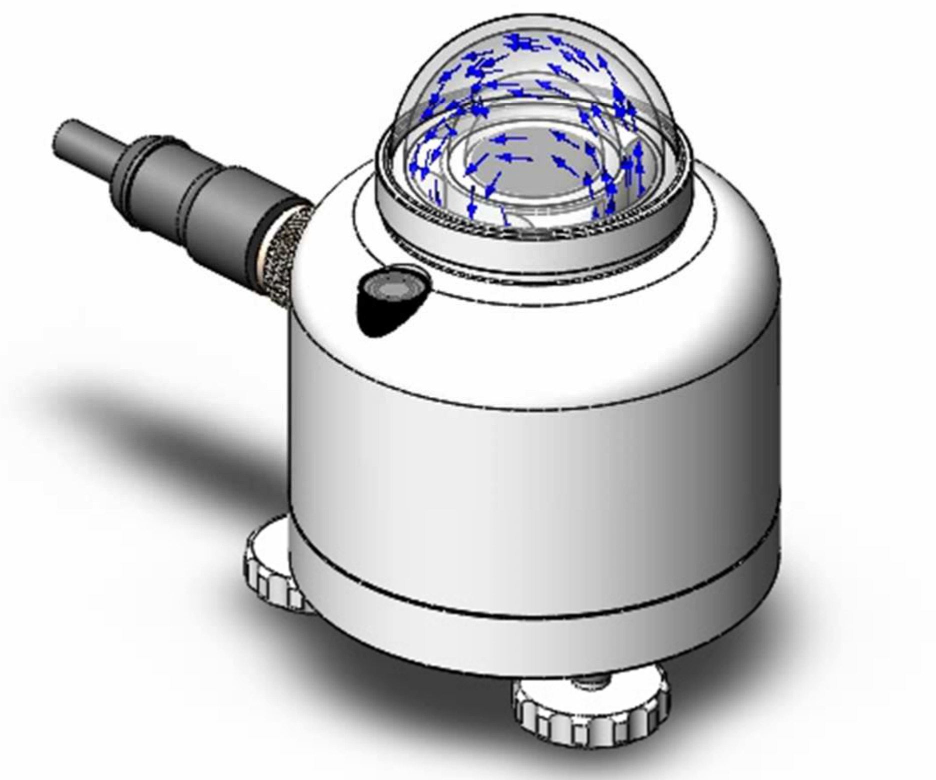
Internal ventilation animation



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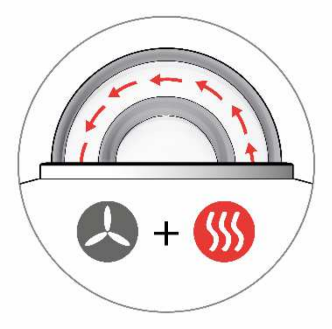
Focus: SR30



- secondary standard
- humidity sensor
- tilt measurement
- heated

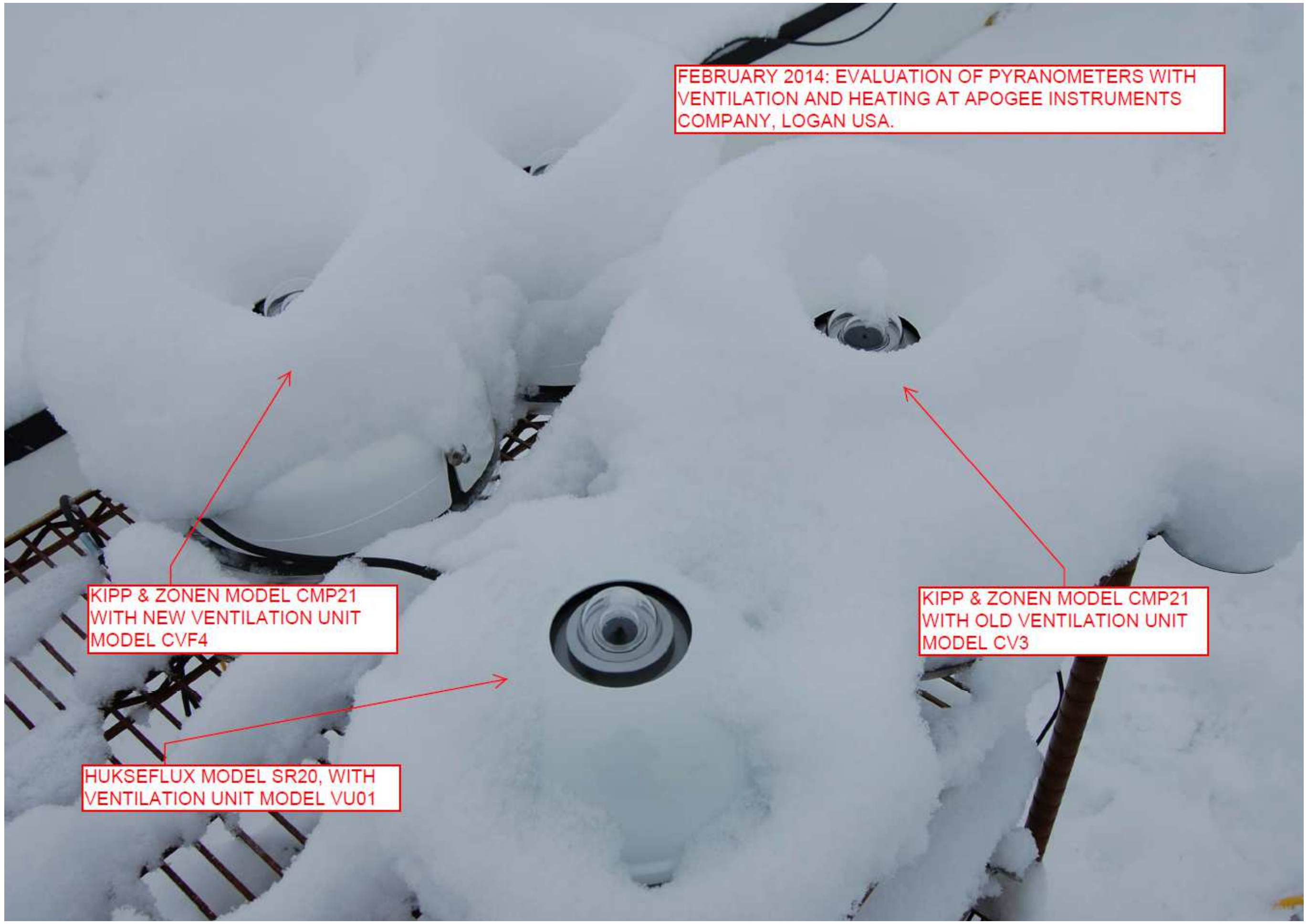
New ventilation & heating

+ 2.1 W

+ 10 W


TTL 2

Powder snow in Utah USA



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Webcam: NOAA USA

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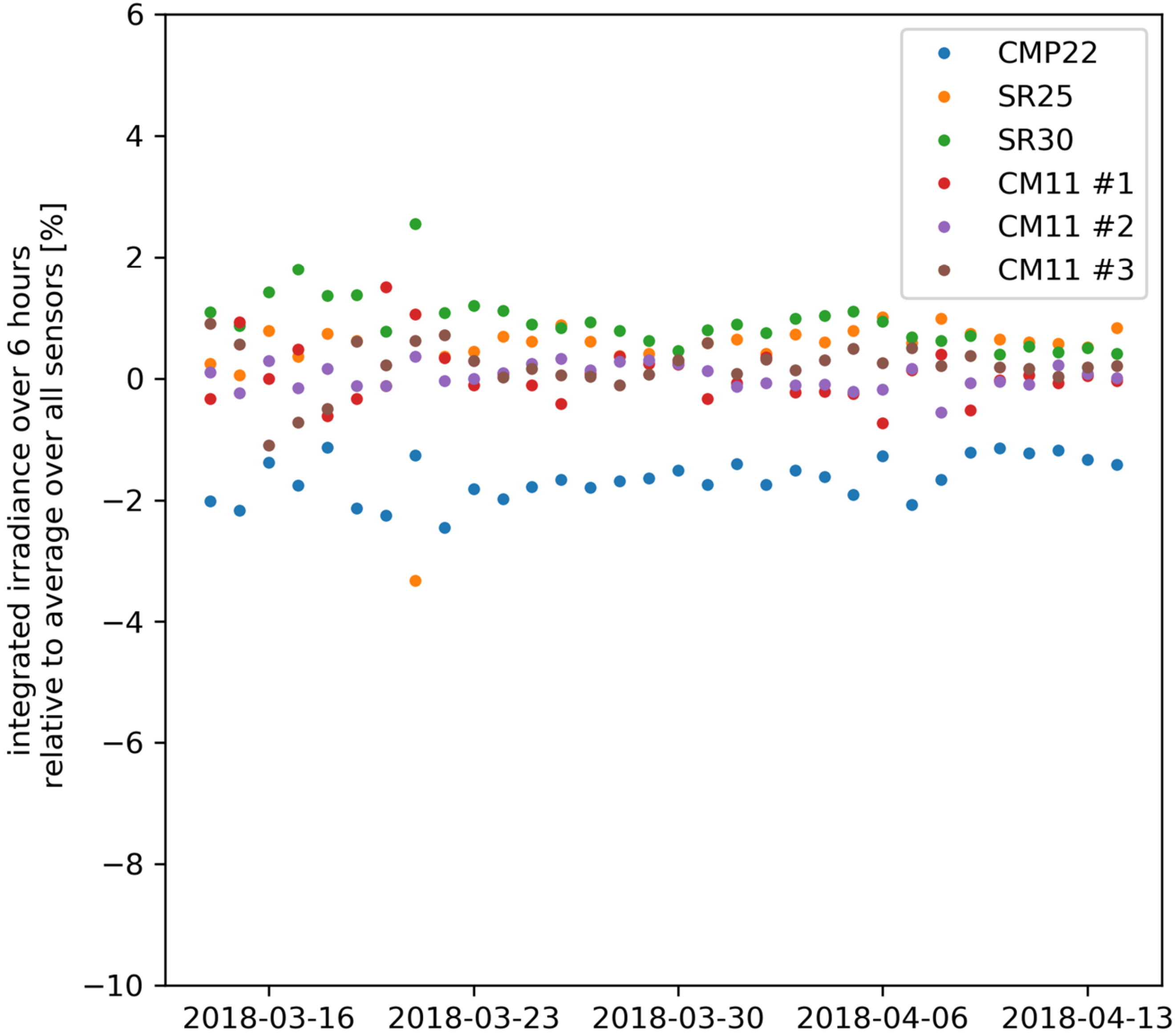
Irradiance top models

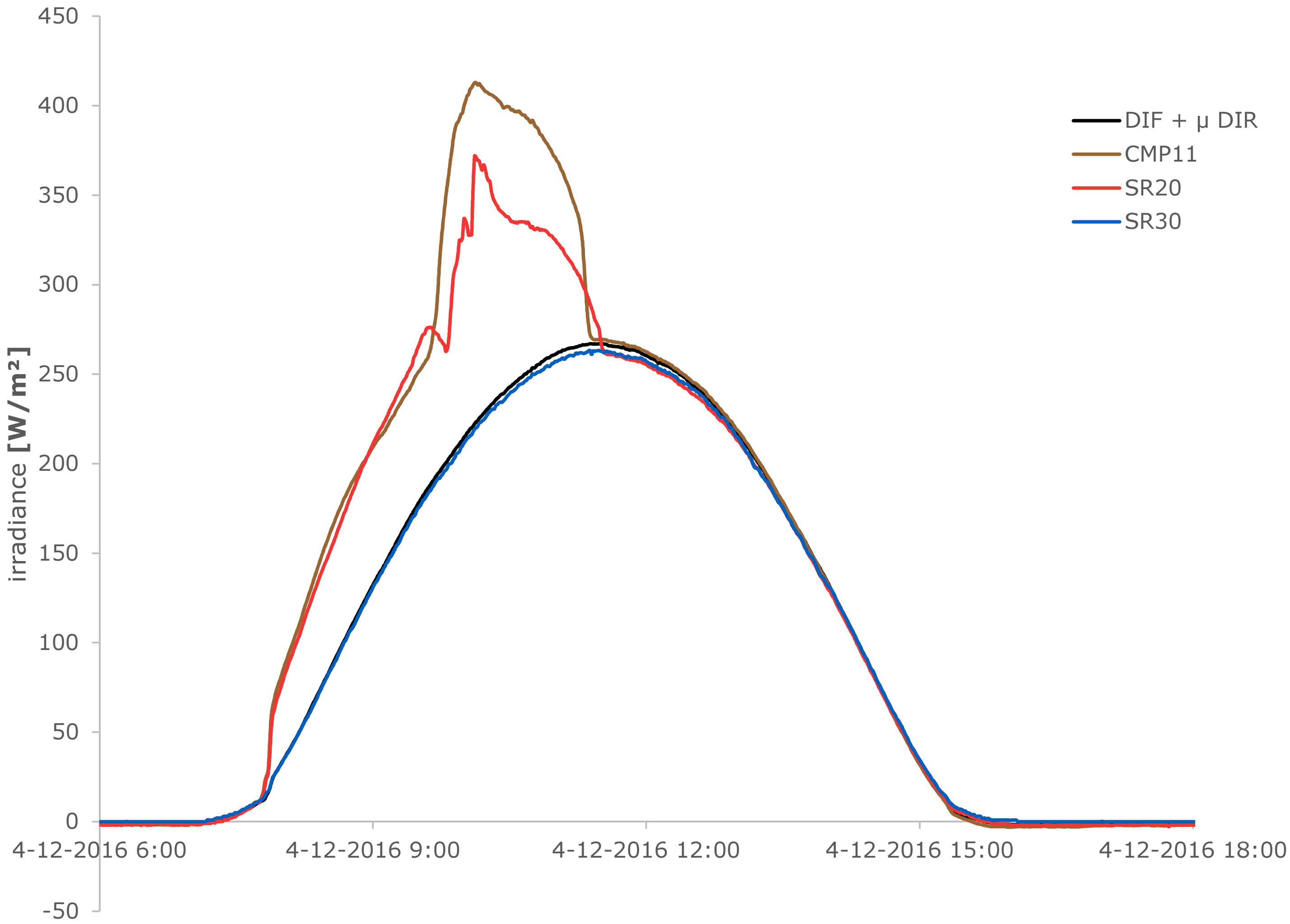


14.4

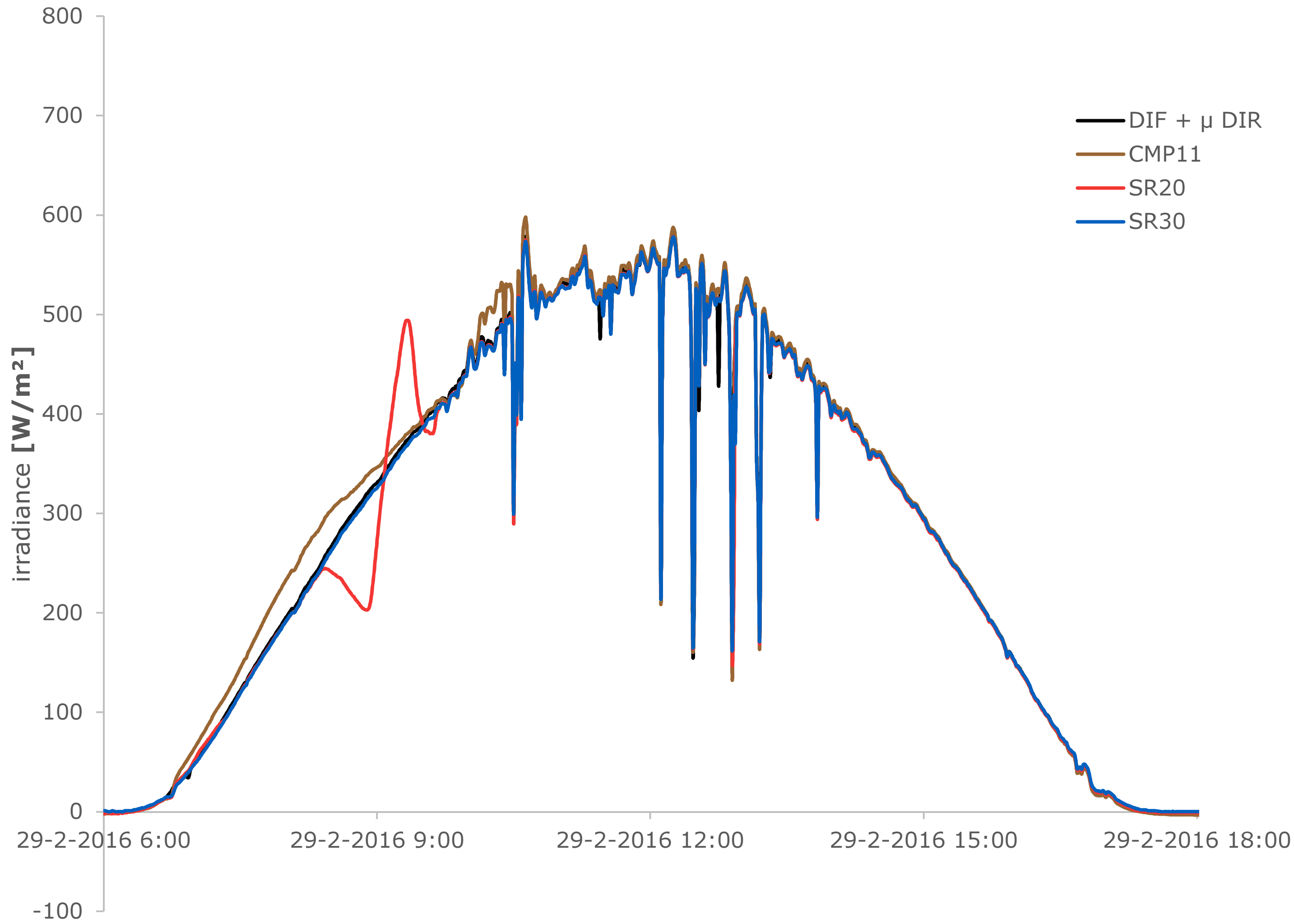
13.2


MS-802F

frost example

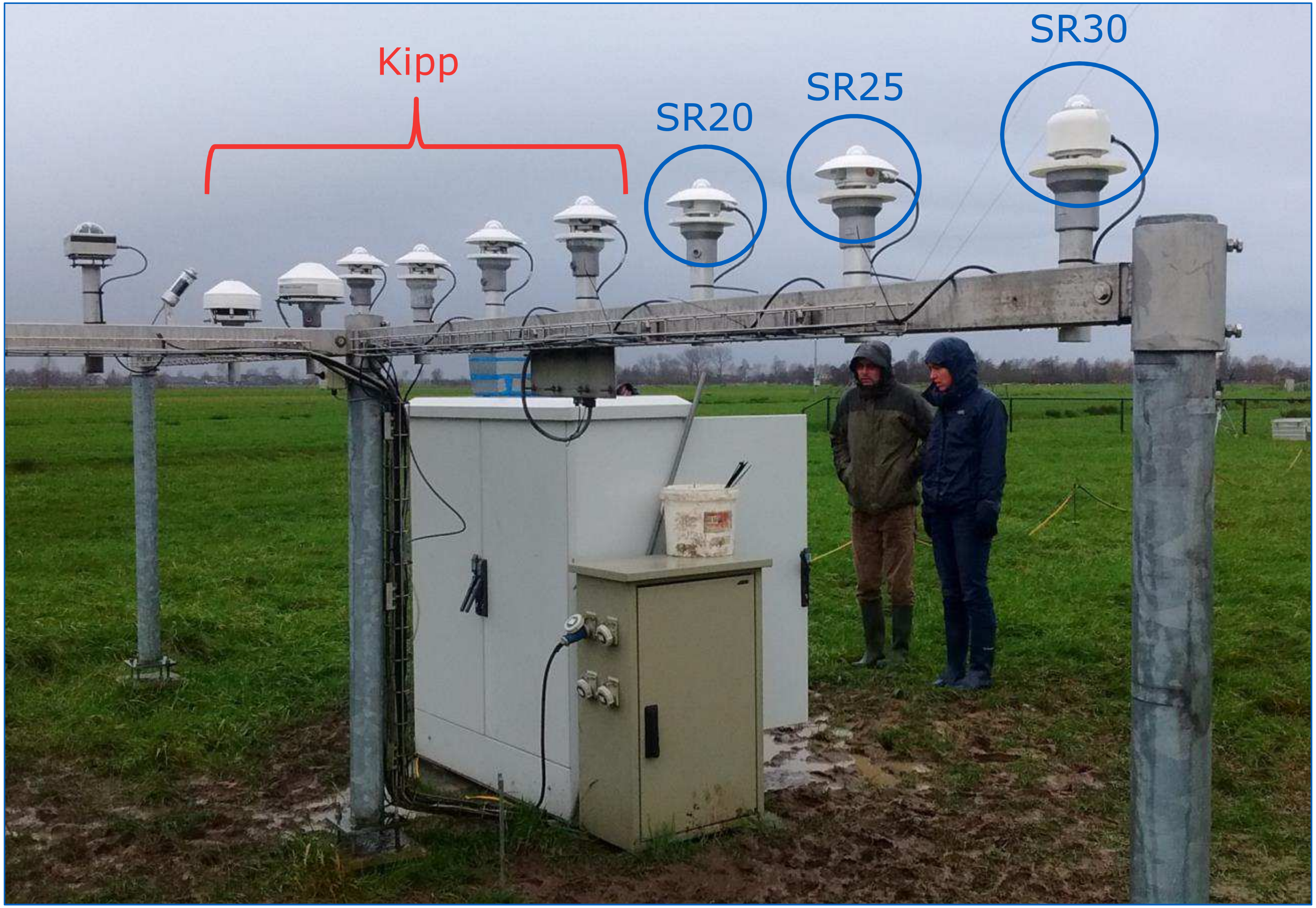


dew example



800
700
600
500
400
300
200
100
0
-100
irradiance [W/m²]
29-2-2016 6:00
29-2-2016 9:00
29-2-2016 12:00
29-2-2016 15:00
29-2-2016 18:00
DIF + μ DIR
CMP11
SR20
SR30

KNMI pyranometer comparison



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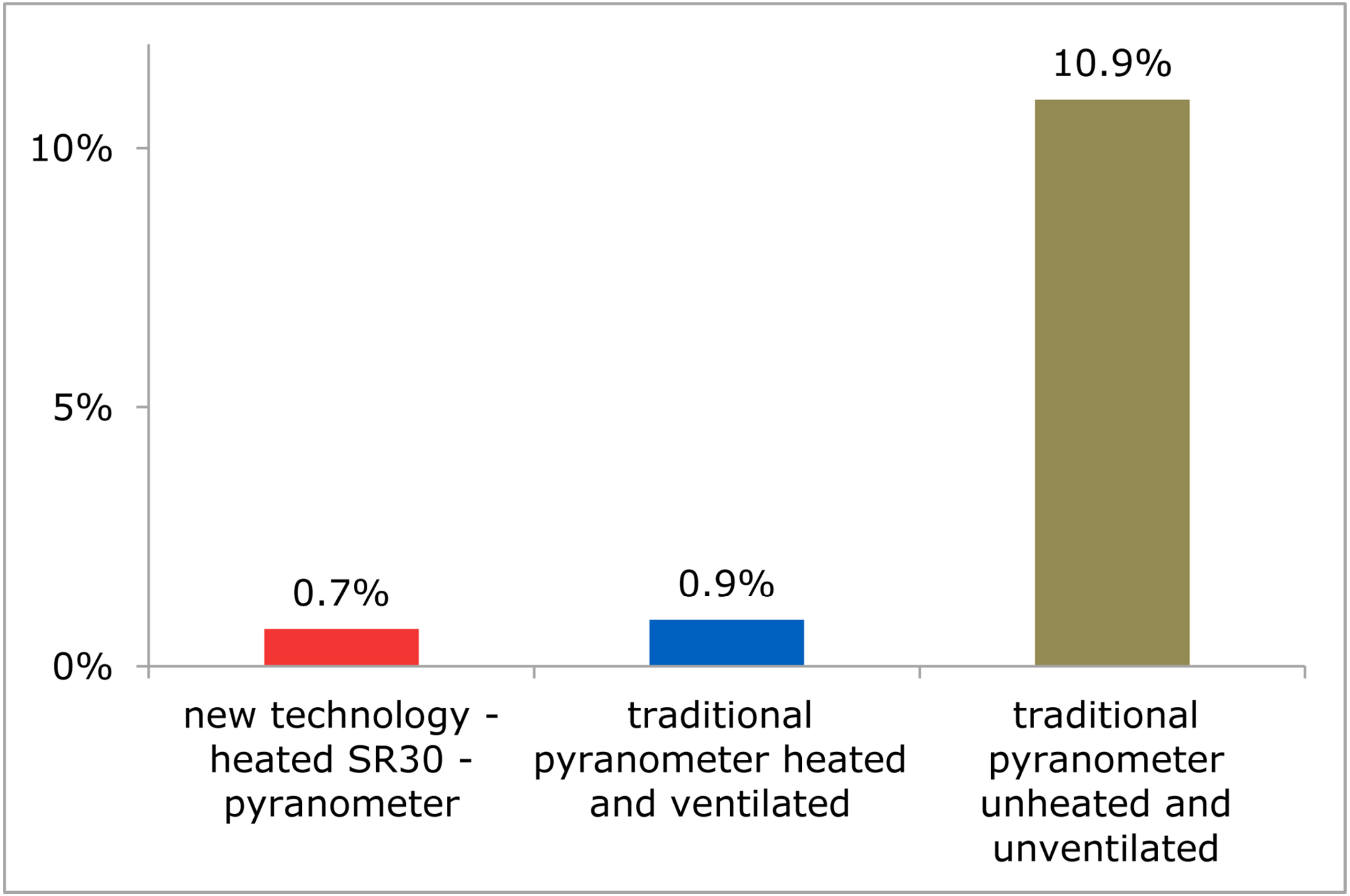
Unreliable data % of time



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ISO 9060 revision

DRAFT INTERNATIONAL STANDARD

ISO/DIS 9060

ISO/TC **180**/SC **1** | Secretariat: **SA**

Voting begins on:
2017-04-17

Voting terminates on:
2017-07-09

Solar energy — Specification and classification of instruments for measuring hemispherical solar and direct solar radiation

Énergie solaire — Spécification et classification des instruments de mesurage du rayonnement solaire hémisphérique et direct

ICS: 27.160

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Summary ISO 9060

- Final Draft
- Estimated date of Issue: SEP 2018

- "Secondary Standard" replaced by "Spectrally Flat Class A"
- POA requires spectrally flat response
- Albedo requires spectrally flat response

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Summary ISO 9060

- Test reports required for every instrument
- Temperature dependence + Directional response

- Not all installed base is OK

- IEC requires compliance to latest version of ISO
- Watch out! stock, retrofitting installed base

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Summary recent developments

- many different developments
- Combination leads to higher accuracies
- IEC 61724-1 acts as accelerator
- Instruments and calibration become better
- Under the best, IEC Class A, conditions uncertainties in the order of 3 % (k=2)
- Watch out: new ISO 9060

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Thank you!