

Glare Prediction for Photovoltaic Panels with Different Reflectance Characteristics: BRDF Estimation and Modeling Using a Simplified Method

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Motivation and purpose

- In recent years, the installation of solar panels on buildings has been promoted as part of efforts to curb global warming and advance energy policy.
- In April 2025, the Tokyo Metropolitan Government enacted an ordinance requiring major homebuilders and similar firms to install solar panels on all newly constructed houses.

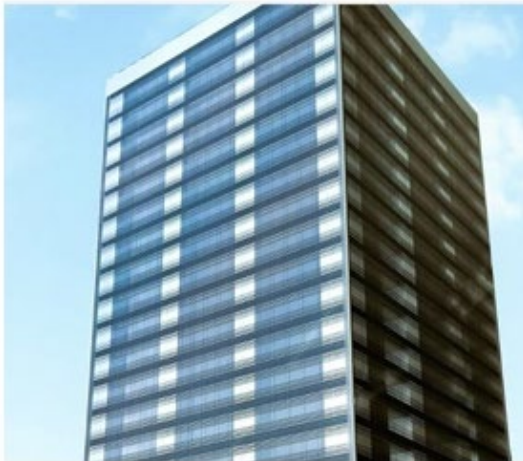


Photo by Kindel Media via Pexels

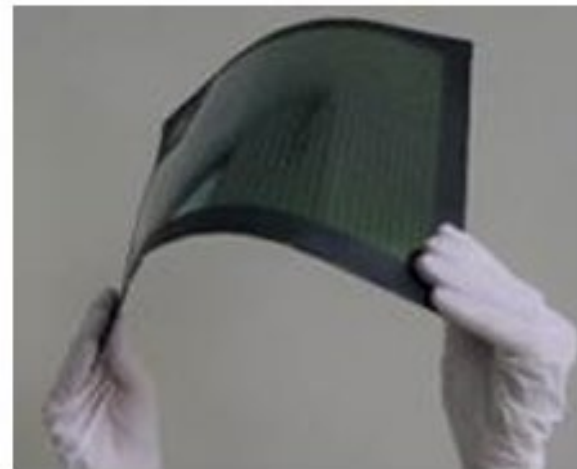
⇒ Increasing installation of solar panels on residential buildings and across urban areas.

Motivation and purpose

- Building-integrated photovoltaics (BIPV) attract attention as a technology well-suited to dense urban environments, because—unlike conventional rooftop-mounted solar panels—they can be installed on many more parts of a building's envelope.
- Perovskite solar cells are lightweight and adaptable to curved surfaces, and they are positioned in national energy policy as a next-generation photovoltaic technology.



BIPV



Perovskite solar cells

Source: METI, *Strategy for Next-Generation Solar Cells*, Nov. 2024, p.13
Images: Panasonic Holdings Corp. / Toshiba Corp.

Motivation and purpose

Concerns about reflection-induced glare (glare caused by reflected light) associated with the installation of solar panels



Example of reflected light from solar panels



Photo: Danilo Marcelino / Pexels

Concerns about glare experienced by pedestrians

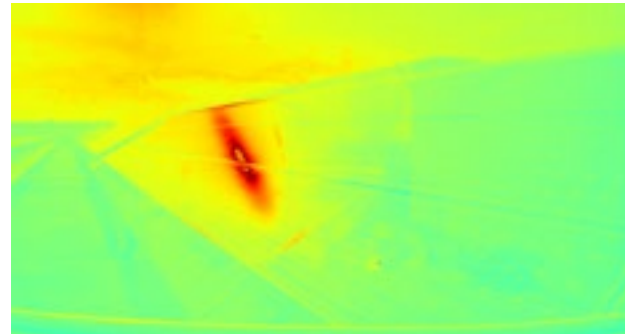
Advance glare prediction and assessment are essential considerations for maintaining a favorable visual environment.

Motivation and purpose

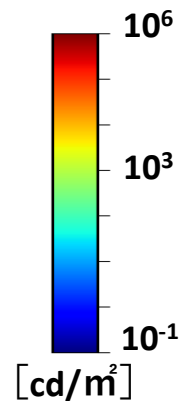
- Anti-reflection coating on the surface of solar panels
- While the coating reduces overall reflectance (by roughly 2–4 %), it also introduces surface scattering.



Solar panel reflection



Luminance image of solar panel reflection



Measurement of reflection characteristics is necessary to clarify the factors that generate reflection-induced glare and to evaluate glare accurately.

Motivation and purpose

The purpose is
to accurately reproduce the reflections from solar panels !



Accurately measure the
reflection characteristics of
solar panels

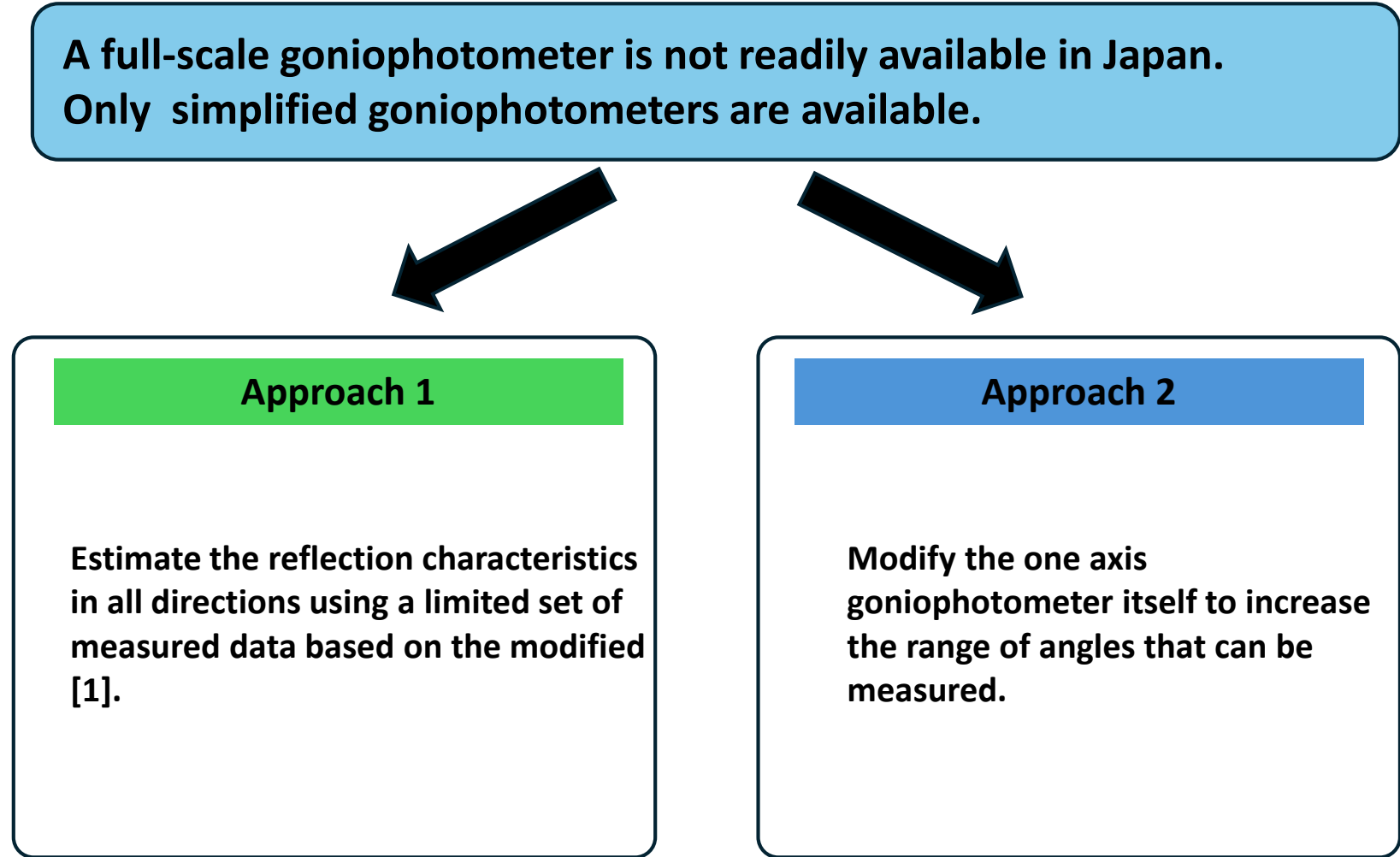


Comparison between measurements
and simulations

Verification of the reproduction of
reflection patterns

Overcome limited measurement directions

**A full-scale goniophotometer is not readily available in Japan.
Only simplified goniophotometers are available.**



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graph TD; A["A full-scale goniophotometer is not readily available in Japan.  
Only simplified goniophotometers are available."] --> B["Approach 1  
Estimate the reflection characteristics in all directions using a limited set of measured data based on the modified [1]."]; A --> C["Approach 2  
Modify the one axis goniophotometer itself to increase the range of angles that can be measured."];
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Approach 1

Estimate the reflection characteristics in all directions using a limited set of measured data based on the modified [1].

Approach 2

Modify the one axis goniophotometer itself to increase the range of angles that can be measured.

[1]: Chikako Yabe, “Simplified Estimation Method of BRDF for Building Materials and Prediction of Indoor Luminance Distribution,” Doctoral dissertation, Kyoto University.

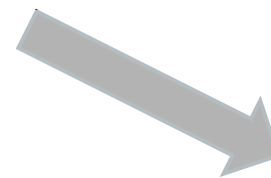
Overcome limited measurement directions

**A full-scale goniophotometer is not readily available in Japan.
Only simplified goniophotometer are available.**



Approach 1

**Estimate the reflection characteristics
in all directions using a limited set of
measured data based on the modified
[1].**



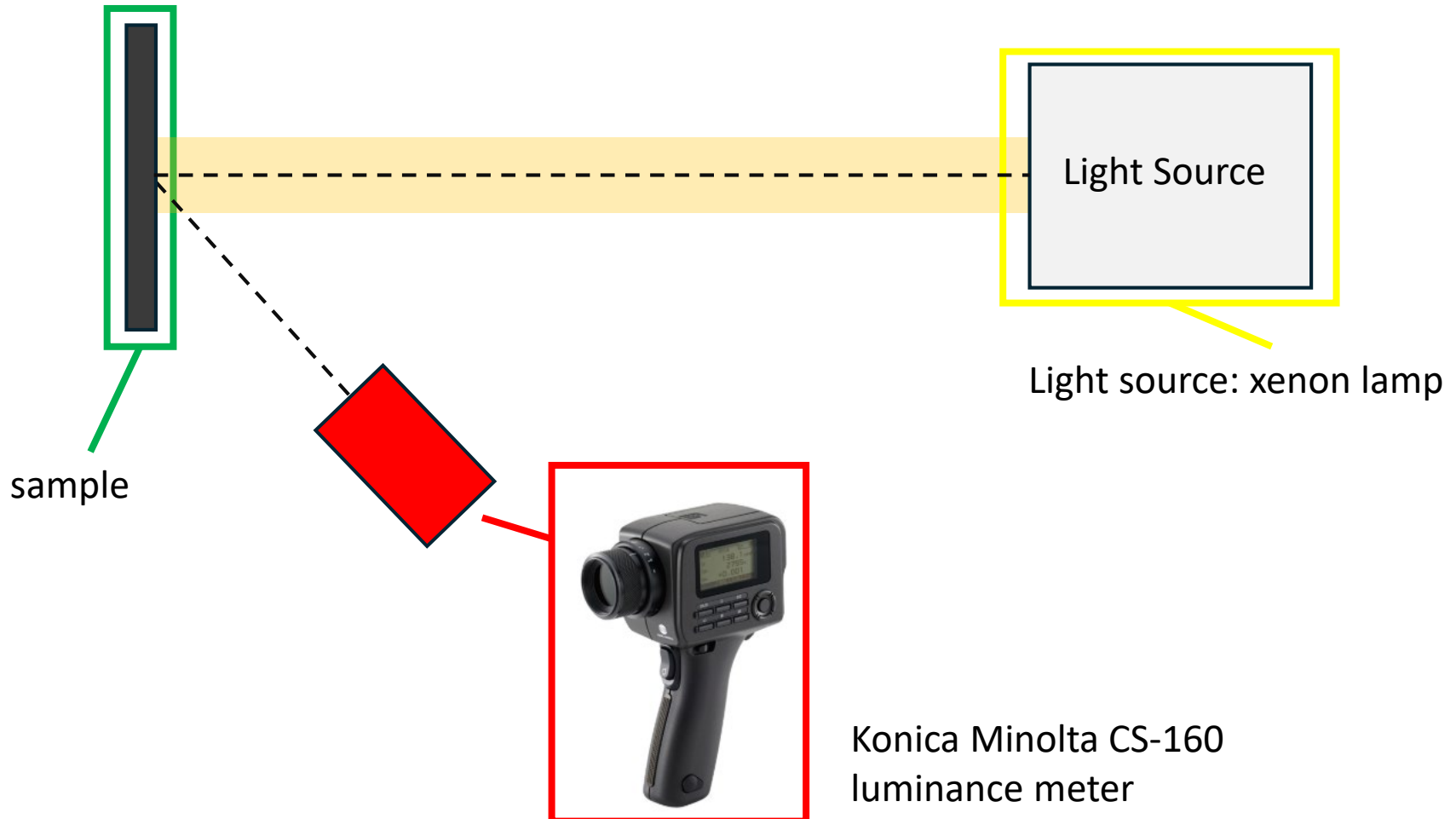
Approach 2

**Modify the one axis
goniophotometer itself to increase
the range of angles that can be
measured.**

[1]: Chikako Yabe, “Simplified Estimation Method of BRDF for Building Materials and Prediction of Indoor Luminance Distribution,” Doctoral dissertation, Kyoto University.

BRDF acquisition [approach1]

■ Explanation of the one axis goniophotometer



BRDF acquisition [approach1]

■ Measurement angles

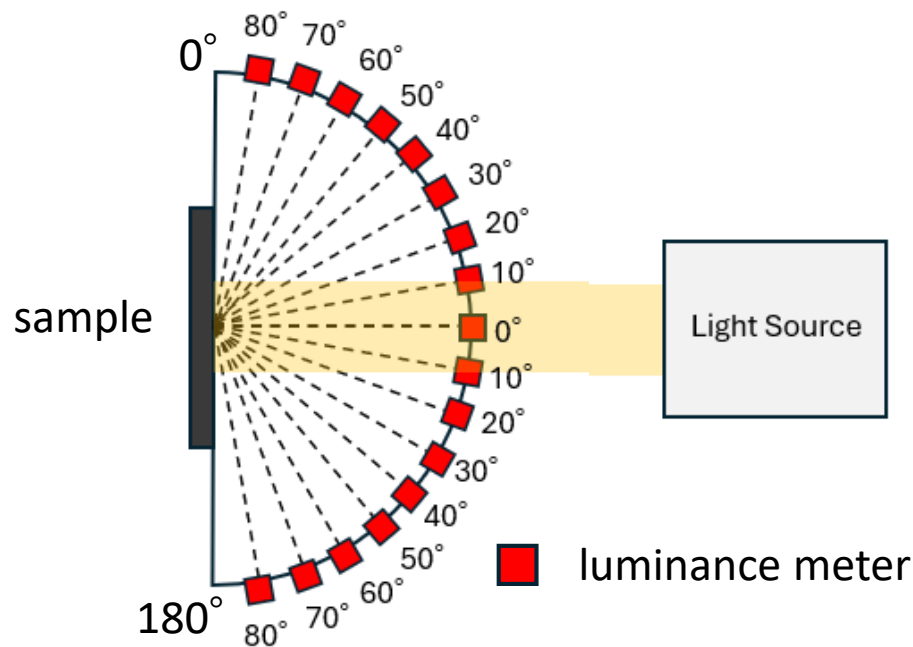
Incident elevation angles θ_i (10° , 20° , 30° , 40° , 50° , 60° , 70° , 80°)

Incident azimuth angle φ_i (0° , 90° , 180° , 270°)

Reflected angle 14 directions

+ $(\theta_i, \varphi_i) = (0^\circ, 0^\circ)$

Example: incident elevation angle 0° , incident azimuth angle 0°



Reflected angle 14 directions

Azimuth angle φ_s (0°)

Elevation angle θ_s (20° , 30° , 40° , 50° , 60° , 70° , 80°)

Azimuth angle φ_s (180°)

Elevation angle θ_s (20° , 30° , 40° , 50° , 60° , 70° , 80°)

The reflected elevation angles within $\pm 10^\circ$ of the incident elevation angle cannot be measured.

BRDF acquisition [approach1]

■ Measurement angles

Incident elevation angles θ_i (10° , 20° , 30° , 40° , 50° , 60° , 70° , 80°)

Incident azimuth angle φ_i (0° , 90° , 180° , 270°) $+ (\theta_i, \varphi_i) = (0^\circ, 0^\circ)$

Reflected angle 14 directions

Measurable angles $(8 \times 4 + 1) \times 14 = 462 \text{ directions}$

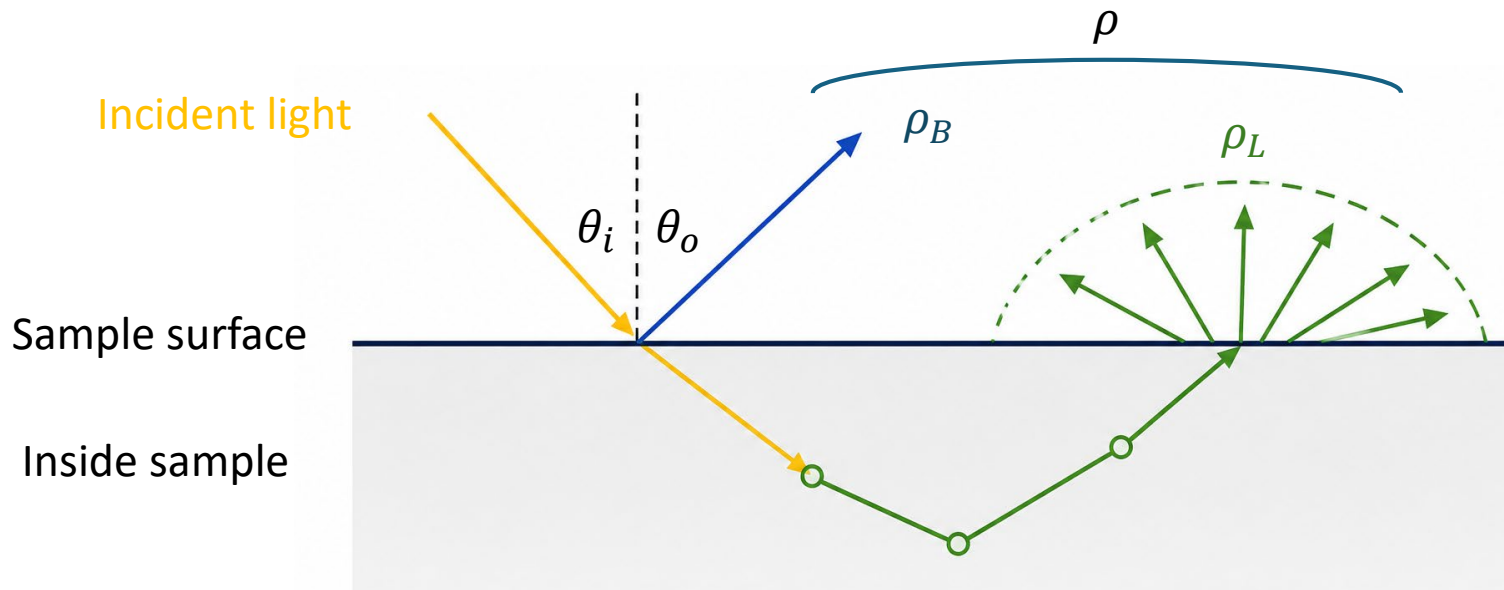
Accurate reflection simulations demand accurate reflection data, yet measuring only 462 directions provides an insufficient characterization of the panel's reflectance.

STEP 0 : Basic assumption

Total reflectance distribution function can be separated into layer reflection component and boundary reflection component.

$$\rho(\theta_i, \varphi_i) = \rho_L(\theta_i, \varphi_i) + \rho_B(\theta_i, \varphi_i)$$

- $\rho_B(\theta_i, \varphi_i)$: Boundary reflection component [1/sr]
- $\rho_L(\theta_i, \varphi_i)$: Layer reflection component [1/sr]
- $\rho(\theta_i, \varphi_i)$: Total reflectance distribution function [1/sr]



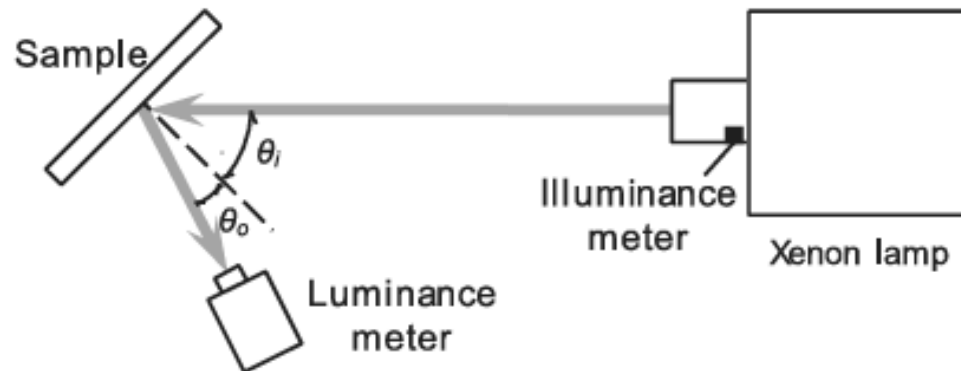
STEP 1 : Calculate the total reflectance distribution function $\rho(\theta_i, \varphi_i)$

The total reflectance distribution function was measured using the one axis goniophotometer .

$$\rho(\theta_i, \varphi_i) = \frac{L(\theta_i, \varphi_i) \cdot \cos \theta_o}{E(\theta_i, \varphi_i)} \quad E(\theta_i, \varphi_i) = \frac{\pi \cdot L_{ds}(\theta_i, \varphi_i)}{r_{ds}}$$

- $L(\theta_i, \varphi_i)$: Luminance of light reflected from the sample surface [cd/m^2]
- $E(\theta_i, \varphi_i)$: Illuminance on the sample surface [lx]
- θ_o : Reflection elevation angle
- L_{ds} : Reflected luminance from the standard white reference plate [cd/m^2]
- r_{ds} : Reflectance of the standard white reference plate [-]

The standard white reference plate was assumed to be a uniform diffuse reflector, with $r_{ds} = 0.96$.

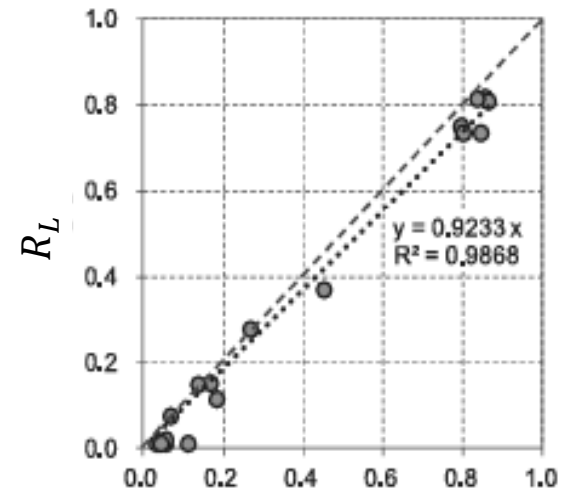


STEP 1 : Calculate layer reflection component $\rho_L(\theta_i, \varphi_i)$

- The diffuse reflectance, R_D , was calculated using the spectral diffuse reflectance, $R(\lambda)$, measured with a spectrophotometer.
- Since a strong correlation was observed between the diffuse reflectance, R_D , and the layer reflectance, R_L . $\Rightarrow R_D$ was used as R_L .
- Using the obtained layer reflectance, R_L , the layer reflection component, ρ_L , was calculated assuming lambertian reflection.

$$R_D = \frac{\int_{360}^{740} E_{\text{xenon}}(\lambda) \cdot R(\lambda) \cdot V(\lambda) d\lambda}{\int_{360}^{740} E_{\text{xenon}}(\lambda) \cdot V(\lambda) d\lambda}$$

$$\rho_L(\theta_i, \varphi_i) = R_L \frac{\cos \theta_o}{\pi}$$



- R_L : Layer reflectance
- R_D : Diffuse reflectance
- $\rho_L(\theta_i, \varphi_i)$: Layer reflection component [1/sr]
- $E_{\text{xenon}}(\lambda)$: Spectral irradiance of the xenon lamp light source [W/(m² · nm)]
- $R(\lambda)$: Spectral diffuse reflectance of each building material
- $V(\lambda)$: Photopic spectral luminous efficiency

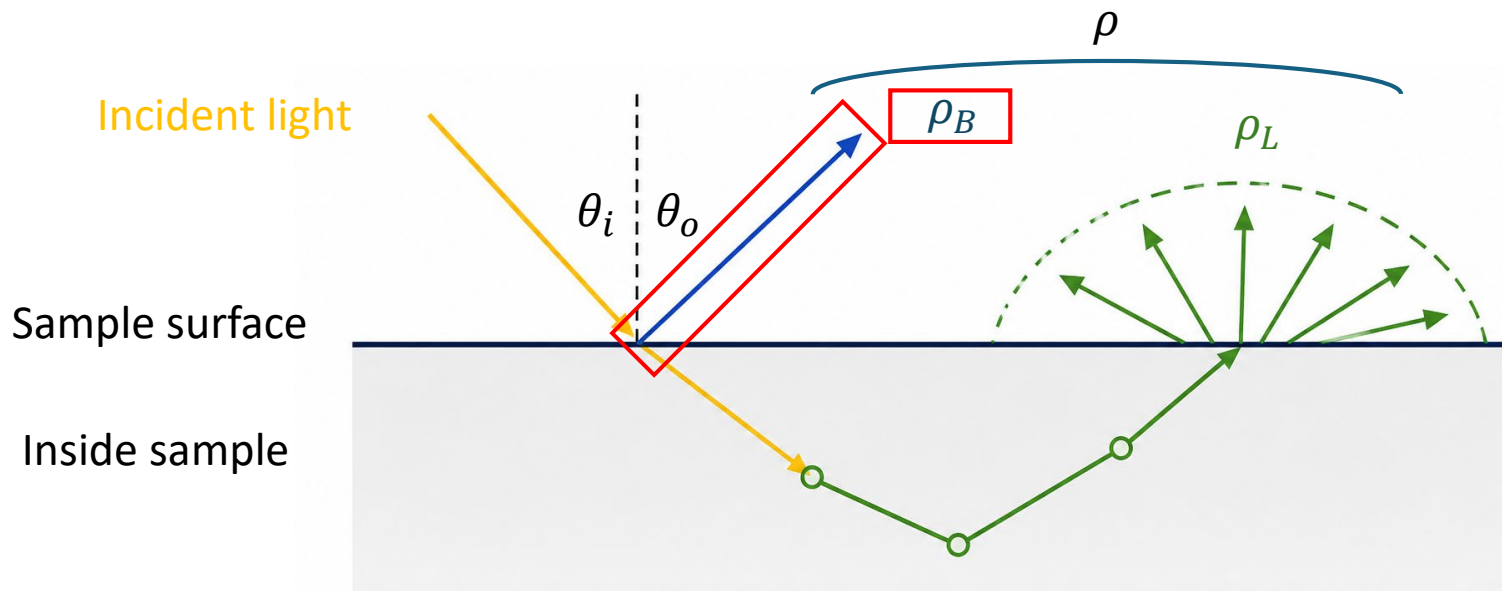
R_D
Relationships between
 R_D and R_L

STEP 2 : Calculate boundary reflection component $\rho_B(\theta_i, \varphi_i)$

The boundary reflection component, $\rho_B(\theta_i, \varphi_i)$, was estimated by subtracting the estimated layer reflection component, $\rho_L(\theta_i, \varphi_i)$, from the total reflectance distribution function, $\rho(\theta_i, \varphi_i)$, measured using the one axis goniophotometer.

$$\rho_B(\theta_i, \varphi_i) = \rho(\theta_i, \varphi_i) - \rho_L(\theta_i, \varphi_i)$$

- $\rho_B(\theta_i, \varphi_i)$: Boundary reflection component [1/sr]
- $\rho_L(\theta_i, \varphi_i)$: Layer reflection component [1/sr]
- $\rho(\theta_i, \varphi_i)$: Total reflectance distribution function [1/sr]



STEP 3 : Calculate coefficient $K(\theta_i, \varphi_i)$

- Using the obtained boundary reflection component, $\rho_B(\theta_i, \varphi_i)$, the coefficient $K(\theta_i, \varphi_i)$ was calculated for each measured incident angle.
- Since there are 462 directions, $K(\theta_i, \varphi_i)$ is also calculated for each of the 462 directions.

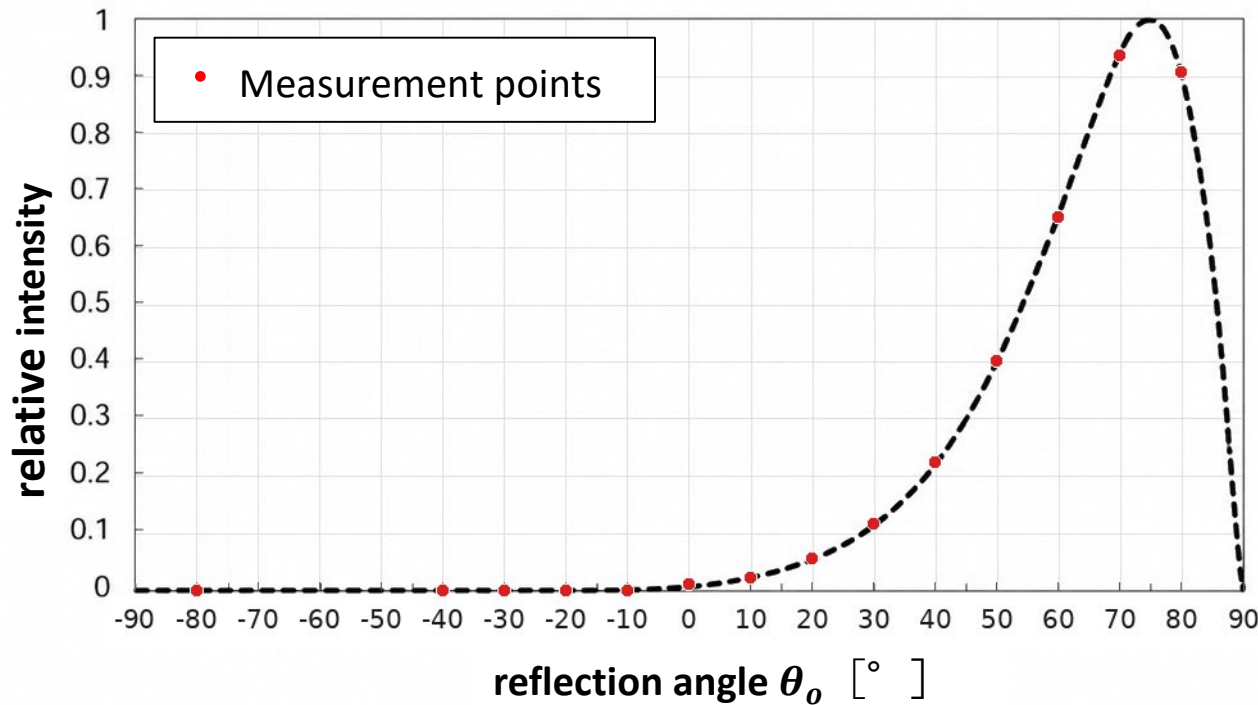
$$K(\theta_i, \varphi_i) = \frac{1}{0.5} \int_0^{\frac{\pi}{2}} \rho_B(\theta_i, \varphi_i) \frac{4 \cos \theta_f \cos \theta_i}{m(\theta_i, \theta_o) R(\psi_f)} d\theta_f$$

- $K(\theta_i)$: Coefficient [–]
- $m(\theta_i, \theta_o)$: Coefficient that represents the masking phenomenon [–]
- $\rho_B(\theta_i, \varphi_i)$: Estimated value of the boundary reflection component [1/sr]
- $R(\psi_f)$: Micro-facet reflectance following Fresnel's law [–]
- ψ_f : Angle of incidence onto the micro-facet [rad]
- $p_f(\theta_f, \varphi_f)$: Micro-facet distribution function [1/sr]
- θ_f, φ_f : Micro-facet tilt angle and tilt azimuth angle [rad]

STEP 4 : Estimate boundary reflection component $\rho_B'(\theta_i, \varphi_i)$

Using the calculated coefficient $K(\theta_i, \varphi_i)$, the boundary reflection component, $\rho_B'(\theta_i, \varphi_i)$, at unmeasured angles is estimated.

$$\rho_B'(\theta_i, \varphi_i) = K(\theta_i, \varphi_i) m(\theta_i, \theta_o) R(\psi_f) p_f(\theta_f, \varphi_f) / 4 \cos \theta_f \cos \theta_i$$



Relative distribution of $\rho_B'(\theta_i, \varphi_i)$ versus reflection angle at an incident angle of 60°

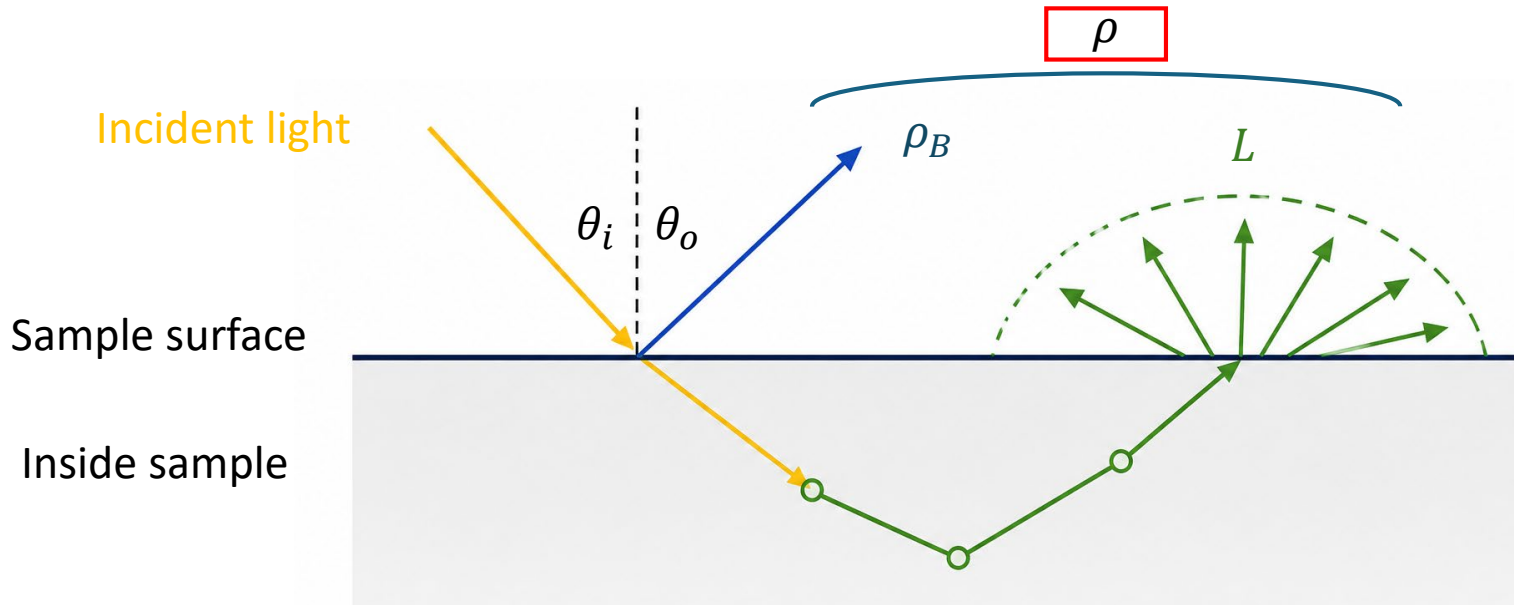
STEP 4 : Estimate

the total reflectance distribution function $\rho'(\theta_i, \varphi_i)$

By adding the layer reflection component, $\rho_L(\theta_i, \varphi_i)$, and the calculated boundary reflection component, $\rho_B'(\theta_i, \varphi_i)$, the total reflectance distribution function, $\rho'(\theta_i, \varphi_i)$, at unmeasured angles can be estimated.

$$\rho'(\theta_i, \varphi_i) = \rho_L(\theta_i, \varphi_i) + \rho_B'(\theta_i, \varphi_i)$$

- $\rho_B'(\theta_i, \varphi_i)$: Boundary reflection component [1/sr]
- $\rho_L(\theta_i, \varphi_i)$: Layer reflection component [1/sr]
- $\rho'(\theta_i, \varphi_i)$: Total reflectance distribution function [1/sr]



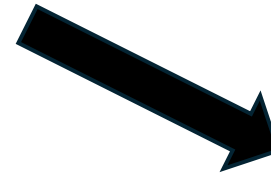
Overcome limited measurement directions

**A full-scale goniophotometer is not readily available in Japan.
Only a simplified goniophotometer is available.**



Approach 1

Estimate the reflection characteristics in all directions using a limited set of measured data based on the modified [1].

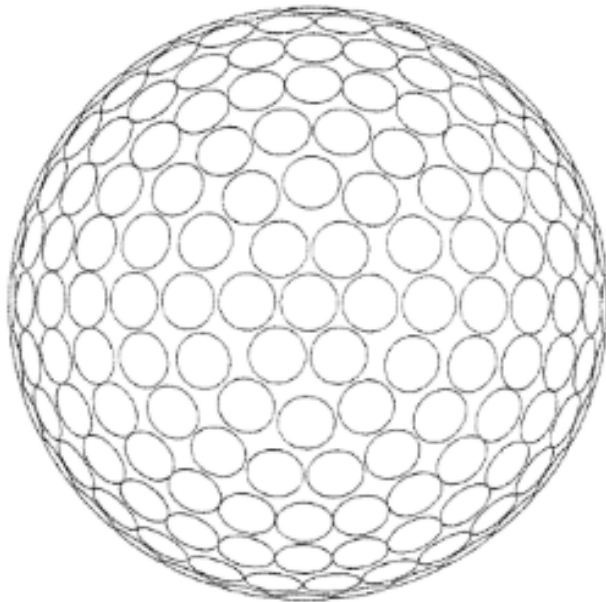


Approach 2

Modify the one axis goniophotometer itself to increase the range of angles that can be measured.

BRDF measurement using 3D-printed [approach2]

To capture the reflectance characteristics in greater detail, we fabricated a measurement aid with a 3D printer.



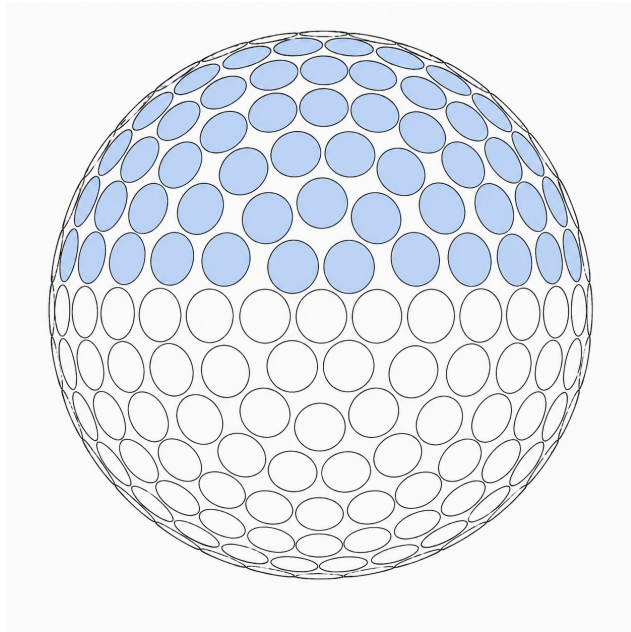
the 145-patch Tregenza subdivision



3D-printed object

BRDF measurement using 3D-printed [approach2]

The dome has 64 holes, allowing us to measure the reflection characteristics of the sample over reflection azimuth angles from 0° to 180° .



the 145-patch Tregenza subdivision

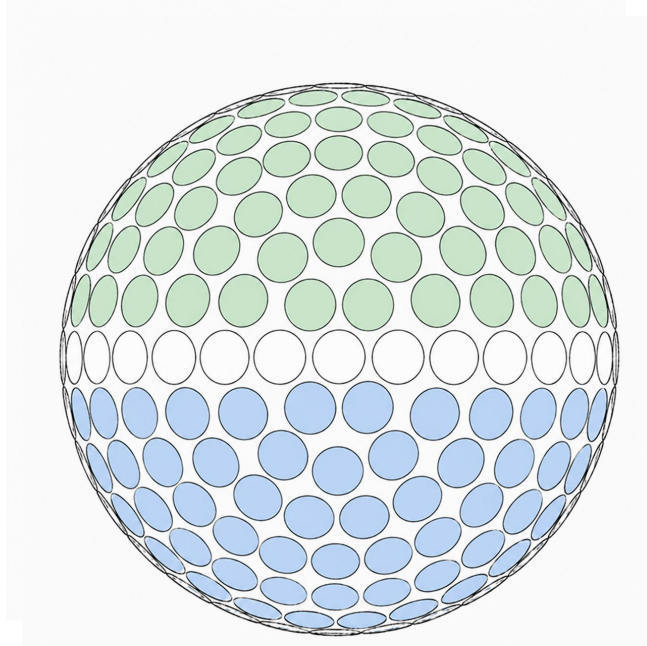


3D-printed object

 64 directions

BRDF measurement using 3D-printed [approach2]

By flipping the sample upside down, we can also measure 64 directions corresponding to reflection azimuth angles from 180° to 360° .



the 145-patch Tregenza subdivision



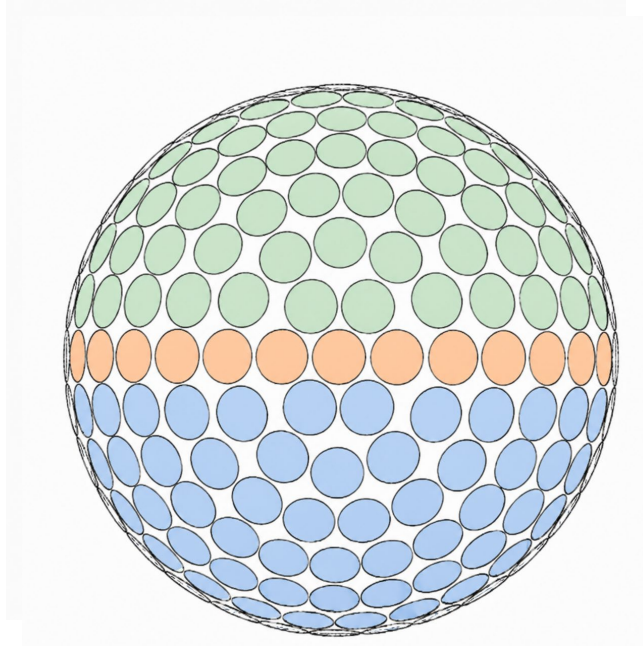
3D-printed object

 64 directions

 64 directions

BRDF measurement using 3D-printed [approach2]

The remaining 17 directions are parallel to the table, so they can be measured using the existing rail system.



the 145-patch Tregenza subdivision

-  64 directions
-  64 directions
-  17 directions



142 directions

The reflected elevation angles within $\pm 10^\circ$ of the incident elevation angle cannot be measured.

BRDF measurement using 3D-printed [approach2]

Previously, measurements were limited to **462 directions**

With the new setup, we can now sample **4686 directions**

Incident elevation angles θ_i (10° , 20° , 30° , 40° , 50° , 60° , 70° , 80°)

Incident azimuth angle φ_i (0° , 90° , 180° , 270°)

Reflected angle 142 directions

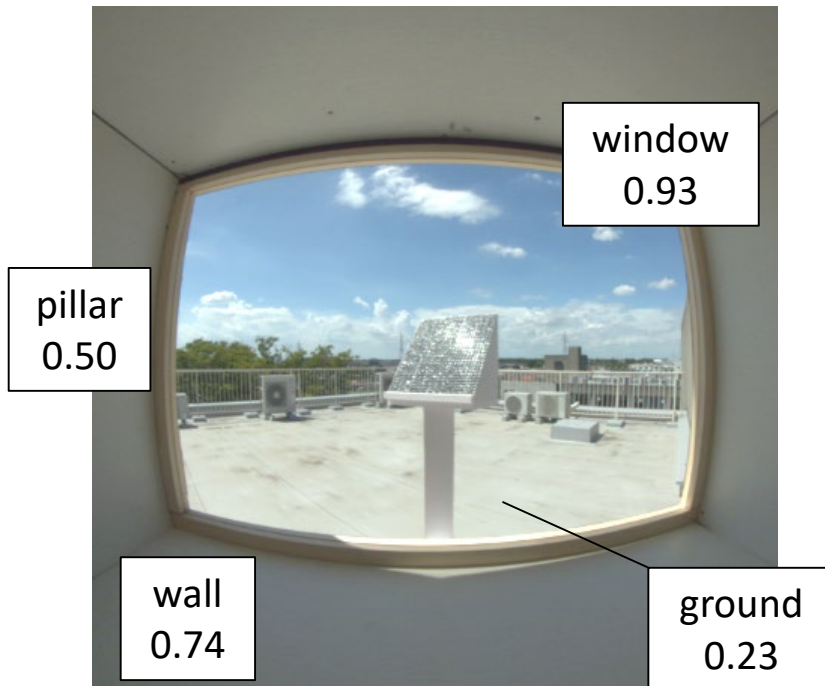
+ $(\theta_i, \varphi_i) = (0^\circ, 0^\circ)$

Measurable angles $(8 \times 4 + 1) \times 142 = \mathbf{4686 \text{ directions}}$

Luminance images: Experiment setup

■ Measurement Overview

- **Date & Time:** 8,19 August 2026
- **Location:** Rooftop (latitude 35.918° , longitude 139.907°)
- **Material reflectance and transmittance:** As shown in the image on the left



**View from the camera
mounted in the 3d model**

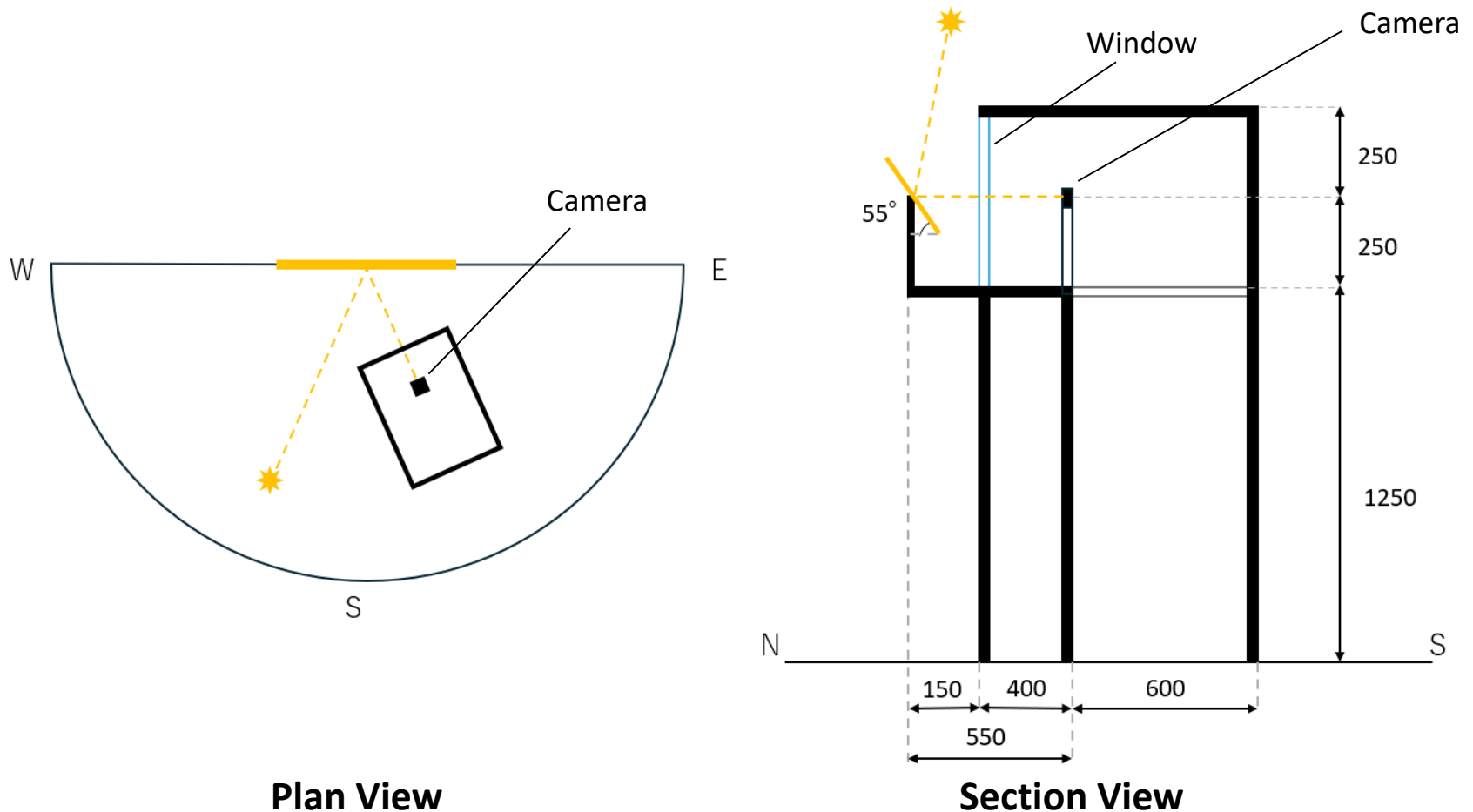


Roof Installed 3d model

Luminance images: Experiment setup

■ Measurement Overview

- The photovoltaic panel was installed facing south at a height of **1,500 mm** and tilted at **55°**
- The camera was positioned at a height of **1,500 mm** and **550 mm** away from the panel.
- The box was constructed to **simulate an indoor environment**.



Luminance images: Experiment setup

■ Measurement Overview

Capture HDR images through the window.

RICOH THETA Z1 + L-CEPT¹ for HDR luminance measurement¹



Captured image by THETA Z1



1: [Microsoft Word - CIE 2019 Proceedings - Cover for individual papers.docx](#)

Yamaguchi et al., “Development of Generic Colorimetry System for Evaluation of Lighting Environment,” Proceedings of the 29th CIE Session, 2019.

Luminance images: Experiment setup

■ Measurement Overview

Capture sky images for use in the simulation.

Canon R5M2 (with a Canon EF 8-15 F4 fisheye
+ ND3) + pylinearhdr¹



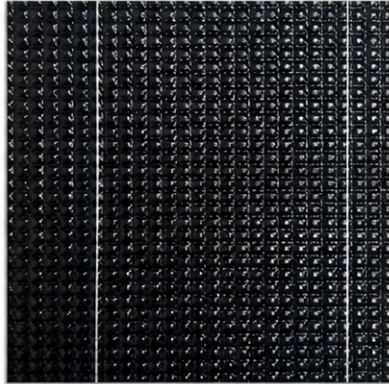
Captured sky image



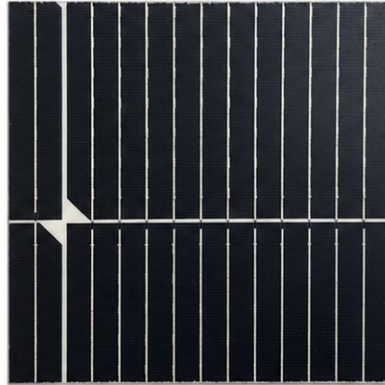
1: [GitHub - stephanwaz/linearhdr: CLI for converting raw camera sequence to HDRI](https://github.com/stephanwaz/linearhdr) · [GitHub](https://github.com/Wasilewski/IA-Refined-Workflow-to-Calibrate-HDR-Images-of-Daylit-Scenes)
Wasilewski et al., IA Refined Workflow to Calibrate HDR Images of Daylit Scenes, LEUKOS, 2026

Sample selection and preparation

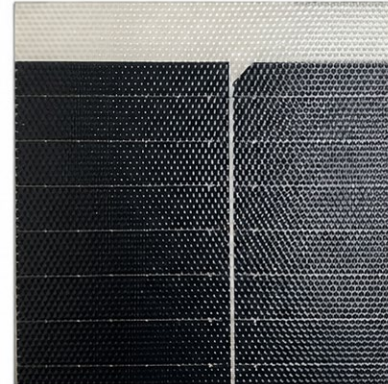
■ Silicon solar cell



Type 1
Low reflectance



Type 2
Medium reflectance

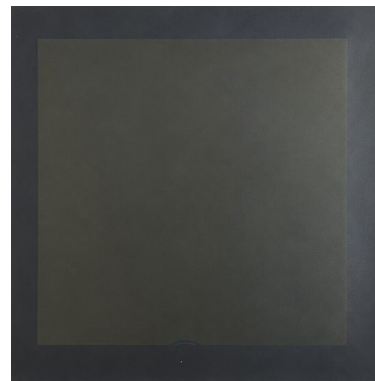


Type 3
High reflectance

■ Perovskite solar cell



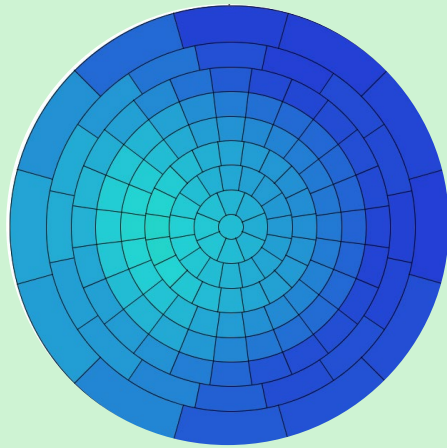
Type 1
Low reflectance



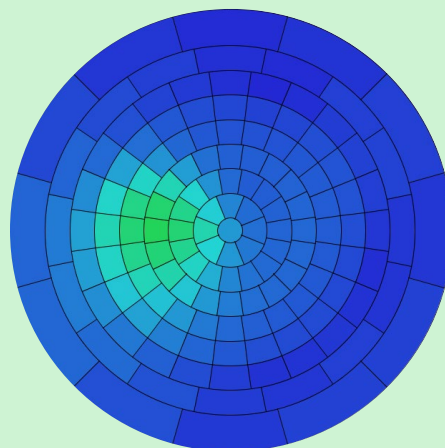
Type 2
High reflectance

Tensor Tree BRDFs at a 30° Incident Angle

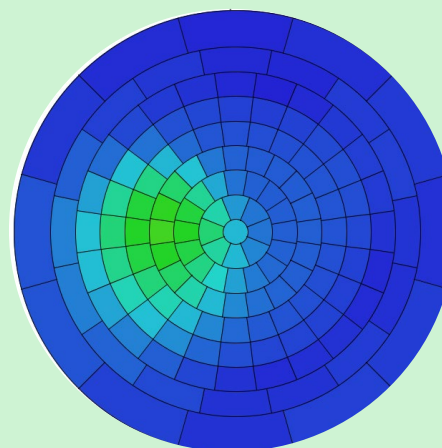
■ Silicon solar cell



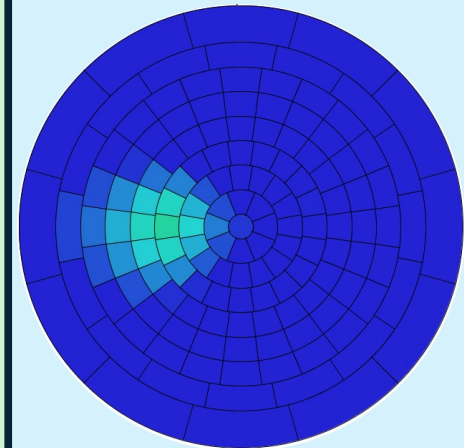
Type 1
Low reflectance



Type 2
Medium reflectance

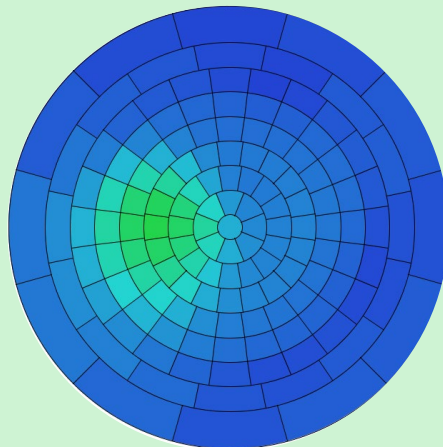


Type 3
High reflectance

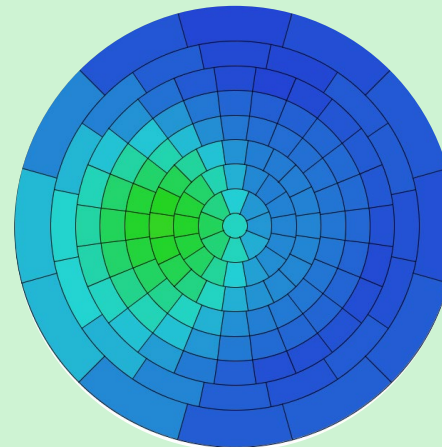


Type 3
High reflectance

■ Perovskite solar cell



Type 1
Low reflectance



Type 2
High reflectance

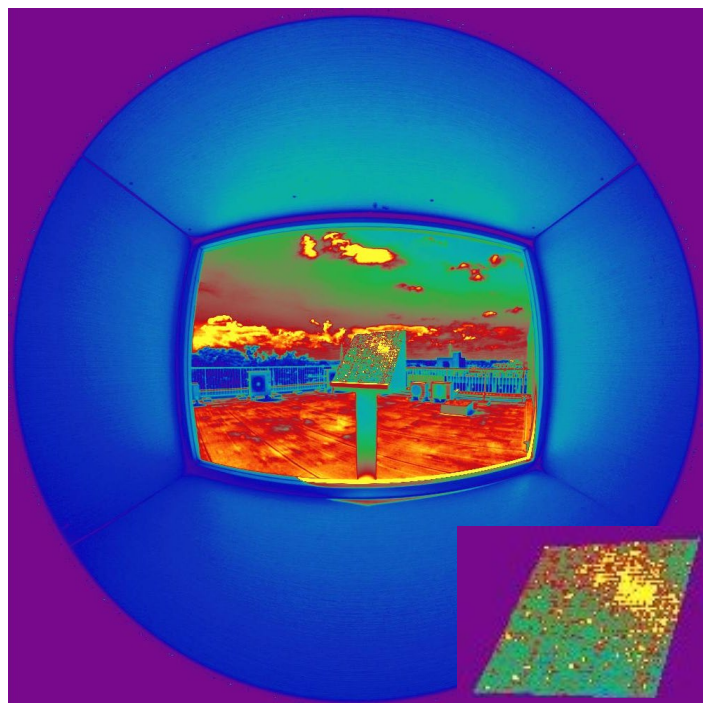
approach1

approach2

Comparison of simulated and measured luminance images

■ Silicon solar cell Type 1 Low reflectance _approach 1

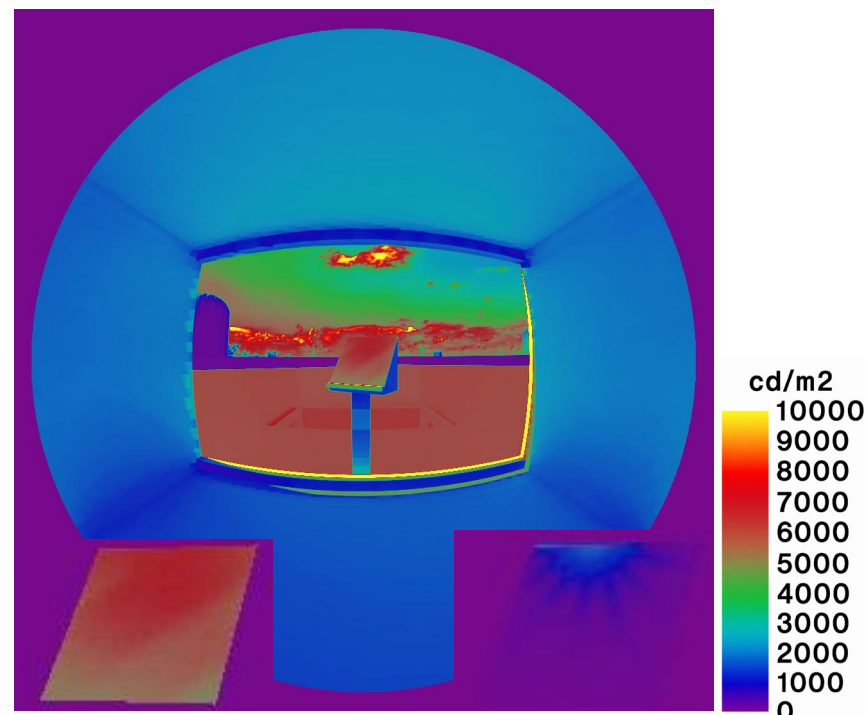
Measured luminance image



Enlarged view of the panel

Average luminance : 6014 cd/m^2
95th percentile luminance : 13317 cd/m^2
Maximum luminance : 95965 cd/m^2

Simulated luminance image



Enlarged view of the panel
(left : void BSDF light : void mirror)

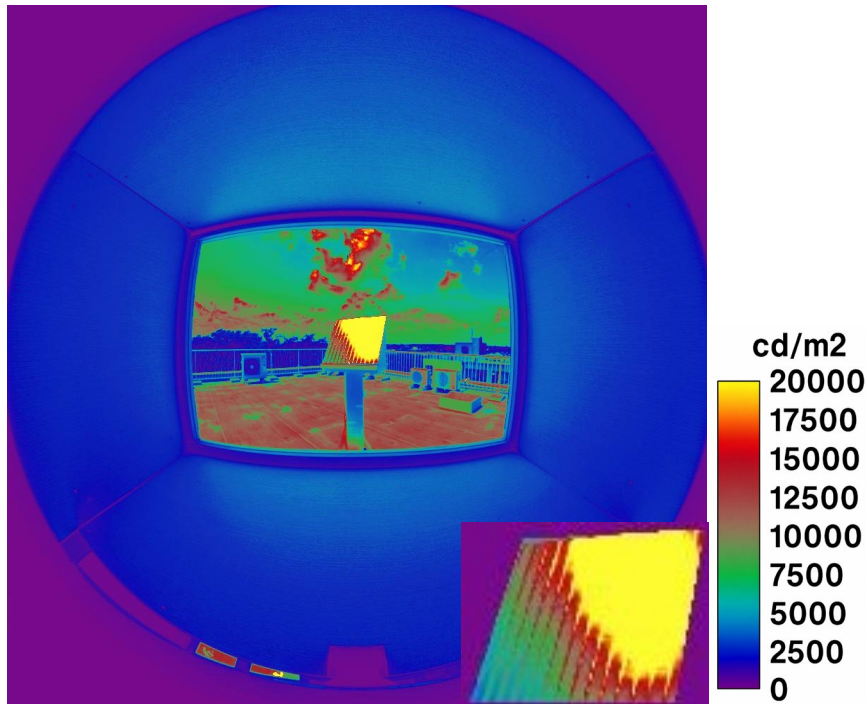
Average luminance : 6014 cd/m^2 (912 cd/m^2)
95th percentile luminance : 6907 cd/m^2 (3453 cd/m^2)
Maximum luminance : 7244 cd/m^2 (6037 cd/m^2)
void BSDF(void mirror)

Calculated considering only the panel contribution.

Comparison of simulated and measured luminance images

■ Silicon solar cell Type 2 Medium reflectance _approach 1

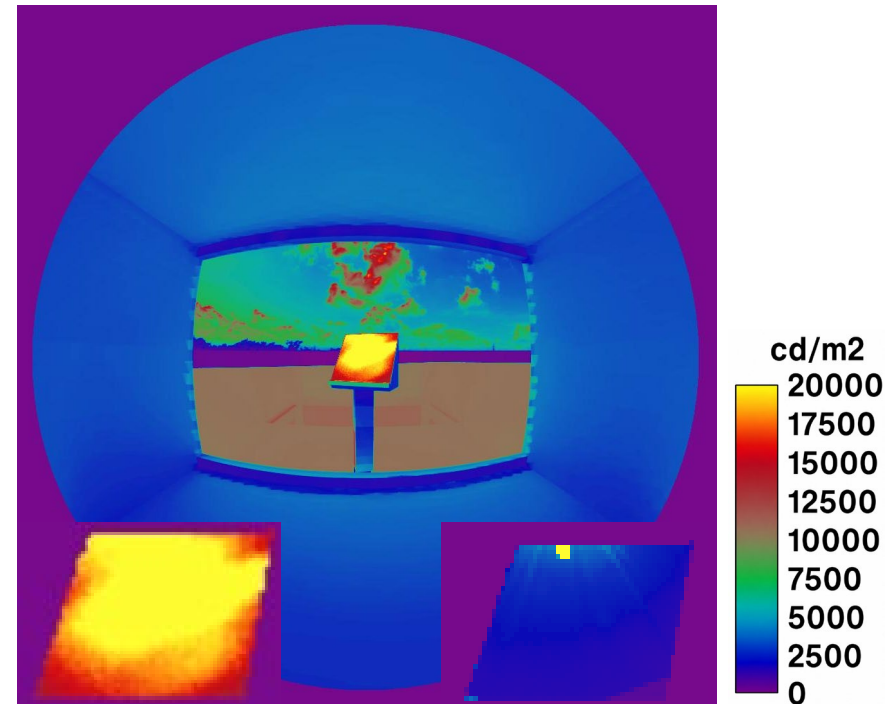
Measured luminance image



Enlarged view of the panel

Average luminance : 33394 cd/m²
95th percentile luminance : 86278 cd/m²
Maximum luminance : 114560 cd/m²

Simulated luminance image



Enlarged view of the panel
(left : void BSDF light : void mirror)

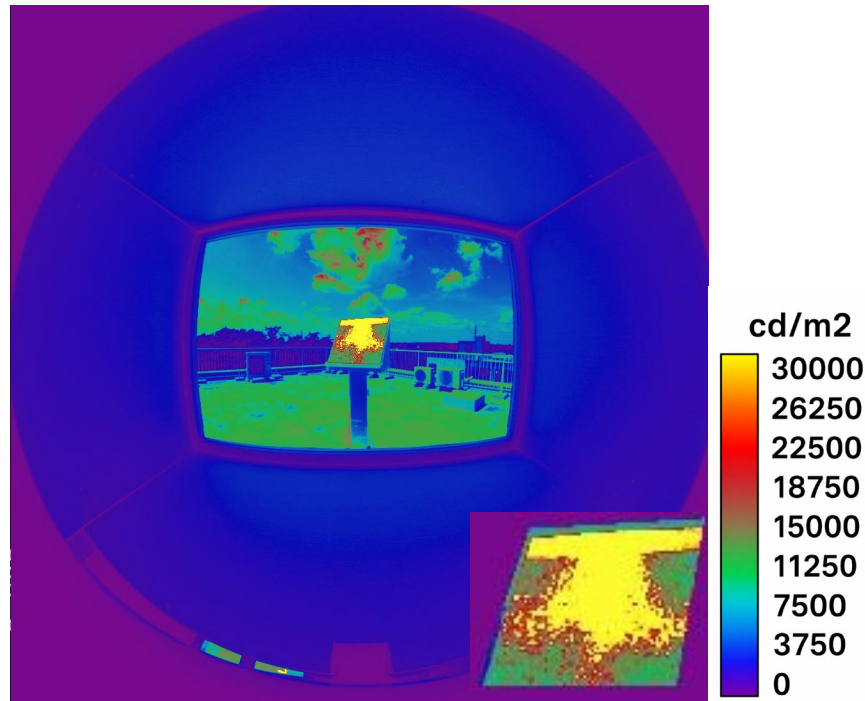
Average luminance : 19399 cd/m² (353,905 cd/m²)
95th percentile luminance : 22865 cd/m² (3196 cd/m²)
Maximum luminance : 24596 cd/m² (274,262,138 cd/m²)
void BSDF(void mirror)

Calculated considering only the panel contribution.

Comparison of simulated and measured luminance images

■ Silicon solar cell Type 3 High reflectance _approach 1

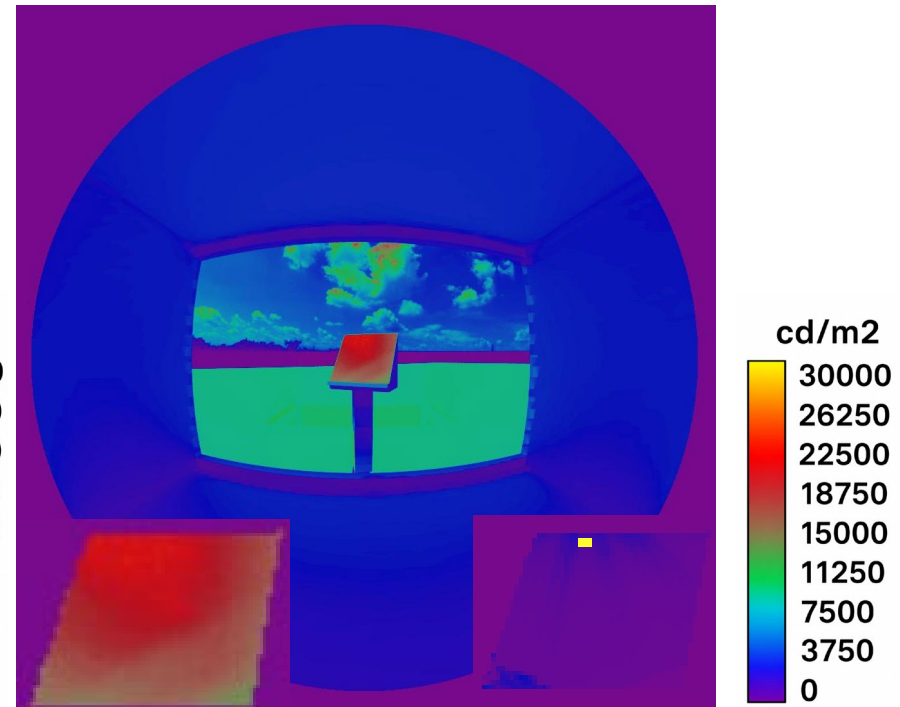
Measured luminance image



Enlarged view of the panel

Average luminance : 27474 cd/m²
95th percentile luminance : 63008 cd/m²
Maximum luminance : 102388 cd/m²

Simulated luminance image



Enlarged view of the panel
(left : void BSDF light : void mirror)

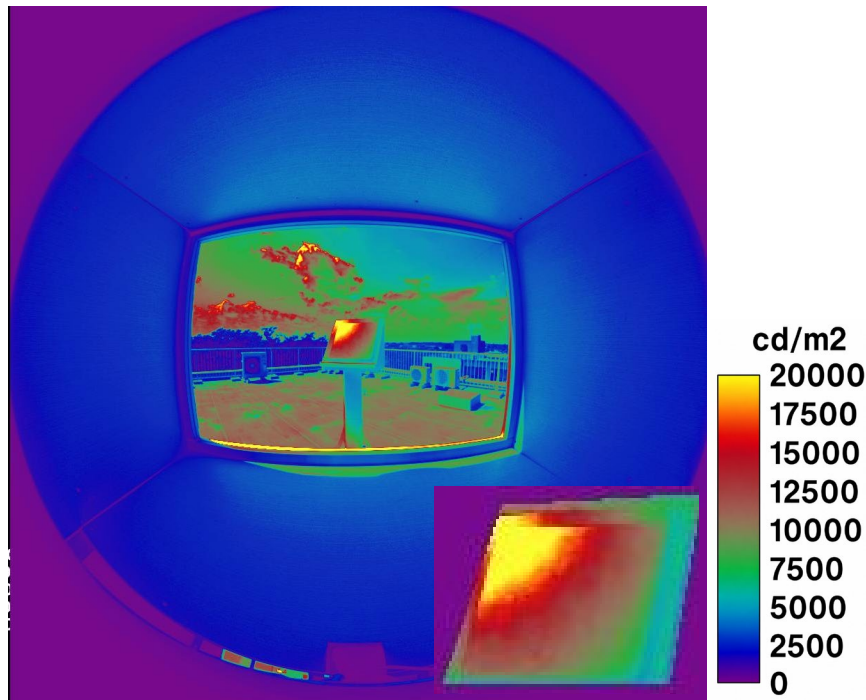
Average luminance : 19416 cd/m² (127,235 cd/m²)
95th percentile luminance : 23437 cd/m² (1464 cd/m²)
Maximum luminance : 24320 cd/m² (95,266,263 cd/m²)
void BSDF(void mirror)

Calculated considering only the panel contribution.

Comparison of simulated and measured luminance images

■ Perovskite solar cell Type 1 Low reflectance _approach 1

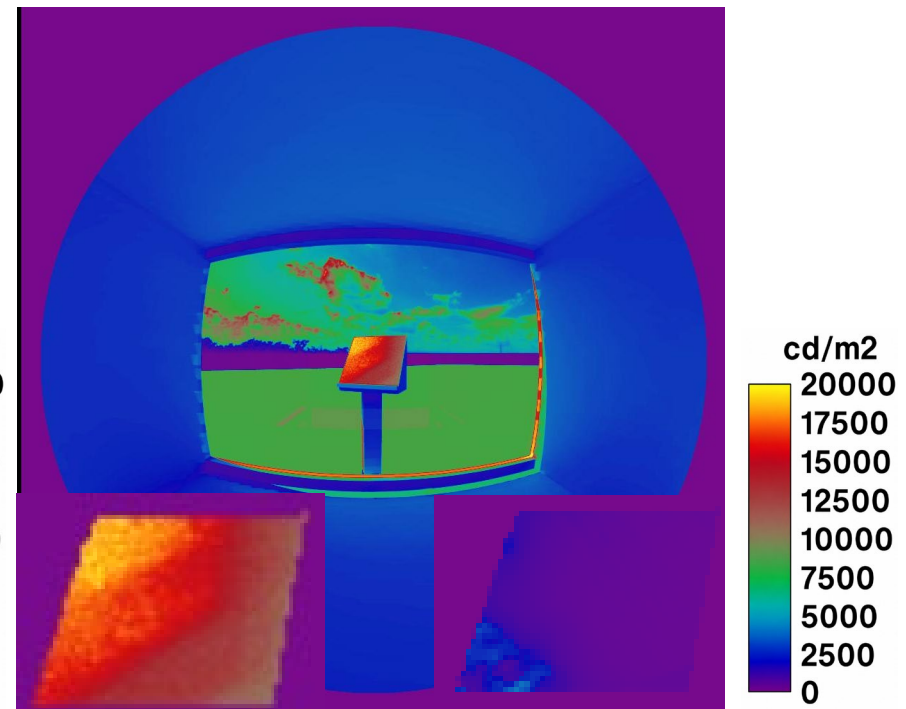
Measured luminance image



Enlarged view of the panel

Average luminance : 11623 cd/m^2
95th percentile luminance : 20674 cd/m^2
Maximum luminance : 28282 cd/m^2

Simulated luminance image



Enlarged view of the panel
(left : void BSDF light : void mirror)

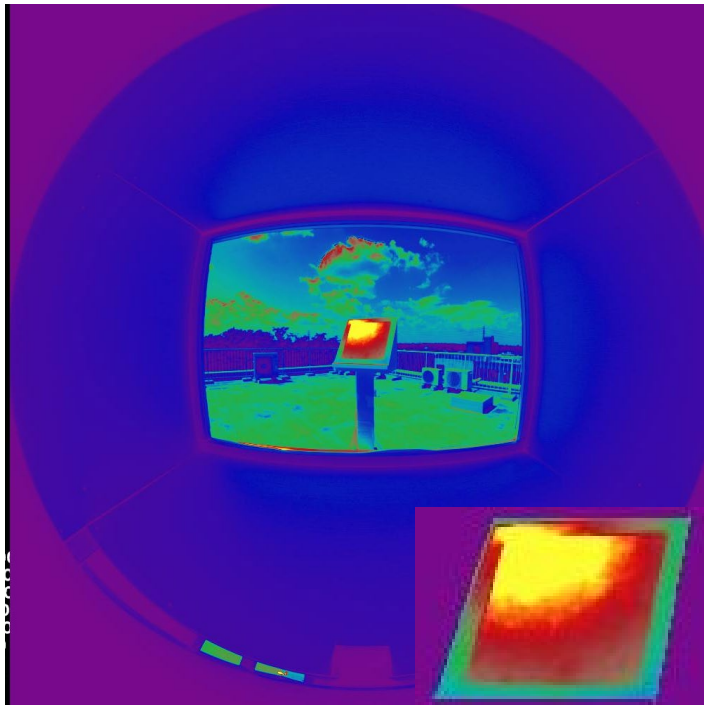
Average luminance : 14718 cd/m^2 (657 cd/m^2)
95th percentile luminance : 18345 cd/m^2 (1948 cd/m^2)
Maximum luminance : 19801 cd/m^2 (3976 cd/m^2)
void BSDF(void mirror)

Calculated considering only the panel contribution.

Comparison of simulated and measured luminance images

■ Perovskite solar cell Type 2 High reflectance _approach 1

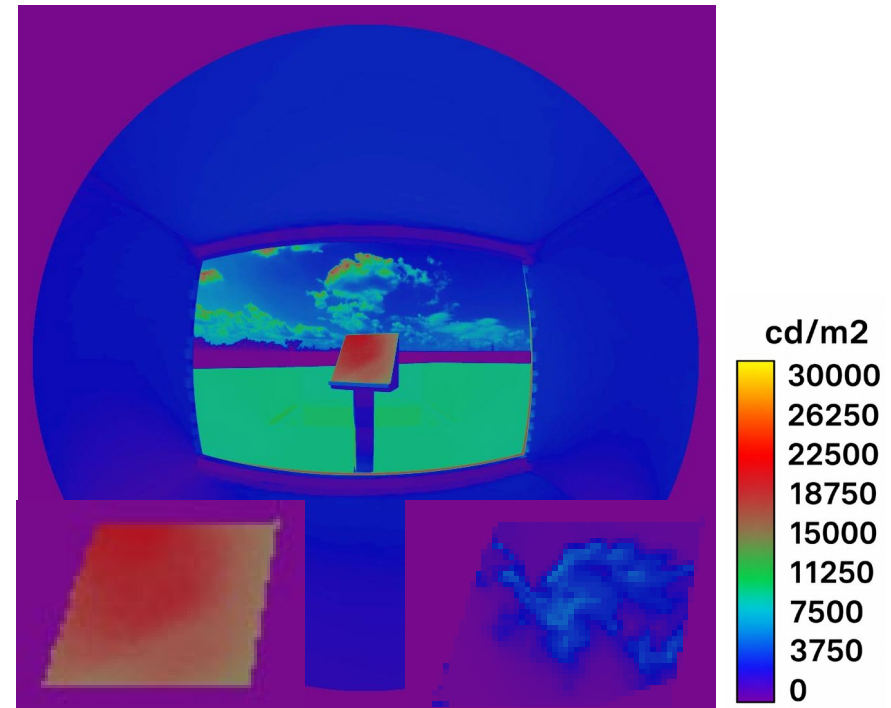
Measured luminance image



Enlarged view of the panel

Average luminance : 20840 cd/m^2
95th percentile luminance : 36158 cd/m^2
Maximum luminance : 42602 cd/m^2

Simulated luminance image



Enlarged view of the panel
(left : void BSDF light : void mirror)

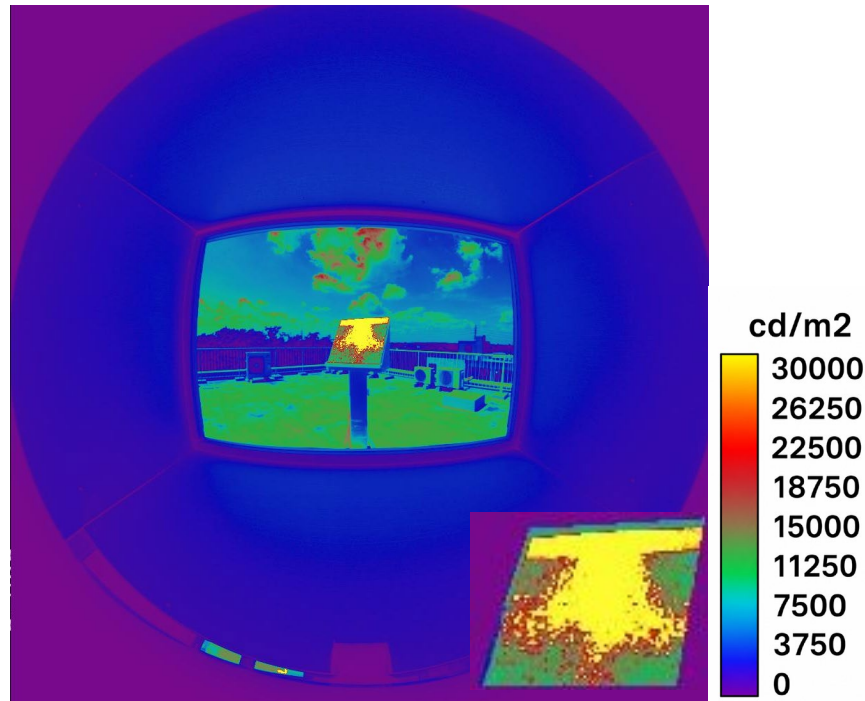
Average luminance : 18035 cd/m^2 (1795 cd/m^2)
95th percentile luminance : 21230 cd/m^2 (4293 cd/m^2)
Maximum luminance : 22278 cd/m^2 (5739 cd/m^2)
void BSDF(void mirror)

Calculated considering only the panel contribution.

Comparison of simulated and measured luminance images

■ Silicon solar cell Type 3 High reflectance_approach 2

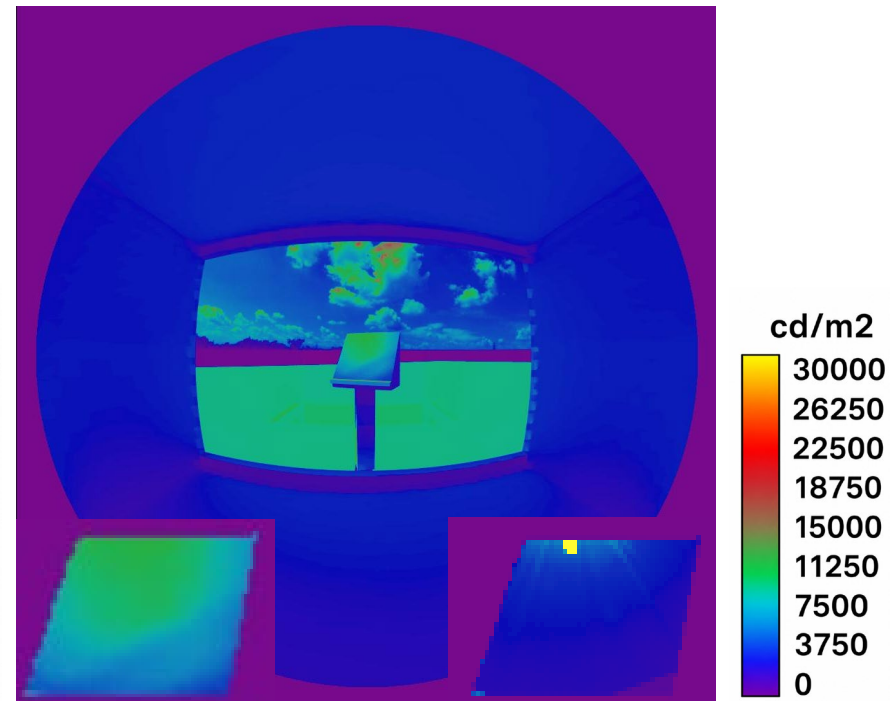
Measured luminance image



Enlarged view of the panel

Average luminance : 27474 cd/m^2
95th percentile luminance : 63008 cd/m^2
Maximum luminance : 102388 cd/m^2

Simulated luminance image



Enlarged view of the panel
(left : void BSDF light : void mirror)

Average luminance : 8035 cd/m^2 ($353,905 \text{ cd/m}^2$)
95th percentile luminance : 10689 cd/m^2 (3196 cd/m^2)
Maximum luminance : 11468 cd/m^2 ($274,262,138 \text{ cd/m}^2$)
void BSDF(void mirror)

Calculated considering only the panel contribution.

Conclusion

- **Smooth surfaces, especially perovskite solar cells:**
Reflection patterns were reproduced to some extent.
- **Textured silicon solar cells:**
Reflection characteristics were not reproduced accurately.
- **Maximum luminance:**
Large discrepancies remained.
- **Possible reason:**
Microscopic surface textures cause complex reflection distributions, including:
 - spread around the specular direction
 - local reflection peaks
 - azimuthal variationsBecause the simplified estimation method uses measurements from only a limited number of directions, these complex reflection characteristics could not be fully captured, resulting in larger differences from the actual reflection distribution.
- **Future work:**
 - Measurements using a full-scale goniophotometer are also planned to improve the reproduction of PV reflection characteristics.
 - Further validation of the 3D-printed measurement method is required.