

Optimal Parameters for Photon Flow in VR Spaces: A Case Study in a Real-World Architectural Space

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Outline

1. Motivation and Purpose

- Photon Flow
- Previous Work (2025 WS) — Colour-Encoded Directional Photon Flow
- Lighting Designer Feedback
- Critical Challenge — Parameter Dependencies in Photon Maps

2. Derivation of Optimal Parameters

- Optimal photon count
- Experiment Overview
- Optimal extinction coefficient

3. Case Study: Syourinji Kannon-do Temple

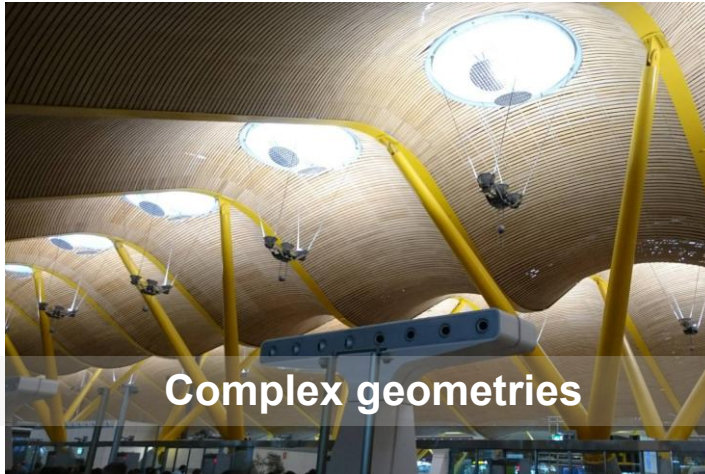
- Overview of the Target Space
- Parameter Application based on Proposed Formulas
- Lighting Designer Feedback & Evaluation

4. Conclusion and Future Work

- Conclusion
- Future Work & TODO

1. Motivation and Purpose

Buildings with complex geometries and lighting environments



Understanding the flow of light within a space is sometimes difficult.



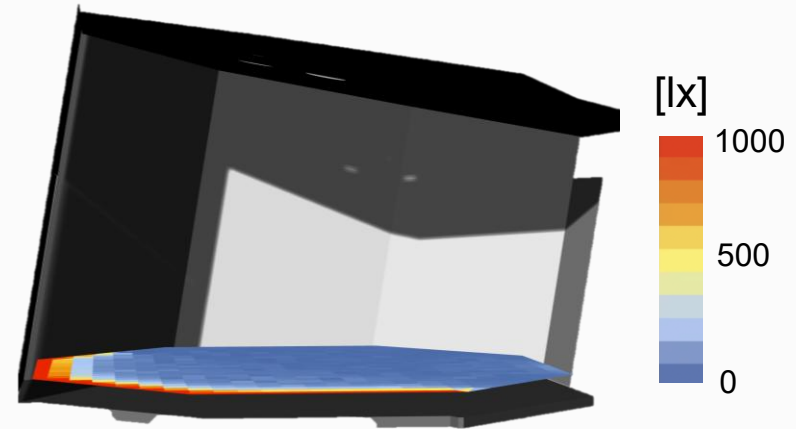
Capturing a 3-dimensional light field is crucial for evaluating and predicting the appearance of spaces and objects.

1. Motivation and Purpose

Luminance distribution

Currently commonly used methods for describing light environments (2-dimensional).

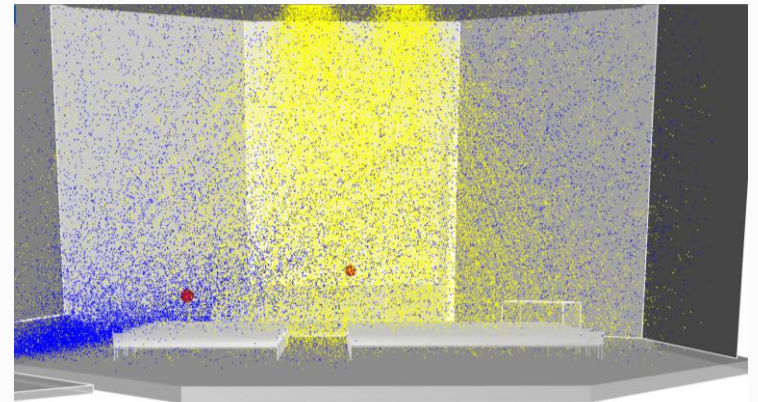
- > It is often difficult to capture **the light field** within a space.



Photon Flow

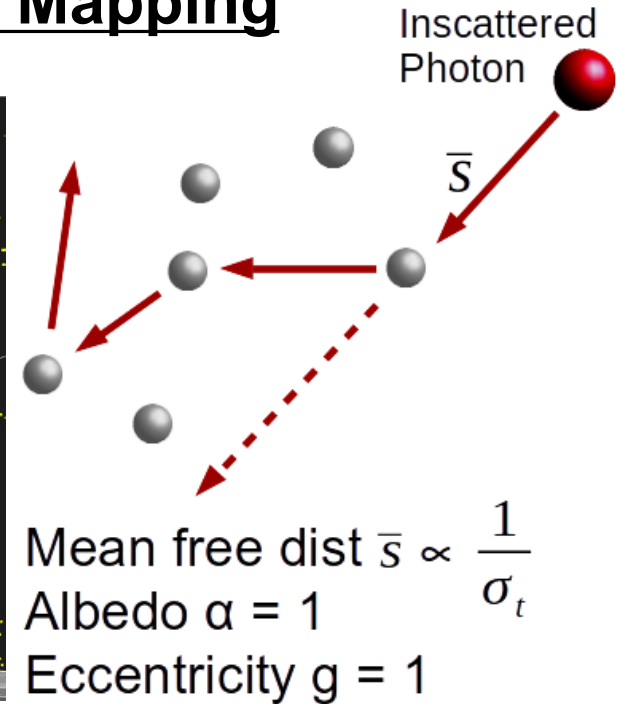
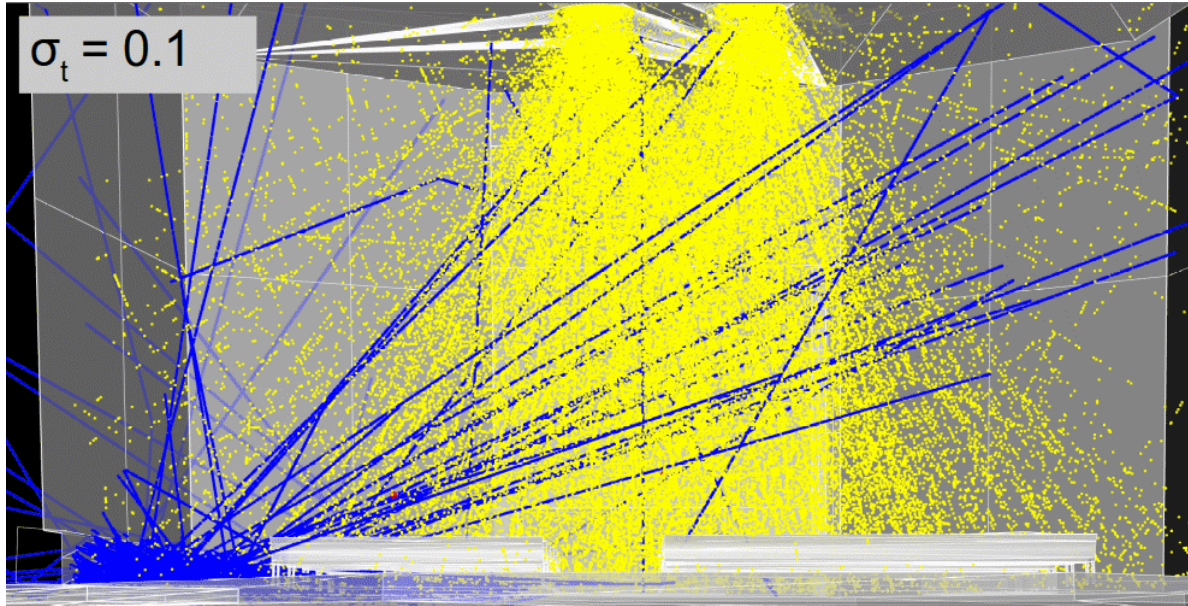
3-dimensional description method for light environment using Volume Photon Mapping.

- > Describing **the light field** in a space.



1. Motivation and Purpose

Photon Flow: Based on Volume Photon Mapping

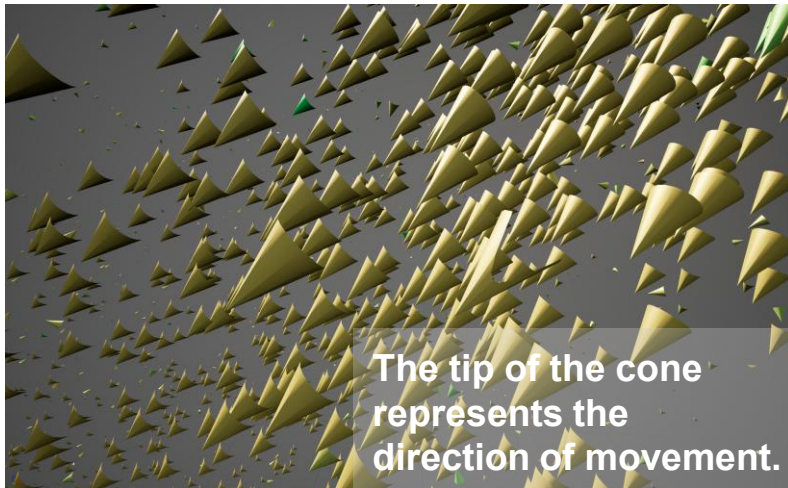


- Volume photons deposited in nonabsorbing / nonscattering mist
- Approximates directional light distribution in 3D space
- Photon Density $\propto$ extinction σ_t
- Stored attributes: RGB flux, position (x,y,z) and direction
- Estimate illuminance at arbitrary location in space

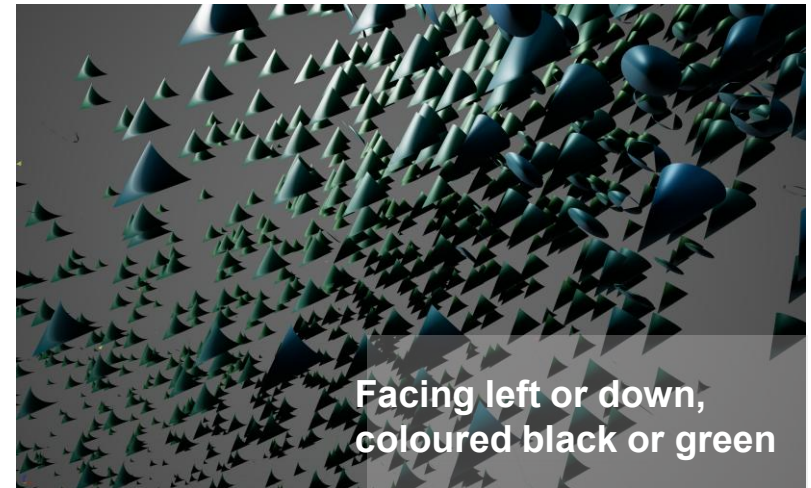
1. Motivation and Purpose

Previously Proposed: **Colour-Encoded Directional Photon Flow**

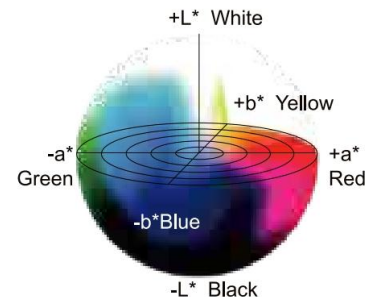
Conical photon



Colour-encoded conical photon

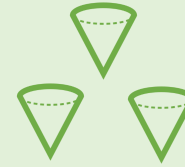


We adopted a technique that encodes directional information using colour for each photon.



1. Motivation and Purpose

Conical Photon Flow



Generate volume photon map ($\alpha = g = 1$)

`mkpmap -apV pmap.vpm <nPhotons> -me .001 .001 .001 octree.oct`



density of photons along a ray

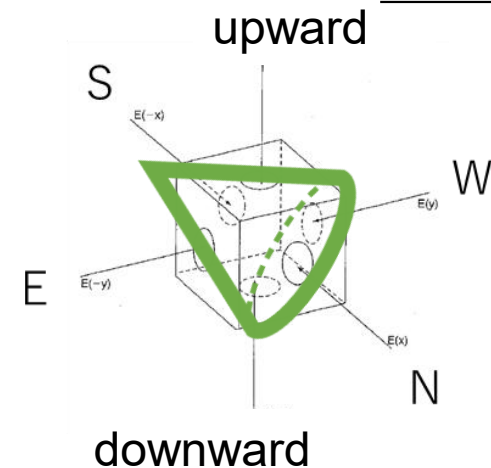
Output photons as point list

`pmapdump -a -N+ -n <nPhotons> pmap.vpm > points.xyz`

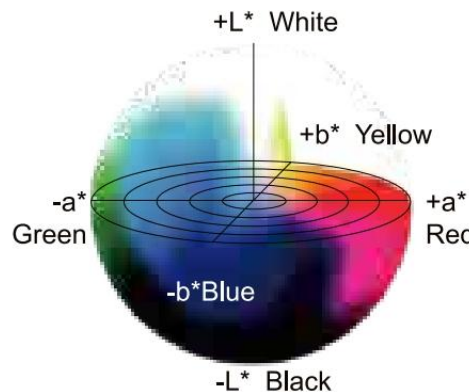


-N option : **Output xyz vector information** in the direction of movement for each Photon

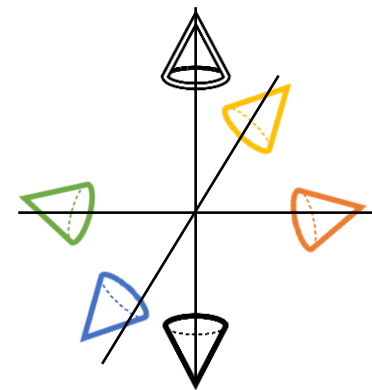
Colour-Encoded Conical Photon Flow



xyz directional information



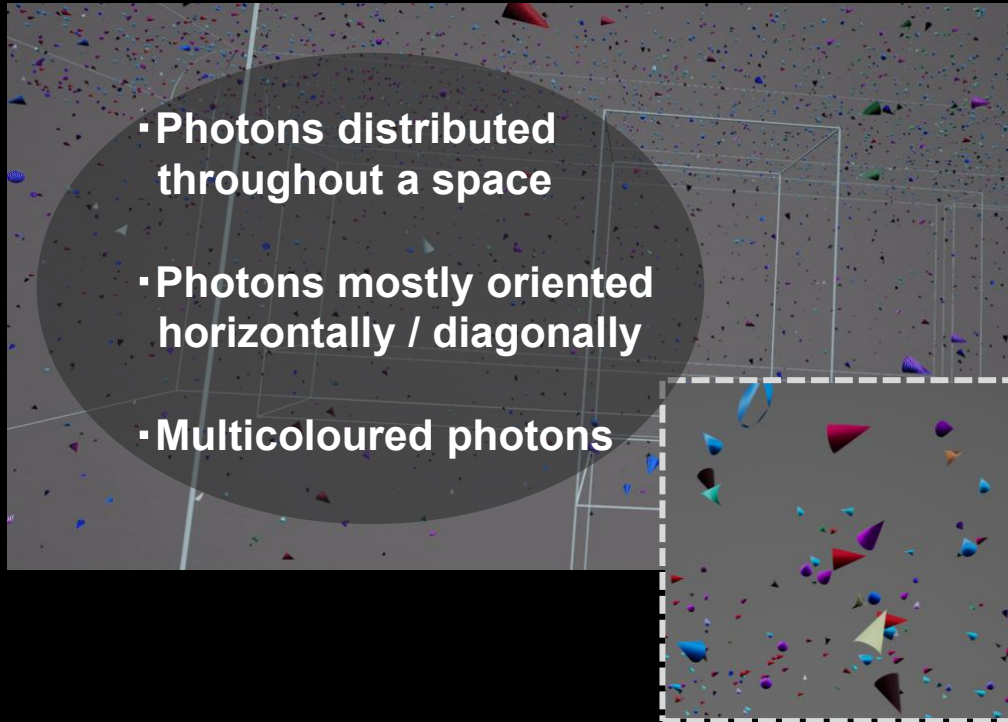
Lab colour space



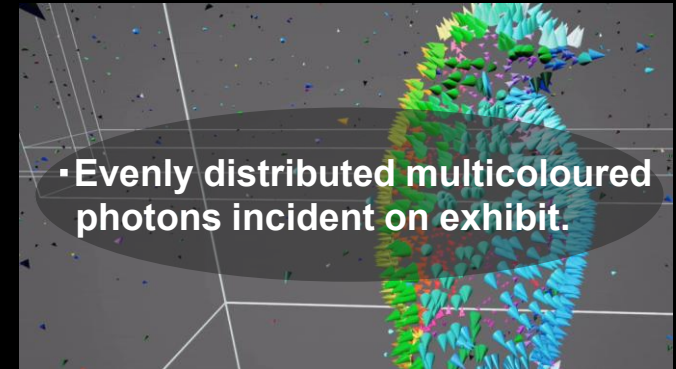
Lab colour

1. Motivation and Purpose

Visualization of Photon Flow



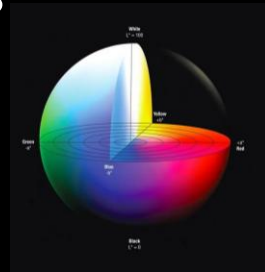
This approach made 3D light propagation and shaded-area predictions far more intuitive.



Current Space



From Spotlights



1. Motivation and Purpose

Lighting designers observed Photon Flow using VR.



Proposed expression methods with Photon Flow

- ***The propagation direction** of each photon is discernible*
→ *Facilitates communication between designers and non-experts*
- *Potential use to **compare light flow in distinct regions***
- *The distribution of colour-encoded conical photons facilitates the prediction **of shaded areas***



Potential for a **practical tool!**

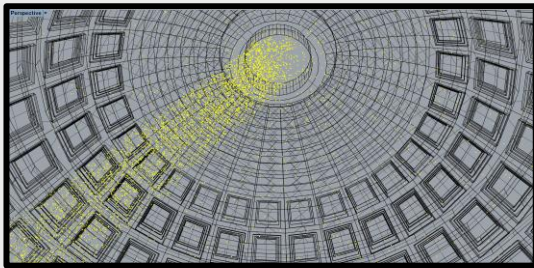
1. Motivation and Purpose

Critical Limitations in Practice

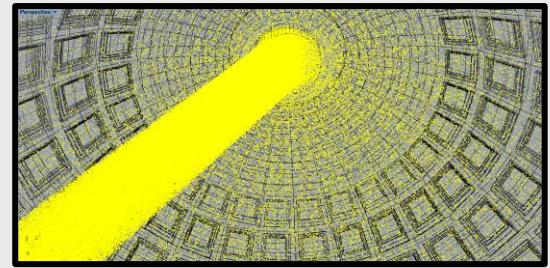
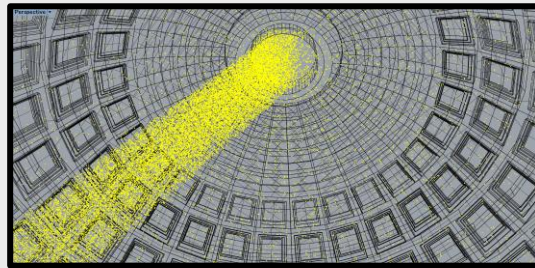
- Heavy Reliance on Trial-and-Error:

Photon parameters (#photons, σt) are abstract and hard to tune without expert experience.

Photon Count

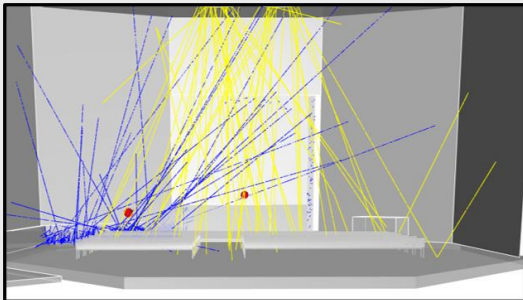


Few/Fast

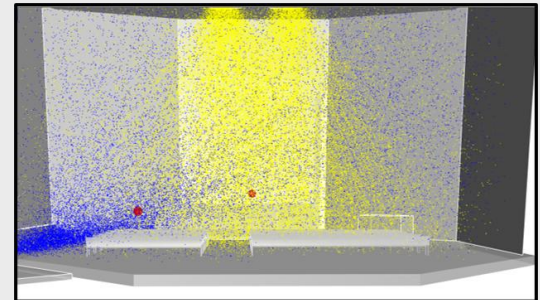
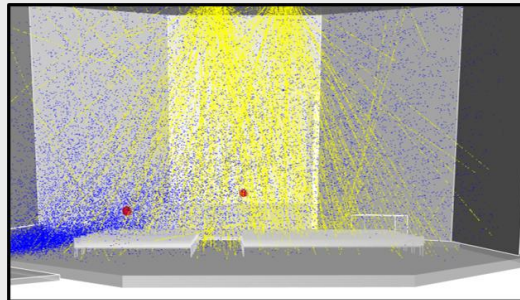


Many/Slow

Extinction Coefficient σ



High/Fast



Low/Slow

1. Motivation and Purpose

Critical Limitations in Practice

- **Risk of Misjudging Scalar Illuminance:**

When photon counts are identical, observers may confuse visual photon density with scalar illuminance, misinterpreting **the actual light intensity**.

- **Need for Automated Parameter Setup:**

Lighting designers need **predictive formulas** rather than manual, iterative parameter tuning.

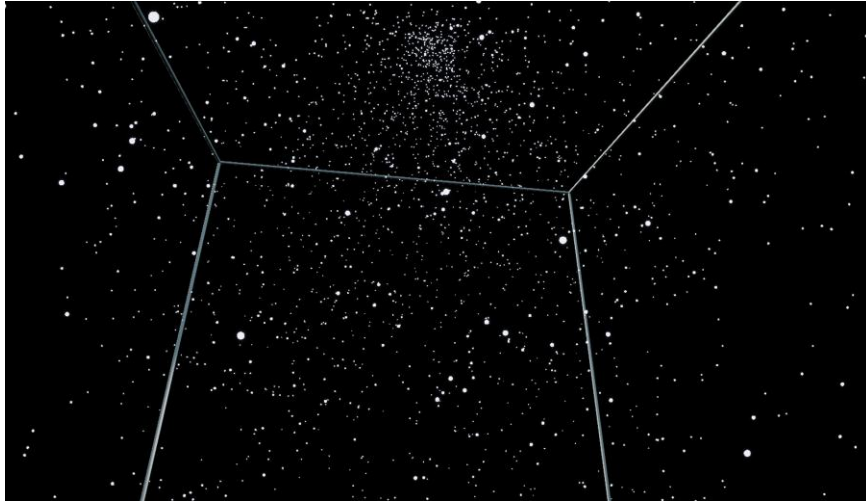


Establish predictive formulas for optimal parameter determination and validate them in a real-world architectural space.

2. Derivation of Optimal Parameters

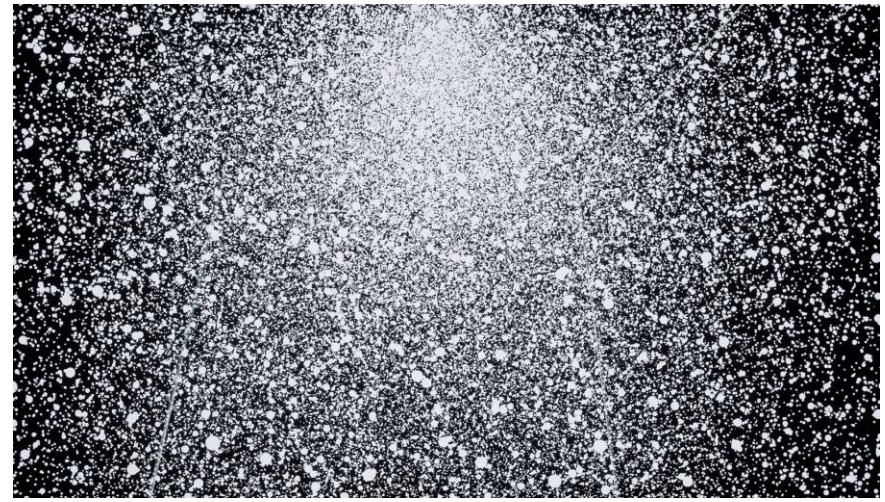
How many photons are required
for Photon Flow visualization in VR?

Photon Count



too few photons

Insufficient Information



too many photons

Information overload
Computational overload

**It is difficult to perceive differences
in density and flow of light.**

Two Evaluation Axes for Optimal Photon Count

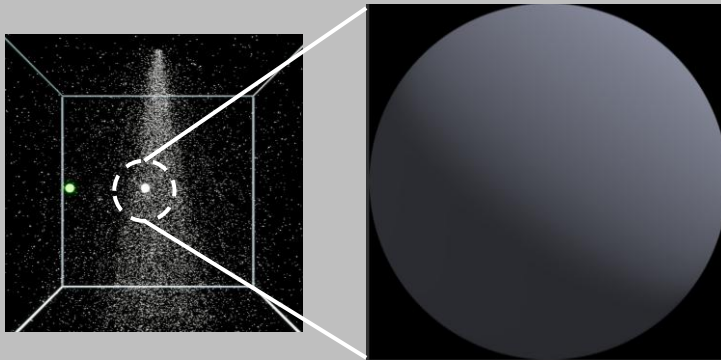
Two distinct evaluation criterias are established to determine the optimal photon count according to simulation objectives.

Physical Aspect

Accuracy of Physical Light Field(PLF) perception

PLF Definition:

*Physical distribution of radiance as a function of location and direction**



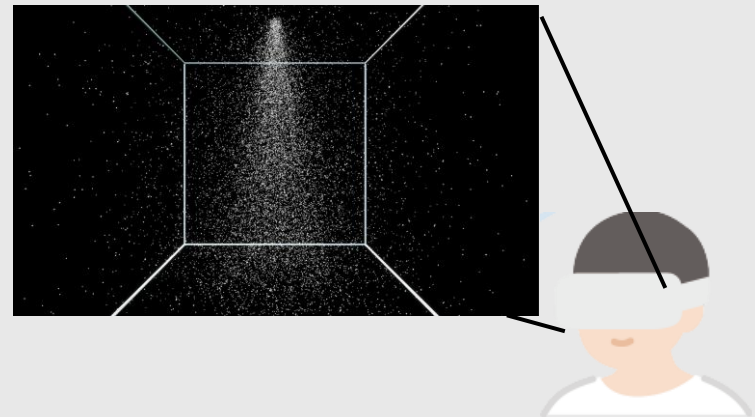
Accuracy for shading cast on a white sphere placed in the space

Visual Aspect

Ease of Understanding the Overall Light Environment

Discernibility of

- light source positions
- flow of light



Evaluation based on subjective impression ratings

Research Workflow

[Step 1] Formulating a Hypothesis

Hypothesized Formula of the optimal photon count through Preliminary Subjective Observation



[Step 2] Hypothesis Testing

Subjective Experiment for Validation of the formula

- ① Physical Aspect : Shading estimation (27-image test)**
- ② Visual Aspect : Impression of spatial light environment**

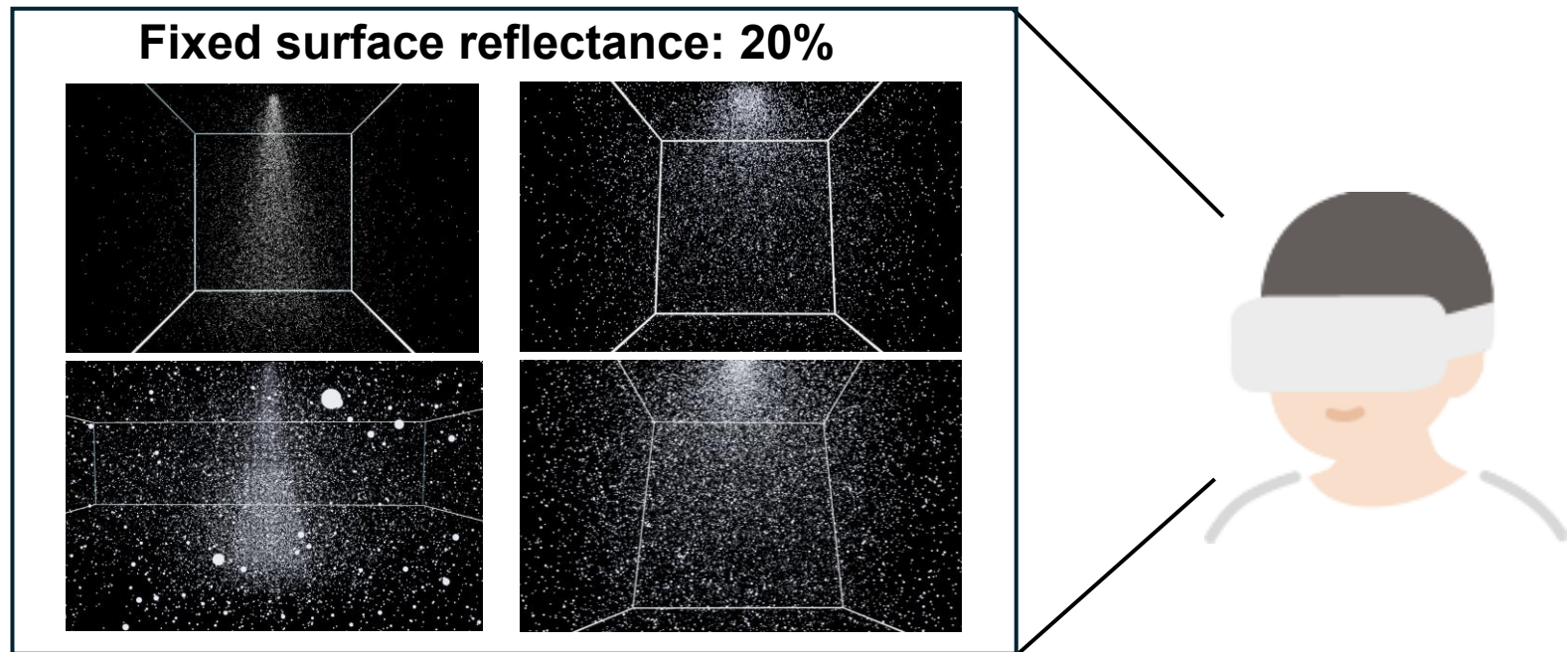


[Step 3] Refining Determination Formulas

Construction of Determination Formulas of the optimal photon count

Formulation of Hypothesized Formula

To construct the hypothesized formula, we subjectively determined the optimal photon count under various conditions.



Key Criteria

Discernibility of

- Light source positions
- Flow of light

Factor

- Room volume
- Room geometry
- Light distribution angle

Formulation of Hypothesized Formula

Initial Hypothesis

Optimal photon count increases in proportion to physical Room Volume (V).

Finding

No clear linear correlation observed between Optimal photon count and Room Volume.

Second hypothesis

Correlation with human perception of Spaciousness(Sp)*

$$Sp = 10^{(0.27 \log V + 1.40)} \quad V: \text{room volume}[\text{m}^3]$$

A clear linear correlation confirmed between Optimal photon count and Spaciousness.

$$N_{\text{photon}} = k \cdot Sp$$

N_{photon} : optimal photon count
 Sp : Spaciousness

* H. Miyake et al., "Quantification of the effect of lighting environment on spaciousness of interior space," Proc. Conf. CIE 2021,

Formulation of Hypothesized Formula

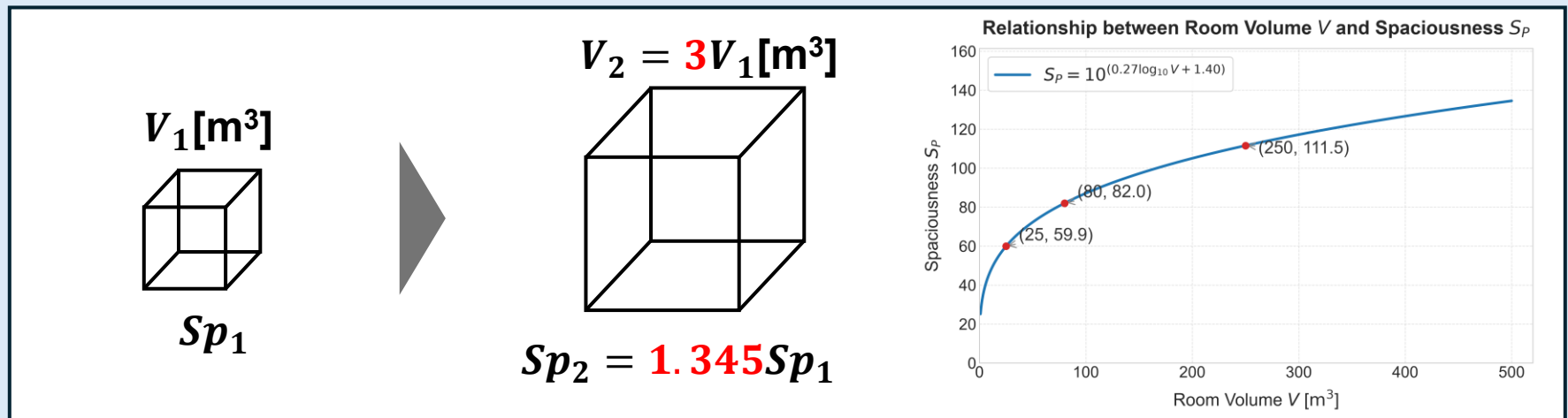
How do we calculate Spaciousness?

We used the simplified equation from Miyake et al. study*

$$*Sp = 10^{(0.020 \log(L_{average}) + 0.27 \log(V_{recog}) + 1.40)} \quad (\text{Miyake et al.})$$

$$Sp = 10^{(0.27 \log V + 1.40)} \quad V: \text{room volume [m}^3\text{]} \quad (\text{This study})$$

Study* suggests spaciousness increases logarithmically with room volume



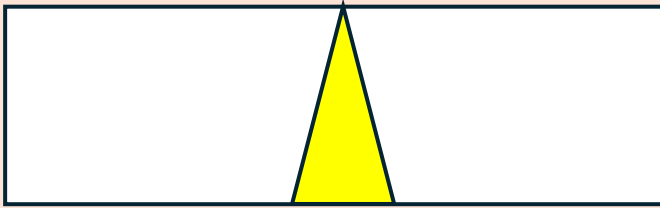
Perceived photon density also increases logarithmically.

$$N_{photon} = k \cdot Sp$$

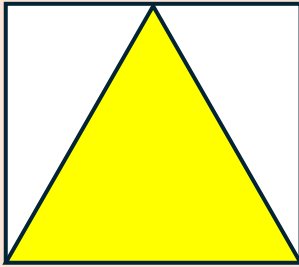
Formulation of Hypothesized Formula

Third hypothesis

Even with identical room volumes,
depending on light distribution and
Low ceiling (flat room) + Narrow space



High ceiling + Wide ambient lighting



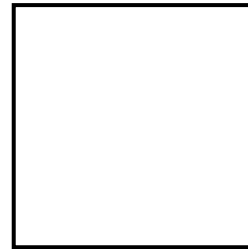
Lig

What is Room Index (K)?

A metric representing 3D spatial proportions

$$K = \frac{W \times L}{H \times (W + L)}$$

W : Width, L : Length, H : Luminaire Height



Small K
Tall Space



Large K
Flat Space

ers

ace

Hypothesized formula for the optimal photon count

$$N_{photon} = \left(a + b \cdot \frac{K}{\theta} \right) \cdot Sp$$

N_{photon} : optimal photon count

Sp : Spaciousness

K : room index

θ : light distribution angle[°]

Formulation of Hypothesized Formula

$$N_{\text{photon}} = \underbrace{\left(a + b \cdot \frac{K}{\theta} \right)}_{\textcircled{1}} \cdot \underbrace{Sp}_{\textcircled{2}}$$

N_{photon} : optimal photon count

Sp : Spaciousness

K : room index

θ : light distribution angle[°]

① Required Photon Count per Unit Spaciousness

$$\left(a + b \cdot \frac{K}{\theta} \right)$$

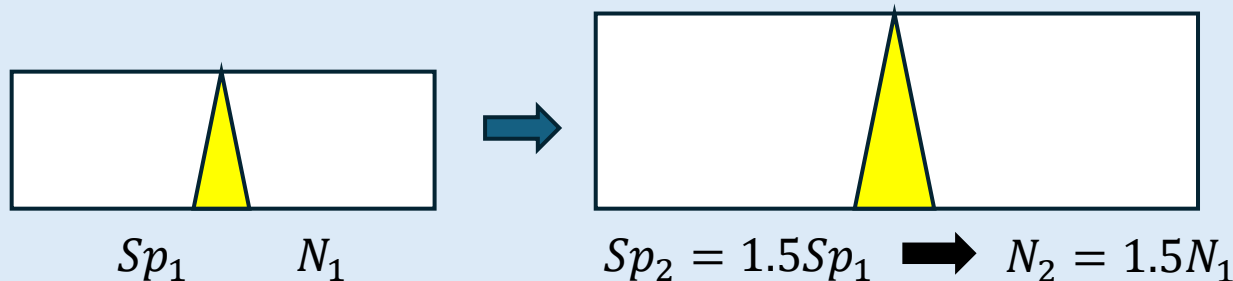
a : Baseline Photon Density

Represents the minimum required photon density independent of room geometry (K) or beam angle (θ).

② Direct Proportionality to Spaciousness

Sp

Under constant geometry (K) and beam angle (θ), the total required photon count scales in direct proportion to Sp .



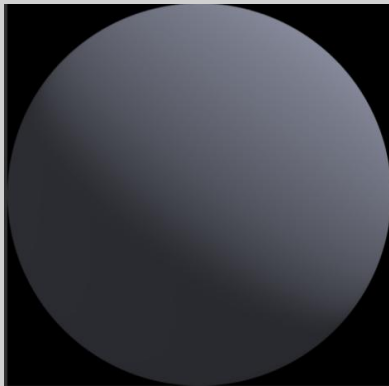
Experiment Overview

participants observed Photon Flow displayed on an HMD.

This experiment aimed to validate the hypothesized formulas from two aspects.

Physical Aspect

Prediction of shading assuming a white sphere is placed at a specific position

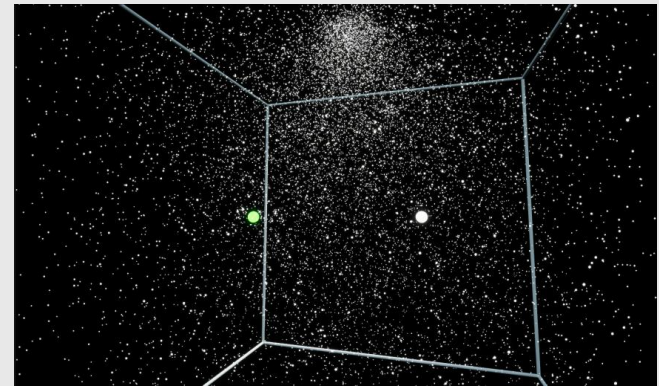


Local light distribution

- Directionality
- Intensity
- Diffuseness

Visual Aspect

Impression evaluation on the ease of understanding the lighting environment



Overall light distribution

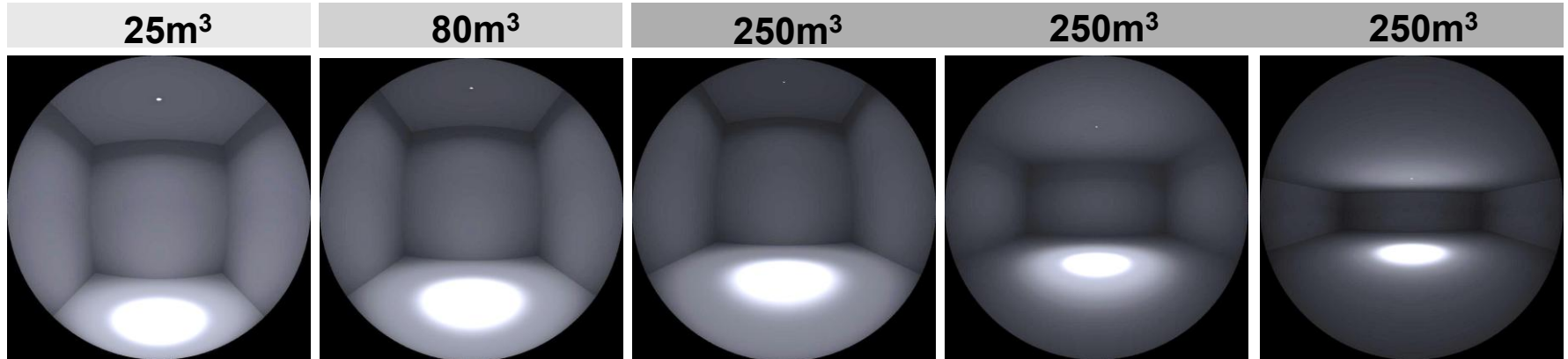
Reconstruction of the optimal parameter calculation formula based on the results.

Experimental Conditions

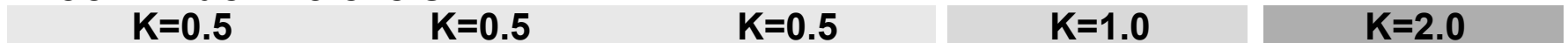
5 experimental factors

1. Room Volume (V)
2. Room Index (K)
3. Light distribution Angle (θ)
4. Target Evaluation Position
5. Photon Count (N_{photon})

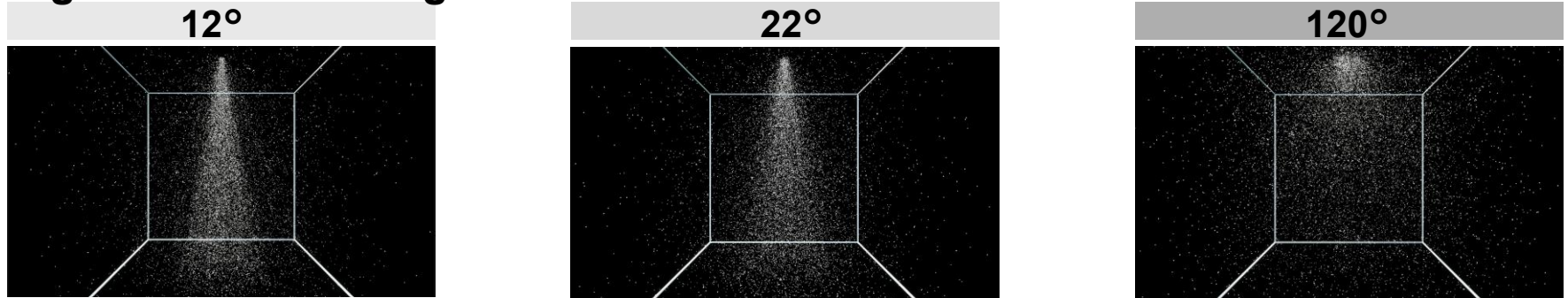
Volume : 3levels



Room index : 3levels

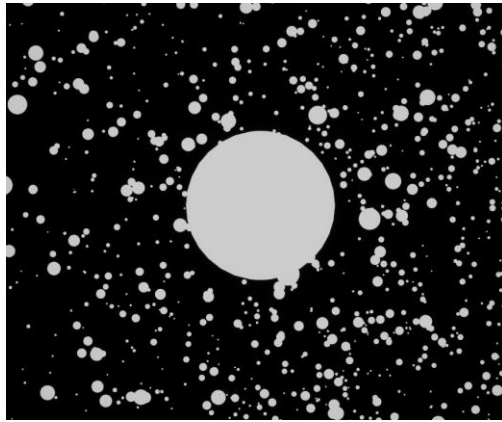


Light distribution angle : 3levels

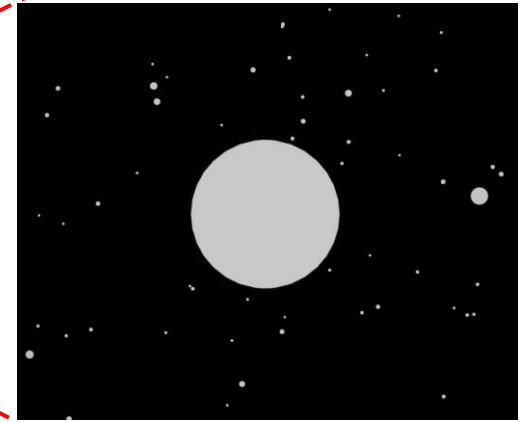
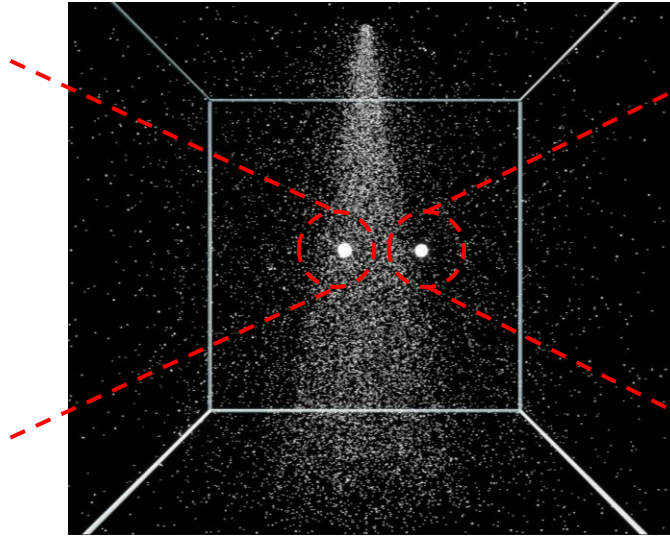


Experimental Conditions

The evaluation target positions : 3 levels



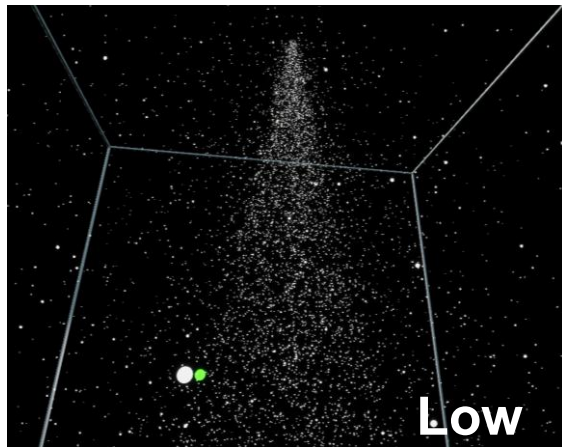
Position A



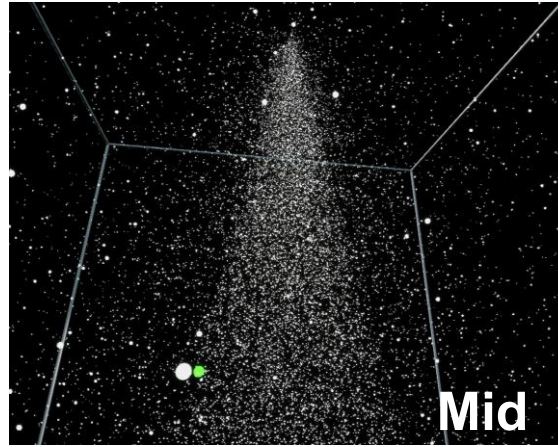
Position B

Photon counts : 3 levels

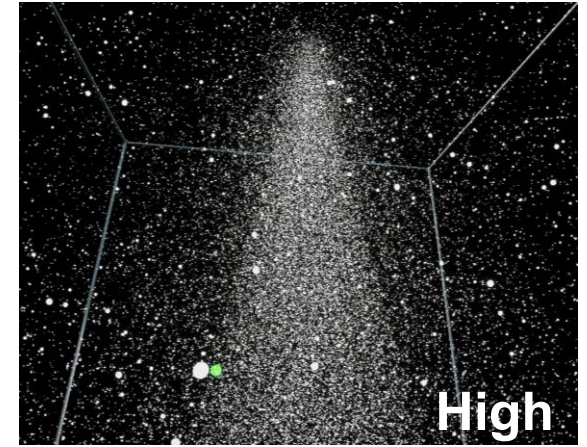
Estimated optimal count $\times 1/3$



Estimated optimal count



Estimated optimal count $\times 3$



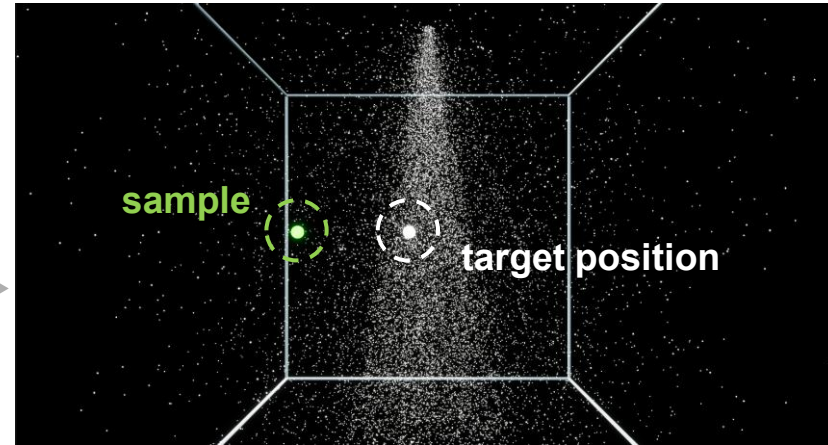
Experimental Procedure

1



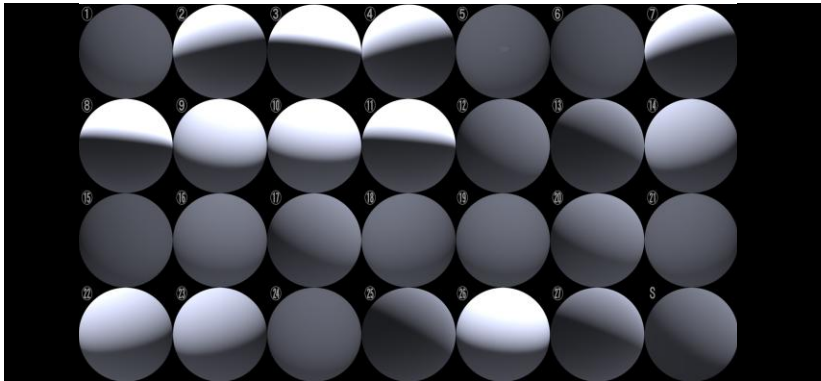
A sample white sphere was presented, and participants memorized its position and shading pattern.

2



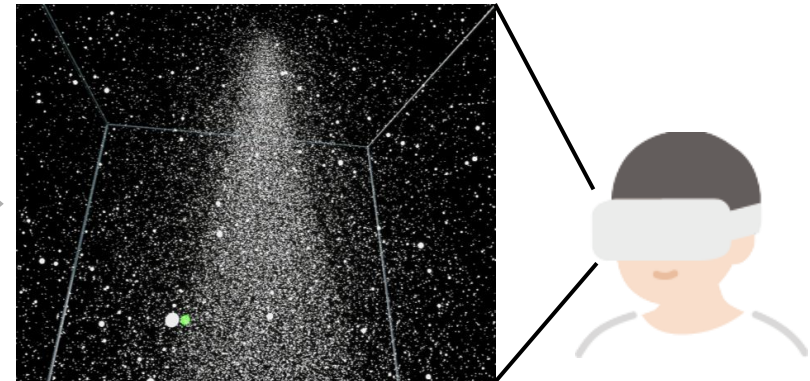
Participants observed the Photon Flow in the VR space.

3 Physical aspect



Participants selected the image matching the predicted shading from 27 candidate images

4 Visual aspect



Participants evaluated the ease of understanding the light environment on a 7-point scale.

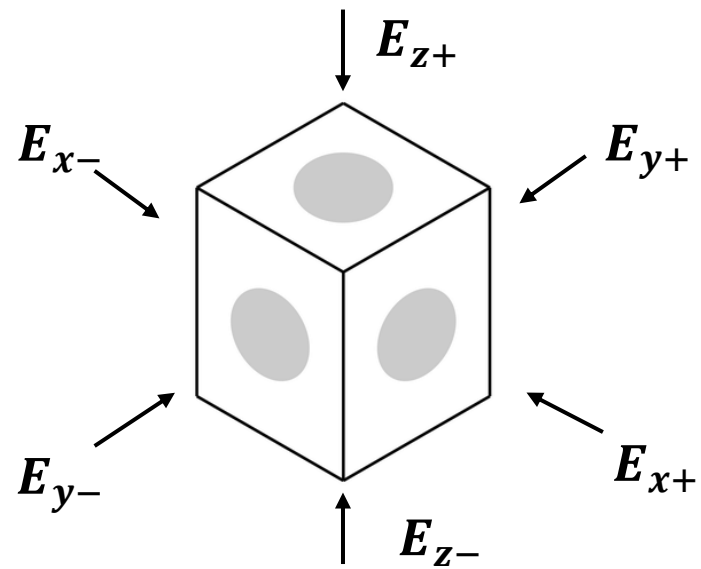
Formulation of Optimal Photon Count Formula : Physical Aspect

Formulation of Optimal Photon Count Formula: **Physical Aspect**

***Diffuseness : $D = 1 - \frac{E_{vector}}{4E_{scalar}}$**

$$E_{vector} = \sqrt{E_{(x)}^2 + E_{(y)}^2 + E_{(z)}^2}$$

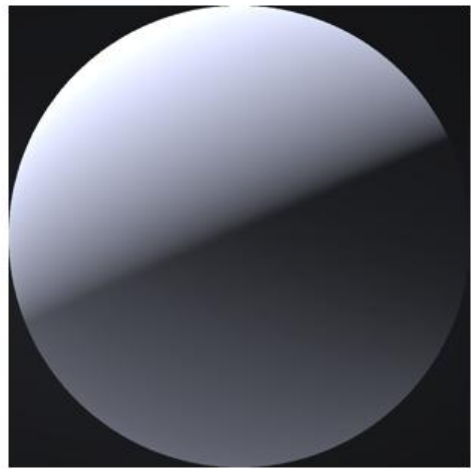
$$E_{scalar} = \frac{E_{vector}}{4} + E_{symmetric}$$



*Kartashova et al..”The global structure of the visual light field and its relation to the physical light field”, J. Vis. 2016.



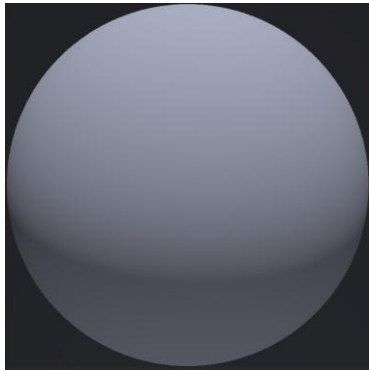
High D : Soft, blurred shading



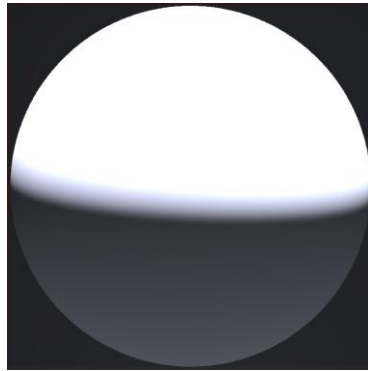
Low D : Sharp, distinct shading

Formulation of Optimal Photon Count Formula: **Physical Aspect**

Calculated the difference in Diffuseness between the target position and the subject-selected position



D_v



D_p

$$D_{Diff} = D_v - D_p$$

D_v : Diffuseness of the correct image at the target position

D_p : Diffuseness of the image selected by the participant

Standardization of the data variance per condition

$$D_{ij}^2 = \left(\frac{D_{Diff}}{\sigma_D} \right)^2$$

D_{Diff} : Diffuseness difference of the image selected by the subject

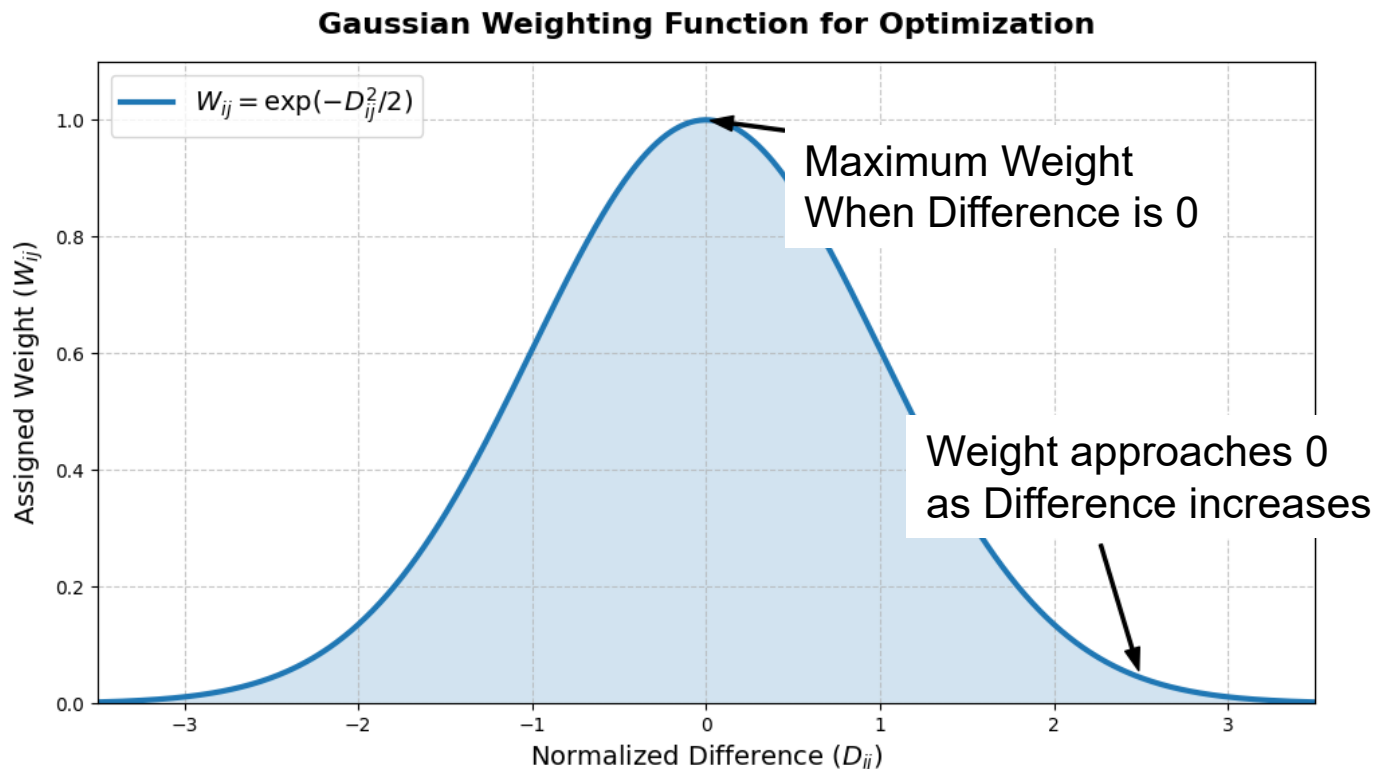
σ_D : Standard deviation of the Diffuseness differences for all 27 images under the given condition

Formulation of Optimal Photon Count Formula: **Physical Aspect**

Derivation of Weighting Factors

$$W_{ij} = \exp\left(-\frac{D_{ij}^2}{2}\right)$$

A larger weight is assigned to selections with a smaller **Diffuseness difference**.

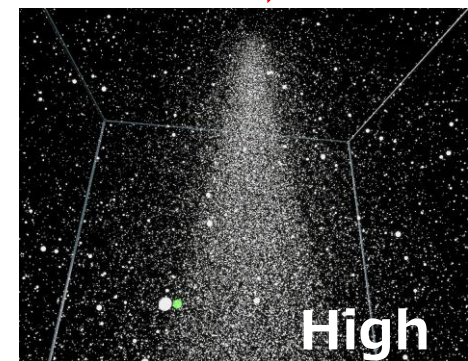
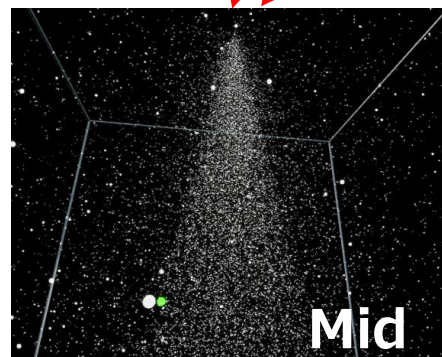
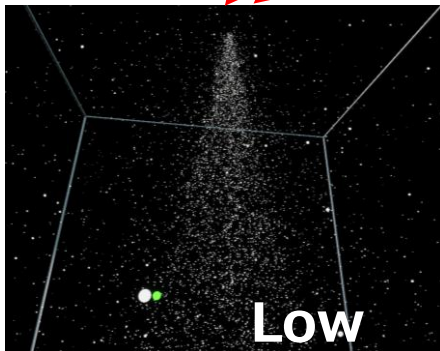


Formulation of Optimal Photon Count Formula: **Physical Aspect**

Optimal photon count $N_{optimal}$ were calculated using a weighted average based on impression evaluation scores.

$$\log(N_{weight}) = \frac{(\text{Log}N_{Low} * W_{Low}) + (\text{Log}N_{Mid} * W_{Mid}) + (\text{Log}N_{High} * W_{High})}{W_{Low} + W_{Mid} + W_{High}}$$

$$N_{optimal} = 10^{\log(N_{weight})}$$

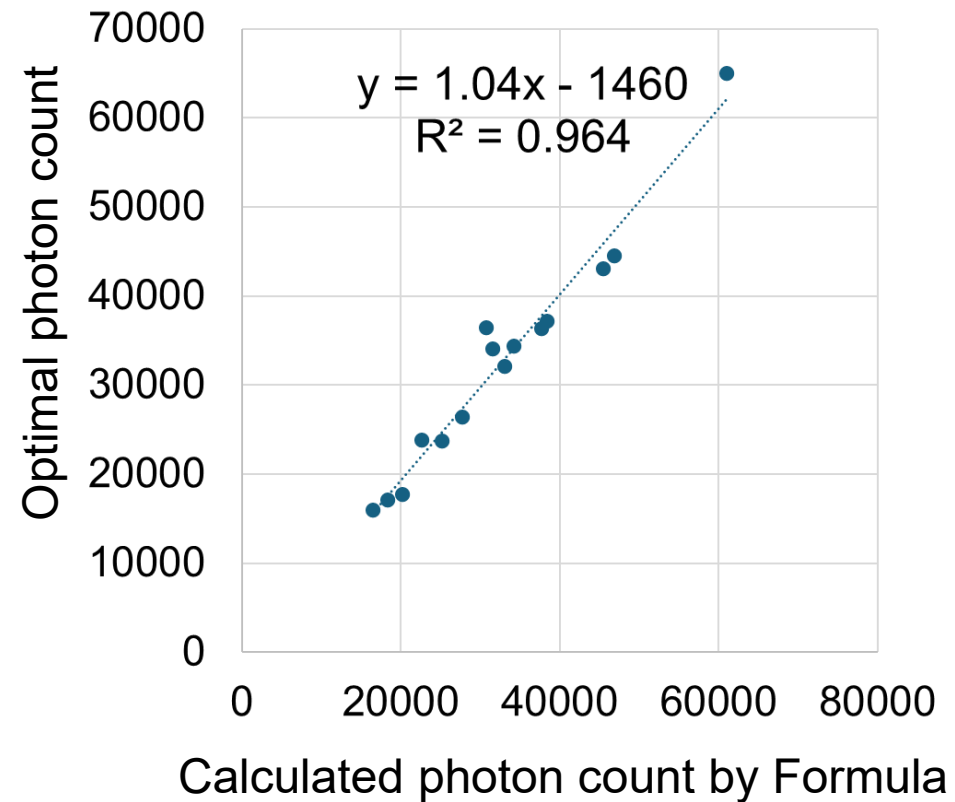
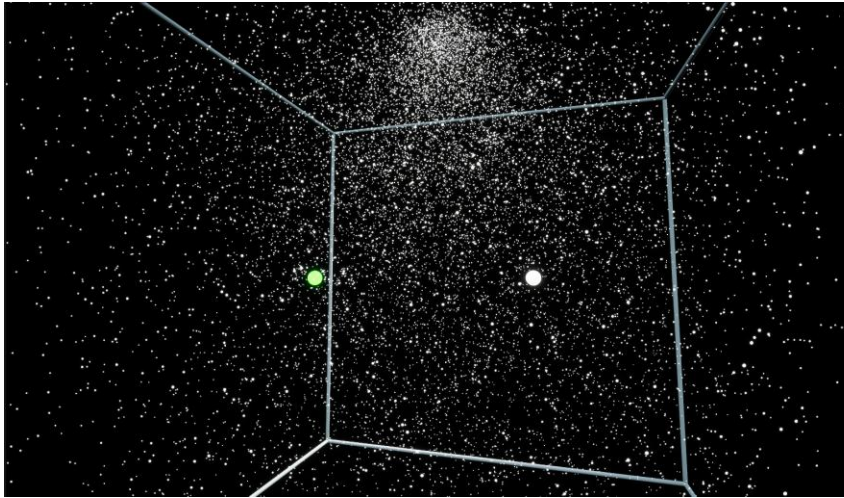


Calculated weighting factors for each photon count under identical spatial and lighting conditions.

Formulation of Optimal Photon Count Formula: **Physical Aspect**

Derived Formula

$$N_{\text{photon}} = \left(269 + 1668 \cdot \frac{K}{\theta} \right) \cdot SP$$



The scatter plot compares the formula's calculated count with the weighted average count.

Formulation of Optimal Photon Count Formula

Physical Aspect emphasis

Optimal Photon Count Formula

$$N_{\text{photon}} = \left(269 + 1668 \cdot \frac{K}{\theta} \right) \cdot SP$$

Physical Aspect emphasis

Accurate perception of the physical light field.

Visual Aspect emphasis

Optimal Photon Count Formula

$$N_{\text{photon}} = \left(269 + 1246 \cdot \frac{K}{\theta} \right) \cdot SP$$

Visual Aspect emphasis

Intuitive grasp of the overall light environment.

(Not included in this presentation)

Users can now automatically determine the photon count based on their specific goal.

What is the optimal extinction coefficient
in VR space?

Research Objective

Extinction Coefficient σ

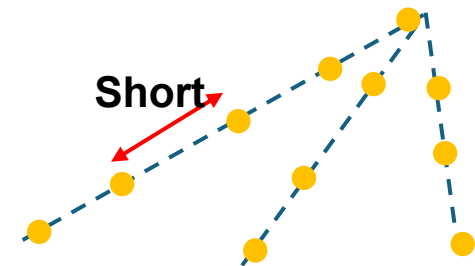
The extinction coefficient σ is a parameter that determines the distance over which photons are stored

The average distance $\bar{s}_{avg}$ traveled by a photon through space without being stored is given by:

$$\bar{s}_{avg} = \frac{1}{\sigma}$$

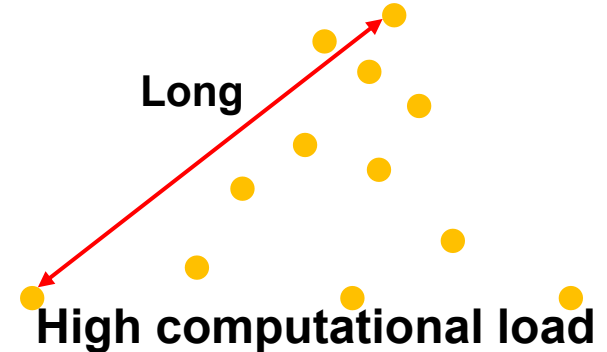


Large extinction coefficient



Ray effects occur

Small extinction coefficient

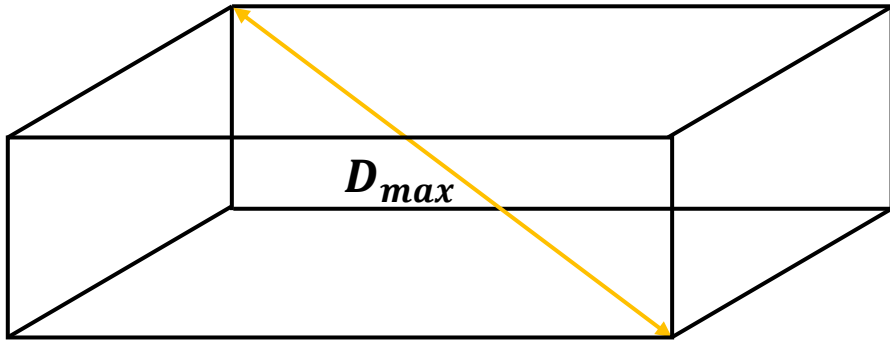


Determine a suitable value to avoid ray effects without excessive computational overhead.

Previous studies

Previous studies

The extinction coefficient was considered to be determined by the maximum spatial distance D_{max} .



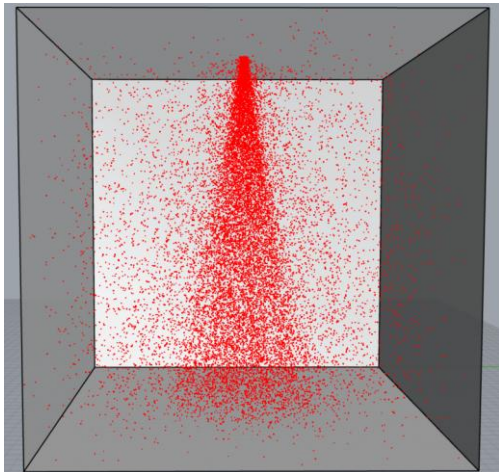
Formulation of the extinction coefficient

$$\sigma = \frac{a}{D_{max}}$$

The specific constant a was unknown.

Calculation of Constant a Using a Reference Model

$2920 \times 2920 \times 2920 [\text{mm}^3]$ beam angle : 12°



$$D_{max} = \sqrt{2920^2 + 2920^2 + 2920^2} = 5050 \text{ [mm]}$$

Extinction coefficient σ that avoids ray effects

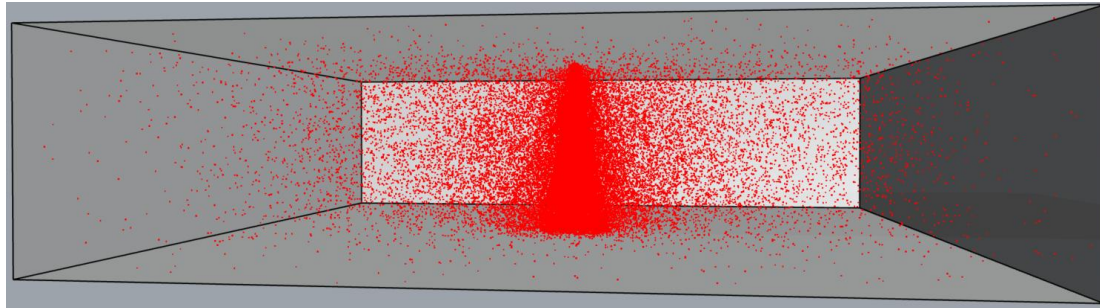
$$\sigma = 0.001 \text{ [mm}^{-1}\text{]}$$

$$\sigma = \frac{5}{D_{max}} \text{ [mm}^{-1}\text{]}$$

Previous studies

Application to Other Spaces and Identification of Issues

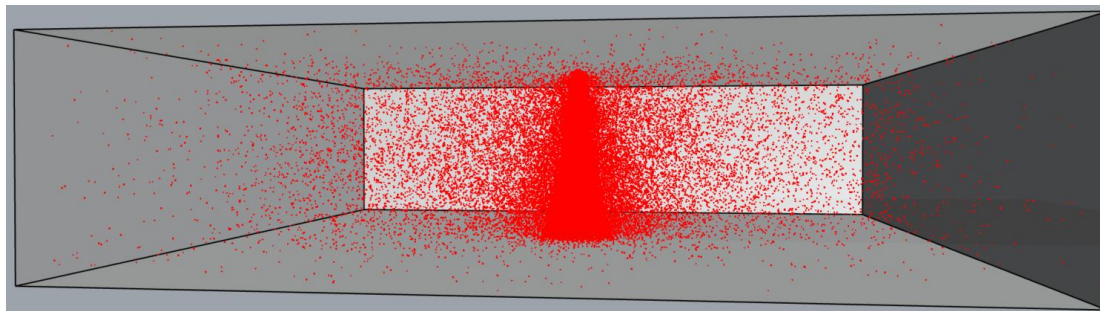
$10000 \times 10000 \times 2500 [\text{mm}^3]$ beam angle : 12°



$$D_{max} = \sqrt{10000^2 + 10000^2 + 2500^2} \\ = 14360 \quad [\text{mm}]$$

$$\sigma = \frac{5}{D_{max}} = 0.00034 \quad [\text{mm}^{-1}]$$

No ray effects occur.



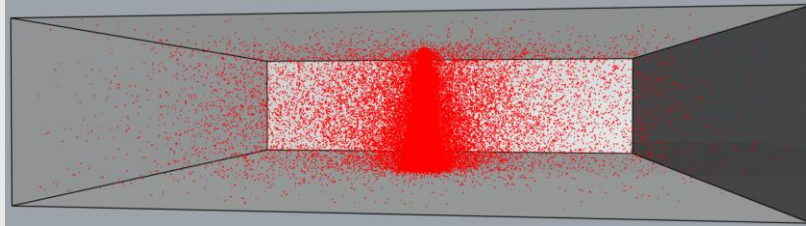
$$\sigma = 0.001 \quad [\text{mm}^{-1}]$$

In a flat space with a narrow light distribution, ray effects do not occur even if the extinction coefficient is large.

This can reduce the computational load in flat spaces.

Constructed Optimal Extinction Coefficient Formula

In a flat space with a narrow beam angle,



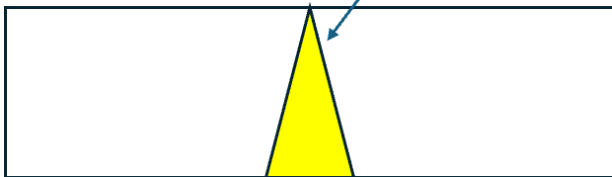
$$\sigma = 0.001 \text{ [mm}^{-1}\text{]}$$

Ray effects are less likely to occur, even when a larger extinction coefficient is applied.

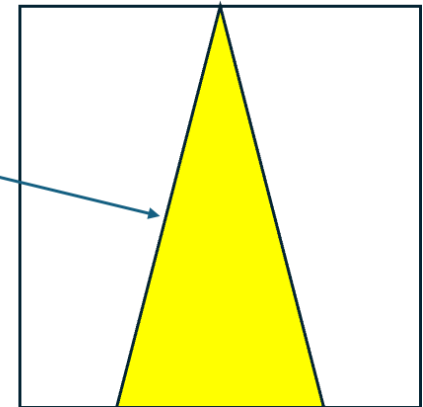
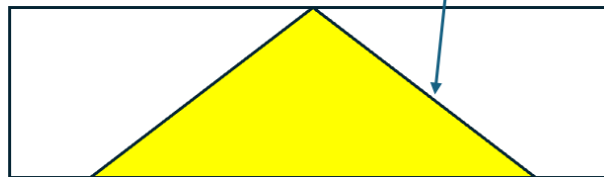
Hypothesis:

Ray effects are determined by the maximum reach distance of direct light.

A Short Distance
→ σ : large



A Long Distance
→ σ : small



Constructed Optimal Extinction Coefficient Formula

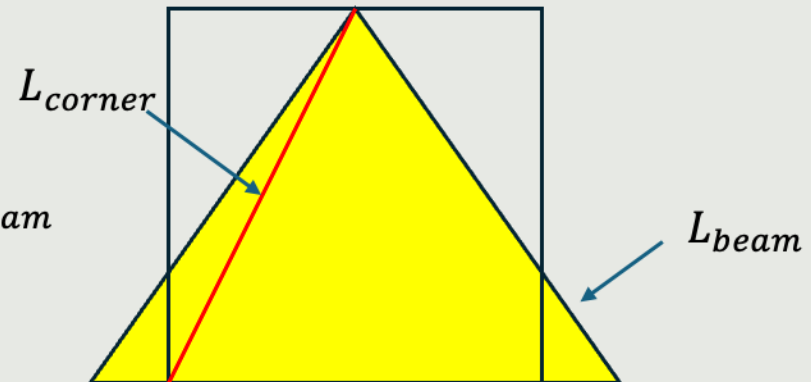
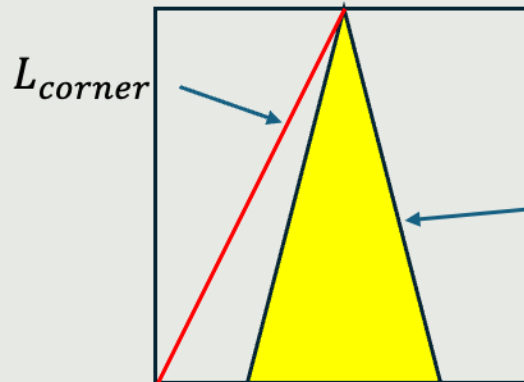
Prediction formula using the maximum reach distance of direct light L_{ray} :

$$\sigma = \frac{a}{L_{ray}}$$

maximum reach distance of direct light $L_{ray} = \min(L_{beam}, L_{corner})$

$$L_{beam} = \frac{H}{\cos\left(\frac{\theta}{2}\right)}$$

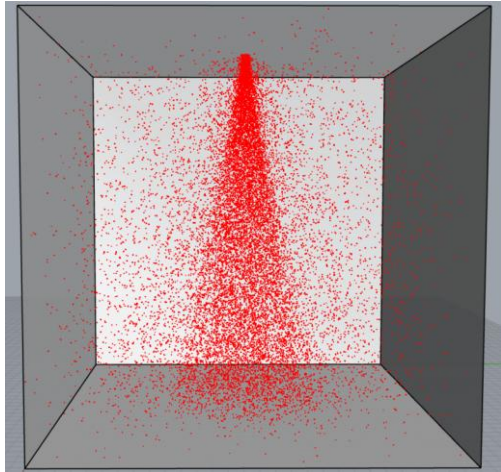
$$L_{corner} = \sqrt{\left(\frac{W}{2}\right)^2 + \left(\frac{D}{2}\right)^2 + H^2}$$



Constructed Optimal Extinction Coefficient Formula

Calculation of Constant a Using a Reference Model

$2920 \times 2920 \times 2920[\text{mm}^3]$ beam angle : 12°



$$L_{ray} = 2890 \quad [\text{mm}]$$

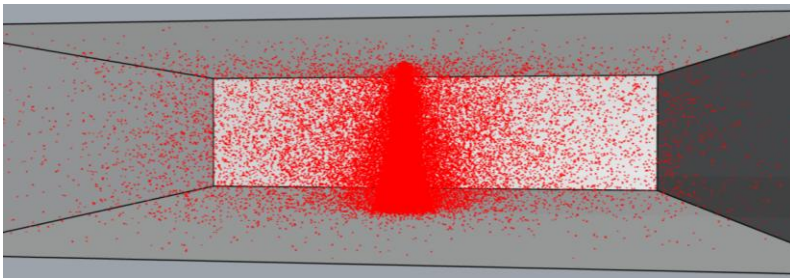
Extinction coefficient σ that avoids ray effects

$$\sigma = 0.001 \quad [\text{mm}^{-1}]$$

Optimal Extinction Coefficient Formula

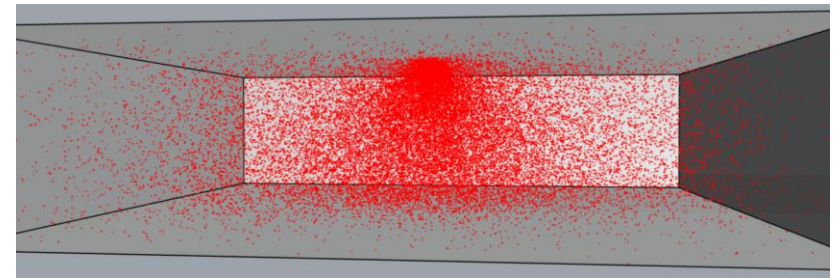
$$\sigma = \frac{2.89}{L_{ray}}$$

Application to Other Models



$10000 \times 10000 \times 2500[\text{mm}^3]$ beam angle : 12°

$$\sigma = 0.00118 \quad [\text{mm}^{-1}]$$



$10000 \times 10000 \times 2500[\text{mm}^3]$ beam angle : 120°

$$\sigma = 0.00059 \quad [\text{mm}^{-1}]$$

No ray artifacts occurred in any model.

Conclusion

Established a formula to determine the optimal extinction coefficient

Optimal Extinction Coefficient Formula

$$\sigma = \frac{2.89}{L_{ray}}$$

- **No ray effects generated under our tested conditions.**
- **Reduces computational load in flat spaces with narrow light distribution.**



Eliminates manual trial-and-error:

Instantly computes optimal extinction coefficients solely from geometry and beam angle.

3. Case Study: Application to Syourinji Temple

3. Case Study: Syourinji Kannon-do Temple

Subject : Kannon Hall at Shorin-ji Temple, Nara Prefecture



- **The uniform lighting environment** of a space filled with light, symbolized by the **“canopy”**
- Lighting that minimizes the attention to the visual presence of glass

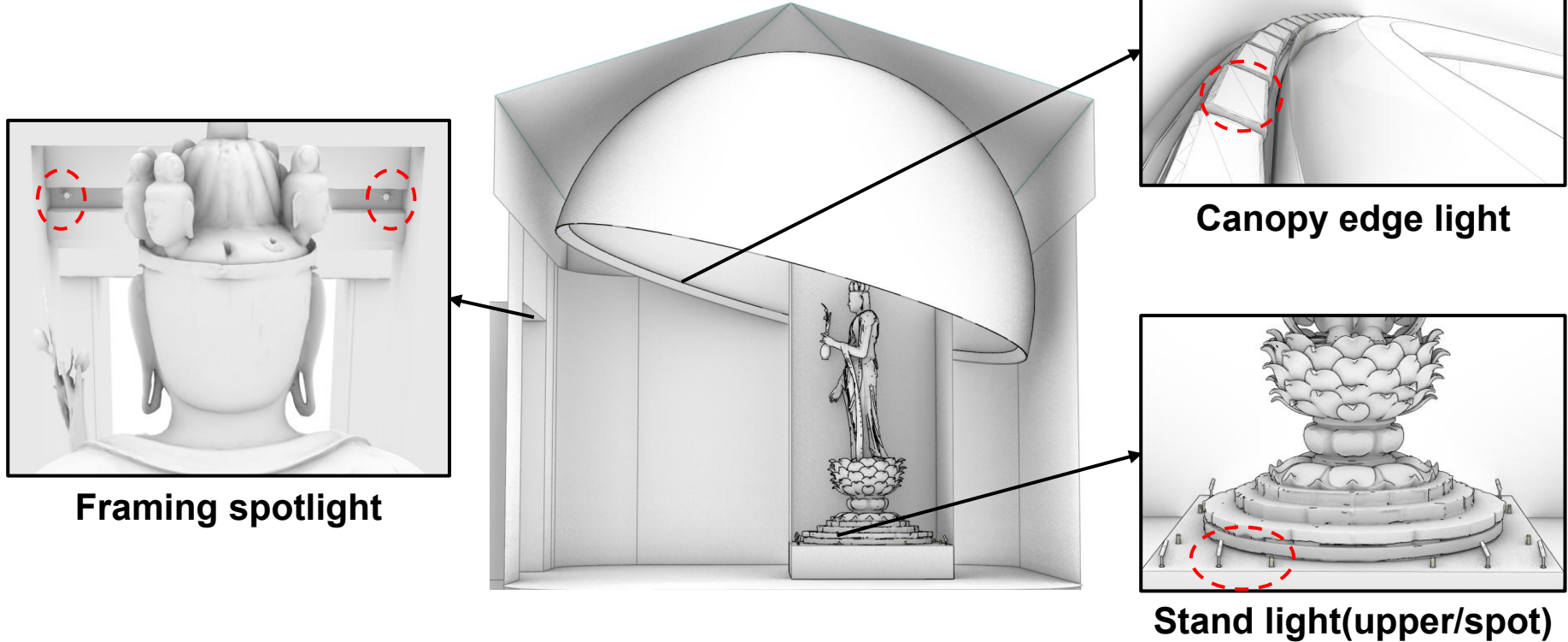


Location:
692 Shimo, Sakurai-shi,
Nara Prefecture

We applied the derived formula to a physical space to validate its effectiveness and the reproducibility of the light field.

3. Case Study: Syourinji Kannon-do Temple

Lighting Systems and Design Intent

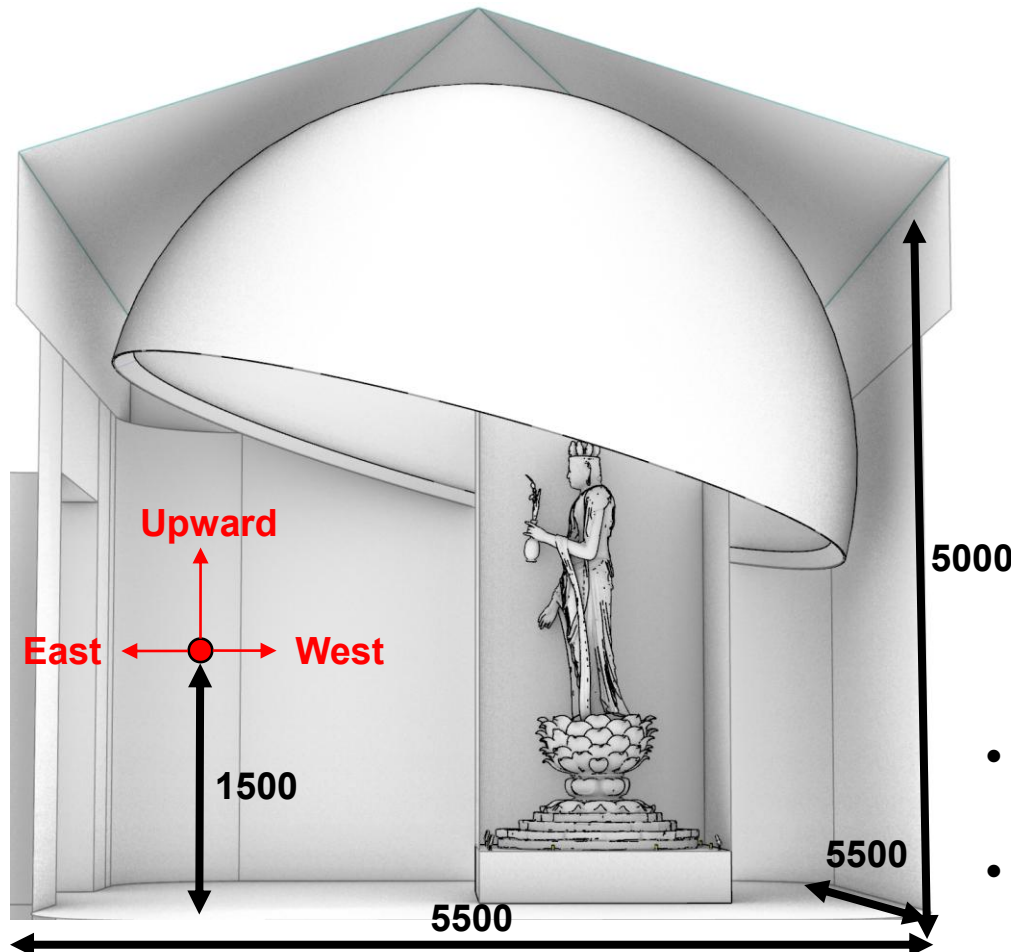


- **Canopy edge light :**
Diffused light that envelops the entire space from above.
- **Framing spotlight :**
A focused, sharp beam of light used to highlight specific parts of a Buddhist statue.
- **Stand light(upper/spot) :**
Light that emphasizes three-dimensionality from the base or sides.

3. Case Study: Syourinji Kannon-do Temple

Objective and Overview of Measurement

In order to accurately reproduce the lighting environment in the simulation, illuminance, luminance, and surface information (reflectance) were obtained.

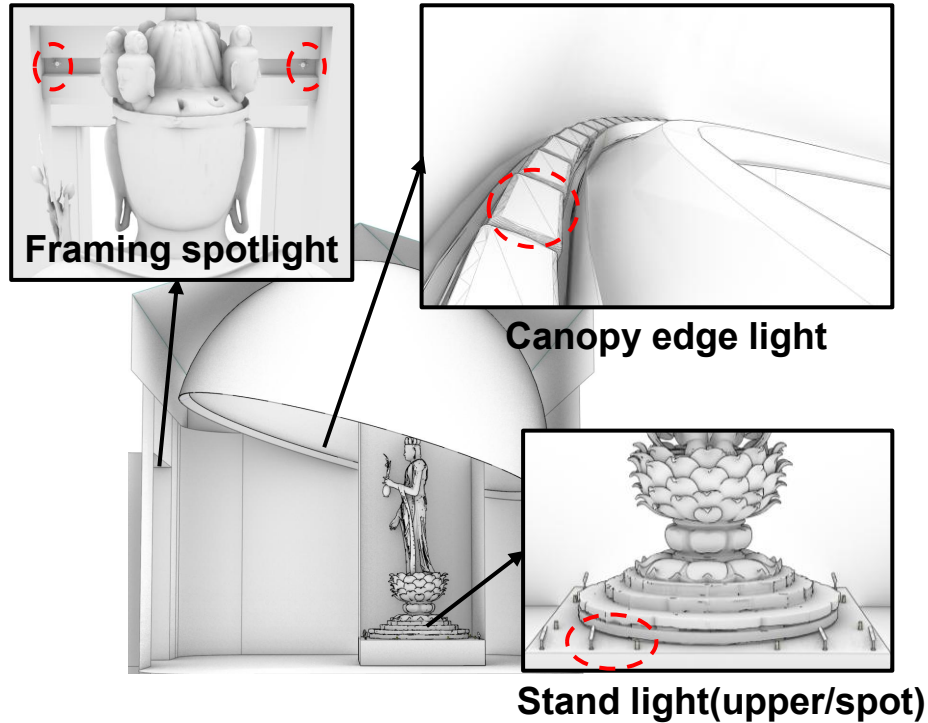


Measurement details

- Measurement items:
illuminance, luminance, reflectance
 - Illuminance measurement direction:
horizontal direction and
2 vertical directions
 - Measurement points:
1 point (in the diagram)
 - Measurement height:
1 level ($H = 1500 \text{ mm}$)
-
- Imported measured reflectance and light distribution data into **Radiance**
 - Calculated illuminance, luminance distribution at measurement point

3. Case Study: Syourinji Kannon-do Temple

Comparison of Measured and Calculated Values



Measurement Protocol

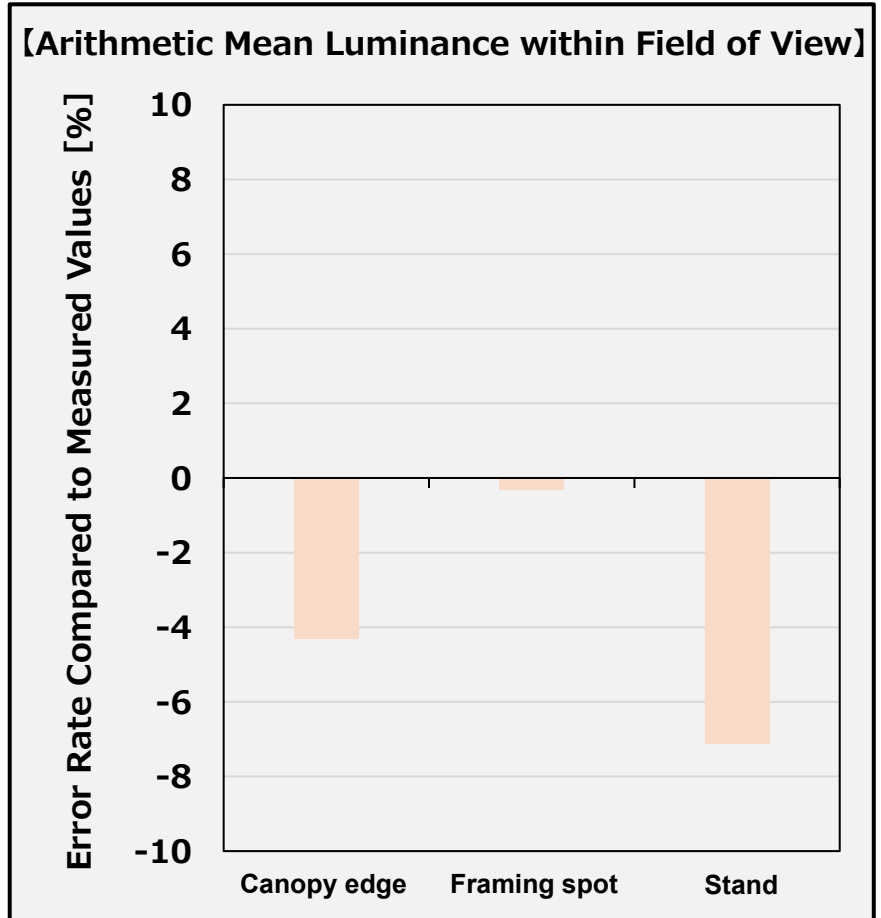
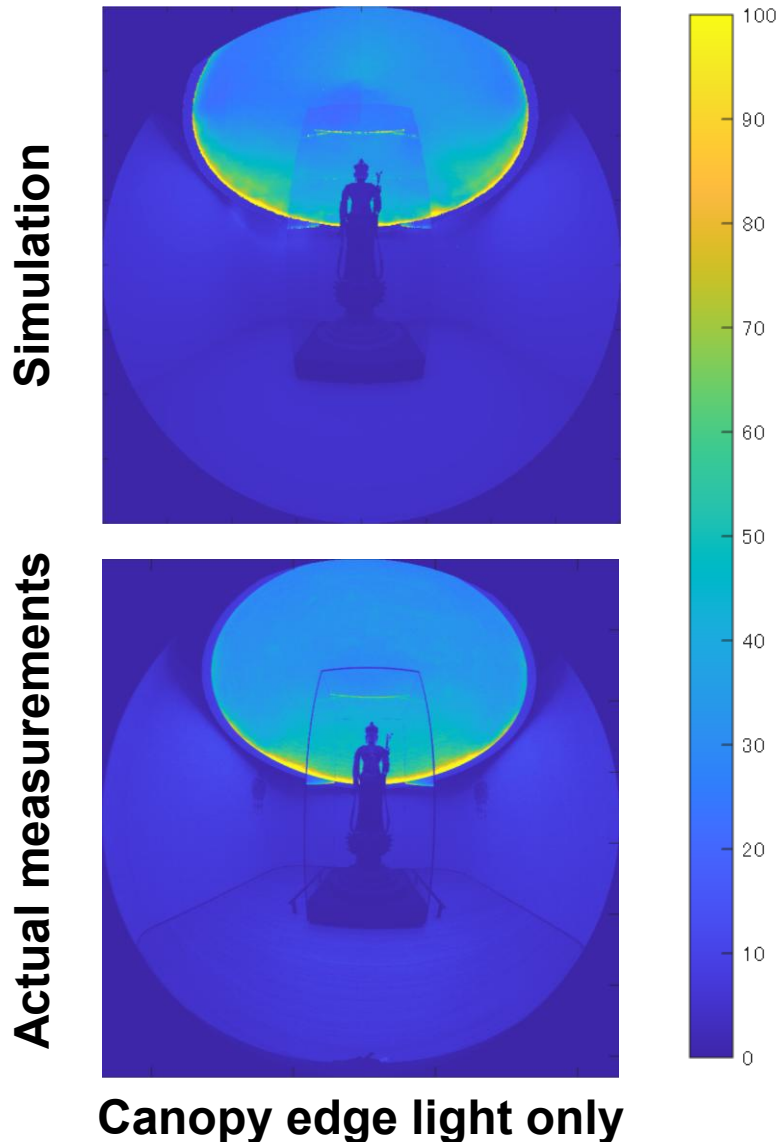
- 1.All ON: Actual operational status
- 2.Canopy edge light only
- 3.Framing spotlight only
- 4.Stand light(upper/spot) only



On-site Measurement Scenes
Stand light(upper/spot)

3. Case Study: Syourinji Kannon-do Temple

Comparison of Measured and Calculated Values



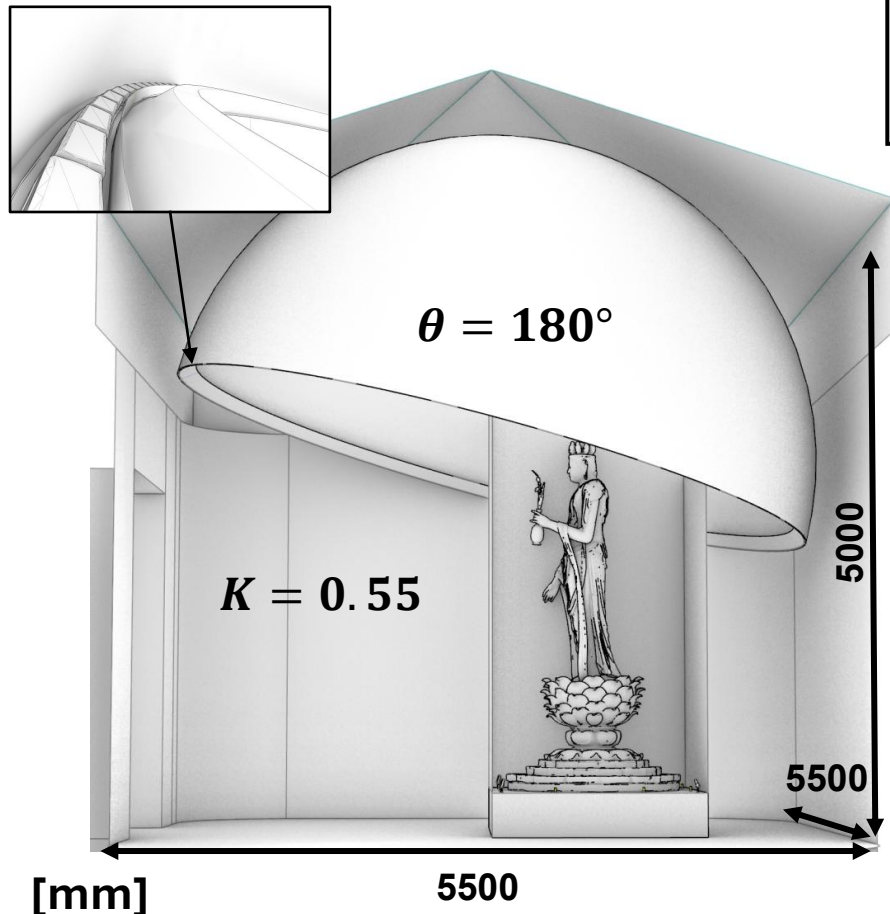
The lighting environment was reproduced by simulation within $\pm 10\%$

3. Case Study: Syourinji Kannon-do Temple

Parameter Application based on Proposed Formulas

①: Photon Count for Main Indirect Lighting

Applied the derived formula to calculate the optimal photon count for complex indirect lighting based on room index (K) and distribution angle (θ).



$$N_{\text{photon}} = \left(269 + 1668 \cdot \frac{K}{\theta} \right) \cdot SP$$

Spaciousness Sp calculated from the room volume

$$Sp = 10^{0.27 \log(V) + 1.40}$$

$$Sp \approx 97.57$$

Optimal Photon Count:

$$N_{\text{photon}} = 26743.61$$

```
mkpmap -dp 20000 -ds 0.002 -apv vpm/###.vpm 26743  
-me .001 .001 .001 -ma 1 1 1 -mg 1 -fo -apD .1 -t 5 -n 12  
oct/###.oct
```

Ray effect was suppressed by applying the extinction coefficient σ .

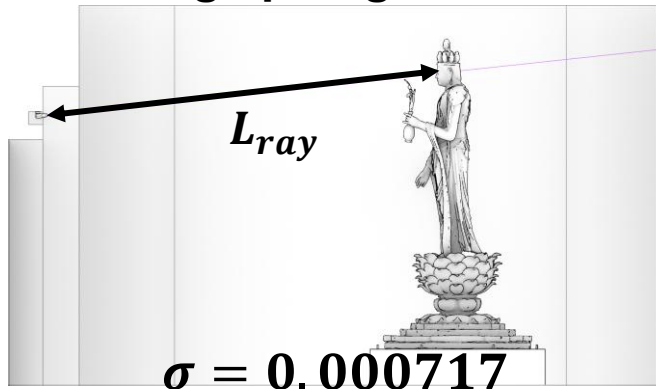
3. Case Study: Syourinji Kannon-do Temple

Parameter Application based on Proposed Formulas

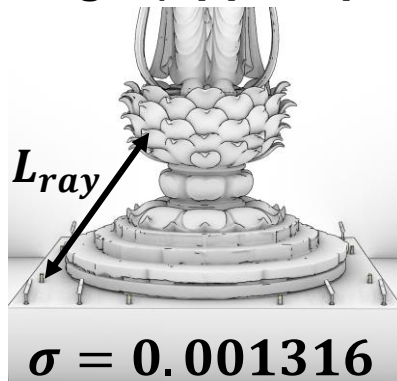
②: Extinction Coefficient & Ray Effect Control

The extinction coefficient (σ) was calculated using the maximum reach distance (L_{ray}) to flexibly balance suppressing visual noise and tracing direct light paths.

• Framing spotlight



• Stand light(upper/spot)



$$\sigma = \frac{2.896}{L_{ray}}$$

L_{ray} was defined as the actual straight-line distance from the luminaire to the target surface.

Flexible Ray Effect Control

A: Photon Trajectory

Retain subtle ray lines to visually indicate beam bounds and target coverage.

B: Noise Reduction

Seamlessly perceive the continuous light gradient without visual distraction.

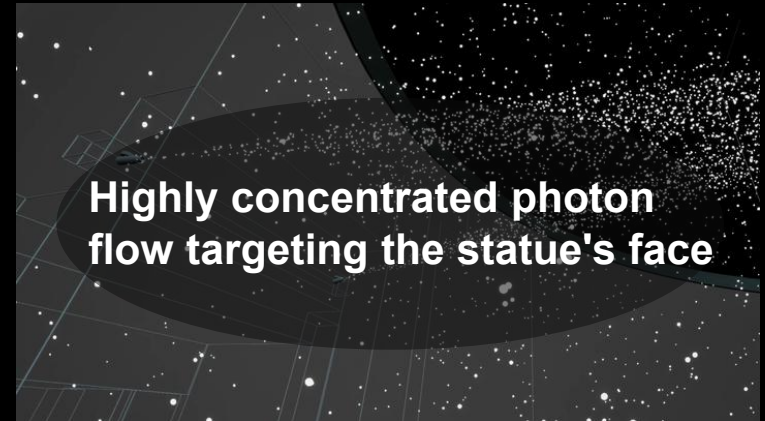
```
mkpmap -dp 50000 -ds 0.001 -apv vpm/###.vpm 30k  
-me .001 .001 .001 -ma 1 1 1 -mg 1 -fo -apD .1 -t 5 -n 12 oct/###.oct
```

3. Case Study: Syourinji Kannon-do Temple

Lighting Environment Description Method Using Photon Flow



Canopy edge light



Framing spotlight



Stand light(upper/spot)

The reconstructed 3D Light Field successfully reveals the interaction between smooth indirect light and sharp accent lighting without manual parameter tuning.

3. Case Study: Syourinji Kannon-do Temple

Feedback from Lighting Designers

① Intuitive Perception of Light Behavior

- **Light Wrap-Around (Bounce):**

Clear distinction in how indirect light wraps around the statue's face and body.

- **Reading Design Intent:**

Enabled lighting designers to instantly recognize targeting intent and light distribution.



② From Parameter Tuning to Interactive Design Tool

- **Freedom from Trial-and-Error:**

Automated formula setup allows lighting designers to focus on lighting evaluation rather than rendering parameters.

- **Beyond Static CG:**

Evaluated as a highly practical, interactive design tool for real-time lighting exploration and decision-making.



4. Conclusion and Future Work

4. Conclusion and Future Work

Conclusion

- **Addressed 2025 Challenge (Parameter Dependencies):**
Established prediction formulas for **optimal photon count (N_{photon})** and **extinction coefficient (σ)**, resolving the trial-and-error setup identified in WS 2025.
- **Validation in Real-World Architectural Space:**
Applied to Syourinji Kannon-do Temple, achieving an **accurate 3D light field reconstruction** that balances indirect bounce light and sharp accent beams.
- **Design Value in Practice:**
Confirmed by lighting designer as an **interactive lighting exploration tool** that clearly communicates design intent and light wrap-around behavior.

4. Conclusion and Future Work

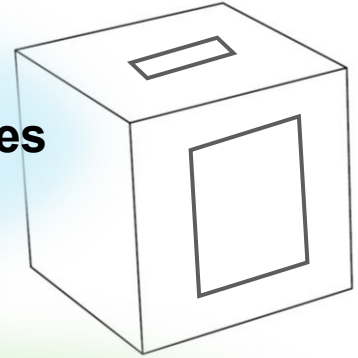
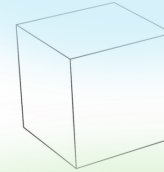
Future Work & TODO

- Expansion to other factors affecting photon count:

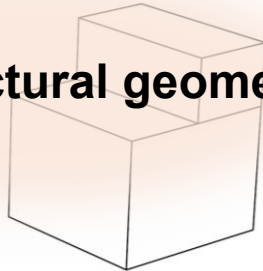
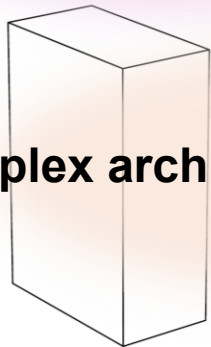
Number of luminaires



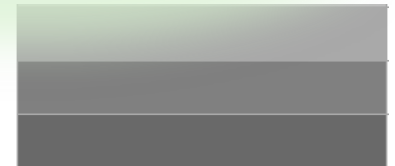
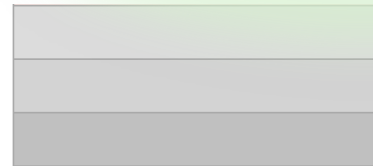
Windowed spaces



Complex architectural geometries



Material reflectance



- Hyperspectral simulation integration:
Implement optimal extinction and photon count, add support for hyperspectral simulation in photon map.
- Integration into Architectural Workflow:
Apply Photon Flow to **ongoing design projects** for early-stage consensus building.

Thank you for your attention.

Questions and comments are welcome.