# Reference pyranometer calibration procedures in national radiation centra in Central Europe

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# Why to unify/compare regional calibration procedures?

- To figure out consistent spatial distribution of global solar irradiance, the data provided by national radiation networks should be consistent

- The general methods for achievement of the global solar irradiance measurement traceability to the WRR recommended by the WMO can be differently modified

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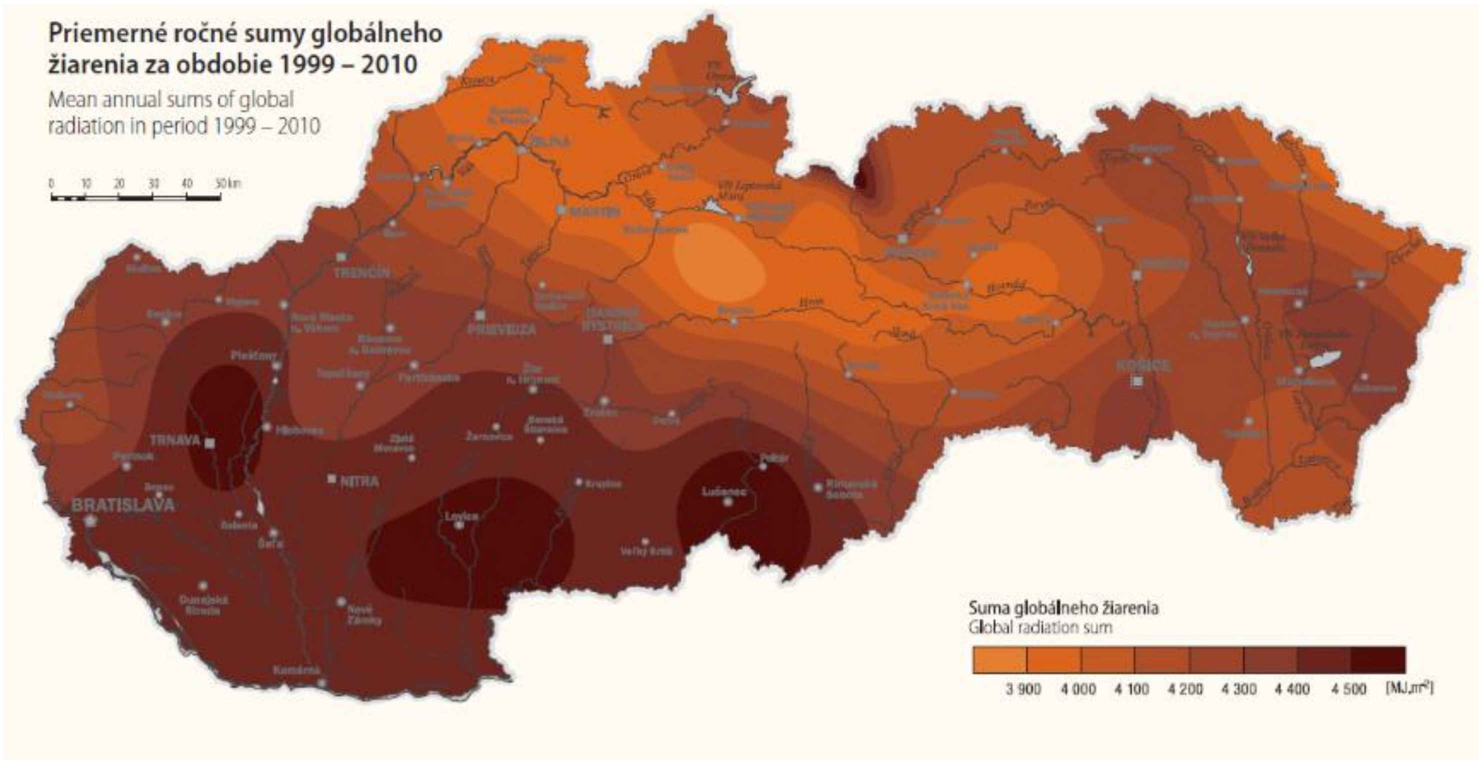
# Why to unify/compare regional calibration procedures?




Mean annual sums of global solar irradiance over Slovakia, 1999 - 2010

# Decision

- To compare the calibration procedures of reference pyranometer in the Central European NRC (Slovakia, Bohemia, Hungary)
- One selected pyranometer KZ CMP 11 Nr. 131449 was calibrated in every participated NRC from June till October 2018
- Evaluated parameters: needed technical equipment, data sampling, principle of the calibration method, calibration equation, condition stability control, auxiliary data, advantages/disadvantages of method, responsivity of the pyranometer - its daily course and dependence on SZA

# SK: ARC SHMU Poprad-Ganovce

- Calibration was performed on the roof
- Calibrated pyranometer was installed in ventilation unit on the solar tracker
- Instant data entered the calibration equation
- Auxiliary data: GLO, DIF, DIR, weather characteristics, AOD and water vapor content, long-wave irradiance
- Altitude 706 m a.s.l.

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# 1. SK : ARC SHMU Poprad-Ganovce

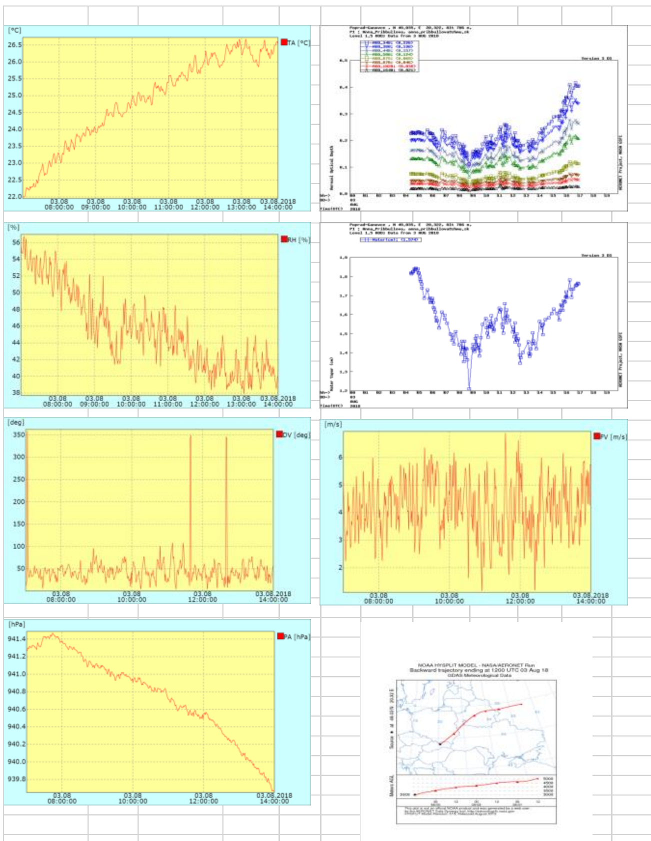
**Calibration by reference to standard pyrheliometer using the sun as source with removable shading disc for the pyranometer**

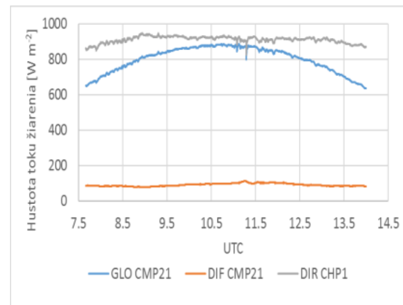
**August 3, 2018**

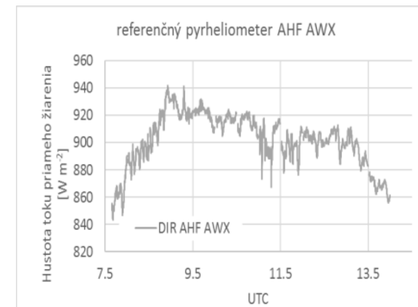
morning Sc, St, Ci, then getting clear, about midday Ci, Cu 1-5/8,wind 1-7 m/s NE, NNE

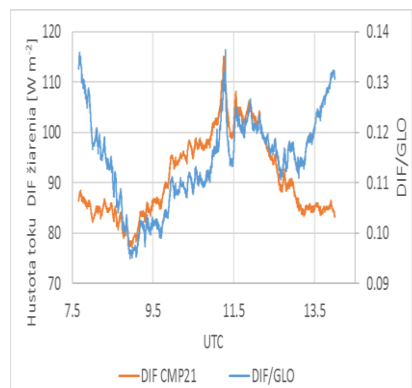
# Calibration by reference to standard pyrheliometer using the sun as source with removable shading disc for the pyranometer

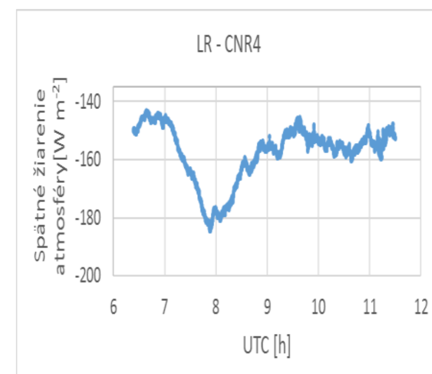
## Monitored auxiliary parameters



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# Calibration by reference to standard pyrheliometer using the sun as source with removable shading disc for the pyranometer

## Technical equipment

- Calibrated pyranometer in ventilation unit (ventilation unit is not necessary in this method because thermal offset does not enter the calibration equation) on solar tracker with automatically (or manually) moving shading ball (shading/unshading stage), dataloger

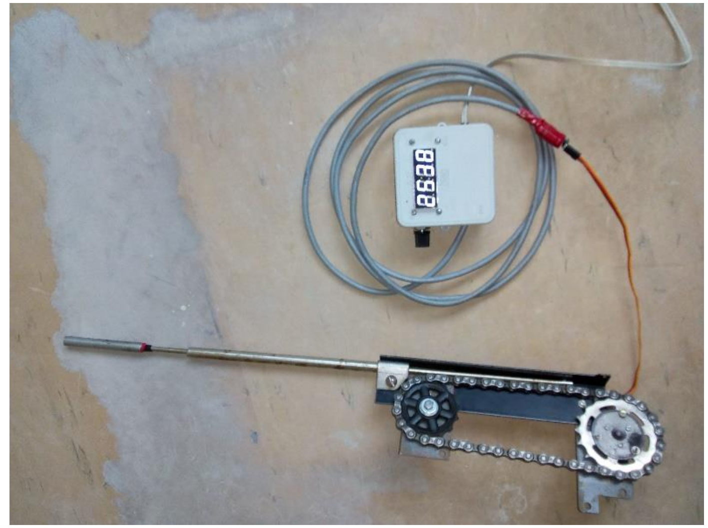
- Reference pyrheliometer AHF AWX with individual control unit 408 M installed on individual solar tracker, PC

# Calibration by reference to standard pyrheliometer using the sun as source with removable shading disc for the pyranometer

**Short description**

- Direct irradiance was measured by the reference pyrheliometer in the IPC measurement mode
- Calibrated pyranometer was shaded for 1 min then unshaded for 1 min, automatic or manual operation can be used
- The direct irradiance incident on horizontally oriented surface from calibrated pyranometer was calculated by subtraction of the last 4 values measured in the period of shading from the last 4 values measured by unshaded calibrated pyranometer
- Data sampling frequency was 5 s, synchronization of the AHF operating PC time and the dataloger time

# Calibration by reference to standard pyrheliometer using the sun as source with removable shading disc for the pyranometer

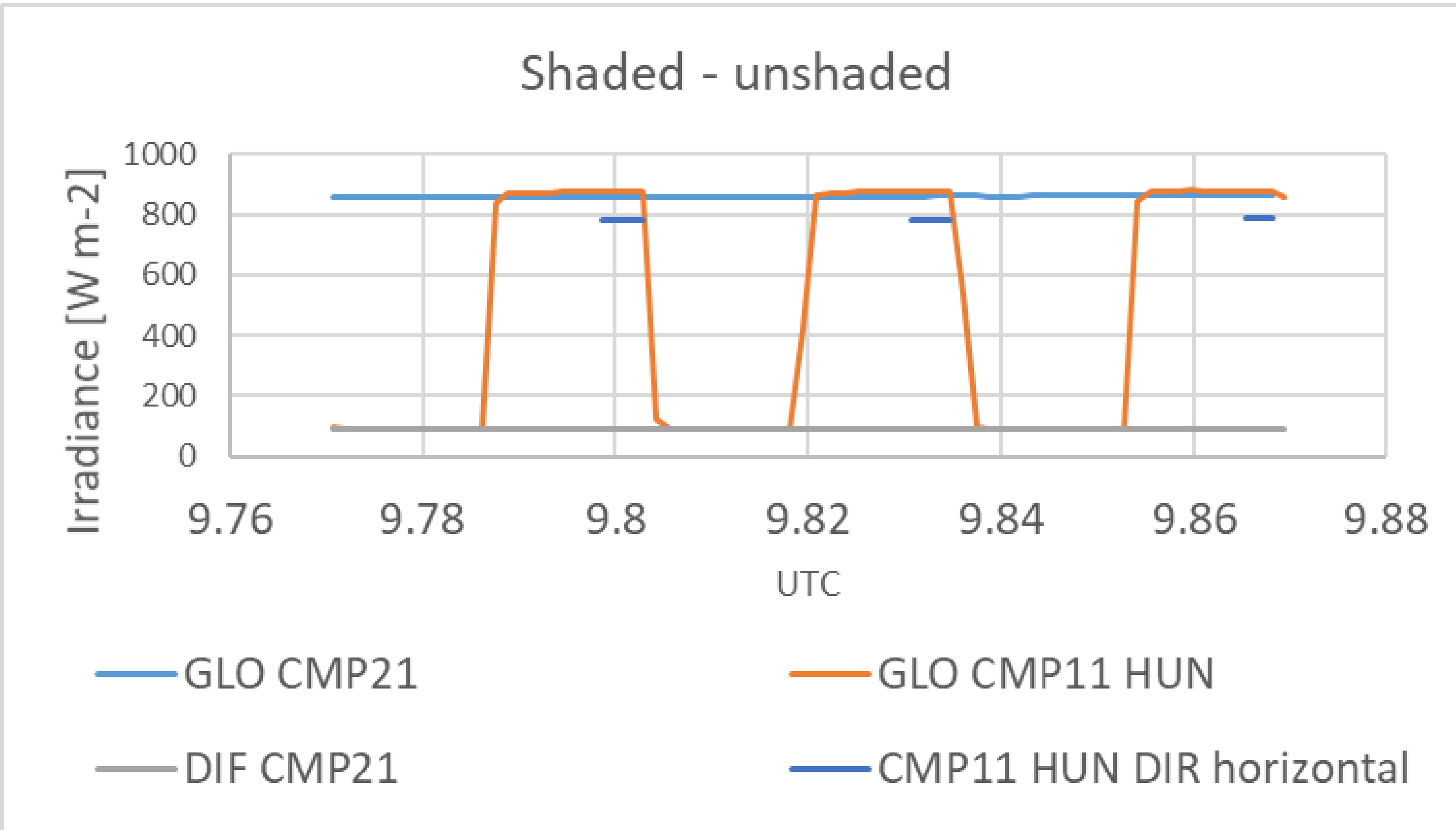


Device for automation of the shading ball position change

Ventilated shaded pyranometer on the solar tracker

Measurements with the cavity pyrheliometers

# Calibration by reference to standard pyrheliometer using the sun as source with removable shading disc for the pyranometer




# Calibration by reference to standard pyrheliometer using the sun as source with removable shading disc for the pyranometer

**Calibration equation**

$$R_i = \frac{mv_i(gl, 131449) - mv_i(diff, 131449)}{I_i * \sin(h_i)}$$

- *Ri* is responsivity of calibrated pyranometer
- $mv_i\ (gl, 131449)$ is voltage output of unshaded calibrated pyranometer
- $mv_i\ (diff, 131449)$ is voltage output of shaded calibrated pyranometer

- $I_i * \sin(h_i)$ is direct irradiance incident on horizontal plane by solar elevation $h_i$

# Calibration by reference to standard pyrheliometer using the sun as source with removable shading disc for the pyranometer

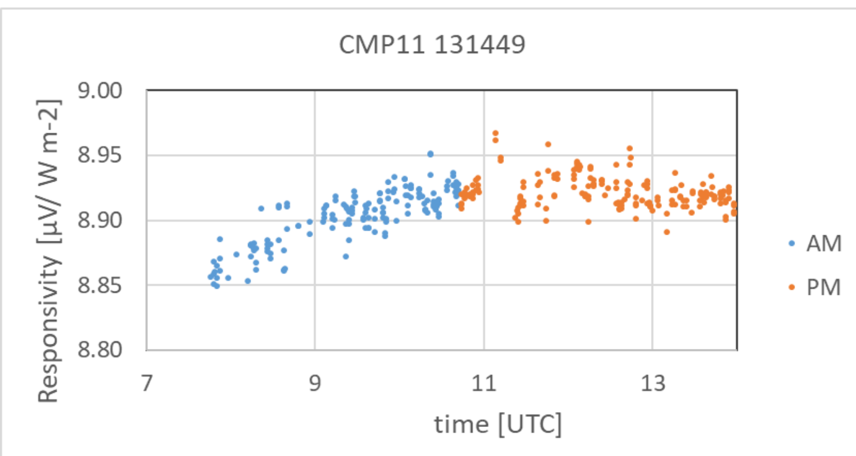
**Condition stability control**

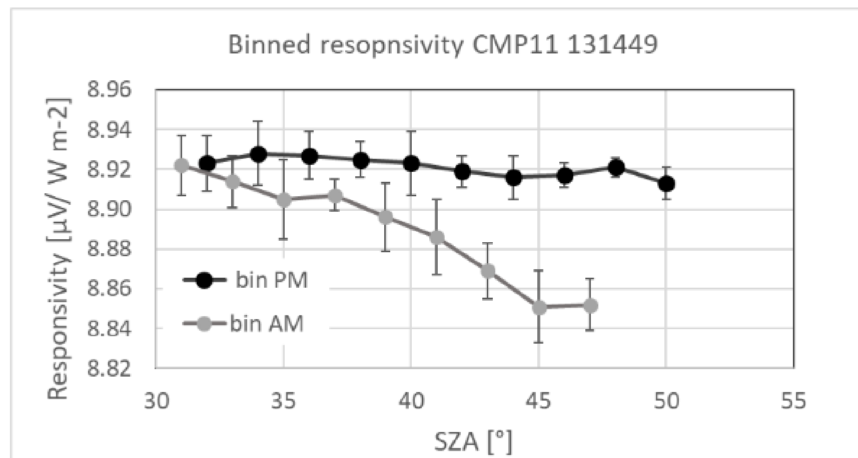
- controlled change in direct and diffuse irradiance between shaded and unshaded phase of the calibrated pyranometer
- when the change in diffuse or direct irradiance exceeded 3 W $m^{-2}$ during the 2 min long period of measurements the data were excluded from the responsivity calculations

# Calibration by reference to standard pyrheliometer using the sun as source with removable shading disc for the pyranometer

## Responsivity

8.891 µV/(W m$^{-2}$) SZA 40 °, extended uncertainty +0.75%; -1.05% for SZA 30 ° - 50°




# Calibration by reference to standard pyrheliometer using the sun as source with removable shading disc for the pyranometer

**Advantages**

- Knowledge of thermal offset of calibrated pyranometer is not needed
- No additional instrument uncertainty, besides reference pyrheliometer, enters the responsivity calculation
- Simple technical equipment needed
- Periodical and frequent shading and revelation of calibrated pyranometer can be organized by automatic shading system

**Disadvantages**

- Stable cloudless atmospheric condition is needed
- Unknown heating/cooling effects of frequently shaded and unshaded pyranometer
- Man-power consuming method without automatic shading system

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# 2. SK : ARC SHMU Poprad-Ganovce

**Calibration by a reference to a standard pyrheliometer and shaded reference pyranometer**

**July 3, 2018**

in the morning 1/8 Sc, later 2/8 Cu - 4/8 Sc,

wind 0.5-6.0 m/s N-NNW

# Calibration by a reference to a standard pyrheliometer and shaded reference pyranometer

**Technical equipment**

- Calibrated pyranometer in ventilation unit on solar tracker, dataloger
- Reference (shaded, diffuse) pyranometer CMP21 in ventilation unit on solar tracker, dataloger
- Usage of ventilation unit is important for reduction of thermal offset effect
- Reference pyrheliometer AHF AWX installed on individual solar tracker , connected to individual operational unit, PC
- Data sampling every 5 s , synchronization of the AHF operating PC time and the dataloger time

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# Calibration by a reference to a standard pyrheliometer and shaded reference pyranometer

**Short description**

- Direct irradiance measured by reference pyrheliometer in the IPC measurement mode

- The calibrated and reference (shaded) pyranometer measurements were corrected for the thermal offset

- The thermal offset was calculated as mean voltage measured by the solar zenith angles bigger than 105 ° on the calibration day

# Calibration by a reference to a standard pyrheliometer and shaded reference pyranometer

**Condition stability control**

- visually checked sky 30° around the solar disc

# Calibration by a reference to a standard pyrheliometer and shaded reference pyranometer

**Short description**

- The reference global irradiance was calculated as sum of direct irradiance of reference pyrheliometer incident on horizontally oriented plain and diffuse irradiance of the reference pyranometer

- The reference shaded pyranometer responsivity should be determined with small uncertainty (well calibrated reference pyranometer)

# Calibration by a reference to a standard pyrheliometer and shaded reference pyranometer

**Calibration equation**

$$R_i = \frac{mv_i(gl, 131449) - off(gl, 1331449)}{I_i * \sin(h_i) + ci * (mv_i(diff, CMP21) - off(diff, CMP21))}$$

*Ri* is responsivity of calibrated pyranometer

$mv_i$ *(gl, 131449)* is voltage output of unshaded calibrated pyranometer

$I_i * \sin(h_i)$ is direct irradiance incident on horizontal plane by solar elevation $h_i$

$mv_i$ *(diff, CMP21)* is voltage output measured by shaded reference pyranometer,

*off(gl, 131449)* is thermal offset of unshaded calibrated pyranometer

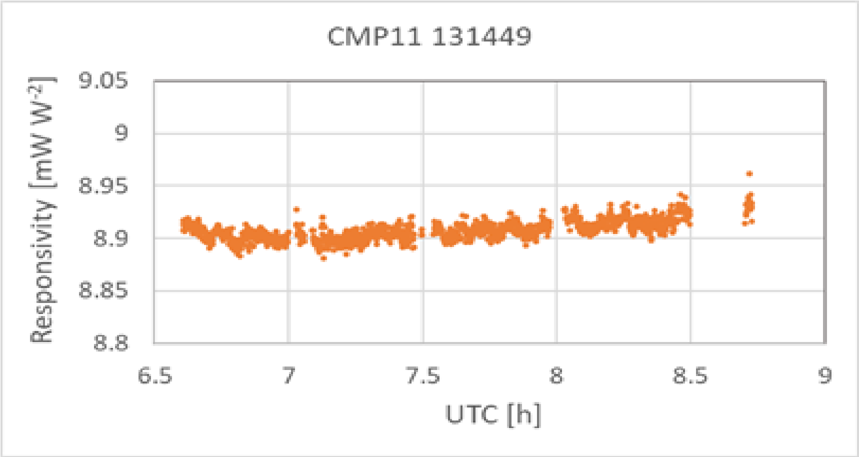
*off(diff, CMP21)* is thermal offset of reference diffuse pyranometer

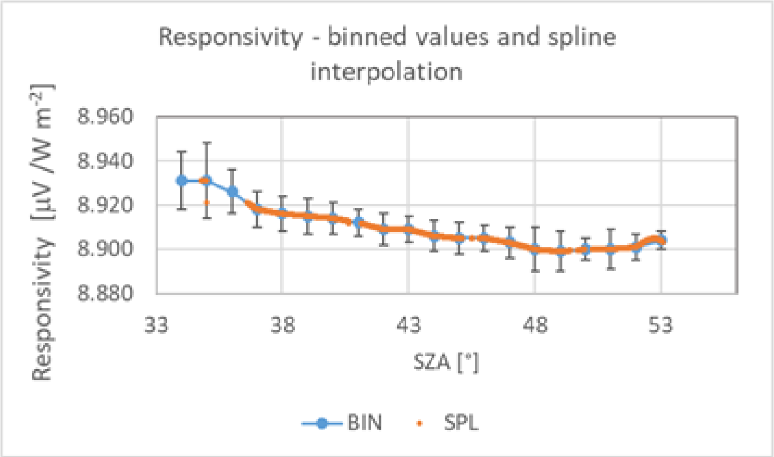
$c_i$ is the **diffuse pyranometer sensitivity**

# Calibration by a reference to a standard pyrheliometer and shaded reference pyranometer

## Responsivity

8.915 μV/(W m$^{-2}$) for SZA 40 ° , uncertainty +1.01%; -0.76% for SZA 33 ° - 53°
thermal offset of calibrated pyranometrer was -1.5 W m$^{-2}$, for the reference pyranometer it was -1.9 W m$^{-2}$





# Calibration by a reference to a standard pyrheliometer and shaded reference pyranometer

## Advantages

- The method is not as sensitive to atmospheric stability as "**Calibration by reference to standard pyrheliometer using the sun as source with removable shading disc for the pyranometer"** method
- Less man-power needed
- Easy calculation of responsivity

## Disadvantages

- Knowledge of thermal offset of shaded reference pyranometer and calibrated pyranometer is necessary, ventilation of both pyranometers can reduce the thermal offset influence on calibration results
- Uncertainty of the reference diffuse pyranometer sensitivity influences calibration results
- Complicated calculation of the responsivity uncertainty

# HU : HMI Budapest

- Calibration was performed close to the ground
- Calibrated and reference pyranometers were in the ventilation units on  the solar trackers
- Instant data entered the calibration equation
- Auxiliary data: GLO, DIF, DIR, weather characteristics
- Altitude 150 m a.s.l.

# 2. HU : HMI Budapest

**“Similarity” method for the calibration of reference pyranometer**

**October 5, 2018**

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# “Similarity” method for the calibration of reference pyranometer

## Technical equipment

- Calibrated pyranometer in ventilation unit on solar tracker in shaded, control position (left) and unshaded calibration position (right)

# “Similarity” method for the calibration of reference pyranometer

## Technical equipment

- Reference absolute pyrheliometer HF; reference shaded pyranometer in ventilation unit on the solar tracker (left)
- Campbell Scientific CR3000 data logger with Agilent multimeter (right), PC
- Sampling every 3s
- 30 s averaging time-window

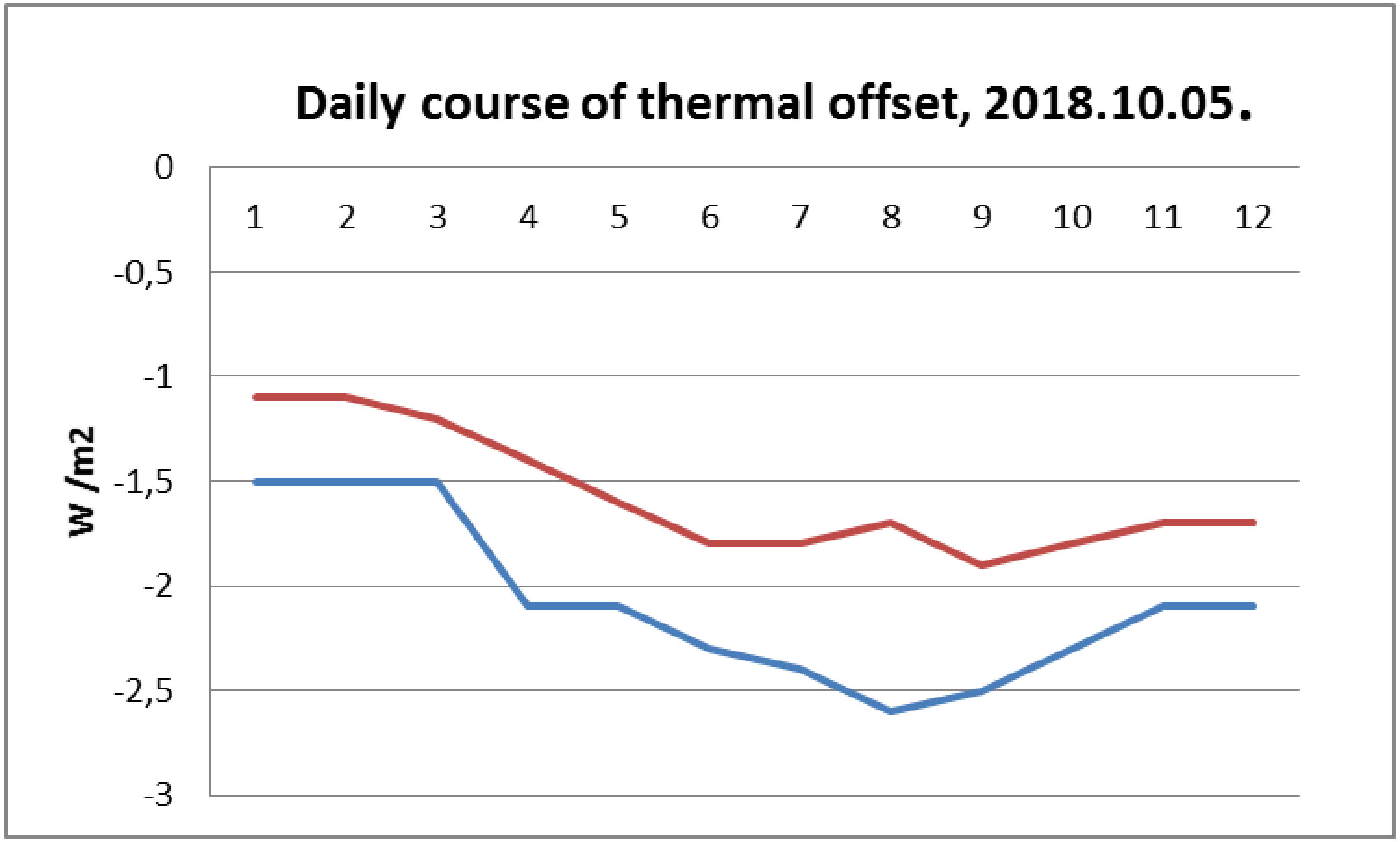
# “Similarity” method for the calibration of reference pyranometer

**Short description**

- The calibration procedure has two phases, the measurement and control period
- The beginning of the series is the control phase (about 20 min) when the reference pyrheliometer is shaded and the calibrated pyranometer is shaded to determine the regression relation between the reference and the calibrated pyranometer in the diffuse mode. The transfer or “similarity” constant is the ratio between the voltage output of the calibrated and the reference pyranometer
- In the measurement phase (about 40 min) the calibrated pyranometer is unshaded, voltage output of the control diffuse pyranometer multiplied by the transfer constant is subtracted from the voltage outputs of the calibrated pyranometer – resulting voltage is caused by the horizontal direct irradiance
- Thermal offset is supposed to be compensated (pyranometers in ventilation unit)

# “Similarity” method for the calibration of reference pyranometer

**Measured thermal offset**




# “Similarity” method for the calibration of reference pyranometer

**Condition stability control**

- Using the standard deviation of 30 s averages which where calculated for every measured component

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# “Similarity” method for the calibration of reference pyranometer

## Calibration equation

$$R_i = \frac{mv_i(gl,131449) - mv_i(diff,131449)}{I_i * \sin(h_i)}, \quad mv_i(diff,13449) = c_i * mv_i(diff,131448),$$

*Ri* is responsivity of calibrated pyranometer

$mv_i\ (gl,\ 131449)$ is voltage output of unshaded calibrated pyranometer

$I_i * \sin(h_i)$ is direct irradiance incident on horizontal plane by solar elevation $h_i$

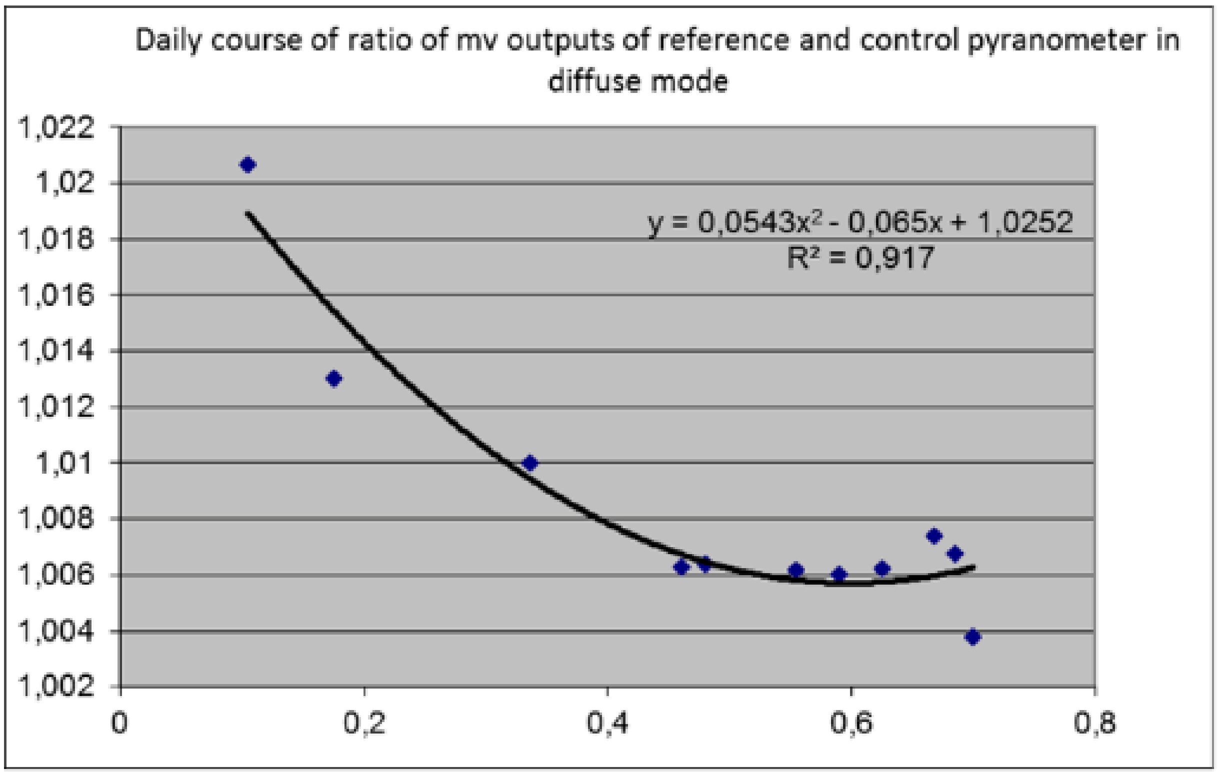
$mv_i\ (diff,\ 131449)$ is voltage output measured by shaded calibrated pyranometer

$mv_i\ (diff,\ 131448)$ is voltage output measured by shaded reference pyranometer,

$c_i$ is the regression coefficient determined during shading phase of measurement

# "Similarity" method for the calibration of reference pyranometer

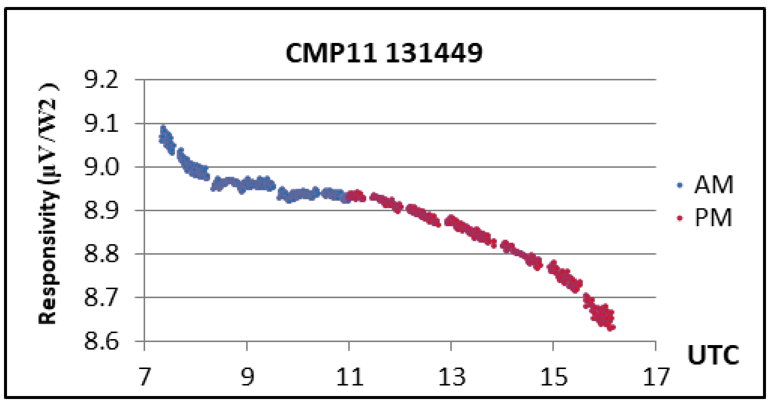
**Daily course of the c parameter**

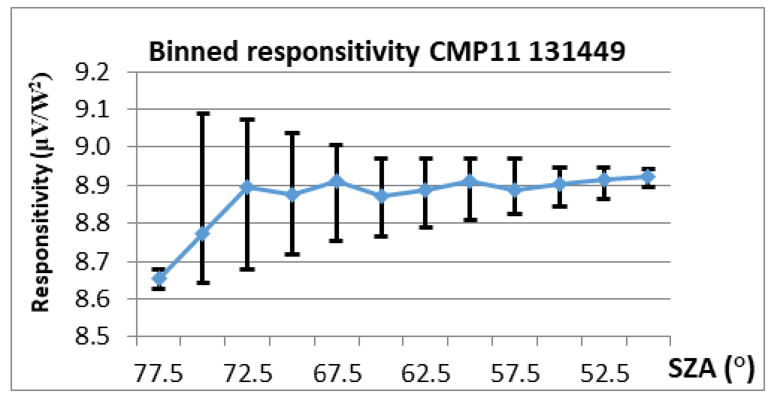



# “Similarity” method for the calibration of reference pyranometer

## Responsivity

8.921 μV/(W m$^{-2}$), for SZA 50°;  8.898 μV/(W m$^{-2}$) for SZA 50° - 70°




# "Similarity" method for the calibration of reference pyranometer

**Advantages**

- not man-power consuming method because after the control phase of series the operation of instruments are working automatically
- large number of data which is giving possibility for statistical analysis.
- the reference shaded pyranometer is not needed to be calibrated
- the method is not very sensitive to the stability of atmospheric condition.

**Disadvantages**

- it is recommended to use a reference pyranometer which has very similar behaviour compared to the calibrated one - ideal if the pyranometers have serial numbers which are very close  each  to other
-  using of additional simple solar tracker to keep the shade ball in position for the calibrated pyranometer in control phase can give a more comfortable way for calibration but using it is not mandatory

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# CZ : SOO Hradec Králové CHMI

- Calibration was performed on the SOO roof
- Calibrated and reference pyranometers were in the ventilation unit on the solar tracker
- 1 min AVG data entered the calibration equation
- Auxiliary data: GLO, DIF, DIR, weather characteristics
- Altitude 235 m a.s.l.

# 3. CZ : SOO Hradec Králové CHMI

**Modified method Calibration by reference to standard pyrheliometer using the sun as source with removable shading disc for the pyranometer**

**August 20, 2018**

1 - 2/10 of Ci, Cu

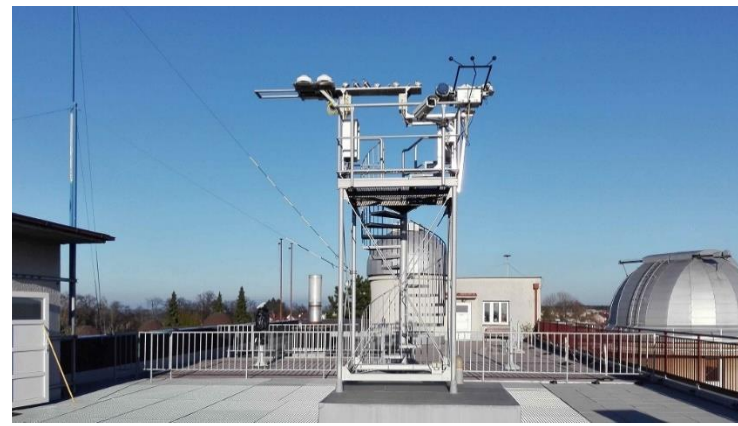


# Modified method Calibration by reference to standard pyrheliometer using the sun as source with removable shading disc for the pyranometer

**Technical equipment**

- calibrated pyranometer in ventilation unit on solar tracker with shading ball, multimeter Agilent , on the roof
- shaded reference pyranometer (shading ball) in ventilation unit on the solar tracker, multimeter Agilent , on the roof
- reference cavity pyrheliometer on separate solar tracker connected to separate control unit with dataloger placed at the balcony

# Modified method Calibration by reference to standard pyrheliometer using the sun as source with removable shading disc for the pyranometer



Pyranometers on the roof of the SOO HK CHMI

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# Modified method Calibration by reference to standard pyrheliometer using the sun as source with removable shading disc for the pyranometer

**Short description**

- Calibrated pyranometer was shaded for about 8 min. The regression relation (linear regression with  2 parameters: slope and intercept) between the voltages representing the diffuse irradiance measured by the calibrated and the reference pyranometer was set.
- Calibrated pyranometer was unshaded for about 3 - 4 series of the AHFmeasurements in the IPC mode (1 – 1.3 h). The direct irradiance incident on horizontally oriented plane  was calculated by subtraction of diffuse irradiance of calibrated pyranometer (calculated from the diffuse irradiance of the reference pyranometer using  known regression relation) from the global  irradiance measured by calibrated pyranometer.

# Modified method Calibration by reference to standard pyrheliometer using the sun as source with removable shading disc for the pyranometer

**Short description**

- The regression relation is derived from data measured in two periods of shading – at the beginning and at the end of every period with unshaded calibrated pyranometer.
- The reference direct irradiance incident on horizontally oriented surface was calculated from direct irradiance measurements of reference pyrheliometer
- AHF data sampling interval was 1 s , pyranometer data sampling interval was 5 s
- Thermal offset is not evaluated (pyranometers are in ventilation units)

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# Modified method Calibration by reference to standard pyrheliometer using the sun as source with removable shading disc for the pyranometer

**Stability control**

- Standard deviation of 1 min AVG of direct irradiance  is evaluated and serves as the measure of data quality.
-  The  1  min AVG of the direct irradiance incident on horizontally oriented plane from the reference AHF and from pyranometers are plotted in the graph. The individual points departing significantly  each from other aer excluded from the responsivity calculation.

# Modified method Calibration by reference to standard pyrheliometer using the sun as source with removable shading disc for the pyranometer

**Calibration equation**

$$R_i = \frac{mv_i(gl,131449) - mv_i(diff,131449)}{I_i * \sin(h_i)},\qquad mv_i(diff,13449) = c_i * mv_i(diff,CM21) + d_i,$$

*Ri* is responsivity of calibrated pyranometer

$mv_i$ *(gl, 131449)* is voltage output of unshaded calibrated pyranometer

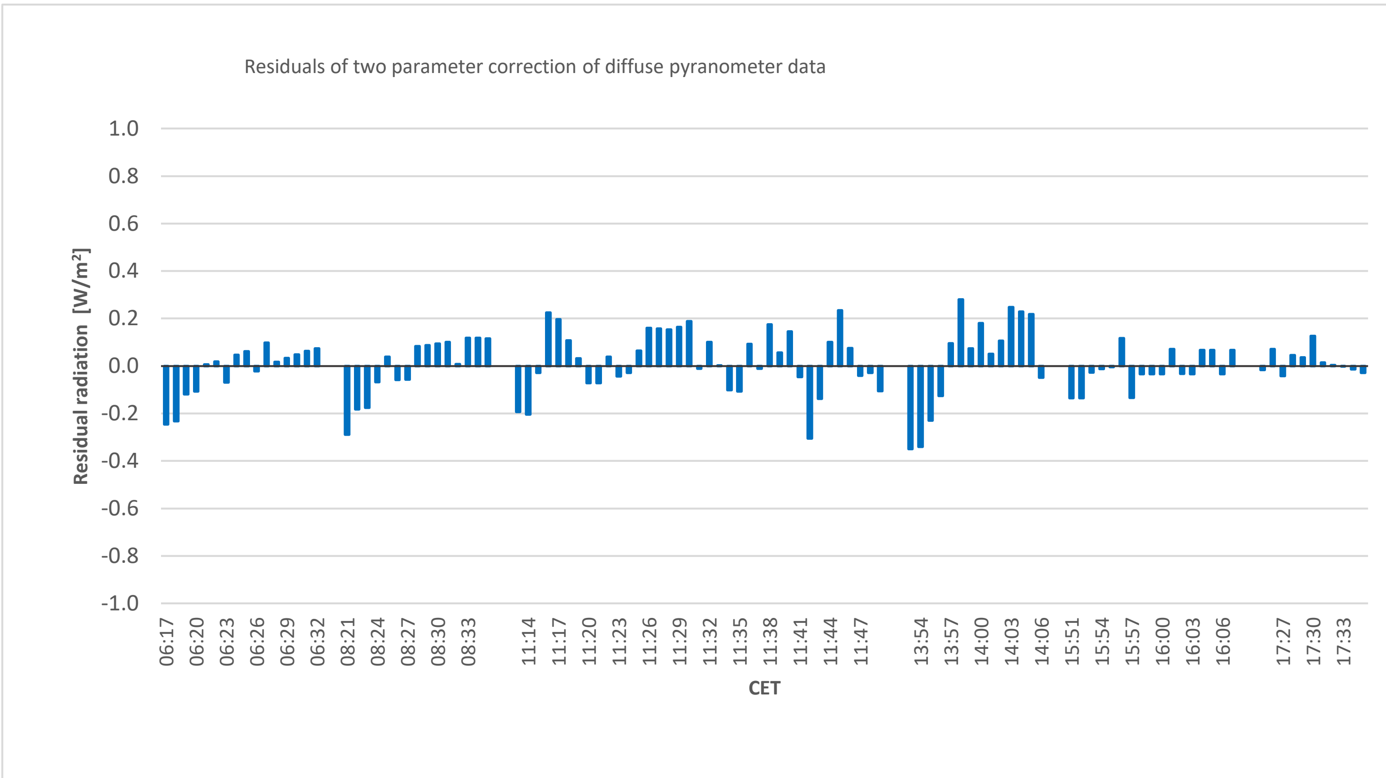
$mv_i$ *(diff, 131449)* is voltage output measured by shaded calibrated pyranometer

$I_i * \sin(h_i)$ is direct irradiance incident on horizontal plane by solar elevation $h_i$

$mv_i$ *(diff, CM21)* is voltage output measured by shaded auxiliary pyranometer

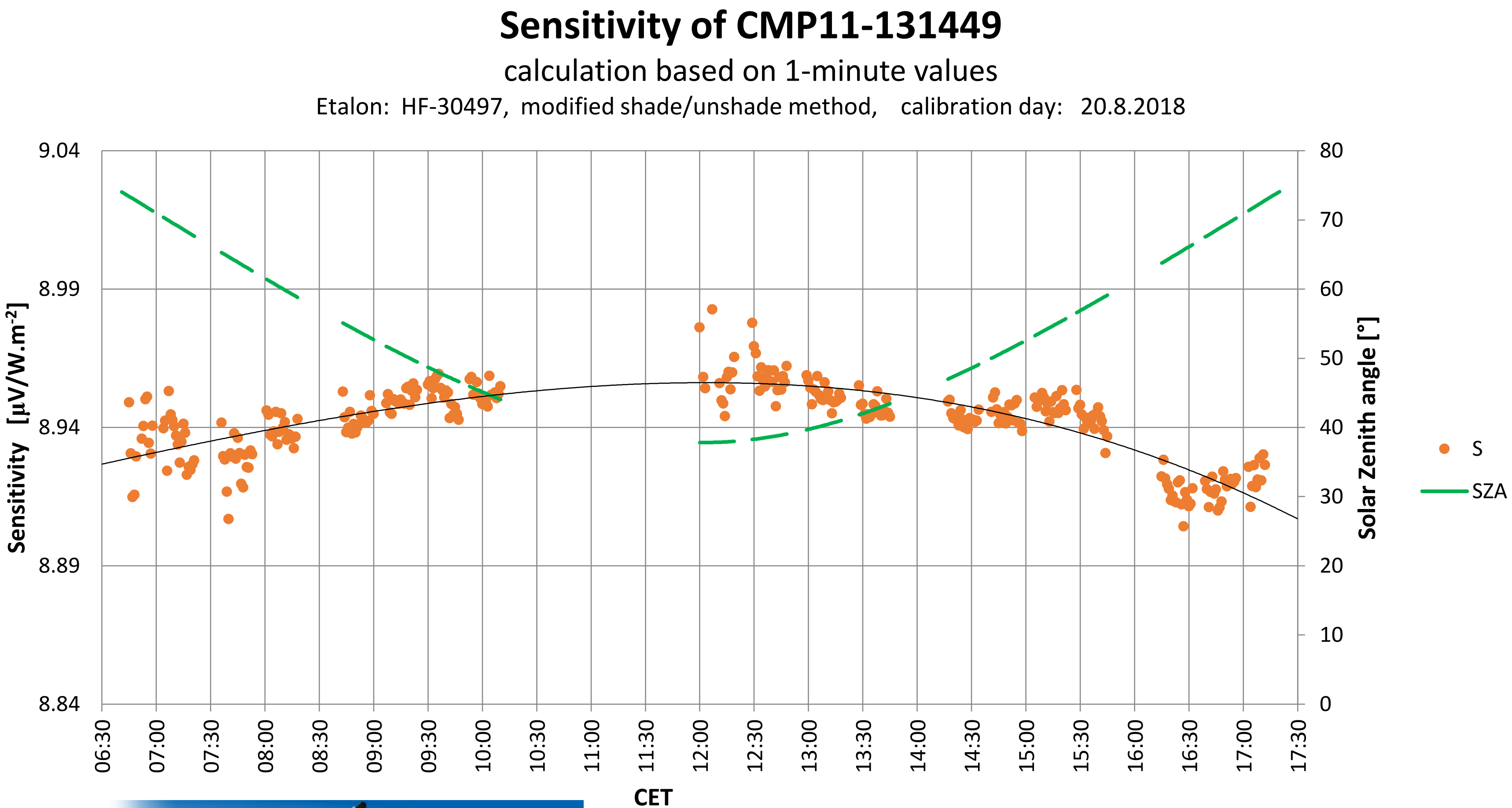
$c_i$ , $d_i$ are the regression coefficients determined during “shading” phase of measurement

# Modified method Calibration by reference to standard pyrheliometer using the sun as source with removable shading disc for the pyranometer




Residulas of the regression relations between the calibrated and the reference diffuse pyranometers.

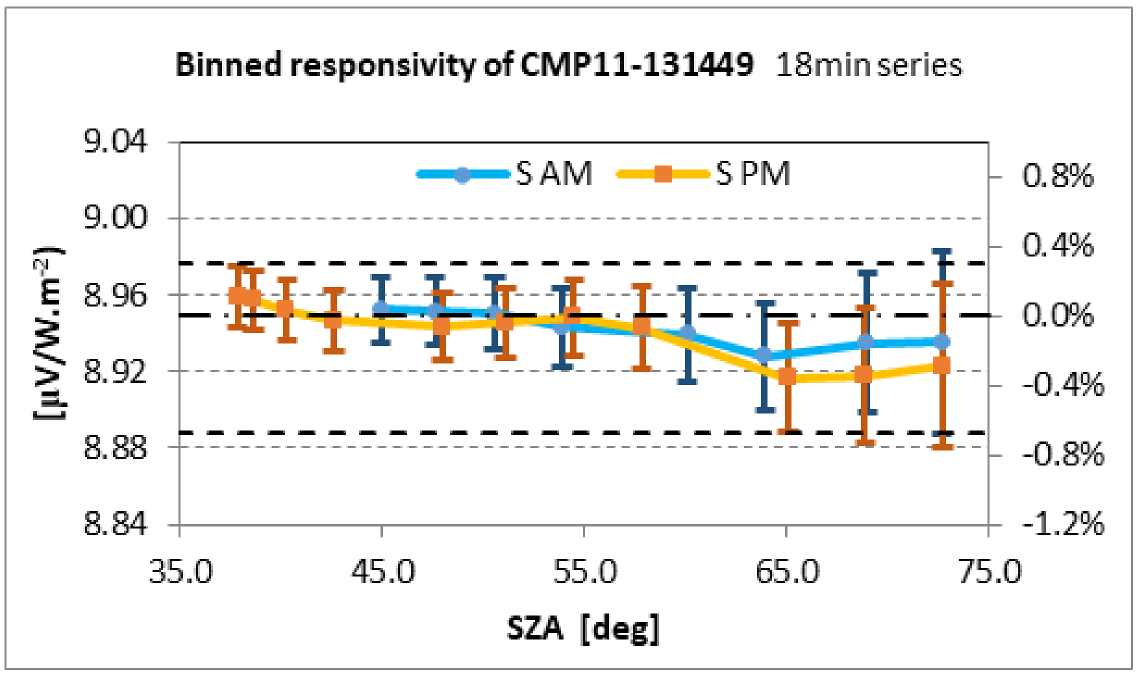
# Modified method Calibration by reference to standard pyrheliometer using the sun as source with removable shading disc for the pyranometer




# Modified method Calibration by reference to standard pyrheliometer using the sun as source with removable shading disc for the pyranometer

**Responsivity** 8.95 μV/(W $m^{-2}$) by SZA 46 °

**$u_c$ = +0.30% .. - 0.67%** (SZA= 38°- 65°), **k=2**




# Modified method Calibration by reference to standard pyrheliometer using the sun as source with removable shading disc for the pyranometer

**Advantages**

- not man-power consuming because (after the control phase of series the instruments are working automatically), operation of instruments is comfortable
- the method is not very sensitive to the stability of atmospheric condition
- Ttwo regression constants simulate very well the behaviour of shaded pyranometer in the phase of unshading, including the LW influence

**Disadvantages**

- complicated uncertainty calculation
- complicated calculation of regression parameters

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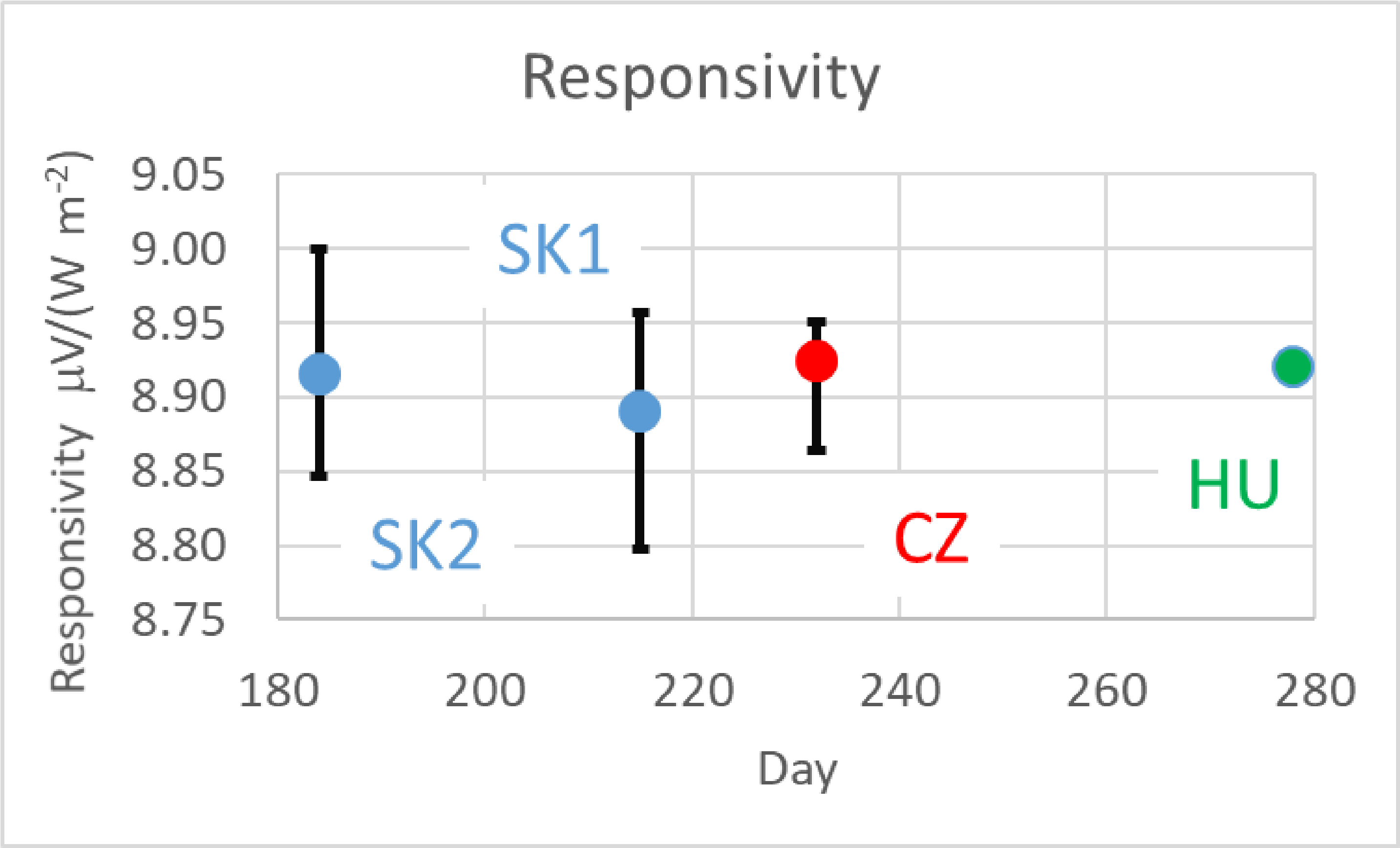
# Conclusions




# Conclusions

The same pyranometer was calibrated  at 3 NRC using 4 methods by different:

- calibration equation
- altitude and meteorological condition
- technical equipment
- approach to the thermal offset evaluation (ventilation units were used for all pyranometers)
- ranges of solar zenith angles
- sampling periods
- stability control

**Responsivity values were  in the range of 8.891 – 8.950 $\mu$V/(W m$^{-2}$).**

# Thank you for the attention...

## References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