DTU

PVPerformance MODELING COLLABORATIVE

# Incident Angle Modifier (IAM) Round Robin Updates

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# Outline

- Incident angle modifier (IAM)
  - Theory and measurement procedure
- IAM round robin history
- Results
  - High level
  - Delta to Fresnel
  - Model fitting
  - Impact on energy rating (IEC 61853)
- Conclusions

# The Incidence Angle Modifier (IAM)

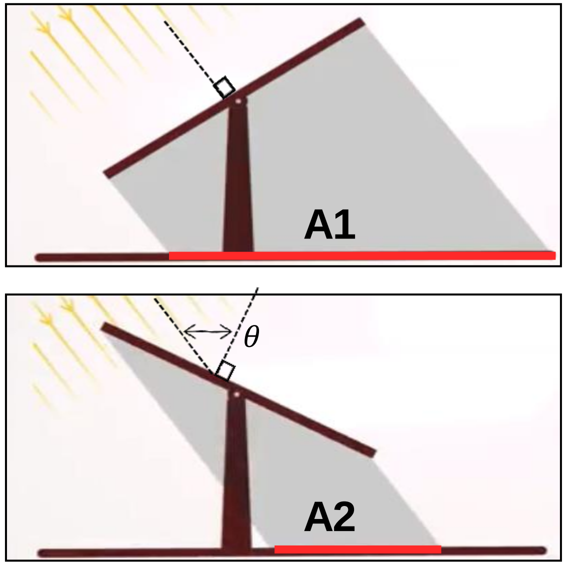
- When a PV device is not positioned normal to the sun, a loss of effective irradiance occurs due to **geometry** and **reflection**.
- Geometrical effect (Lambert Cosine Law)
  - Reduction of irradiance is proportional to cosine(AOI).

**Normal Incidence**

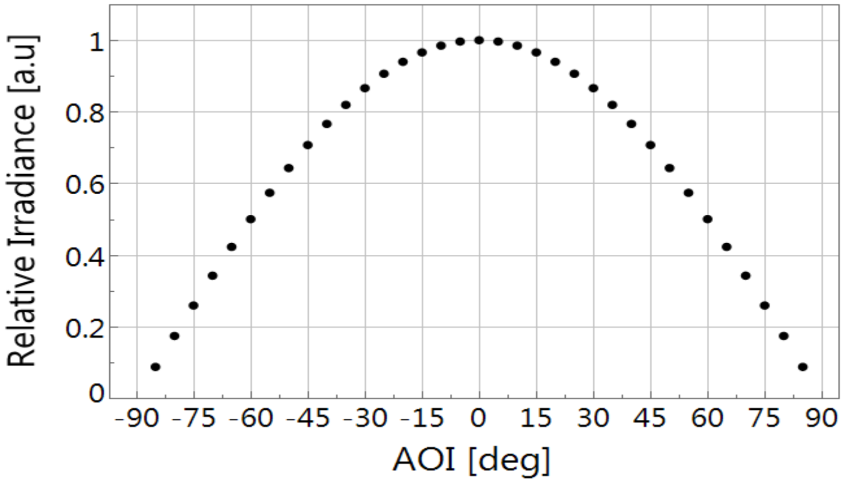
**AOI (θ) = 0°**

**Non-normal Incidence**

**AOI (θ) > 0°**



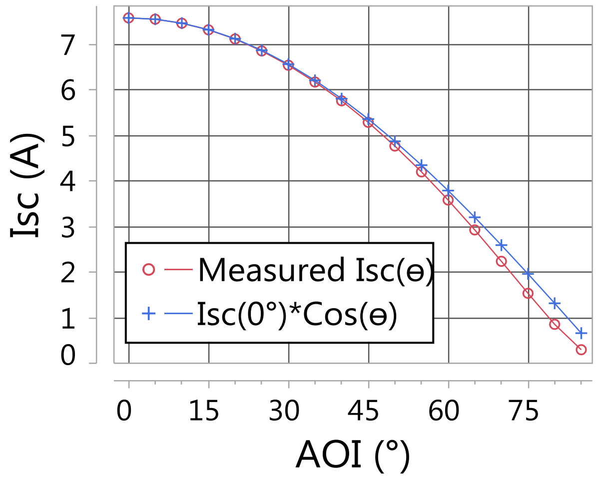

$$A2 = A1 * \cos(\theta)$$



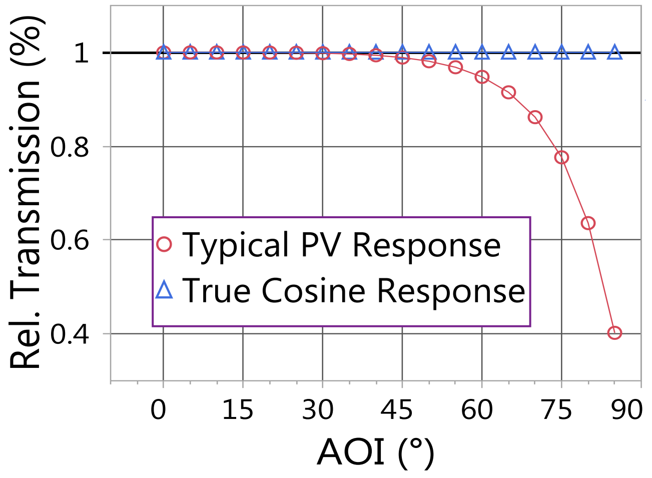
# The Incidence Angle Modifier (IAM)

- The IAM normalizes the cosine effect to isolate reflection losses.
- IAM is obtained by measuring short circuit current ($I_{SC}$) over a range of AOIs (θ).
  - Normalized to the $I_{SC}$ measured at normal incidence (AOI = 0).
  - Indoor and outdoor test procedures are stipulated in IEC 61853-2:2016


$$\mathrm{IAM}(\theta) = \frac{I_{SC}(\theta)}{\cos(\theta) * I_{SC}(0°)} = \frac{\textit{Beam irrad. received by PV Device}}{\textit{Total beam irrad. available to PV Device}}$$



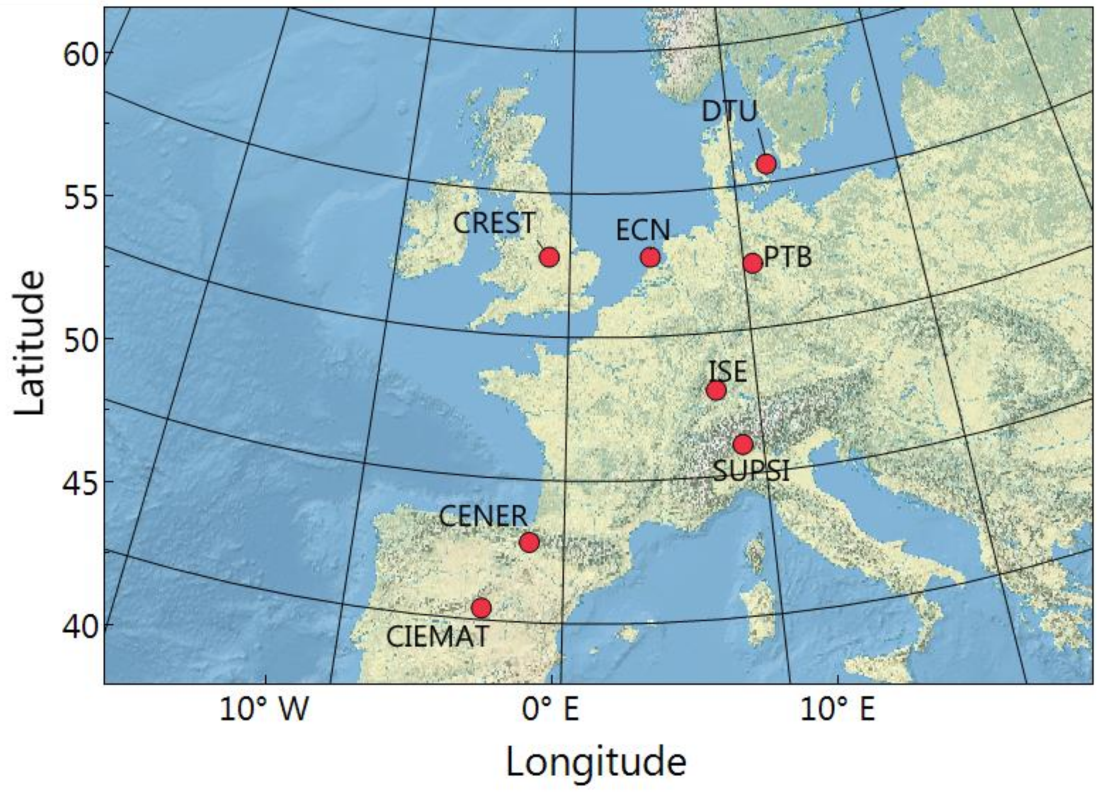

$$\frac{I_{SC}(\theta)}{I_{SC}(0°) * \cos(\theta)}$$



# International IAM Round-Robin Recap

**The results from 8 European labs showed:**

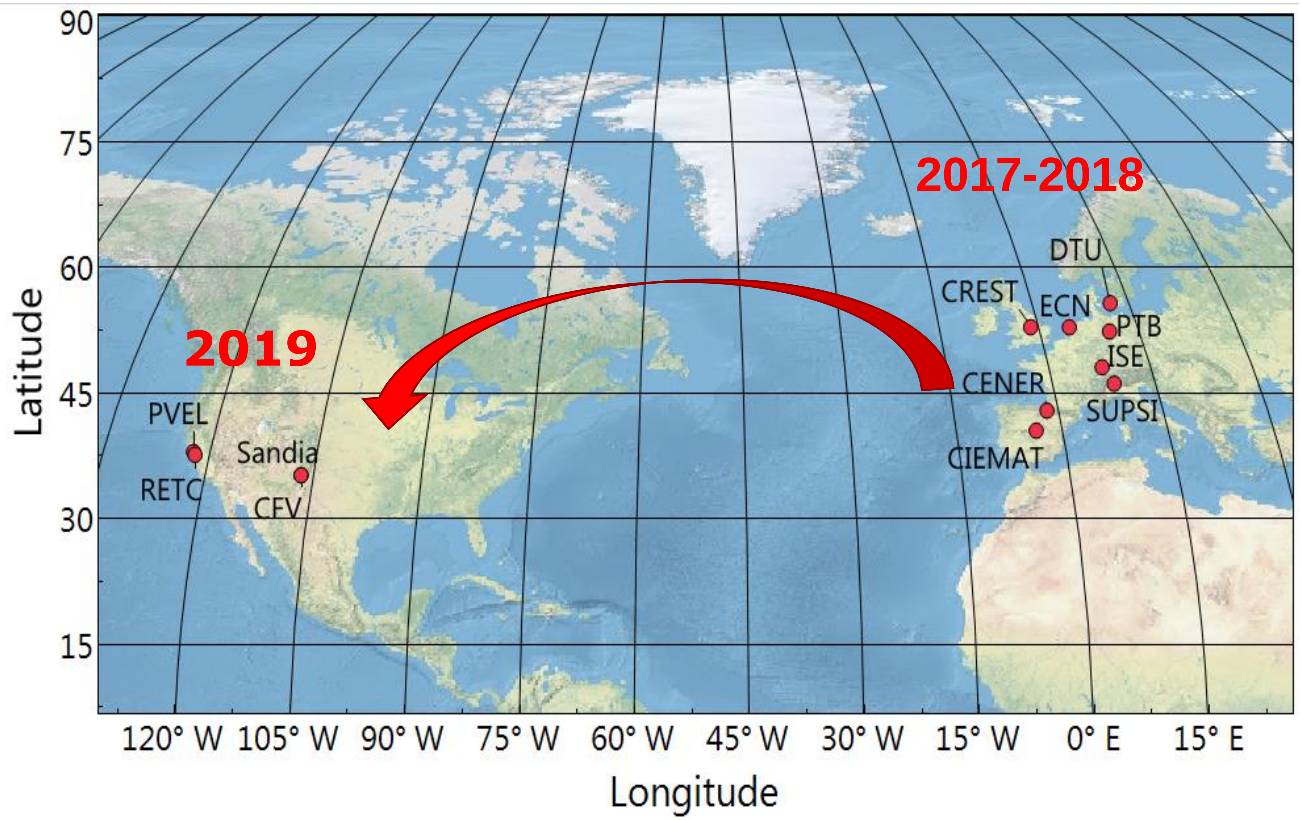
- Five of eight labs were comparable w/in their stated $U_C$ out to ±80° AOI [1].
- IAM measurements at ±85° AOI are challenging!
  - 75% range + low comparability w/in $U_C$.
- Two labs w/ suspect measurements due to:
  - Misalignment of DUT w/ axis of rotation.
  - Excessive reflections w/in the test bed.
- Samples w/ identical BoM were sent to these two labs for retest.
  - The two suspect IAM profiles from these labs are **not** included in this presentation.
  - 1 available retest dataset is presented instead.




**[1] N. Riedel et al., 2018, Proc. of 35th EUPVSEC, 5BO.10.4**

# International IAM Round-Robin Recap

- In Jan. ‘19 the DUTs were shipped to the US.
- Only 1 of 8 European labs performed the IAM measurements outdoors.
  - Comparability of methods?
- 3 of 4 US labs performing the IAM test outdoors.
  - 2 labs have yet to measure the DUTs.
- Labs are asked to measure from ±85° in 5° steps.
- Labs asked to report:
  - IAM for each angle of incidence (AOI) θ
  - $U_C$ (k=2) of IAM(θ)
    - Only 7 of 10 labs provided $U_C$



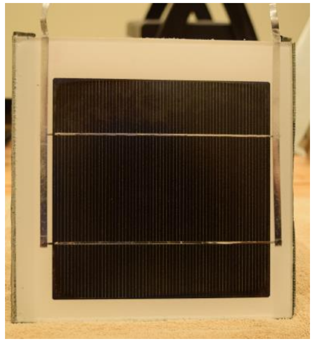
# Devices Under Test (DUTs)

- Common characteristics among all DUTs:
  - Cell size:156 mm x 156 mm
  - Glass: 3.2 mm thick, finely textured PV glass
    - **No anti-reflective coating (ARC)**
  - Encapsulant: ethylene-vinyl acetate (EVA)
  - The glass edges were covered with tape

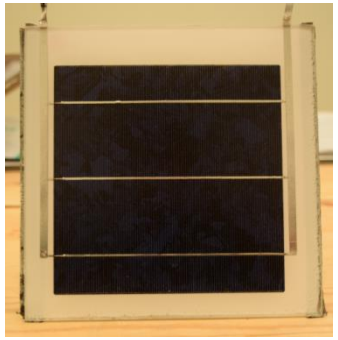
- Three different cell surface textures
  1. Standard mono-silicon **(Mono-si)**
  2. mc-Si black silicon textured under reactive ion etch (RIE) treatment **(Black-Si A)**
  3. mc-Si black silicon textured under atmospheric pressure dry etching (ADE) treatment **(Black-Si B)**

Mono-Si

Black-Si A

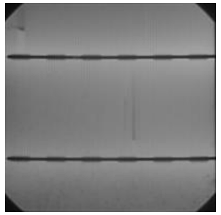


Black-Si B

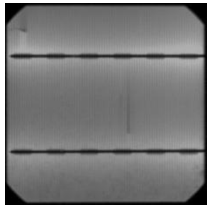


All DUTs have the same glass, so the IAM measurements [not surprisingly] show little difference.

**Only the measurements of the Mono-Si sample will be presented here.**

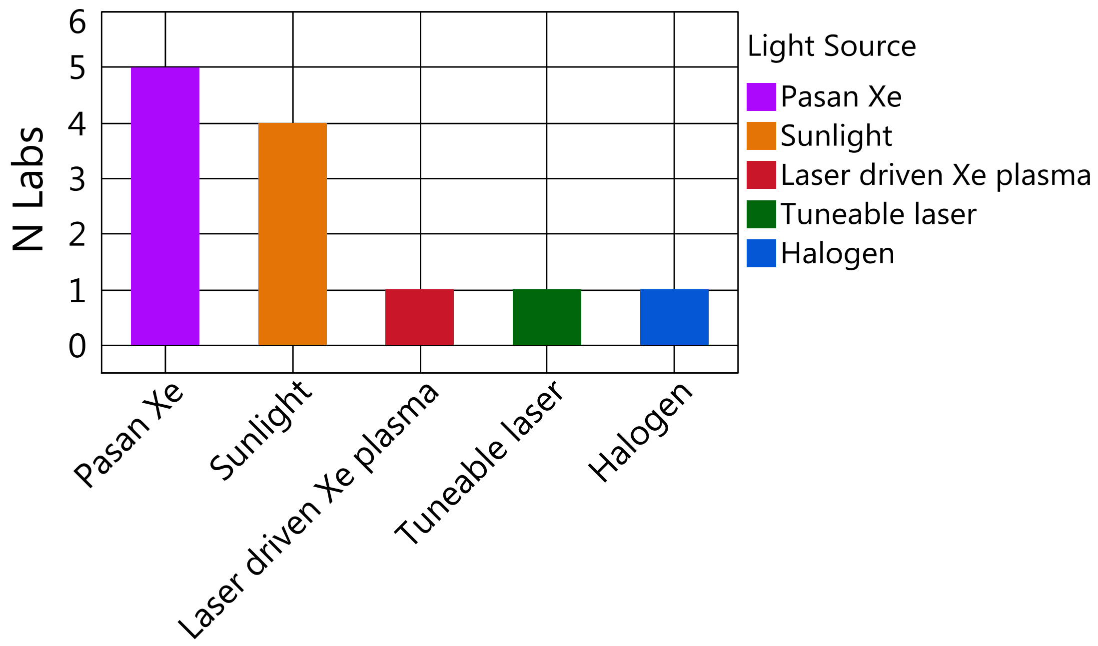


Initial EL of mono-Si DUT



Most Recent EL of mono-Si DUT

# Participating Laboratory Measurement Systems

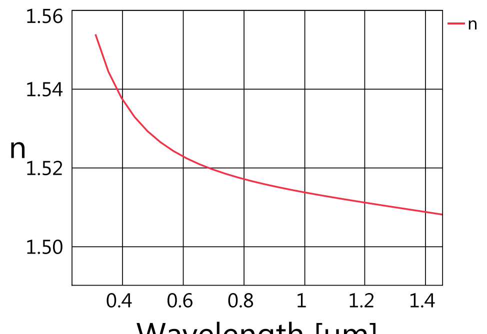



| | Automated Rotation Stage | Manual Rotation Stage | Total |
|---|---|---|---|
| Xe Flash (Pasan) | 2 | 3 | 5 |
| Sunlight | 3 | 1 | 4 |
| Halogen | 1 | 0 | 1 |
| Laser driven Xe plasma | 1 | 0 | 1 |
| Tuneable laser | 1 | 0 | 1 |
| Total | 8 | 4 | 12 |

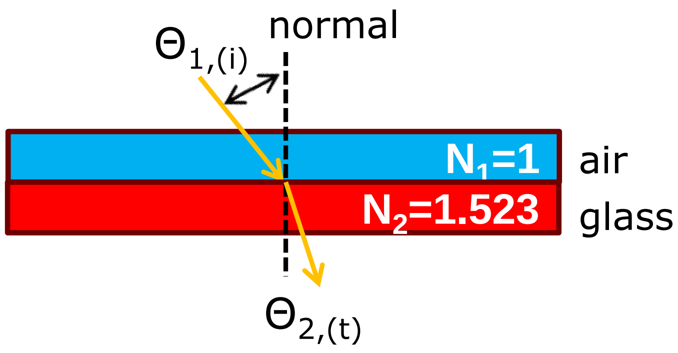
- Five unique light sources.
- Light sources represent different illumination levels and spectral distributions.
- Various approaches for rotating the DUTs.
  - From single cells -> mini modules -> full-sized modules.
- Two labs w/ outdoor test systems remain to measure the DUTs (end of summer ‘19?).
- Labs have been assigned anonymous ID#s

# Comparing Measurements to Theory

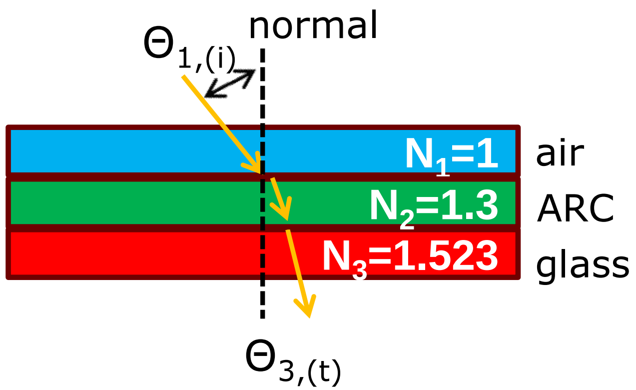
- The following slides will refer to the Fresnel model.
  - This is a simplified approach to calculating the IAM using Snell's law and the Fresnel equations [2].
- For the single slab model (no ARC) ***n2* = 1.523.**
- For the two slab model (ARC) ***n2* = 1.3** and ***n3* = 1.523.**
- Unpolarized light (50% p-polarized, 50% s-polarized).



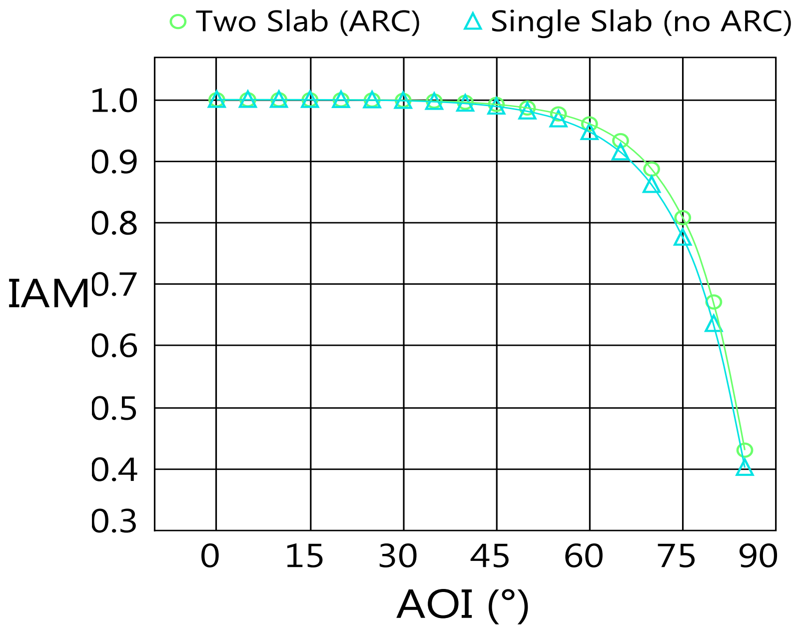

**Spectral dependence of refractive index *n* of soda lime glass [3]**




**Single slab model (glass w/ no ARC)**



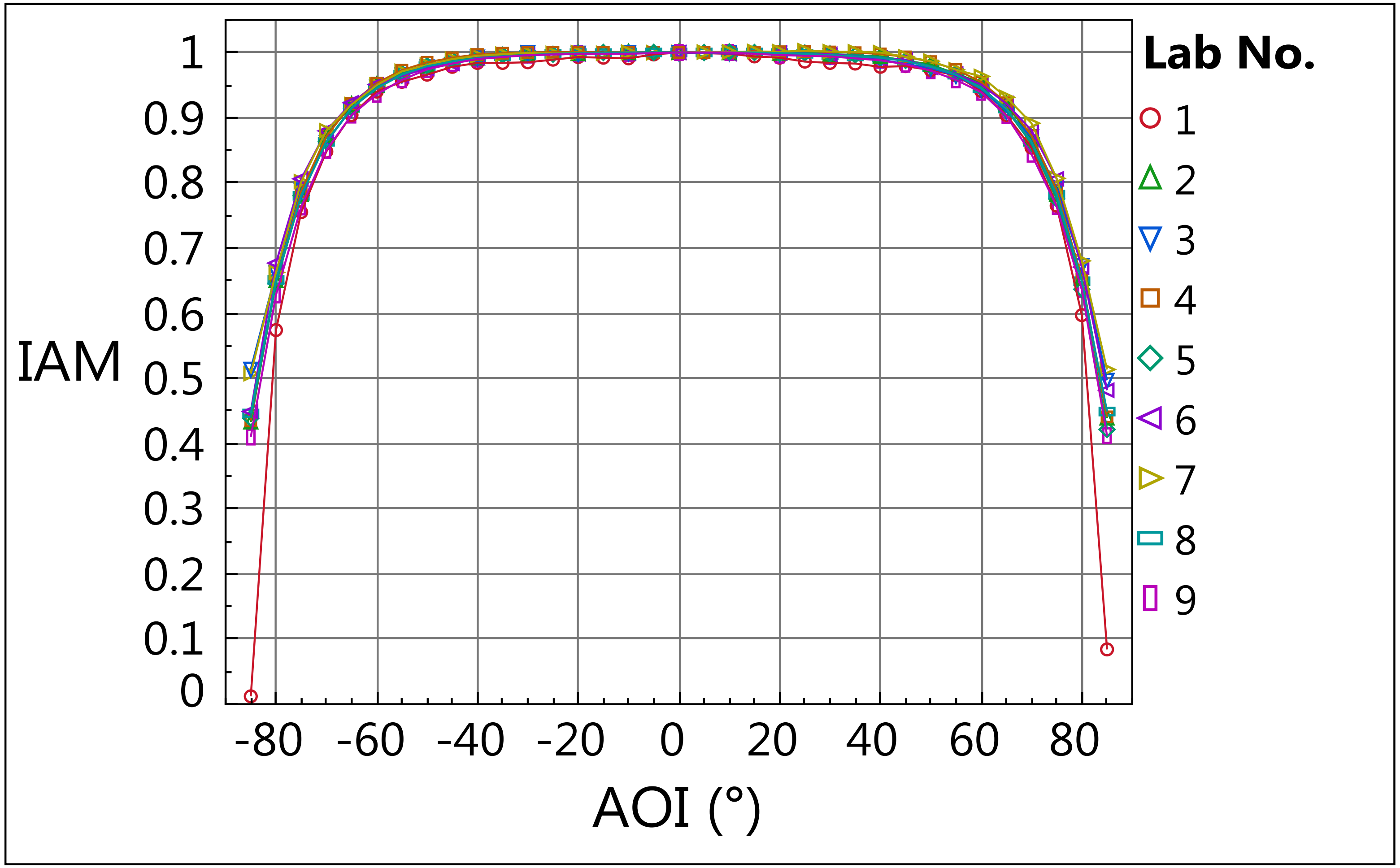

**Two slab model (glass w/ ARC)**





[2] A. Dobos, PV Watts V5 Manual, 2014.
[3] M. Rubin. Optical properties of soda lime silica glasses, Sol. Energy Mater. 1985.

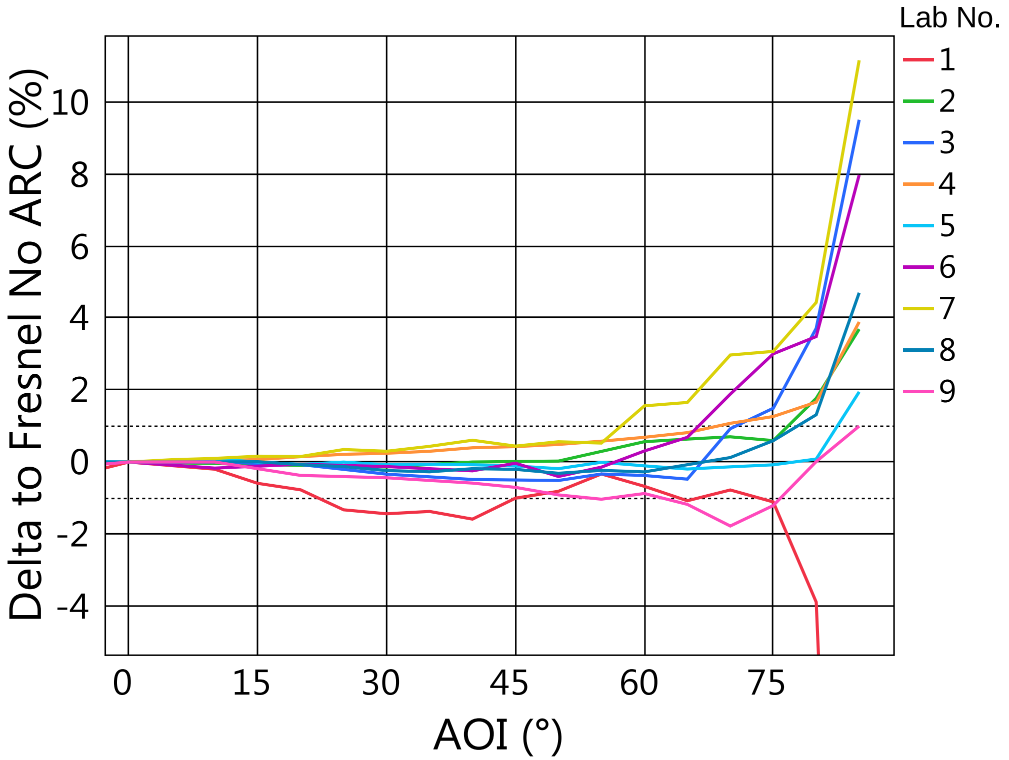
# Results – All Labs



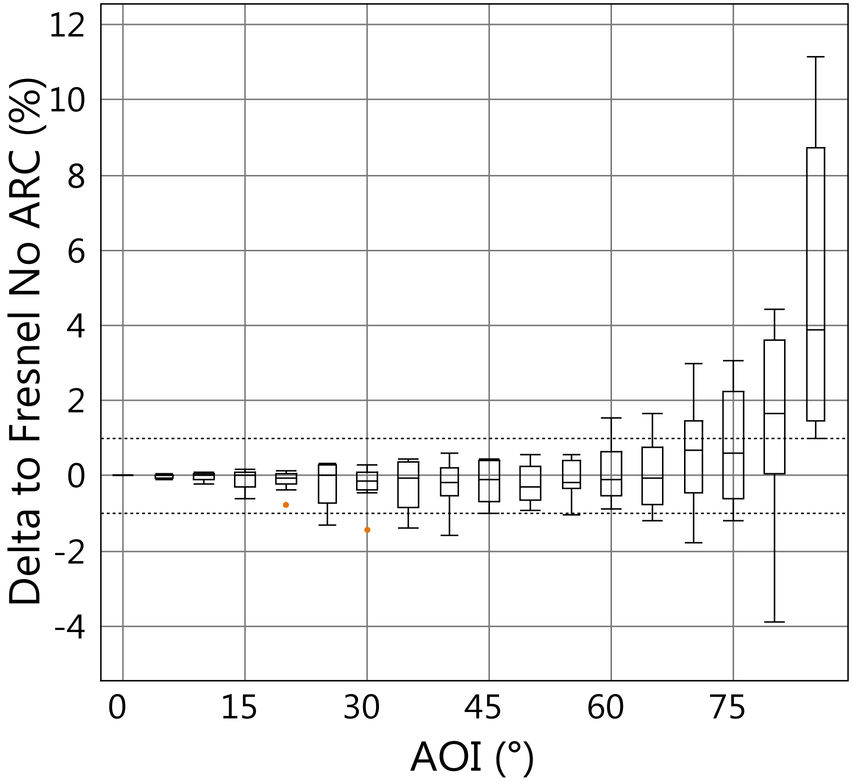

Results from the Mono-Si sample.

- 8 of 9 labs show IAM differences of < 2% at ±80°
  - (Symmetry requirement of IEC 61853-2)
- Lab No. 1 shows IAM symmetry of 2.3% at ±80°
- If Lab 1's measurement at 85° AOI is excluded:
  - The measurement range at 85° decreases from 40% to 10%.

# Results – Delta to Fresnel Model w/o ARC

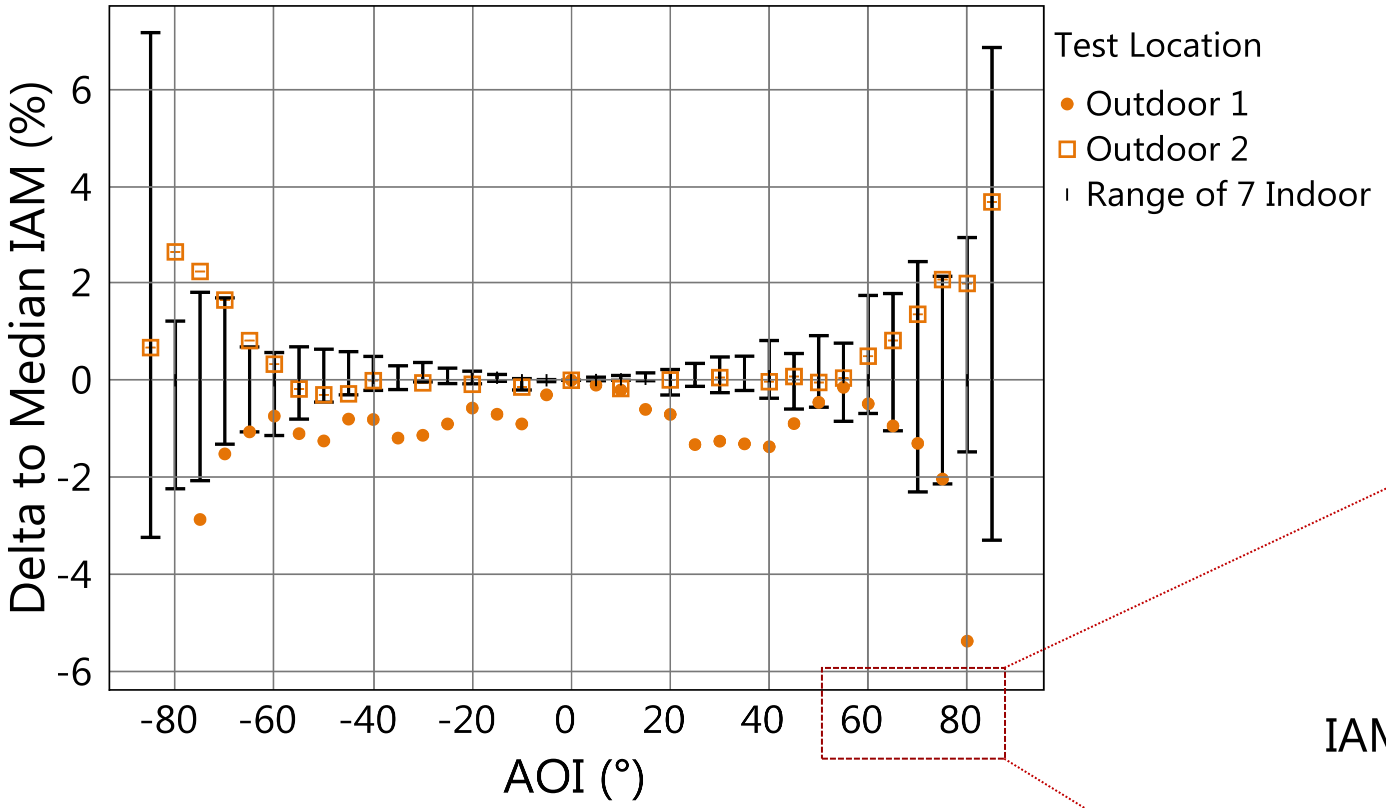



- Median IAM(θ) shows agreement w/in ±1% of Fresnel no ARC model out to 75° AOI.



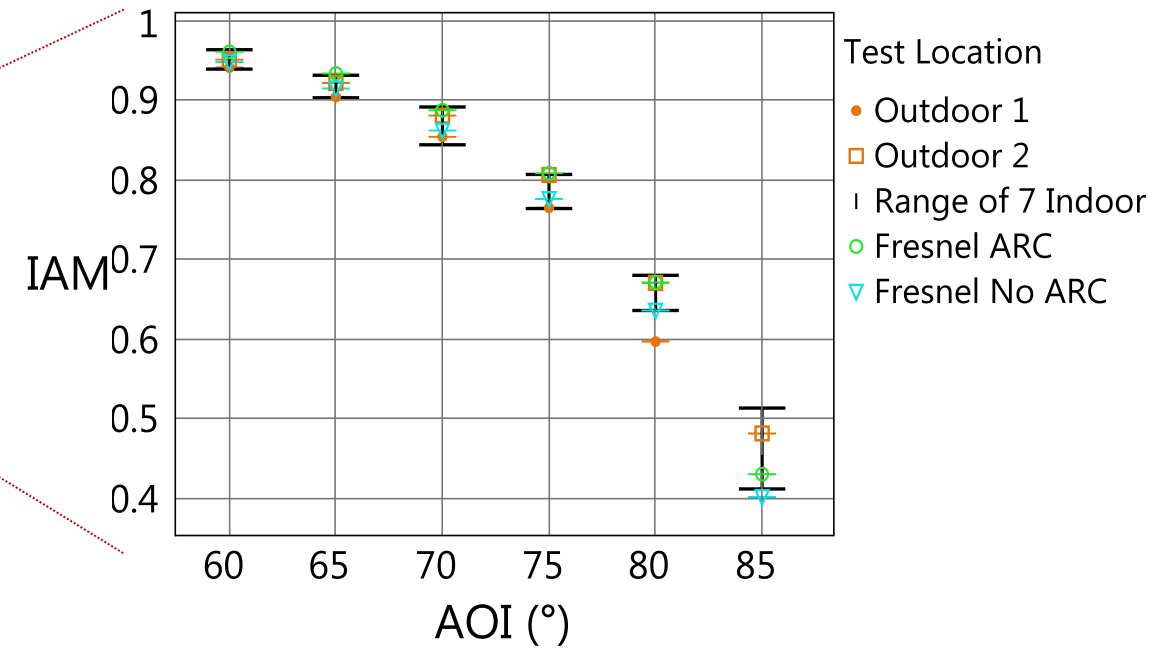

$$\Delta = (IAM(\theta)_{lab} - IAM(\theta)_{Fresnel}) \cdot 100$$

# Results – Delta to Median by Test Location

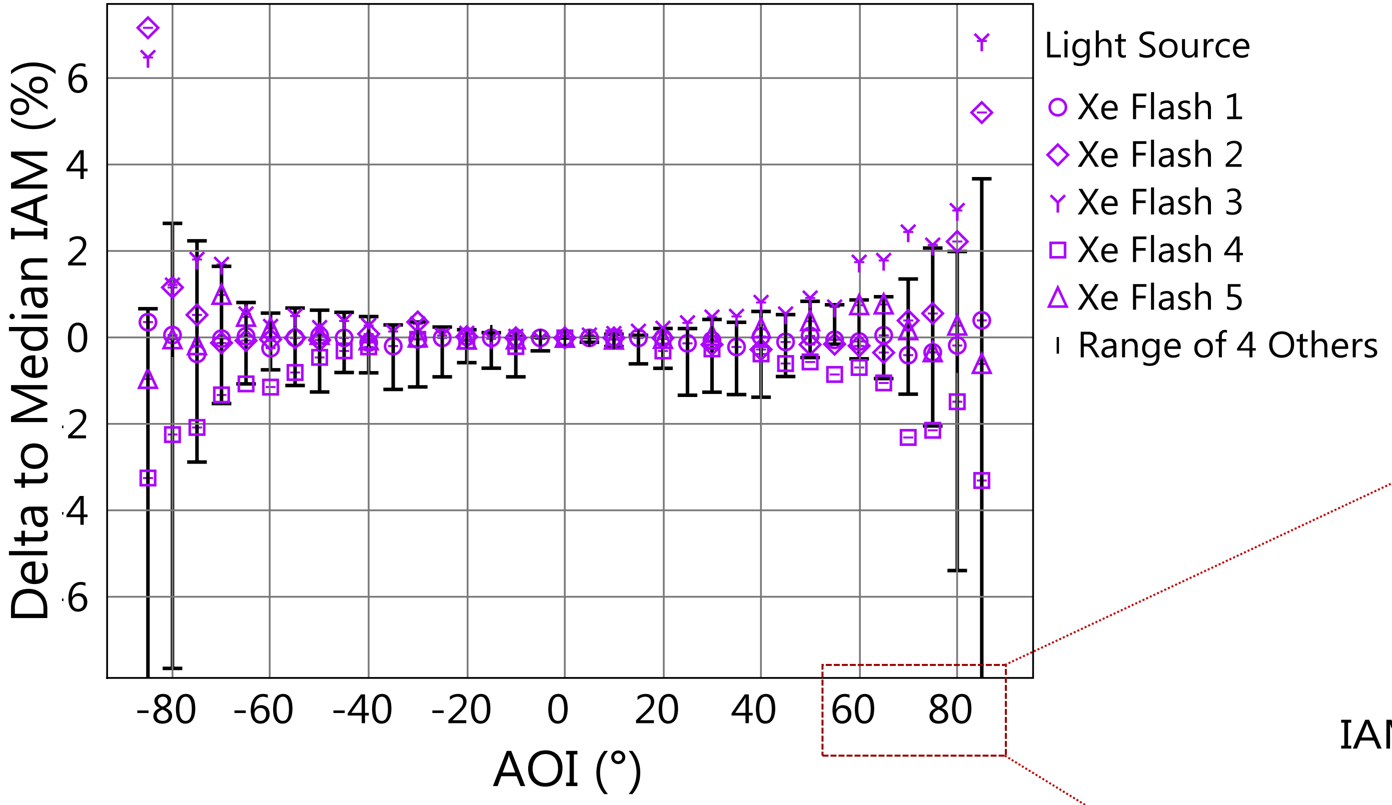



- IAM results not dependent on test location (i.e. indoor vs. outdoor).
- 'Outdoor 2' IAM measurements tend to follow Fresnel ARC model

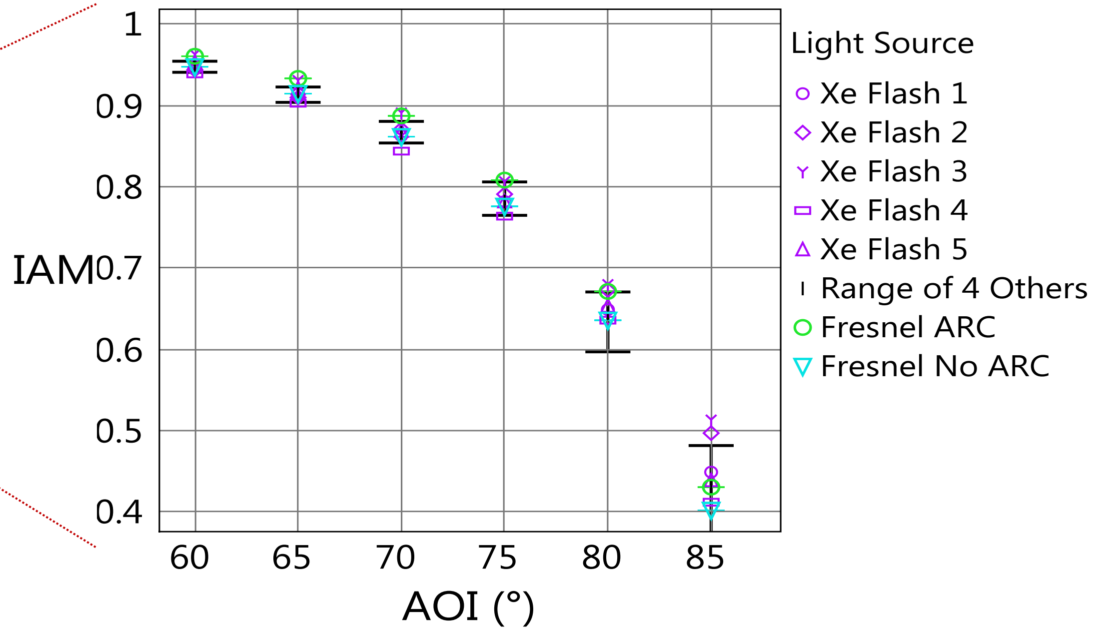
$$\Delta = \left(IAM(\theta)_{lab} - IAM(\theta)_{RR\ Median}\right) \cdot 100$$



# Results – Delta to Median by Light Source




- IAM results not dependent on light source used.
- 5 Xe Flash systems show no clear tendency toward agreement with a particular Fresnel model.




$$\Delta = \left(IAM(\theta)_{lab} - IAM(\theta)_{RR\ Median}\right) \cdot 100$$

# Angular Loss Models

1. **ASHRAE**
   - Single parameter ($b_0$)

$$IAM(\theta) = 1 - b_0\left(\frac{1}{\cos\theta} - 1\right)$$

2. **Martin and Ruiz**
   - Single parameter ($a_r$)

$$IAM(\theta) = \frac{1-\exp({\cos\theta}/{a_r})}{1-\exp({-1}/{a_r})}$$

3. **Sandia**
   - $5^{th}$ order polynomial fit (5 coefficients)

4. **Physical model (DeSoto)**
   - Based on Snell's and Bougher's laws.
   - Two coefficients (K and L)

$$IAM(\theta) = \frac{e^{-\left(\frac{KL}{\cos\theta_r}\right)}\left[1 - \frac{1}{2}\left(\frac{\sin^2\theta_r - \theta}{\sin^2\theta_r + \theta} + \frac{\tan^2\theta_r - \theta}{\tan^2\theta_r + \theta}\right)\right]}{e^{(-KL)}\left[1 - \left(\frac{1-n}{1+n}\right)^2\right]}$$

$$\theta_r = \sin^{-1}\left(\frac{1}{n}\sin\theta\right),\ n = 1.523$$

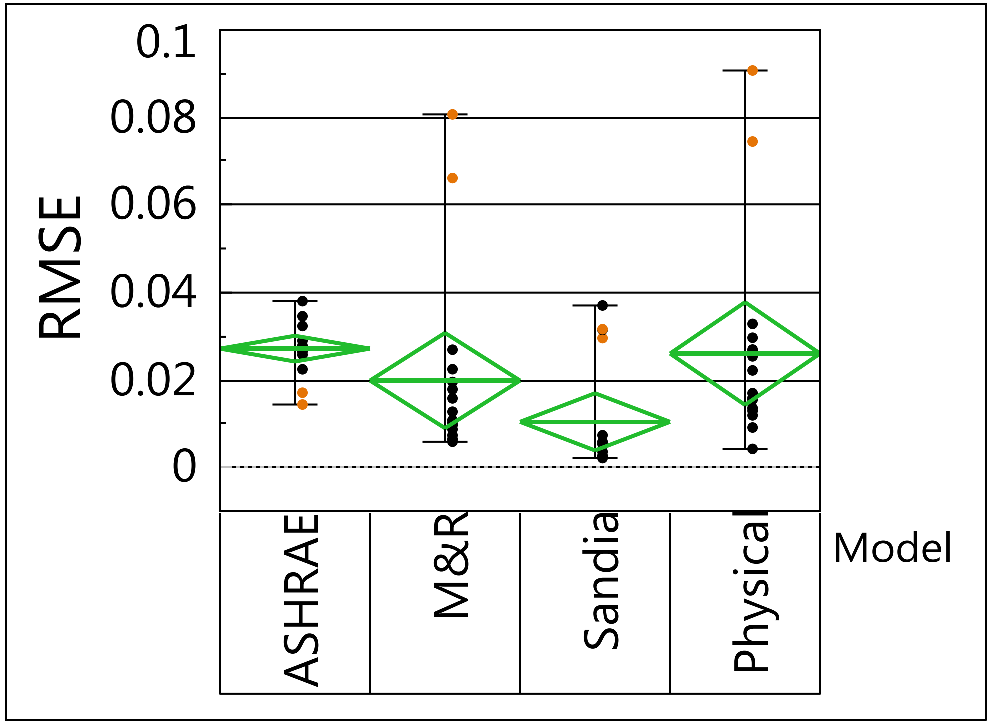
Model coefficients are extracted from the measured IAM data using a Gauss-Newton fitting method.

# Model Fitting Results

**Coefficients and goodness of fit summary for ASHRAE and Martin & Ruiz models**

| Lab | $a_r$ | $b_0$ | $a_r$ RMSE | $b_0$ RMSE |
|---|---|---|---|---|
| 1 | 0.221 | 0.089 | 0.073 | 0.016 |
| 2 | 0.157 | 0.056 | 0.013 | 0.027 |
| 3 | 0.155 | 0.053 | 0.025 | 0.035 |
| 4 | 0.163 | 0.058 | 0.007 | 0.026 |
| 5 | 0.169 | 0.059 | 0.007 | 0.028 |
| 6 | 0.155 | 0.055 | 0.013 | 0.025 |
| 7 | 0.149 | 0.052 | 0.019 | 0.028 |
| 8 | 0.165 | 0.058 | 0.011 | 0.027 |
| 9 | 0.178 | 0.062 | 0.008 | 0.033 |

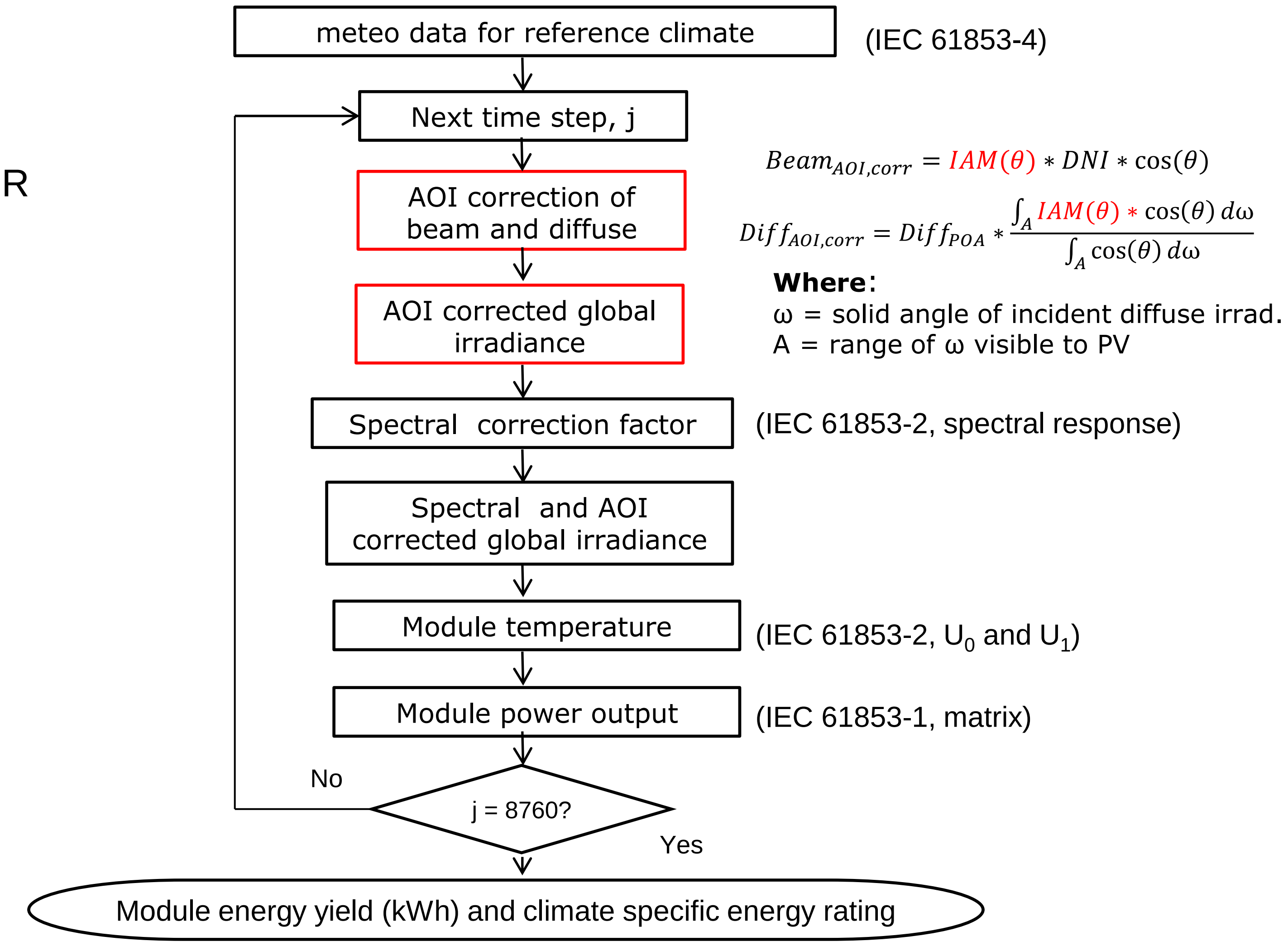
- Table shows average $a_r$ and $b_0$ coefficients from the forward (+AOI) and reverse (-AOI) measurement directions.




- Variability chart shows goodness of fit results from fitting 4 models to 9 labs' measurements of the mono-si sample.
- RMSE from fitting forward and reverse directions shown.
- Orange dots represent Lab Outdoor 1.

# IAM $U_C$ Impact on Energy Rating (IEC 61853-3)

- The climate specific energy rating (CSER) was calculated using the IAM data measured by the RR labs and IEC CDV 61853-3 procedures.
- DTU measured spectral response (SR), multi-G (@25° C) and multi-T (@1000 W/m²).
- Assumptions made for $U_0$ and $U_1$ based on [4].
  - $U_0$ = 26 W/m²·K, $U_1$ = 6 W·s/m³·K
- All calculations done for South facing 20° tilt.




**Energy Rating Workflow (IEC CDV 61853-3)**

[4] M. Koehl et al. Modeling of the NOCT based on outdoor weathering. Sol. Energy Mater. Sol. 2011

# IAM $U_C$ Impact on Energy Rating (IEC 61853-3)

**Climate Specific Energy Rating (CSER) = module performance ratio (MPR)**

$$CSER = \frac{EY \cdot 1000\left[\frac{W}{m^2}\right]}{P_{STC} \cdot H}$$

EY = Annual energy yield [Wh]
H = Annual insolation in array plane [Wh/m$^2$]
$P_{STC}$ = Power at STC [W]

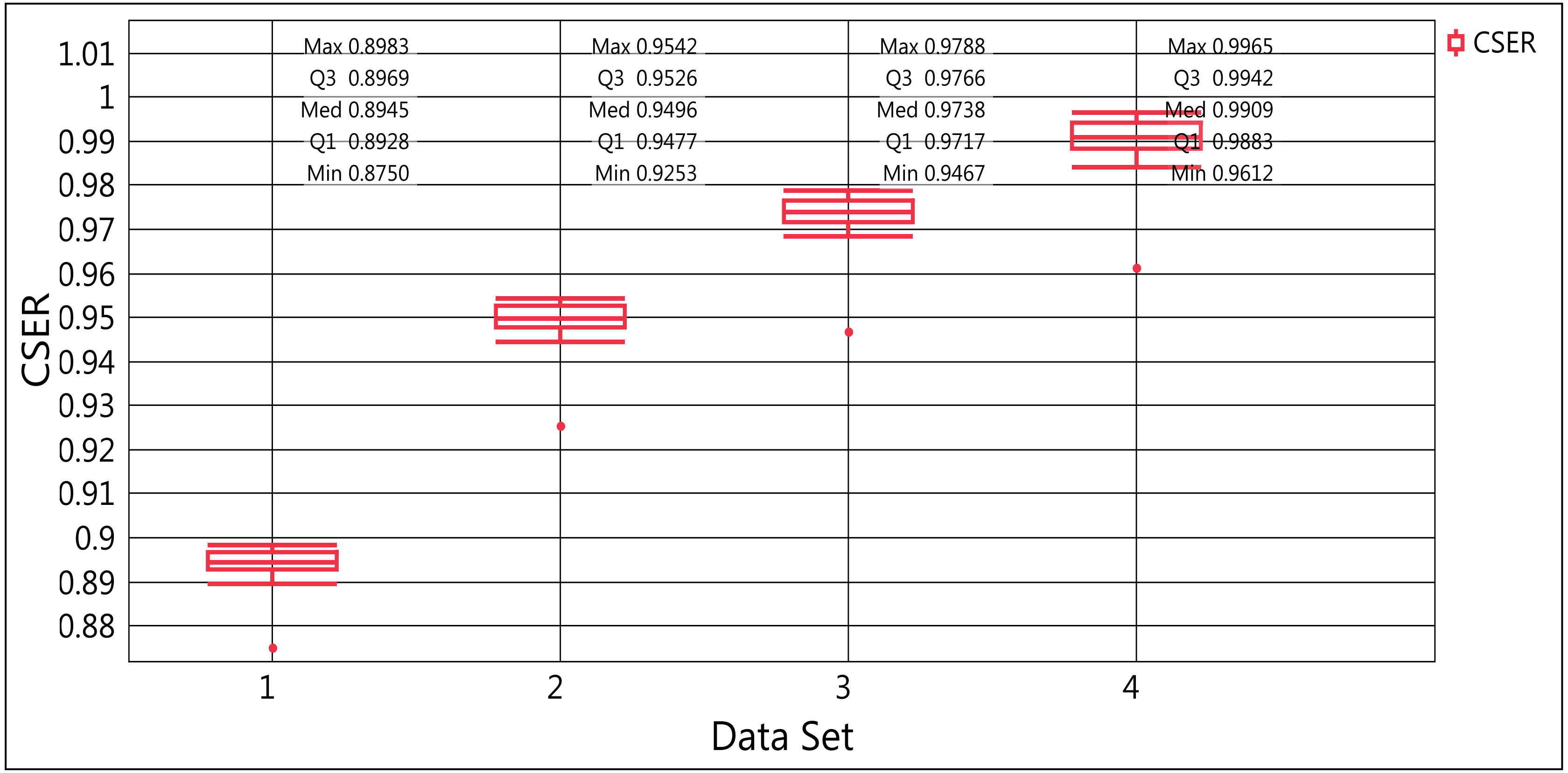
| Data Set | Lat./Long. | Climate |
|---|---|---|
| 1 | 38° N, 3° W | Mediterranean |
| 2 | 48° N, 12° E | Temperate continental |
| 3 | 54° N, 24° E | Continental (Central Europe) |
| 4 | 56° N, 4° W | Temperate coastal |

**The four reference climates suggested by [5].**

[5] T. Huld et al., PV energy rating datasets for Europe, Sol. Energy. 2016.

# IAM $U_C$ Impact on Energy Rating (IEC 61853-3)

- When the reported IAM measurements are used to calculate CSER:
- CSER varies by **0.9-1.2%**
  - If lab 1 is excluded
- CSER varies by 2.3-3.5%
  - if lab 1 is included.




▪ Red dot below lower whisker represents lab 1.

# Conclusions

- **Improved agreement in IAM measurements compared to 2018 RR results.**
  - Retests and filtering of suspect measurement profiles.

- **Differences in robust IAM measurements from 8 international laboratories cause ~1% difference in climate specific energy rating.**

- **Median IAM agrees w/in $\pm$1% of Fresnel model when AOI $\leq$ 75°**
  - The simple Fresnel model can be reasonably used in this range as a sanity check when measuring DUTs with smooth glass.
  - **To Do**: Calculate angular losses via ray trace simulations w/ ISFH.

- **IAM results not dependent on type of measurement system used.**
  - Suggests that experience can count for something.

# Thank you!

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