

The uncertainty in yield forecasts due to the ever-changing solar spectrum

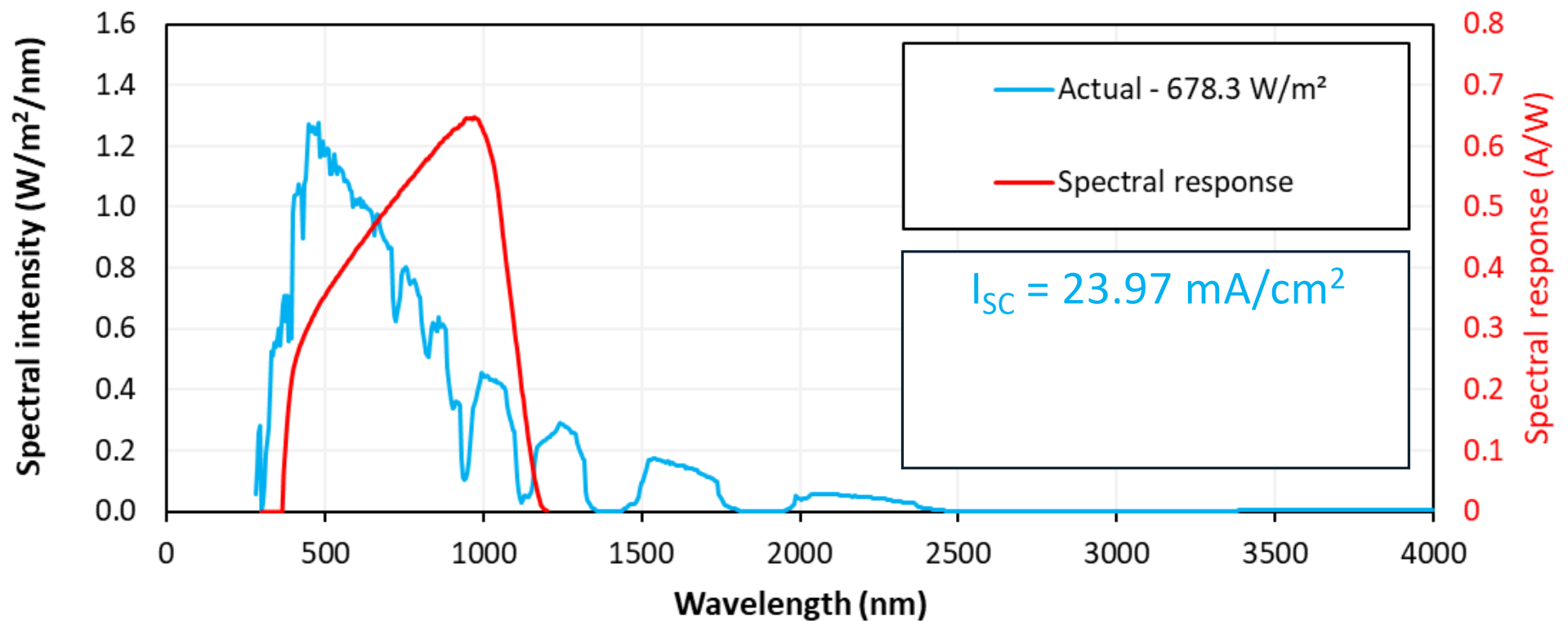
PVPMC Workshop
9-May-2024



Keith McIntosh, Malcolm Abbott and Ben Sudbury

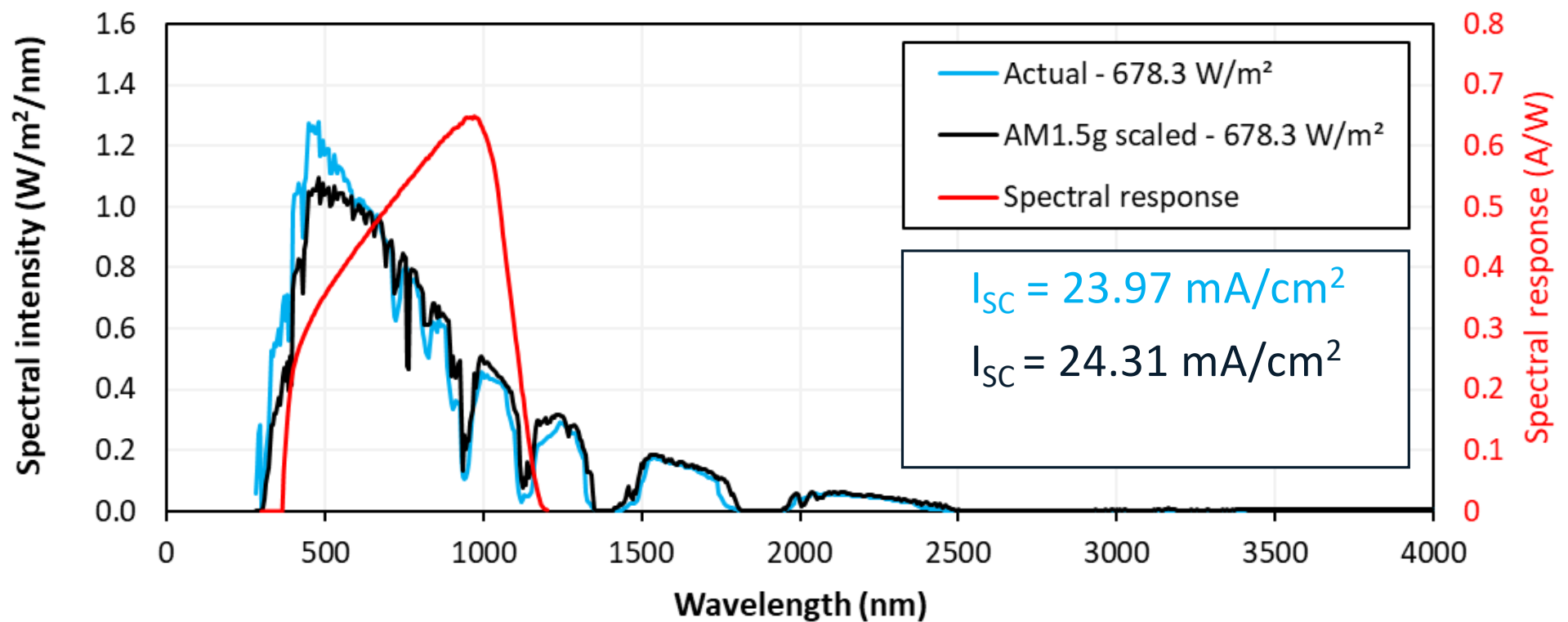
Spectral effect

$$I_{SC} = \int SR(\lambda) \cdot \Phi(\lambda) \cdot d\lambda$$



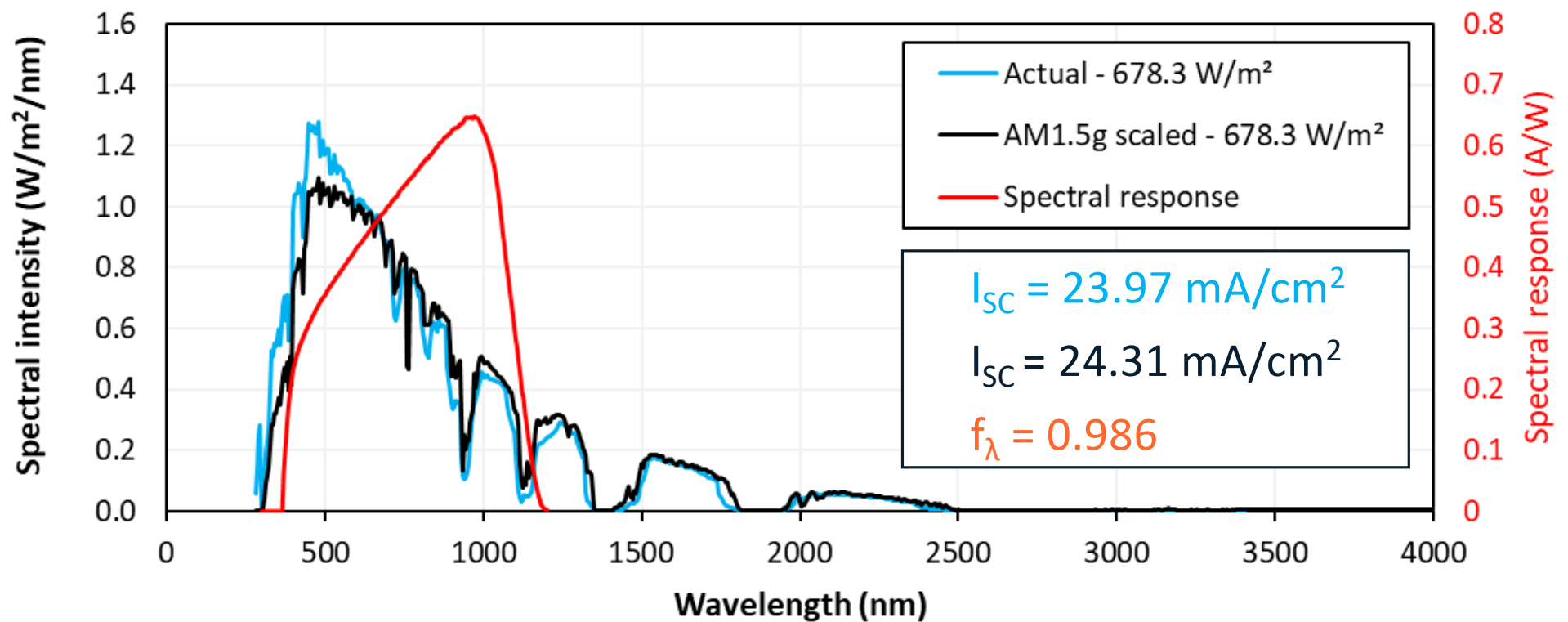
Spectral effect

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Spectral effect

$$I_{SC} = \int SR(\lambda) \cdot \Phi(\lambda) \cdot d\lambda$$



Spectral correction factor, f_λ

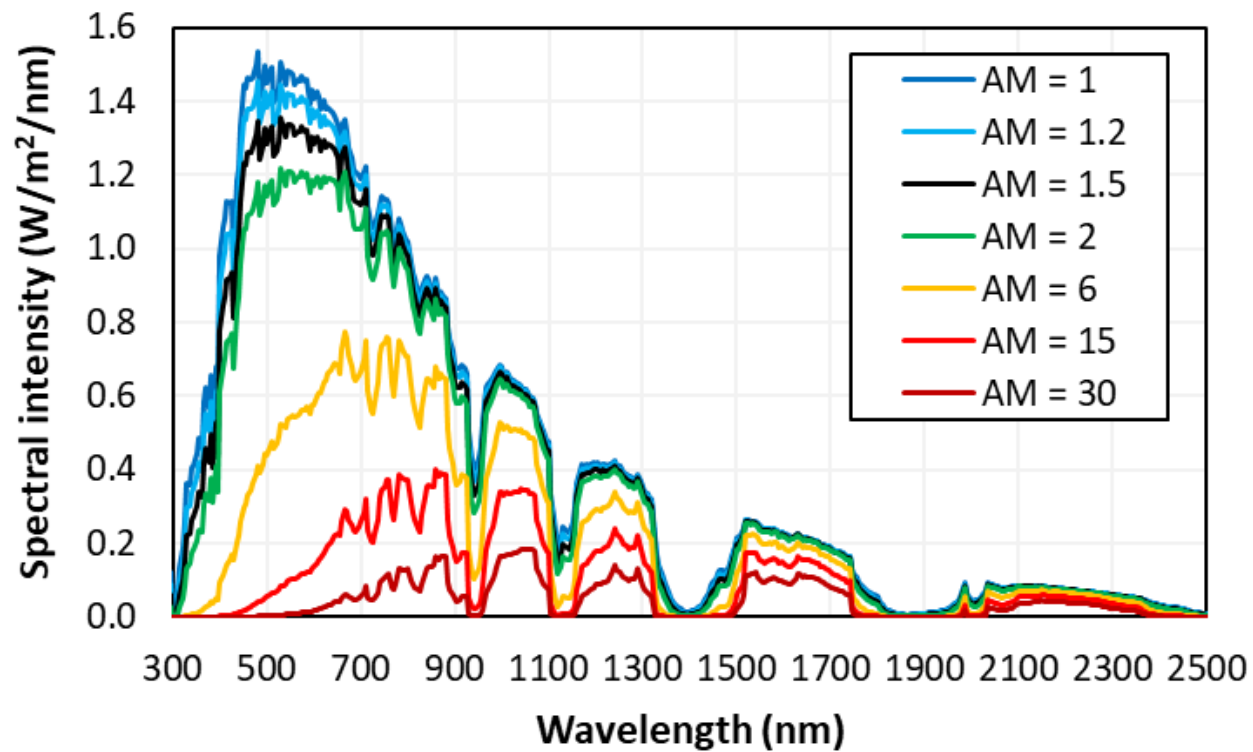


$$I_{sc} = f_\lambda \cdot I_{sc \text{ AM1.5g}} \quad \leftarrow \text{Most common definition}$$

$$\text{Yield} = f_\lambda \cdot \text{Yield}_{\text{AM1.5g}} \quad \leftarrow \text{Annual } f_\lambda$$

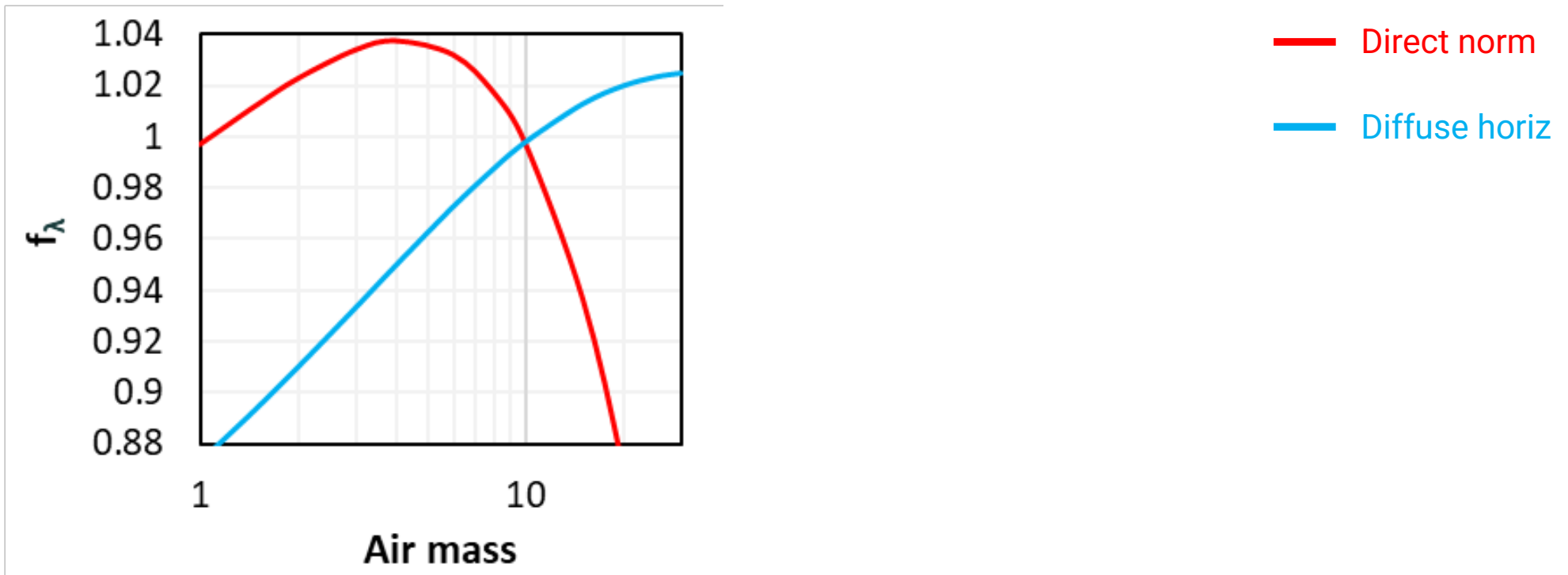
What affects f_λ

Impact of air mass



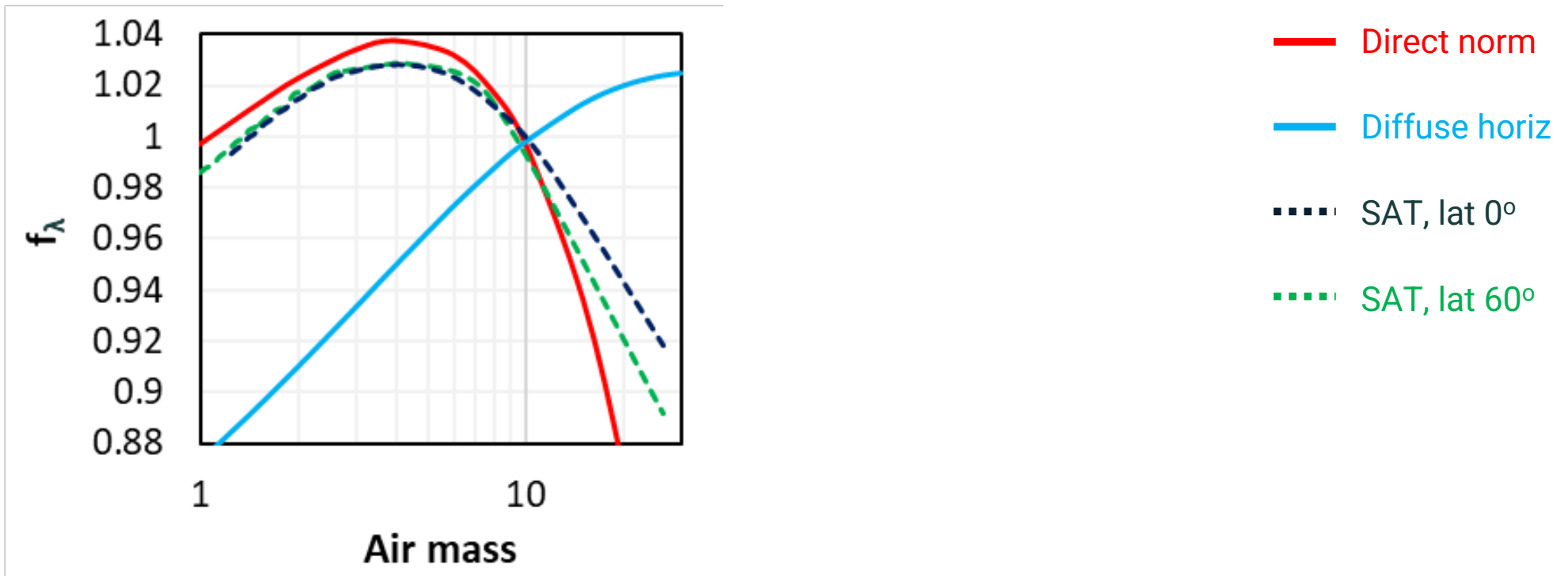
Simulated with SPECTRL2. All parameters at default AM1.5g values except AM.

Impact of air mass



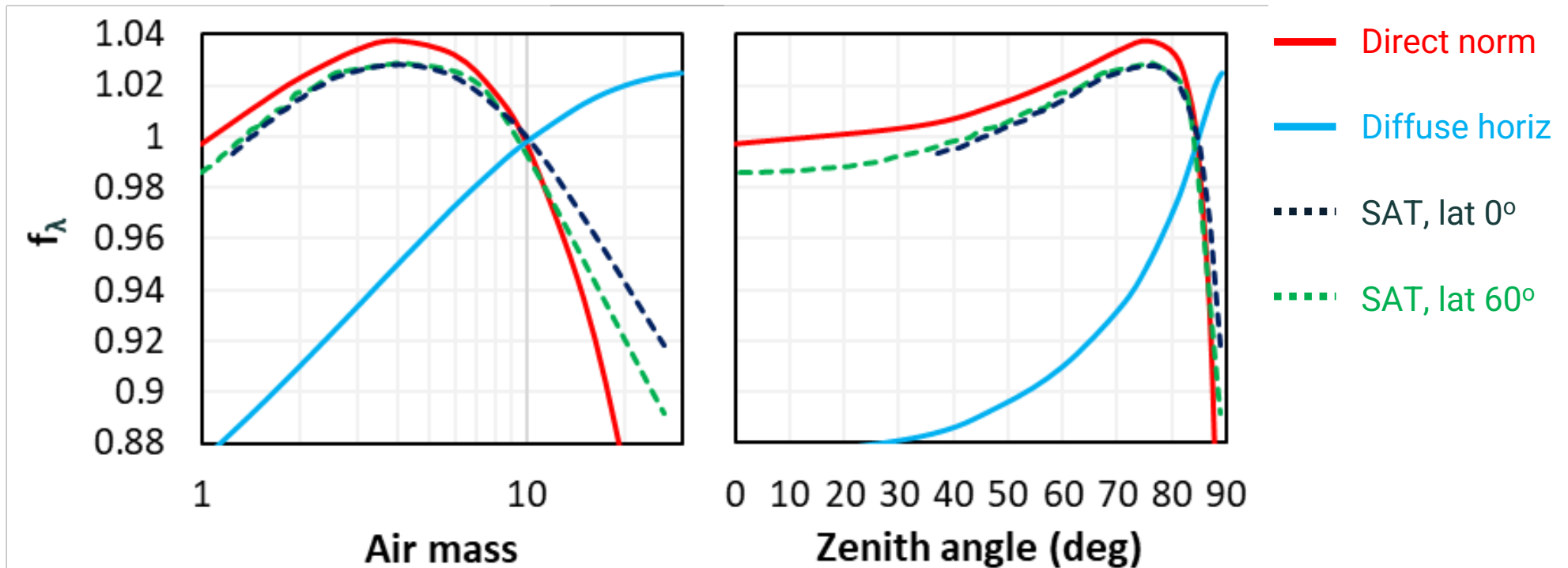
Monofacial modern c-Si module under clear skies, simple analytical optical model

Impact of air mass



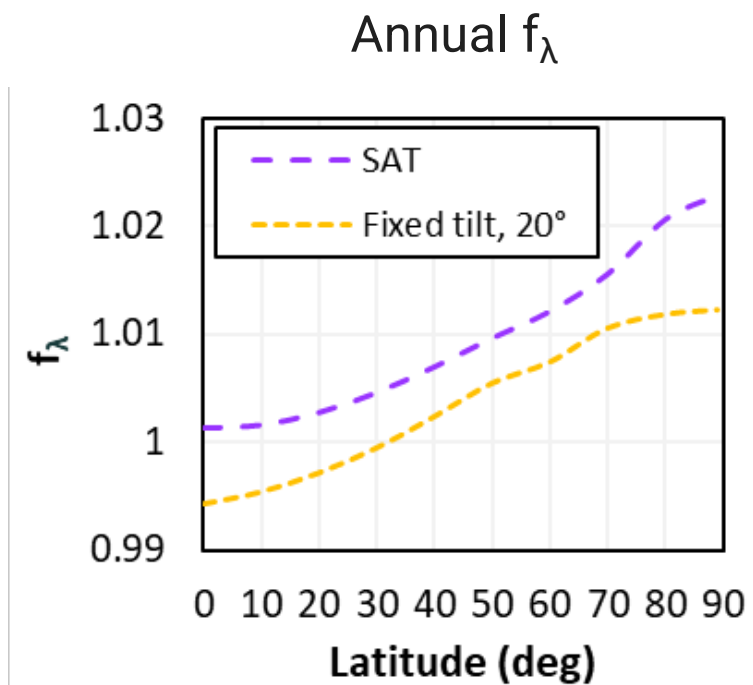
Monofacial modern c-Si module under clear skies, simple analytical optical model

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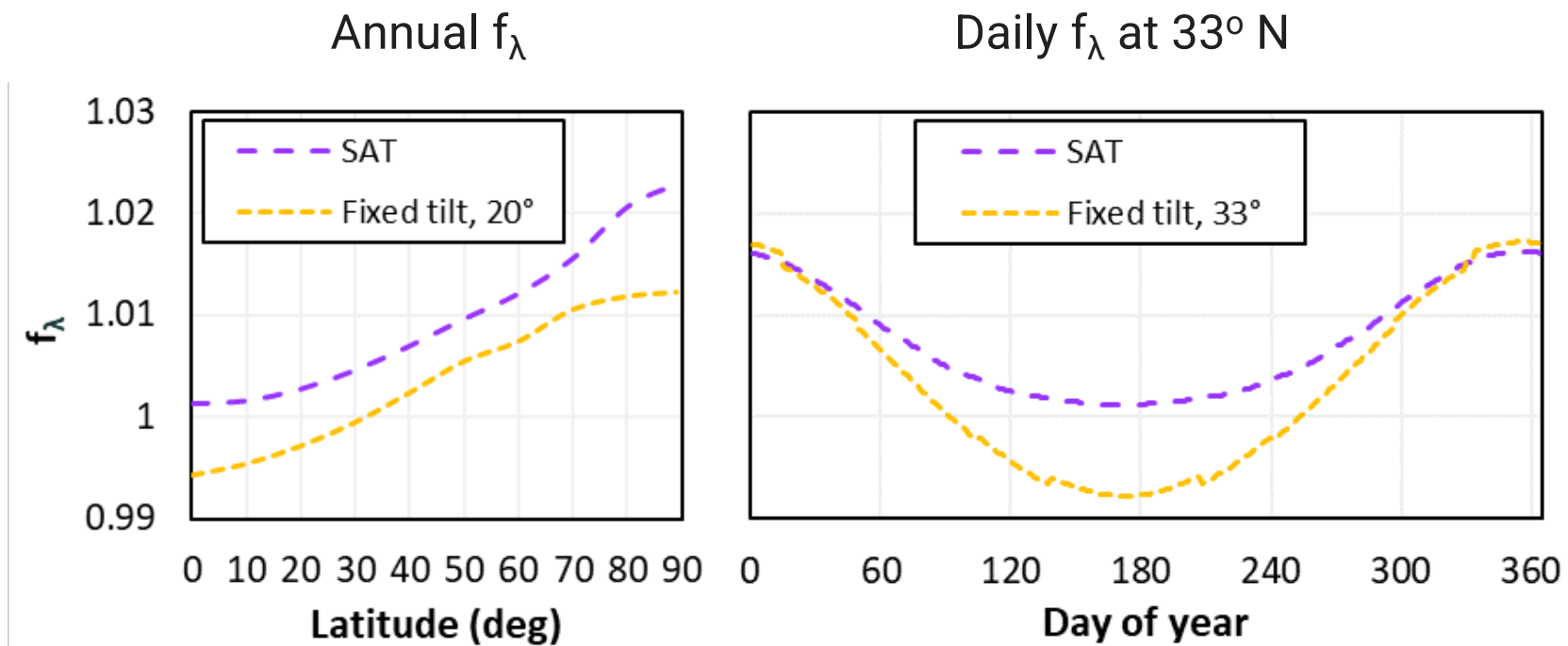
Monofacial modern c-Si module under clear skies, simple analytical optical model

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Monofacial modern c-Si module under clear skies, simple analytical optical model

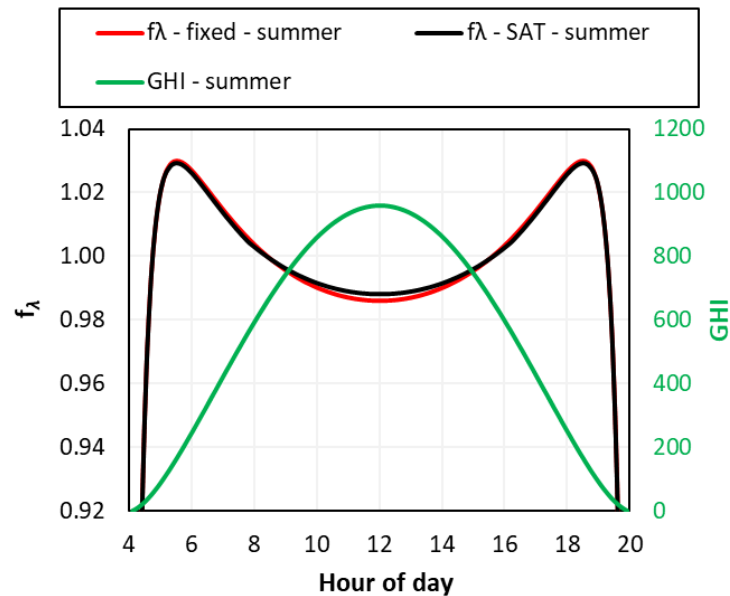
Impact of air mass



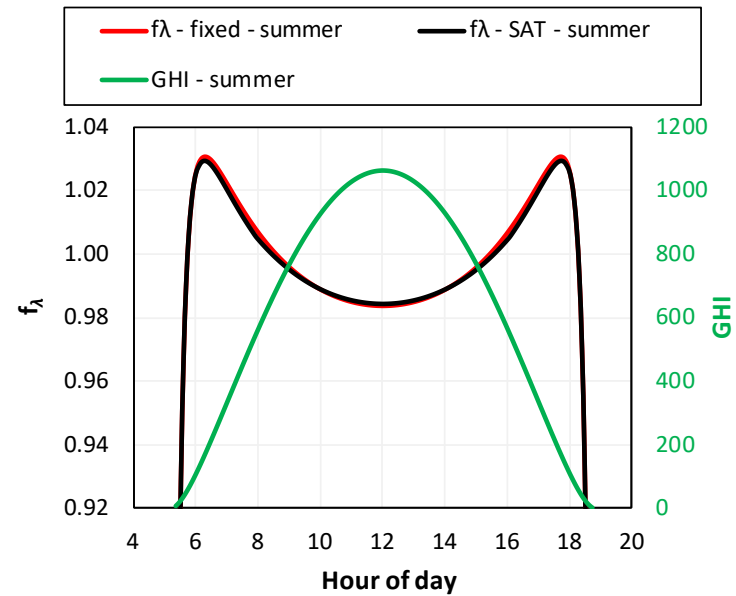
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Impact of air mass

f_λ
60° N, solstice



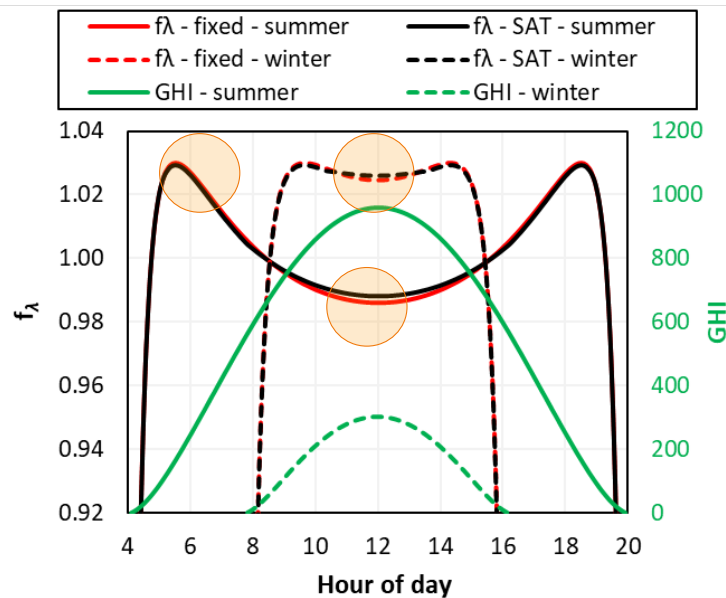
f_λ
23° N, solstice



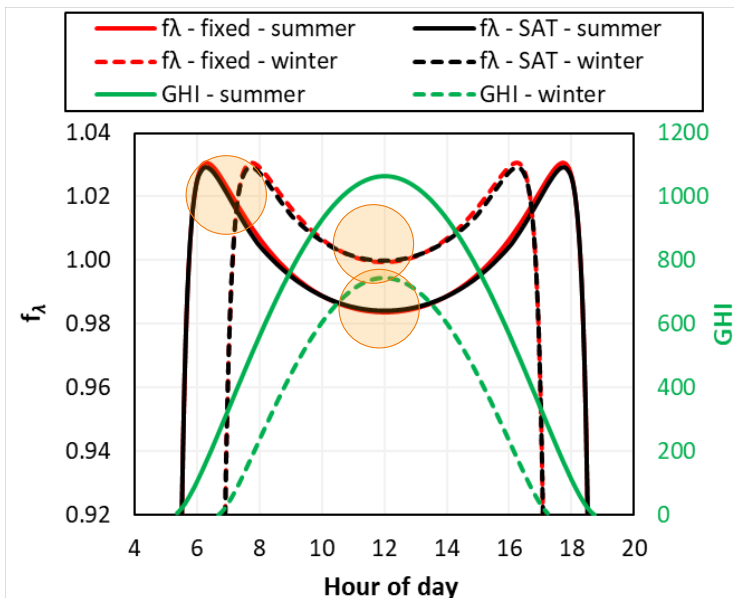
Monofacial modern c-Si module under clear skies, simple analytical optical model

Impact of air mass

Instantaneous f_λ
60° N, solstice



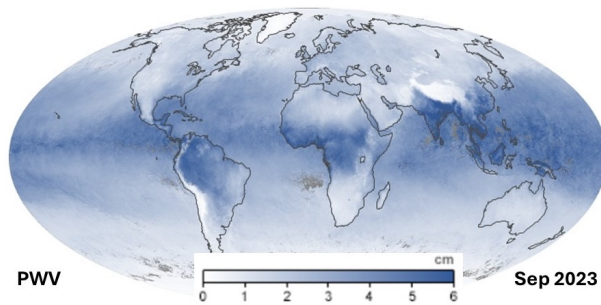
Instantaneous f_λ
23° N, solstice



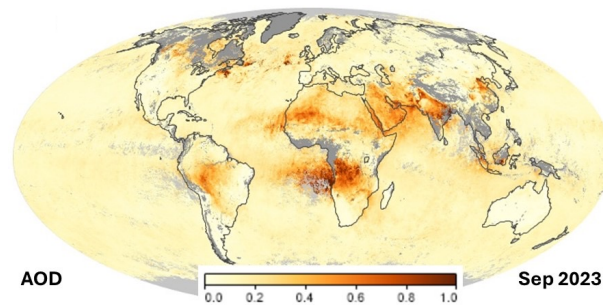
Monofacial modern c-Si module under clear skies, simple analytical optical model

Impact of atmosphere — clear skies

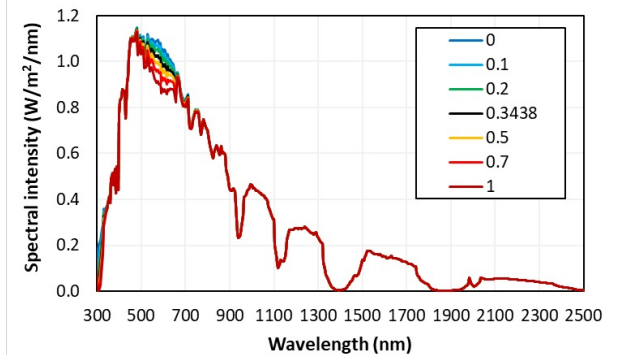
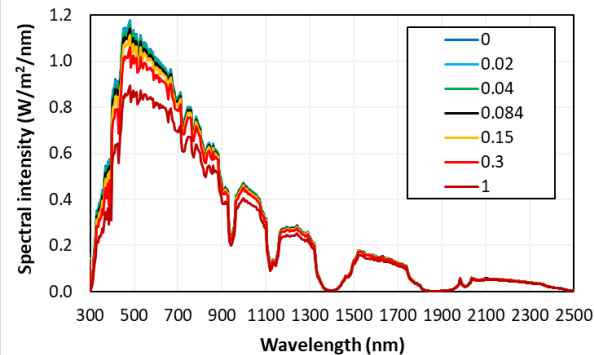
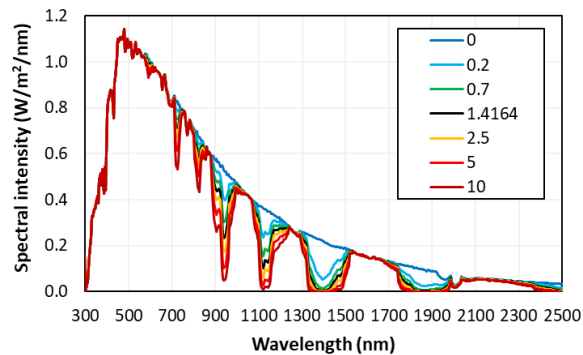
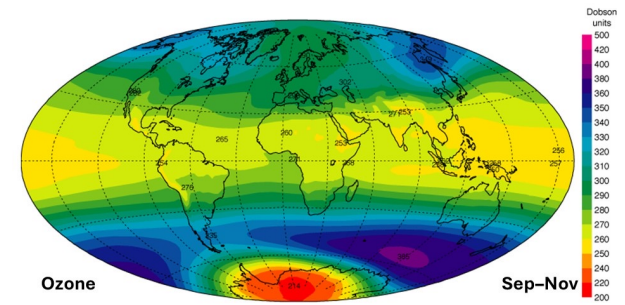
Precipitable water vapor



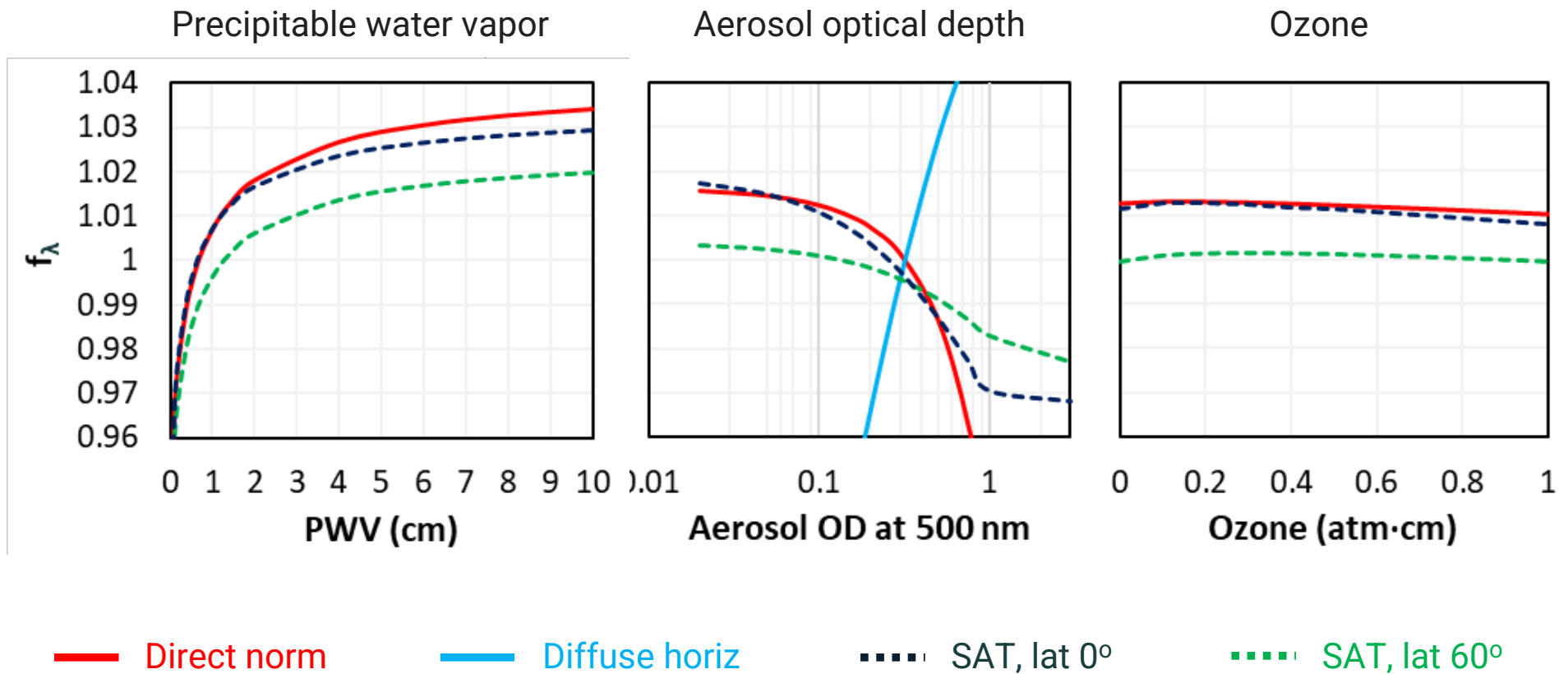
Aerosol optical depth



Ozone



Impact of atmosphere — clear skies



Other impacts

- Cloudiness
- System configuration
 - SAT vs fixed
- Module EQE(λ)
 - Front side
 - Rear side
- Albedo
 - Far-field
 - Nearby

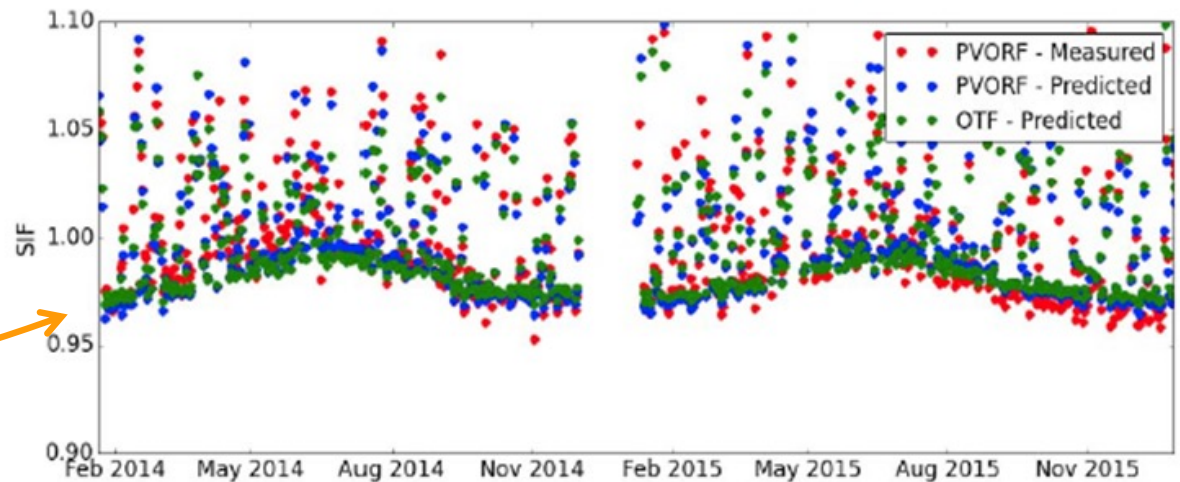
Measurements of f_λ
c-Si systems

Measurements of f_λ

Duck and Fell, 2016

- I_{SC} and $\Phi(\lambda)$ approaches
- Newcastle, Australia
- Fixed tilt, $\sim 33^\circ$

- Clear skies:
 f_λ 2–3% higher in winter



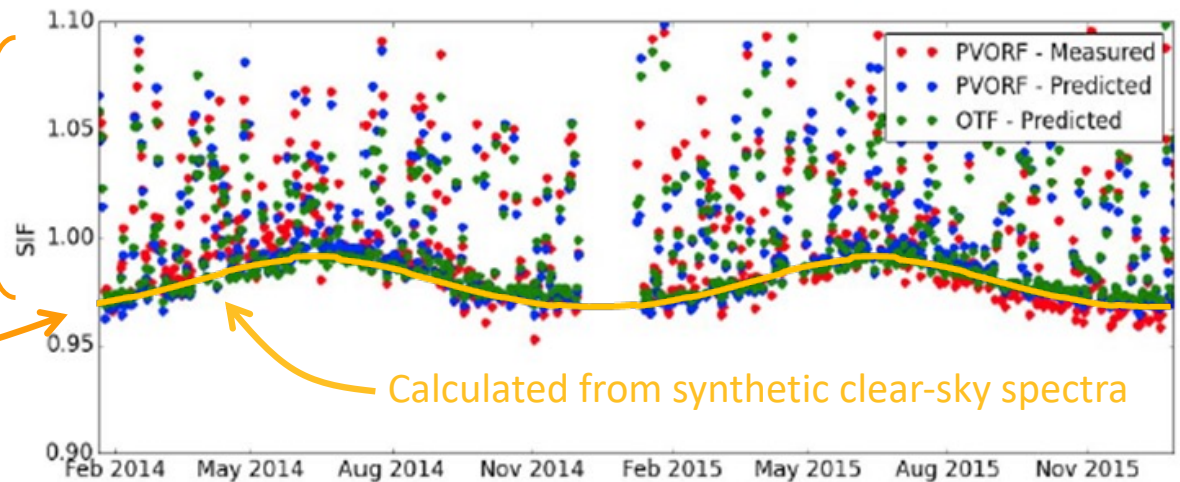
Measurements of f_λ

Duck and Fell, 2016

- I_{SC} and $\Phi(\lambda)$ approaches
- Newcastle, Australia
- Fixed tilt, $\sim 33^\circ$

- Cloudy skies: f_λ up to 13% higher

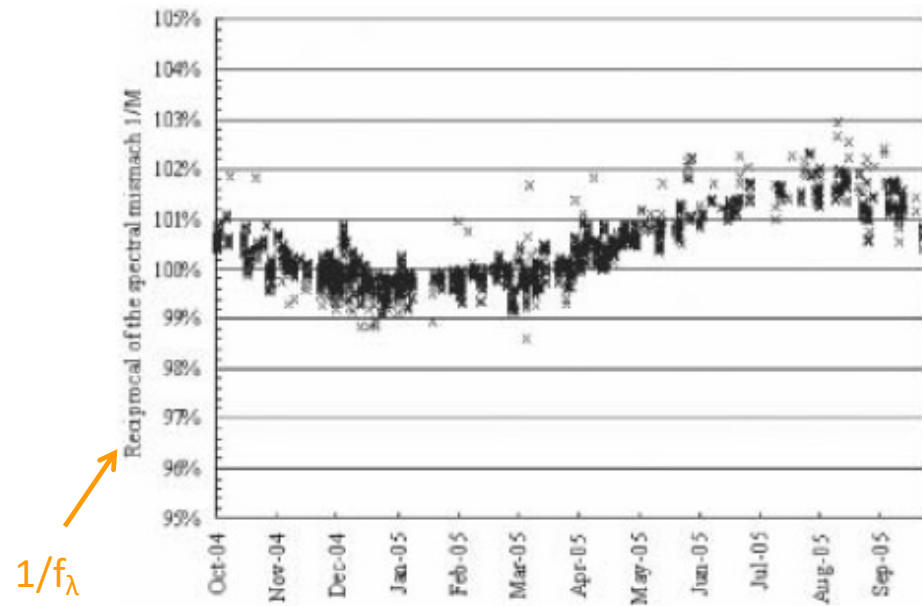
- Clear skies: f_λ 2–3% higher in winter



Measurements of f_λ

Tsutsui and Kurokawa, 2008

- I_{SC} approach
- Tokyo, Japan
- Fixed tilt, 30°
- $\theta_{inc} < 50^\circ$, neglects varying cloud
- f_λ 2.5% higher in winter

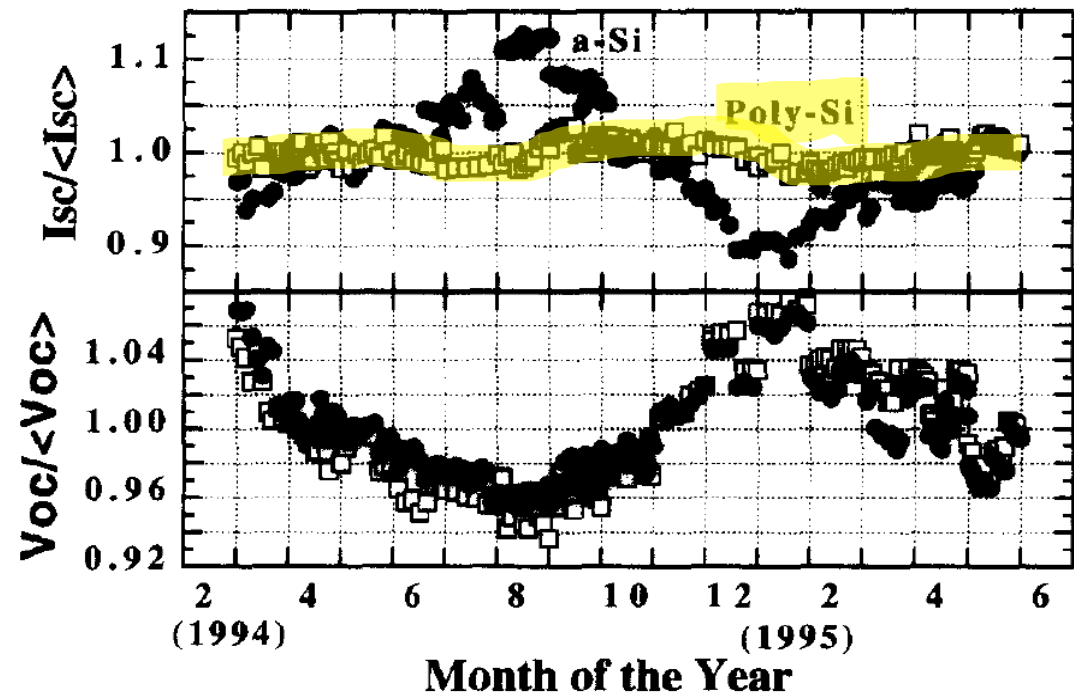


J. Tsutsui and K. Kurokawa, "Investigation to estimate the short circuit current by applying the solar spectrum," Progress in Photovoltaics, 16(3), pp.205-211, 2008.

Measurements of f_λ

Akhmad *et al.* 1997

- I_{SC} approach
- Kobe, Japan
- Fixed tilt, 35°
- Limited to clearish sky
- $f_\lambda \sim 3\%$ higher in fall/winter

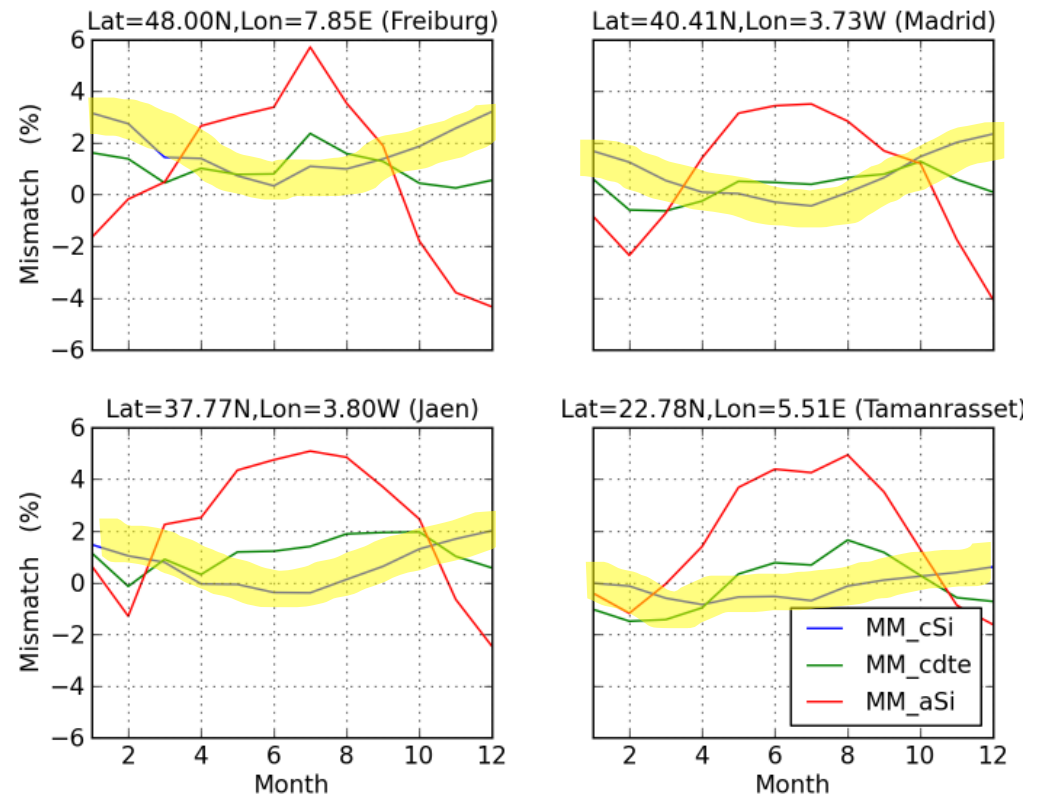


K Akhmad *et al.* "Outdoor performance of amorphous silicon and polycrystalline silicon PV modules." *Solar Energy Materials and Solar Cells*, 46(3), pp.209-218, 1997.

Measurements of f_λ

Amillo *et al.* 2015

- $\Phi(\lambda)$ approach to 4000 nm (satellite)
 - 4 × EU locations
 - Fixed tilt, 20°
 - Monthly average
-
- $f_\lambda \sim 3\%$ higher in winter – higher lat
 - $f_\lambda \sim 2\%$ higher in winter – lower lat



A.M.G. Amillo *et al.*, "Application of satellite-based spectrally-resolved solar radiation data to PV performance studies," *Energies*, 8(5), 3455-3488, 2015.

Measurements of f_λ

Marion 2012

- I_{SC} approach
- Golden CO, USA
- Fixed tilt, 40°

- $f_\lambda \sim 3\%$ higher in winter

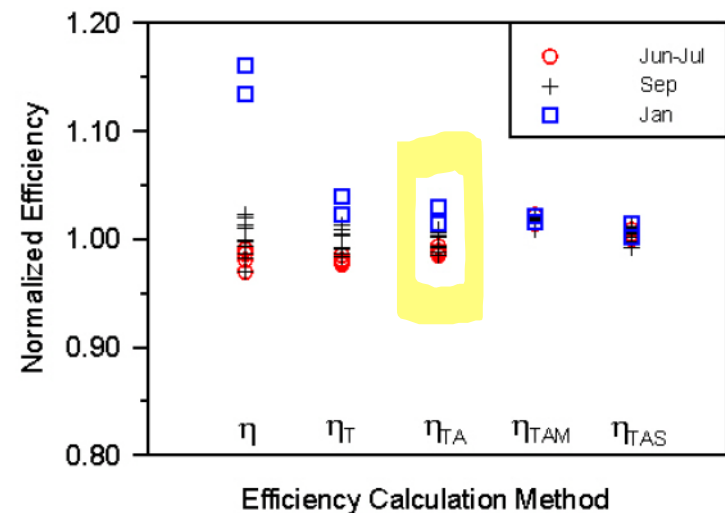


Figure 1 Normalized daily efficiencies for the single-crystal Si 0442 PV module: no corrections (η); temperature corrections (η_T); temperature and AOI corrections (η_{TA}); temperature, AOI, and spectral mismatch corrections, (η_{TAM}); and temperature, AOI, and Sandia air-mass corrections, (η_{TAS}).

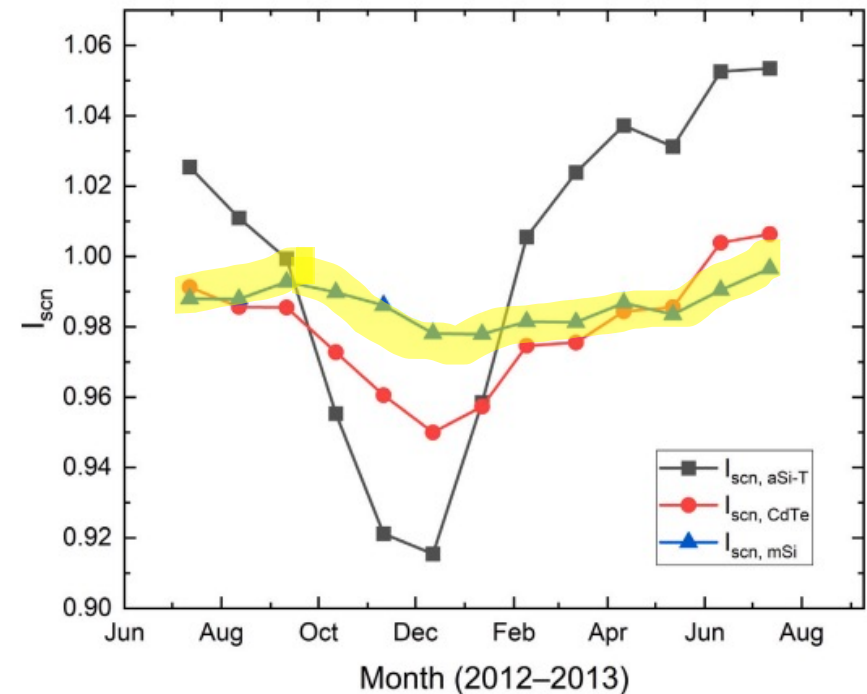
B. Marion, "Influence of atmospheric variations on photovoltaic performance and modeling their effects for days with clear skies," 38th IEEE PVSC (pp. 003402-003407) 2012.

Measurements of f_λ

Daxini *et al.*, 2023

- I_{SC} approach
- Golden
- Fixed tilt

- $f_\lambda \sim 2\%$ lower in winter

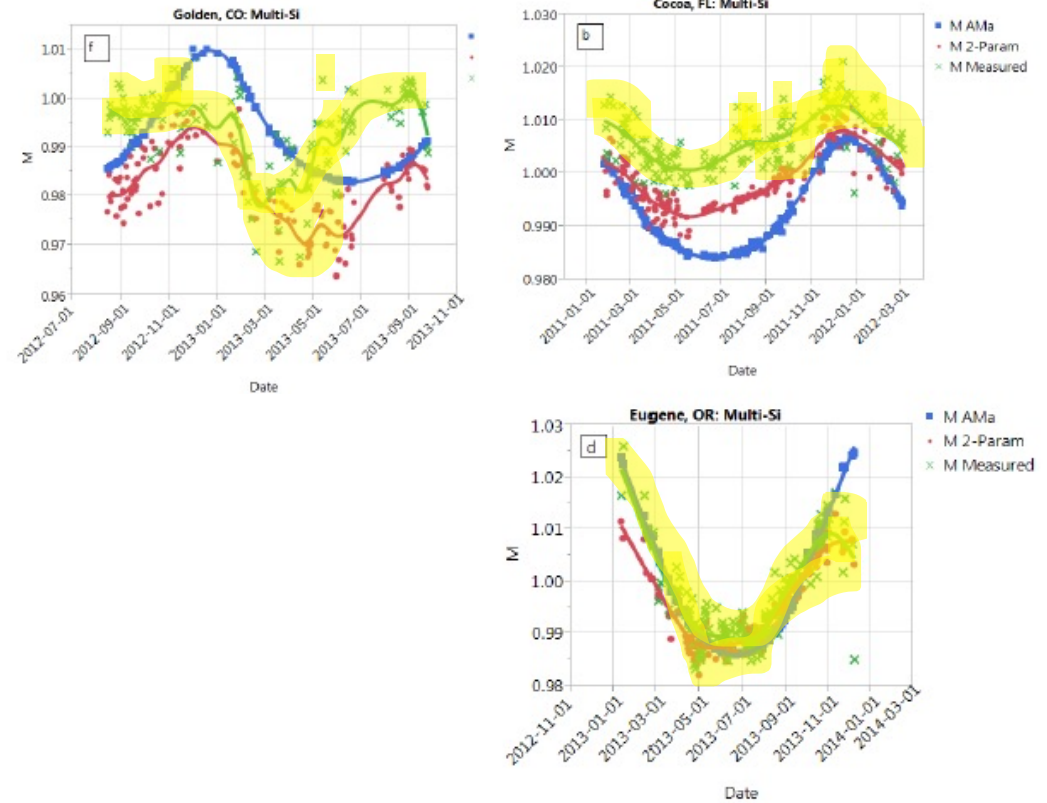


Lee and Panchula, "Variation in spectral correction of PV module performance based on different precipitable water estimates," 43rd IEEE PVSC (pp. 2692-2697) 2016.

Measurements of f_{λ}

Lee and Panchula, 2016

- I_{SC} approach
 - Three sites, USA
 - Fixed tilt
 - Clear skies
-
- $f_{\lambda} \sim 1-3\%$ higher in winter

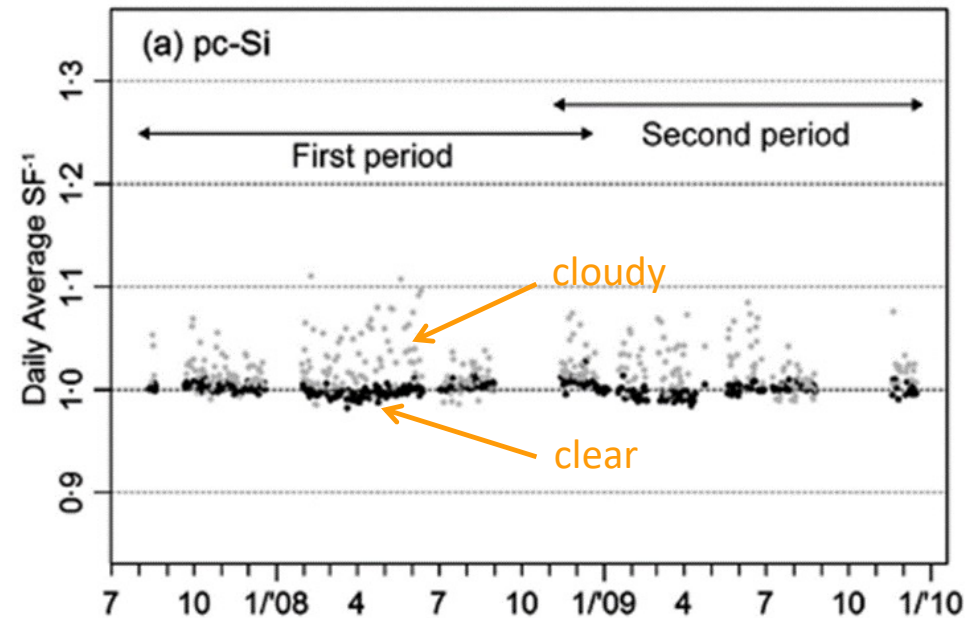


Lee and Panchula, "Variation in spectral correction of PV module performance based on different precipitable water estimates," 43rd IEEE PVSC (pp. 2692-2697) 2016.

Measurements of f_λ

Ishi *et al.* 2011

- $\Phi(\lambda)$ approach to 1700 nm
- Various, Japan
- Fixed tilt, various tilt
- 10 am to 2 pm
- $f_\lambda \sim 0-10\%$ higher when overcast

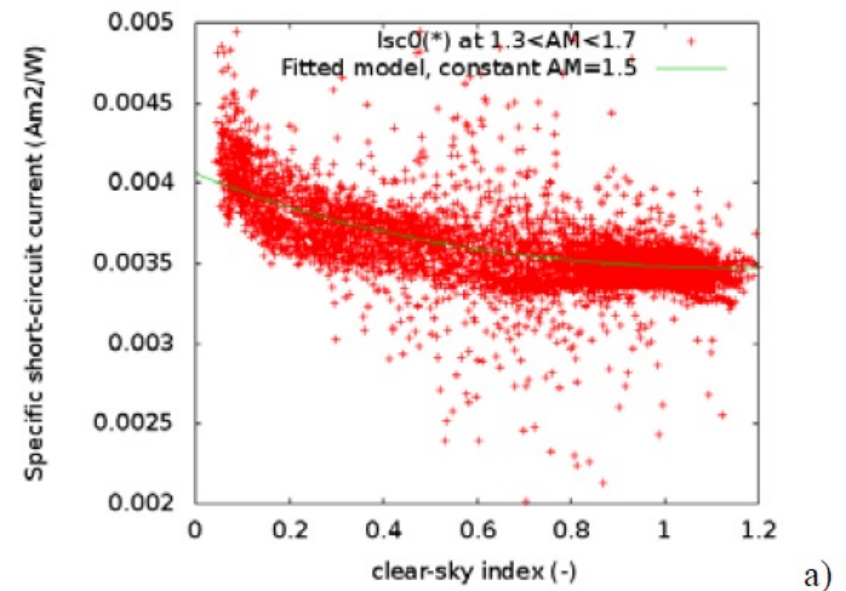


T. Ishii et al. "Solar spectral influence on the performance of photovoltaic (PV) modules under fine weather and cloudy weather conditions. Progress in Photovoltaics: Research and Applications, 21(4), pp.481-489, 2011.

Measurements of f_λ

Huld *et al.* 2009

- I_{SC} approach
- Ispra, Italy
- Fixed tilt, 35° in summer, 55° in winter,
- $GTI > 50 \text{ W/m}^2$
- $f_\lambda \sim 10\text{--}25\%$ higher when overcast

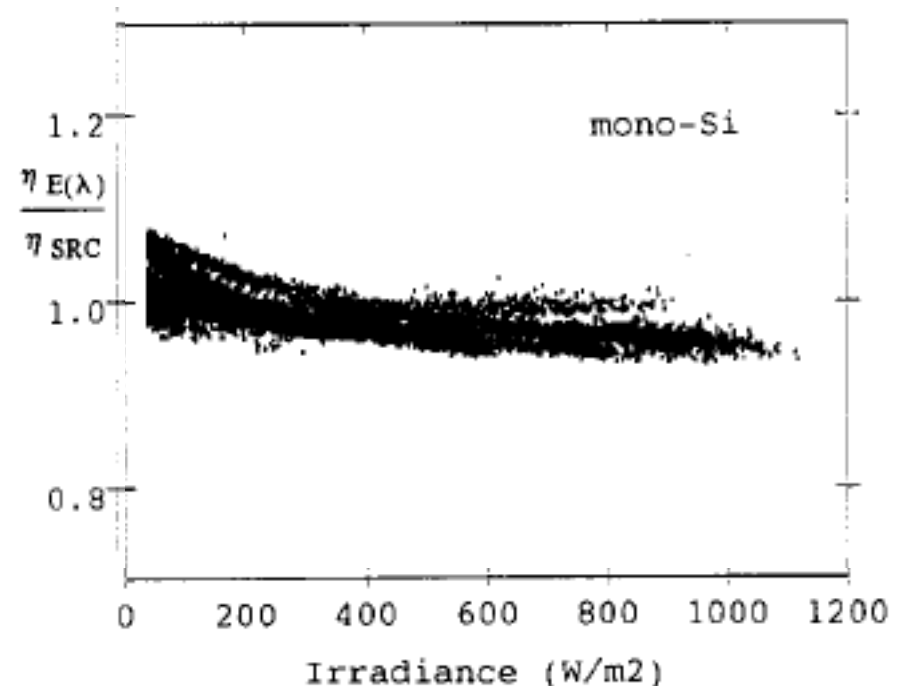


T. Huld *et al.*, "A simple model for estimating the influence of spectrum variations on PV performance," 24th EU PVSEC, Hamburg, Germany (pp. 3385-3389), 2009.

Measurements of f_λ

Nann and Emery 1992

- $\Phi(\lambda)$ approach to 1050 nm & fit
- Stuttgart, Germany
- Fixed tilt, 48°
- $f_\lambda \sim 5\text{--}10\%$ higher when overcast



D. Dirnberger *et al.*, "On the impact of solar spectral irradiance on the yield of different PV technologies," *Solar Energy Materials and Solar Cells*, 132, pp.431-442, 2015.

Measurements of f_λ

Campanelli *et al.*, 2024

- $\Phi(\lambda)$ approach to 1700 nm & fit
- Not sure of the details yet

- f_λ roughly 10% higher when overcast

See poster
over there!



D. Dirnberger *et al.*, "On the impact of solar spectral irradiance on the yield of different PV technologies," Solar Energy Materials and Solar Cells, 132, pp.431-442, 2015.

Measurements of f_λ — summary

- f_λ varies significantly from unity
- Clear-sky:
 - f_λ is often 2–3% higher in winter than summer.
- Cloudy-sky:
 - f_λ tends to increase as cloudiness increases.
 - f_λ is 0–25% higher when overcast than when clear??
 - Lots of scatter.
 - Possible systematic error.

Modelling f_λ

King model (Sandia performance model)



- Measure $f_{\lambda}(AM)$
 - Particular module & location
 - 2D tracker
 - Clear sky

- Fit polynomial

$$f_1(AM_a) = a_0 + a_1 \cdot AM_a + a_2 \cdot (AM_a)^2 + a_3 \cdot (AM_a)^3 + a_4 \cdot (AM_a)^4$$

- Concerns
 - Complicated experiment
 - Particular module & location
 - Weighted to direct light spectra
 - Poor fit for $AM > 5$

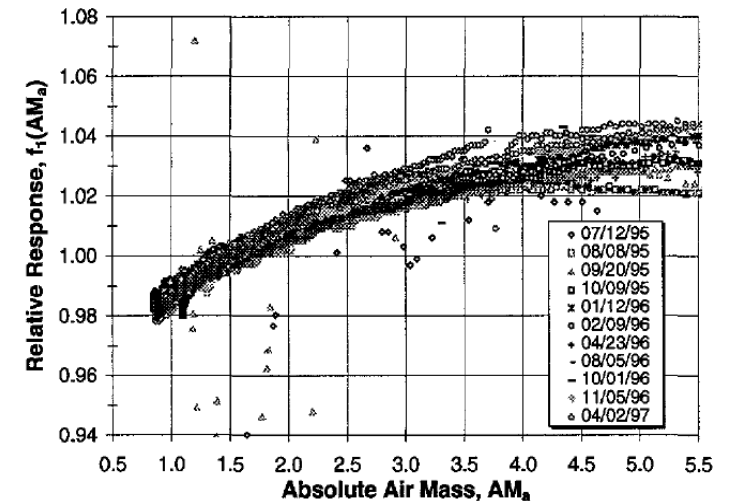


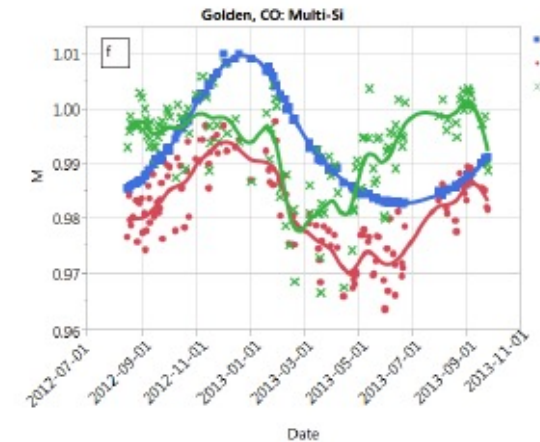
Fig. 3. AM_a Functions measured over a two year period for a c-Si reference cell (MK-22).

D.L. King, "Measuring solar spectral and angle-of-incidence effects on photovoltaic modules and solar irradiance sensors," 26th IEEE photovoltaic specialists conference-1997 (pp. 1113-1116) 1997.

First Solar model, Lee & Panchula



- Generate synthetic spectra
 - Clear sky with SMARTS using defaults
 - $1 < AM < 5$
 - $0 < PWV < 5$ cm
- Calculate $f_{\lambda}(AM, PWV)$
 - Particular module, configuration & location



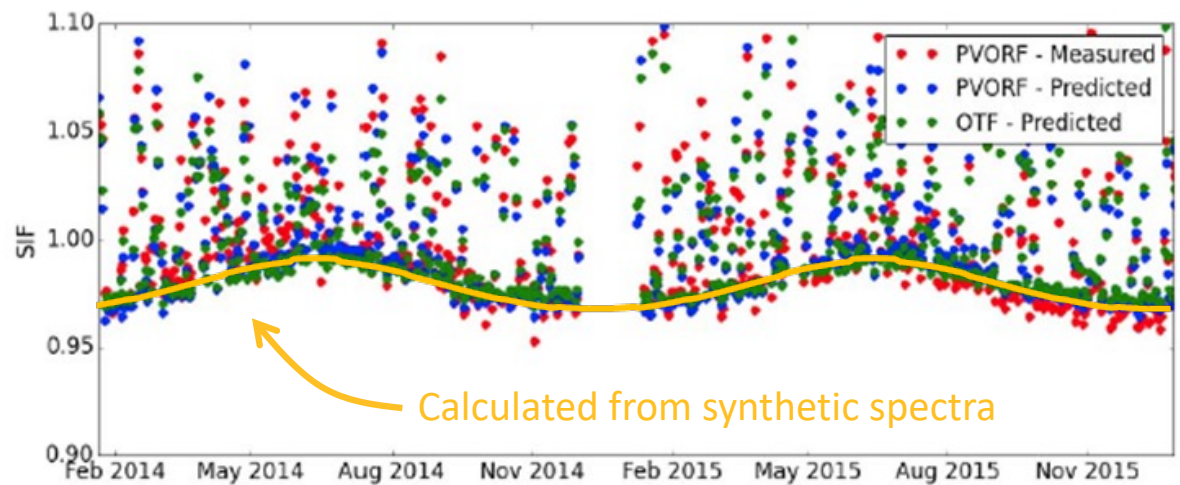
- Fit equation

$$M = b_0 + b_1 \cdot AM_a + b_2 \cdot p_{wat} + b_3 \cdot \sqrt{AM_a} + b_4 \cdot \sqrt{p_{wat}} + b_5 \cdot \frac{AM_a}{\sqrt{p_{wat}}}$$

- Concerns
 - Limited to clear skies
 - Specific to module, configuration & location for default AOD
 - Loses information from synthetic spectra via parameterization
 - Poor fit for $AM > 5$

Synthetic spectra

- Clear-skies data predicted by SPECTRL2
 - typical c-Si EQE
 - Fixed tilt, $\sim 33^\circ$
 - Default AM1.5g atmos inputs
 - Only AM varying



Synthetic spectra

- Marion 2012
 - SMARTS
 - Analytical optical model
 - Monthly f_λ for fixed c-Si in Golden
 - Clear-sky
- $\pm 3\%$ error with $f_\lambda = 1$
- $< 1\%$ error with determined f_λ .

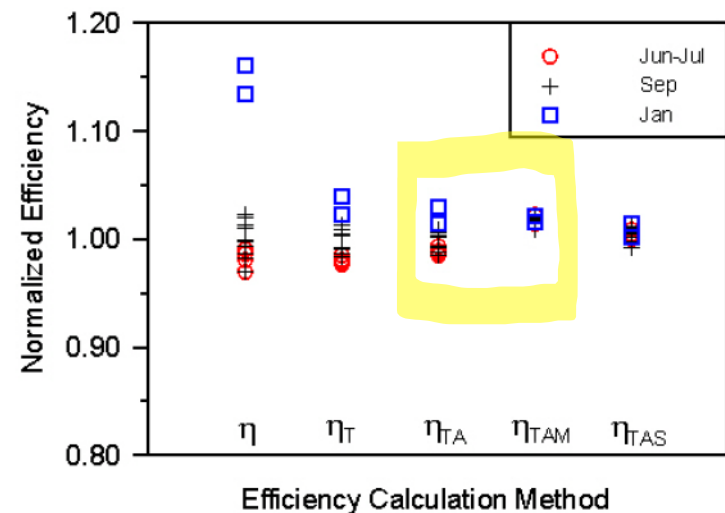


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Predictions of f_λ — summary

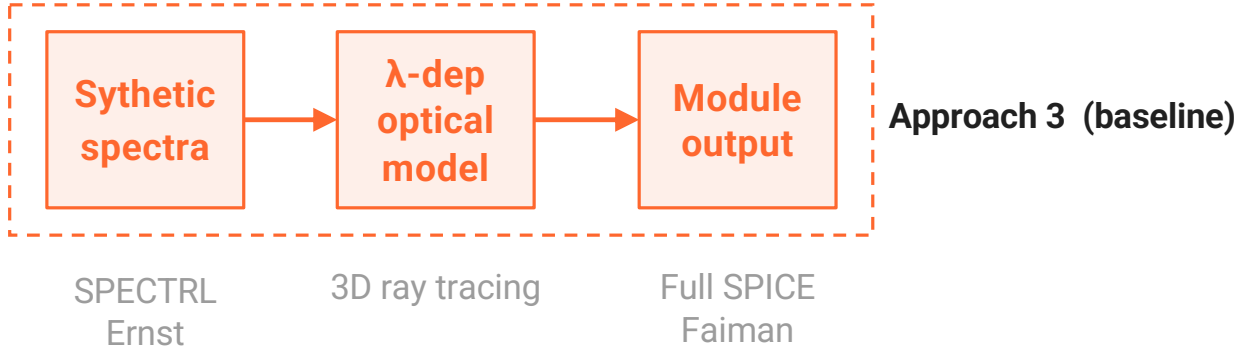
- Parameterizations of experimental data
 - e.g., King, Nann, Duck & Fell
 - determined for a particular location, configuration & module
- Parameterizations of synthetic spectra
 - e.g., Lee & Panchula, Caballero
 - determined for a particular location, configuration & module
- Synthetic spectra
 - evidence of clear-sky models agree with experimental data
 - universal

f_λ in yield forecasts

- Approach 1: Neglect spectral effects, $f_\lambda = 1$
 - Default for c-Si in PVSyst, SAM, PlantPredict, SolarFarmer, others
- Approach 2: First Solar model, $f_\lambda(\text{AM}, \text{PWV})$
 - Available in PVSyst, SAM, PlantPredict, SolarFarmer, others
 - Does it work for all systems?
 - What are the best coefficients?
- Approach 3: Synthetic spectra at all times
 - Available in SunSolve, PV Atlas, NSRDB (FARMS-NIT)
 - Possible with modern computing power
 - Atmospheric inputs for clear skies are widely available for all sites.

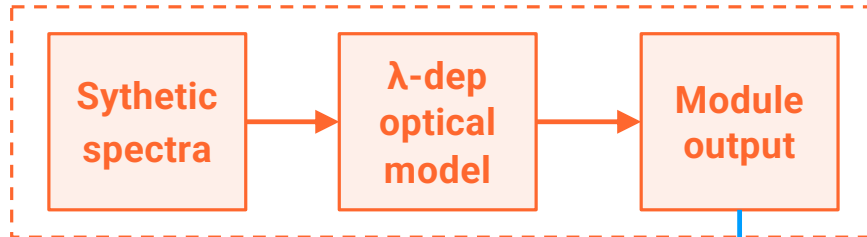
This work

SunSolve



This work

SunSolve



SPECTRL
Ernst

3D ray tracing

Approach 3 (baseline)

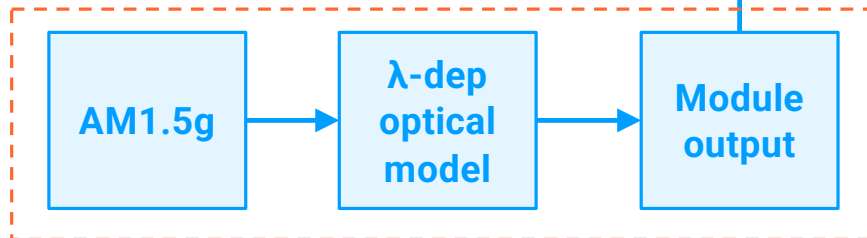
First Solar
King

f_{λ}

Parameter-
ization

Approach 2

SunSolve

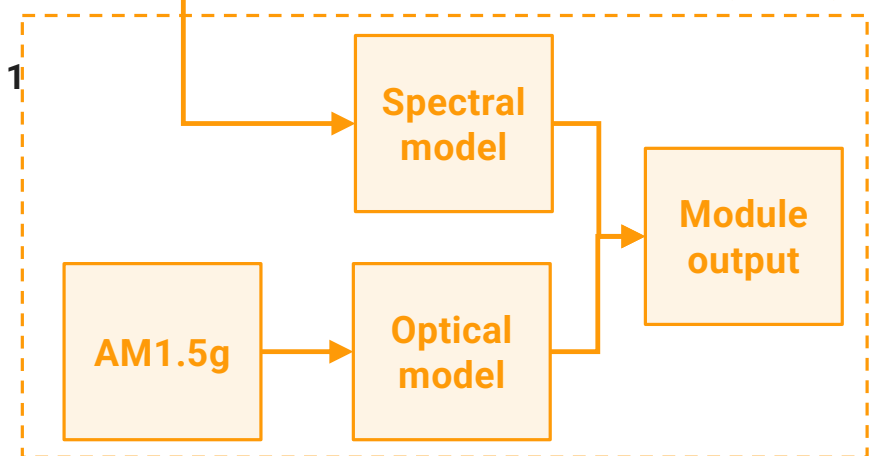


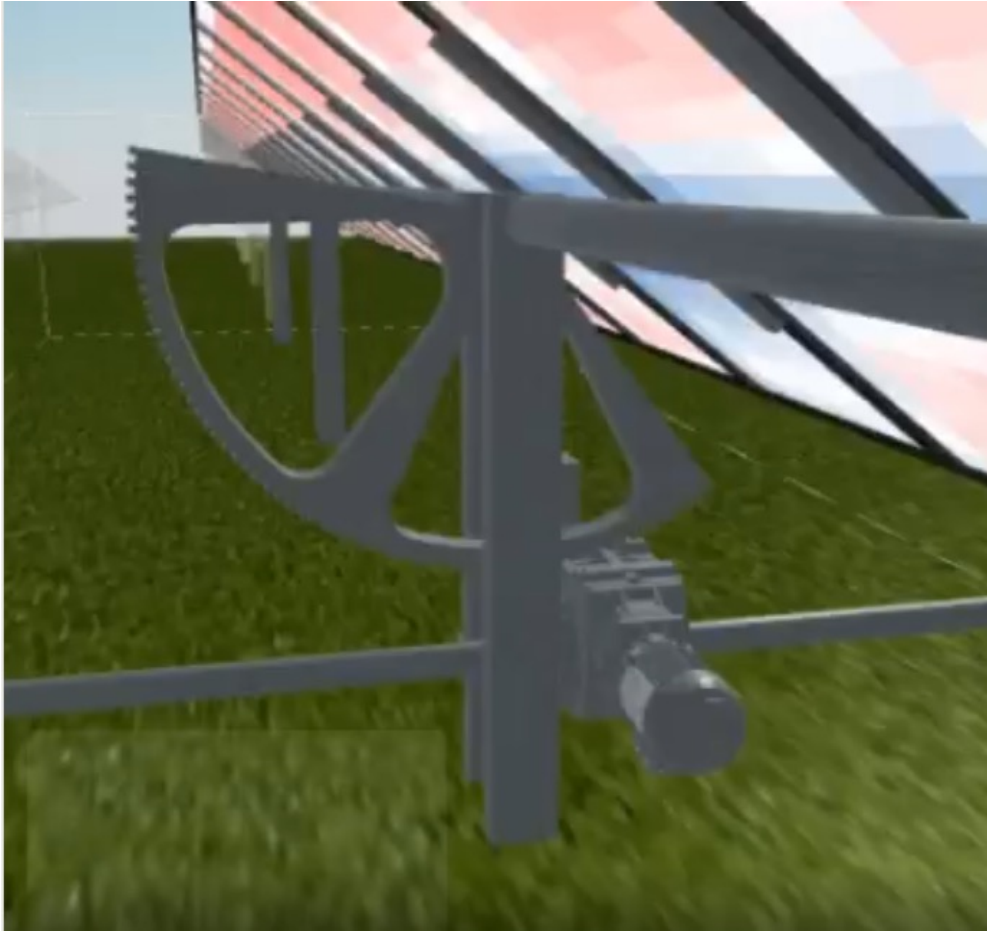
SPECTRL
Ernst

3D ray tracing

Full SPICE
Thermal model

E.g., PVSyst

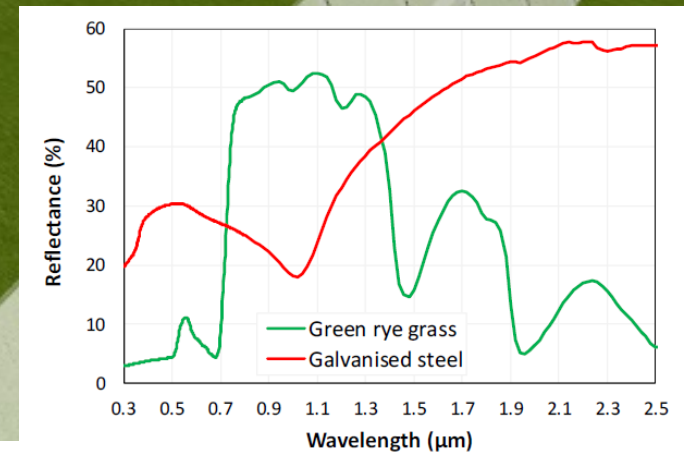
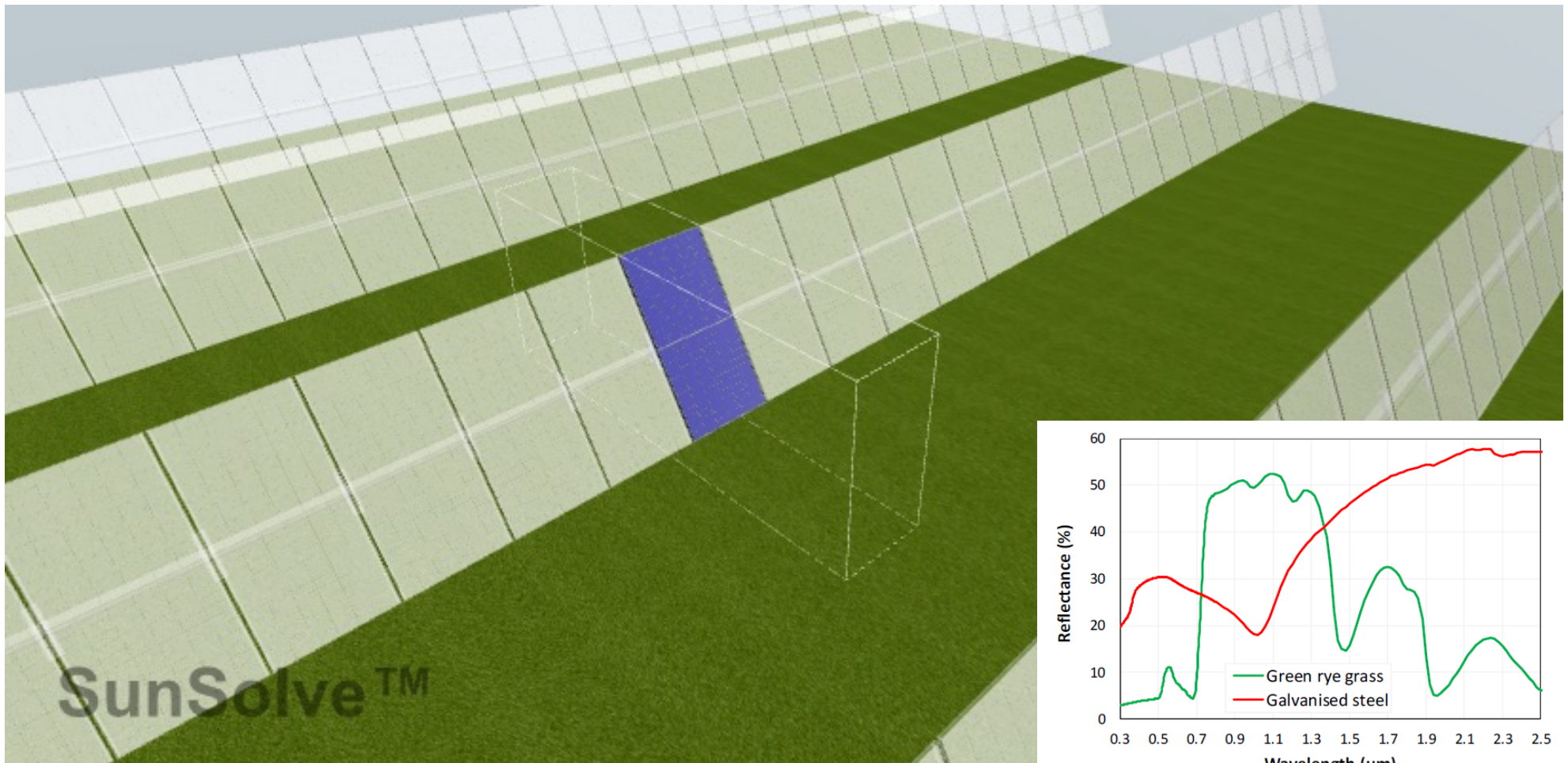




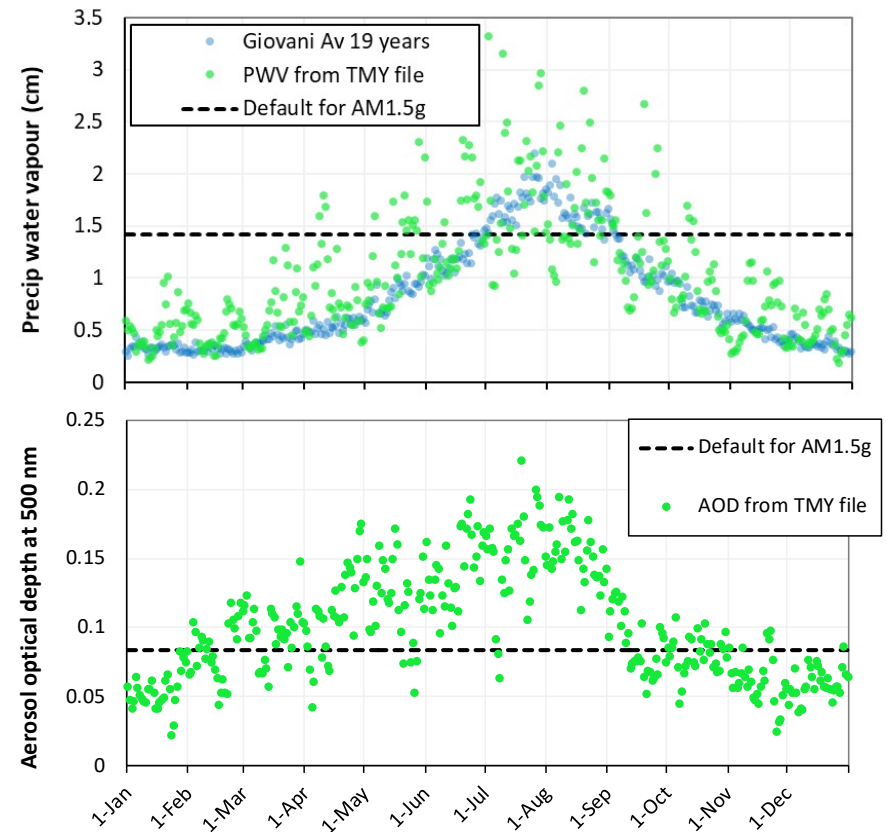
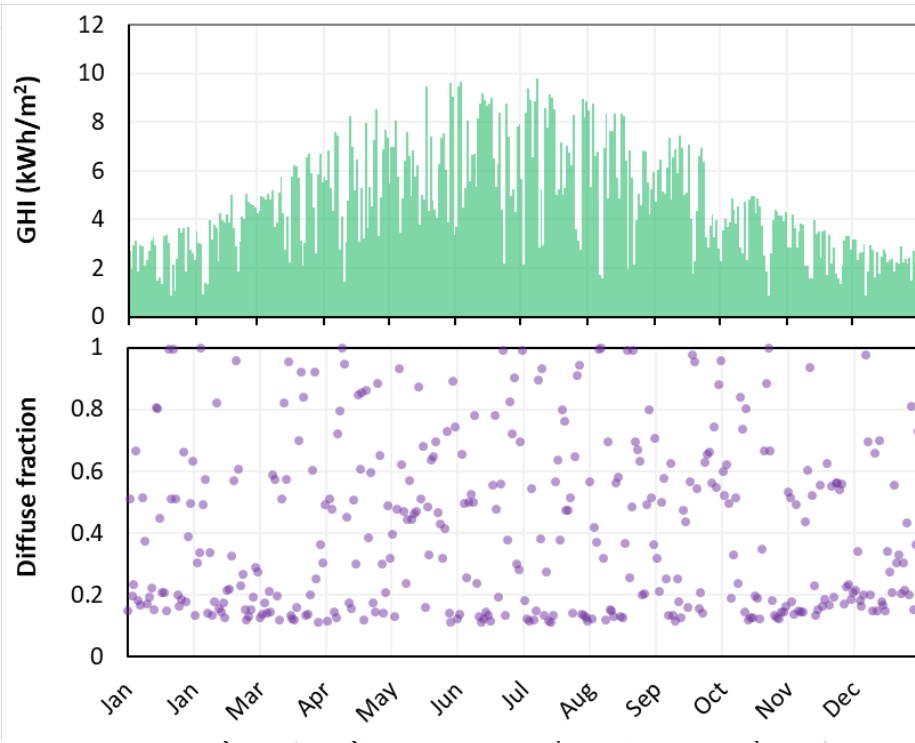
SunSolve

- Synthetic spectra
- 3D ray tracing
- SPICE solver
- Thermal solver
- Solve
 - annual yield
 - irradiance patterns
 - cell and module mismatch
 - bifacial factors for PVSyst
- Any time step ≥ 5 min
- Yield solutions take 1 – 10 mins

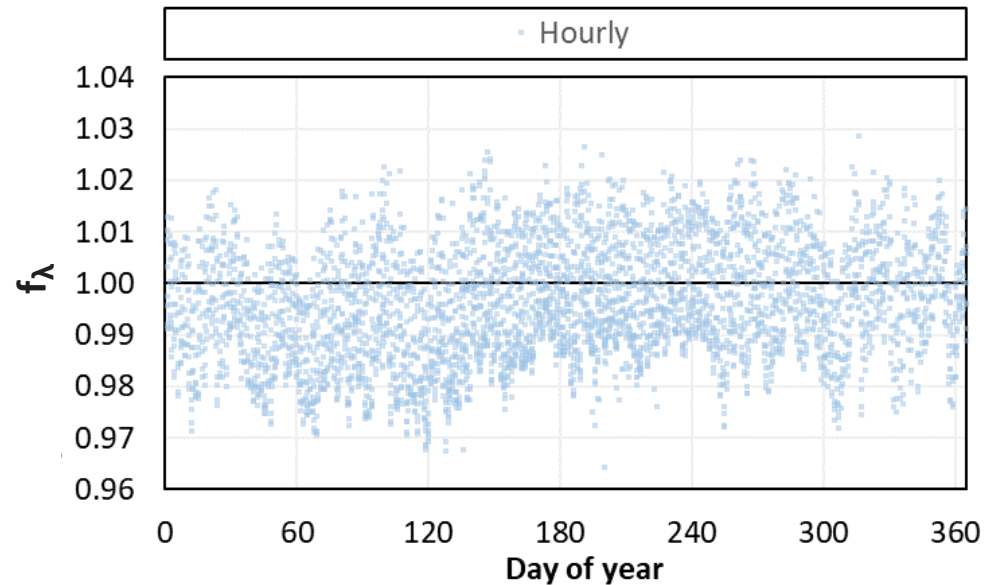
Example: Bifacial SAT



Example: Bifacial SAT — Golden USA



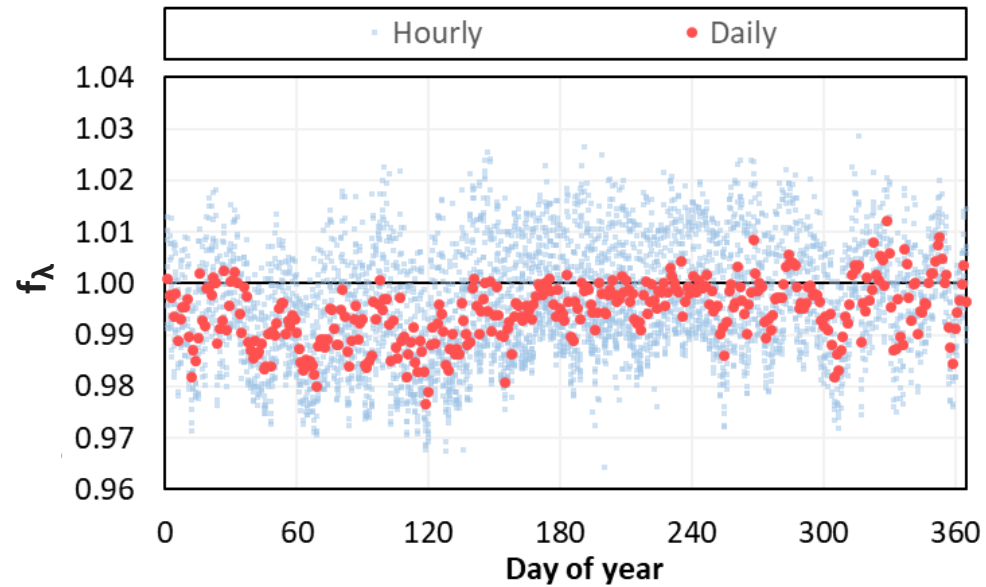
Example: Bifacial SAT — Golden USA



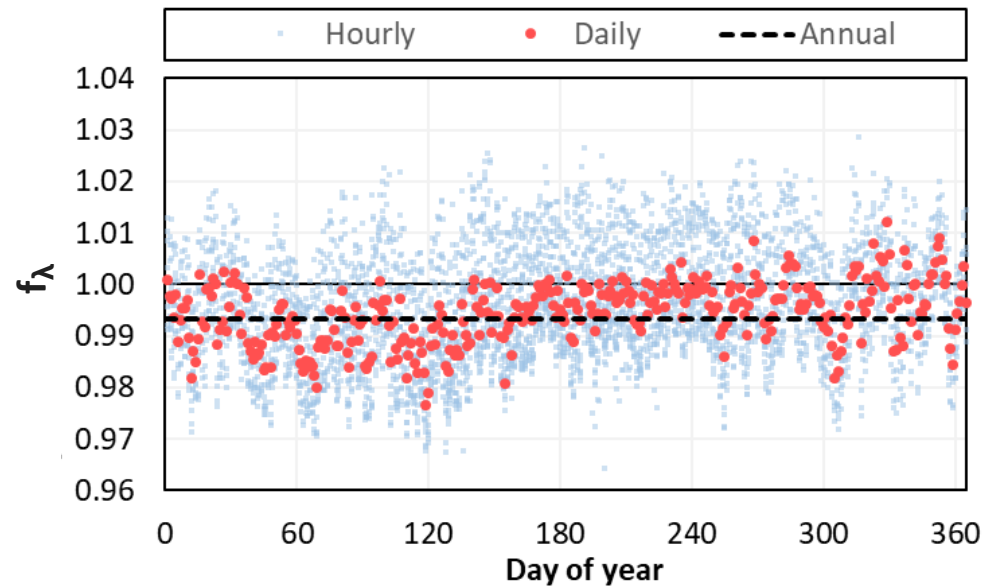
f_λ = ratio of I_{SC} with synthetic spectra to I_{SC} with AM15g.

A positive value means that neglecting spectral effects will underestimate the module I_{SC} .

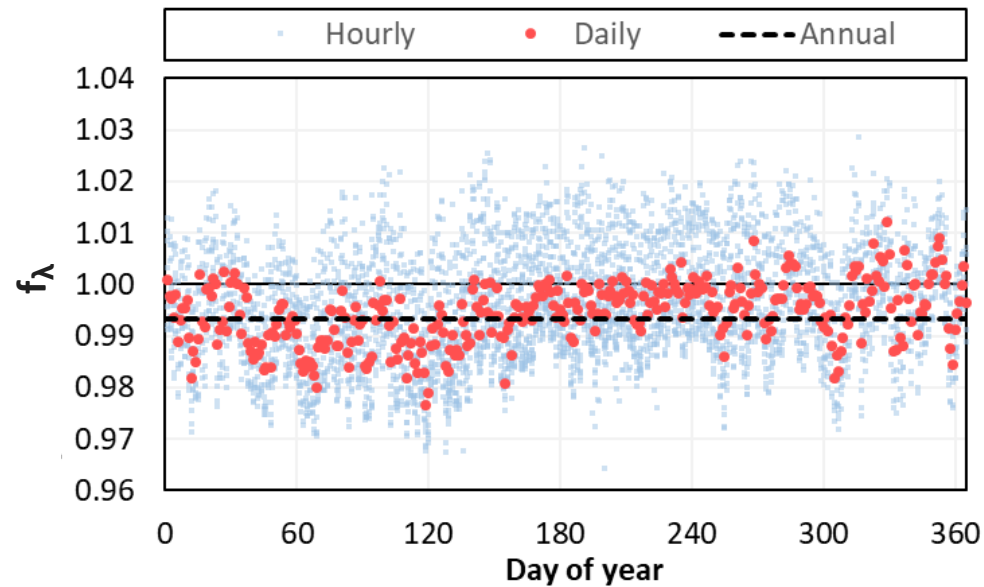
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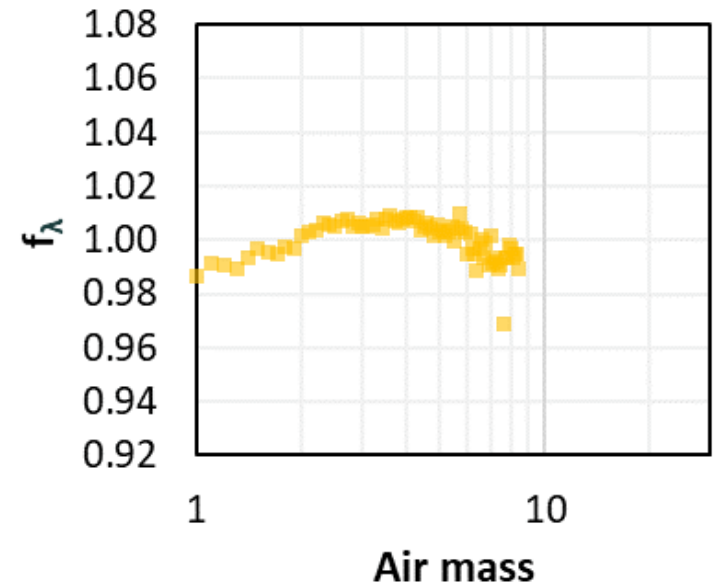
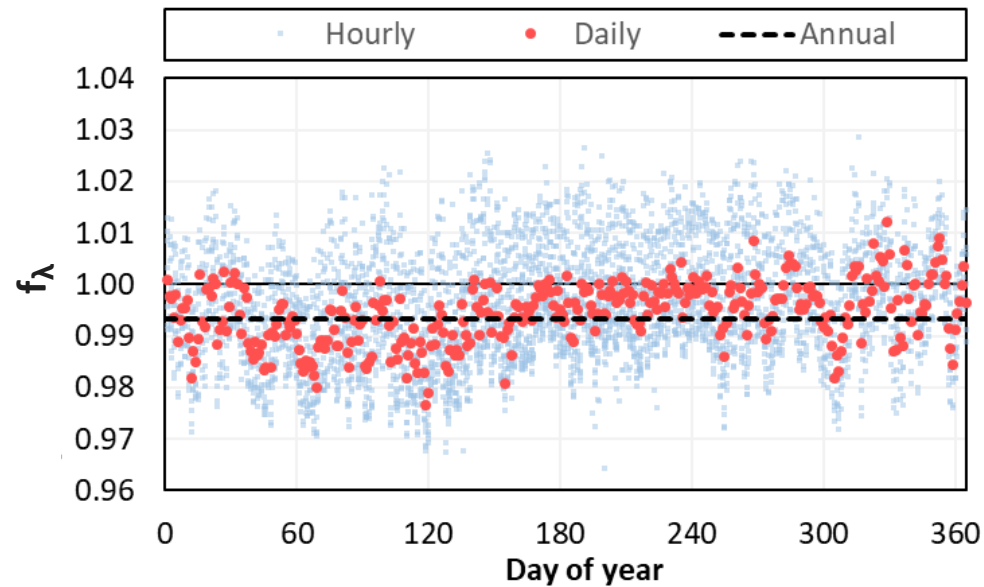
Example: Bifacial SAT — Golden USA



Model	AM1.5g
Yield MBE (%)	+0.64
Daily error about mean (%)	± 1.18
Hourly error about mean (%)	± 2.07

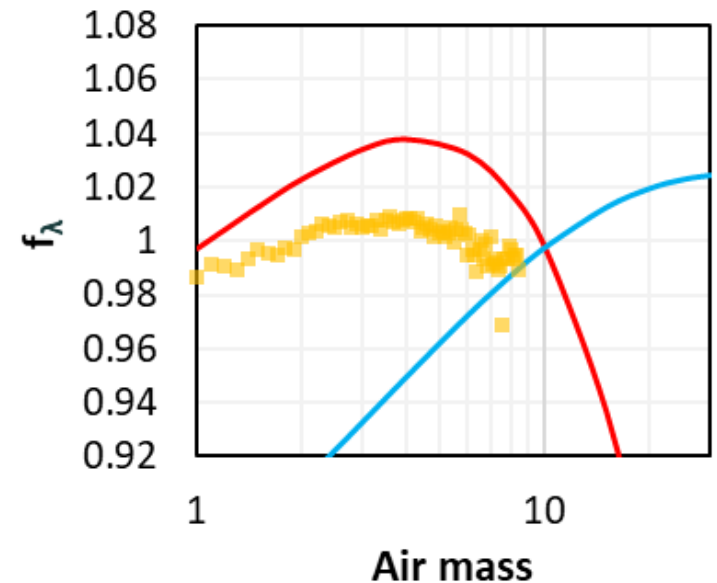
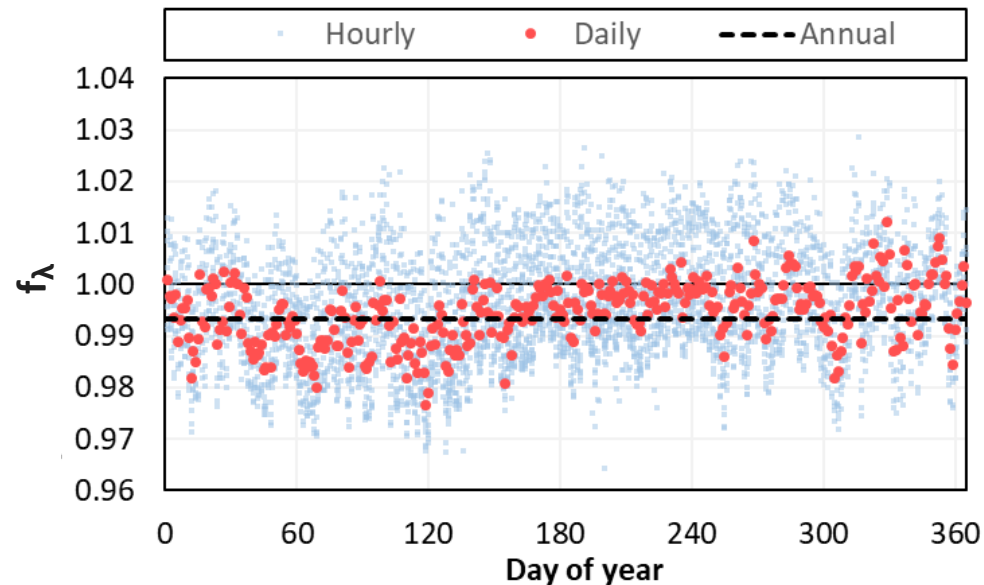
Error is 95% confidence interval about the mean.

Example: Bifacial SAT — Golden USA



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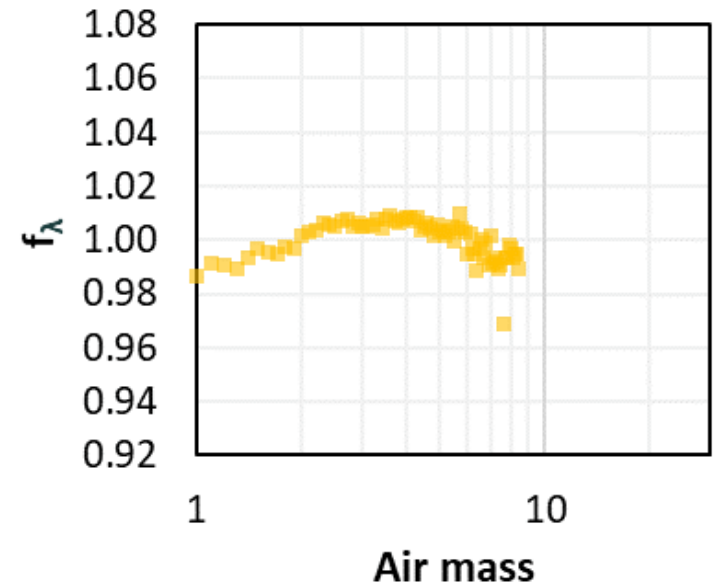
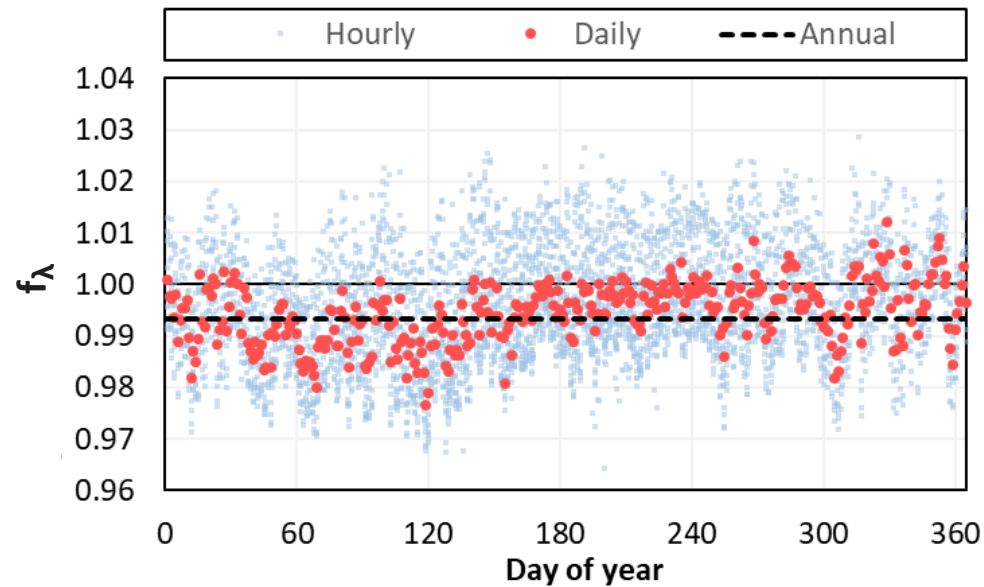


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— Direct norm

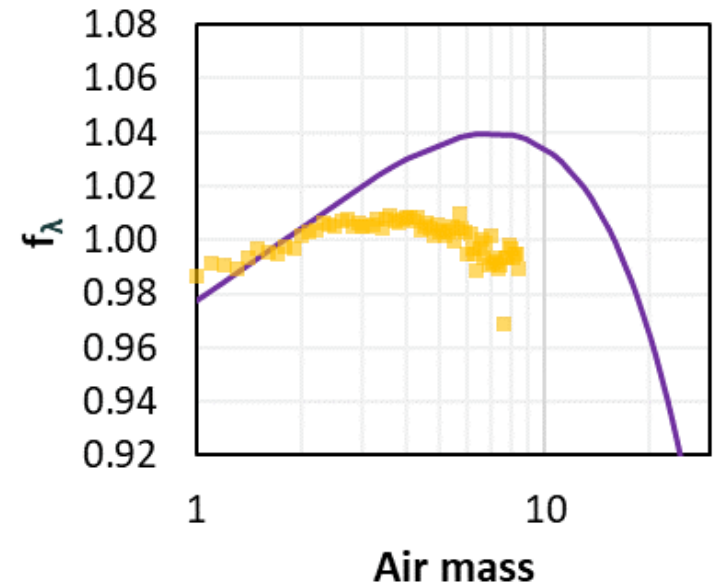
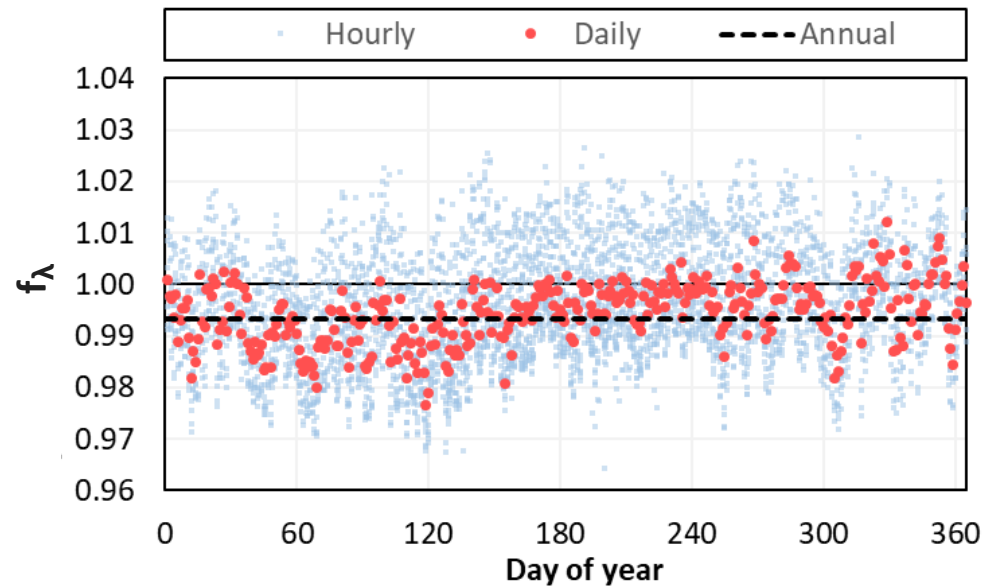
— Diffuse horiz

Example: Bifacial SAT — Golden USA



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Daily error about mean (%)	± 1.18
Hourly error about mean (%)	± 2.07

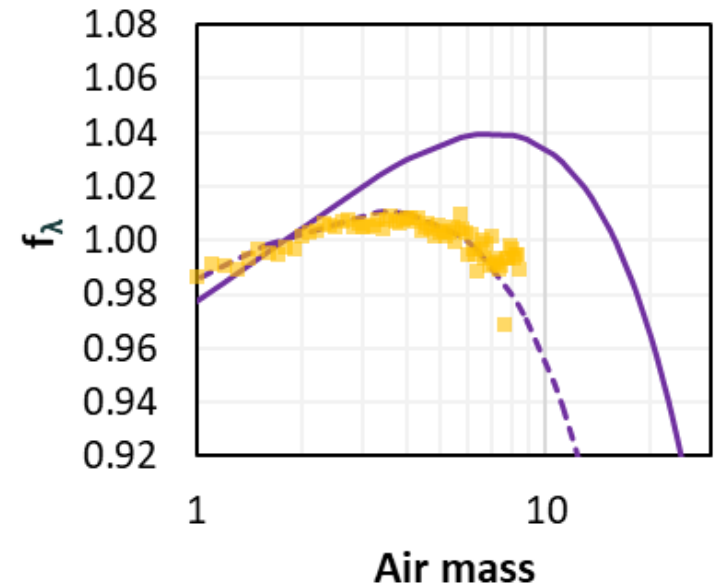
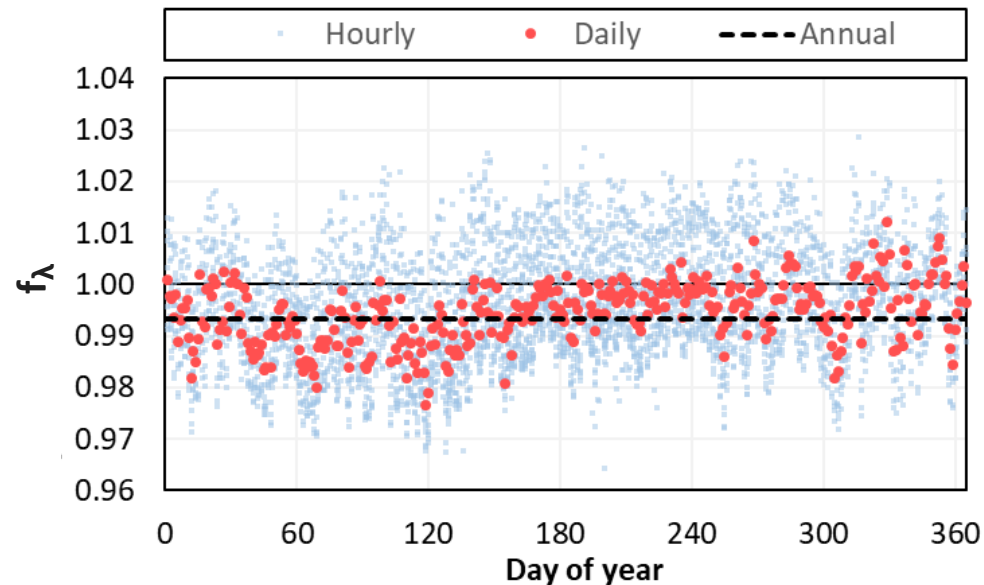
Example: Bifacial SAT — Golden USA



— FS defaults

Model	AM1.5g	First Solar Default coeffs
Yield MBE (%)	+0.64	−0.14
Daily error about mean (%)	±1.18	±1.05
Hourly error about mean (%)	±2.07	±2.82

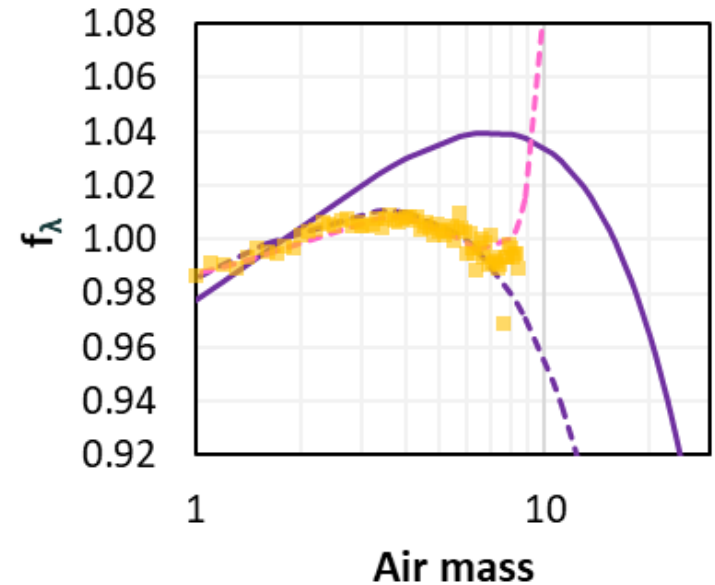
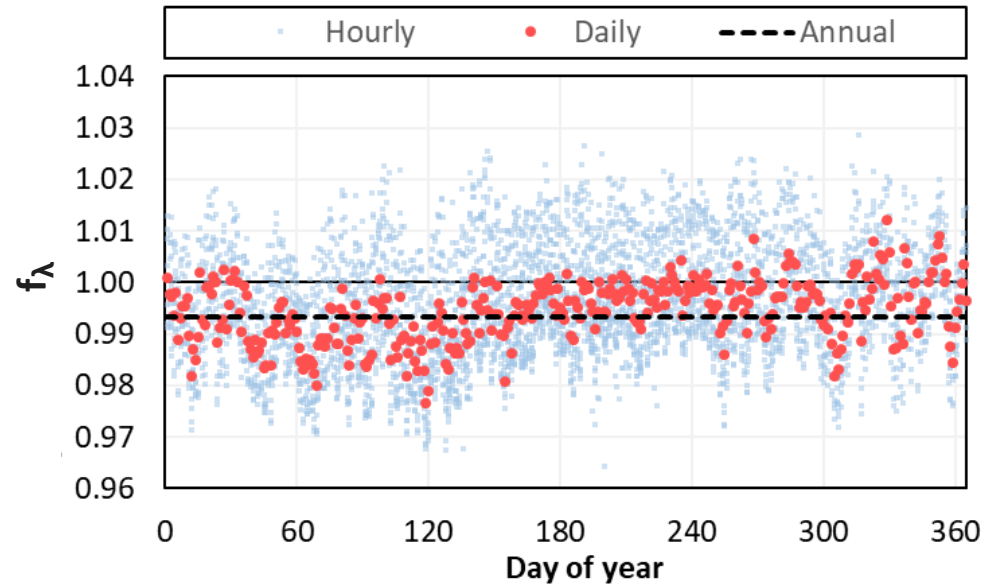
Example: Bifacial SAT — Golden USA



— FS defaults - - - FS fit

Model	AM1.5g	First Solar Default coeffs	First Solar Best-fit
Yield MBE (%)	+0.64	−0.14	−0.00
Daily error about mean (%)	±1.18	±1.05	±0.40
Hourly error about mean (%)	±2.07	±2.82	±0.81

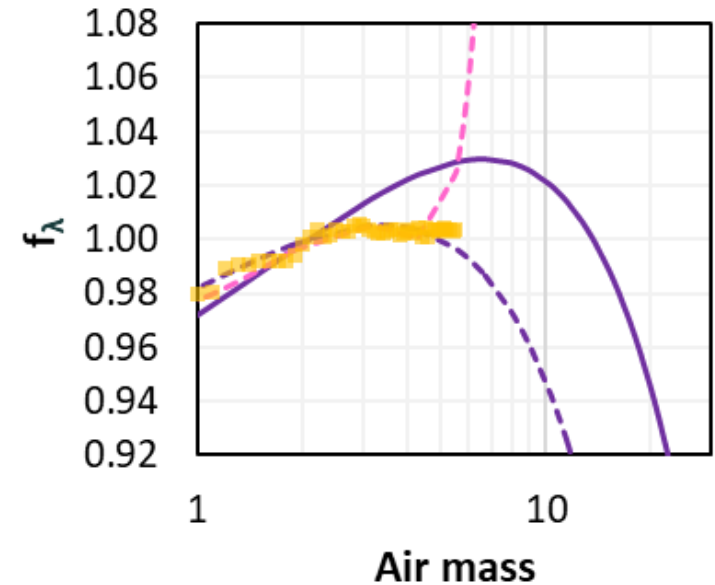
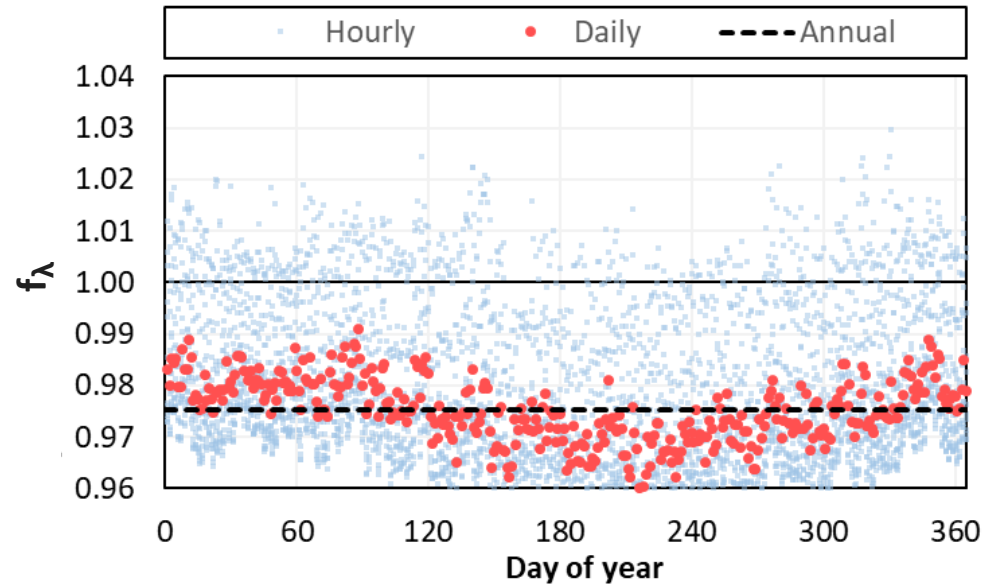
Example: Bifacial SAT — Golden USA



— FS defaults FS fit King fit

Model	AM1.5g	First Solar Default coeffs	First Solar Best-fit	King Best-fit
Yield MBE (%)	+0.64	−0.14	−0.00	+0.04
Daily error about mean (%)	±1.18	±1.05	±0.40	±1.31
Hourly error about mean (%)	±2.07	±2.82	±0.81	±1.49

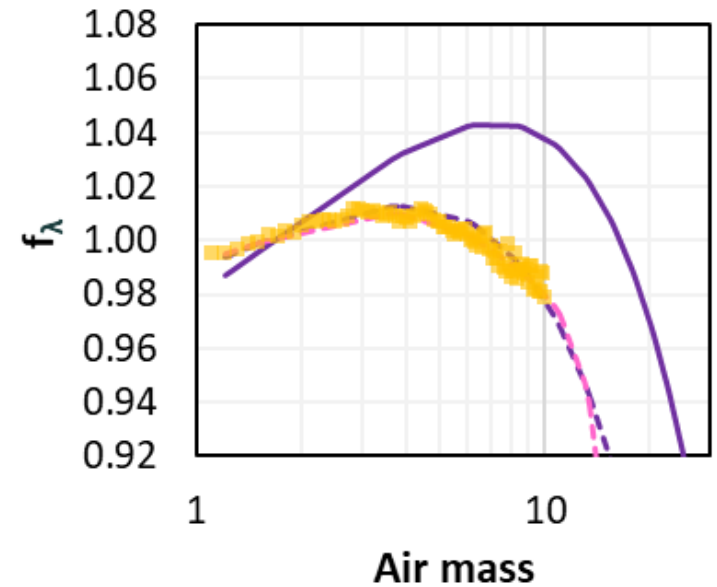
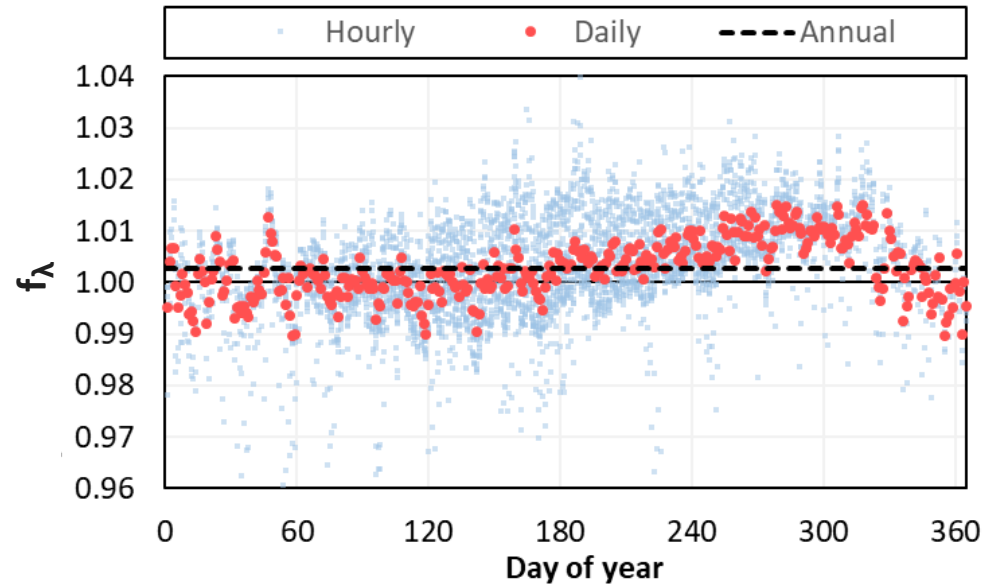
Example: Bifacial SAT — Chajnantor CHL



— FS defaults FS fit King fit

Model	AM1.5g	First Solar Default coeffs	First Solar Best-fit	King Best-fit
Yield MBE (%)	+2.51	−0.91	+0.03	+0.01
Daily error about mean (%)	±1.24	±0.97	±0.42	±1.49
Hourly error about mean (%)	±2.99	±2.02	±0.60	±1.57

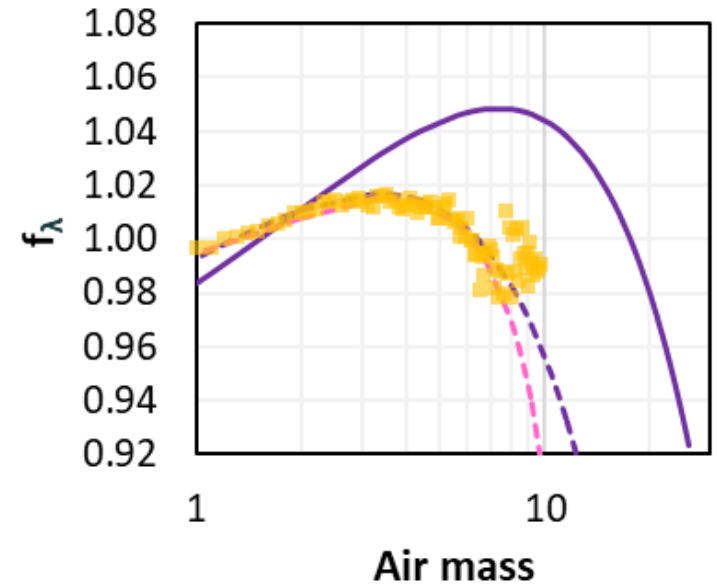
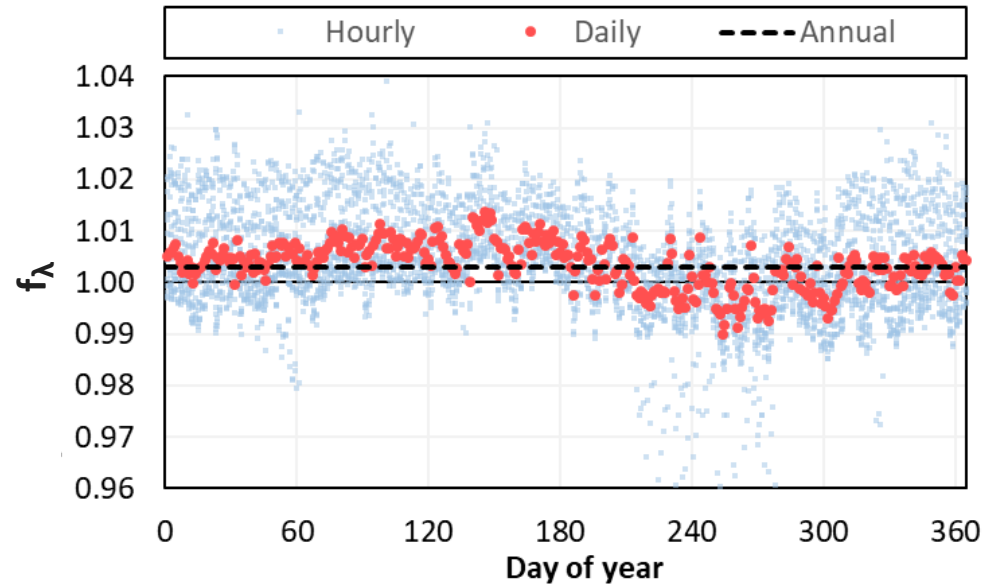
Example: Bifacial SAT — Agder NOR



— FS defaults FS fit King fit

Model	AM1.5g	First Solar Default coeffs	First Solar Best-fit	King Best-fit
Yield MBE (%)	−0.26	+0.47	−0.06	−0.03
Daily error about mean (%)	±1.09	±3.05	±0.68	±1.08
Hourly error about mean (%)	±1.64	±3.72	±0.89	±1.22

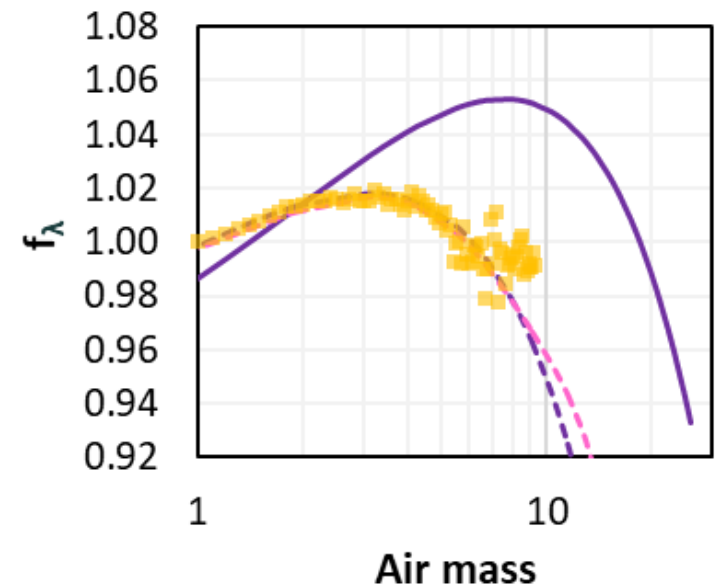
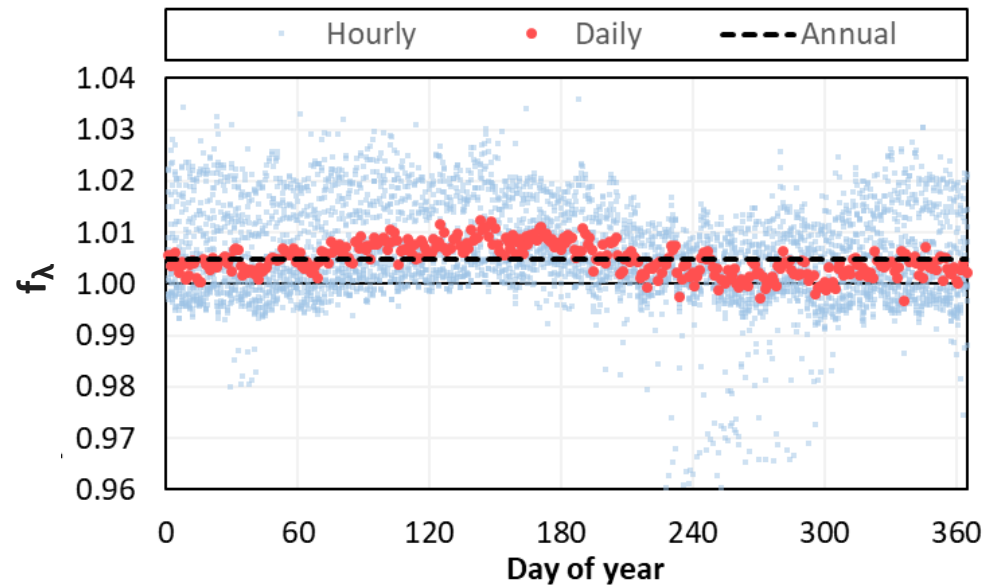
Example: Bifacial SAT — Cordoba ARG



— FS defaults FS fit King fit

Model	AM1.5g	First Solar Default coeffs	First Solar Best-fit	King Best-fit
Yield MBE (%)	−0.28	−0.18	−0.01	+0.00
Daily error about mean (%)	±0.89	±0.78	±0.29	±0.92
Hourly error about mean (%)	±1.80	±3.49	±1.12	±1.95

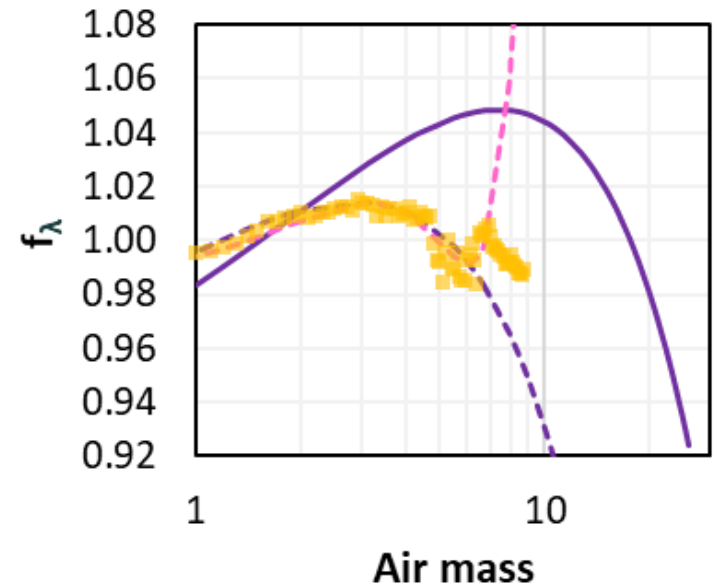
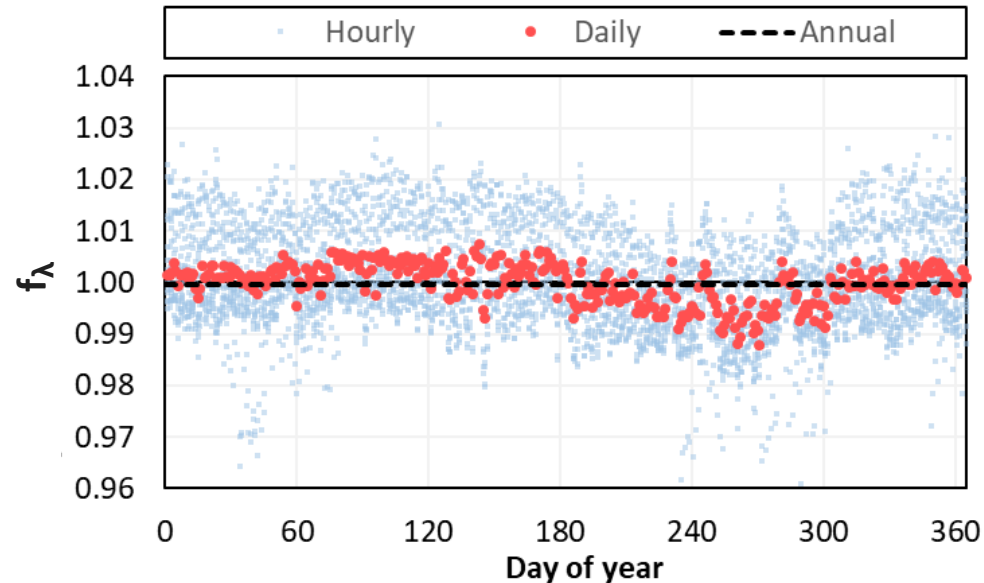
Example: Bifacial SAT — Sao Paulo BRA



— FS defaults FS fit King fit

Model	AM1.5g	First Solar Default coeffs	First Solar Best-fit	King Best-fit
Yield MBE (%)	−0.46	−0.45	−0.03	−0.01
Daily error about mean (%)	±0.59	±0.62	±0.27	±0.46
Hourly error about mean (%)	±1.69	±3.97	±1.35	±1.32

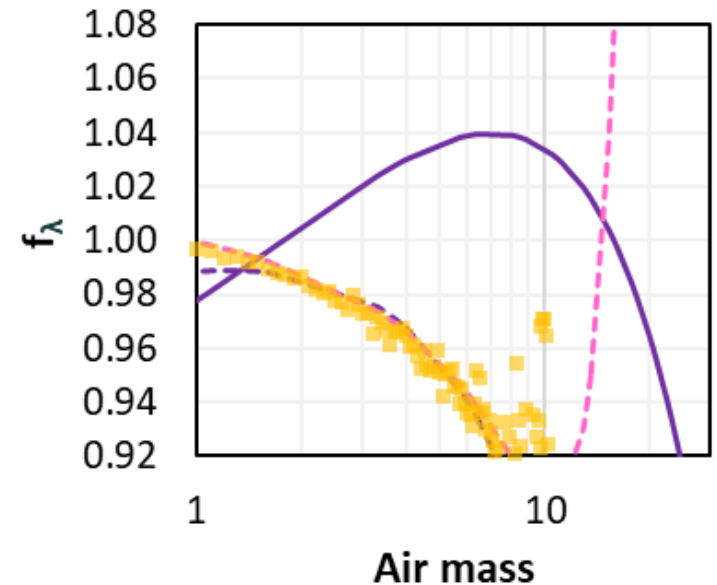
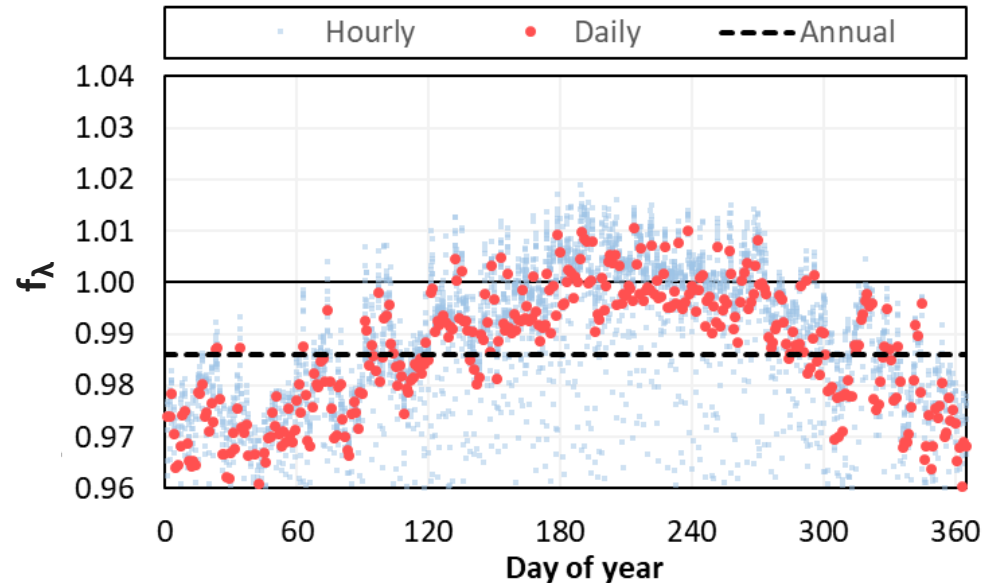
Example: Bifacial SAT — Pretoria ZAF



— FS defaults - - - FS fit King fit

Model	AM1.5g	First Solar Default coeffs	First Solar Best-fit	King Best-fit
Yield MBE (%)	+0.04	−0.48	−0.01	+0.02
Daily error about mean (%)	±0.76	±0.73	±0.32	±0.86
Hourly error about mean (%)	±1.86	±3.76	±1.48	±3.28

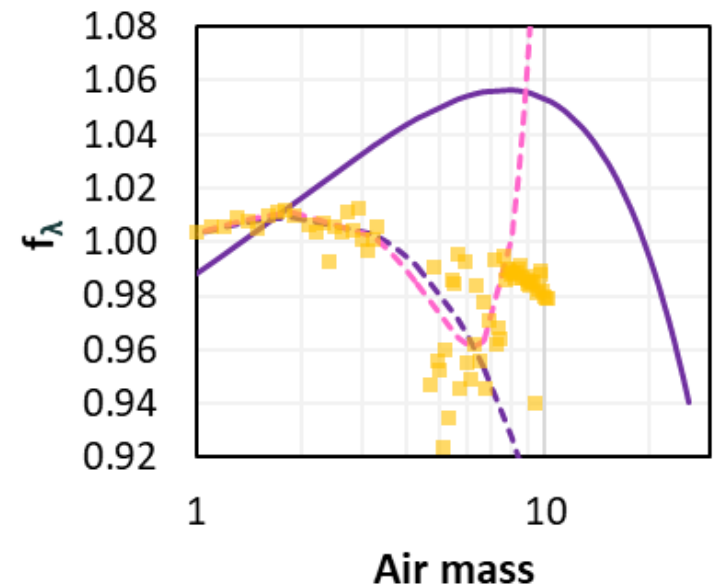
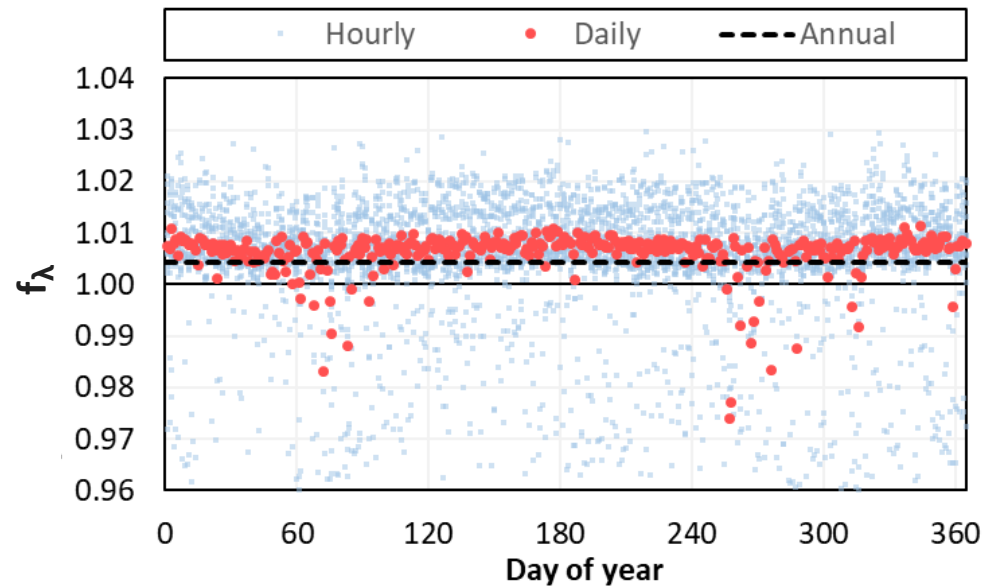
Example: Bifacial SAT — Beijing CHN



— FS defaults FS fit King fit

Model	AM1.5g	First Solar Default coeffs	First Solar Best-fit	King Best-fit
Yield MBE (%)	+1.29	+1.31	+0.11	+0.19
Daily error about mean (%)	±2.47	±2.64	±1.17	±1.85
Hourly error about mean (%)	±4.71	±7.55	±3.24	±3.30

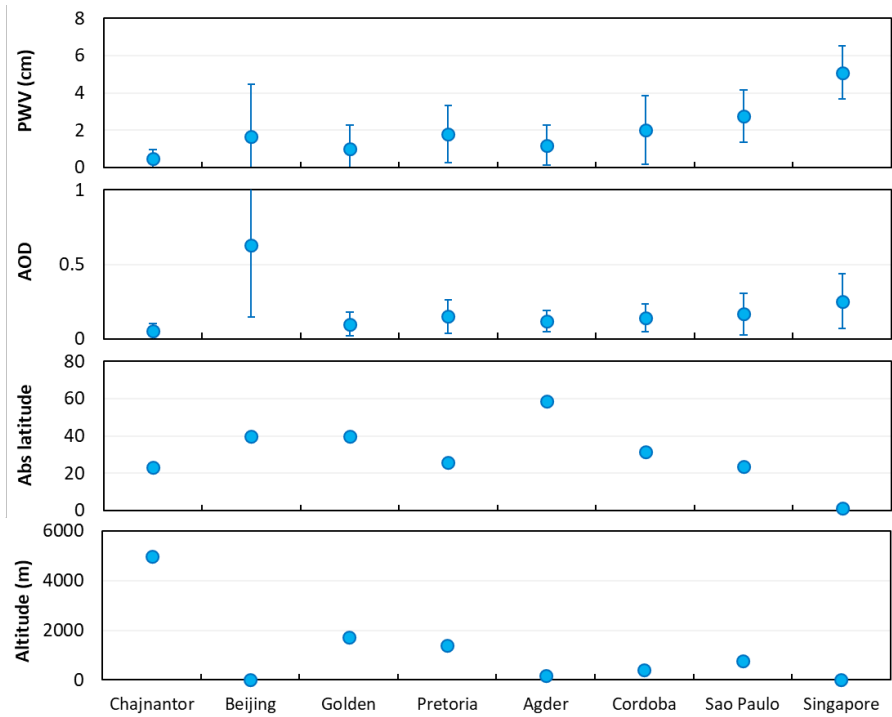
Example: Bifacial SAT — Singapore



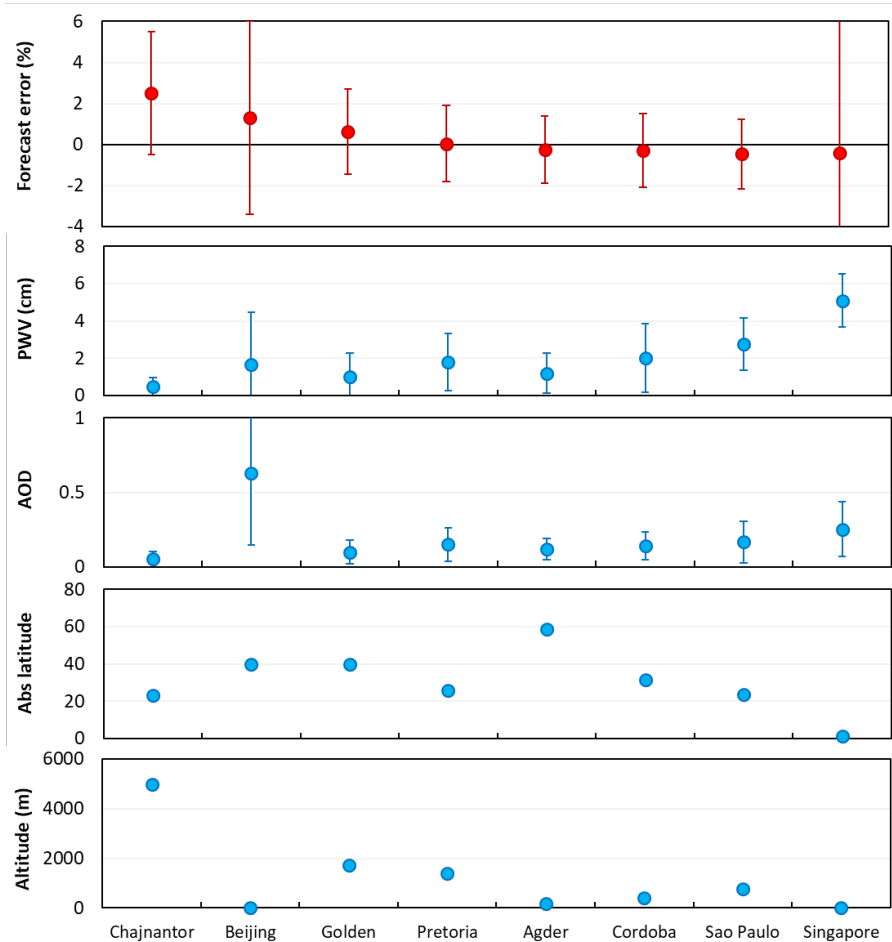
— FS defaults FS fit King fit

Model	AM1.5g	First Solar Default coeffs	First Solar Best-fit	King Best-fit
Yield MBE (%)	−0.41	−0.17	+0.07	+0.13
Daily error about mean (%)	±2.86	±2.92	±2.84	±2.85
Hourly error about mean (%)	±8.73	±11.18	±8.87	±9.51

Bifacial SAT — eight example locations



Bifacial SAT — eight example locations

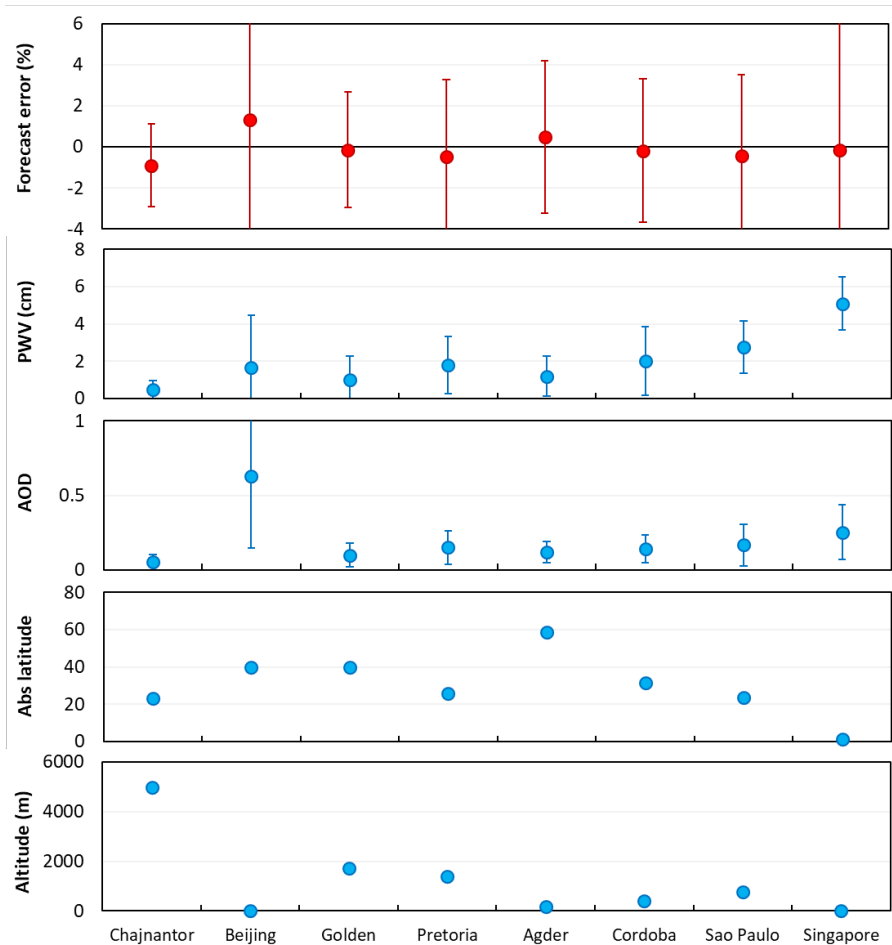


Spectral correction: None

Yield bias: **-0.5% to +2.5%**

Hourly error
about mean: **±2% typical, up to ±9%**

Bifacial SAT — eight example locations

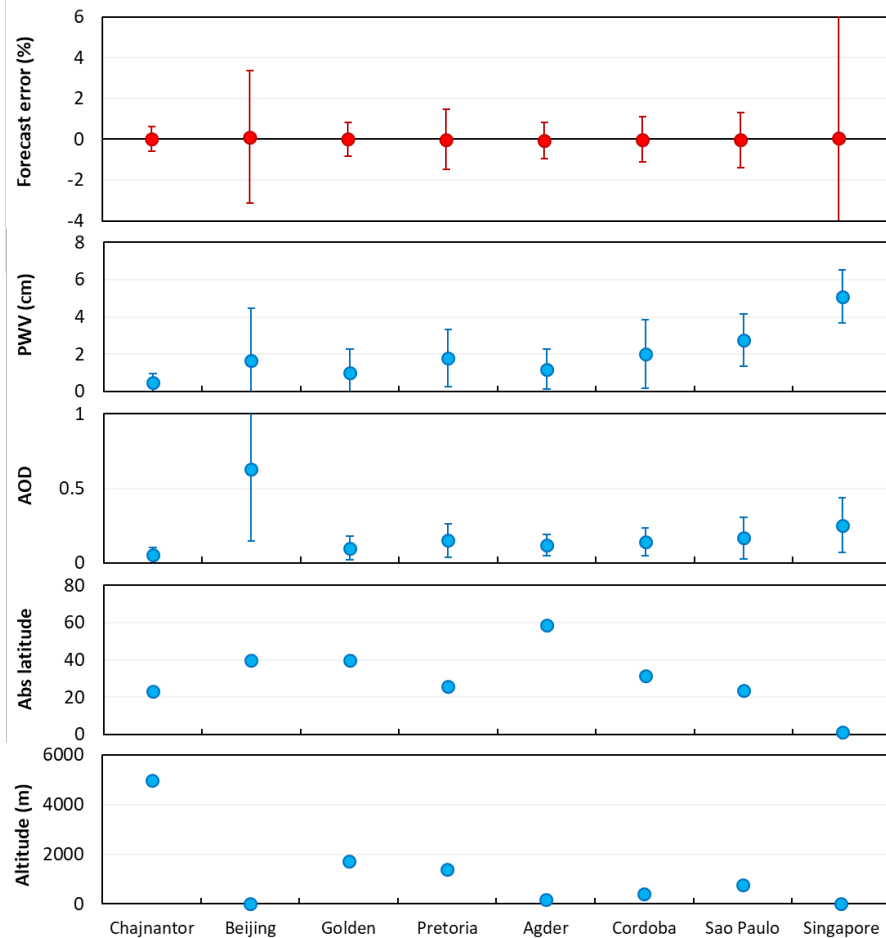


Spectral correction: FS default coeffs

Yield bias: **-0.9% to +1.3%**

Hourly error
about mean: **±3% typical, up to ±11%**

Bifacial SAT — eight example locations



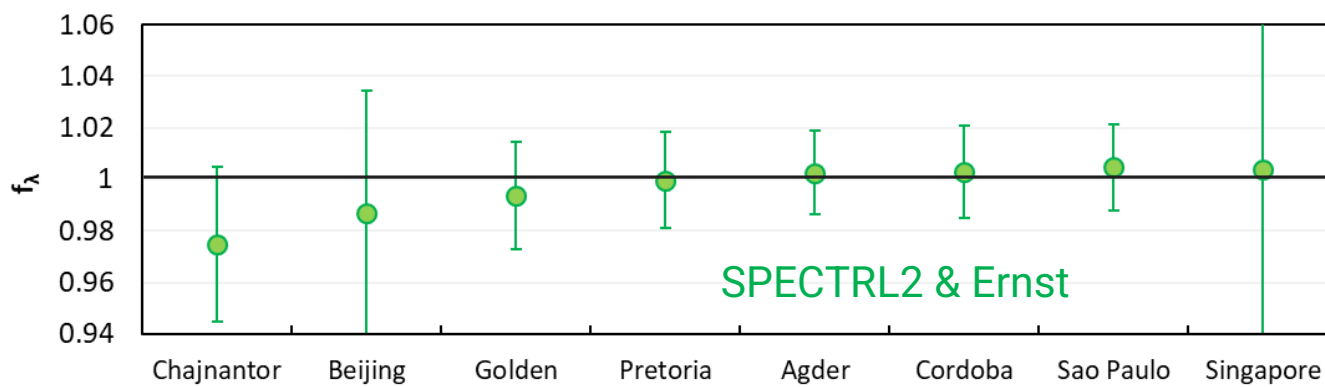
Spectral correction: FS fitted coeffs

Yield bias: —

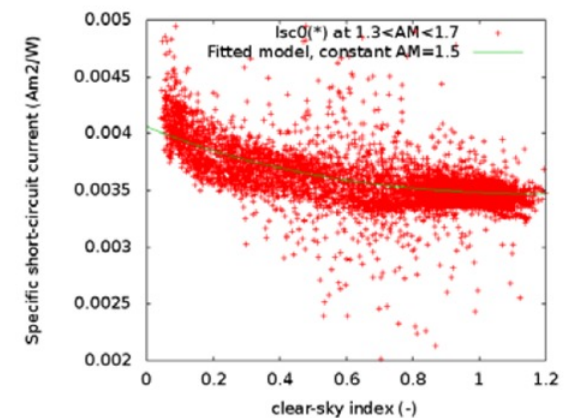
Hourly error
about mean: **±1% typical, up to ±9%**

Bifacial SAT — eight example locations

Spectral correction factor



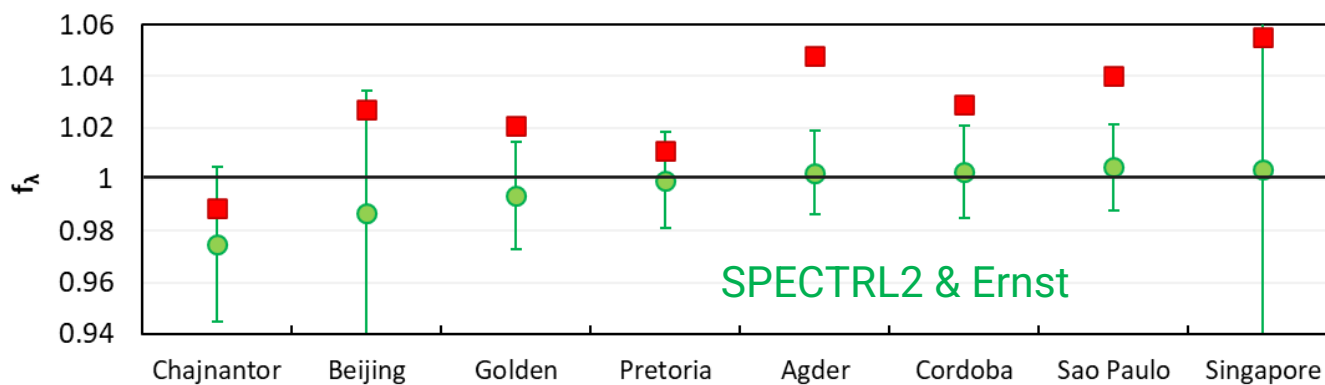
Huld cloudy-sky model



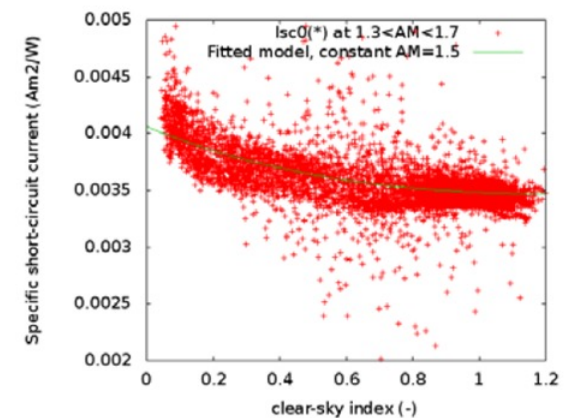
Bifacial SAT — eight example locations

Spectral correction factor

SPECTRL2 & Ernst & Huld cloudy-sky correction



Huld cloudy-sky model



- Spectral effects are significant for c-Si systems:
 - annual f_λ varies by $\pm 2\%$ depending on location,
 - f_λ is 1–3% higher in winter than summer,
 - f_λ can vary by as much as 5% on a clear day,
 - f_λ can increase by 0% to 25% (?) on an overcast day.
- PVSyst, SolarFarmer, PlantPredict etc. include FS model for f_λ .
 - Default coefficients are inaccurate.
 - Fitted coefficients greatly reduce error.
- SunSolve computes synthetic spectra at every time step.
 - Compute f_λ at any time. Determine coefficients for FS model.

Thank you



Find us:

SunSolve desk during “office hours”
(Parallel sessions C after lunch)

www.sunsolve.info