

Spectroradiometric Characterization of the NIST Pulsed Solar Simulator

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Outline

1. Overview of solar industry trends
2. SI-traceable solar cell calibrations: 3 different approaches
3. Photovoltaic work at NIST
4. Description of the NIST solar simulator
5. Characterization of the spectroradiometer for measurement of pulsed solar simulator
6. Determination of the uncertainties
7. Conclusions

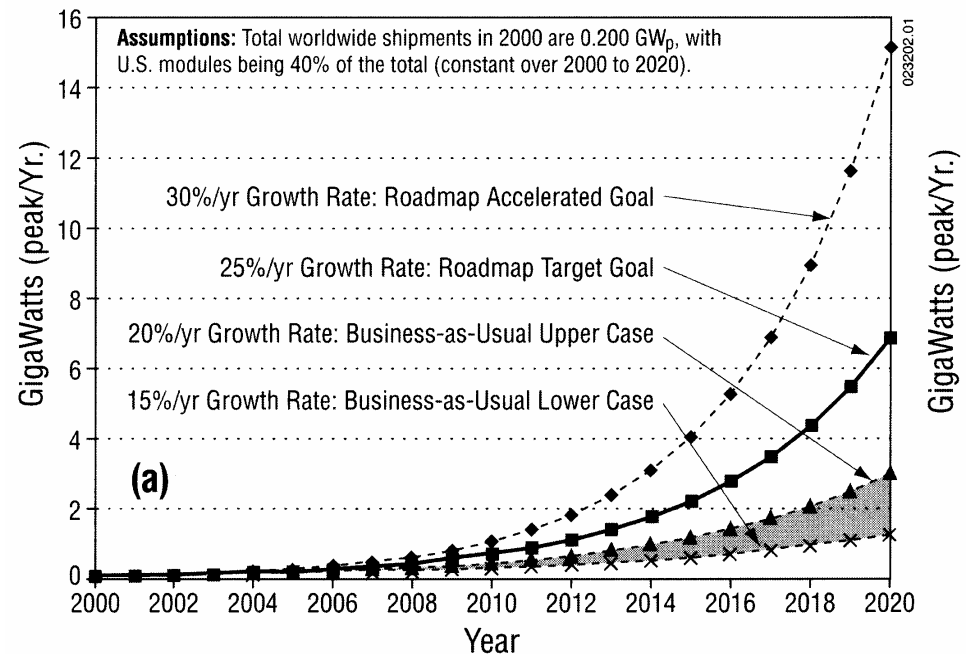
The Photovoltaic Industry

■ Worldwide PV Shipments

- 1998 - \$1.5 billion
- 2020 - \$27 billion

■ Price History

- 1959 - \$1000 per Watt
- 1973 - \$100 per Watt
- 1980 - \$10 per Watt
- 12/06 - \$5.47 per Watt
- 02/10 - \$4.20 per Watt
- Goal of \$2.00 per Watt

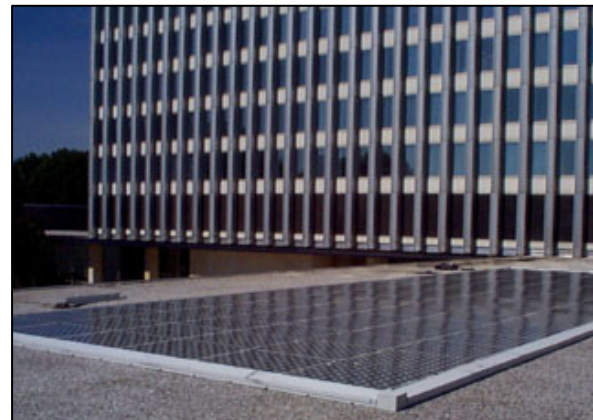


PV Growth Strategy 2000-2020
PV Technology Roadmap Workshop, 6/99

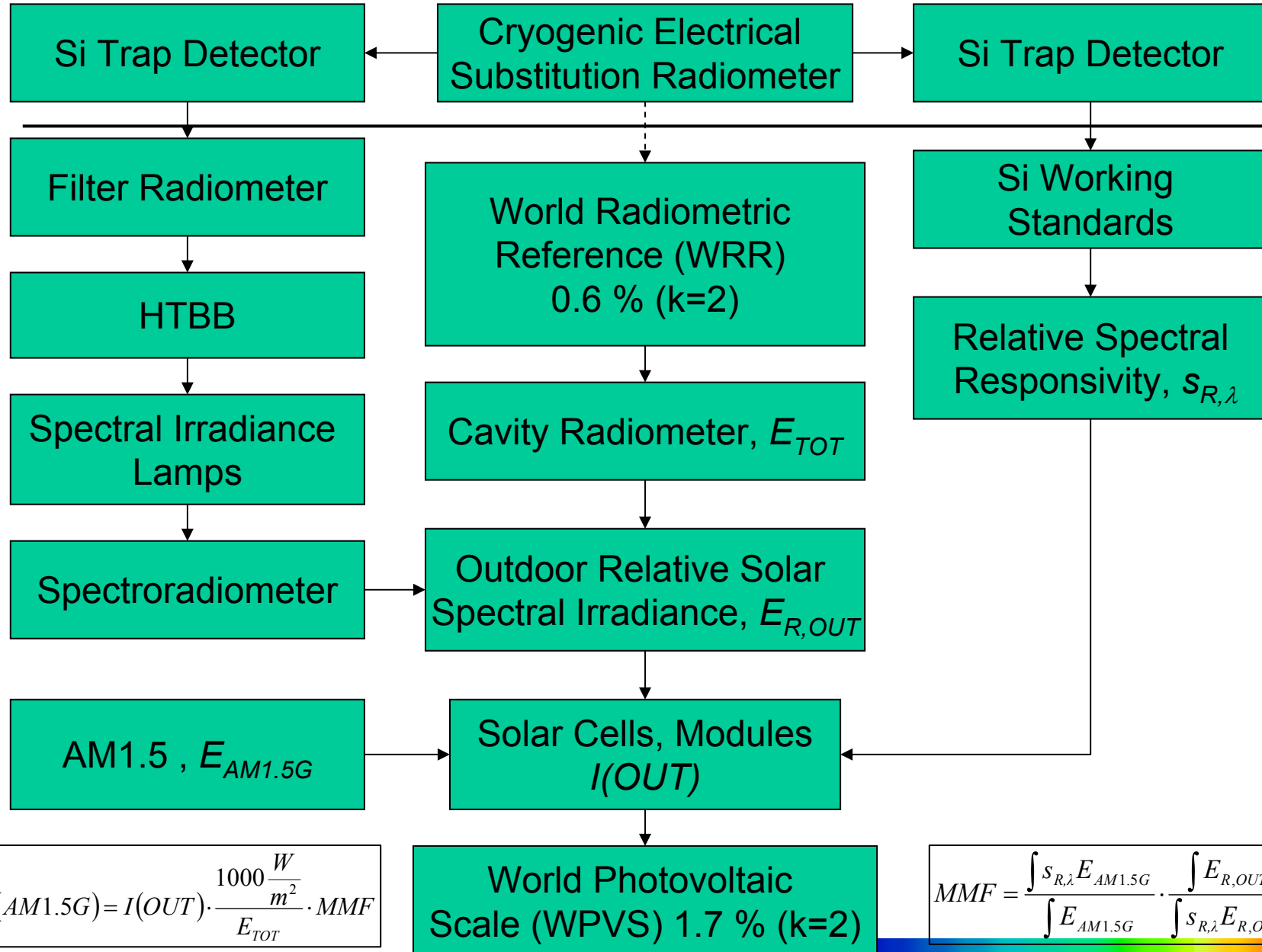
Photovoltaic Industry

■ PV Manufacturers and Technologies

- Single-Crystalline – Sun Power (Back Contact)
- Polycrystalline – BP Solar, Sharp, Kyocera Solar, Mitsubishi, GE
- Polycrystalline String Ribbon – ASE Americas, Evergreen Solar
- Silicon Film – General Electric
- Amorphous Silicon – United Solar Ovonic Corporation
- Cadmium Telluride – First Solar
- Copper Indium Diselenide/Copper Indium Gallium Diselenide – Wurth Solar, Global Solar, Shell Solar



NREL Realization Traceability (Global Sunlight Method)



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

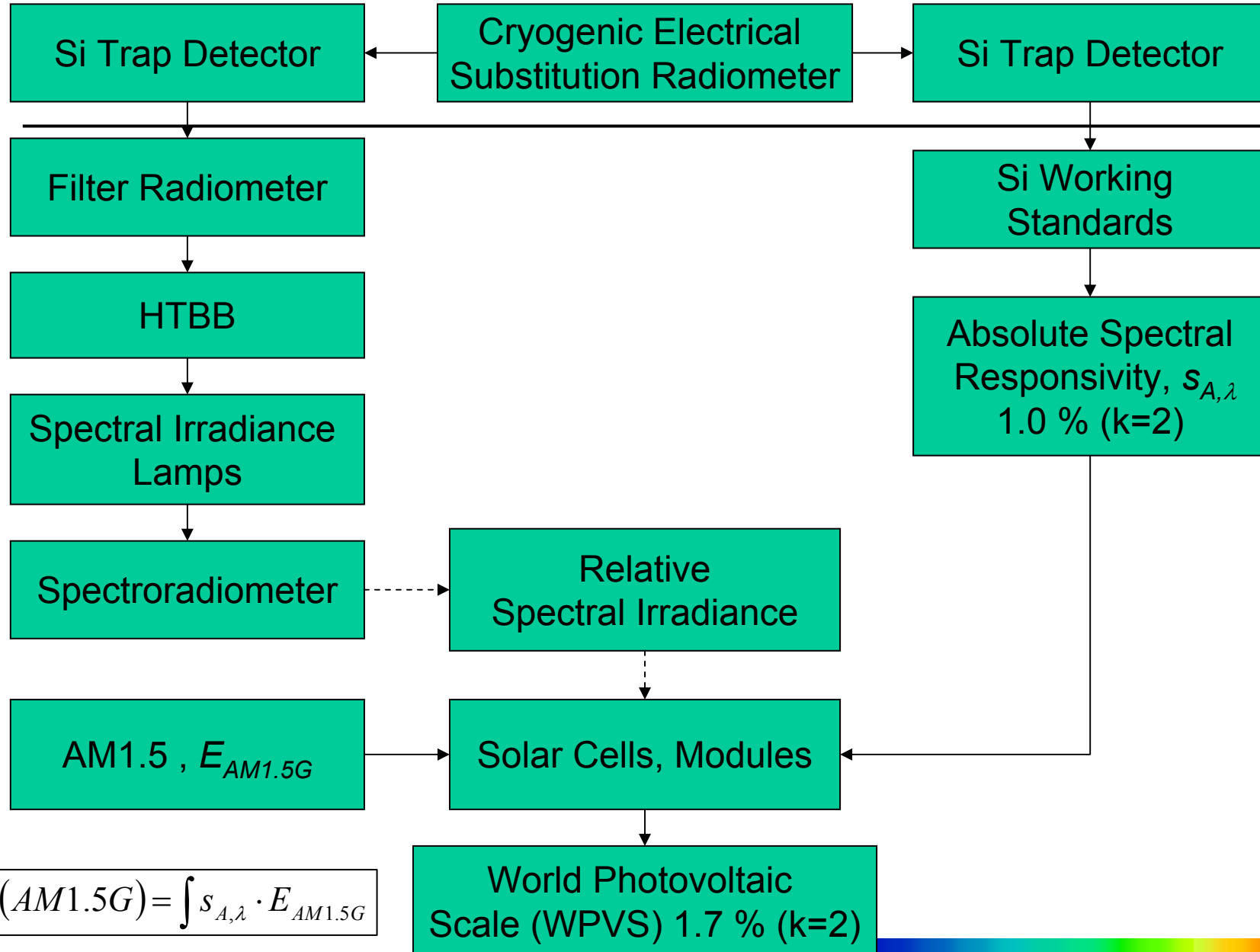
CEOS WGCV March 2, 2010

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

OPTICAL TECHNOLOGY DIVISION

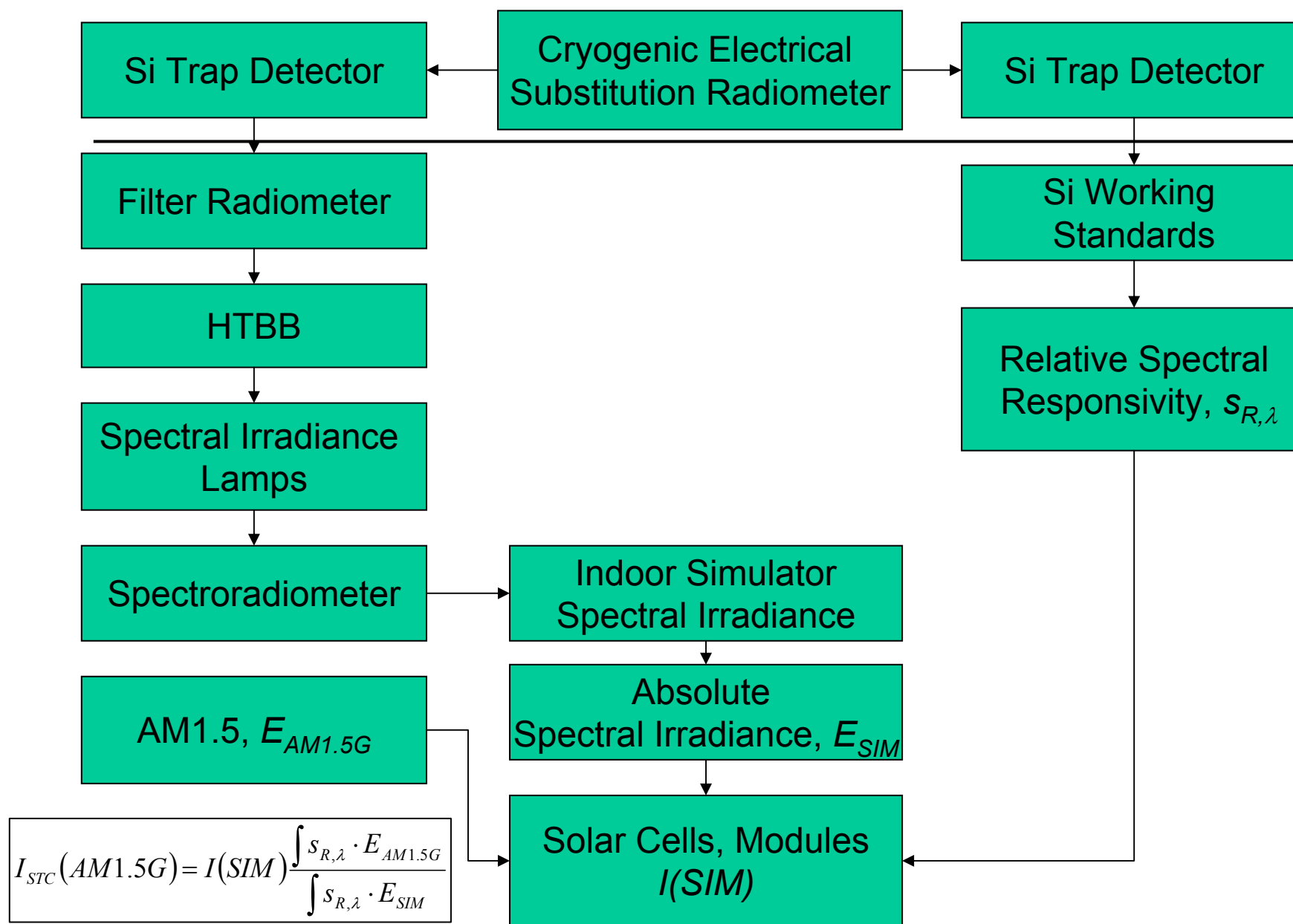
NIST

PTB Realization Traceability (Absolute Responsivity Method)



$$I_{STC}(AM1.5G) = \int s_{A,\lambda} \cdot E_{AM1.5G}$$

NIST Realization Traceability (Solar Simulator Method)



NIST Long-Pulsed Solar Simulator Specifications

1. IEC Standard 60904-9 Class AAA Simulator
 - A. Spectral match: 0.75-1.25 for 6 wavelength-intervals
 - B. Irradiance non-uniformity: $\leq \pm 2 \%$
 - C. Irradiance temporal instability: $\leq \pm 2 \%$
2. Flash Plateau: 36 ms
 - A. IV scan interval: ≤ 1 ms
 - B. Variable scan delay : 1 – 12 ms
3. Irradiance Range: $\sim 500 - 1100$ W/m²
4. Maximum irradiated area: 2.4 m diagonal
5. Spectral composition filters
6. Constructed 12/2006



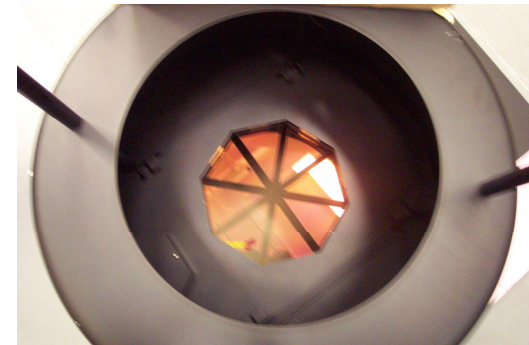
Solar Simulator Components



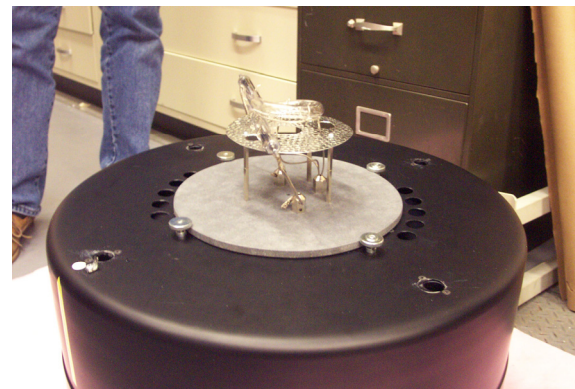
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Optical Assembly



Shutter/Filter



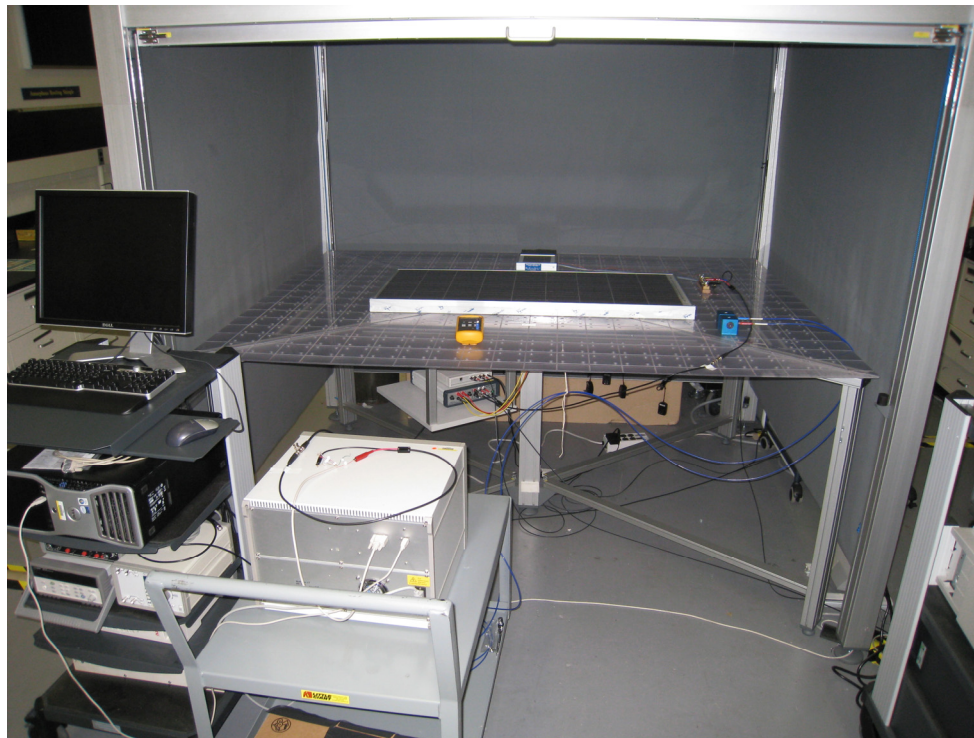
Xeon Lamp Assembly

OPTICAL TECHNOLOGY DIVISION

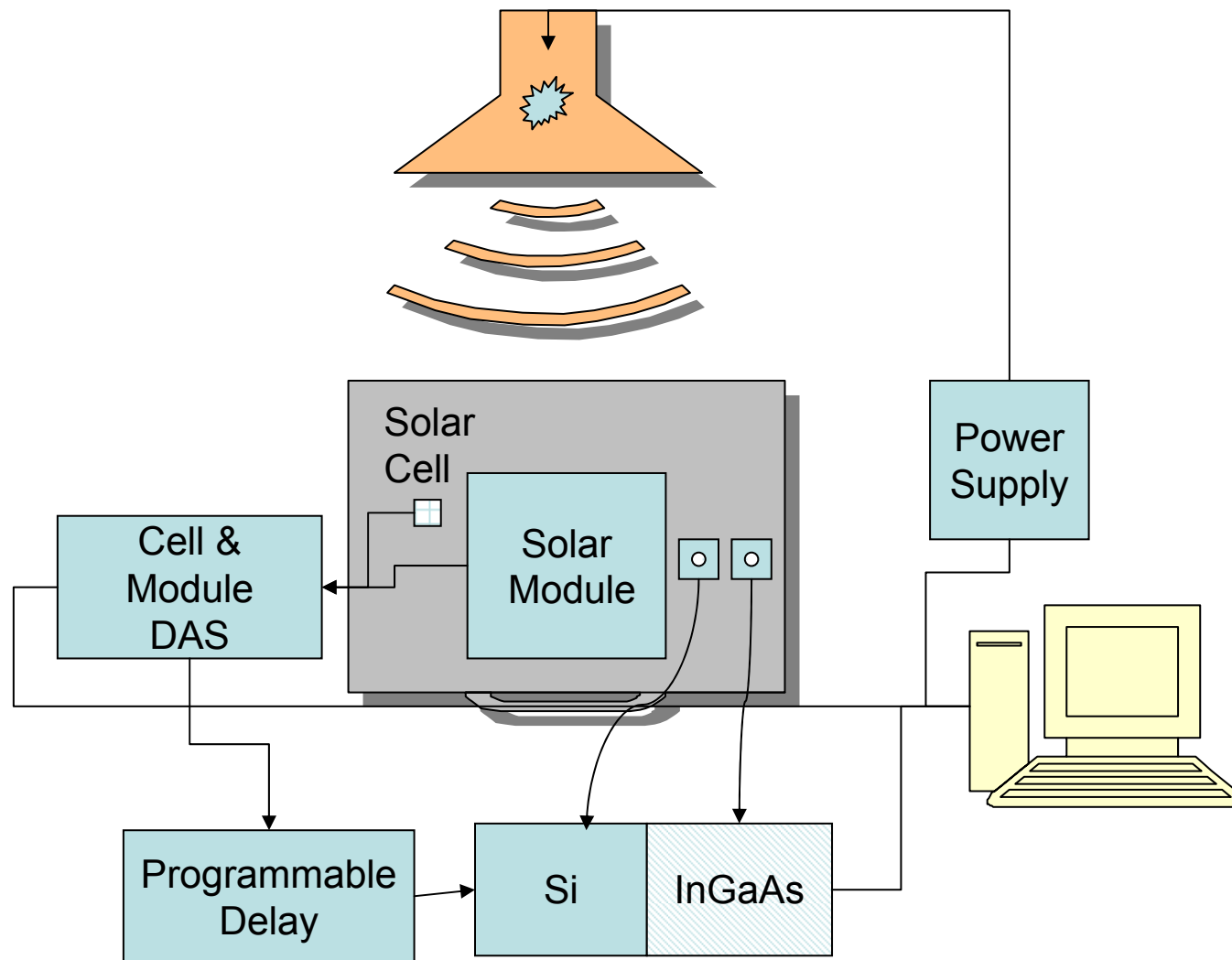
NIST

Specifications of the photodiode arrays

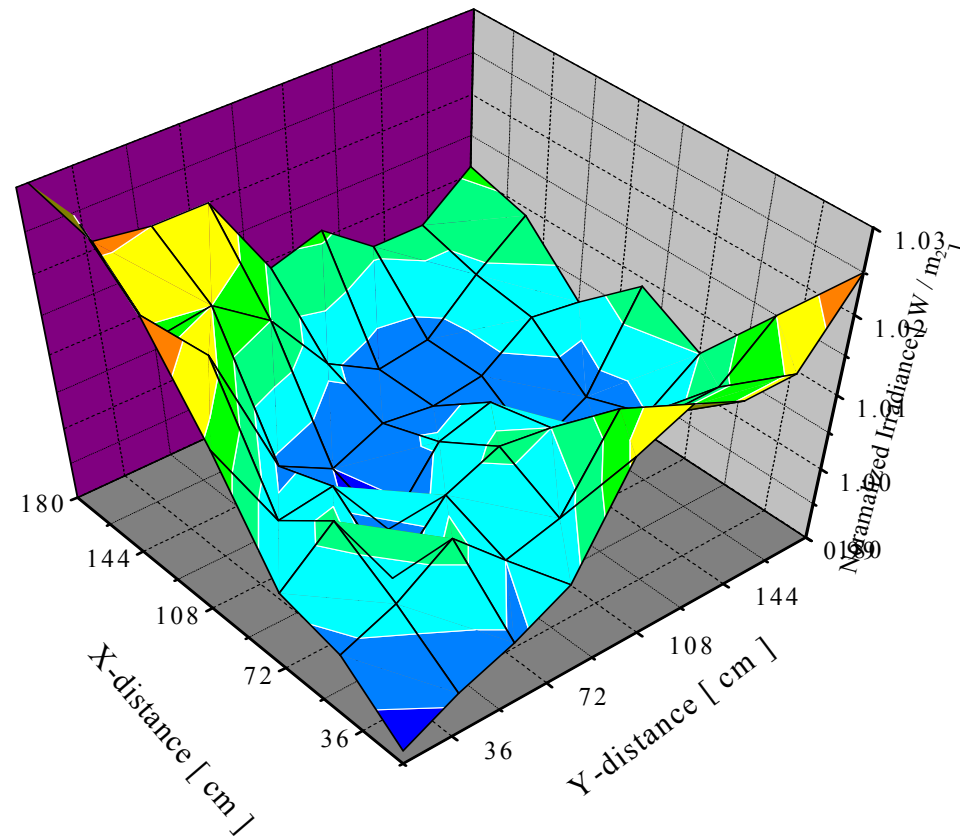
Sensor	Spectral Bandwidth [nm]	Number of elements	Wavelength range	Integration Time
Si PDA	3	1024	200 nm to 950 nm	2 ms to 3600 ms
TE-cooled InGaAs	5	512	950 nm to 1700 nm	2 ms to 1600 ms



Schematic of the solar simulator setup

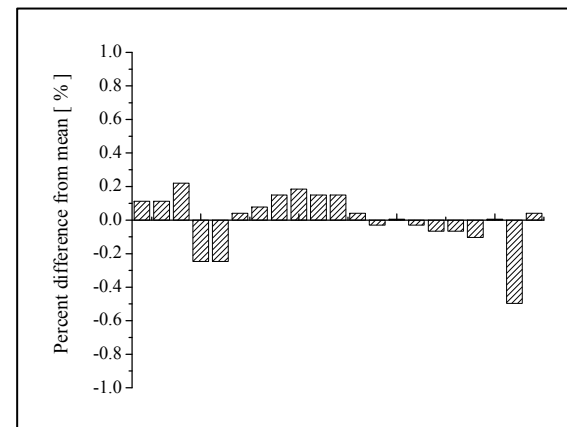
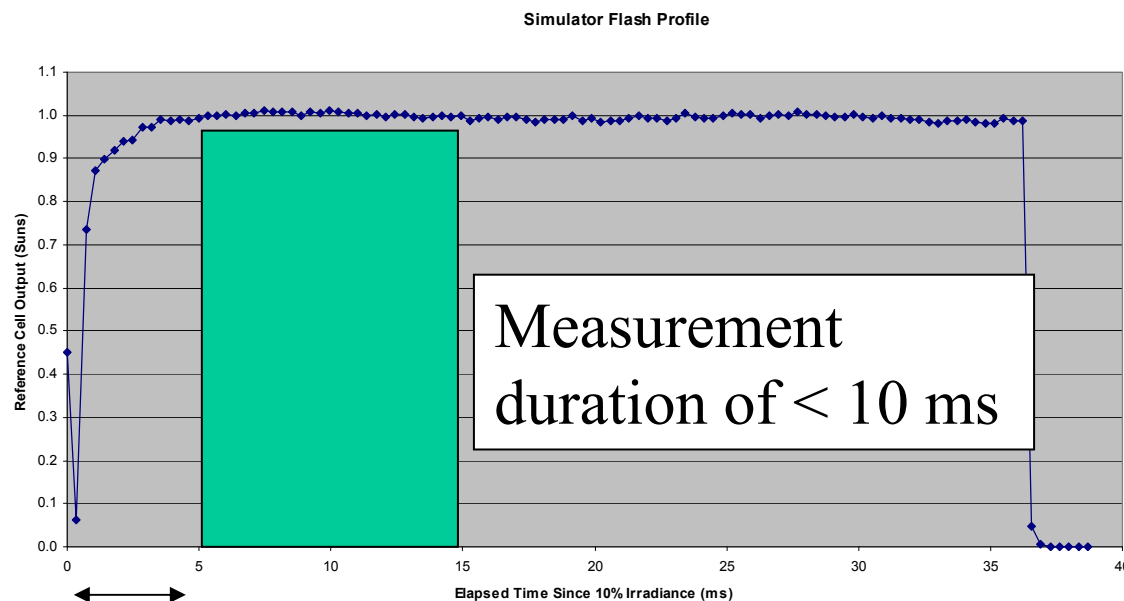


Spatial uniformity measured with solar cell



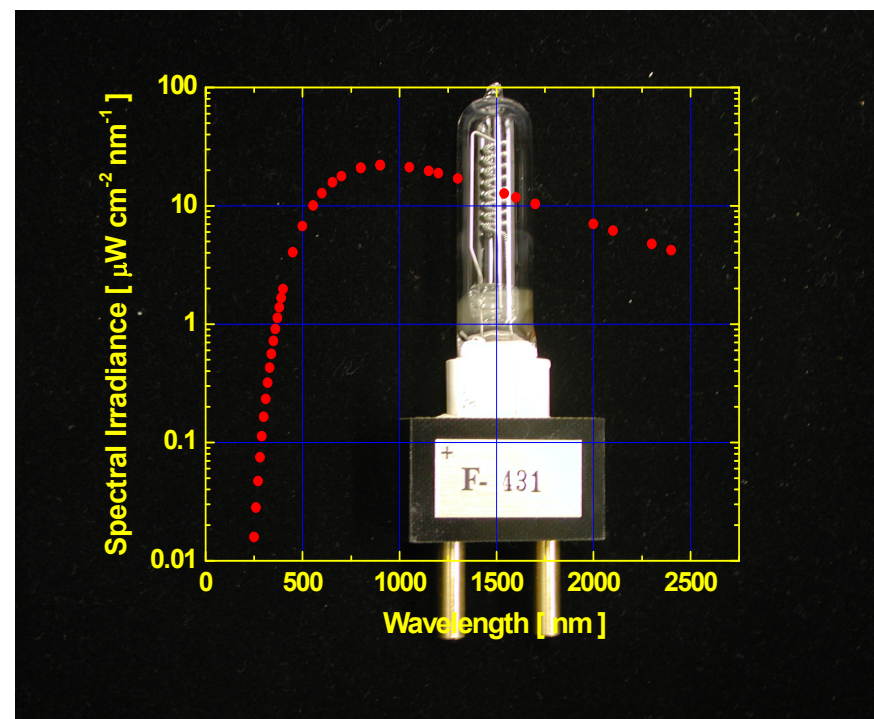
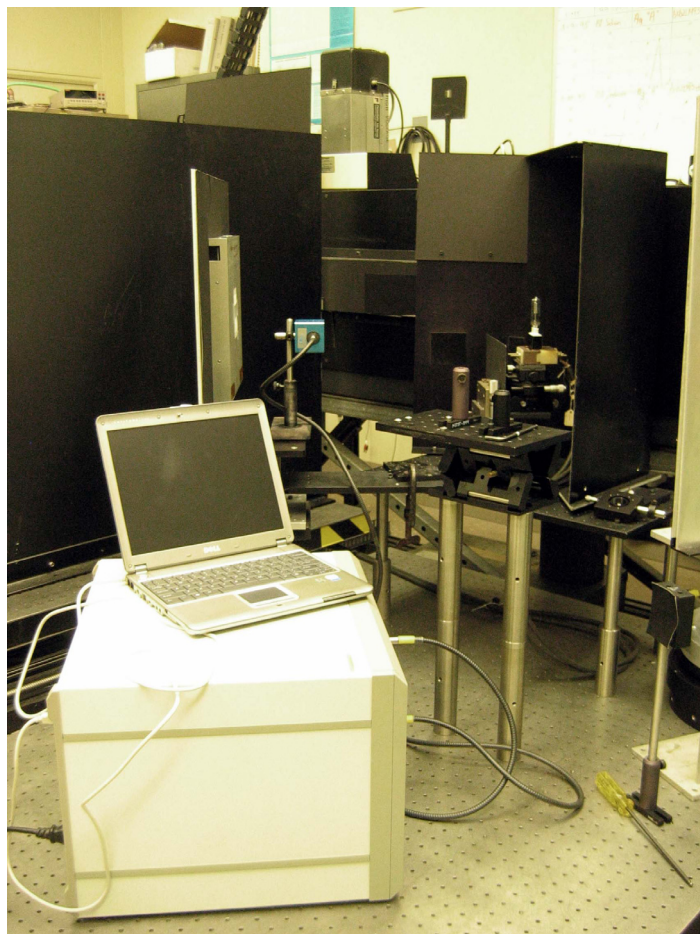
Temporal control of the measurement

Pulse duration of 36 ms

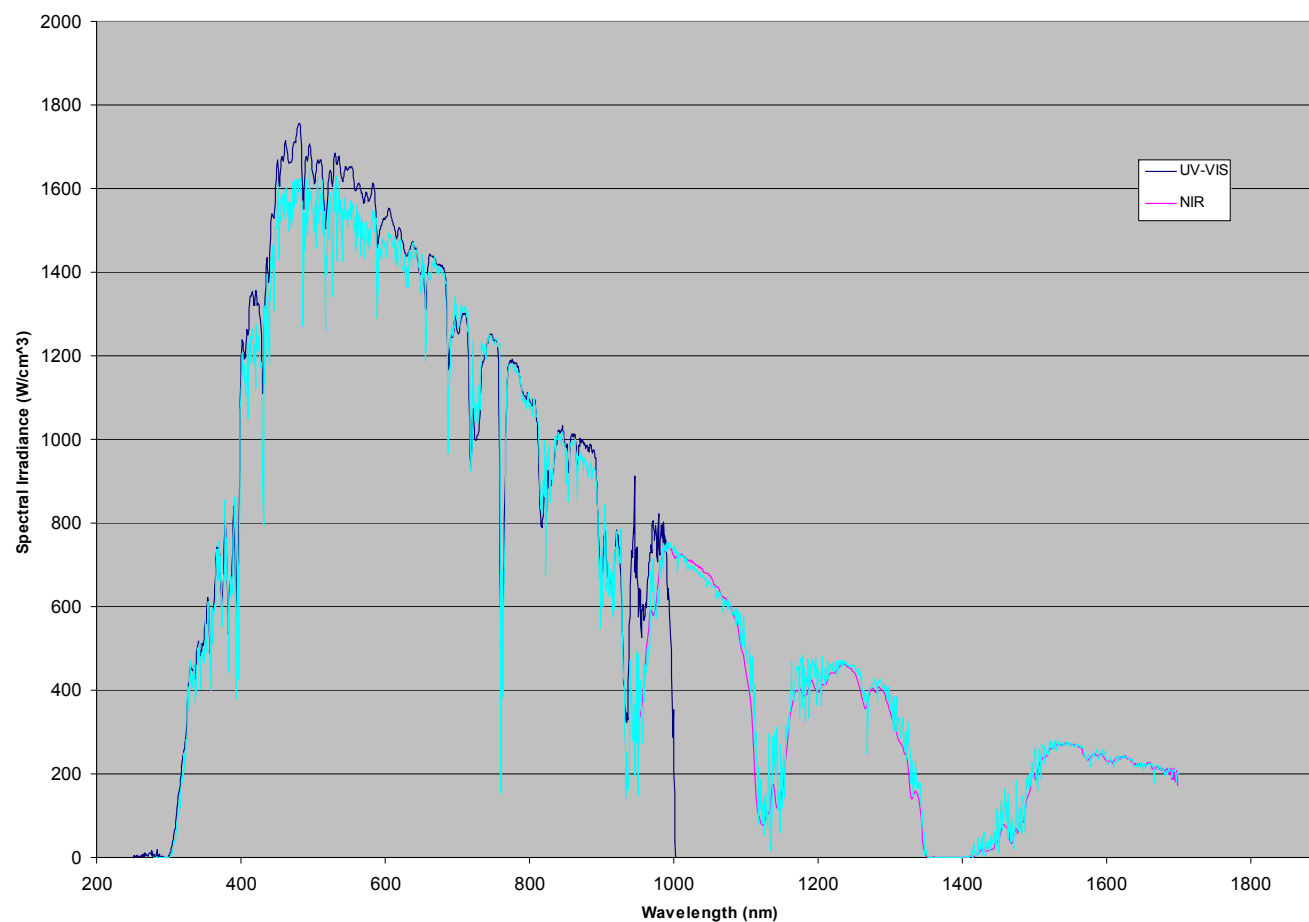


Controlled delay

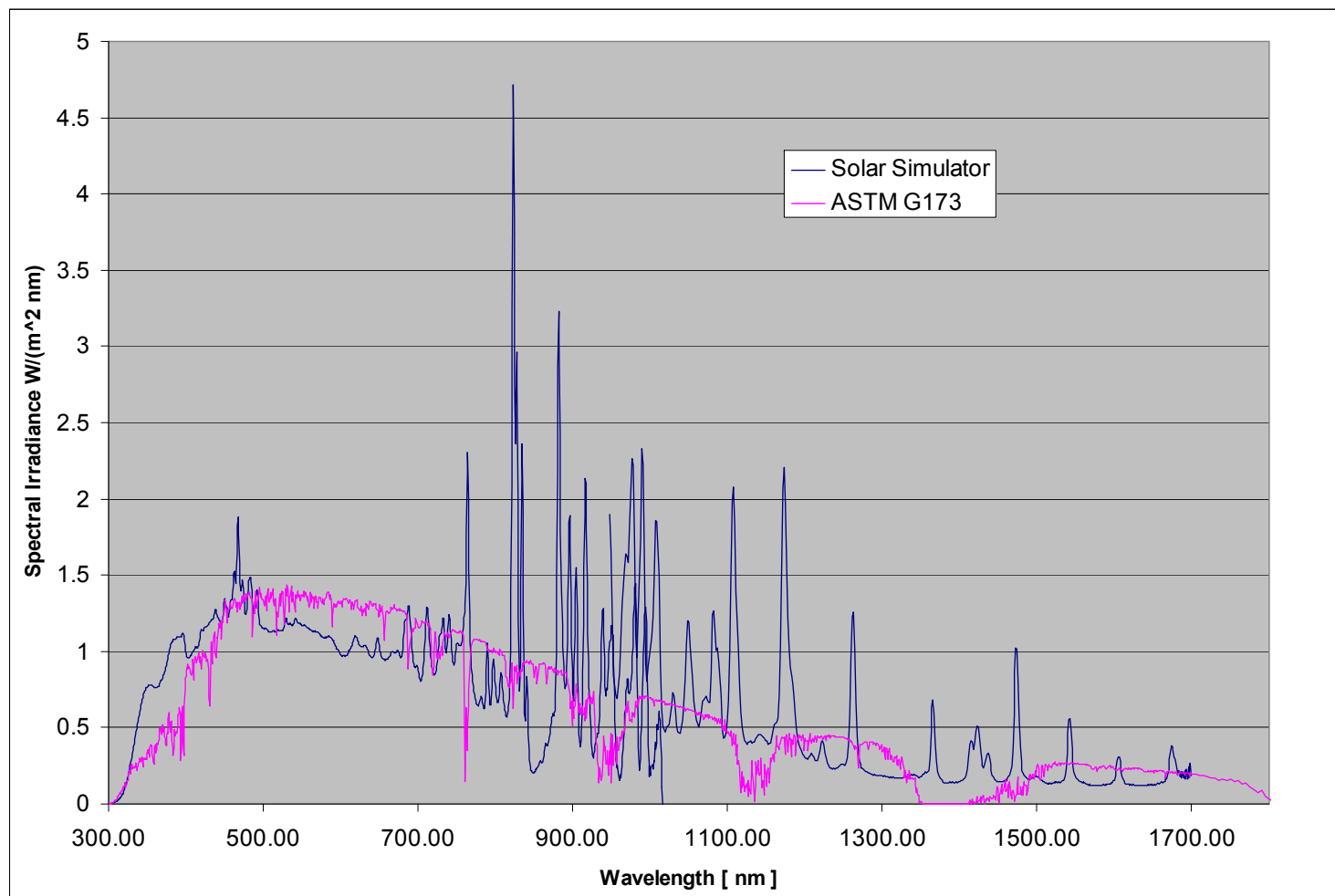
Calibration for spectral irradiance responsivity



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 ²]	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 calibrations

	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

Conclusions

1. Need for solar cell calibrations will increase.
2. Three different approaches to SI-traceable solar cell calibrations exist.
3. Commercial fast PDA's are capable of low uncertainty measurements of pulsed solar simulators.