Pathway for Fair and Scientific Rating to Solar Cars – challenge by IEC TC82 PT600 team for International Standardization

Kenji Araki, University of Miyazaki (JP)

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Testing, Modeling, Rating….

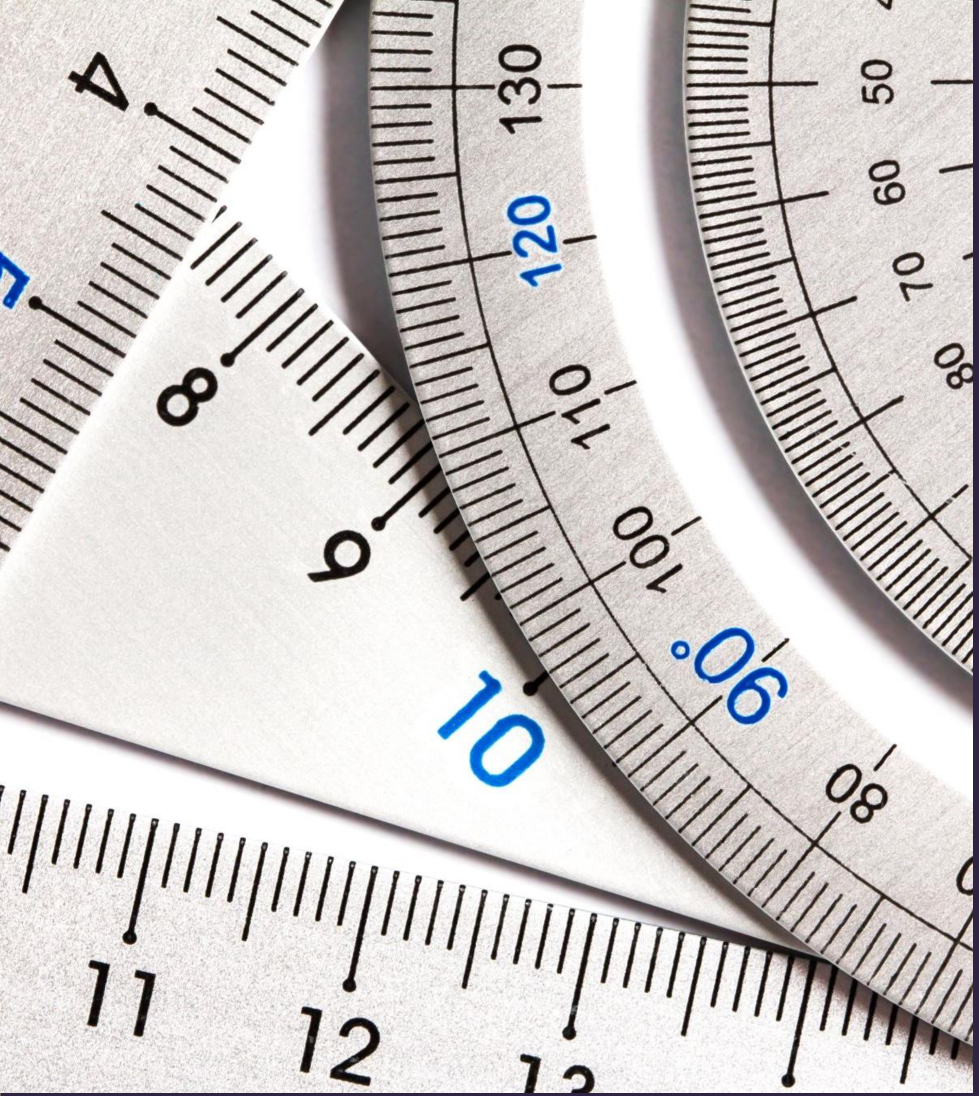
Testing nonplanar PVs → Modeling outdoor power → Energy rating

Including,

Curved PV:	Impact by the curved surface
	Performance
	Testing with reproducibility
Solar irradiance:	Non-uniform shading environment
	Arbitrary aperture orientation
Partial shading:	Non-uniform probability matrix

The PV standardization activities are done through voluntary contributions by scientists and engineers worldwide.

Many other contributors were involved behind the stage.

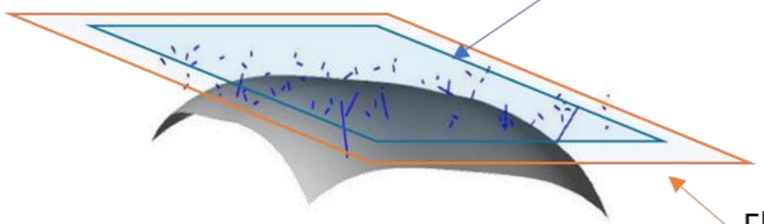


Why

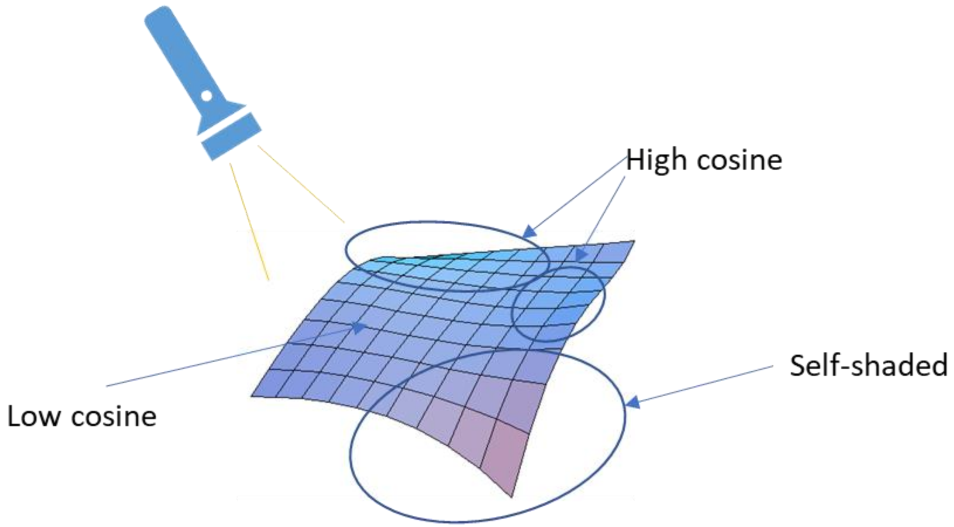
VIPV behaves differently

VIPV needs a new standardization

Why curved PV perform less?



1. Shrunk aperture
→ Less input power



2. Local cosine and self-shading loss
→ Mainly affects in mismatching loss

Typical PV calculation

Uniform hemispherical sky, no shadow, static and flat plane

PV anywhere

Non-uniform and frequently shading, non-planar PV, Moving

Parked in the sun
Inherent mismatching by a curved surface

Partial shading (Parking)
Inherent mismatching by a partial shading

Dynamic partial shading
The relative position of the partial shadow moves.

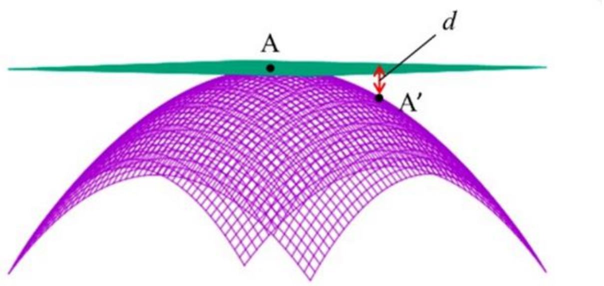
NEW APPROACH OVERVIEW

CALCULATION SHIFT

So, we need a calculation shift (1)

Arithmetic with Trigonometric Functions

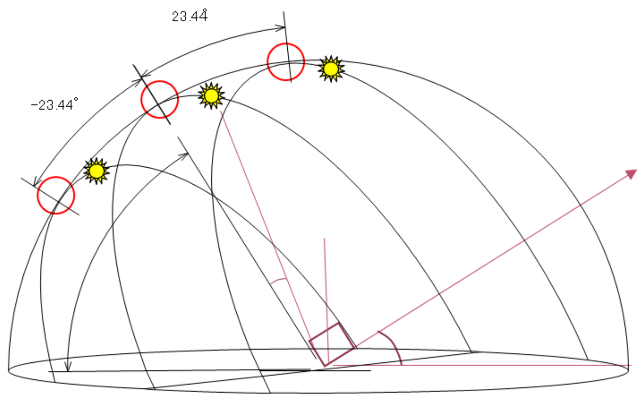
Vector Computations



$$d = \{\mathbf{P}(u^1 + \mathrm{d}u^1, u^2 + du^2)\} - \mathbf{P}(u^1, u^2)\} \cdot \mathbf{N}$$

So, we need a calculation shift (2)

Absolute ground coordinates



Local coordinates with 3D rotation

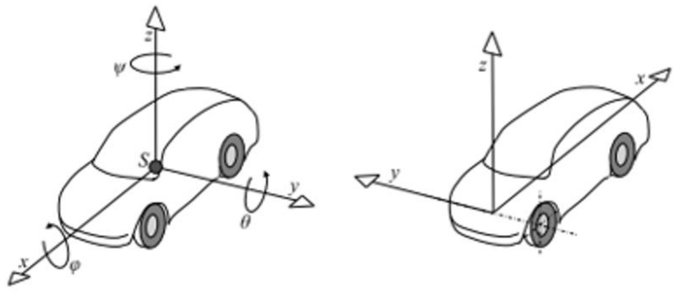


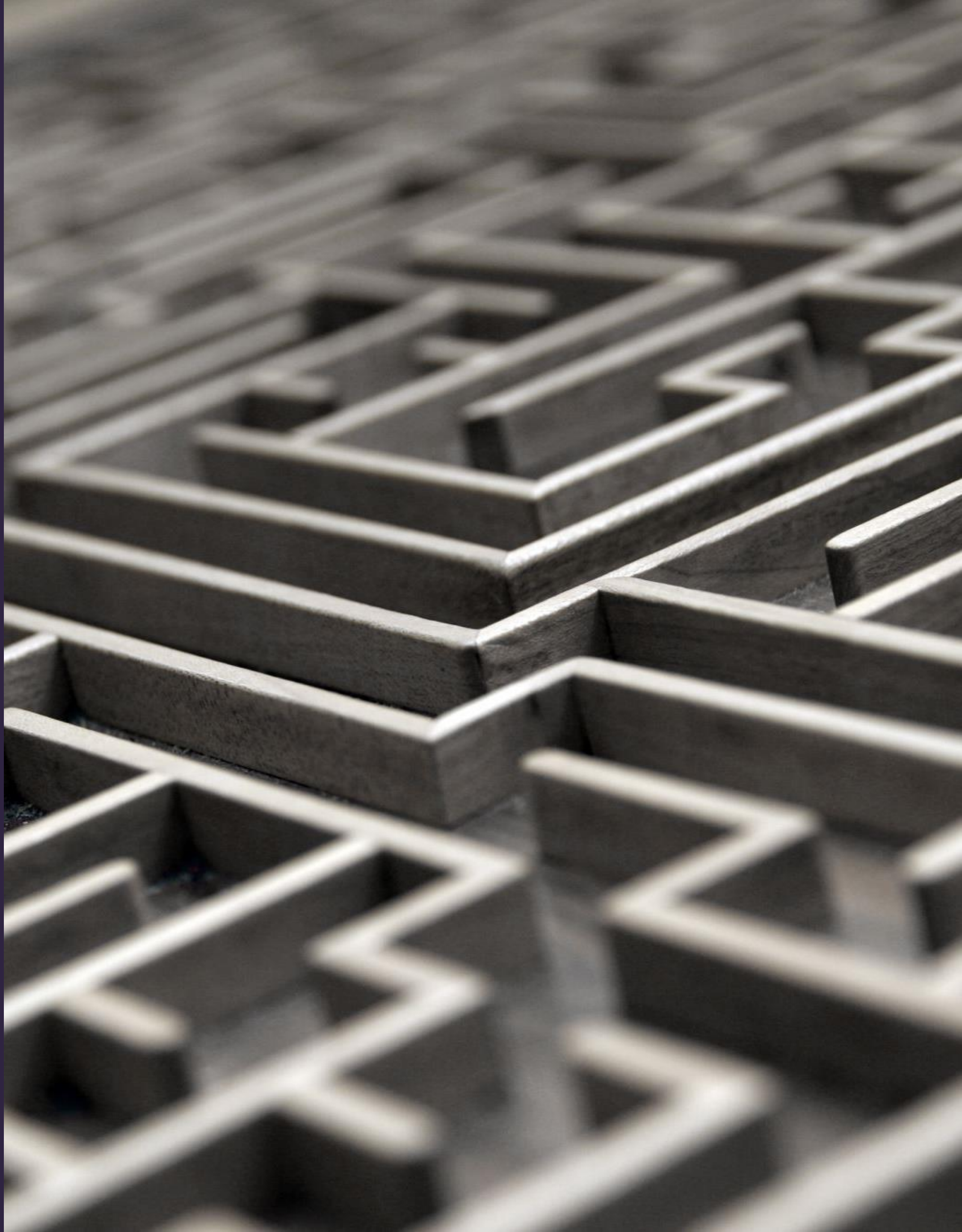
Bild 2.1: *Koordinatensystem entsprechend DIN 70000 (links) und in der Konstruktion angewendetes Koordinatensystem (rechts)*

Several other differences…

	Before calculation shift	After calculation shift
Basic math	Arithmetic with trigonometric functions	Vector computations
Coordinate system	Absolute ground coordinates	Local coordinates with 3D rotation
Sky model	Uniform hemisphere sky (Shading ratio - Scalar)	Non-uniform shading on hemisphere sky (Shading matrix - Matrix)
Partial shading	Time integration with weighting	Probabilities and expected values
Shape of PV cells and modules	Flat surface	Curved surface (Differential geometry)
Stress calculation	Bending load to a thin plate	Buckling by 3D bending (Differential geometry)
Ray orientation	Cosine	The inner product between the normal vector of the surface element and rays
IAM (Angular response)	IAM curve by the angle of the ray	4-Tensor

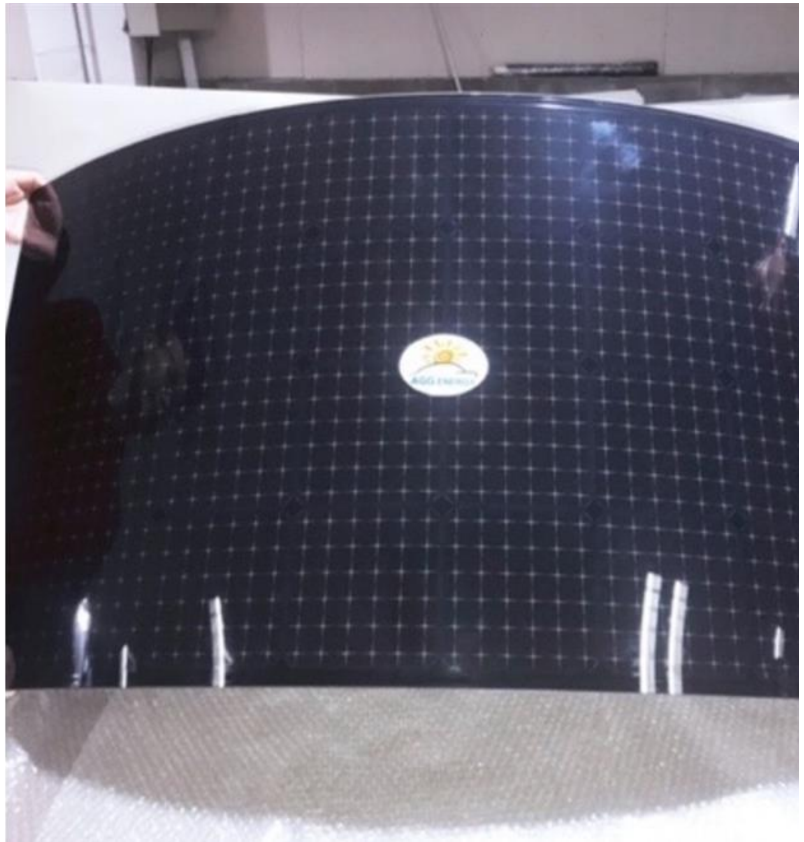
REPRODUCIBLE TESTING IN ANY WAY

THE SHOW MUST GO ON! WE NEED TO LOOK FOR A PRACTICAL COMPROMISE.



Testing is challenging

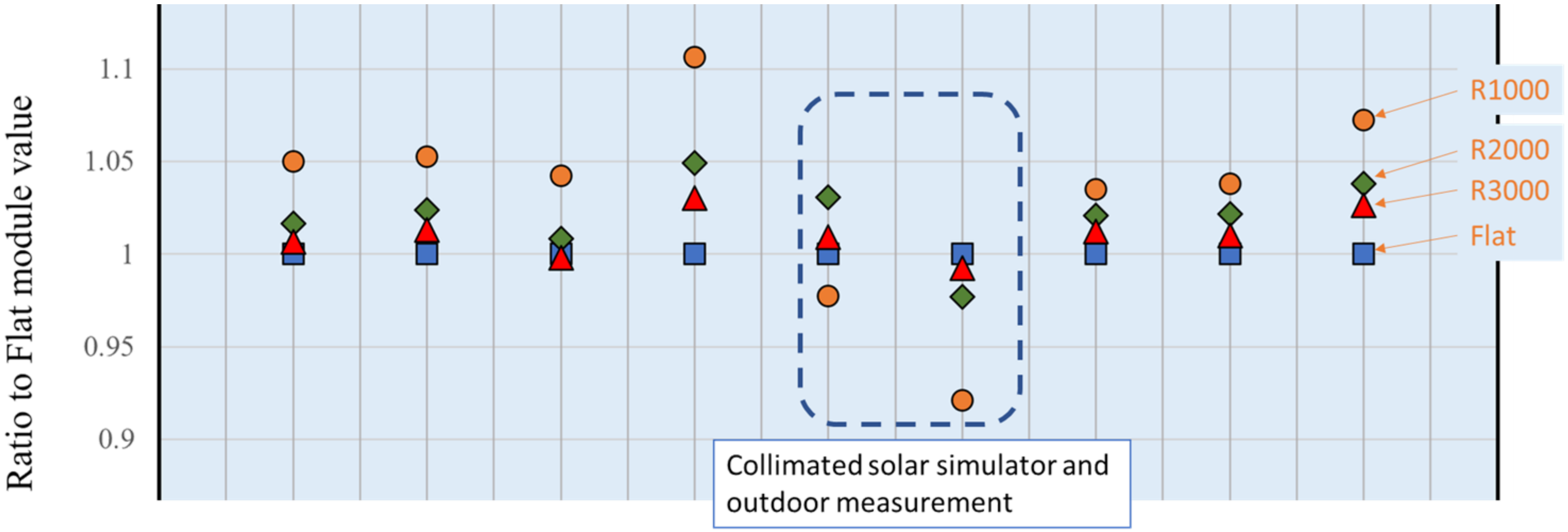
International round-robin tests by testing laboratories and research institutes in several rounds.



Special thanks to IEC TC82 and Nanjing AGG Energy.

Inherent measurement errors

Depending on the curvature, test results by testing laboratories for curved PV were not reproducible and accompanied by systematic error (plus bias except for collimated solar simulators).

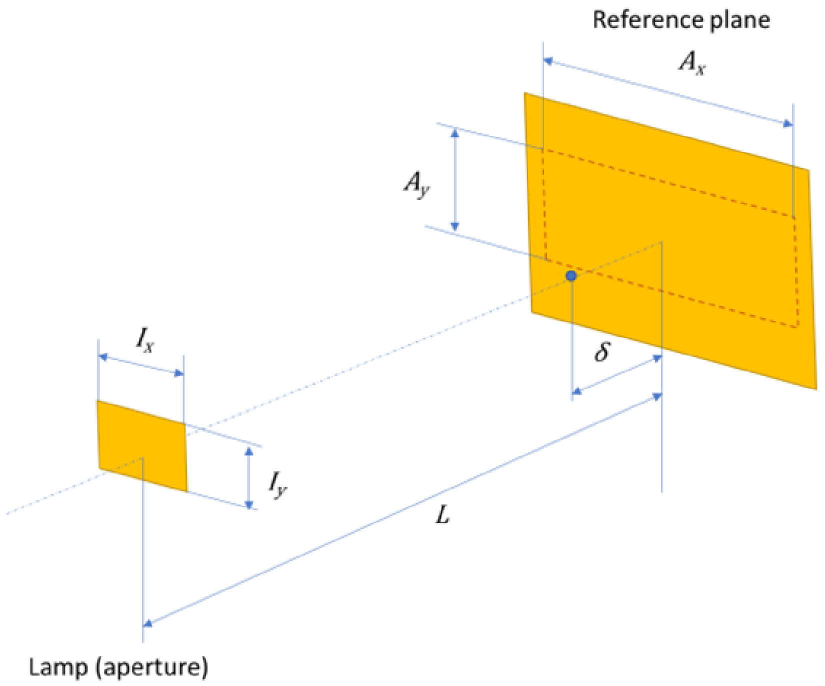


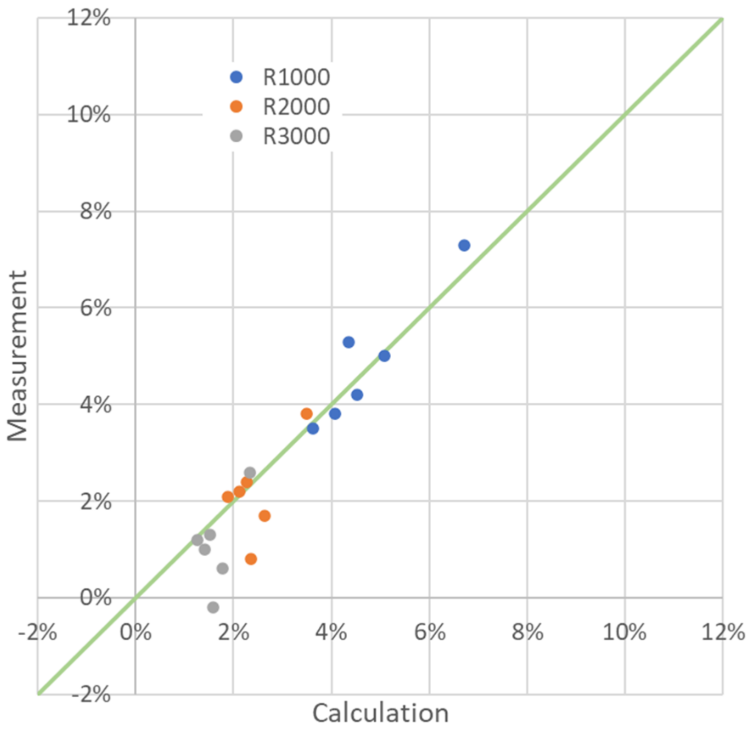
Note:

- It is a quick plot using rapid communications from testers. Some of the results differ from their final reports.
- Expecting a round-robin tester (researcher) make journal papers in a detailed analysis of the behavior of the curved PV.

Requirements for the solar simulators and constrains in curved PV modules

However, since the discussion would not proceed if the results were " in principle impossible to test," we began discussing **under what conditions the results would be accepted as test results.**



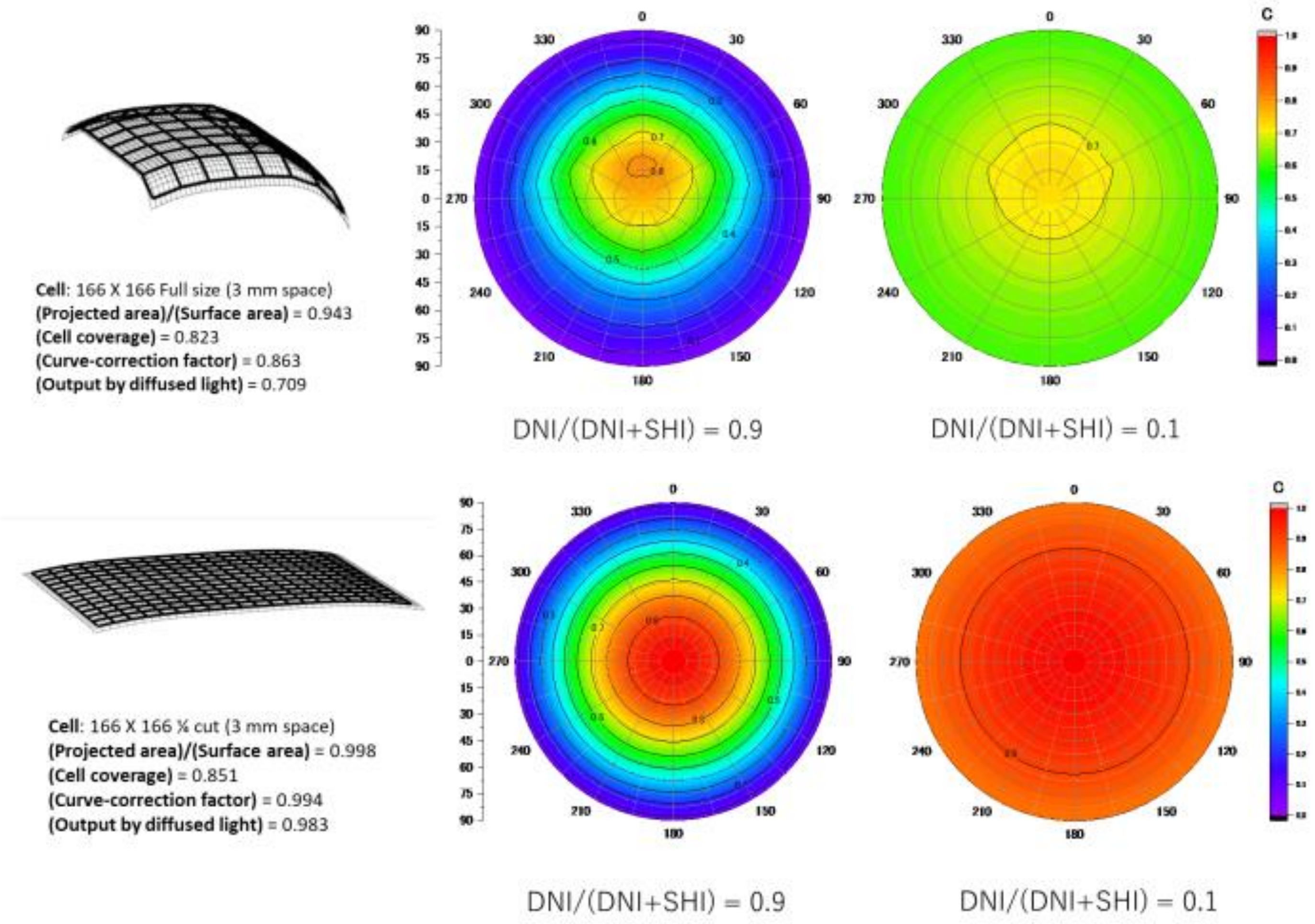


Another round of blind tests by testing laboratories worldwide is going on.

MODELING OUTDOOR POWER

USING THE TEST RESULTS

The power output is not a simple cosine factor for curved modules.

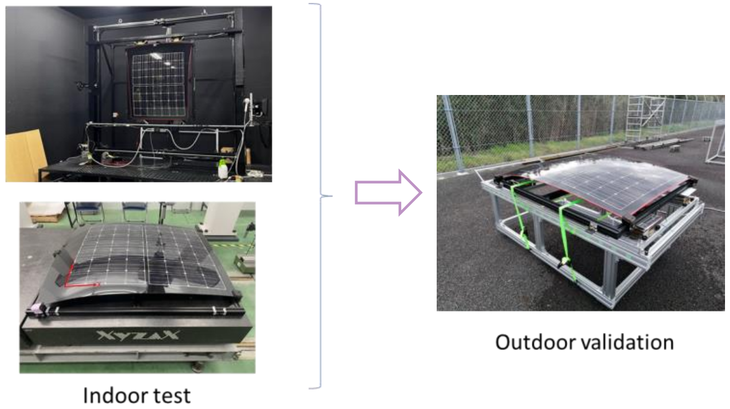


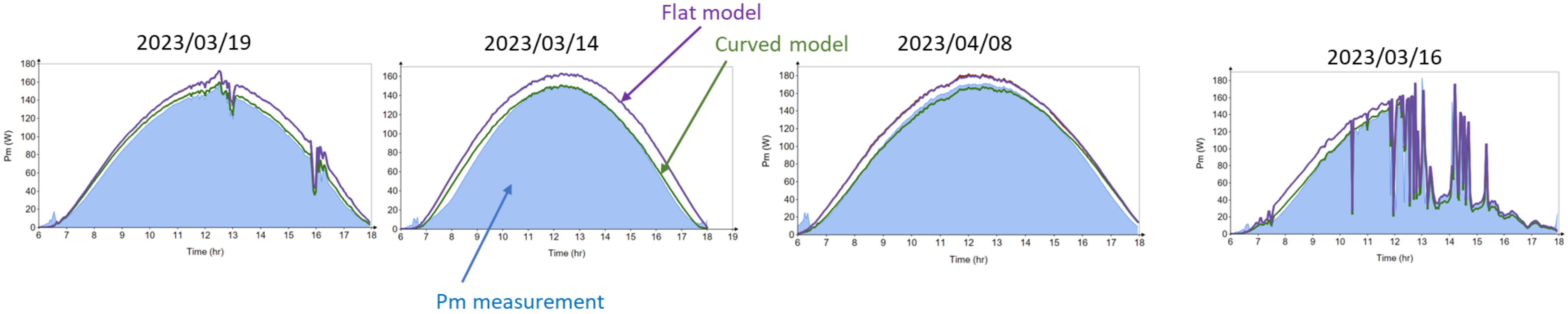
The weighting factor by the incident angle varies by the curve shape and function of the DNI/DHI ratio.

It is not axially symmetrical so that 2D expression is necessary (not a simple IAM).

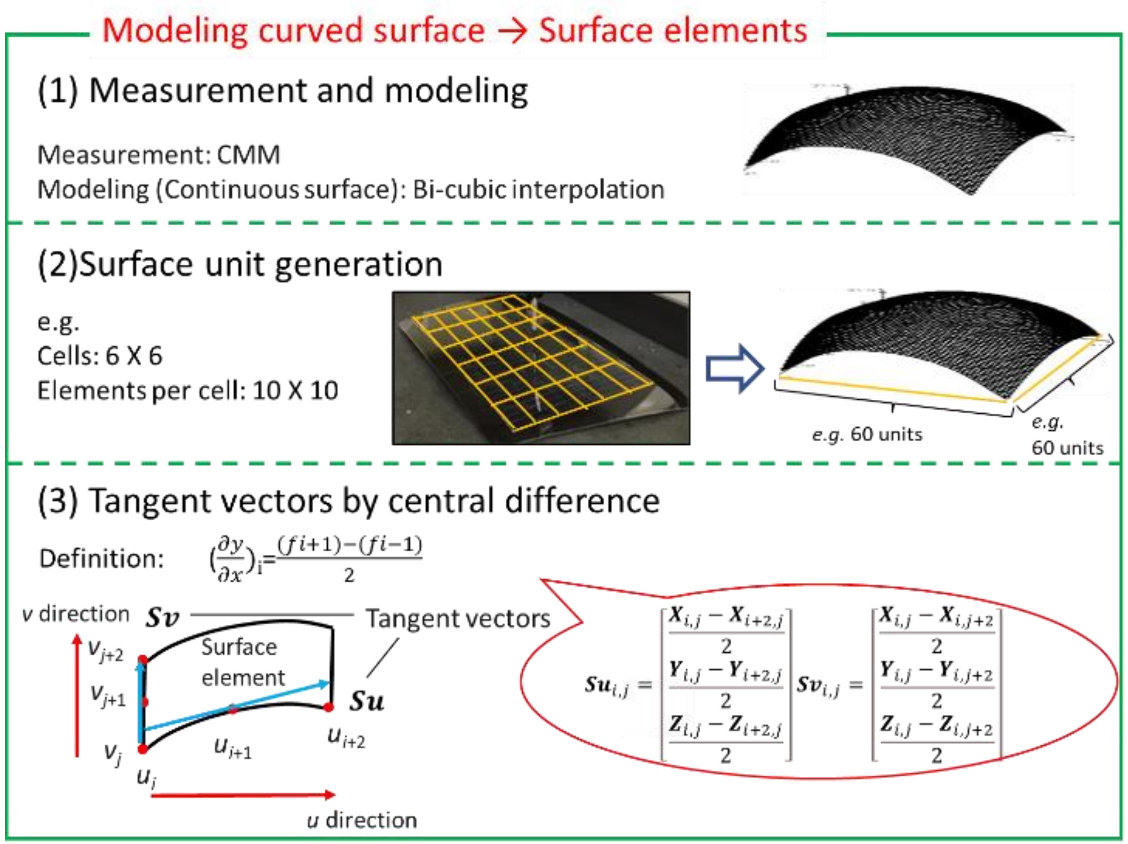
Flat PV: (Indoor test) = (Outdoor operation), in principle

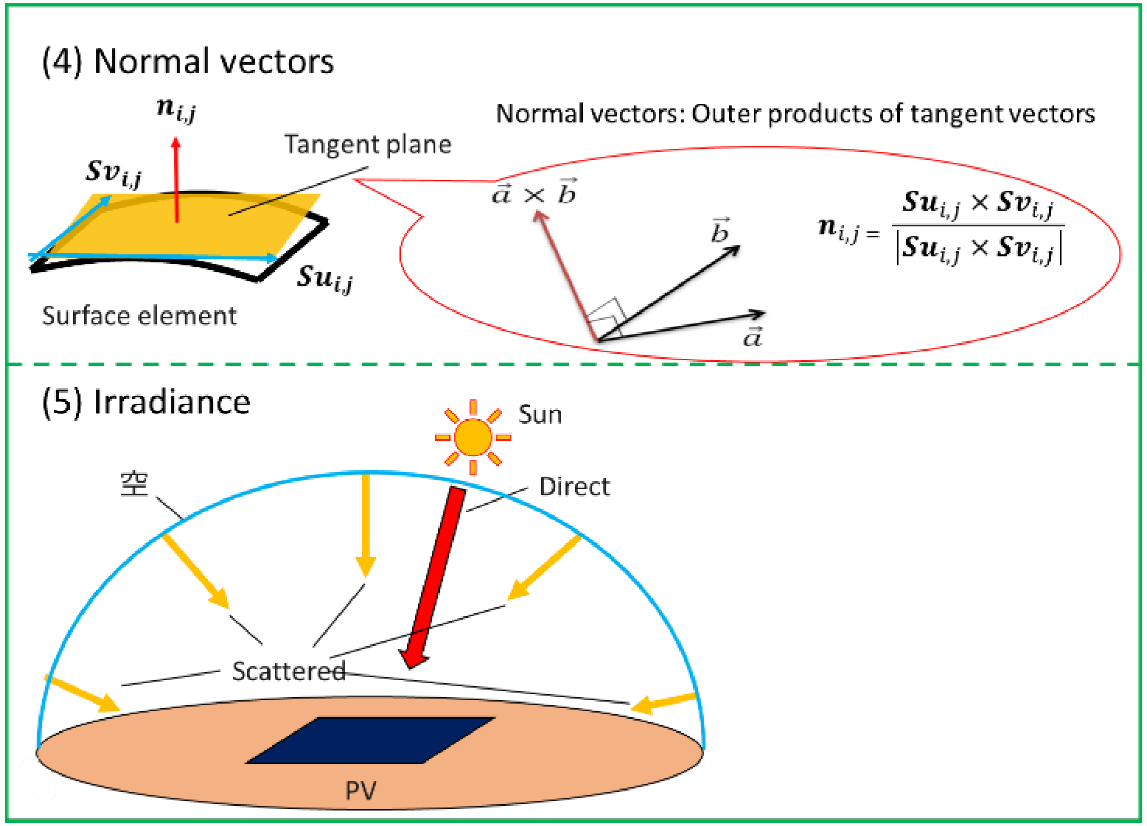
Curved PV: (Indoor test) ≠ (Outdoor operation), inherently



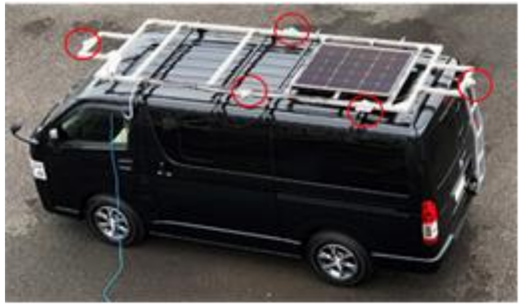


Non-planar PVs can be handled by vectors and matrices





5-axes measurements with redundancy of variation of irradiance environment



Lightly shaded zone

Medium shaded zone

Deep shaded zone

Orthogonal 5-axes validation is essential for a general model that meets entire seasons, sun height, and type of shading environment.

A few drive experiments often lead to biased validation affected by specific shading environment combined with limited sun-position. Redundant measurement (4-axes) helps avoid such misleading.

Binarization and 2D histogram

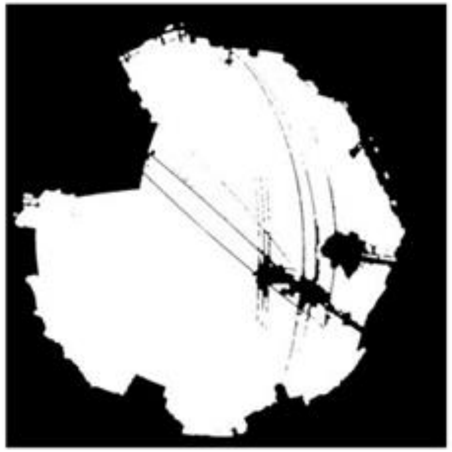
Original image (Gray-scale)

Not suitable to recognition of the shading objects.

1. Brightness of the building wall often more significant than sky.
2. Lens flare by the sun.
3. Spot noise by dirt.

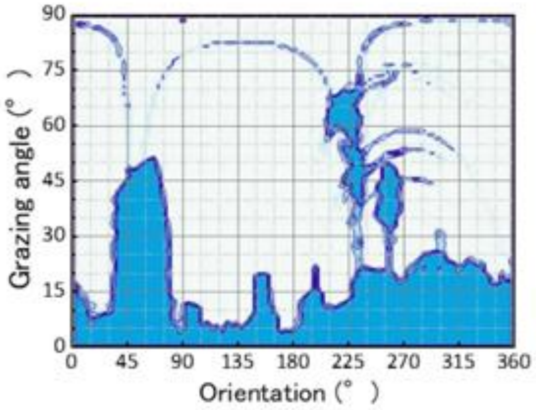
Filtered image

Enhancement difference between sky and shading objects. Removing image noises while keeping detailed structure (cables *etc.*)



Binarization

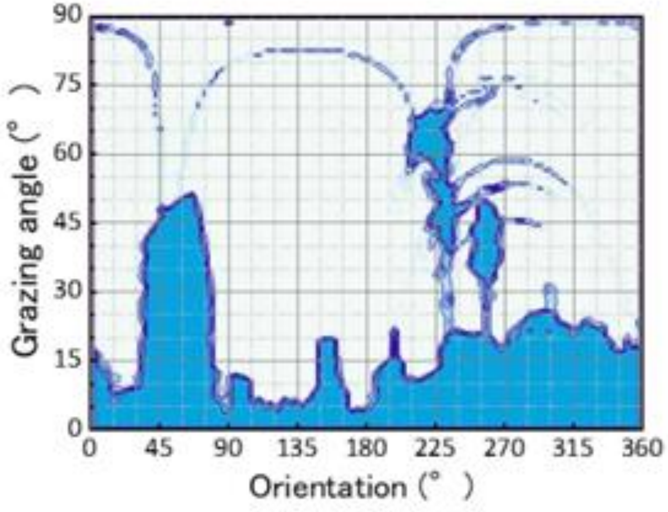
Shading object = 0, Sky = 1
It is numerically removing white islands inside the building (spot-like) generated by the side-effects of filtering.



Coordinate transformation

Generation of a discriminant matrix (shading probability) by 2D histogram.

Aperture matrix



$$E = \begin{pmatrix} E_{0,0} & E_{0,1} & \cdots & E_{0,88} & E_{0,89} \\ E_{1,0} & E_{1,1} & & E_{1,88} & E_{1,89} \\ \vdots & & \ddots & \vdots & \\ E_{88,0} & E_{88,1} & \cdots & E_{88,88} & E_{88,89} \\ E_{89,0} & E_{89,1} & & E_{89,88} & E_{89,89} \end{pmatrix}$$

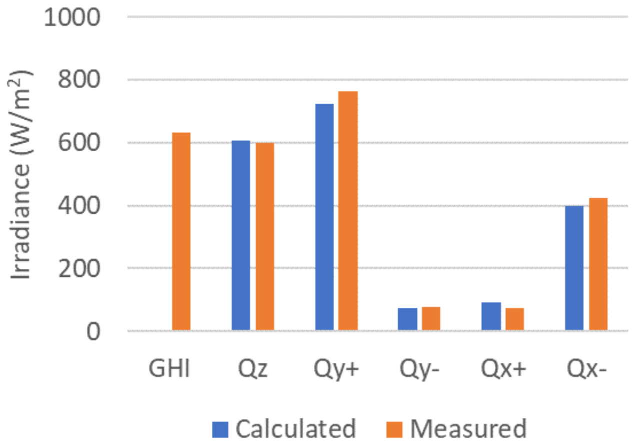
The bin of Elevation angles

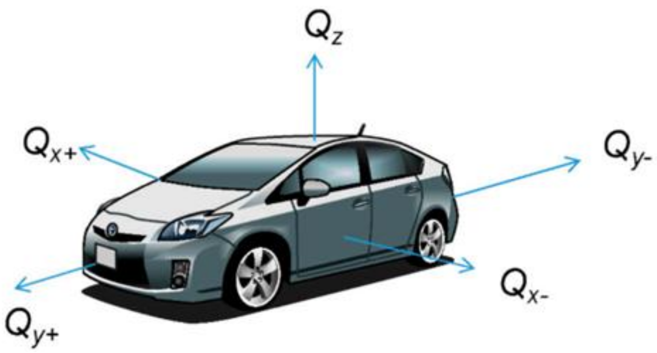
0° - 1°
1° - 2°
⋮
88° - 89°
89° - 90°

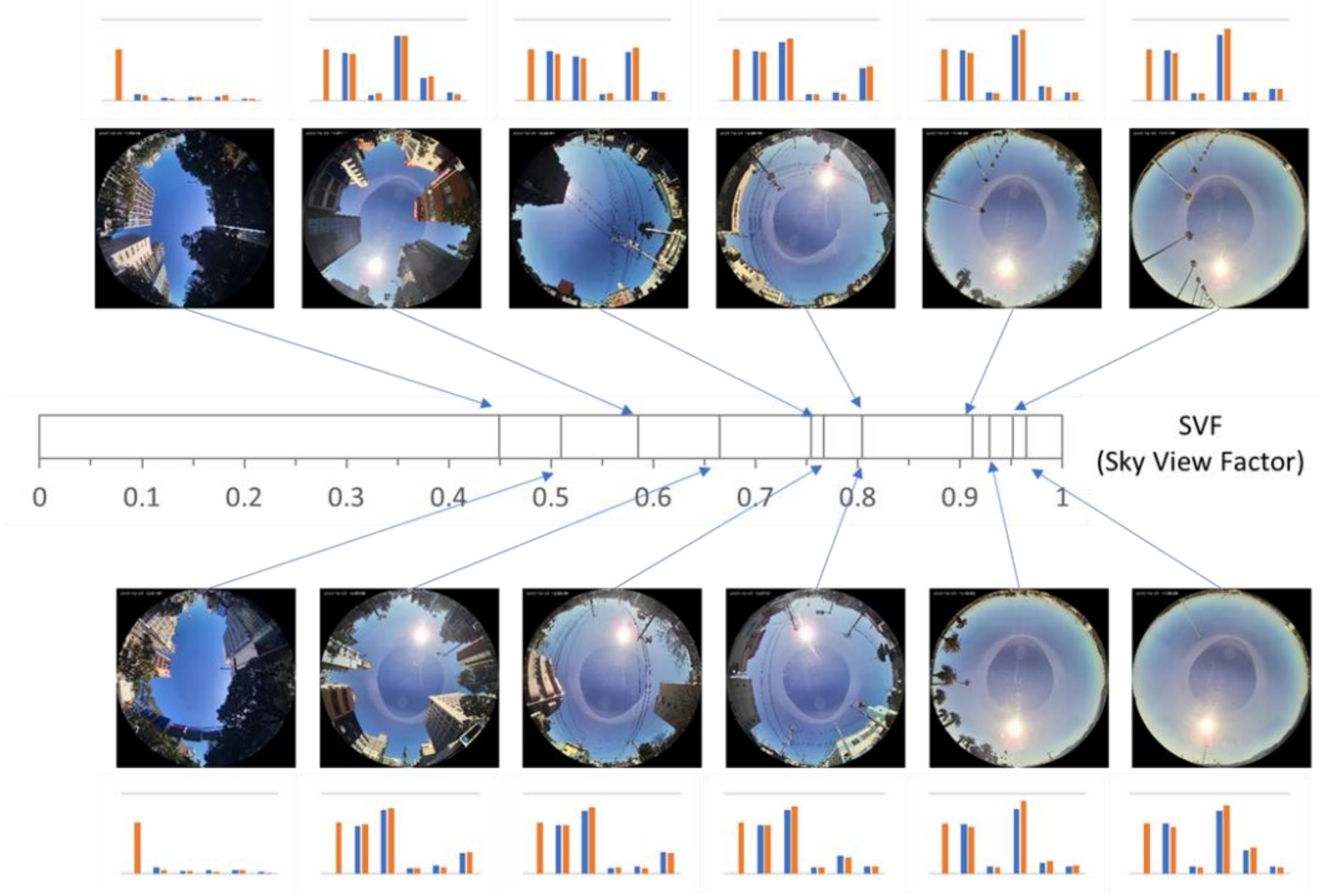
The bin of Orientation angles

0° - 4°
4° - 8°
......
352° - 356°
356° - 360°

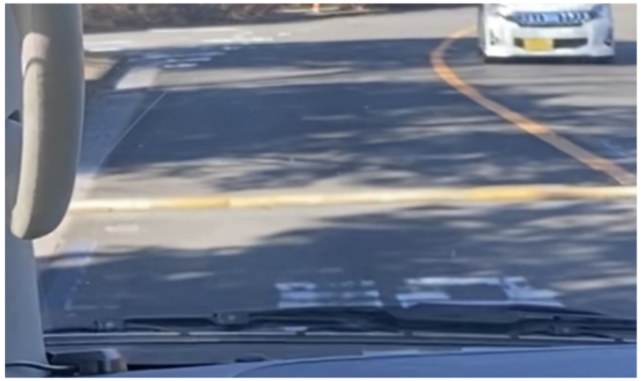
The real-world ≠ Uniform irradiance, but it can be predicted by advanced calculations





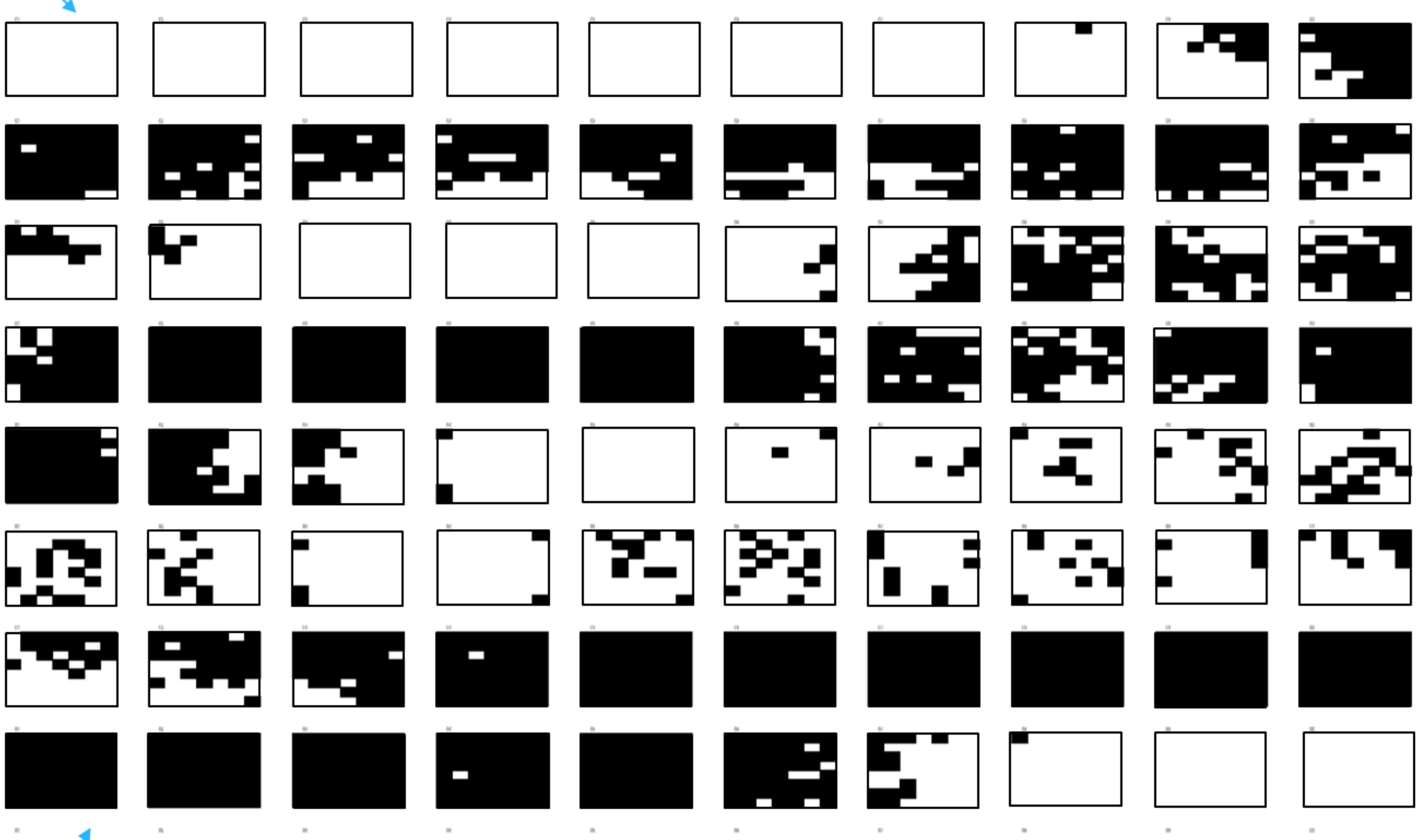


Non-uniformity is frequently observed onto the PV modules – Partial shading



Actual shading condition

NO shading



100% shading

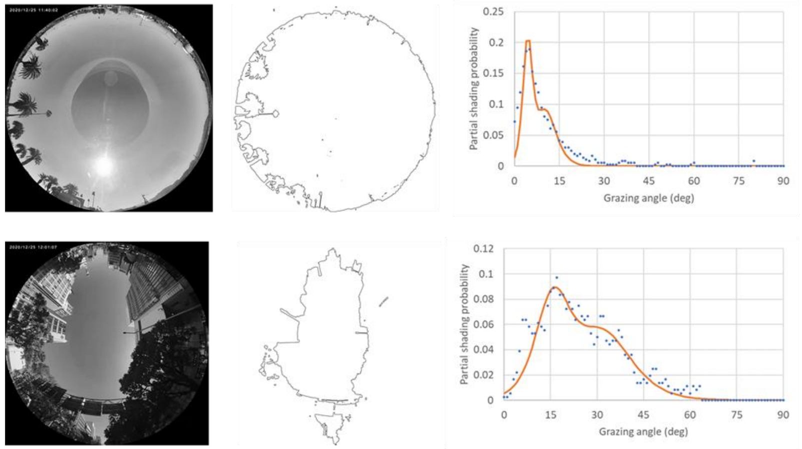
Partial/dynamic shading impacts differently by where the car parks or drives.

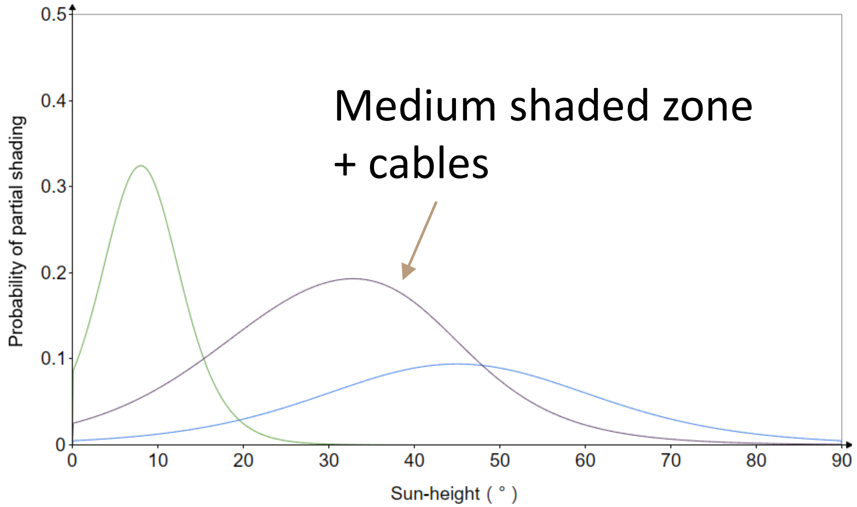
Parked in the sun
Inherent mismatching by a curved surface

Partial shading (Parking)
Inherent mismatching by a partial shading

Dynamic partial shading
The relative position of the partial shadow moves.

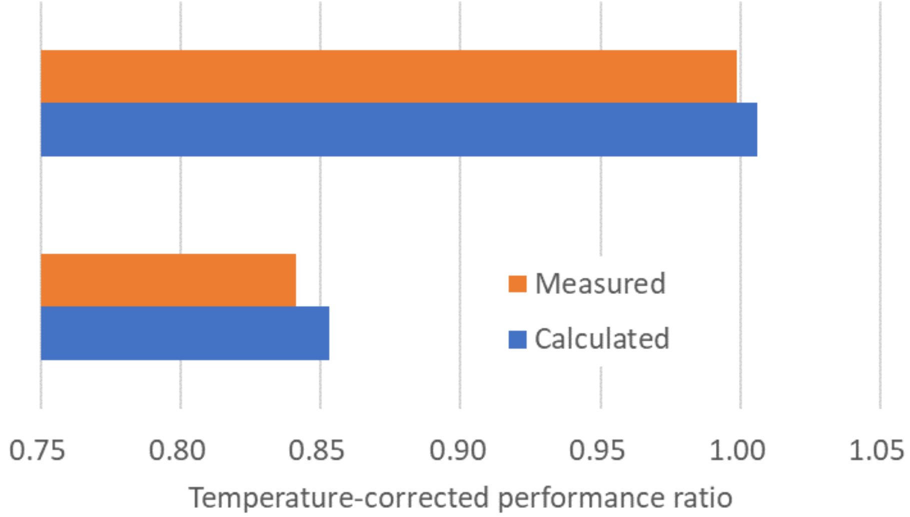
Modeling and validating performance ratio under partial shading





Validation by
performance ratio

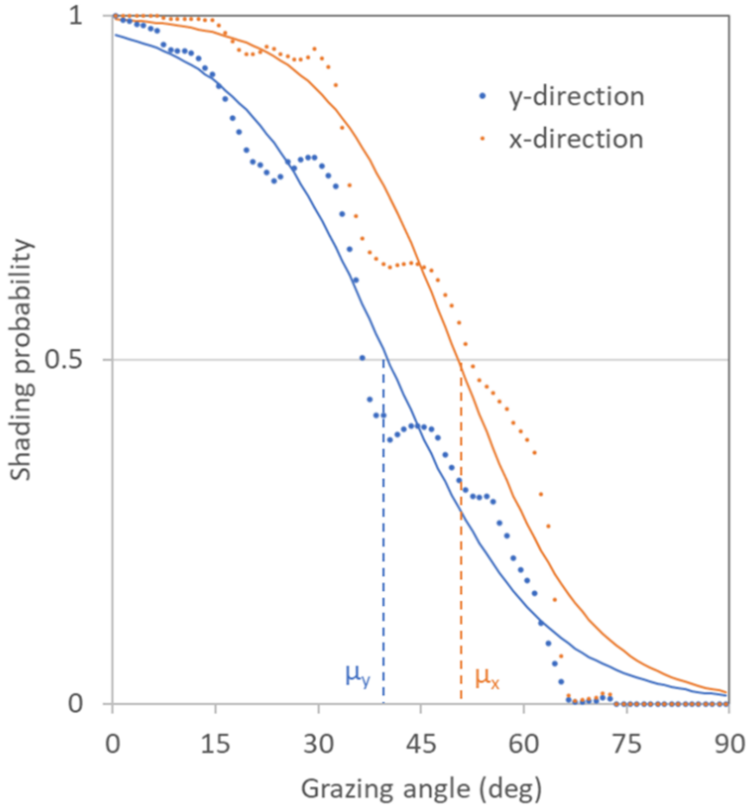
Medium shaded zone
with power cables

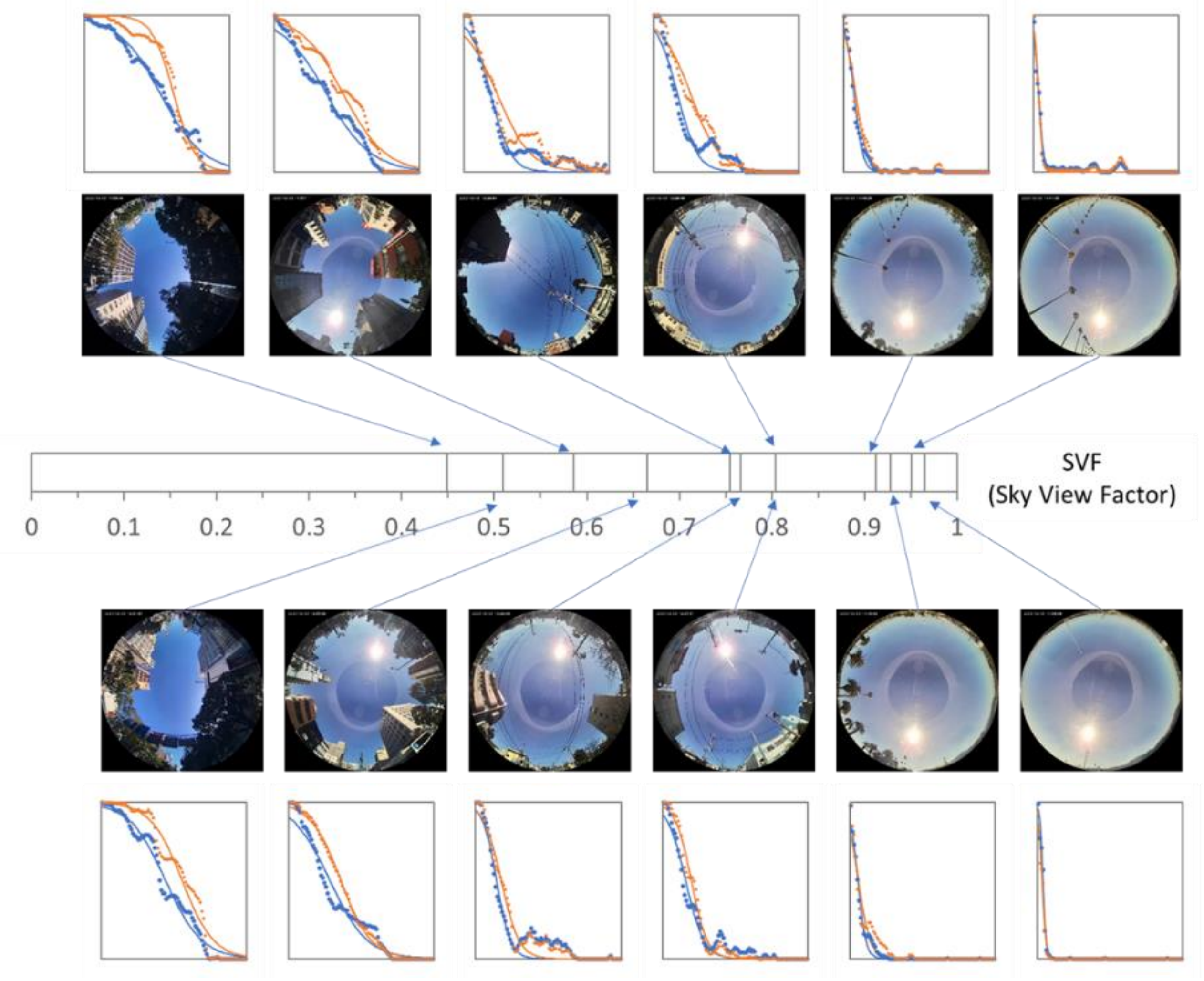


ENERGY RATING

SIMPLE AND TRANSPARENT CALCULATION FOR EVERYONE

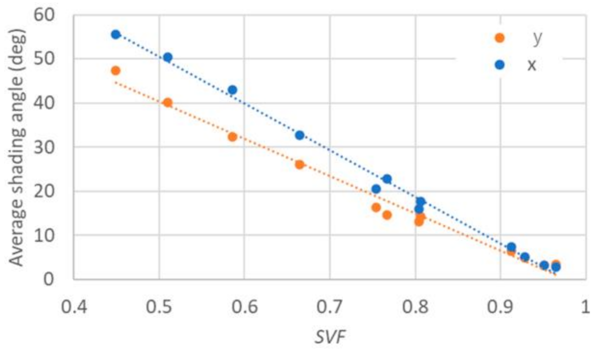
Shading probability curves

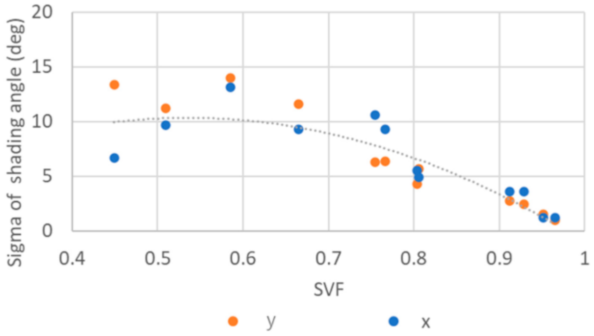




Distribution curve functions

$$F(x) = 1 - \frac{1}{1 + \exp\left(-\frac{x - \mu_s}{s}\right)}$$





Lightly shaded zone

Medium shaded zone

Deep shaded zone

Zones and orientations		SVF	μ_s	s
Lightly shaded zone	+Y and -Y	0.9	9°	3°
	+X and -X		7°	
Medium shaded zone	+Y and -Y	0.7	30°	9°
	+X and -X		24°	
Deep shaded zone	+Y and -Y	0.5	50°	10°
	+X and -X		40°	

Shading probability for energy rating calculation

Annual irradiation of the site

↓

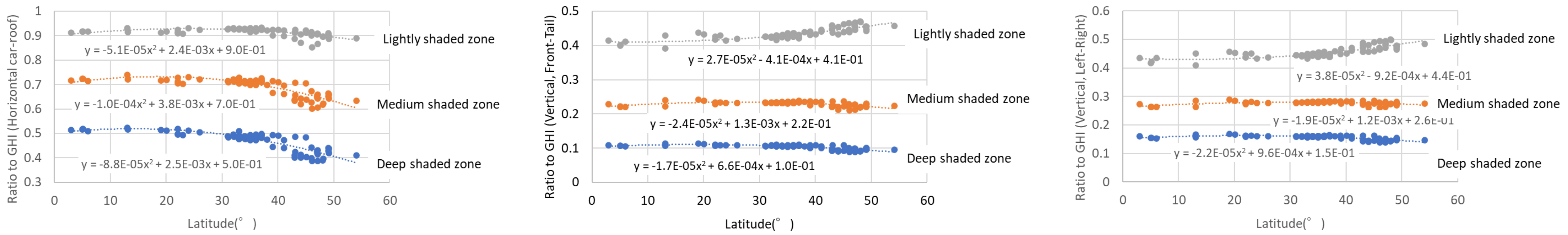
Zone correction

↓

VIPV irradiation

(VIPV irradiation) = (Annual irradiation of the site) ·(Zone correction)

Calculation of the correction factor of each zone as a function of latitude.



Solar irradiation rating for VIPV given by a spreadsheet

Annual irradiation of the site → GHI at Tokyo : 1369 kWh/m^2; Latitude at Tokyo : 35.7°

↓

Zone correction → Coefficients : Parabolic function of the latitude; GHI on each plane : (Correction factor) ×(GHI on the ground)

↓

VIPV irradiation

↓

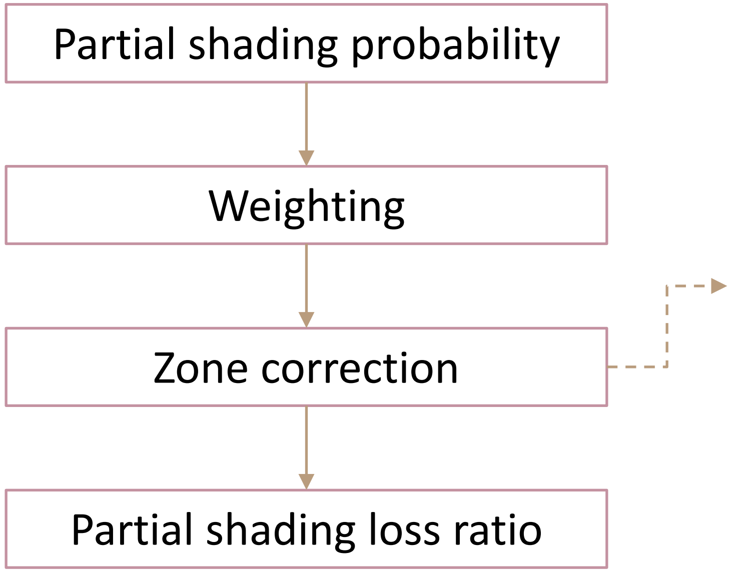
For example, GHIs of the car roof are;

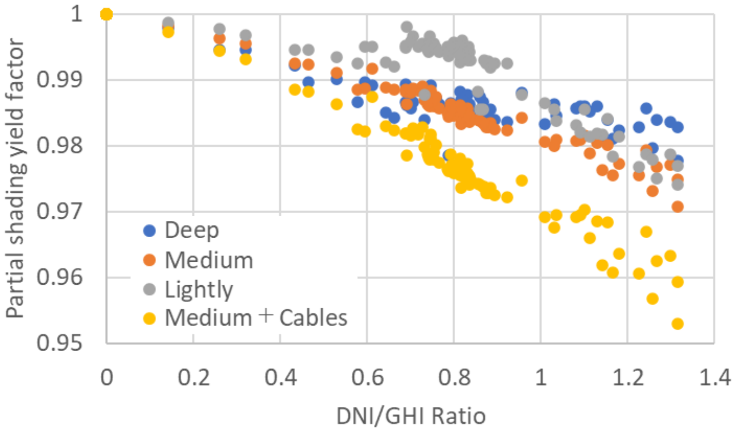
Lightly shaded zone: 1262 kWh/m^2
Medium shaded zone: 961 kWh/m^2
Deep shaded zone: 654 kWh/m^2

GHI (kWh/m2)	1369
Latitude (deg)	35.7

		Coefficients			Correction factor	Irradiance (kWh/m2)
		a	b	c		
Lightly shaded zone	Car-roof	-5.11E-05	2.44E-03	9.00E-01	0.92	1262
	Car-side (Front-tail)	3.78E-05	-9.19E-04	4.36E-01	0.45	617
	Car-side (Left-right)	2.65E-05	-4.13E-04	4.13E-01	0.43	591
Medium shaded zone	Car-roof	-1.02E-04	3.76E-03	6.98E-01	0.70	961
	Car-side (Front-tail)	-1.86E-05	1.16E-03	2.62E-01	0.28	383
	Car-side (Left-right)	-2.45E-05	1.28E-03	2.18E-01	0.23	318
Deep shaded zone	Car-roof	-8.80E-05	2.48E-03	5.02E-01	0.48	654
	Car-side (Front-tail)	-2.19E-05	9.63E-04	1.52E-01	0.16	217
	Car-side (Left-right)	-1.75E-05	6.58E-04	1.04E-01	0.11	144

Partial shading probability (1): Energy loss by partial shadings





Partial shading factor on the car roof (Single-string module)

For multiple strings, the factor pf(N) is calculated as;

$$pf(N) = 1-(1-pf(1))/N$$

where

N: Number of strings

Unlike simple shading, the partial shading factor is affected by direct irradiation and is a weak function by latitude.

Partial shading probability (2): Spreadsheet solution

Partial shading probability

↓

Weighting

↓

Zone correction

↓

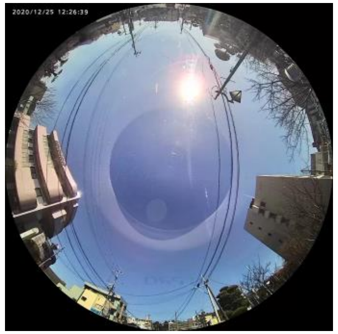
Partial shading loss ratio

Besides the basic category, power cables along streets substantially affect partial shading loss.

DNI (kWh/m^2)	1474
GHI (kWh/m^2)	1282
DNI/GHI	0.870

		Coefficients			Loss factor
		a	b	c	
Lightly shaded zone	Car-roof	-2.3E-02	1.0E-02	-8.0E-03	0.991
	Car-side (Front-tail)	-1.9E-02	3.0E-03	-1.1E-02	0.988
	Car-side (Left-right)	-2.3E-02	5.0E-03	-1.3E-02	0.987
Medium shaded zone	Car-roof	-6.0E-03	-1.1E-02	-1.8E-02	0.984
	Car-side (Front-tail)	-7.0E-03	-1.3E-02	-1.6E-02	0.983
	Car-side (Left-right)	-5.0E-03	-1.4E-02	-1.9E-02	0.983
Deep shaded zone	Car-roof	4.6E-05	-1.4E-02	-1.6E-02	0.986
	Car-side (Front-tail)	-1.0E-03	-1.5E-02	-1.7E-02	0.985
	Car-side (Left-right)	0.0E+00	-1.2E-02	-1.3E-02	0.989
Medium shaded zone + Cables	Car-roof	-8.0E-03	-2.1E-02	-2.9E-02	0.975
	Car-side (Front-tail)	-1.5E-02	-2.3E-02	-2.4E-02	0.969
	Car-side (Left-right)	-7.0E-03	-1.9E-02	-2.6E-02	0.977

Medium shaded zone



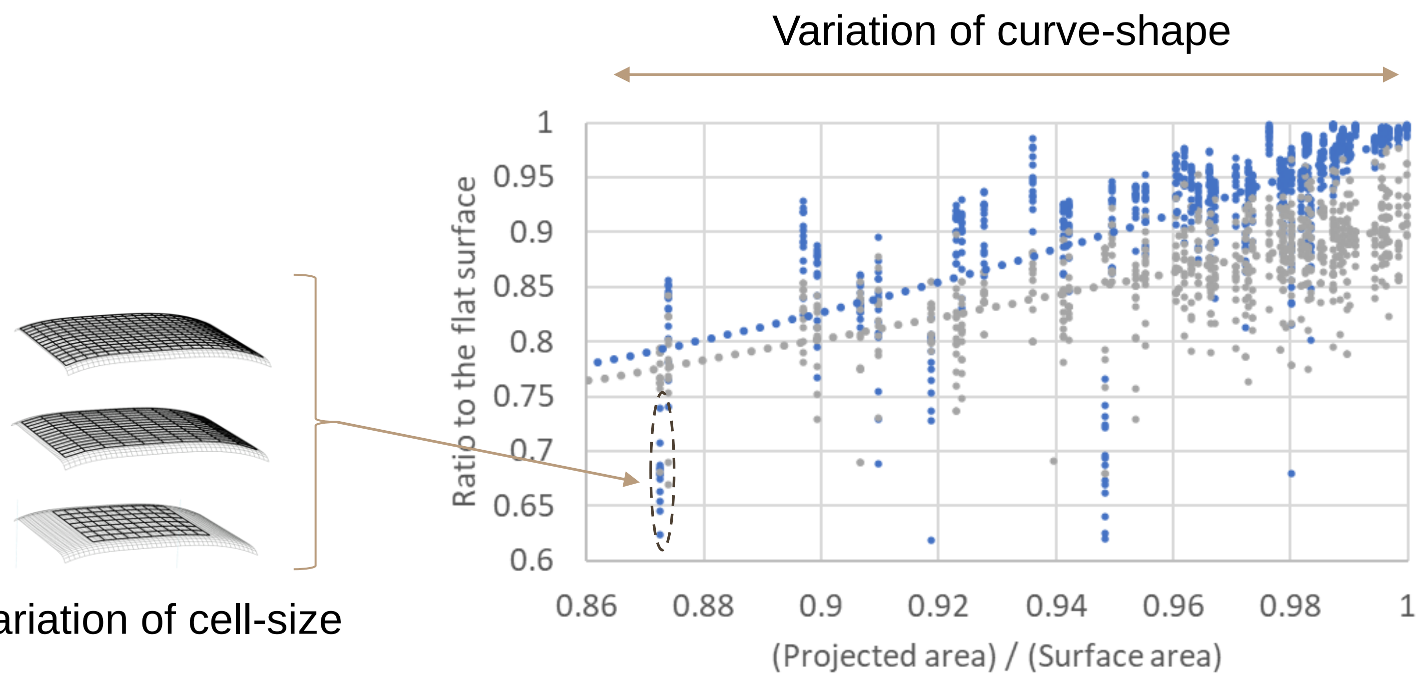
Medium shaded zone with power cables

Not yet!

We need a direct test method for 2D angular response to curved module

Besides the basic category of the shading objects, the following factors substantially affect the energy yield by the inherent mismatching loss by curved surface:

- Curve-shape
- Size of solar cells
- Number of strings
- Latitude
- DNI/GHI

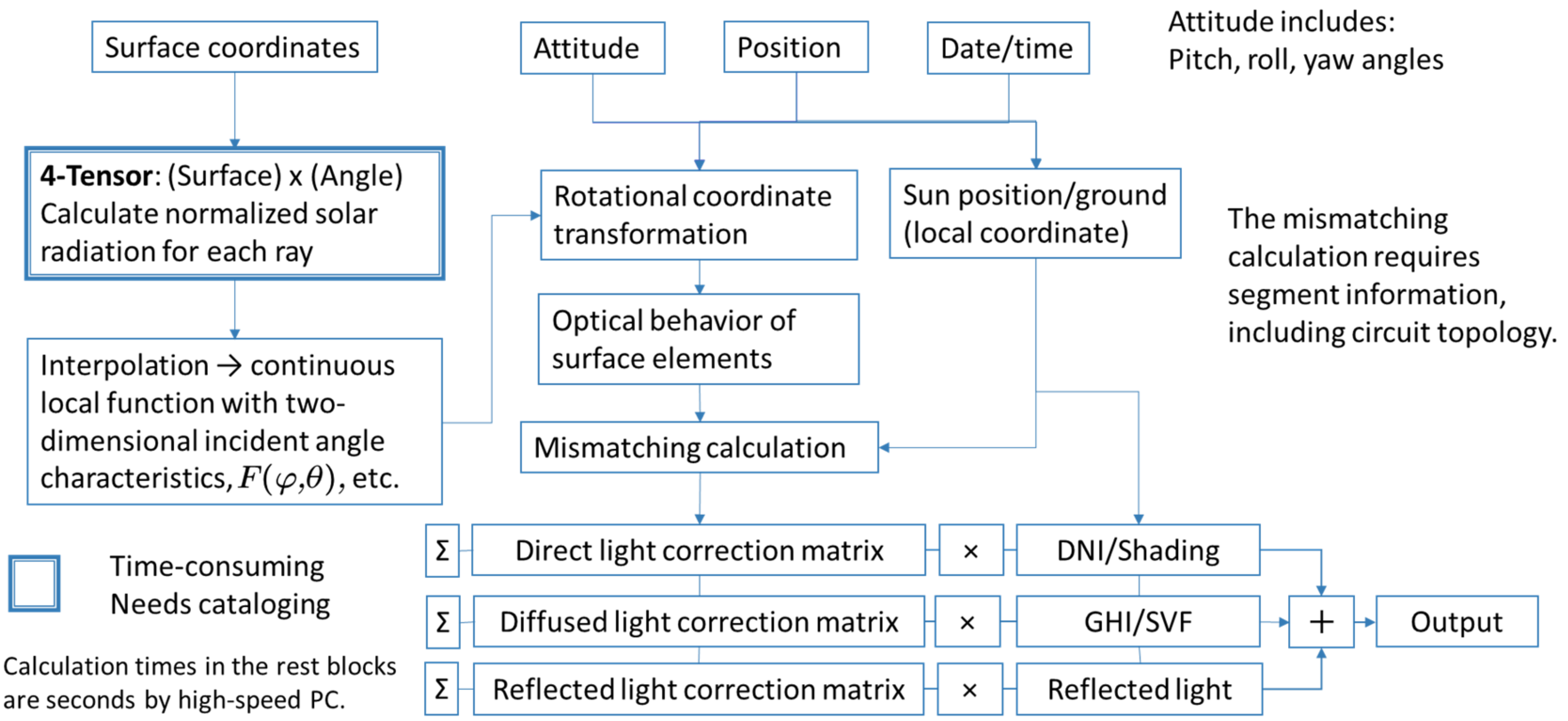


- It is affected by the shading zone and latitude.
- Calculated by (61 curved surfaces) X (14 cell sizes)
- The number of strings varies by cell size (ex., 2 for 166 full-size and 33 for 166 1/16 cut).

ADVANCED COMPUTATION FOR PV PERFORMANCE

AS AN OUTCOME OF OUR ACTIVITIES

Interaction to the curved surface can be calculated by introducing a 4-tensor



Structure of the nested **Matrix** (4-tensor) as the key parameter for modeling non-uniform shading environment

$$k = 0..NN-1, l = 0..NN-1$$

Index of ray angles.

$$i = 0..N-1, j = 0..N-1$$

Index of surface elements of the curved surface.

$$\varphi_k = 0° + \frac{k \cdot 360°}{NN}, \theta_l = 0° + \frac{l \cdot 90°}{NN}$$

Vector of ray angles (two parameters).

$$MM = \begin{bmatrix} M_{0,0} & M_{0,1} & M_{0,2} & & M_{0,l} & & M_{0,NN-1} \\ M_{1,0} & M_{1,1} & M_{1,2} & \cdots & M_{1,l} & \cdots & M_{1,NN-1} \\ M_{2,0} & M_{2,1} & M_{2,2} & & M_{2,l} & & M_{2,NN-1} \\ \vdots & \vdots & \vdots & \ddots & & & \\ M_{k,0} & M_{k,1} & M_{k,2} & & M_{k,l} & \cdots & M_{k,NN-1} \\ \vdots & \vdots & \vdots & \cdots & \vdots & \ddots & \vdots \\ M_{NN-1,0} & M_{NN-1,1} & M_{NN-1,2} & & M_{NN-1,l} & \cdots & M_{NN-1,NN-1} \end{bmatrix}$$

Irradiance ratio to plane surface on each ray used for irradiance calculation.

$$M_{k,l} = \begin{bmatrix} m_{0,0} & m_{0,1} & m_{0,2} & & m_{0,j} & & m_{0,N-1} \\ m_{1,0} & m_{1,1} & m_{1,2} & \cdots & m_{1,j} & \cdots & m_{1,N-1} \\ m_{2,0} & m_{2,1} & m_{2,2} & & m_{2,j} & & m_{2,N-1} \\ \vdots & \vdots & \vdots & \ddots & & & \\ m_{i,0} & m_{i,1} & m_{i,2} & & m_{i,j} & \cdots & m_{i,N-1} \\ \vdots & \vdots & \vdots & \cdots & \vdots & \ddots & \vdots \\ m_{N-1,0} & m_{N-1,1} & m_{N-1,2} & & m_{N-1,j} & \cdots & m_{N-1,N-1} \end{bmatrix}$$

Irradiance ratio to plane surface on each surface elements (nested to above matrix and used for power generation calculation).

$$I_{k,l} = mean(M_{k,l})$$

Relative irradiance to the plane surface.

Examples of PV applications that require advanced computation.

https://m3systems.eu/en/haps-in-addition-to-cospas-sarsat-for-search-and-rescue-operations/

Advanced analysis on BIPV

Complexed curved surfaces in various mobilities

Wavy PV arrays, installed in gorges, on the sloped surface, w/ tree shadings, etc.,

All applications are now researched by the University of Miyazaki (JP).

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This work was the R&D results of the NEDO project, and it is utilized in the standardization project for VIPV (PT600).

We are University of Miyazaki (JP).

4 km to surfin’ and beach running
https://www.aotai.gr.jp/photo/index.html

3 km to trail running (10 km-long gorge)
https://www.miyazaki-city.tourism.or.jp/spot/10134

Excellent foods after research works
Champion Beef 2019 - 2022
https://www.ecozzeria.jp/events/special/nikufesta0124.html