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Experimental Validation of GUV Simulation Tools for Fluence Rate & Irradiance Prediction

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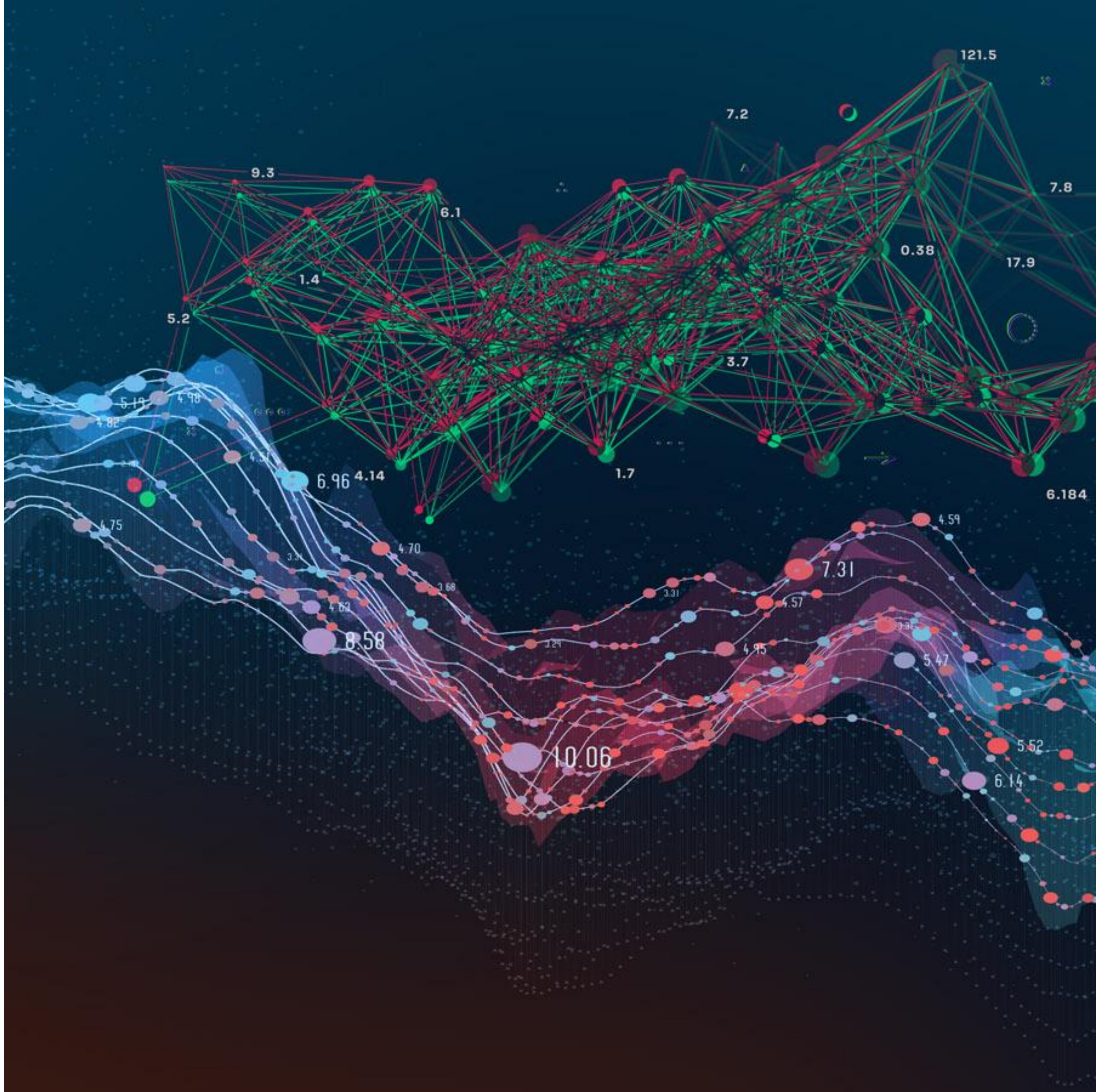


Background

- Germicidal ultraviolet (GUV) has been used in hospital settings for decades
- Upper-room (UR) GUV systems have been most common, so most past studies focused on them
- There are fewer studies using whole-room (WR) GUV systems because they are newer
- They are becoming more popular, so this study included one
- Effectiveness and safety of the GUV system depend on various factors, including GUV fluence rate and irradiance
- Providing an effective GUV fluence rate, while not exceeding safety limits, is crucial for GUV system design

Upper-Room (UR) GUV

Whole-Room (WR) GUV

Motivation

- Accurately predicting fluence rate and irradiance are key for GUV system design
- GUV is currently designed using architectural lighting tools
- There is little to no research on the accuracy of these tools in the GUV range (200 – 280 nm)
- Inaccuracies in software predictions can have greater health and safety implications for GUV than for visible light

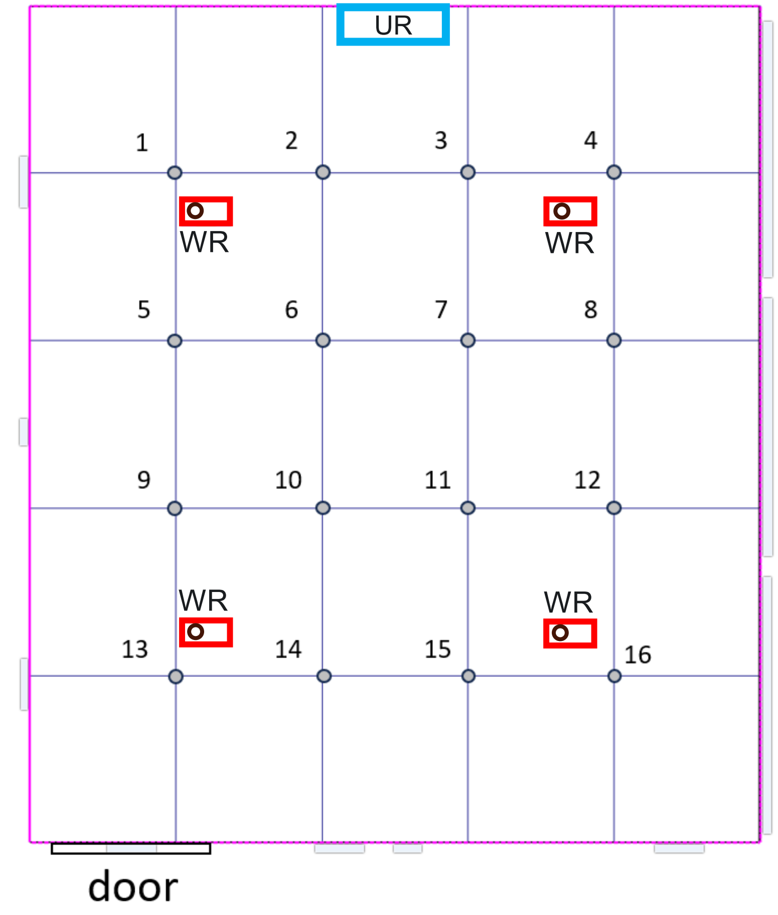
Goal of study

- To evaluate two commercially available simulation tools, Visual (Acuity Lighting) and Photopia (LTI Optics), against chemical actinometry and radiometric measurements in an experimental chamber for upper-room (UR) and whole-room (WR) GUV systems

Experimental setup

- IAQ Chamber at Purdue University
  - 14' W x 16' L x 8.92' H
  - White painted walls and ceiling
  - Concrete floor
  - Polycarbonate windows, metal and wooden panels
- GUV luminaires
  - Whole-room – 222 nm peak wavelength
  - Upper-room – 254 nm peak wavelength
- Measurement grids
  - 2.8' x 3.2' spacing
  - Fluence rate
    - 18" below ceiling
    - 36" below ceiling
  - UV-C Irradiance
    - 36" below ceiling (71" above floor, standing)
    - 56" below ceiling (51" above floor, seating)

Windows
Fluence rate & irradiance points
Irradiance points only



Simulations comparisons

<u>Fluence Rate:</u>

- Visual vs Actinometry
- Photopia vs Actinometry

<u>Irradiance:</u>

- Visual vs Radiometry
- Photopia Radiometry

	Fluence Rate	Irradiance
WR	✓	✓
UR	✓	-

Spherical Actinometry

"An actinometer is a chemical system or a physical device by which the number of photons in a beam absorbed into the defined space of a chemical reactor can be determined integrally or per time." (Kuhn *et al*., 2004, Pure Appl. Chem., **76**, 12, 2105-2146).

Spherical actinometry allows measurement of local fluence rate in a system.

<u>Experiment details:</u>

- Iodide/Iodate solution
- 1 cm diameter quartz spheres
- UV_{222} exposure time: 3 hours
- UV_{254} exposure time: 25 minutes

Radiometry

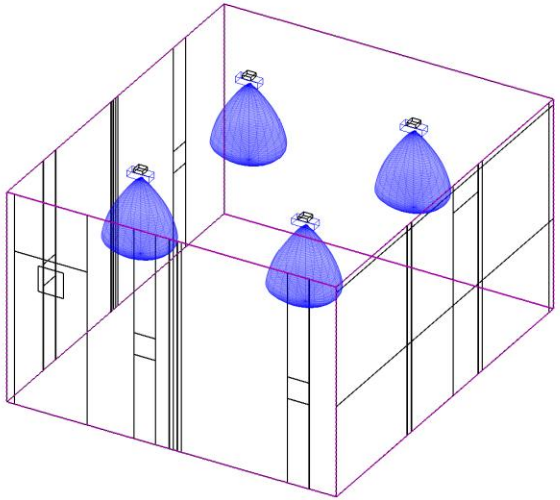
- Irradiance measurements were collected using a handheld-format radiometer (Gigahertz-Optik X1-UV-3727-5) with a one second integration time.
- The radiometer was mounted on a gimbal and was aimed straight up (i.e., at zenith) for skin irradiance measurements.

https://www.gigahertz-optik.com/en-us/product/x1-1-uv-3727/

Gimbal setup

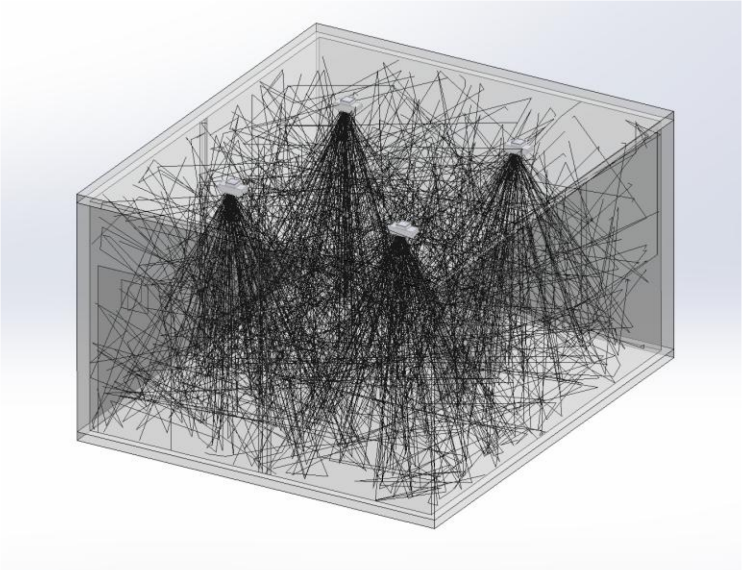
Visual simulations

- Uses the deterministic radiosity technique
  - Calculates energy exchange between small patches of surfaces
  - Based on inverse-square law
  - All surfaces are assumed to be perfectly diffuse and spectrally uniform
- User-configurable parameters:
  - Material reflectances
  - IES file
  - Light Loss Factors (LLFs)



Photopia simulations

- Uses the probabilistic ray-tracing technique
  - Models optical radiation as individual rays
  - Ray directions upon emanation from light sources are determined based on probabilities
  - Can handle surface specularity and spectral distributions
- User-configurable parameters:
  - Material types & reflectances
  - IES file
  - Light Loss Factors (LLFs)
  - Number of rays
  - Reaction count
    - Number of bounces for each ray before it's discarded
  - Sphere/sensor size



Material reflectances

- All surfaces were modeled as perfectly diffuse and spectrally uniform in Visual and Photopia

Feature	Material	Published reflectance	
		222 nm (whole room)	254 nm (upper room)
Floor	Concrete	5.1% [1]	15.4% [3]
Walls & Ceiling	White paint	7.8% [2]	6.7% [3]
Windows	Polycarbonate	8.2% [2]	8.2% *
Panels & Door	Metal	28.9% [2]	24.5% [3]
Panel	Wood	8.6% [2]	4.7% [3]

* No data for polycarbonate at 254 nm, so estimated it based on 222 nm

1. Claus, Holger, and Catherine C. Cooksey. "Reflectance measurements of building materials in the far UVC (222 nm) wavelength range." *UV and Higher Energy Photonics: From Materials to Applications 2022*. Vol. 12201. SPIE, 2022.
2. Ushio America - Application Note - Reflectance of Materials at 222 nm (9/2022).
3. Endo, Tomonori, et al. "Discussion on effect of material on UV reflection and its disinfection with focus on Japanese Stucco for interior wall." *Scientific Reports* 11.1 (2021): 21840.

Statistical method for validation

- Median Relative Bias Error (MRBE)

$$\frac{Predicted - Measured}{Measured} X\ 100\%$$

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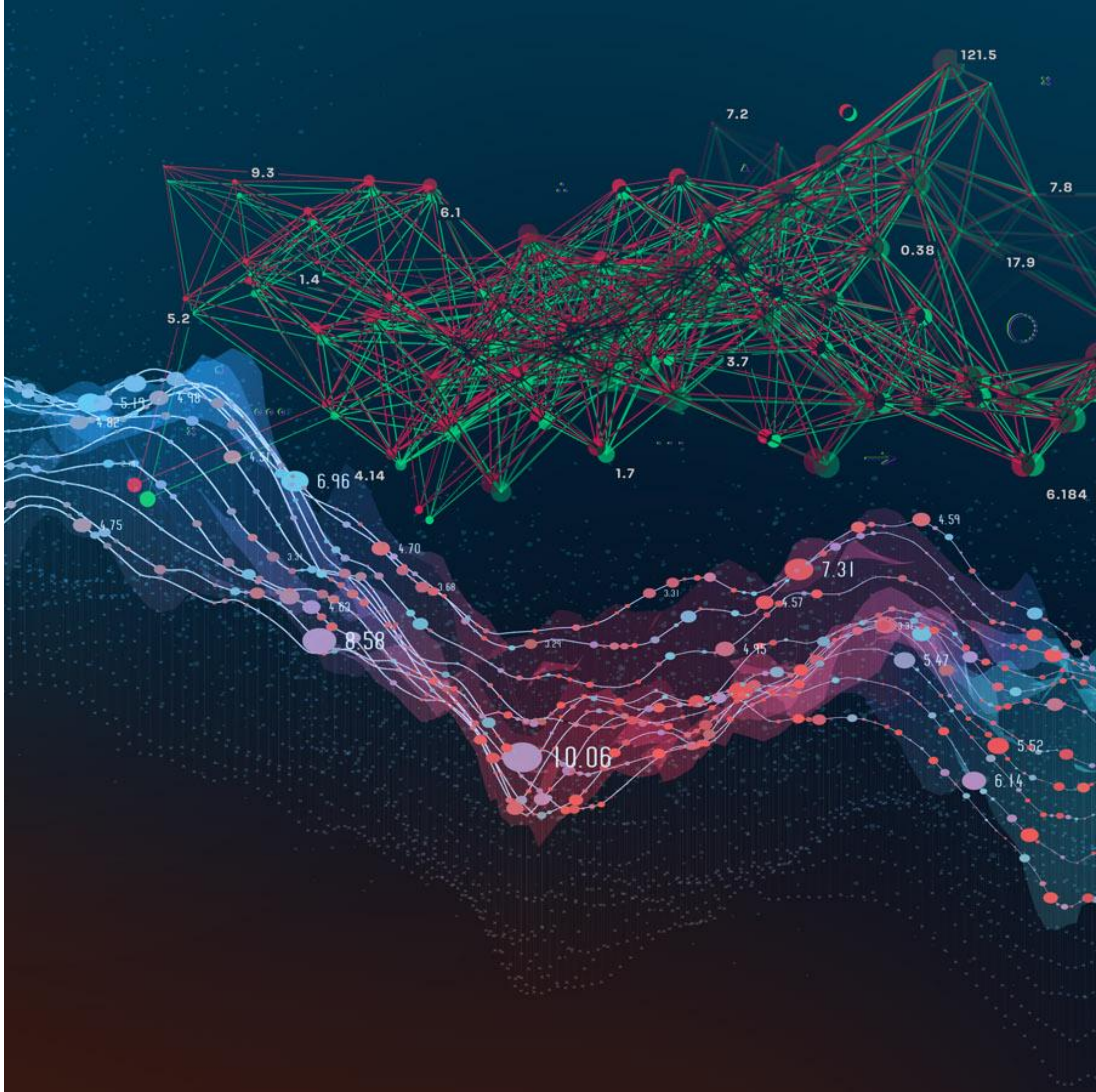
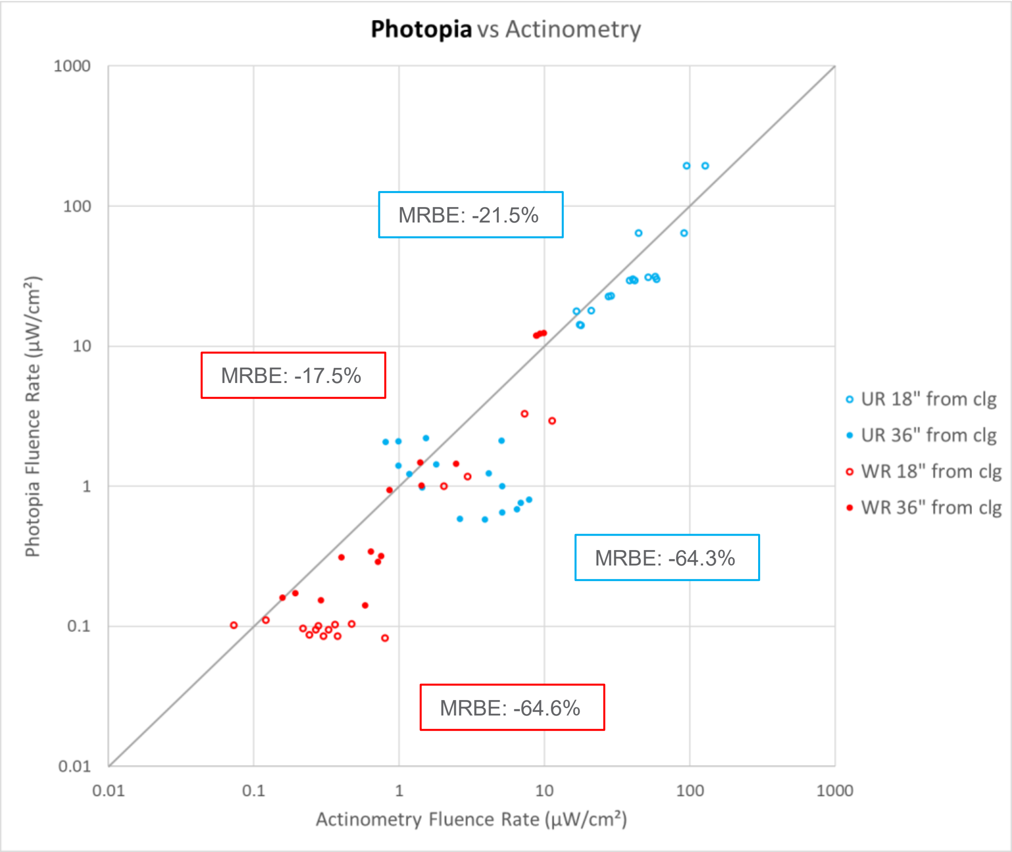
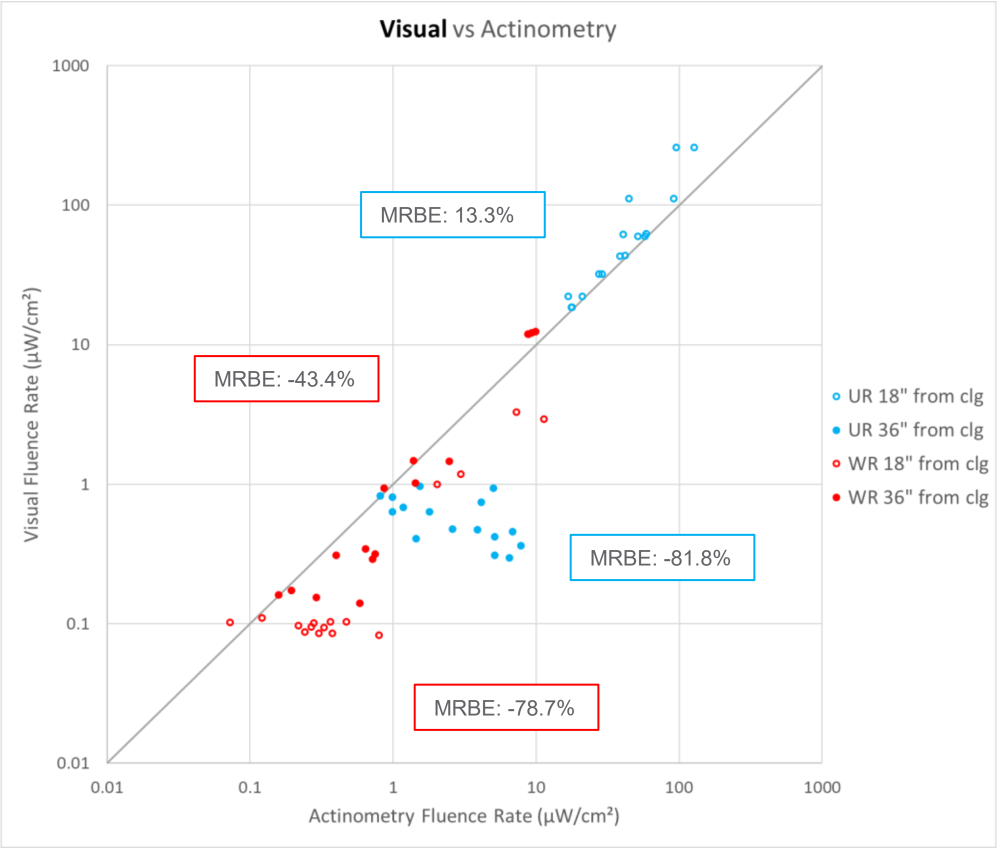
Preliminary Fluence Rate Results



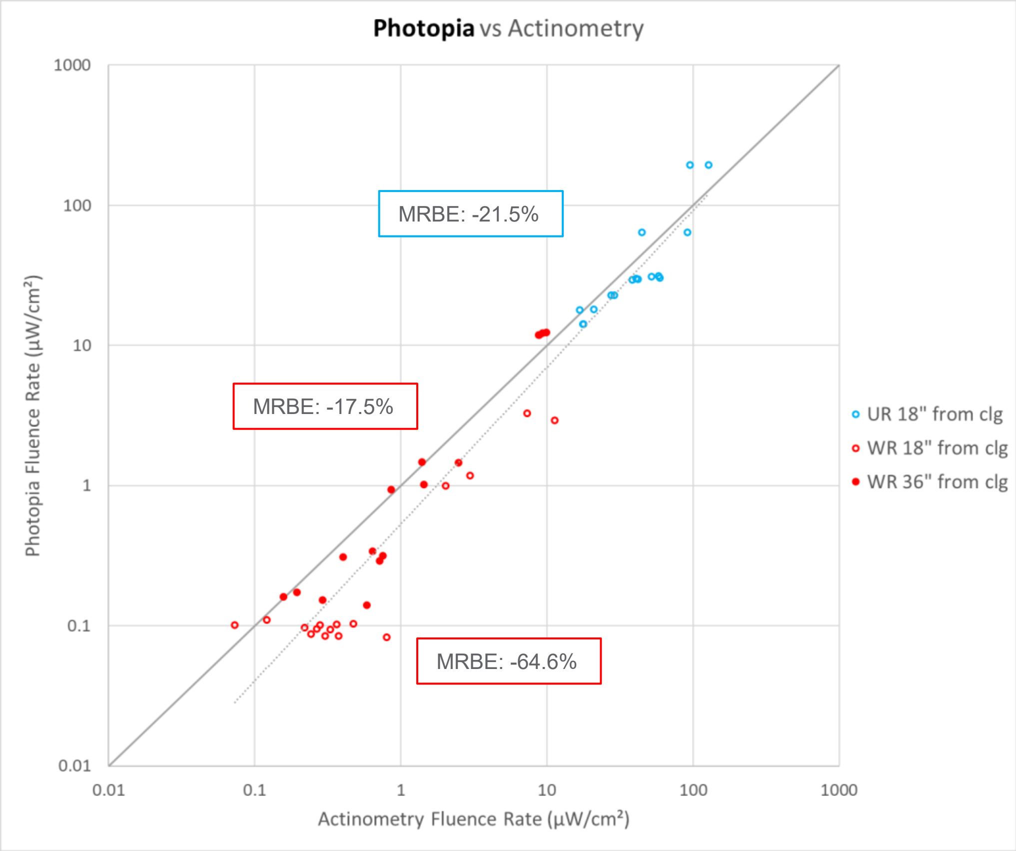
Fluence Rate (µW/cm²) Simulations vs Actinometry

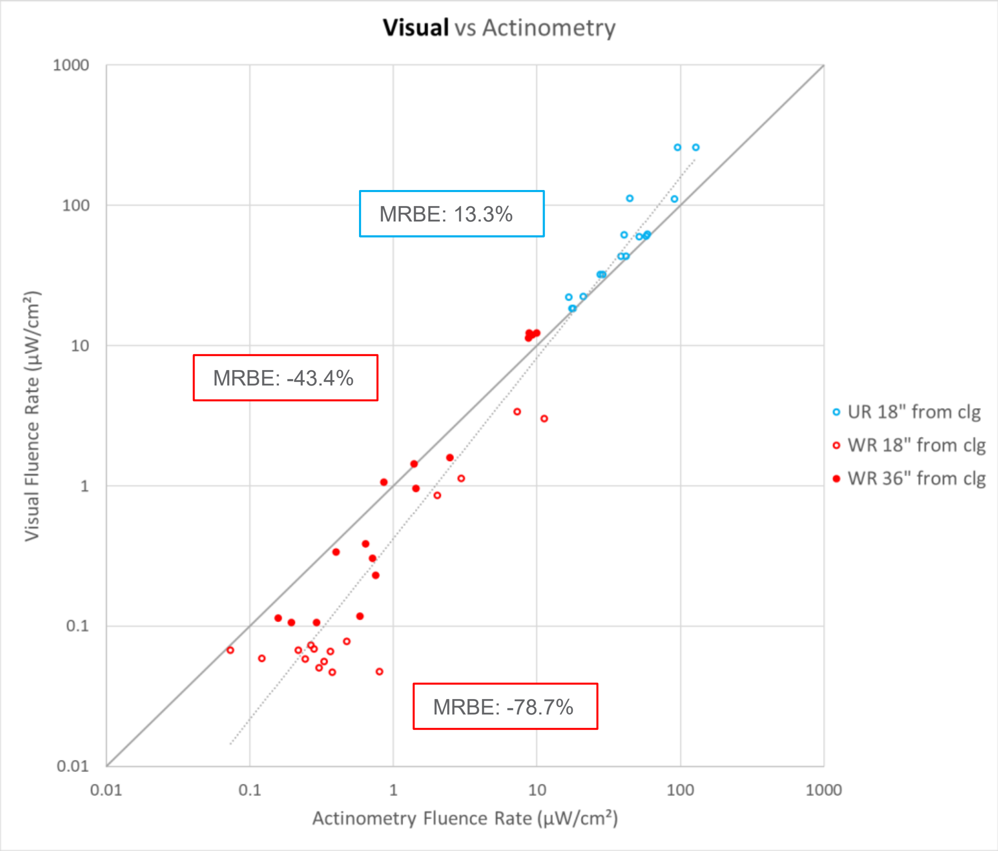




- Simulations predicted lower fluence rate compared to actinometry results for most points.
- Closer agreement between simulations and actinometry in the 18-in plane for UR where the fluence rate is highest.
- The higher the fluence rate, the closer the relative agreement between simulations and actinometry, except for the UR 36-in plane.

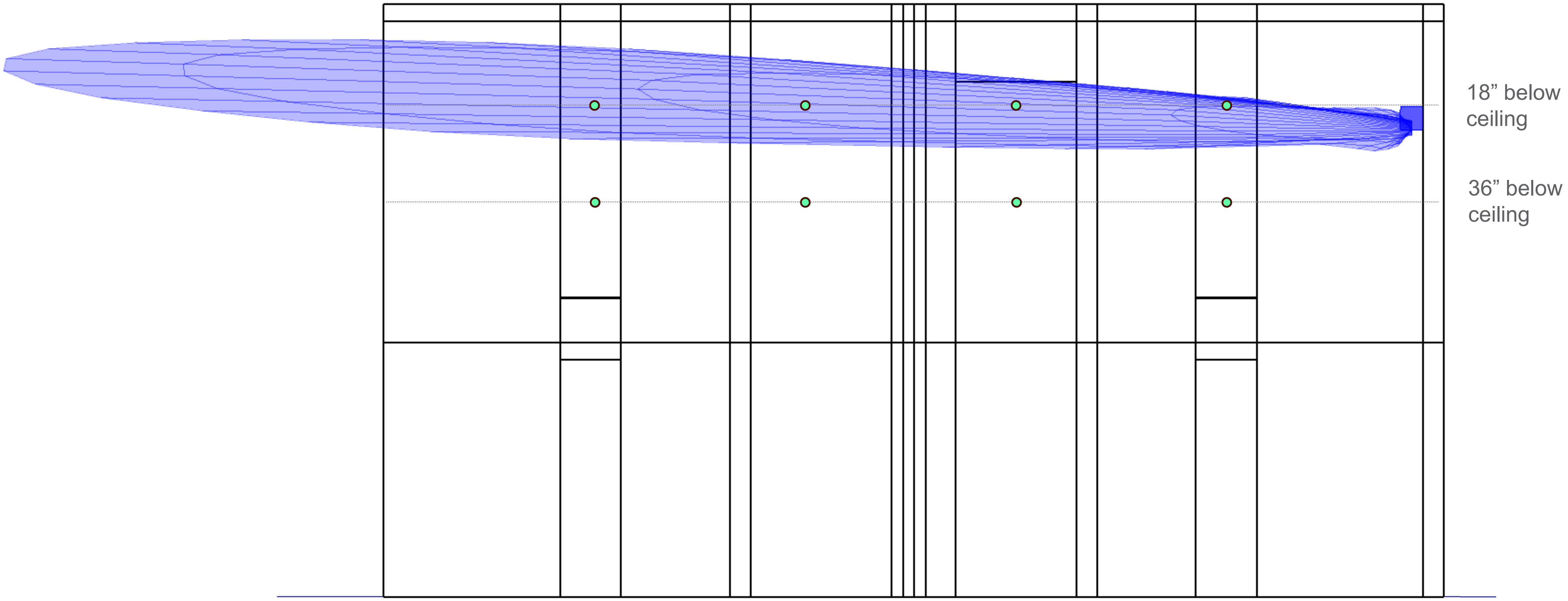
Fluence Rate (μW/cm²)
Simulations vs Actinometry – UR 36 in removed



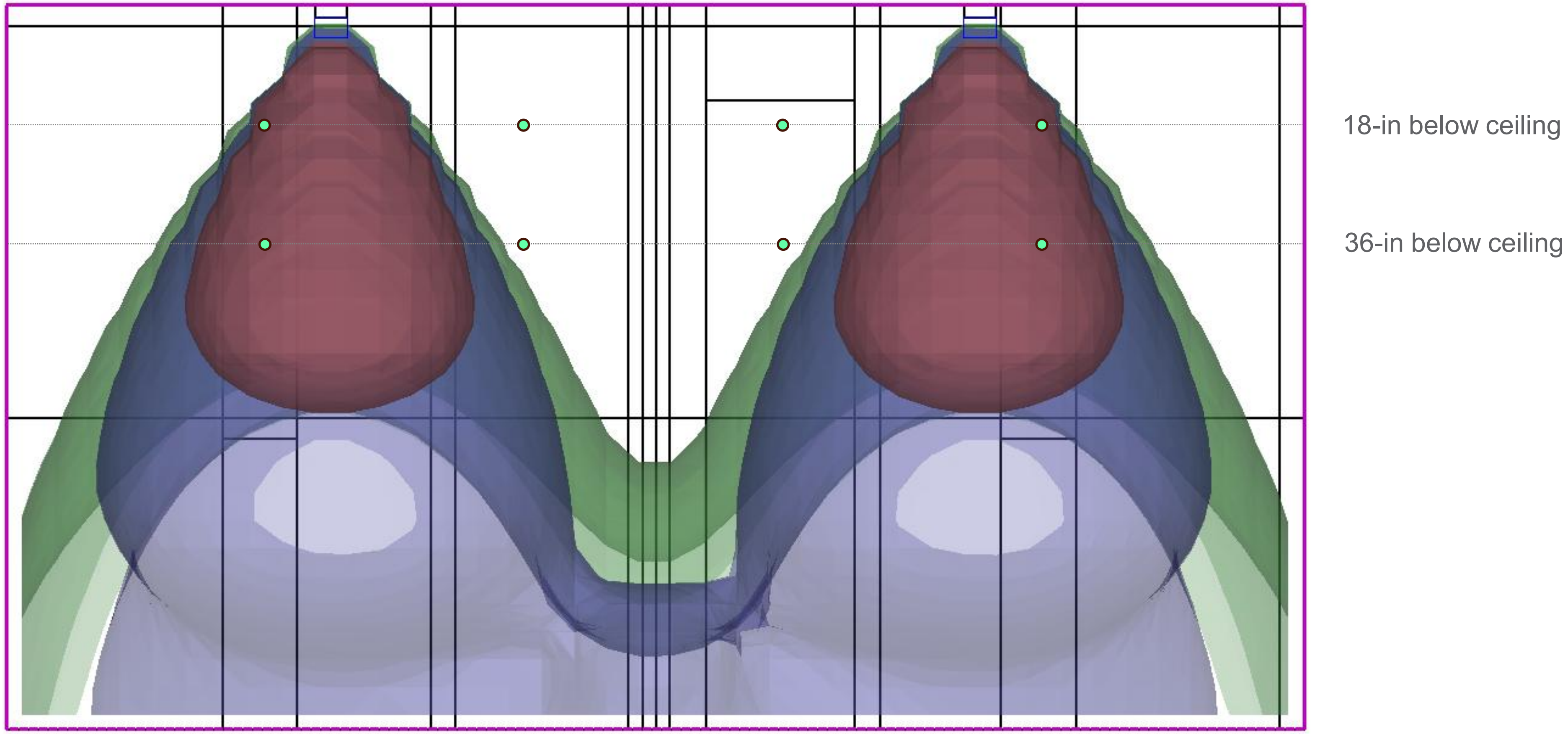


- Removing the points for the UR at 36 in shows a much closer trend for better agreement between simulations and actinometry as the fluence rate increases.
- Need to investigate the disagreement between simulations and measurements at low fluence rate values.

Upper Room - Luminaire Radiant Intensity Distribution



Whole-Room Fluence Rate Points



Contour 1	✓	green	1	(µW/cm²)
Contour 2	✓	blue	2	(µW/cm²)
Contour 3	✓	red	5	(µW/cm²)

Average Fluence Rate Comparison (μW/cm²)

WR	Photopia	Visual	Actinometry
18 in	0.59	0.55	1.72
36 in	3.43	3.40	2.94
Overall	2.01	1.97	2.33

UR	Photopia	Visual	Actinometry
18 in	50.3	76.0	48.8
36 in	1.23	0.59	3.51
Overall	25.8	38.3	26.2

- Photopia & Visual predict lower fluence rate than actinometry for most points at 36 in WR, except for a few higher values, forcing the average fluence rate to be higher than measured by actinometry.
- The total average fluence rate for UR is dominated by the larger values of the 18-in plane. Even though the 36-in plane has a poor agreement between simulations & actinometry, the values are very low, not contributing as significantly to the total average.
- There is a close agreement between Photopia and Actinometry for UR. Visual's worse agreement with actinometry may be due to some points located too close to the luminaire (at a distance less than 5-times the largest dimension of the luminaire), where the inverse-square law may fail to work.

Summary

- Simulations predictions have lower values than actinometry measurements for most points.
- Agreement between simulations predictions & actinometry is poor at low fluence rate values; it gets better as the fluence rate increases except for the 36-in (lower) plane for the UR system.
- The best agreement between simulations and actinometry in terms of average fluence rate is between Photopia and actinometry for the UR system.
- Visual may have an issue predicting fluence rate for UR systems for points that are close to the luminaire.
- Higher fluence rate values are much more influential for average fluence rate prediction.

Preliminary Conclusions

- Differences between simulated and measured fluence rate can have health and safety implications.
- The use of design software may be more accurate when designing to higher fluence rates.
- The strategic placement of measurement and simulation calculations points for both systems is important to characterize the fluence rate.
- The disagreement between simulations and actinometry at low fluence rate values needs to be investigated.

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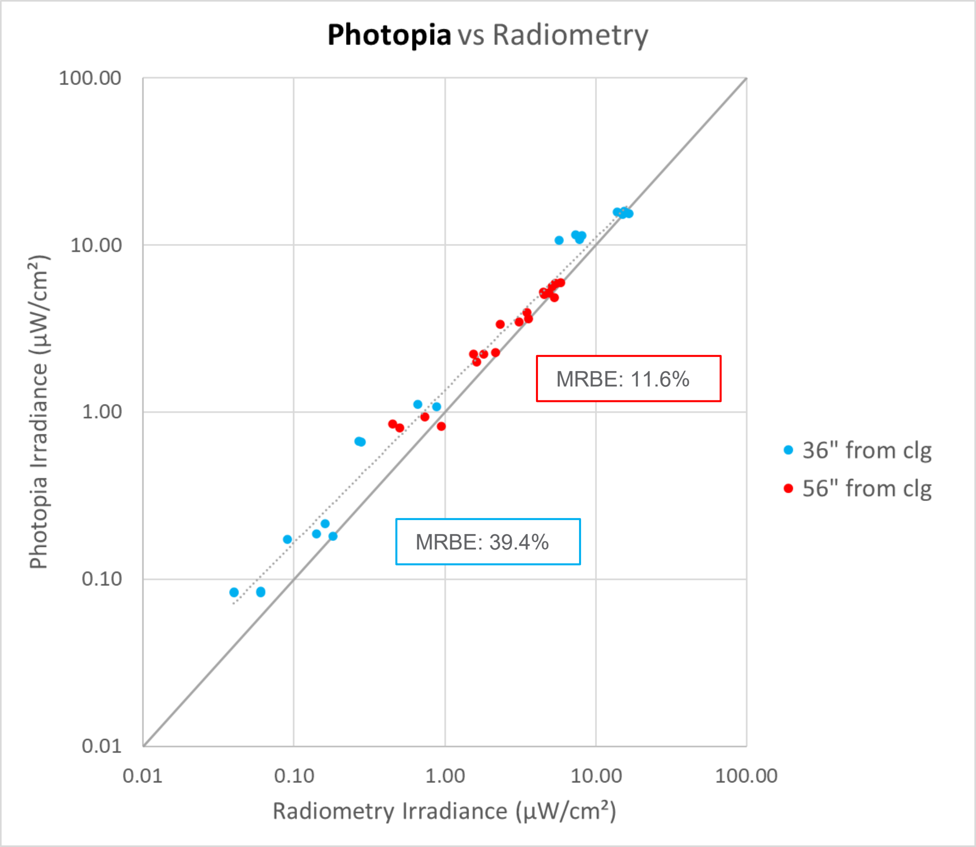
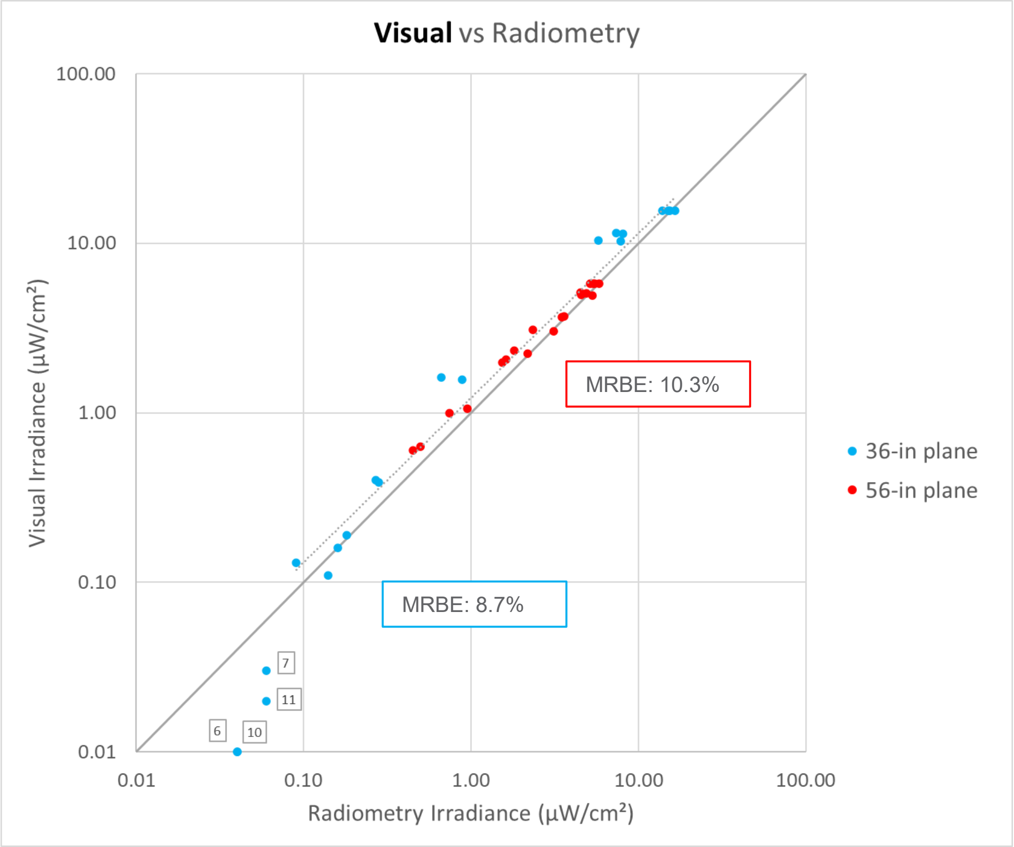
Preliminary Irradiance Results

Irradiance ($\mu W/cm^2$) Simulations vs Radiometry





- Both Visual and Photopia predicted higher irradiance values than measured for most points.
- The 56-in plane had a closer agreement between Photopia simulations and measurements than the 36-in plane.
- The 4 outliers for Visual were the points in the middle of the room that had very low irradiance values.

Average Irradiance ($\mu W/cm^2$)

	Photopia	Visual	Radiometry
18 in	3.51	3.43	3.17
36 in	5.56	5.53	4.63
Total	4.53	4.48	3.90

23

Summary

- Simulations predicted higher irradiance values than measured for most points and on average.
- Simulations for irradiance agreed better with measurements than simulations for fluence rate, which is more complex to measure.

Limitations

- One WR luminaire appeared to have lower output than the others based on the irradiance measurements right underneath the luminaires, possible due to manufacturing tolerances or service life.
- The IES files for the luminaires were not for the specific units measured in the field.
- Room reflectance values were estimated and not measured.
- All surfaces were assumed to be diffuse for all simulations.

Next steps

- Investigate discrepancies between simulations predictions and measurements at low fluence rate values.
- Conduct similar experiment at second site, PNNL Lighting Science & Technology Laboratory, to compare findings.
- Develop manuscript to submit to peer-reviewed journal.

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Thank you

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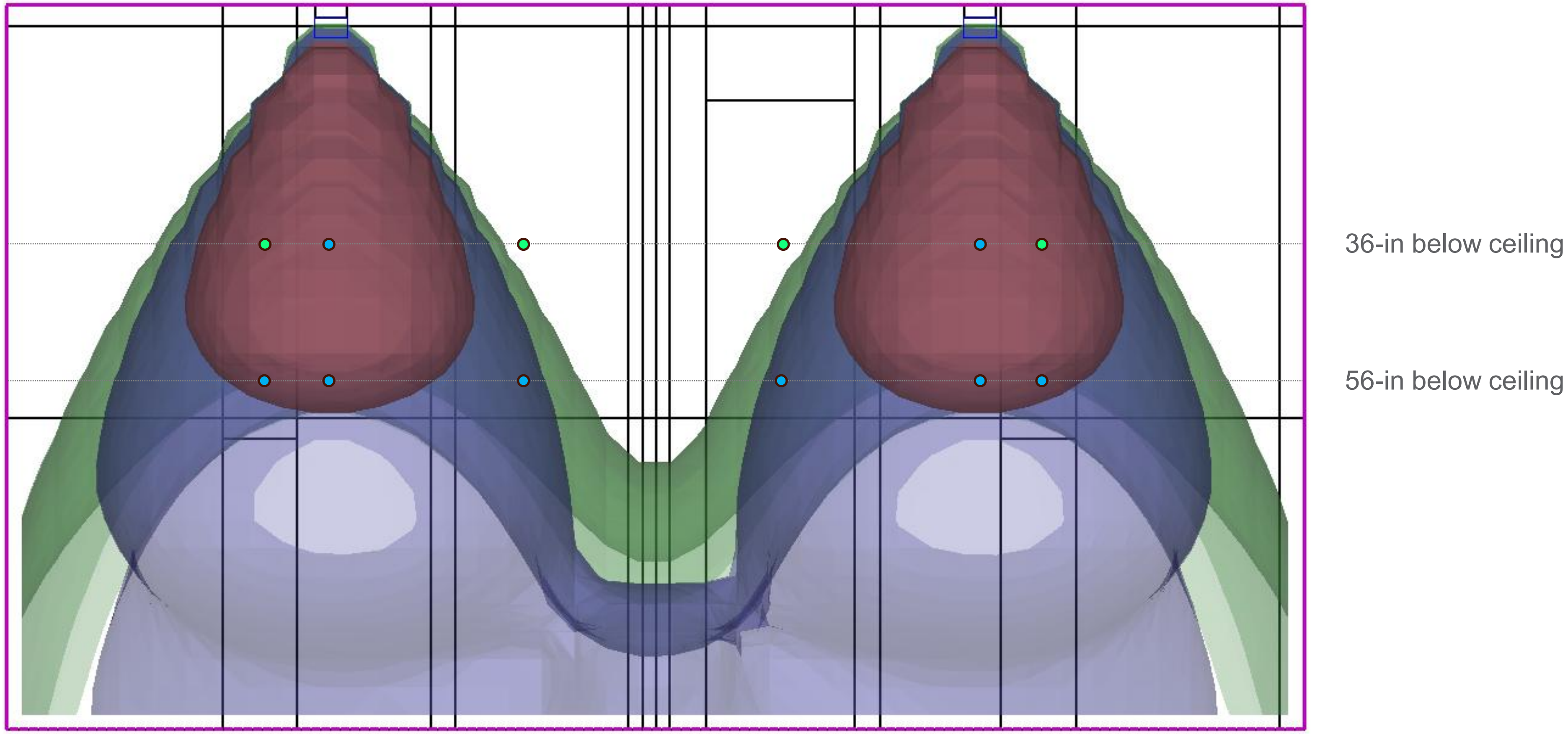
Slides below are for reference

Whole-Room Irradiance Points



- Fluence rate & irradiance points
- Irradiance points only

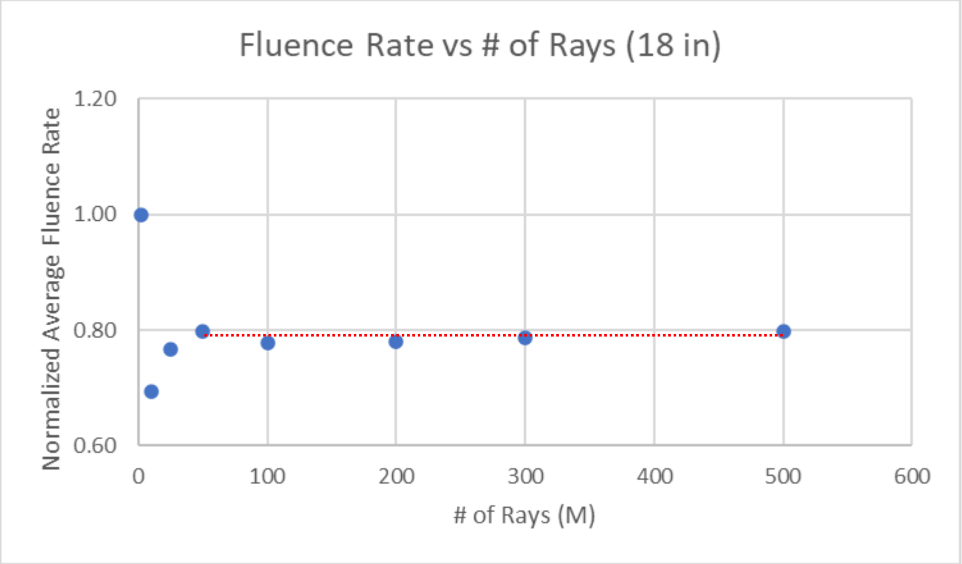
Contour 1	1	($\mu W/cm^2$)
Contour 2	2	($\mu W/cm^2$)
Contour 3	5	($\mu W/cm^2$)

Number of rays – Whole room

- 1-cm spheres, reaction count: 3

18 in - Fluence Rate (μW/cm²)

# rays (M)	2.5	10	25	50	100	200	300	500
Point 1	4.64	2.07	3.21	3.37	3.10	3.28	3.12	3.23
Point 2	0.05	0.06	0.06	0.05	0.05	0.05	0.05	0.05
Point 3	0.04	0.06	0.06	0.05	0.06	0.05	0.05	0.05
Point 4	0.87	0.91	1.14	1.13	1.02	1.02	1.10	1.13
Point 5	0.04	0.10	0.06	0.08	0.07	0.06	0.06	0.07
Point 6	0.10	0.07	0.06	0.07	0.06	0.06	0.06	0.06
Point 7	0.05	0.06	0.07	0.07	0.06	0.06	0.06	0.06
Point 8	0.04	0.12	0.07	0.07	0.07	0.07	0.07	0.07
Point 9	0.02	0.06	0.04	0.06	0.07	0.07	0.07	0.07
Point 10	0.04	0.08	0.06	0.07	0.06	0.06	0.06	0.06
Point 11	0.08	0.07	0.07	0.07	0.06	0.06	0.06	0.06
Point 12	0.06	0.10	0.10	0.06	0.09	0.08	0.11	0.09
Point 13	4.10	3.07	2.52	2.80	2.91	2.90	2.89	2.85
Point 14	0.03	0.06	0.05	0.05	0.05	0.05	0.05	0.05
Point 15	0.03	0.05	0.06	0.06	0.05	0.05	0.05	0.05
Point 16	1.03	0.87	0.99	0.85	0.94	0.83	0.95	1.00
avg	0.70	0.49	0.54	0.56	0.55	0.55	0.55	0.56

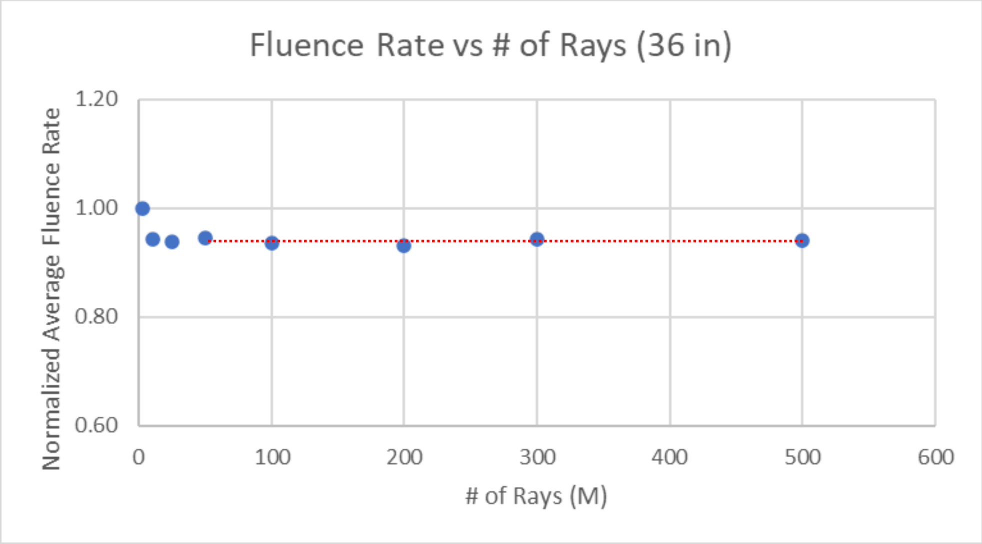


Number of rays – Whole room

- 1-cm spheres, reaction count: 3

36 in - Fluence Rate (μW/cm²)

# rays (M)	2.5	10	25	50	100	200	300	500
Point 1	13.39	13.72	12.91	12.30	12.23	12.19	12.19	12.30
Point 2	1.71	0.74	0.87	1.06	0.95	0.89	1.01	0.88
Point 3	1.27	1.83	1.64	1.59	1.32	1.49	1.46	1.54
Point 4	12.19	10.66	12.02	12.21	11.74	11.57	11.95	11.52
Point 5	0.51	0.16	0.38	0.23	0.28	0.30	0.29	0.28
Point 6	0.08	0.13	0.08	0.11	0.10	0.10	0.11	0.11
Point 7	0.15	0.08	0.12	0.12	0.13	0.09	0.10	0.09
Point 8	0.64	0.37	0.11	0.30	0.27	0.27	0.26	0.26
Point 9	0.24	0.16	0.34	0.39	0.35	0.30	0.32	0.30
Point 10	0.08	0.05	0.20	0.11	0.11	0.09	0.10	0.10
Point 11	0.54	0.07	0.13	0.11	0.12	0.12	0.12	0.11
Point 12	0.07	0.33	0.17	0.34	0.33	0.33	0.27	0.28
Point 13	10.93	12.11	11.40	11.82	12.11	12.13	12.01	12.11
Point 14	1.32	0.92	1.05	0.96	0.82	0.85	0.92	0.90
Point 15	1.93	0.92	1.16	1.43	1.55	1.45	1.48	1.46
Point 16	12.37	11.97	11.35	11.25	11.39	11.32	11.55	11.77
avg	3.59	3.39	3.37	3.39	3.36	3.34	3.38	3.38



IAQ Chamber