New method for predicting the solar radiation environment based on scalar irradiance using volume photon mapping

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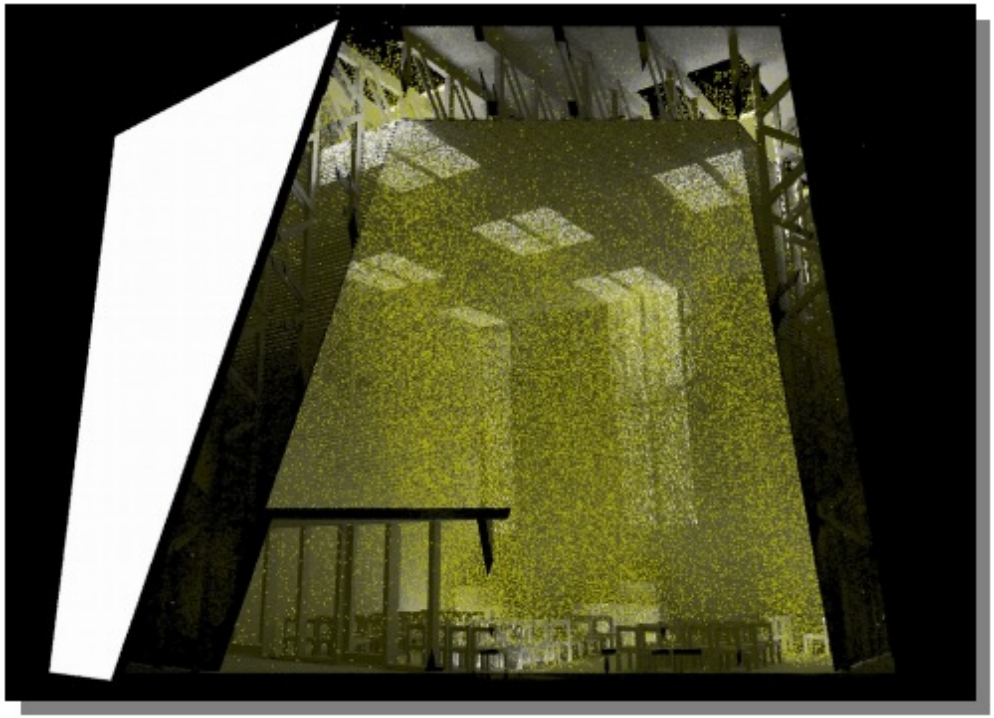
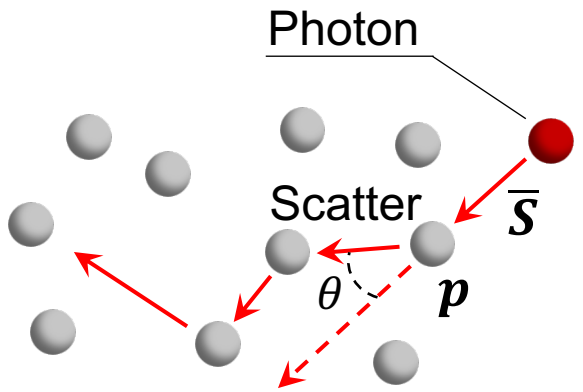
Radiance Workshop 2022 in Toronto

Photon Flow: Volume Photon Mapping

■ Research so far





Mean free distance : $\overline{s}$

$$\overline{s} = -\frac{log\xi}{\sigma_t}, \qquad \xi \in [0,1]$$

Absorption : p

$$p = 1 - \sigma_\alpha, \qquad \sigma_\alpha \in [0,1]$$

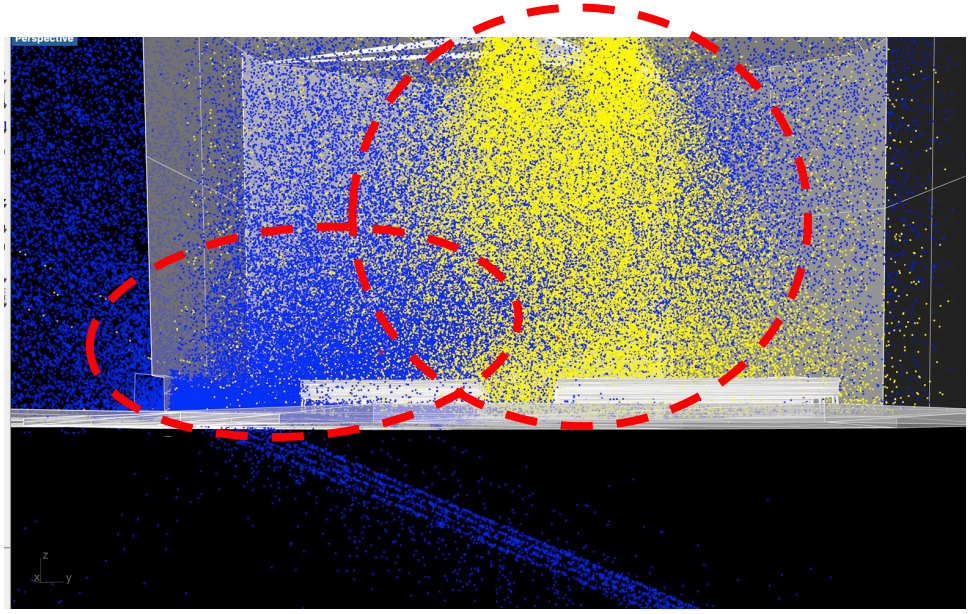
- Volume photons deposited in nonabsorbing / nonscattering mist
- Directional light distribution as particles (photons) in volume
- Photons carry RGB flux, direction
- Estimate illuminance on arbitrary surface (≙ photon density)

Photon Flow: Volume Photon Mapping

- Research so far

Kaze-No-Oka Crematorium Hall

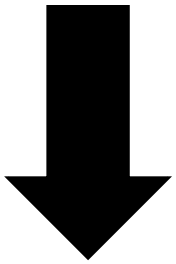
Designed by Fumihiko Maki, built 1995-97 in Nakatsu, Japan

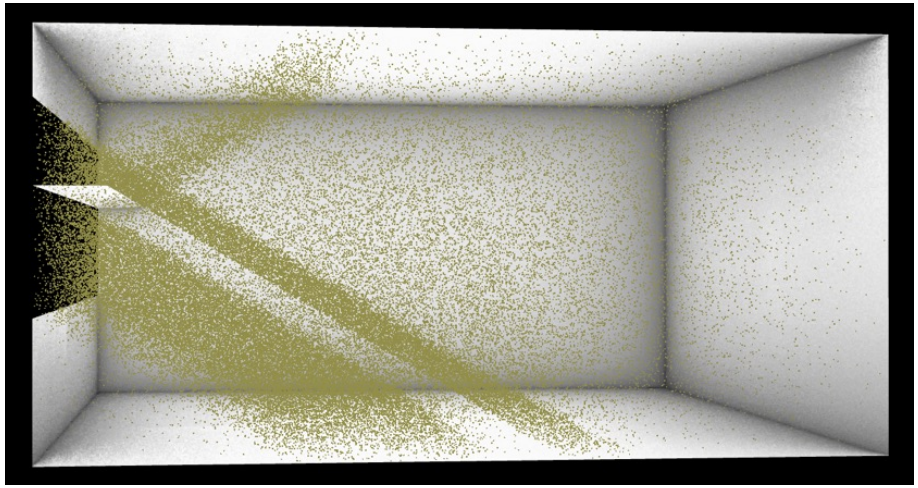


Photon Flow: Volume Photon Mapping

Advantages of photon flow using volume photon mapping

- A visual understanding of light distribution at a given season and time.
- Efficient calculation
  - when complex shadings included
    e.g. specular, data-driven BSDF



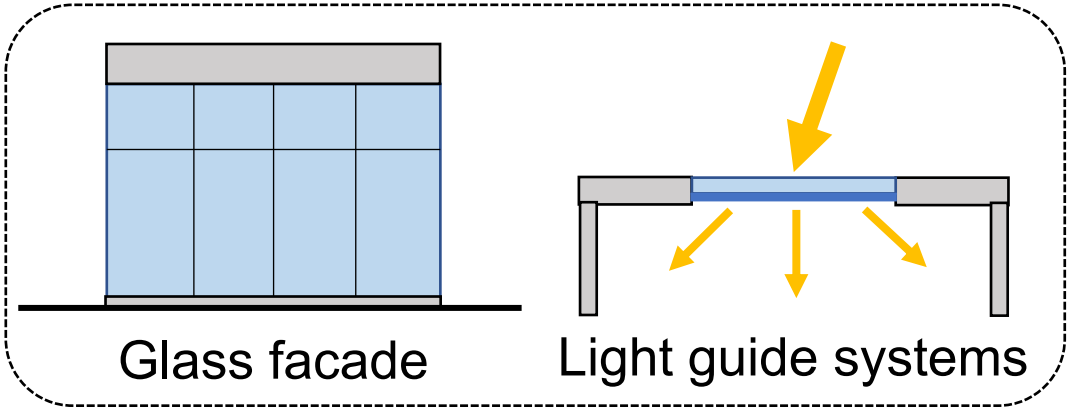


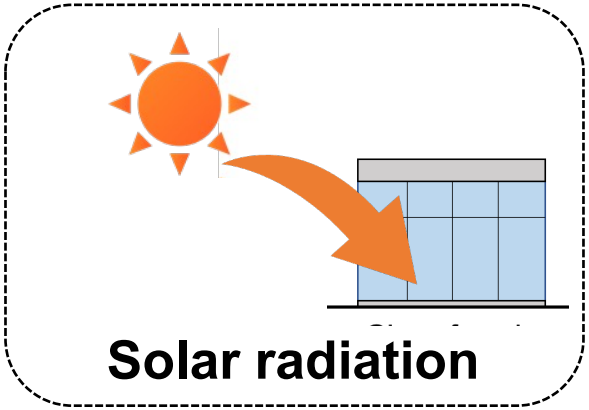
Apply to the thermal environment evaluation

Why do we challenge to apply Photon Flow to the thermal field ?

Introduction

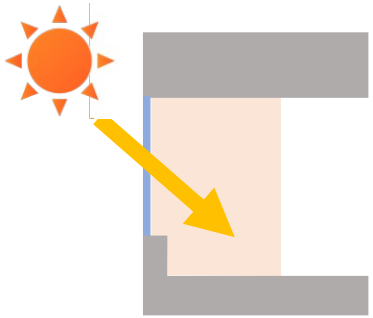
To ensure **view** and **daylight provision**…





What are the negative effects of **solar radiation** ?

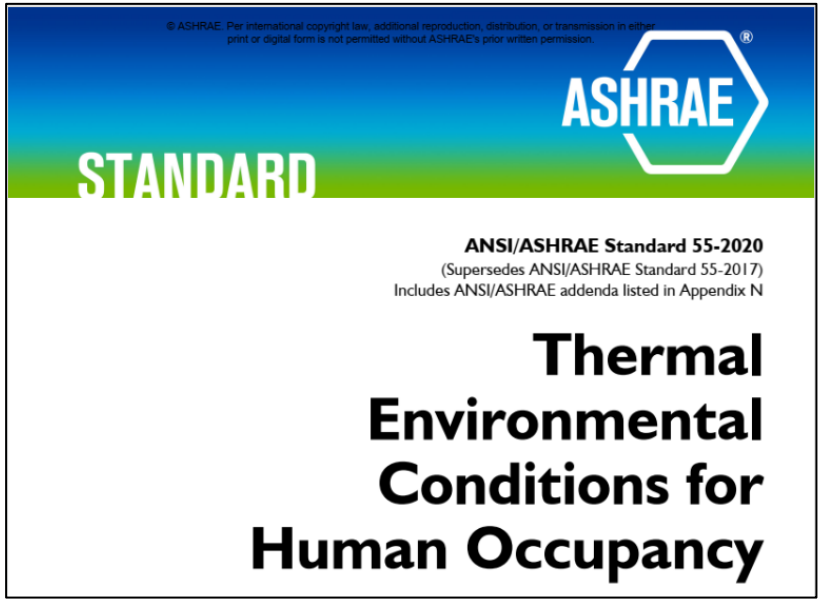
- Worsening of comfort in perimeter zones
- Significant impact on the air conditioning load

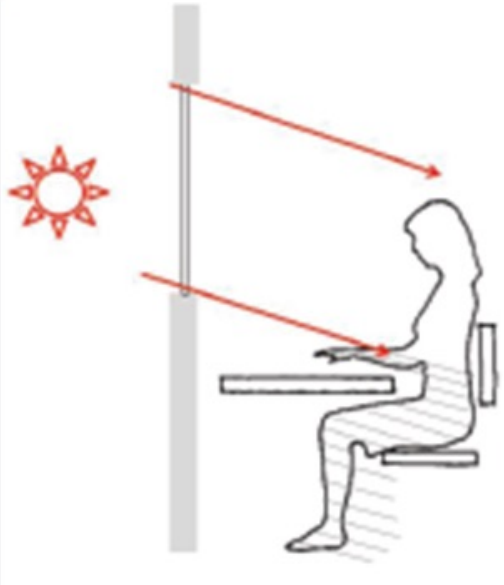


Solar radiation should be fully considered
in the early stages of design.

Introduction

ASHRAE provides a method to evaluate thermal comfort that takes into account the effects of solar radiation.





Introduction

ASHRAE provides a method to evaluate thermal comfort that takes into account the effects of solar radiation.

ERF_{solar}

(Effective Radiation Field by solar radiation absorbed on the body's surface)

Effective Radiation Field :
Measured net radiation flux to the human body [W/m^2]

A new PMV (Predicted Mean thermal sensation Votes)

for occupants exposed to solar radiation

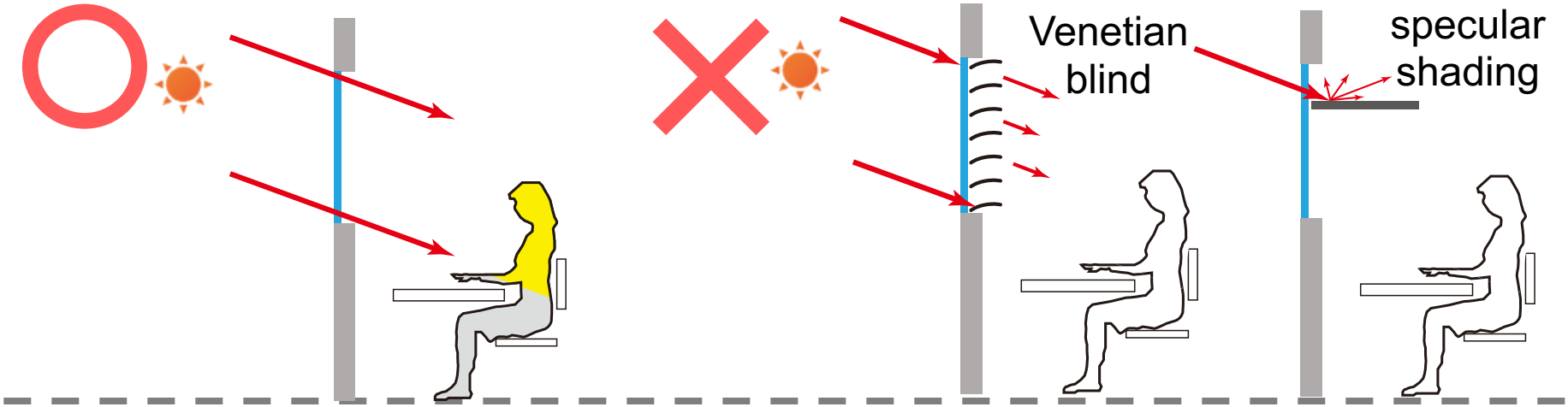
Introduction

ASHRAE provides a method to evaluate thermal comfort that takes into account the effects of solar radiation.

Problems with this method ….

- **The following variables are difficult to approximate when complex window equipment is installed.**
  - The percentage of sky from the position of each occupant
  - The percentage of bodies exposed to direct sunlight

Cases of window equipment ASHRAE can and cannot evaluate



Introduction

ASHRAE provides a method to evaluate thermal comfort that takes into account the effects of solar radiation.

Problems with this method ….

- **The following variables are difficult to approximate when complex window equipment is installed.**
  - The percentage of sky from the position of each occupant
  - The percentage of bodies exposed to direct sunlight

It takes too much time to **calculate with Standard Radiance (rtrace)**

by Zani et al. (2018).

Research Aims

The aim of this study is

to propose
a new method using **volume photon mapping**
to evaluate **ERFsolar with efficient calculation**
when complex window equipment (specular included) is installed.

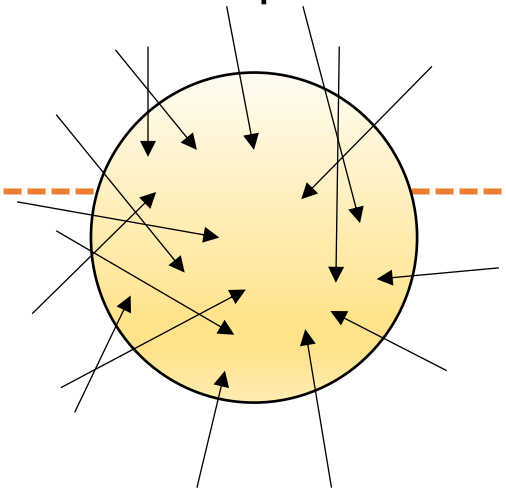
What's more …

With Photon Flow,
it would be possible to **visualize the effects of solar radiation**.

Verification Flow

What is Scalar irradiance obtained from volume photon mapping ?

- **Scalar illuminance** (Average sphere illuminance) 【lm/m^2】
  - Average illuminance on the surface of the microsphere in a space



- **Scalar irradiance** 【W/m^2】

$$\textit{Scalar irradiance} = \frac{\textit{Radiant flux incident on the surface of the microsphere}}{\textit{Surface area of the microsphere}}$$

- **Scalar irradiance** is an extension of the scalar illuminance.
- **Scalar irradiance** can be evaluated from Photon density.
- **Scalar irradiance** has never used in the thermal environment of building.

Verification Flow

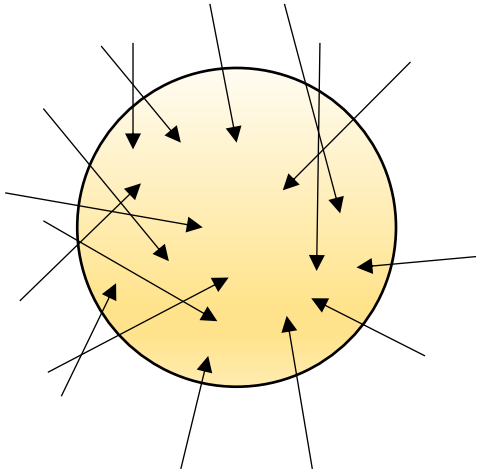
ERF_{solar} (Effective radiation field by solar radiation [W/m^2])

Effective radiation field : Measured net radiation flux to or from the human body

Comparison

Scalar irradiance [W/m^2]

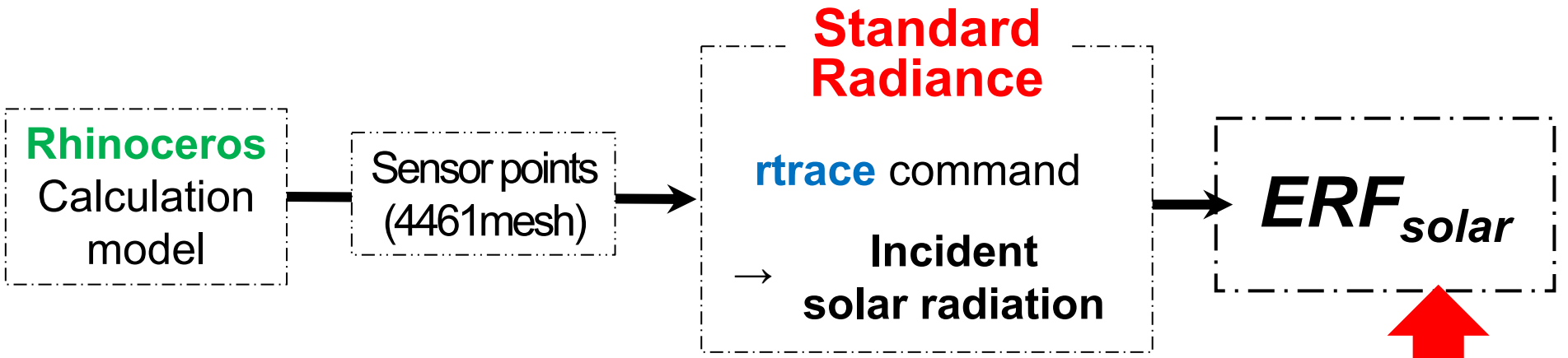
$$Scalar\ irradiance = \frac{Radiant\ flux\ incident\ on\ the\ surface\ of\ the\ sphere}{Surface\ area\ of\ the\ sphere}$$



We verify whether the scalar irradiance derived from volume photon mapping can predict the solar radiation environment for occupants.

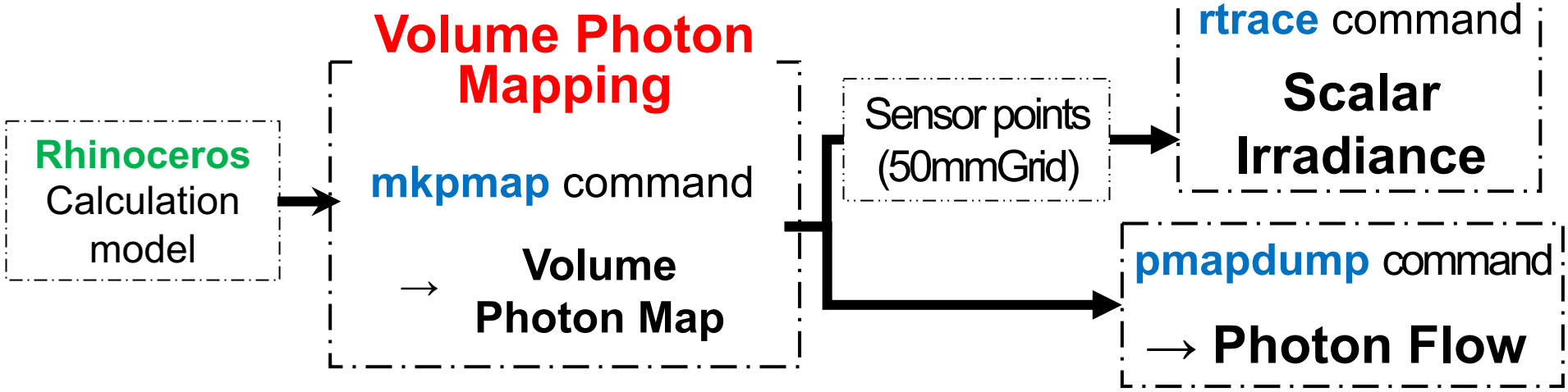
Verification Flow

Method 1



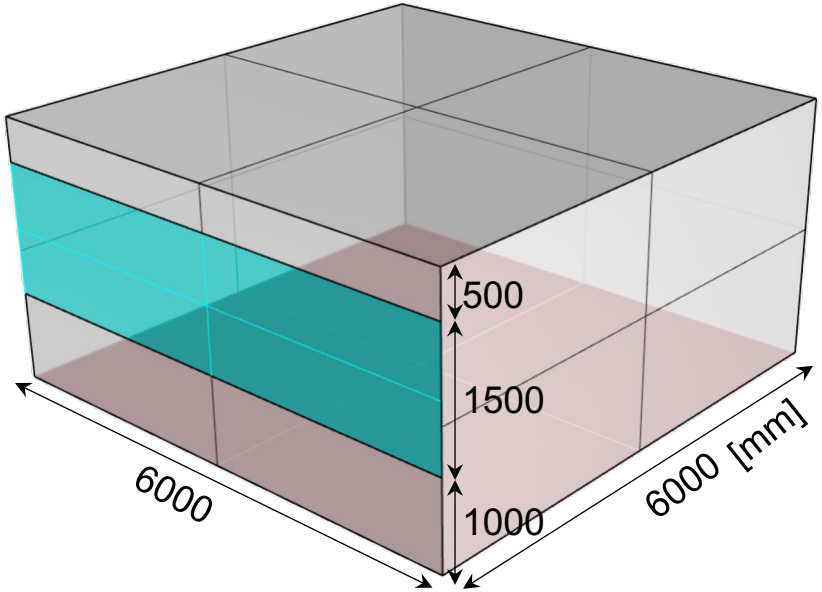
Comparison

Method 2

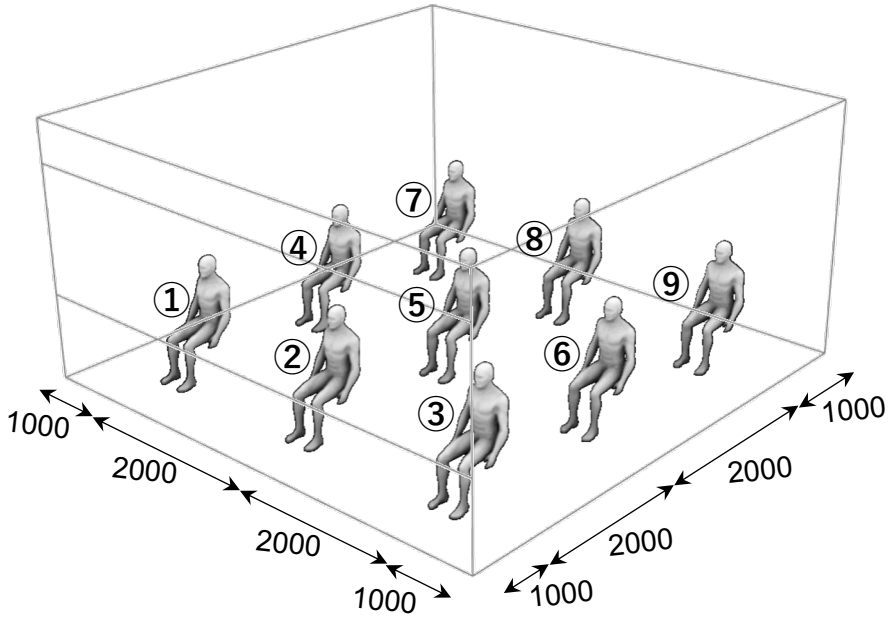


Calculation Model : No Shading

➢ Calculation model



➢ Occupants' position



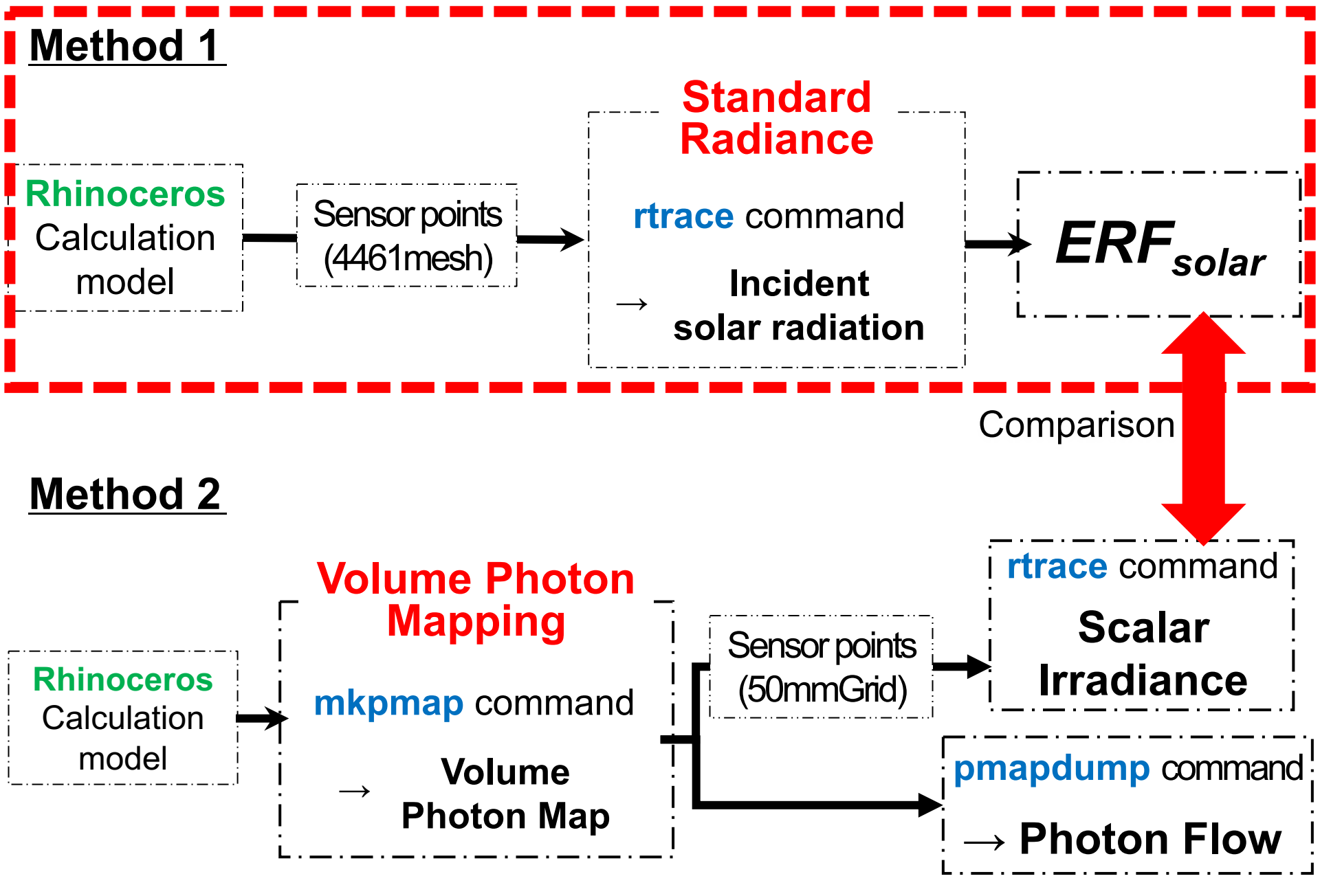
➢ Input value

reflectance	floor	0.2
	wall	0.5
	ceiling	0.7
transmittance	glass	0.8

➢ Sky data

Create sunny sky in Tokyo using gendaylit command

Verification Flow



Method 1 : Calculate ERF_{solar} based on Standard Radiance

Rhinoceros
Calculation model

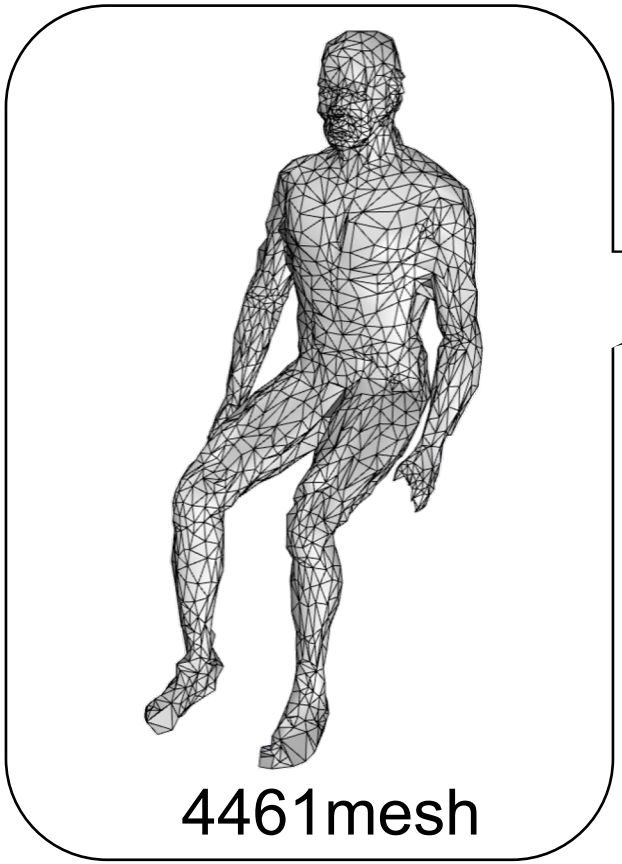
Sensor points (4461mesh)

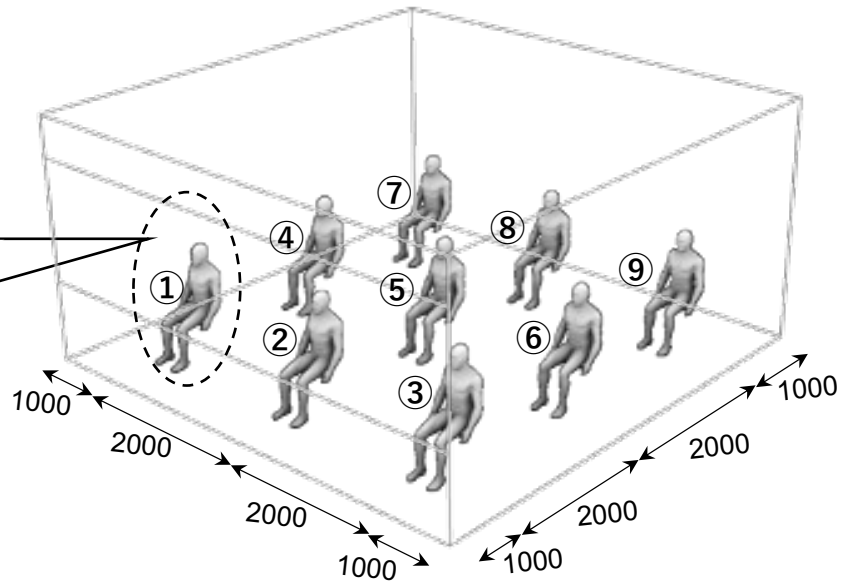
Standard Radiance

rtrace command

→ **Incident solar radiation**

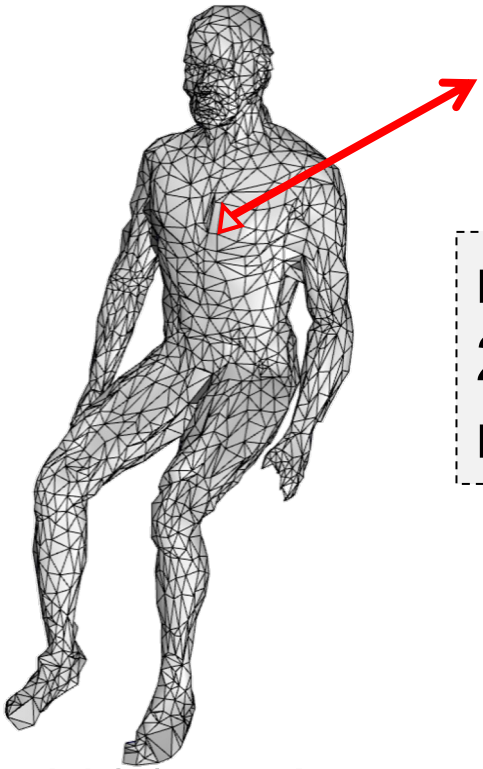
ERF_{solar}





Method 1 : Calculate ERF_{solar} based on Standard Radiance

Rhinoceros Calculation model → Sensor points (4461mesh) → **Standard Radiance** (**rtrace** command → **Incident solar radiation**) → ***ERF_{solar}***



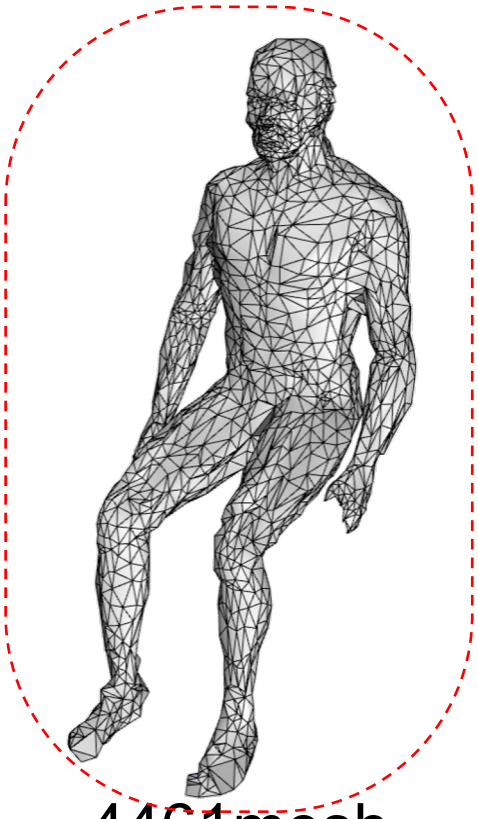
4461mesh

Calculate the incident solar radiation (E_{solar}) for each mesh

```
rtrace -aa 0.15 -ab 6 -ad 4096 -ar 256 -as
2048 -dr 1 -dt 0.15 -h -I ***.oct < ***.pts |
rcalc -e '$1=(0.265*$1+0.67*$2+0.065*$3)*1'
```

Method 1 : Calculate ERF_{solar} based on Standard Radiance

Rhinoceros Calculation model → Sensor points (4461mesh) → **Standard Radiance**: **rtrace** command → **Incident solar radiation** → ERF_{solar}



4461mesh

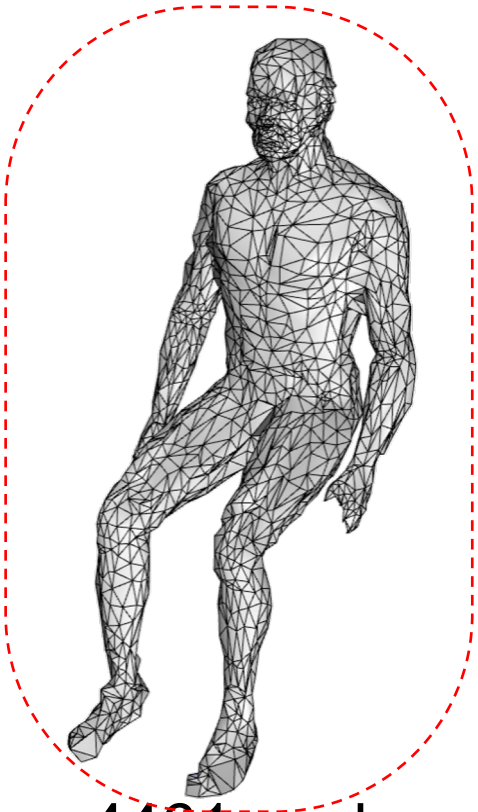
Input the incident solar radiation calculated by rtrace

$$ERF_{solar} = \frac{\alpha_{SW}}{\alpha_{LW}} \sum_{i=1}^{4461} \frac{E_{solar,i} A_i}{A}$$

Calculate $\boldsymbol{ERF_{solar}}$ according to the ASHRAE APPENDIX C formula

Method 1 : Calculate ERF_{solar} based on Standard Radiance

Rhinoceros Calculation model → Sensor points (4461mesh) → **Standard Radiance** (**rtrace** command → **Incident solar radiation**) → ***ERF_{solar}***



4461mesh

$$ERF_{solar} = \frac{\alpha_{SW}}{\alpha_{LW}} \sum_{i=1}^{4461} \frac{E_{solar,i} A_i}{A}$$

Other factors

A : the total mesh area of the manikin [m^2]

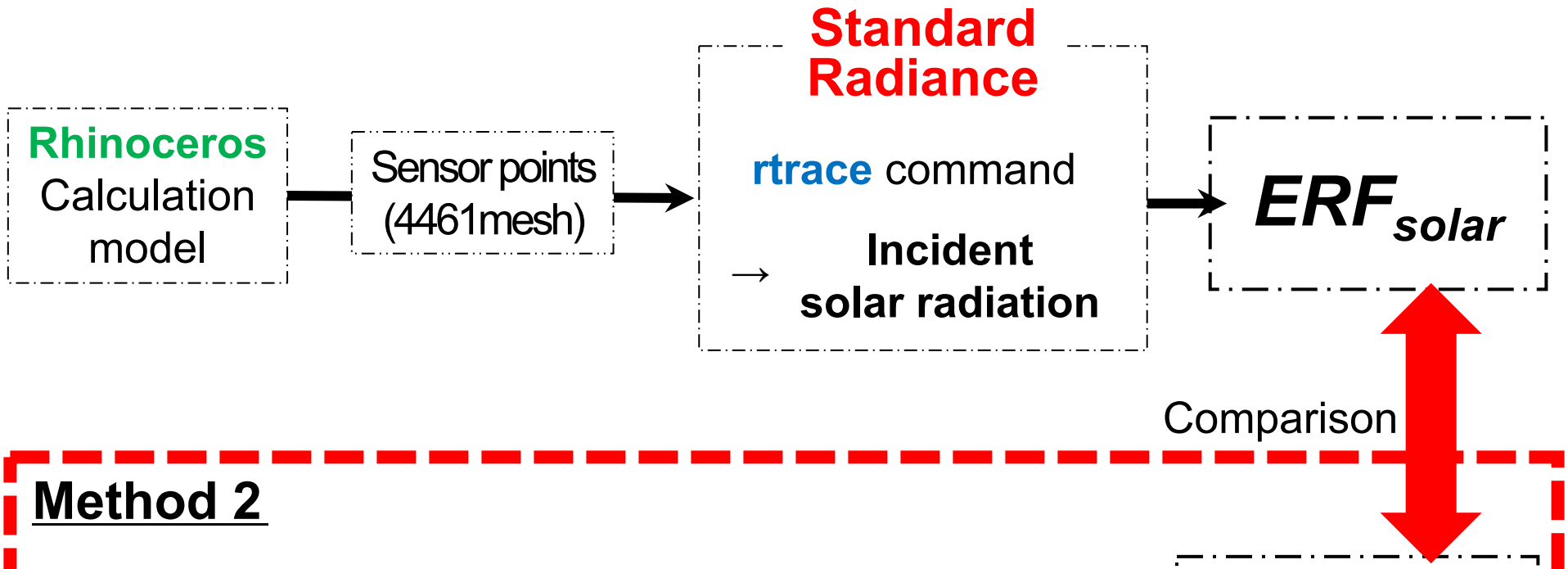
A_i : the mesh area of the i_{th} mesh [m^2]

α_{SW} : Short-wave radiation absorptivity

α_{LW} : Long-wave radiation absorptivity

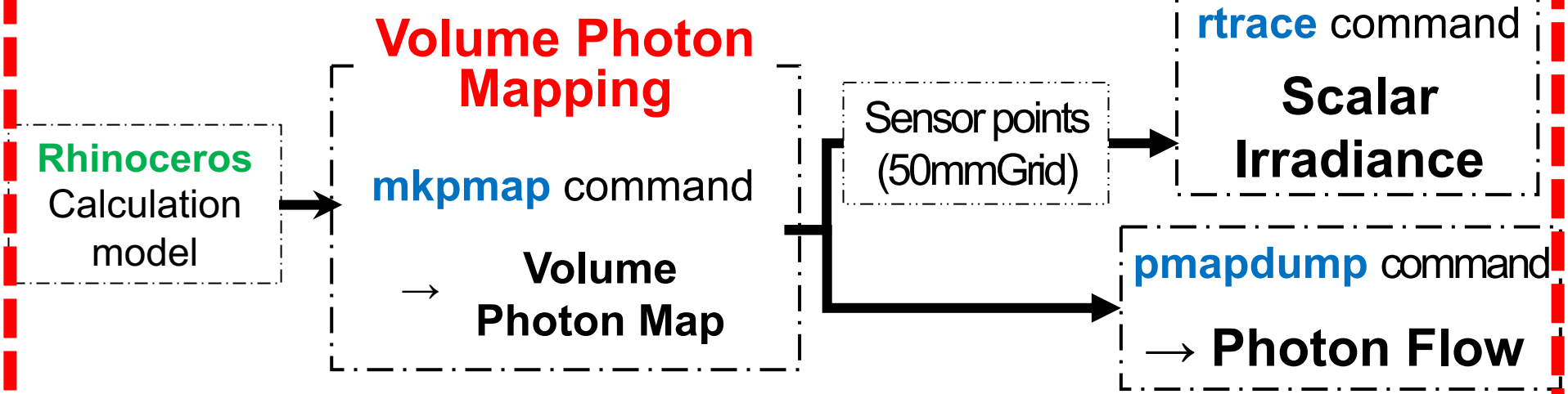
Verification Flow

Method 1

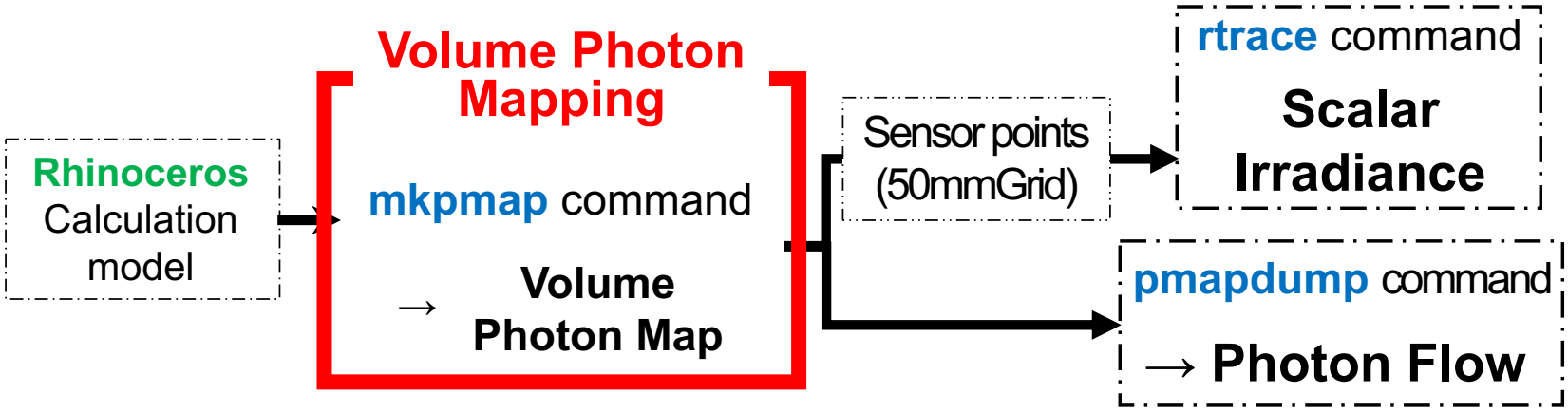


Comparison

Method 2



Method 2 : Calculate Scalar Irradiance based on Volume Photon Map



1) Make volume photon map

```
mkpmap -me .1 .1 .1 -ma 1 1 1 -mg 1 -apo+ window -aph
floor -aph wall -aph ceiling -aph window -apV ***vpm 100k
-n 4 -apD .1 -t 1 -fo ***.oct
```

Method 2 : Calculate Scalar Irradiance based on Volume Photon Map

1) Make volume photon map

```
mkpmap -me .1 .1 .1 -ma 1 1 1 -mg 1 -apo+ window -aph
floor -aph wall -aph ceiling -aph window -apV ***vpm 100k -
n 4 -apD .1 -t 1 -fo ***.oct
```

【Major parameters】

- *-me* : Defines linear photon density along path
- *-apo[+|-]* : Set the photon port
- *-aph* : Defines all polygons using the material modifier mod as part of a polyhedral region of interest(ROI)
- *-apV <pm> <N>* : Output volume photon map included *N* photons

Method 2 : Calculate Scalar Irradiance based on Volume Photon Map

Rhinoceros
Calculation model

Volume Photon Mapping

mkpmap command

→ **Volume Photon Map**

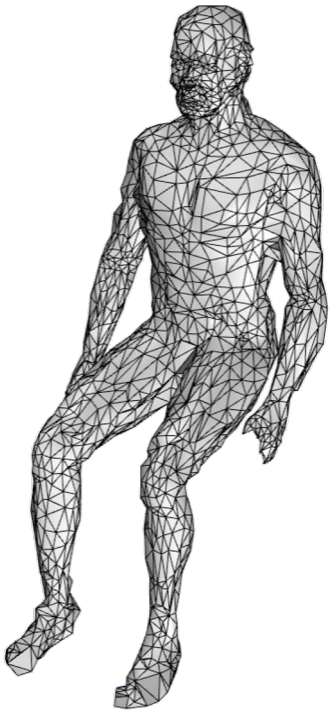
Sensor points (50mmGrid)

rtrace command

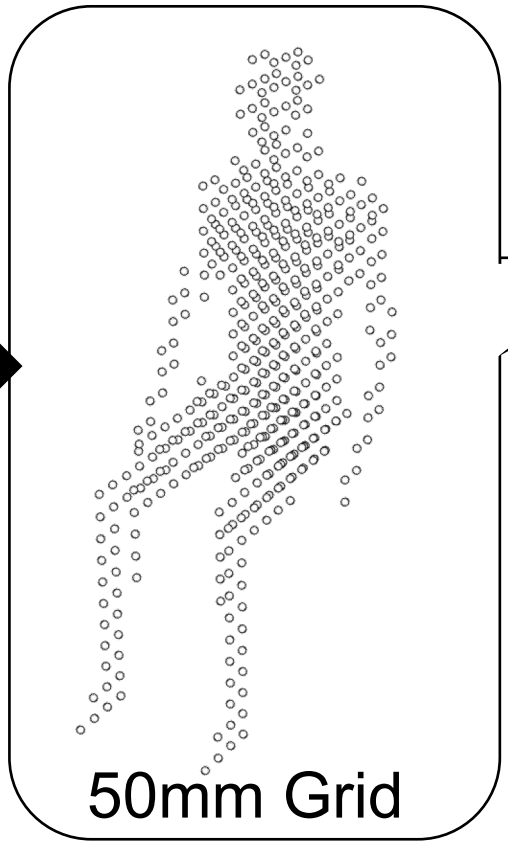
Scalar Irradiance

pmapdump command

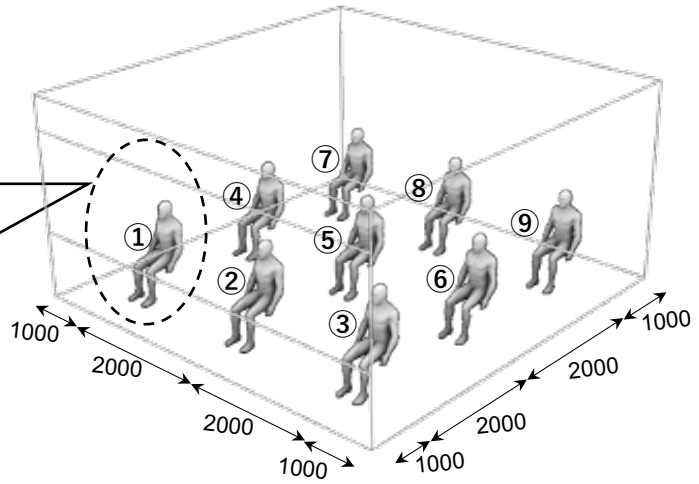
→ **Photon Flow**



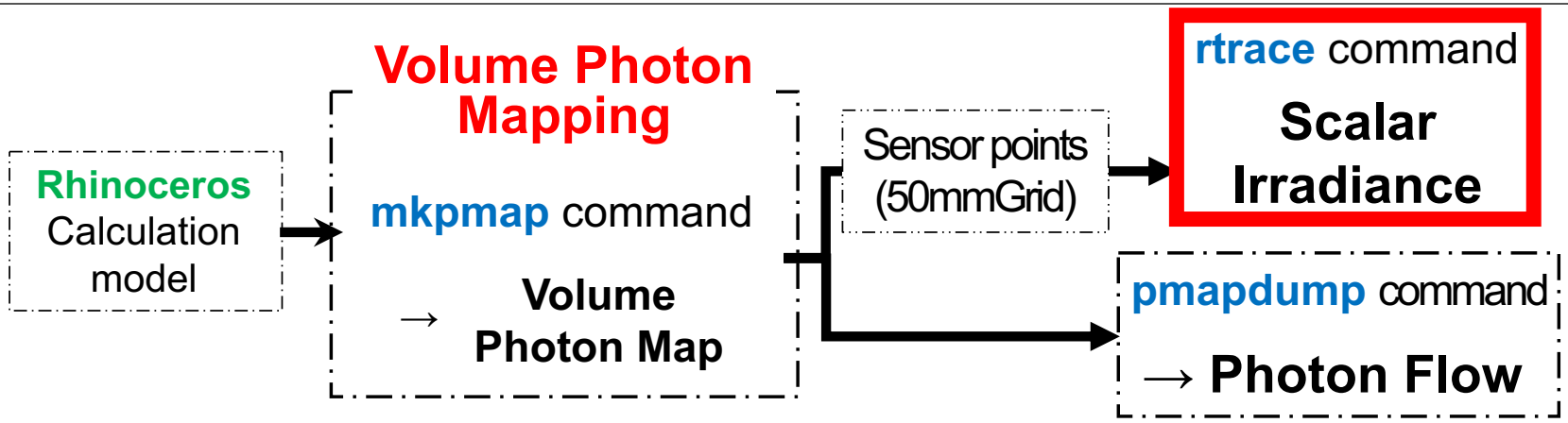
4461mesh



50mm Grid



Method 2 : Calculate Scalar Irradiance based on Volume Photon Map

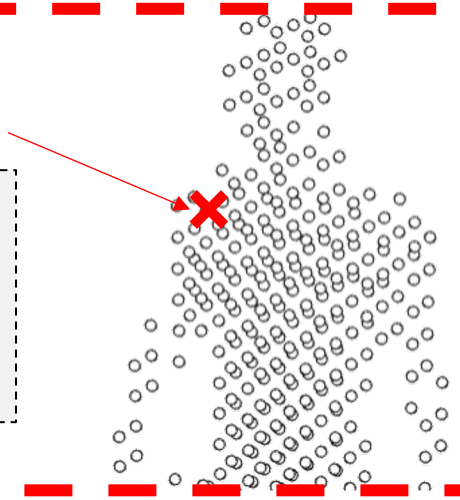


1) Create volume photon map

```
mkpmap -me .1 .1 .1 -ma 1 1 1 -mg 1 -apo+ window -aph
floor -aph wall -aph ceiling -aph window -apV ***.vpm 100k
-n 4 -apD .1 -t 1 -fo ***.oct
```

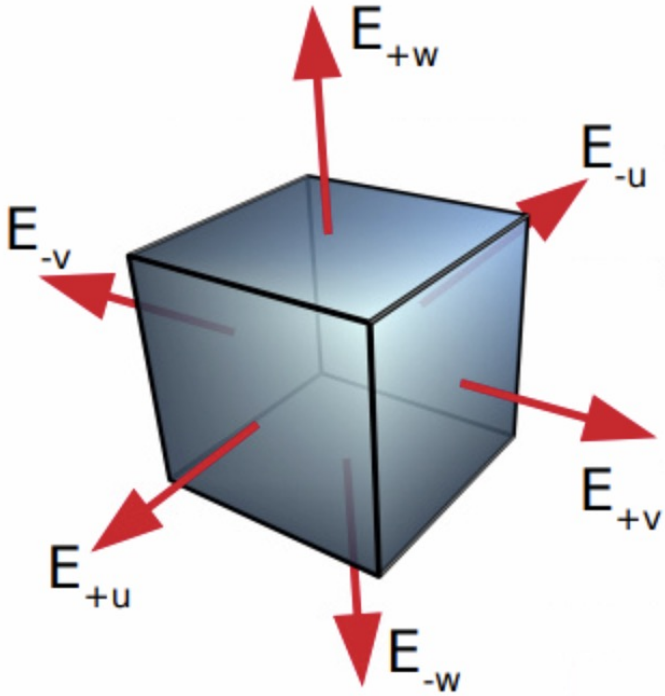
2) Calculate scalar irradiance for each point

```
rtrace -h -I -ap ***.vpm 1000 -aS- ***.oct
< ***.pts | rcalc -e '$1=
1*(0.265*$1+0.67*$2+0.065*$3)'
```



Method 2 : Calculate Scalar Irradiance based on Volume Photon Map

Cubic illuminance: approximate scalar Illuminance by 6 measurements on cube faces along orthogonal u,v,w axes



$$\text{Vector illum } \vec{E}_i = E_{+i} - E_{-i}, \quad i \in \{u, v, w\}$$

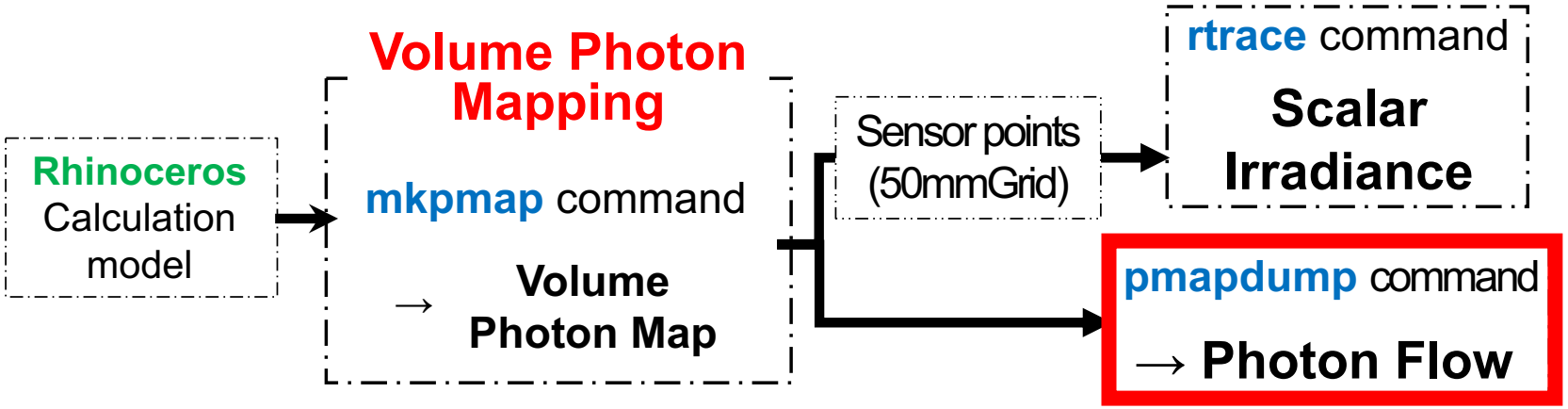
$$\text{Symmetric illum } \tilde{E} = \frac{\tilde{E}_u + \tilde{E}_v + \tilde{E}_w}{3},$$

$$\text{where } \tilde{E}_i = \frac{E_{+i} + E_{-i} - |\vec{E}_i|}{2}, \quad i \in \{u, v, w\}$$

$$\textbf{Scalar illum } E_s = \tilde{E} + \frac{\|\vec{E}\|}{4}$$

※In this study, replace illuminance with irradiance.

Method 2 : Calculate Scalar Irradiance based on Volume Photon Map



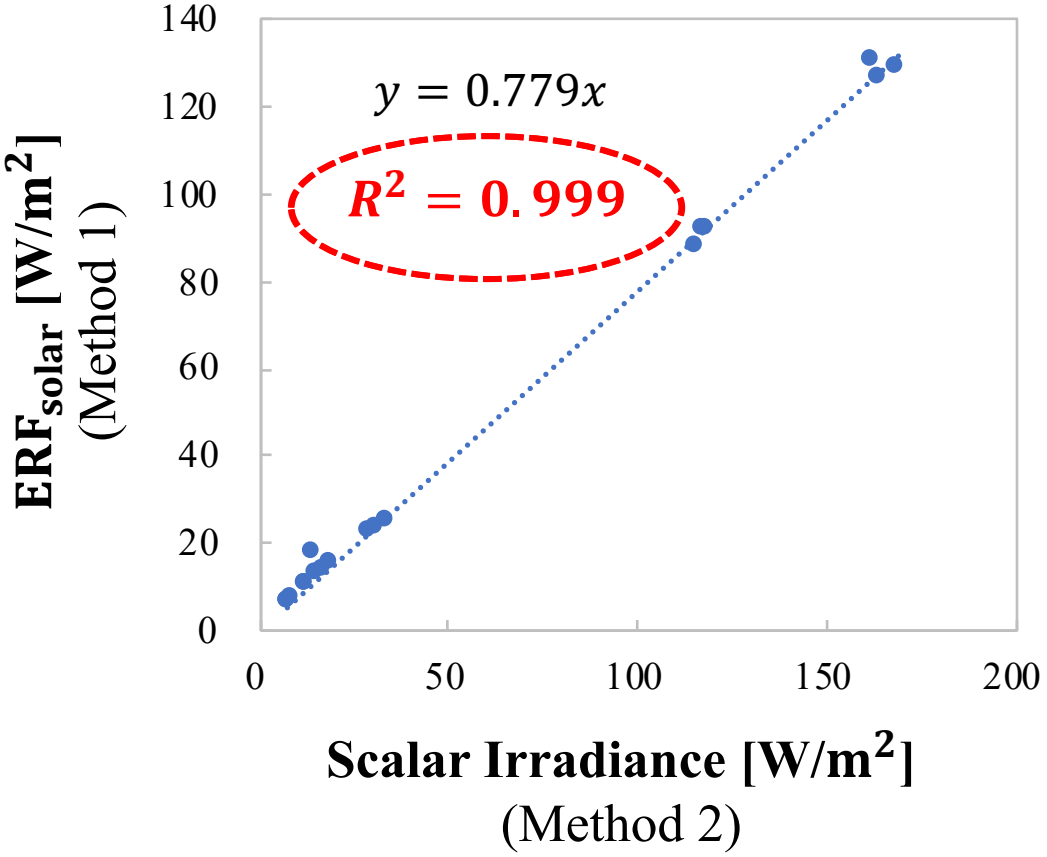
3) Visualization of photons

```
pmapdump -a -f -n 100k ***.vpm > ***.xyz
```

Visualise the photon distribution from a photon map file

Comparison between Method1 and Method2

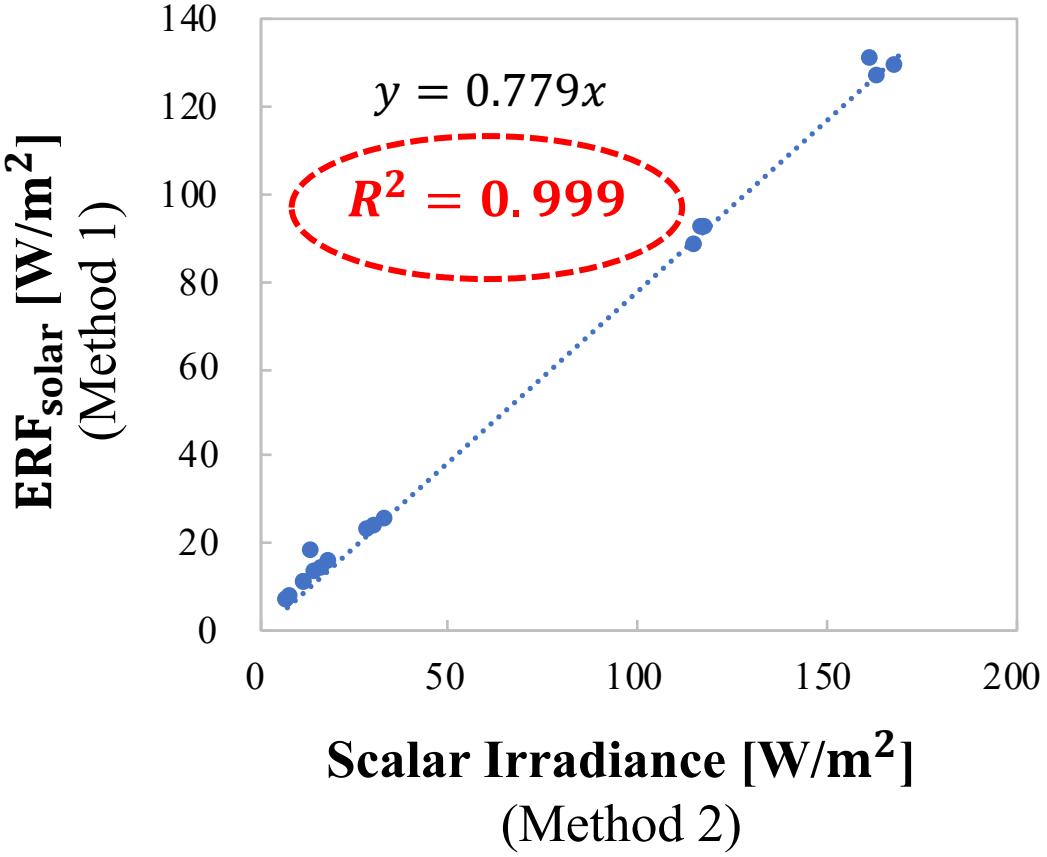
- Result of 12:00 on the summer and winter solstices (sunny day)



The coefficient of determination shows a strong agreement (0.999)

Comparison between Method1 and Method2

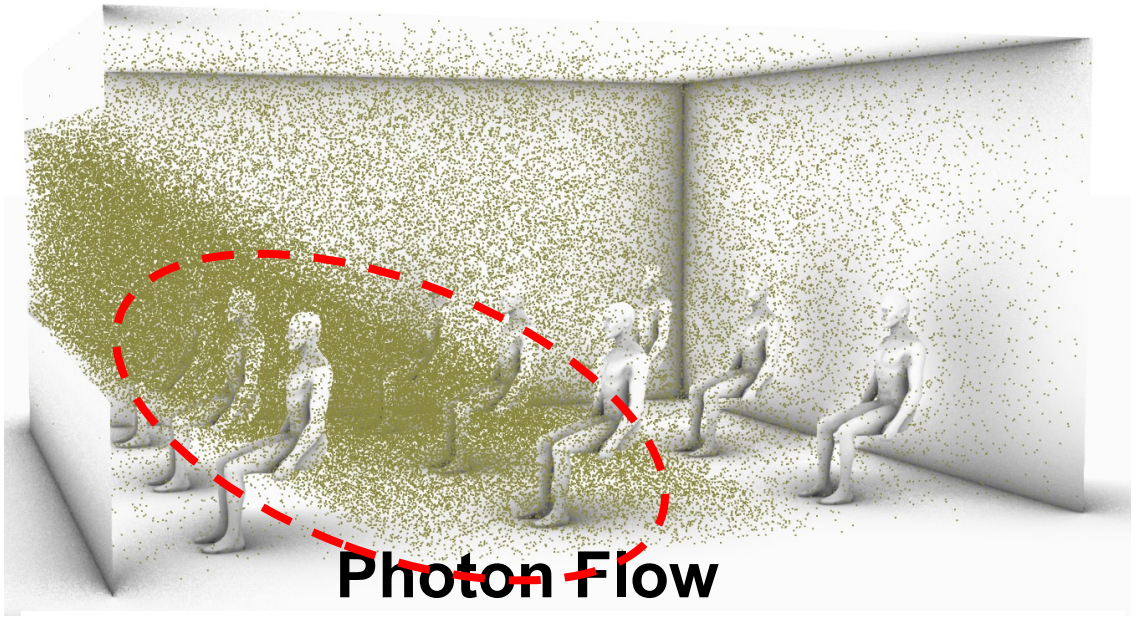
- Result of 12:00 on the summer and winter solstices (sunny day)

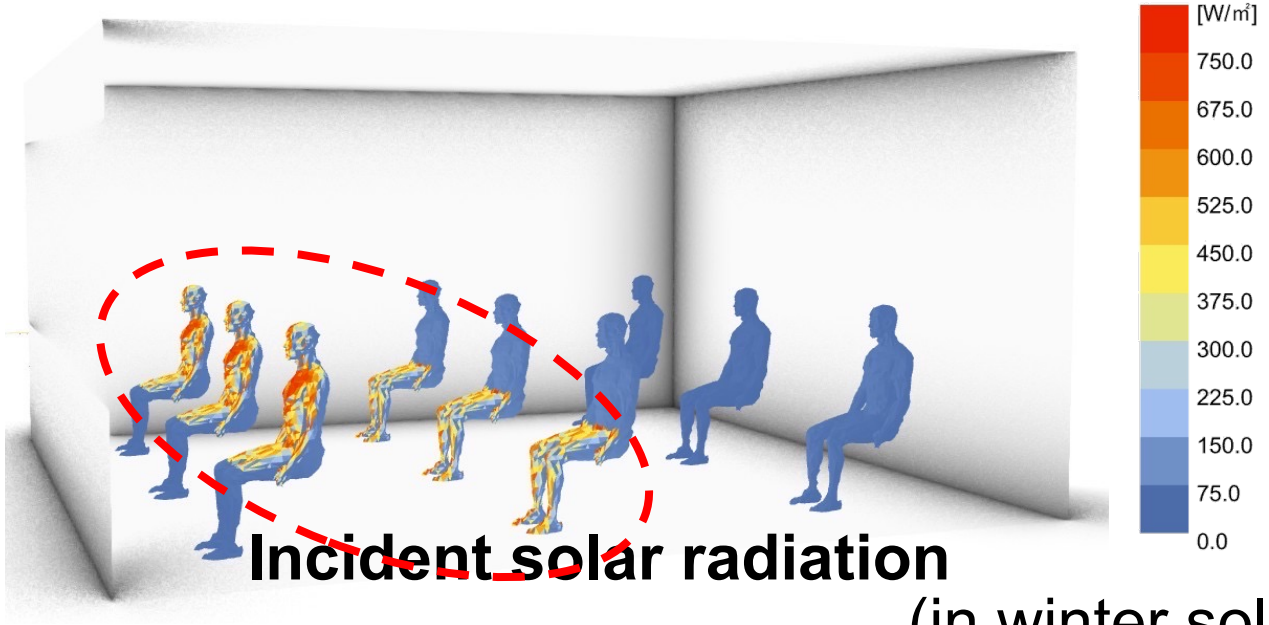


The coefficient of determination shows a strong agreement (0.999)

Scalar irradiance has a strong correlation with ERF_{solar}

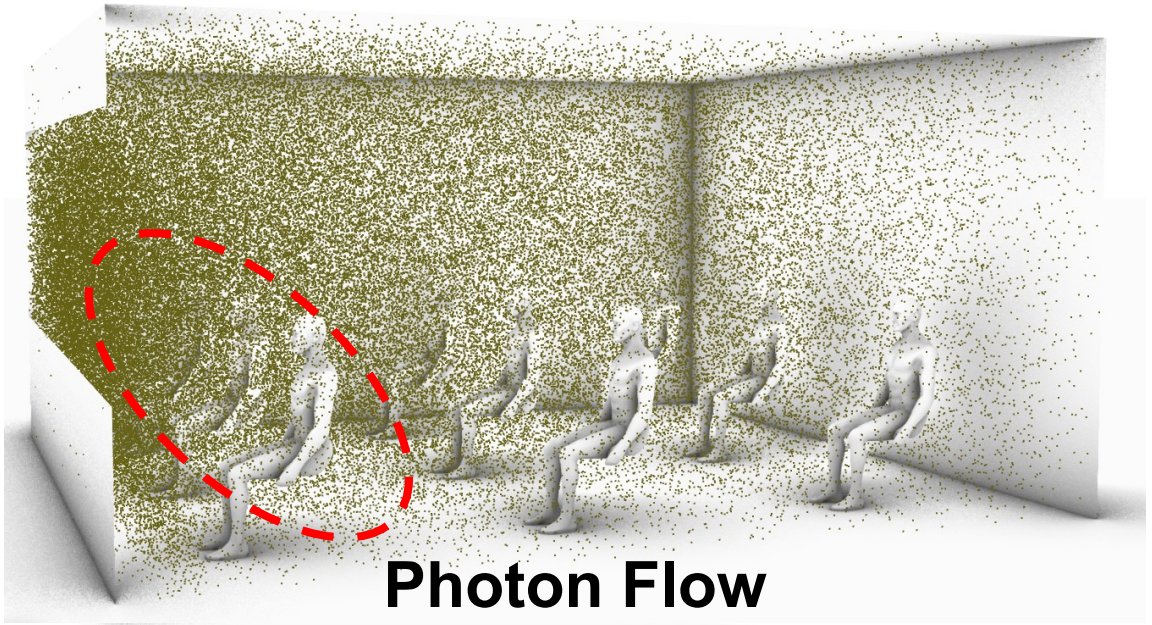
Visualization of solar radiation



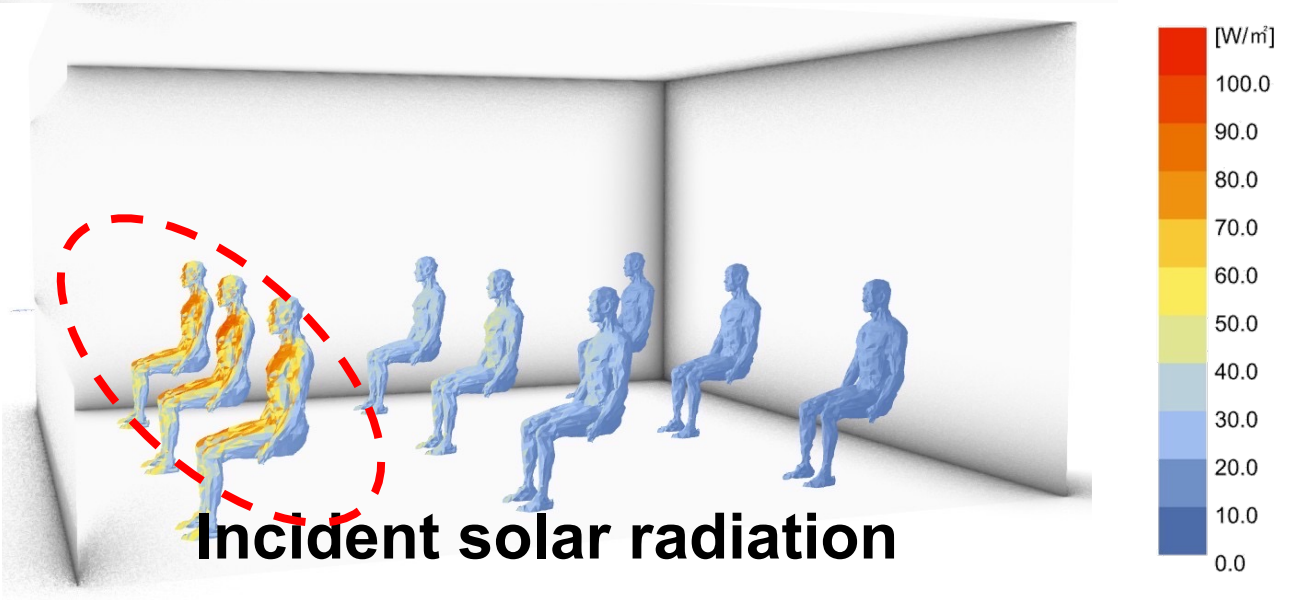


(in winter solstices)

Visualization of solar radiation



Photon Flow



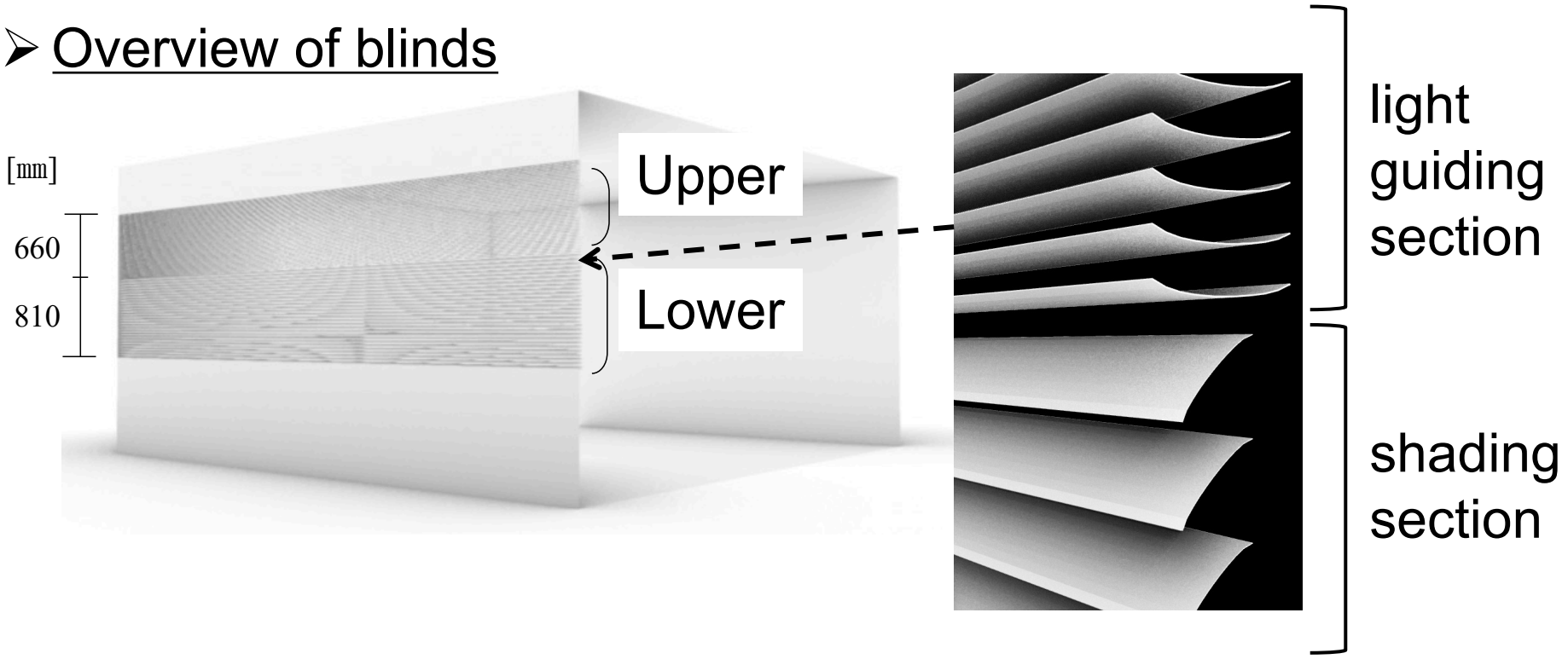
Incident solar radiation

(in summer solstices)

Calculation Model : Complex Shading

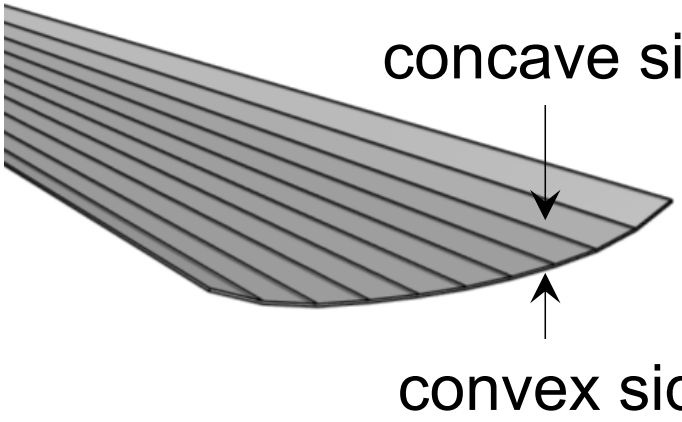
◆Calculate with **Shading including the specular component**

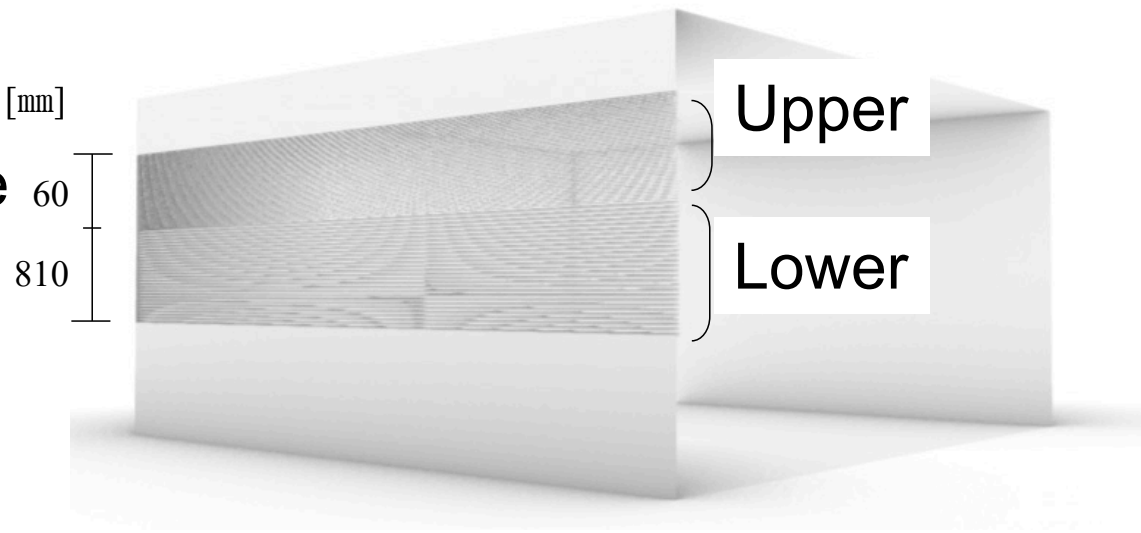
➢ Overview of blinds



Calculation Model : Complex Shading

➢ Overview of blinds





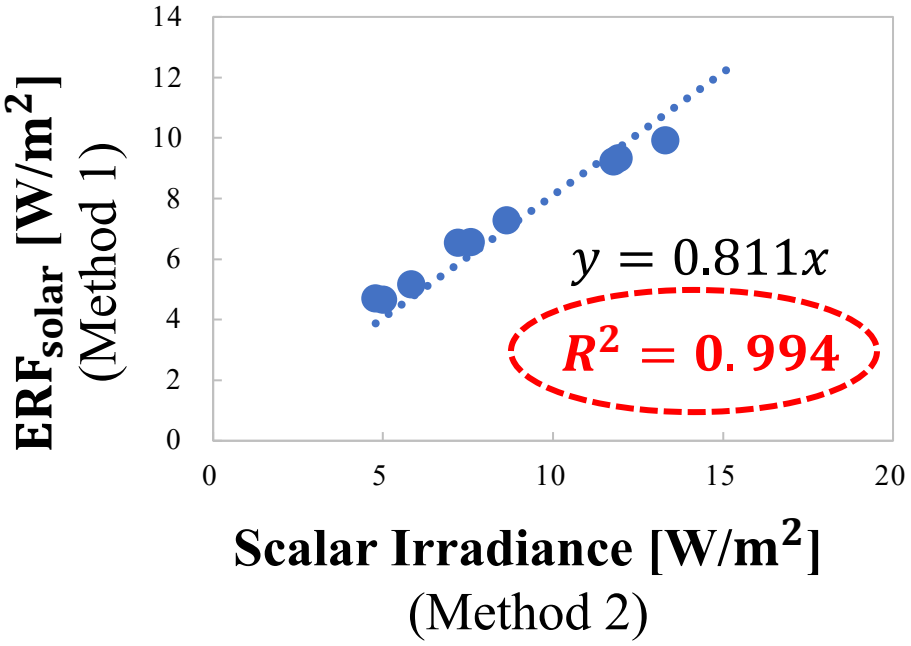
➢ Set value

	Upper slat				Lower slat (45°)	
	concave side		convex side			
	Total	Diffuse	Total	Diffuse	Total	Diffuse
Solar reflectance [%]	80	10	50	50	70	70
Specular [%]	70		0		0	

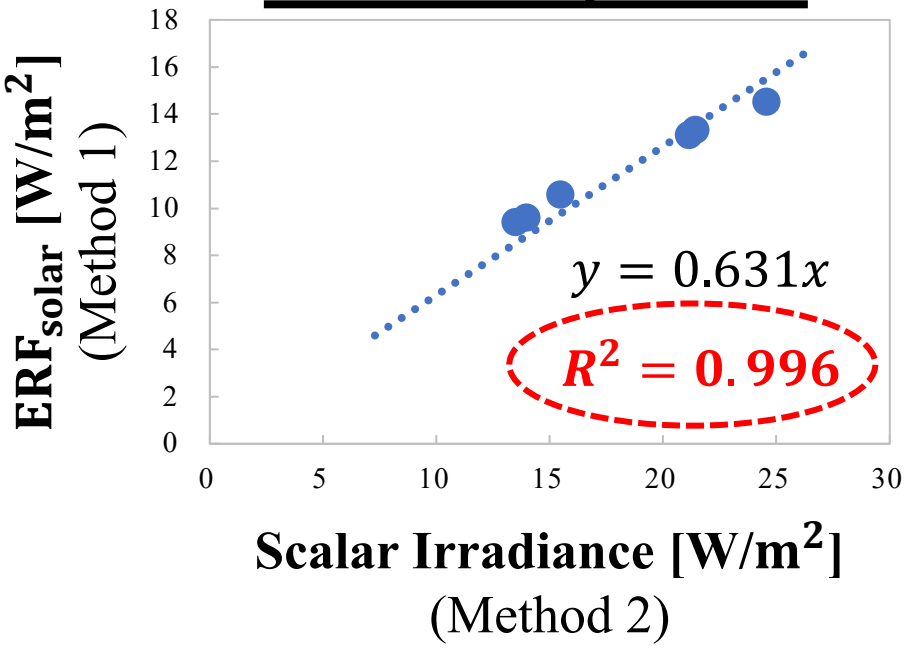
Comparison between Method1 and Method2

➢ Result of 12:00 on the summer and winter solstices (sunny day)

Shading :
diffuse only



Shading :
diffuse + specular

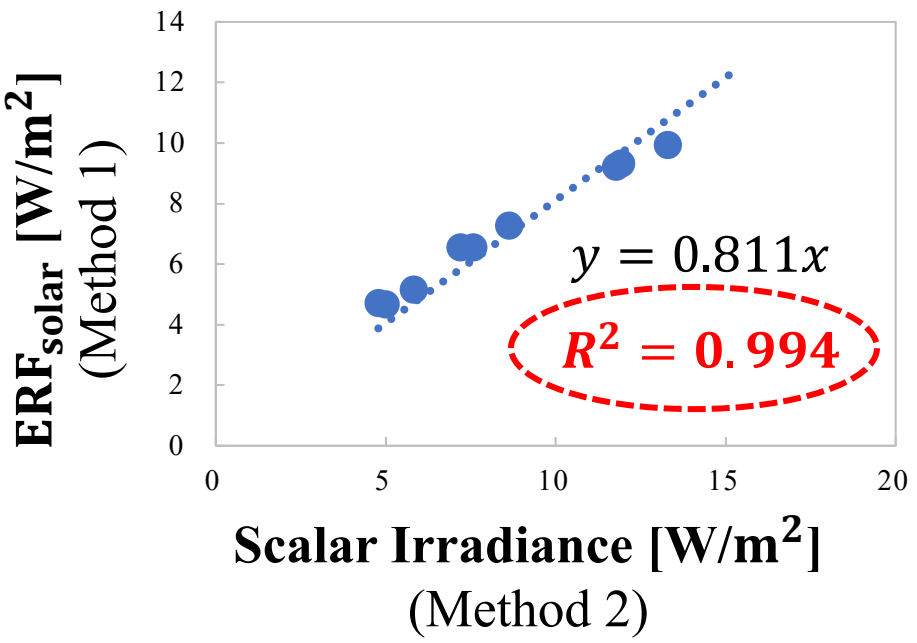


The coefficient of determination shows a strong agreement

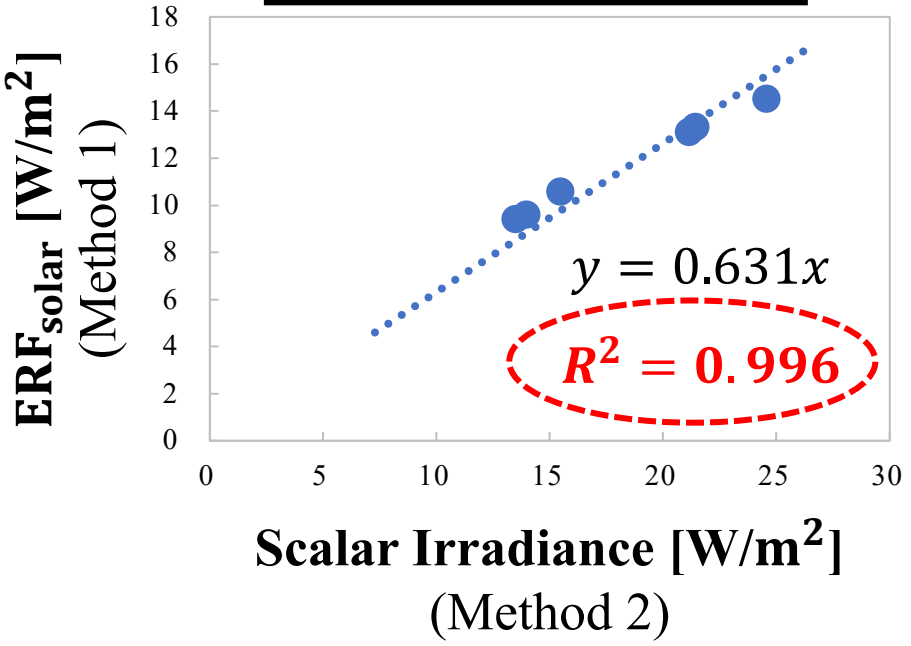
Comparison between Method1 and Method2

➢ Result of 12:00 on the summer and winter solstices (sunny day)

Shading :
diffuse only



Shading :
diffuse + specular



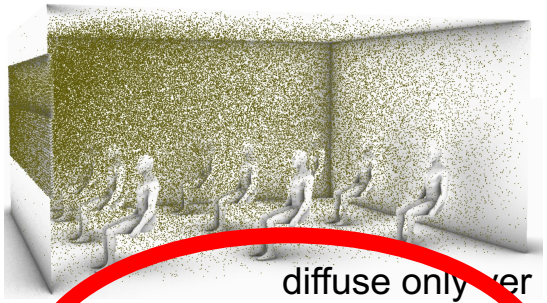
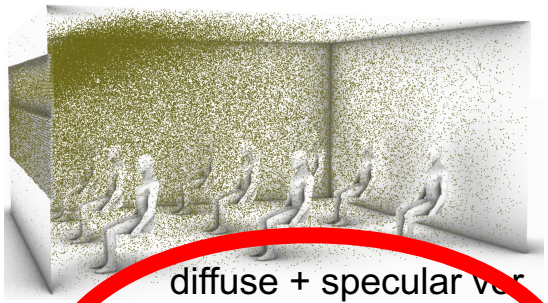
The coefficient of determination shows a strong agreement

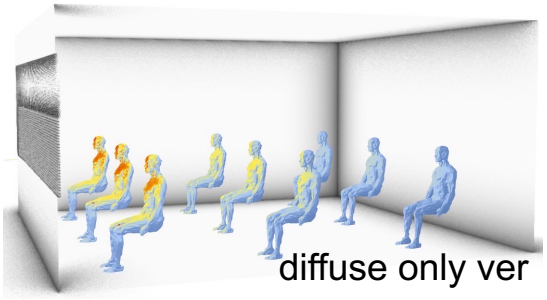
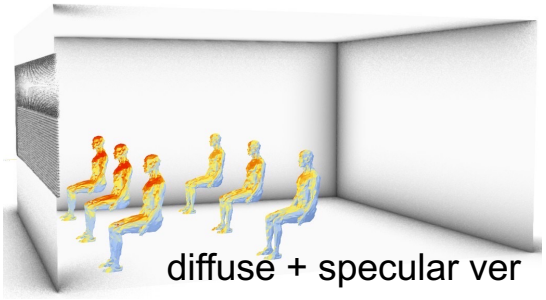
⬇

Scalar irradiance has a strong correlation with ERF_{solar}

Comparison of computational load

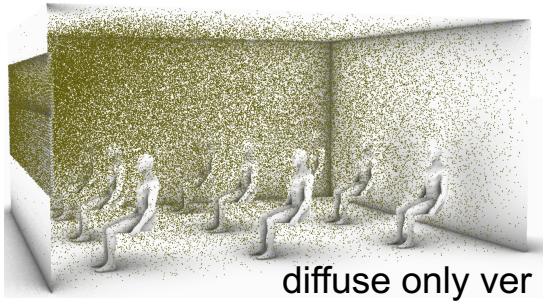
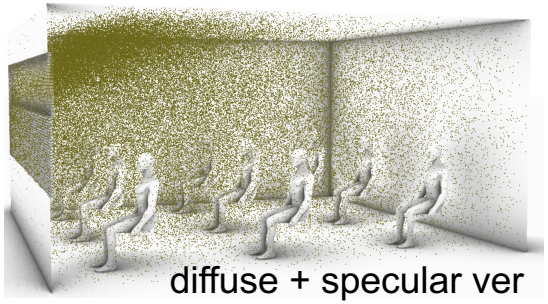
➢ Under the complex shading

Volume Photon Mapping (Method 2)		
	 diffuse only ver	 diffuse + specular ver
Calculation time	**3 min**	**3 min**

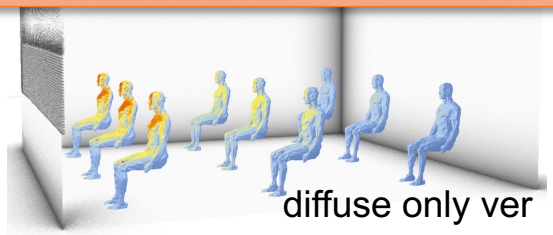
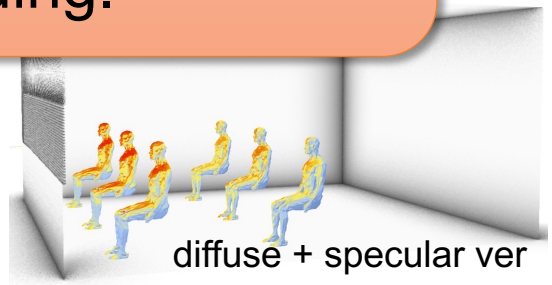
Classic Radiance (Method 1)		
	 diffuse only ver	 diffuse + specular ver
Calculation time	**12h 55min**	**65h 30min**

Comparison of computational load

➢ Under the complex shading

Volume Photon Maping (Method 2)		
	 diffuse only ver	 diffuse + specular ver
Calculati		

Volume Photon Map Method is
more computationally efficient,
under complex shading.

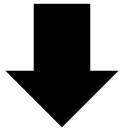
	 diffuse only ver	 diffuse + specular ver
Calculation time	**12h 55min**	**65h 30min**

Conclusion

The thermal comfort considering solar radiation shown in ASHRAE Standard 55

Scalar Irradiance ⟷ ERF_{solar}

The correlation was confirmed.



The **Volume Photon Mapping** method can

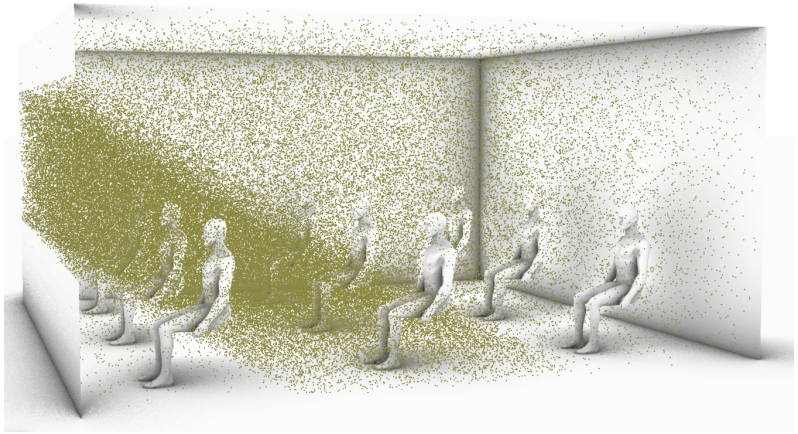
predict the solar radiation environment

with high accuracy.

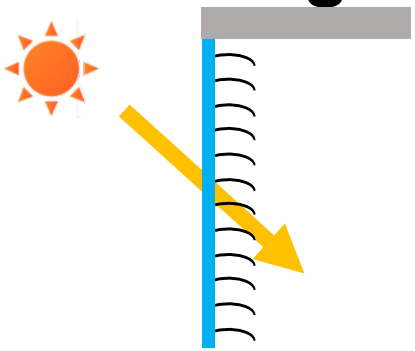
Conclusion

Volume Photon Mapping and **Phton Flow** has **advantages** compared to ERF_{solar} in terms of …

1) Visualization of the effect of solar radiation

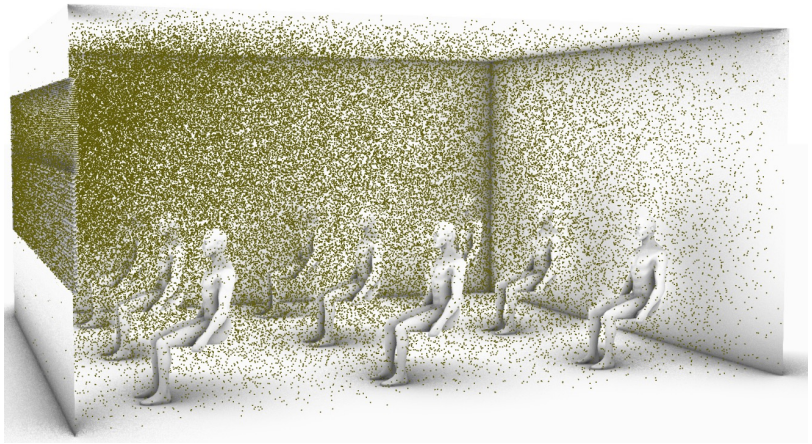


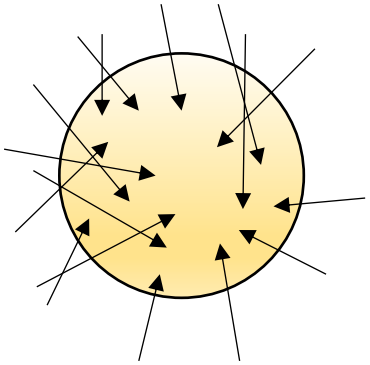
2) Efficient calculation under complex shadings (especially specular included)



Future plan

- Verification under **various shading and building conditions with actual measurement**
  - continue to expand the possibilities of the method using scalar irradiance.



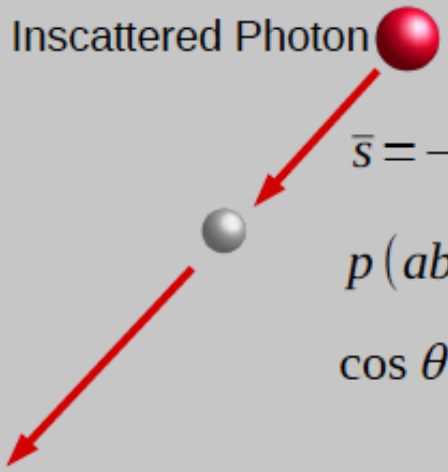


Thank you for your attention!!

Volume Photon Scattering in Photon Flow

"Hack" *mist* so it does not interfere with photon flow!

- Extinction σ_t → photon density along path; does not alter overall density, but flux/photon → **needs correction!**
- No absorption: **force albedo α = 1**
- Forward scattering only: **force eccentricity g = 1**



$$\bar{s} = -\frac{\log \xi}{\sigma_t}, \quad random\ \xi \in [0,1]$$

$$p(absorption) = 0 \rightarrow \alpha = 1$$

$$\cos\theta = 1 \rightarrow g = 1$$

Input values required for ERF_{solar} for ASHRAE's method

Symbol	Description	Set Value	Unit
f_{svv}	Fraction of sky vault exposed to body	0.039	-
I_{dir}	Direct solar beam intensity	839	W/m^2
f_{bes}	Fraction of the possible body surface exposed to sun	0.494(0)	-
T_{sol}	Window system glazing unit plus shade solar transmittance	0.800(0.493)	-
α_{SW}	Short-wave radiation absorptivity	0.700	-
f_{eff}	Fraction of body surface exchanging radiation with surroundings	0.696	-
h_r	Radiation heat transfer coefficient	6.00	W/m^{2}K
I_{diff}	Direct solar beam intensity	72.6	W/m^2
I_{TH}	Total horizontal solar intensity	500	W/m^2
f_p	Projected area factor	-	-
E_{solar}	Total short-wave solar radiant flux	-	W/m^2

※These are the values at the center position at 12:00 on the winter solstice.
In the calculation in Chapter 4, f_{bes} and T_{sol} are changed to the values in ( ).

These coefficient set up mainly according to ASHRAE's description.

generate sky

- Case of winter solstice sky at 12 pm.

```
gendaylit 12 22 12 -W 839.0 76.0 -a 35.69 -o -139.76 -m -135.0 -O 1
```

imput the irradiance values
obtaind from .epw data for Otemachi
Tokyo

output is set to the solar
radiance