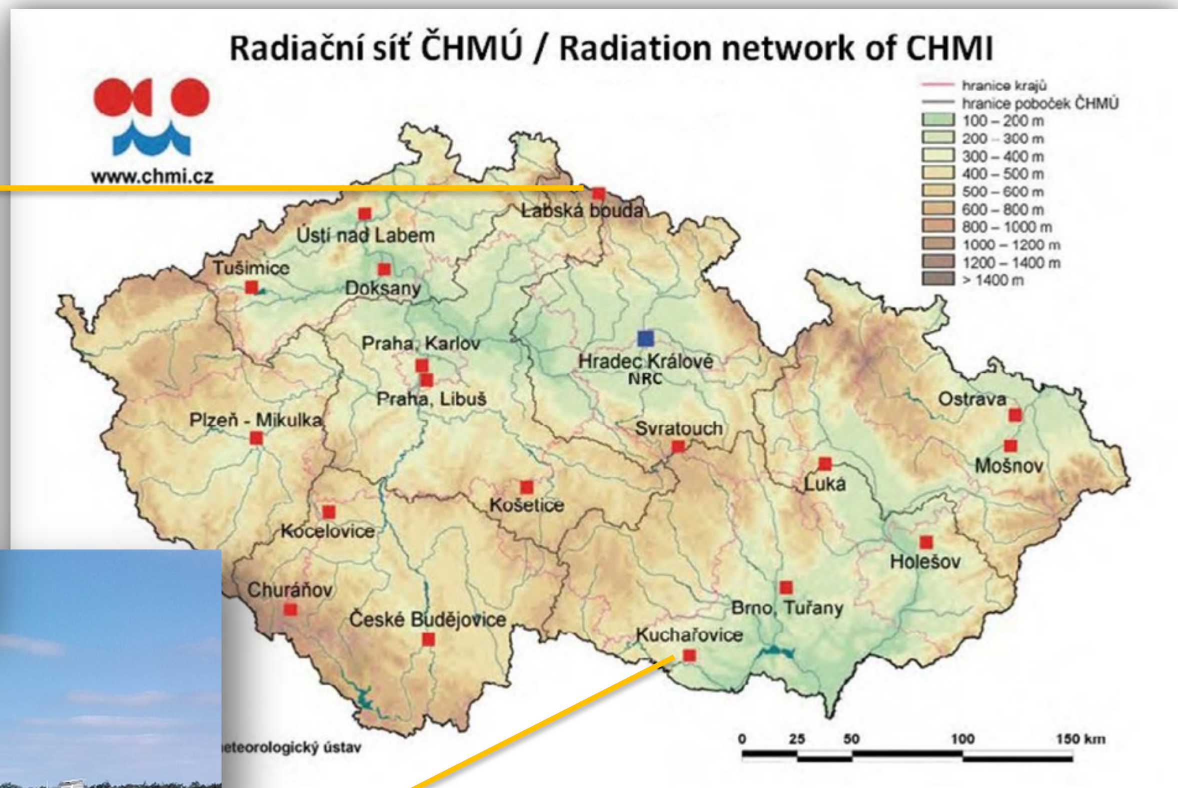
CZECH
HYDROMETEOROLOGICAL
INSTITUTE

The Modification of Shade/Unshade Method of Std Pyranometer Calibration Sources of the Uncertainty

Jiri Pokorny
jiri.pokorny@chmi.cz

Davos, IPC-XIII, 2021

- 19 stations, Global radiation, professional staff
- 6 of them with Diffuse radiation
- 1 (SOO HK) with SW reflected, LW up/dn, UV total/spectral radiation



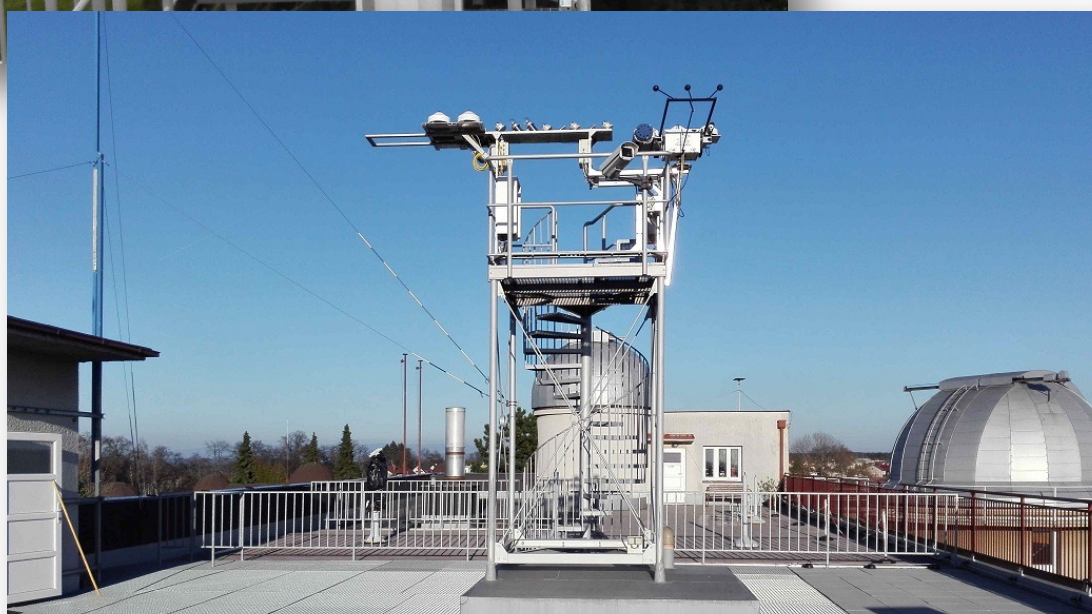
Field pyranometer DAS :

- usually 2-sec sampling
- 1-minute averages

SOO Hradec Kralove (NRC)

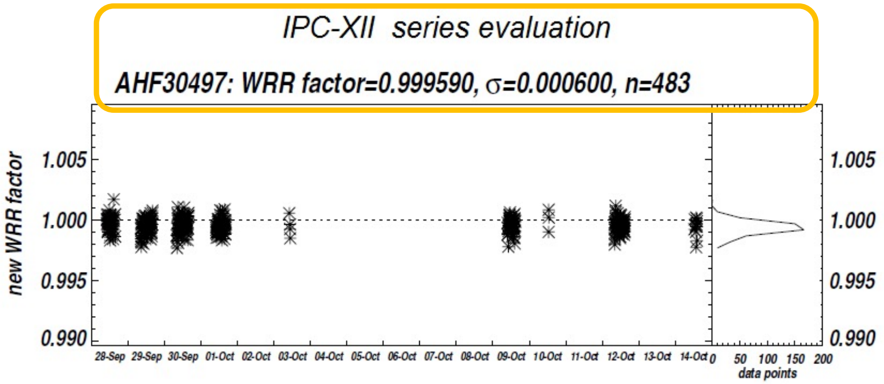
Top view layout

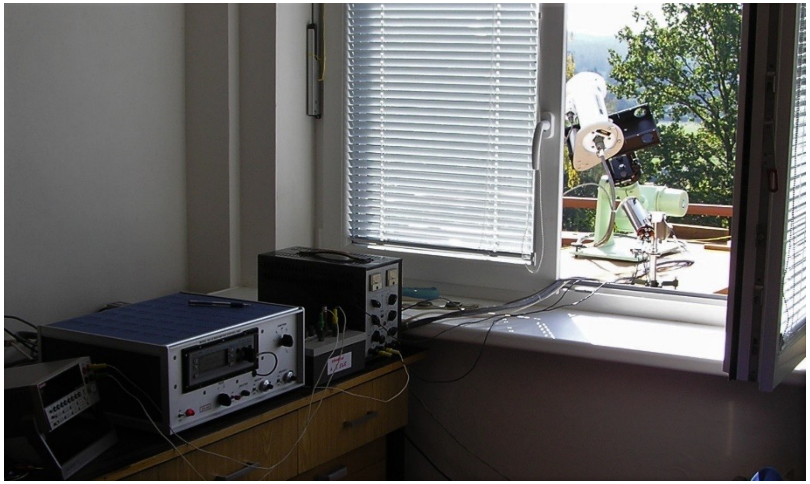
NIP (CH1)		SPUV		on 2AP operational
LWDN (CGR4)	DIF (CM11)	GLB (CMP21)		
Sunshine duration	(SD5) . . . (SD6)			calibration
(CMp11)	UVB	(CMp11)		
(CMp11)	UVB	(CMp11)		



SOO facilities
on the roof of the
Astronomical Observatory

Primary Standard - Radiometer HF 30497





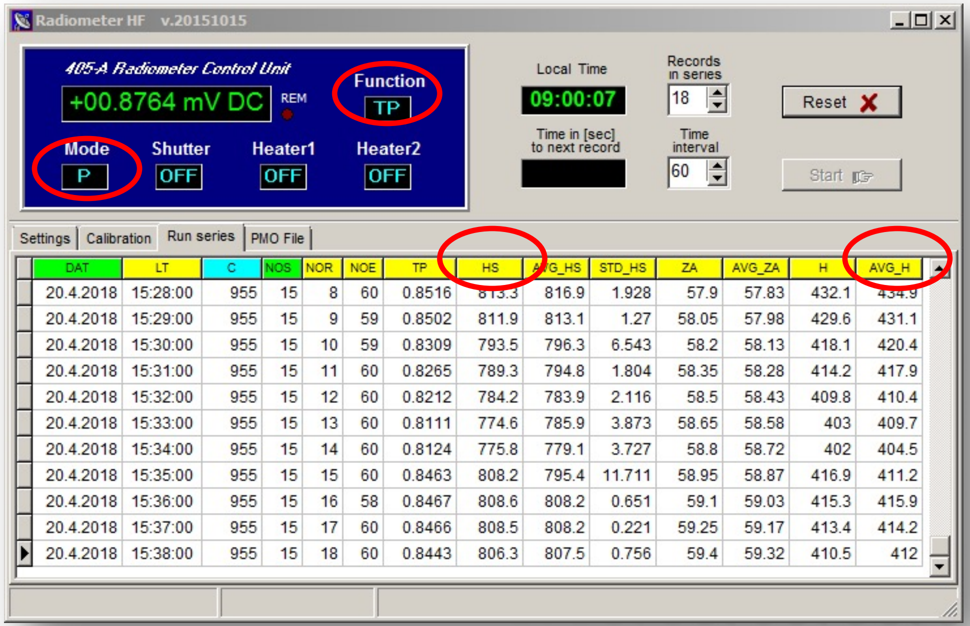
Calibration day at the SOO HK

AHF 30497 WRR factor (history)

Instrument	IPC-VIII	IPC-IX	IPC-X	IPC-XI	IPC-XII
AHF30497		0.997740	0.999350	0.999623	0.999589

HF 30497 results from IPCs, PMO Davos:

- stable sensitivity confirmed
- U_{95} = 0.22 % (k=2, scale WRR)



DAT	LT	C	NOS	NOR	NOE	TP	HS	AVG_HS	STD_HS	ZA	AVG_ZA	H	AVG_H
20.4.2018	15:28:00	955	15	8	60	0.8516	813.3	816.9	1.928	57.9	57.83	432.1	434.9
20.4.2018	15:29:00	955	15	9	59	0.8502	811.9	813.1	1.27	58.05	57.98	429.6	431.1
20.4.2018	15:30:00	955	15	10	59	0.8309	793.5	796.3	6.543	58.2	58.13	418.1	420.4
20.4.2018	15:31:00	955	15	11	60	0.8265	789.3	794.8	1.804	58.35	58.28	414.2	417.9
20.4.2018	15:32:00	955	15	12	60	0.8212	784.2	783.9	2.116	58.5	58.43	409.8	410.4
20.4.2018	15:33:00	955	15	13	60	0.8111	774.6	785.9	3.873	58.65	58.58	403	409.7
20.4.2018	15:34:00	955	15	14	60	0.8124	775.8	779.1	3.727	58.8	58.72	402	404.5
20.4.2018	15:35:00	955	15	15	60	0.8463	808.2	795.4	11.711	58.95	58.87	416.9	411.2
20.4.2018	15:36:00	955	15	16	58	0.8467	808.6	808.2	0.651	59.1	59.03	415.3	415.9
20.4.2018	15:37:00	955	15	17	60	0.8466	808.5	808.2	0.221	59.25	59.17	413.4	414.2
20.4.2018	15:38:00	955	15	18	60	0.8443	806.3	807.5	0.756	59.4	59.32	410.5	412

Screen of the HF 30497 control program

Pyranometer calibration by reference to Std pyrheliometer with Auxiliary diffusion pyranometer (modified Shade/Unshade method)

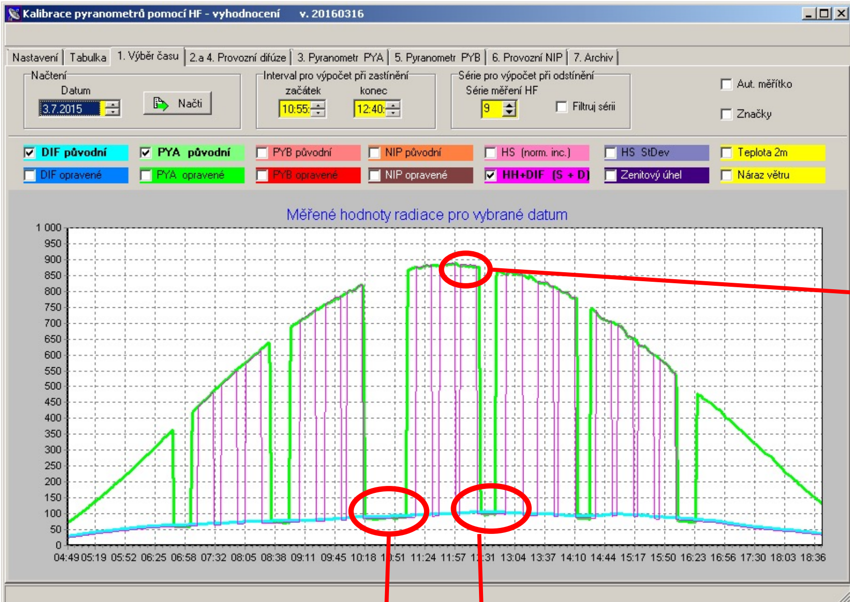
Motivation:
- lack of the „perfect calibration“ days in CZ
- need of using days with clouds
- solving the problem of unstable diffusion (while DNI is stable)
- Sh/Unsh : transition to unshade must be long enough with respect to pyr. time constant

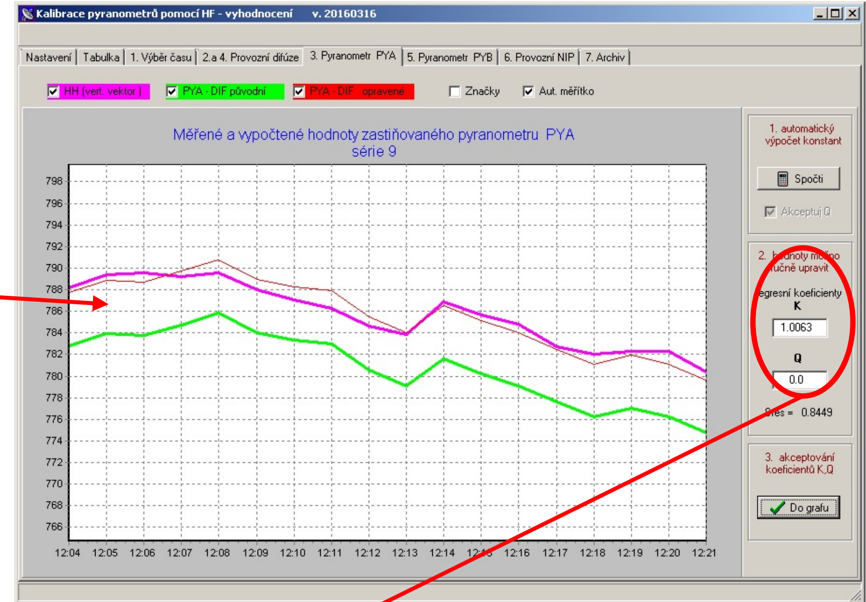
Solution:
- creating auxiliary diffusion variable (**DIF**calc)
- in the Shade phase – to „teach“ **DIF**calc to show the values of **Pyranometer under Test** shaded -> lin. regression -> K, Q. Done in the post processing!
  In fact, two Shade phases are used for regression: before and after **each** Unshade sequence
- using K, Q during corresponding **PuT** unshaded sequence
  treating **DIF**calc as if it was **PuT** shaded

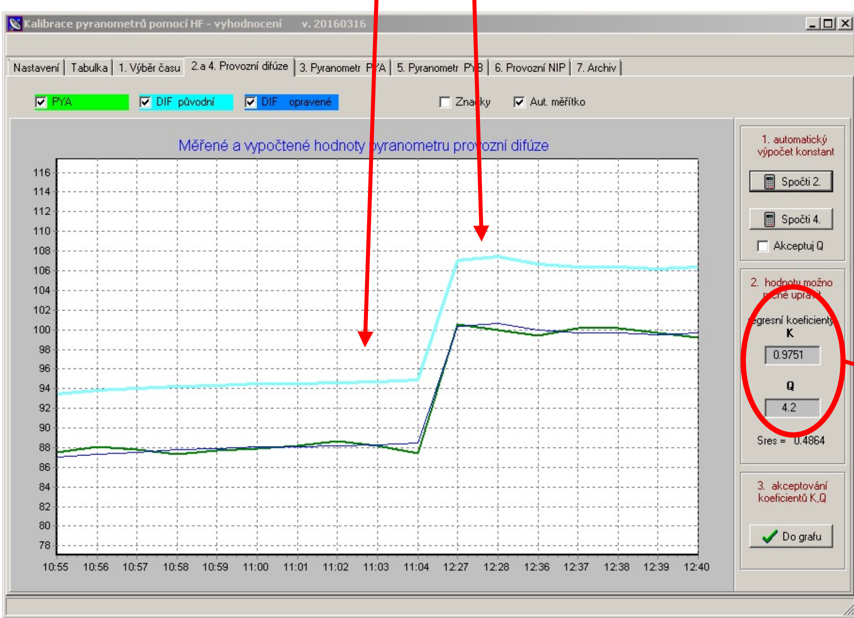
To the comliance with CIMO Guide 8/2006, Chapter 7 (quotation to the calibration method):

7.3.1.2 **BY REFERENCE TO A STA NDARD PYRHELIOMETER**

This method is simlar to the method of the preceding paragraph except that the diffuse radiation is measured by the same pyranometer. The direct component is eliminated temporarily from the pyranometer by shading the whole outer dome of the instrument as in section 7.3.1.1. The period required for occulting depends on the steadiness of the radiation flux and the response time of the pyranometer, including the time interval needed to bring the temperature and long-wave emission of the glass dome to an equilibrium; three to 10 minutes should generally be sufficient.







K, Q : here, final coefficients of lin. regression

$$H_s * \cos(SZA) = \mathbf{K} * (GLB_{unsh} - GLB_{sh}) + \mathbf{Q}$$

K, Q : here, auxiliary coefficients, evaluated by lin. regression

$$GLB_{sh} \cong DIF_{calc} = k * DIF + q$$

… to previous snap

Basic equation

$$S_i = \frac{S_0 * G_i - S_0 * D_i}{N_i * \cos(Z_i)} = \frac{U_{Gi} - U_{Di}}{N_i * \cos(Z_i)} \qquad \text{(Eq. 1)}$$

transformed for regression

$$N_i * \cos(Z_i) = \frac{S_0}{S_i} * (G_i - D_i) \quad (+\ Q\ )$$

$\frac{S_0}{S_i} \rightarrow$ K

Calibration of the Secondary standard pyranometer

The basic equation for sensitivity evaluation for "Shade/unshade" calibration method

$$S_i = \frac{S_0 * G_i - S_0 * D_i + S_0 * D_{res}}{N_i * \cos(Z_i)} = \frac{U_{Gi} - U_{Di} + U_{Dres}}{N_i * \cos(Z_i)} \quad \text{(Eq. 1)}$$

Transformation for graphic interpretation, where the rate can be expressed as a deviation in [%]

$$\frac{S_i}{S_0} = \frac{G_i - D_i + D_{res}}{N_i * \cos(Z_i)}$$

D_{res} ... *residuals of two parameter regression* (Eq.1a)

$$D_{res} = D_i - \left(K_j * D_{aux,i} + Q_j\right) \qquad \overline{D_{res}} \approx 0 \quad \text{(Eq.1aa)}$$

Uncertainty sensitivity coefficients calculation

$$c_{i,UG} = \frac{\partial Si}{\partial UGi} = \frac{1}{N_i * \cos(Z_i)} \quad \text{(Eq. 1b)}$$

$$c_{i,UD} = \frac{\partial Si}{\partial UDi} = \frac{-1}{N_i * \cos(Z_i)} \quad \text{(Eq. 1c)}$$

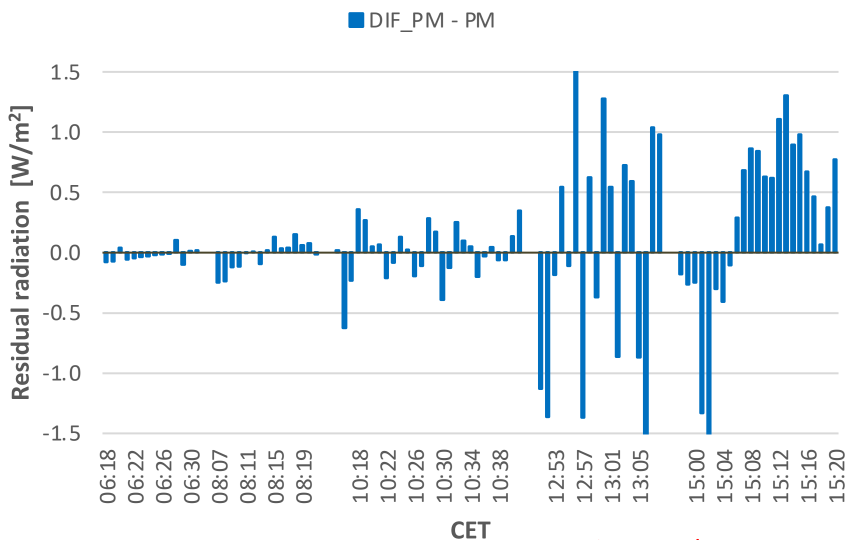
$$c_{i,UDres} = \frac{\partial Si}{\partial UDres} = \frac{1}{N_i * \cos(Z_i)} \quad \text{(Eq. 1d)}$$

$$c_{i,N} = \frac{\partial Si}{\partial Ni} = \frac{-(U_{Gi} - U_{Di})}{N_i^2 * \cos(Z_i)} \quad \text{(Eq. 1e)}$$

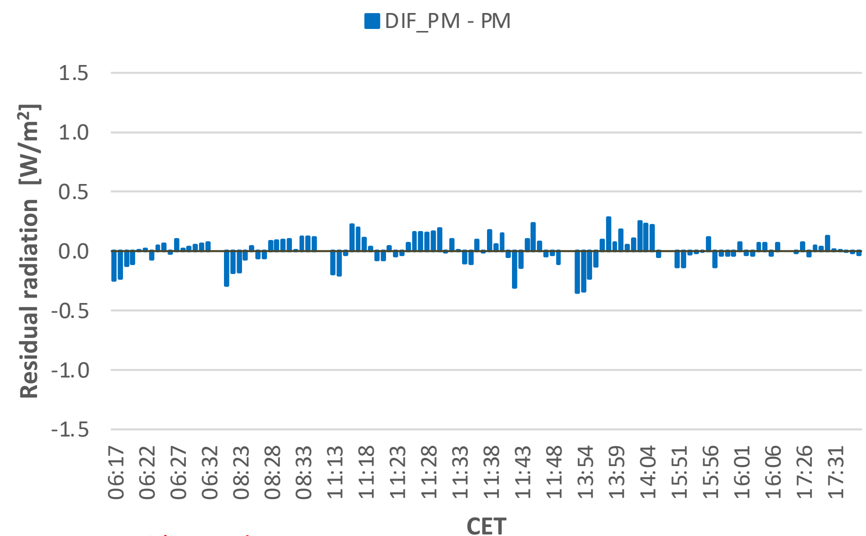
$$c_{i,Z} = \frac{\partial Si}{\partial Zi} = \frac{(U_{Gi} - U_{Di}) * tg(Z_i)}{N_i * \cos(Z_i)}$$

$D_i \approx$ const. (Eq. 1f)

Shaded CMP11-131449 (Hung.) modelling
Residuals of two parameter correction of diffuse pyranometer data
(acquired during the intervals of shading on calibration day 13.8.2018)

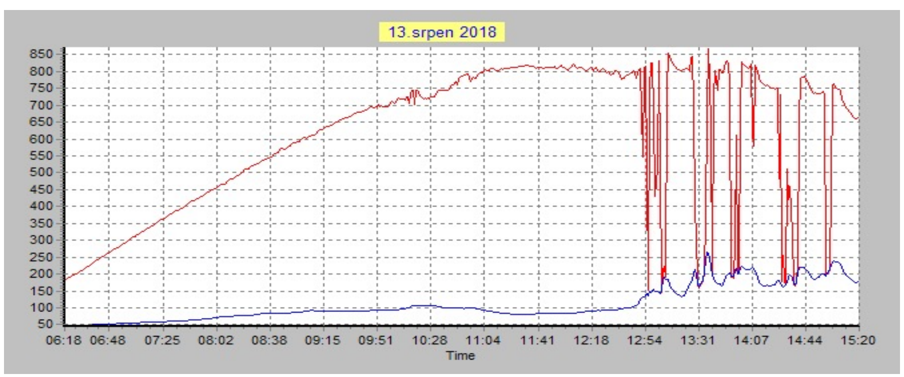


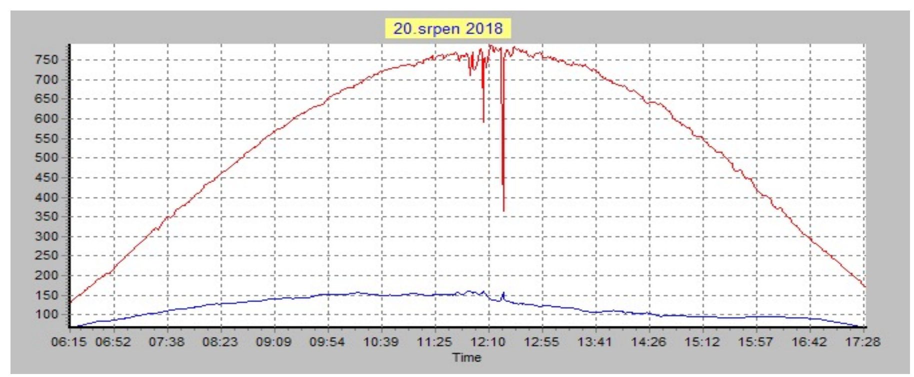
Shaded CMP11-131449 (Hung.) modelling
Residuals of two parameter correction of diffuse pyranometer data
(acquired during the intervals of shading on calibration day 20.8.2018)



Time marks on upper snaps are not equidistant !

Daily run of the global and diffuse radiation on the corresponding days





Uncertainty calculator

Pyranometer calibration – shade/unshade method with auxiliary diffusion pyranometer

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
3	*Enter values into the yellow cells in the table*															
4																
5		**Value**	**U**			**Value**	**U [%]**	**U**	**Offset**	**a=U+Offset**	**distrib.**	**u**	**c**	**c * u**	(c * u)^2	**% of Sum**
6	S_0 [µV/W.m^{-2}]	8.79														
7	D_{res} [W.m^{-2}]	0.00	0.00		U_{Dres} [µV]	0.00		0.00			**N**	0.000	0.001356	0.00000	0.00E+00	0.0%
8	**GLB** [W.m^{-2}]	800			U_G [µV]	7032.0	0.003	0.21	3.5	3.711	**R**	2.143	0.001356	0.00291	8.45E-06	35.3%
9	**DIF** [W.m^{-2}]	60			U_D [µV]	527.4	0.003	0.02	0	0.016	**R**	0.009	0.001356	0.00001	1.54E-10	0.2%
10	LW_{off} [W.m^{-2}]	-3			U_{LW} [µV]	-26.4		-26.37								
11	**Z** [deg]	35	0.003		**Z** [radians]	0.610865		0.000052			**R**	0.00003	5.733	0.00017	3.00E-08	2.1%
12	**Tilt** [deg]	0	0		**Tilt** [radians]	0.000000		0.000000			**R**	0.00000		0.00000	0.00E+00	0.0%
13	**NIP** [W.m^{-2}]	900			**N** [W.m^{-2}]	900	0.101%	0.91			**R**	0.525	0.009803	0.00514	2.65E-05	62.5%
14	Accept WRR/SI	(Y or N)	n		**WRR/SI**	1	0.180%	0.00			*(=2σ)*	0.000	0.009803	0.00000	0.00E+00	0.0%
15													SUM	0.00824	3.49E-05	
16	**S** [µV/W.m^{-2}]		**8.823**	**± 0.006**		≈ ±	0.07%						SQRT = u_B		0.006	
17																
18																
19																
20	*WRR/SI ratio =*		*1.0034*	±	*0.0018*	*(2σ)*	*2010, Irradiance mode*									
21	*See "O4_05_Suter_WRR_SI_Comparison_to_DARA.pdf"*															
22																
23	*NIP = ACR, **AHF 30497**, open window (without glas)*															
24	*WRR/NIP ratio (IPC-XII) =*		0.99959 ± 0.0006			*(1σ)*	*(483 points)*									
25																
26	*DC accuracy of DMM Agilent, see "34970A User Guide", page 404 :*															
27	*Range 100 mV, 24 hod, 23±1°C*															
28	*±(% of reading + % of range) =*	±	0.003	±	*0.0035*		*(% of range = offset)*									
29																

Uncertainty calculator

Pyranometer calibration – shade/unshade method with auxiliary diffusion pyranometer

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
3	*Enter values into the yellow cells in the table*															
4																
5		**Value**	**U**			**Value**	**U [%]**	**U**	**Offset**	**a=U+Offset**	**distrib.**	**u**	**c**	**c * u**	$(c * u)^2$	**% of Sum**
6	S_0 [µV/W.m^{-2}]	8.79														
7	D_{res} [W.m^{-2}]	0.00	1.00		U_{Dres} [µV]	0.00		8.79			N	2.017	0.001356	0.00274	7.48E-06	24.9%
8	GLB [W.m^{-2}]	800			U_G [µV]	7032.0	0.003	0.21	3.5	3.711	R	2.143	0.001356	0.00291	8.45E-06	26.5%
9	DIF [W.m^{-2}]	60			U_D [µV]	527.4	0.003	0.02	0	0.016	R	0.009	0.001356	0.00001	1.54E-10	0.1%
10	LW_{off} [W.m^{-2}]	-3			U_{LW} [µV]	-26.4		-26.37								
11	Z [deg]	35	0.003		Z [radians]	0.610865		0.000052			R	0.00003	5.733	0.00017	3.00E-08	1.6%
12	Tilt [deg]	0	0		Tilt [radians]	0.000000		0.000000			R	0.00000		0.00000	0.00E+00	0.0%
13	NIP [W.m^{-2}]	900			N [W.m^{-2}]	900	0.101%	0.91			R	0.525	0.009803	0.00514	2.65E-05	46.9%
14	Accept WRR/SI	(Y or N)	n		WRR/SI	1	0.180%	0.00			(=2σ)	0.000	0.009803	0.00000	0.00E+00	0.0%
15													SUM	0.01097	4.24E-05	
16	S [µV/W.m^{-2}]		**8.823**	**± 0.007**		≈	± 0.07%						SQRT = u_B		0.007	
17																
18																
19																
20	*WRR/SI ratio =*		*1.0034*	±	*0.0018*	*(2σ)*	*2010, Irradiance mode*									
21	*See "O4_05_Suter_WRR_SI_Comparison_to_DARA.pdf"*															
22																
23	*NIP = ACR, **AHF 30497**, open window (without glas)*															
24	*WRR/NIP ratio (IPC-XII) =*		0.99959 ± 0.0006			*(1σ)*	*(483 points)*									
25																
26	*DC accuracy of DMM Agilent, see "34970A User Guide", page 404 :*															
27	*Range 100 mV, 24 hod, 23±1°C*															
28	*±(% of reading + % of range) =*	±	0.003	±	*0.0035*		*(% of range = offset)*									
29																

Uncertainty calculator

Pyranometer calibration – shade/unshade method with auxiliary diffusion pyranometer

Enter values into the yellow cells in the table

	Value	U
S_0 [µV/W.m^{-2}]	8.79	
D_{res} [W.m^{-2}]	0.00	1.00
GLB [W.m^{-2}]	800	
DIF [W.m^{-2}]	60	
LW_{off} [W.m^{-2}]	-3	
Z [deg]	35	0.003
Tilt [deg]	0	0
NIP [W.m^{-2}]	900	
Accept WRR/SI	(Y or N)	n

	Value	U [%]	U	Offset	a=U+Offset	distrib.	u	c	c * u	(c * u)^2	% of Sum
U_{Dres} [µV]	0.00		8.79			N	2.017	0.001356	0.00274	7.48E-06	24.9%
U_G [µV]	7032.0	0.003	0.21	3.5	3.711	R	2.143	0.001356	0.00291	8.45E-06	26.5%
U_D [µV]	527.4	0.003	0.02	0	0.016	R	0.009	0.001356	0.00001	1.54E-10	0.1%
U_{LW} [µV]	-26.4		-26.37								
Z [radians]	0.610865		0.000052			R	0.00003	5.733	0.00017	3.00E-08	1.6%
Tilt [radians]	0.000000		0.000000			R	0.00000		0.00000	0.00E+00	0.0%
N [W.m^{-2}]	900	0.101%	0.91			R	0.525	0.009803	0.00514	2.65E-05	46.9%
WRR/SI	1	0.180%	0.00			(=2σ)	0.000	0.009803	0.00000	0.00E+00	0.0%
								SUM	0.01097	4.24E-05	
								SQRT = u_B		0.007	

S [µV/W.m^{-2}]	**8.823 ± 0.007**	≈ ± 0.07%

WRR/SI ratio = 1.0034 ± 0.0018 (2σ) 2010, Irradiance mode

See "O4_05_Suter_WRR_SI_Comparison_to_DARA.pdf"

*NIP = ACR, **AHF 30497**, open window (without glas)*

WRR/NIP ratio (IPC-XII) = 0.99959 ± 0.0006 (1σ) (483 points)

DC accuracy of DMM Agilent, see "34970A User Guide", page 404 :

Range 100 mV, 24 hod, 23±1°C

±(% of reading + % of range) = ± 0.003 ± 0.0035 (% of range = offset)

Uncertainty calculator

Pyranometer calibration – shade/unshade method with auxiliary diffusion pyranometer

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
3	*Enter values into the yellow cells in the table*															
4																
5		**Value**	**U**			**Value**	**U [%]**	**U**	**Offset**	**a=U+Offset**	**distrib.**	**u**	**c**	**c * u**	$(c*u)^2$	**% of Sum**
6	S_0 [µV/W.m^{-2}]	8.79														
7	D_{res} [W.m^{-2}]	0.00	1.00		U_{Dres} [µV]	0.00		8.79			**N**	2.017	0.001356	0.00274	7.48E-06	19.7%
8	**GLB** [W.m^{-2}]	800			U_G [µV]	7032.0	0.003	0.21	3.5	3.711	**R**	2.143	0.001356	0.00291	8.45E-06	21.0%
9	**DIF** [W.m^{-2}]	60			U_D [µV]	527.4	0.003	0.02	0	0.016	**R**	0.009	0.001356	0.00001	1.54E-10	0.1%
10	LW_{off} [W.m^{-2}]	-3			U_{LW} [µV]	-26.4		-26.37								
11	**Z** [deg]	35	0.003		**Z** [radians]	0.610865		0.000052			**R**	0.00003	5.733	0.00017	3.00E-08	1.3%
12	**Tilt** [deg]	0	0.05		**Tilt** [radians]	0.000000		0.000873			**R**	0.00050		0.00289	8.34E-06	20.8%
13	**NIP** [W.m^{-2}]	900			**N** [W.m^{-2}]	900	0.101%	0.91			**R**	0.525	0.009803	0.00514	2.65E-05	37.1%
14	Accept WRR/SI	(Y or N)	n		**WRR/SI**	1	0.180%	0.00			*(=2σ)*	0.000	0.009803	0.00000	0.00E+00	0.0%
15													SUM	0.01386	5.08E-05	
16	**S** [µV/W.m^{-2}]		**8.823**	**± 0.007**		≈	± 0.08%						**SQRT = u_B**		**0.007**	
17																
18																
19																
20	*WRR/SI ratio =*		*1.0034*	±	*0.0018*	*(2σ)*	*2010, Irradiance mode*									
21	*See "O4_05_Suter_WRR_SI_Comparison_to_DARA.pdf"*															
22																
23	*NIP = ACR, **AHF 30497**, open window (without glas)*															
24	*WRR/NIP ratio (IPC-XII) =*		0.99959 ± 0.0006			*(1σ)*	*(483 points)*									
25																
26	*DC accuracy of DMM Agilent, see "34970A User Guide", page 404 :*															
27	*Range 100 mV, 24 hod, 23±1°C*															
28	*±(% of reading + % of range) = ±*		0.003	±	*0.0035*		*(% of range = offset)*									
29																

Uncertainty calculator

Pyranometer calibration – shade/unshade method with auxiliary diffusion pyranometer

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
3	*Enter values into the yellow cells in the table*															
4																
5		**Value**	**U**			**Value**	**U [%]**	**U**	**Offset**	**a=U+Offset**	**distrib.**	**u**	**c**	**c * u**	$(c * u)^2$	**% of Sum**
6	**S_0** [µV/W.m^{-2}]	8.79														
7	**D_{res}** [W.m^{-2}]	0.00	1.00		U_{Dres} [µV]	0.00		8.79			**N**	2.017	0.001356	0.00274	7.48E-06	16.3%
8	**GLB** [W.m^{-2}]	800			U_G [µV]	7032.0	0.003	0.21	3.5	3.711	**R**	2.143	0.001356	0.00291	8.45E-06	17.4%
9	**DIF** [W.m^{-2}]	60			U_D [µV]	527.4	0.003	0.02	0	0.016	**R**	0.009	0.001356	0.00001	1.54E-10	0.1%
10	**LW_{off}** [W.m^{-2}]	-3			U_{LW} [µV]	-26.4		-26.37								
11	**Z** [deg]	35	0.003		Z [radians]	0.610865		0.000052			**R**	0.00003	5.733	0.00017	3.00E-08	1.0%
12	**Tilt** [deg]	0	0.1		Tilt [radians]	0.000000		0.001745			**R**	0.00101		0.00578	3.34E-05	34.5%
13	**NIP** [W.m^{-2}]	900			**N** [W.m^{-2}]	900	0.101%	0.91			**R**	0.525	0.009803	0.00514	2.65E-05	30.7%
14	Accept WRR/SI	(Y or N)	n		**WRR/SI**	1	0.180%	0.00			*(=2 σ)*	0.000	0.009803	0.00000	0.00E+00	0.0%
15													SUM	0.01675	7.58E-05	
16	**S** [µV/W.m^{-2}]		**8.823**	**± 0.009**		≈	± 0.10%						**SQRT = u_B**		**0.009**	
17																
18																
19																
20	*WRR/SI ratio =*		*1.0034*	±	*0.0018*	*(2 σ)*	*2010, Irradiance mode*									
21	*See "O4_05_Suter_WRR_SI_Comparison_to_DARA.pdf"*															
22																
23	*NIP = ACR, **AHF 30497**, open window (without glas)*															
24	*WRR/NIP ratio (IPC-XII) =*		0.99959 ± 0.0006			*(1 σ)*	*(483 points)*									
25																
26	*DC accuracy of DMM Agilent, see "34970A User Guide", page 404 :*															
27	*Range 100 mV, 24 hod, 23±1°C*															
28	*±(% of reading + % of range) =*	*±*	0.003	±	*0.0035*		*(% of range = offset)*									
29																

Uncertainty calculator calculates the Type B standard uncertainty of the calibration facility, for one calibration point
Legend, Explanatory notes

WRR/SI ratio =	*1.0034 ± 0.0018*	*(2 σ)*	*2010, Irradiance mode*	

See "O4_05_Suter_WRR_SI_Comparison_to_DARA.pdf"

NIP = ACR, ***AHF 30497****, open window (without glas)*

WRR/NIP ratio (IPC-XII) =	0.99959 ± 0.0006	*(1 σ)*	*(483 points)*	

DC accuracy of DMM Agilent, see "34970A User Guide", page 404 :
Range 100 mV, 24 hod, 23±1°C

±(% of reading + % of range) = ±	0.003 ± 0.0035		*(% of range = offset)*

D_{res} input

D_{res}, input U, *represents the standard deviation of residuals of calibrated pyranometer to auxiliary pyranometer regression.*
The regression is built on 10 + 10 datapoints ("shaded" minute values) on both sides of the interval when pyranometer under test is unshaded.
D_{res}*, input* ***Value,*** *represents the systematic error of Dres, and changes the mean of resulting pyranometer sensitivity.*
In principle, ***D_{res} Value*** *= regression residuals mean ≈* ***0***

DMM offset U_G, U_D

The U_G and U_D are measured in the DMM cycle with the time difference < 0.5 s, so their offsets are expected to be the same value. In the equation one eliminates the other.
The use of just one offset value reflects the possible offset shift during the time difference between shade and unshade phase.

Tilt + Z uncertainty

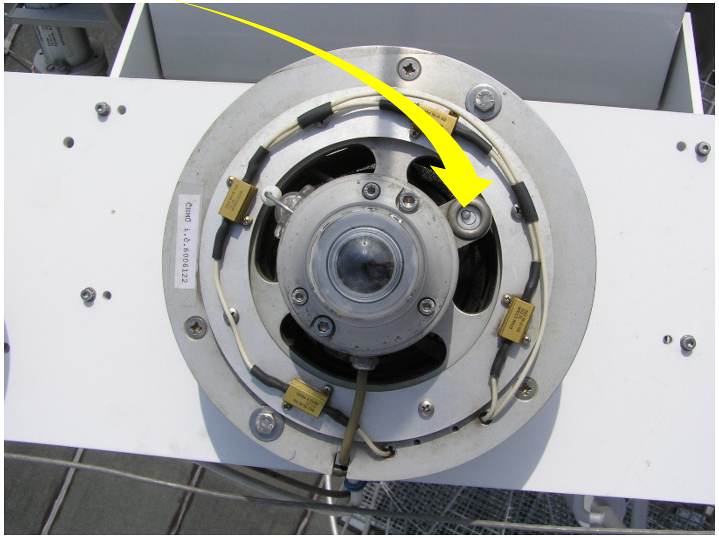
Effectively, the tilt of sensor acts as the small change of Z. In the uncertainty sensitivity coefficient calculation, the argument ***cos(Z + tilt)*** *is used insted of* ***cos(Z)****.*
Note the same sensitivity coefficient ***c_z*** *in the* ***c * u*** *calculation, both for the row of* ***Z*** *and* ***Tilt****.*
Value of ***Tilt*** *can be entered either as the constant* ***Value*** *(systematic error of bubble level), or as the uncertainty* ***U*** *(e.g. insufficiently robust mounting, error of solar tracker vertical axis alignment...)*
While constant ***Value*** *enters the* ***c * u*** *calculation directly, for uncertainty* ***U*** *input, the rectangular distribution function is used.*

WRR/SI

You can accept the WRR/SI (estimation 2010) for final evaluation.
Note that beside the final uncertainty ***U_B****, also the pyranometer sensitivity mean is systematicaly shifted.*

Bubble level Sensitivity vs. Accuracy (Precission)

The picture shows the example of well known experience: The pyranometer (without leveling screws) is being installed on the surface of the ventilation unit aligned horizontally according to the **pyranometer previously mounted.**



Specifications	CMP 3	CMP 6	CMP10 & CMP 11	CMP 21	CMP 22
Classification to ISO 9060:1990	Second Class	First Class	Secondary Standard	Secondary Standard	Secondary Standard
Spectral range (50 % points)	300 to 2800 nm	285 to 2800 nm	285 to 2800 nm	285 to 2800 nm	200 to 3600 nm
Sensitivity	5 to 20 µV/W/m^2	5 to 20 µV/W/m^2	7 to 14 µV/W/m^2	7 to 14 µV/W/m^2	7 to 14 µV/W/m^2
Impedance	20 to 200 Ω	20 to 200 Ω	10 to 100 Ω	10 to 100 Ω	10 to 100 Ω
Expected output range (0 to 1500 W/m^2)	0 to 30 mV	0 to 30 mV	0 to 20 mV	0 to 20 mV	0 to 20 mV
Maximum operational irradiance	2000 W/m^2	2000 W/m^2	4000 W/m^2	4000 W/m^2	4000 W/m^2
Response time (63 %) Response time (95 %)	< 6 s < 18 s	< 6 s < 18 s	< 1.7 s < 5 s	< 1.7 s < 5 s	< 1.7 s < 5 s
Zero offsets (a) thermal radiation (at 200 W/m^2) (b) temperature change (5 K/h)	 < 15 W/m^2 < 5 W/m^2	 < 12 W/m^2 < 4 W/m^2	 < 7 W/m^2 < 2 W/m^2	 < 7 W/m^2 < 2 W/m^2	 < 3 W/m^2 < 1 W/m^2
Non-stability (change/year)	< 1 %	< 1 %	< 0.5 %	< 0.5 %	< 0.5 %
Non-linearity (100 to 1000 W/m^2)	< 1.5 %	< 1 %	< 0.2 %	< 0.2 %	< 0.2 %
Directional response (up to 80° with 1000 W/m^2 beam)	< 20 W/m^2	< 20 W/m^2	< 10 W/m^2	< 10 W/m^2	< 5 W/m^2
Spectral selectivity (350 to 1500 nm)	< 3 %	< 3 %	< 3 %	< 3 %	< 3 %
Temperature response	< 5 % (-10 °C to +40 °C)	< 4 % (-10 °C to +40 °C)	< 1 % (-10 °C to +40 °C)	< 1 % (-20 °C to +50 °C)	< 0.5 % (-20 °C to +50 °C)
Tilt response (0° to 90° at 1000 W/m^2)	< 1 %	< 1 %	< 0.2 %	< 0.2 %	< 0.2 %
Field of view	180°	180°	180°	180°	180°
Accuracy of bubble level	< 0.2°	< 0.1°	< 0.1°	< 0.1°	< 0.1°
Temperature sensor output				10 K Thermistor (optional Pt-100)	10 K Thermistor (optional Pt-100)
Detector type	Thermopile	Thermopile	Thermopile	Thermopile	Thermopile
Operational temperature range	-40 °C to +80 °C	-40 °C to +80 °C	-40 °C to +80 °C	-40 °C to +80 °C	-40 °C to +80 °C
Storage temperature range	-40 °C to +80 °C	-40 °C to +80 °C	-40 °C to +80 °C	-40 °C to +80 °C	-40 °C to +80 °C
Humidity range	0 to 100 % non-condensing	0 to 100 % non-condensing	0 to 100 % non-condensing	0 to 100 % non-condensing	0 to 100 % non-condensing
Ingress Protection (IP) rating	67	67	67	67	67
Recommended applications	Economical solution for routine measurements in weather stations, field testing	Good quality measurements for hydrology networks, greenhouse climate control	Meteorological networks, PV panel and thermal collector testing, materials testing	Meteorological networks, reference measurements in extreme climates, polar or arid	Scientific research requiring the highest level of measurement accuracy and reliability

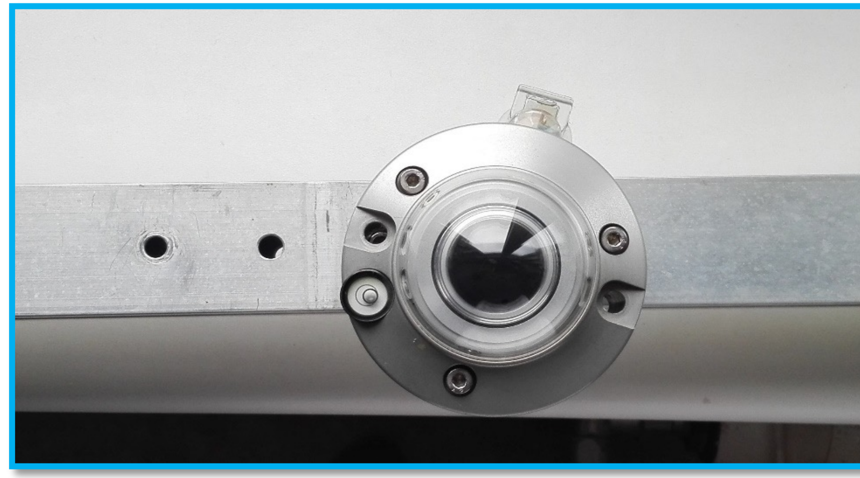
Note: The performance specifications quoted are worst-case and/or maximum values

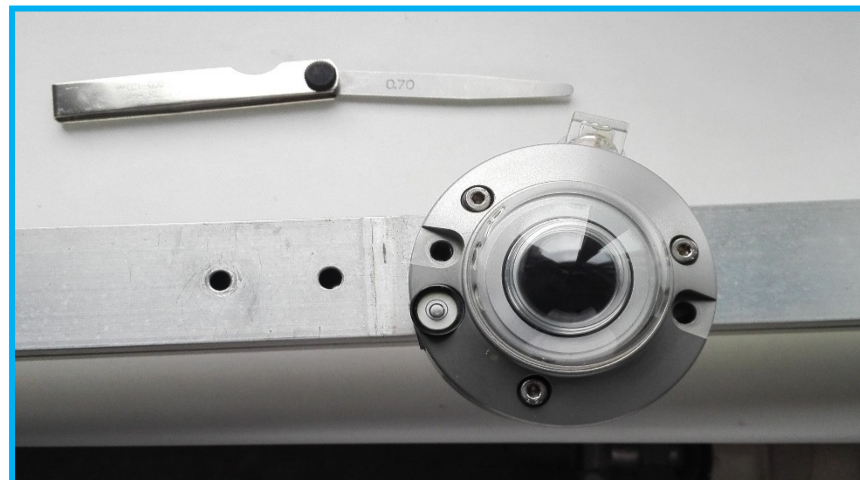
Standard 10k Thermistor or optional Pt-100 temperature sensor with CMP 21 and CMP 22

Individual directional response and temperature dependence test data with CMP 21 and CMP 22

48

Instalation to check the bubble level **sensitivity**





- Metalic girder (profile 40 x 20) with the active length 860 mm
- Slit gauge, thickness "s"

Five pyranometers tested:

1) CM11-058764 s= 0.7 mm
2) CM11-976462 s= 0.7 mm
3) CM21-970437 s= 0.7 mm
4) CMP11-090854 s= 0.7 mm
5) CMP11-139647 s= 0.7 mm

Tilt = arctg(0.7 / 860) = 0.047°

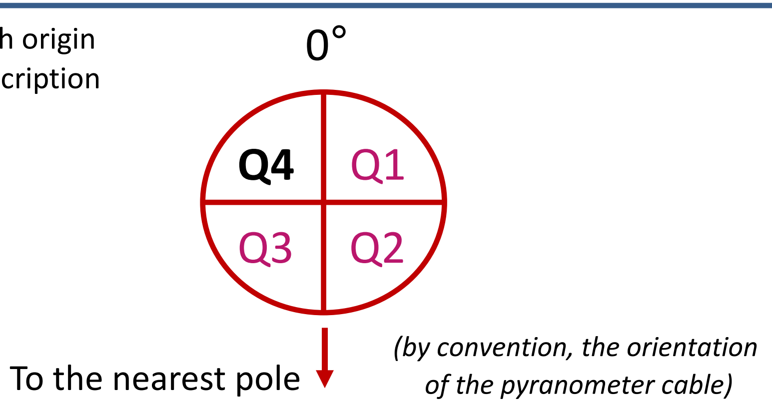
Conclusion: bubble SENSITIVITY (the bubble moving from center and touching inner circle) is 0.5°

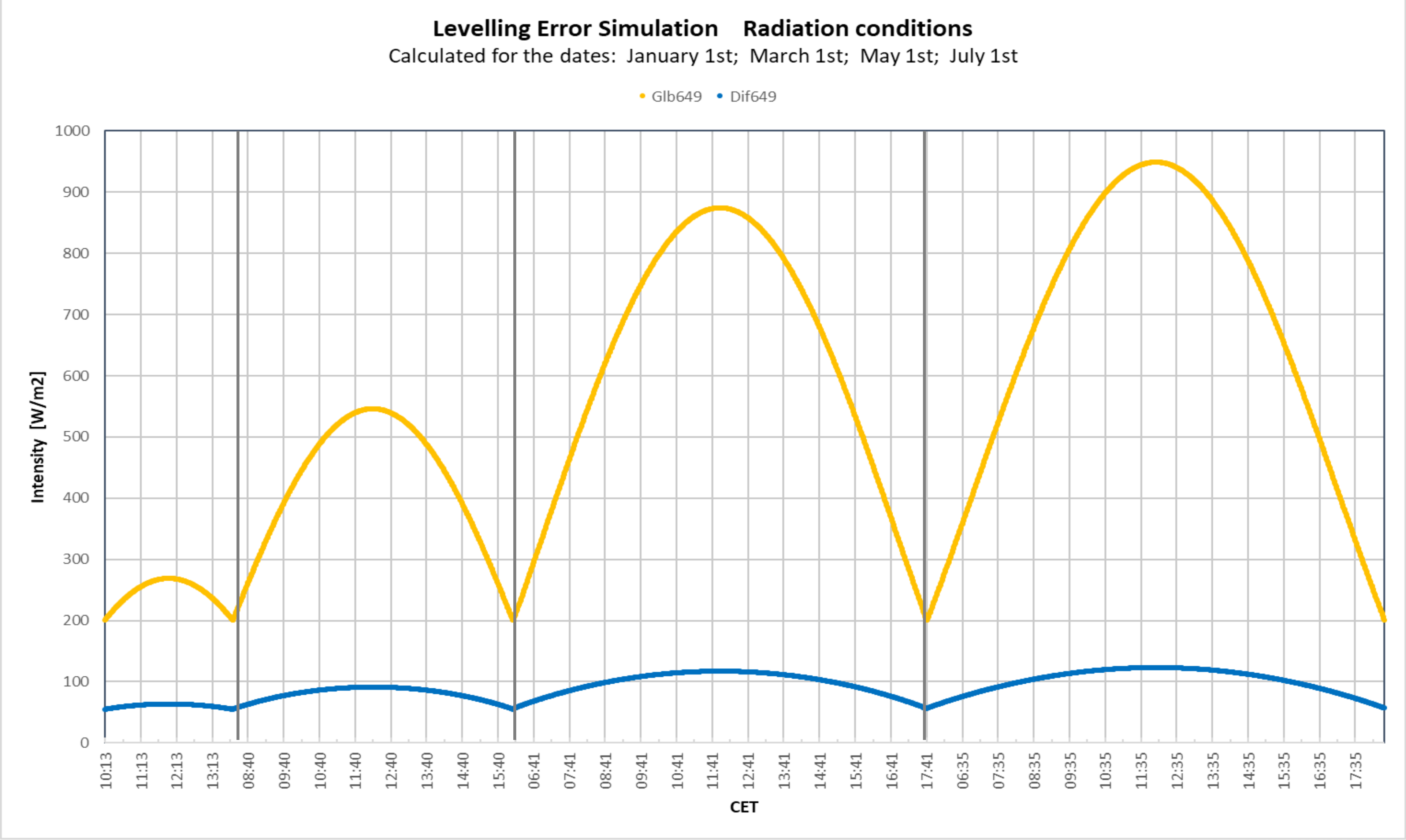
But another thing is bubble level PRECISSION !
According to the experiences of CHMI/SOO, even when the bubble is in the center, some pyranometer bottom plane tilt reaches 0.1° (K&Z specifications).

Levelling error simulation

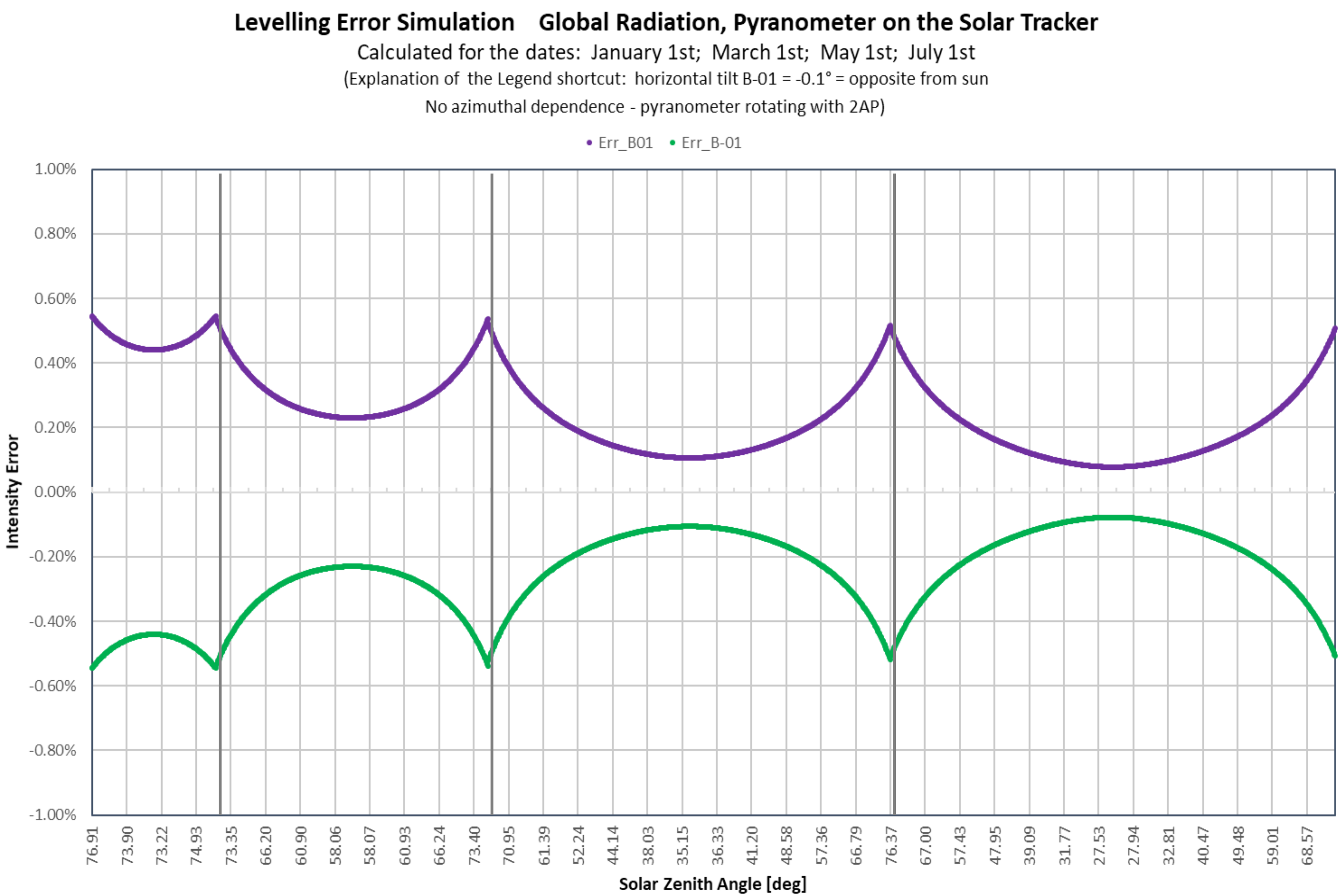
- For pyranometers NOT radiometricaly leveled, depending on the vectors of the components, we can expect in the worst case error of „Z“ exceeding 0.1 deg:
  - 0.1 deg, the inborn error (unprecission) of the bubble level itself
  - uncertainty of setting (reproducibility, unstability of the holder…)
- We hardly know, what is the **azimuth** of the normal of pyranometer tilt. It causes the surprising „Z“ errors, namely in the situation, when the pyranometer is calibrated on the solar tracker (shade/unshade) and finally used fix mounted
- A model was created for evaluation the error of the global radiation intensities, caused by the bubble level error, oriented to various directions. On the next snaps there is an example of the output intensity error, calculated only for the quadrant **Q4**, to which the inclined vertical axis of pyranometer is projected.
- It is obvious that for Q1 the resulting curves in the graph will be vertically symetrical, for Q3 and Q2 respectively, they will be horizontally symetrical

Legend to the azimuth origin and the quadrant description for the next snaps





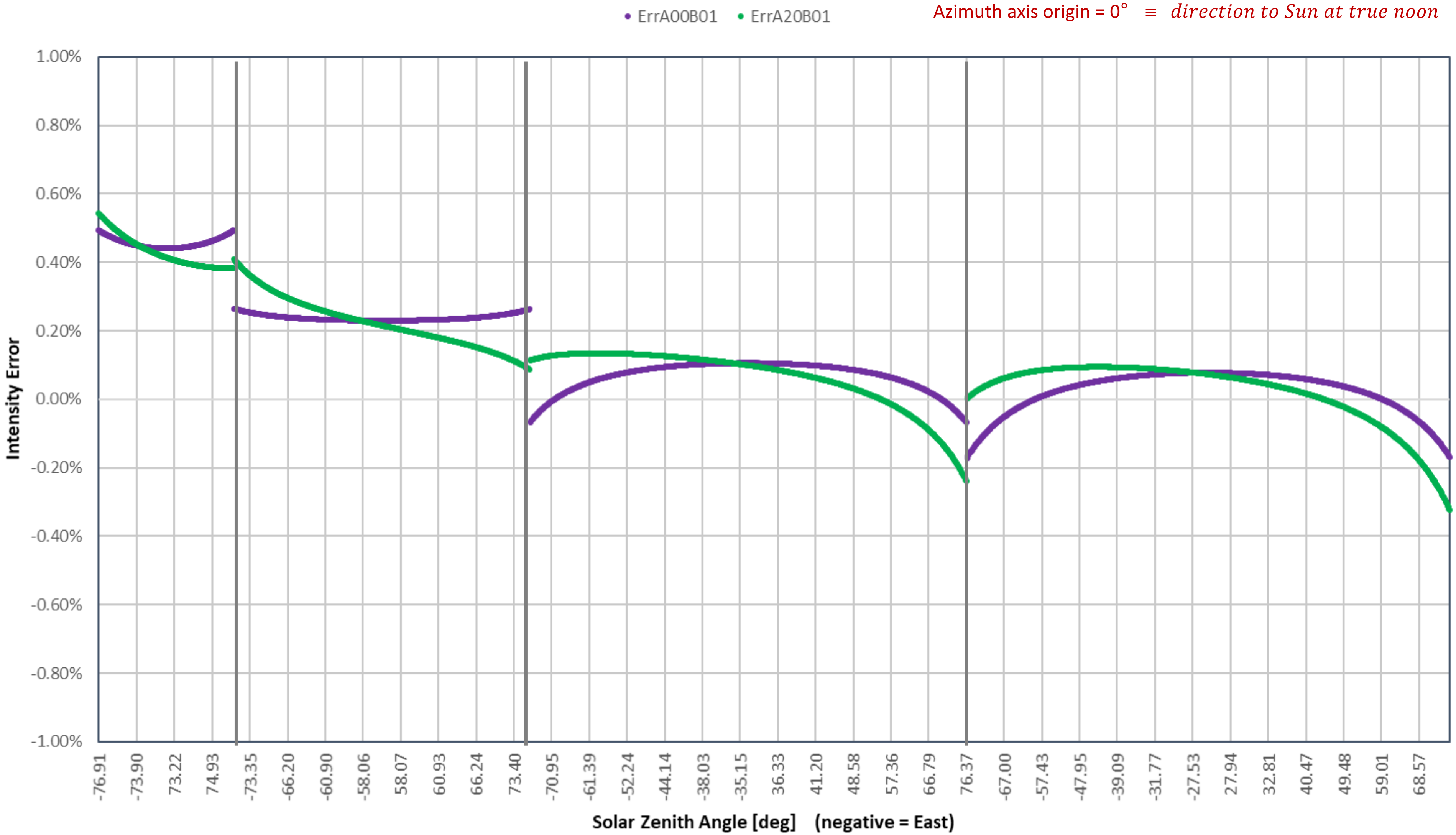
Model input values - theoretical values of the typical clear day runs of GLB and DIF at Lat. 50° (N)
(The simulation can be done for any curves – even the real values measured could be used instead)


Levelling Error Simulation Global Radiation, Pyranometer on the Solar Tracker
Calculated for the dates: January 1st; March 1st; May 1st; July 1st
(Explanation of the Legend shortcut: horizontal tilt B-01 = -0.1° = opposite from sun
No azimuthal dependence - pyranometer rotating with 2AP)
Err_B01
Err_B-01
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
-0.20%
-0.40%
-0.60%
-0.80%
-1.00%
Intensity Error
76.91
73.90
73.22
74.93
73.35
66.20
60.90
58.06
58.07
60.93
66.24
73.40
70.95
61.39
52.24
44.14
38.03
35.15
36.33
41.20
48.58
57.36
66.79
76.37
67.00
57.43
47.95
39.09
31.77
27.53
27.94
32.81
40.47
49.48
59.01
68.57
Solar Zenith Angle [deg]

Levelling Error Simulation   Global Radiation, Pyranometer fixed

Calculated for the dates: January 1st; March 1st; May 1st; July 1st

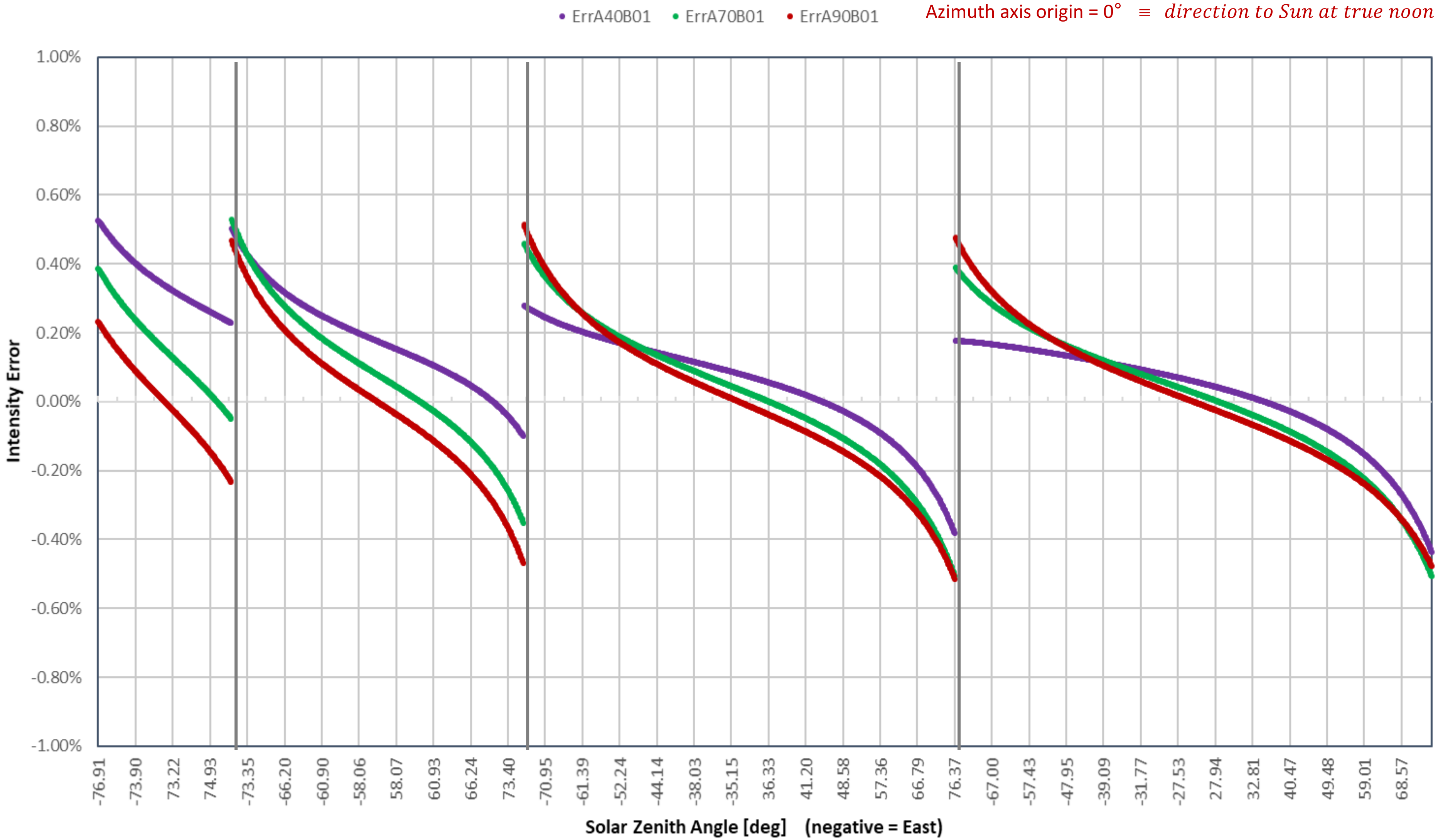
(Explanation of the Legend shortcut: horizontal tilt B01 = 0.1°, azimuth of the Normal A20 = 20° from south to east)



Levelling Error Simulation Global Radiation, Pyranometer fixed

Calculated for the dates: January 1st; March 1st; May 1st; July 1st

(Explanation of the Legend shortcut: horizontal tilt B01 = 0.1°, azimuth of the Normal A20 = 20° from south to east)

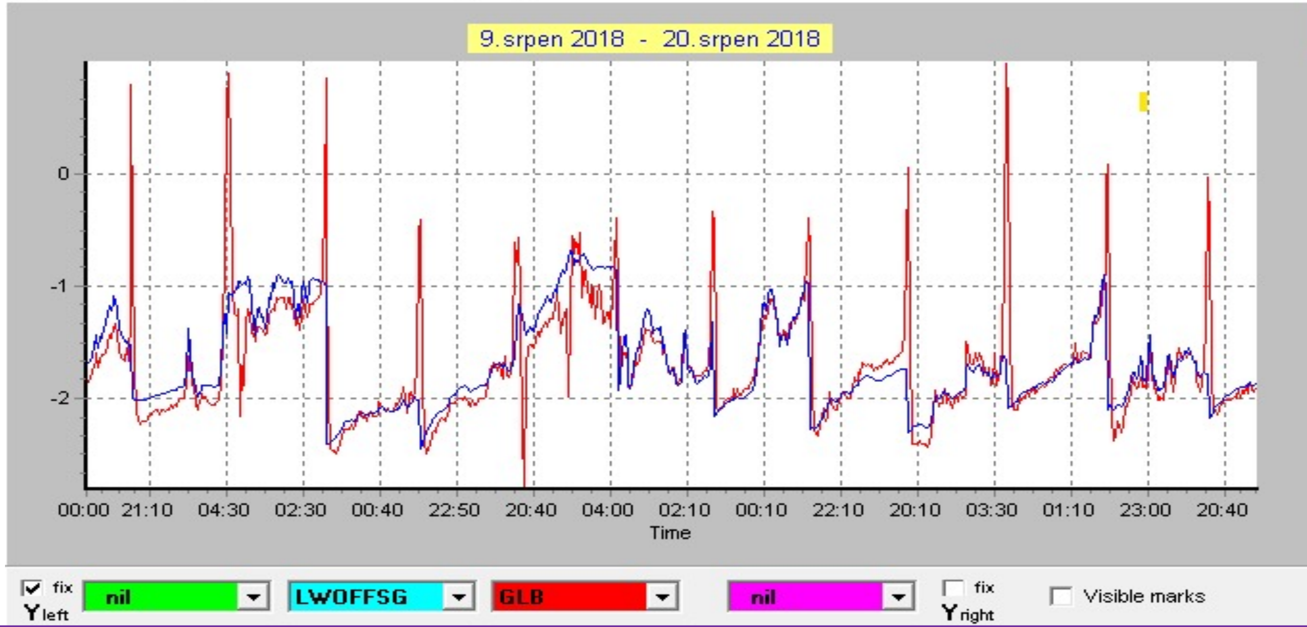


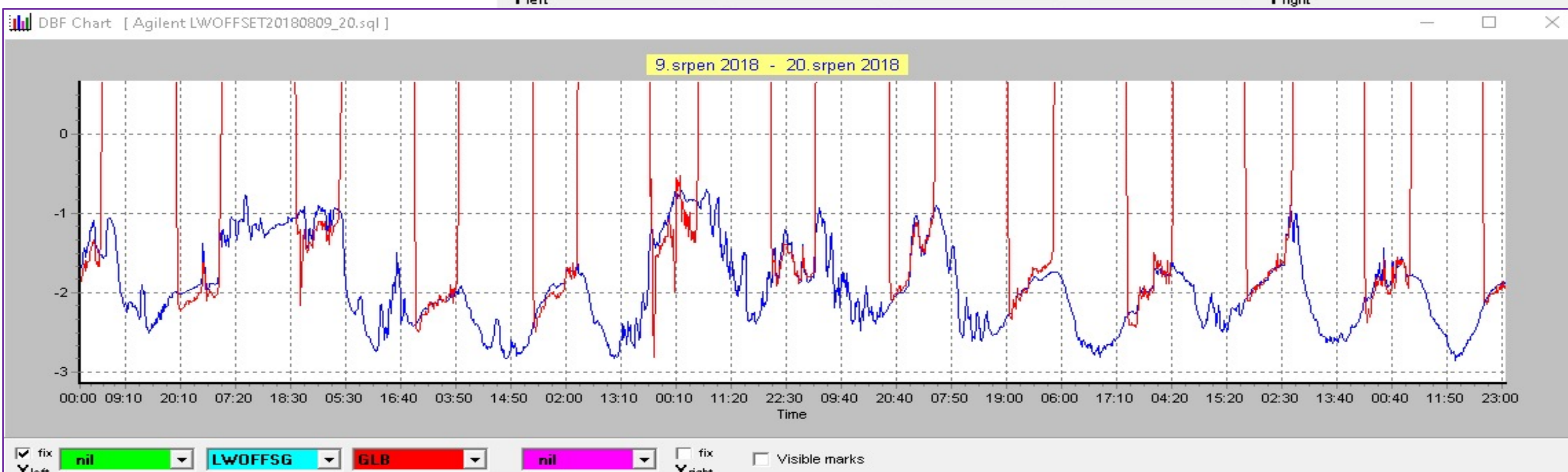
Ventilated Pyranometers Daily LW Offset Evaluation

Night values of GLB

- corellated with *„instr. IR Net“*
- and „extrapolated“ to daytime
  (by means of linear regresion constants)

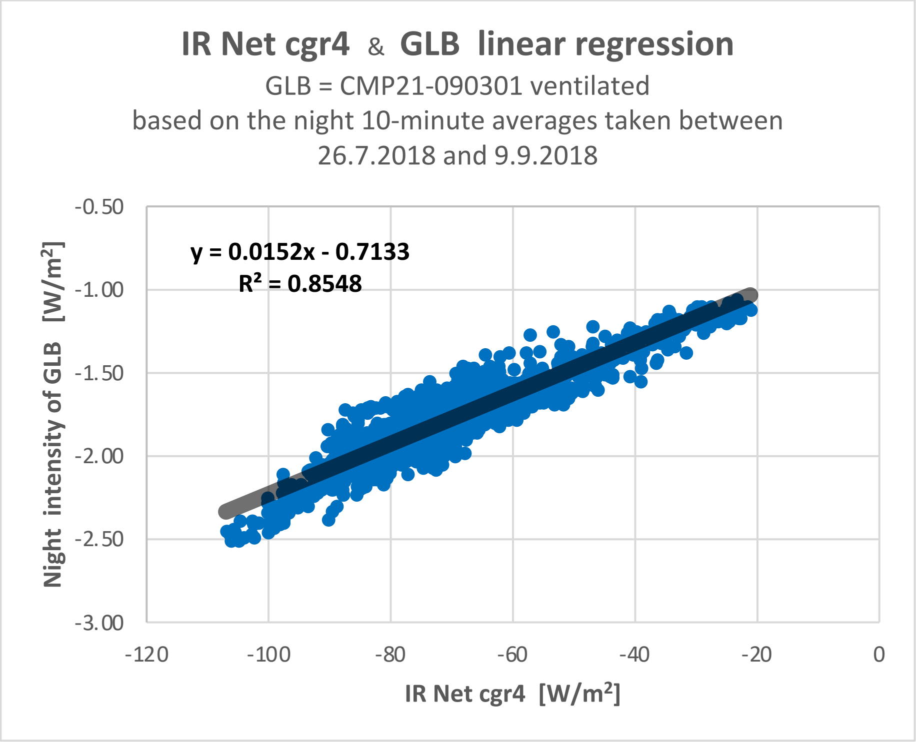
If only it is so simple ☹

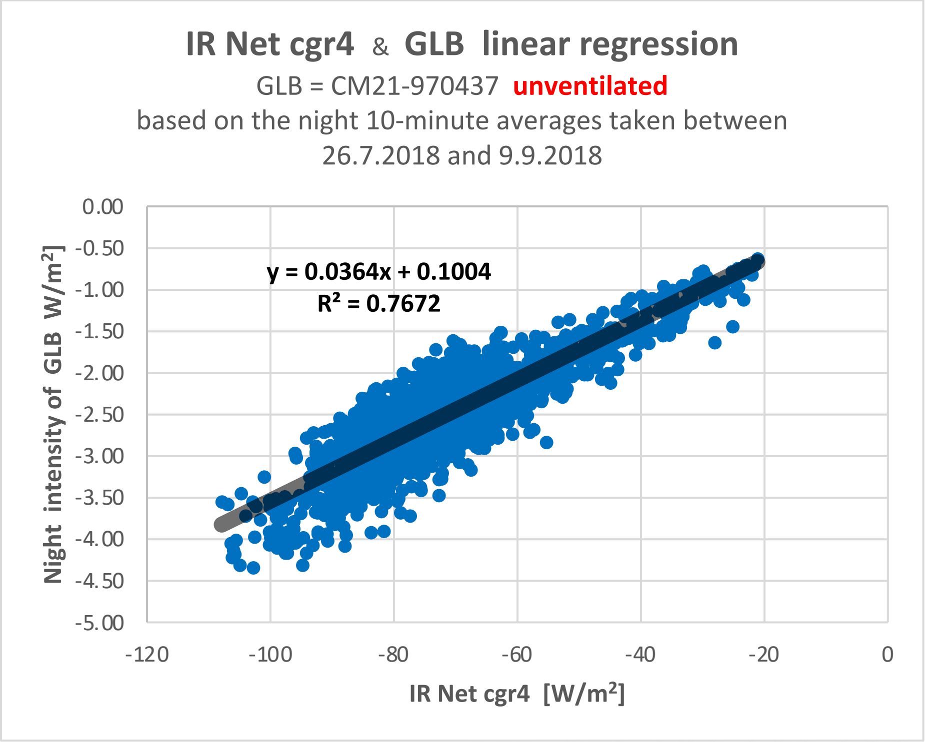




Correlation between the night values of

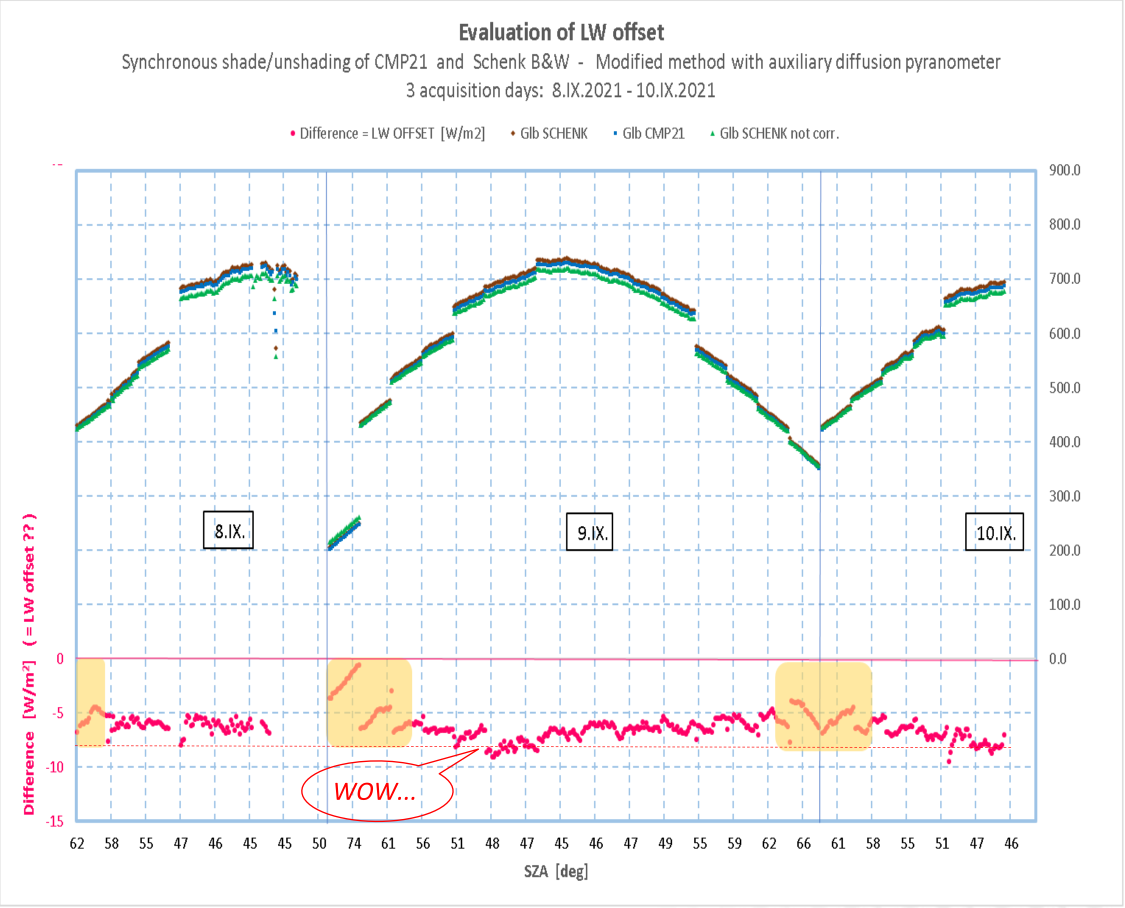
- Ventilated pyranometer and „instrumental IR Net“ of CGR4 (IR Net = Usens / C !!)
- The same for another pyranometer, unventilated, run simultaneously (just for the brief comparison)





Another method to reveal ventilated CMP21 pyranometer daytime LW offset values
Preliminary results

- Based on **simultaneous** calibration of CMP21 and B&W pyranometer
- Calibration method of modified sh/ush with auxiliary diffusion pyranometer
- Processed in series (IPC)
- 6 shading events per day
- Using of the Modified Shade/Unshade calibration method with aux. diffusion pyranometer gives far enough time to stabilize values even of pyranometers with **long time constant** (like B&W)



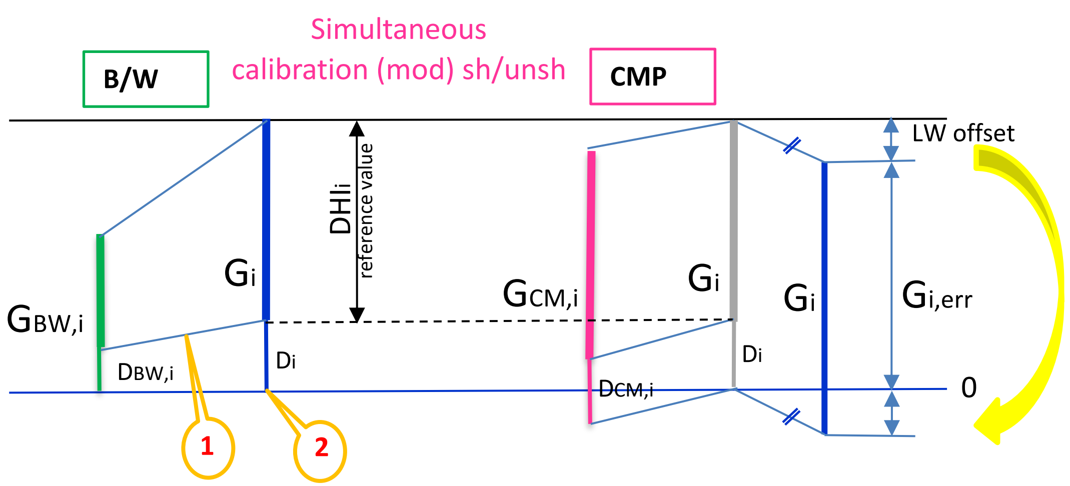
Another method to reveal ventilated CMP21 pyranometer daytime LW offset values (cont.)

$$S_{CM,i} = \frac{S_{CM,o} * (G_{CM,i} - D_{CM,i})}{N_i * \cos(Z_i)} \leftarrow D_{CM,i} = K_{CM,j} * D_{A,i} + Q_{CM,j}$$

one aux. diffuse pyranometer for both

$$S_{BW,i} = \frac{S_{BW,o} * (G_{BW,i} - D_{BW,i})}{N_i * \cos(Z_i)} \leftarrow D_{BW,i} = K_{BW,j} * D_{A,i} + Q_{BW,j}$$

CM	index of pyranometer CMP21
BW	index of B&W pyranometer
i	index of 1 minute average
j	index of shade event
K, Q	coefficients of regression
$S_{CM,0}$, $S_{BW,0}$	constants, original sensitivity of CMP21, B&W resp. (data are stored in W/m²)



Assumptions

1) Irrad -> Emf linearity: $D_{BW,i} / G_{BW,i} = D_i / G_i$

2) B/W zero offset ≈ 0 even for Gi >> 0

Another method to reveal ventilated CMP21 pyranometer daytime LW offset values (discussion)

Have I made an error ?

- I do not create the calibration curve of B&W
- I do not use the calibration curve of CMP
- ➢ I just compare pairs of „on line“ calibrated values of both pyranometers - modified sh/unsh method with aux. DIF
- Proper shading of untypical diameter of B&W sensor ? ... Hardly, special shading ball, D, L (keeping opening and slope angle for B&W ≡ CMP)
- Temperature dependence error of B&W ?, CMP ? ... No, both just calibrated !
- Zenith angle dependence error of B&W ?, CMP ? ... No, both just calibrated !
- LW offset of B&W ? ... Negligible at nighttime.
- LW offset of B&W ? ... During daytime ??... spectral influence -> B, -> W ? How much ?
- Linearity of Irrad. -> Emf conversion ? ... YES, it can cause an error, especially on B&W pyr. How much ?

Possible improvement:

- „IPC“ series (binning) should be shortened to comply with the rapidly changing sensitivity of B&W at high SZA
- Using PSP 8-48 instead of SCHENK 8101 !!

Problem:

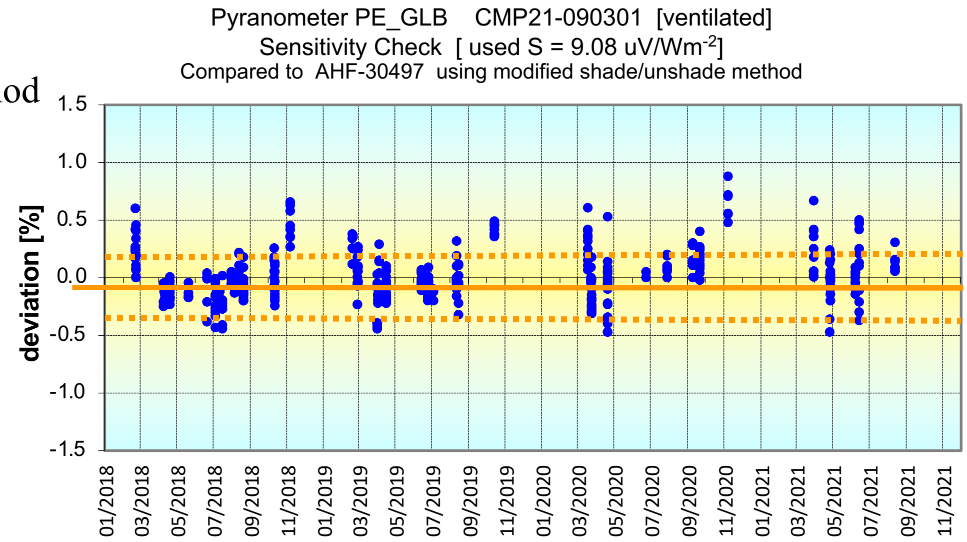
- *No PSP on SOO*

Conclusions:

- Daily LW offset seems to be significantly greater than -3 W/m^2
- The offset value depends on meteorological conditions (LW, and ??)
- How to treat correctly the daily LW offset error with the operational pyranometers if no LW measurements in situ
  - on calibration process with std. pyranometer as the reference ?
  - while correcting the data measured ?

Secondary standard pyranometer

Check of sensitivity – modified Shade/unshade method
- repeatedly during the whole year
- CMP21 permanently exposed to the sun



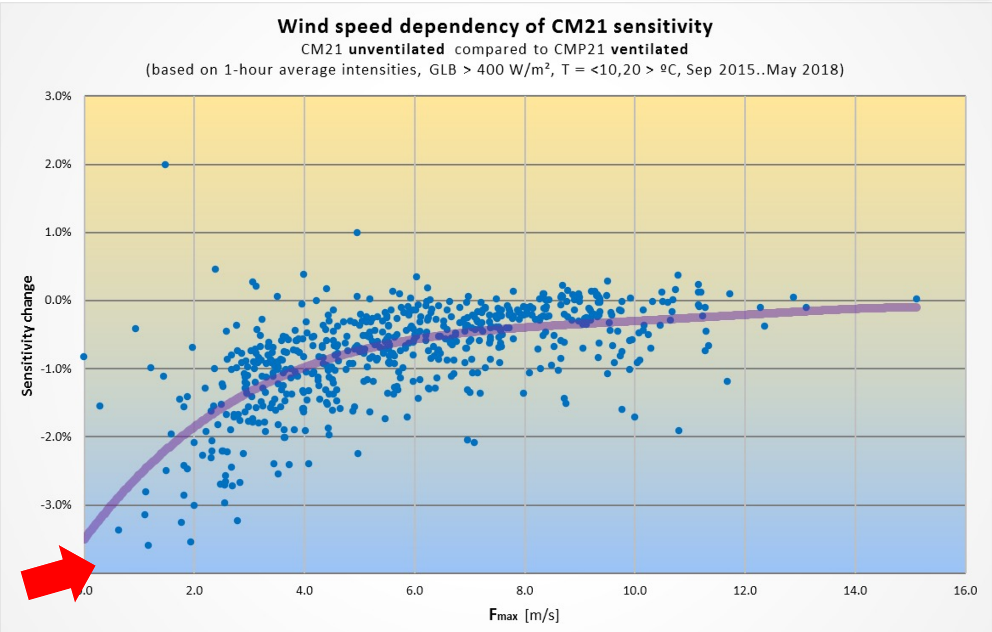
Calibration results – sensitivity check
- U_{95} = 0.35 % (k=2, scale WRR)
- keeps stable sensitivity for years

Operational pyranometers

Calibration by comparison with the Secondary std.
- every 2 years at least
- usually 5-7 sunny days
- **since 2008 ventilated**

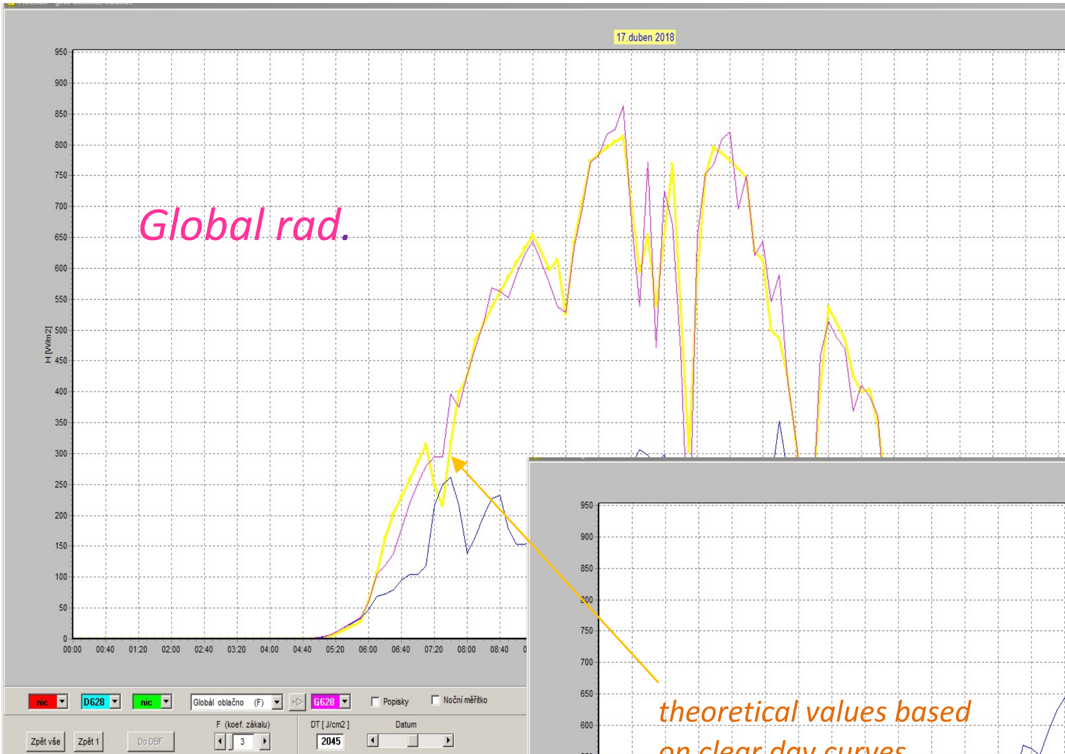
Calibration results (pyranometer ventilated)
- U_{95} = 0.95 – 1.05 % (k=2, scale WRR)

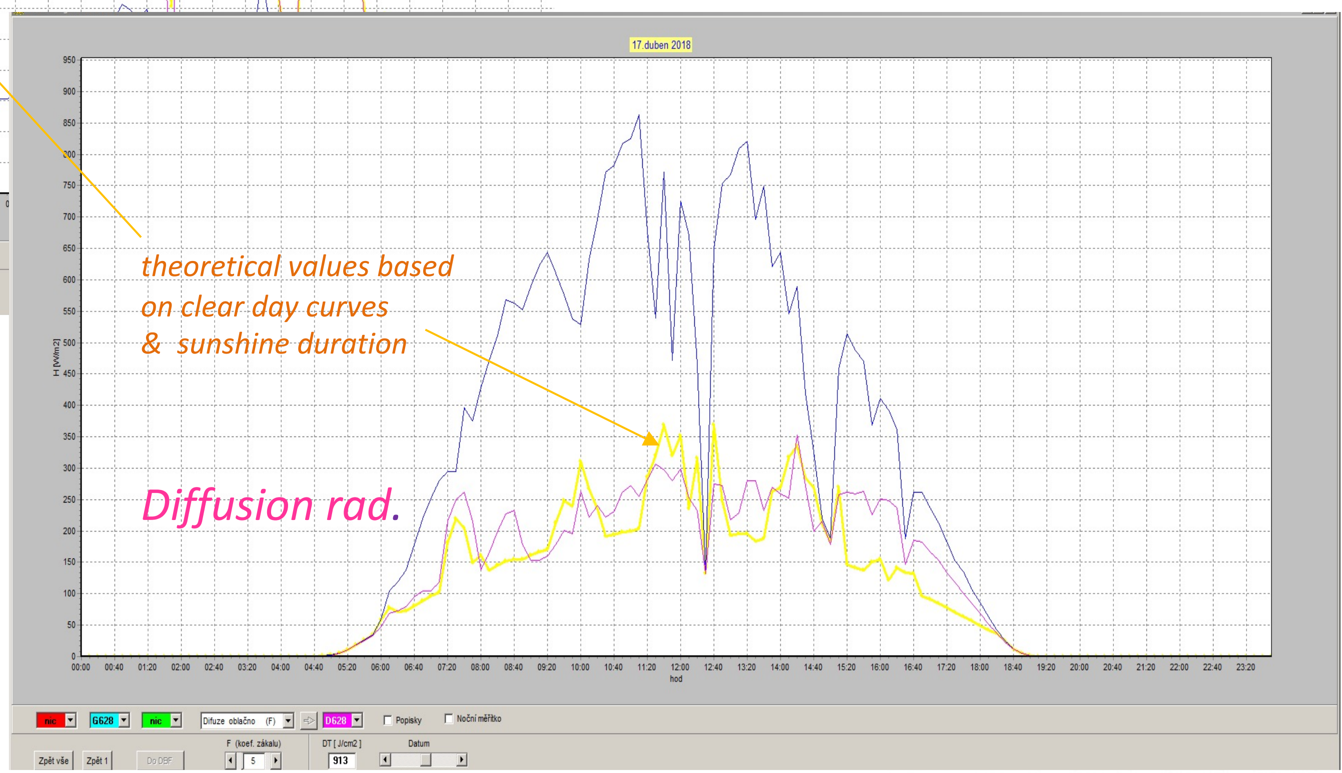
Formerly, when used unventilated
- unstable (night) offset, typ. -4 .. -1 W/m²
- apparent wind speed dependency of sensitivity !



Radiation data QC

- Validation monthly
- Comparison with theoretical values
  - of clear day
  - of cloudy day (& sunshine duration)
- Check of shading ring, CM121, setting
- Filling in the gaps, shades
- Comparison among stations
- Compensation of offsets





Archives:

- Central dtb „CLIDATA“
  - 1-min averages CET
- Dtb SOO „SolRad“
  - 1-min averages TST
  - 10-min averages TST

Author expresses thanks especially to Thomas Carlund, Zoltan Nagy, Anna Pribulova and Ibrahim Reda, for the consultations and advises.
Further comments, critics and advises will be appreciated.
Ref.: F. Vignola, J. Michalsky, T.Stoffel „Solar and Infrared Radiation Measurements“, CRC Press, 2017