Test Method for Current-Voltage Characterization of Perovskite PV-Modules

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TÜV Rheinland Solar

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Agenda overview

- Introduction and Motivation
- IV measurement test method
  - ✓ Metastability
  - ✓ Hysteresis
  - ✓ Reproducibility
- Uncertainty of spectral mismatch
- Linearity
- Measurement Uncertainty
- Summary and Conclusions

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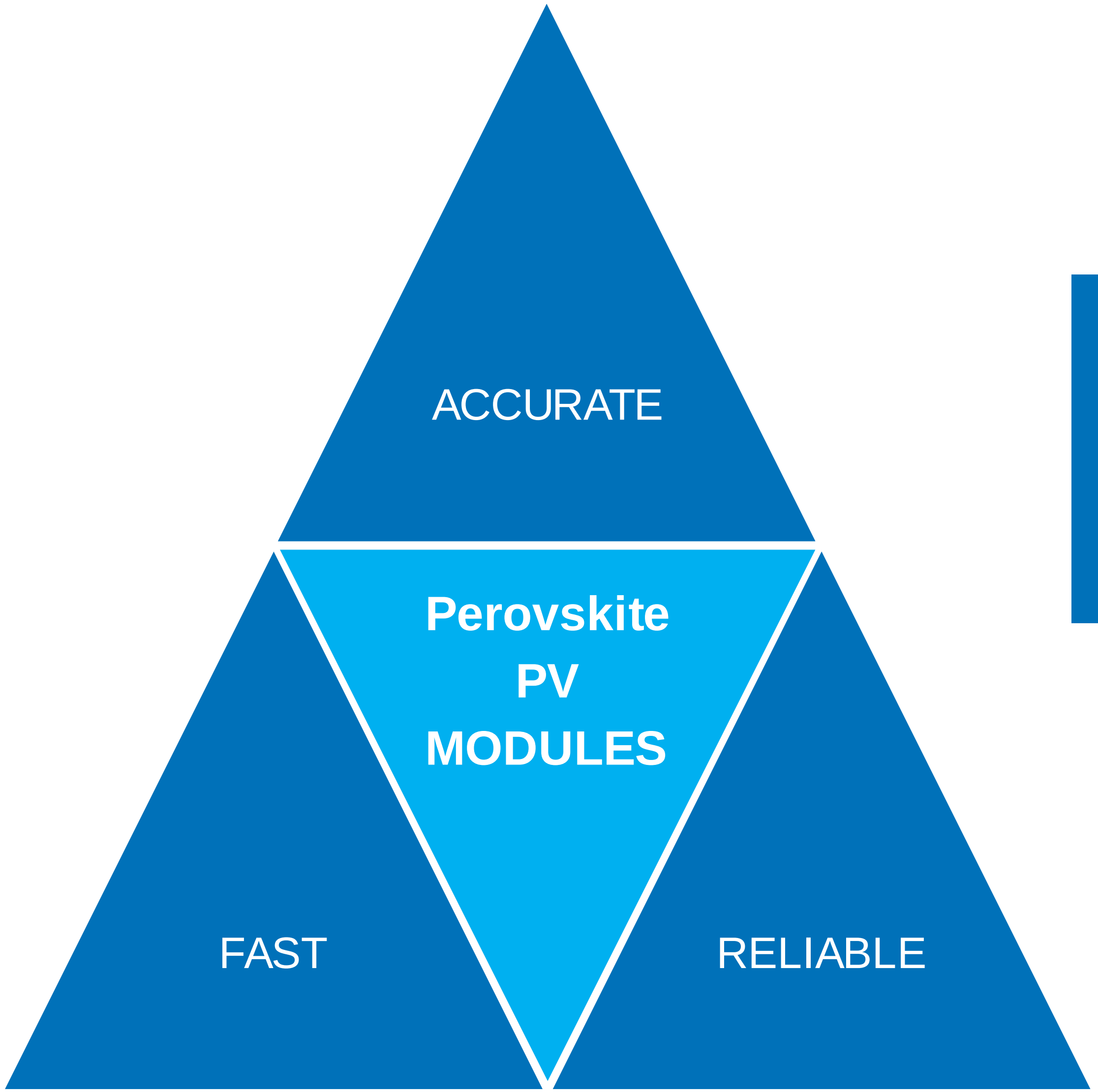
Objective

- Source: https://www.microquanta.com/en/

Objective

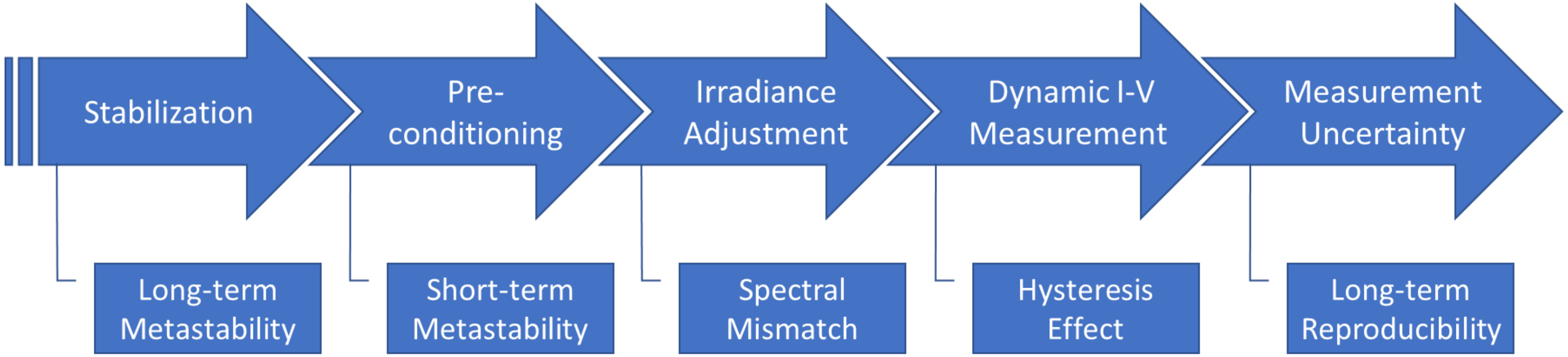


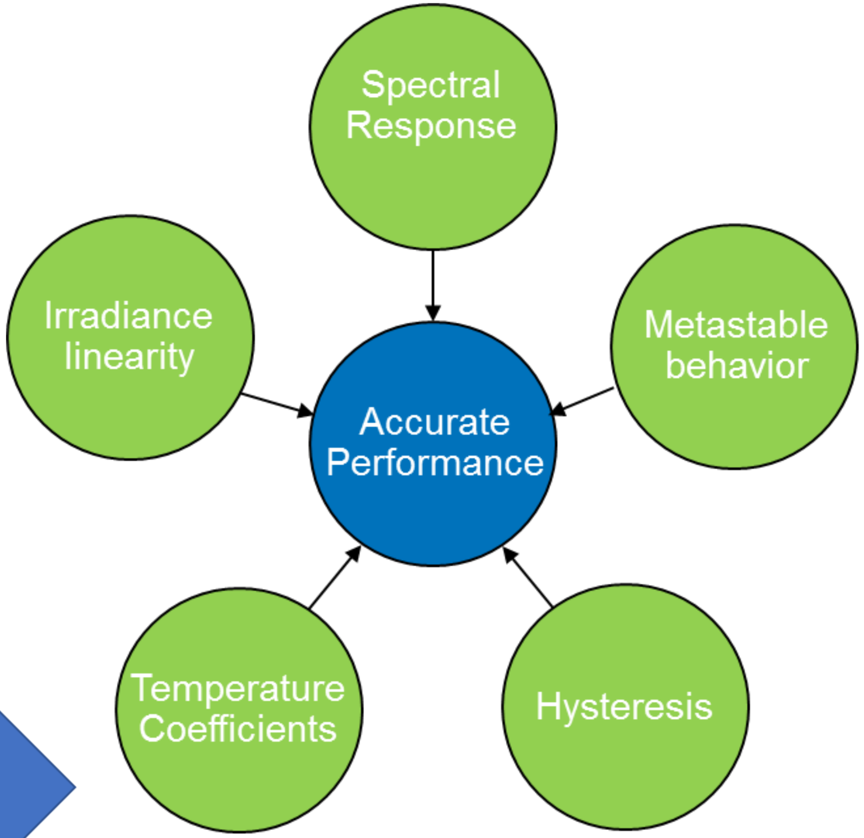
!

GUARANTEED
ACCEPTABLE
UNCERTAINTY

Review of Measurement Problems for Perovskite PV-Modules

- IV measurement in steady-state simulator: metastability, hysteresis, irradiance linearity, temperature linearity
- Spectral Response: slow response, metastability
- Measurement uncertainty





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Test method

SAMPLES

Perovskite PV modules: glass-glass, 2 m x 1 m;

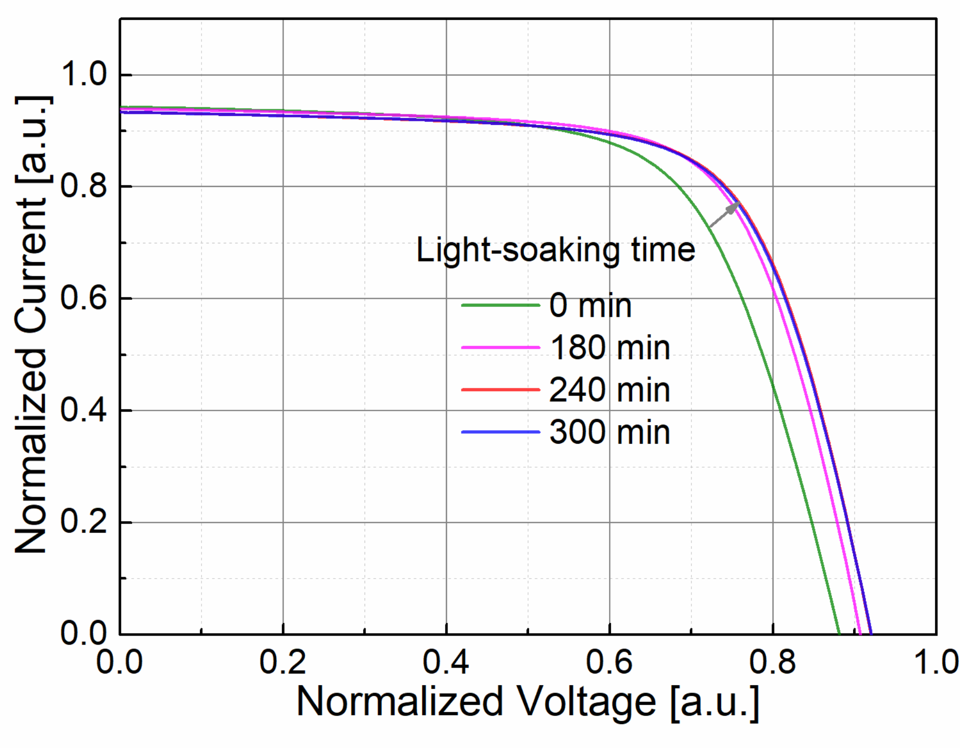
EXPERIMENTAL SETUP

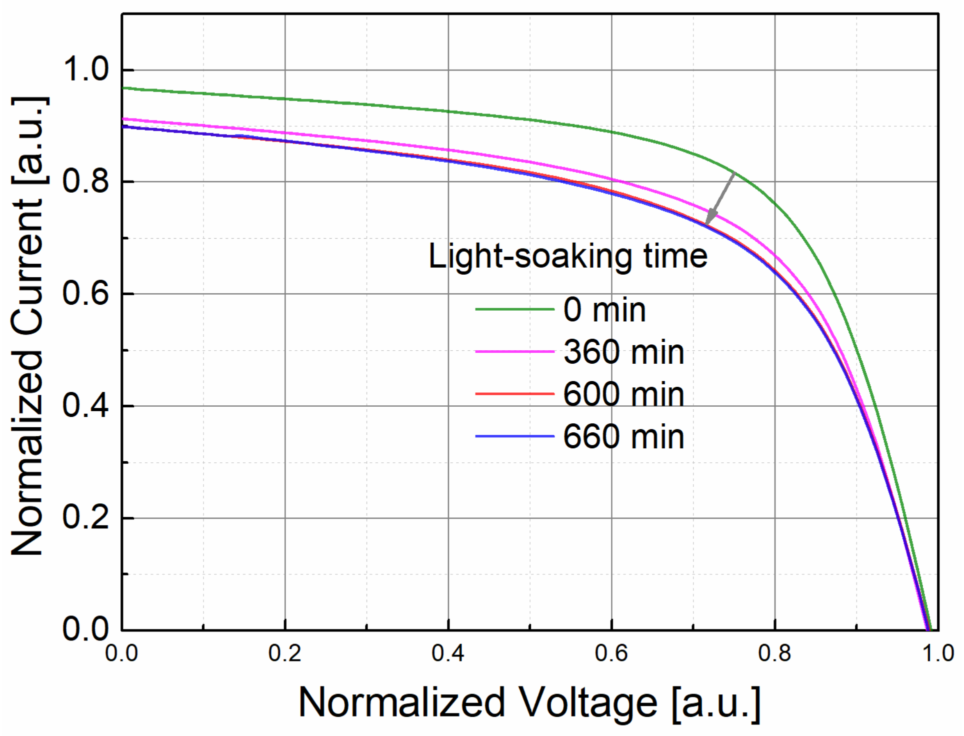
- Solar simulator: BBA+ steady-state metal halide lamp;
- Temperature control: air conditioners and electrical fans;
- DC electronic load: Keithley 2380-500-30;

TEST PROCEDURE

1. Preconditioning: approx. 10 h, constant illumination, close to Vmp;
2. Dynamic I-V curve at 33 ± 2 °C: from Voc to Isc, typical sweep time 3-5 min;
3. Dynamic I-V curve at higher temperatures: typically 40 °C, 50 °C, 60 °C;
4. Calculation of temperature coefficients;
5. I-V curve correction to STC (according to IEC 60891);
6. Evaluation of the measurement uncertainty.

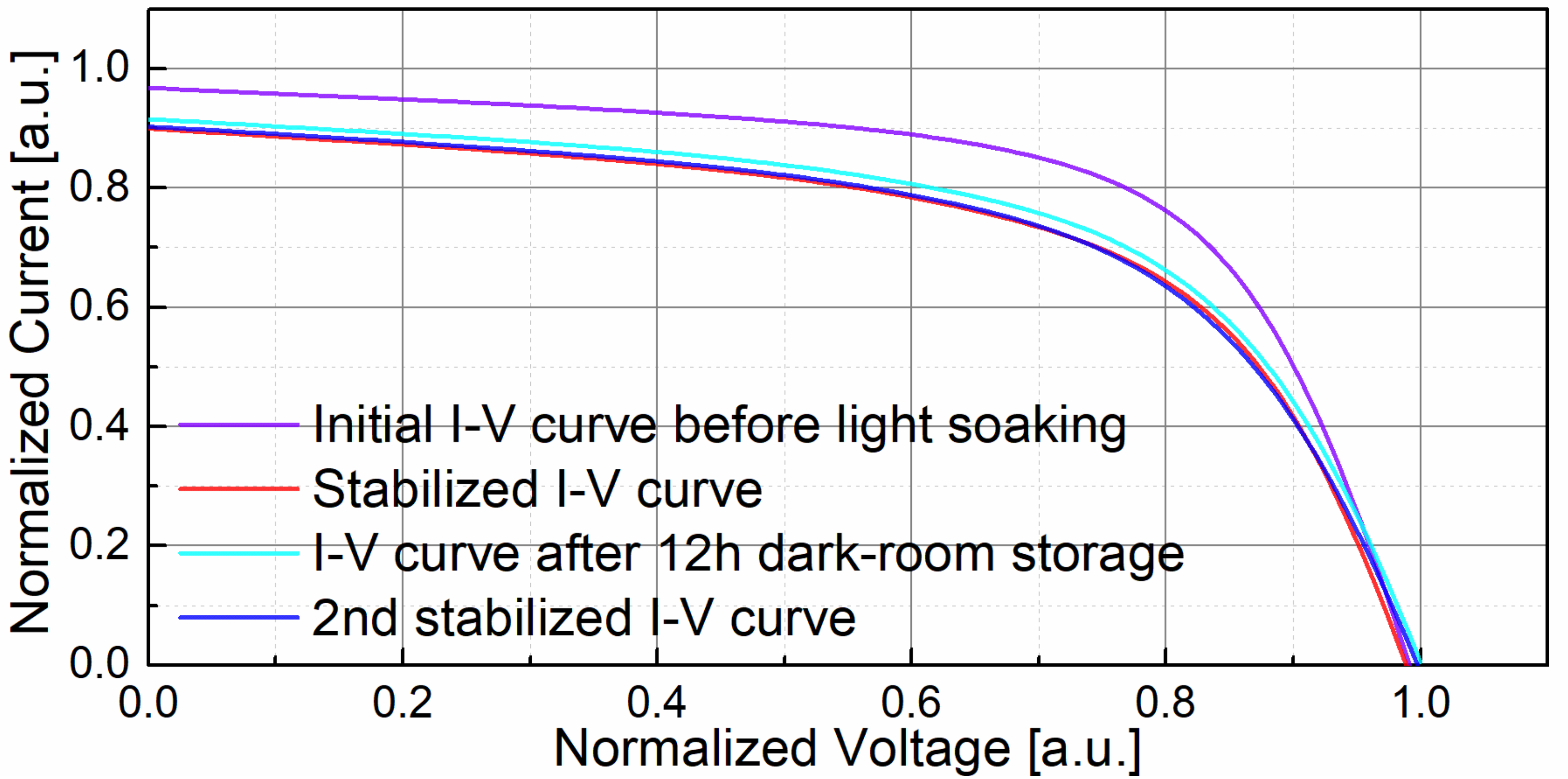
Long-term metastability





- Different perovskite modules may exhibit different stabilization profiles (degradation or even recovery)
- Initial light soaking at MPP mode is required to stabilize correctly the sample; else the results are not reproducible.
- IEC 61215 stabilization procedures for thin-film modules can be suitably adopted.

Short-term metastability



- Short-term variations due to reversible degradation and/or annealing, as well as recovery from dark ageing may also occur.

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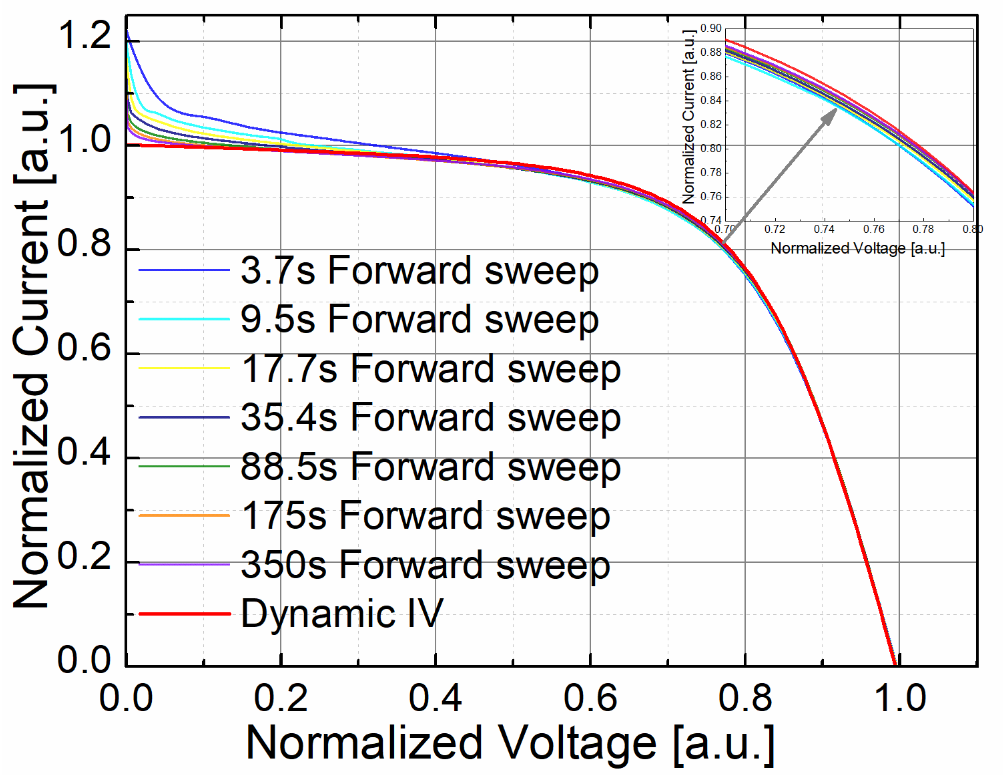
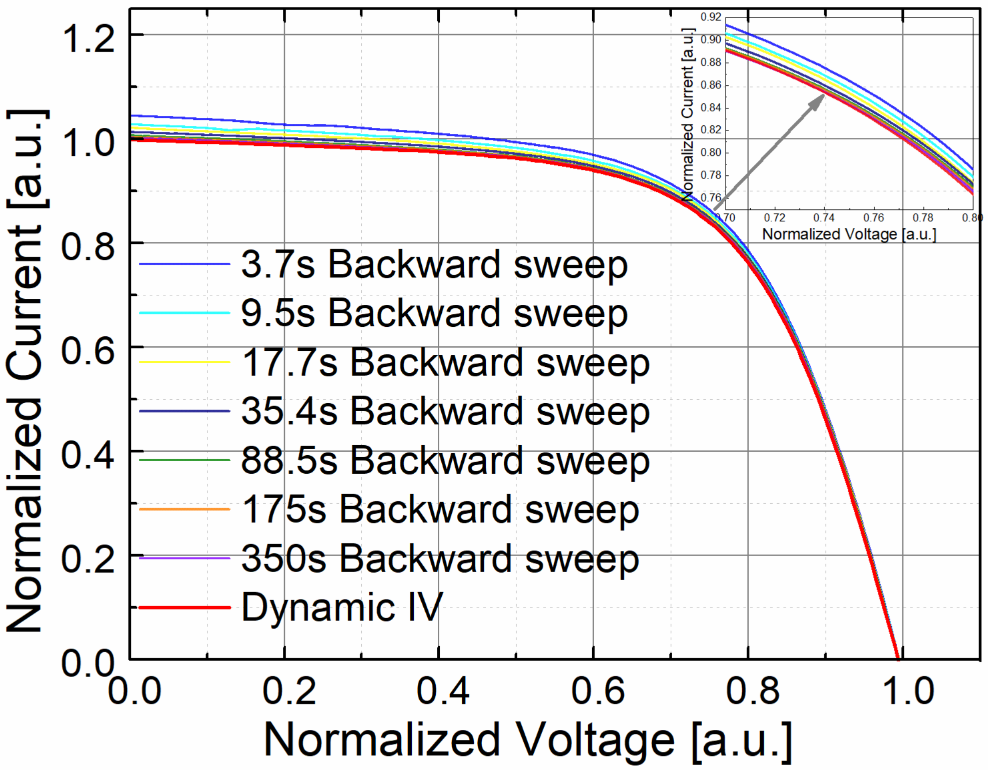
Hysteresis (transient effects)





- Transient effects that can cause hysteresis in measurement.
- Comparison between forward and reverse voltage reveals the magnitude of the errors, but does not lead to accurate measurements (even when measurement time >350s).

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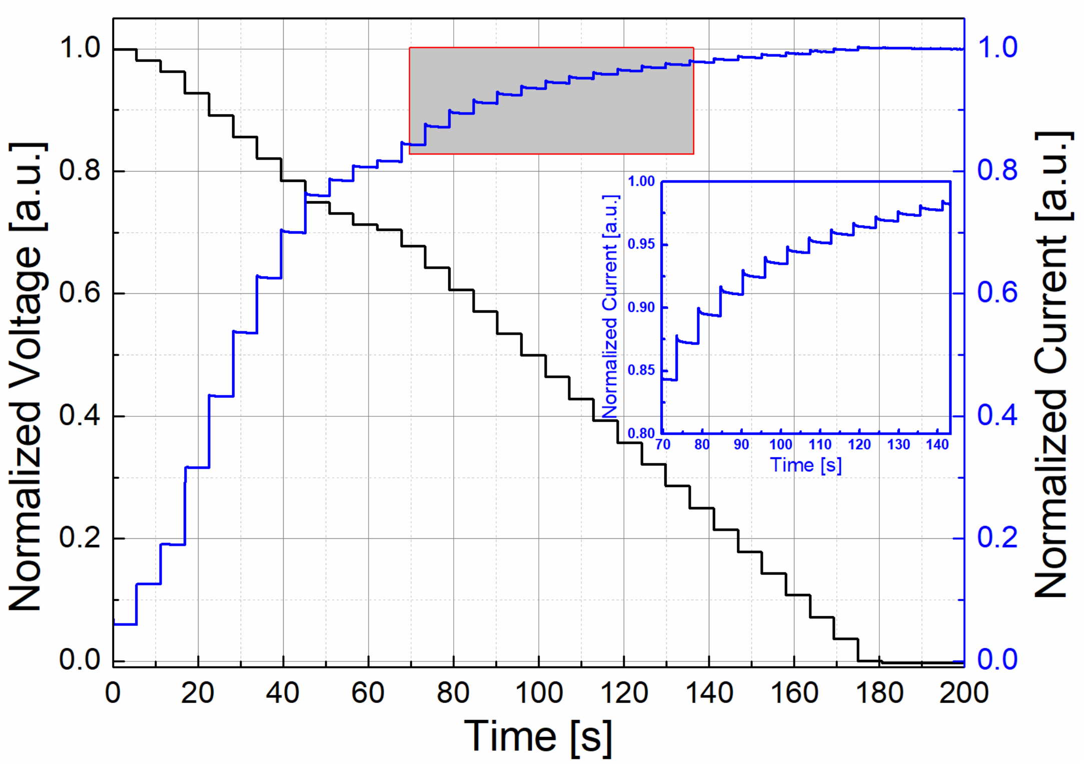
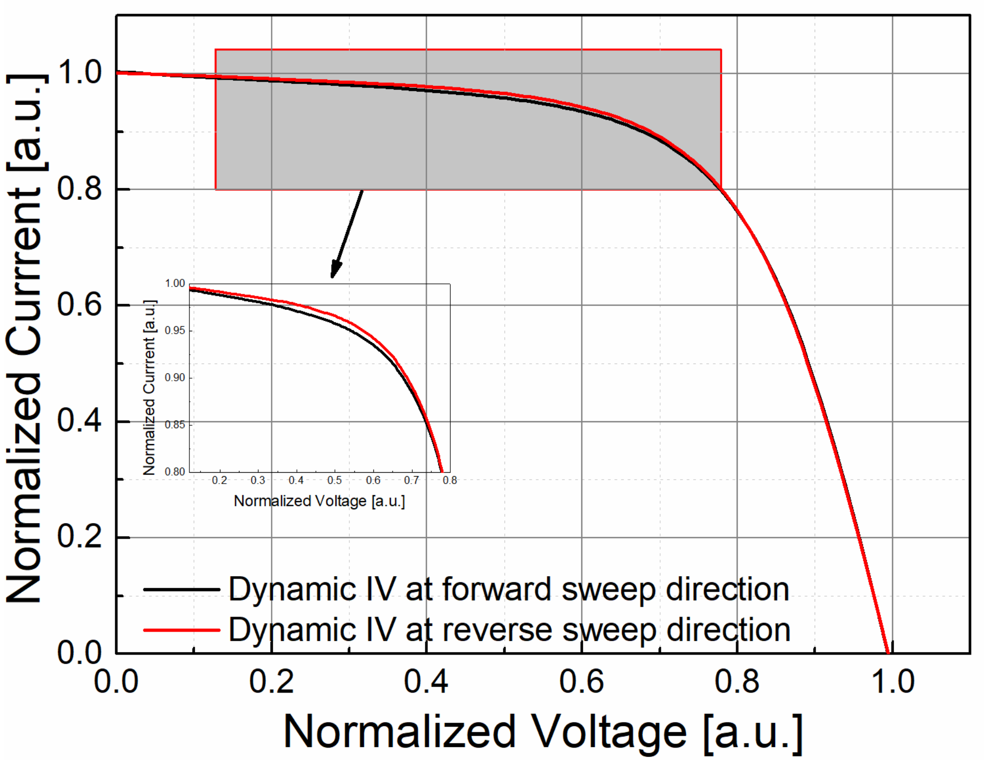
Dynamic IV





- Application of *dynamic IV* resulted in best accuracy and can be effectively utilized to resolve transient effects due to hysteresis.
- Agreement between forward and reverse within 0.3%, or better can be achieved.

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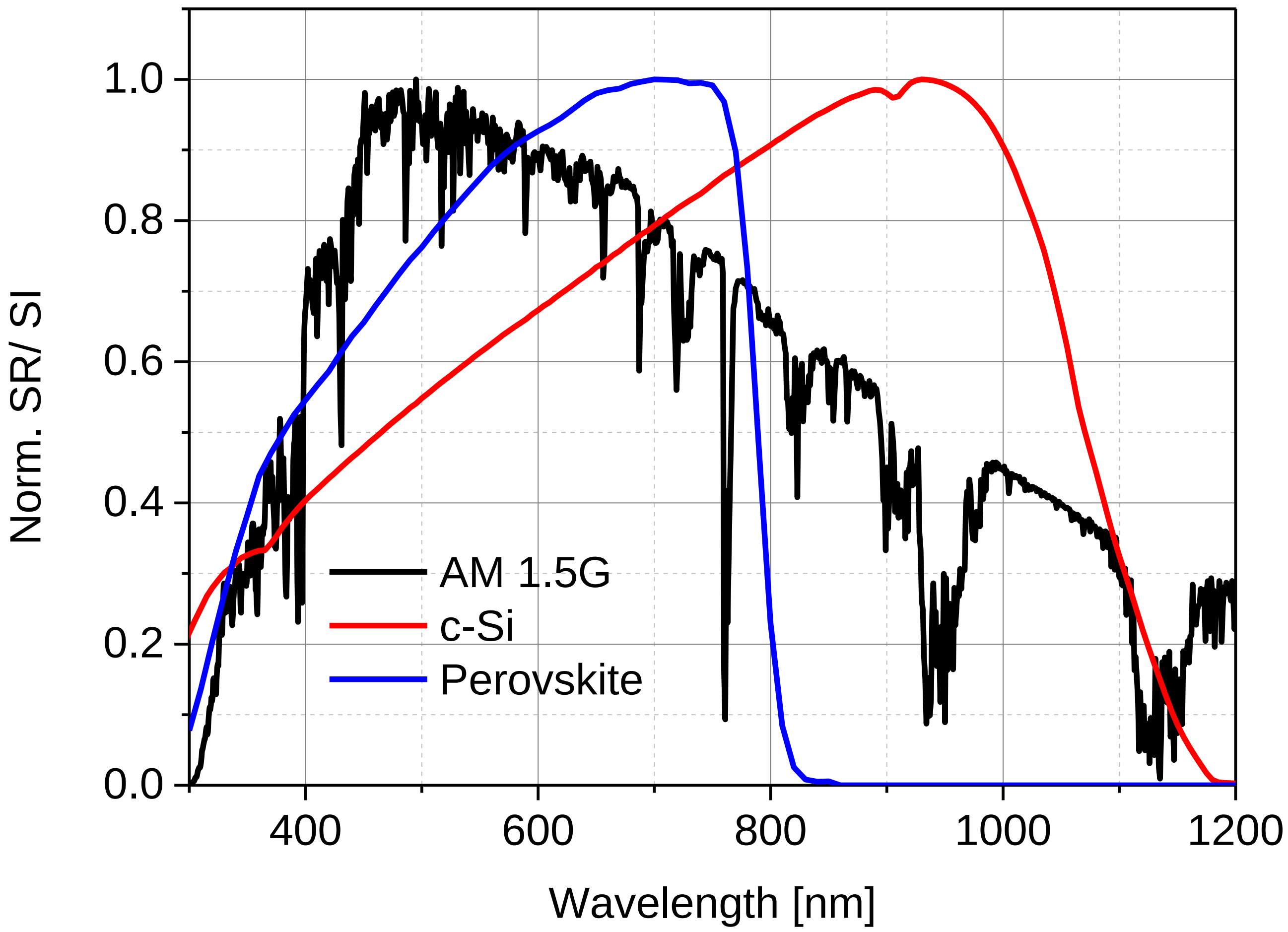
Why is spectral mismatch important?

- **Difference in *SR* between c-Si reference cell and perovskite DUT**

  ⇒ Significant spectral mismatch (up to 10%)

  ⇒ High uncertainty arises from >900 nm (assuming a c-Si reference cell)

  ⇒ Choice of reference cell becomes important



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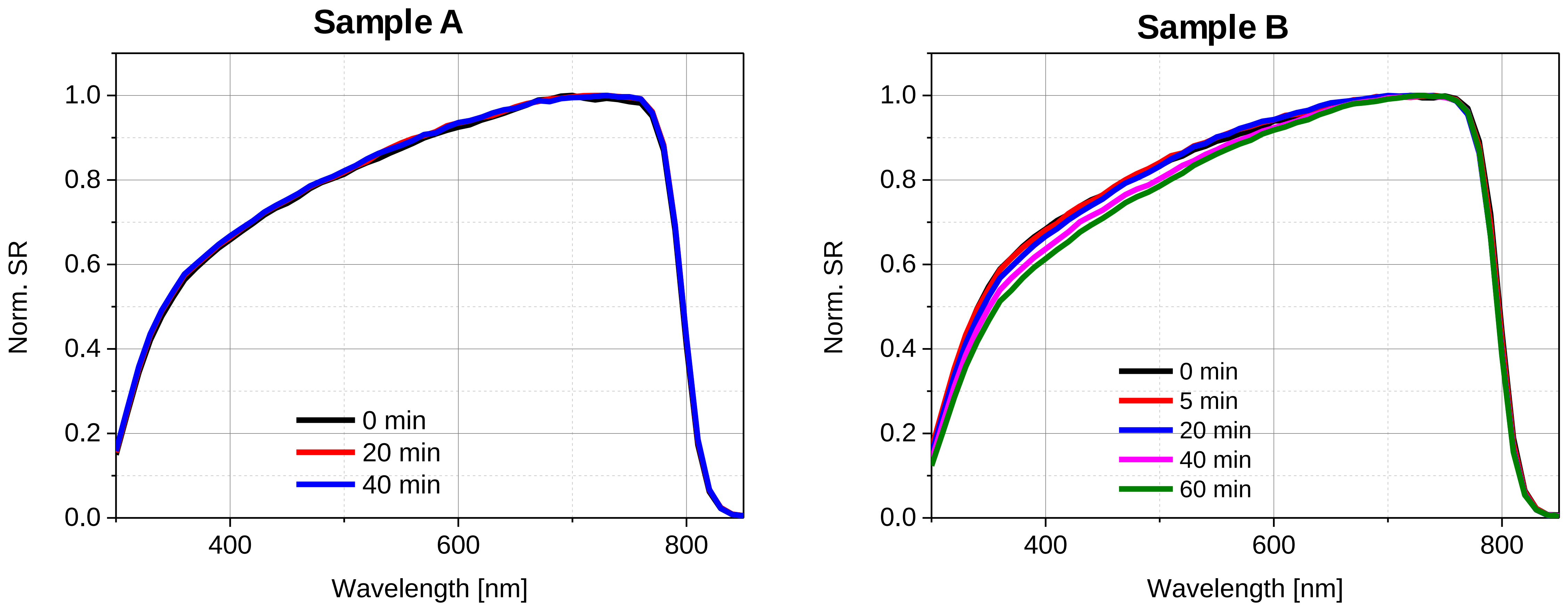
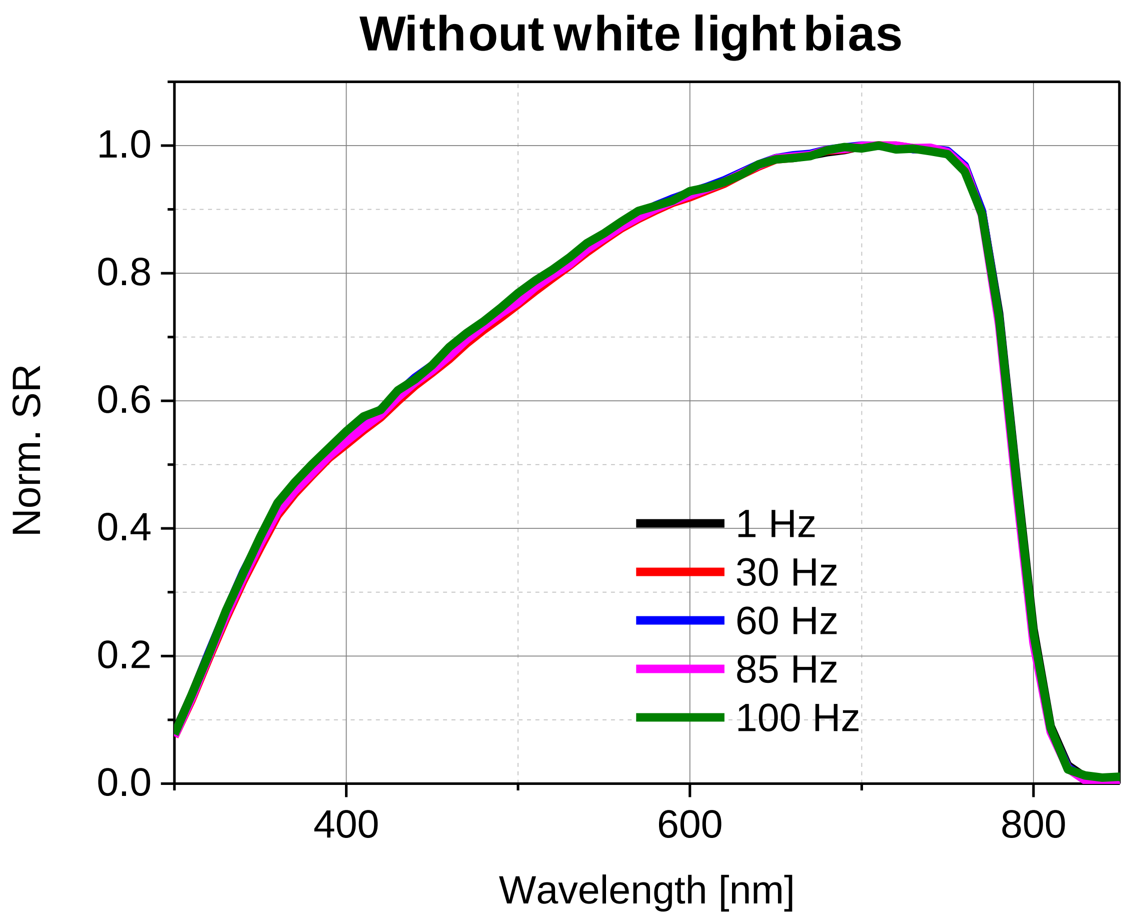
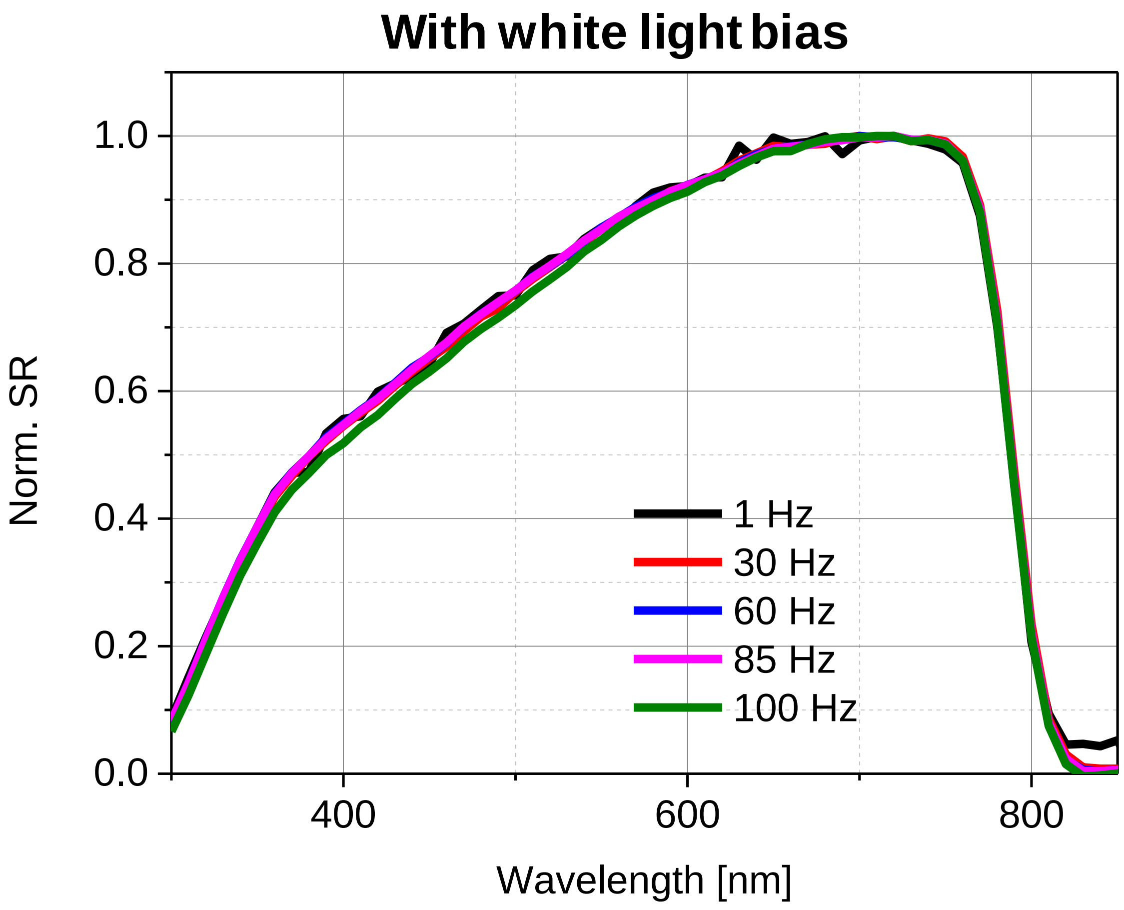
Light soaking effect



- Different PSC samples may exhibit different stabilization profiles.
- Initial light soaking is required to stabilize the spectral responsivity of the sample.

Various chopping frequency





- Chopping frequency does not affect the normalized spectral responsivity of the studied PSC.

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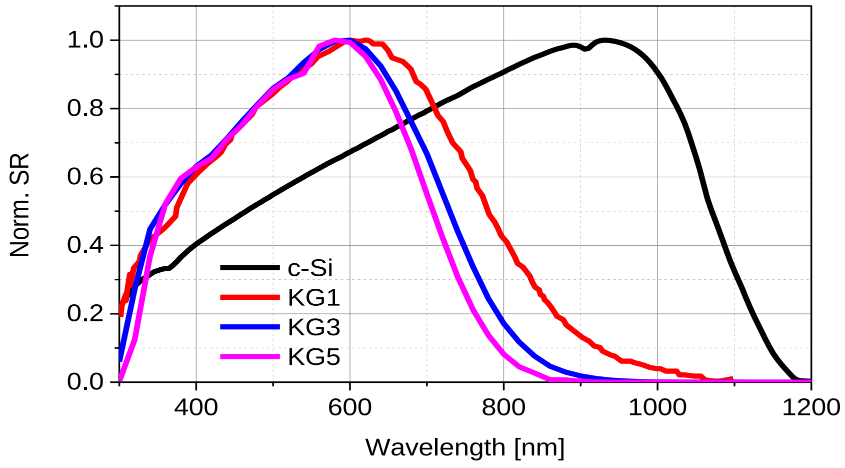
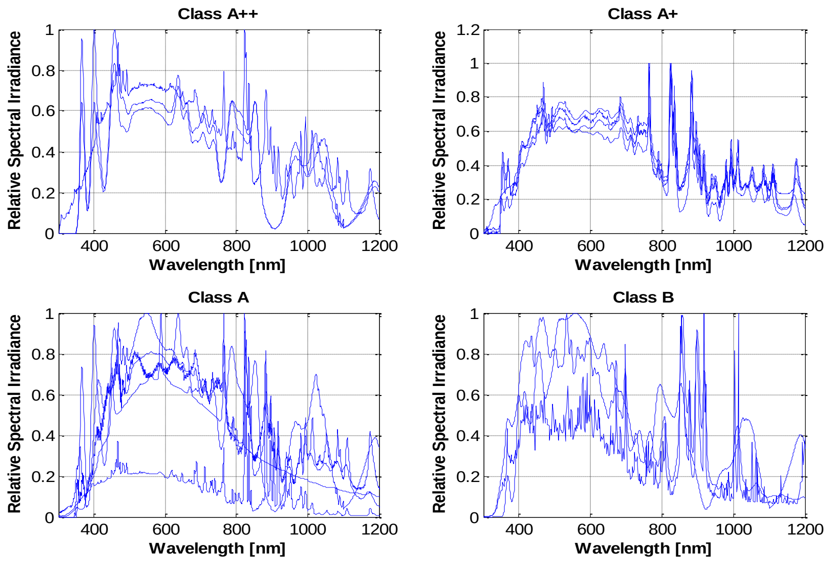
Uncertainty of Spectral Mismatch using Monte Carlo analysis

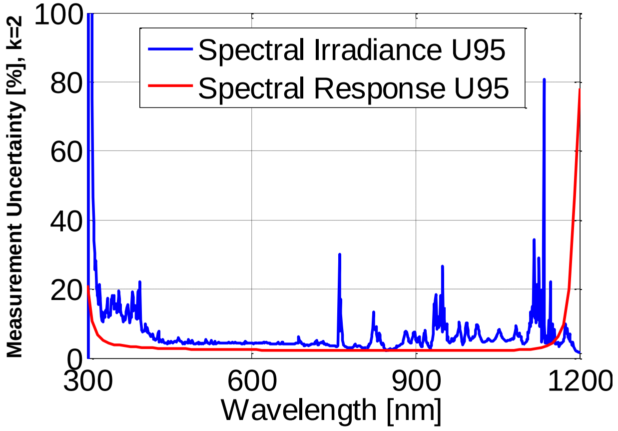




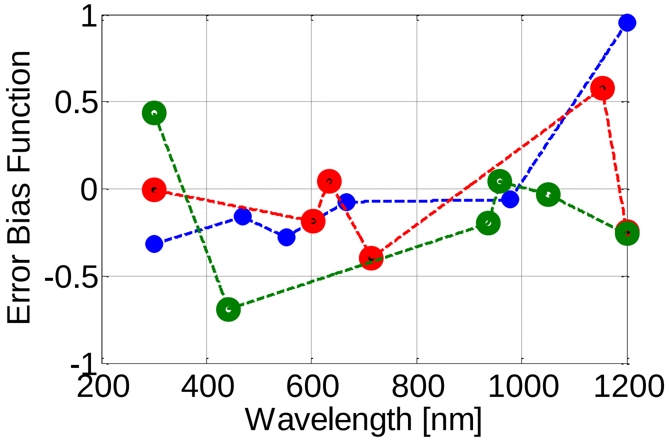
Sample	Type	Qty
DUT *SR*	Encapsulated Perovskite Cells (cut-off wavelength: ~850 nm)	10
Reference Cell *SR*	c-Si unfiltered	1
	c-Si with KG1	1
	c-Si with KG3	1
	c-Si with KG5	1
Solar Simulator Spectra	A++	3
	A+	4
	A	5
	B	3

Uncertainty of Spectral Mismatch using Monte Carlo analysis

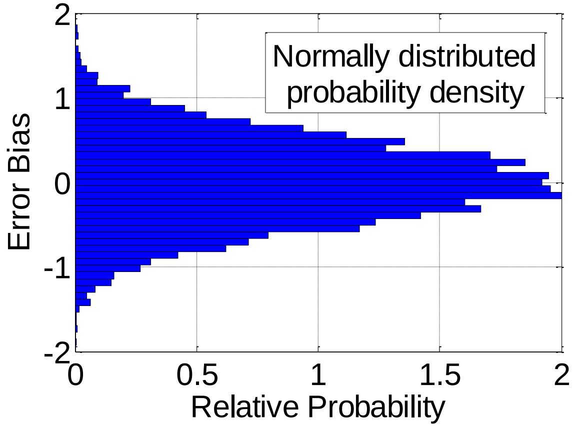
Meas. Uncertainty (k=2)



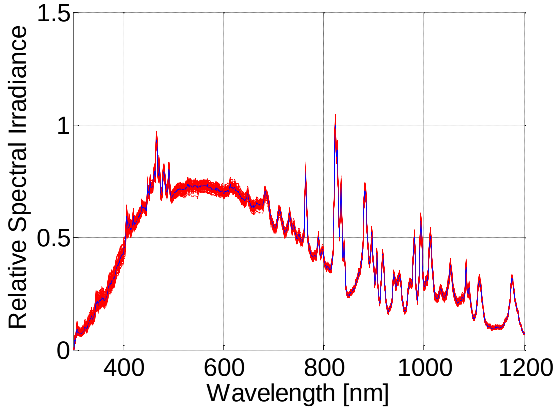
Error Bias Function



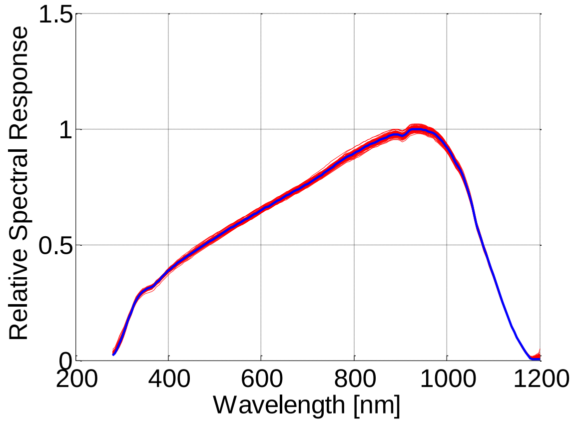
Error Bias Distrib.



Spectral Irradiance with Error Bias



Spectral Response with Error Bias



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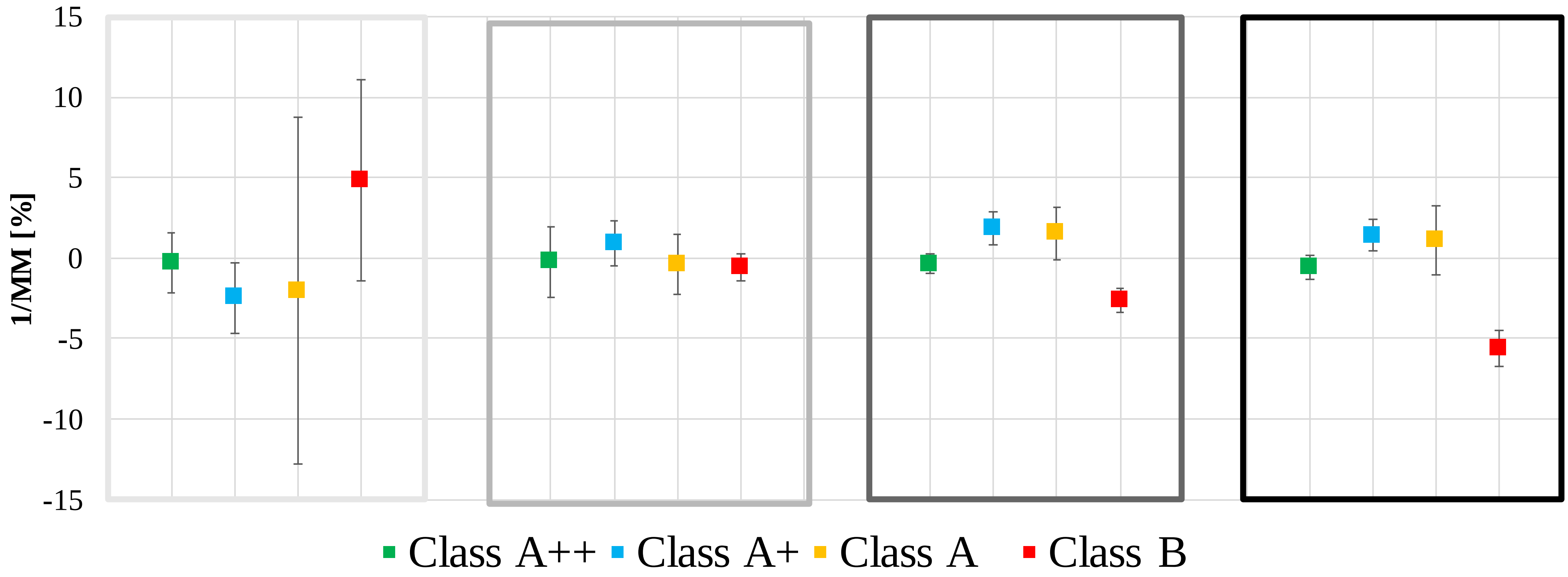
Uncertainty of spectral mismatch factor **without correction**



Reference	c-Si unfiltered	c-Si with KG1	c-Si with KG3	c-Si with KG5
Cut-off:	1250nm	1000nm	850nm	800nm
Perovskite solar cell (DUT) cut-off: 850nm				

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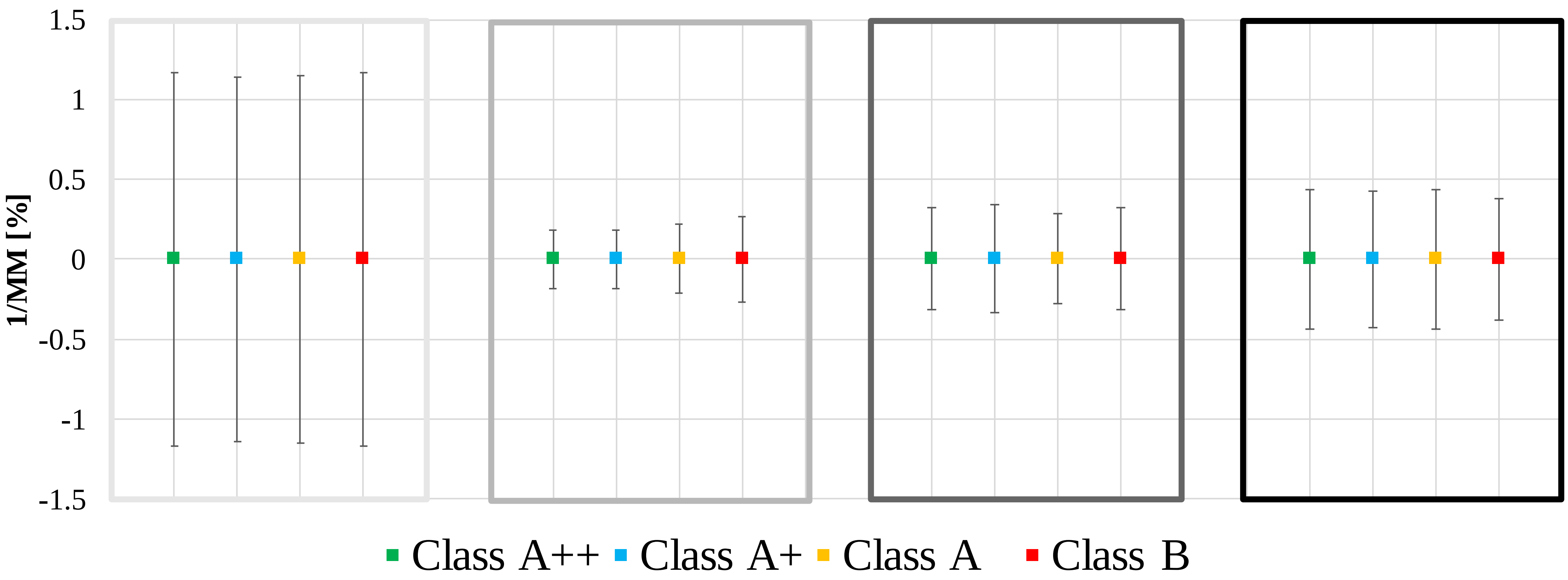
Uncertainty of spectral mismatch factor **with correction**



Reference	c-Si unfiltered	c-Si with KG1	c-Si with KG3	c-Si with KG5
Cut-off:	1250nm	1000nm	850nm	800nm
Perovskite solar cell (DUT) cut-off: 850nm				

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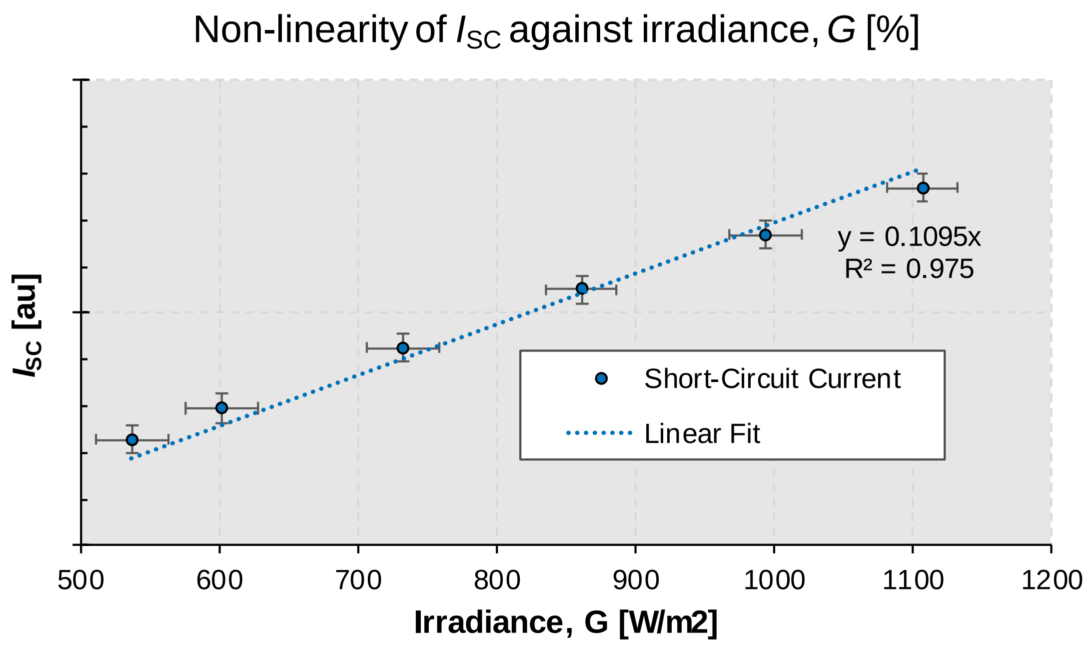
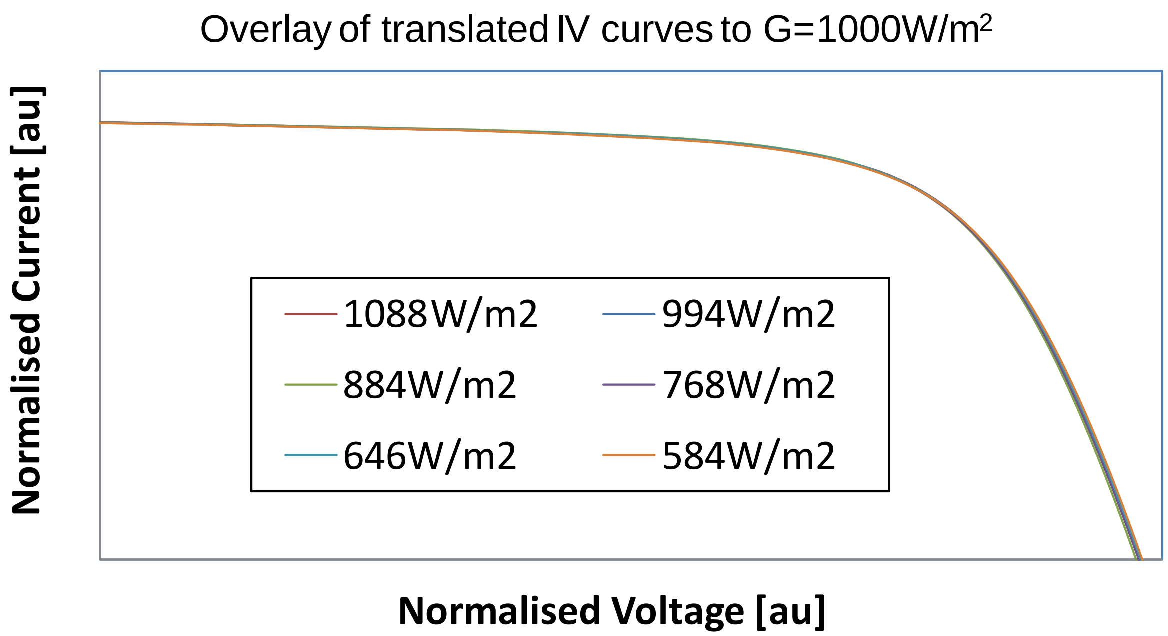
Linearity of I_{SC} with Irradiance





- IEC 60904-10 was utilized to measure the linearity of Perovskite modules with irradiance.
  ⇒ Perovskite devices may exhibit strong non-linearity that needs to be addressed.

- IEC 60891, cor. proc. 2 was utilized to correct *IV* curves and evaluate the agreement in *IV* translation.
  ⇒ Accurate *IV* corrections can be achieved (0.4%)

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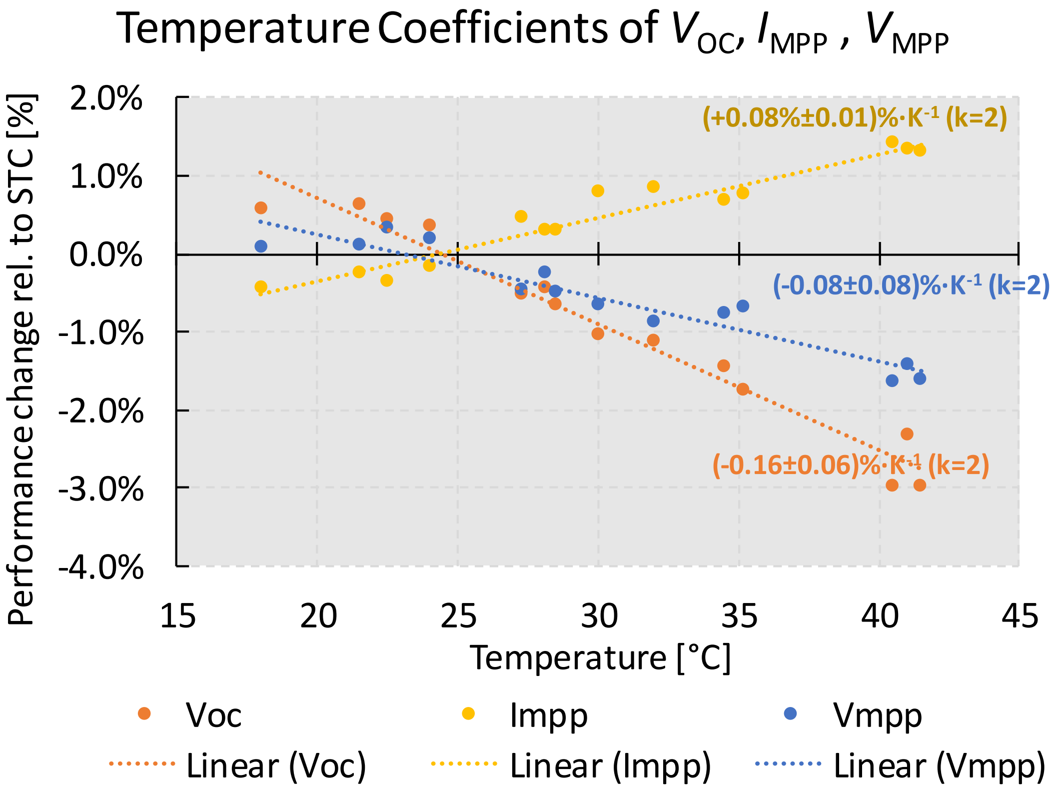
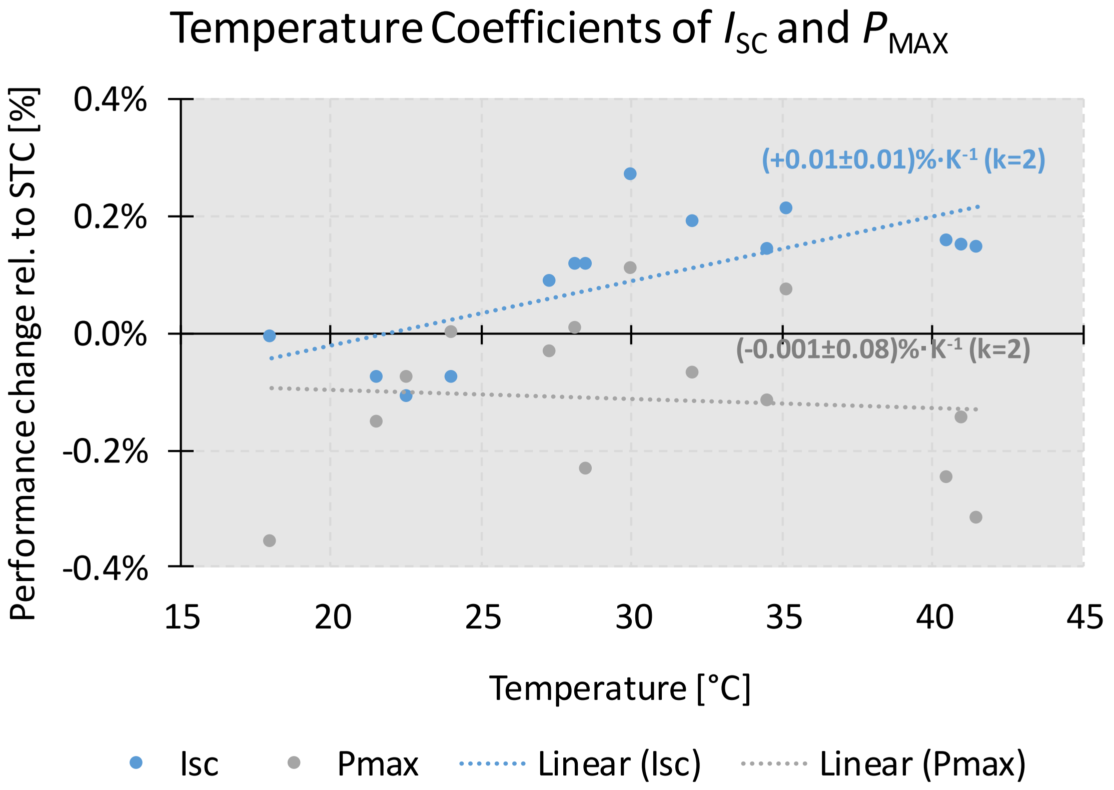
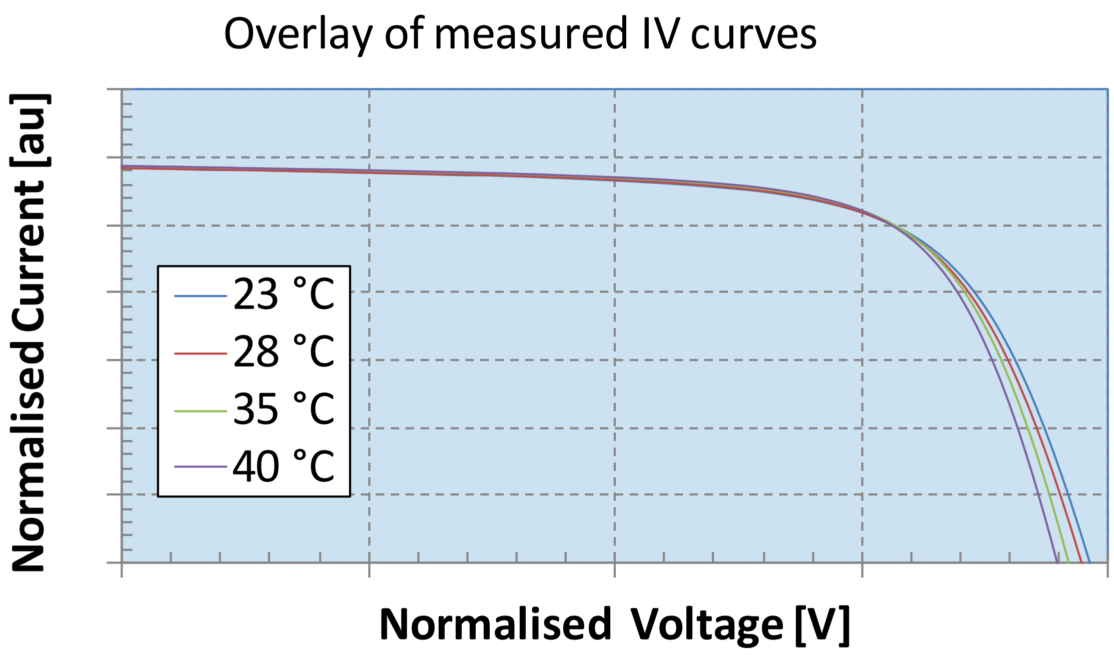
Temperature coefficients

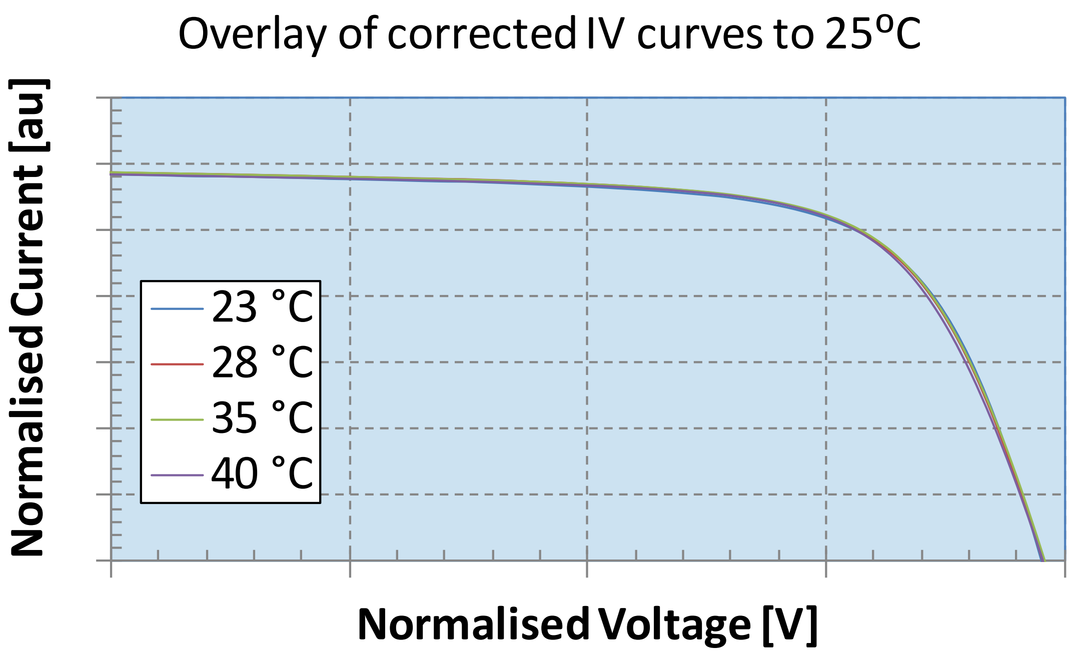




- Temperature coefficients were measured in accordance with IEC 61853 standard.
- *β*, appears sensitive to temperature (-0.16%/K), while *α* (+0.01%/K) and *δ* (0.00%/K) are insensitive to temperature.

Temperature coefficients





- Temperature coefficients were measured in accordance with IEC 60891 standard.
- *β*, appears sensitive to temperature (-0.16%/K), while *α* (+0.01%/K) and *δ* (0.00%/K) are insensitive to temperature.
- IEC 60891, cor. proc. 2 was utilized to correct *IV* curves and evaluate the agreement in *IV* translation. Accurate *IV* corrections can be achieved (0.3%)

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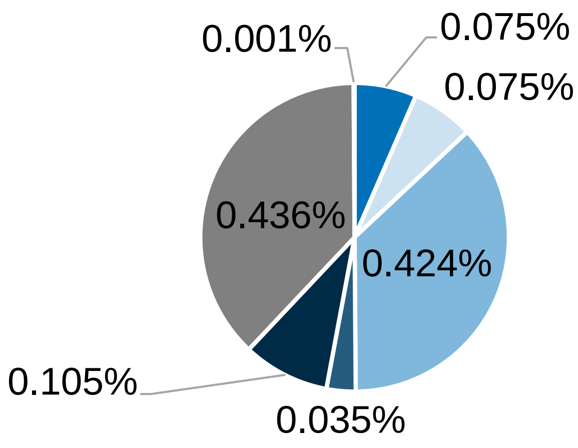
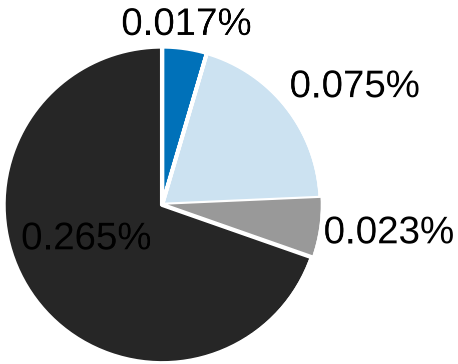
Measurement Uncertainty

Standard Uncertainty Distribution at I_{MPP}



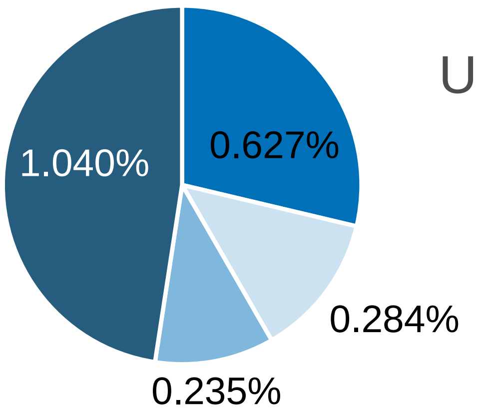
Standard Uncertainty Distribution at V_{MPP}



- Voltage/current measurement
- Device hysterisis
- Non-uniformity of irradiance
- Misalignment
- Positioning
- Reference irradiance
- Temperature-related

Case of Study:
Class BAA+ system
REF: c-Si (filtered)
DUT: PSC

Standard Uncertainty Distribution at P_{MAX}



U_{95} @ P_{MAX}
~ 2.6%

- Impp meas. unc. (excl. reproducibility)
- Vmpp meas. unc. (excl. reproducibility)
- Pmax repeatability
- Pmax reproducibility

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Conclusions

- Due to their **slow response**, **metastable behaviour** and **spectral mismatch**, the characterisation of perovskite technologies is a challenging task.
- **Light soaking** is required to stabilise perovskite devices. **IEC 61215 stabilization procedures** for **thin film modules** is a good starting basis and could be adopted accordingly.
- **Dynamic IV** can be utilized to counter hysteresis artefacts.
- **Spectral mismatch correction** can limit the **uncertainty** of spectral mismatch within **± 1.3%, k=2**. The **combination** of **spectral mismatch correction** and a **matched reference device** can reduce the uncertainty further to **±0.2%, k=2**.
- The **linearity** of Perovskite devices **may differ to ideal** behavior. The later is particularly important, if long range irradiance corrections are applied.
- **Measurement uncertainty** of Perovskite devices is an **object of current research**. It is **limited** by the measurement **reproducibility** (< 2.0%, k=2). The **uncertainty at P_{MAX}** can reach **2.6%, k=2** in a controlled measurement environment.

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Thank you for your attention !

More information can be found:
Q.Gao, C.F.J.Lau, E.Lee, C. Monokroussos, “Test Method of Current-voltage Characteristaion of Perovskite PV-module”, EUPVSEC 2019. https://www.eupvsec-proceedings.com/proceedings?fulltext=perovskite&paper=48720

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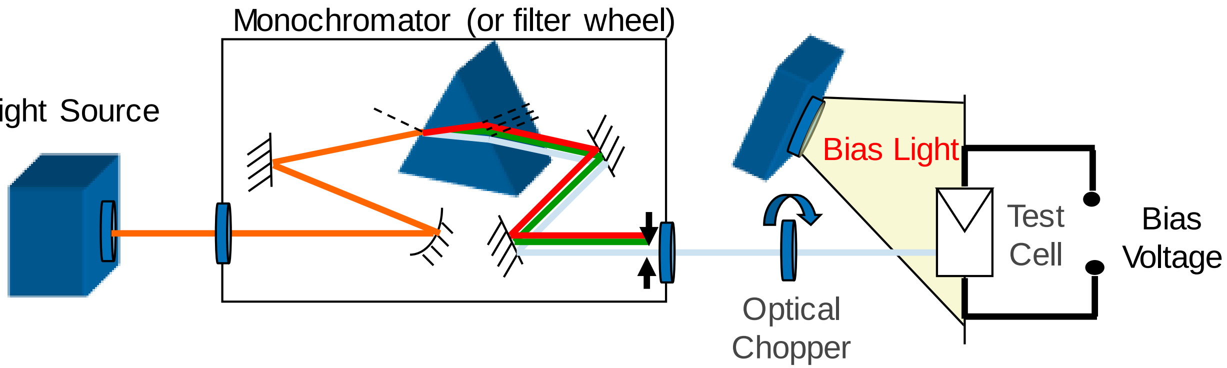
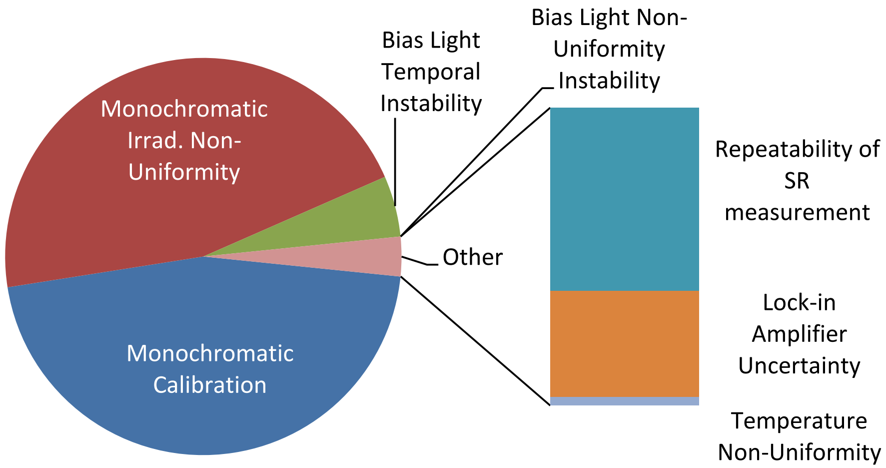
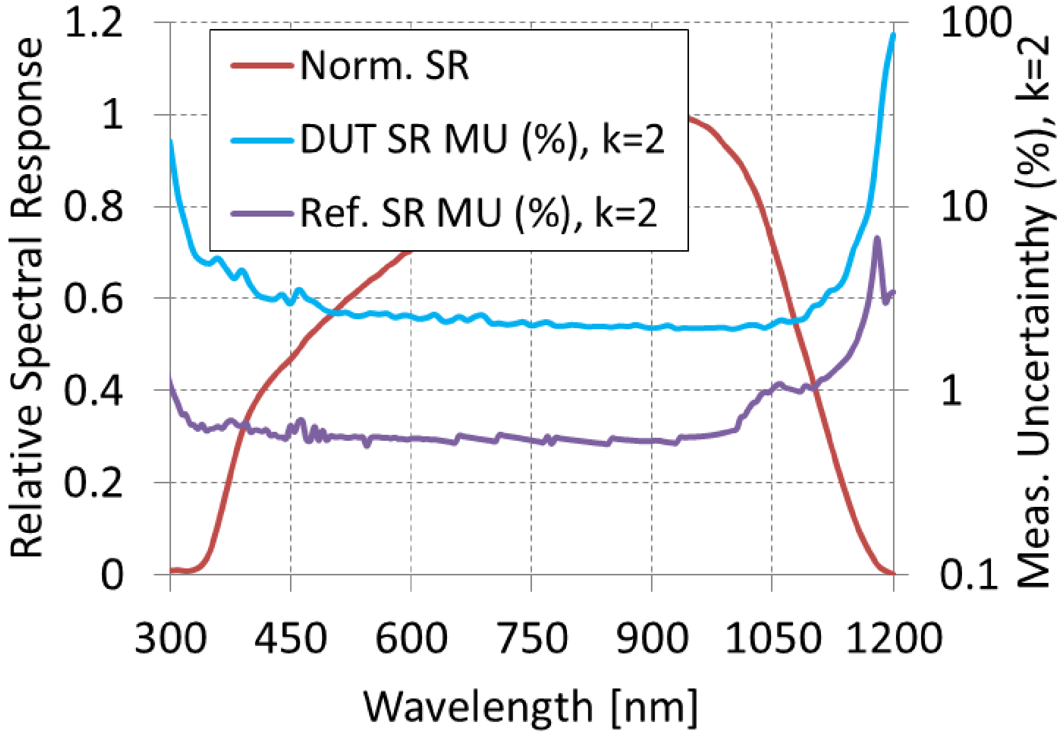
Example of Uncertainty in Relative Spectral Response



Example of meas. unc. distribution @950nm
±2.16%, k=2





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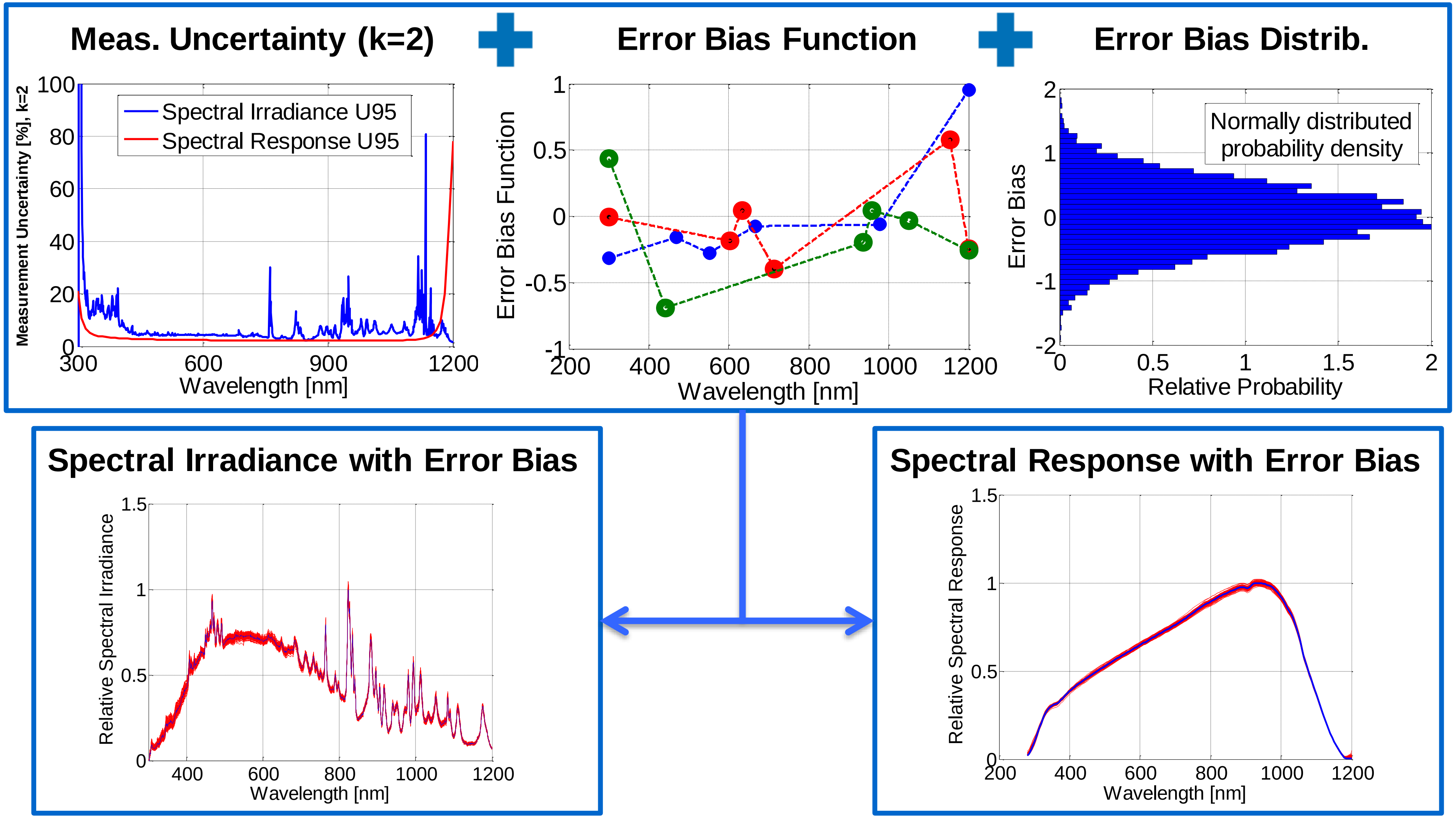
Simulating Random Error Bias



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