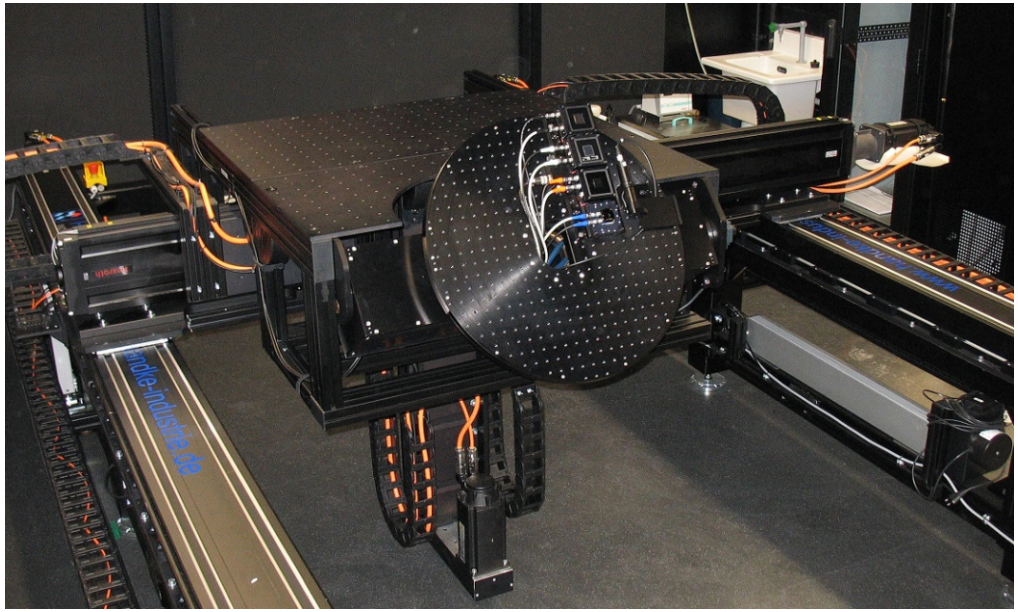
Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

PhotoClass

Sensitivity analysis for energy rating: Linearity, T-coefficient and AOI dependence of a reference solar cell



EMRP
European Metrology Research Programme
Programme of EURAMET

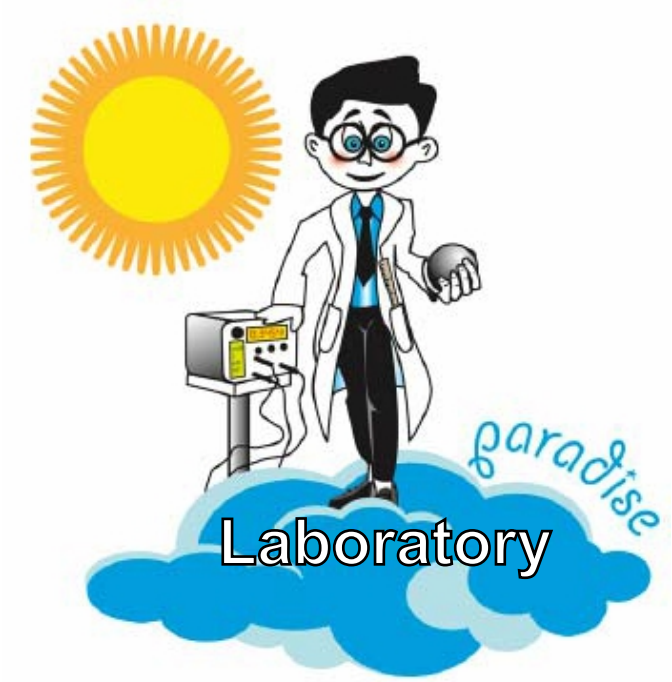
The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

Thomas Fey

30.03.2017

Motivation

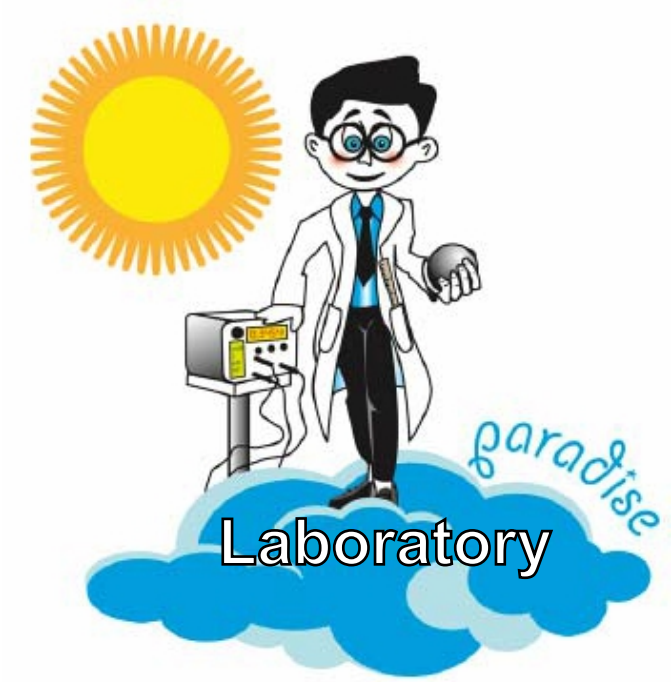
Bruce W Forgan,
WMO RAV Metrology Workshop
Melbourne, November 2011
Australian Goverment
Bureau of Meteorology



Standard Test Conditions (STC):

- **Solar cell temperature, T = 25 °C**
- **Irradiance, E = 1000 W m^{-2}**
- **Reference solar spectrum AM 1.5 (IEC 60904-3)**

Motivation



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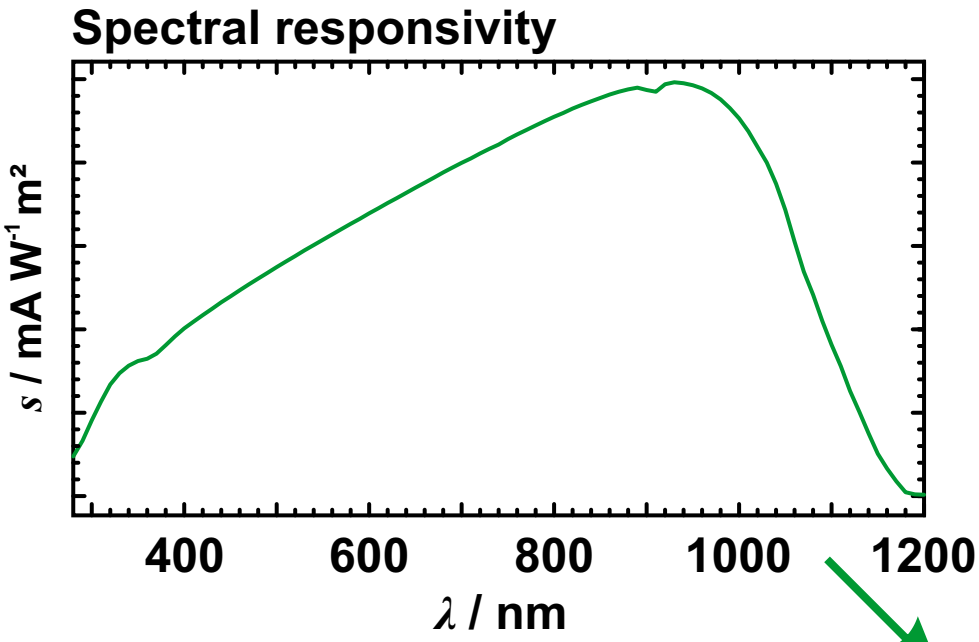
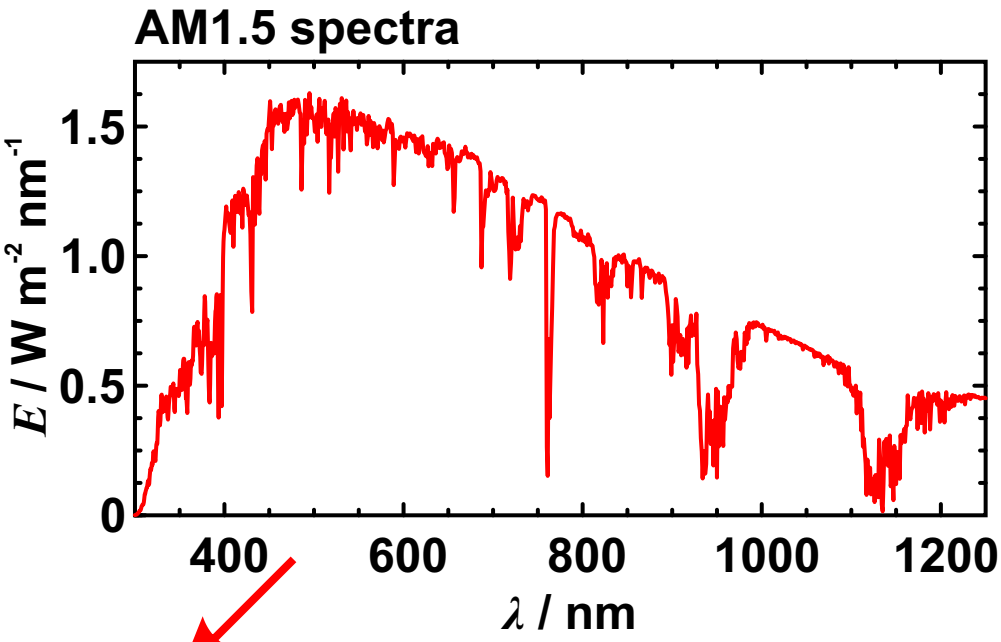
Standard Test Conditions (STC):
- Solar cell temperature, T = 25 °C
- Irradiance, E = 1000 W m^{-2}
- Reference solar spectrum AM 1.5 (IEC 60904-3)

Reality:
- Temperatures up to 75 °C
- Irradiance less than 1000 W m^{-2}
- AMx, direct + diffuse

IEC 61853

State of the Art

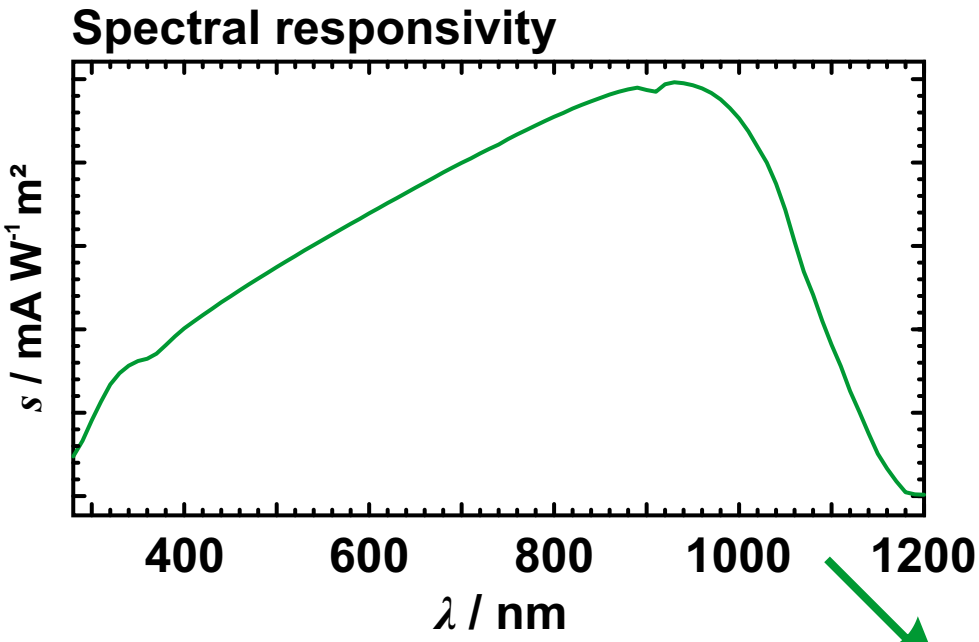


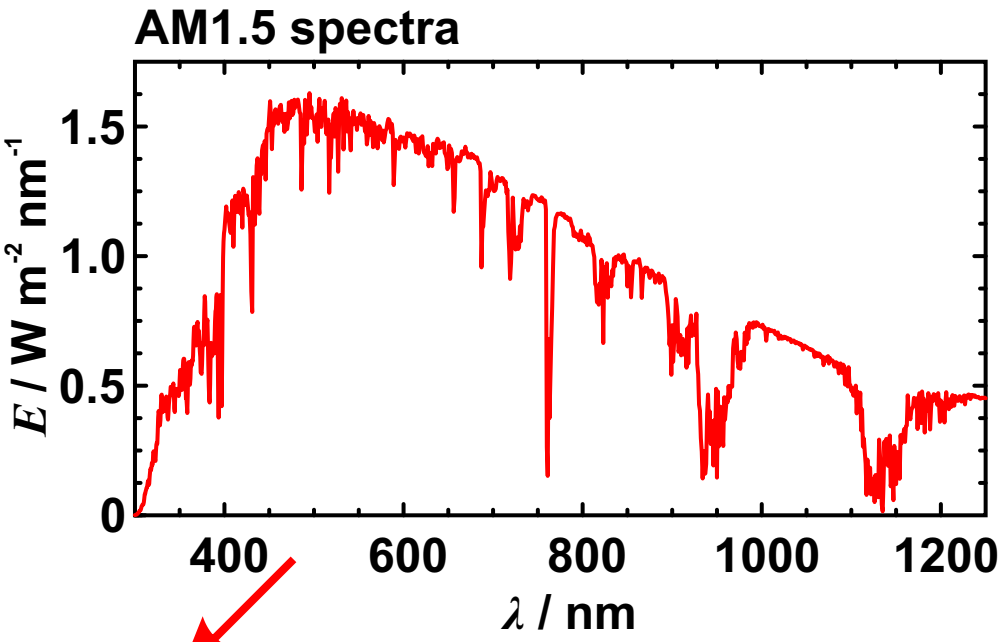


$$I = \int s(\lambda) \cdot E(\lambda) \mathrm{d}\lambda$$

➡ **Spectral and integral measurement methods**

Further parameters





$$I = \int s(\lambda) \cdot E(\lambda) \mathrm{d}\lambda$$

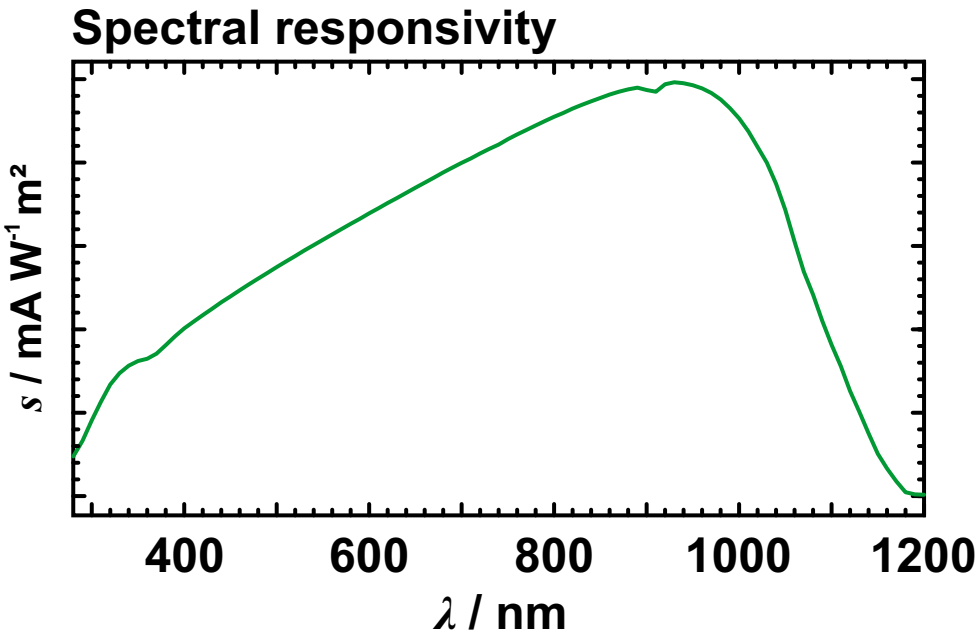
Spectral responsivity(λ):

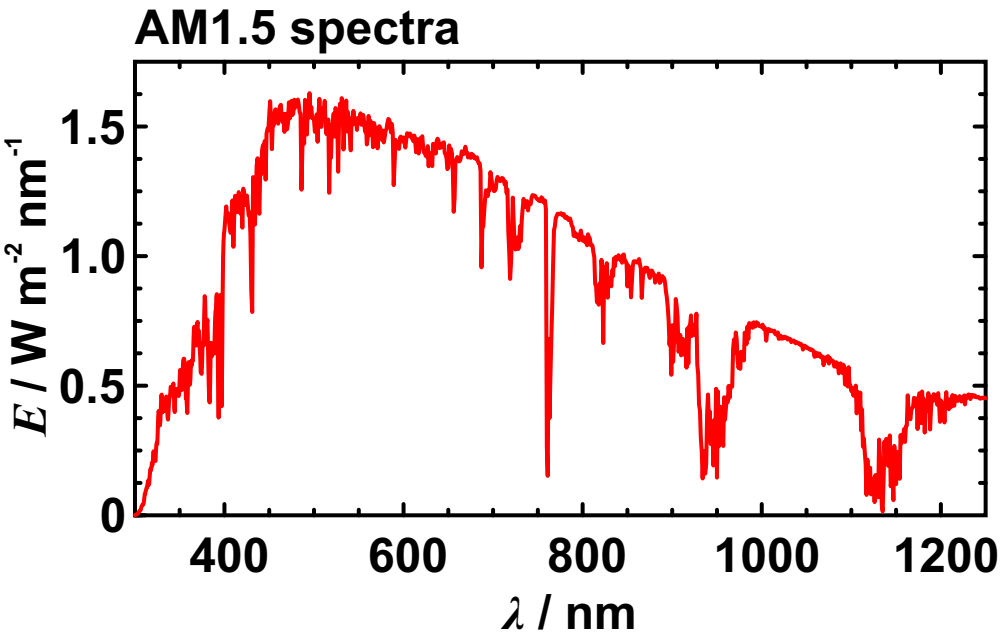
1. Linearity
2. Temperature
3. AOI dependence

Irradiance/Radiance (λ):

1. AMx
2. Direct, diffuse and albedo

New approach





$$\rightarrow \quad I_{SC} = \int_{\lambda} \int_{\Omega} s(\lambda, E, T, \Omega) \cdot (L_{\lambda,\,\mathrm{direct}}(\Omega,\lambda) + L_{\lambda,\,\mathrm{diffuse}}(\Omega,\lambda) + L_{\lambda,\,\mathrm{albedo}}(\Omega,\lambda))\, \mathrm{d}\Omega\, \mathrm{d}\lambda$$

Spectral responsivity(λ):

1. Linearity
2. Temperature
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Irradiance/Radiance (λ):

1. AMx
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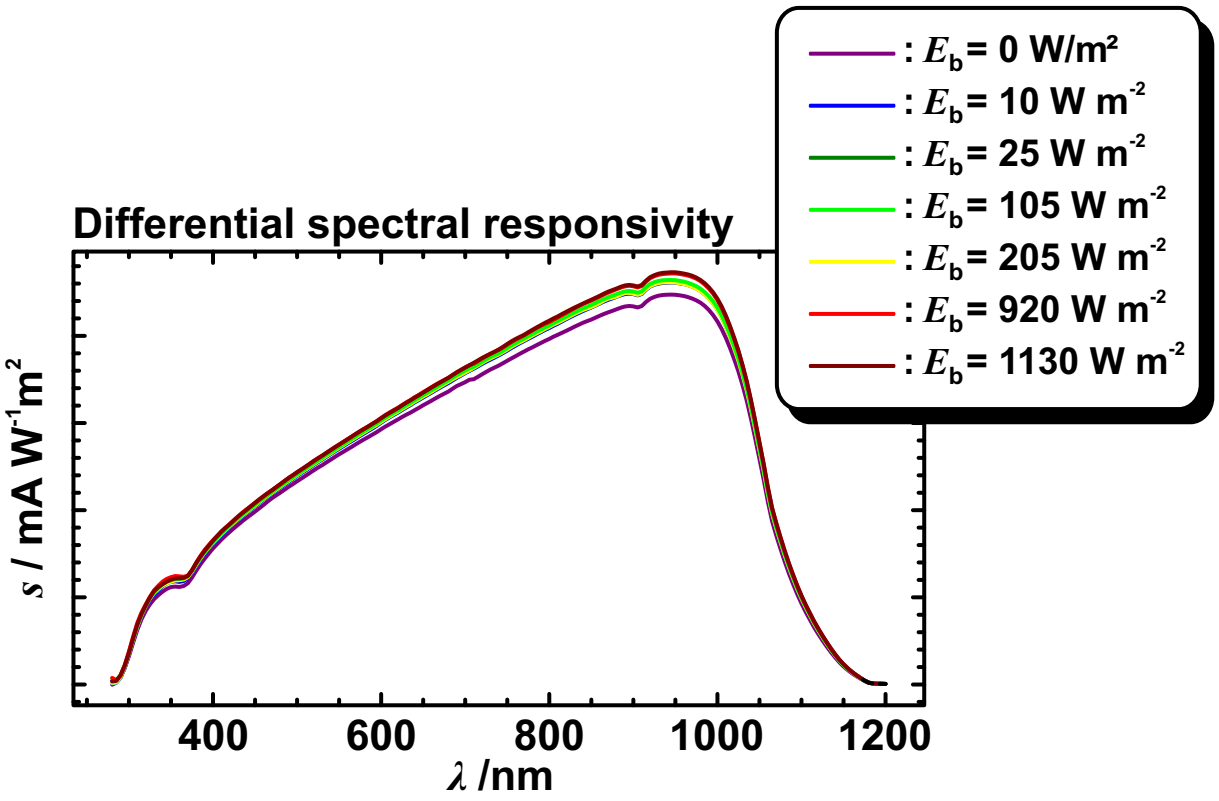
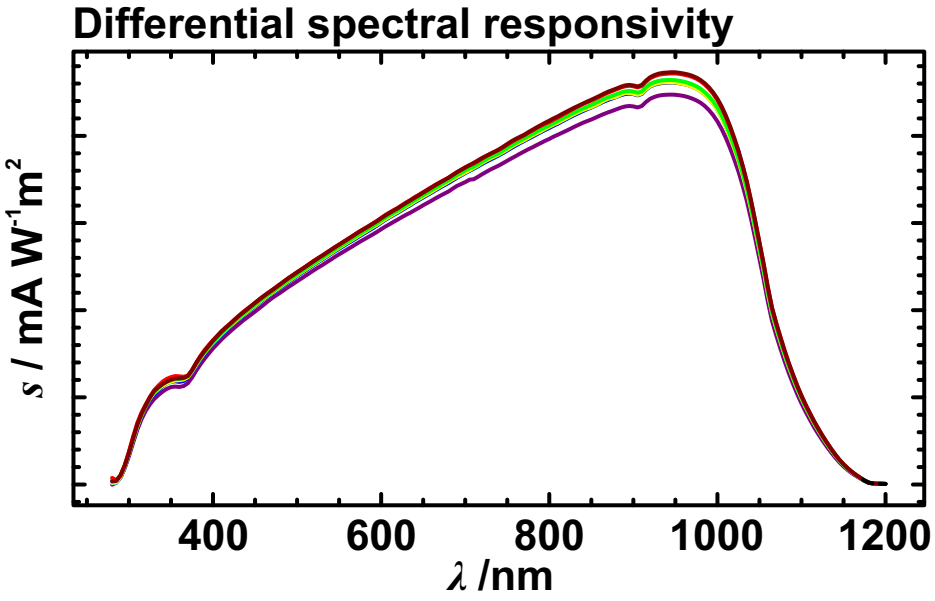
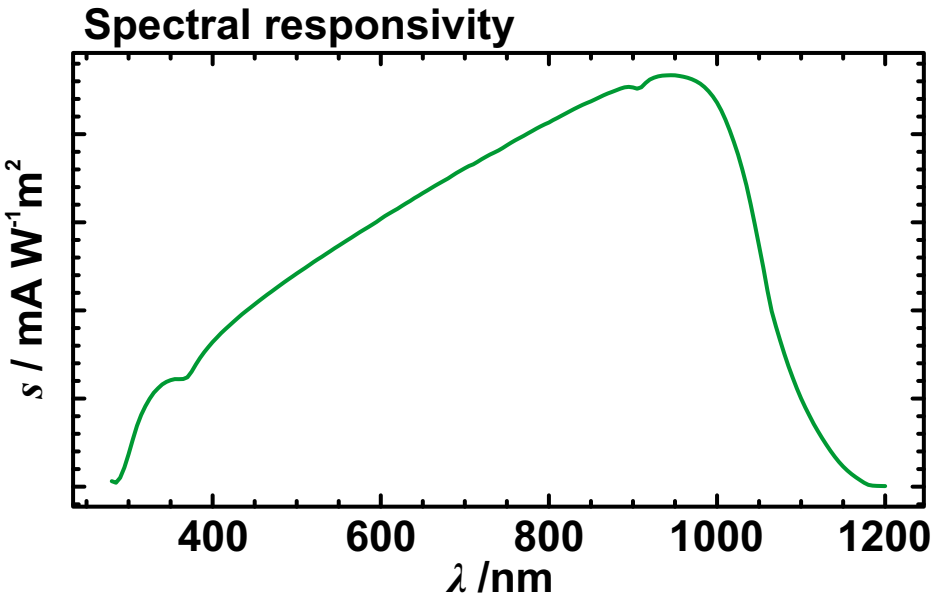
DSR-method

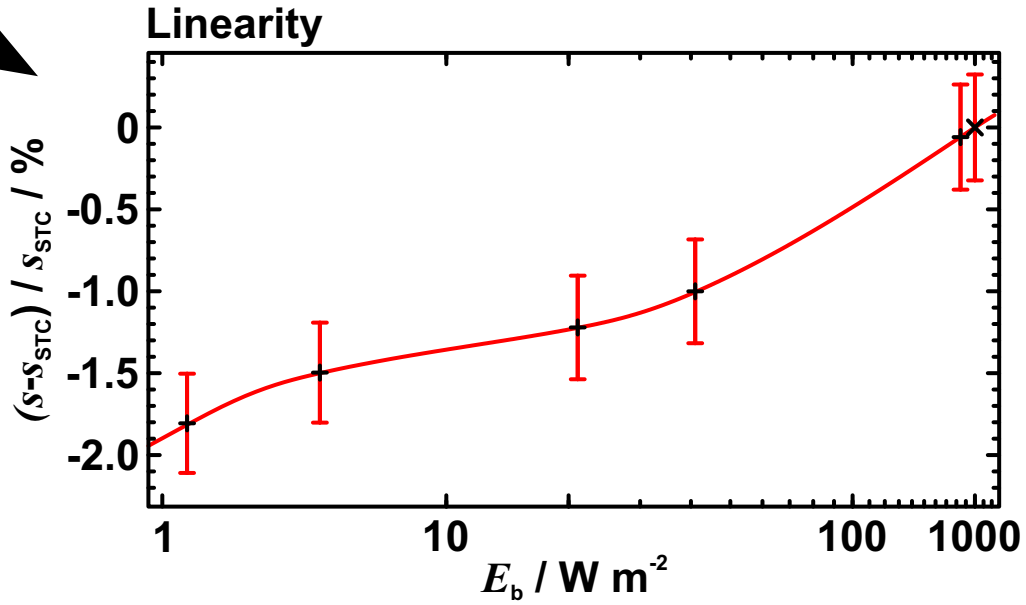


Metzdorf, J.: Calibration of solar cells.
The differential spectral responsivity method.
Applied Optics, 26:1701–8, 1987.

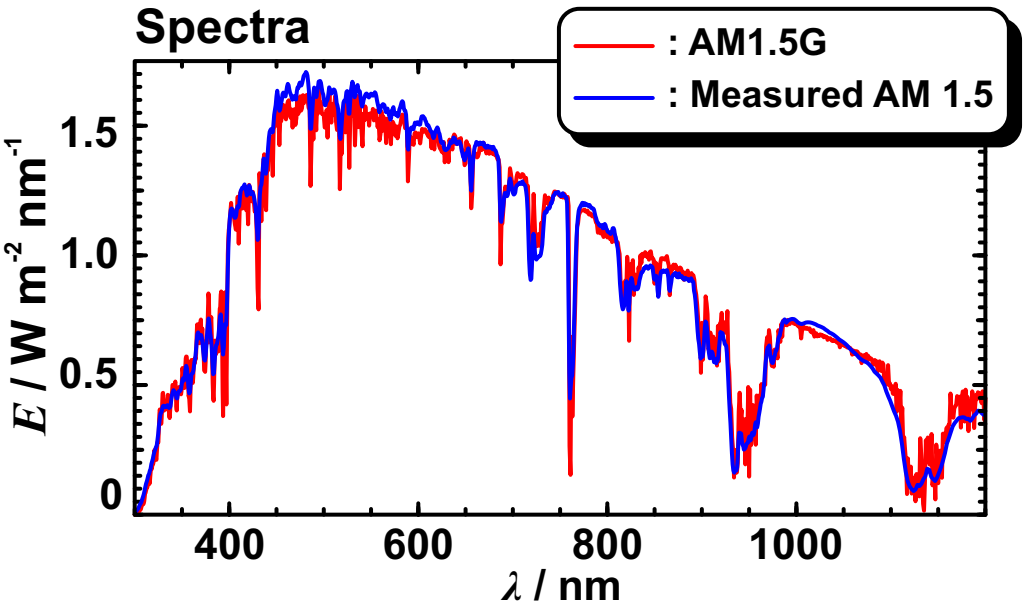
Spectral responsivity and Linearity

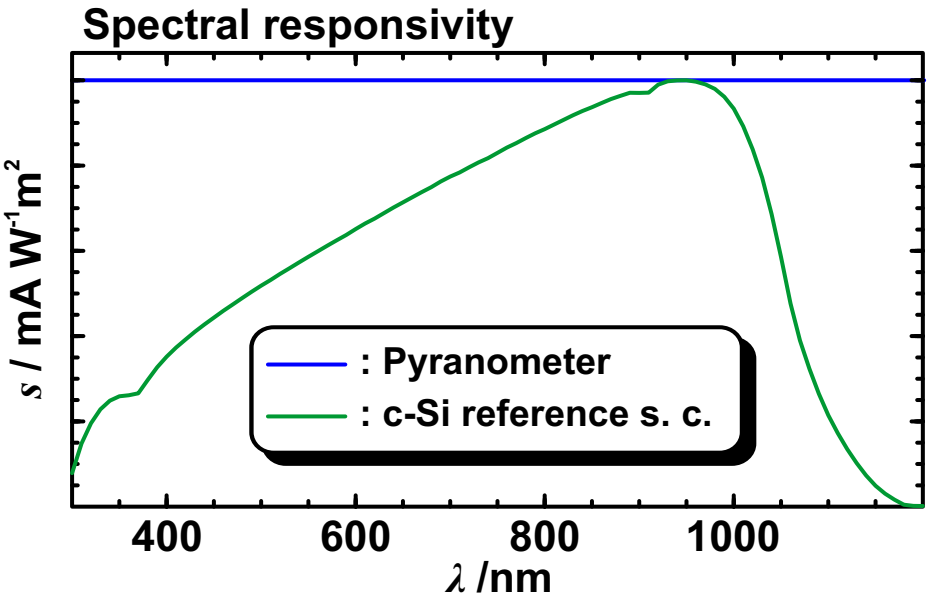






Spectral mismatch correction





$$I_{STC}^{DUT} = \frac{1}{M} \cdot \frac{I_{STC}^{REF}}{I_{meas.}^{REF}} \cdot I_{meas.}^{DUT}$$

REF - Reference solar cell
DUT - Device under test
STC - Standard test conditions

$$M = \frac{\int E_{meas.}(\lambda) \cdot s^{DUT}(\lambda) d\lambda}{\int E_{AM1.5}(\lambda) \cdot s^{DUT}(\lambda) d\lambda} \cdot \frac{\int E_{AM1.5}(\lambda) \cdot s^{REF}(\lambda) d\lambda}{\int E_{meas.}(\lambda) \cdot s^{REF}(\lambda) d\lambda}$$

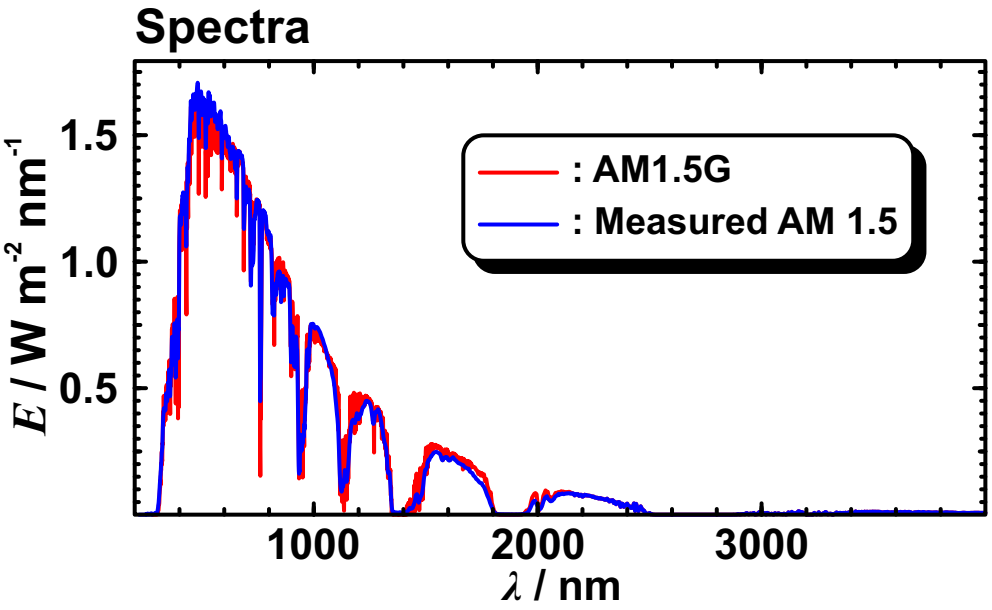
with “bandpass filters“
300 nm < λ < 1200 nm

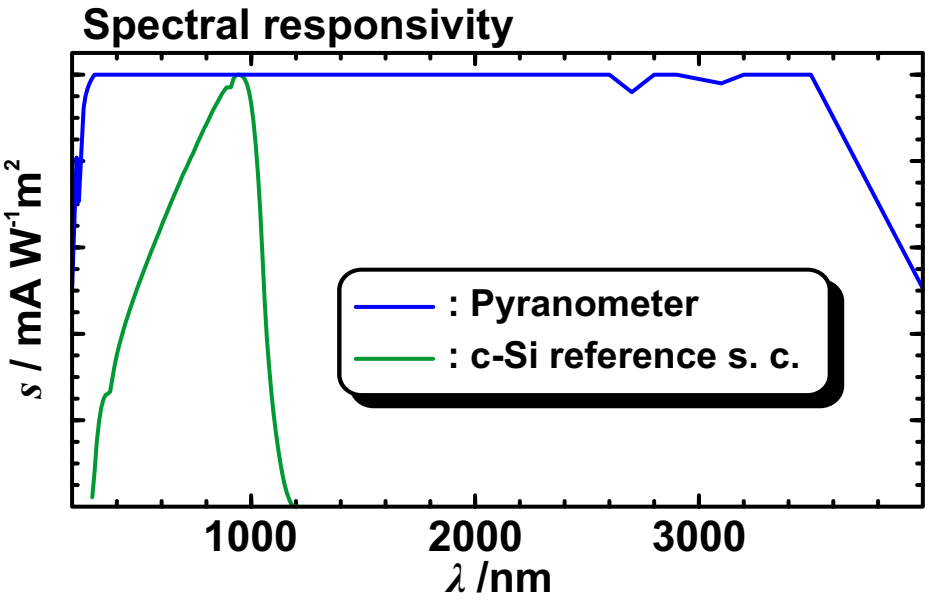
= 1.00006 ≙ 0.006 %

WRONG!

IEC 60904-7

Spectral mismatch correction





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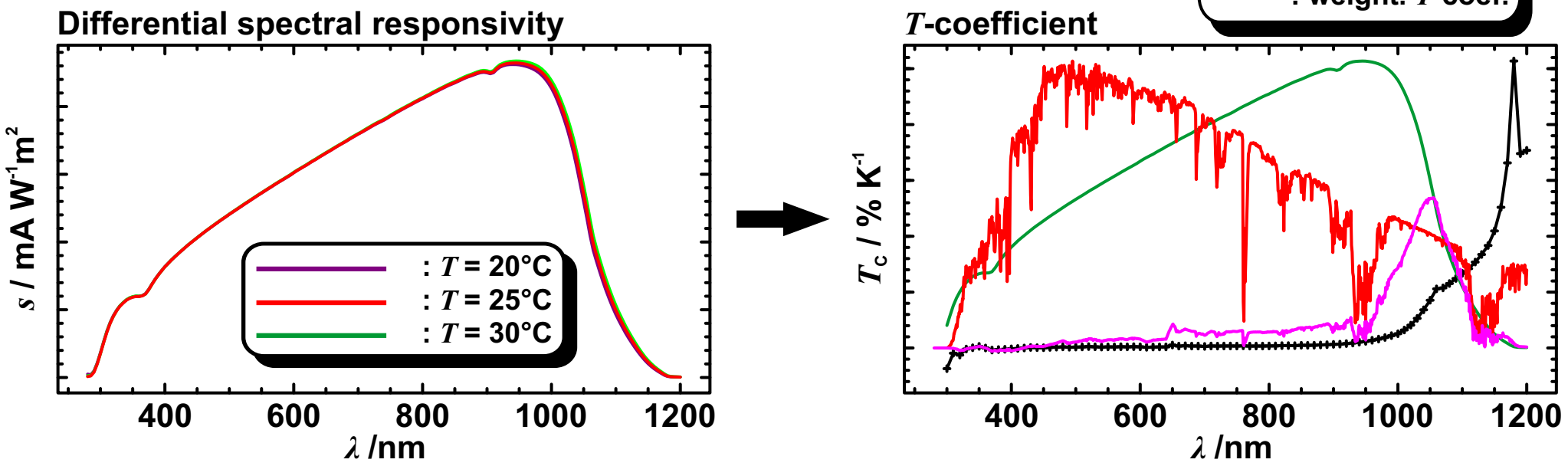
full spectral range

$= 0.986 \quad \triangleq 1.4\ \%$

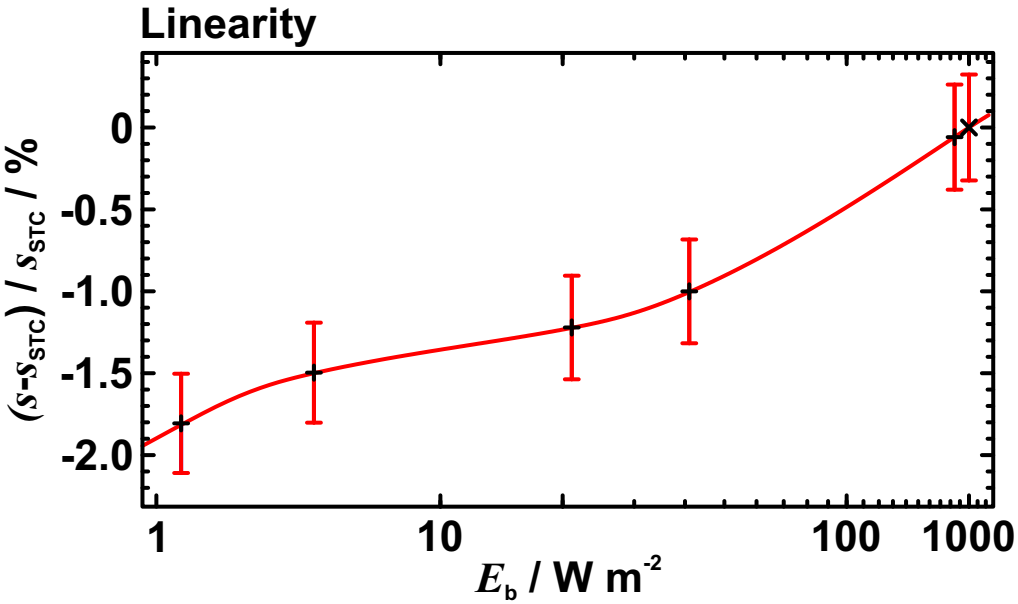
IEC 60904-7

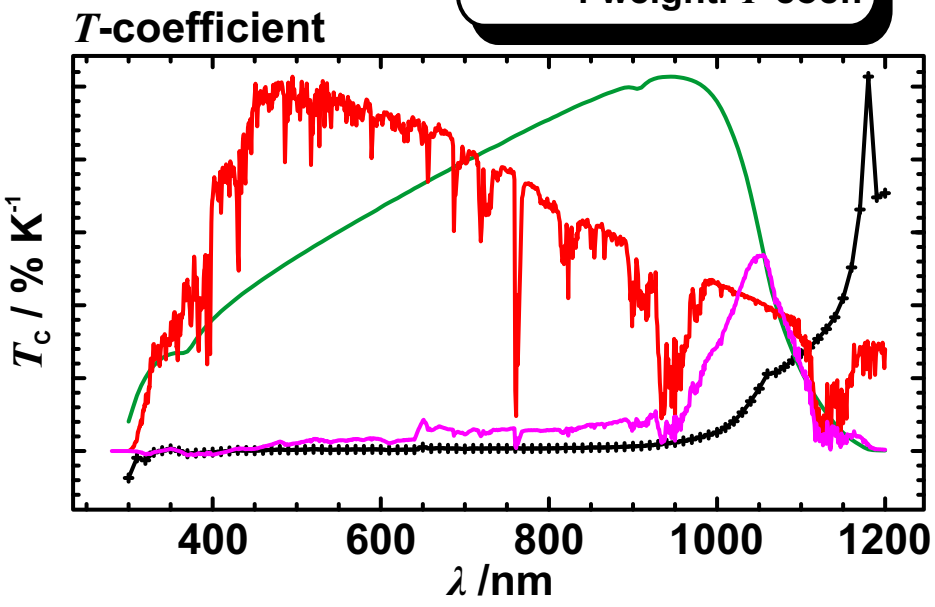
T-coefficient



AM1.5 weigthed T-coefficient : 900 ± 100 ppm/K

Linearity + T-coefficient



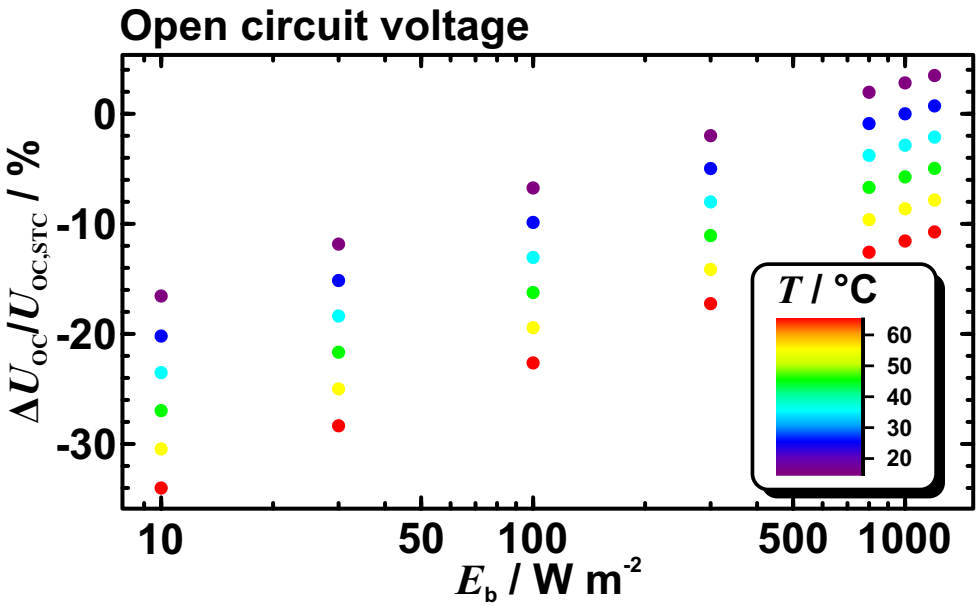


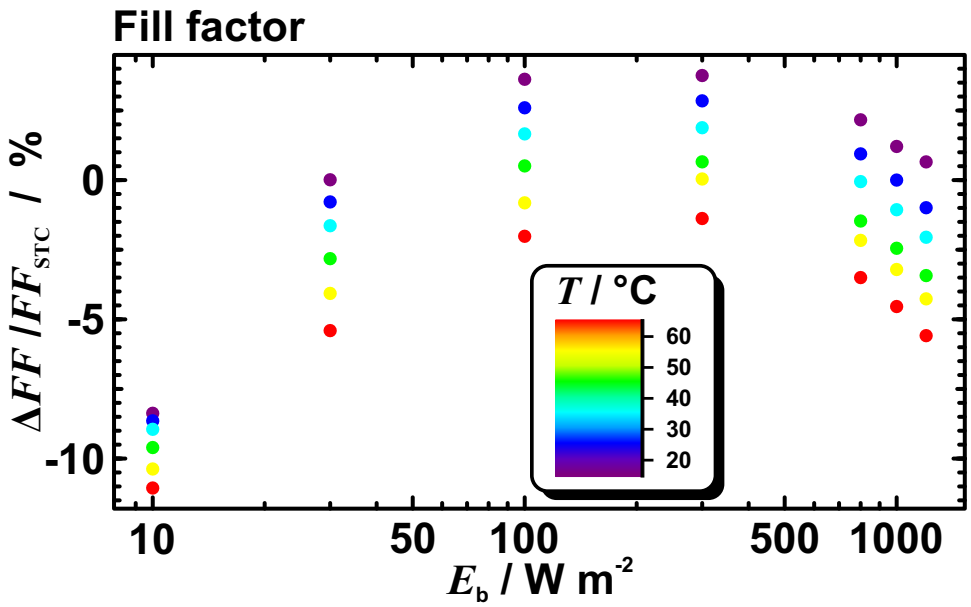
Relative change of short circuit current, ΔI_{sc} / %

Irradiance W m^{-2}	Temperature 15 °C	25 °C	50 °C	75 °C
1100	(-0.8)	0.1	2.3	4.6
1000	-0.9	0	2.2	4.5
800	-1.1	-0.2	2.0	4.3
600	-1.3	-0.4	1.8	4.1
400	-1.5	-0.6	1.6	(3.9)
200	-1.9	-1.0	(1.2)	(3.5)
100	-2.1	-1.2	(1.0)	(3.3)

IEC 61853-1

Efficiency



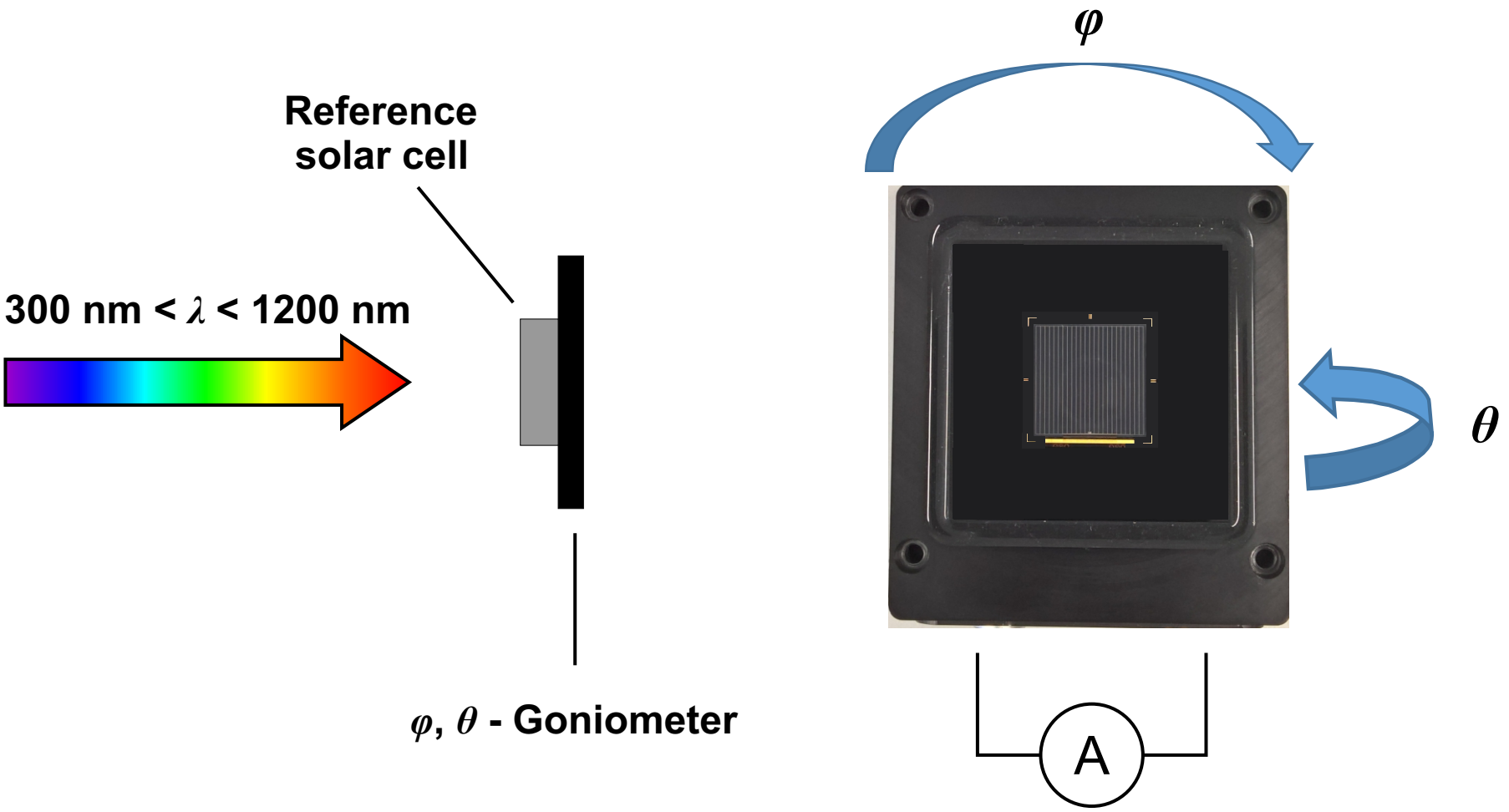


Relative change of efficiency, $\Delta\eta$ / %

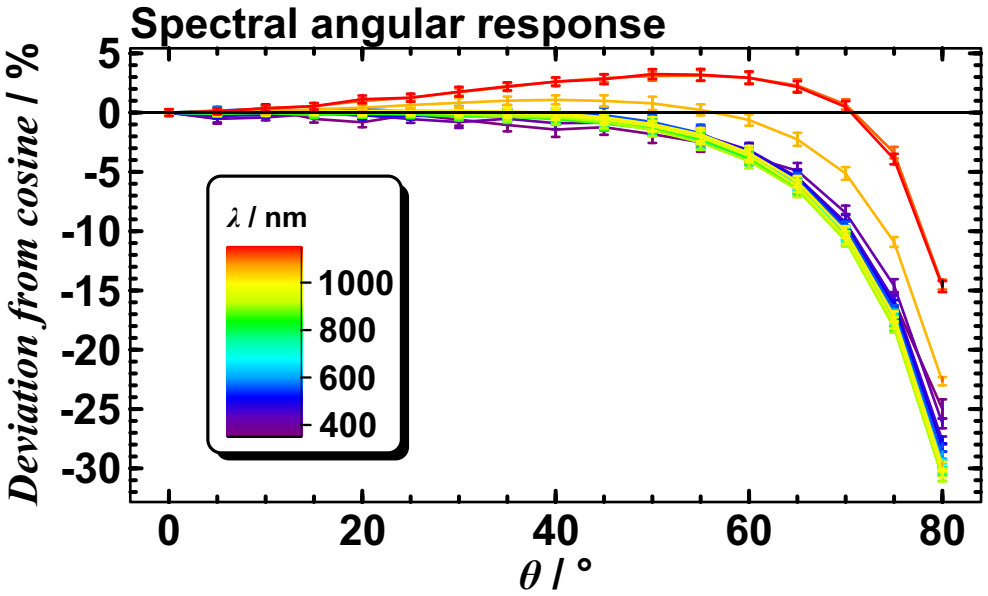
Irradiance	Temperature			
W m^{-2}	15 °C	25 °C	50 °C	75 °C
1100	(2.8)	0	-8	-16
1000	3	0	-8	-16
800	3	0	-8	-16
600	2	-1	-9	-18.5
400	0.6	-2.5	-10.5	(-19.5)
200	-2.7	-5.5	(-14)	(-22.5)
100	-5.5	-8.5	(-17)	(-25.5)

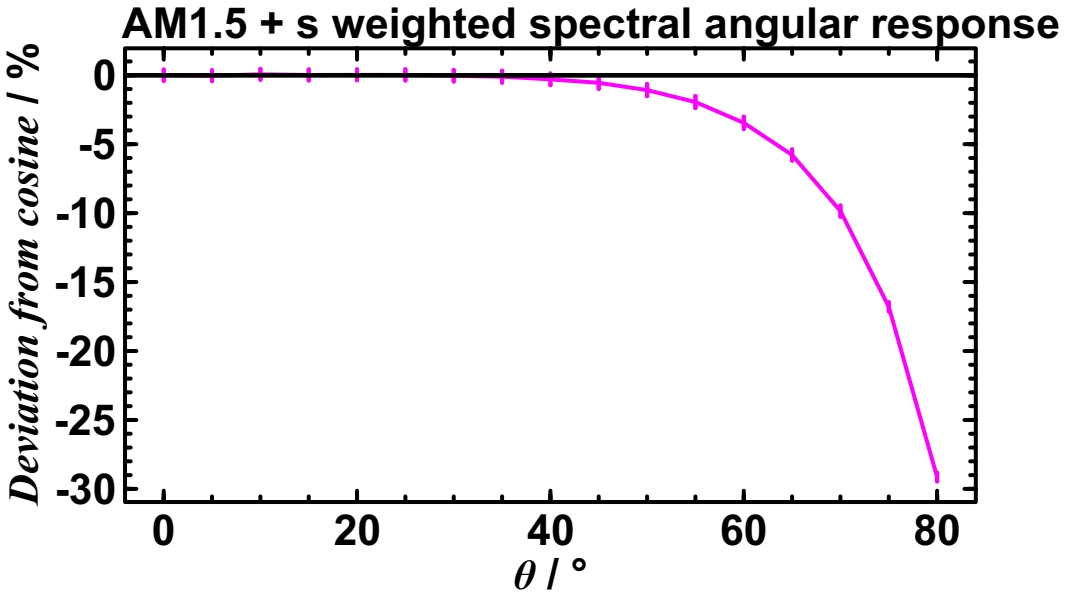
IEC 61853-1

φ, θ - Goniometer



Spectral angular response





Summary

Calculation of I_{SC}(/P_{max}):
Consideration of linearity, temperature, AOI dependence and spectral distribution

$$I_{SC} = \int_{\lambda} \int_{\Omega} s(\lambda, E, T, \Omega) \cdot (L_{\lambda,\,direct}(\Omega,\lambda) + L_{\lambda,\,diffuse}(\Omega,\lambda) + L_{\lambda,\,albedo}(\Omega,\lambda))\, d\Omega\, d\lambda$$

- **Spectral mismatch: 1.4 % at "AM1.5" conditions**

Energy rating matrix (15°C < T < 75 °C, 100 Wm^{-2} < E < 1100 Wm^{-2})
- **Isc: -2.1 % to 4.6%**
- **η: -18.5 % to 3 %**

Spectral and integral AOI dependence shown

Recent activities:Outdoor measurements

Solar cells

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°

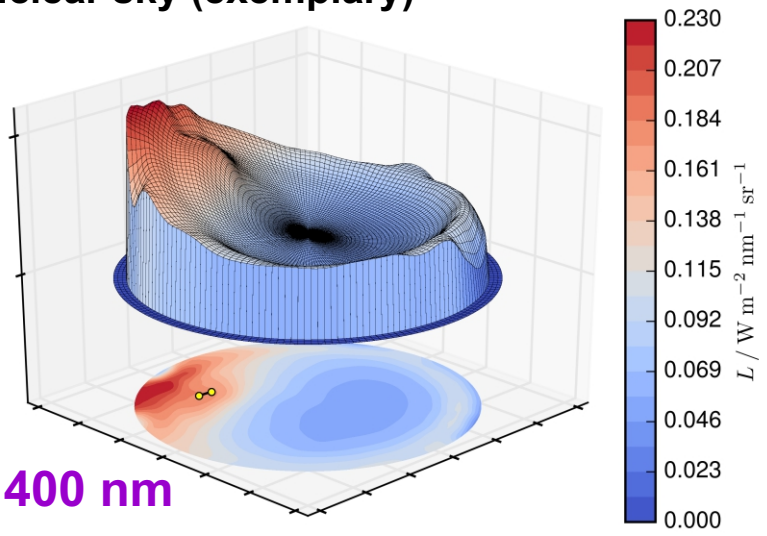
UV+VIS spectrometer
Wavelength range: 220 - 1020 nm
Bandwidth : 3.7 nm
Sampling interval : 0.8 nm

Infrared spectrometer
Wavelength range: 780 - 1650 nm
Bandwidth: 9 nm
Sampling interval: 2.1 nm

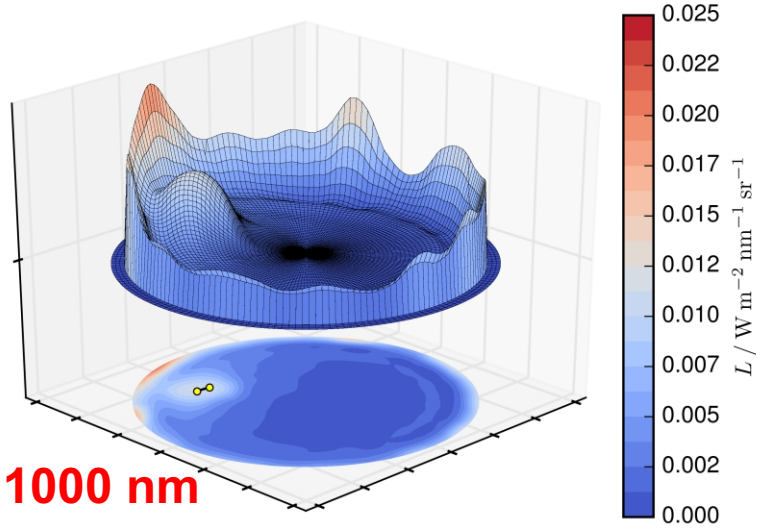
Extended IR spectrometer
Wavelength range: 1500 - 2150 nm
Bandwidth: 15 nm
Sampling interval: 4 nm

Recent activities:Diffuse spectral distribution

...clear sky (exemplary)

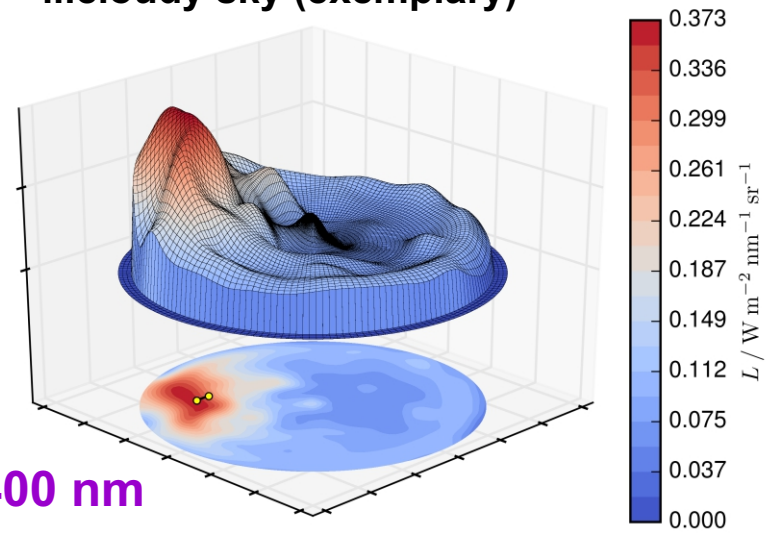


λ = 400 nm

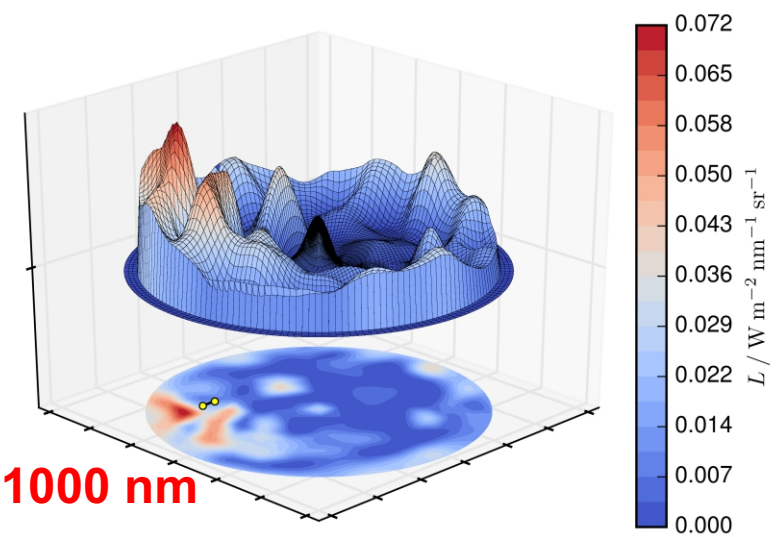


λ = 1000 nm

Diffuse radiance...
...cloudy sky (exemplary)

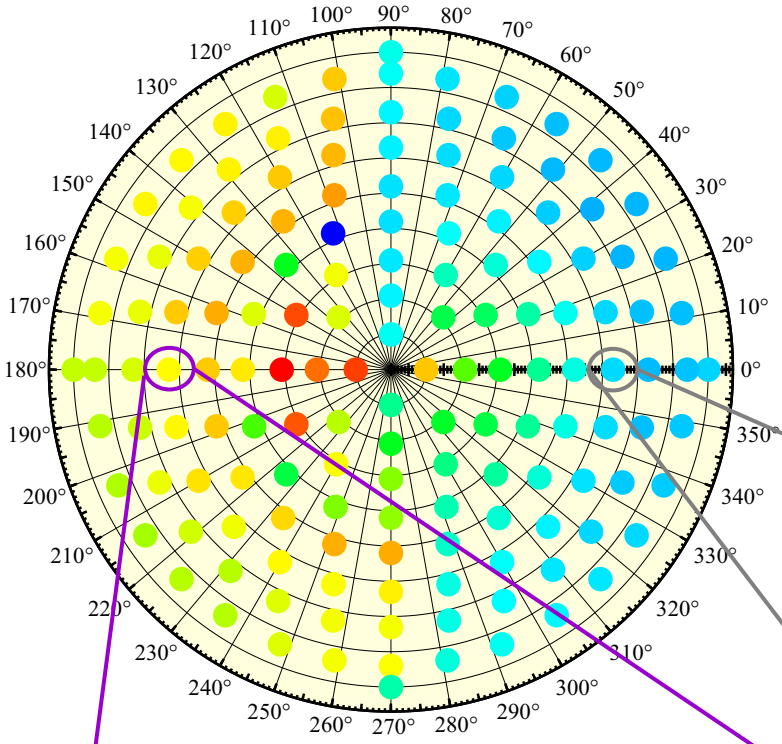


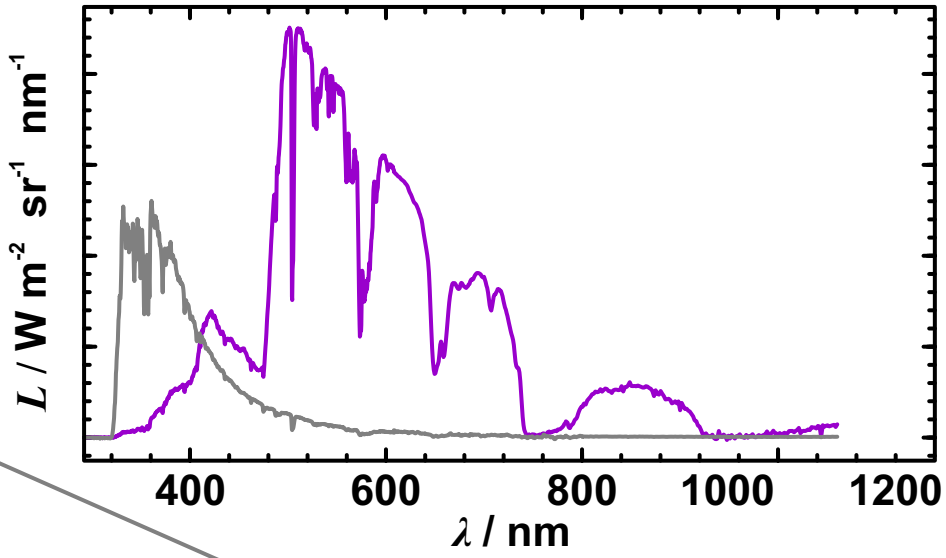
λ = 400 nm



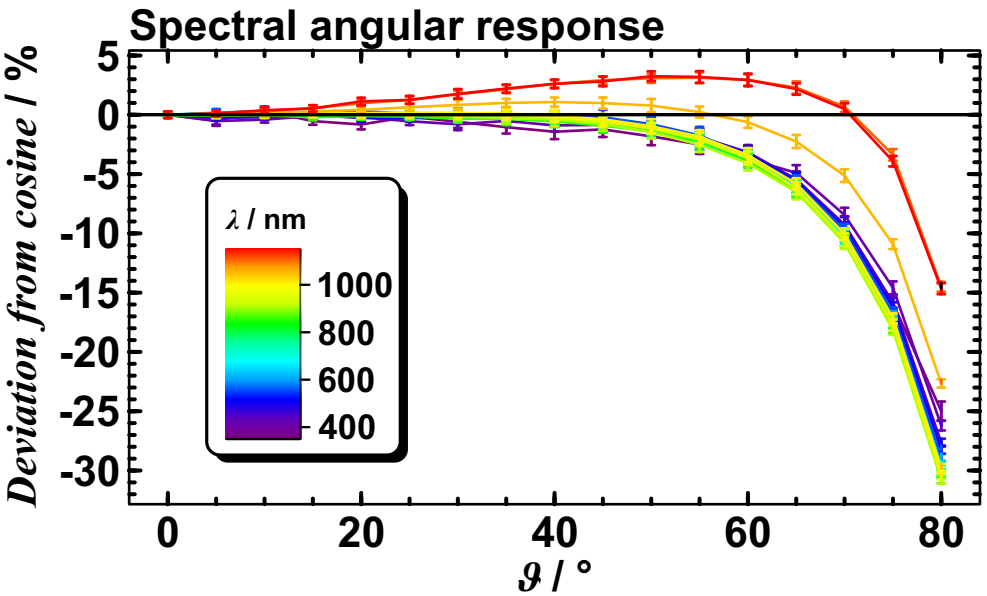
λ = 1000 nm

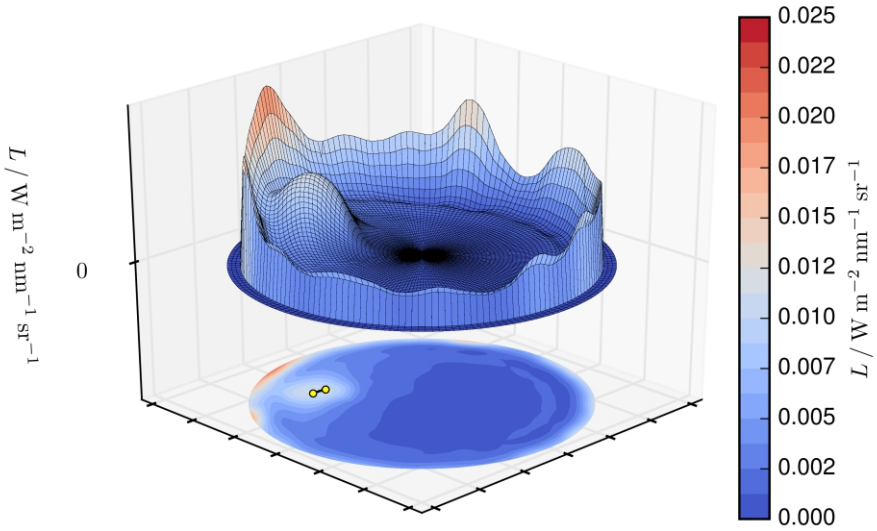
Recent activities:Diffuse spectral distribution





Recent activities:Spectral angular correction





λ = 1000 nm

➡ will be published soon

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