

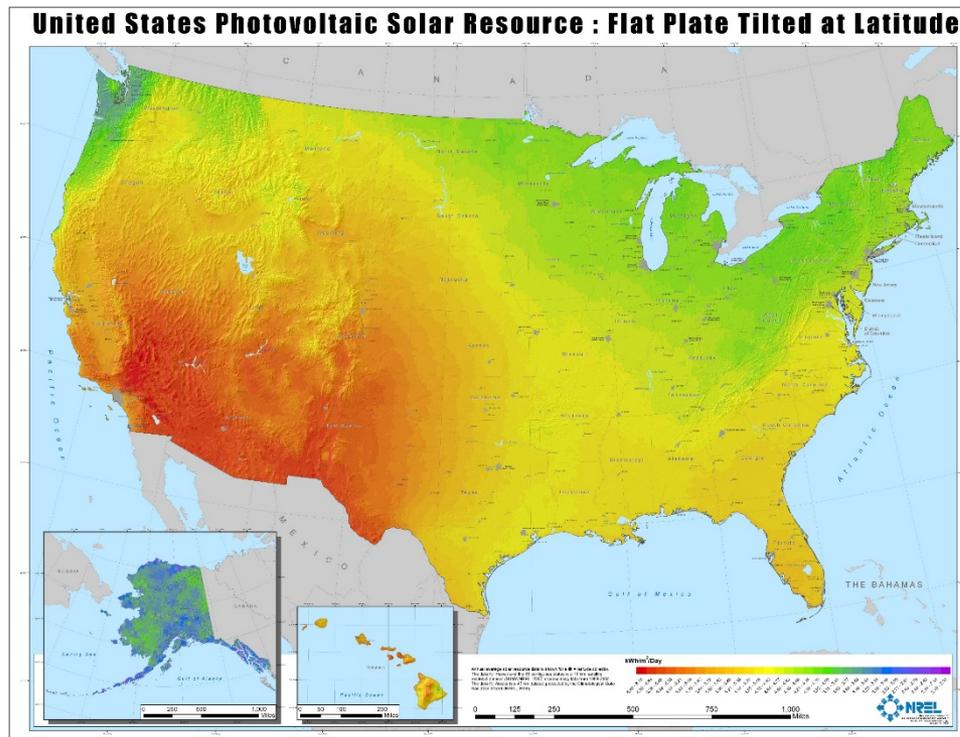
# Radiometric Measurement Traceability Paths for Photovoltaic Calibrations

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NIST



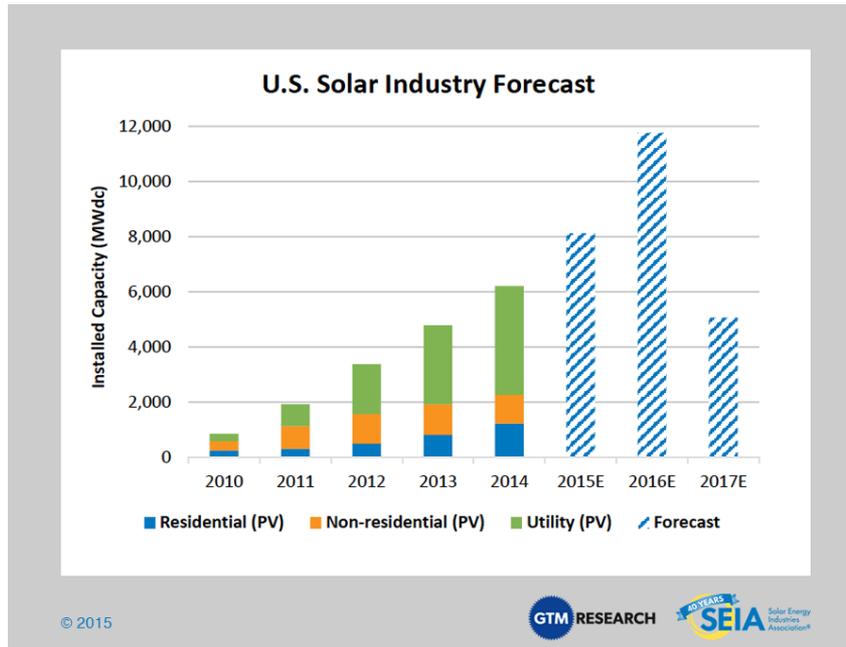
# Solar energy and PV

- Solar radiation: free and abundant!
- Photovoltaics (PV): direct energy conversion from solar to electricity
- PV is a clean renewable energy source (no air pollution, quiet operation etc)
- Significant reduction in costs (from \$1000/W in 1959 to ~\$1/W in 2012)
- Have reached grid parity in California, Texas, New York and others by 2016.



# PV at a glance

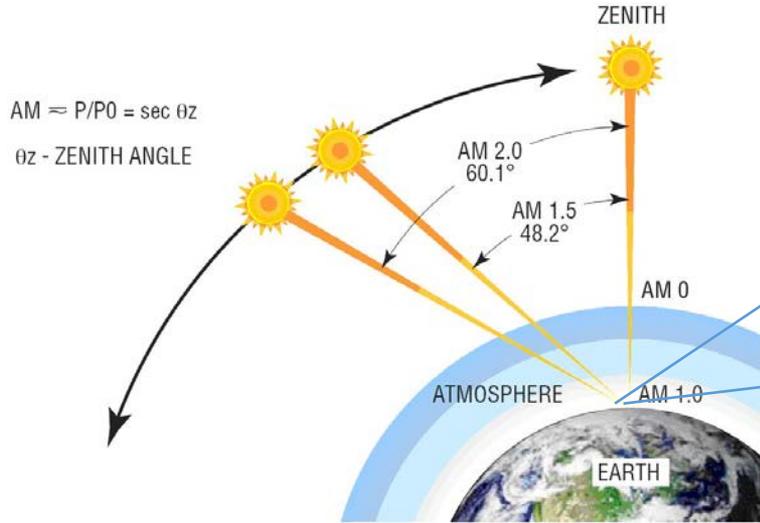
## Stats



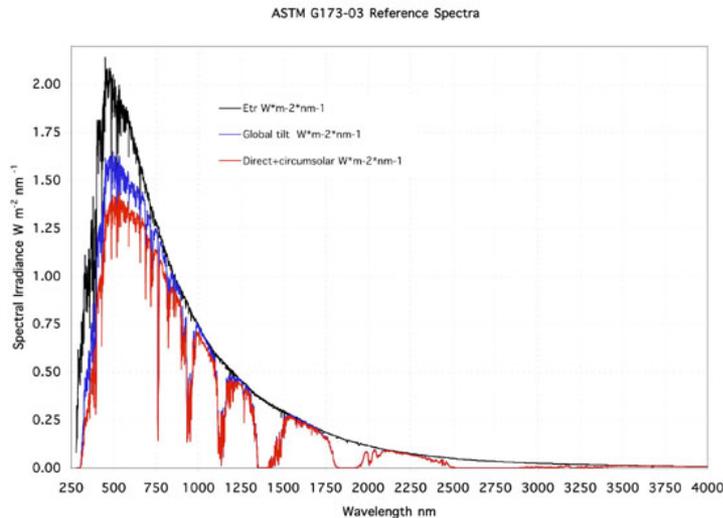
## PV tech roadmap and our mission

- Key issue for manufacturers: increase **panel efficiency and power ratings**,
- Need for distinguishing leading suppliers in a crowded market.
- Accurate power rating measurements and verification
- Fast and reliable Inline manufacturing tools
- Module degradation and monitoring in the field

# Standard Test Conditions (STC) for power rating and efficiency



**STC:**  
 Air Mass 1.5 (AM1.5),  
 25 deg C,  
 1000 W/m<sup>2</sup>



# Spectral mismatch error

Spectral mismatch parameter ( $M$ ): Measure of error in PV device testing from

1. Mismatch between spectral response of PV test device and PV reference cell
2. Mismatch between the test light source and the reference spectrum (e, AM 1.5)

$$M = \frac{\int_{\lambda_1}^{\lambda_2} E_s(\lambda) R_t(\lambda) d\lambda}{\int_{\lambda_3}^{\lambda_4} E_s(\lambda) R_r(\lambda) d\lambda} \times \frac{\int_{\lambda_3}^{\lambda_2} E_r(\lambda) R_r(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_4} E_r(\lambda) R_t(\lambda) d\lambda}$$

$E_s(\lambda)$  : spectral irradiance of the source,  $\text{W m}^{-2} \text{nm}^{-1}$

$E_r(\lambda)$  : reference spectral irradiance,  $\text{W m}^{-2} \text{nm}^{-1}$

$R_r(\lambda)$  : spectral response of reference cell,  $\text{A W}^{-1}$

$R_t(\lambda)$  : spectral response of test cell,  $\text{A W}^{-1}$

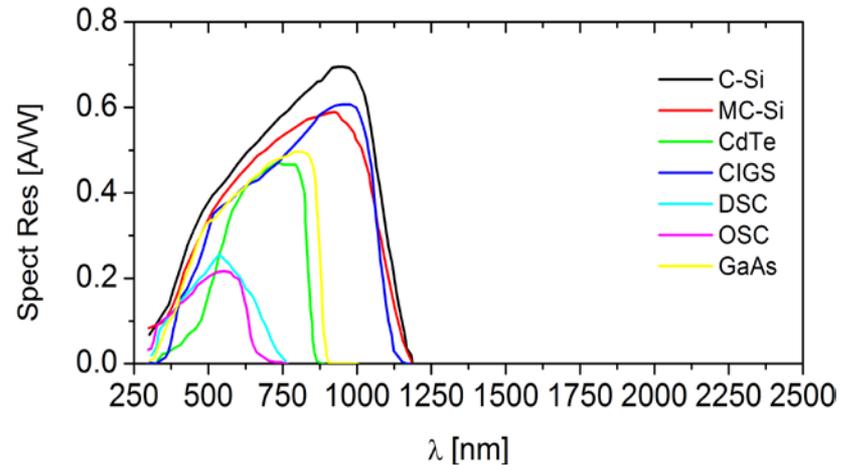
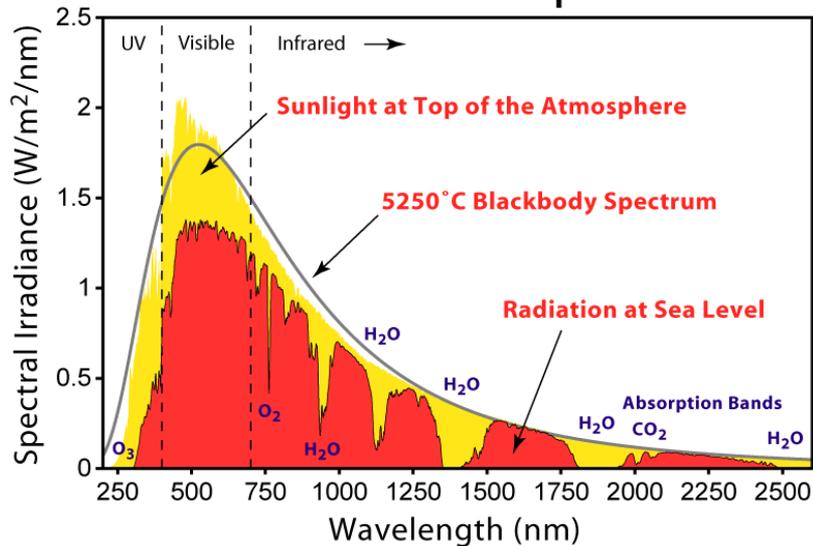
- **To calculate this error** must establish procedure to determine the spectral irradiance of our *indoor lighting source* & spectral responsivity of both the *reference cell* and the *device under test*.
  - For spectral irradiance, calibrated spectroradiometers directly traceable to NIST FEL lamps
  - **For spectral responsivity, two facilities have been established.**

# Spectral responsivity

Solar cell spectral responsivity  $SR(\lambda)$ : *The measurement of the wavelength dependence of the photocurrent relative to the # of incident photons.*

$$SR(\lambda) = I_{ph}(\lambda)/P(\lambda)$$

## Solar Radiation Spectrum



- Essential for solar cell efficiency and rating certification under STC.
- SR varies among different cell technologies.
- SR of reference cells do not necessarily match SR of device under test.

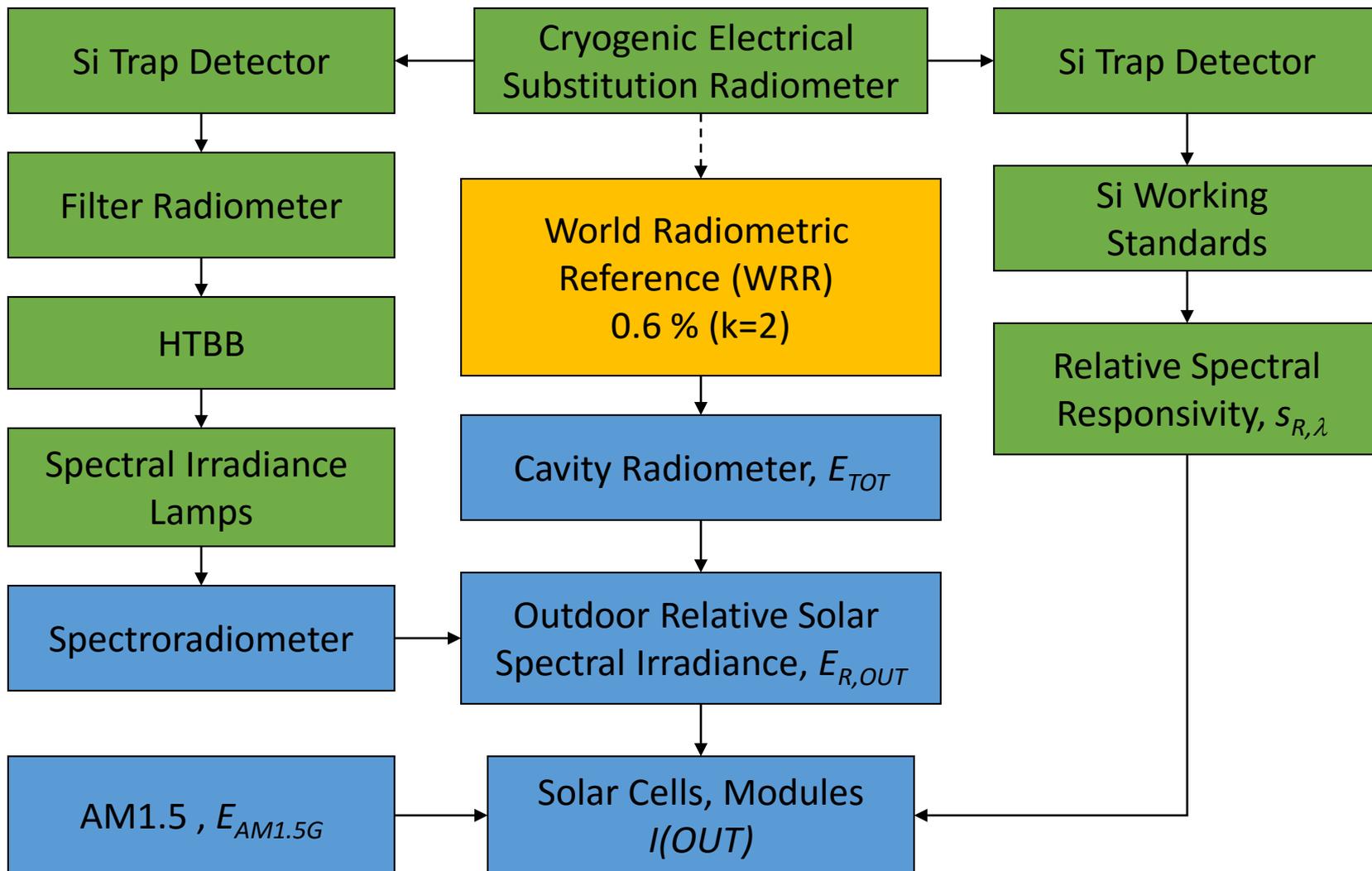
# Three different methods for calibrating solar cells

1. Outdoor method
2. Solar simulator method
3. Differential Spectral Responsivity (DSR) method



# Outdoor Method (NREL)

# NIST SSD Standards



$$I_{STC}(AM1.5G) = I(OUT) \cdot \frac{1000 \frac{W}{m^2}}{E_{TOT}} \cdot MMF$$

World Photovoltaic Scale (WPVS) 1.7 % (k=2)

$$MMF = \frac{\int s_{R,\lambda} E_{AM1.5G} \cdot \int E_{R,OUT}}{\int E_{AM1.5G} \cdot \int s_{R,\lambda} E_{R,OUT}}$$

# How is the broad-band total irradiance scale (World Radiometric Reference (WRR)) disseminated?



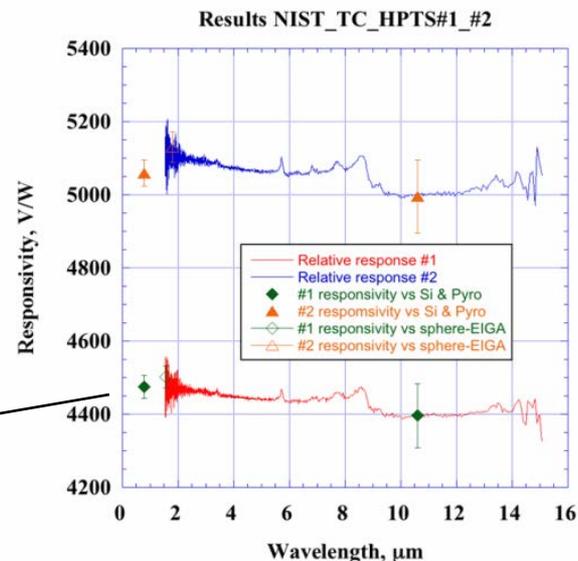
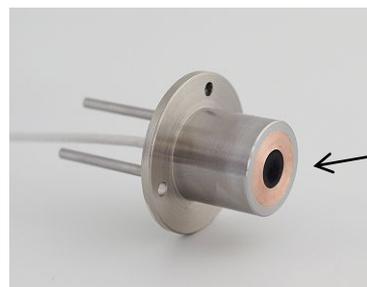
- Every 5 years the International Pyrheliometer Comparisons are held.
- The Eleventh IPC (IPC-XI) took place at PMOD/WRC (Davos, Switzerland) from September 27 to October 15, 2010.
- Eighty-seven participants came from 40 countries to calibrate 99 pyrheliometers.



# NIST has 3 Eppley AHF pyrheliometers



Recommended by NREL who has provide the custom software to run this unit.

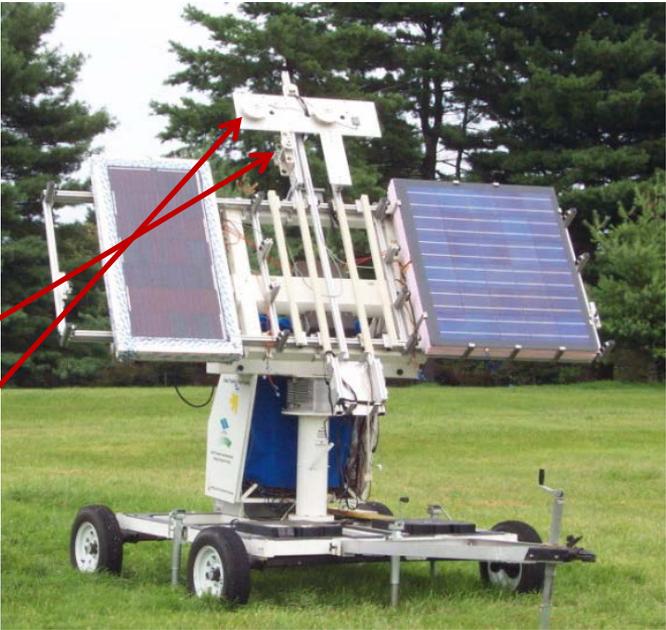


# Calibration of Field Instruments

Absolute Cavity  
Pyrheliometer

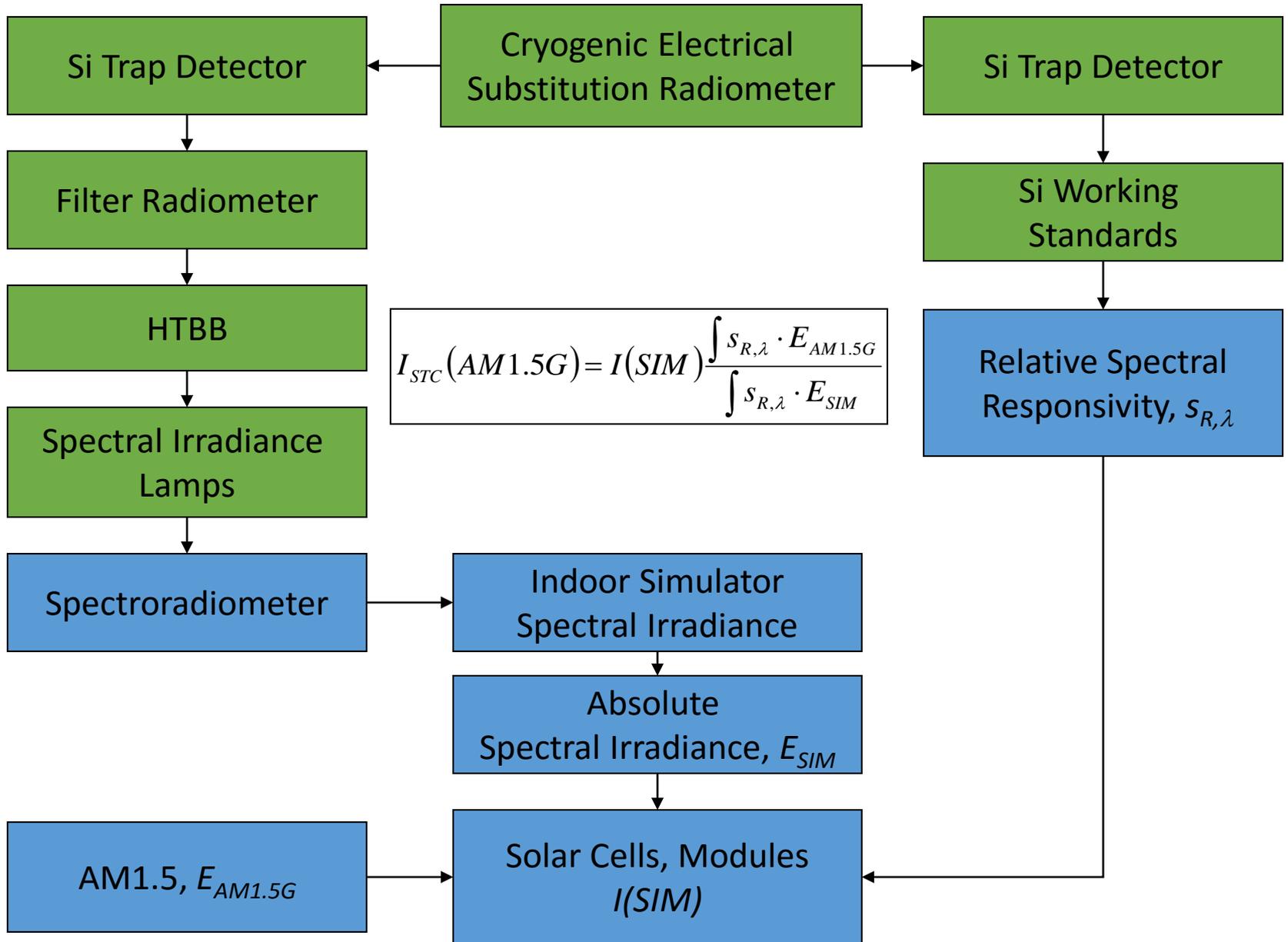


Commercial  
Pyrheliometer



Pyranometer

# Solar Simulator Method

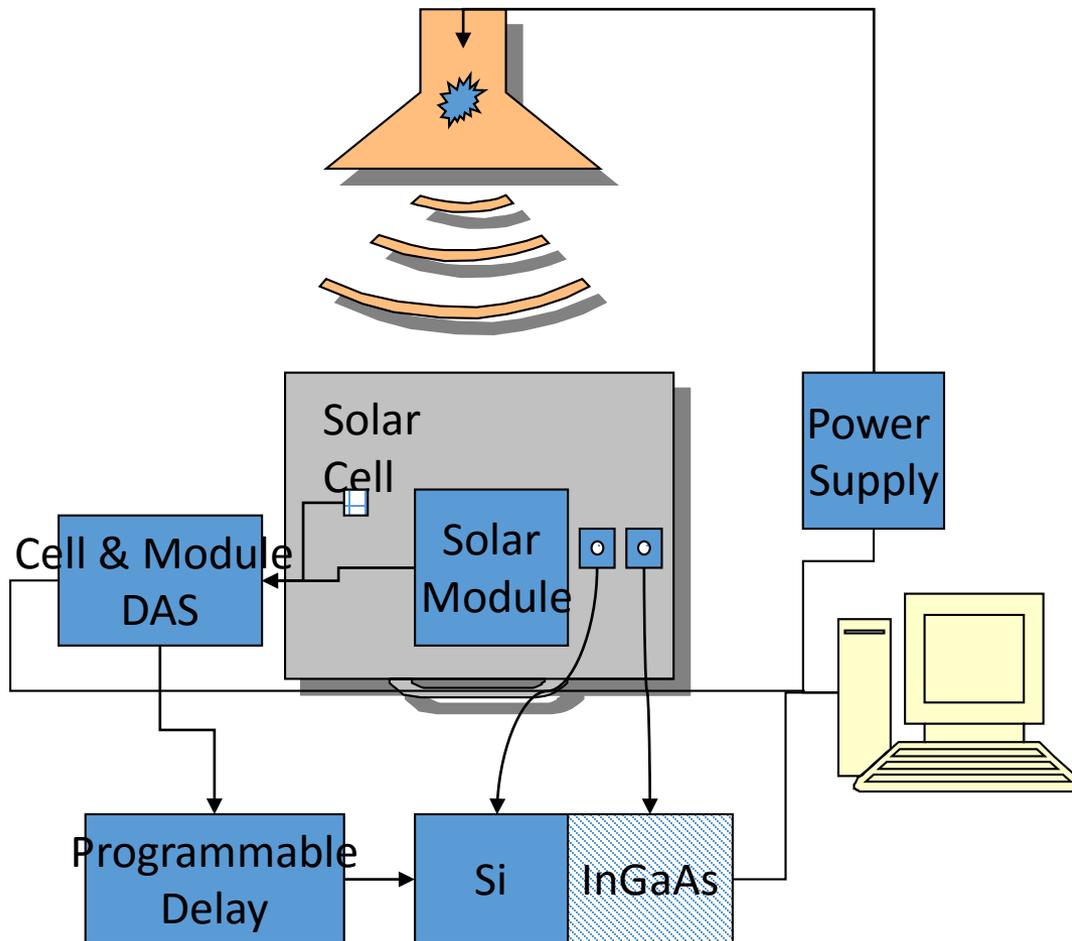


# PV testing methodology

Testing usually performed under indoor lighting conditions. Issues to consider:

1. Quality and rating of the solar simulator
  - A. Spectral irradiance match to the Standard Test Conditions (STC)(AM 1.5)
  - B. Uniformity of the illumination
  - C. Temporal stability of the light source
2. Spectral responsivity and calibration of a reference cell.
3. Spectral responsivity of the test cell or module.
4. Determination of a spectral mismatch factor,  $M$ .
5. Current-voltage (I-V) measurements of the device.
6. Correction of the I-V curve using  $M$ .
7. Determination of the module parameters, including power conversion efficiency and power rating

# PV Indoor testing method



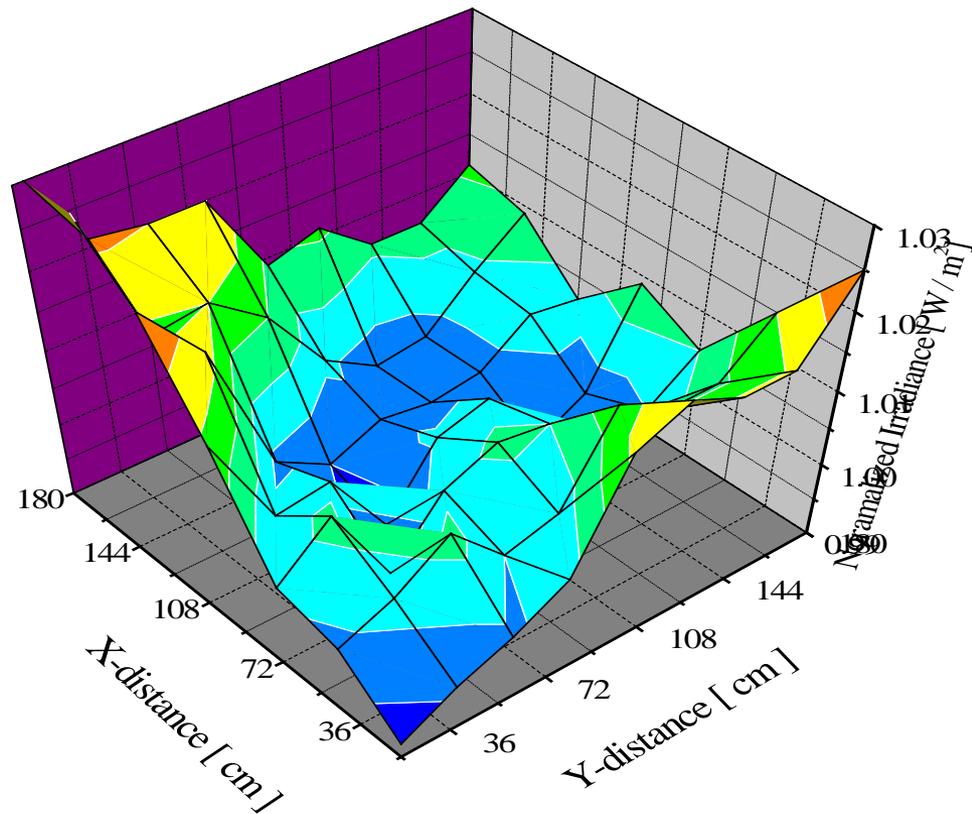
- Place specimen and calibrated reference cell under a simulator
- Adjust simulator output until reference cell produces an output close to its certified value at standard conditions (temp, spectrum)
- Determine output of specimen by performing current-voltage measurements.
- Make slight corrections based on reference cell to normalize the specimen's output to standard conditions.

# NIST Solar simulator

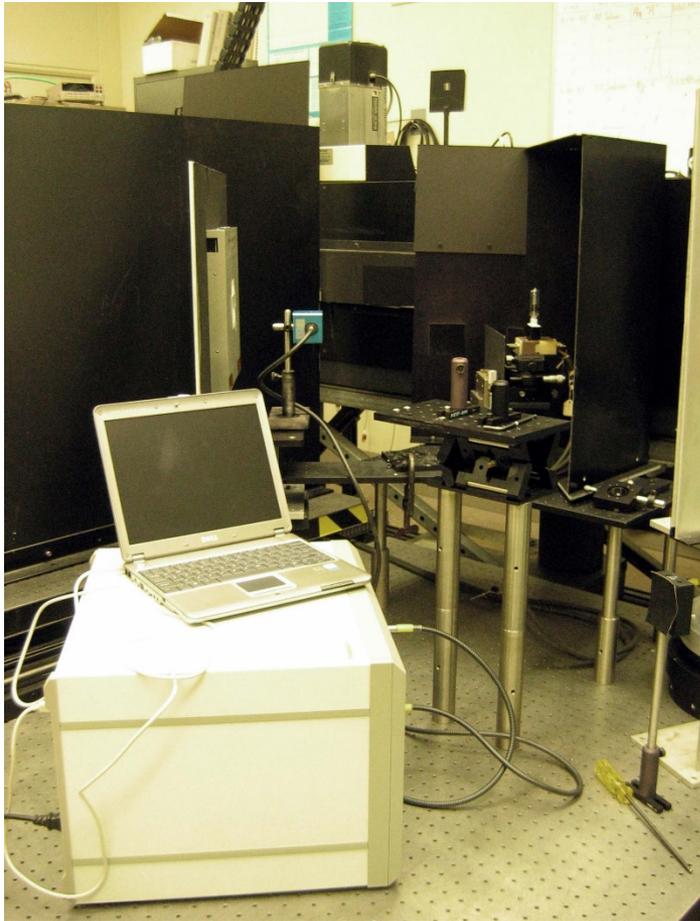


1. IEC Standard 60904-9 Class AAA Simulator
  1. Spectral match: 0.75-1.25 for 6 wavelength-intervals
  2. Irradiance non-uniformity:  $\leq \pm 2 \%$
  3. Irradiance temporal instability:  $\leq \pm 2 \%$
2. Flash Plateau: 36 ms
  1. IV scan interval:  $\leq 1$  ms
  2. Variable scan delay : 1 – 12 ms
3. Irradiance Range:  $\sim 500 - 1100$  W/m<sup>2</sup>
4. Maximum irradiated area: 2.4 m diagonal
5. Spectral composition filter

# Spatial uniformity measured with solar cell



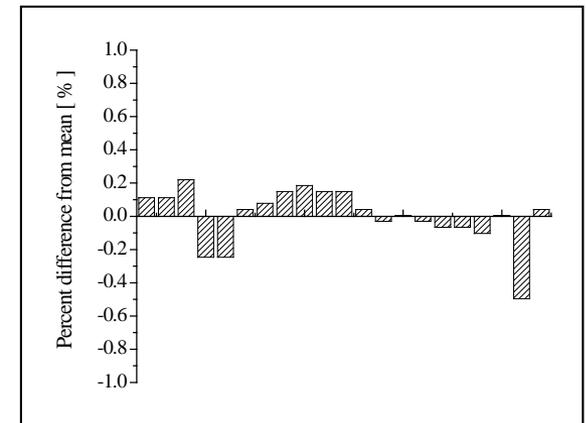
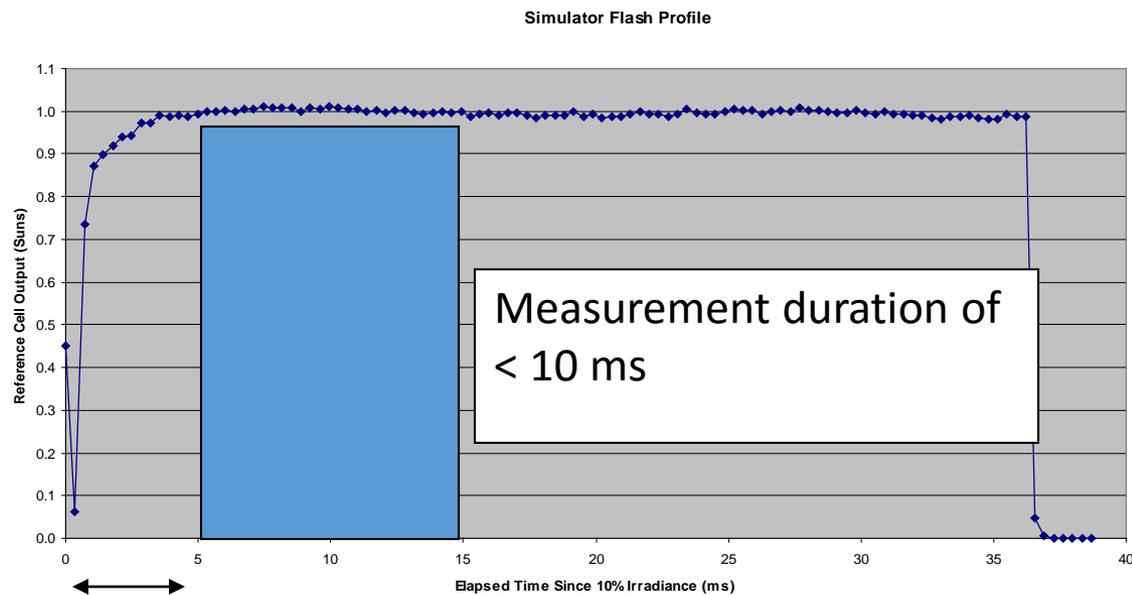
## Calibration for spectral irradiance responsivity



Calibrations using the NIST 1000 W FEL lamps at 50 cm (integration time of 200 ms)

# Temporal control of the measurement

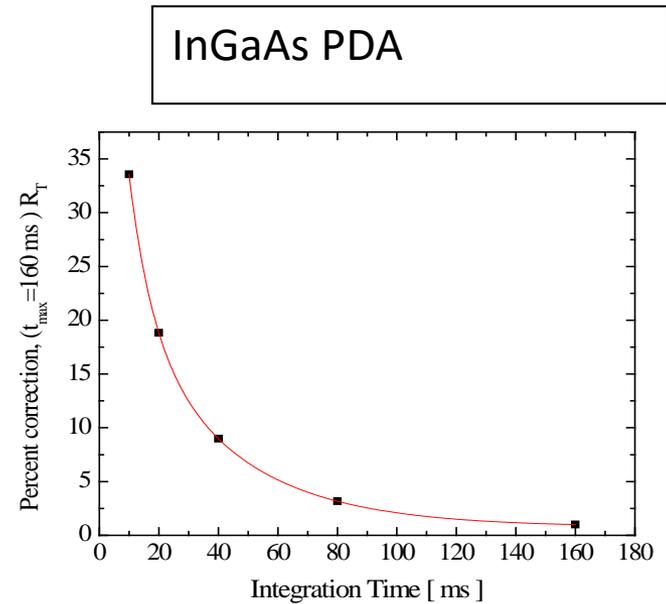
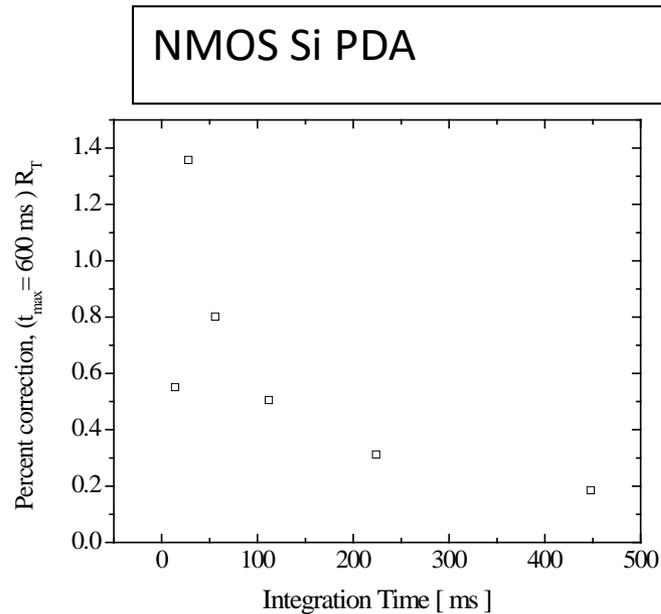
Pulse duration of 36 ms



Controlled delay



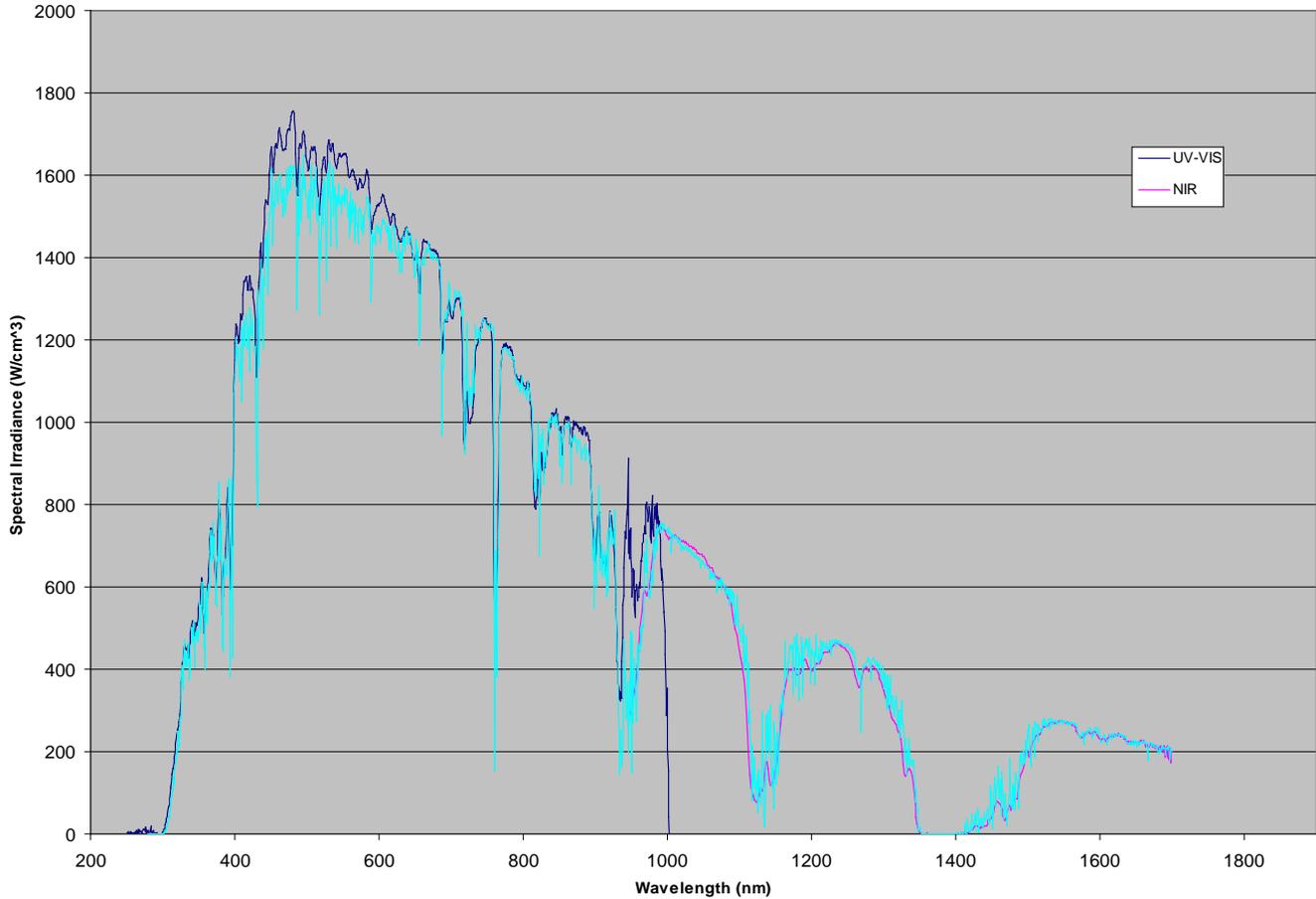
# Si and InGaAs PDA nonlinearity corrections



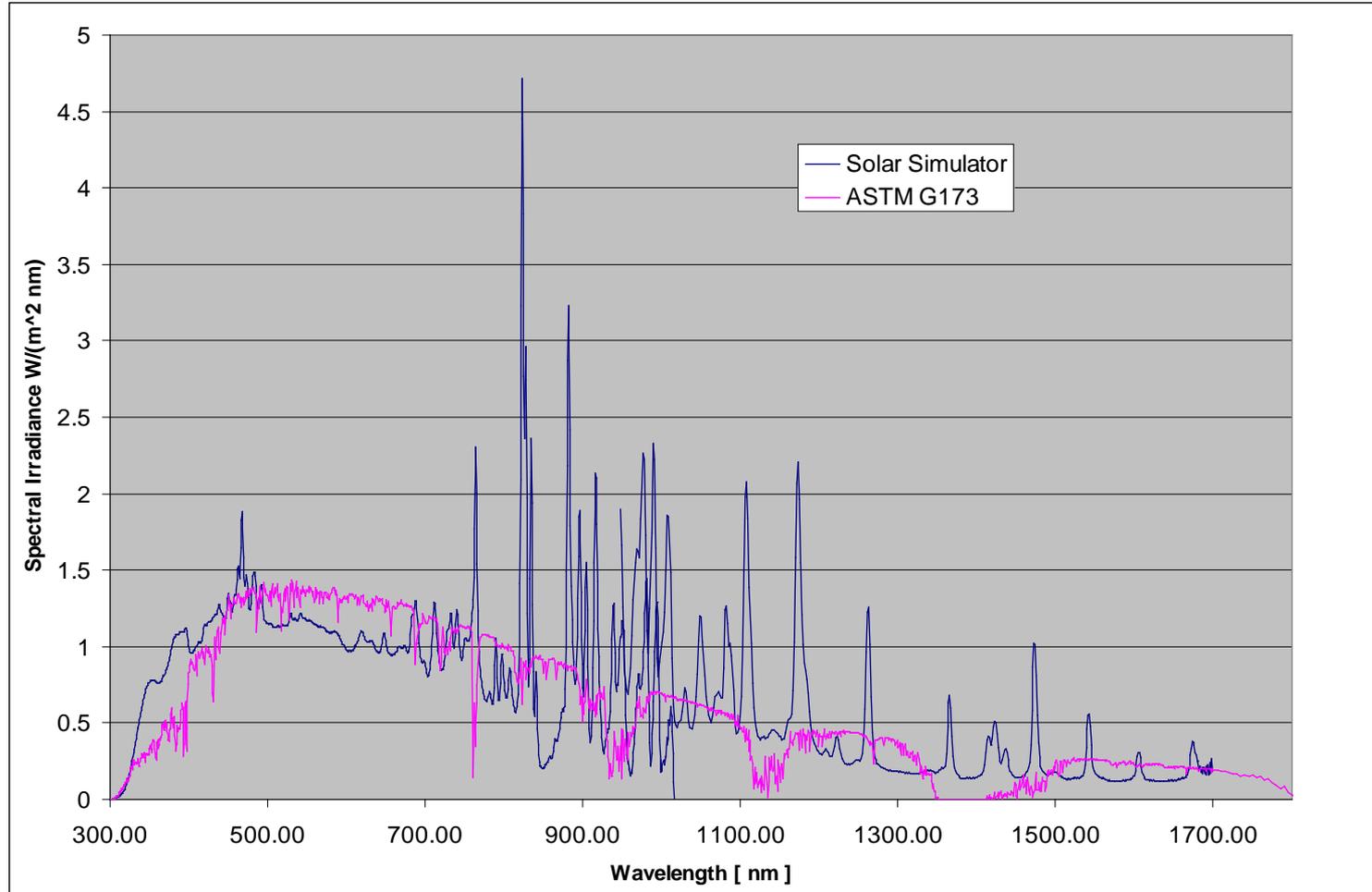
Measurements  
performed outside

$$R_C = \left( \frac{1}{1 + \frac{R_T}{100}} \right) \cdot \left( \frac{S_T - S_D}{\tau} \right)$$

# Outdoor measurements compared to ASTM G173



# Comparison of indoor simulator with ASTM G 173



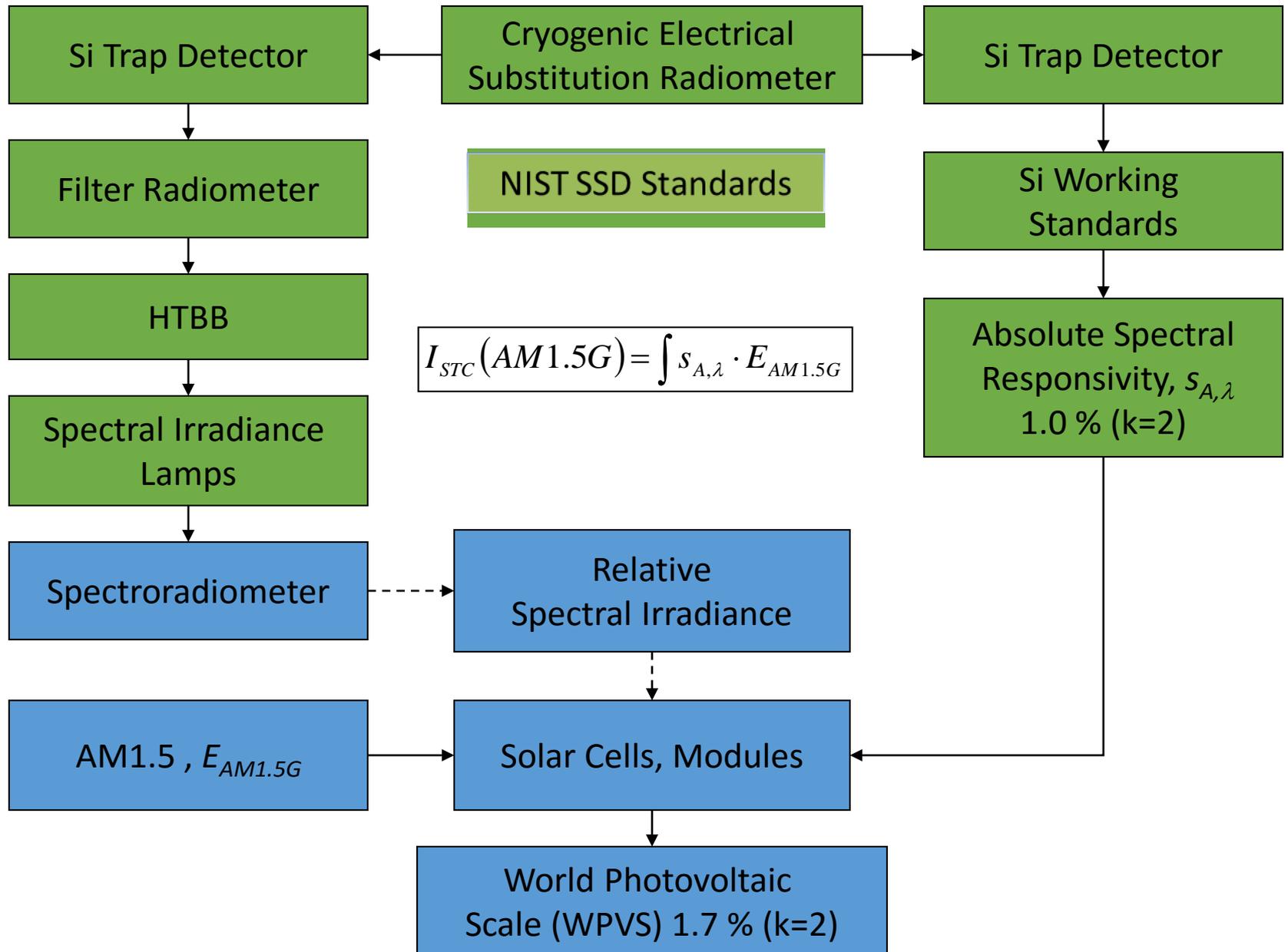
# Classification according to IEC ratios

Beginning Wavelength [ nm ]	Ending Wavelength [ nm ]	Integrated Irradiance [ W/m <sup>2</sup> ]	Measured Percentages	IEC Standard Percentages	IEC Ratio	Class Rating
400	500	125.82	18.03%	18.4%	0.98	A
500	600	114.10	16.35%	19.9%	0.82	A
600	700	103.25	14.79%	18.4%	0.80	A
700	800	100.82	14.45%	14.9%	0.97	A
800	900	105.80	15.16%	12.5%	1.21	A
900	1100	148.15	21.23%	15.9%	1.33	B
	Total	697.94				

# Uncertainties of the NIST solar simulator

	Uncertainty Component	Si [ % ]	InGaAs [ % ]
	Wavelength Range	300 nm to 950 nm	950 nm to 1700 nm
1	NIST Spectral Irradiance Scale	0.5	0.25
2	Signal Noise	0.25	0.25
3	Temporal Stability of Spectroradiometer	0.5	0.5
4	Spectroradiometer Stray Light	0.25	0.25
5	Linearity Correction	0.5	0.75
6	Wavelength Calibration	0.1	0.1
	Total Uncertainty	0.94	1.00
	Expanded Uncertainties (k=2)	1.88	2.01

# Differential Absolute Responsivity (DSR) NIST Method



# Conclusion

1. Utilization of photovoltaic energy generation is increasing rapidly, and electrical power generated through PV has now achieved grid parity in many states in the US.
2. Radiometric measurements and standards are critical in assigning conversion efficiencies and power ratings.