Smarter Sunlight

IOI LED Solar Simulator Differentiators



INNOVATIONS IN OPTICS

Experts in High Power
Solid-State Illuminators & Systems



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OVERVIEW

Solar Simulator Applications

Solar Simulator Technology

Definitions (IEC Class, SPC, SPD)

IOI LumiSun Competitive Advantages

Bifacial Configuration

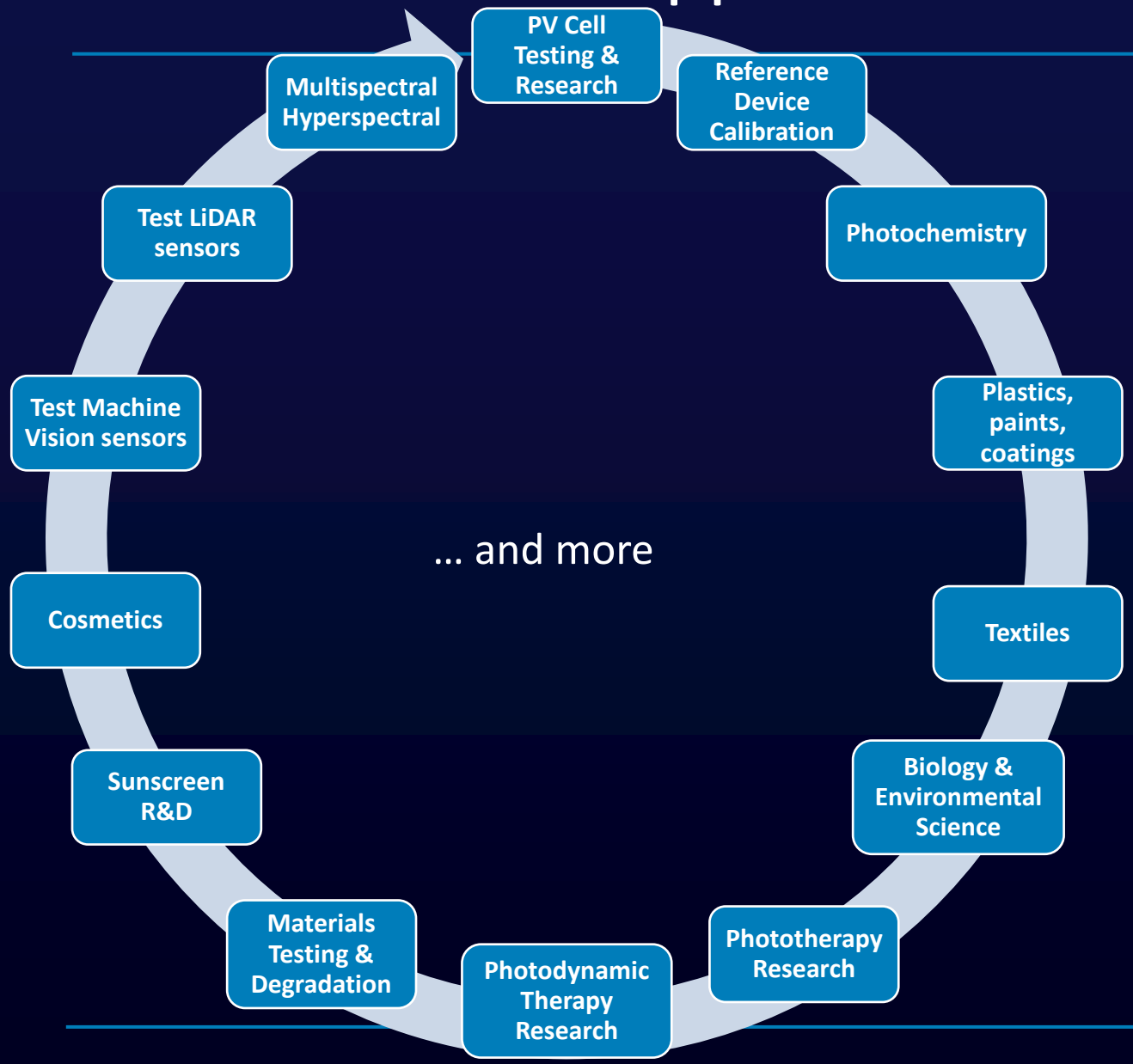
AM0 and AM1.5G

LumiSun Solar Simulator Family

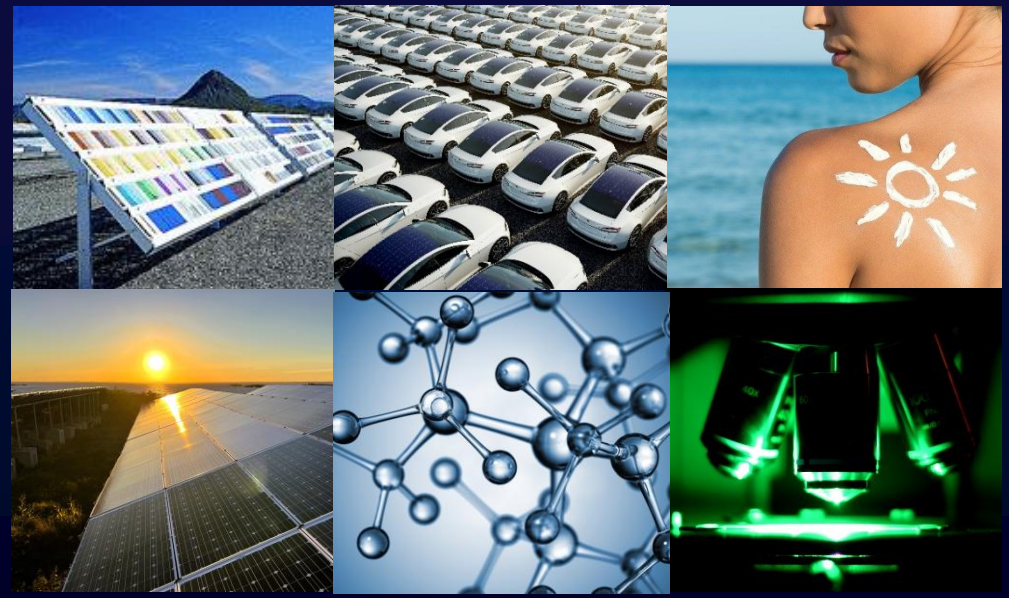


INNOVATIONS IN OPTICS

Solar Simulator Applications



Spectral stability, accuracy, and reliability are important

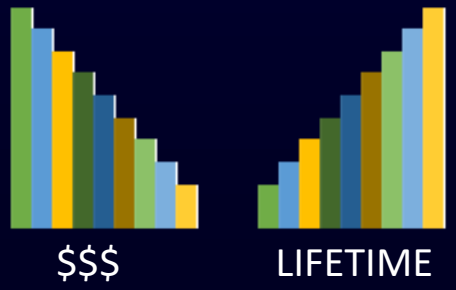


Solar Simulator Technology

- LED Solar Simulators (fastest growing, cutting-edge R&D)
- Xenon Arc Lamp Steady State (previously industry standard)
- Metal Halide Lamp (UV Aging)
- Flash Solar Simulators (Pulsed Xenon or LED)
- Continuous Multi-Source Hybrid Simulators
  - Extends spectrum into deep UV or far IR, but calibration challenges
- High Flux Concentrated (10 – 1000 Suns)
  - CPV cells, concentrator optics

Advantages of LED Solar Simulators

Low Cost	Individually Controllable λ's	Tunability of spectrum	Energy Efficient Low voltages	No explosive bulb failure	No shutter, fewer optics, no igniters
Test many cell technologies	Spatially Uniform	High Temporal Stability	Electronic Switching for λ's	No warm-up/ cool-down	Pulse drive flexibility
Operate at lower temperatures	Long Life - reduce downtime	Cost Effective Solutions	Friendly to environment (no Hg, ozone)	Fast Control µsec	Compact & easy to integrate





IOI LumiSun Solar Simulator Differentiators

Differentiator	Customer Benefit
Very Low Spectral Deviation	More accurate point-by-point reproduction of AM1.5G and AM0 spectra, resulting in improved measurement accuracy and repeatability in addition to A+A+A+
Class A+ Uniformity for Each Individual Wavelength	Enables accurate independent wavelength operation for tandem cells, perovskites, EQE studies, and current-matching measurements.
Imaging Optical System	Reduced sensitivity to sample height and working-distance variations
Superior Depth of Field	More consistent measurements across different sample geometries and fixture configurations
Long Working Distance	More space for fixtures, probes, chambers, and instrumentation
Independent λ Control	Enables spectral tuning, tandem-cell optimization, and advanced photovoltaic research
Wide Dynamic Range (0.1 to 1.2 Suns)	Supports low-light, degradation, bifacial, albedo, and variable-irradiance testing
AM0 and AM1.5G Capability	One instrument supports both terrestrial and space solar testing
Long Working Distance	Simplifies integration with chambers, probe stations, and automation systems
LED-Based System	No lamp replacement, low maintenance, and excellent stability

Performance Metrics: IEC Class, SPC, SPD

Spectral Match

Spatial Non-uniformity

Temporal Instability

Classification per IEC	Minimum λ Range for Evaluation (nm)	Spectral Match to all Intervals (%)	Spatial Non-Uniformity of Irradiance (%)	Temporal Instability (%)	
				Short Term (STI) %	Long Term (LTI) %
A+	300 - 1200	87.5 to 112.5	1	0.25	1
A	400 - 1100	75 to 125	2	0.5	2
B	400 – 1100	60 to 140	5	2	5
C	400 – 1100	40 to 200	10	10	10

Spectral Coverage

$$SPC = \left(\sum_{E_{SIM}(\lambda) > 0.1 * E_{AM1.5}(\lambda)} E_{AM1.5}(\lambda) \cdot \Delta\lambda \Big/ \sum_{300\ nm}^{1200\ nm} E_{AM1.5}(\lambda) \cdot \Delta\lambda \right) \cdot 100\%$$

Spectral Deviation

$$SPD = \sum_{300nm}^{1200\ nm} |E_{SIM}(\lambda) - E_{AM1.5}(\lambda)| \cdot \Delta\lambda \Big/ \sum_{300\ nm}^{1200\ nm} E_{AM1.5}(\lambda) \cdot \Delta\lambda \cdot 100\%$$

IEC 60904-3, 60904-9

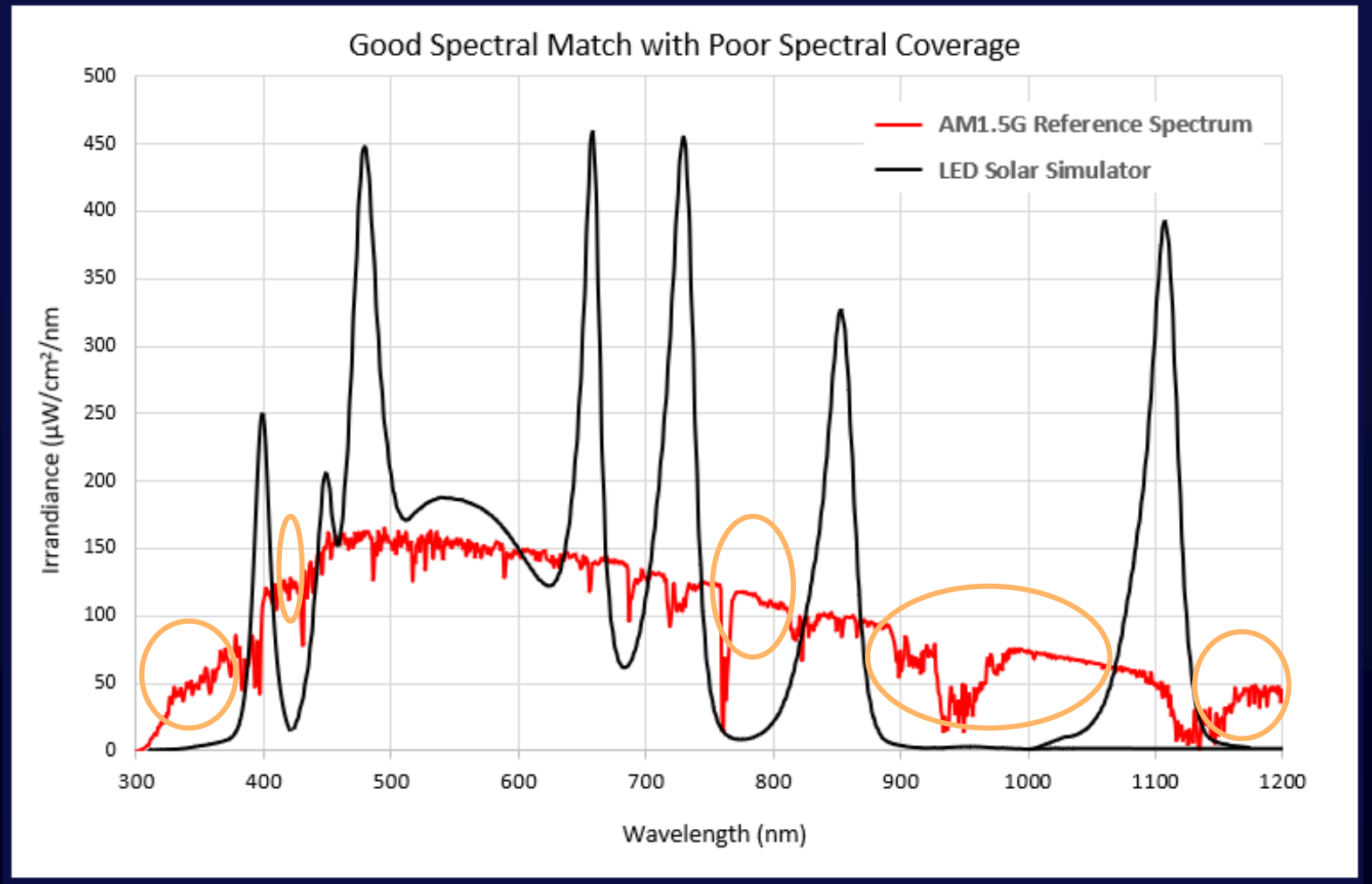
Spectral Coverage (SPC) & Spectral Match

Often confused, but fundamentally different

SPC describes the λ range UV to VIS to NIR

Spectral Match is how accurately the solar simulator spectrum matches the reference standard within 6 defined sub-bands

Spectral Match is easy to achieve compared to Spectral Deviation

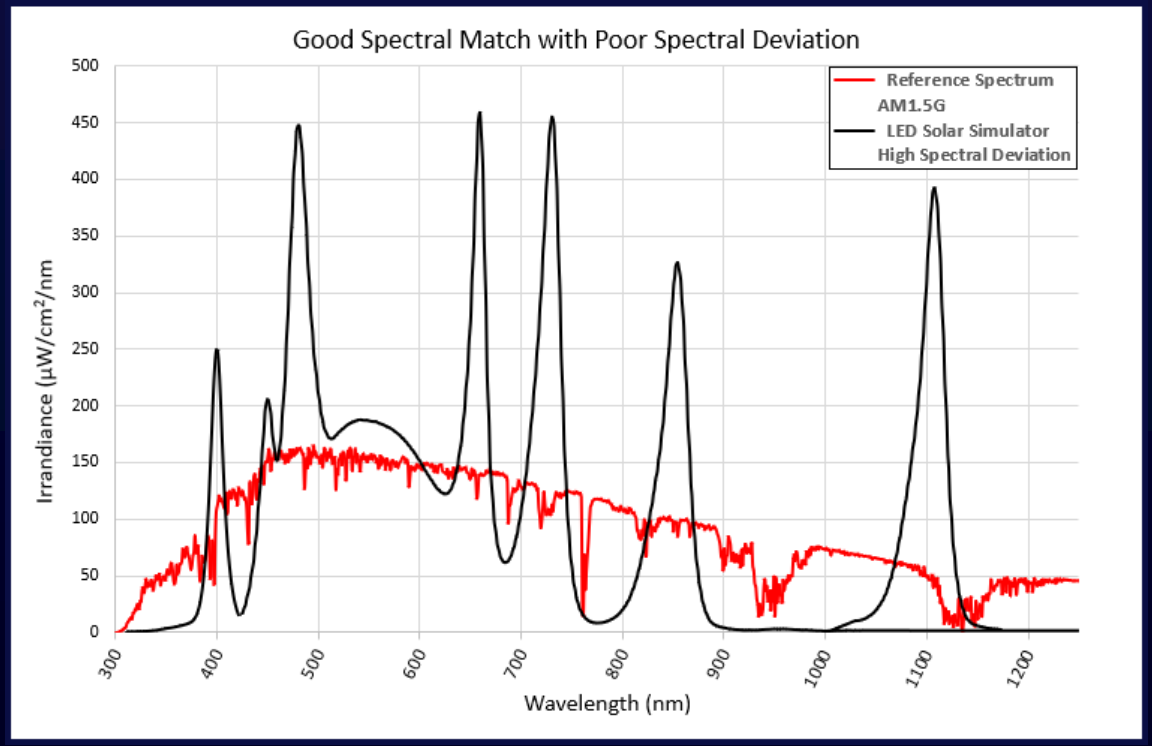


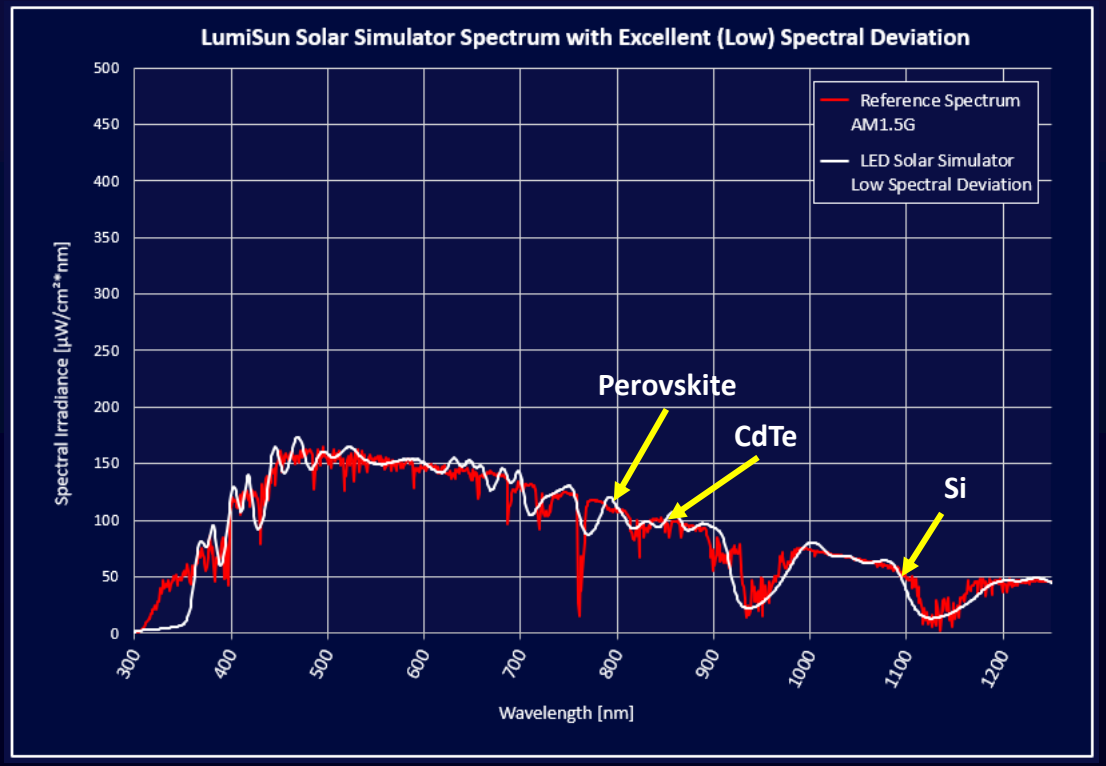
Achieving Low Spectral Deviation (SPD)

- Why is this important?
  SPD is detailed point by point
- Accuracy increases
- Class A+ Spectral Match is not sufficient

Low spectral deviation via greater
# of die and λ distribution

< 9% 400 - 1100nm
< 12% 350 - 1250nm

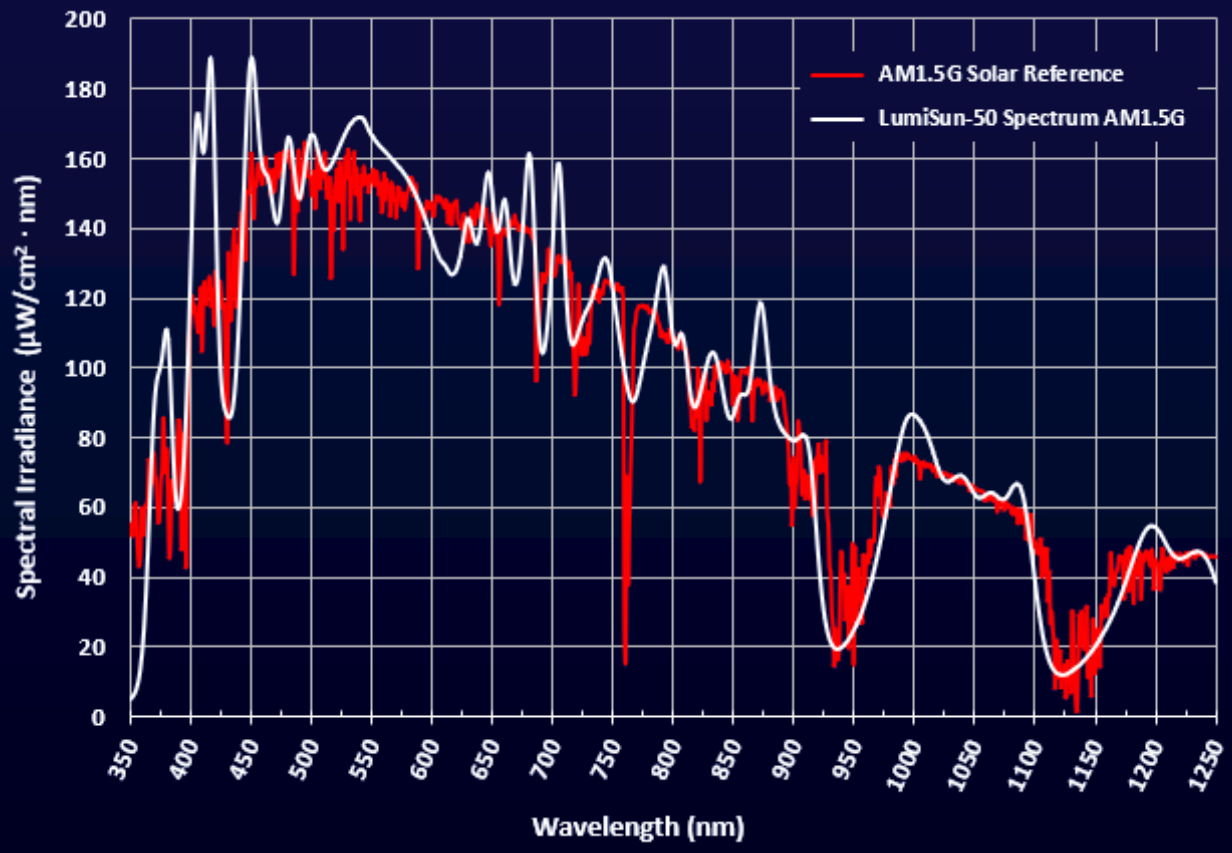


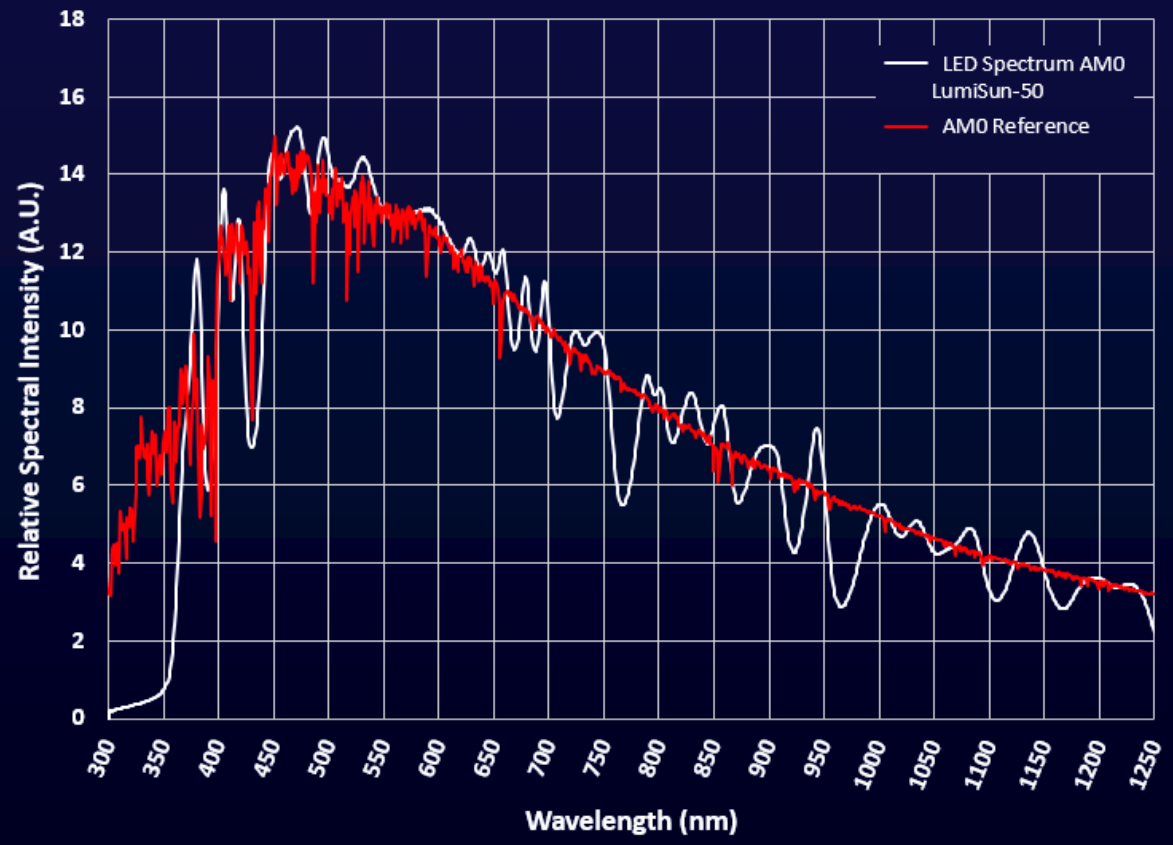


LumiSuns Exceptional SPD Increases Accuracy

Low spectral deviation via greater # of die and λ distribution

< 9% 400 - 1100nm
< 12% 350 - 1250nm
< 15% 300 - 1250nm

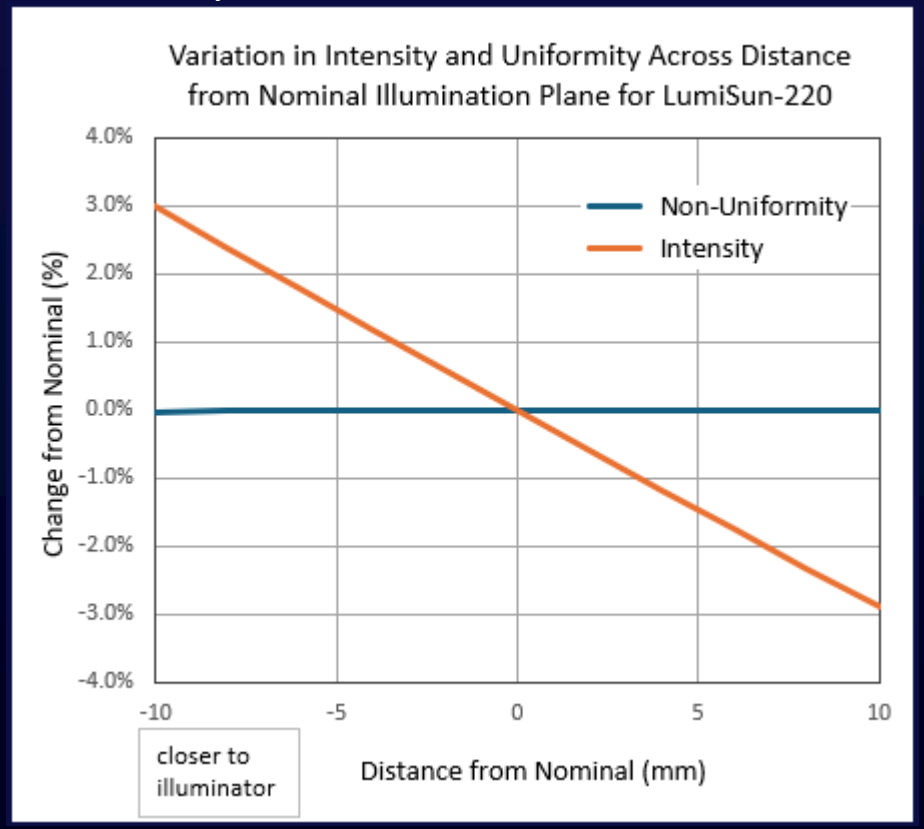




Non-uniformity and Depth of Focus

- IOI maximizes uniformity and ease of alignment via imaging

Non-uniformity change < 0.005 % over +/- 10mm
Intensity variation < 3.0 % over +/- 10mm



Excellent low nonuniformity < 0.8% for all λ's ***and*** for individual λ's

0.995	0.997	0.998	0.997	0.997	0.998	0.996	0.992
0.995	1.000	1.000	0.998	0.997	0.999	0.996	0.993
0.995	0.999	0.997	0.996	0.995	0.998	0.998	0.993
0.992	0.996	0.993	0.993	0.991	0.996	0.995	0.990
0.993	0.997	0.995	0.993	0.994	0.998	0.996	0.991
0.994	0.999	0.996	0.996	0.995	0.999	0.996	0.991
0.994	0.997	0.997	0.997	0.996	0.999	0.995	0.989
0.995	0.997	0.997	0.995	0.994	0.996	0.991	0.985

Excellent Uniformity for Each Wavelength

- ✓ Improved accuracy when λ groups are operated independently
- ✓ All regions of the solar cell receive the same spectrum
- ✓ Better tandem-cell characterization
- ✓ More accurate current-matching studies
- ✓ Improved precision in degradation testing
- ✓ Better layer-specific photovoltaic measurements

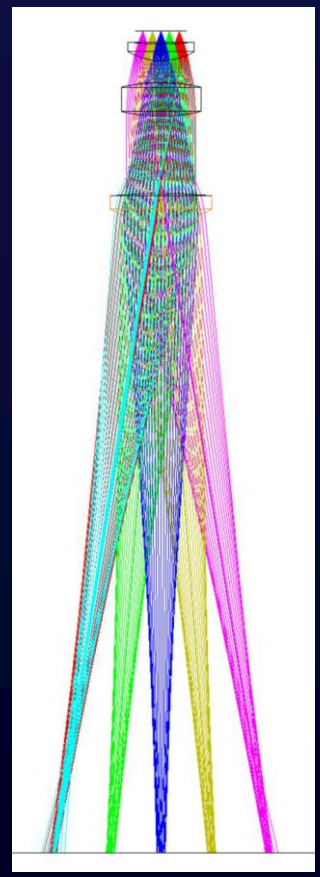


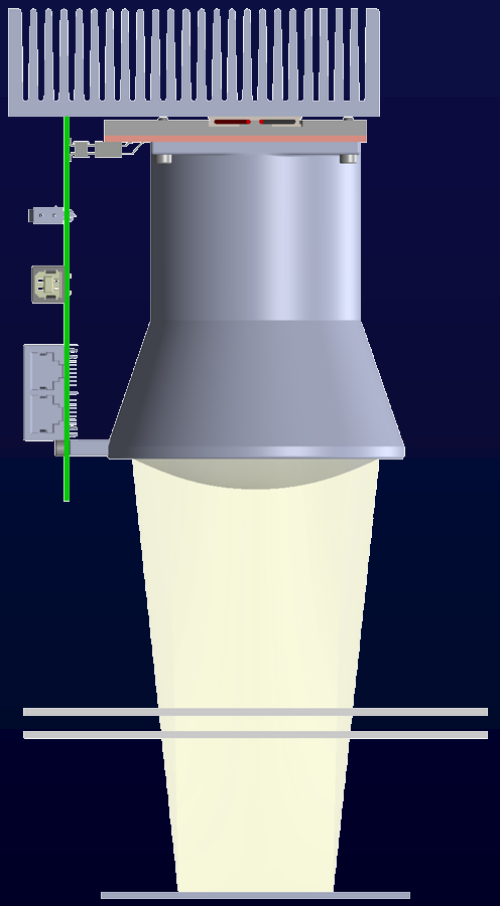
Superior Depth of Field & Long Working Distance

IOI's LumiSuns image to the sample plane
via a unique optical system

Benefits include:

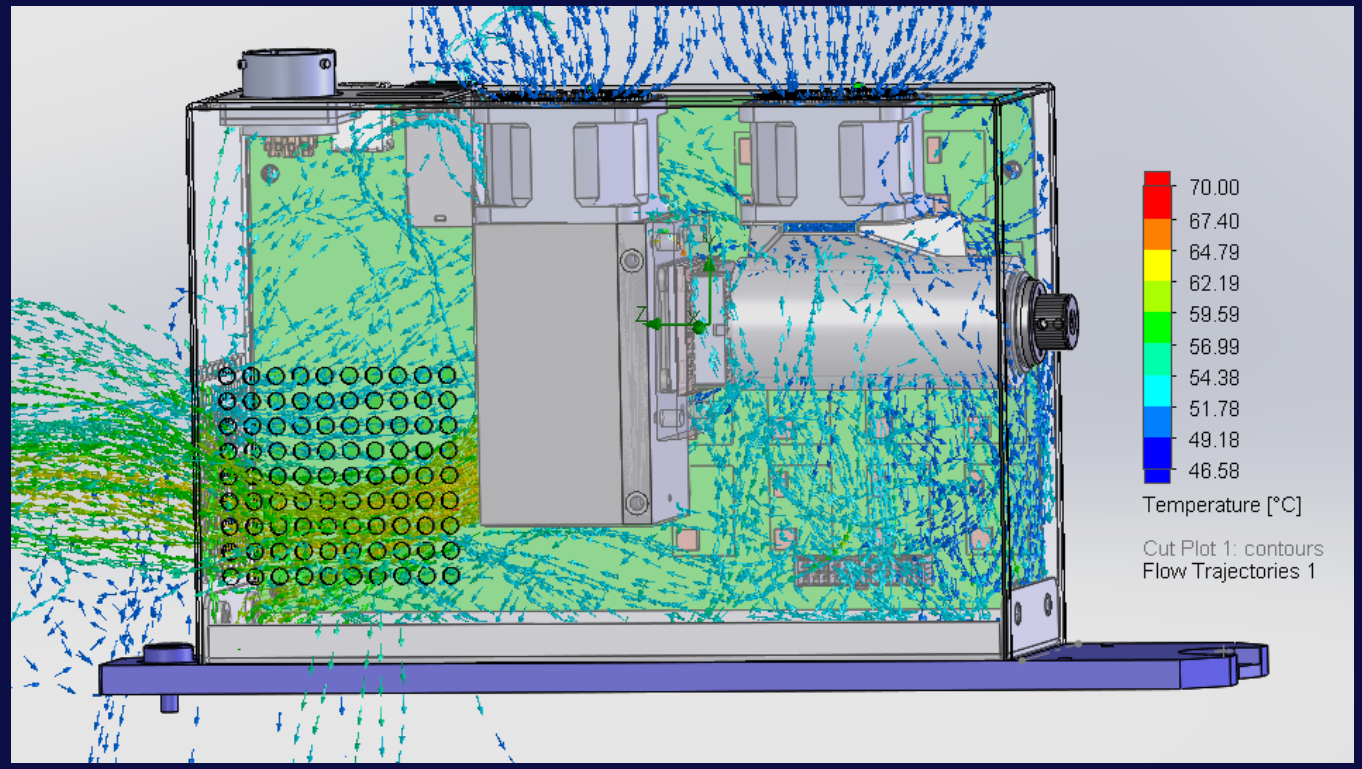
- ✓ Reduced sensitivity to working-distance changes
- ✓ Reduced sensitivity to sample height variations
- ✓ Improved repeatability
- ✓ Greater tolerance to fixture variation
- ✓ Easier integration with environmental chambers
- ✓ Flexible integration with automated and evolving research setups
- ✓ More space for fixtures, probes, chambers, and instrumentation





Temporal Stability

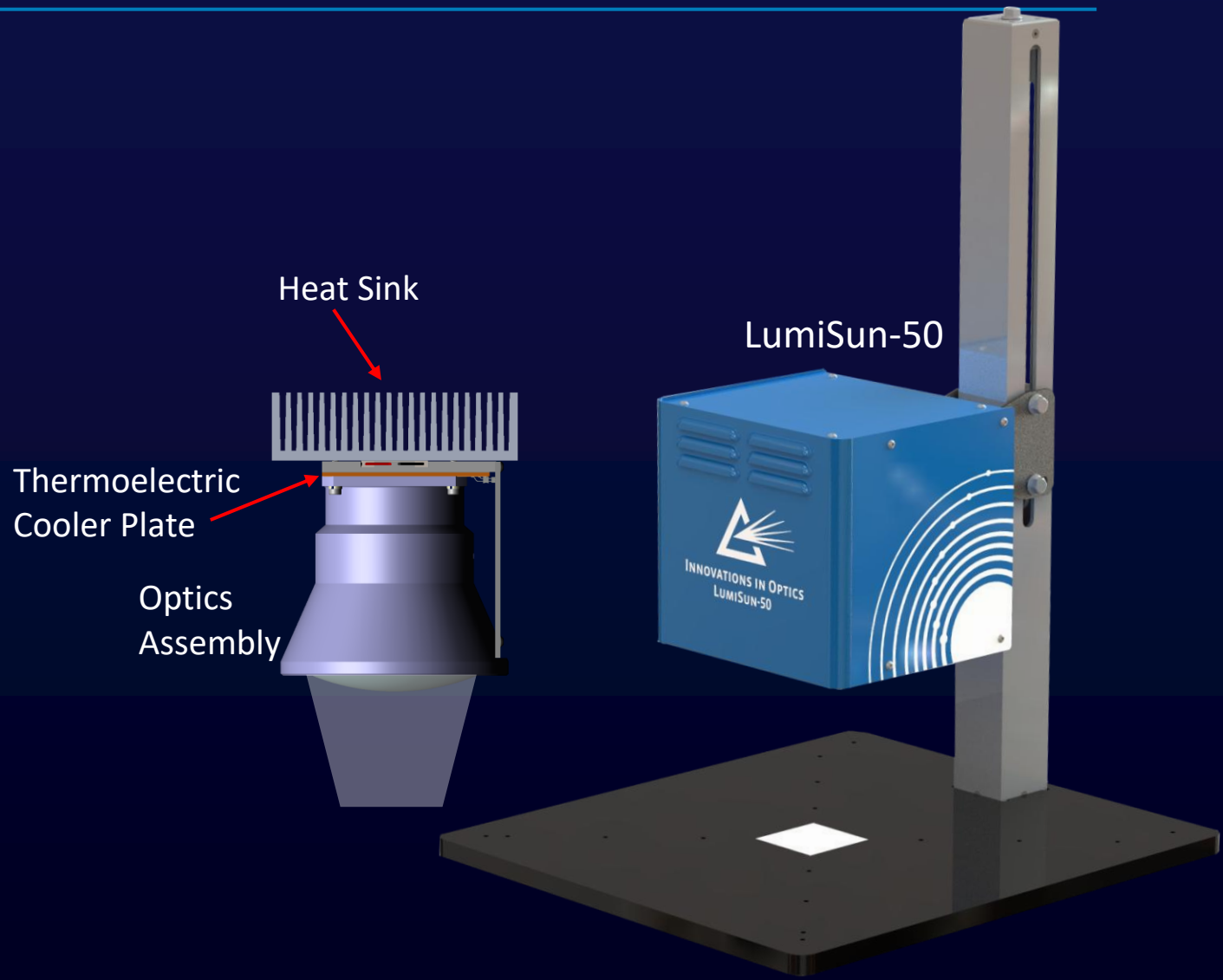
- Thermal management is critical to achieve temporal stability and long lifetime
- LED die flux and wavelength shift with temperature and drive current
- Multi-channel LED systems (20 to 40 λ's) benefit dramatically from TEC stabilization because spectral mixing remains constant.



Example of thermal analysis incorporates LEDs, TECs, high efficiency heat sinks, forced convection and ambient temperature changes.

Maximized Temporal Stability

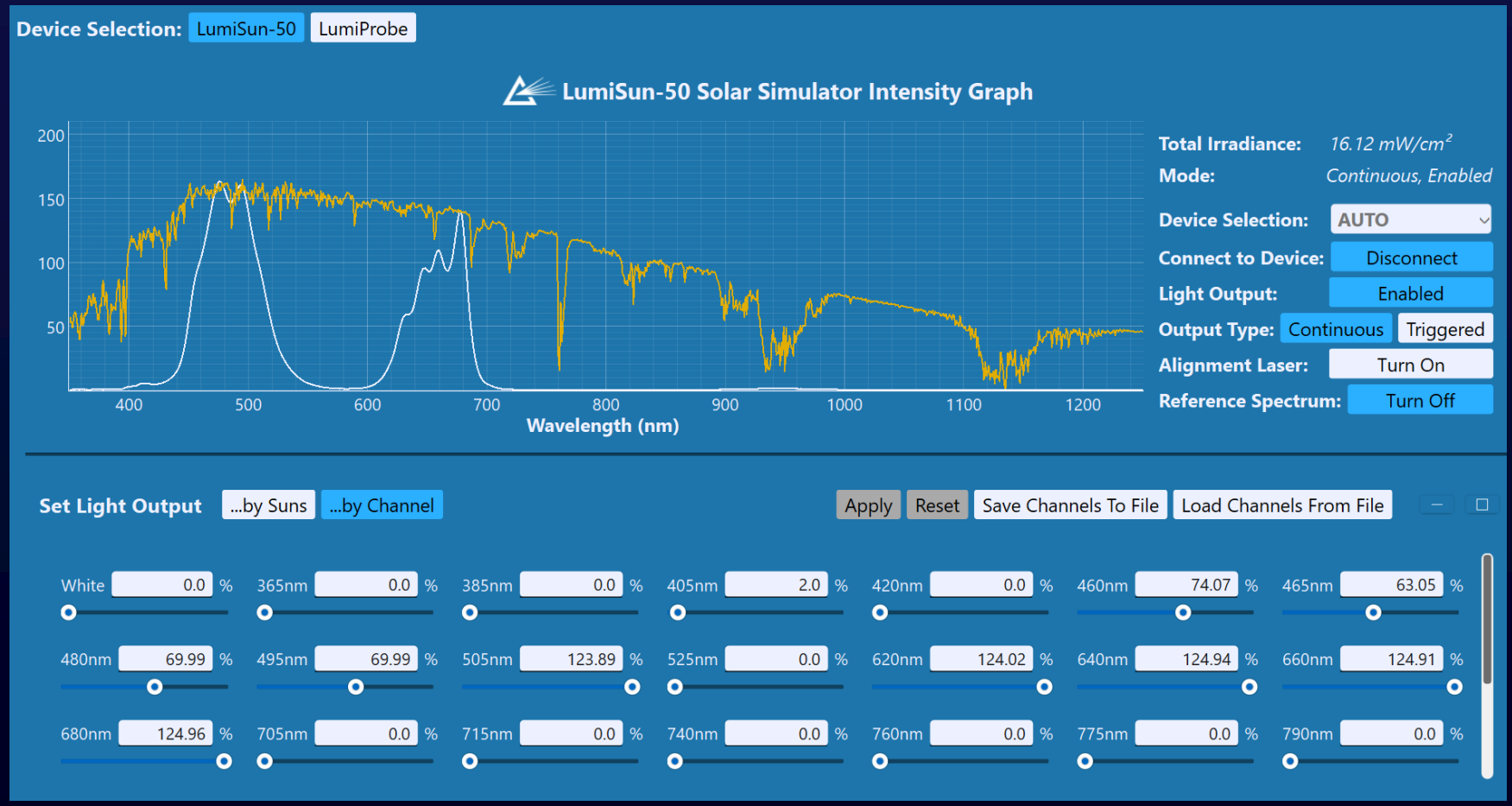
- Passive cooling may vary by 2-5˚C
- TEC module actively controls the temperature of the light source
- TEC can hold a setpoint to 0.05 to 0.1˚C with proper control
- TEC minimizes the time to stable output < 10ms
- Class A+ Temporal Instability < 0.25%
  LumiSun-50 < 0.1% STI



Independent Wavelength Control

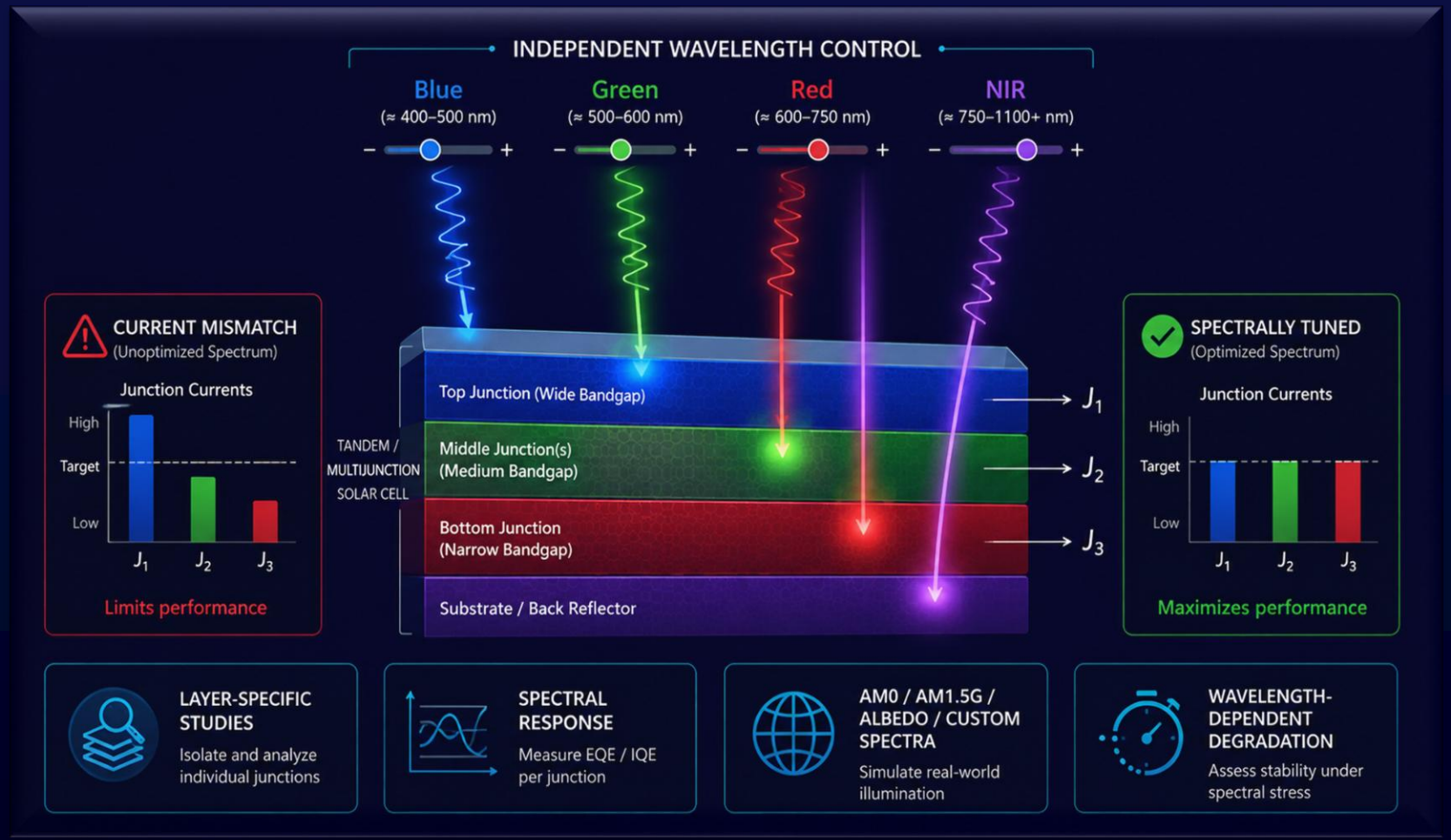
- Precise electronic control is critical
- Drive multiple LEDs and wavelengths
- Set # of Suns
- Customize spectrum
- Include headroom for future calibration
- High-speed drivers
  - Suitable for flash testing
  - Lamp-based need shutters

Blue and Red LED Die Regions ON



Advantages of Independent Wavelength Control

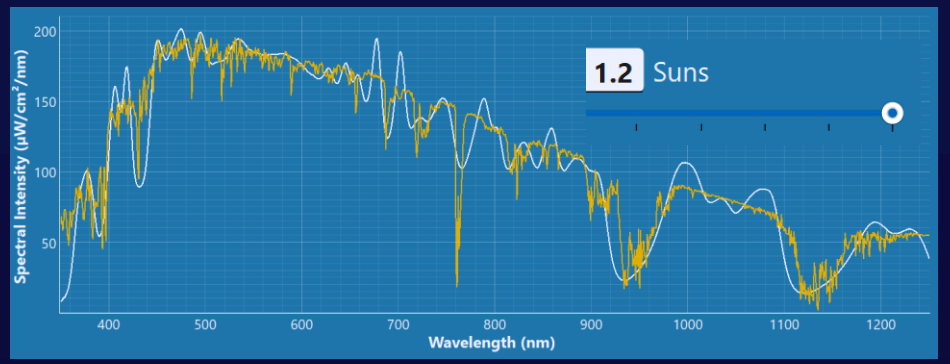
- Tune individual spectral bands independently
- Optimize tandem and multijunction current matching
- Perform layer-specific and spectral response studies
- Study spectral sensitivity and mismatch
- Create AM0, AM1.5G, albedo, and custom spectra
- Investigate wavelength-dependent degradation

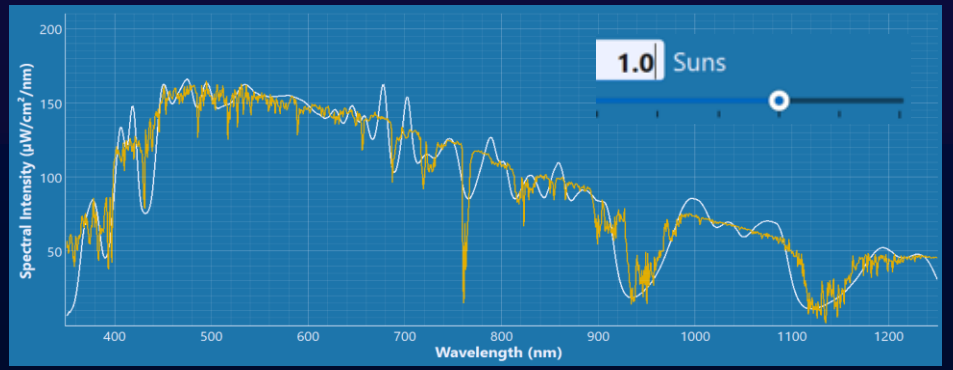


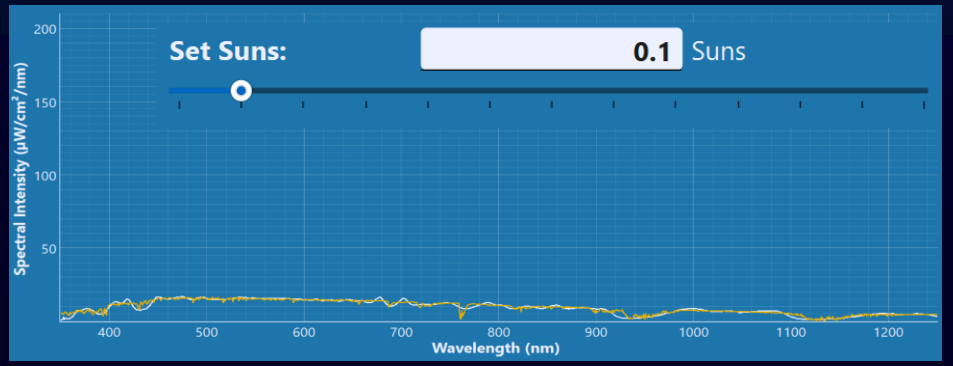
One Simulator – Many Operating Conditions

0.1 to 1.2 Suns: from low-light operation through elevated irradiance without changing the setup

- ✓ Characterize PV performance from low-light through elevated irradiance
- ✓ Evaluate device behavior under changing real-world illumination conditions
- ✓ Measure efficiency, IV response, current and voltage as a function of irradiance
- ✓ Supports indoor/low-light PV, bifacial, stability and variable-irradiance studies
- ✓ Use the same calibrated platform across the full 0.1 to 1.2 Sun operating range

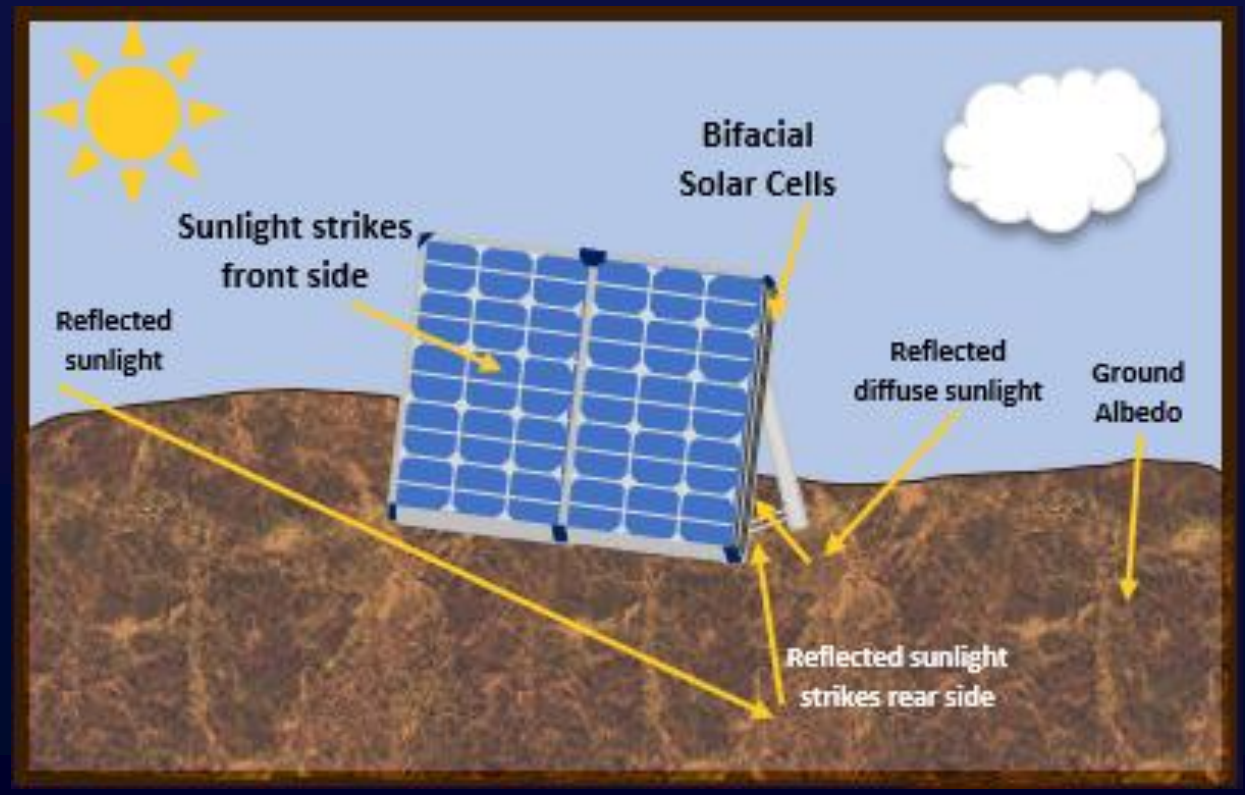


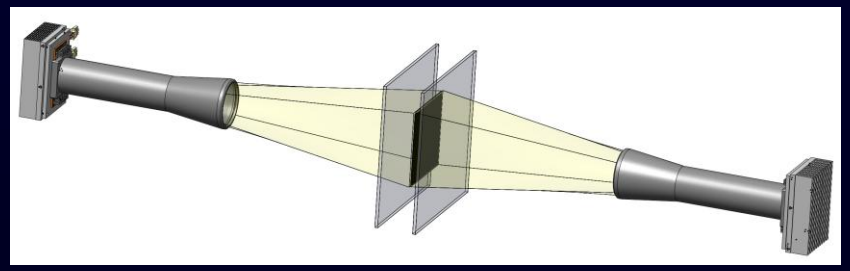




Bifacial Configuration for Modern PV

- More surface area to absorb photons
- Combine with tandem or multijunction solar cells
  - Front side absorbs visible
  - Rear side absorbs NIR
- Increased efficiency 30%
- LumiSun can operate below 0.10 Suns with λ control to match rear side

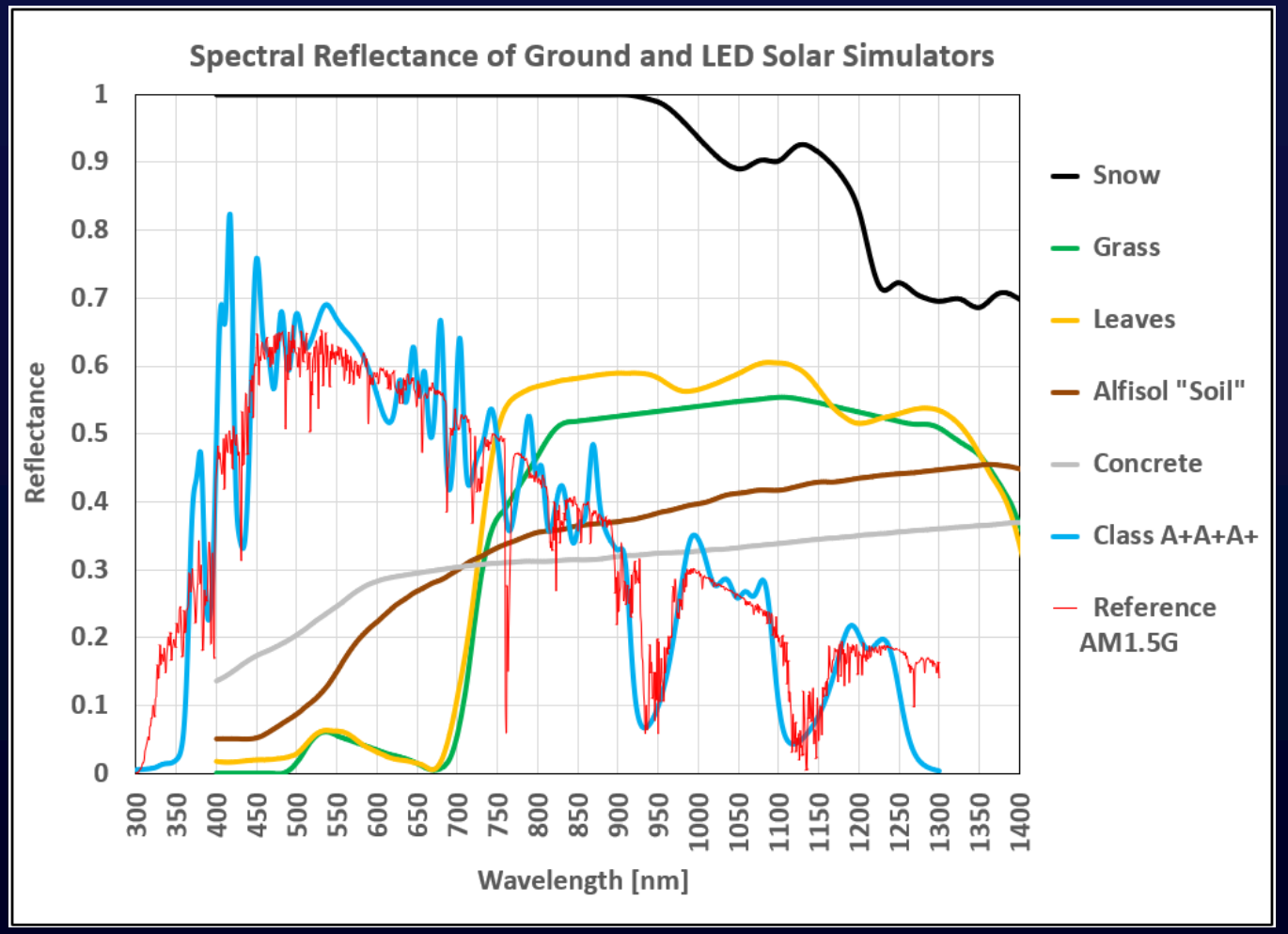




Dual solar simulators to study front side and rear side of solar coupon (albedo emulator)

LED Solar Simulator for Albedo Emulation

- LED Solar Simulator with 35 λ's and low spectral deviation
- Tunable rear-side illumination
- Applications
  - Bifacial PV module characterization
  - Tracker & ground condition modeling
  - Multijunction cells in bifacial configuration
  - Agricultural PV research
  - Building integrated PV

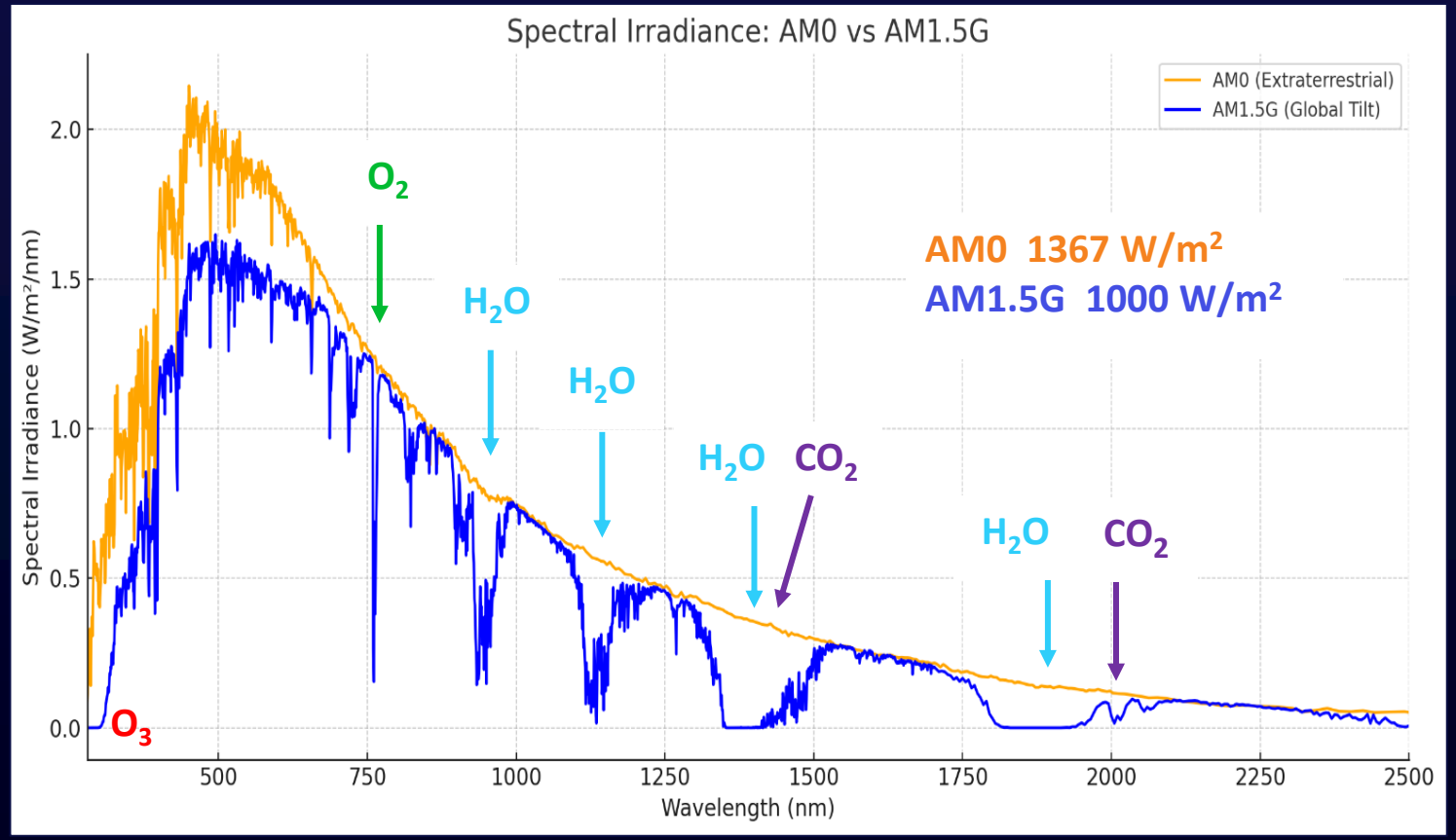


Modern PV is highly sensitive to rear-side irradiance
Bifacial, HJT, TOPCon, tandem perovskite/silicon

AM0 and AM1.5G Capability in One Platform

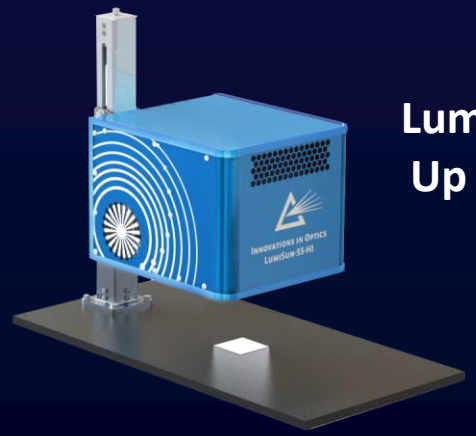
- AM0 - Higher irradiance for space, satellite, UV studies
- AM1.5G - Atmospheric attenuation and molecular absorption bands
- Additional high-power λ's for AM0 maintain low spectral deviation
- One LED solar simulator supports both terrestrial and space PV applications

Allows the same DUT and measurement setup to be evaluated under both reference spectra



LED Solar Simulator Differentiators

- Each LED solar simulator has a purpose
- Illumination field size, spectral range, # Suns



LumiSun-55-HI
Up to 20 Suns

HIGH BRIGHTNESS



LumiSun-500

PV PANELS

LumiSun-220

WAFERS





LumiSun-50
LumiSun-UV

R & D



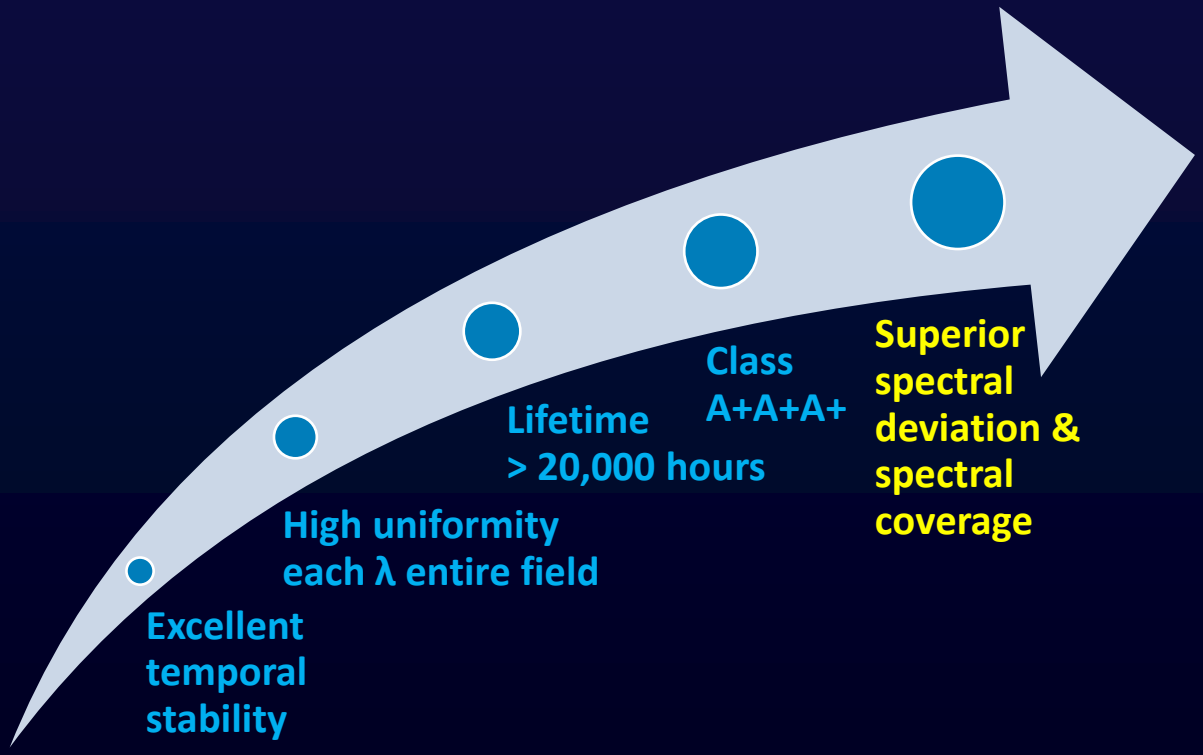
LumiProbe

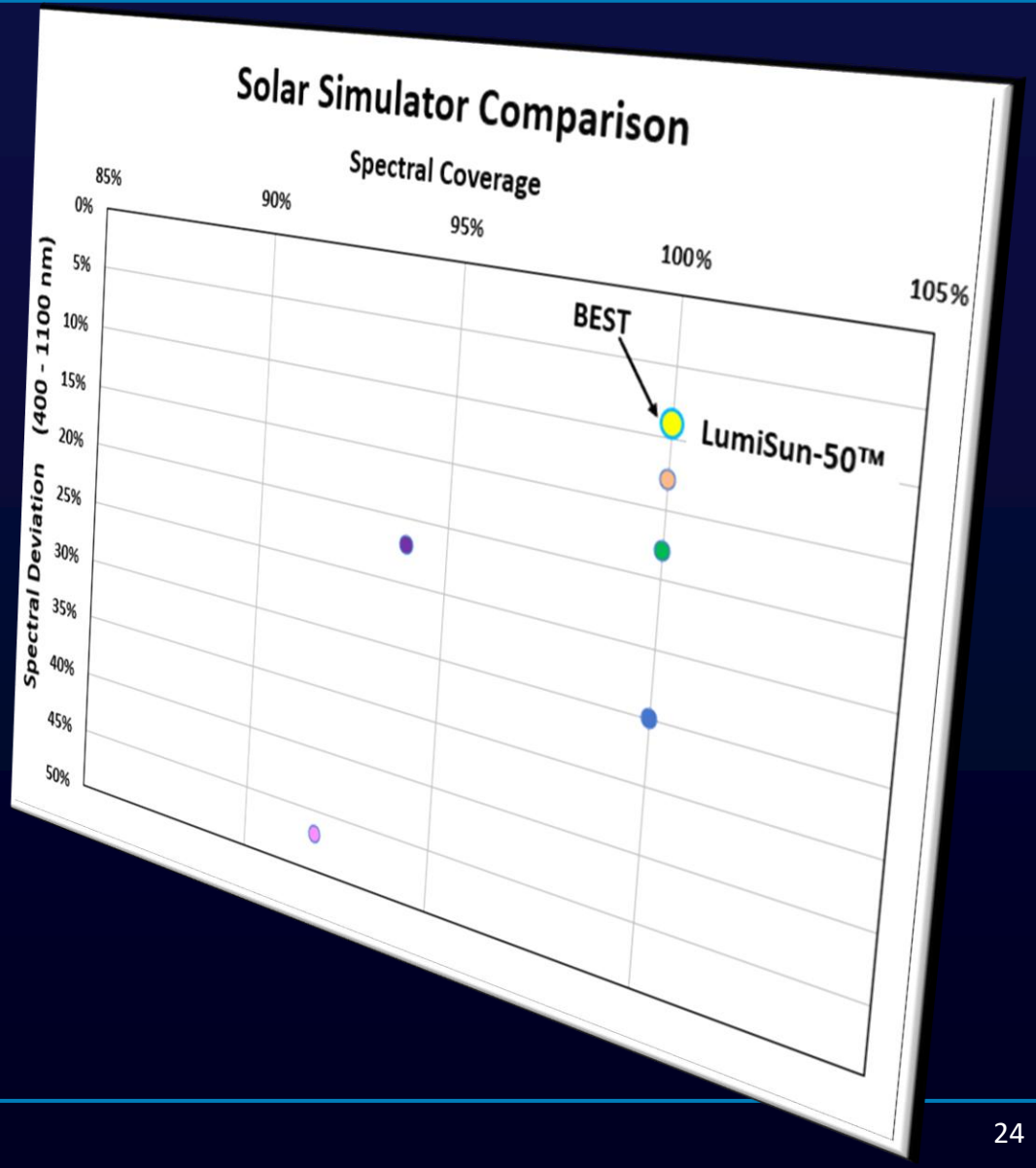
PV Characterization

Not to scale

Optimum Performance for Solar Simulators

Broad spectral coverage and low spectral deviation enable high accuracy in testing and research.



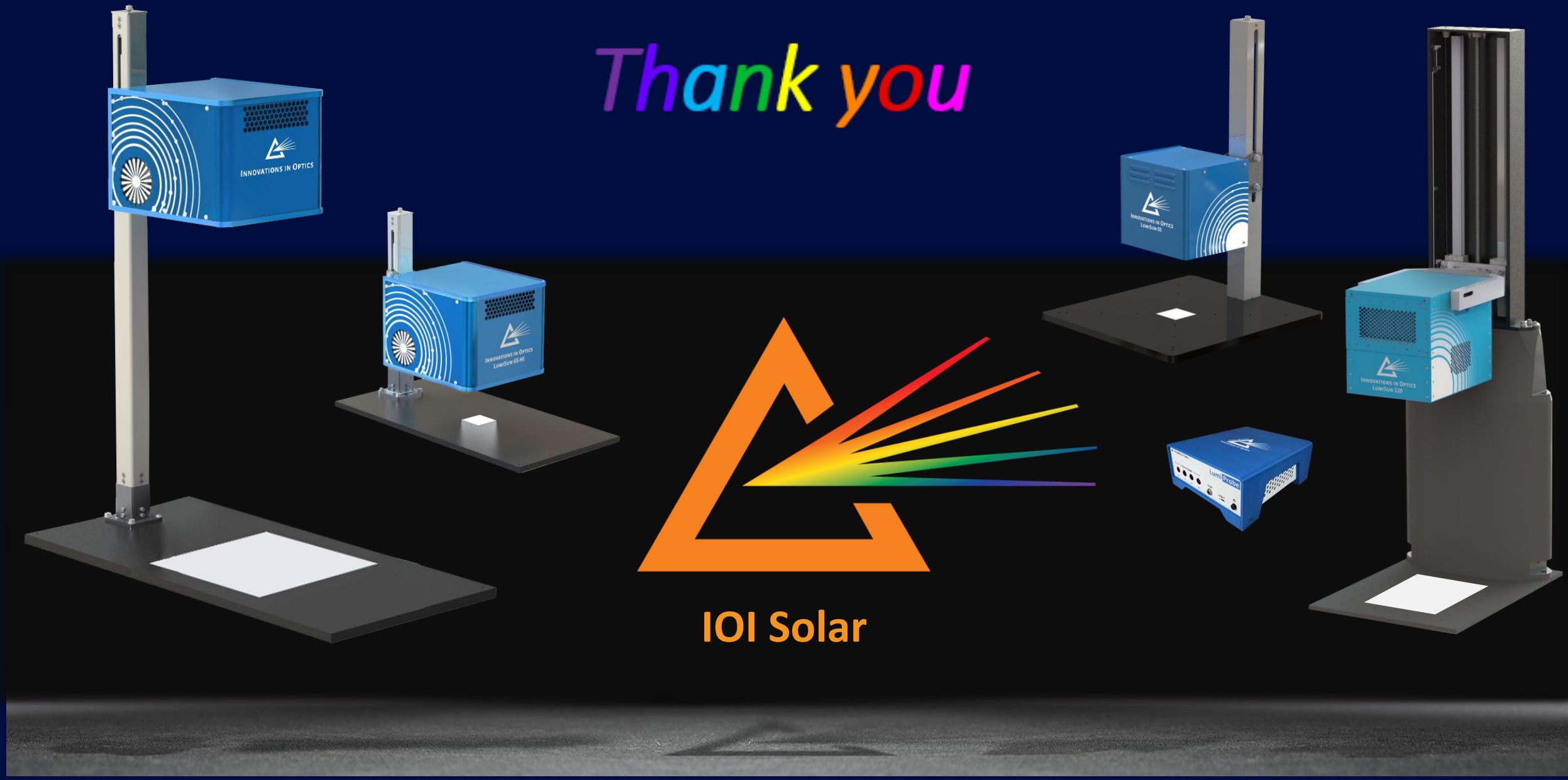




Why IOI Solar?

Conventional solar simulators have been configured with Xenon short-arc lamps, QTH lamps, and metal halide discharge lamps. Yet, illuminators with solid state sources such as IOI's LED solar simulators offer many key advantages:

- ✓ Highly uniform optical output power from 0.1 to 20 Suns
- ✓ Spectral stability over long lifetime delivering a more reliable and consistent simulation of the sun
- ✓ Environmentally friendly (unlike arc lamps) – no mercury, ozone, or UVC emission
- ✓ Energy efficient – LEDs operate at lower voltage and temperatures, and have longer service life
- ✓ Lower operational costs – Testing down-time is lessened, and productivity increased, no warmup, cool down, shutters, filters, or high-voltage igniters that lamps require
- ✓ Customizable spectrum with individual wavelength control (AM0 and AM1.5G)



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High Power Solid-State Illuminators
Replacing Arc Lamps