# A Differential Spectral Responsivity Measuring System for Solar Cell Calibration

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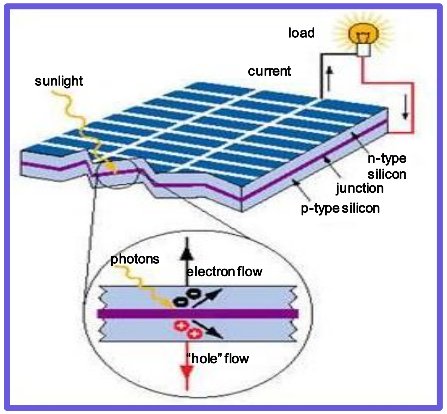
NEWRAD 2011, Maui, Hawaii
20 Sep 2011

# Outlines

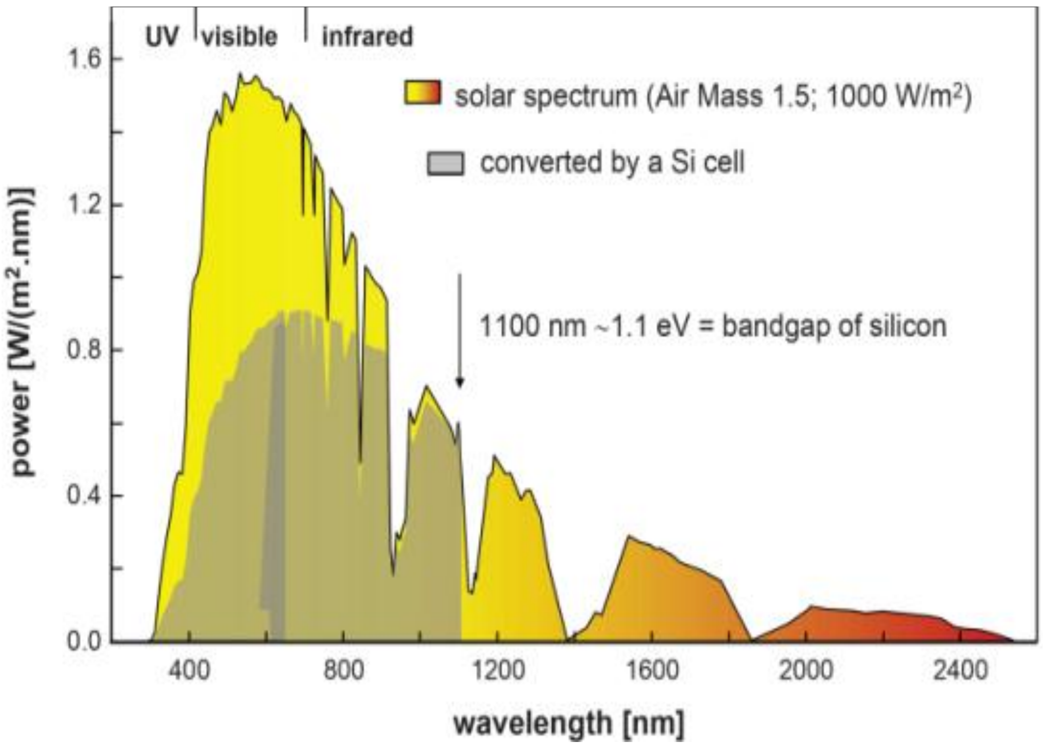
- Introduction
- Differential spectral responsivity (DSR)
- DSR measurement system at NMC
- Measurement result and uncertainty budget
- Summary
- Future works
- References

# Solar cell efficiency

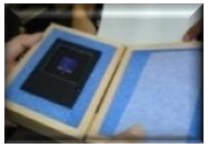
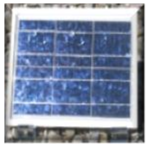


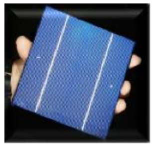

$$\eta = \frac{P_{electical}}{P_{Optical}}$$

$$= \frac{V_{oc} \cdot I_{sc} \cdot FF}{E_{tot} \cdot A}$$

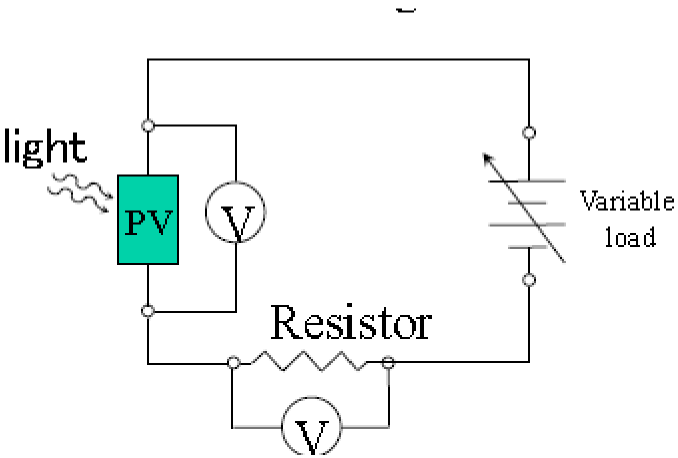


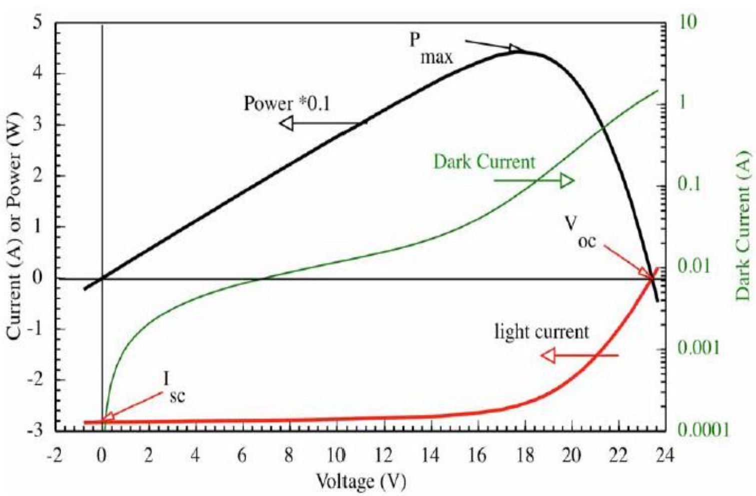

- Current world records: (25.0 ± 0.5)% for Si single cell, (42.3 ± 2.5) % for InGaP/GaAs/InGaAs multi-junction cell
- Main challenges: higher cell efficiency and lower production cost
- High accuracy calibration of cell efficiency requires **primary standard traceable to SI radiometric unit** for spectral responsivity and quantum efficiency



# Characterisation/calibration of a solar cell

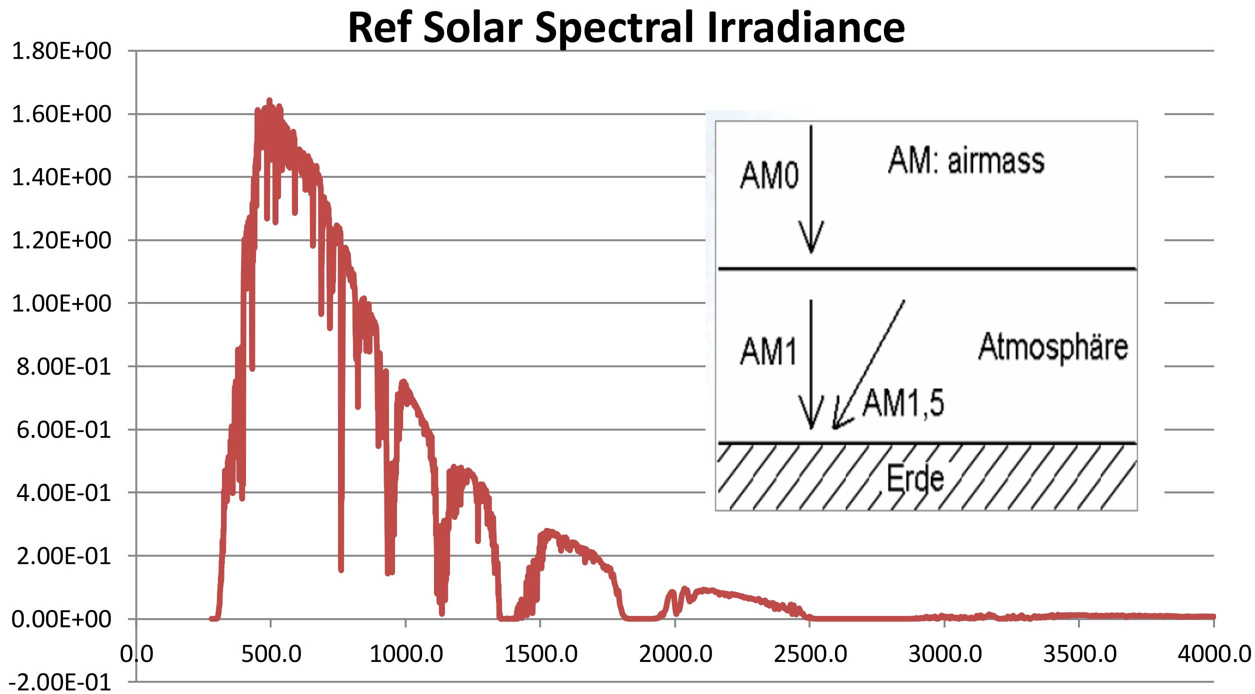


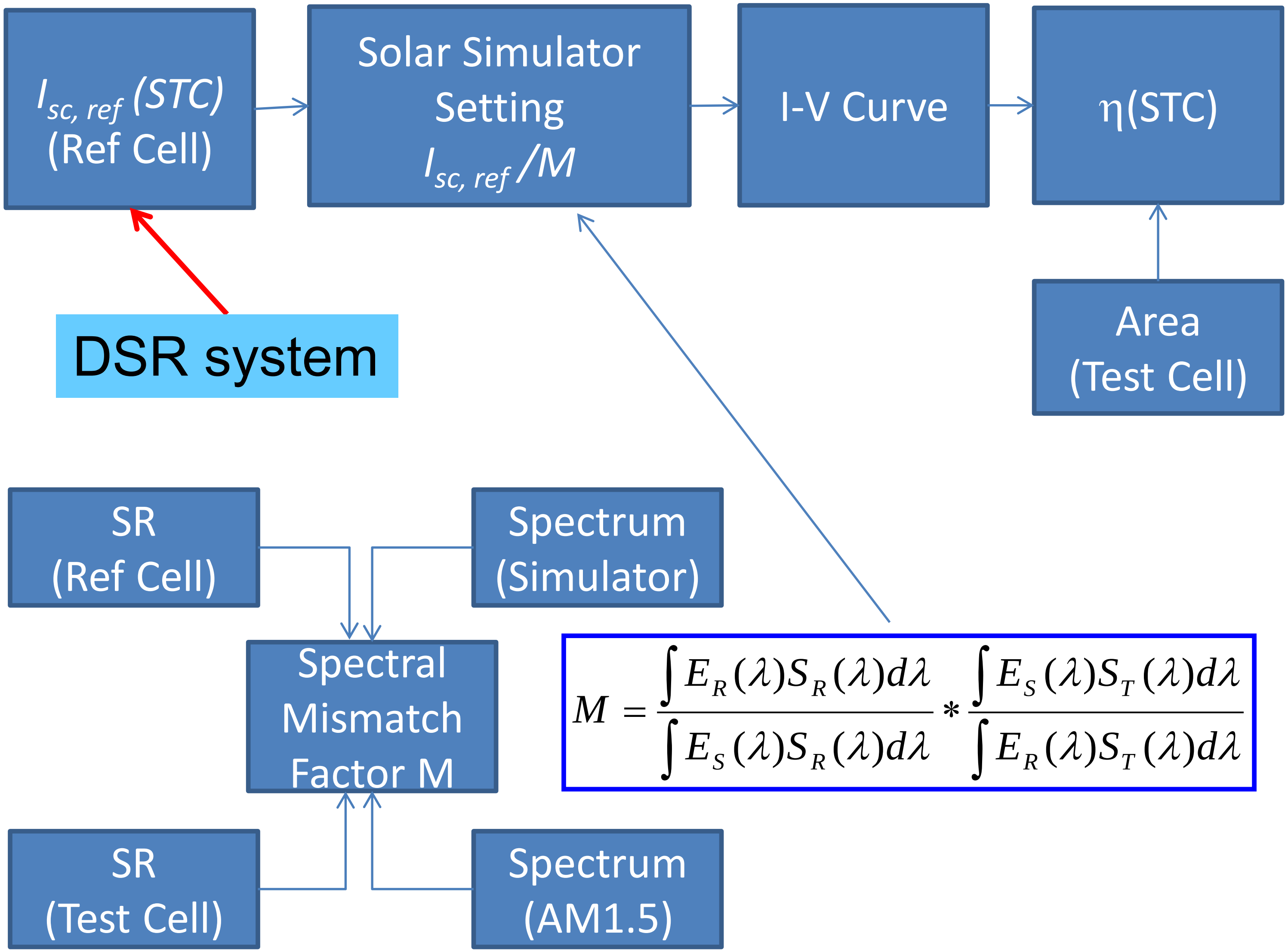

- Key parameters to be determined:
  - ➪ Short circuit current $I_{sc}$
  - ➪ Open circuit voltage $V_{oc}$
  - ➪ Maximum power $P_{max}$
  - ➪ Fill factor FF
  - ➪ Area A
  - ➪ etc
- Full characterisation requires the measurement of I-V curve done by an I-V tester under standard testing conditions (STC)

# Standard testing conditions

- Solar cell temperature 25ºC
- Spectral distribution: AM1.5 global ref spectrum (IEC 60904-3, Ed.2, 2008)
- total irradiance level 1000W/m$^2$ (with respect to ref solar spectrum)



# Efficiency measurement using a solar simulator




$$M = \frac{\int E_R(\lambda) S_R(\lambda) d\lambda}{\int E_S(\lambda) S_R(\lambda) d\lambda} * \frac{\int E_S(\lambda) S_T(\lambda) d\lambda}{\int E_R(\lambda) S_T(\lambda) d\lambda}$$

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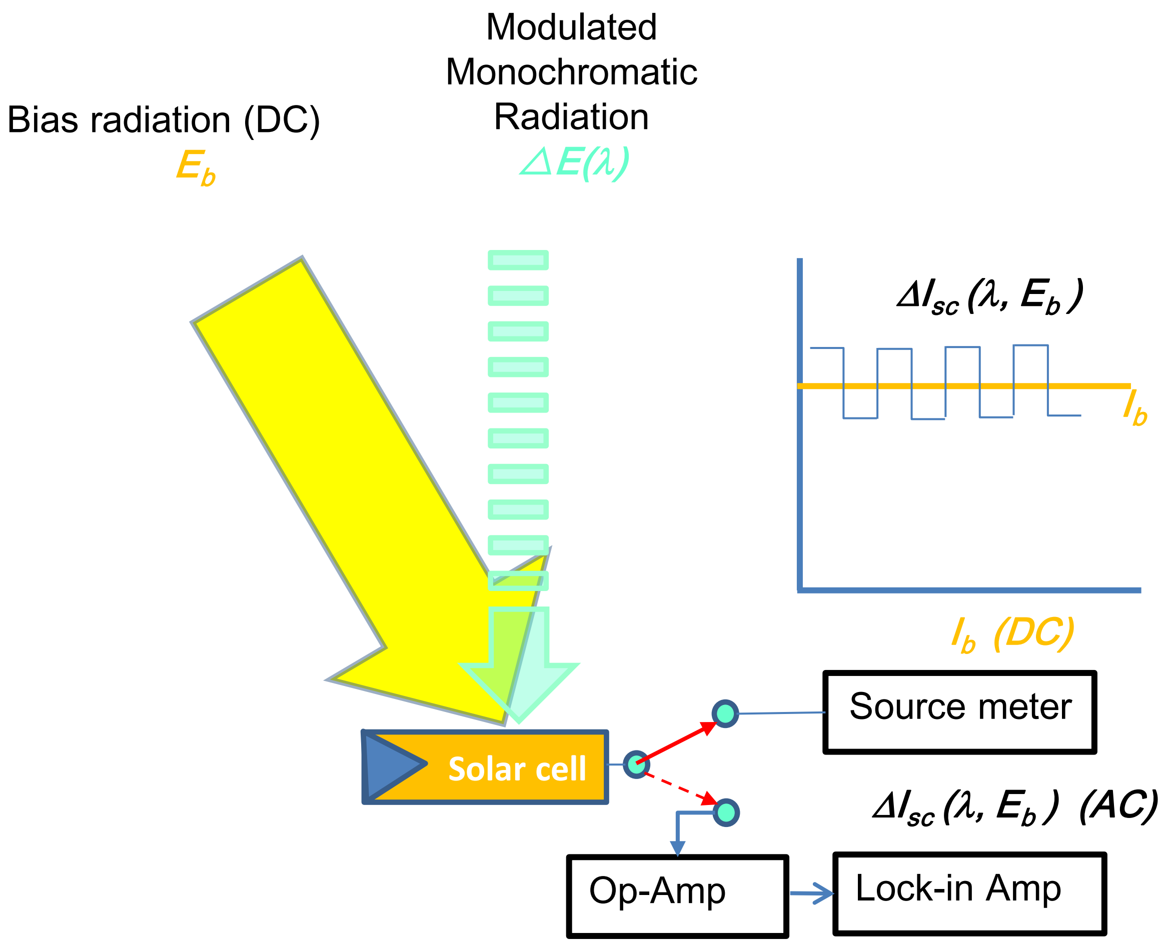
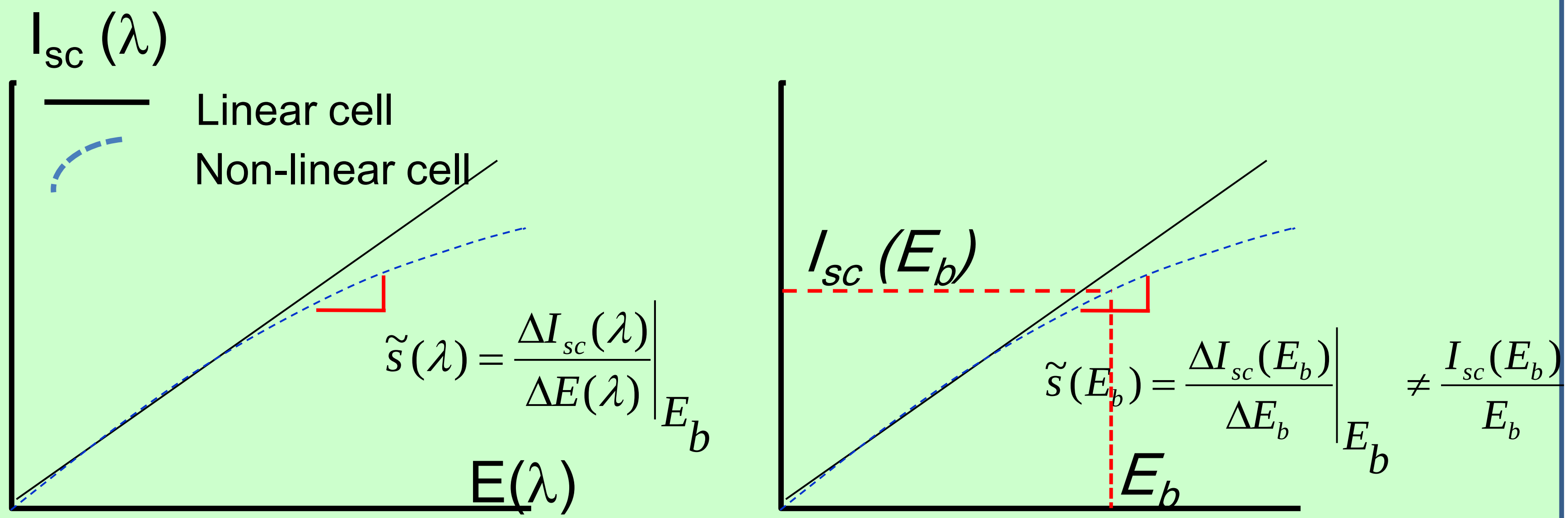
# DSR measurement technique



# SR & DSR and broadband responsivity




- Linear cell (SR independent from irradiance level)

$$s(\lambda) = \frac{I_{sc}(\lambda)}{E(\lambda)} = \left.\frac{\Delta I_{sc}(\lambda)}{\Delta E(\lambda)}\right|_{E_b} \qquad s(E_b) = \frac{I_{sc}(E_b)}{E_b} = \left.\frac{\Delta I_{sc}(E_b)}{\Delta E_b}\right|_{E_b}$$

- Non-linear cell: SR varies with irradiance level so that cannot be measured at low irradiance level ⇨ DSR measurement at different bias level is required to get the broadband responsivity under STC condition $s_{STC}$ ⇨ SCC under STC condition $I_{STC}$

# DSR measurement process (1)

a) Measure the value of absolute DSR at a specific wavelength ($\lambda_o$) and short circuit current without bias , $Isc(E_o)$ :

$$\tilde{s}(\lambda_0, I_{sc}(E_0)) \qquad (1)$$

b) Measure function of relative DSR at different bias levels ($E_b$ ) in a specified wavelength range (Si cell: 280 nm -1200 nm):

$$\tilde{s}_{rel}(\lambda, I_{sc}(E_b)) \qquad (2)$$

c) Combine (1) & (2), absolute DSR :

$$\tilde{s}(\lambda, I_{sc}(E_b)) = \tilde{s}(\lambda_0, I_{sc}(E_0)) * \tilde{s}_{rel}(\lambda, I_{sc}(E_b)) \qquad (3)$$

# DSR measurement process (2)

d) DSR as function of short circuit current (SCC) of the solar cell under test in accordance with IEC AM1.5 solar spectrum:

$$\tilde{s}_{AM\,1.5}(I_{sc}(E_b)) = \frac{\int_0^\infty \tilde{s}(\lambda, I_{sc}(E_b))E_{\lambda,AM\,1.5}(\lambda)d\lambda}{\int_0^\infty E_{\lambda,AM\,1.5}(\lambda)d\lambda} \qquad (4)$$

e) Calculate value of $I_{STC}$ under STC :

$$1{,}000W/m^2 = E_{STC} = \int_0^{I_{STC}} \frac{dI_{sc}}{\tilde{s}_{AM\,1.5}(I_{sc})} \qquad (5)$$

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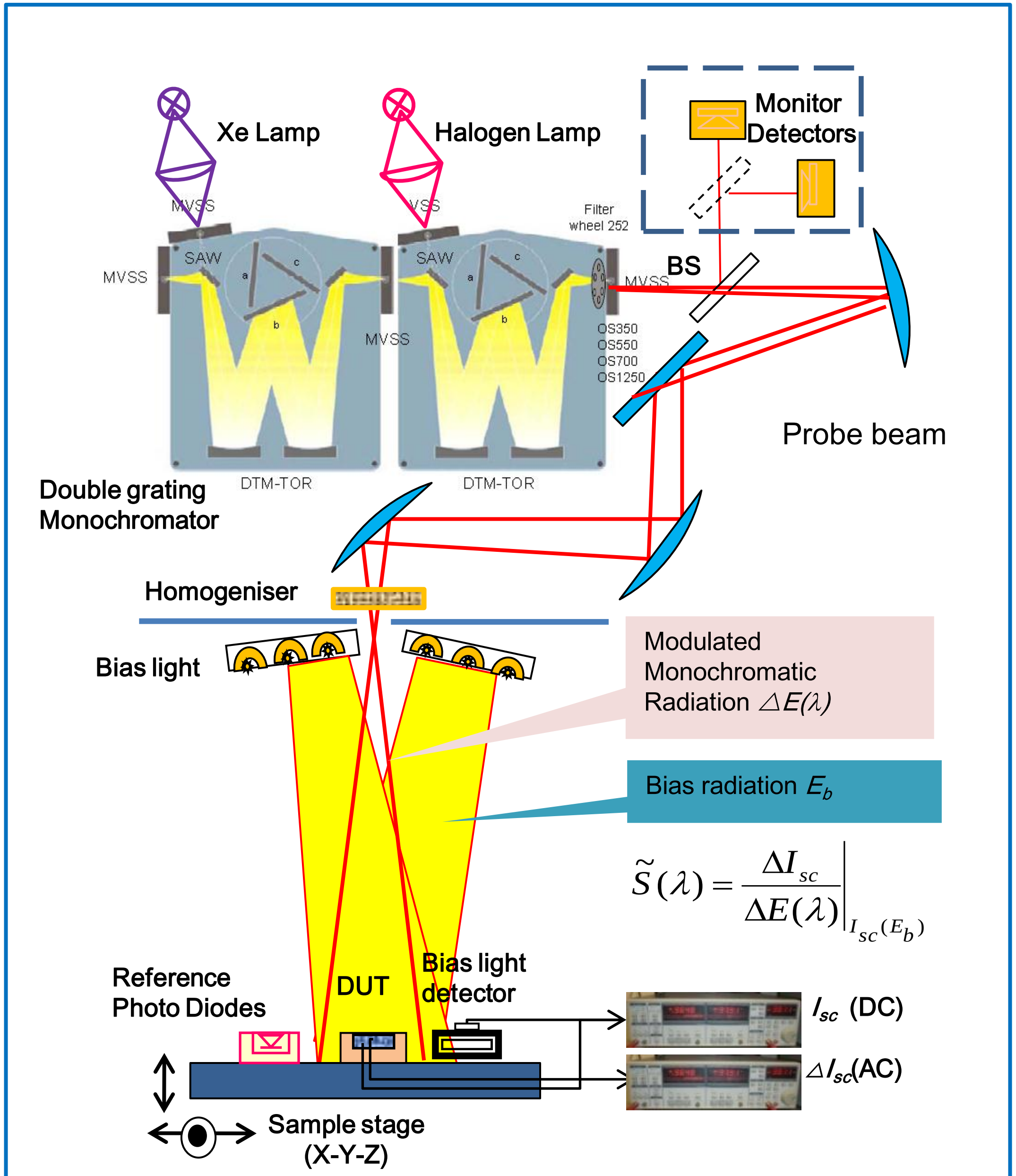
# Layout of DSR facility at NMC




- Bias lighting irradiance: 0.1 – 1.2 sun
  - monitored by a ref solar cell
- Reference standards used: Si-PD & InGaAs PD with precision apertures
  - Only measure probe beam w/o bias
  - Ac signal only
- DUT
  - 20 x 20 mm (WPVS design) up to 6” single cell
  - Measure both bias and probe beams
  - Bias: DC signal ($I_{sc}$ ) with probe blocked
  - Probe: AC signal only with bias present, DC component removed by a high pass filter& ac coupling
- Ref PDs,Ref solar cell & test sample solar cell all on a temperature controlled, motorised x-y-z stage
- Monintor detectors (Si & InGaAs PDs)
  - Ac signal only, recorded simultaneous with ref PD or DUT during scans
  - to monitor the changes of probe beam
  - served as reference across different scans
- A microlens array (flattop) beam homogeniser probe beam nonuniformity <1%

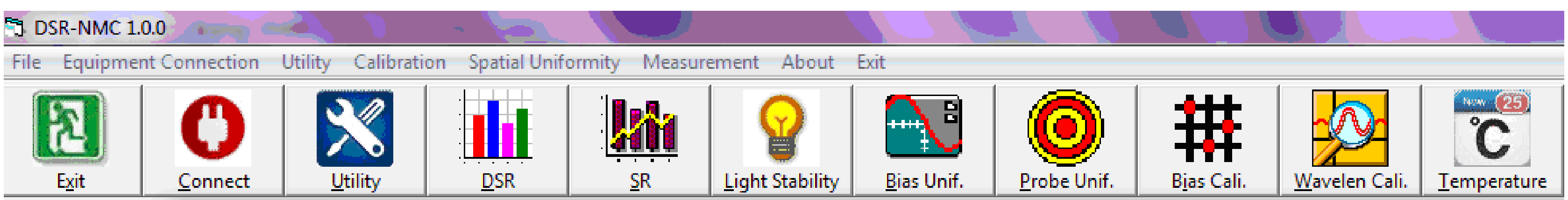
# NMC's DSR measurement system

- A multi-functional system

| | | | |
|---|---|---|---|
| System Connection | Utility | Temperature Monitor | Wavelength Calibration |
| Lamp Stability | Bias Irradiance Calibration | (Probe/Bias) Beam Uniformity | Solar Cell Spatial Uniformity (Mapping) |
| Linearity Measurement | SR Calibration | DSR Calibration | Temperature Coefficient Measurement |

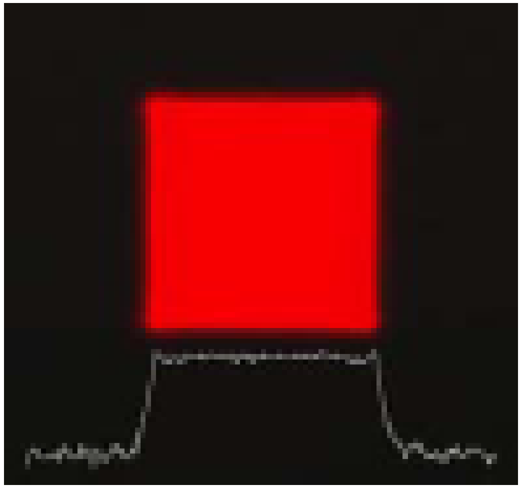
System characterisation functions

Measurement functions



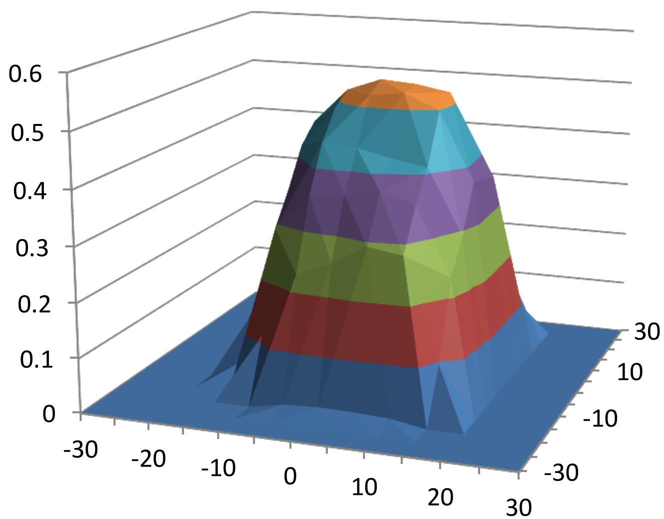
# Microlens array beam homogeniser (SUSS MicroOptics)

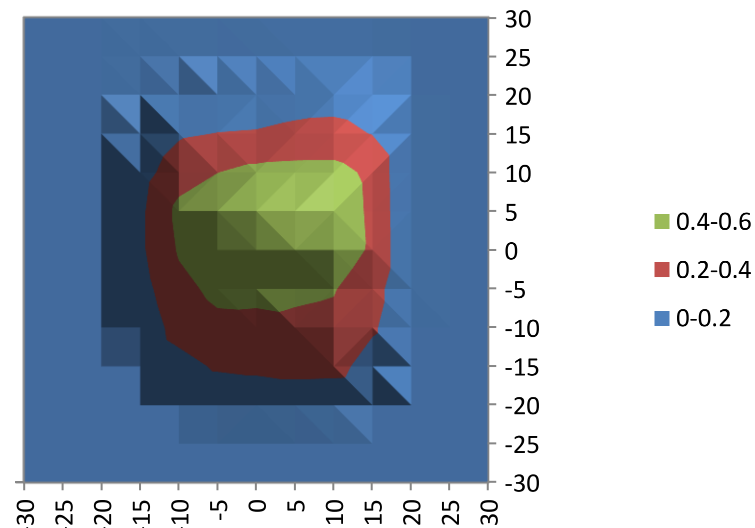
- Key specifications:
  - Array structure: two sets of cylindrical lenses crossed each other
  - Lens material: fused silica, Spectral transmittance of lens material (280 nm – 2400 nm): >85 %
  - Size: 50 mm (L) x 50 mm (W) x 2.25 mm (T), Clear aperture (Active area): 49 mm (L) x 49 mm (W)
  - Lens pitch: 250 um
  - Beam divergence angle after the microlens array: ± 5°



# Probe beam uniformity (w/o homogeniser)

Non-uniformity (NU) over area 20 mm x 20 mm, Halogen lamp, band width 5nm, wavelength 650 nm



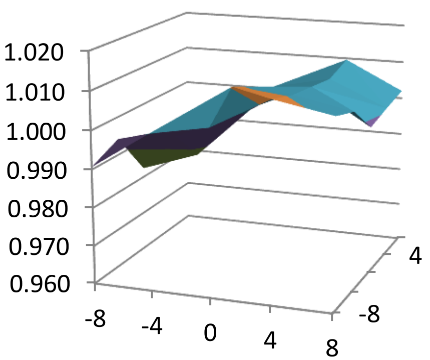



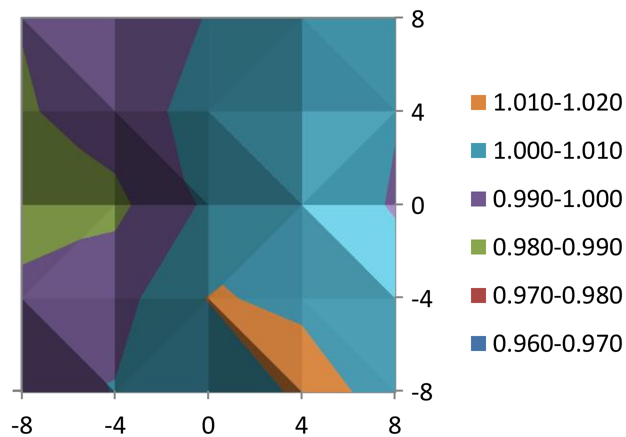

$$NU = \frac{Max - Min}{Max + Min} = 32\%$$

# Probe beam uniformity (with homogeniser)

Halogen lamp 800W, PV cell: 20 mm x 20 mm, Ref PD aperture: 4 mm

WL: 650 nm



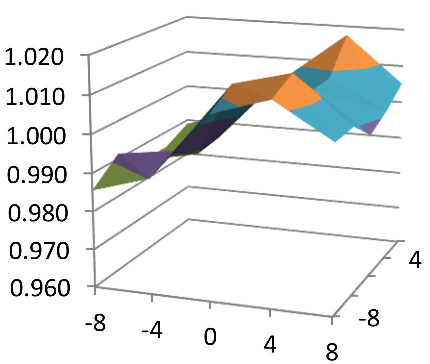



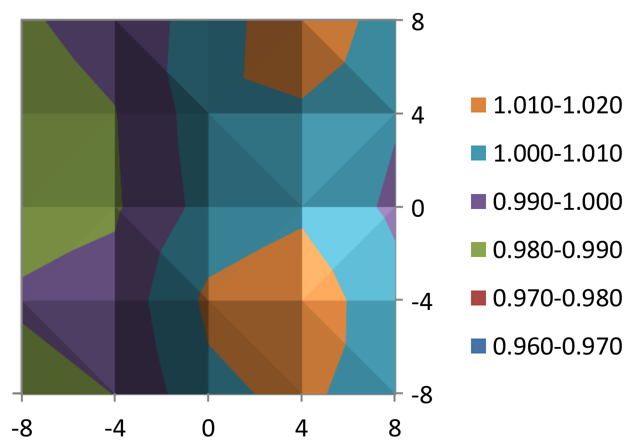

| | | | | |
|---|---|---|---|---|
| 0.990684 | 1.000586 | 1.003360 | 1.011550 | 1.008690 |
| 0.994197 | 0.996244 | 1.010296 | 1.009384 | 1.006357 |
| 0.982454 | 0.987584 | 1.001803 | 1.008317 | 0.998927 |
| 0.988859 | 0.994830 | 1.004042 | 1.007302 | 1.000572 |
| 0.990424 | 0.991274 | 1.000614 | 1.009628 | 1.002023 |

| | | |
|---|---|---|
| Ave | 1.0000 | |
| NU | 1.5% | |
| **Correction** | **0.9982** | **(-0.18%)** |

$$Correction = \frac{E(DUT)}{E(Ref-PD)}$$

WL: 1000 nm

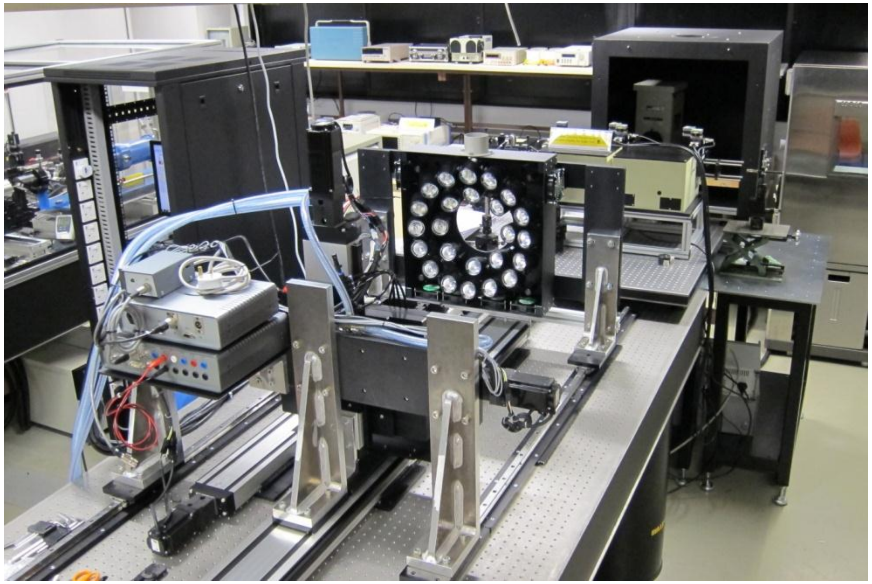


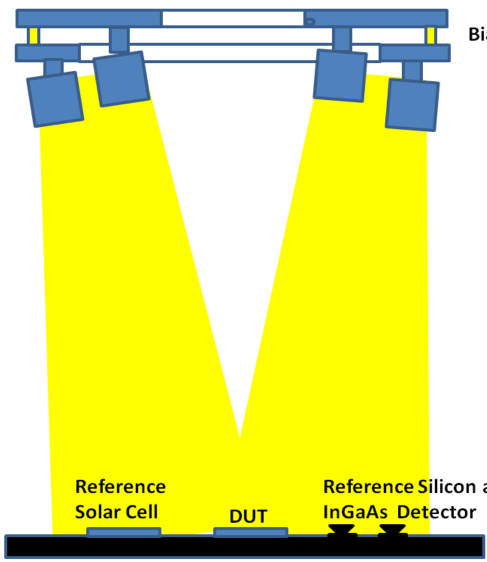



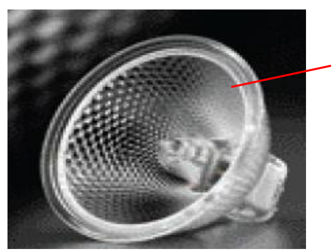

| | | | | |
|---|---|---|---|---|
| 0.985601 | 0.990153 | 1.007646 | 1.012401 | 1.003347 |
| 0.991372 | 0.993448 | 1.012057 | 1.015844 | 1.003644 |
| 0.985772 | 0.988785 | 1.003695 | 1.008327 | 0.997904 |
| 0.985717 | 0.989686 | 1.005431 | 1.008579 | 1.000916 |
| 0.988959 | 0.993247 | 1.004685 | 1.017637 | 1.005147 |

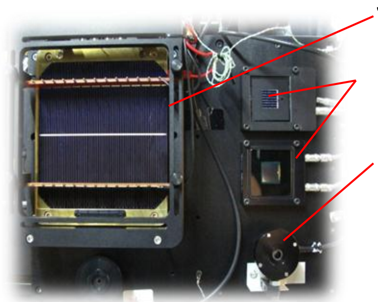
| | | |
|---|---|---|
| Ave | 1.0000 | |
| NU | 1.6% | |
| **Correction** | **0.9963** | **(-0.37%)** |

# Bias light system



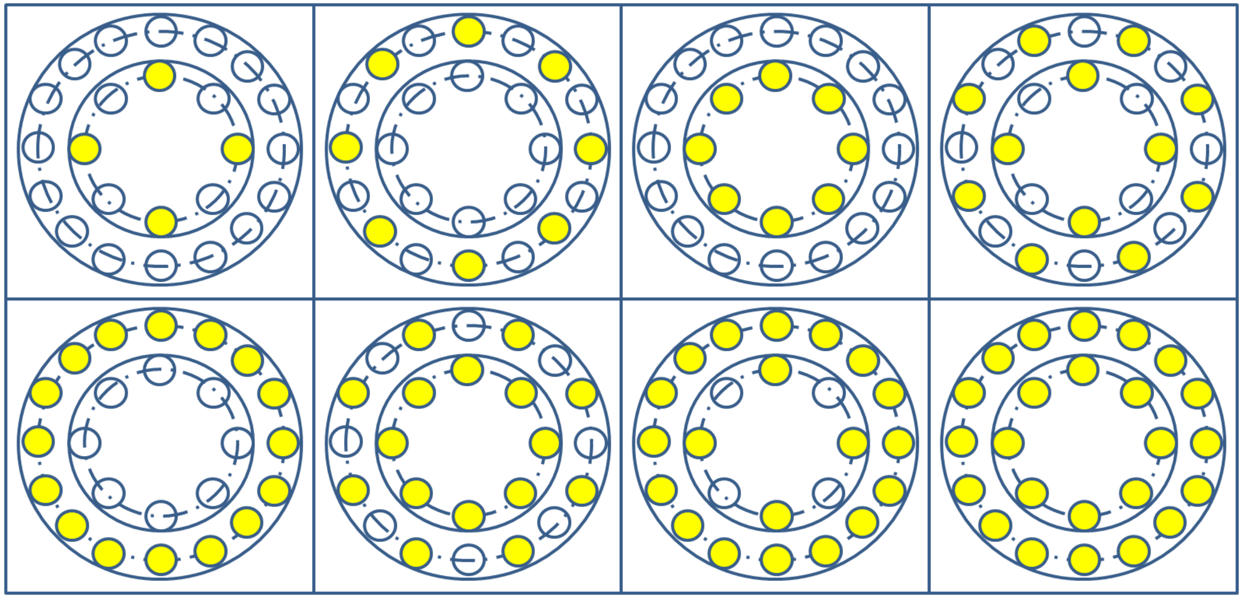


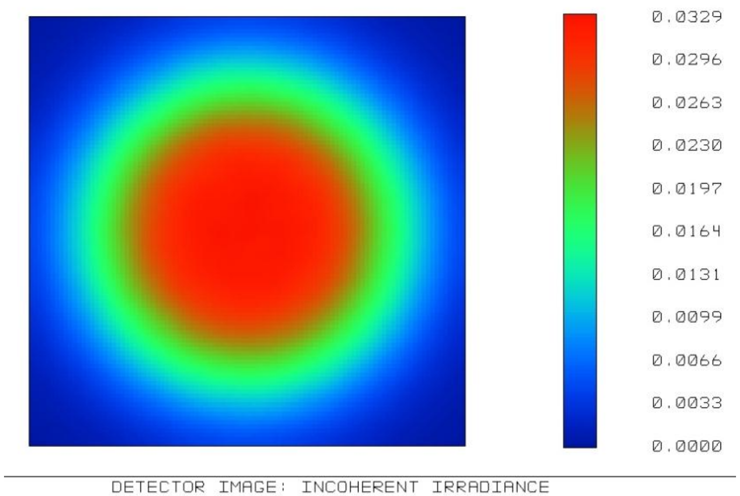



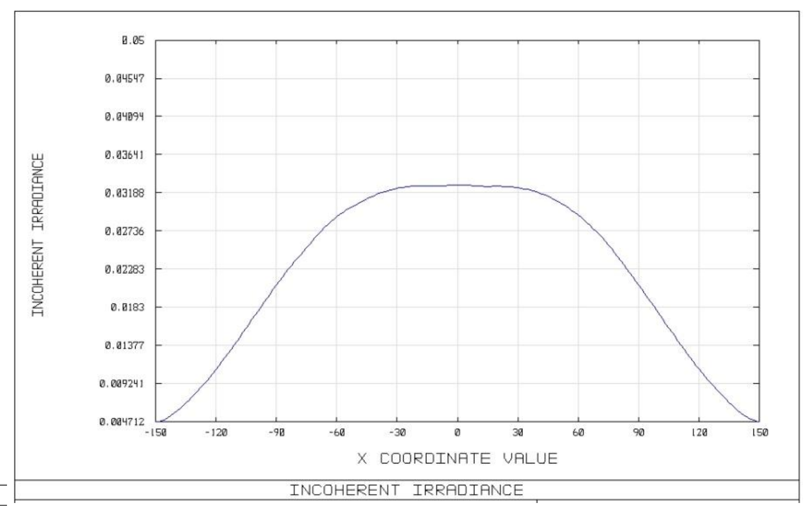




- 24x50W (12V)/24° Halogen lamps with multilens reflector
- Colour temperature: 3050k
- Two layer structure
- Different lamp combinations selectable by switches
- Distance of bias light holder to sample stage adjustable by motorised stages for both
- Able to provide uniform bias irradiance from 0.1 – 1.2 standard sun
- Best spatial uniformity achievable <2% on 20 mm x 20 mm sample

# Software simulation for bias beam uniformity at different configurations

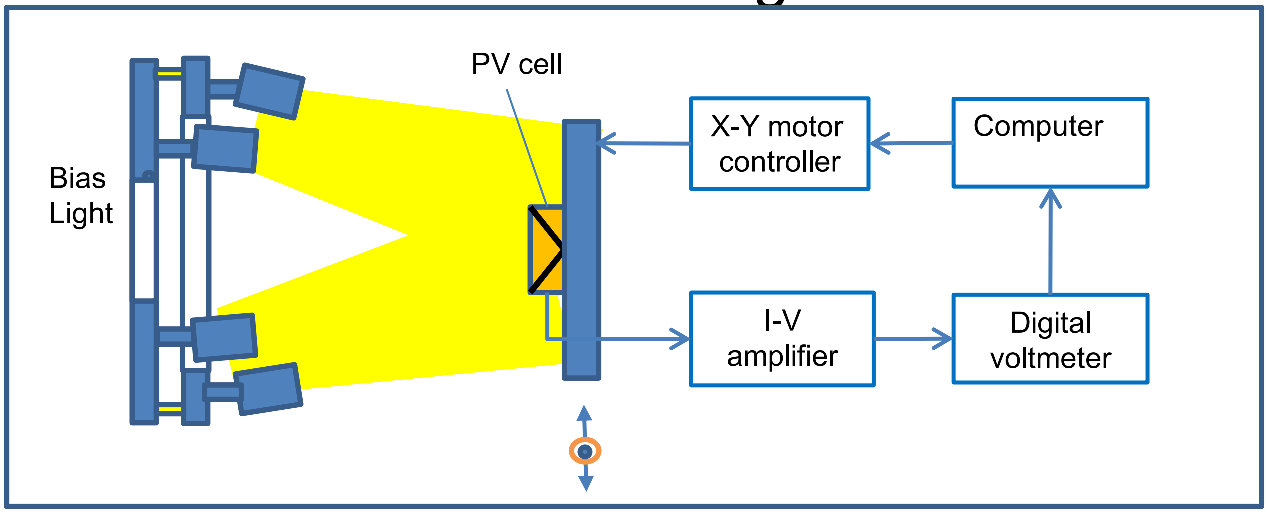




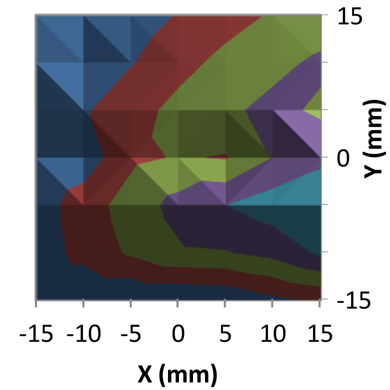



# Bias beam uniformity measurements

## Method 1: PV cell scanning

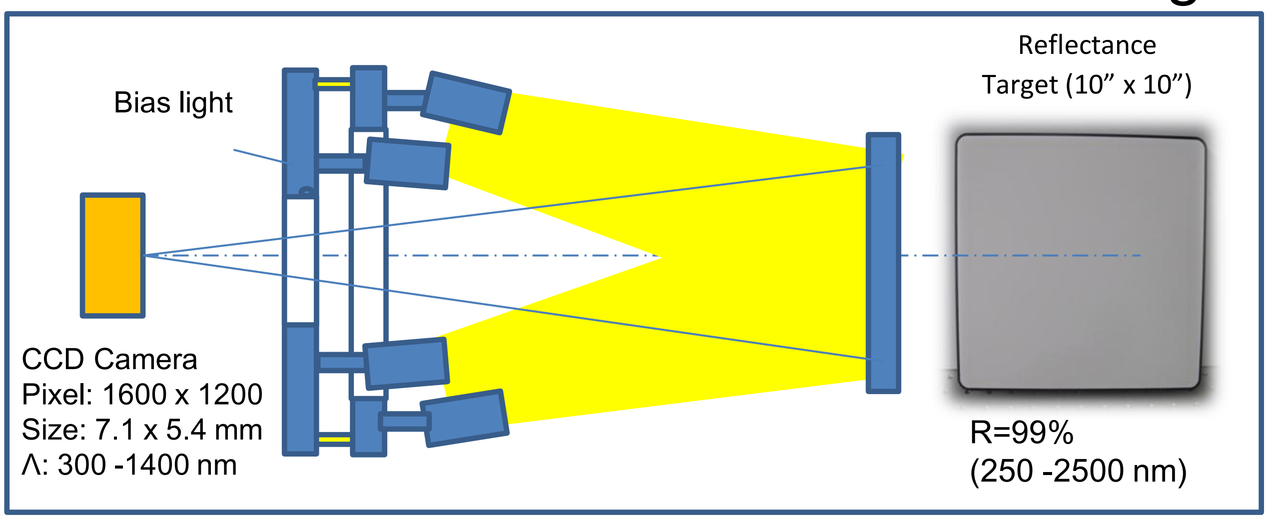



**PV cell scanning**
**(Uniformity : <2%)**

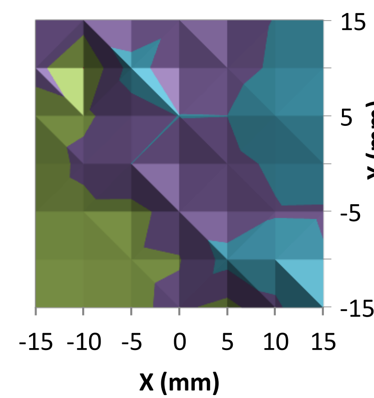



Contour scale : 0.5%

## Method 2: CCD camera + reflectance target

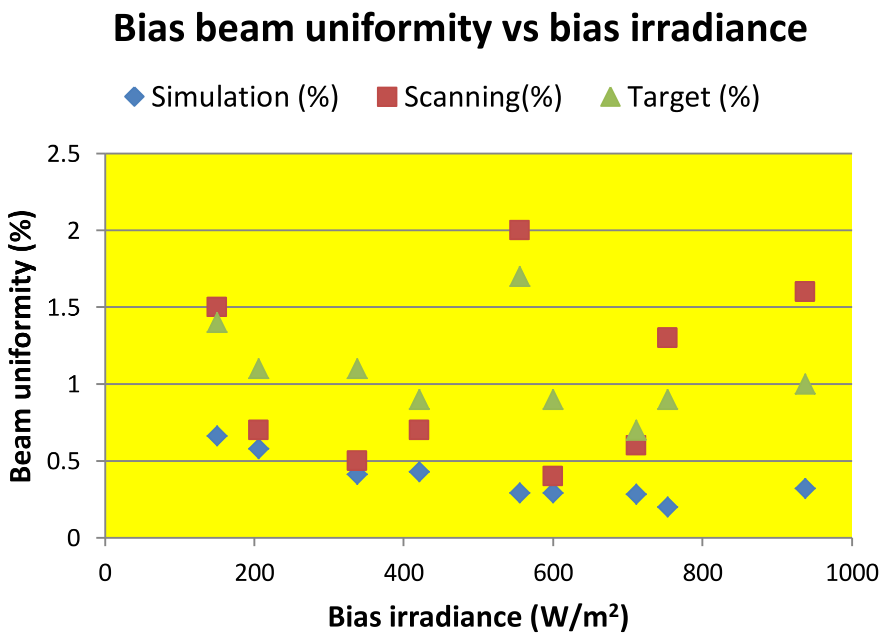


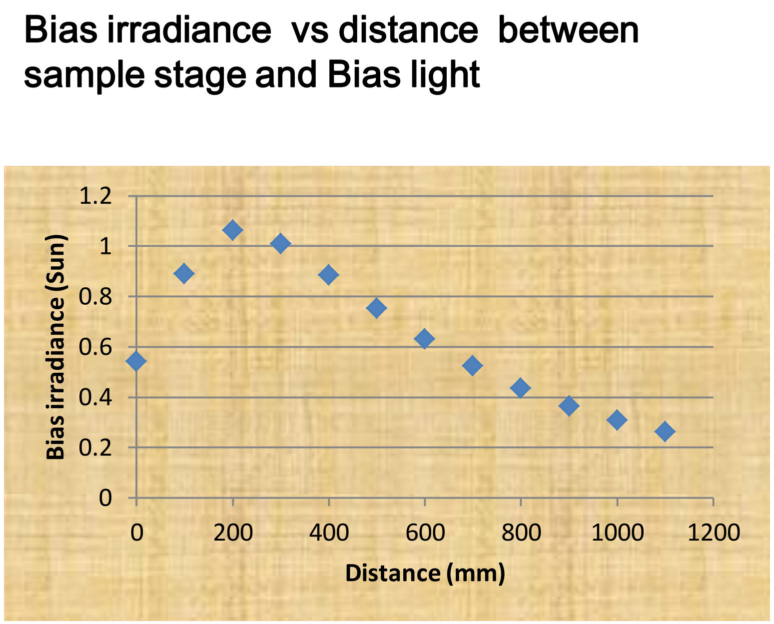

**CCD Camera**
**(uniformity: <1%)**




Contour scale : 0.5%

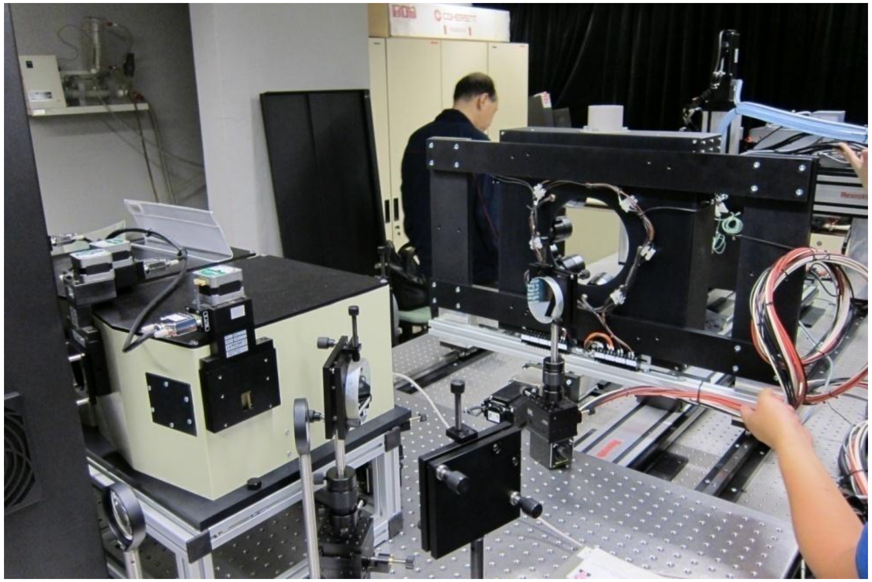
# Bias beam uniformity measurement results

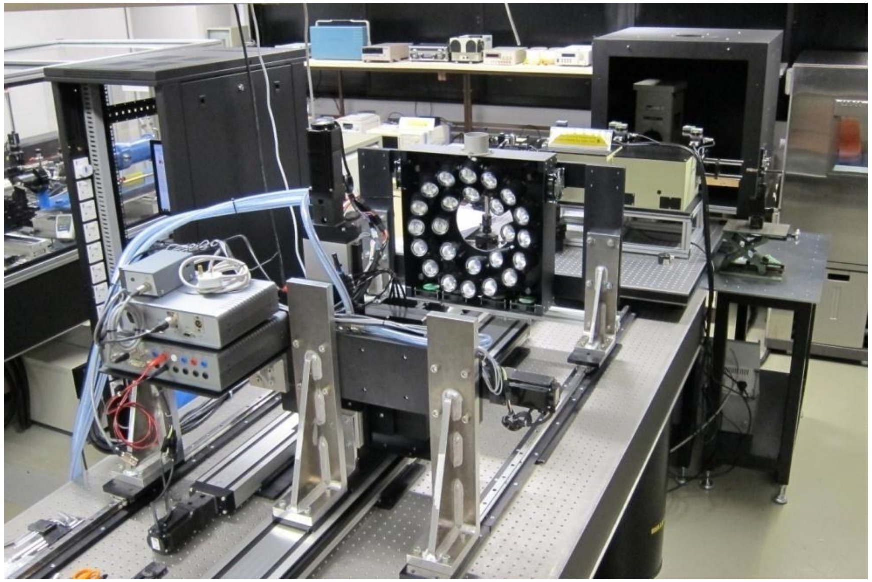


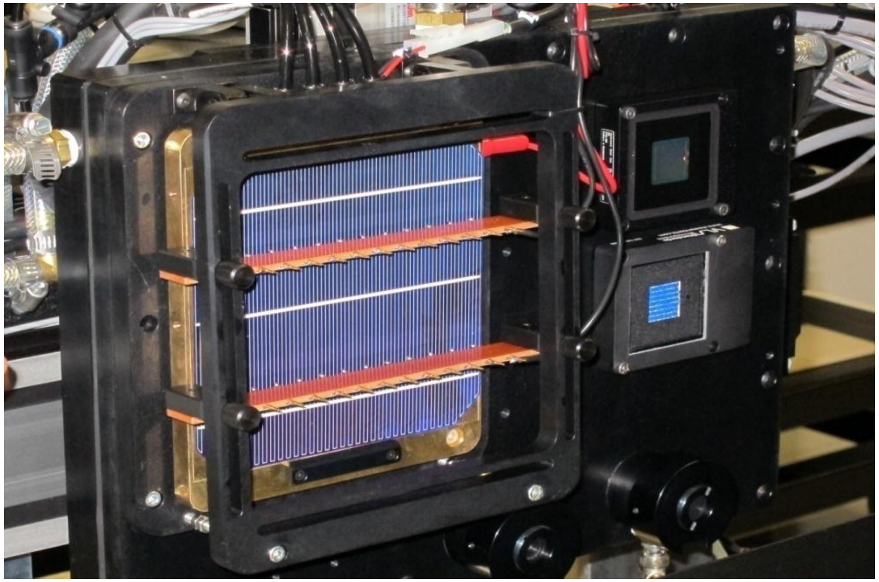




**Possible causes of difference btw simulation and real measurements:**

- Different spatial optical power distribution of individual lamp
- Different geometric construction and alignment of individual lamp
- Retro-reflection, multiple reflection and stray light in real measurement
- Temperature effect and light intensity drift during measuring period using scanning method







Photos of DSR system at NMC

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# Measurement results

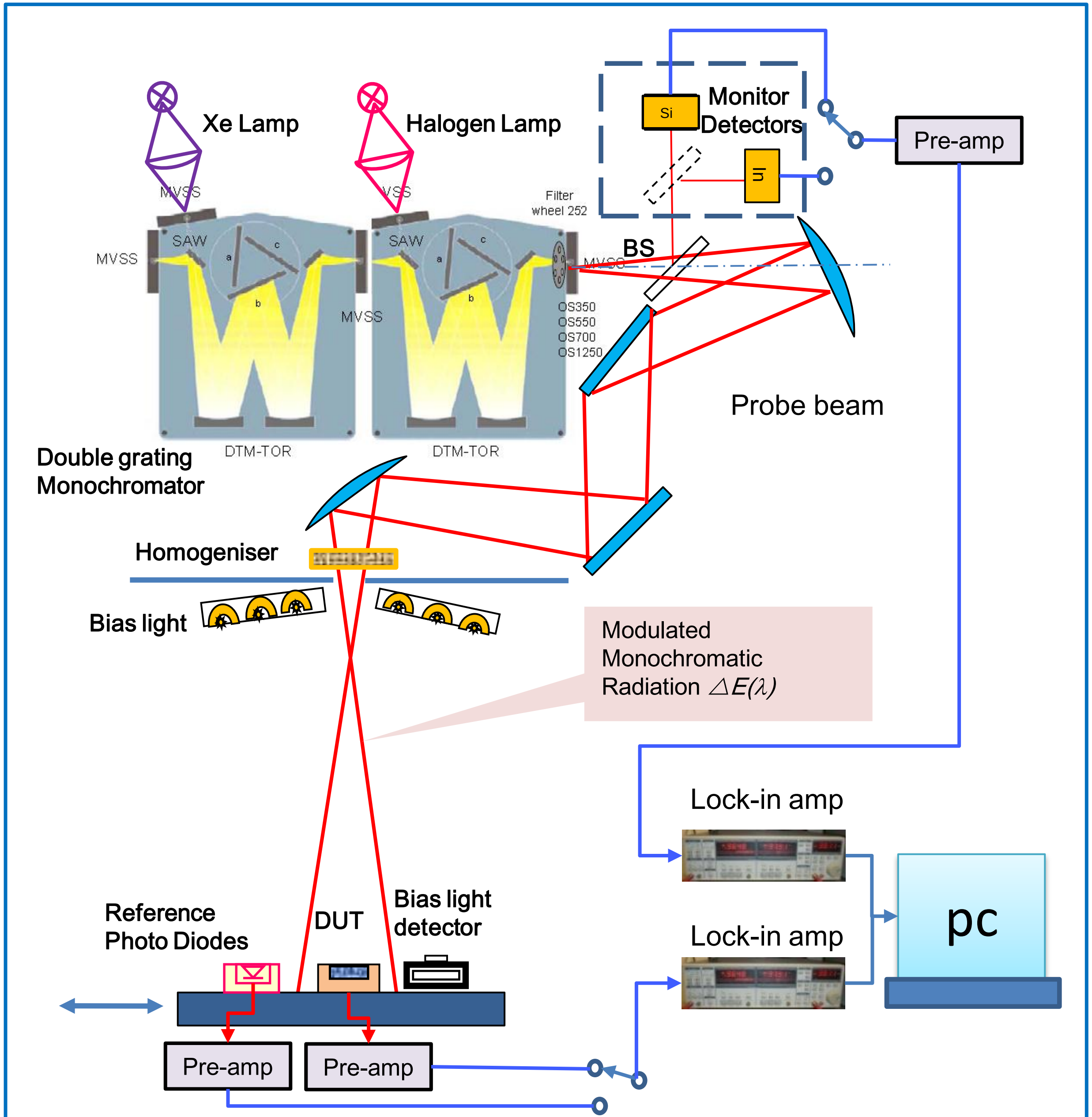
Absolute SR measurement result

| Wavelength (nm) | Absolute SR ($mA \cdot W^{-1} \cdot m^2$) PTB | Unc (%) PTB | Absolute SR ($mA \cdot W^{-1} \cdot m^2$) NMC | Unc (%) NMC | Deviation (%) s(NMC)/s(PTB) |
|---|---|---|---|---|---|
| 650 | 0.15333 | 0.5 | 0.15244 | 0.5 | -0.58 |

Short circuit current measurement result

| $I_{STC}$ (mA) PTB | $U(I_{STC})$(%) PTB | $I_{STC}$ (mA) NMC | $U(I_{STC})$(%) NMC | Deviation (%) I(NMC)/I(PTB) |
|---|---|---|---|---|
| 115.46 | 0.5 | 115.1 | 2.0 | -0.31 |

# Uncertainty evaluation of SR measurement




SR of PV cell, $s_s(\lambda)$:

$$s_t(\lambda) = \frac{\dfrac{V_t(\lambda)}{V_{t,m}(\lambda)\cdot G_t}}{\dfrac{V_s(\lambda)}{V_{s,m}(\lambda)\cdot G_s}} s_s(\lambda) + \Delta s_\lambda(\lambda) \qquad (6)$$

$s_s(\lambda)$ : spectral responsivity of reference photodiode;
$V_t(\lambda)$ & $V_{t,m}(\lambda)$: signal & monitor voltages of test PV cell;
$G_t$ : Gain of pre-amplifier for test PV cell measurement
$V_s(\lambda)$ & $V_{s,m}(\lambda)$ : signal & monitor voltages of ref photodiode;
$G_s$ : Gain of pre-amplifier for ref photodiode measurement
$\Delta s_\lambda(\lambda)$: wavelength error of monochromator

# Unc equation of SR measurement

The main sources of uncertainty can be modelled from eq. (6) through partial differentiation. Assuming all components are not correlated, relative uncertainty, $u(s_t)/s_t$, can be derived as follows:

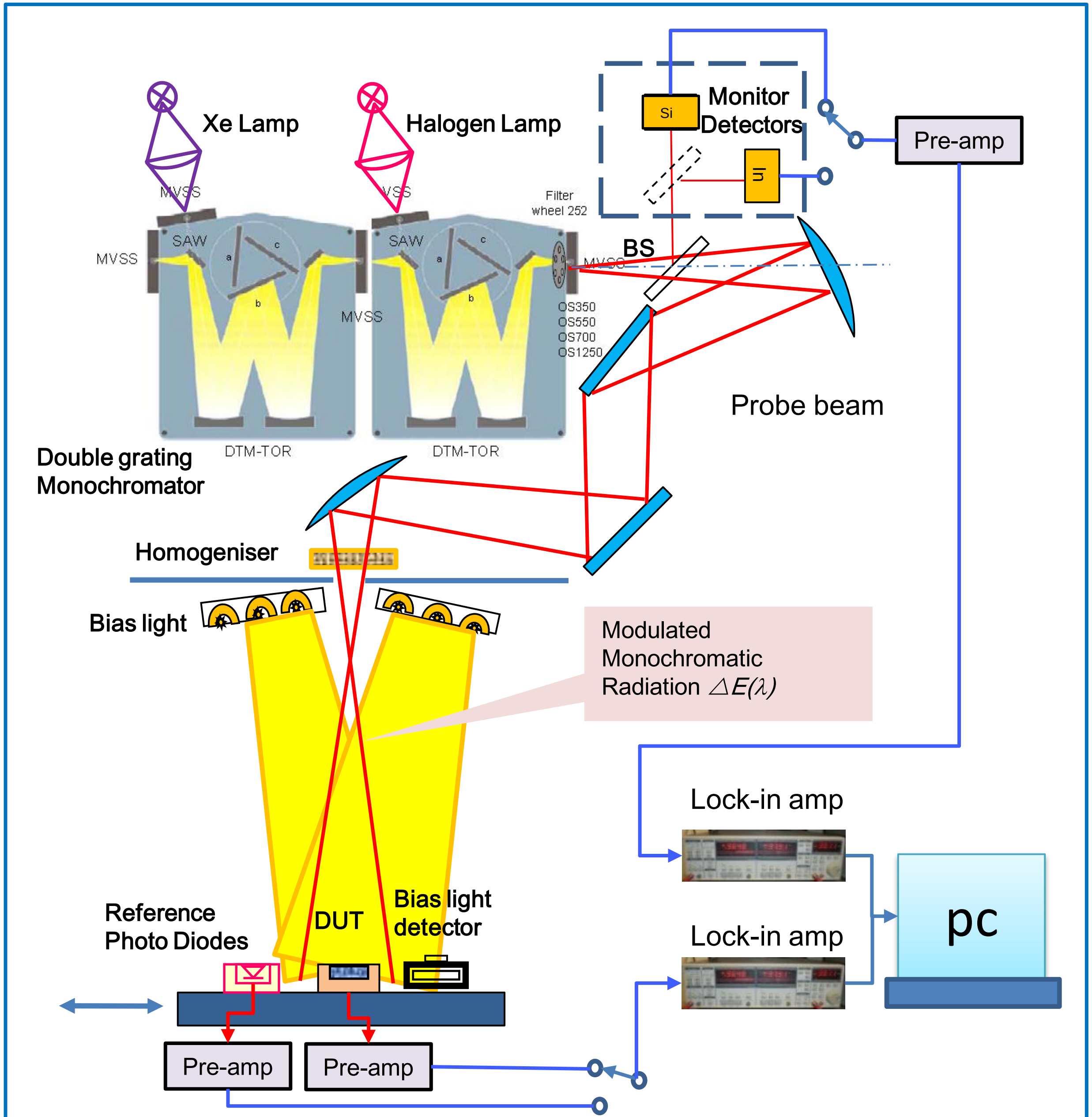
$$\left(\frac{u(s_t)}{s_t}\right)^2 = \left(\frac{u(V_t)}{V_t}\right)^2 + \left(\frac{u(V_{t,m})}{V_{t,m}}\right)^2 + \left(\frac{u(V_s)}{V_s}\right)^2 + \left(\frac{u(V_{s,m})}{V_{s,m}}\right)^2 + \left(\frac{u(G_s)}{G_s}\right)^2 + \left(\frac{u(G_t)}{G_t}\right)^2 + \left(\frac{u(s_s)}{s_s}\right)^2 + \left(\frac{u(\Delta s_\lambda)}{s_t}\right)^2$$

| Unc Type | Uncertainty component | | |
|---|---|---|---|
| $u(V_t)/V_t$ | Signal repeatability of test PV cell | Positioning of test PV cell | |
| $u(V_{t,m})/V_{t,m}$ | Monitor repeatability during test PV cell measurement | | |
| $u(V_s)/V_s$ | Signal repeatability of std PD | Positioning of std PD | Unc of area correction for Test PV cell & std PD |
| $u(V_{s,m})/V_{s,m}$ | Monitor repeatability during std PD measurement | | |
| $U(G_s)/G_s$ | Calibration uncertainty of gain of pre-amplifier of std PD | | |
| $U(G_t)/G_t$ | Calibration uncertainty of gain of pre-amplifier of test PV cell | | |
| $U(s_s)/s_s$ | Calibration uncertainty of std PD | | |
| $U(\Delta s_\lambda)/s_t$ | Uncertainty due to wavelength calibration unc.of monochromator | | |

# Unc budget of absolute SR measurement (650 nm)

| u(x) | Source of uncertainty | type | Value (%) | $C_i$ | Probability distribution | k | $u(x_i)$ (%) | $u_i(y)$ (%) | DoF |
|---|---|---|---|---|---|---|---|---|---|
| u(a1) | Signal repeatability of test PV cell | A | 0.01 | 1 | Normal | 1 | 0.01 | 0.01 | 9 |
| u(a2) | Unc. due to positioning of test PV cell | B | 0.1 | 1 | Rectangular | 1.73 | 0.06 | 0.06 | ∞ |
| u(b1) | Monitor repeatability during test PV cell measurement | A | 0.09 | 1 | Normal | 1 | 0.09 | 0.09 | 9 |
| u(c1) | Signal repeatability of std PD | A | 0.02 | 1 | Normal | 1 | 0.02 | 0.02 | 9 |
| u(c2) | Unc. due to positioning of std PD | B | 0.1 | 1 | Rectangular | 1.73 | 0.06 | 0.06 | ∞ |
| u(c3) | Unc. due to area correction for Test PV cell & std PD | B | 0.2 | 1 | Rectangular | 1.73 | 0.12 | 0.12 | ∞ |
| u(d1) | Monitor repeatability during std PD measurement | A | 0.03 | 1 | Normal | 1 | 0.03 | 0.03 | 19 |
| u(e) | Cal. unc. of amplifier gain of test PV cell | B | 0.05 | 1 | Normal | 2 | 0.025 | 0.025 | ∞ |
| u(f) | Cal. unc. of amplifier gain of std PD | B | 0.05 | 1 | Normal | 2 | 0.025 | 0.025 | ∞ |
| u(g) | Cal. Unc. of std PD | B | 0.3 | 1 | Normal | 2 | 0.15 | 0.15 | ∞ |
| u(h) | Unc. due to wavelength unc. (0.3 nm) | B | 0.06 | 1 | Rectangular | 1.73 | 0.035 | 0.035 | ∞ |
| | Combined uncertainty (k=1) | | | | | | | 0.24 | |

# Uncertainty evaluation of DSR measurement




DSR of PV cell, $s_s(\lambda)$:

$$s_t(\lambda) = \frac{\dfrac{V_t(\lambda)}{V_{t,m}(\lambda)\cdot G_t}}{\dfrac{V_s(\lambda)}{V_{s,m}(\lambda)\cdot G_s}} s_s(\lambda) + \Delta s_\lambda(\lambda) + \Delta s_T(\lambda) + \Delta s_B(\lambda) \quad (7)$$

$s_s(\lambda)$ : spectral responsivity of reference photodiode;

$V_t(\lambda)$ & $V_{t,m}(\lambda)$: signal & monitor voltages of test PV cell;

$G_t$ : Gain of pre-amplifier for test PV cell measurement

$V_s(\lambda)$ & $V_{s,m}(\lambda)$ : signal & monitor voltages of ref photodiode;

$G_s$ : Gain of pre-amplifier for ref photodiode measurement

$\Delta s_\lambda(\lambda)$: wavelength error of monochromator

$\Delta s_T(\lambda)$: Uncertainty due to temperature effect

$\Delta s_B(\lambda)$: Uncertainty due to bias light instability

# Unc equation of DSR calibration

The main sources of uncertainty can be modelled from eq. (7) (only relative measurement components and temperature effect) through partial differentiation. Assuming all components are not correlated, relative uncertainty, $u(s_t)/s_t$, can be derived as follows:

$$\left(\frac{u(DSR)_t}{(DSR)_t}\right)^2 = \left(\frac{u(V_t)}{V_t}\right)^2 + \left(\frac{u(V_s)}{V_s}\right)^2 + \left(\frac{u(G_s)}{G_s}\right)^2 + \left(\frac{u(G_t)}{G_t}\right)^2 + \left(\frac{u(\Delta s_\lambda)}{s_t}\right)^2 + \left(\frac{u(\Delta s_T)}{s_t}\right)^2 + \left(\frac{u(\Delta s_B)}{s_t}\right)^2$$

| **Unc type** | **Uncertainty component** | |
|---|---|---|
| $u(V_t)/V_t$ | Signal repeatability of test PV cell | Unc. due to positioning of test PV cell |
| $u(V_s)/V_s$ | Signal repeatability of std PD | Unc. due to positioning of std PD |
| $U(G_s)/G_s$ | Calibration uncertainty of gain of amplifier of std PD | |
| $U(G_t)/G_t$ | Calibration uncertainty of gain of amplifier of test PV cell | |
| $U(\Delta s_\lambda)/s_t$ | Uncertainty due to wavelength calibration of monochromator | |
| $U(\Delta s_T)/s_t$ | Uncertainty due to temperature effect | |
| $U(\Delta s_B)/s_t$ | Uncertainty due to bias light instability and bias beam uniformity | |

# Unc budget of DSR calibration (650 nm)

| u(x) | Source of uncertainty | type | Value (%) | $C_i$ | Probability distribution | k | $u(x_i)$ (%) | $u_i(y)$ (%) | DoF |
|---|---|---|---|---|---|---|---|---|---|
| u(CT) | Signal repeatability of test PV cell | A | 0.57 | 1 | Normal | 1 | 0.57 | 0.57 | 2 |
| u(a1) | Unc. due to positioning of test PV cell | B | 0.1 | 1 | Rectangular | 1.73 | 0.06 | 0.06 | ∞ |
| u(CR) | Signal repeatability of std PD | A | 0.46 | 1 | Normal | 1 | 0.46 | 0.46 | 2 |
| u(c1) | Unc. due to positioning of std PD | B | 0.1 | 1 | Rectangular | 1.73 | 0.06 | 0.06 | ∞ |
| u(e) | Cal. unc. of amplifier gain of test PV cell | B | 0.05 | 1 | Normal | 2 | 0.025 | 0.025 | ∞ |
| u(f) | Cal. unc. of amplifier gain of std PD | B | 0.05 | 1 | Normal | 2 | 0.025 | 0.025 | ∞ |
| u(g) | Unc. due to wavelength unc. (0.3 nm) | B | 0.06 | 1 | Rectangular | 1.73 | 0.035 | 0.035 | ∞ |
| u(h) | Uncertainty due to temperature effect (+/-1$^{o}$C) | B | 0.076 | 1 | Rectangular | 1.73 | 0.044 | 0.044 | ∞ |
| u(i) | Uncertainty due to bias light instability and non-uniformity | B | 0.5 | 1 | Rectangular | 1.73 | 0.29 | 0.29 | ∞ |
| | Combined uncertainty (k=1) | | | | | | 0.80 | | |

# Uncertainty evaluation for $I_{sc}$ under STC

- Sources of uncertainty for $I_{sc}$ under STC
  - Calibration uncertainty of ref PDs
  - Aperture area calibration uncertainty of PDs
  - Area measurement of DUT
  - Positioning of Ref PD and DUT
  - Probe beam uniformity
  - Bias beam uniformity: Xe, Halogen
  - DC Current measurement: repeatability, drift during scan, source meter, shunt resistance
  - AC current measurement (relative): repeatability, linearity of amplifiers & lock-in amplifier
  - AC current measurement (absolute): probe beam uniformity, aperture area of Ref PDs, repeatability
  - DSR measurement: bias stability and uniformity

# Uncertainty budget of $I_{STC}$ calibration

The uncertainty budget of $I_{STC}$ calibration is as shown in table below:

| Unc type | Uncertainty component | Unc value (%) |
|---|---|---|
| A | Repeatability of DSR measurements | 0.5 |
| B | Absolute SR calibration at specified wavelength | 0.24 |
| B | Relative SR calibration | 0.74 |
| B | Positioning of test PV cell and ref PD | 0.1 |
| B | Spectral mismatch between bias radiation and reference solar spectrum | 0.2 |
| B | Non-linearity of the amplifiers | 0.1 |
| B | Mismatch of test PV cell area and std PD area (after correction) | 0.1 |
| B | Temperature effect on test PV cell (+/- 1 K) | 0.08 |
| B | Short circuit current ($I_{SC}$) measurement by DVM and std resistor | 0.05 |
| | Combined uncertainty (k=1) | 1.0 |

# Summary

- DSR system has been set up at NMC-A*STAR
- Absolute responsivity at 650 nm of the test PV cell was calibrated at NMC with uncertainty of 0.5% (k=2)
- Deviation of absolute responsivities at 650 nm between NMC and PTB calibrations is -0.58%
- Short circuit current under standard test conditions ($I_{STC}$) of the test PV cell was calibrated at NMC with uncertainty of 2.0% (k=2)
- Deviation of $I_{STC}$ between NMC and PTB calibration is -0.31%

# Future works

- Study and improve repeatability of relative SR measurements
- Study and improve repeatability of DSR measurements
- Investigation of bias light instability effect on $I_{STC}$ measurements
- Investigation of temperature effect on $I_{STC}$ measurements
- Investigation of spectral bandwidth effect on $I_{STC}$ measurements

# Acknowledgement

This work is funded by Science & Engineering Research Council of A*STAR of Singapore

The Authors would like to thank **Dr Stefan Winter** of PTB for information on the PTB DSR system and **Dr Keith Emery** of NREL for advice on signal detection system

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# THANK YOU !