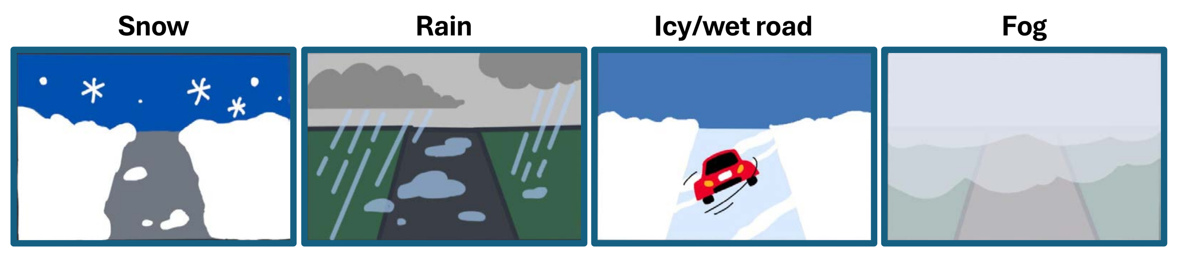
Investigating the Visual Information Degradation in Adverse Weather

Background

- A dependable outdoor vision system must include mechanisms that guarantee satisfactory performance under adverse weather conditions.
- In bad weather, key characteristics of light are significantly altered by atmospheric particles, causing image quality degradation and erroneous sensing. Therefore, bad weather is often considered as the bottleneck of Automated Driving Systems [1].
- In the U.S., fog is responsible for 9% of weather-related fatalities, despite being one of the rarest weather occurrences [2].



Snow	Rain	Icy/wet road	Fog
210,341 accidents	573,000 accidents	900,000 accidents	28,533 accidents
740 fatalities (~0.35%)	430 fatalities (~0.08%)	4,500 fatalities (~0. 5%)	500 fatalities (~1.75%)

Average Annual Weather-Related Car Accidents [3]

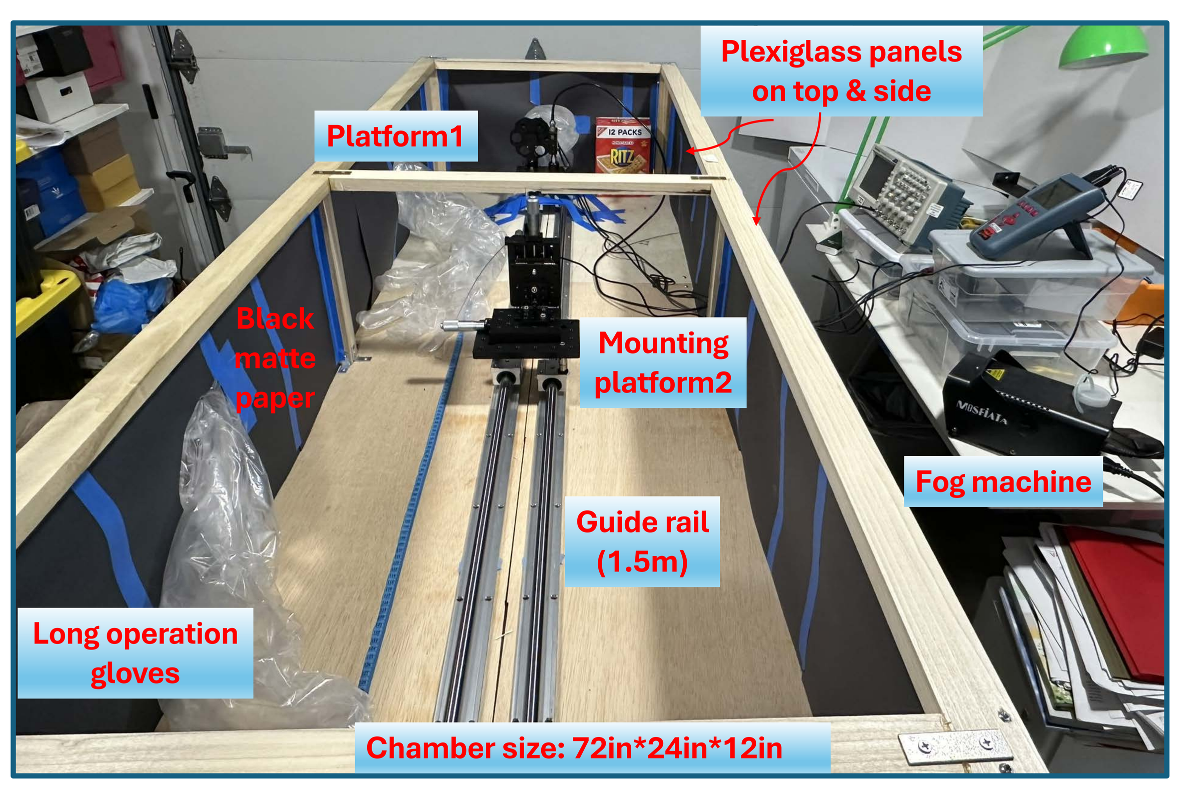
- Models [4-6] describing the visual manifestations by the atmosphere have been developed to partially restore clear day scene properties. These models either require multiple images taken under different atmospheric conditions, or prior knowledge about the scene. Therefore, it is difficult to fulfill in a practical setting.
- In addition, very few studies have investigated the visual degradation in nighttime fog where artificial light is often the sole illumination source.

Goals

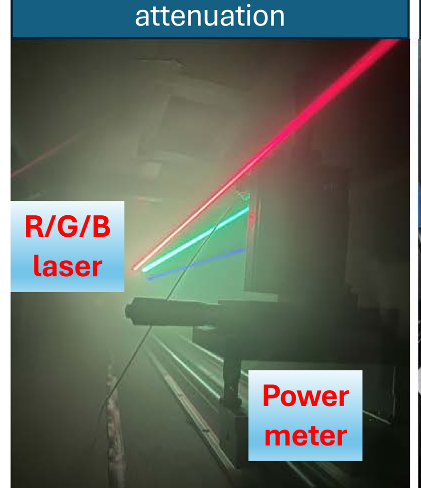
1. To quantify the degree of monochrome image degradation under nighttime fog environments (as experiment #1).
2. To develop new algorithms for recovering pertinent scene properties from foggy images (as experiment #2).

Methods/Materials

- Image quality measured in experiment #1:
  - Wavelength dependent radiance attenuation (visibility reduction)
  - Image edge sharpness (resolution reduction)
  - Image contrast ratio (contrast reduction)
- Tests were conducted inside a homebuilt sealed 72-inch-long fog chamber.
- Tests were conducted at multiple fog density levels (up to 9) and multiple camera distances (up to 8) for each density level.
- Two flashlights mounted next to camera provided sole source of illumination.

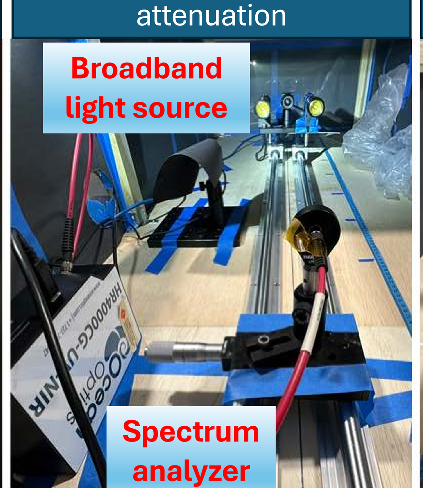


Radiance attenuation measured by power attenuation



- 3 class I lasers @ 405/520/635 nm.
- Measure power attenuation vs. distance at each fog density.

Radiance attenuation measured by spectrum attenuation



- Two identical flashlights as the broadband light sources.
- Measure spectrum attenuation at each fog density.

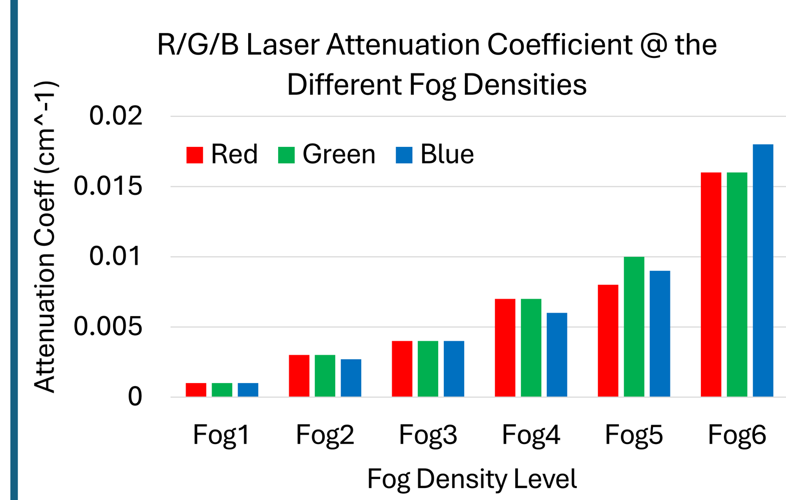
Image degradation measured using a resolution target

- A monochrome camera with two flashlights provide illumination.
- Measure image contrast and edge sharpness vs. distance at each fog density.

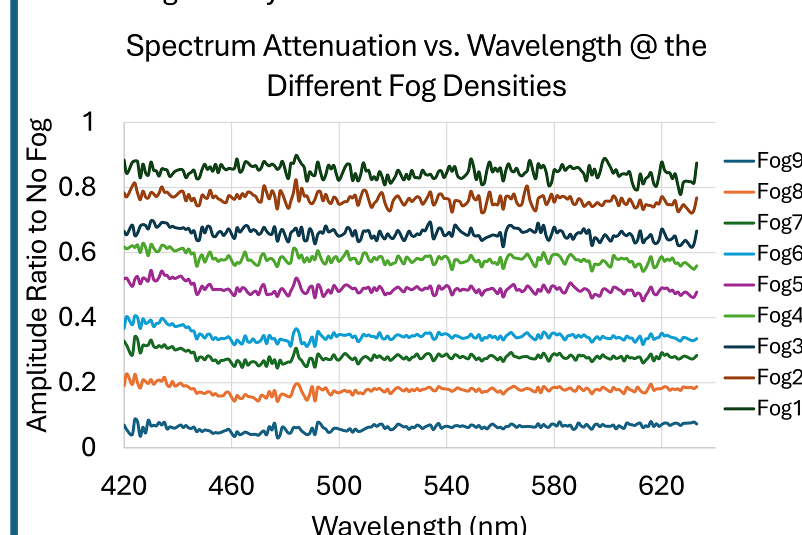
Experiment #1 Results

Radiance Attenuation

- The attenuation coefficient did not change appreciably with the wavelength at all fog density levels.

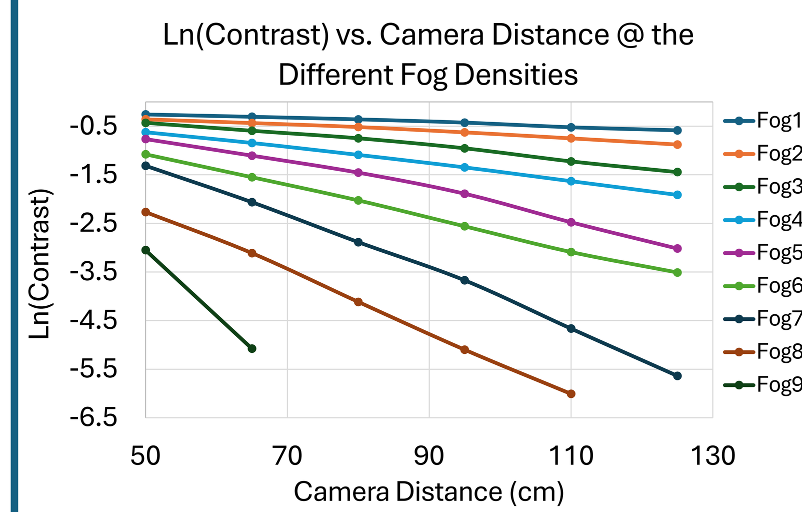


- The spectrum attenuation was wavelength independent at all fog density levels.

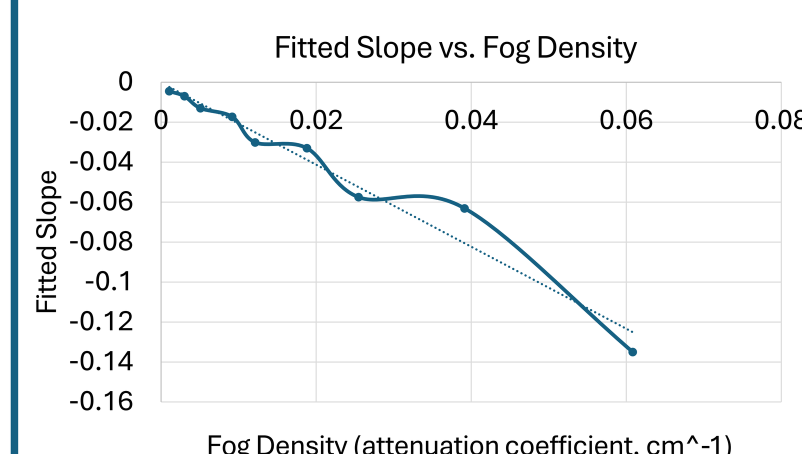


Contrast Reduction

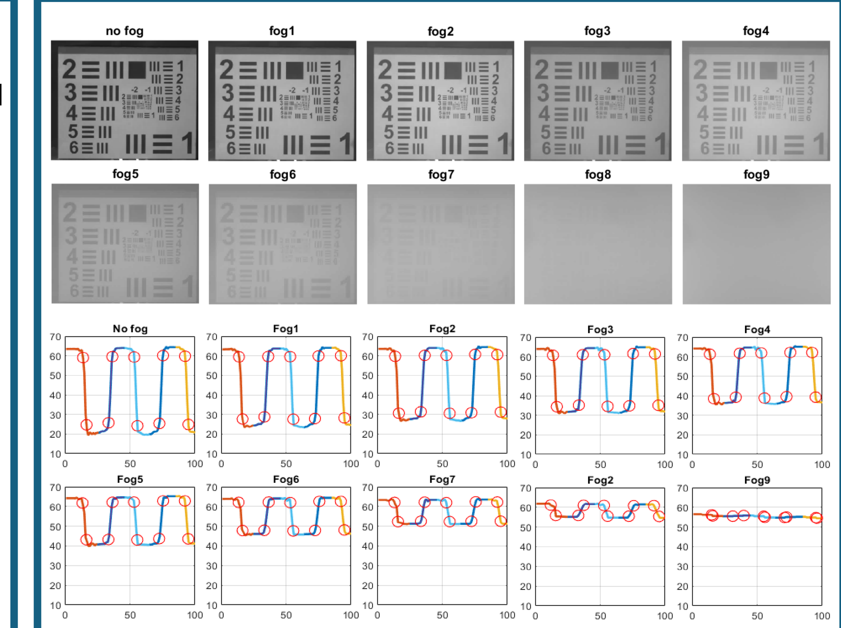
- Ln(contrast) is linearly proportional to camera distance.
- Increase in fog density forms a group of vertically shifted lines with gradually increasing slopes.



- The fitted slope (of the lines in figure above) is linearly proportional to fog density, indicating the contrast ratio also changes exponentially with fog density.



Edge Sharpness



Examples of target images and edge sharpness measurement under the different fog densities.

- Edge sharpness was invariant to fog density at the beginning, until the fog became dense.

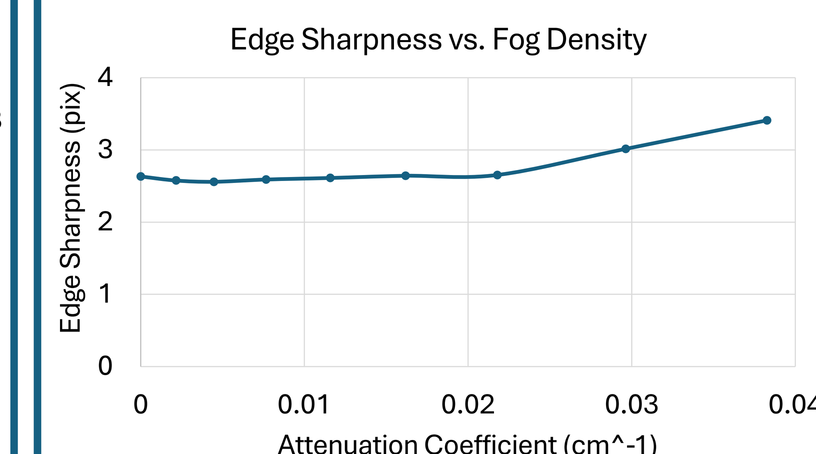
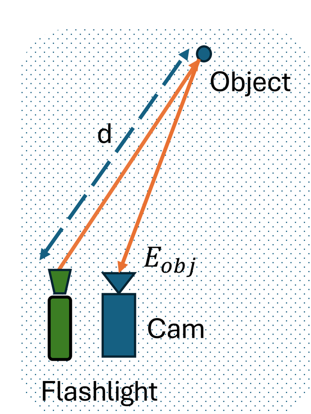
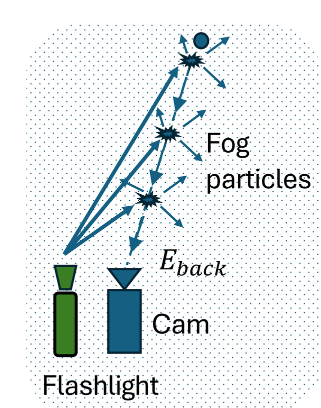


Image Formation Model Based on Contrast Reduction

- Under the forward illumination configuration, the brightness of any pixel can be divided into two parts: direct illumination and back scattering.
- The model requires a forward illumination source next to the camera as the sole light source in the scene.

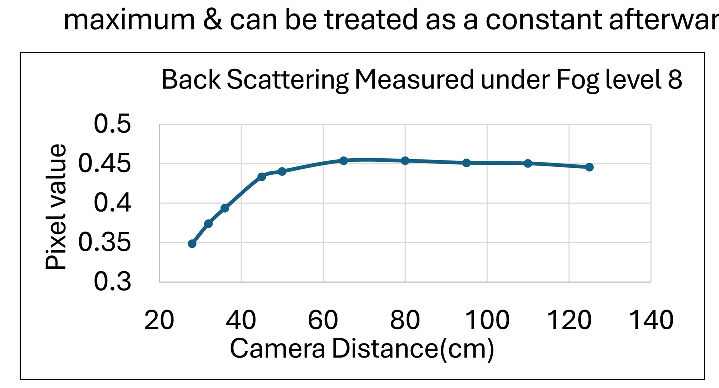


- Part 1, Direct Illumination
- Subject to double pass attenuation
  $E_{obj} = I * r * \exp(-2 * \beta * d)$
  I: radiance of flashlight
  r: reflectivity of the obj

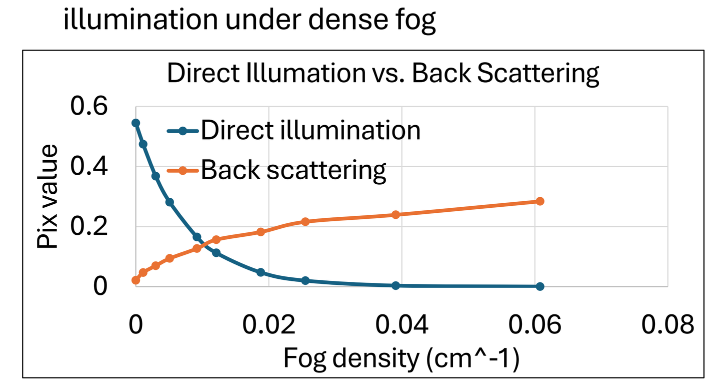


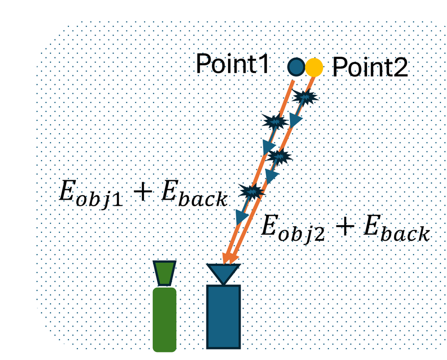
- Part 2, Back Scattering
- Back scattering rises quickly to the maximum
- E_{back} >> E_{obj} in dense fog
- Both were experimentally verified

- Observation 1: back scattering rises quickly to the maximum & can be treated as a constant afterwards.



- Observation 2: back scattering >> direct illumination under dense fog





- With these two observations, the contrast of two adjacent scene points have a close-form expression:

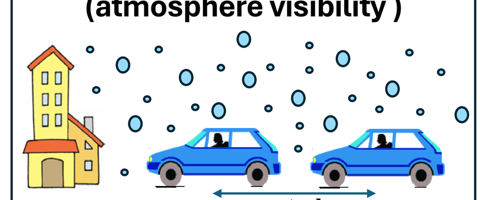
$$C = \frac{E_{obj1} - E_{obj2}}{2 * E_{back} + E_{obj1} + E_{obj2}} \cong \frac{E_{obj1} - E_{obj2}}{2 * E_{back}}$$

$$C = \frac{I * \Delta r}{2 * E_{back}} * \exp(-2 * \beta * d)$$

$$\boxed{C \propto \exp(-2 * \beta * d)}$$

New Algorithms for Scene Properties Recovery

Predict fog density (atmosphere visibility)

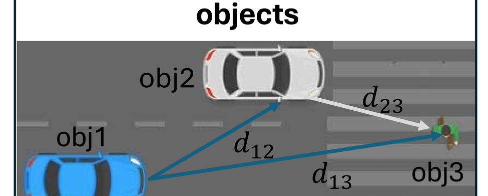


- Object has contrast C_{d1} while vehicle @ the 1st location & C_{d2} while vehicle @ the 2nd location.
- The fog density (atmosphere visibility):

$$C \propto \exp(-2 * \beta * d)$$
$$\frac{C_{d1}}{C_{d2}} = \exp(-2 * \beta * \Delta d)$$
$$\beta = \ln\left(\frac{C_{d1}}{C_{d2}}\right)/(2 * \Delta d)$$

- Two images @ two distances, Δd easily known.

Estimate distances among objects



- Two objects have contrast C_1 & C_2, distance between them Δd_{12}:

$$\frac{C_1}{C_2} = \exp(-2 * \beta * \Delta d_{12})$$
$$\Delta d_{12} = \ln\left(\frac{C_1}{C_2}\right)/(2 * \beta)$$

- β from previous step.
- Objects need to have similar contrast ratio under the clear weather and similar line of sight to camera.

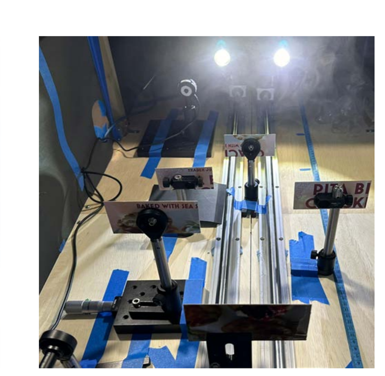
Recover 3D structure under camera coordinates

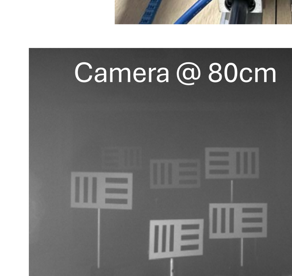
- Identical objects under two weather conditions, distance to camera :

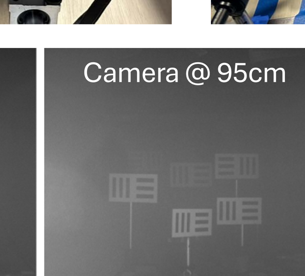
$$\frac{C_{\beta 1}}{C_{\beta 2}} = \exp(-2 * \Delta\beta * d)$$
$$d = \ln\left(\frac{C_{\beta 1}}{C_{\beta 2}}\right)/(2 * \Delta \beta)$$

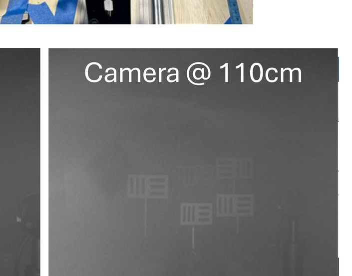
- Object's 3D coordinates under camera can be further recovered using pixel location & focal.
- Two images @ two weather conditions.

- Algorithms were tested with multiple planar targets mounted at the different locations.
- Algorithm1 & 2 share the same setup, algorithm 3 requires a change in fog density.



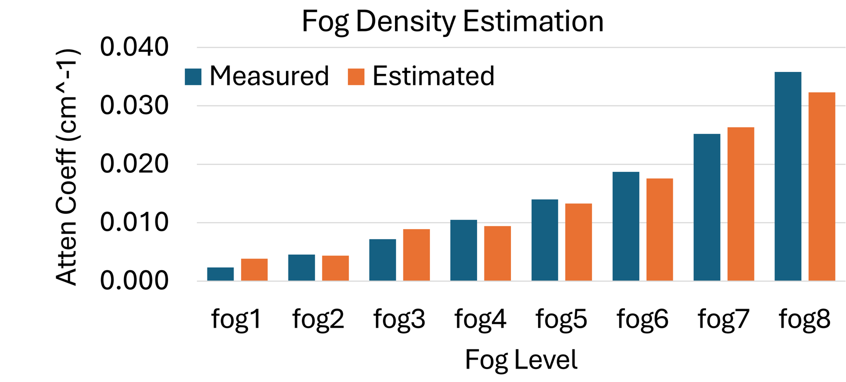




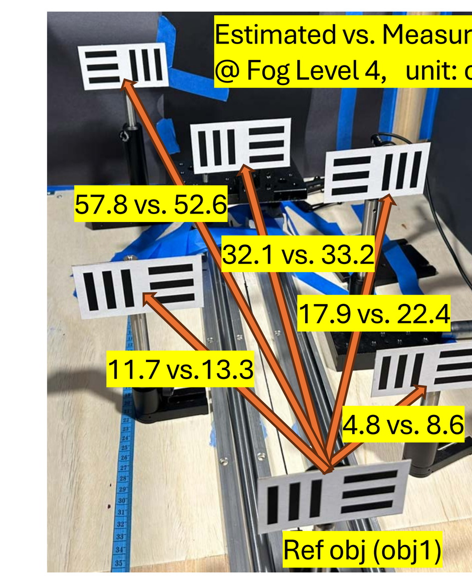


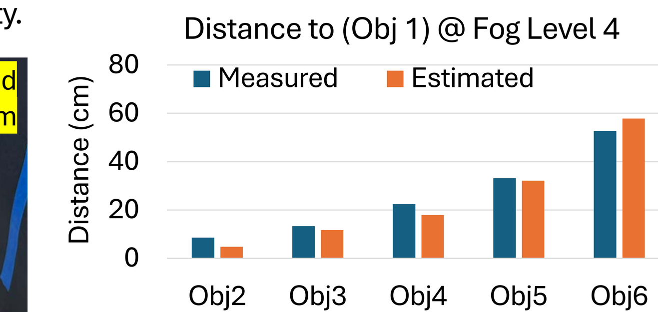
Experiment #2 Results

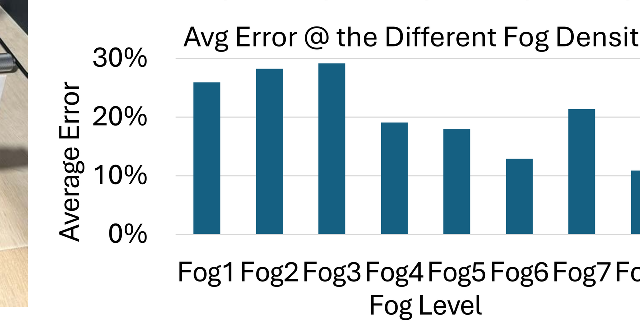
- Fog density estimation, average accuracy for all fog density levels tested was 88%.



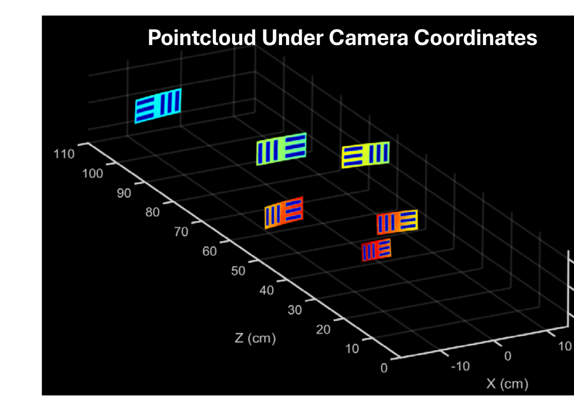
- Relative distance estimation, average accuracy (over all distances) for all fog densities tested was 80%.
- Accuracy improves with fog density.

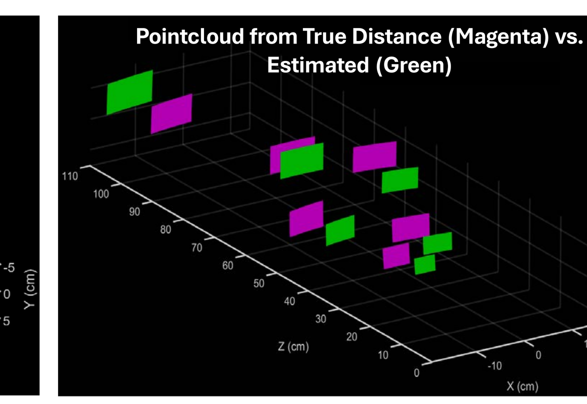




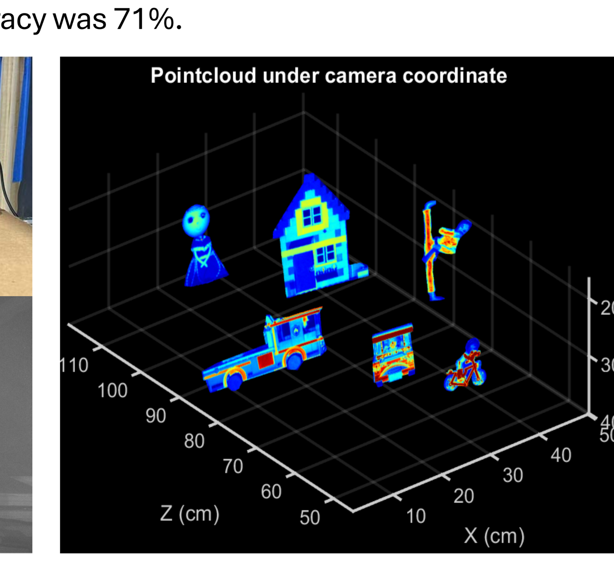


- 3D structure recovery, average (Z) accuracy (of all objects) for all fog densities tested was 78%.





- Tested with more realistic (but still high contrast) objects for 3D structure recovery, average (Z) accuracy was 71%.



Conclusions

- Radiance attenuation and contrast ratio degradation were demonstrated as the two major visual manifestations by fog. It was further illustrated that attenuation did not change appreciably with wavelength, while contrast ratio changed exponentially with both fog density and the scene depth.
- Although fog adversely impacted the visual perception, it encoded information about the scene structure and weather conditions. The three algorithms proposed in this study could be used to recover pertinent scene properties in restrictive situations (nighttime fog with forward illumination). Follow-up experiments conducted demonstrated the effectiveness of these algorithms.

References

[1]: Yuxiao Zhang a, et al. (2021). "Perception and Sensing for Autonomous Vehicles under Adverse Weather Conditions: A Survey." - *ISPRS Journal of Photogrammetry and Remote Sensing*, Elsevier, 9 Jan. 2023, www.sciencedirect.com/science/article/pii/S0924271622003367.

[2]: (No Author), (2024). "What Are the Effects of California Weather on Car Accidents?", https://westcoasttriallawyers.com/california-car-accident-lawyer/weather-conditions.

[3]: Sansom, Allan, "Weather-Related Car Accidents: Understanding the Risks and Seeking Compensation" https://www.boginmunns.com/blog/weather-related-car-accidents-understanding-the-risks-and-seeking-compensation/.

[4]: Narasimhan, Srinivasa G. (2003). "Models and Algorithms for Vision through the Atmosphere", www.researchgate.net/publication/234481036_Models_and_Algorithms_for_Vision_through_the_Atmosphere.

[5]: Nayar, Shree K., and Srinivasa G. Narasimhan. (2011). "Vision in Bad Weather" – *Proceedings of the Seventh IEEE International Conference on Computer Vision*, https://ieeexplore.ieee.org/document/790306

[6]: Nayar, Shree K., and Srinivasa G. Narasimhan. (2002). "Vision and the Atmosphere" – *International Journal of Computer Vision,* https://link.springer.com/article/10.1023/A:1016328200723

All images, figures, photos and plots were created by author.