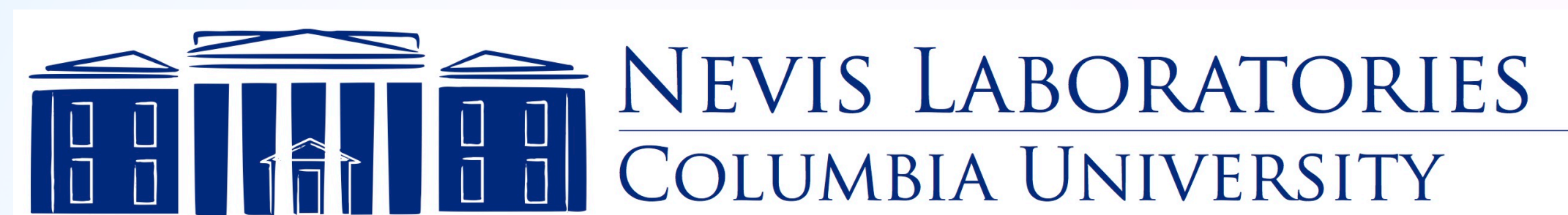


Autonomous Robotic Measurement of Far UV-C Irradiance for Validation of Indoor Lighting Installations

Summer REU Final Report

Lillianne Bakshi | Advisor: Dr. David Welch | July 31, 2026



Lillianne Bakshi

A little about me...

- Rising senior at UC Irvine
- Major: Applied Physics (biomedical concentration)
- Post-Grad plans: gap year + grad school application



Our Invisible Problem...

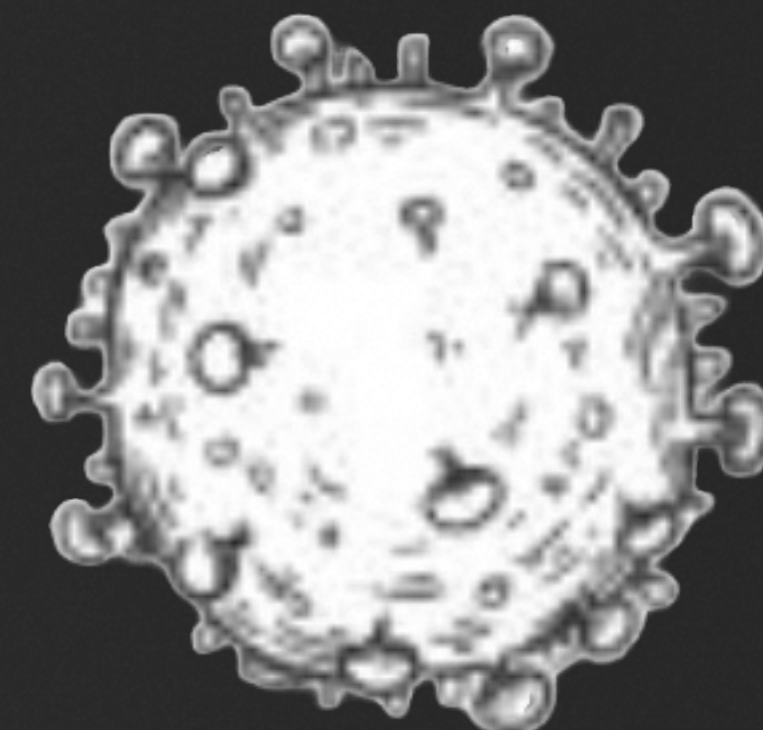
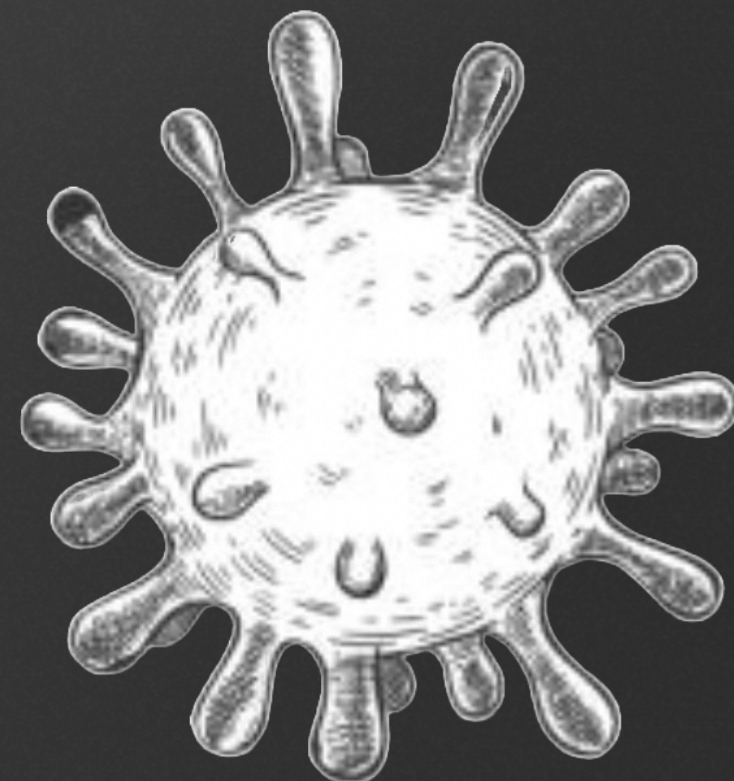
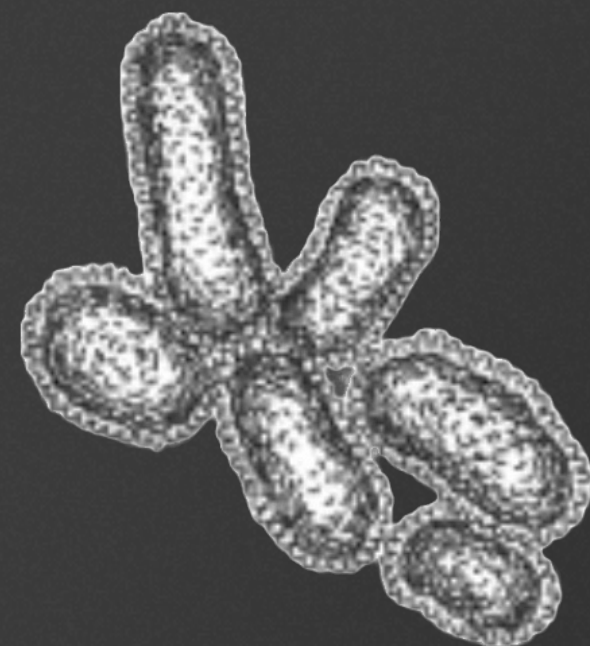
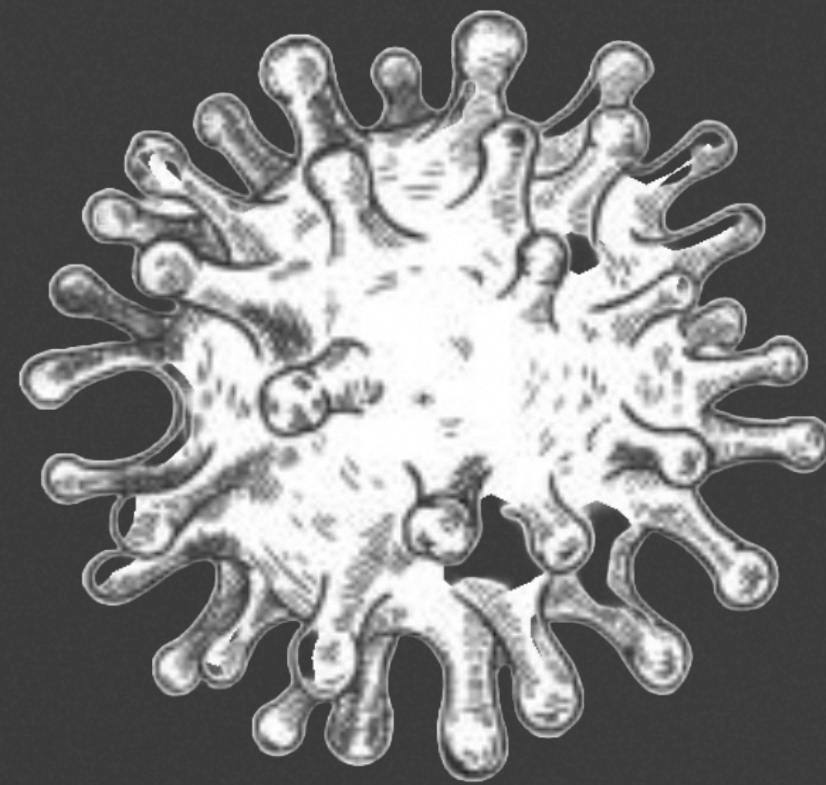
Airborne disease: a massive, invisible burden

COVID-19: ~27M deaths worldwide

Tuberculosis: ~1.6M deaths/year

Influenza: ~1B infections/year

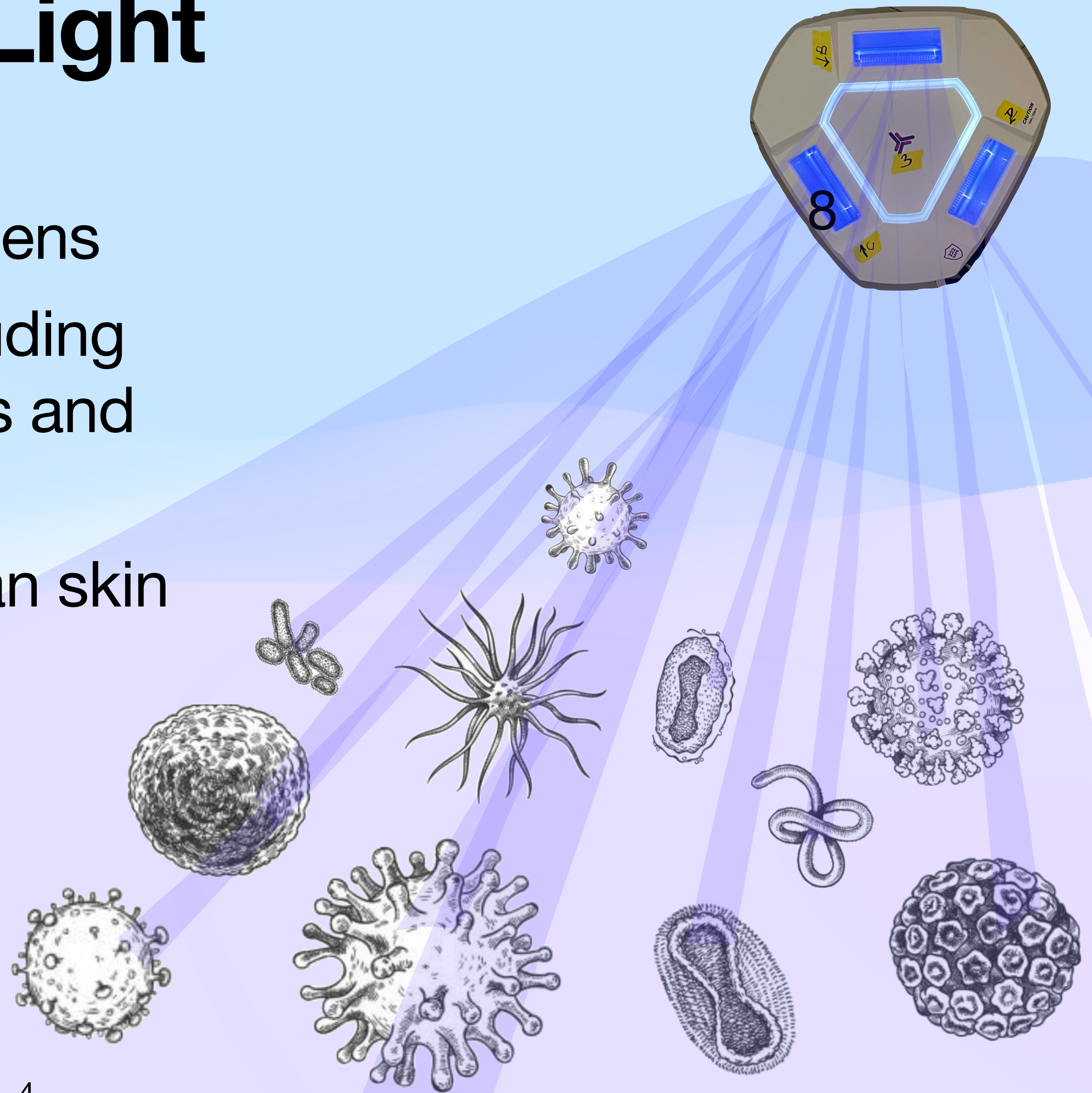
Increasing likelihood for another pandemic!



254nm UV (Ultraviolet) Light

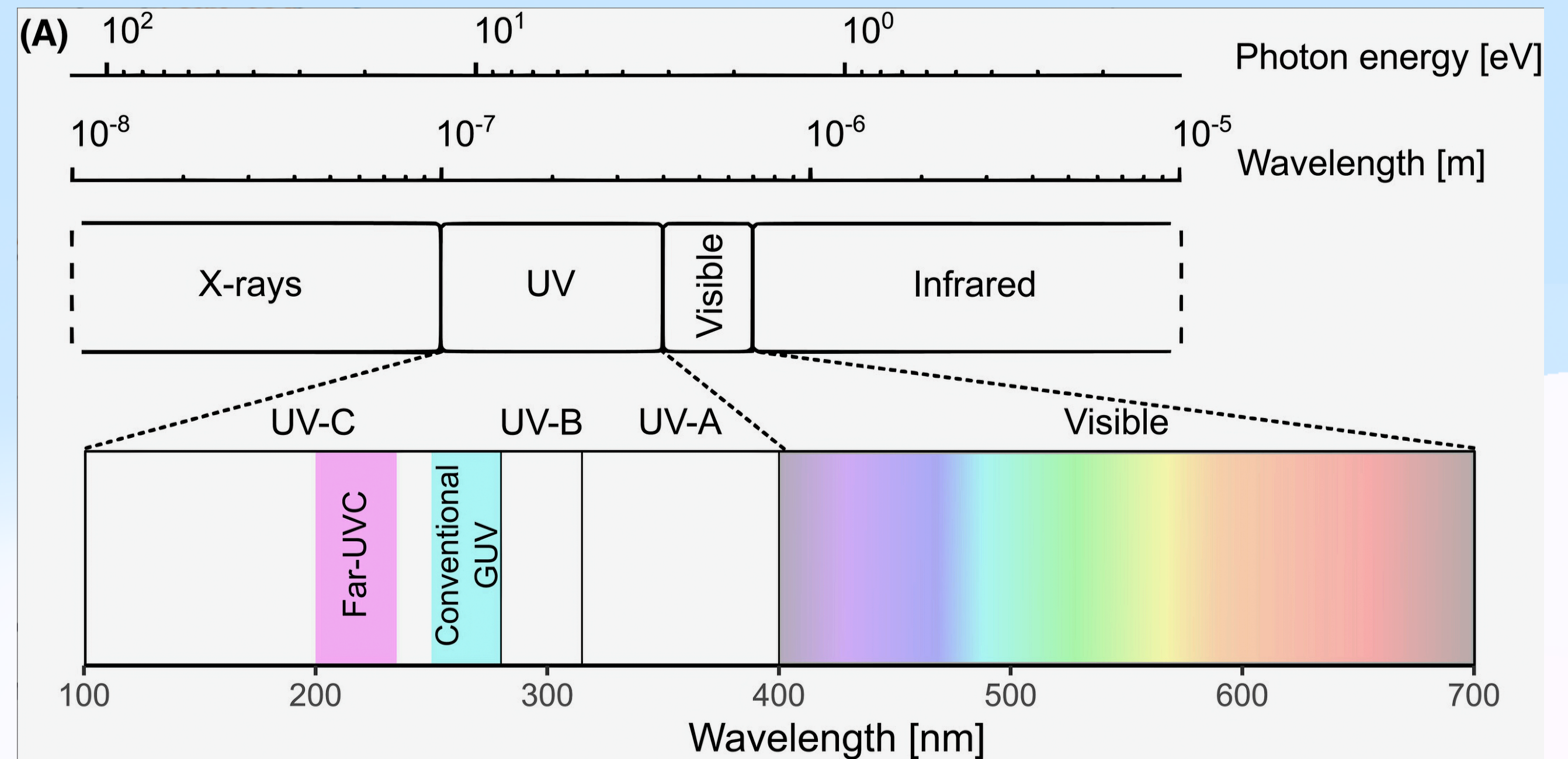
An Invisible Solution

- Used since the 1940s to kill pathogens
- Effective against any microbe, including emerging microbes (unlike antibiotics and innoculation)
- *This wavelength* can damage human skin and eyes: unsafe for direct exposure



Germicidal UV: Wavelength Classification

- UV-A, UV-B, and UV-C classified by wavelength from longer wavelength (A) to shorter wavelength (C)
- UV Light has wavelength 100nm - 400 nm
- Conventional UVC is at 254nm using low pressure mercury lamp
- *Far-UVC is from 200nm - 235nm

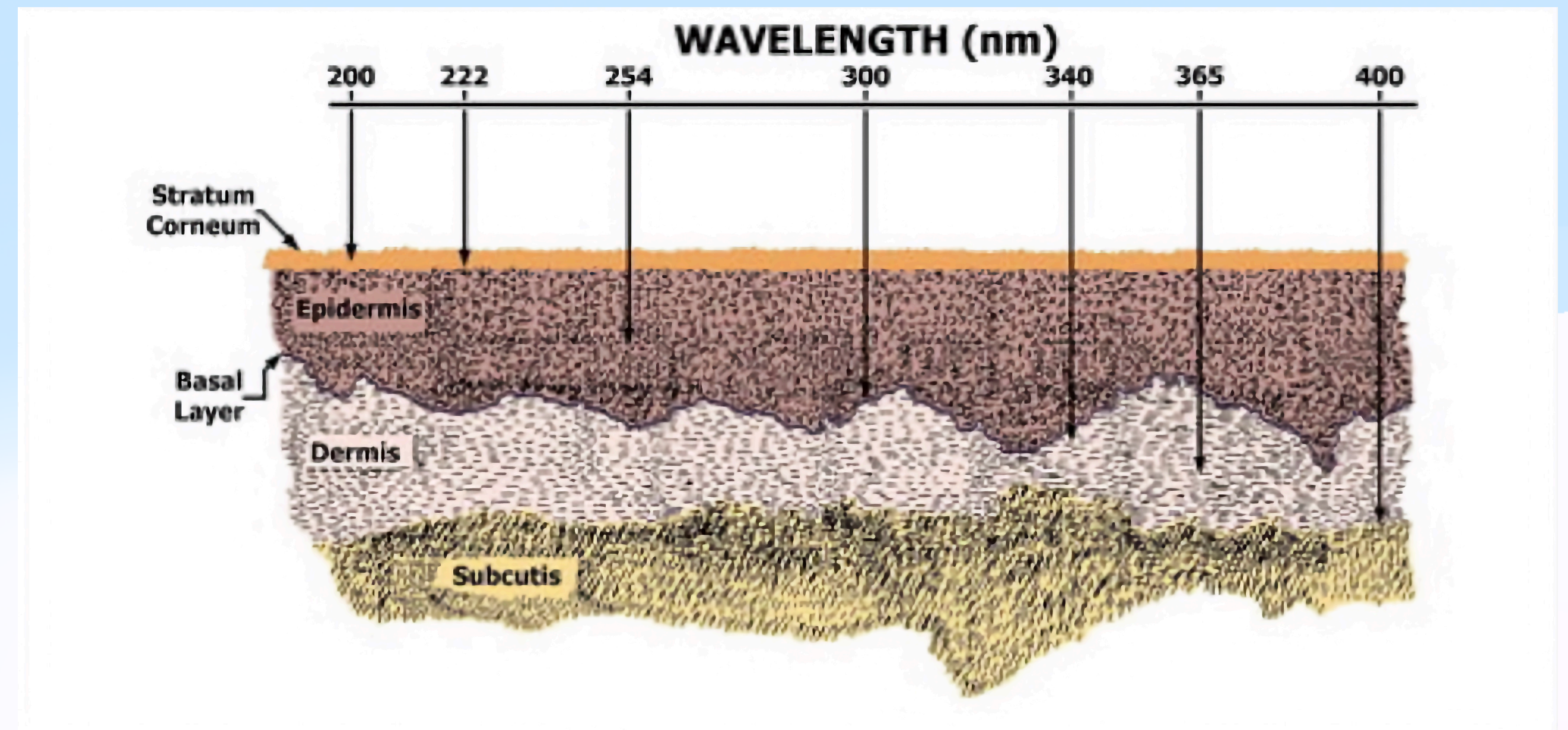


Görlitz M, Justen L, Rochette PJ, et al. Assessing the safety of new germicidal far-UVC technologies. Photochem Photobiol. 2024; 100: 501-520.

Far-UVC: A Safer Wavelength

Columbia has pioneered work in far-UVC

- Doesn't penetrate skin- mostly absorbed in the dead cell layer at the surface
- Topmost layer of cells on the eye are sloughed off quickly, so damage here is not a concern
- Effective at inactivating any microbe
- Columbia has shown outstanding efficacy against influenza and coronaviruses



Blatchley ER III, Brenner DJ, Claus H, Cowan TE, Linden KG, Liu Y, *et al.* Far UV-C radiation: An emerging tool for pandemic control. *Crit. Rev. Environ. Sci. Technol.* 2022;53(7):733–753. doi:10.1080/10643389.2022.2084315

Far UV-C Installation

Whole Room Exposure

- Even though safe doses of far-uv-c are anti-microbial we need to verify that installations operate at recommended safety exposure limits for UV light

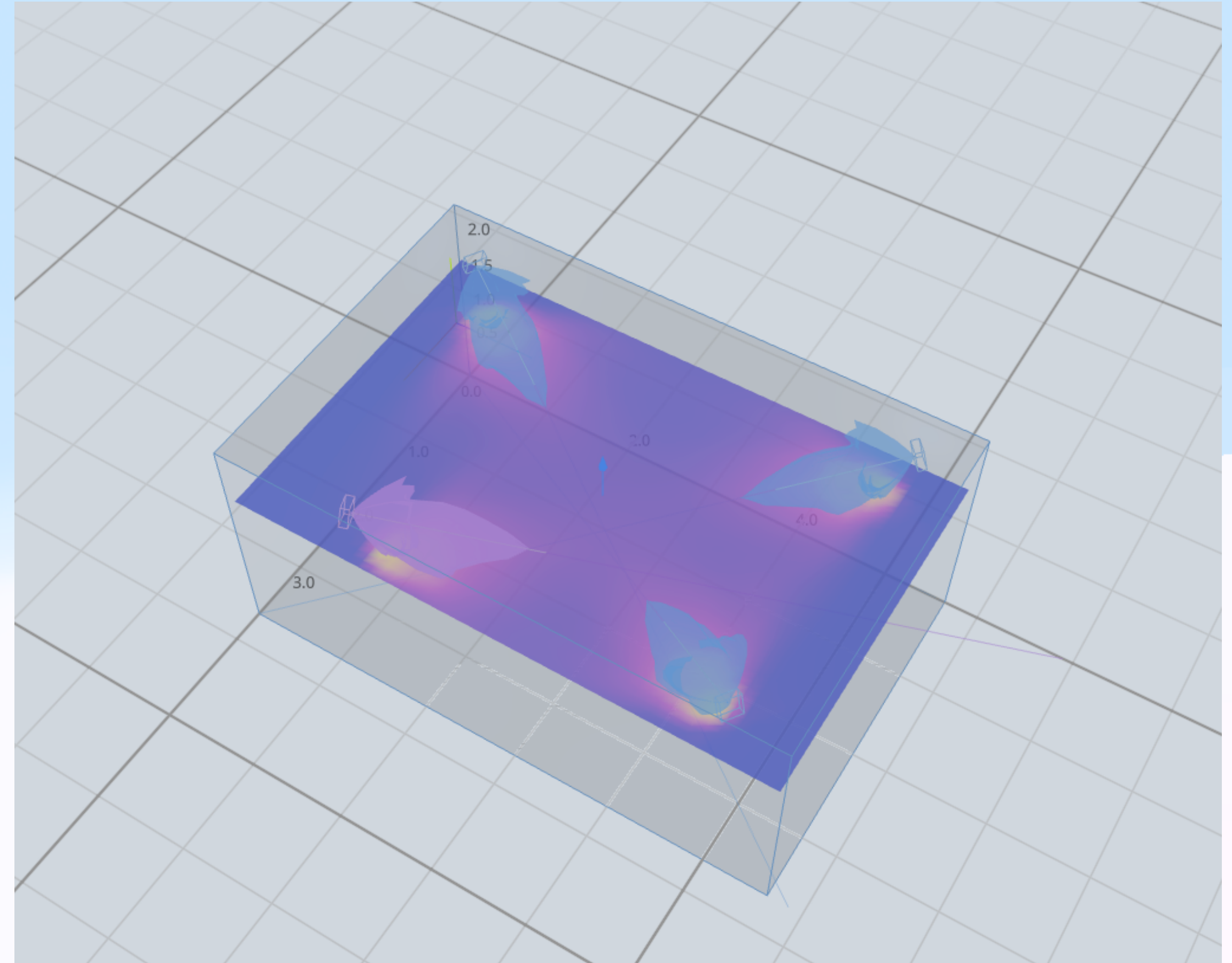


<https://news.columbia.edu/ultraviolet-technology-virus-covid-19-UV-light>

Light Installation Simulation

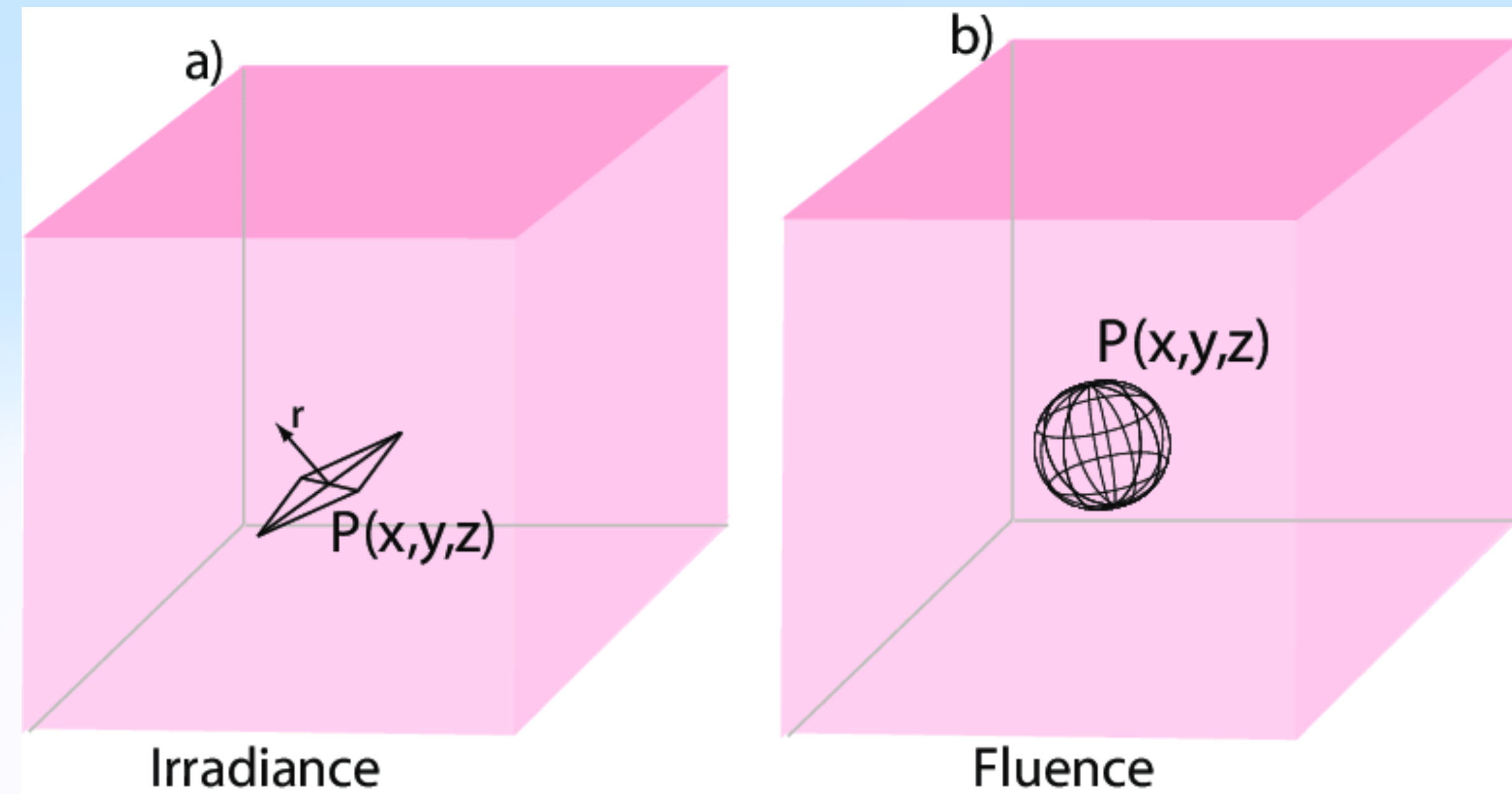
Illuminate Software

- Modify a simulated room to precise dimensions
- Select from a variety of light fixtures and modify its position and orientation
- Calculate skin dose, eye dose, and total room fluence



Exposure Metrics

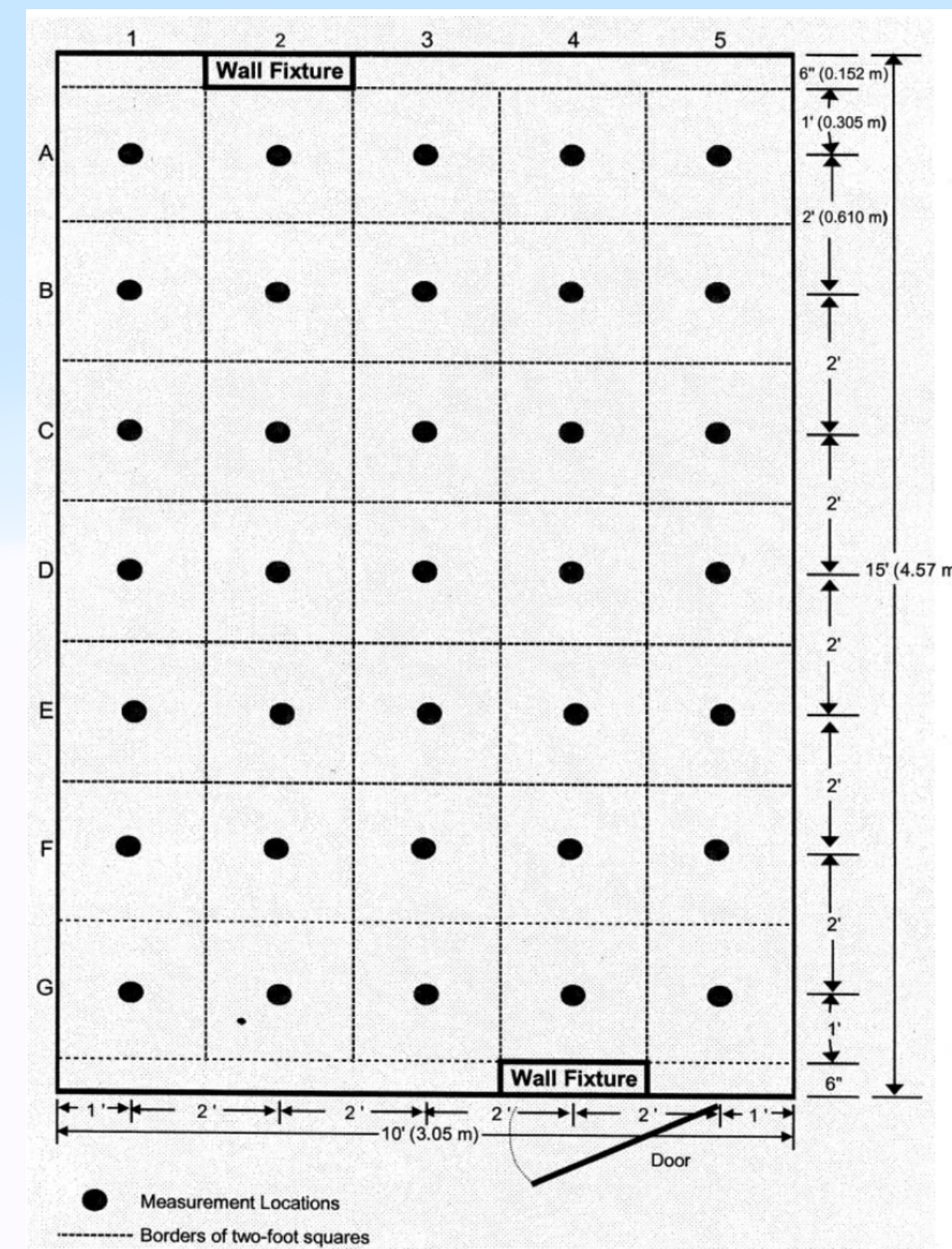
Irradiance vs Fluence



Current validation method for Far-UVC installations

Grid Method

- measurement at 0.5m intervals within a room
- Linear interpolation between measurements
- Verify exposure levels for safety



Rudnick, S. N., First, M. W., Sears, T., Vincent, R. L., Brickner, P. W., Ngai, P. Y., Zhang, J., Levin, R. E., Chin, K., Rahn, R. O., Miller, S. L., & Nardell, E. A. (2012). Spatial distribution of fluence rate from upper-room ultraviolet germicidal irradiation: Experimental validation of a computer-aided design tool. *HVAC&R Research*, 18(4), 774-794.

Motivation for Robotic Irradiance Mapping

- Grid measurements are slow and labor-intensive
- 0.5m spacing misses fine spatial variations in irradiance
- Requires manual positions

Goal: Build an automated system for higher resolution irradiance mapping

System Requirements

- **Robot**
 - Mobility
 - Mapping
 - Communication
- **Light sensing**
- **Simultaneous light and position data acquisition**

TurtleBot

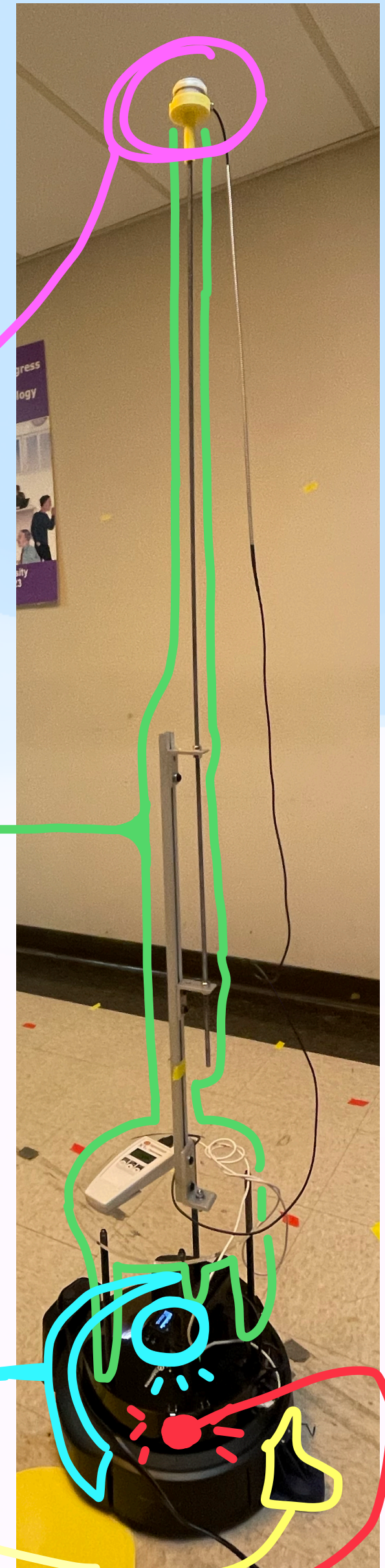
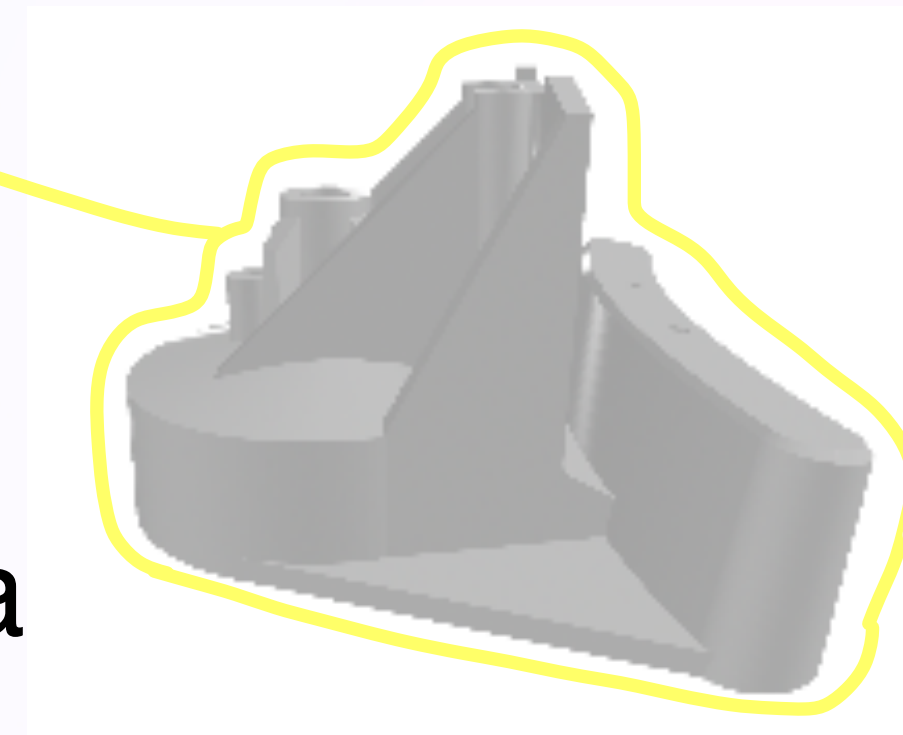
(Who I've spent most of my time in NY with)



Hardware Modifications

Light Sensing, Mapping, and Communication abilities

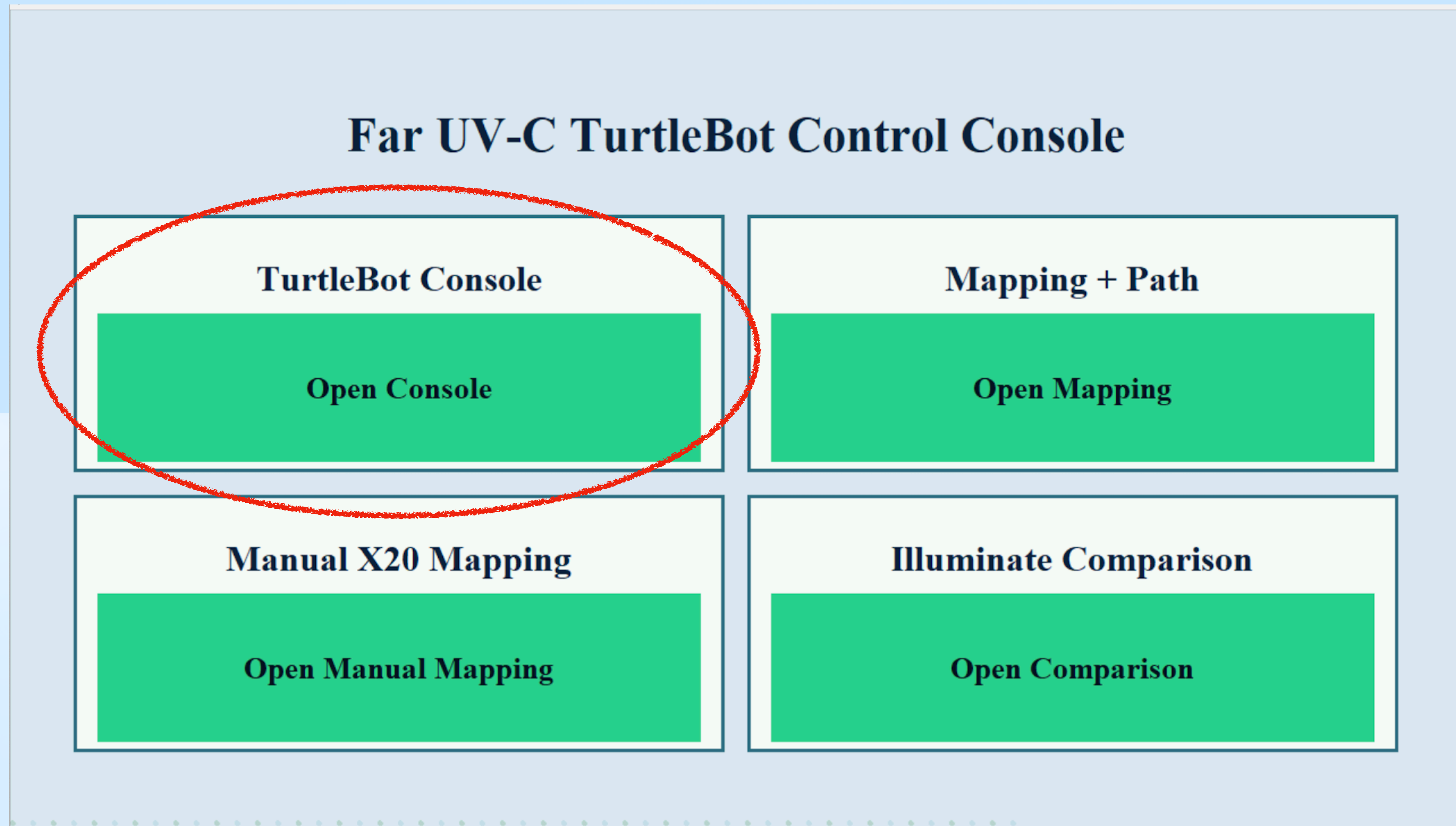
- LiDAR Sensor and Bumper Sensor
- GigaHertz X20 Sensor - 222nm specific
- Light sensor Stand- adjustable height
- Caster wheel
- All sensors plug into an onboard Raspberry Pi which communicates to a computer via WiFi



Graphical User Interface (GUI) for Robot Operation/Communication

- Start and Stop programs**
- Visualization (heatmaps and room maps)**
- Design and Send Paths for Robot to follow**
- Comparison between heatmaps**

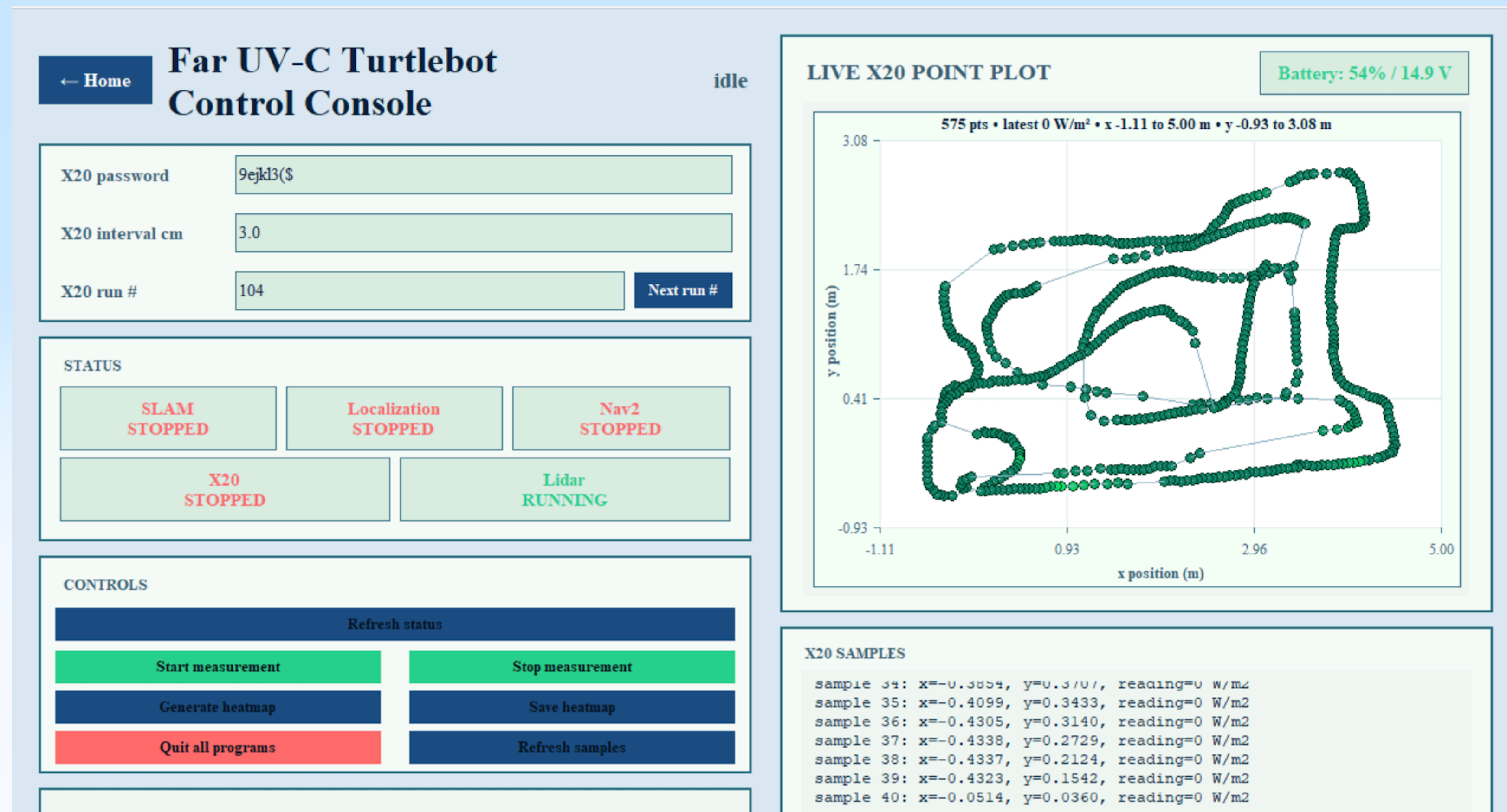
Graphical User Interface Designed for Data Acquisition and Analysis



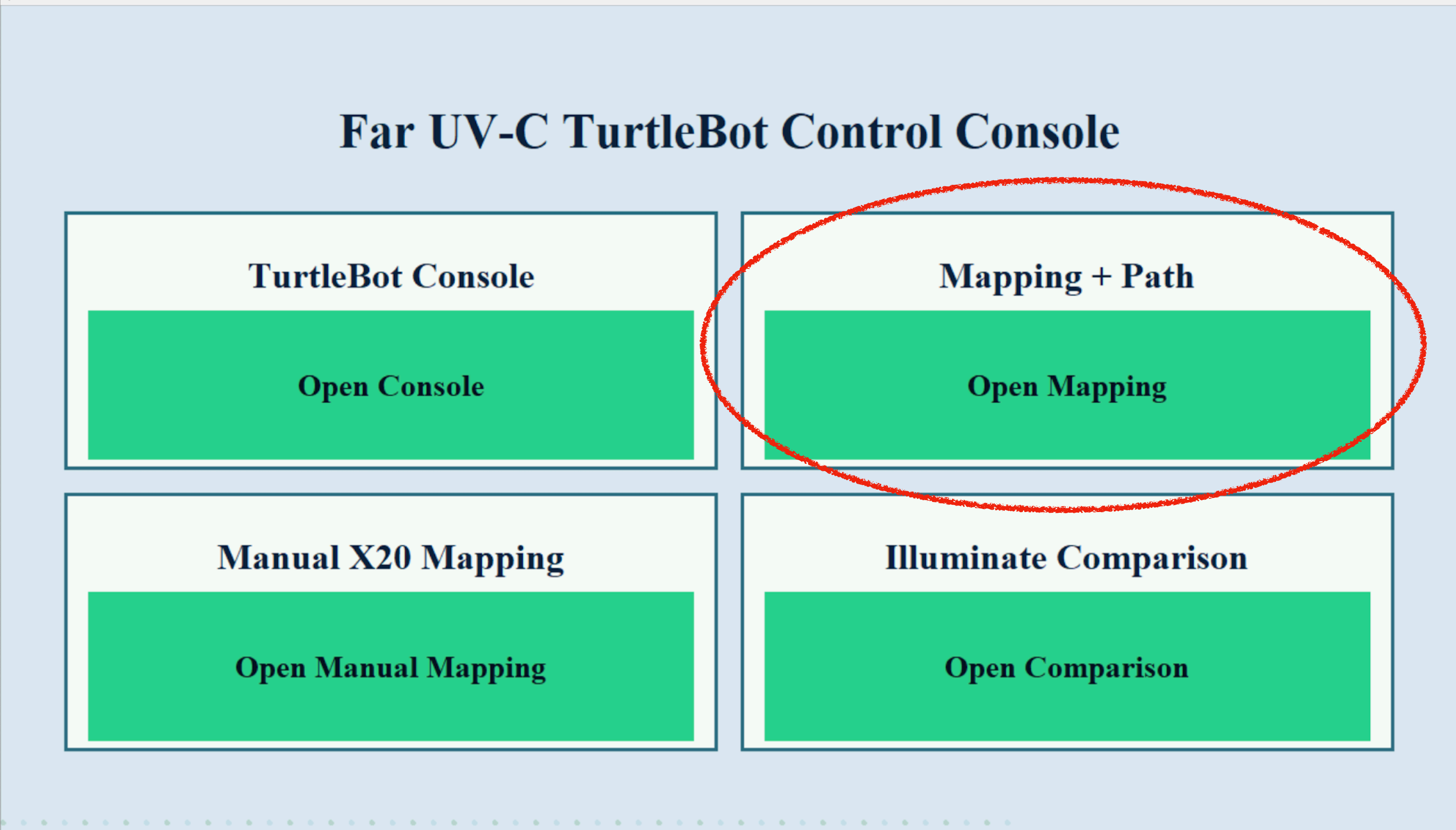
Data Acquisition: Sensor Console

Graphical User Interface (GUI)

- General information on TurtleBot state
- Light Sensor Data Acquisition
 - Specify collection interval
 - Monitor data points collected
 - Heatmap Generation



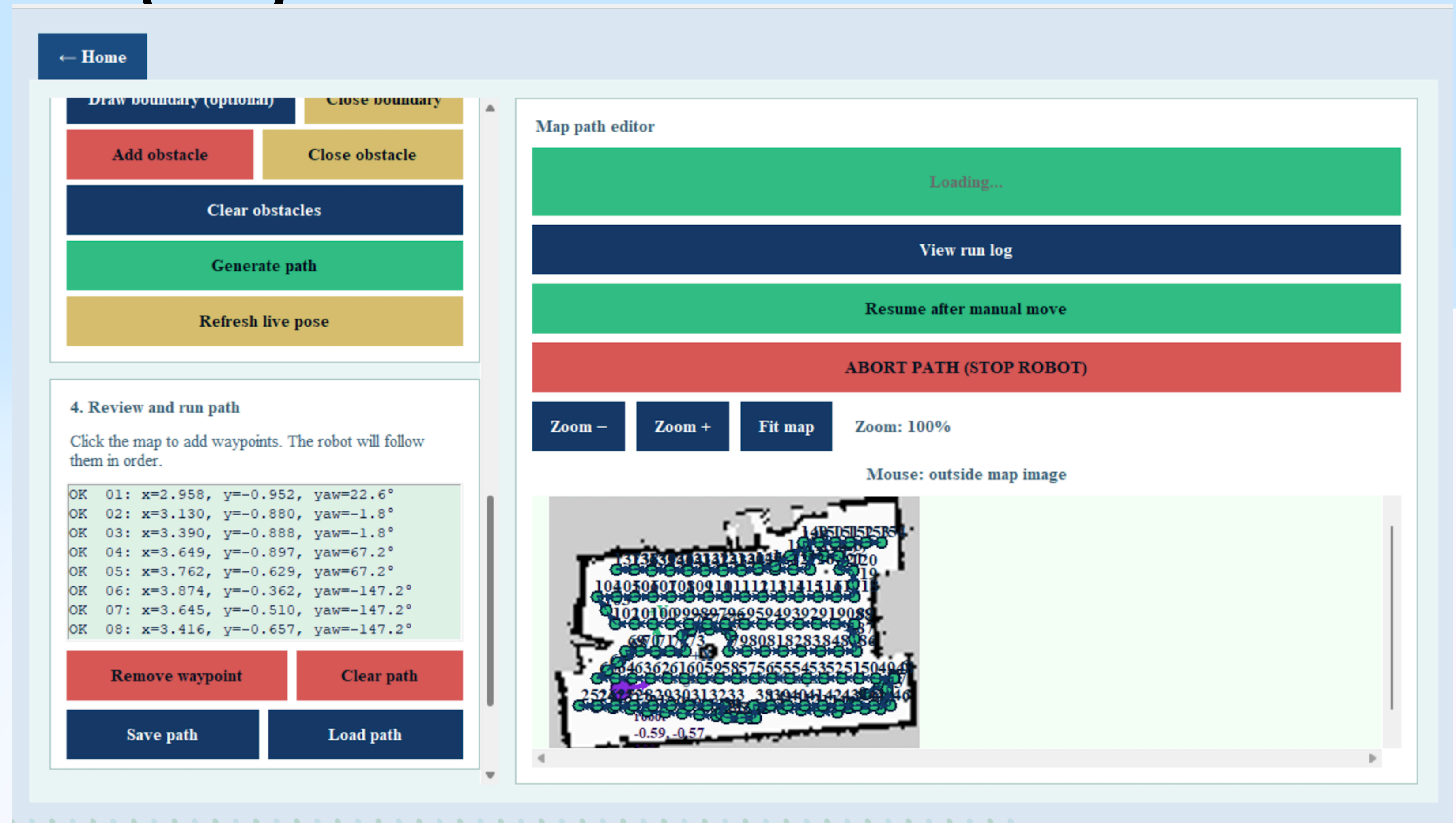
Graphical User Interface Designed for Data Acquisition and Analysis



Data Aquisition: Mapping + Path Console

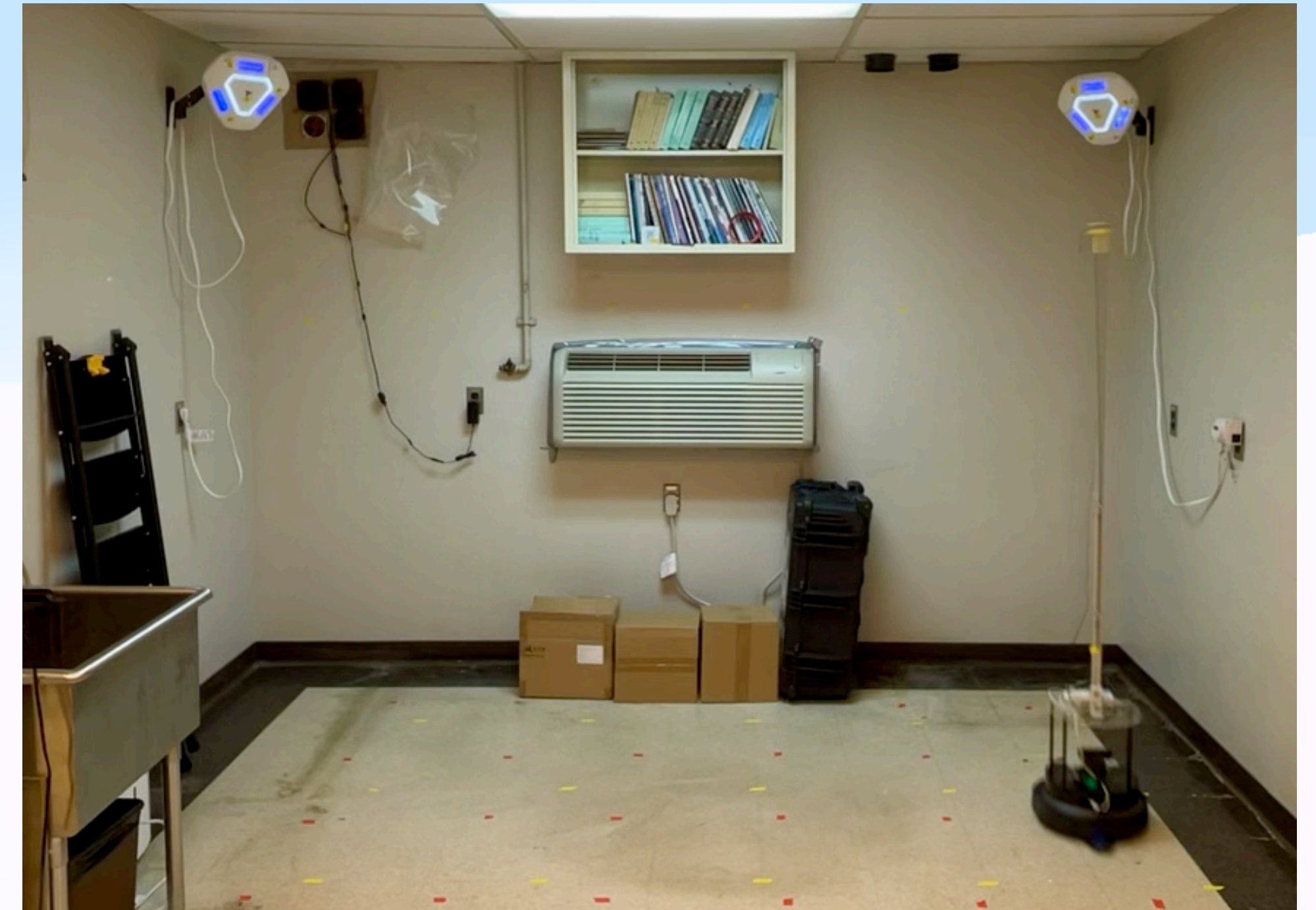
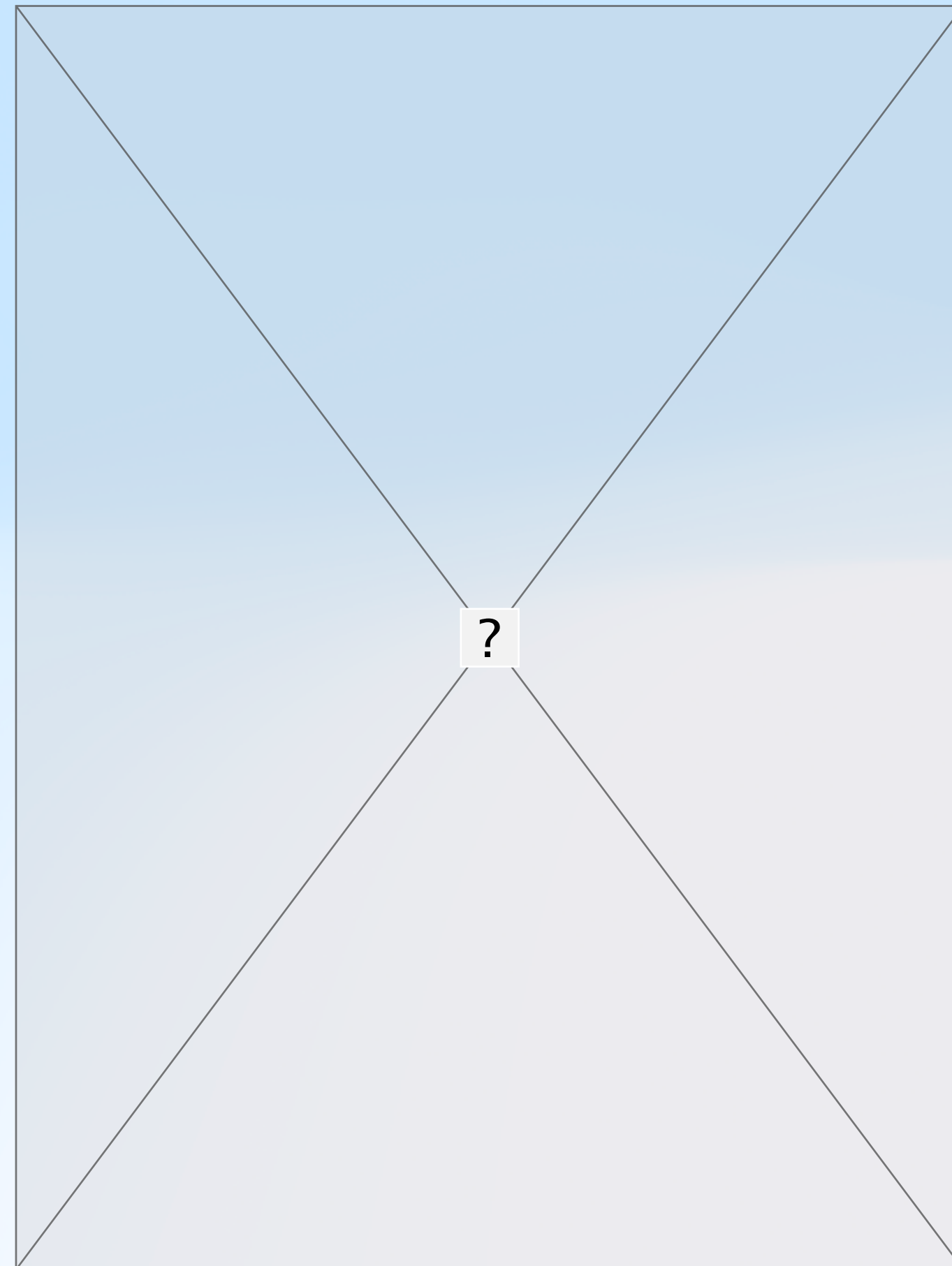
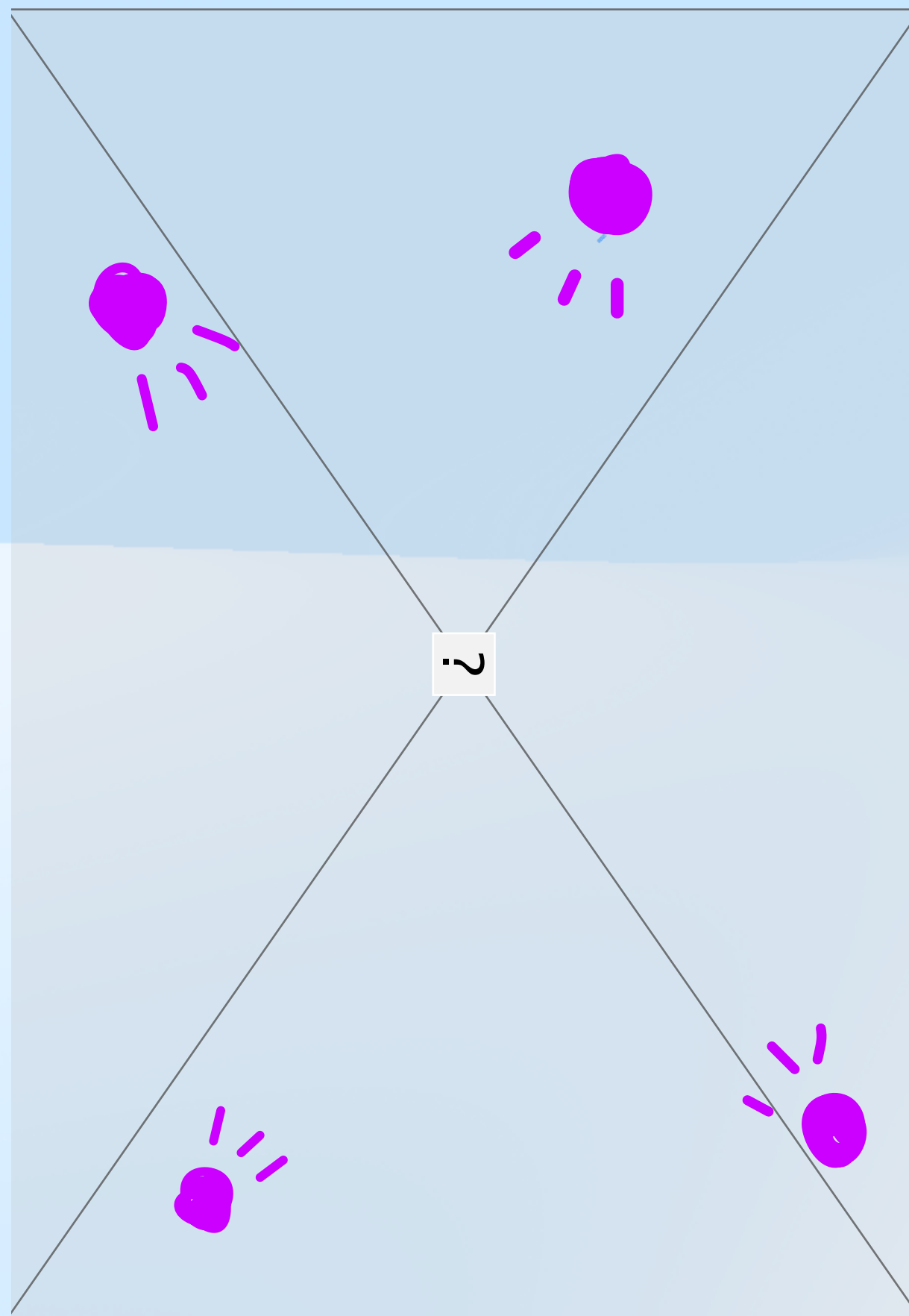
Graphical User Interface (GUI)

- Map a room
- Share positional data on TurtleBot
- Design path and send path to TurtleBot



Data Aquisition: Mapping + Path

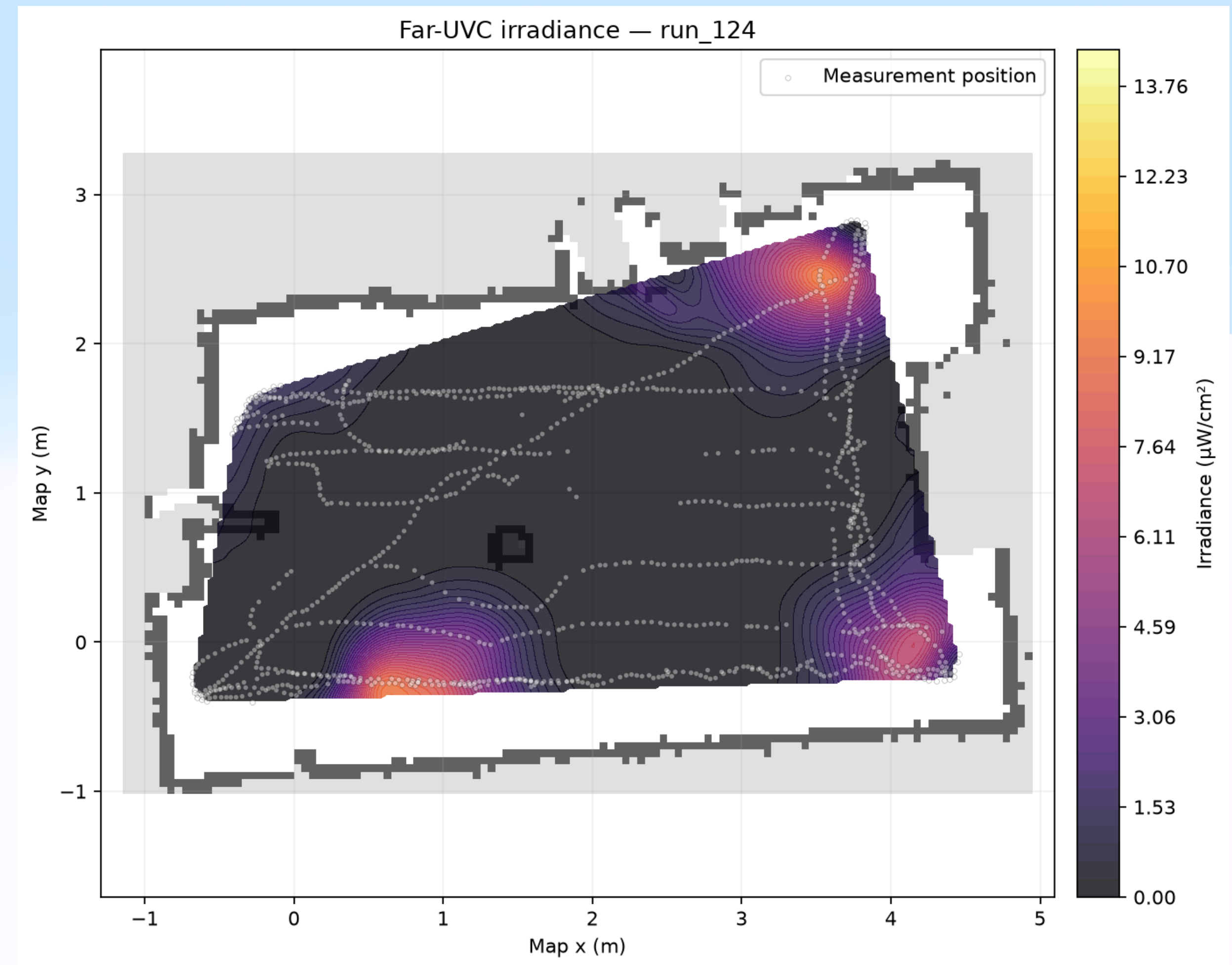
Map vs. Actual Room



Heatmap Generation

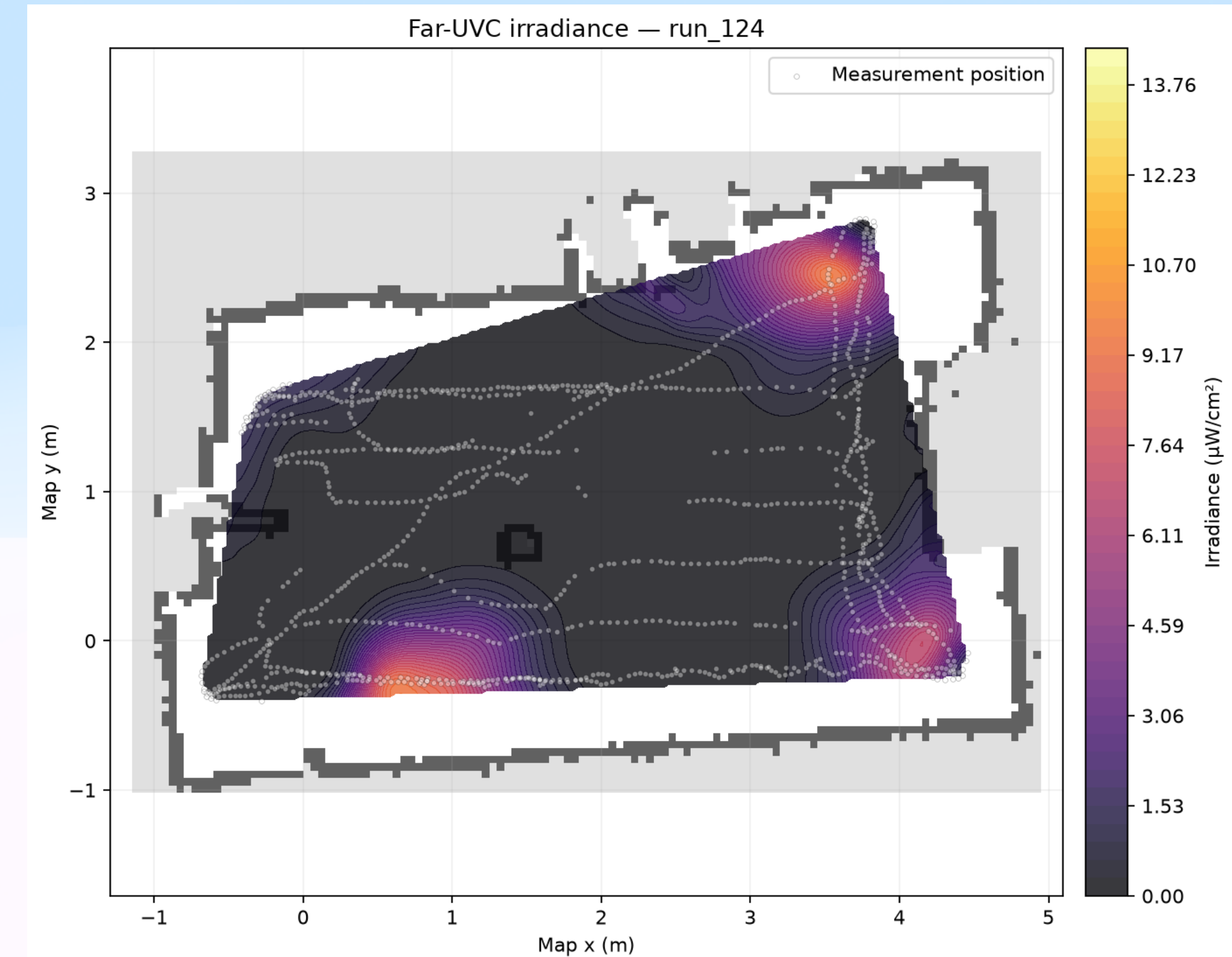
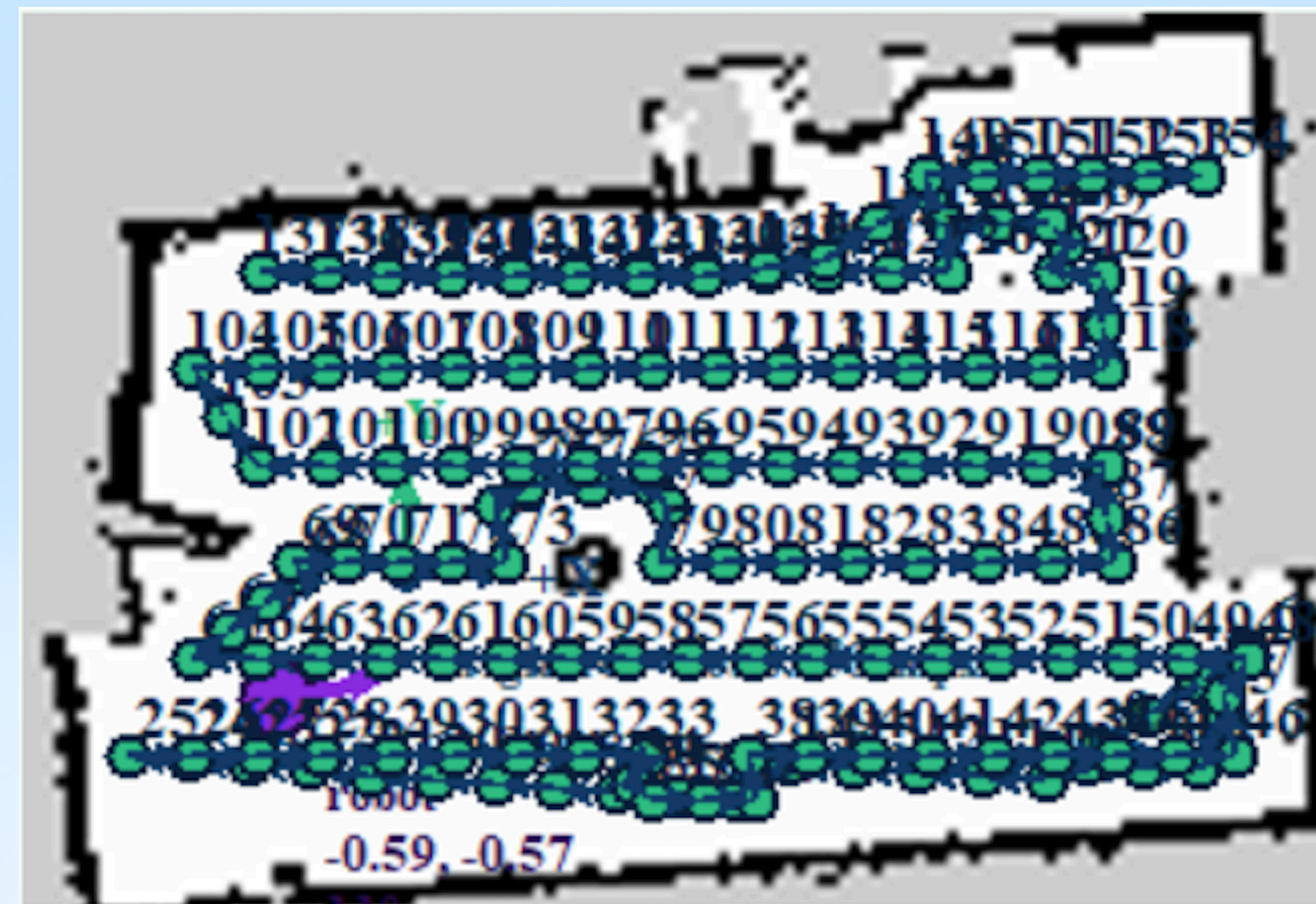
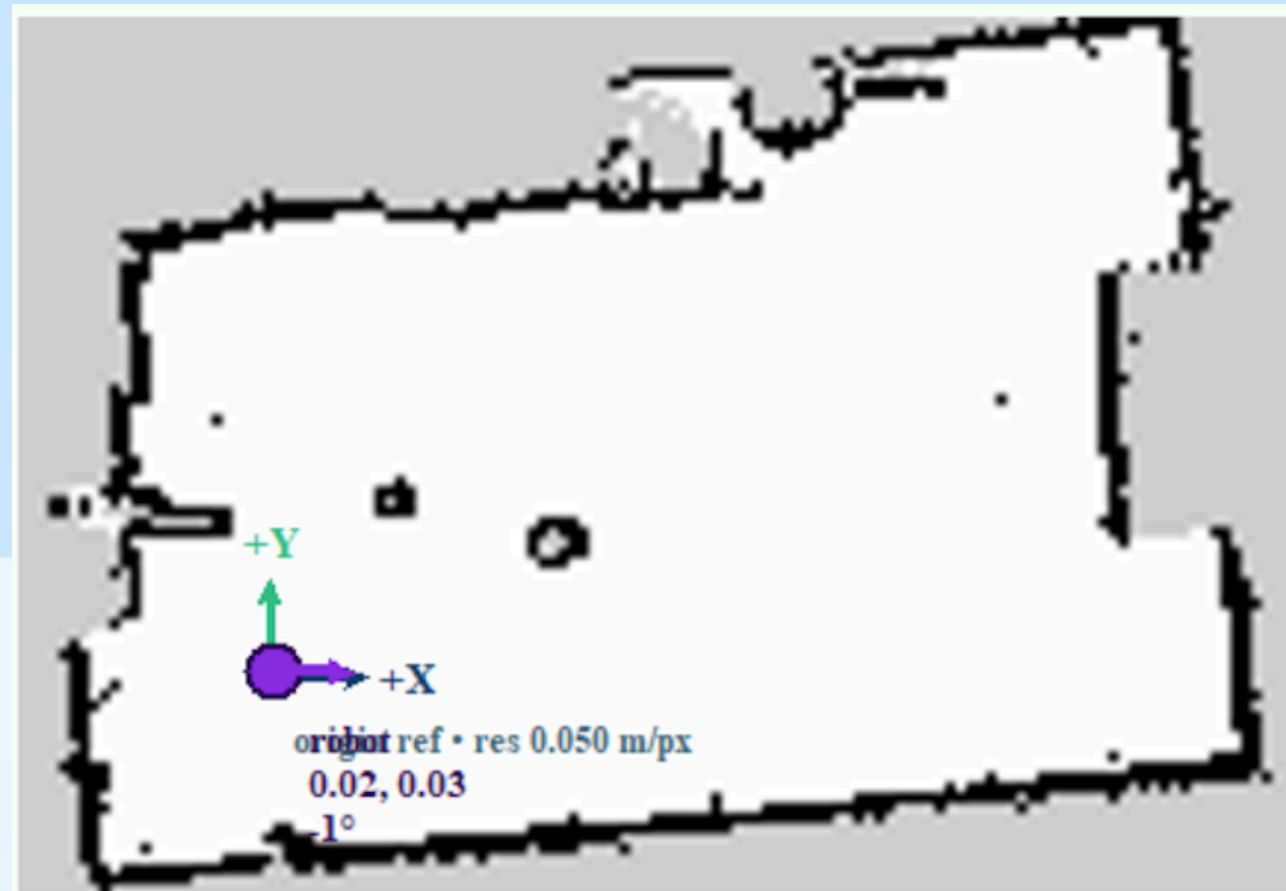
Interpolation with physical constraints

- Discrete irradiance points input
- Remove negative readings
- Thin-plate-spline RBF interpolation package
- White sample markers
- Spatially accurate

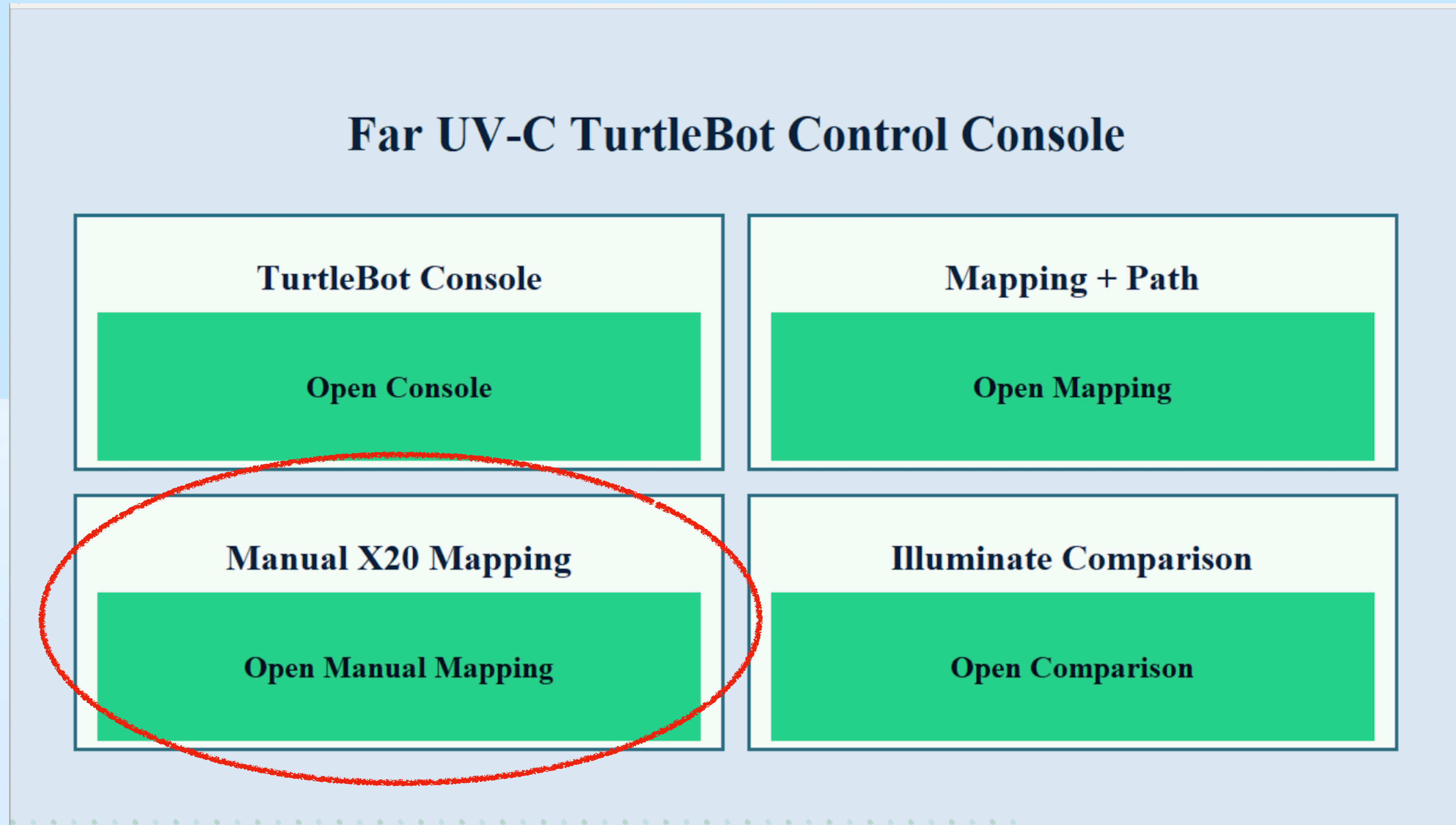


Data Acquisition: Map -> Path -> Heatmap

Interpolate Between light map data collection points to build heat map



Graphical User Interface Designed for Data Acquisition and Analysis



Data Aquisition: Manual Mapping

Graphical User Interface (GUI)

- Use for grid method

[← Home](#)

Manual X20 Mapping

Start measurement to enable saved-map position tracking. Drive with the remote; no light data is recorded until you press Take measurement. Each sample is saved with its map x and y coordinates.

Run number

113

Start measurement

Stop measurement

Position map: uses the loaded or latest saved map

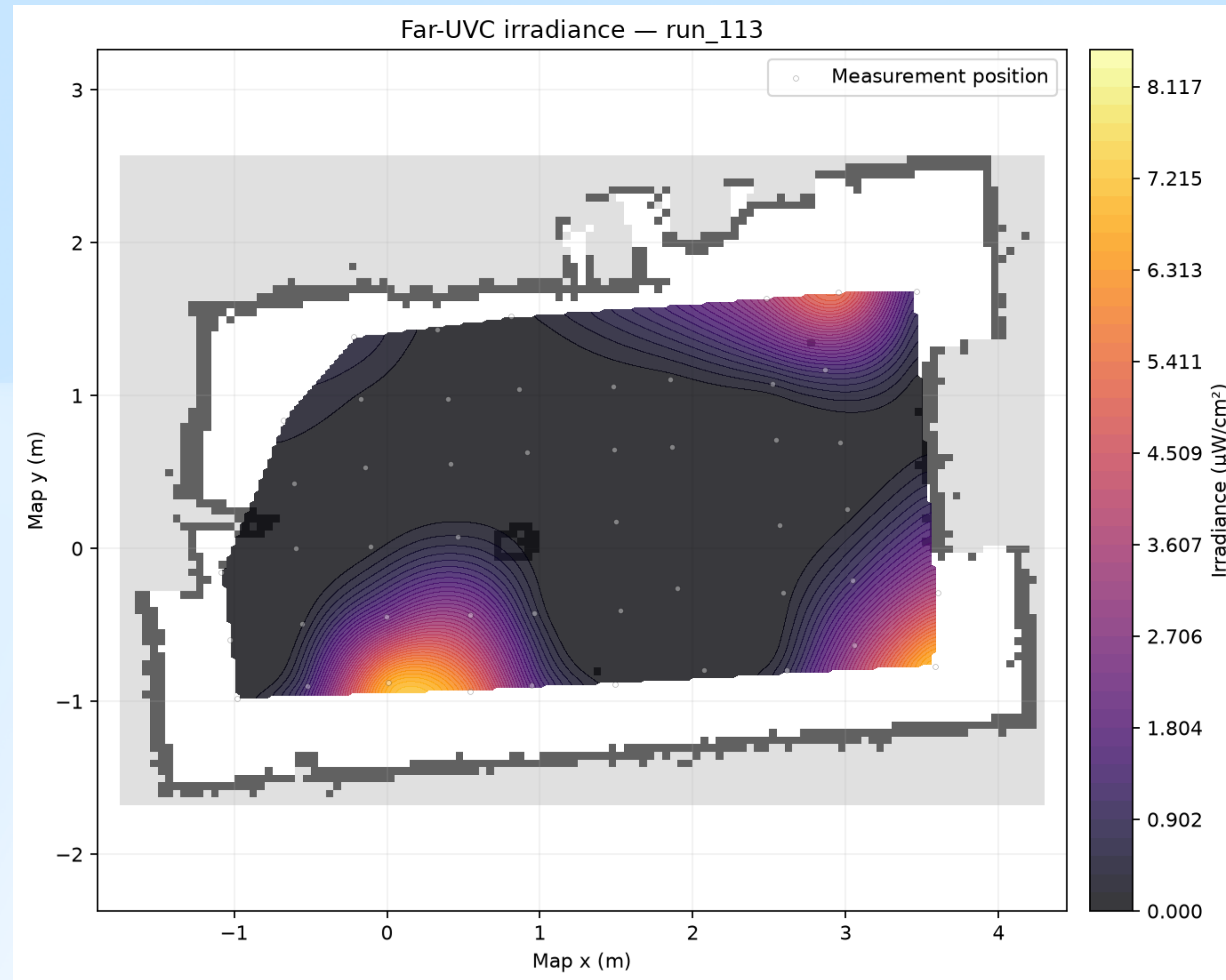
Choose an unused run number, then start measurement.

TAKE MEASUREMENT

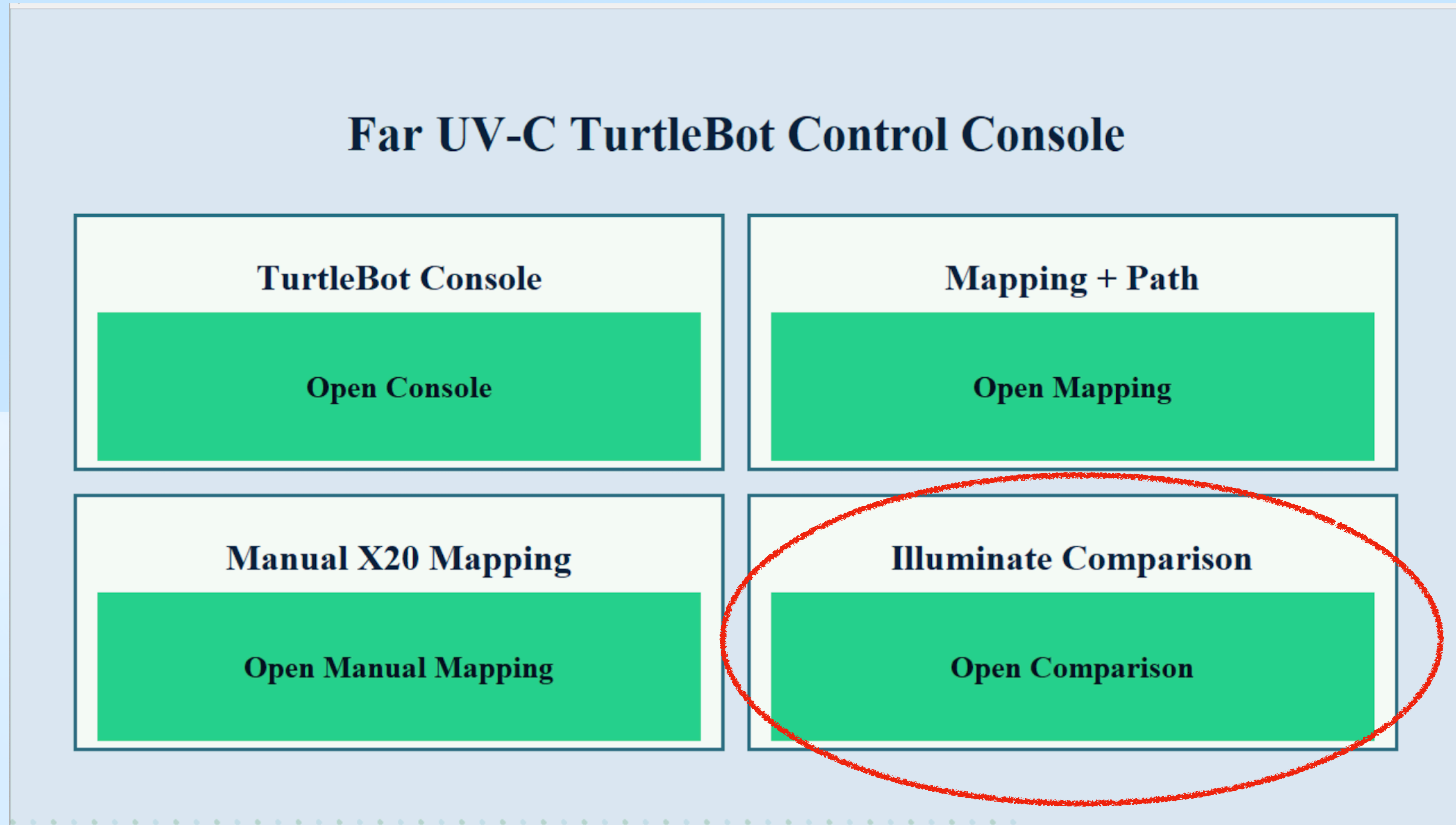
Last measurement: none

Data Aquisition: Manual Mapping

Grid Method done with TurtleBot



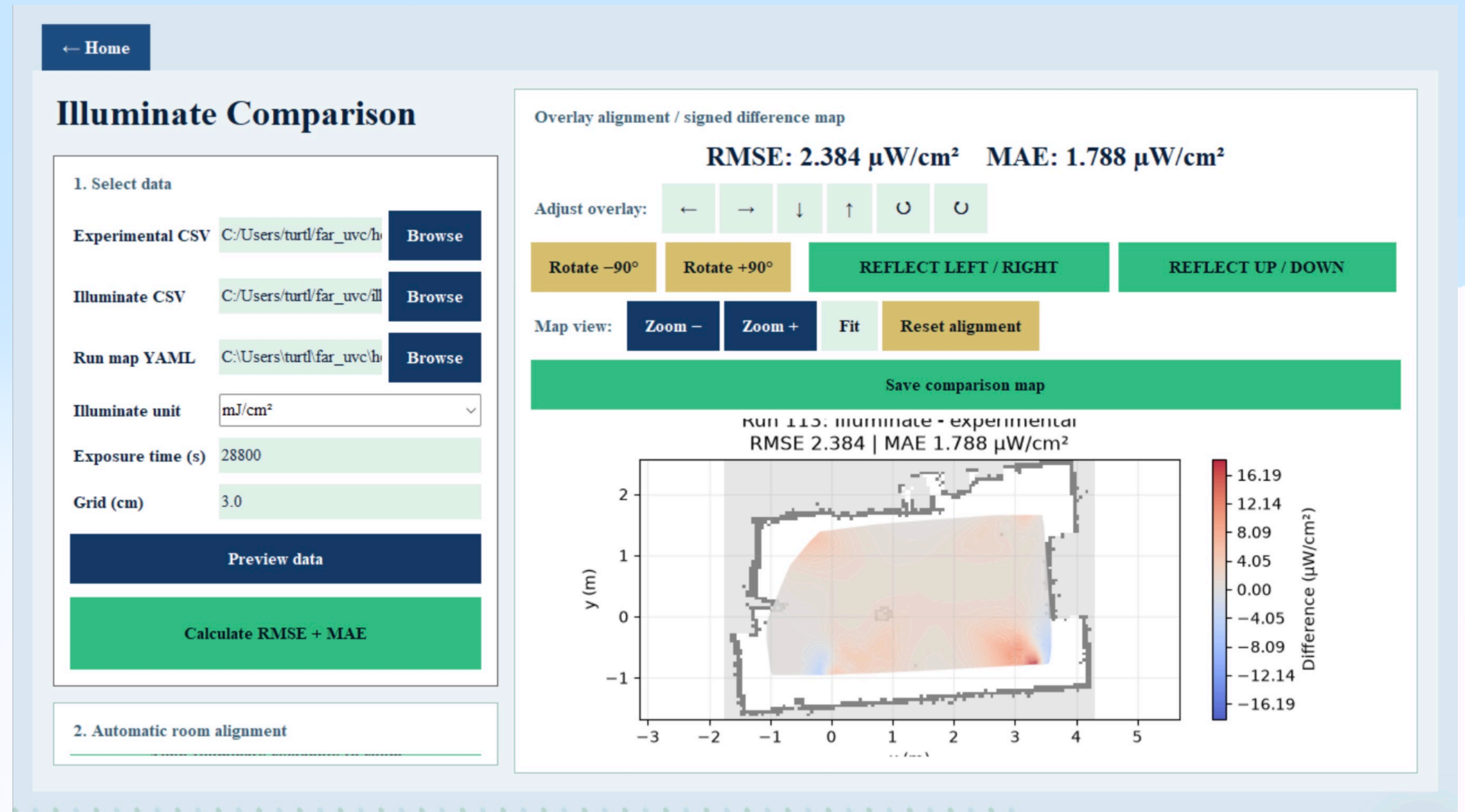
Graphical User Interface Designed for Data Acquisition and Analysis



Heatmap Alignment

Comparing experiment to simulation

- Interpolate both fields
- Register different coordinates
- Translate in x and y
- Rotate by theta
- Align shared features
- Then compare pointwise



Error Metrics

Quantifying agreement- Lower MAE and RMSE = Stronger Agreement

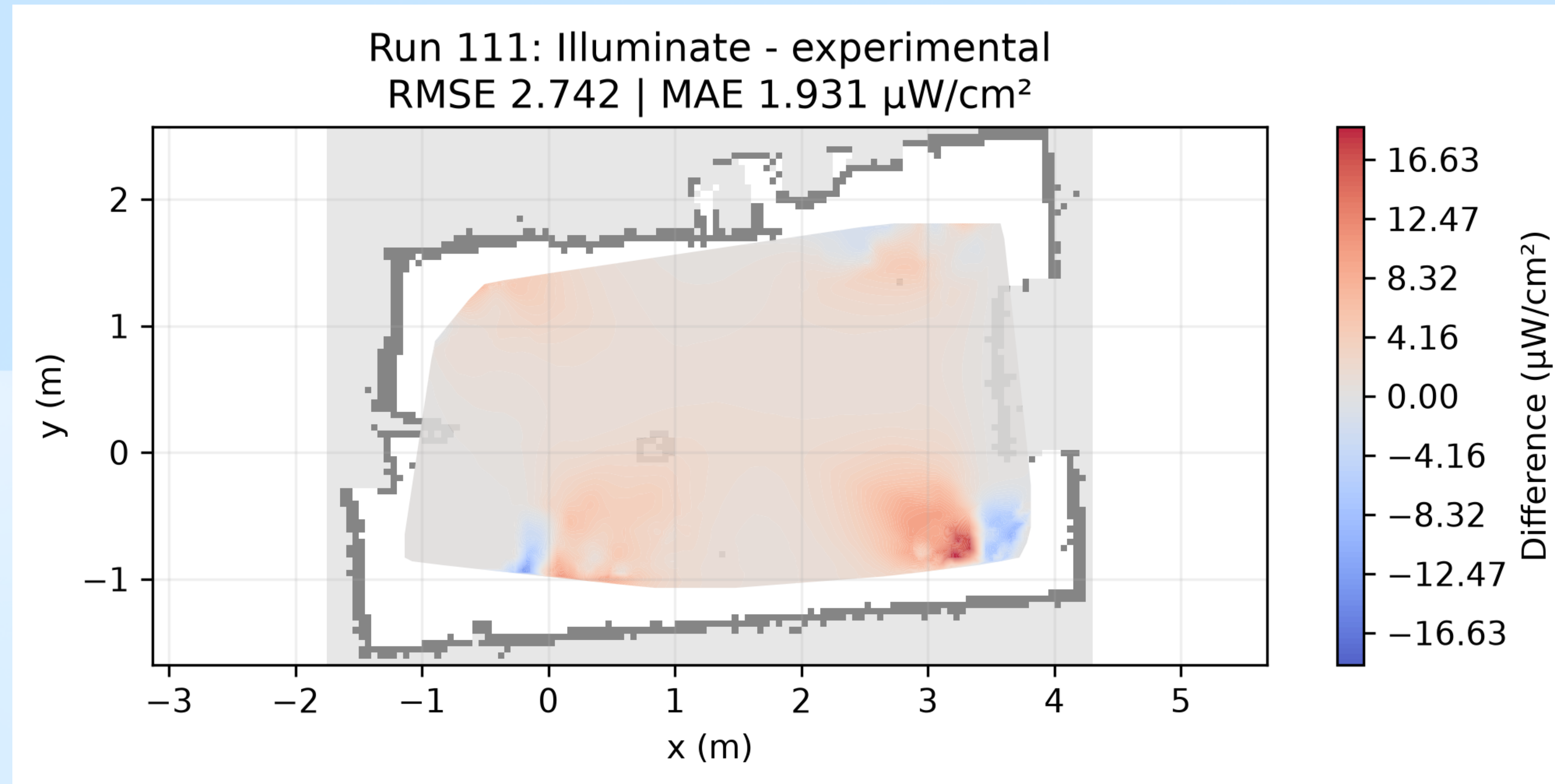
- **Difference Map**
 - $D_i = S_i - M_i$
 - Shows where simulation over- or under-predicts irradiance
- **Mean Absolute Error (MAE)**
 - Average Error across the room
- **RMSE large-error weight**
 - Weights larger discrepancies more heavily

$$\text{MAE} = \frac{1}{N} \sum_{i=1}^N |S_i - M_i|$$

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^N (S_i - M_i)^2}$$

Illuminate Heatmap vs Robot Heatmap

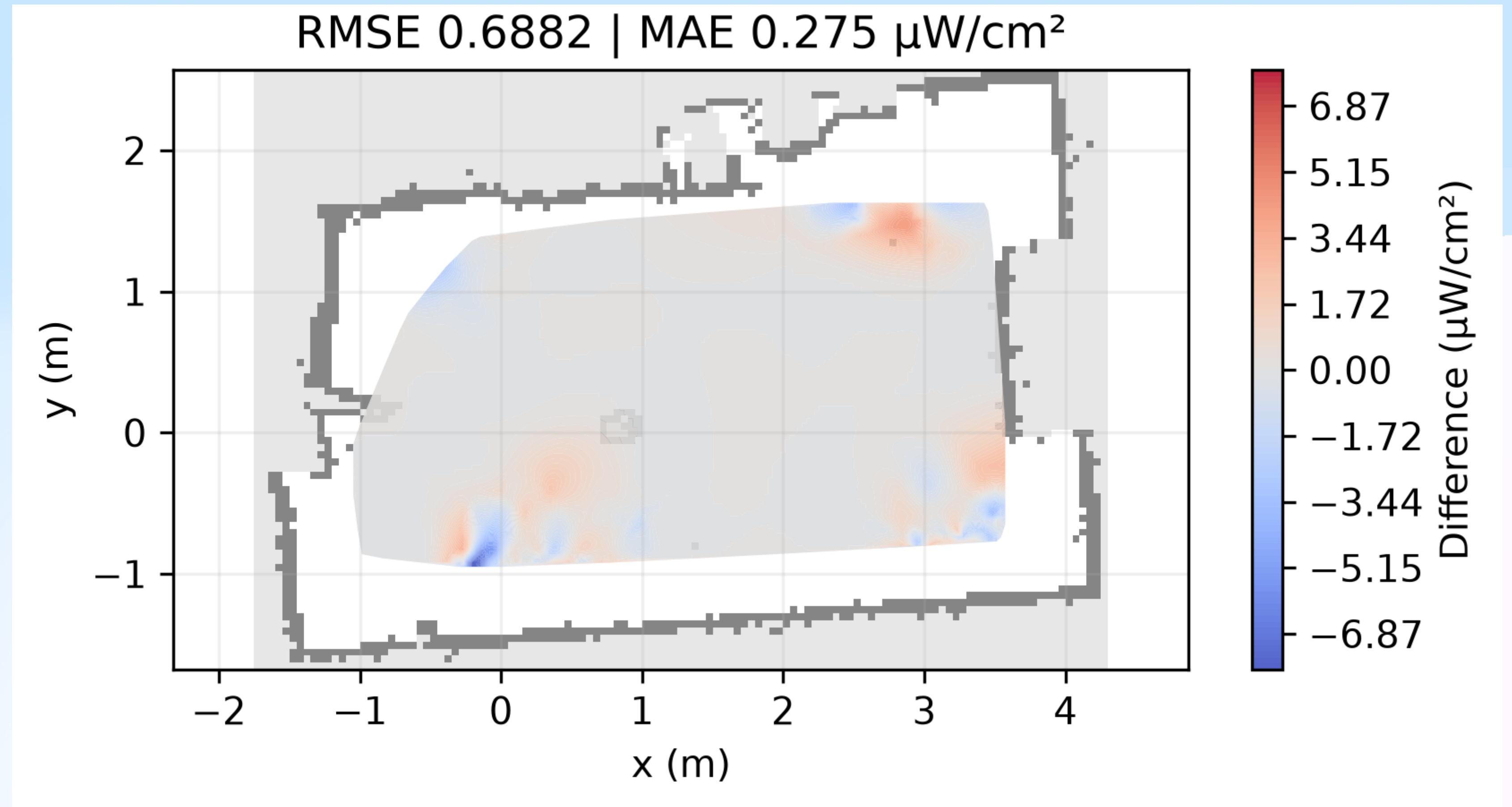
Illuminate (red), Experimental Measurement (blue)



Grid Method vs Autonomous Robotic Method

Grid Method (red) - Autonomous Robot Method (blue)

- Grid Method
 - ~45 minutes
 - Fully manual
- Robotic Method
 - ~1 minute to map (manual)
 - ~4 minutes for path generation (autonomous)
 - 15-20 minutes for data collection (autonomous)

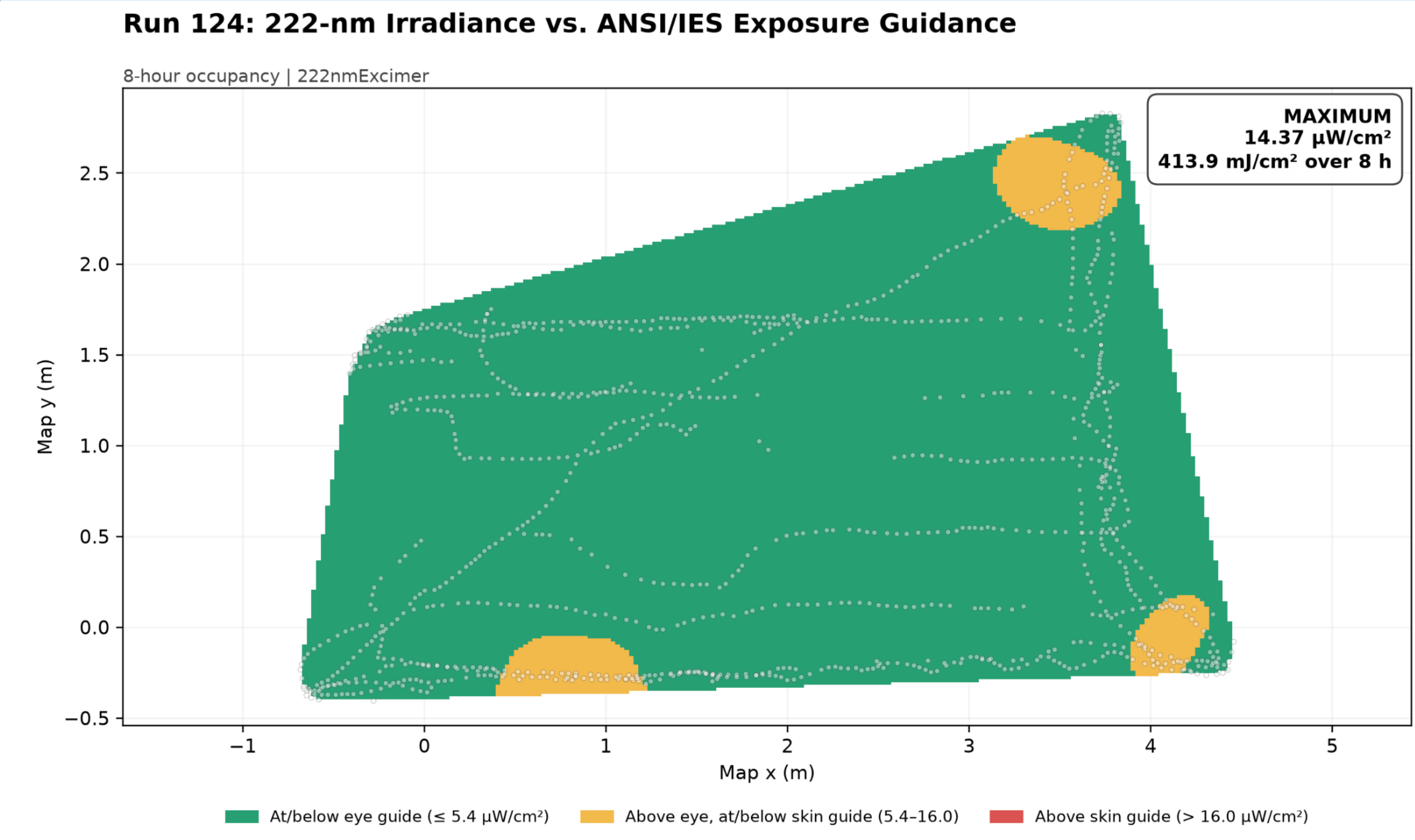


Heatmap Results

Color Coated for Exposure Guidelines

Daily exposure	Eye-based limit	Skin-based limit
8 hours	5.4 $\mu\text{W}/\text{cm}^2$	16 $\mu\text{W}/\text{cm}^2$
4 hours	10.8 $\mu\text{W}/\text{cm}^2$	32 $\mu\text{W}/\text{cm}^2$
2 hours	21.6 $\mu\text{W}/\text{cm}^2$	64 $\mu\text{W}/\text{cm}^2$
1 hour	43.2 $\mu\text{W}/\text{cm}^2$	127–128 $\mu\text{W}/\text{cm}^2$

Source: Illuminating Engineering Society, *ANSI/IES RP-27.1-22: Recommended Practice: Risk Group Classification and Minimization of Photobiological Hazards from Ultraviolet Lamps and Lamp Systems*, IES, 2022, Annexes A–B.



Conclusion

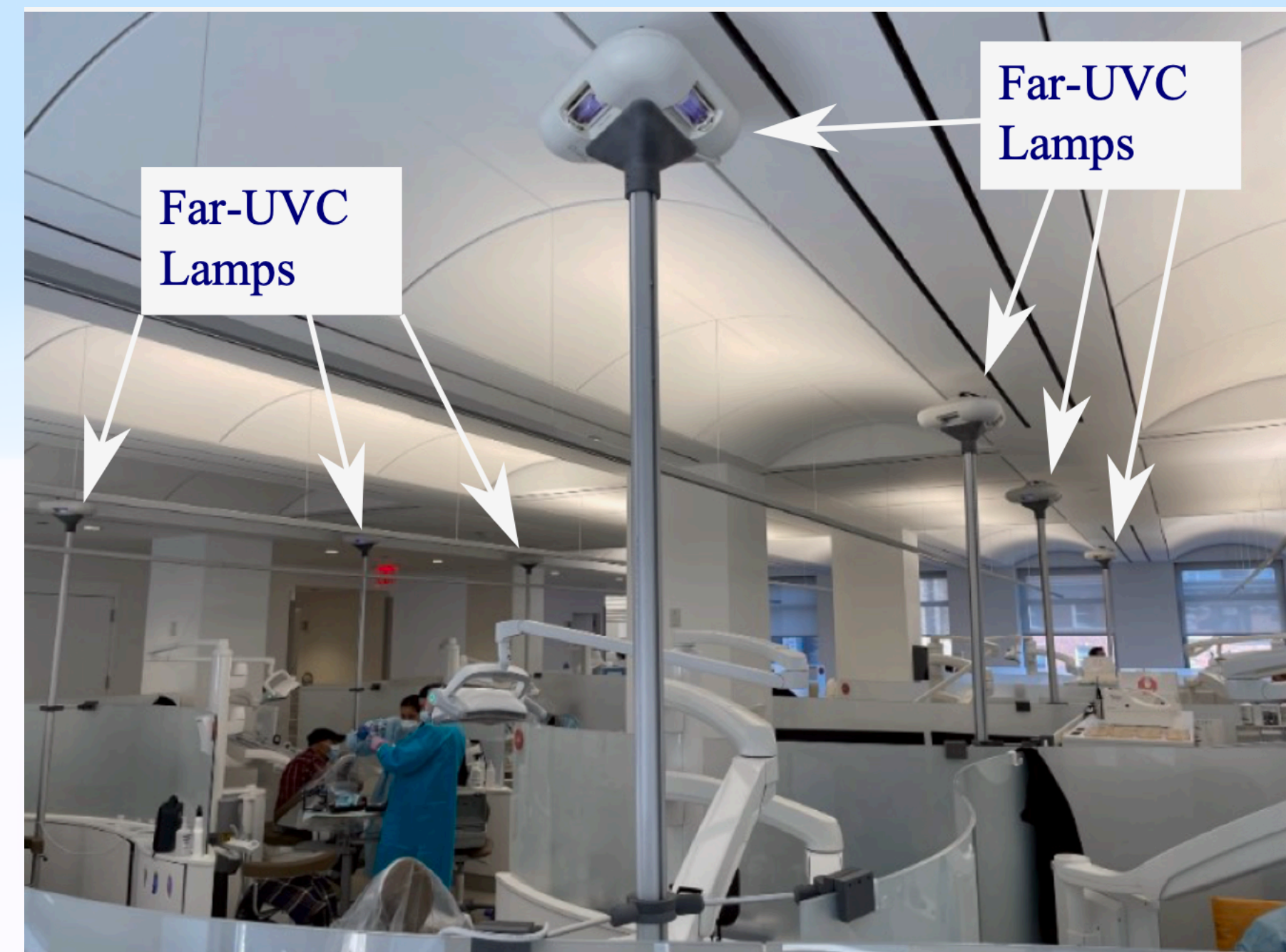
Autonomous robot can accurately map invisible Far-UVC light.

- Replaces slow manual grid surveys with faster, higher-resolution autonomous measurements.
- Enables direct comparison between Illuminate predictions and real-world irradiance measurements.
- Provides an efficient method for validating Far-UVC installations in occupied spaces.
- Supports verification that installations comply with safety guidelines

Discussion and Next Steps

Where the method goes next

- More complex rooms
- Add Linear Actuator for automated height adjustment
- Additional sensor types- fluence
- Refined analysis for comparing simulation with experimental



Welch et al., Journal of Hospital Infection, 2026, 168, 105–113.

Acknowledgments

- Prof. David Welch, Advisor
- Prof. *Manuela Buonanno, Prof. Naresh Deoli, and Prof. Guy Garty
- Prof. Reshmi Mukherjee and Prof. Georgia Karagiorgi
- Amy Garwood and Asia Latt
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Thank you. Questions?