EMRP PHOTOCLASS: TOWARDS AN ENERGY-BASED PARAMETER FOR PHOTOVOLTAIC CLASSIFICATION

3- day Training course at JRC Ispra

D5.2.1
(Training course)

H. Müllejans, E. D. Dunlop
JRC, Ispra, Italy

April 2017

Final

Partners: **JRC**

Deadline: April 2017

1. Introduction

The present deliverable is a part of the JRP project ENG55 'Towards an energy-based parameter for photovoltaic classification' (PhotoClass) and is deliverable D5.2.1. of Task 5.2 '(Training)'

The aim of Task 5.2 is to transfer the best state-of-the-art measurement practices firstly to al JRP-participants which require them and secondly to stakeholders.

Therefore a 3-day training course was held at the JRC, Ispra, from 3rd to 5th of April 2017. Here the final programme and the presentations are collected.

PHOTOCLASS training course participants			
surname	**name**	**Organisation**	**country**
Arp	Jürgen	PV lab	Germany
Bardizza	Giorgio	JRC / ESTI	EU
Baumgartner	Hans	MIKES	Finland
Berg	Steven	VSL	Netherlands
Betts	Tom	LU	United Kingdom
Bothe	Karsten	ISFH	Germany
Brecl	Kristijan	Uni Ljubljana	Slovenia
Danzl	Pi	ECN	Netherlands
Dubard	Jimmy	LNE	France
Dunlop	Ewan	JRC / ESTI	EU
Fey	Thomas	PTB	Germany
Field	Mike	JRC / ESTI	EU
Galleano	Roberto	JRC / ESTI	EU
Gomez Rodriguez	Trinidad	INTA	Spain
Gracia	Ana	JRC / ESTI	EU
Hohl-Ebinger	Jochen	FhG ISE	Germany
Huld	Thomas	JRC / ESTI	EU
Iñigo Petrina	Jauregui	CENER	Spain
Kenny	Robert	JRC / ESTI	EU
Kröger	Ingo	PTB	Germany
Lopez	Juan	JRC / ESTI	EU
Martínez Fuente	Graciano	INTA	Spain
Molinero	Ruben Roldan	SUPSI	Switzerland
Müllejans	Harald	JRC / ESTI	EU
Parravicini	Jacopo	Uni Bicocca Milano	Italy
Pavanello	Diego	JRC / ESTI	EU
Quesnel	Francois	INES	France
Riechelmann	Stefan	PTB	Germany
Salis	Elena	JRC / ESTI	EU
Sample	Tony	JRC / ESTI	EU
Shaw	David	JRC / ESTI	EU
Theristis	Marios	Uni Cyprus	Cyprus
Trigo Escalera	Juan Francisco	CIEMAT	Spain
Tsanakas	Ioannis	IFE	Norway
Winter	Stefan	PTB	Germany
Zaaiman	Wim	JRC / ESTI	EU

PHOTOCLASS 3-day Training course at JRC Ispra

Programme

DAY1: Monday 3rd April 2017

14:00 *Welcome and brief introduction to JRC*

Diana Rembges, JRC, acting Head of Unit of Energy Efficiency and Renewables

Session 1: based on WP2 Reference devices: 14:00-17:30

Presentations: 14:00 – 15:00

The new reference cells (J. Hohl-Ebinger, ISE-FhG)

LED-based differential spectral response setup for reference solar cell mini modules (H. Baumgartner, MIKES)

Reference device intercomparison: protocol and first results (I. Kröger, PTB)

Coffee break: 15:00 – 15:30

Hands-on activities: 15:30-17:30

Calibration (secondary) of reference modules (Pulsed solar simulator PASAN IIIb)

SR of reference cells (dedicated steady-state solar simulator ORIEL) and
SR of reference modules (dedicated pulsed solar simulator PASAN2)

DAY2: Tuesday 4th April 2017

Session 2: based on WP3 Detector characterisation: temperature dependence 9:00-12:30

Presentations: 9:00-10:00

Overview: Facilities and methods for temperature dependence measurements (I. Kröger, PTB)

Overview: Facilities and methods for angular dependence (I. Kröger, PTB)

Coffee break: 10:00 – 10:30

Hands-on activities: 10:30-12:30

Temperature coefficient of reference cells (dedicated steady-state solar simulator WACOM with Peltier)

Temperature coefficient of reference modules (natural sunlight)

Lunch break: 12:30 – 14:00

Session 3: based on WP3 Detector characterisation: linearity: 14:00-17:30

Presentations: 14:00 – 15:00

Compressive sensing (T. Betts, LU)

Polychromatic SR (T. Betts, LU)

Overview: Facilities and methods for linearity measurements (I. Kröger, PTB)

Coffee break: 15:00 – 15:30

Hands-on activities: 15:30-17:30

Linearity of reference cells (steady-state solar simulator WACOM with ND filters)

Linearity of reference devices (steady-state solar simulator APOLLO, multiple lamps)

DAY3: Wednesday 5th April 2017

Session 4: based on WP4 Source characterisation methods: 9:00-12:30

Presentations: 9:00-10:00

Solar cell chuck for temperature characterisation (G. Martínez, INTA)

Comparison of spectroradiometers (I. Kröger, PTB)

Spectral sky scanning (S. Riechelmann, PTB)

Coffee break: 10:00 – 10:30

Hands-on activities: 10:30-12:30

Measurement of spectral irradiance of natural sunlight and WACOM solar simulator

Calibration of spectroradiometers (laser laboratory)

END

PHOTOCLASS 3-day Training course at JRC Ispra

Programme

Session 1: based on WP2 Reference devices

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Session 3: based on WP3 Detector characterisation: linearity

Compressive sensing (T. Betts, LU)

Polychromatic SR (T. Betts, LU)

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Fraunhofer ISE CalLab PV Cells

Development of new WPVS reference cells

Jochen Hohl-Ebinger

Fraunhofer Institute for
Solar Energy Systems ISE

JRC, Ispra, 03.04.2017

Secondary Calibration for Production
Traceable to SI-Units

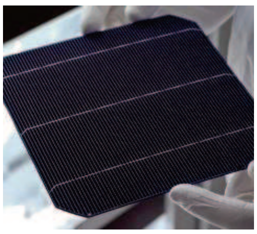
Cell selected from Production[1]

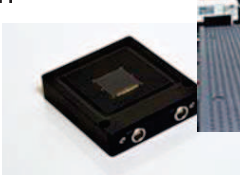
- Centre of power (current) distribution
- Stable performance[2]
- Uniform performance
- High R_P

NMI

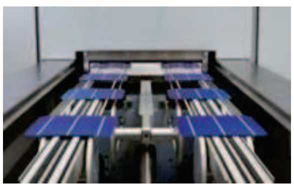
(PTB)

Secondary Calibration





Cell Production



 [1] W. Warta, et. al., 24th EUPVSEC (2009), [2] M. Schubert, et. al., SolMat 138, (2015)

The Aim ….
WP 2 of ENG55 Photoclass

PhotoClass

- ……of this work package is to develop new PV reference devices that exhibit device **stability** of better than 0.1 %, and provide a wider coverage of operating **spectral range** and **linearity**. Such reference devices are necessary for the transfer of the spectral response and short circuit current under standard test conditions (STC) from NMI's to calibration labs and eventually to industry.

WP 2
Tasks

PhotoClass

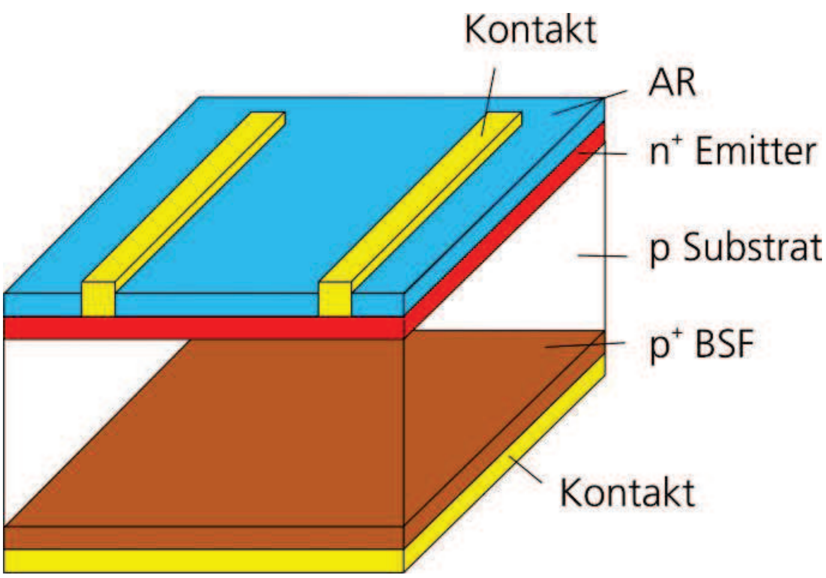
- Definition of the specifications required for the new reference devices (Questionnaire)
- Investigation of optical properties of different cell structures
- Optimization by use of device simulation
- Spectral adaption
- Optimization of encapsulation

Specifications

- High priority:
  - Long term stability in ISC and IV-curve lower than 0.5% for a period of at least 1 year
  - Linearity deviation < 1% over a wide irradiance range from 100 W/m² - 1200 W/m²
  - Good thermal contact of solar cell to back side of housing
  - Size 2x2 cm², front glass reflectivity specular
- Medium priority:
  - Spectral range (extended UV-, IR response), Extension in IR region < 2000nm
  - Fast signal response < 10ms
  - Size 6” x 6”

D2.1.4 (Optical Properties…):
Cell Structure

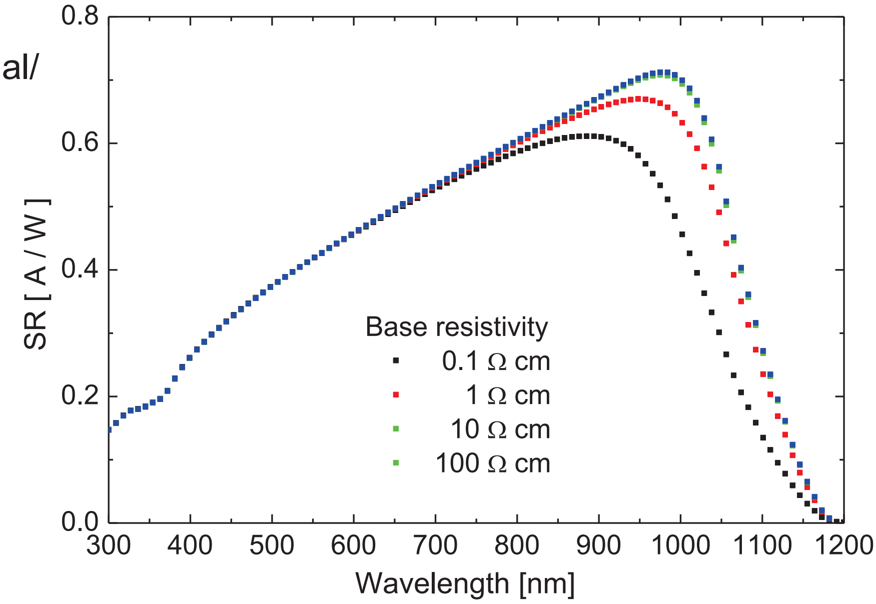
- p-type cell structure used as reference cells



D2.1.4 (Cell opt. and sim)

p-type cell structure

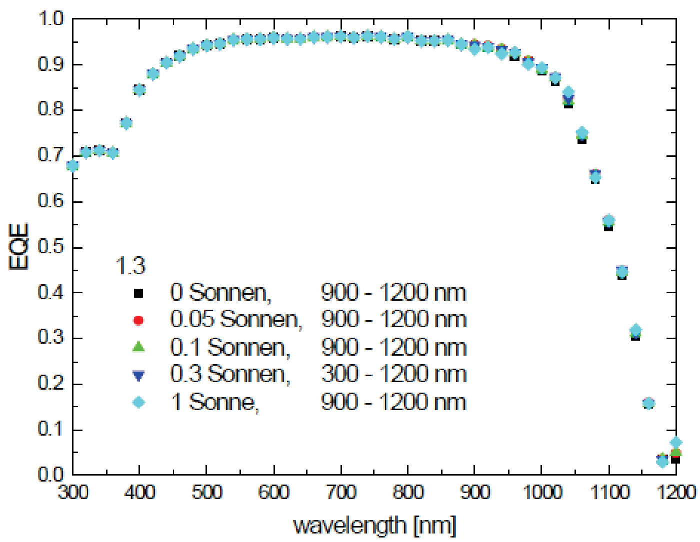
- Simulation (PC1D) of p-type cell structure using different material/ base resistivity



D2.1.4 (Optical Properties…):

Cell Structure

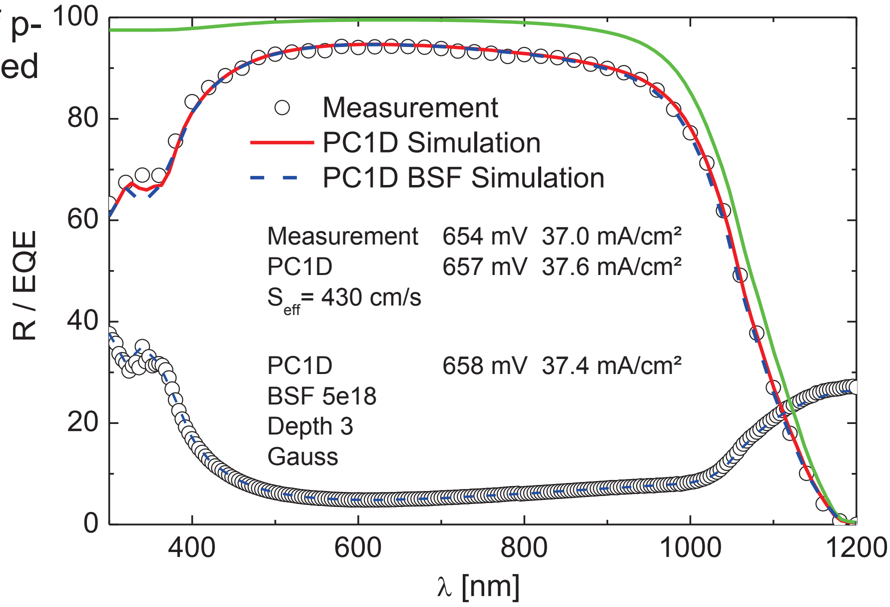
- p-type cell, SiO, LFC



D2.1.4 (Cell opt. and sim)

p-type cell structure

- Simulation (PC1D*) and measurement of p-type cell structure used as reference cells



*P. A. Basore, et al., Proceedings of the 20th IEEE Photovoltaic Specialists Conference, Las Vegas, Nevada, USA, 1988, pp. 389-96

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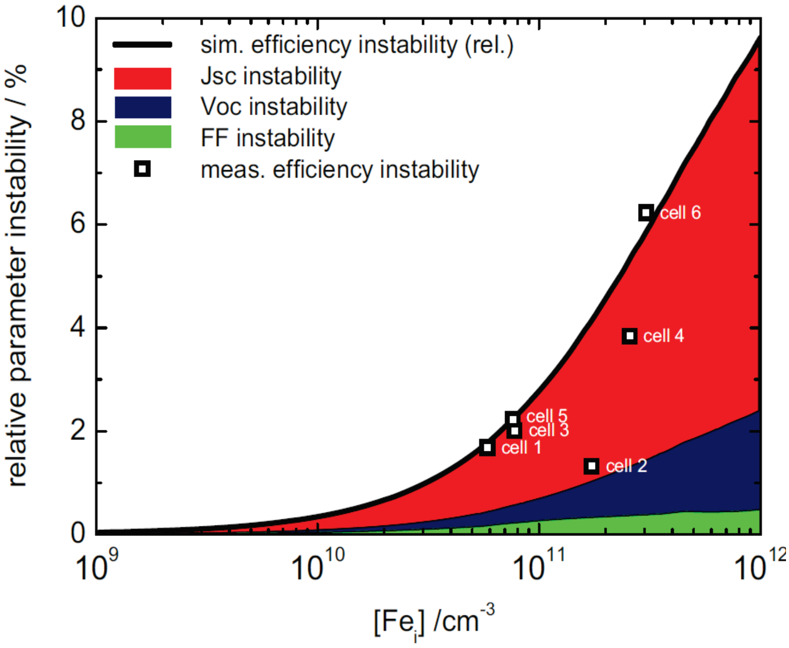
D2.1.4 (Cell opt. and sim)

p-type cell structure

- With increasing cell efficiency / carrier lifetime Fe contamination becomes more prominent
- Simulation (PC1D) of p-type cell structure with different Fe contamination



M. C. Schubert, et al., Solar Energy Materials and Solar Cells, vol. 138, pp. 96-101, 2015.

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D2.1.4 (Cell opt. and sim)
Passivation on p-type / n-type

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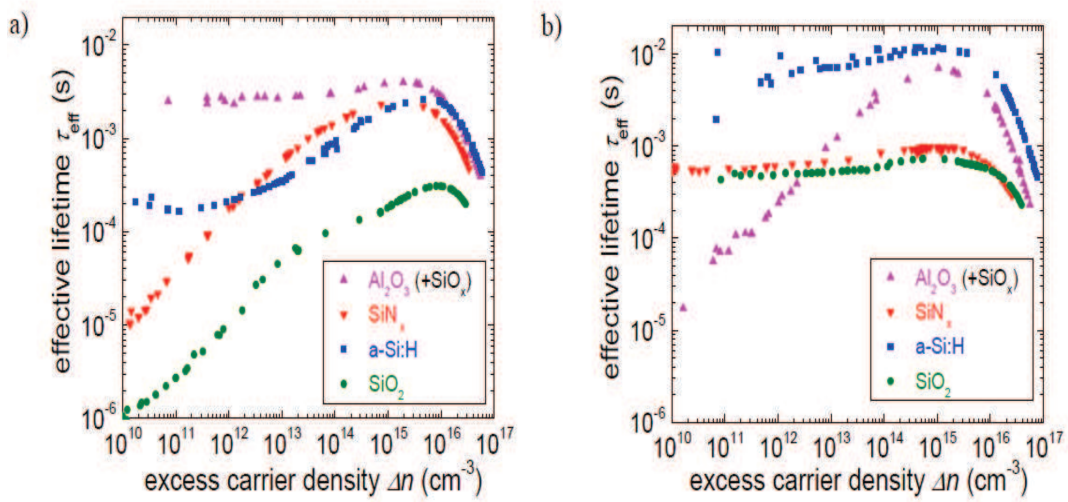
- Injection dependence of different passivation layers down to very low intensities



K. Rühle, *et al.*, *Energy Procedia*, vol. 27, pp. 406-11, 3-5 Apr 2012.

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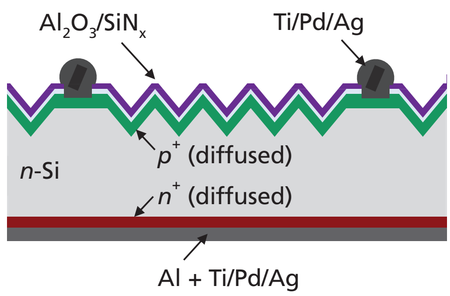
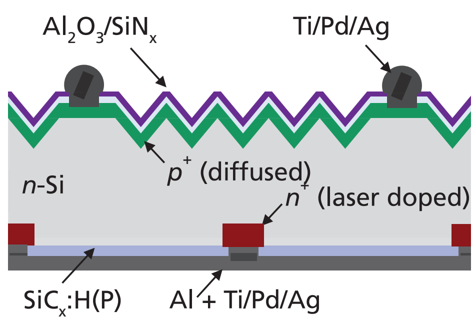
D2.1.4 (Optical Properties…):
Cell Structure

PhotoClass

- n-type cell structure used as reference cells





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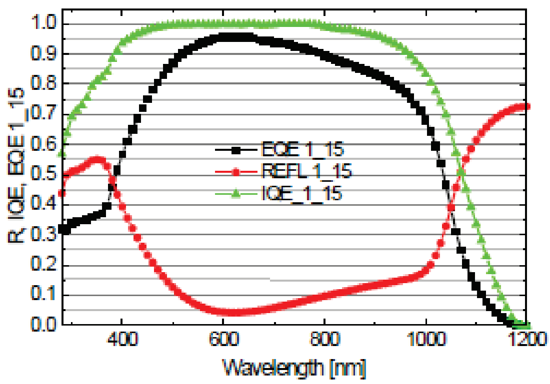
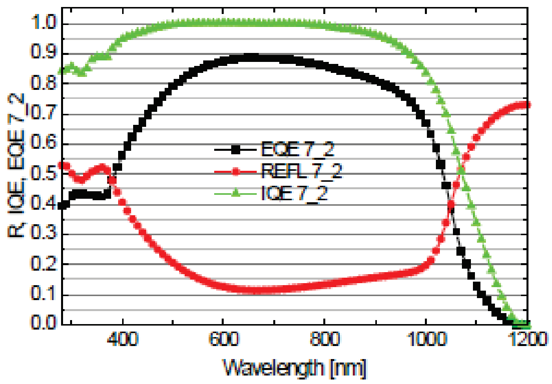
D2.1.4 (Optical Properties…):
Cell Structure

PhotoClass



n-type cell, SiN, planar



n-type cell, SiO, planar

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D2.1.4 (Cell opt. and sim)
n-type cell structure

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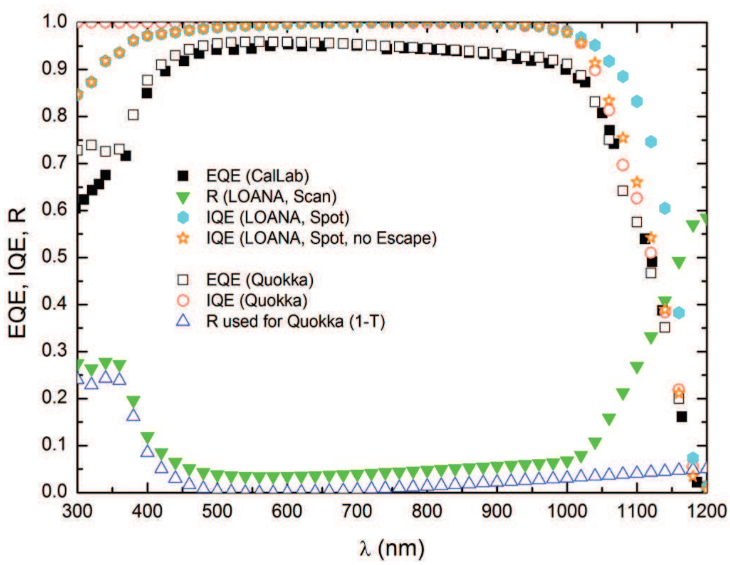
- Measurement and Simulation (Quokka*) of n-type cell structure



*A. Fell, *IEEE Transactions on Electron Devices,* vol. 60, pp. 733-8, 2013.

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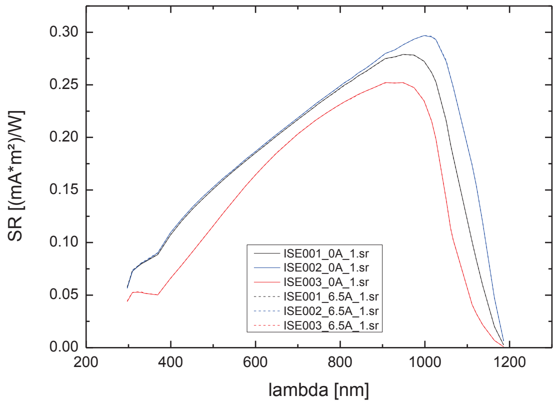
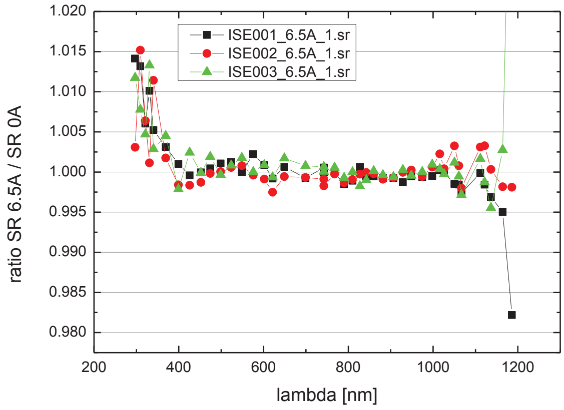
D2.1.4 (Cell opt. and sim)
Linearity of present cell structures

- Measurement of spectral response and
- The determination of it's linearity





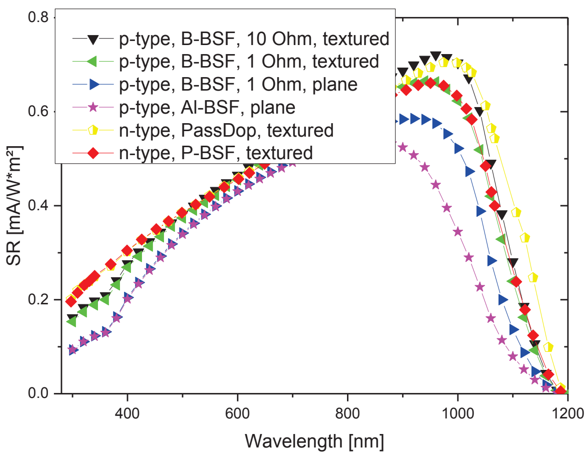
D2.1.5 (Report):

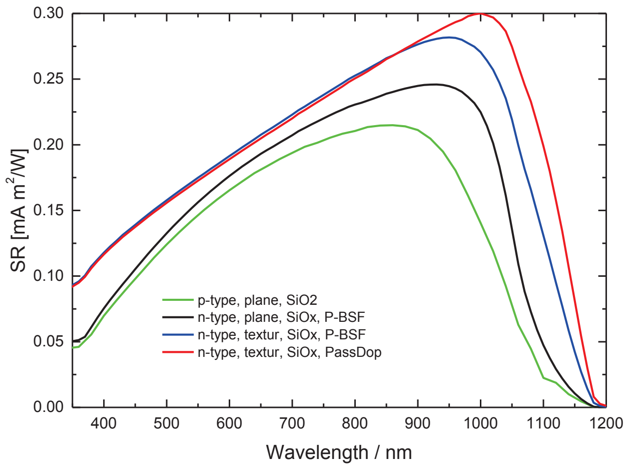
- Report on the spectral adaption of reference cells for thin film application

D2.1.5 (Adapted Reference Cells)
cell structure

PhotoClass

- Variation of spectral response with different p- and n-type silicon cell technologies





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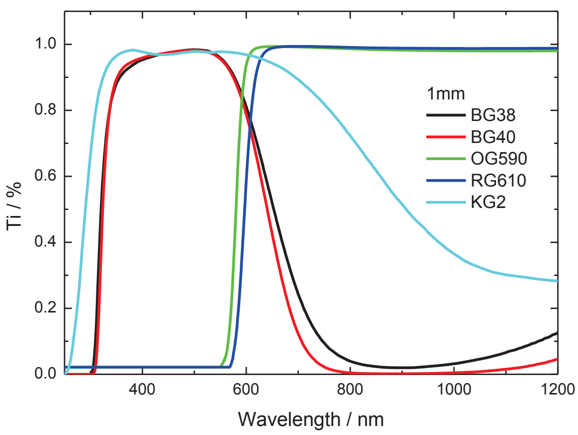
D2.1.5 (Adapted Reference Cells)
Filters combined with cells

PhotoClass

- Variation of spectral transmission of absorption filter combined with different cells
- Calculation of spectral adaption and optimized filter thickness



$$API = \int \left| \frac{s^{TC}(\lambda)}{\int s^{TC}(\lambda) d\lambda} - \frac{s^{RC}(\lambda)}{\int s^{RC}(\lambda) d\lambda} \right| E_{\lambda,SIM}(\lambda) d\lambda$$

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D2.1.5 (Adapted Reference Cells)
Filters combined with cells

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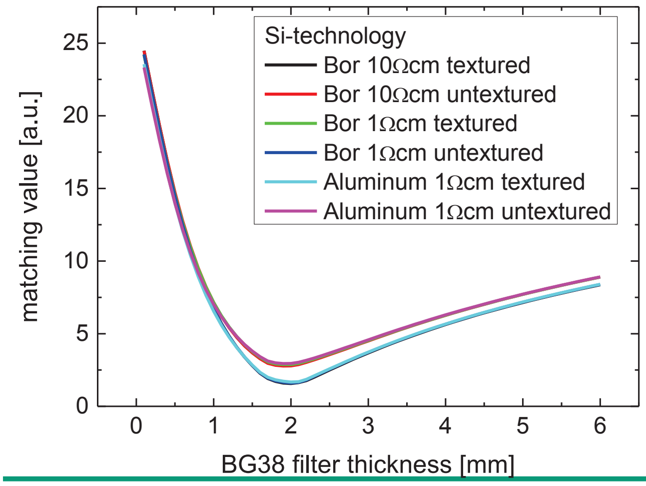

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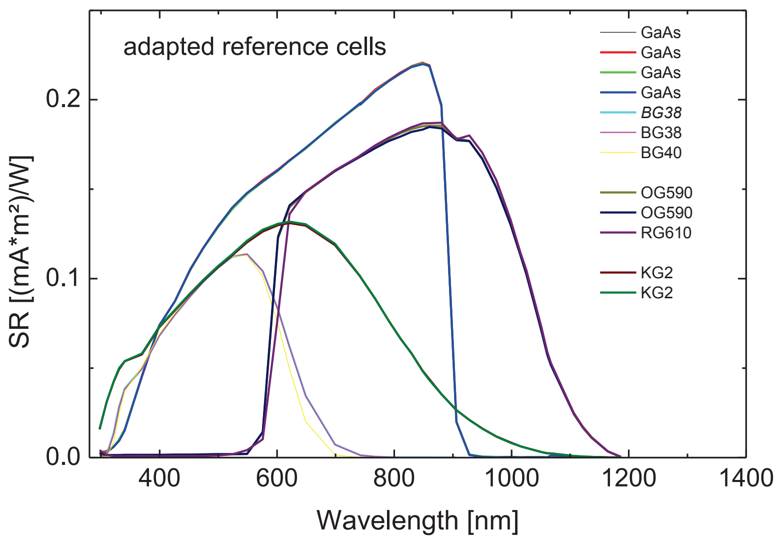
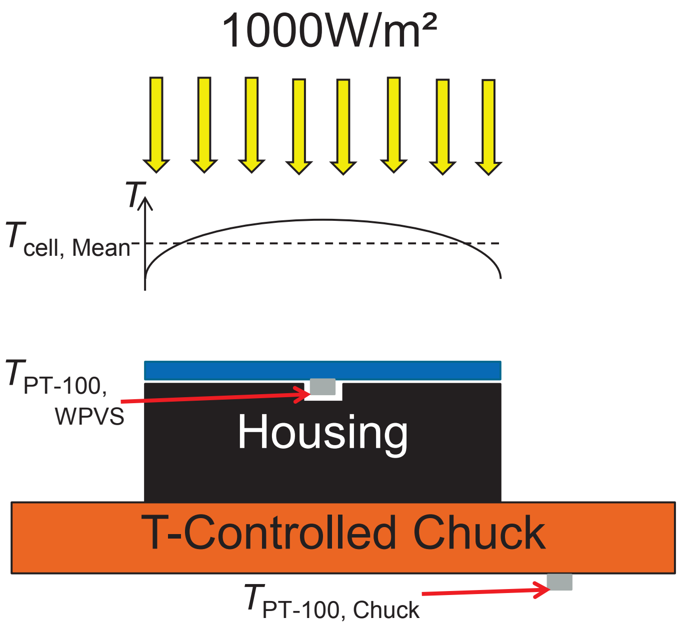
D2.1.5 (Adapted Reference Cells)
Filters combined with cells

- Spectral match of different filtered cells and TF-technologies



Test / Ref. Cell	a-Si	µ-Si	CdTe
Si, planar, BG38			
Si, planar, BG40			
Si, planar, OG590			
Si, planar, RG610			
Si, planar, KG2			
GaAs			

Thermal Conduction of Housing
Improved!



„old“ housing

Cell ID	Δ T_1 [K]	Δ T_2 [K]
028-2013	0.6	5
031-2013	0.3	4

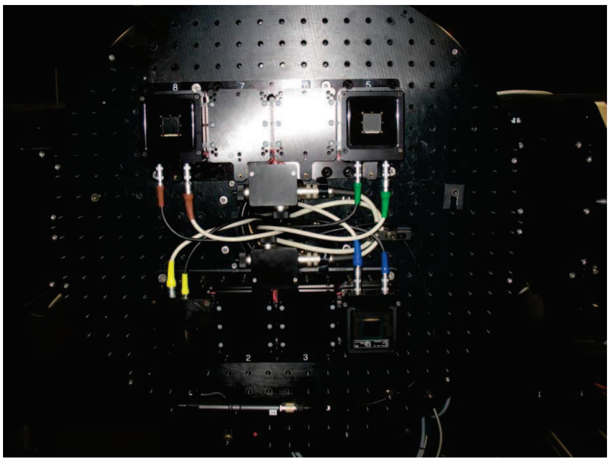
„new“ housing

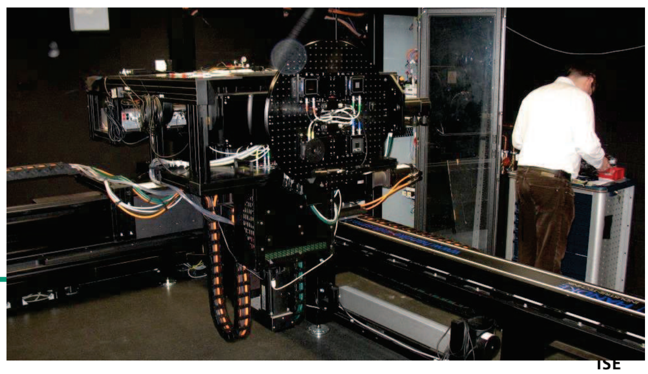
Ext. ID	Δ T_1 [K]	Δ T_2 [K]
039-2015	0.23	2.4
040-2015	0.32	2

$\Delta T_1 = T_{cell, Mean} - T_{PT-100, WPVS}$

$\Delta T_2 = T_{PT-100, WPVS} - T_{PT-100, Chuck}$

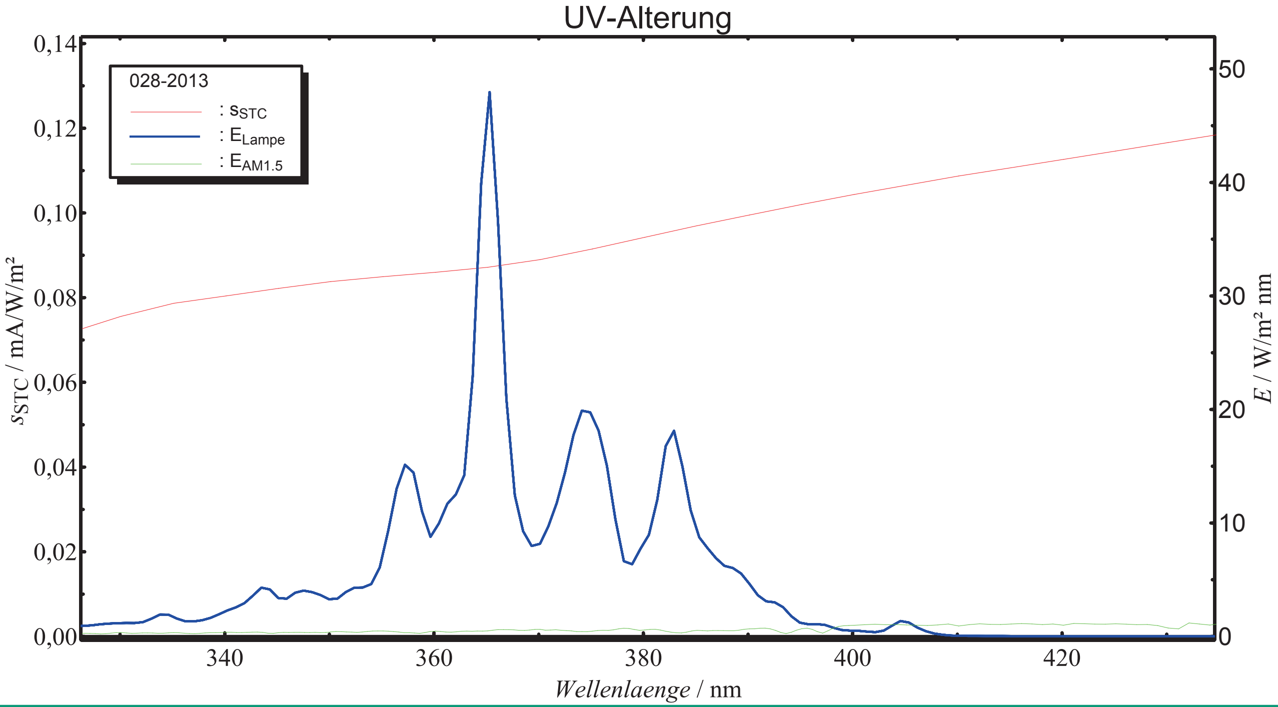
New Reference Cells
UV-Ageing at PTB





New Reference Cells

UV-Spectrum



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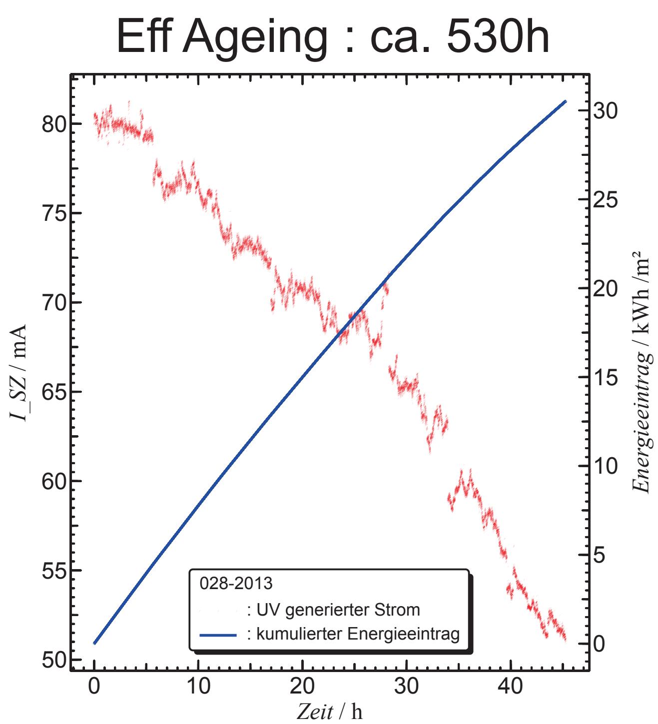
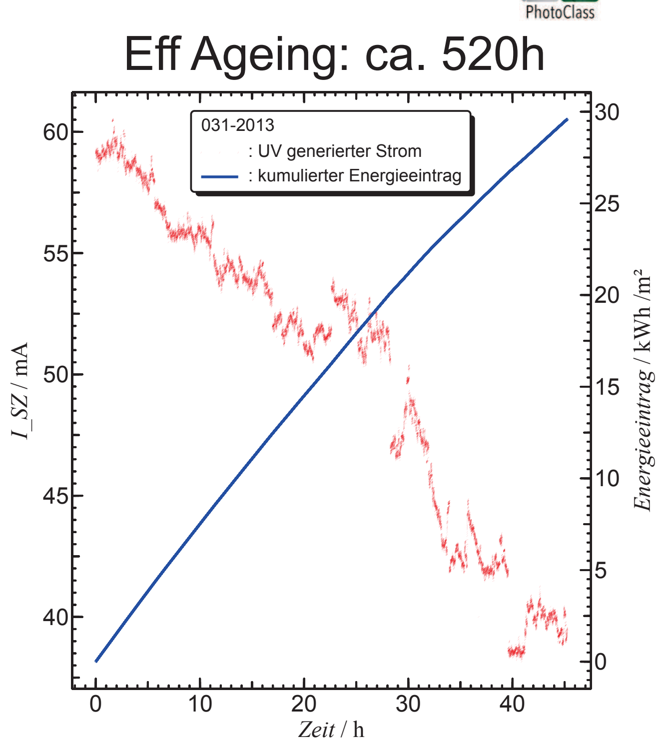
Aging of UV-Lamps





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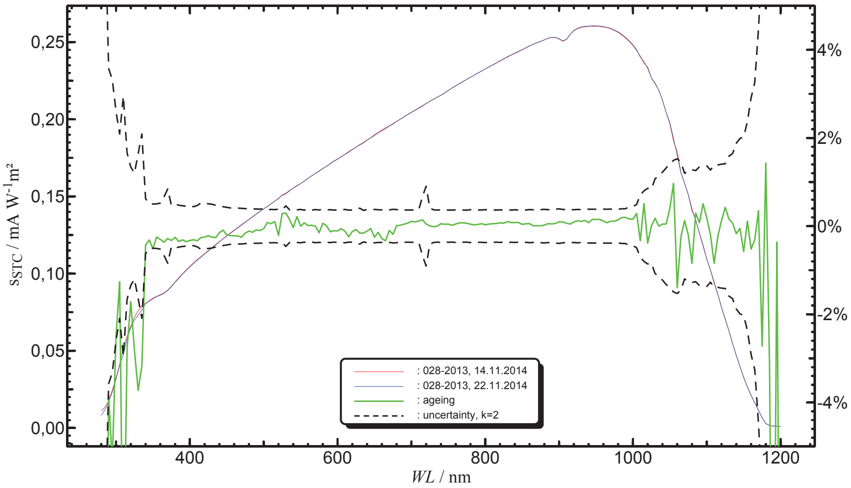
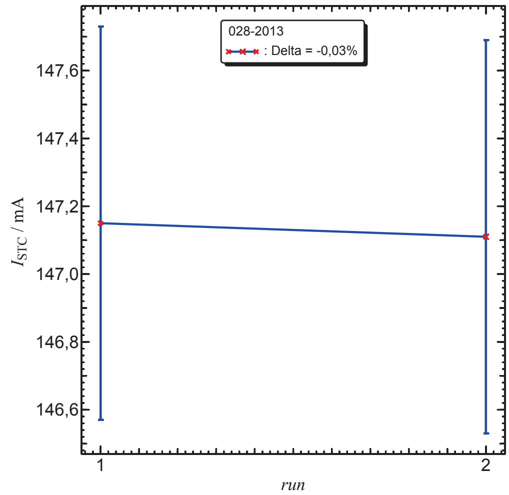
New Reference Cells
Before and After Aging

Control Measurement PTB Reference cell:
- Before aging: I_{STC}=(146,38 ± 0.57)mA
- After ageing: I_{STC}=(146,38 ± 0.58)mA

→ Setup and reference cell stabile





New Reference Cells
Before and After Aging

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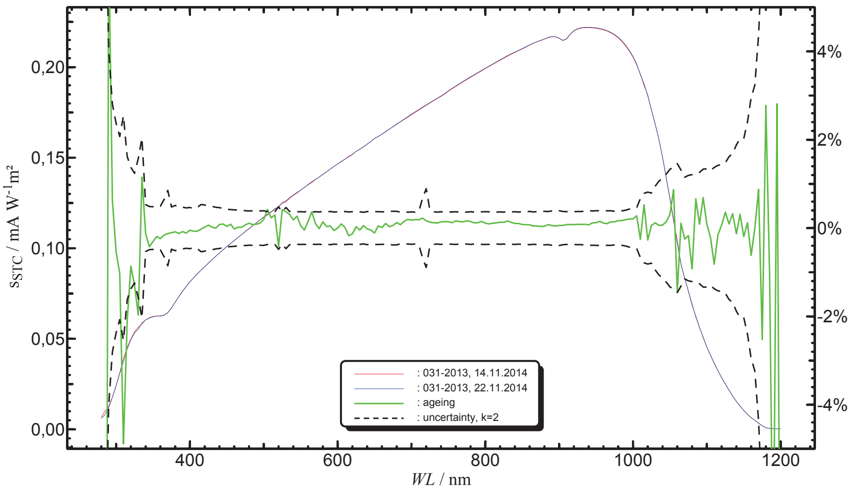
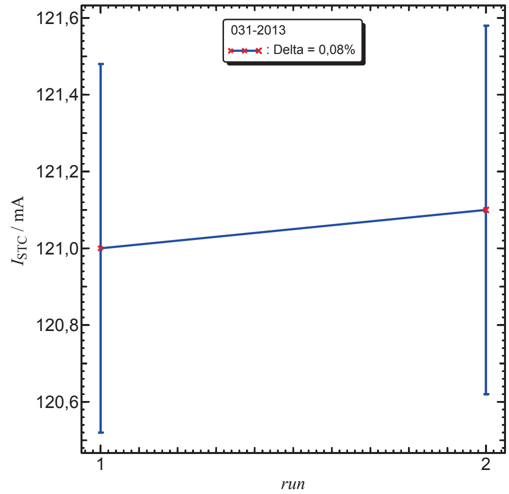
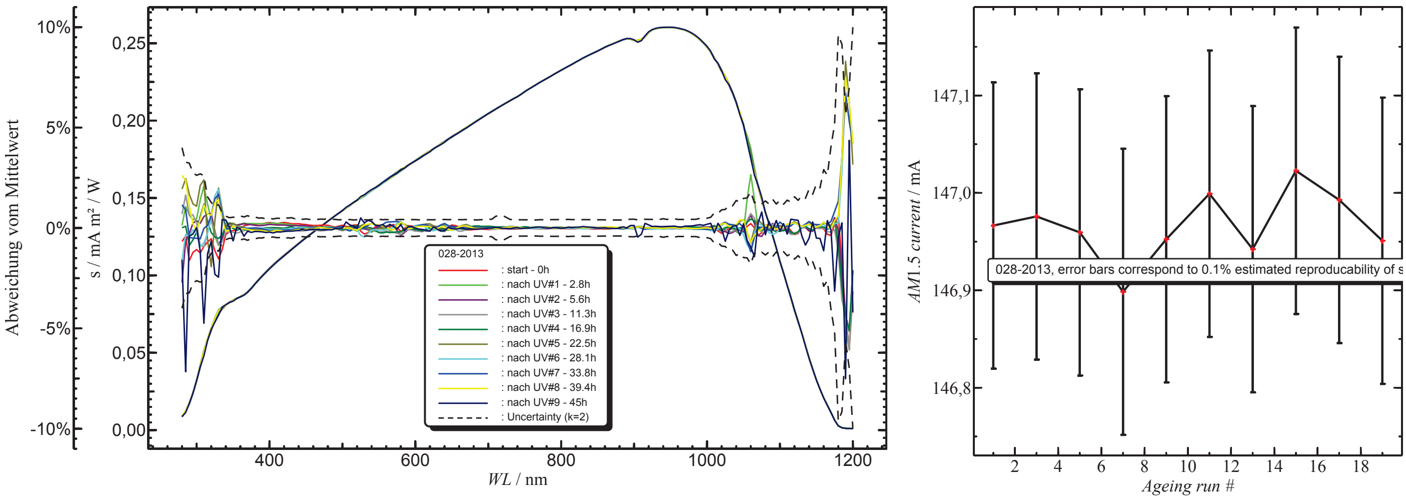




New Reference Cells
Spectral Response During Ageing



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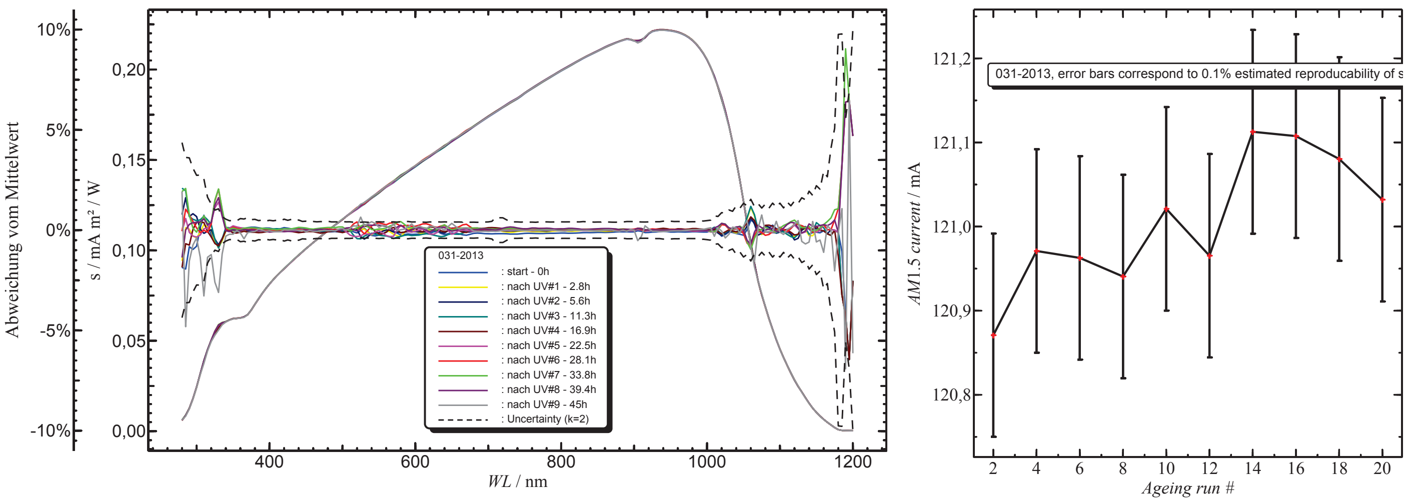
New Reference Cells
Spectral Response During Ageing



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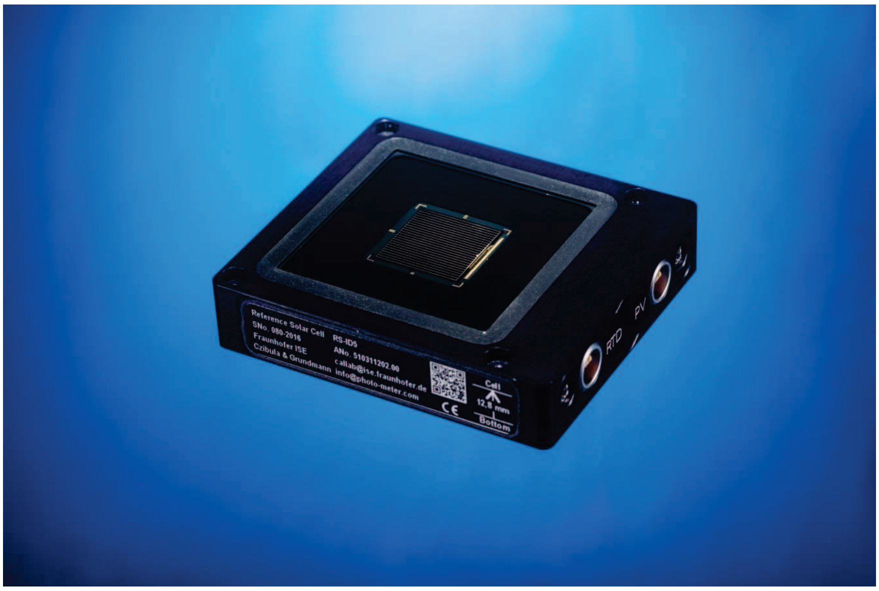
New Reference Cells
Available



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Acknowledgment

Thank You Very Much for Your Attention!

This work was partly funded by the EMRP ENG55 project "Towards an energy-based parameter for photovoltaic classifi-cation". The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

Jochen Hohl-Ebinger

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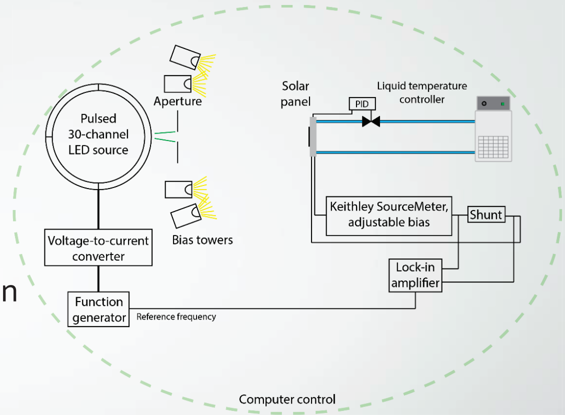
LED-based differential spectral response setup for solar cell mini modules

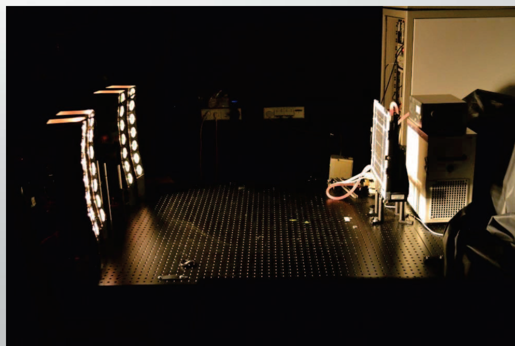
Hans Baumgartner, MIKES – VTT

Ispra 2017

LED-based DSR setup

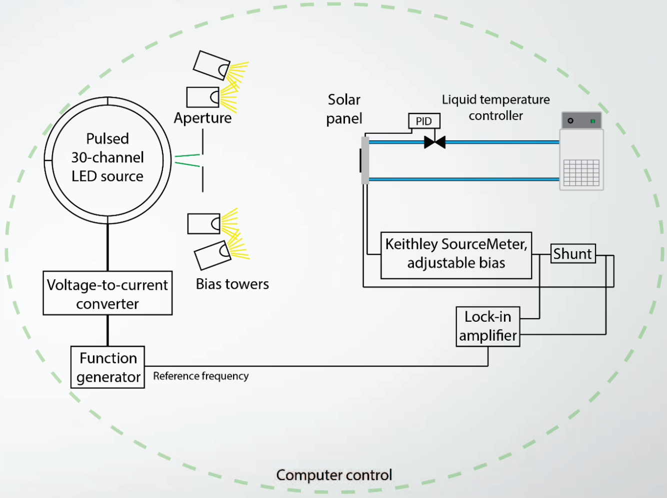


- For spectral responsivity, linearity, and calibration of solar cells.
- Six halogen bias light towers.
- Seven 50 W dichroic lamps in each tower to produce the bias intensity of ~1000 W/m².
- Aluminum mounting base with liquid cooling to stabilize the temperature of the sample panel.

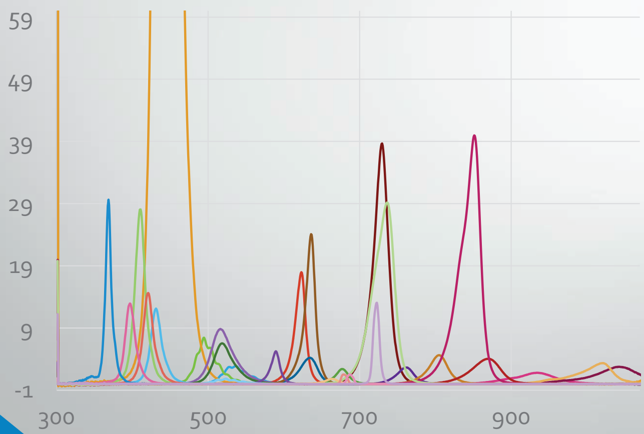


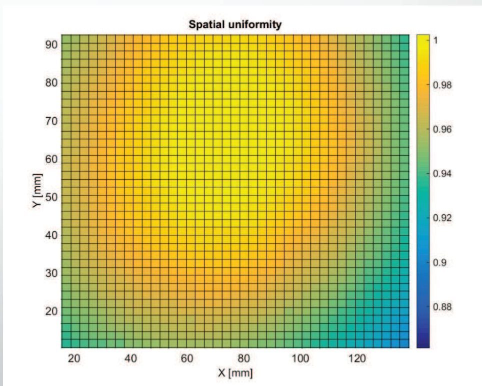
LED-based DSR setup

- LED carousel with 30 replaceable, high power LEDs for monochromatic light.
- Wavelength range 360 – 1300 nm.
- Operated using current pulses, interconnected with a lock-in amplifier.
- The temperature of every LED is independently controlled and stabilized.

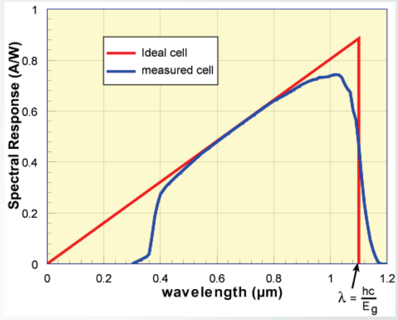


Channels and bias uniformity



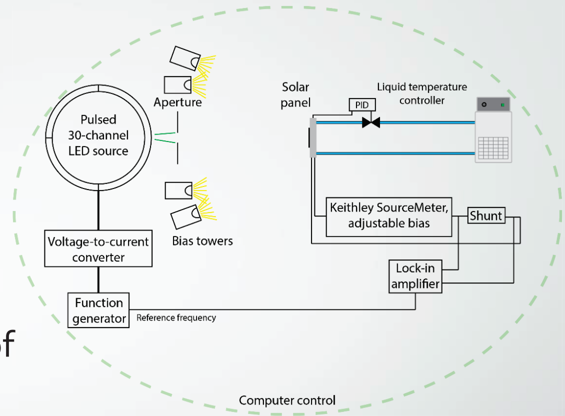


Bandwidth



- The bandwidth of LEDs is typically more than 10 nm.
- The differential spectral responsivity of the solar cell changes within the bandwidth of the LED.
- An iterative signal analysis is used to eliminate the errors related to spectral bandwidth of the "monochromatic" beam.

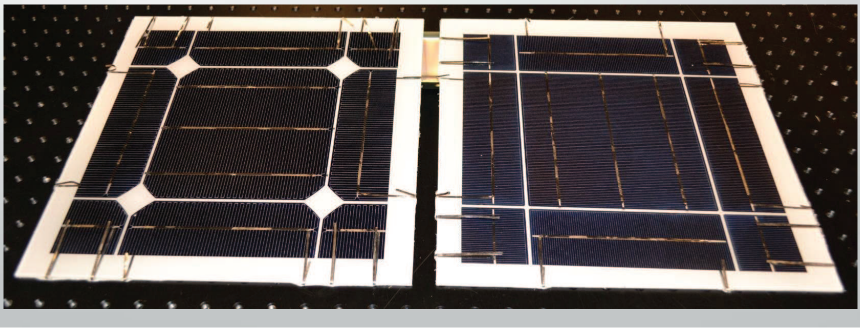
LED-based DSR setup



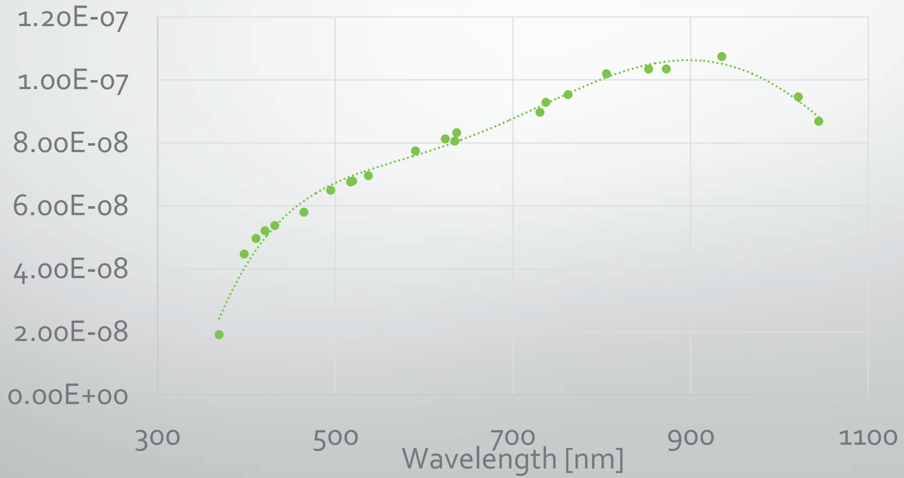
- Traceability to the spectral irradiance scale of National Metrology Institute of Finland.
- Absolute spectral irradiance of the monochromatic light measured with a calibrated spectrometer.
- (Monitor detector for monochromatic light to detect possible changes.)
- (Monocrystalline Si reference solar cell from Fraunhofer.)

Reference mini modules

- Custom size reference solar cell mini modules were build to be used as laboratory reference cells.
- Comprises a single full size 6″ x 6″ solar cell surrounded by 8 cut panels.
- Separate electrical contacts for all cells.
- Two different types of references: single crystal and polycrystalline.



Spectral response of a polycrystalline reference mini module



Acknowledgement

The work leading to this study was funded by the European Metrology Research Programme (EMRP) project "Towards an energy-based parameter for photovoltaic classification." The EMRP is jointly funded by the participating countries within European Association of National Metrology Institutes (EURAMET) and the European Union.

Reference device intercomparison (WP2)

Participants

Participant	facility	period	traceability
PTB	Laser-DSR	July 2015	SI, reference photodiode
JRC	WACOM solar simulator + Filtermonochromator DSR	March 2016	SI+WRR, WPVS reference solar cell
SUPSI	Pasan IIIb + Pasan IIIa + filters	May 2016	SI (PTB), WPVS reference solar cell
REG(Fhg)	XAT solar simulator + Filtermonochromator DSR	June 2016	SI (PTB), WPVS reference solar cell
REG(LU)	PASAN IIIb + Filtermonochromator DSR	September 2016	SI+WRR (ESTI), reference module
VSL	-------------------------	------------------	---
ISFH	Monochromator DSR + WACOM solar simulator	February 2017	SI (PTB), WPVS reference solar cell
TÜV Rheinland		February 2017	
LNE		March 2017	
PTB	DSR	April 2017	SI, reference photodiode
PTB	Laser-DSR	April 2017	SI, reference photodiode

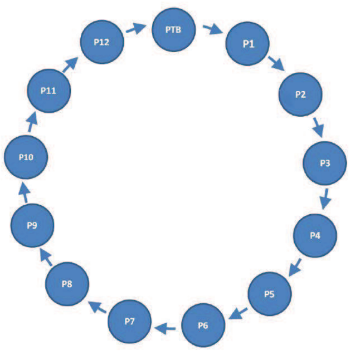
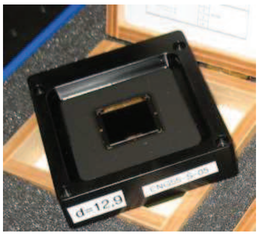


Figure 1 Ring scheme of the intercomparison measurement.

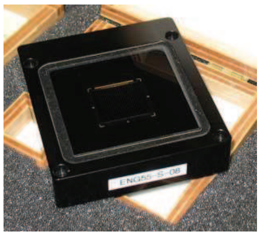
- Parameter to be measured and compared: I_{STC} @ STC; T = 25°C, E = 1000 W/m², AM1.5g of two artefacts

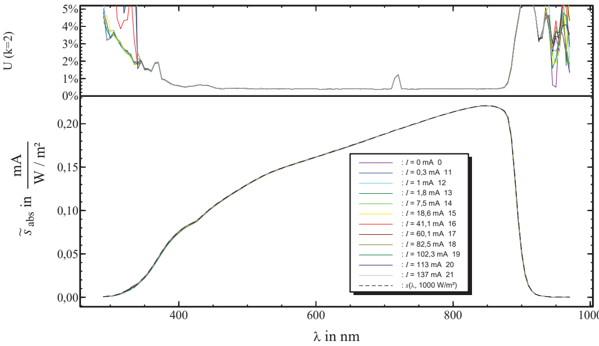
Devices

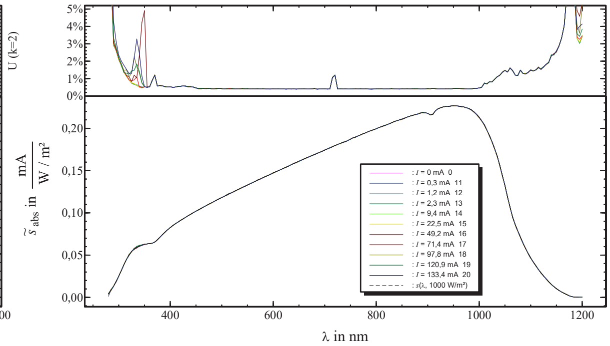
ENG55-S-05
GaAs
No encapsulation



ENG55-S-08
c-Si
encapsulation

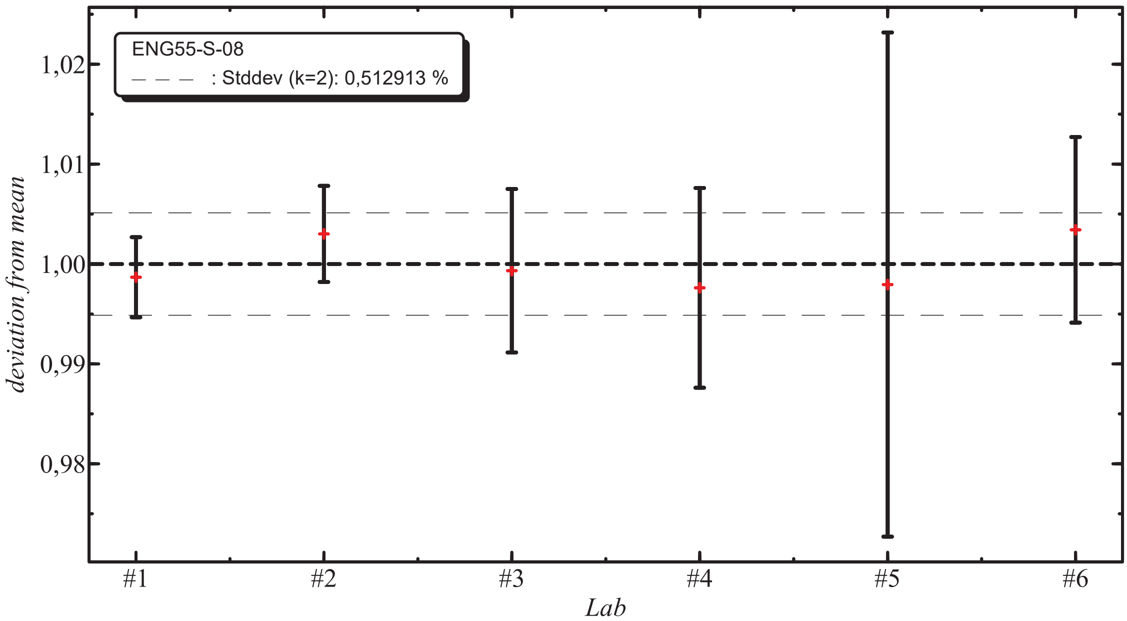






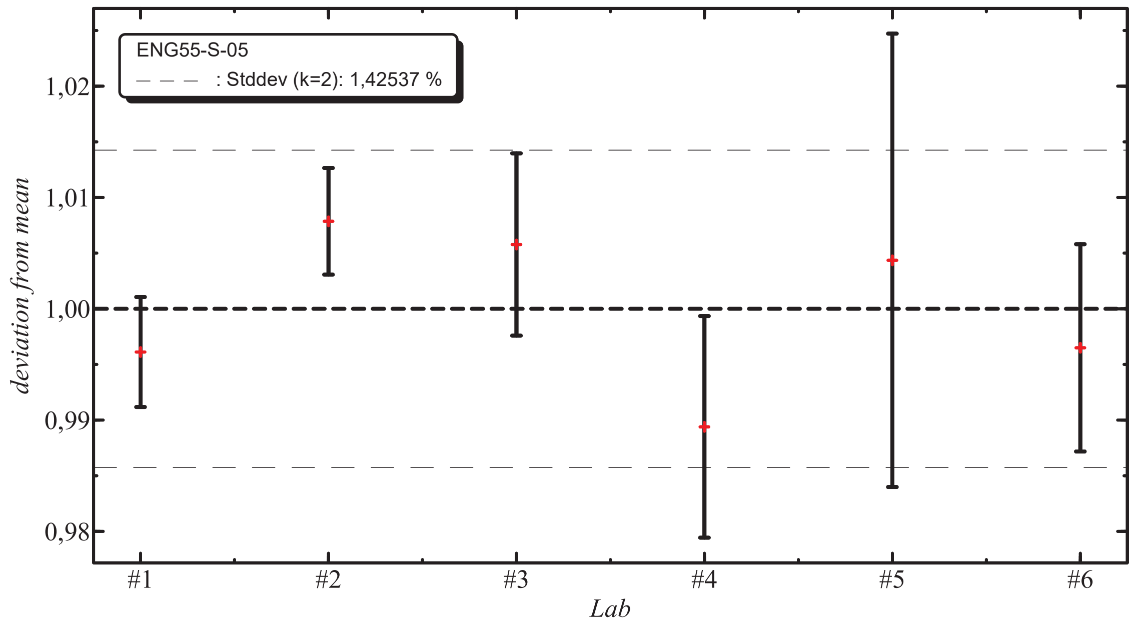
- The two comparison artefacts have been measured by PTB before circulating this to the participants. PTB have taken note of the initial performance (Isc @ STC, stability) of the samples.

Results : ENG55-S-08 (c-Si)



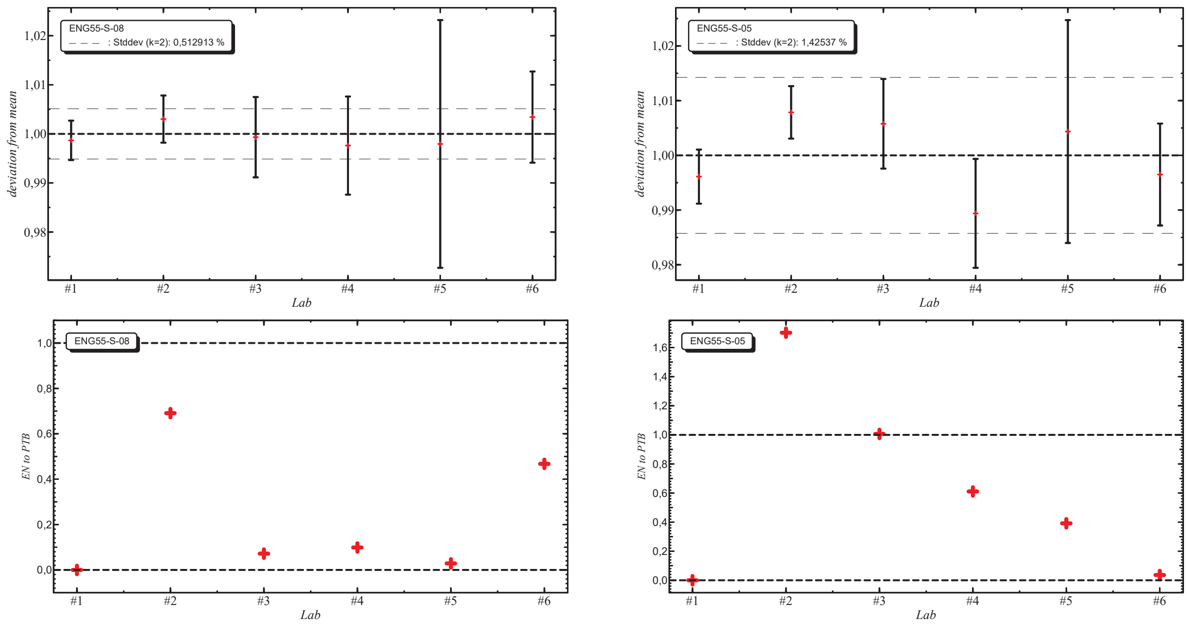
[redacted]

Results : ENG55-S-05 (GaAs)



[redacted]

Summary (preliminary)



- New reference devices can be considered to be very robust and stable
- Very good agreement on c-Si reference device, traceability is fine
- Generally good agreement on GaAs reference device
- Completion soon: Data missing TÜV, LNE, PTB 2nd measurement

Thank you.

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PTB
Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

EMRP
European Metrology Research Programme
Programme of EURAMET
The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

PHOTOCLASS 3-day Training course at JRC Ispra

Programme

Session 1: based on WP2 Reference devices

The new reference cells (J. Hohl-Ebinger, ISE-FhG)

LED-based differential spectral response setup for reference solar cell mini modules (H. Baumgartner, MIKES)

Reference device intercomparison: protocol and first results (I. Kröger, PTB)

Session 2: based on WP3 Detector characterisation: temperature dependence

Overview: Facilities and methods for temperature dependence measurements (I. Kröger, PTB)

Overview: Facilities and methods for angular dependence (I. Kröger, PTB)

Session 3: based on WP3 Detector characterisation: linearity

Compressive sensing (T. Betts, LU)

Polychromatic SR (T. Betts, LU)

Overview: Facilities and methods for linearity measurements (I. Kröger, PTB)

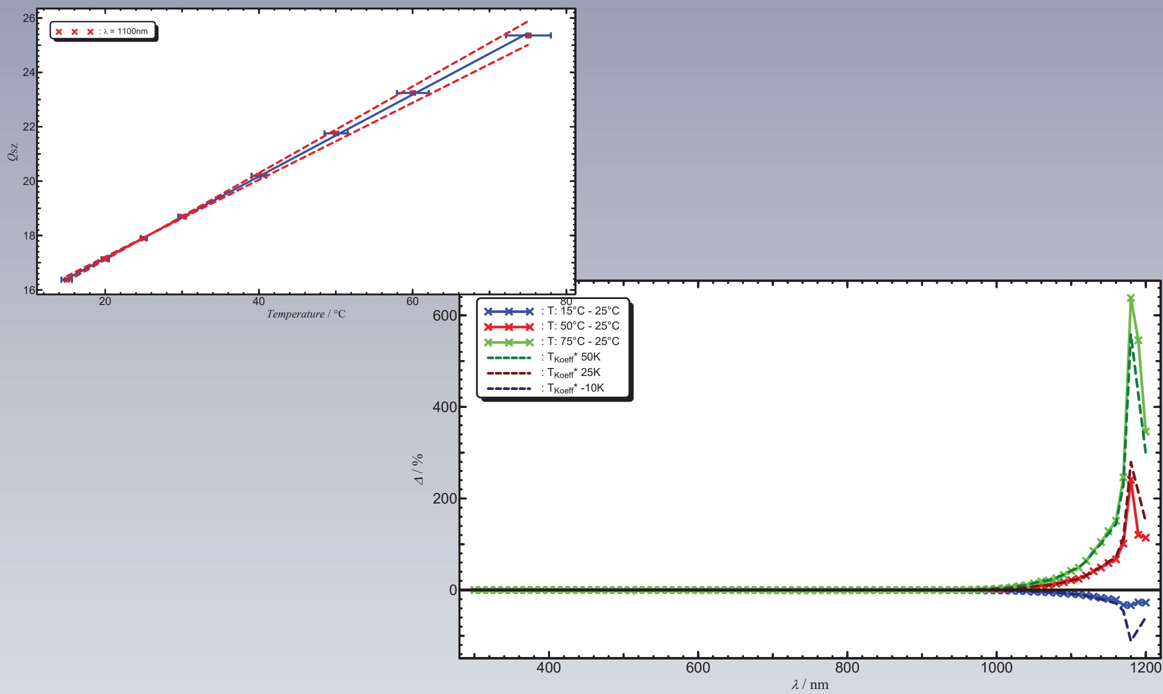
Session 4: based on WP4 Source characterisation methods

Solar cell chuck for temperature characterisation (G. Martínez, INTA)

Comparison of spectroradiometers (I. Kröger, PTB)

Spectral sky scanning (S. Riechelmann, PTB)

Temperature dependence measurements (WP3)



Ingo Kröger
Department 4.1: Photometry and Applied Radiometry
Working Group 4.14: Solar Cells

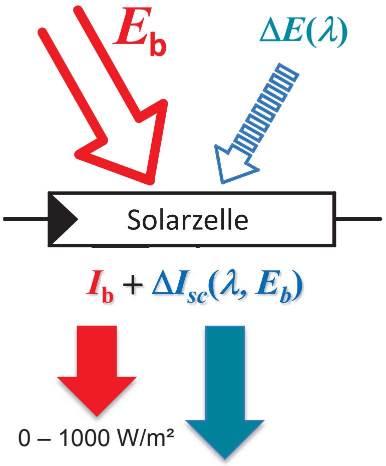
PhotoClass

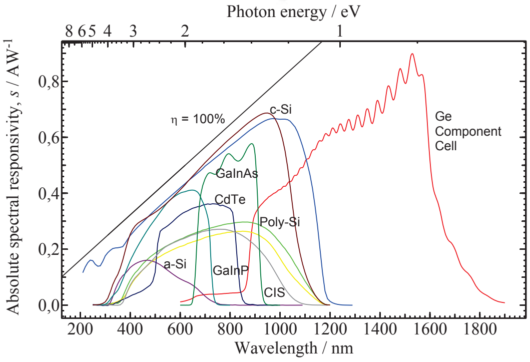
PTB Physikalisch-Technische Bundesanstalt Braunschweig und Berlin

Participants temperature dependent measurements

Participant	Deliverable	Facility, method	T-measurement	samples	period
PTB	D3.3.7	Laser-DSR relative DSR-method Peltier cooling/heating	Attached T-sensor	ENG55-S ENG55-M ENG55-X	12/2015 - 01/2016 12/2016 - 02/2017 02/2017 - 04/2017
LNE	D3.3.8	PASAN IIIC climate chamber	Attached T-sensor	ENG55-X ENG55-XL	07/2016 - 10/2016 08/2016 - 11/2016
JRC	D3.3.9	Apollo/Wacom solar simulator/natural sunlight front bias heating/Peltier heating/cooling	Attached T-sensor	ENG55-S ENG55-M ENG55-X ENG55-XL	03/2016 05/2016 - 06/2016 05/2016 - 06/2016 04/2016 - 07/2016
REG(Fhg)	D3.3.11	Filtermonochromator DSR Peltier/water cooling/heating	Attached T-sensor	ENG55-S ENG55-M ENG55-X	06/2016 - 07/2016 07/2016 - 08/2016 ------
VSL	D3.3.10	Supercontinuum DSR ???	Attached T-sensor	ENG55-S ENG55-M ENG55-X	10/2016 - 11/2016 09/2016 - 10/2016 ------
ISFH	voluntary	Monochromator DSR, relative DSR-method Peltier cooling/heating	Attached T-sensor	ENG55-S (ENG55-M)	02-2017 -------

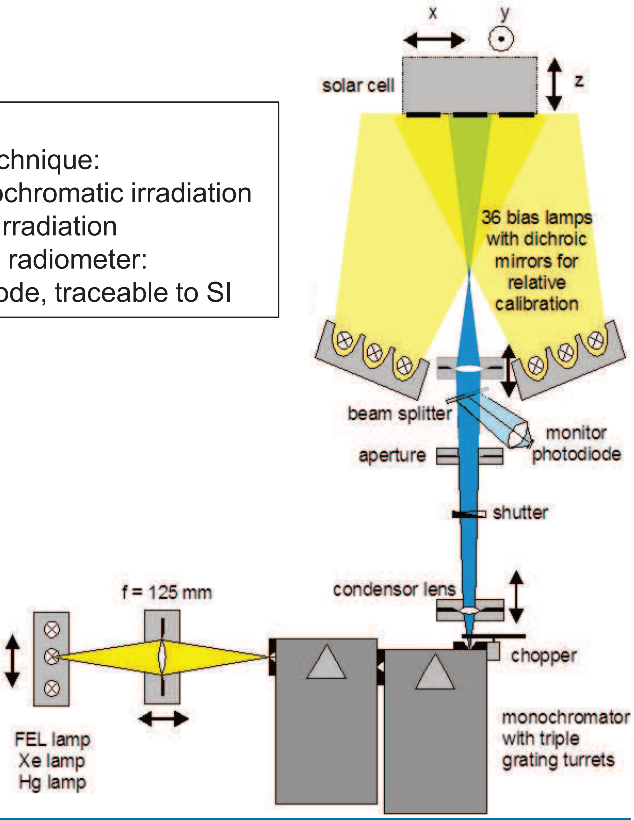
Differential spectral responsivity (DSR) method



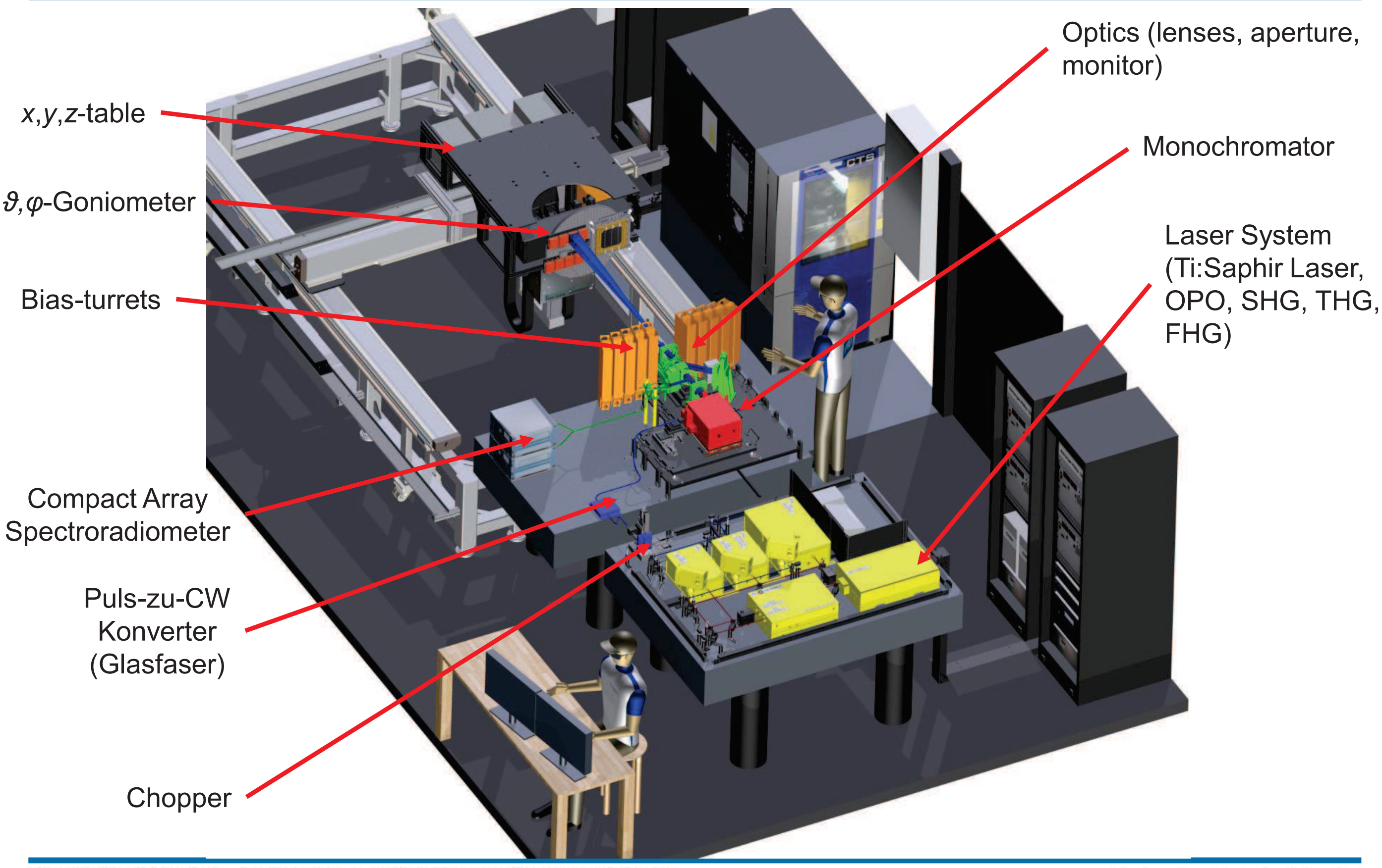


DSR- facility

- 2 beam technique:
  - → monochromatic irradiation
  - → Bias irradiation
- Reference radiometer:
  Photodiode, traceable to SI



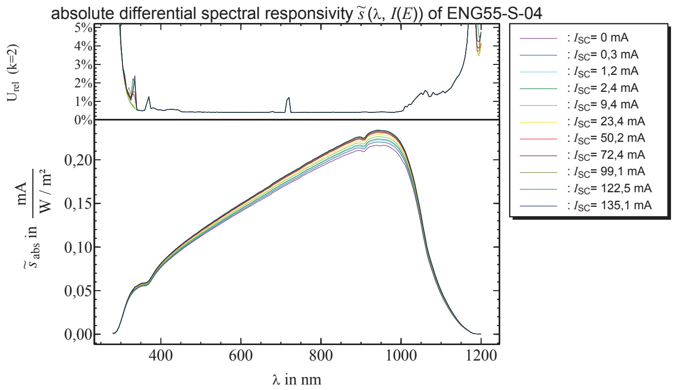
Laser-DSR facility @PTB



DSR fundamentals: From DSR to I_{STC}

Measurements of differential spectral responsivity curves $\tilde{s}_{SZ}(\lambda, E_b)$ at different Bias irradiance levels E_b.
Comparison of solar cell against reference photodiode in homogeneous monochromatic fields, using monitor correction:

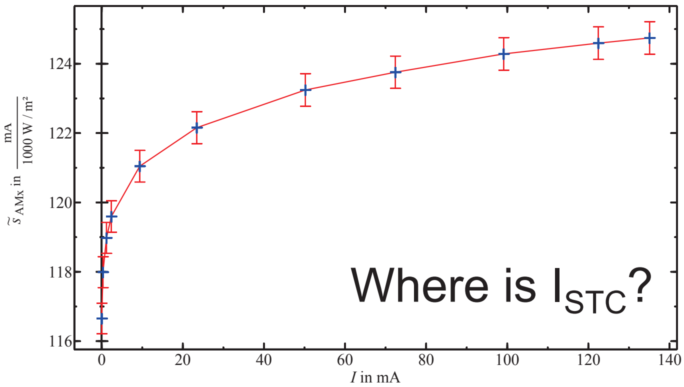
$$\tilde{s}_{SZ}(\lambda, I_{Bias}) = \frac{I_{SZ}(\lambda, I_{Bias}) / I_{MD,SZ}(\lambda)}{I_{Ref}(\lambda) / I_{MD,Ref}(\lambda)} \cdot \tilde{s}_{Ref}(\lambda)$$



Determination of AMx weighted currents $\tilde{s}_{AMx}(I_{SC}(E_b))$ for each DSR curve at given Bias irradiance level $I_{SC}(E_b)$:

$$\tilde{s}_{AMx}(I_{SC}(E_b)) = \frac{\int_0^\infty \tilde{s}(\lambda, I_{SC}(E_B)) \cdot E_{\lambda,AMx}(\lambda) d\lambda}{\int_0^\infty E_{\lambda,AMx}(\lambda) d\lambda}$$

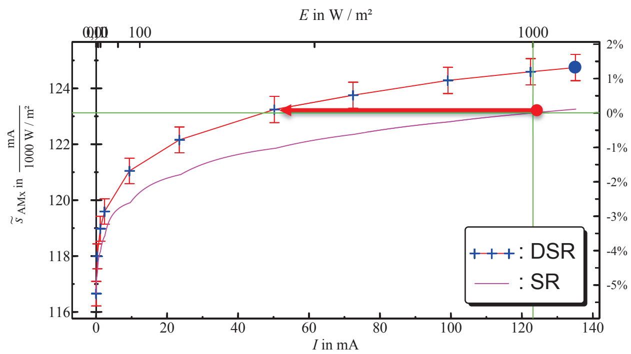
If the solar cell would be linear, $\tilde{s}_{AMx}(I_{SC}(E_b))$ would be constant and $\tilde{s}_{AMx}(I_{SC}(E_b)) = I_{STC}$

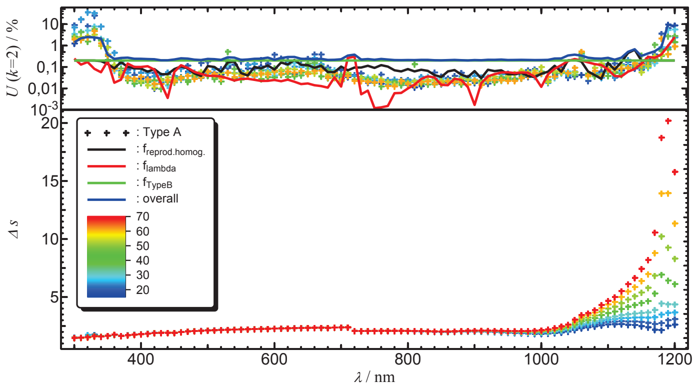


Temperature dependent measurements

Full DSR-calibration at 4 different temperatures exceeds reasonable time scale

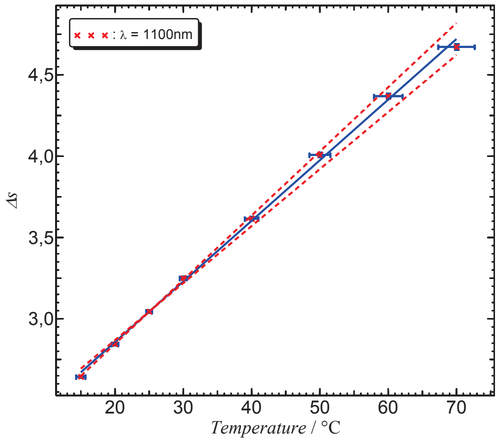
- Only perform relative DSR measurement dependent on solar cell temperature
- Set irradiance level to approx. 300W/m², since in general SR(1000 W/m²) ≈ DSR(300 W/m²)
- Set solar cell temperature to 15°C, 20°C, 25°C, 30°C, 40°C, 50°C, 75°C
- Peltier based heating/cooling: Temperature instability <0.2K

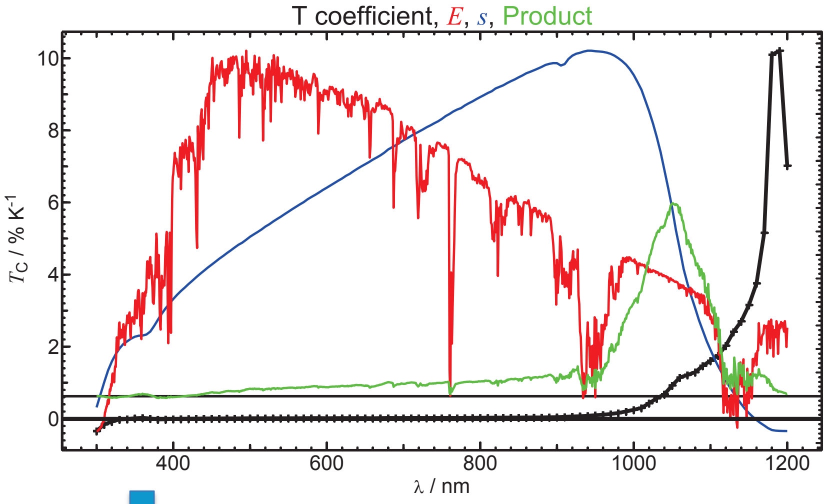




Temperature dependent measurements

- Perform a linear regression for each wavelength
- Determination of spectral temperature coefficient
- Calculation of AM1.5 weighted temperature coefficient using the absolute SR.



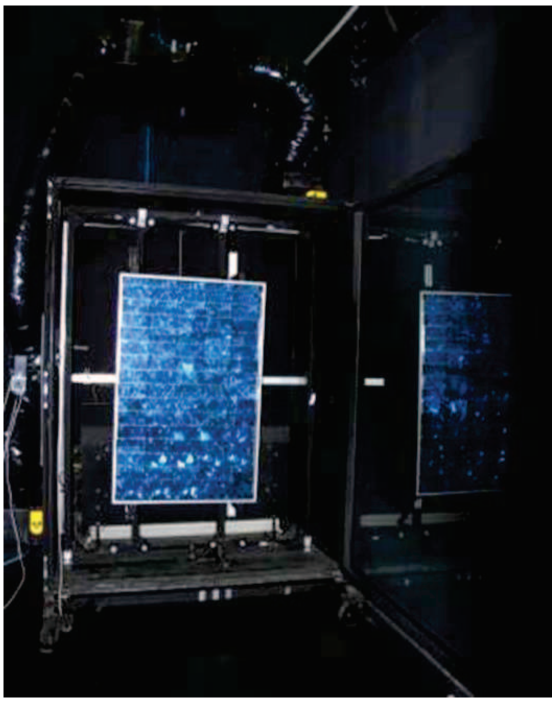


TC I_{SC} : (0.00883 ± 0.00100) %/K

- Since it is a relative measurement, most crucial uncertainty components are
  - Temperature measurement (including uncertainty due to temperature gradient within device)
  - Reproducibility of the measurement (homogeneity, monitor principle, wavelength,…)

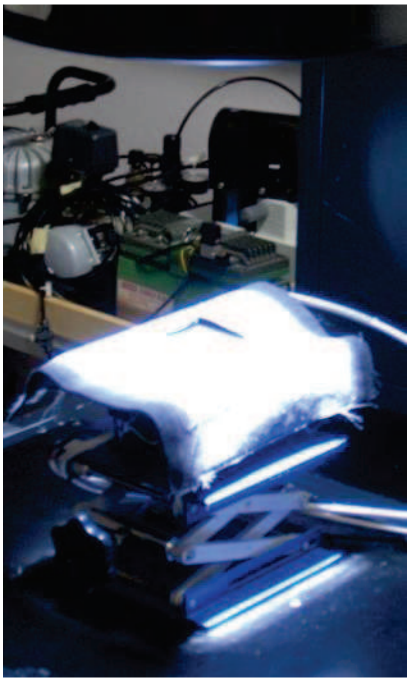
DUT in box with heating/cooling

PV DUT in temperature-controlled box with glass window	
PROS	**CONS**
Simple	Size
T in steady state	Spatial uniformity
Modules and cells	Spectrum
	Irradiance reduction/limitation
	Slow



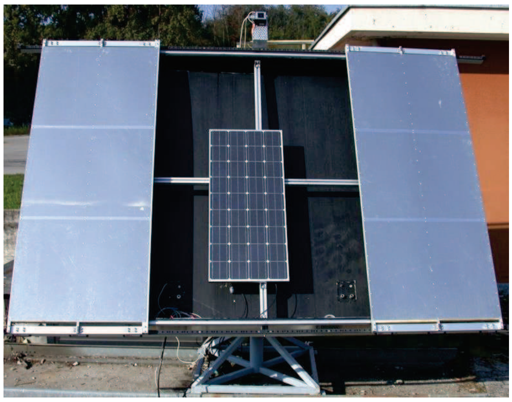
DUT heated/cooled by Peltier

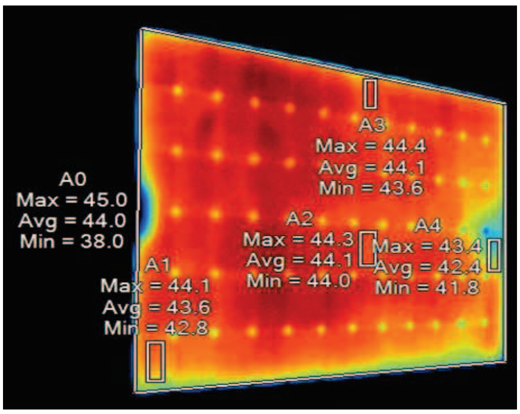
Temperature control with Peltier element for DUT under simulated steady-state irradiance	
PROS	**CONS**
No additional equipment	Only small device
Spectrum stable	
T in (quasi) steady state	
Full T control	
Applicable also to flashers	



Heating by steady-state light source

Use natural or simulated steady-state irradiance	
PROS	**CONS**
No additional equipment	T not steady-state
Spectrum stable	T uniformity
Fast	T range
Simple	(Size)
Natural and simulated sunlight	T gradient junction-sensor
Closer to real world	

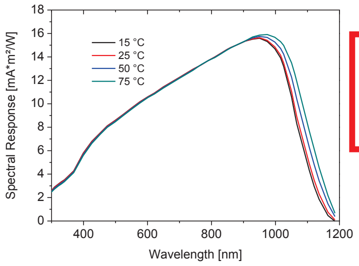




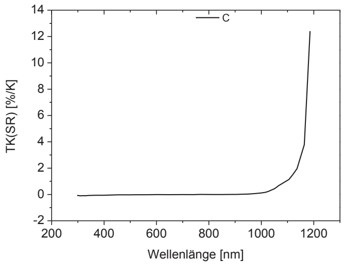
Temperature Coefficients (SR and IV)
Fraunhofer ISE CalLab PV Cells

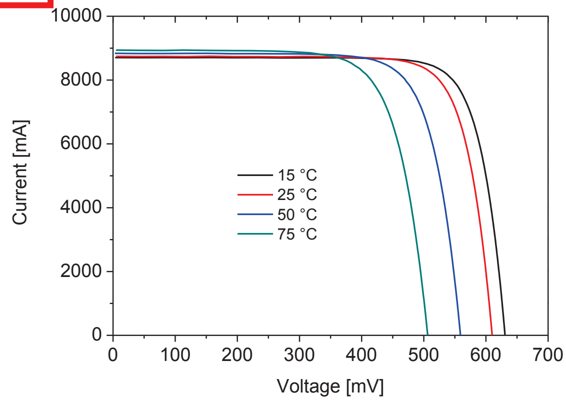
SR(λ) @ 25°C and 75°C measured

SR(λ) @ 15°C und 50°C interpolated



MM(15, 25, 50 und 75°C)





Fraunhofer ISE

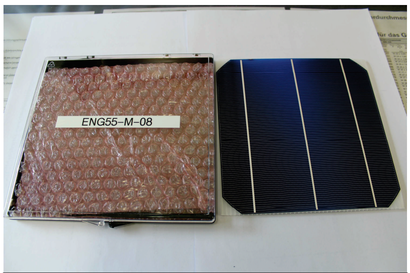
Samples Photoclass project

PTB

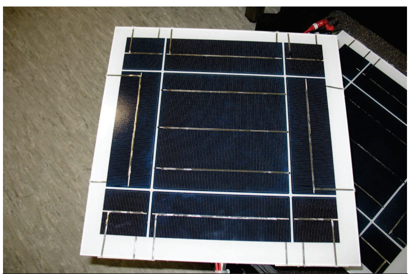
ENG55-S
Reference solar cells

Investigation of:
- Different types
- Different sizes
- Different technologies

Here we show selected measurements of different devices.



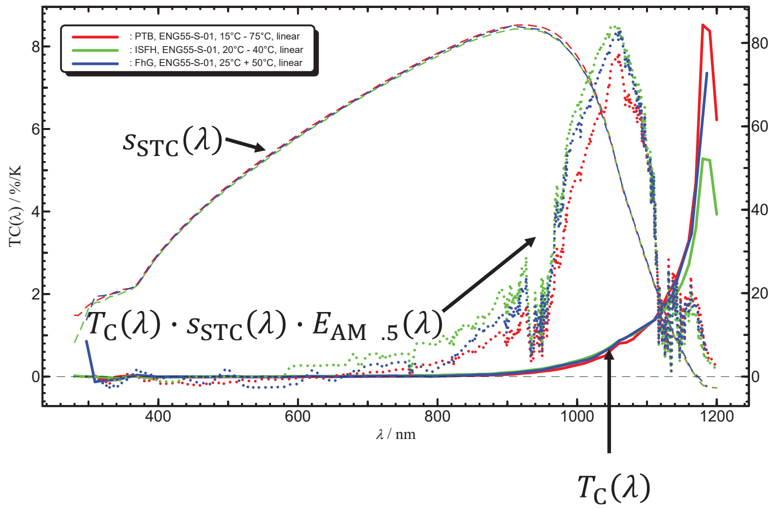
ENG55-M
solar cells

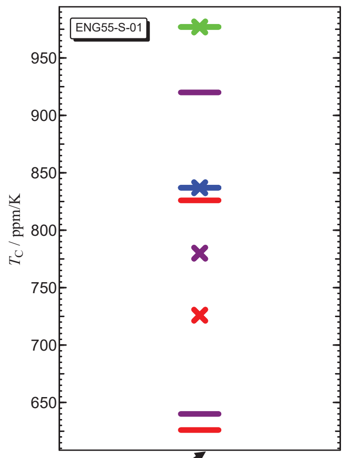


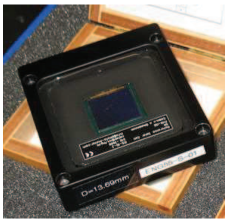
ENG55-X
Mini-Modules

ENG55-XL
Modules

Results – ENG55-S-01



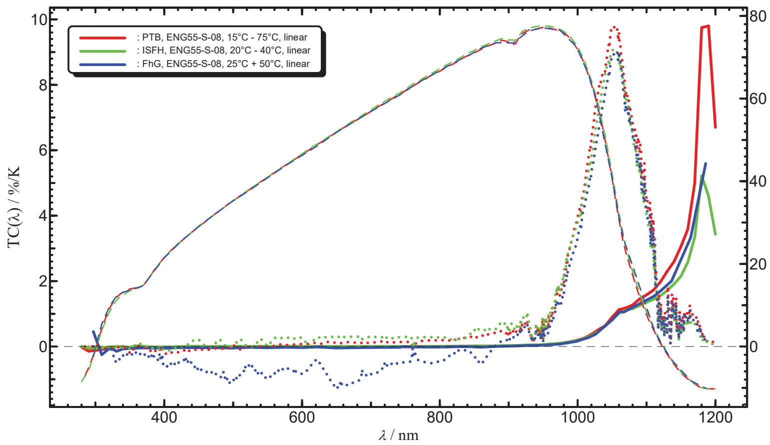


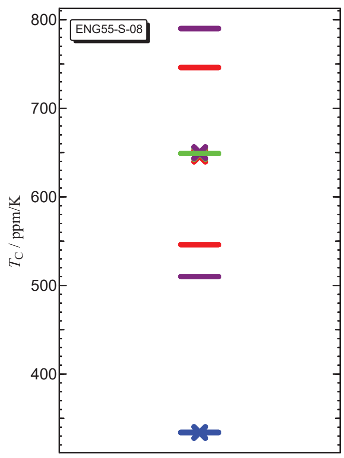


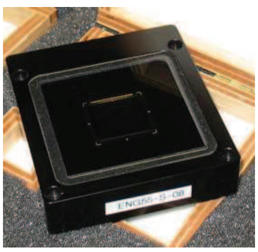
$$T_C = \frac{\int T_C(\lambda) \cdot s_{STC}(\lambda) \cdot E_{AM\ .5}(\lambda) d\lambda}{\int s_{STC}(\lambda) \cdot E_{AM1.5}(\lambda) d\lambda}$$

FhG: DSR
JRC: Solar simulator/natural sunlight
ISFH: DSR
PTB: DSR

Results – ENG55-S-08

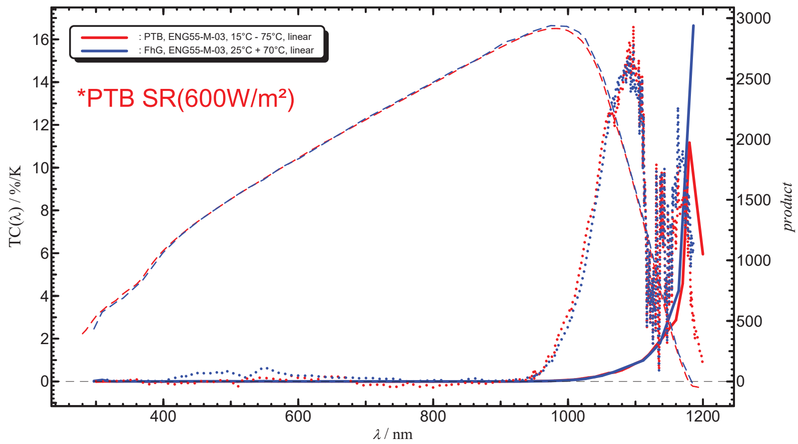


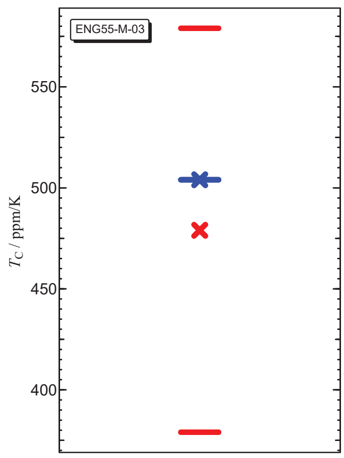




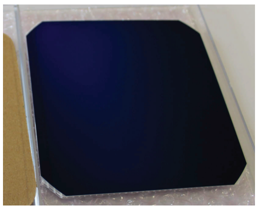
FhG: DSR
JRC: Solar simulator/natural sunlight
ISFH: DSR
PTB: DSR

Results – ENG55-M-03

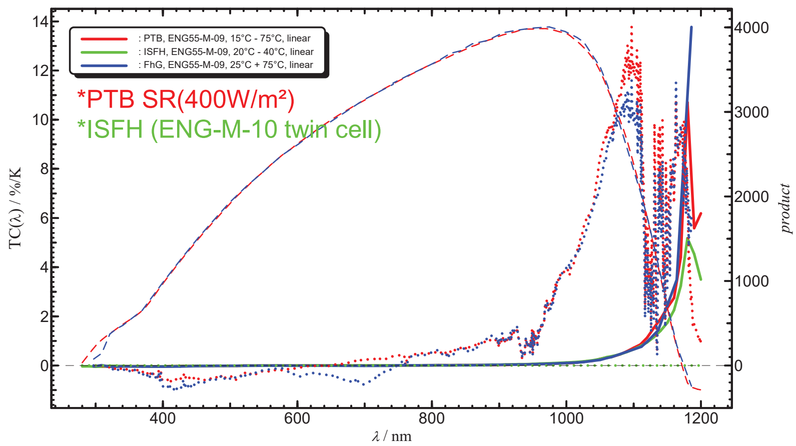


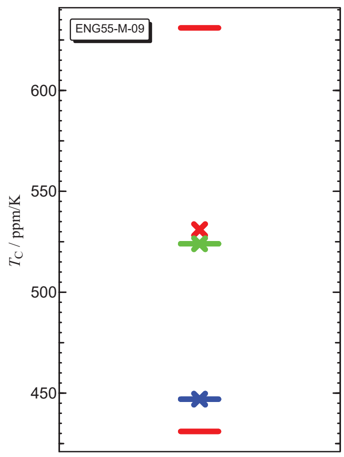


FhG: DSR
JRC: Solar simulator/natural sunlight
ISFH: DSR
PTB: DSR

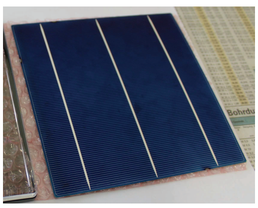


Results – ENG55-M-09

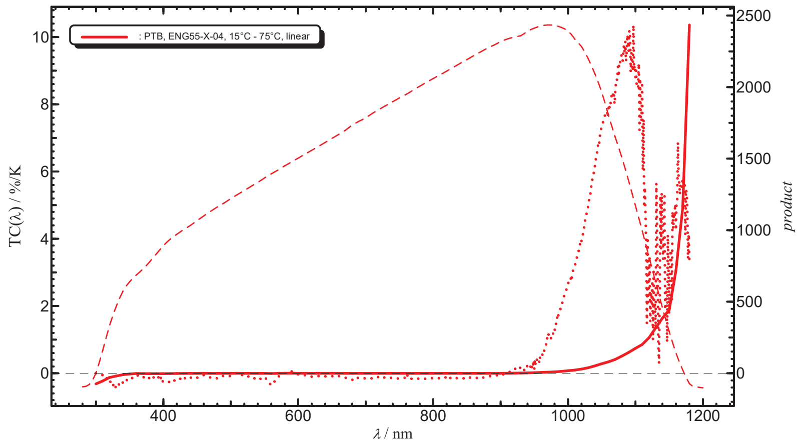


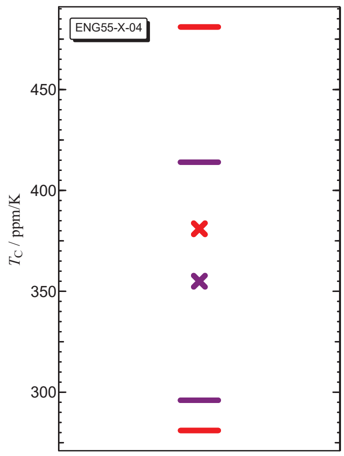


FhG: DSR
JRC: Solar simulator/natural sunlight
ISFH: DSR
PTB: DSR

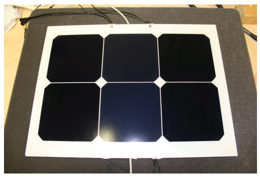


Results – ENG55-X-04

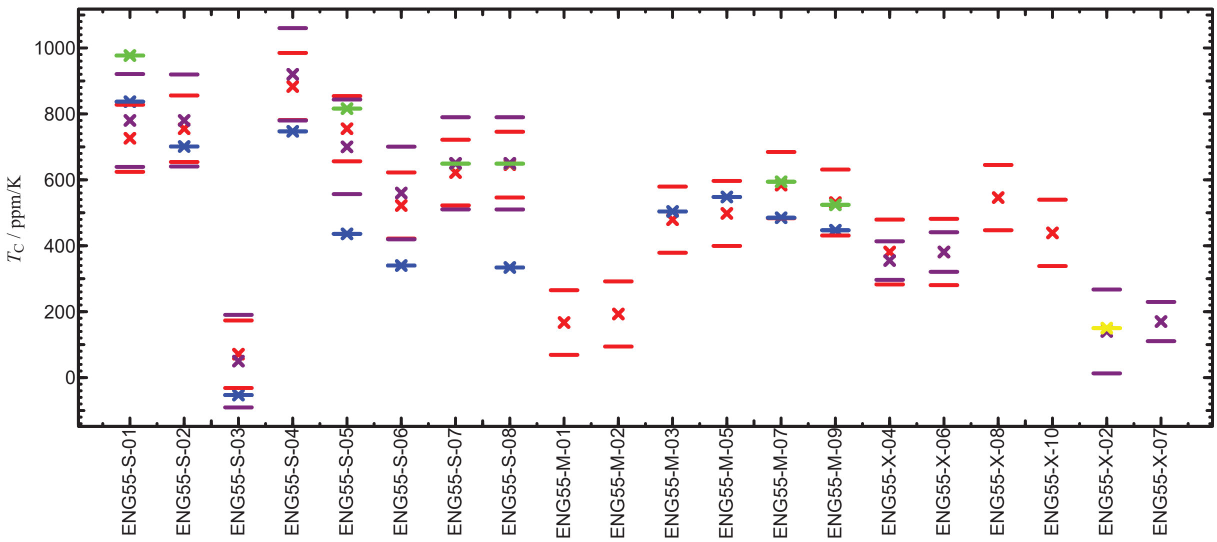




FhG: DSR
JRC: Solar simulator/natural sunlight
ISFH: DSR
PTB: DSR



Results – all S-, M- and X-samples



FhG: DSR
JRC: Solar simulator/natural sunlight
ISFH: DSR
PTB: DSR

- General good agreement within ± 100ppm for all types of devices
- Spectral TC measurements very challenging
- Some individual outliers

Thank you

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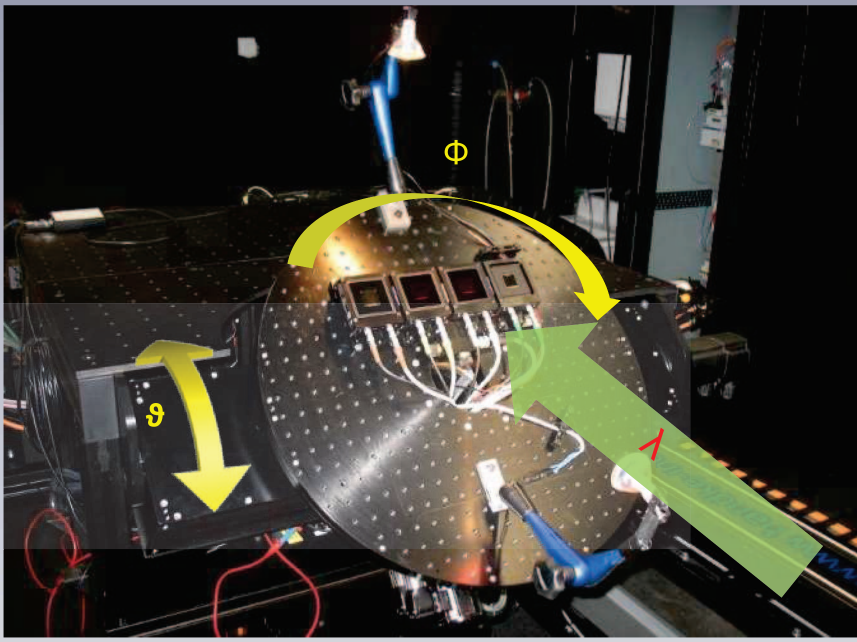
PTB
Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

EMRP
European Metrology Research Programme
Programme of EURAMET

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

Angular dependent measurements (WP3)



Ingo Kröger
Department 4.1: Photometry and Applied Radiometry
Working Group 4.14: Solar Cells

PhotoClass

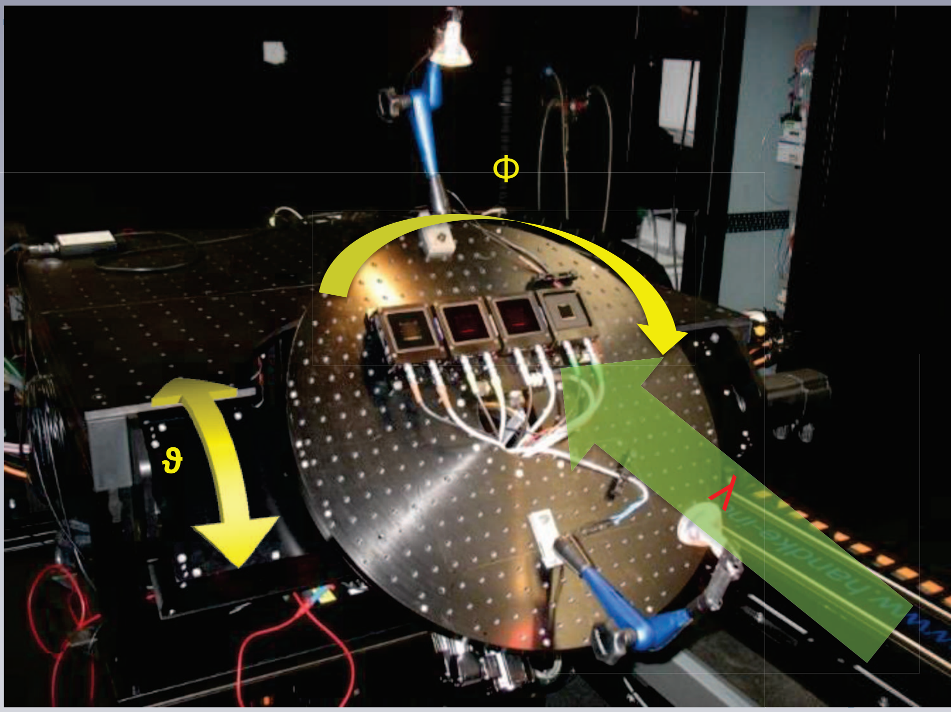
PTB
Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

Participants AOI measurements

PTB

Participant	Deliverable	Facility, method	samples	period
PTB	D3.4.10 D3.4.12	Laser-DSR Spectral angular DSR Integral angular using halogen lamp	ENG55-S ENG55-M ENG55-X	12/2015 - 01/2016 12/2016 - 02/2017 02/2017 - 04/2017
REG(LU)	D3.4.14 D3.4.15	Polychromatic method Natural sunlight	ENG55-S ENG55-M ENG55-X ENG55-XL	08/2016 - 09/2016 11/2016 12/2016 - 01/2016 12/2016 - 02/2016
REG(Fhg)	D3.4.11	Filtermonochromator WLR	ENG55-S ENG55-M	06/2016 - 07/2016 07/2016 - 08/2016
VSL	D3.4.13	Supercontinuum DSR	ENG55-S ENG55-M ENG55-X	10/2016 - 11/2016 09/2016 - 10/2016 ------
SUPSI	voluntary	Solar simulator (???)	ENG55-X ENG55-XL	02/2016 – 03/2016 02/2016 - 03/2016
TÜV-Rheinland	voluntary	Solar simulator(???)	ENG55-X ENG55-XL	--------- 03/2017-04/2017

Angular dependent measurements at PTB

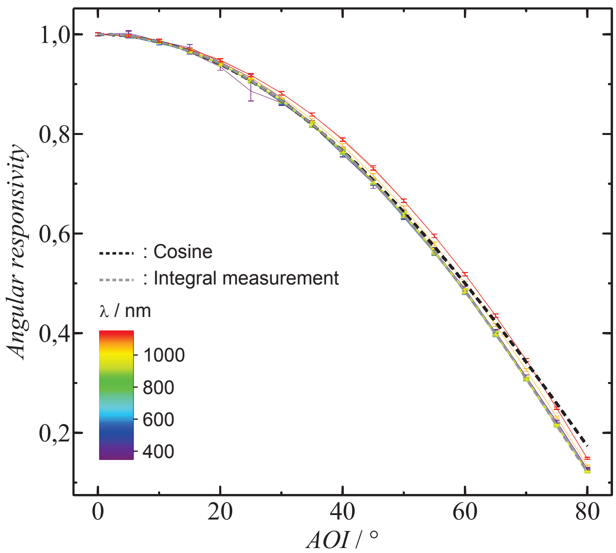


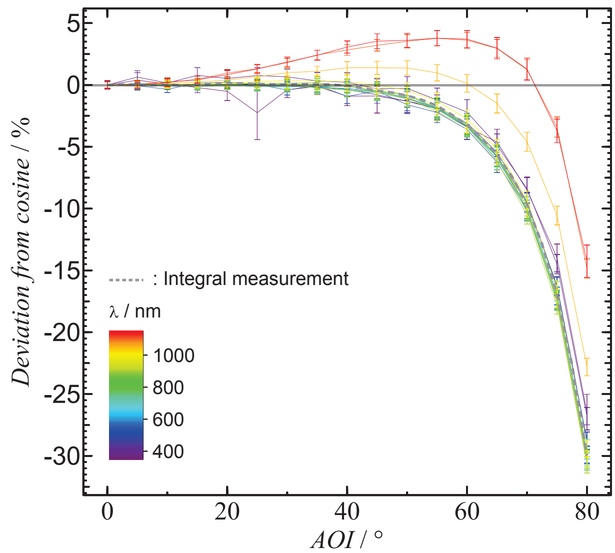
Ingo Kröger
Department 4.1: Photometry and Applied Radiometry
Working Group 4.14: Solar Cells

PhotoClass

Methods overview – DSR (PTB)

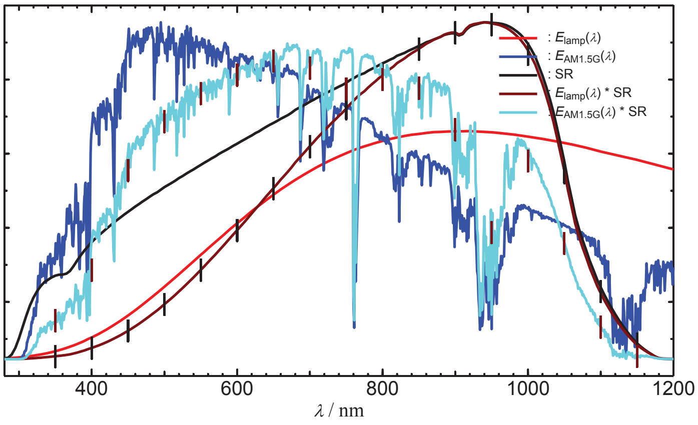
- Normalization of measured current to normal incidence
- Generally wavelength dependent angular response is observed
- Validation: comparison of spectral angular responsivity with integral angular response using a halogen lamp (broadband light source of known spectral irradiance)

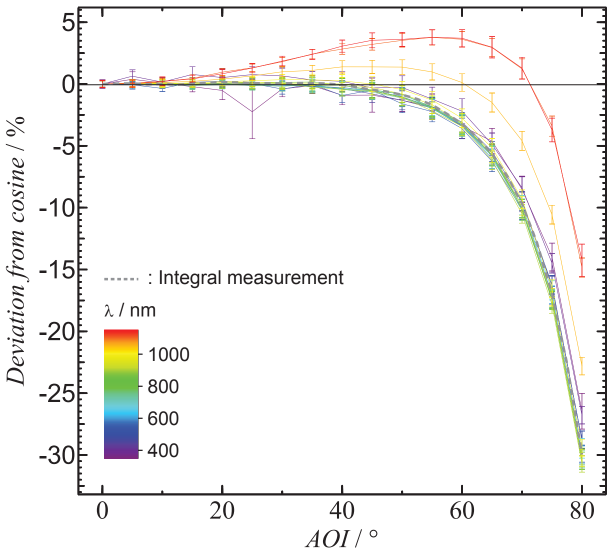




Methods overview – DSR (PTB)

- Calculation of weighted average of spectral angular response for different light sources
  1. Weights: spectral responsivity + AM1.5 spectrum
  2. Weights: spectral responsivity + Halogen lamp spectrum





Methods overview – DSR (PTB)

- Calculation of weighted average of spectral angular response for different light sources
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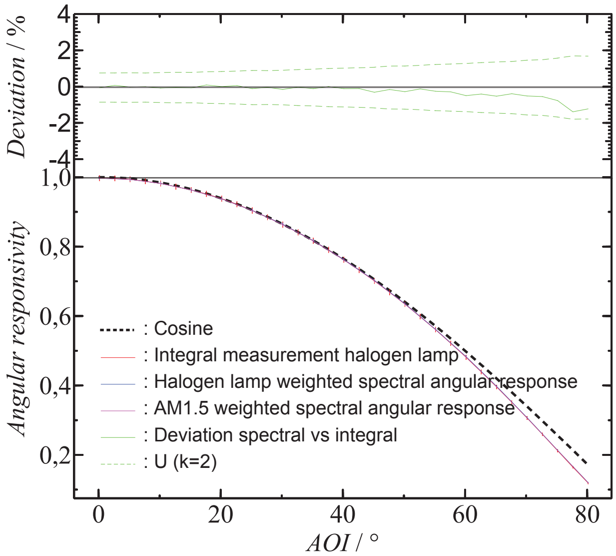
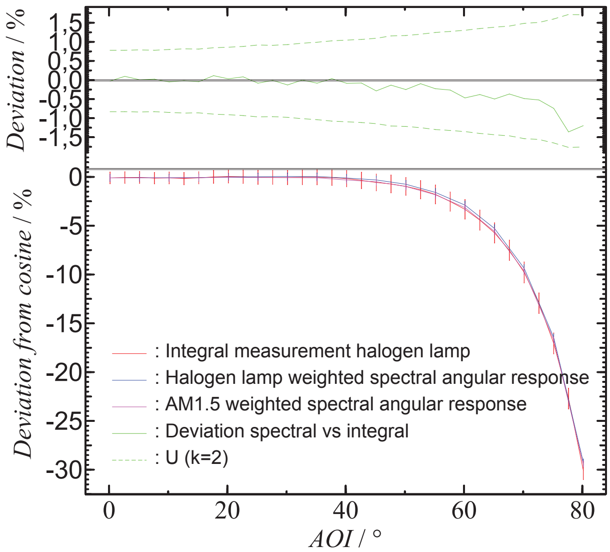


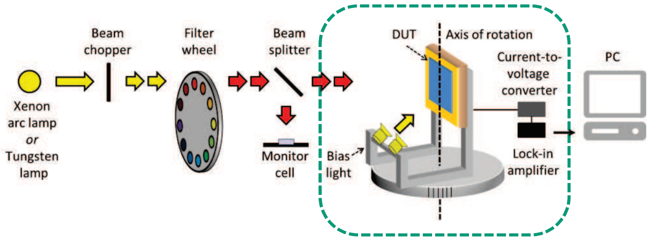


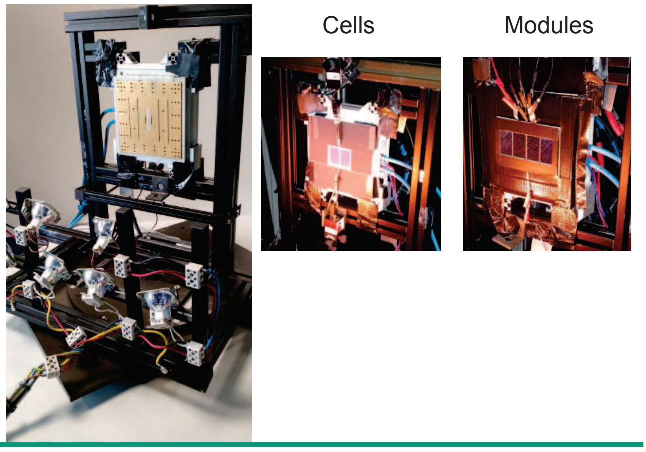
- Experimental halogen lamp angular response agrees well with spectral angular response weighted by spectral responsivity + halogen lamp spectrum
- AM1.5 (or any other spectrum) angular response can be derived from spectral angular response measurements

Angular Spectral Response (SR)
Measurement Setup

Filter monochromator
- Two light sources
- Lock-in procedure
- Fully illuminated sample

Rotary measurement unit
- T-control
- Rotating bias light
  - Separates injection-dep.
- One axis of rotation



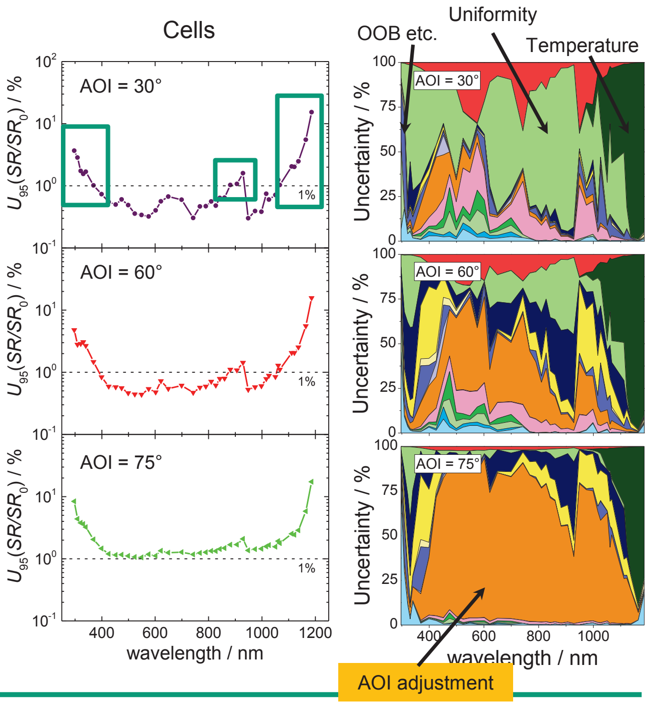


Geisemeyer et al., Angle Dependence of Solar Cells and Modules: The Role of Cell Texturization, DOI: 10.1109/JPHOTOV.2016.2614120

Fraunhofer ISE

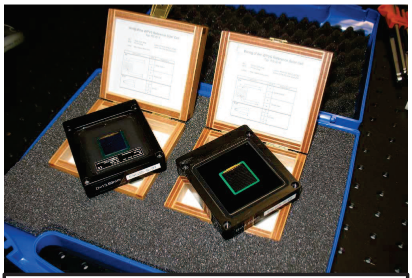
Change in Angular SR
Uncertainty Analysis

AOI = 30°:	95% confidence level typically below 1%
■ UV:	Out-of-band radiation, bandwidth, etc…
■ Visible/: NIR	Position of sample and associated uniformity correction
■ NIR:	Temperature
AOI = 60°:	Increasing influence of adjustment of rotating frame (AOI adjustm.)
AOI = 75°:	AOI adjustment dominates



Fraunhofer ISE

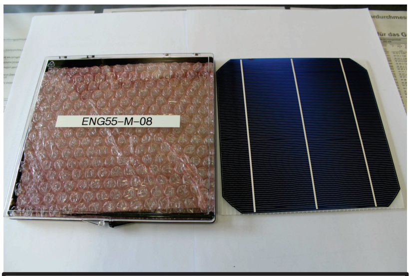
Samples Photoclass project



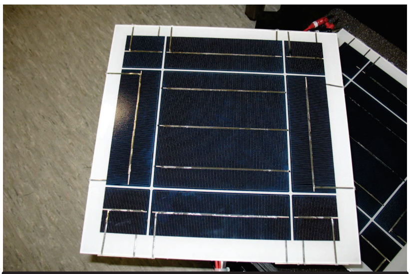
ENG55-S
Reference solar cells

Investigation of:
- Different types
- Different sizes
- Different technologies

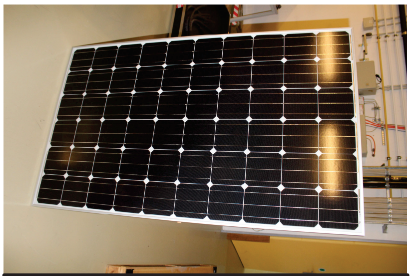
Here we show selected measurements of different devices.



ENG55-M
solar cells

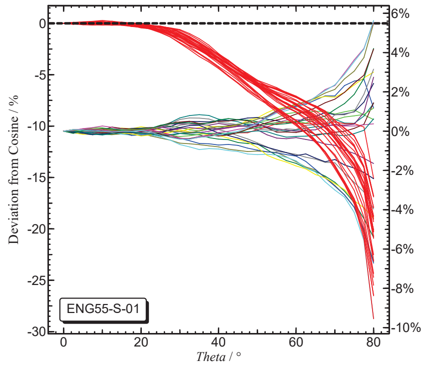


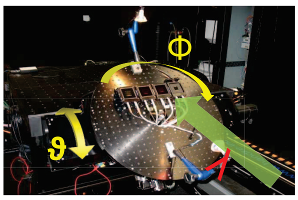
ENG55-X
Mini-Modules

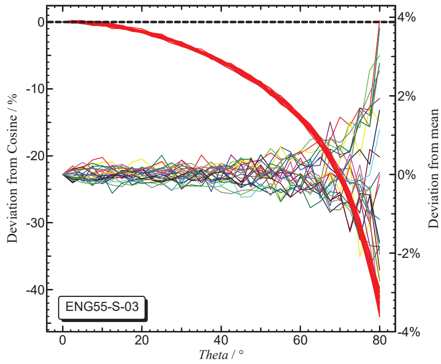


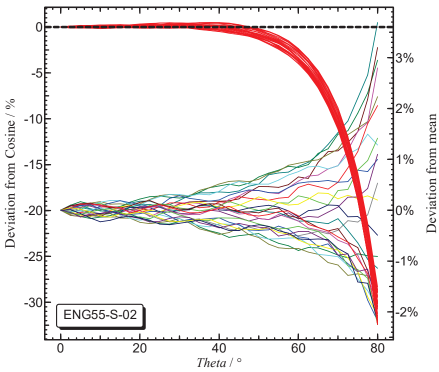
ENG55-XL
Modules

General considerations - Symmetry



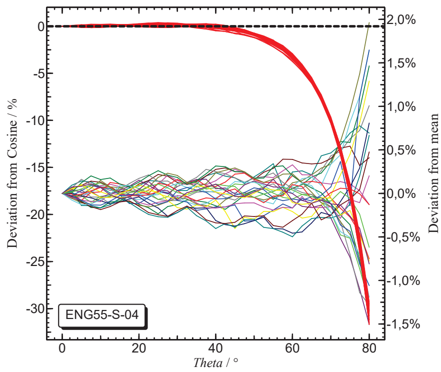




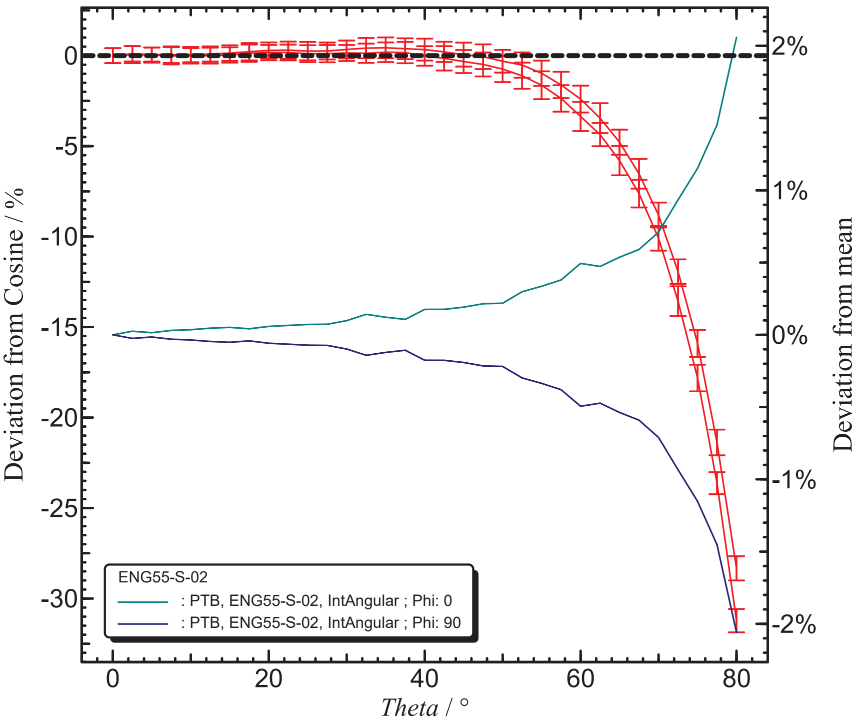


Measurements of AOI dependence for different Phi-angles using halogen lamp

- Angular responsivity of devices is generally not symmetric with respect to in plane rotation (up to ±4%)
- Symmetry strongly depends on device

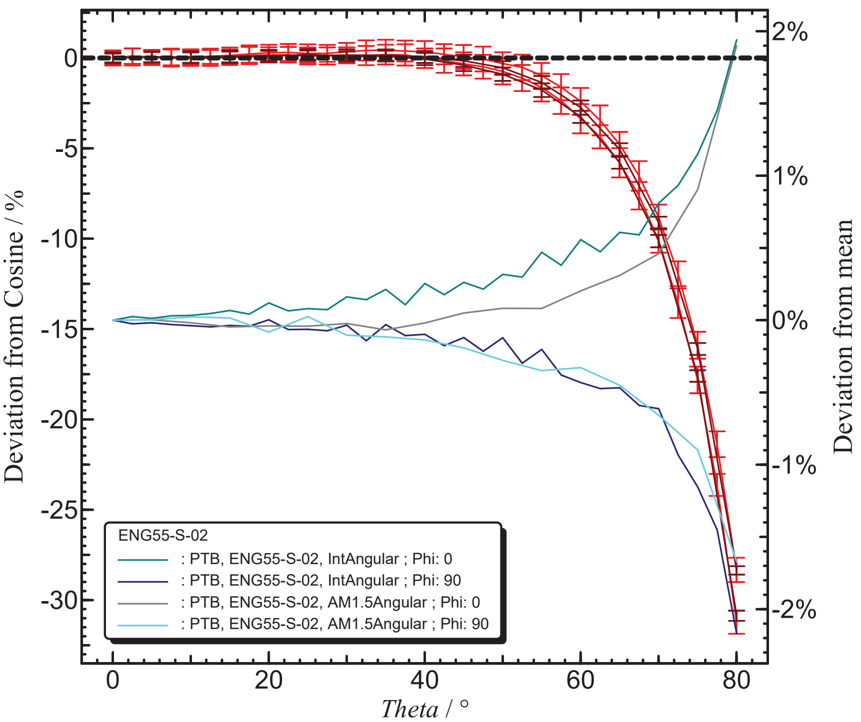


General considerations - Symmetry



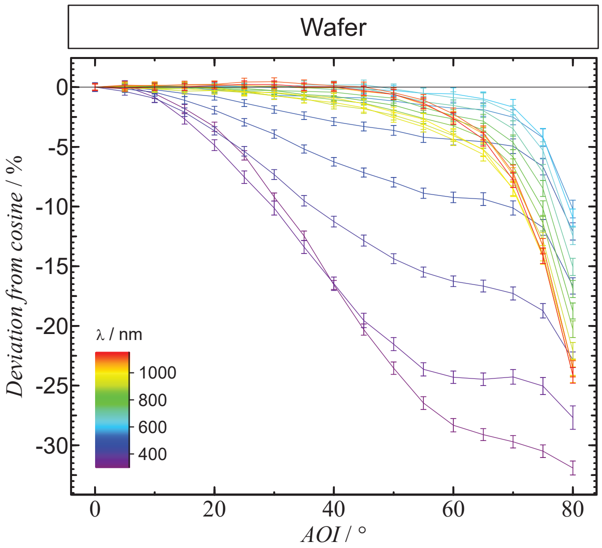
- 90° Symmetry can generally not be assumed

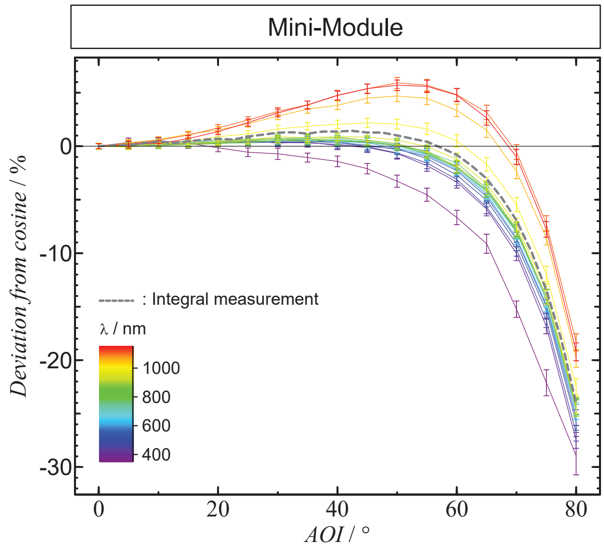
General considerations - Symmetry



- 90° Symmetry can generally not be assumed
- Independant observed for integral angular measurement and spectral angular measurements

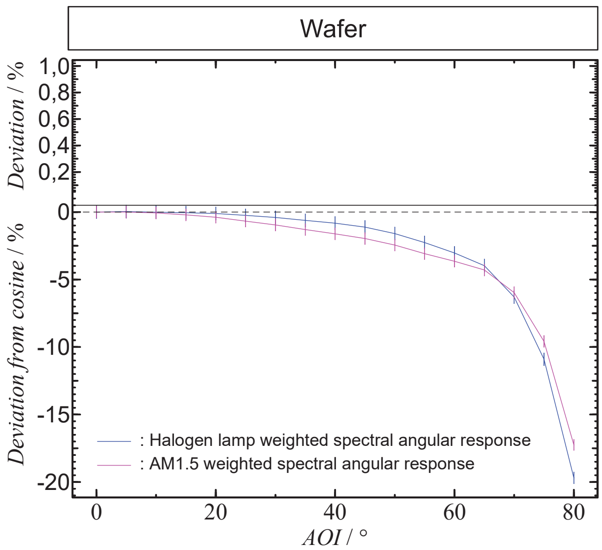
General considerations – Spectral angular response

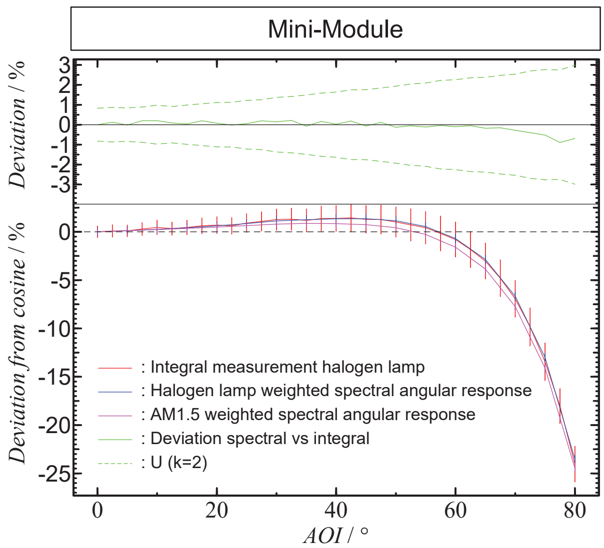




- Very different AOI responsivity for different wavelengths
- Encapsulation has significant effect on spectral angular response
- Super-cosine behaviour for IR due to interreflections

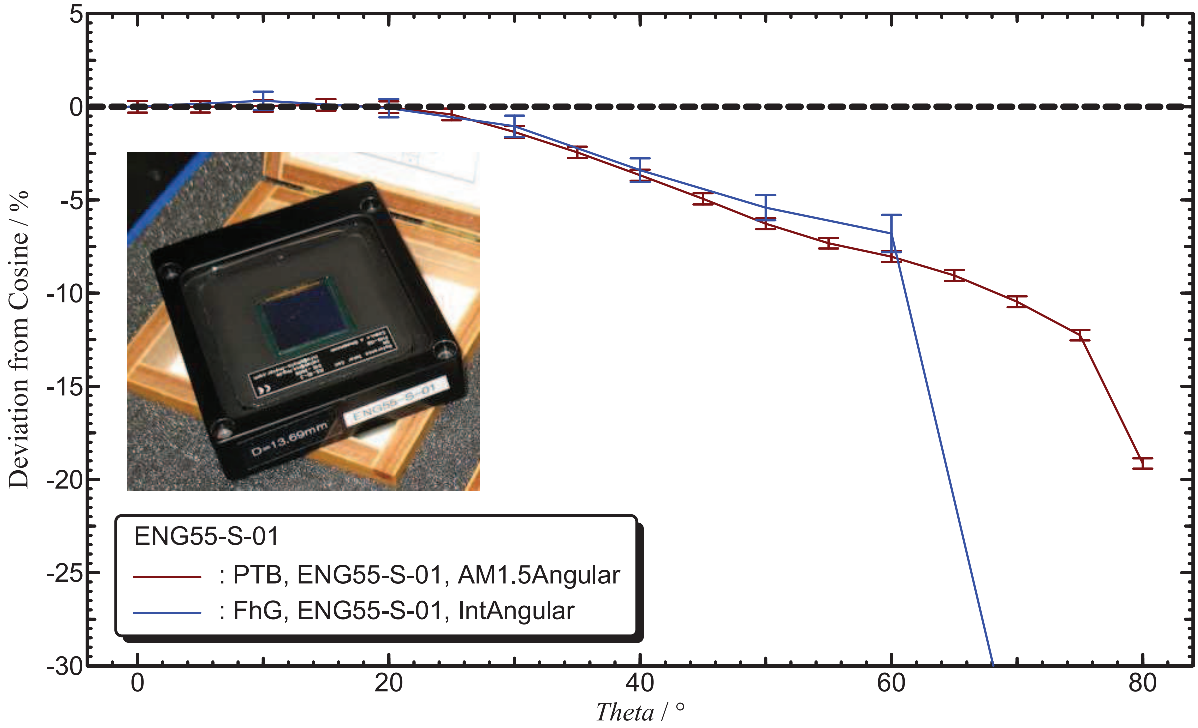
General considerations – Spectral angular response



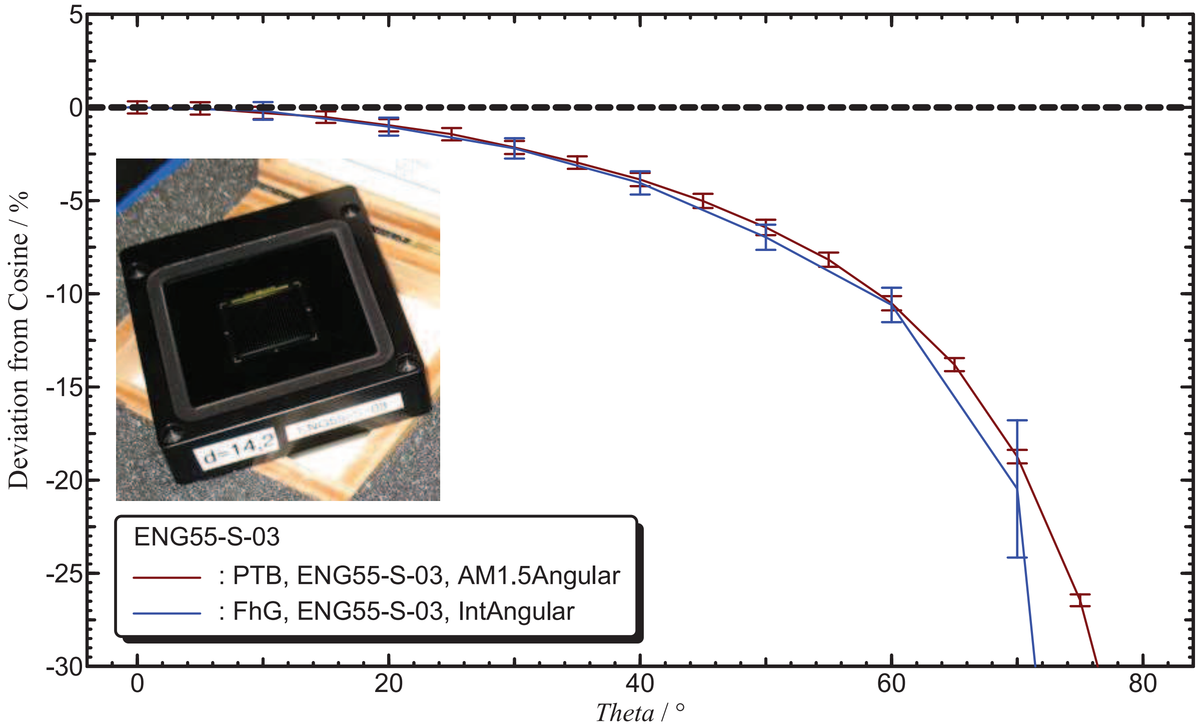


- Strong spectral dependence of AOI responsivity → Spectral mismatch is of importance
- There is significant difference for „halogen lamp angular responsivity“ and „AM1.5 angular responsivity“
- Super-cosine behaviour for IR due to interreflections

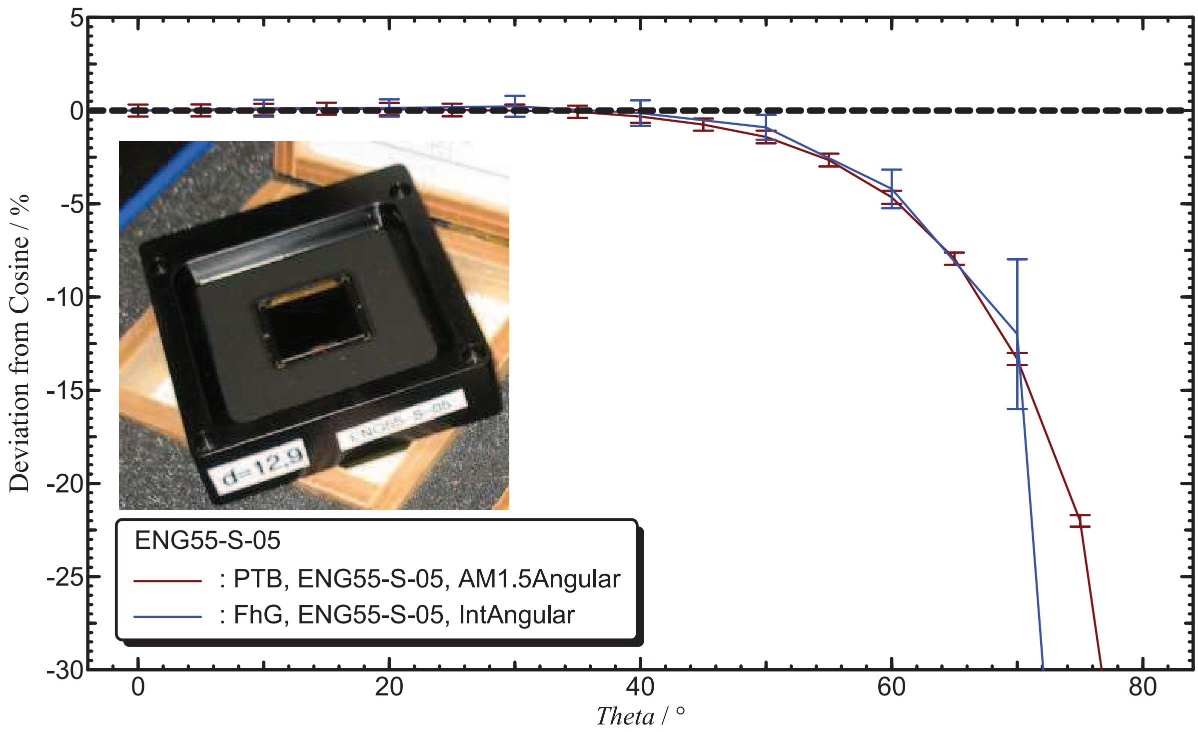
Results – ENG55-S-01



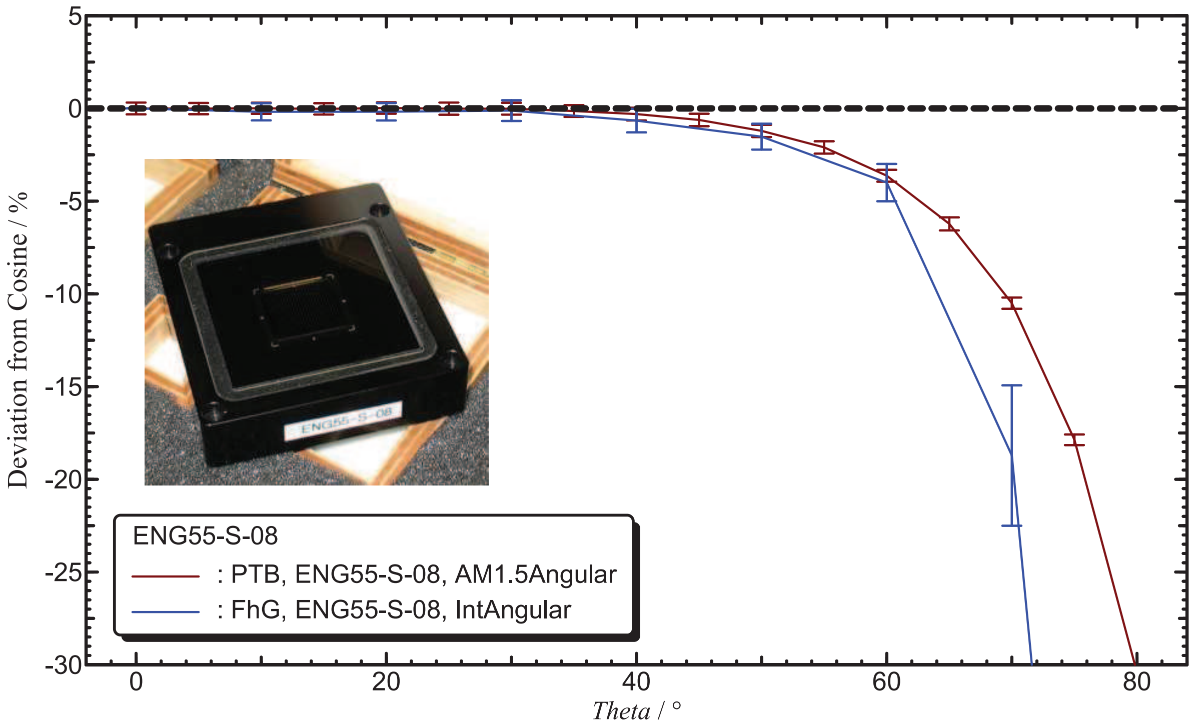
Results – ENG55-S-03



Results – ENG55-S-05



Results – ENG55-S-08



Thank you

EMRP
European Metrology Research Programme
Programme of EURAMET
The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

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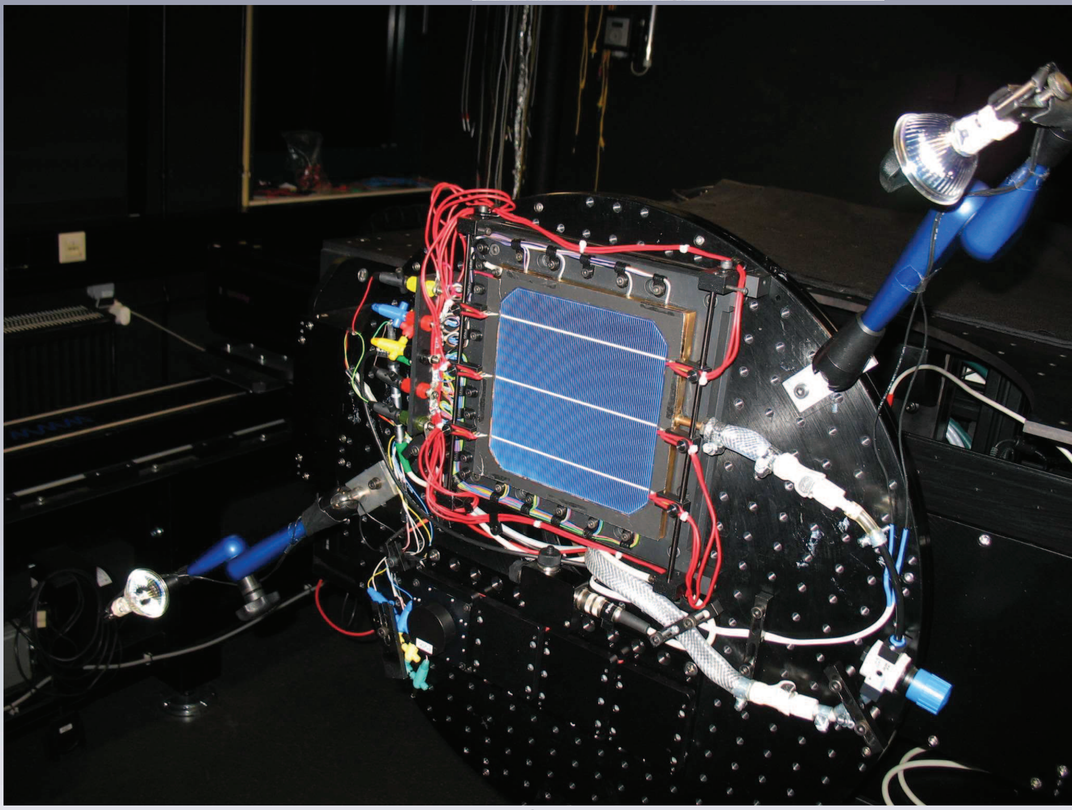

PHOTOCLASS 3-day Training course at JRC Ispra

Programme

Session 1: based on WP2 Reference devices

The new reference cells (J. Hohl-Ebinger, ISE-FhG)

LED-based differential spectral response setup for reference solar cell mini modules (H. Baumgartner, MIKES)

Reference device intercomparison: protocol and first results (I. Kröger, PTB)

Session 2: based on WP3 Detector characterisation: temperature dependence

Overview: Facilities and methods for temperature dependence measurements (I. Kröger, PTB)

Overview: Facilities and methods for angular dependence (I. Kröger, PTB)

Session 3: based on WP3 Detector characterisation: linearity

Compressive sensing (T. Betts, LU)

Polychromatic SR (T. Betts, LU)

Overview: Facilities and methods for linearity measurements (I. Kröger, PTB)

Session 4: based on WP4 Source characterisation methods

Solar cell chuck for temperature characterisation (G. Martínez, INTA)

Comparison of spectroradiometers (I. Kröger, PTB)

Spectral sky scanning (S. Riechelmann, PTB)

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Compressive Sensing

[1]George Koutsourakis, [2]Matt Cashmore, [2]Simon Hall, [1]Martin Bliss, [1]Tom Betts and [1]Ralph Gottschalg

[1]Centre for Renewable Energy Systems Technology (CREST), Loughborough University, Loughborough

[2]National Physical Laboratory (NPL), Teddington

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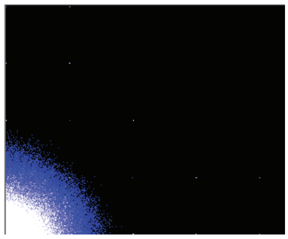
Overview

- Compressed Sensing Theory
- Current Mapping of Photovoltaic Devices
- Simulations
- Experimental Validation

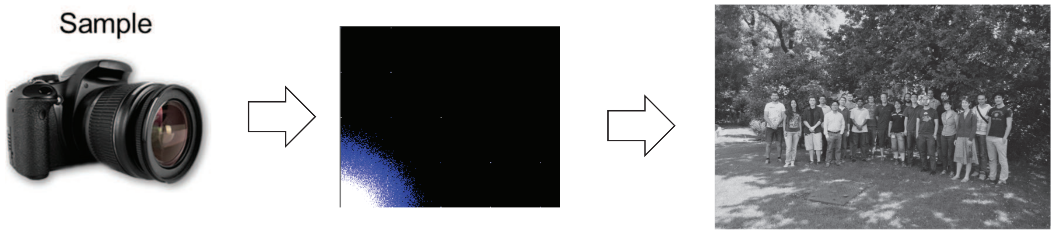
Compressed sensing theory motivation

Applied PV group CREST

DCT coefficients
Discrete Cosine Transform



Reconstruction using only 2% largest DCT coefficients



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Compressed sensing – theory

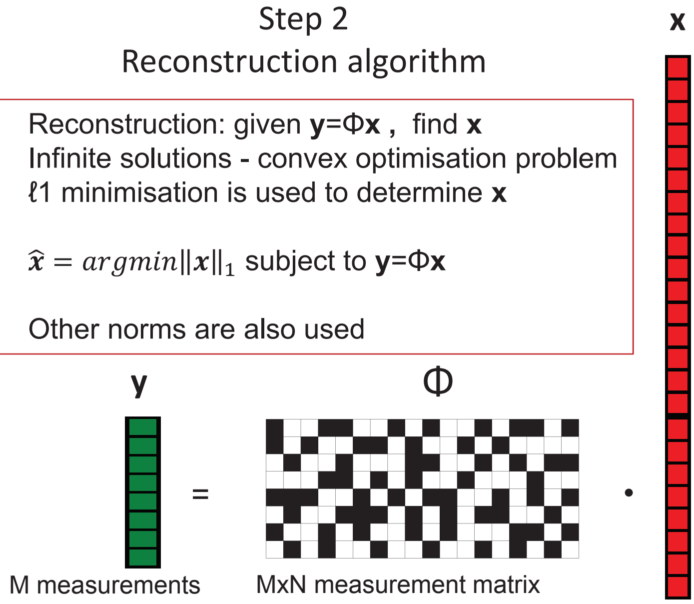
Measuring signal **x** (N elements)

Step 1
Compressive sampling

- M < N linear measurements between **x** and a collection of test functions $\{\varphi_m\}_{m=1}^{M}$
- In other words we measure $\boldsymbol{y[m]} = \langle \boldsymbol{x}, \boldsymbol{\varphi_m} \rangle = \boldsymbol{\Phi[m,n]x[n]}$

Step 2
Reconstruction algorithm

- Reconstruction: given **y=Φx** , find **x**
- Infinite solutions - convex optimisation problem
- ℓ1 minimisation is used to determine **x**
- $\hat{x} = argmin\|x\|_1$ subject to **y=Φx**
- Other norms are also used

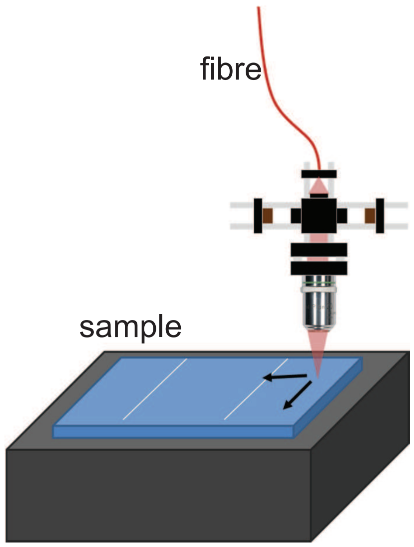


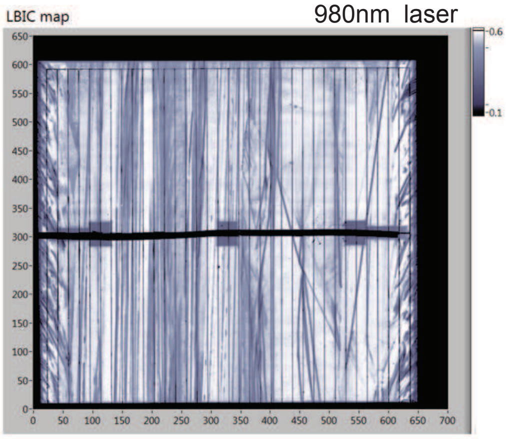
E. Candes, J. Romberg, and T. Tao, "Stable signal recovery from incomplete and inaccurate measurements," *Comm. Pure Appl. Math.*, vol. 59, pp. 1207–1223, 2006.

D. Donoho, "Compressed sensing," *Inf. Theory, IEEE Trans.*, vol. 52, no. 4, pp. 1289–1306, 2006

Current mapping of photovoltaic (PV) devices

- **Light Beam Induced Current (LBIC)** measurements
- Point by point scan of a light beam with a small spot over the area of the sample
- The current response of the device is measured at each point
- Necessary for research but time – consuming, cumbersome measurements





M. Bliss, G. Koutsourakis, T. R. Betts, and R. Gottschalg, "Development of a Solar Cell Spectral Response Mapping System using Multi-LBIC Excitation Multi-LBIC local SR system First Measurements," in PVSAT-12 Proceedings, 2016, pp. 55–58.

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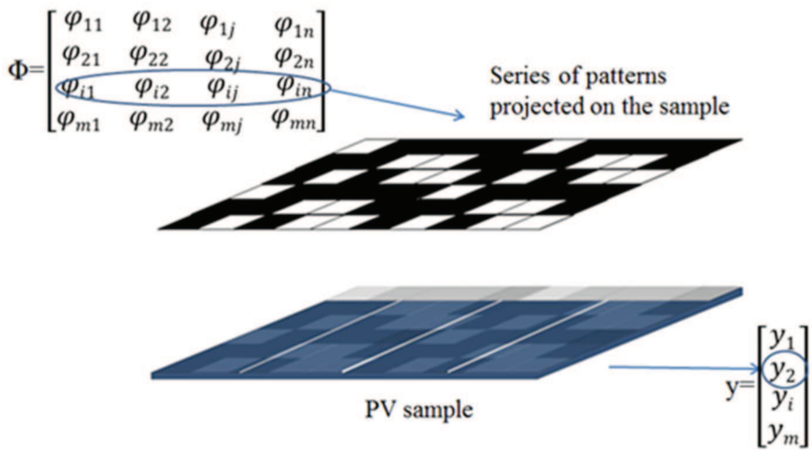
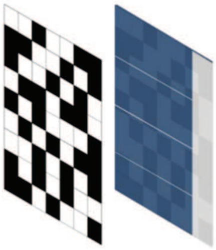
Compressed sensing Current mapping of photovoltaic (PV) devices

- Could we apply compressive sampling?
- *Alternative current mapping method*
- *Reduction of measurement time*
- *Simplify experimental layouts*



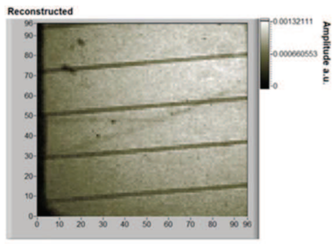
Compressed sensing Current mapping of photovoltaic (PV) devices

Project random patterns on the sample – Fewer measurements



Measure the current for every pattern

Reconstruct current map using an optimisation algorithm



Apply faster and much fewer measurements than what an LBIC scan would need

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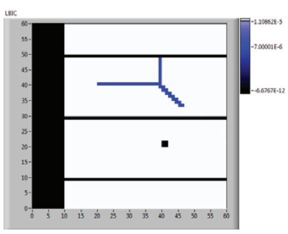
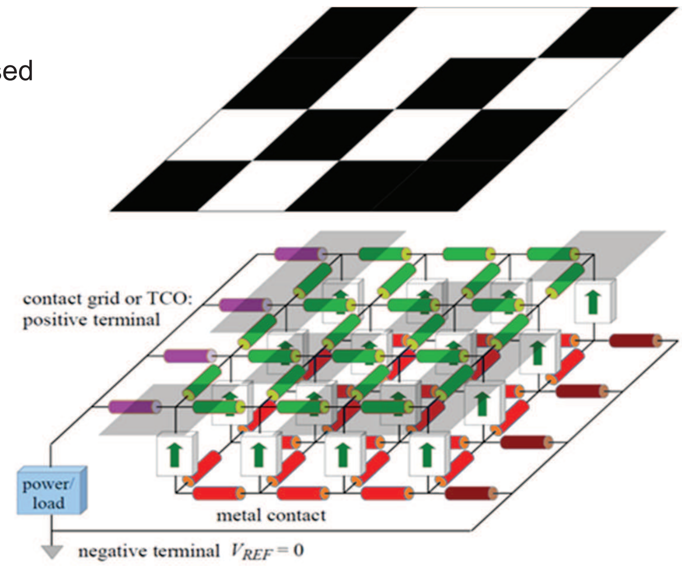
Simulations with PV oriented Nodal Analysis (PVONA)

PVONA is a software toolset specifically developed for solving the spatially-resolved model (SRM) of PV devices.

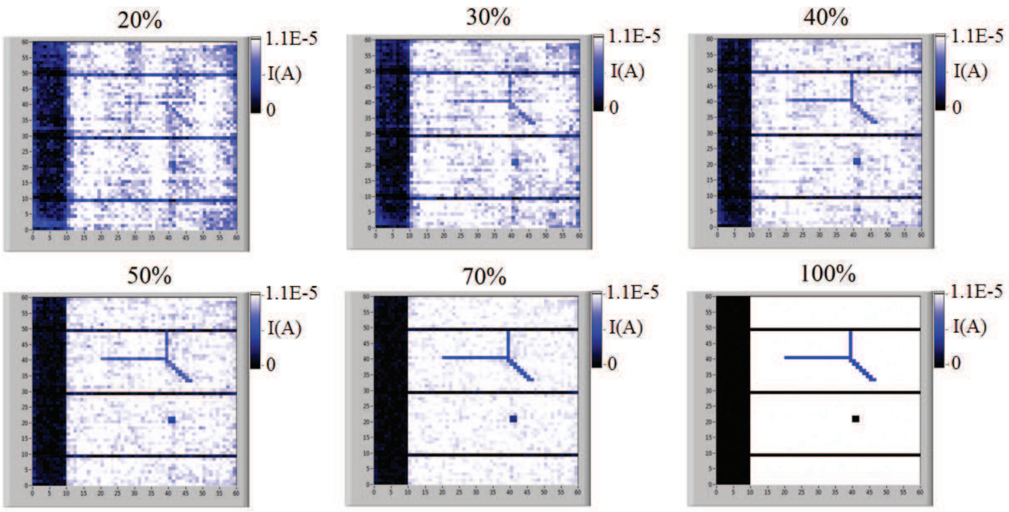
- 1 diode model for PV cells is used
- 60x60 pixel cells were realised
- Simulated area of a PV sample that contains defects





Simulations with PV oriented Nodal Analysis (PVONA)

The percentages express the ratio of number of measurements by the number of pixels in the current map (total number of pixels: 3600)



G. Koutsourakis, X. Wu, M. Cashmore, S. R. G. Hall, M. Bliss, T. R. Betts, and Gottschalg, “Fast Current Mapping of Photovoltaic Devices Using Compressive Sampling,” 31st EUPVSEC Proc., pp. 29 – 34, 2015.

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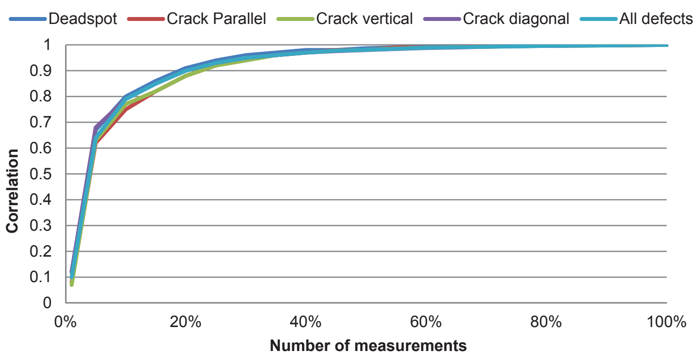
Correlation coefficient:

Pearson's correlation coefficient between actual current map and reconstructed map

$$\rho_{X,Y} = \mathrm{corr}(X,Y) = \frac{\mathrm{cov}(X,Y)}{\sigma_X \sigma_Y}$$

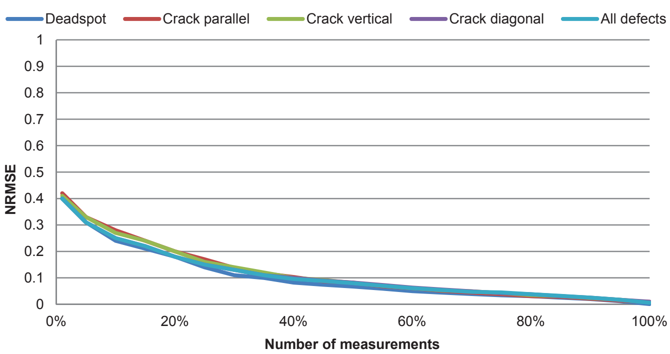


Normalised Root mean square error:

Measure NRMSE between actual current map and CS

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{t=1}^{n} (\hat{y}_t - y)^2}{n}}$$

$$\mathrm{NRMSE} = \frac{\mathrm{RMSE}}{y_{\max} - y_{\min}}$$



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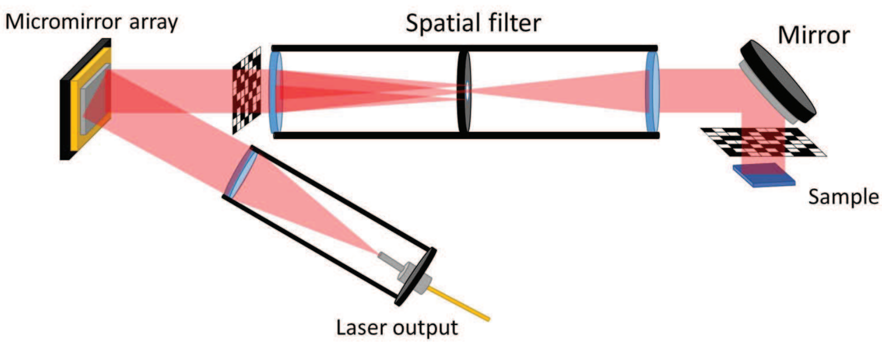
From simulation to experimental validation

Small area experimental setup in NPL (area of scan ~ 1cm x 1cm)



- Simple setup
- High signal to noise ratio – half of the area under measurement is illuminated
- No lock-in techniques used
- Fast transition between patterns – DMD response time ~50μs
- Current sampling speed limited: 10 patterns per second

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The Digital Micromirror Device (DMD)

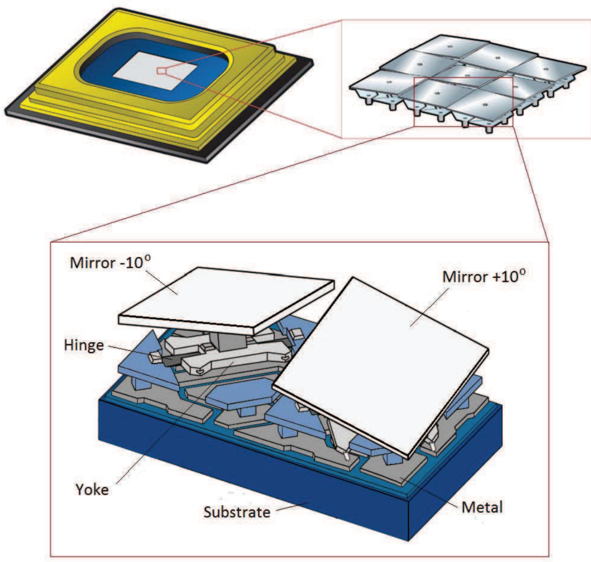
Array of digital micro mirrors

Each mirror has an “on” and an “off” state

Extremely useful for creating and projecting illumination patterns

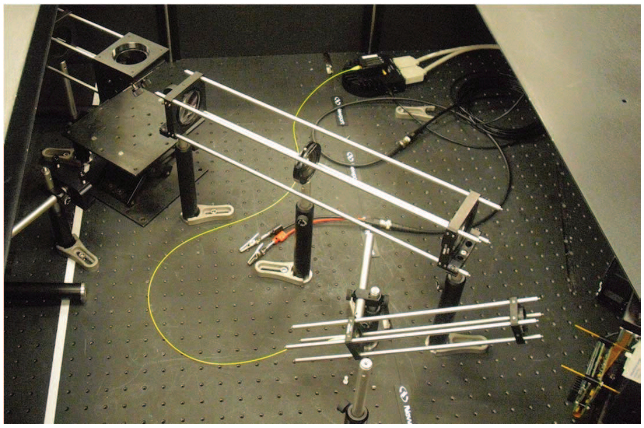
Used in all modern projectors (DLP)

Used in almost all CS imaging applications



From simulation to experimental validation

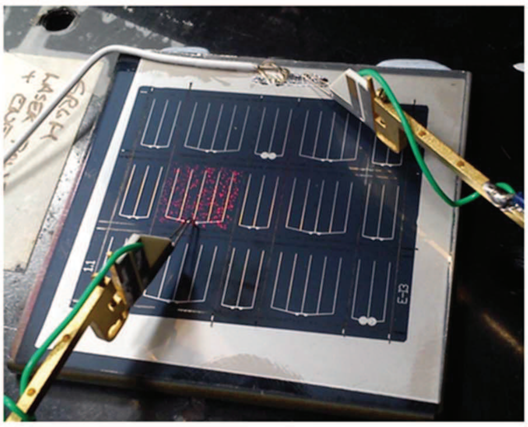
Small area experimental setup at NPL



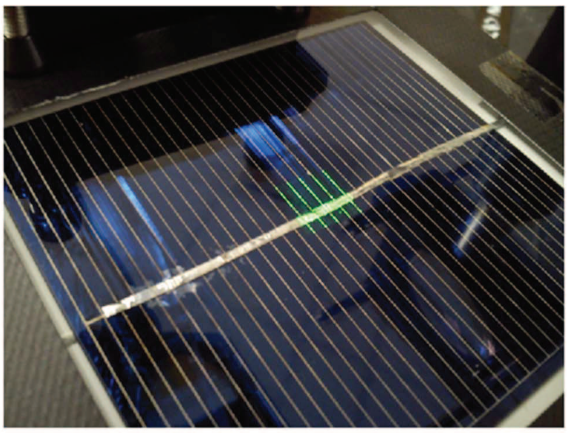
From simulation to experimental validation

Small area experimental setup in NPL

Thin film sample (CIGS)



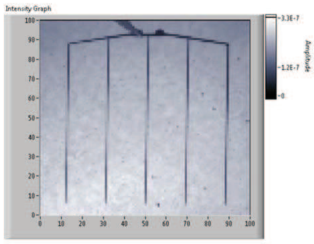
Silicon large sample



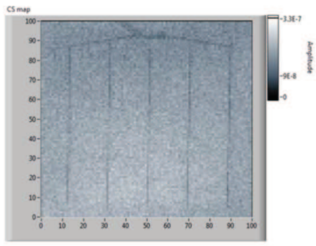
From simulation to experimental validation

Thin film sample (CIGS)

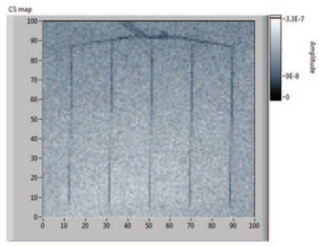
Point by point scan using the DMD



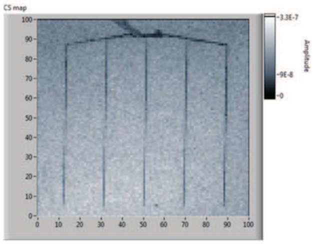
30%



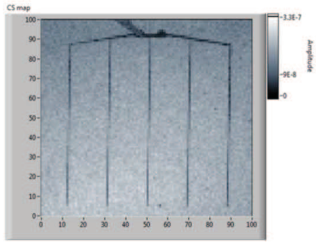
50%



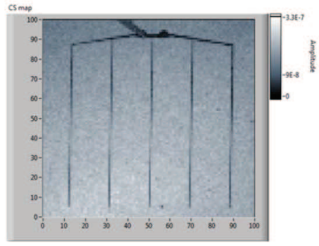
70%



80%



90%



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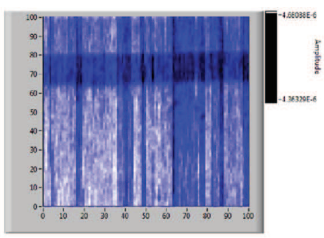
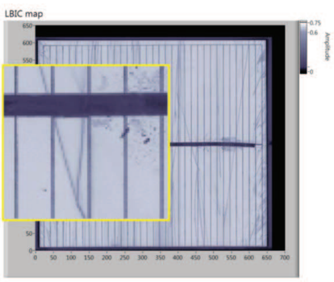
From simulation to experimental validation

Silicon large sample

Point by point scan using the DMD

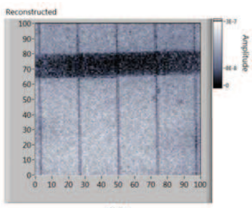


LBIC in CREST (785nm)

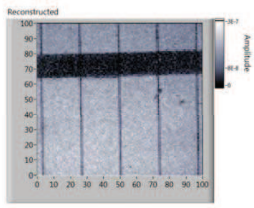


Compressive sampling

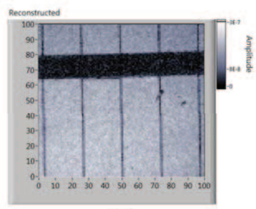
658nm



40%

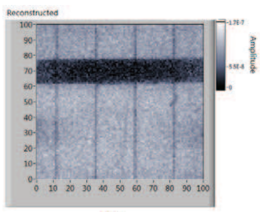


60%

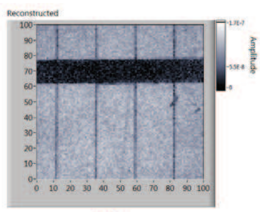


80%

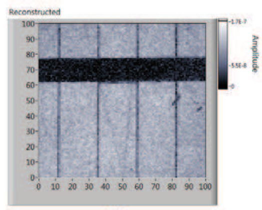
785nm



40%



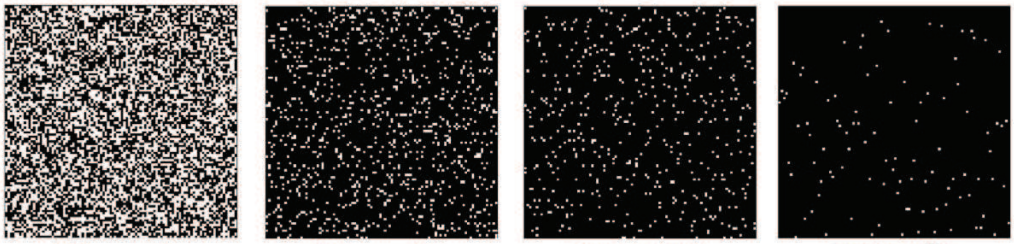
60%



80%

Testing sensing matrices with different sensing matrix sparsity

- The sparser the patterns, the more pixels are dark – micromirrors are set at the off state.
- Testing sparser sensing matrices



50% sparsity 10% sparsity 5% sparsity 1% sparsity

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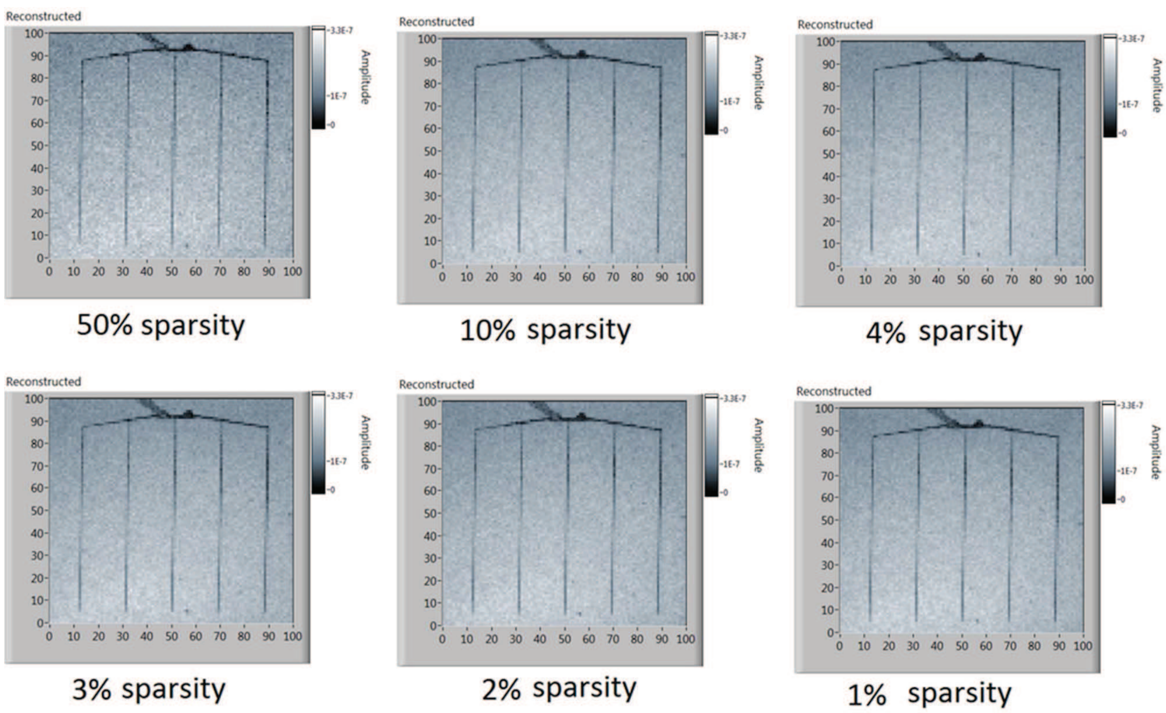
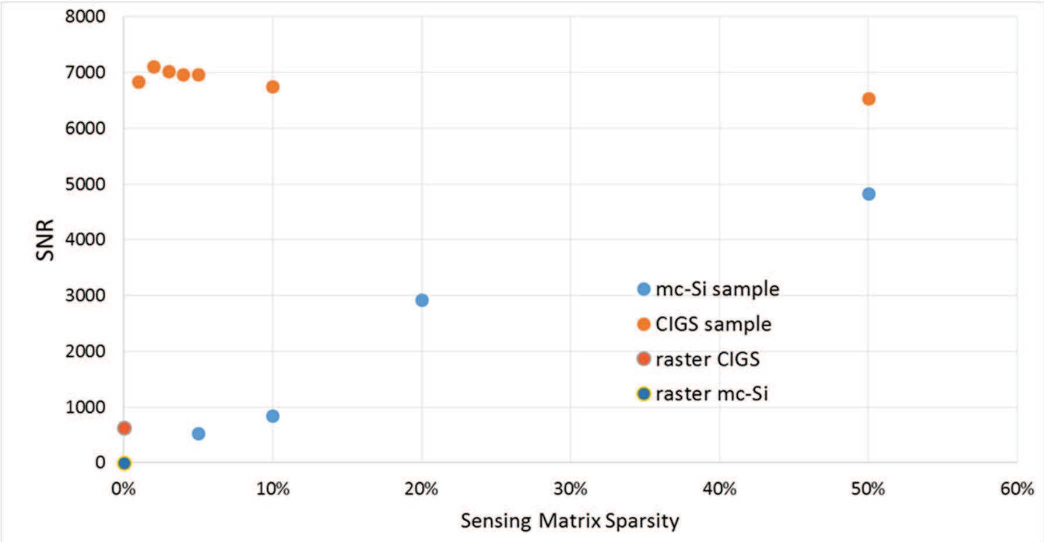
Sensing matrix sparsity- CIGS sample



SNR-Sensing matrix sparsity



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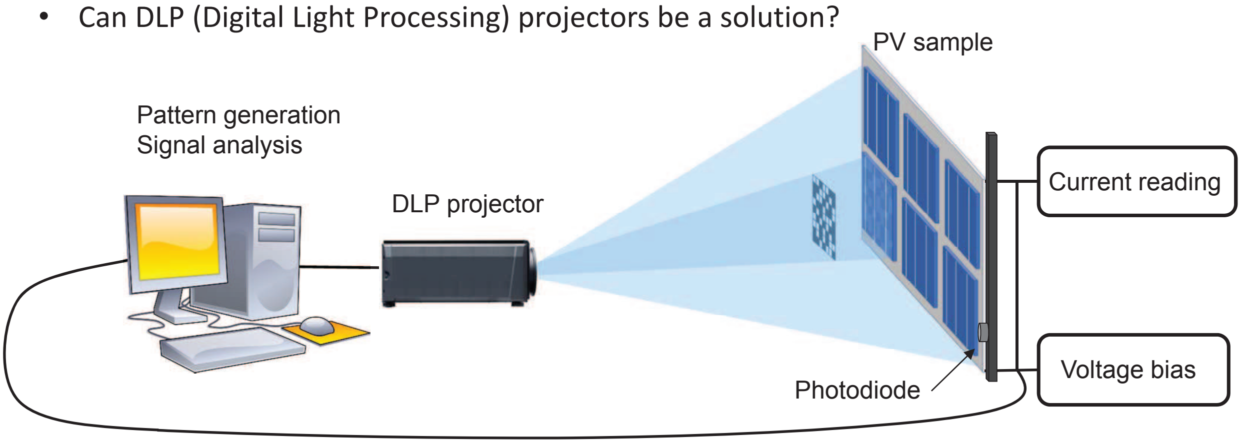
Is large scale CS current mapping possible?

- Project the necessary patterns on the sample for compressive sampling
- Powerful light source
- DMD chip to create the projections
- Can DLP (Digital Light Processing) projectors be a solution?



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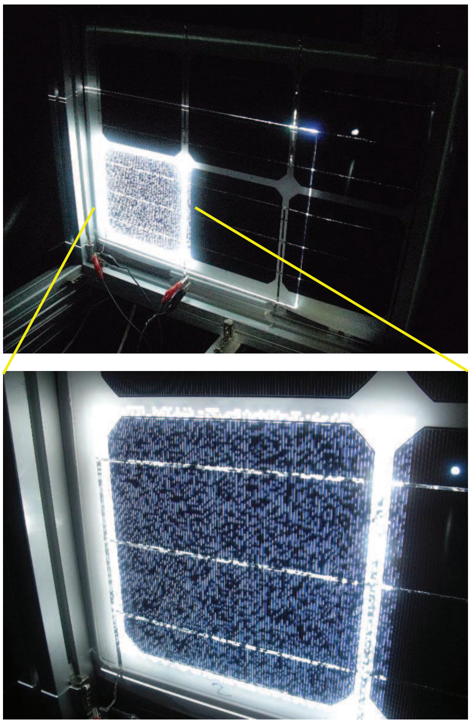
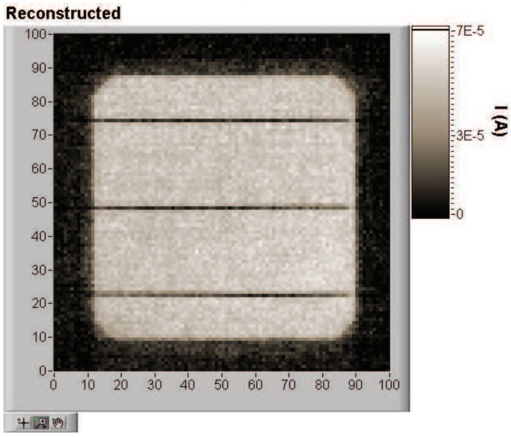
CS current mapping using a DLP projector



10000 pixels
5000 measurements (50%)



Acquired
In 1 hour

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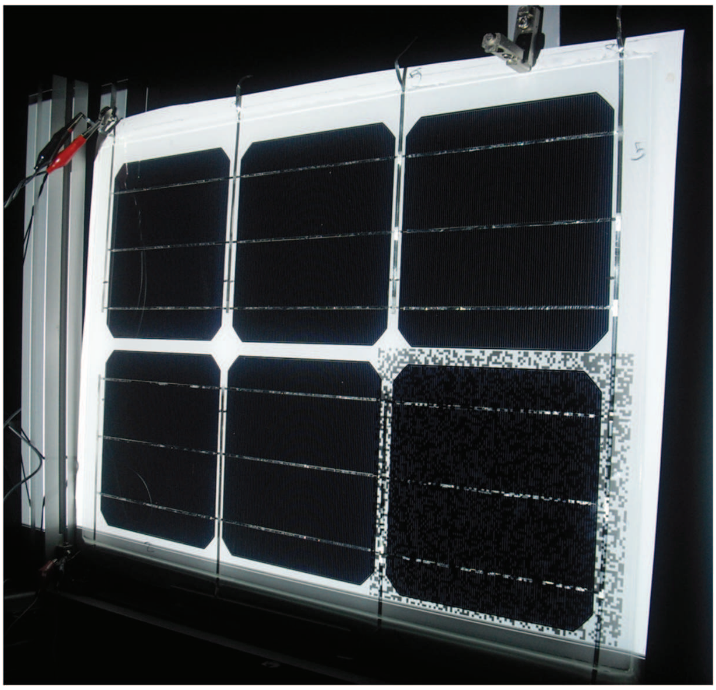
CS current mapping using a DLP projector

- Patterns are projected on a cell
- The rest of the module is fully illuminated
- Cell under measurement sets the limiting current of the module



CS current mapping using a DLP projector

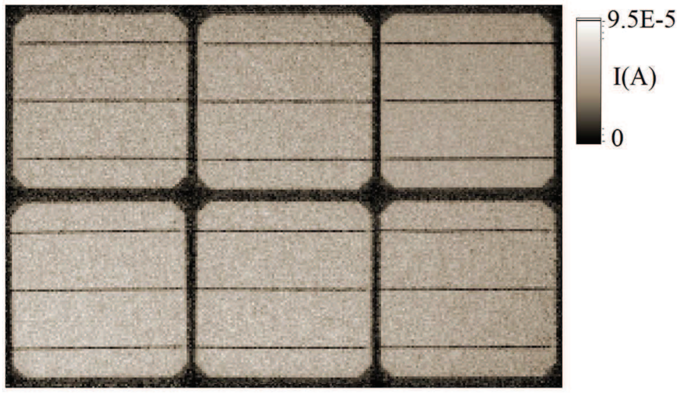
- Results are slightly more noisy than the single cell case
- Projector's non uniform irradiance is obvious
- Still, quantitative results are acquired with just a projector for sampling

50%

60000 pixels

30000 measurements

(6 hours)



G. Koutsourakis, M. Cashmore, M. Bliss, S. R. G. Hall, T. R. Betts, and R. Gottschalg, "Compressed Sensing Current Mapping Methods for PV Characterisation," in IEEE 43nd Photovoltaic Spec. Conf., Portland, 2016.

G. Koutsourakis, M. Bliss, S. R. G. Hall, T. R. Betts, and R. Gottschalg, "Compressed Sensing Current Mapping of PV Devices Using a DLP Projector," in PVSAT-12 Proceedings, 2015.

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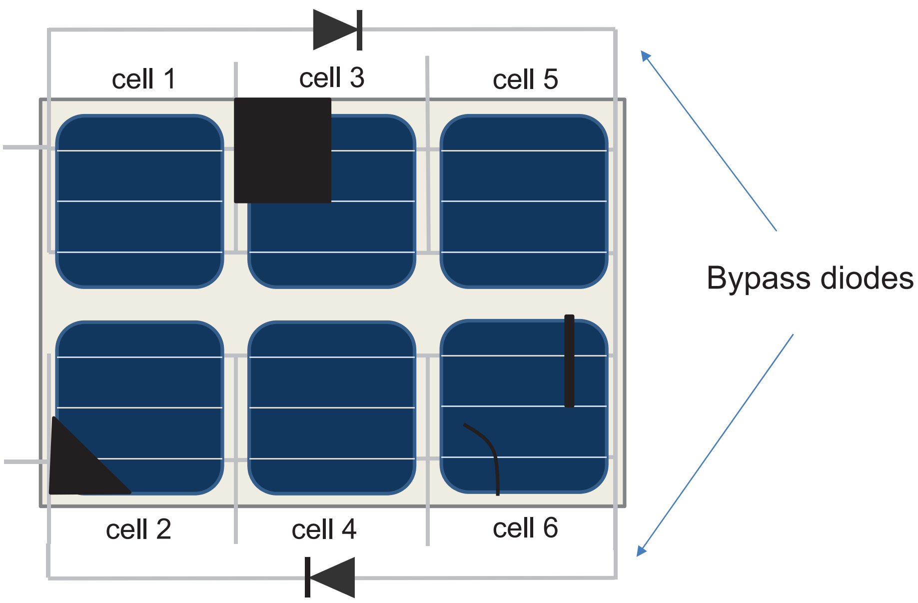
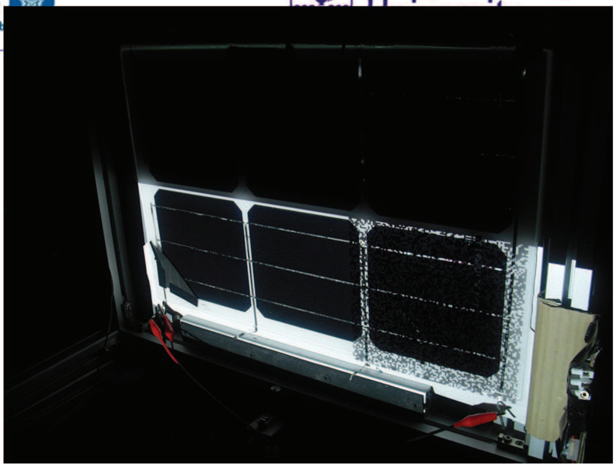
- Bypass diodes added
- 2 strings, 3 cells each

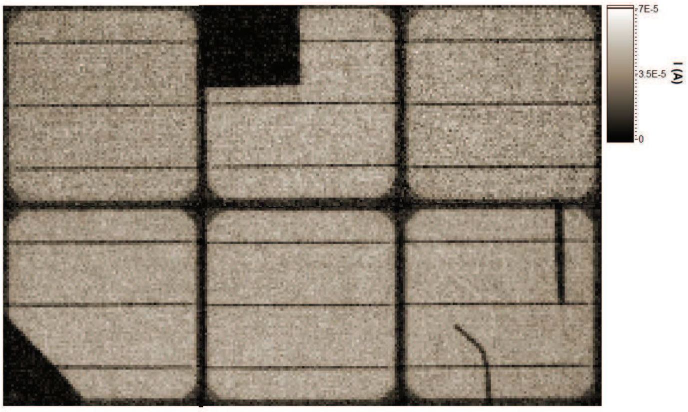


CS current mapping is straightforward even with by-pass diodes

Only possible with a projector system

Slightly decreased SNR



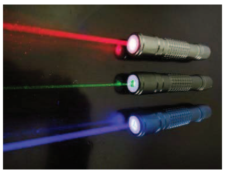


- PV cell measurement SNR ≃ 2000
- PV module without by-pass measurement SNR ≃ 1000
- PV module with by-pass diodes measurement SNR ≃ 700

Is CS current mapping using a DLP projector possible?

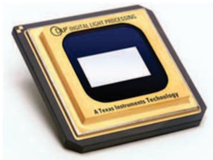
- A custom built projector will provide much faster and more accurate results:

  - No colour wheel
  - Simpler operation and absolute control of DMD
  - Higher power light source
  - Light source of specific wavelength
  - *5 minutes per cell is a realistic target*



High power light source

Optics



DMD

Projection lens

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Conclusions

Compressed sensing current mapping for PV device spatial characterization.

- Fewer measurements applied - reduced measurement time
- High signal to noise ratio
- Simpler experimental layouts

Explored through 2 different experimental layouts

- Small area optical setup
- Commercial DLP projector setup for larger devices and PV modules

There are still issues to be resolved

- *Pixelation*
- *High irradiance on sample difficult to achieve*
- *Large number of algorithms and sensing matrices to investigate*

Thank you for your attention

Original image

5% of DCT coefficients

The research work presented was carried out in part within the EMRP ENG55 project Towards an Energy-based Parameter for Photovoltaic Classification. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

Polychromatic Spectral Response

Husyira Al Husna, Tom Betts

Centre for Renewable Energy Systems Technology (CREST), Loughborough University, Loughborough

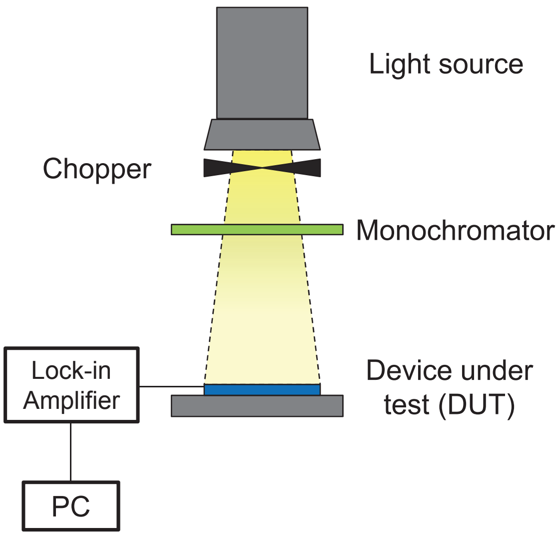
3-day training course at JRC Ispra, 3rd-5th April 2017

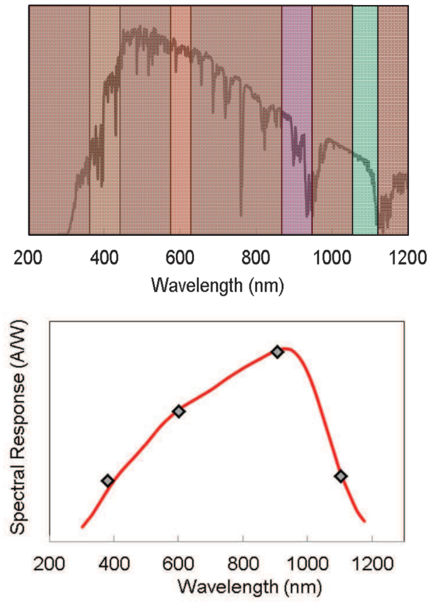
Outline

- Problem: Monochromatic SR measurements on large-area devices (full-sized commercial modules)
- Description of polychromatic concept and methodology
- Measurement setup
- Fitting algorithm
- Results

Introduction

- Conventional monochromatic method





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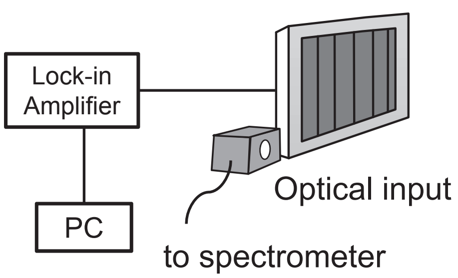
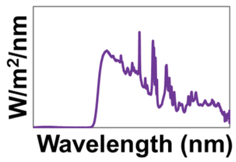
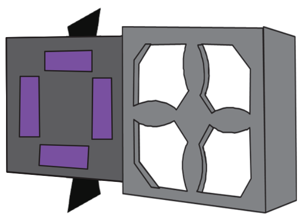
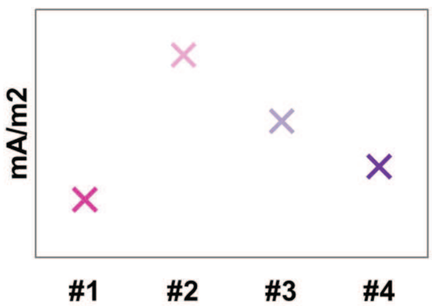
Principle of polychromatic spectral response method







Current (I_{meas})   *Spectral irradiance* (E_{meas})



- SR curve is derive through fitting process
- Measure device up to full-size module
- Simple setup

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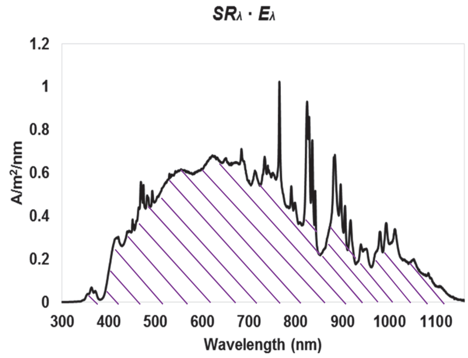
Spectral response extraction

$$I_{model} \; I_{sc} = A \int_{\lambda_{max}}^{\lambda_{min}} SR_{\lambda} E_{\lambda} d\lambda \; SR_{model} E_{\lambda, meas} d_{\lambda}$$

$$SR_{model} = \sum_{i=1}^{5} a_i \, exp\left[-\left(\frac{\lambda - b_i}{ci}\right)^2\right]$$



I_{sc} : short circuit current (A)

A : area of device (m^2)

E_λ : spectral irradiance ($W/m^2/nm$)

$\lambda_{max}, \lambda_{min}$: range of wavelength measurable by spectrometer

SR_{model} : Gaussian function

λ : wavelength (nm)

a, b, c : variables of Gaussian function

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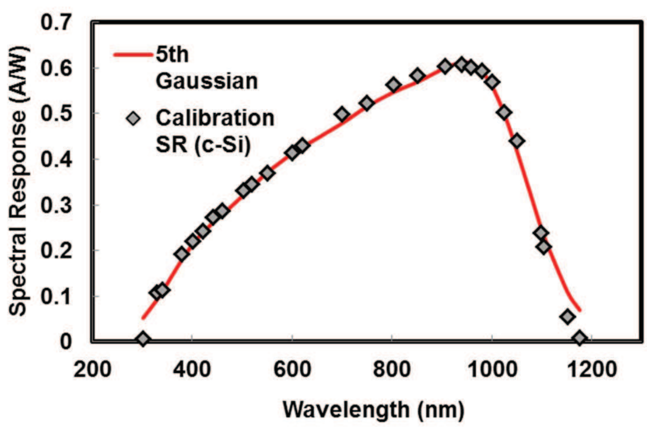
Spectral response extraction

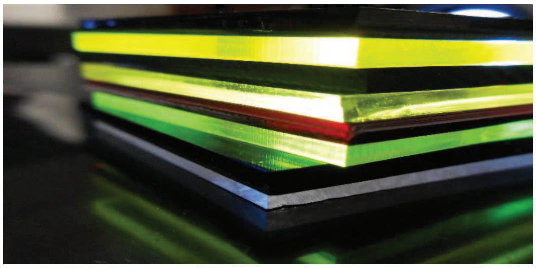
$$SR_{model} = \sum_{i=1}^{5} a_i \, exp\left[-\left(\frac{\lambda - b_i}{c_i}\right)^2\right]$$

5th Gaussian function

Number of coefficients : **15**

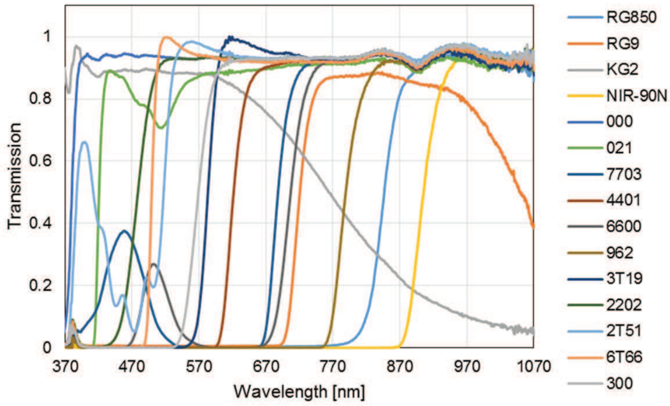


Method implementation



Polychromatic filters

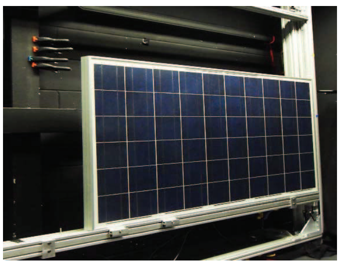
- Thermoplastic and glass
- Overall low cost: thermoplastic about €6 per 40x40 cm piece



Method implementation

Measurement rig

Pasan 3b
solar simulator system

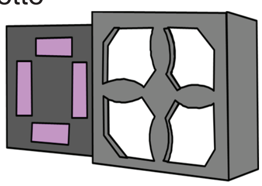


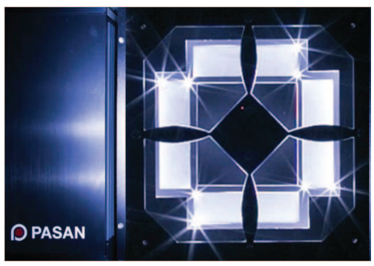
- Max module size: 2x2 m^2
- Light non-uniformity: ~2%

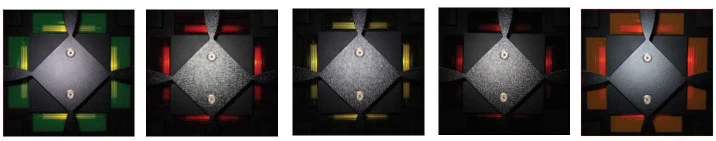
Distance: 8 m

Filter cassette

Four Xe lamps







Polychromatic filters positioned in front of Xe lamps

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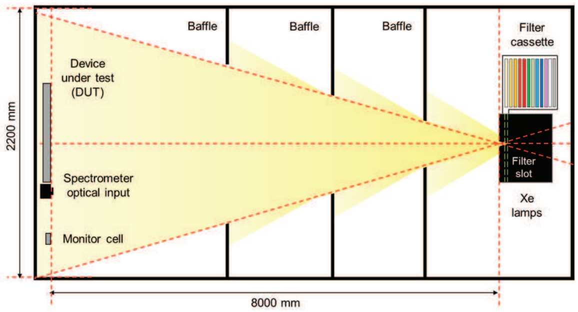
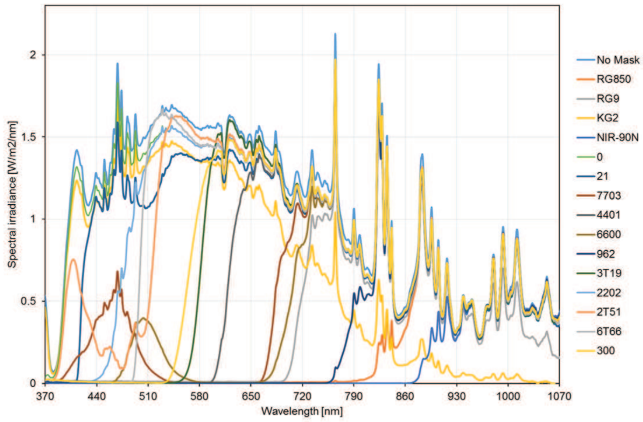
Method implementation





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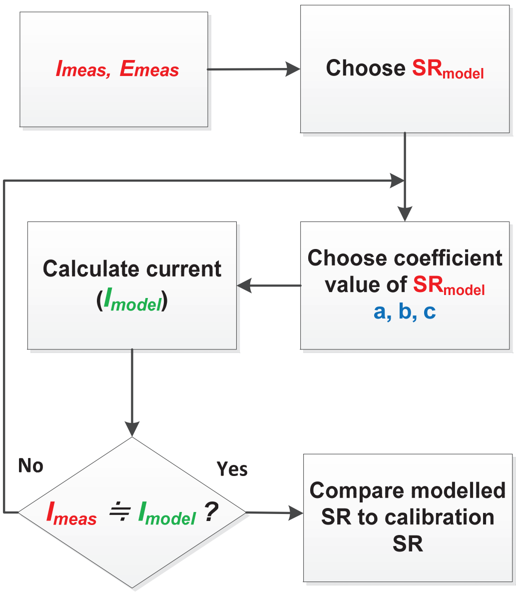
Non-uniformity of measurement plane:

	Horizontal [mm]	Vertical [mm]
Whole plane	0-2000	0-2000
Full size module	0-1800	500-1500
Mini-module	0-1100	600-1300
Cell	300-500	600-700

Filters	Whole plane	Full size module	Mini-module	Cell
NoMask	1.54%	1.28%	1.28%	0.37%
RG850	2.62%	2.42%	1.18%	0.39%
RG9	2.55%	2.14%	1.20%	0.23%
KG2	2.71%	2.04%	0.91%	0.21%
NIR-90N	3.00%	2.17%	2.09%	0.53%
000	1.54%	1.40%	1.31%	0.53%
021	1.48%	1.40%	1.15%	0.48%
7703	1.56%	1.44%	1.27%	0.37%
4401	1.57%	1.41%	1.28%	0.44%
6600	1.68%	1.41%	1.21%	0.41%
962	1.67%	1.45%	1.28%	0.40%
3T19	1.48%	1.36%	1.28%	0.43%
2202	1.42%	1.27%	1.16%	0.42%
2T51	1.47%	1.33%	1.18%	0.44%
6T66	1.40%	1.21%	1.19%	0.46%
300	1.49%	1.32%	1.22%	0.52%

Fitting algorithm



Filter ID	GEL101	GEL103	…	RG850
Wavelength (nm)	Spectral Irradiance, E_{meas} (W/m²/nm)			
350	0.00533	0.03733	…	0
…	…	…	…	…
1050	0.56370	0.64874	…	0.47858
I_{meas} (A)	0.10800	0.11840	…	0.03570

$$I_{model} = A \int_{\lambda_{max}}^{\lambda_{min}} SR_{model} E_{meas} d_{\lambda}$$

$$SR_{model} = \sum_{i=1}^{5} a \, exp\left[-\left(\frac{\lambda - b}{c}\right)^2\right]$$

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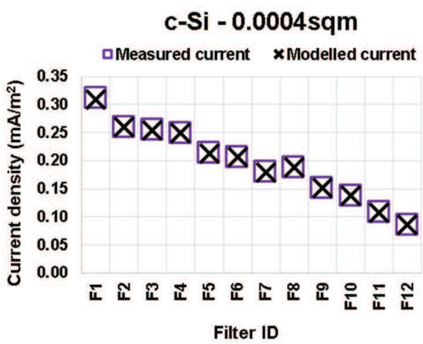
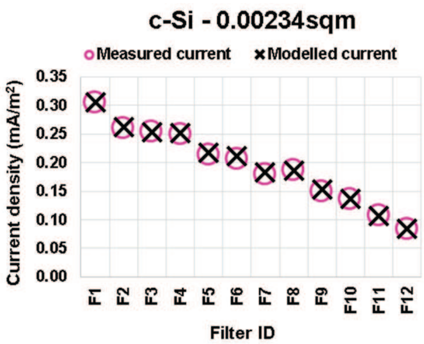
Method validation

$$I_{model} = I_{meas}$$





Fitted coefficient values
(*a, b, c*)

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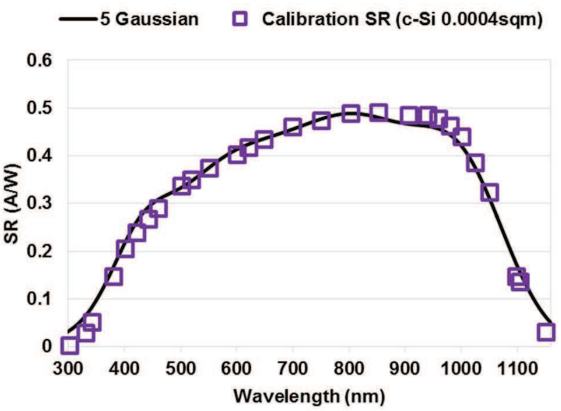
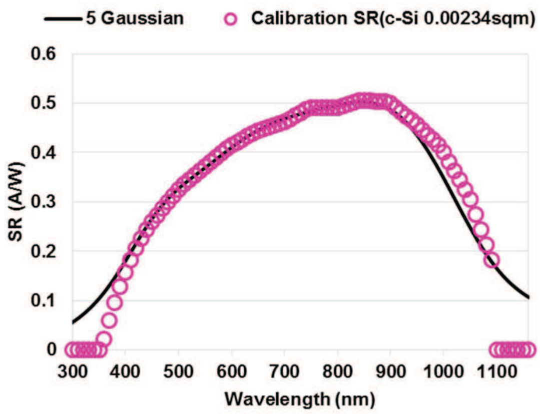
Method validation – small-area devices





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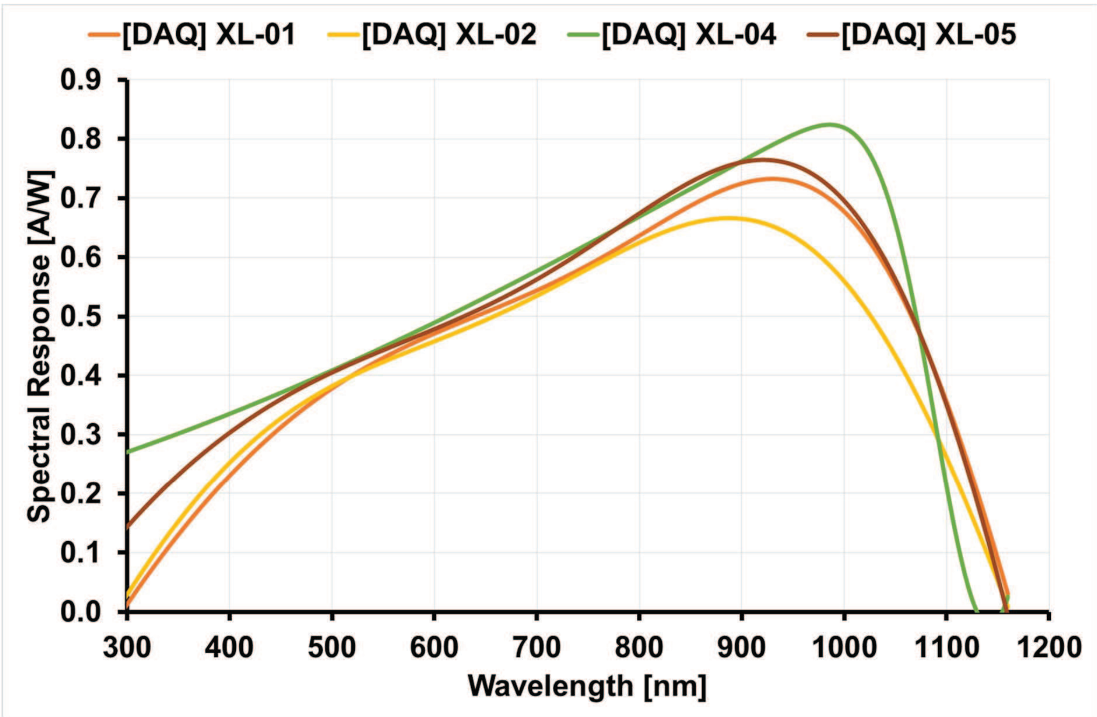
Method applied to full-sized modules



Thank you for your attention

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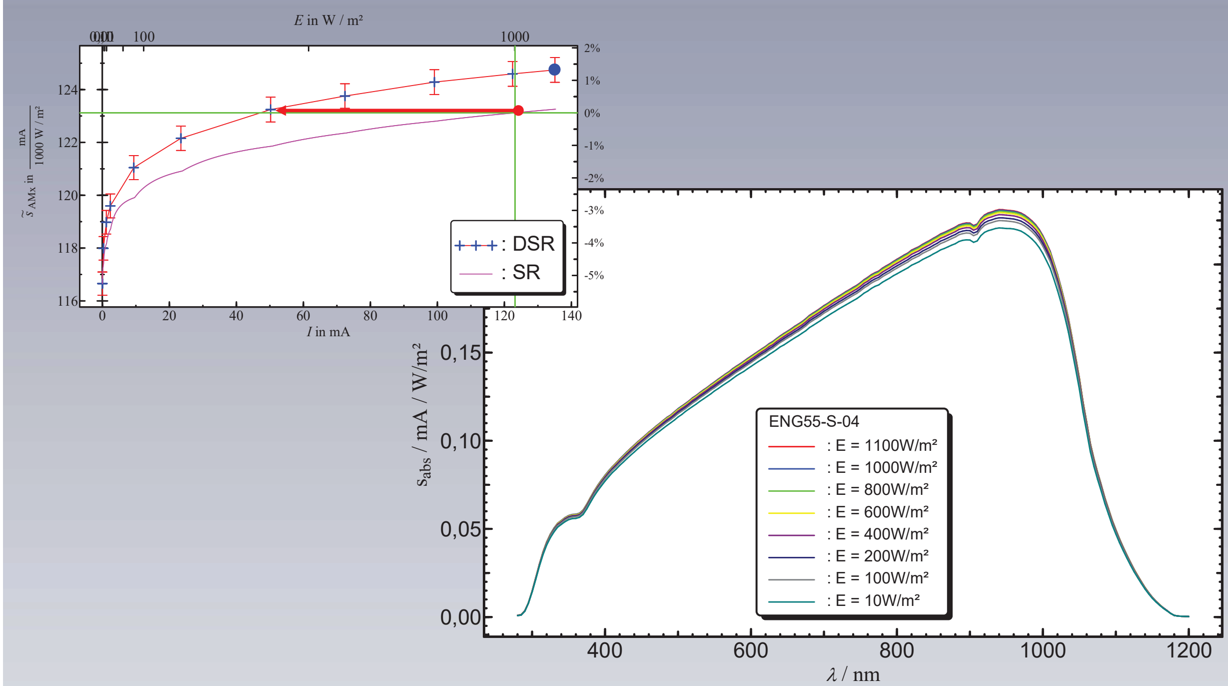
Linearity measurements (WP3)



Ingo Kröger
Department 4.1: Photometry and Applied Radiometry
Working Group 4.14: Solar Cells

PhotoClass

PTB
Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

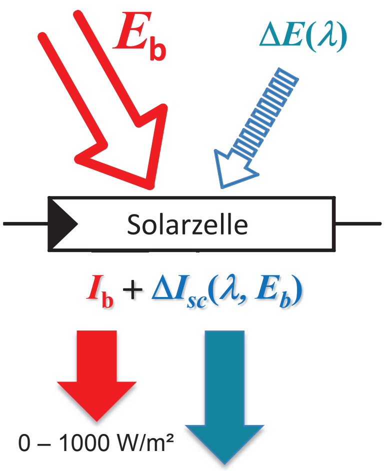
Participants

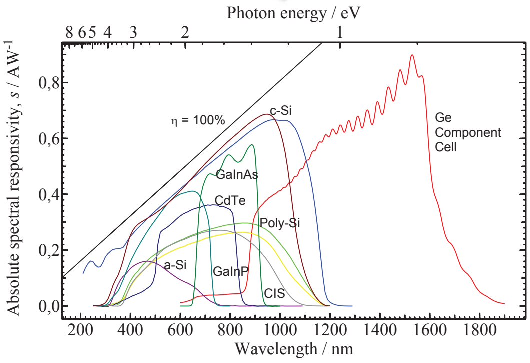
PTB

Participant	Deliverable	Facility, method	samples	period
PTB	D3.2.3	Laser-DSR, DSR-method	ENG55-S ENG55-M ENG55-X	12/2015 - 01/2016 12/2016 - 02/2017 02/2017 - 04/2017
LNE	D3.2.4	PASAN IIIC + Filter set IEC 60904-10	ENG55-X ENG55-XL	07/2016 - 10/2016 08/2016 - 11/2016
JRC	D3.2.5	Apollo solar simulator, two lamp method, Solar simulator + filters IEC 60904-10	ENG55-S ENG55-M ENG55-X ENG55-XL	03/2016 03/2017 05/2016 - 06/2016 05/2016 - 07/2016
REG(Fhg)	D3.2.6	Filtermonochromator DSR, white light response (WLR)	ENG55-S ENG55-M ENG55-X	06/2016 - 07/2016 07/2016 - 08/2016 ------
REG(LU)	D3.2.7	PASAN IIIb + ND filters IEC 60904-10	ENG55-S ENG55-M ENG55-X ENG55-XL	08/2016 - 09/2016 11/2016 12/2016 - 01/2016 12/2016 - 02/2016
ISFH	voluntary	Monochromator DSR, DSR-method	ENG55-S (ENG55-M)	02-2017 -------

Purpose:
- Gaining experience with linearity measurement (new facilities)
- Validation of different methods/facilities (critical assessment on uncertainties)
- Experiences shall have impact on development of IEC standard 60904-10

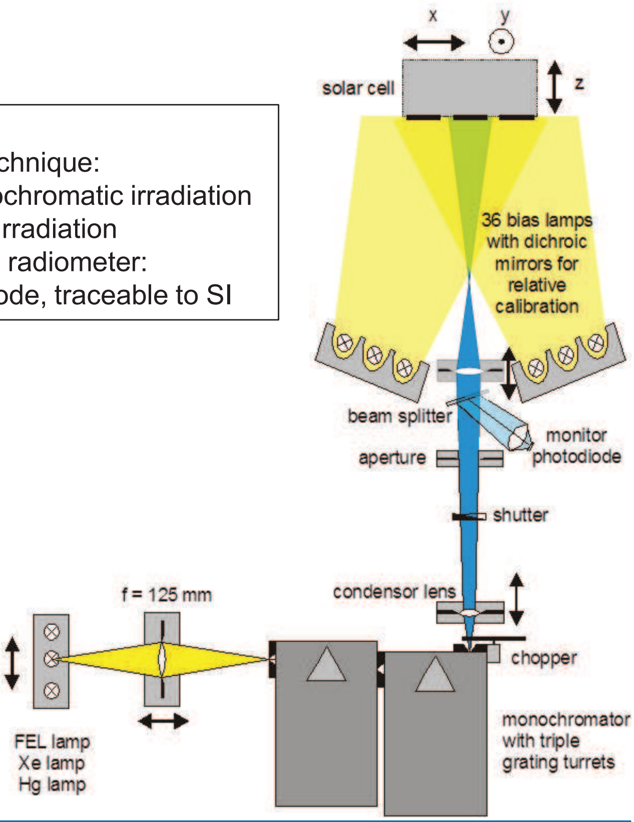
Differential spectral responsivity (DSR) method



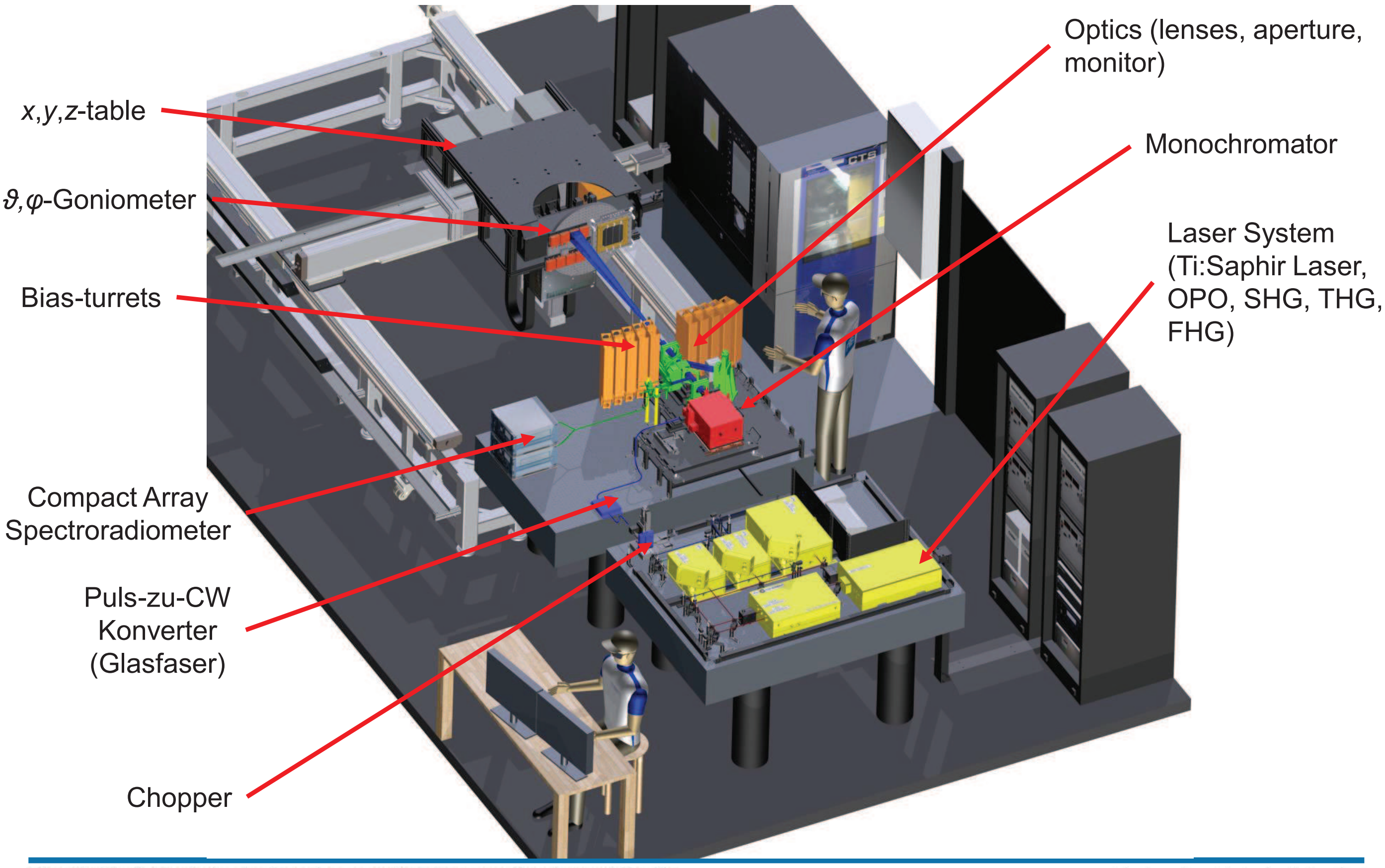


DSR- facility

- 2 beam technique:
  - → monochromatic irradiation
  - → Bias irradiation
- Reference radiometer:
  Photodiode, traceable to SI



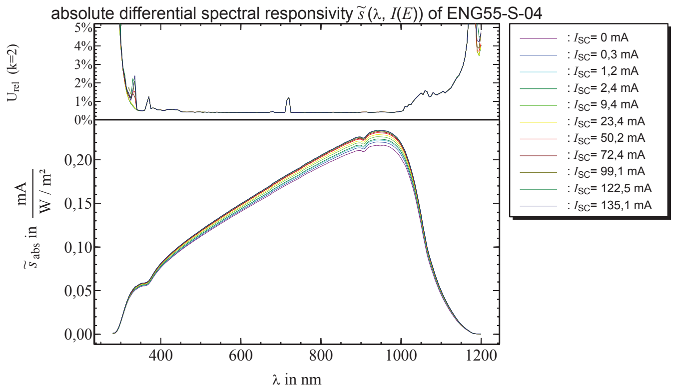
Laser-DSR facility @PTB



DSR fundamentals: From DSR to I_{STC}

Measurements of differential spectral responsivity curves $\tilde{s}_{SZ}(\lambda, E_b)$ at different Bias irradiance levels E_b.
Comparison of solar cell against reference photodiode in homogeneous monochromatic fields, using monitor correction:

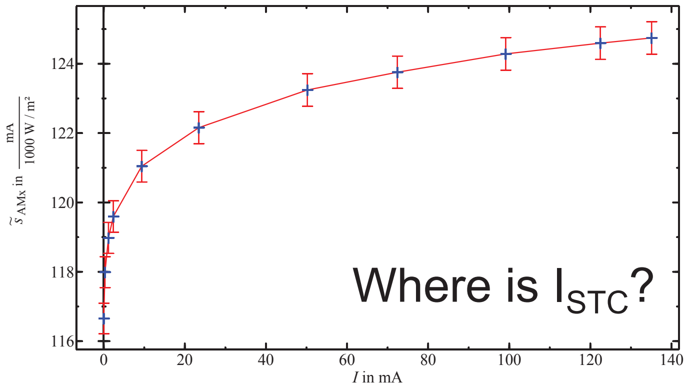
$$\tilde{s}_{SZ}(\lambda, I_{Bias}) = \frac{I_{SZ}(\lambda, I_{Bias}) / I_{MD,SZ}(\lambda)}{I_{Ref}(\lambda) / I_{MD,Ref}(\lambda)} \cdot \tilde{s}_{Ref}(\lambda)$$



Determination of AMx weighted currents $\tilde{s}_{AMx}(I_{SC}(E_b))$ for each DSR curve at given Bias irradiance level $I_{SC}(E_b)$:

$$\tilde{s}_{AMx}(I_{SC}(E_b)) = \frac{\int_0^\infty \tilde{s}(\lambda, I_{SC}(E_B)) \cdot E_{\lambda,AMx}(\lambda) d\lambda}{\int_0^\infty E_{\lambda,AMx}(\lambda) d\lambda}$$

If the solar cell would be linear, $\tilde{s}_{AMx}(I_{SC}(E_b))$ would be constant and $\tilde{s}_{AMx}(I_{SC}(E_b)) = I_{STC}$



DSR fundamentals: From DSR to I_{STC}

BUT, what we actually ***measure*** is the ***differential*** spectral responsivity (chopper, Lock-In technique)

$$\tilde{s}(I_{SC}(E_b)) = \left.\frac{\partial I_{SC}(E_b)}{\partial E}\right|_{E_b}$$

Corresponds to the ***slope*** of the linearity curve at given points E_b

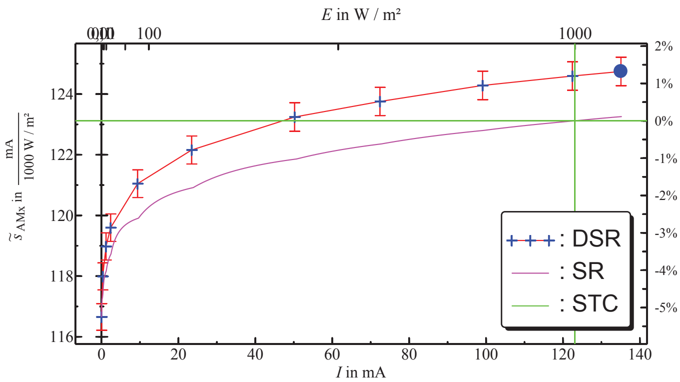
$$\rightarrow \int_0^{1000} dE = 1000 = \int_0^{I_{STC}} \frac{1}{\tilde{s}_{AM1.5}(I_{SC})} dI_{SC}$$

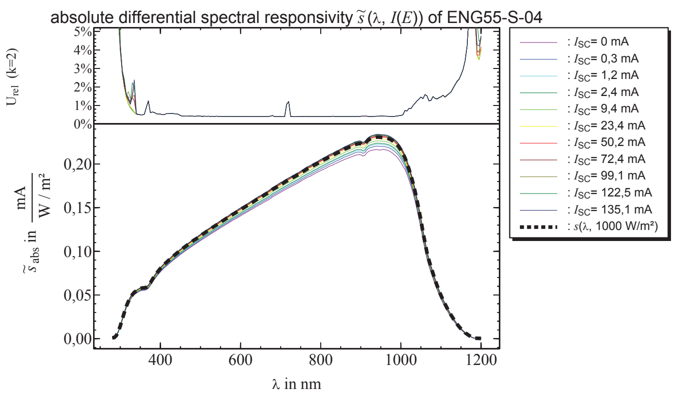
I_{STC} (or any current at given spectrum Amx and irradiance $E_{b,AMx}$) can be derived from numerically solving the upper equation.

$$\rightarrow \boldsymbol{E_{b,AMx}} = \int_0^{I_{SC}(E_b)} \frac{\mathbf{1}}{\tilde{s}_{AMx}(I_{SC})} \mathbf{d}I_{SC}$$

The absolute AMx spectral irradiance responsivity is derived from:

$$s(\lambda, E_{b,AMx}) = \frac{I_{SC}(E_b)}{\int_0^{I_{SC}(E_b)} \frac{dI_{SC}}{\tilde{s}(\lambda, I_{SC})}}$$



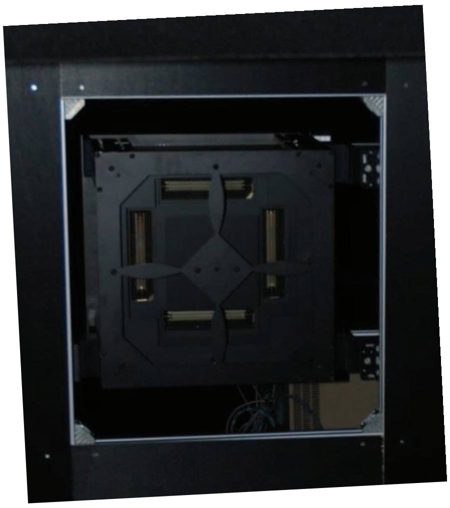


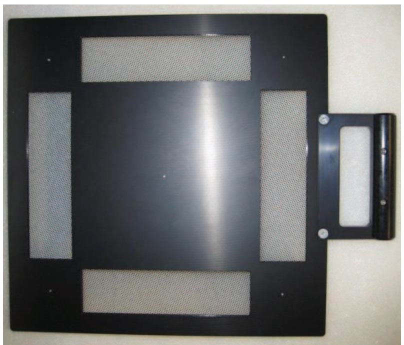
Two-lamp method

Subset of lamps on multi-lamp system: Measure lamp A, lamp B and lamps AB	
PROS	**CONS**
Spectrum irrelevant	Only I_{sc}
Spatial non-uniformity irrelevant	Data analysis not standardized
Could be done with other light sources	Special SS
No reference required	Often, limited steps
Fast measurement	Linearity only between half and full intensity

Masks or ND filters

Use mask or neutral density filters to reduce irradiance on DUT	
PROS	**CONS**
Stable spectrum (mostly)	Spatial non-uniformity
Full IV curves	Linear reference required
	Spectrally uniform transmission of ND filters/masks?
	Limited range/steps



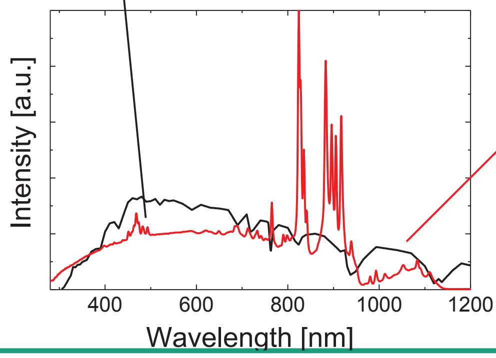


Linearity Determination
Fraunhofer ISE CalLab PV Cells

- DSR Method (PTB)[1]
  - Measurement of *Differential Spectral Response* at various E_{bias}
  - **Calculation** of
- WLR Method (ISE)[2]
  - Measurement of Differential *White Light Response* at various E_{bias}
  - **Measurement** of

$$I_{SCAMX}^{DSR}(E_{bias}) = \int DSR(\lambda, E_{bias})\mathrm{AMX}(\lambda)d\lambda$$

$$I_{SCSPK}^{WLR}(E_{bias}) = \left[\int DSR(\lambda)SPK(\lambda)d\lambda\right](E_{bias})$$



[1]J. Metzdorf, „Calibration of Solar Cells 1, The Differential Spectral Responsivity Method“, Appl. Optics 26 (1987), p. 1701

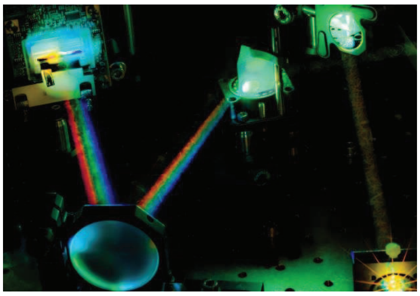
[2] J. Hohl-Ebinger, G. Siefer, and W. Warta, Non-Linearity of Solar Cells in Spectral Response Measurements, 22nd EUPVSEC 2007. Milan, Italy.

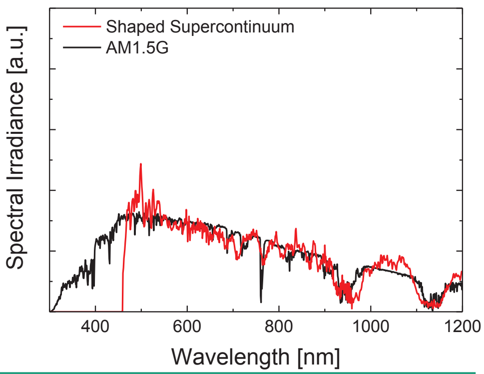
Linearity Determination
Fraunhofer ISE CalLab PV Cells

- WLR Method
  - Fast method => linearity determination of each cell
  - Spectral mismatch can dominate MU (Linearity)

$$I_{SCSPK}^{WLR}(E_{bias}) = \left[\int DSR(\lambda)SPK(\lambda)d\lambda\right](E_{bias})$$

- Spectral improvement
  - Filtering
  - Supercontinuum shaping[1]



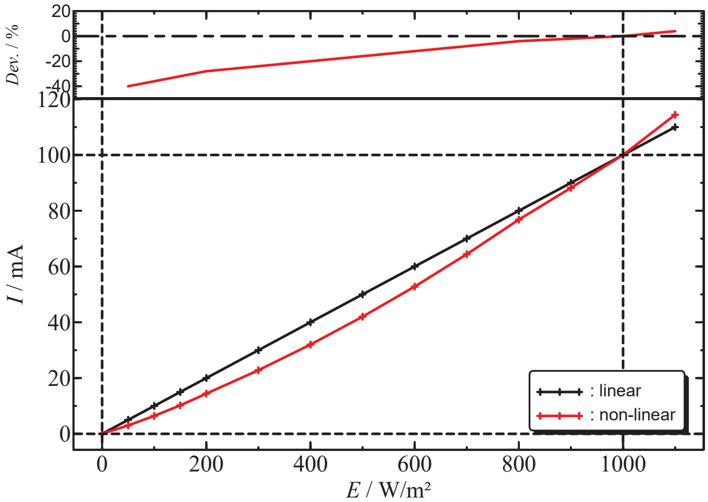


[1]M. Mundus, „Spectrally shaped supercontinuum for advanced solar cell characterization“, 31st EUPVSEC 2015

General considerations on linearity (IEC 60904-10)

- You want to know, how does this device perform compared to a perfect linear device
- You want one criteria for non-linearity, i.e one definition of quantification on non-linearity for testing purposes

Example:
1. Computing a non-linear device, here a device that systemtically underperforms at irradiance levels < 1000W/m²



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Example:
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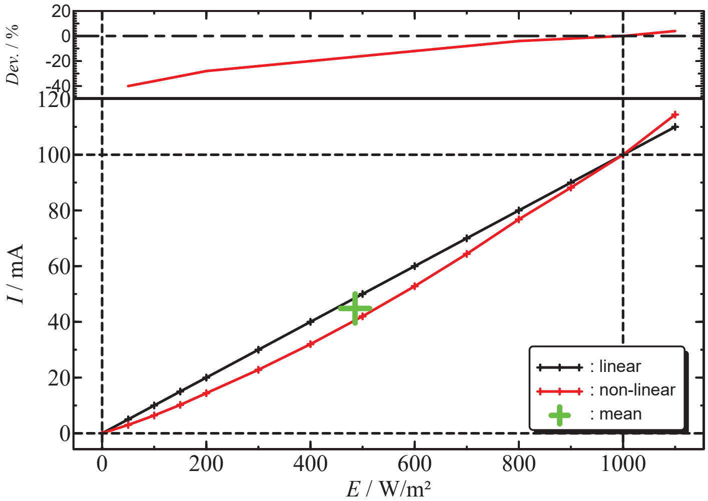
2. Follow procedure of IEC 60904-10

- Measure linearity data $\{X_i, Y_i\}$, i.e. $\{E_i, I_i\}$
- Calculate mean X and mean Y, i.e. E_{mean} ,I_{mean}

$$X = \frac{\sum_{i=1}^{n} X_i}{n} \qquad Y = \frac{\sum_{i=1}^{n} Y_i}{n}$$



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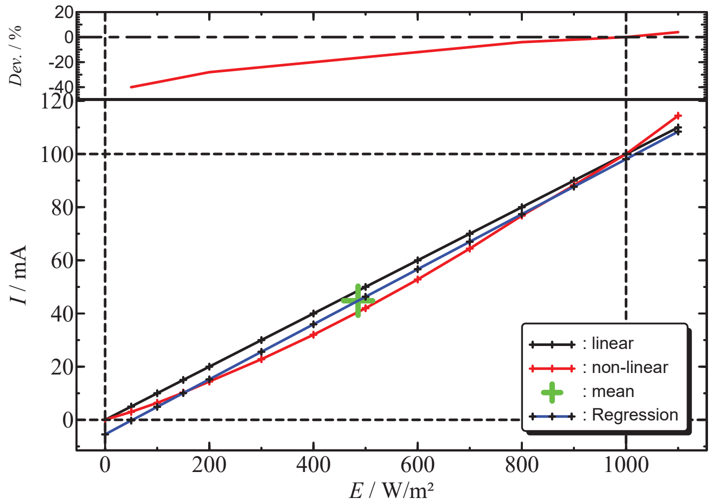

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- Calculate linear regression:

$$m = \frac{\sum_{i=1}^{n}(X_i - X)(Y_i - Y)}{\sum_{i=1}^{n}(X_i - X)^2}$$

$$\hat{Y}_i = mX_i + b$$

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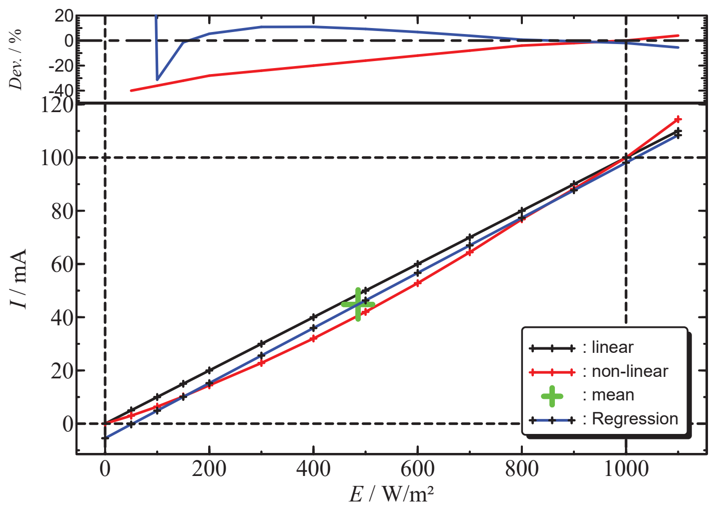

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$$\hat{Y}_i = mX_i + b$$

- Deviation from linearity is:

$$100 \cdot \left(1 - {Y_i}/{\hat{Y}_i}\right)$$

General considerations on linearity (IEC 60904-10)

- You want to know, how does this device perform compared to a perfect linear device
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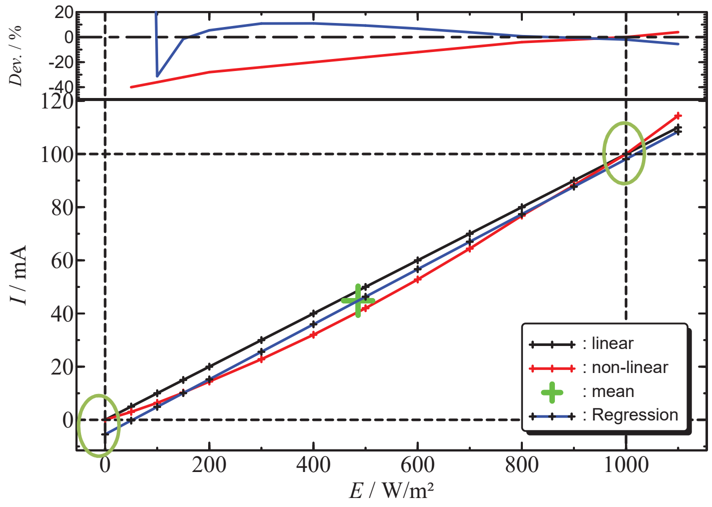

Major issues about the actual standard

- The linear regression ignores the physical facts of the ideal linear cell:
  - $I_{SC}(1000W/m^2)= I_{STC}$
  - $I_{SC}(0W/m^2)= 0$
- The derived deviation from linearity is not a deviation from a linear behaviour of a solar cell but a deviation from a linear regression and hence lead to a different quantification
- These issues have to be solved in the revised IEC 60904-10

General considerations on linearity (IEC 60904-10)

- You want to know, how does this device perform compared to a perfect linear device
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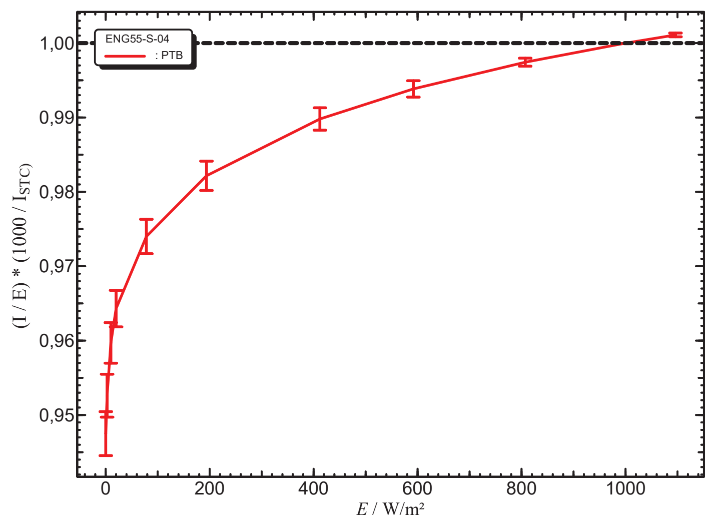


Approach here:

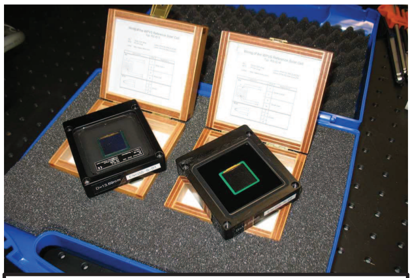
- Scale $I_{SC}(E)$ to 1000 W/m²

$$I_{scale}(E) = \frac{I_{SC}(E)}{E} \cdot \frac{1000}{I_{STC}}$$

- These values are directly applicable for enery rating, sind they are factors relative to I_{STC} that represent the irradiance dependent under/overperformance of the device
- The non-linearity (%) of the device in a defined irradiance range (i.e. 100 W/m² - 1100 W/m² could be defined as:

$$\frac{100 * \left(max\left(I_{scale}(E)\right) - min\left(I_{scale}(E)\right)\right)}{\left(max\left(I_{scale}(E)\right) + min\left(I_{scale}(E)\right)\right)/2}$$

Samples Photoclass project

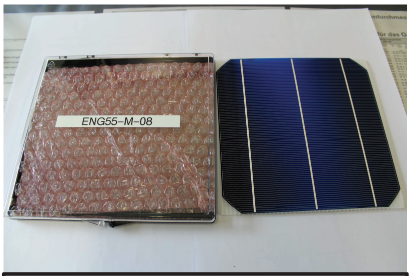


ENG55-S
Reference solar cells

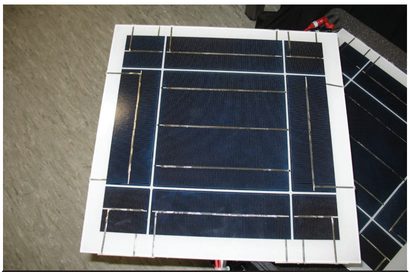
Investigation of:

- Different types
- Different sizes
- Different technologies

Here we show selected measurements of reference devices with different linearity behaviour



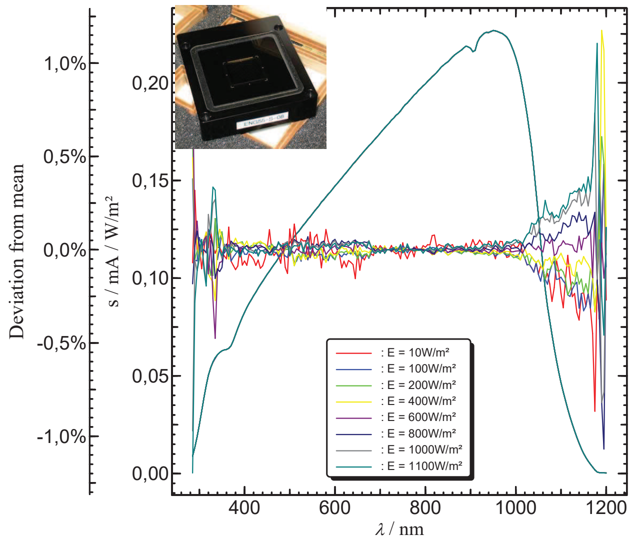
ENG55-M
solar cells

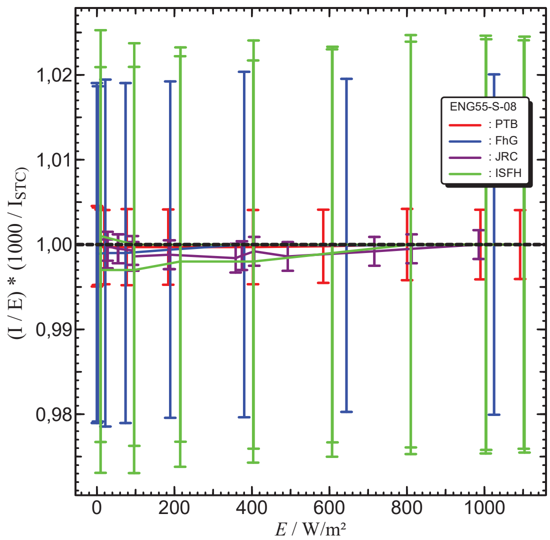


ENG55-X
Mini-Modules

ENG55-XL
Modules

Results – ENG55-S-08

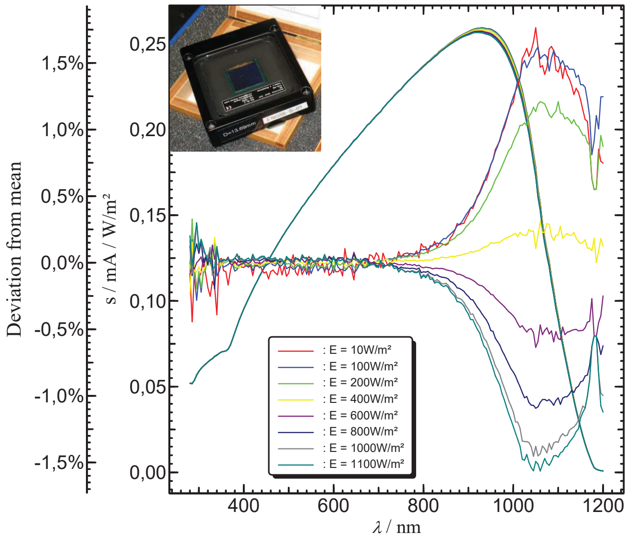


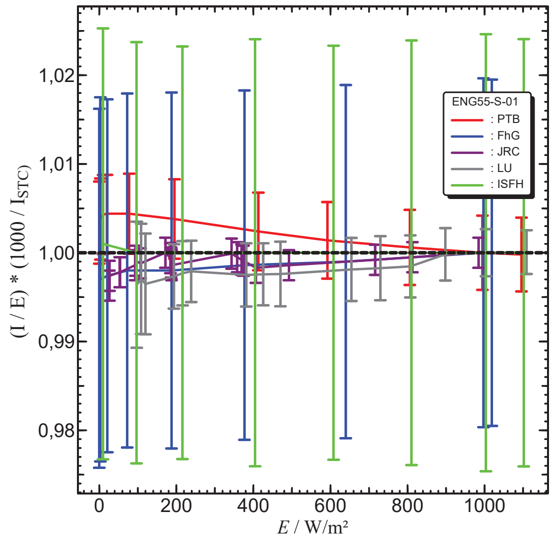


FhG: White light response
JRC: 2 lamp method
ISFH: Differential spectral responsivity
PTB: Differential spectral responsivity
LU: Solar simulator + ND-filters

- c-Si reference solar cell
- very linear

Results – ENG55-S-01

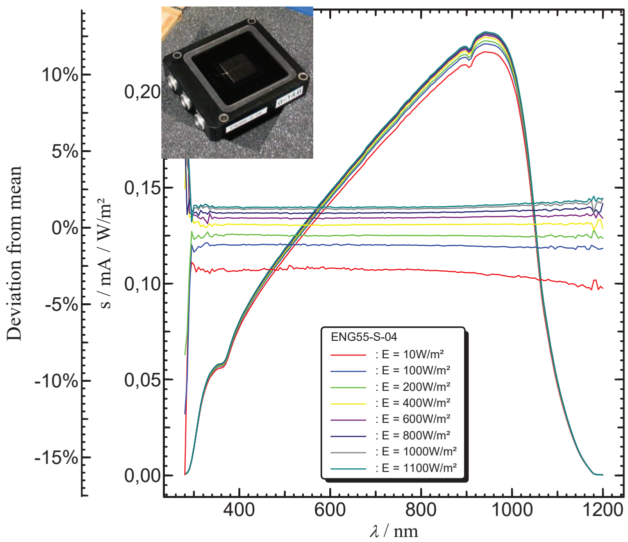


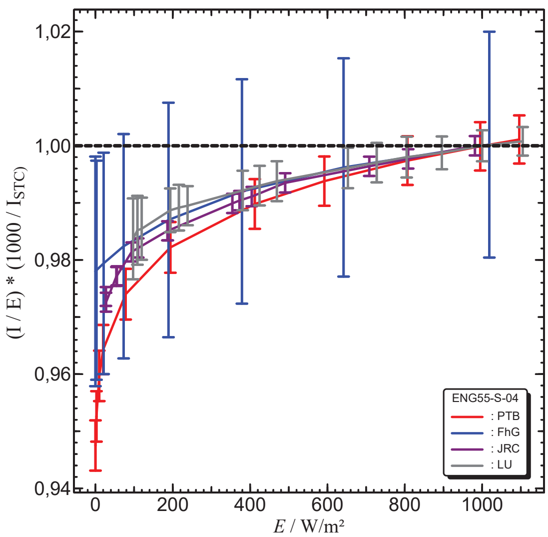


- c-Si reference solar cell
- Non-linearity IR >700nm

FhG: White light response
JRC: 2 lamp method
ISFH: Differential spectral responsivity
PTB: Differential spectral responsivity
LU: Solar simulator + ND-filters

Results – ENG55-S-04





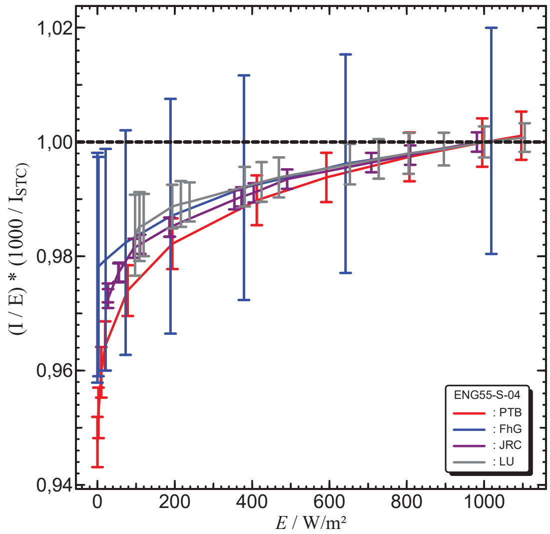
- c-Si reference solar cell
- Very non-linear, whole spectral range

FhG: White light response
JRC: 2 lamp method
ISFH: Differential spectral responsivity
PTB: Differential spectral responsivity
LU: Solar simulator + ND-filters

Conclusions

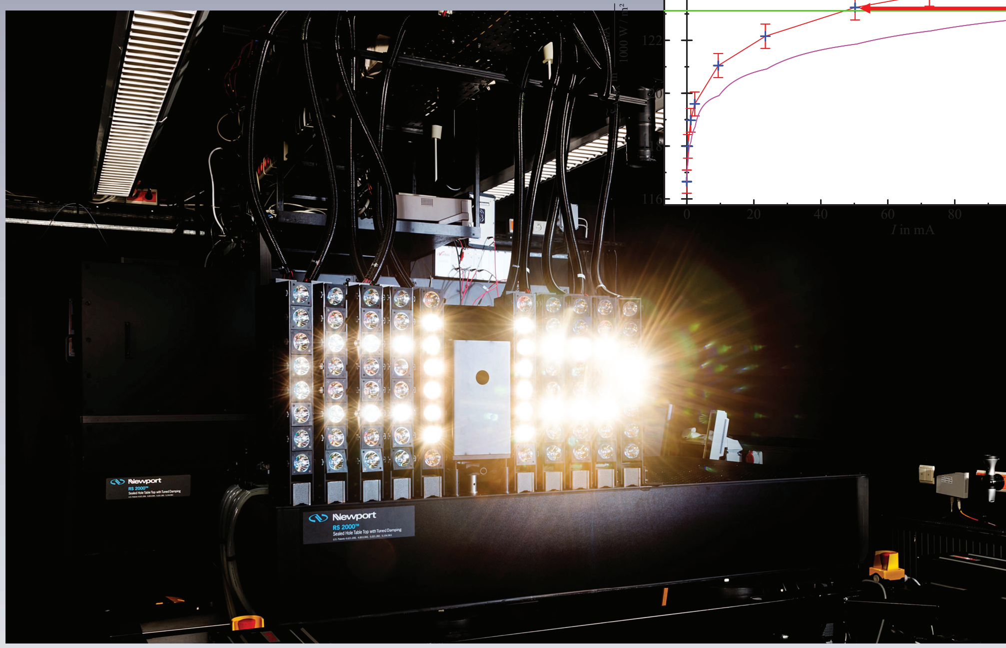
- General good agreement
- Uncertainties have to be reduced for linearity testing. If linearity criterium is set to 2%, expanded uncertainty should be <<2%
- Linearity based on scaled current offers possibility of reduction of measurement uncertainty by taking correlations into account. $I_{SC}(E)$ and I_{STC} are generally highly correlated!

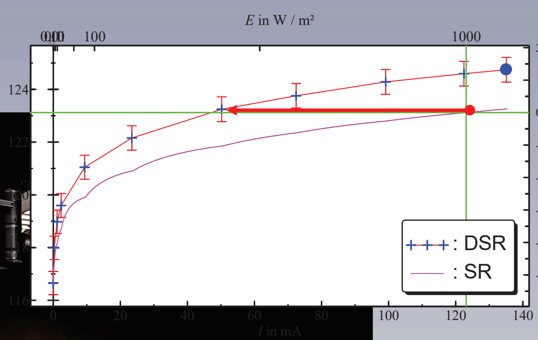
$$I_{scale}(E) = \frac{I_{SC}(E)}{E} \cdot \frac{1000}{I_{STC}}$$



Thank you

EMRP
European Metrology Research Programme
Programme of EURAMET
The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union
PhotoClass
Physikalisch-Technische Bundesanstalt Braunschweig und Berlin





PHOTOCLASS 3-day Training course at JRC Ispra

Programme

Session 1: based on WP2 Reference devices

The new reference cells (J. Hohl-Ebinger, ISE-FhG)

LED-based differential spectral response setup for reference solar cell mini modules (H. Baumgartner, MIKES)

Reference device intercomparison: protocol and first results (I. Kröger, PTB)

Session 2: based on WP3 Detector characterisation: temperature dependence

Overview: Facilities and methods for temperature dependence measurements (I. Kröger, PTB)

Overview: Facilities and methods for angular dependence (I. Kröger, PTB)

Session 3: based on WP3 Detector characterisation: linearity

Compressive sensing (T. Betts, LU)

Polychromatic SR (T. Betts, LU)

Overview: Facilities and methods for linearity measurements (I. Kröger, PTB)

Session 4: based on WP4 Source characterisation methods

Solar cell chuck for temperature characterisation (G. Martínez, INTA)

Comparison of spectroradiometers (I. Kröger, PTB)

Spectral sky scanning (S. Riechelmann, PTB)

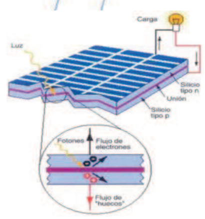
PhotoClass Project

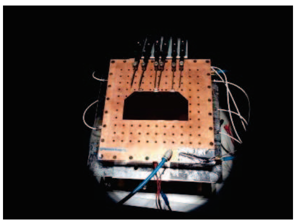
PhotoClass

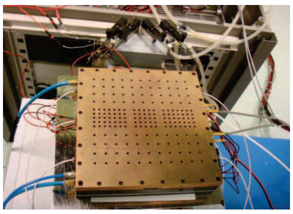
INTA-SPASOLAB (SPAce SOlar cells testing LABoratory)

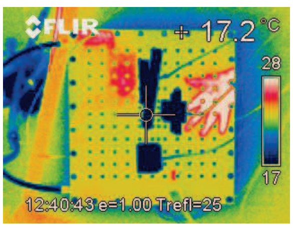
GOBIERNO DE ESPAÑA · MINISTERIO DE DEFENSA · INTA · SPASOLAB INTA SPAIN

JRC Ispra – Training Course 03rd - 05th, April 2017









INDEX

WP 3: Detector Characterisation

Task 3.3 - Temperature dependence of the detector.

- **Preliminary Design:** First Solar Cell Chuck Prototype
- **Final Design:** Second Solar Cell Chuck Prototype
- **Future improvements:** Peltier elements upgrade

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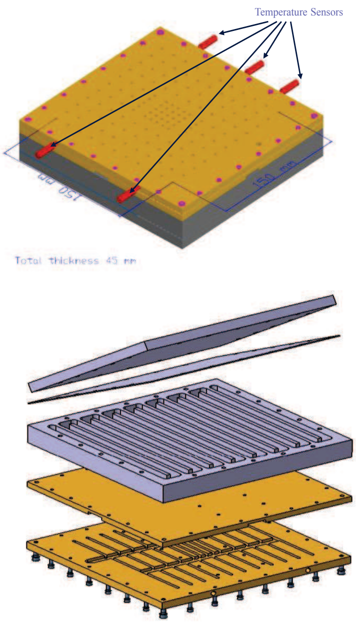
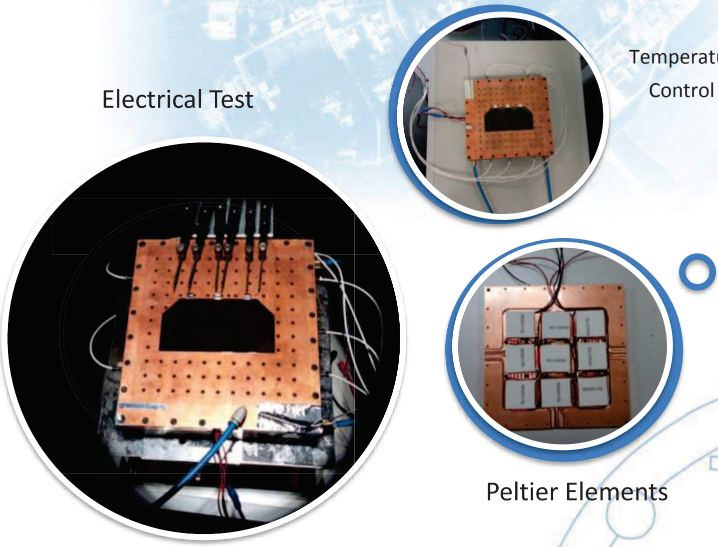
WP 3: Detector Characterisation

Task 3.3 – Temperature dependance of the detector

INTA will design and construct a solar cell chuck for use in temperature characterization of solar cells up to 6" in size (15 ºC > t < 60 ºC). A report will be written by INTA. The design will be shared with other partners and finally characterized at PTB.



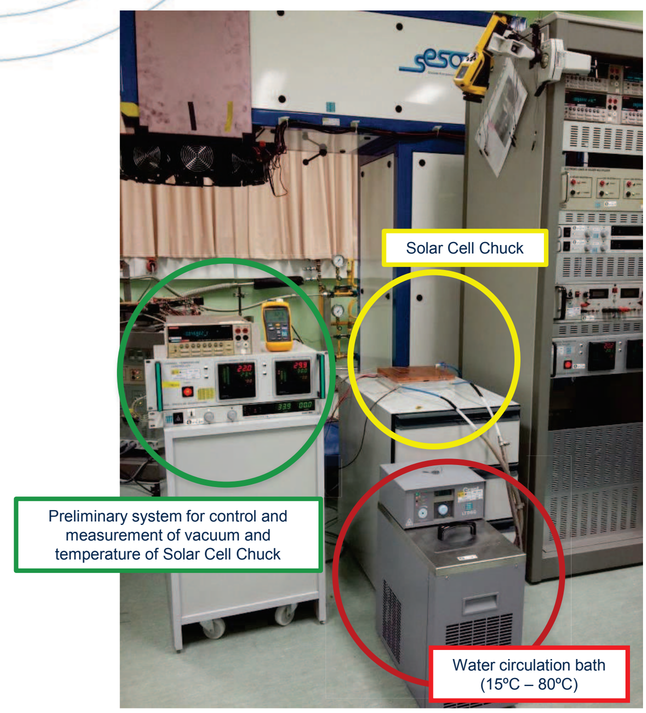
Preliminary Design



First Solar Cell Chuck Prototype

WP 3: Detector Characterisation

Task 3.3 – Temperature dependance of the detector – (*INTA initial temperature and vacuum characterization at Spasolab Laboratory).*



15ºC

		H2O
15,73	15,49	
	15,00	
15,57	15,56	
		H2O

80ºC baño a 40ºC

		H2O
78,47	80,19	
	80	
78	78,16	
		H2O

25ºC

		H2O
25,11	25,47	
	25,00	
25,11	25,18	
		H2O

60ºC baño 40ºC

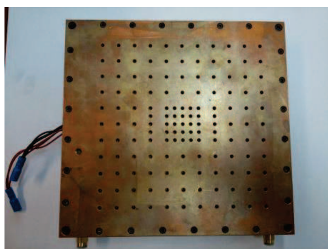
		H2O
59,49	60,35	
	60,00	
59,30	59,65	
		H2O

40ºC

		H2O
40.11	40.41	
	40.00	
39.96	40.07	
		H2O

60ºC baño 20ºC

		H2O
58.66	60.24	
	60.00	
58.35	58.77	
		H2O



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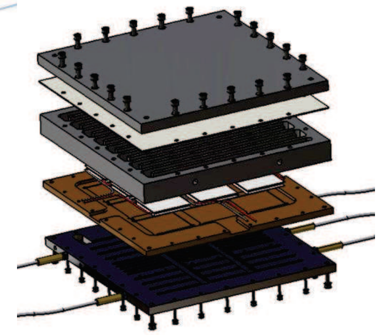
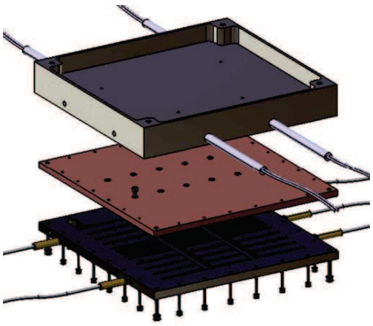
Task 3.3 – Temperature dependance of the detector

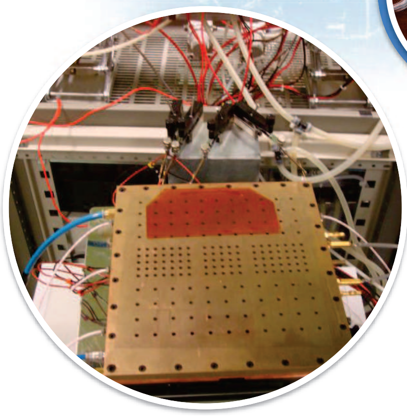
INTA will design and construct a solar cell chuck for use in temperature characterization of solar cells up to 6" in size (15 °C > t < 60 °C). A report will be written by INTA. The design will be shared with other partners and finally characterized at PTB.

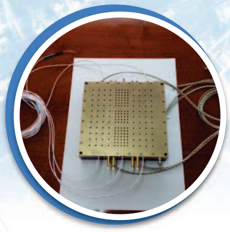




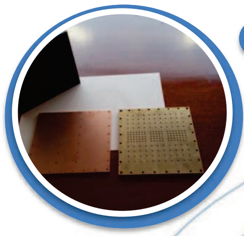
'Final' Design

Electrical Test





Temperature Control



High Temperature Prototype

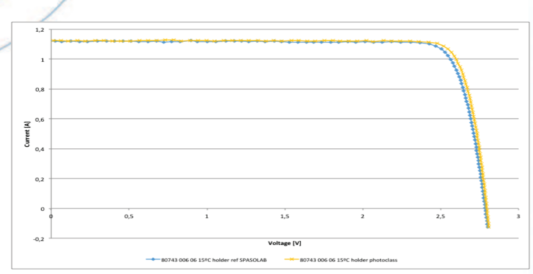
(80º C < T < 200º C)

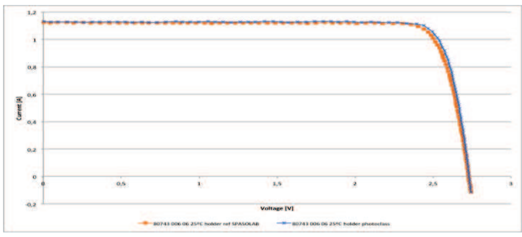
Second Solar Cell Chuck Prototype

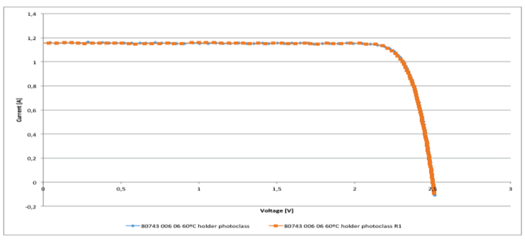
GOBIERNO DE ESPAÑA MINISTERIO DE DEFENSA INTA SPASOLAB INTA SPAIN

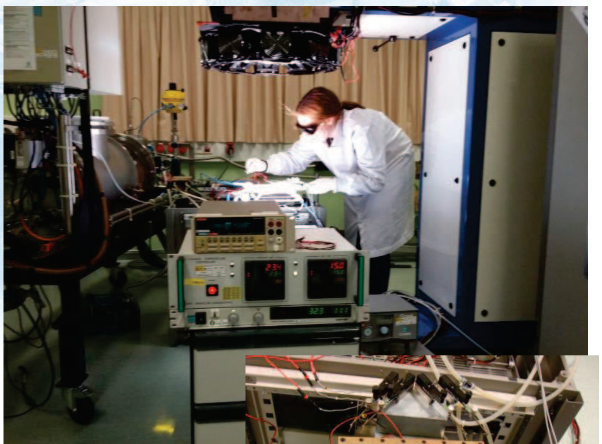
WP 3: Detector Characterisation

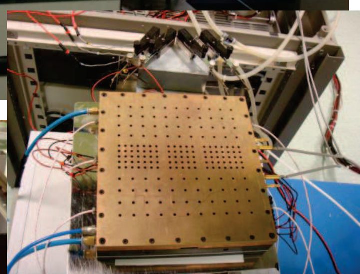
Task 3.3 – Temperature dependance of the detector – (*INTA initial Electrical measurements at Spasolab Laboratory).*

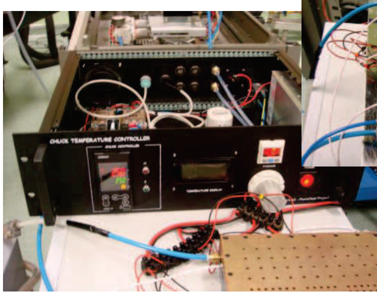












GOBIERNO DE ESPAÑA MINISTERIO DE DEFENSA INTA SPASOLAB INTA SPAIN

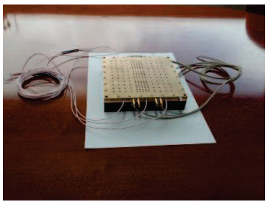
WP 3: Detector Characterisation

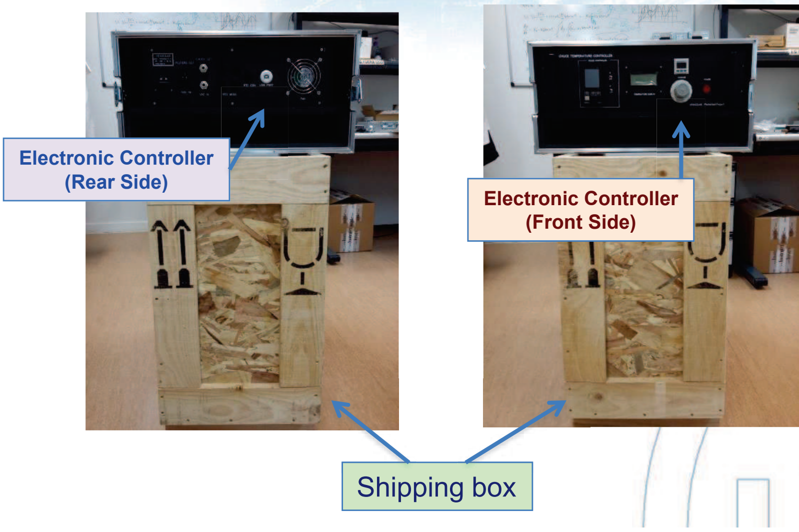
Task 3.3 – Temperature dependance of the detector

Electronic Controller:

INTA have designed a full Electronic controller dedicated to control the operation of 6” Solar Cell Chuck

1. Temperature Control based on Peltier and Resistors elements.
2. Temperature Measurements (5 RTDs [PT100 up to 200 ºC])
3. Vacuum regulation and control for different Solar Cells Areas
4. Adquisition system parameters and control by LabView Software development.





WP 3: Detector Characterisation

Task 3.3 – Temperature dependance of the detector

Electronic Controller:

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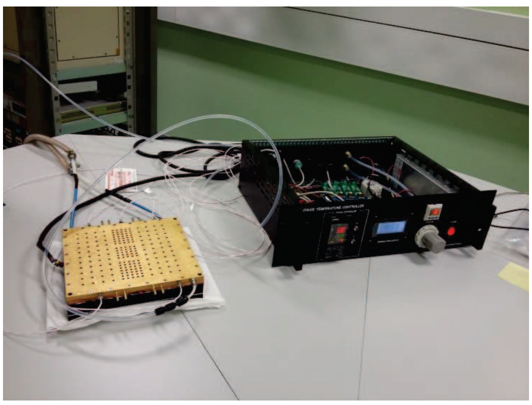
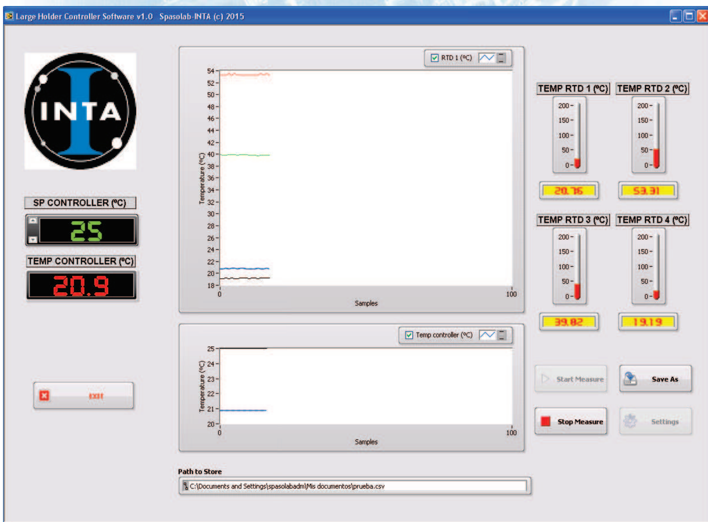




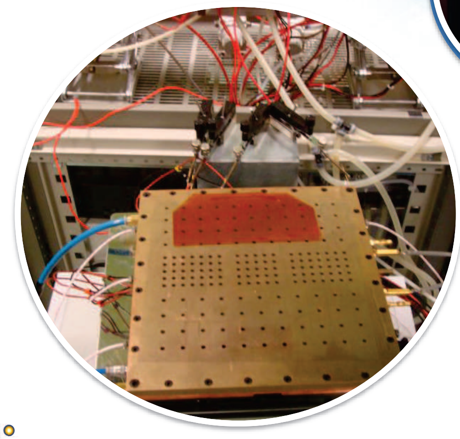
WP 3: Detector Characterisation

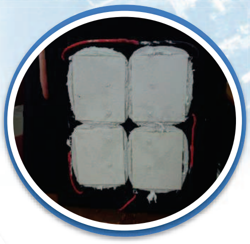
Task 3.3 – Temperature dependance of the detector

Future developments:

Temperature Control based on new Peltier Elements 60 x 60 mm

Electrical Test





Temperature Control

New Peltier Elements
(60 x 60 mm)

PhotoClass

The research work presented was carried out in part within the EMRP ENG55 project Towards an Energy-based Parameter for Photovoltaic Classification. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

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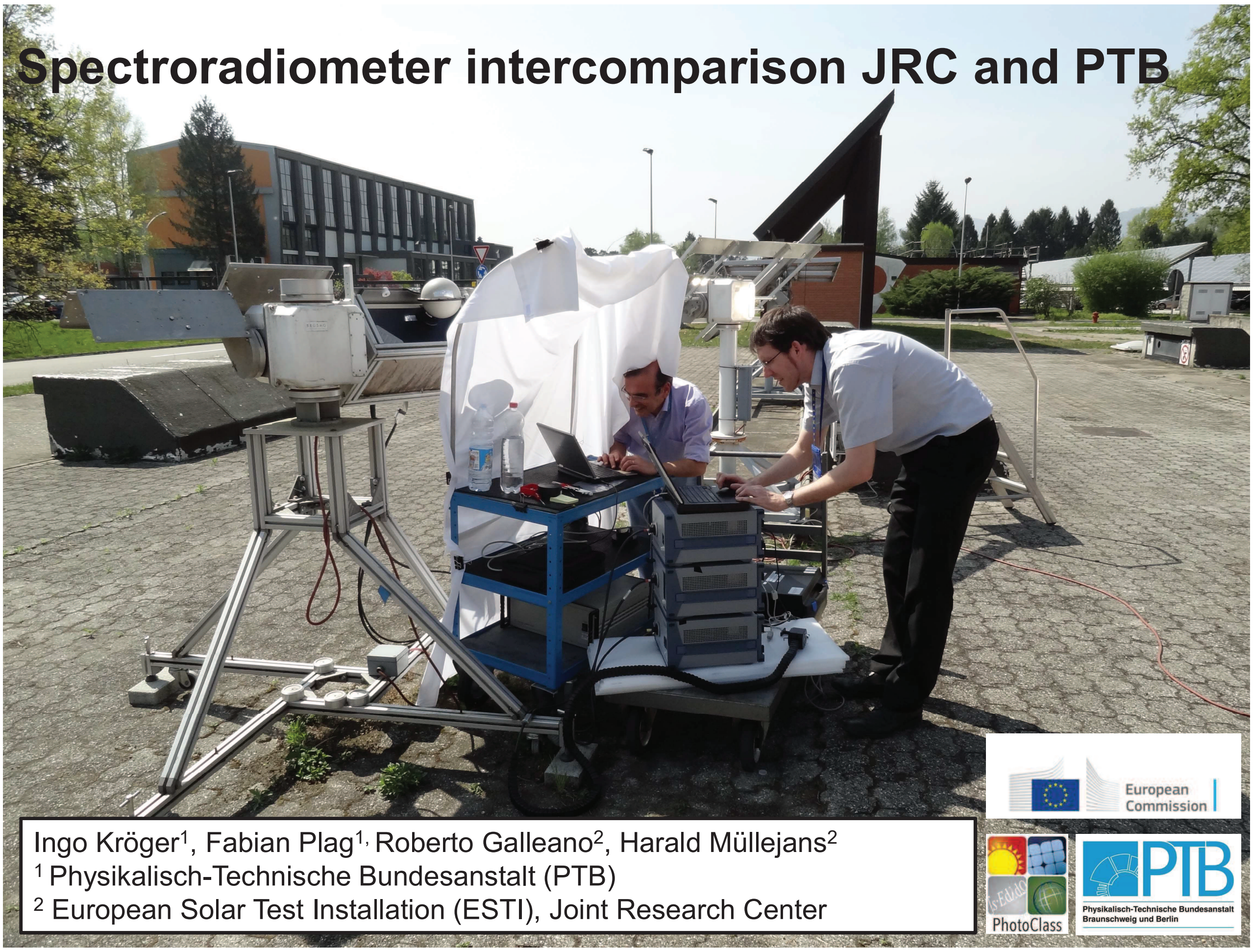
Spectroradiometer intercomparison JRC and PTB



Ingo Kröger[1], Fabian Plag[1], Roberto Galleano[2], Harald Müllejans[2]
[1] Physikalisch-Technische Bundesanstalt (PTB)
[2] European Solar Test Installation (ESTI), Joint Research Center

European Commission

PhotoClass

PTB Physikalisch-Technische Bundesanstalt Braunschweig und Berlin

Motivation

European Commission PTB

- Calibration of solar cells according IEC 60891 (STC: E = 1000W/m², AM1.5G, T_{SZ} = 25°C)
- Spectral Mismatch corrections generally have to be applied when solar cells are measured with simulated sunlight (and even with natural sunlight)
- Measurement of relative spectral irradiance E of the light source is very crucial

$$f_{MM} = \frac{\int E_{\mathrm{AM1.5G}}(\lambda) \cdot s_{\mathrm{DUT}}(\lambda)\mathrm{d}\lambda}{\int E_{\mathrm{Sim}}(\lambda) \cdot s_{\mathrm{DUT}}(\lambda)\mathrm{d}\lambda} \cdot \frac{\int E_{\mathrm{Sim}}(\lambda) \cdot s_{\mathrm{Ref}}(\lambda)\mathrm{d}\lambda}{\int E_{\mathrm{AM1.5G}}(\lambda) \cdot s_{\mathrm{Ref}}(\lambda)\mathrm{d}\lambda}$$

- Measurement uncertainty of spectral irradiance measurement $E_{\mathrm{Sim}}(\lambda)$ propagates to uncertainties of spectral mismatch correction factor f_{MM}
- In order to validate the spectral irradiance measurements, intercomparisons are needed

- Photoclass spectroradiometer comparison JRC ESTI – PTB was performed at JRC ESTI in April 2015
- Both labs have independent traceability for spectral irradiance

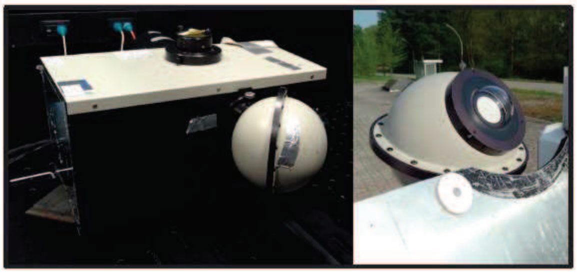
Instrumentation

OI750 spectroradiometer (ESTI)

- Entrance optics:
  integrating sphere coupled directly into rotating grating spectroradiometers
- Detectors:
  Si-PbS sandwich detector
- Spectral range:
  (300 - 1098) nm / (1100 - 2500) nm
- Spectral bandwidth:
  5 nm / 10 nm

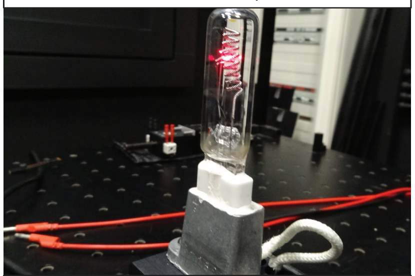
Compact Array Spectroradiometer (PTB)

- Entrance optics:
  integrating sphere coupled via optical fibre into 3 array spectroradiometers
- Detectors:
  Silicon / InGaAs / Ext-InGaAs
- Spectral range:
  (220-1020) nm / (780-1650) nm / (1500-2150) nm
- Spectral bandwidth: 3.7nm / 9 nm / 15 nm



Instrumentation

Standard lamp

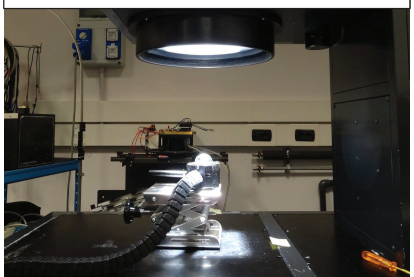


- Radiometric calibration, traceability to SI

Apollo solar simulator

- Multi light source steady state solar simulator

WACOM solar simulator

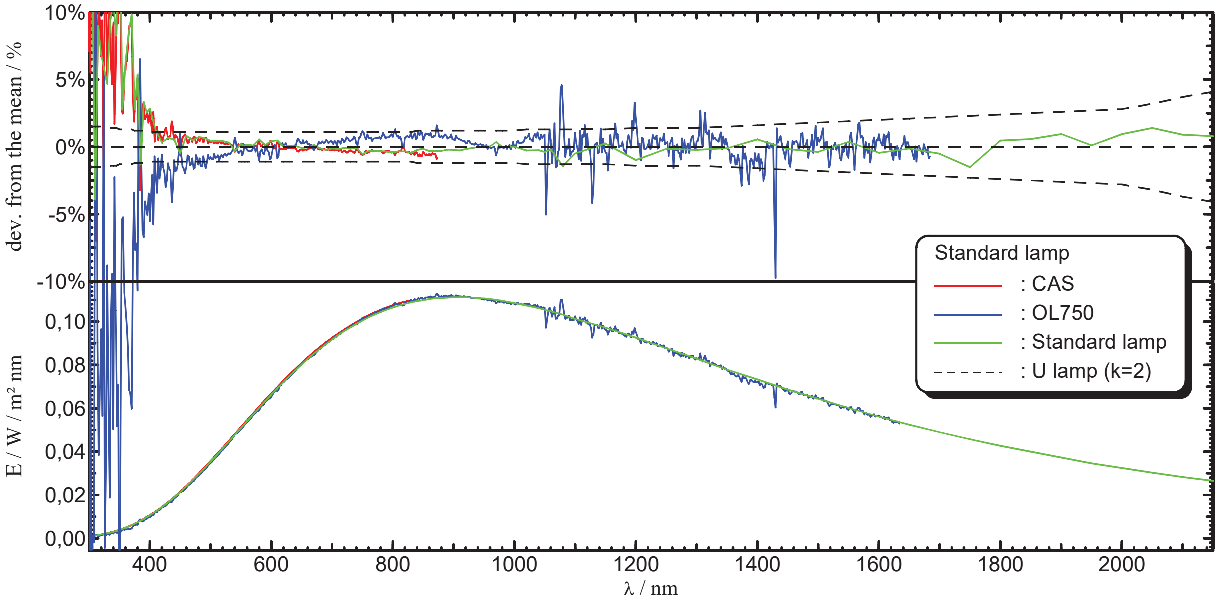


- Steady state solar simulator for solar cells

Natural sunlight

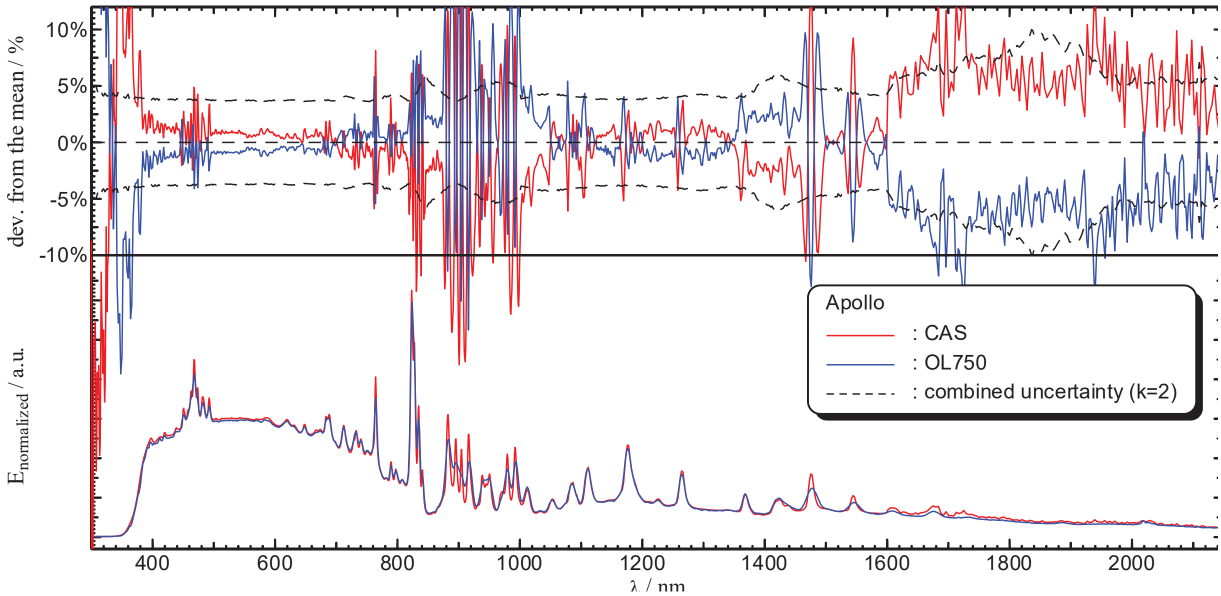
- Direct sunlight at clear sky conditions

Results : standard lamp



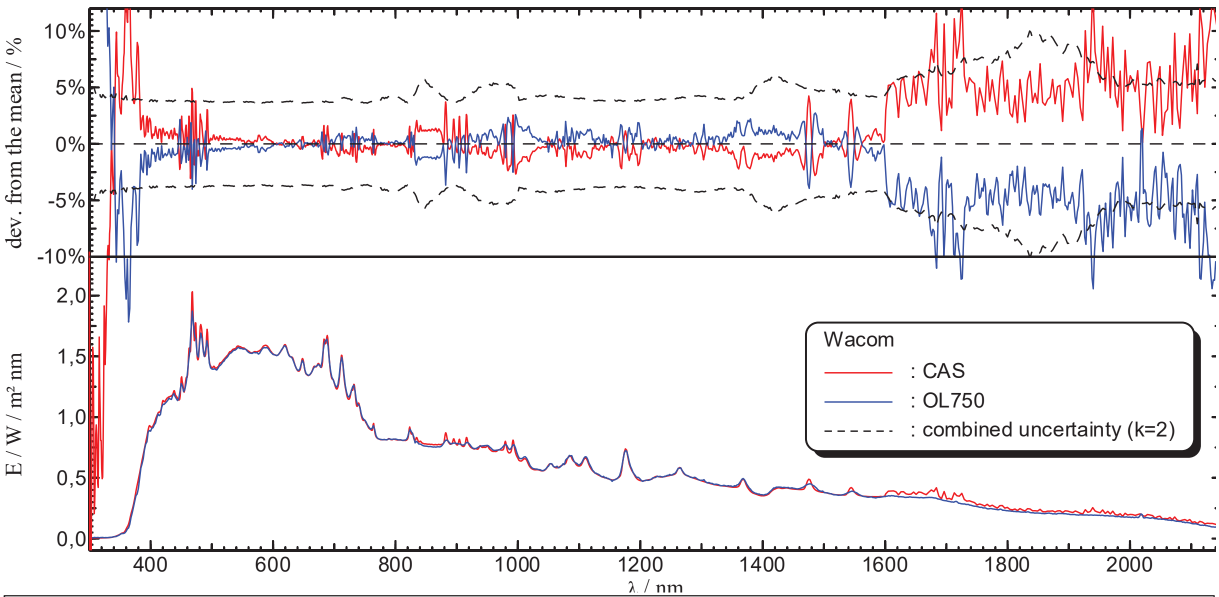
- Generally good agreement within combined uncertainties
- Significant deviation in the UV λ < 450nm

Results : Apollo



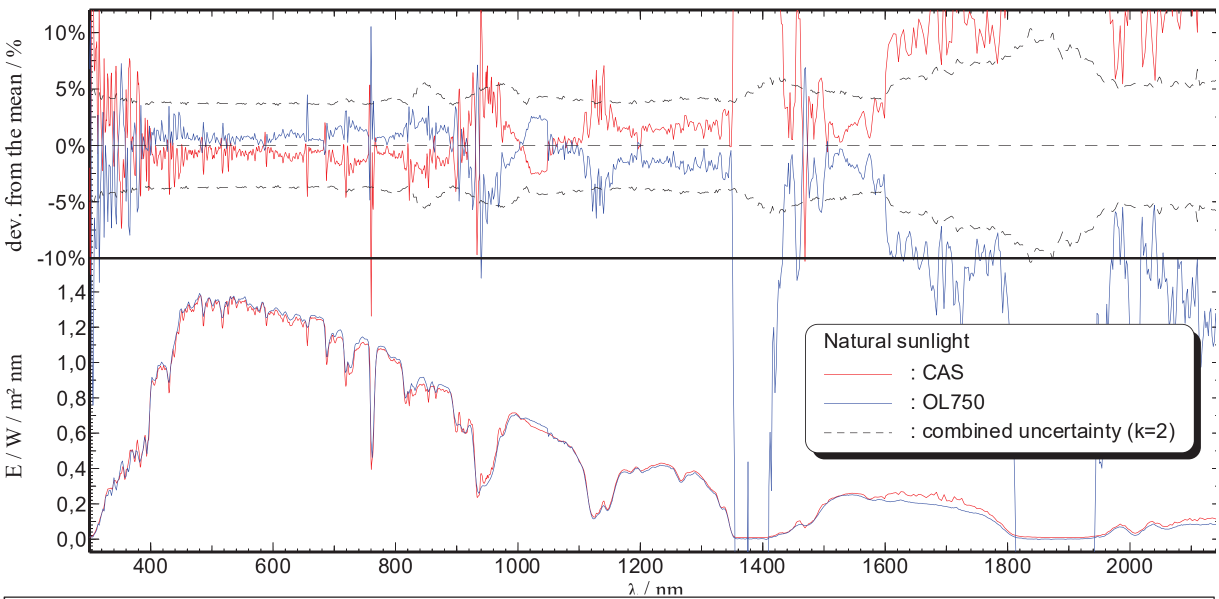
- Generally good agreement within combined uncertainties
- Significant deviation:
  - UV range λ < 400 nm → due to traceability (radiometric calibration)
  - IR range λ > 1600 nm → probably poor linearity correction of ExtInGaAs-CAS from PTB
  - In regions of sharp lines → related to different spectral resolution of both instruments

Results : WACOM



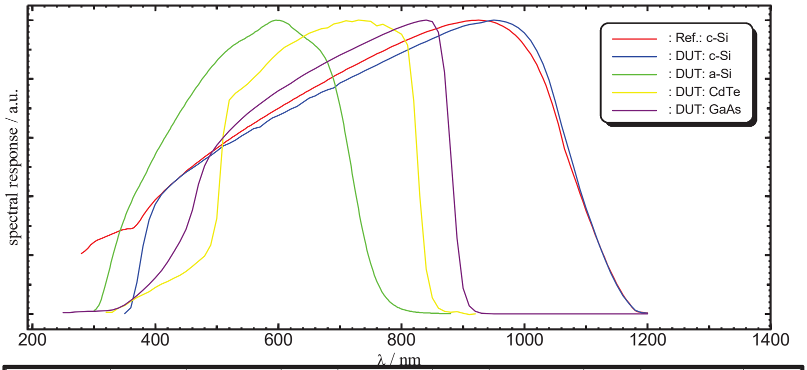
- Generally good agreement within combined uncertainties
- Significant deviation:
  - UV range λ < 400 nm → due to traceability (radiometric calibration)
  - IR range λ > 1600 nm → probably poor linearity correction of ExtInGaAs-CAS from PTB
  - In regions of sharp lines → related to different spectral resolution of both instruments

Results : Natural sunlight



- Generally good agreement within combined uncertainties
- Significant deviation:
  - UV range λ < 400 nm → due to traceability (radiometric calibration)
  - IR range λ > 1600 nm → probably poor linearity correction of ExtInGaAs-CAS from PTB
  - In regions of sharp lines → related to different spectral resolution of both instruments

Study: Impact on spectral mismatch



		Ref.: c-Si DUT: c-Si	Δ/%	Ref.: c-Si DUT: a-Si	Δ/%	Ref.: c-Si DUT: CdTe	Δ/%	Ref.: c-Si DUT: GaAs	Δ/%
Natural sunlight	Ol750 (ESTI)	1.0036	-0.03 %	0.9712	-0.24 %	0.9994	-0.56 %	0.9992	-0.71 %
	CAS (PTB)	1.0033		0.9688		0.9938		0.9921	
Apollo	Ol750 (ESTI)	1.0092	-0.07 %	1.0184	2.39 %	1.0174	1.23 %	1.0004	0.78 %
	CAS (PTB)	1.0085		1.0423		1.0297		1.0082	
Wacom	Ol750 (ESTI)	1.0126	-0.05 %	1.0001	0.49 %	0.9972	-0.05 %	0.9733	0.20 %
	CAS (PTB)	1.0121		1.0050		0.9967		0.9753	

Calculated exemplary spectral mismatch correction factors (MMF)

- Reference: c-Si
- DUT: c-Si, a-Si, CdTe, GaAs
- Spectral irradiance using the spectra from CAS and OL750

Low deviation for:

- Ref. = c-Si and DUT = c-Si with all light sources
- Wacom solar simulator with all devices
- Natural sunlight with all devices

Significant deviation for:

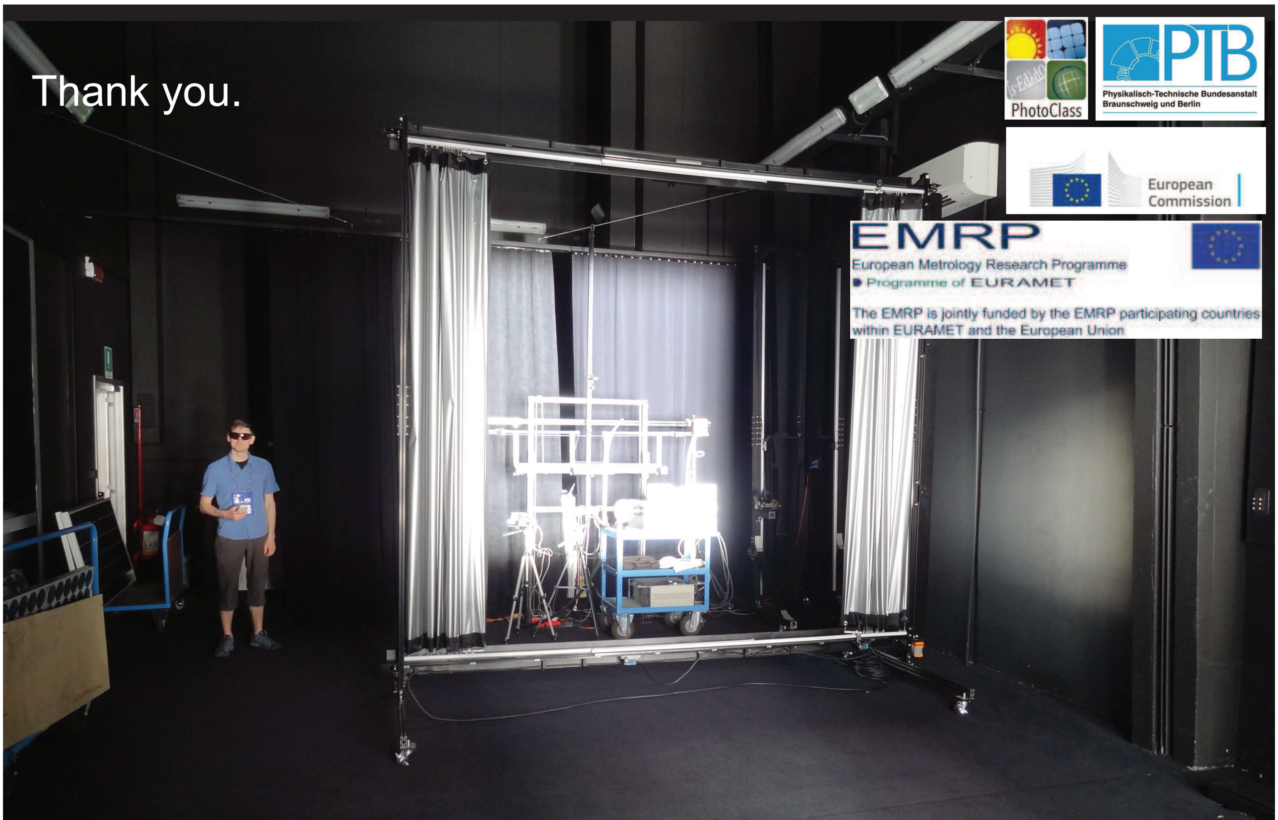
- Apollo solar simulator for large differences in SR between Ref and DUT

Conclusion

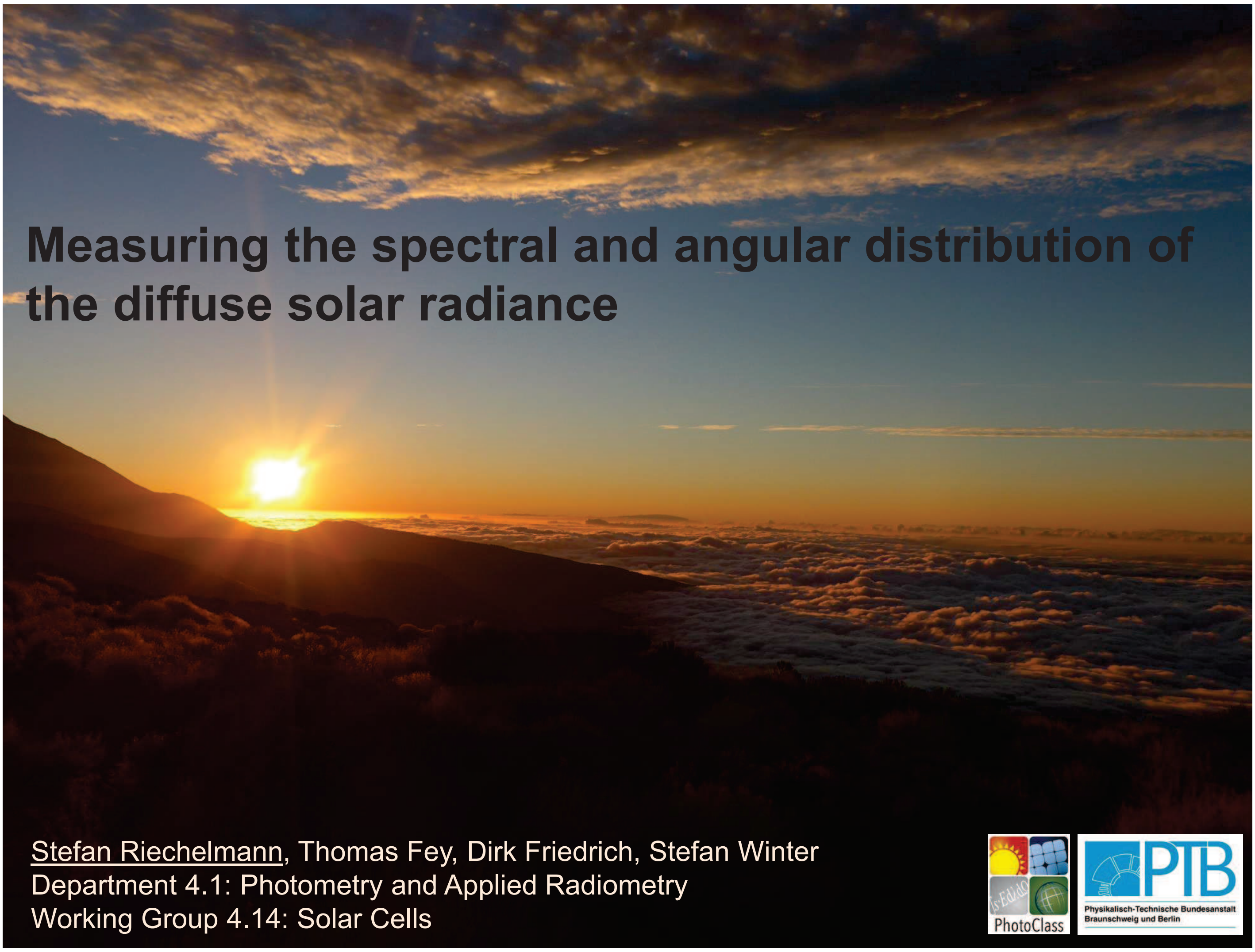
- Intercomparison shows good agreement of measured spectra on an absolute scale within the combined uncertainties
- Significant deviation was found in the UV-region < 400 nm. The origin was identified in the traceability, i.e. the different standard lamps that were used for radiometric calibration.
- Significant deviation occurs at narrow spectral features. That is related to the different spectral resolution of the instruments.
- The differences in spectral irradiance measurements (although mostly within combined uncertainty) can lead to large differences in spectral mismatch factors, especially if spectral mismatch is large.

- Valuable experience for assessment of uncertainty budgets of solar simulator/natural sunlight based calibration
- Next step: Development of Monte-Carlo based uncertainty propagation tool for spectral mismatch factor calculation in Photoclass II project

Thank you.



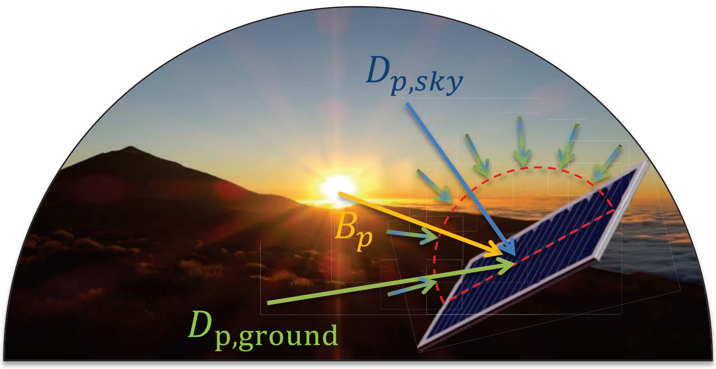
Publication:
Intercomparison of PTB and ESTI Spectroradiometers Using Simulated and Natural Sunlight
Kroeger, I., Galleano, R., Plag, F., Muellejans, H. and Winter, S.
Proceedings of the 32nd European PV Solar Energy Conference and Exhibition (32nd EU PVSEC) (2016) , 2230 - 2233



Measuring the spectral and angular distribution of the diffuse solar radiance

Stefan Riechelmann, Thomas Fey, Dirk Friedrich, Stefan Winter
Department 4.1: Photometry and Applied Radiometry
Working Group 4.14: Solar Cells

Why do we need the angular distribution?



61853-3 (Draft):

Angle of incidence correction of diffuse irradiance is proposed after (Martin and Ruiz 2001):

$$B_{corr} = B_p \left[\frac{1-\exp(-\frac{\cos(\theta)}{a_r})}{1-\exp(-\frac{1}{a_r})}\right]$$

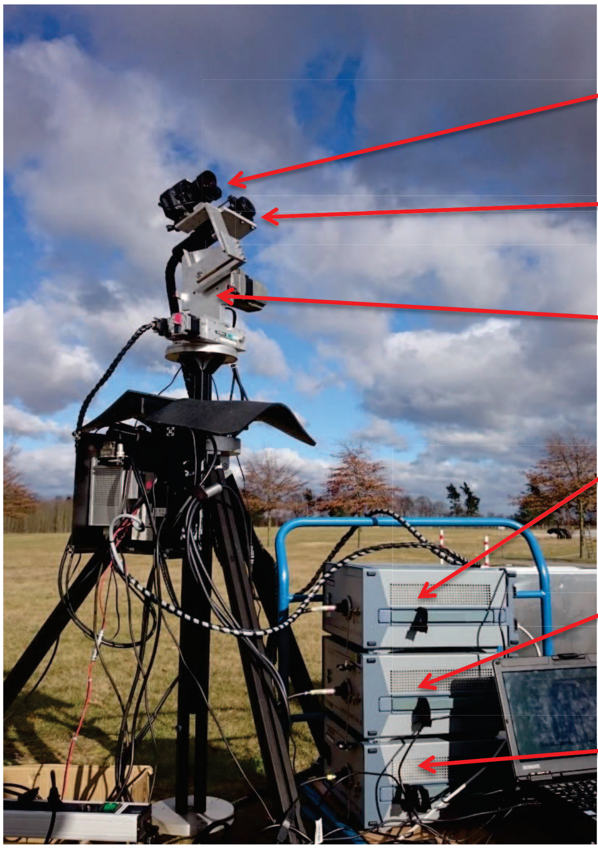
$$D_{corr} = D_p \left\{1 - exp\left[-\frac{1}{a_r}\left(\frac{4}{3\pi}\left(\sin\beta + \frac{\pi-\beta-\sin\beta}{1+\cos\beta}\right) + (0,5a_r - 0,154)\left(\sin\beta + \frac{\pi-\beta-\sin\beta}{1+\cos\beta}\right)^2\right)\right]\right\}$$

- ➢ Assumption of an isotropic distribution of diffuse irradiance

$$D_{p,corr} = \int_\lambda \int_\Omega s(\Omega,\lambda) \cdot \left(D_{p,sky}(\Omega,\lambda) + D_{p,ground}(\Omega,\lambda)\right) d\Omega\, d\lambda$$

➢ If we measure the spectral and angular distribution of a real radiance field, we can evaluate the uncertainty arising from assumptions made in the energy rating.

Measurement equipment - spectrometer



Digital Camera
Field of View: 120°
For quality control and documentation purposes

Entrance Optics
Field of View: 5° FWHM
Stray light reduced design

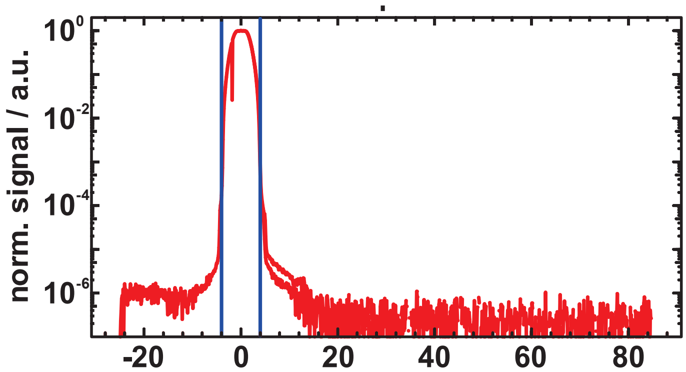
Dual Axis Tracking Unit
Range zenith: -42.5° - 105°
Range azimuth: -10° - 370°

UV+VIS Spektrometer (CAS 140CT – 154)
Wavelength range: 220 - 1020 nm
Bandwidth : 3,7 nm
Sampling interval : 0,8 nm

Infrared Spektrometer (CAS 140CT – 171)
Wavelength range: 780 - 1650 nm
Bandwidth: 9 nm
Sampling interval: 3 nm

Extended IR Spectrometer (CAS 140CT – 175)
Wavelength range: 1500 - 2150 nm
Bandwidth: 15 nm
Sampling interval: 4 nm

Measurement equipment – entrance optics



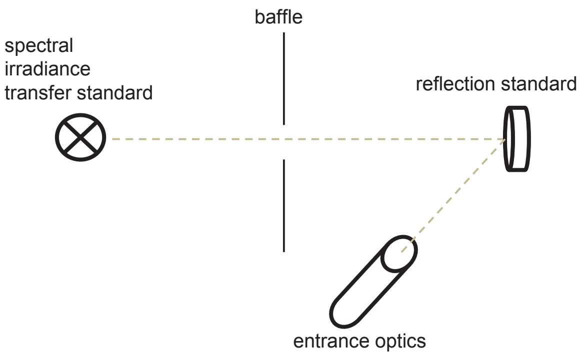
Radiance entrance optics:

Field of View of 5° FWHM

Reduced stray light effects by using black foil for the interior and soot for the baffles.

Stray light at incidence angles > 10° is lower than 10^{-6}.

Measurement equipment – radiance calibration



Radiance emitted by reflection standard:

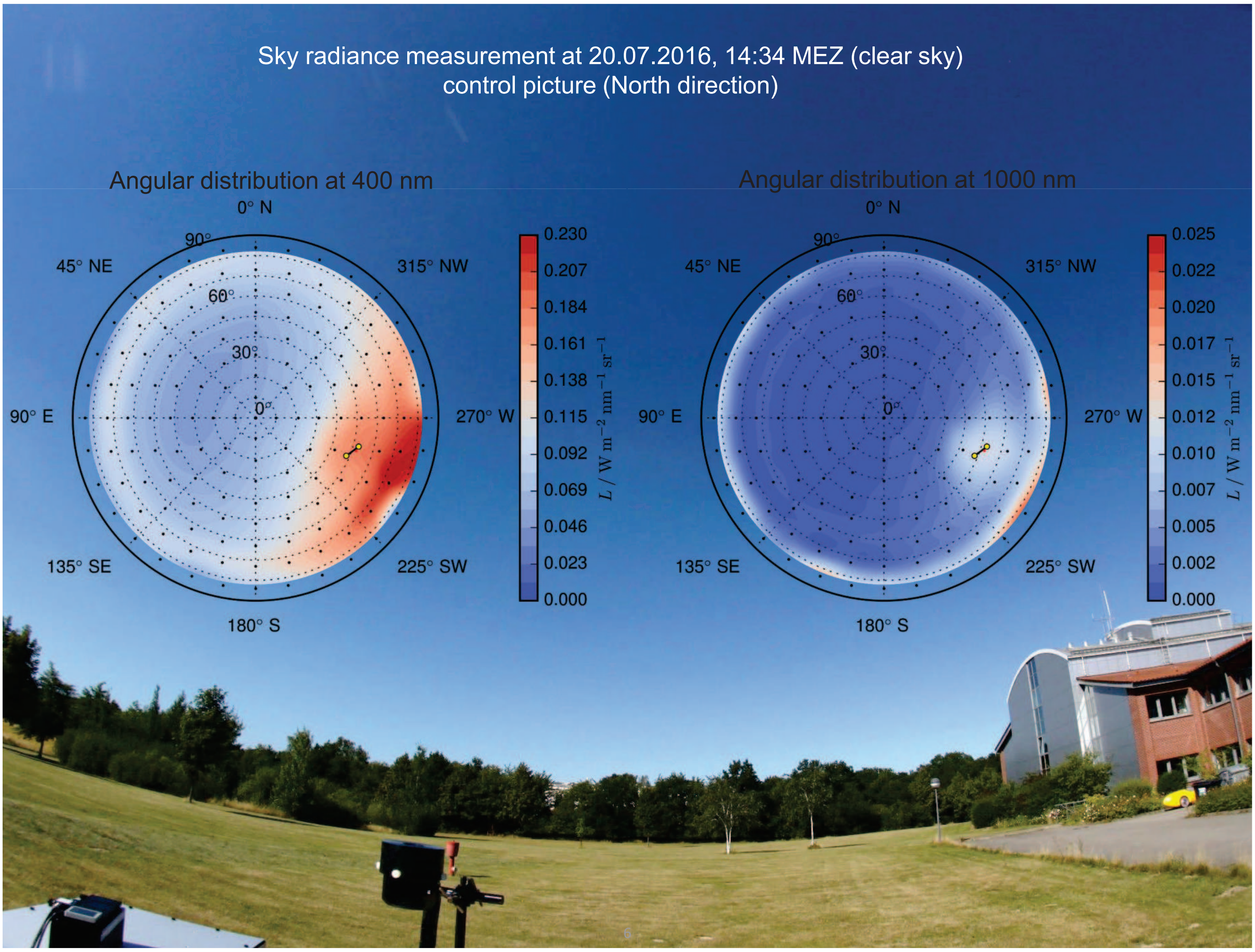
$$L_{\text{lamp},\lambda} = \frac{R(0°, 45°, \lambda)}{\pi} \cdot \mathrm{E}_{\text{lamp},\lambda}$$

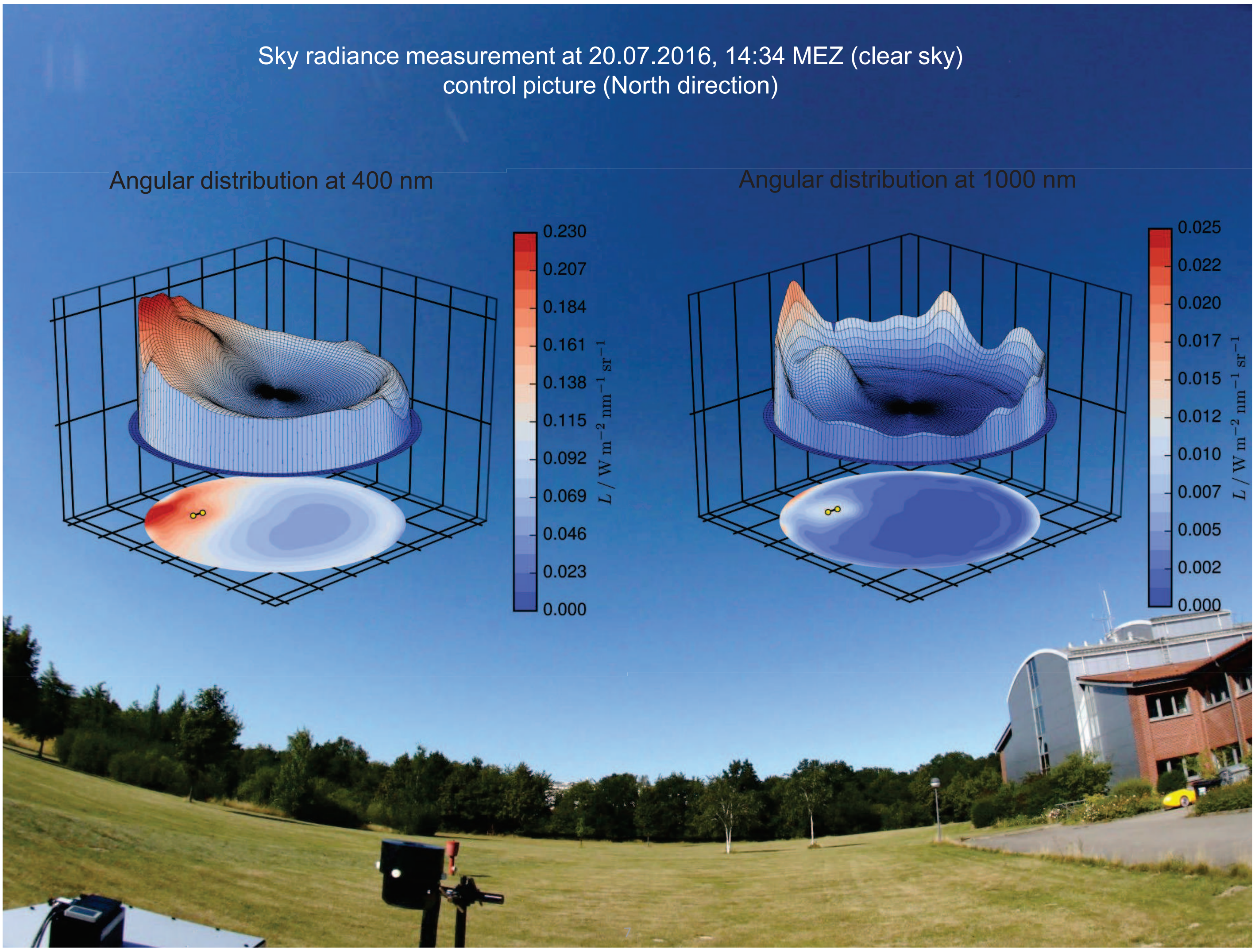
Responsivity of the instrument:

$$\mathrm{r}(\lambda) = \frac{X_{\text{lab}}(\lambda)}{L_{\text{lamp},\lambda}} \left[\frac{counts}{\mathrm{W\,m^{-2}nm^{-1}sr^{-1}}}\right]$$

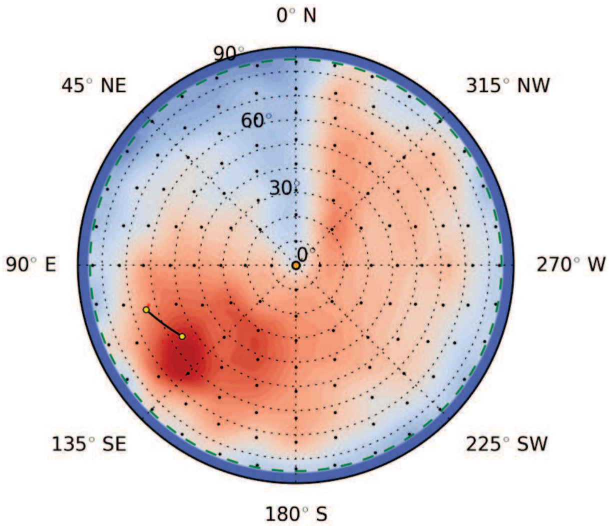
Calibrated outdoor measurement:

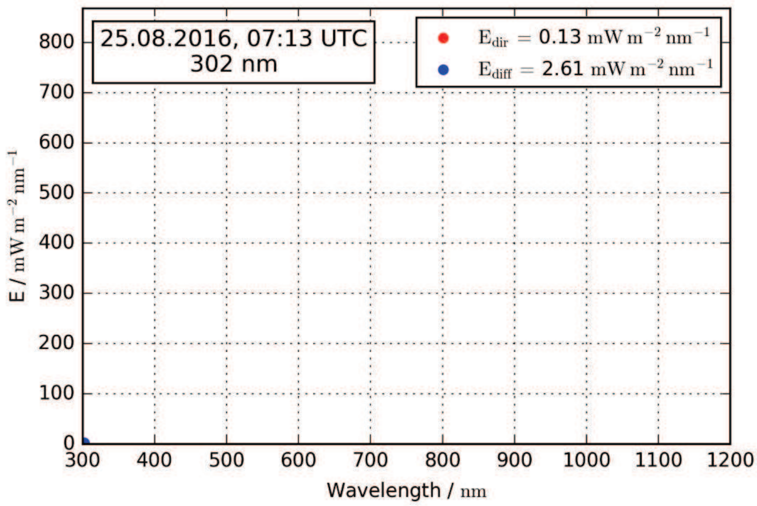
$$\mathrm{L}_{\text{sky},\lambda} = \frac{X_{\text{sky}}(\lambda)}{r(\lambda)} \; [\mathrm{W\,m^{-2}nm^{-1}sr^{-1}}]$$





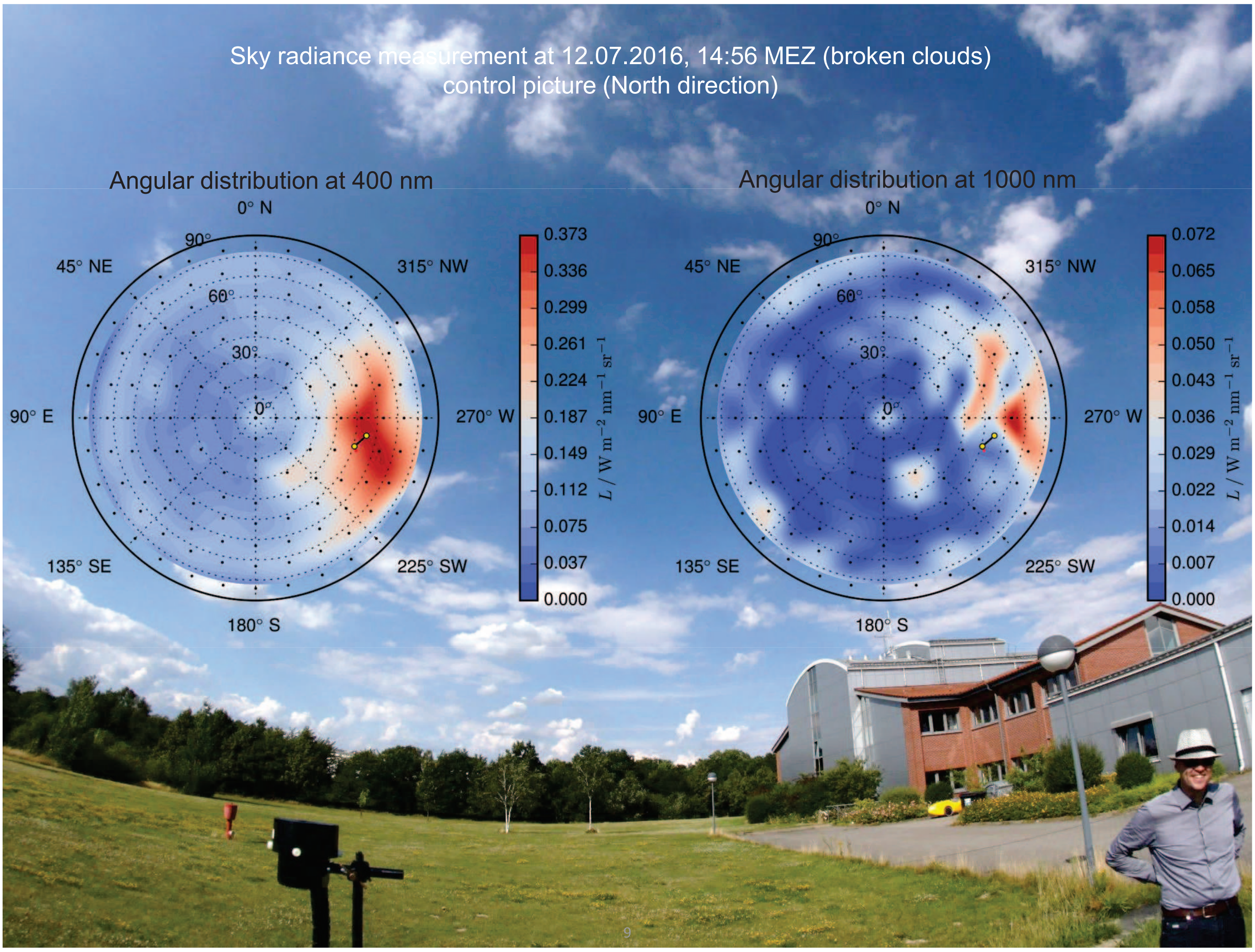
Wavelength dependence of sky radiance

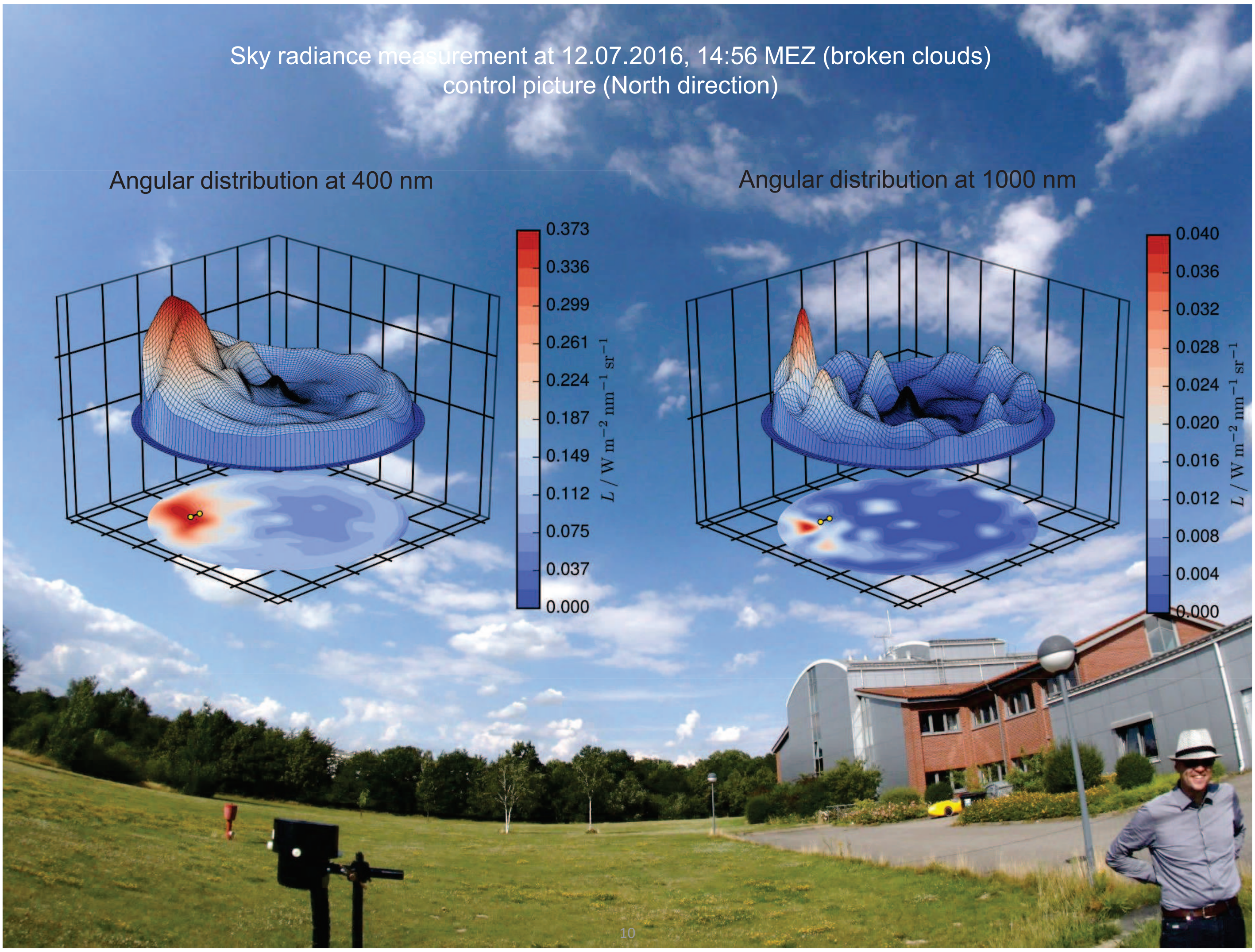




Angular distribution of radiance:
- Black points: 145 measurements
- Yellow points: solar position during scan
- Green line: horizon at 85° zenith angle
- Ground albedo has been calculated based on horizontal global irradiance

Spectral Irradiance:
- Direct irradiance measured at the beginning of the scan
- Diffuse irradiance calculated by integral of the hemisphere


Sky radiance measurement at 12.07.2016, 14:56 MEZ (broken clouds)
control picture (North direction)
Angular distribution at 400 nm
Angular distribution at 1000 nm
0° N
90°
60°
30°
0°
45° NE
315° NW
90° E
270° W
135° SE
225° SW
180° S
0.373
0.336
0.299
0.261
0.224
0.187
0.149
0.112
0.075
0.037
0.000
0.072
0.065
0.058
0.050
0.043
0.036
0.029
0.022
0.014
0.007
0.000
L / W m^{-2} nm^{-1} sr^{-1}
9


Sky radiance measurement at 12.07.2016, 14:56 MEZ (broken clouds)
control picture (North direction)
Angular distribution at 400 nm
Angular distribution at 1000 nm
0.373
0.336
0.299
0.261
0.224
0.187
0.149
0.112
0.075
0.037
0.000
0.040
0.036
0.032
0.028
0.024
0.020
0.016
0.012
0.008
0.004
0.000
L / W m^{-2} nm^{-1} sr^{-1}
10

Follow-up tasks

- **Comparison to integrating measurement instruments (i.e. solar cells, pyranometer)**
- **Weatherproof housing for measurement equipment**
- **Longer time series of measurements**
  Especially necessary for performance evaluation under cloudy conditions
- **Comparison to isotropic / anisotropic models**

Acknowledgements

This work was supported by the European Metrology Research Programme (EMRP) Project ENG55 PhotoClass, which is jointly funded by the EMRP participating countries within EURAMET and the European Union.