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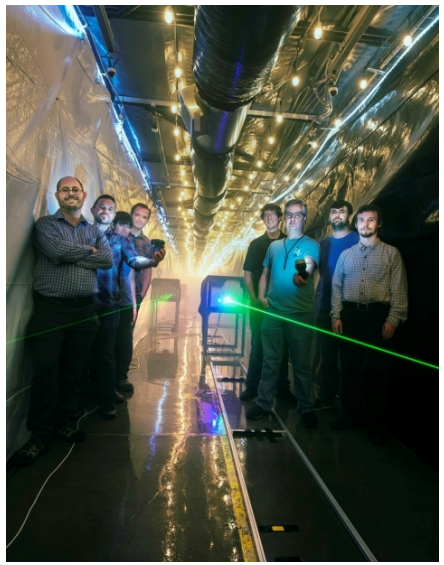

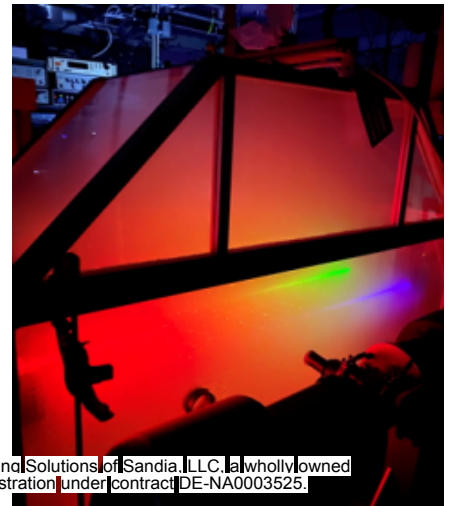

Development and Characterization of a Tabletop Fog Chamber

Presented by: Christian A. Pattyn[1]

Jake Zenker[1], Elihu Deneke[1], Lekha Patel[1], Brian J. Redman[1], John D. van der Laan[1], Ryan L. Hastings[2], David W. Alexander[2], Kevin J. Webb[2], Andrew Glen[1], Andres L. Sanchez[1], Karl Westlake[1], Brian Z. Bentz[1], and Jeremy B. Wright[1*]

[1]Sandia National Laboratories, P.O. Box 5800, Albuquerque, United States
[2]Purdue University, West Lafayette, IN 47907, United States
[*]fog@sandia.gov

SPIE Defense & Commercial Sensing 2022
Orlando, Florida, United States

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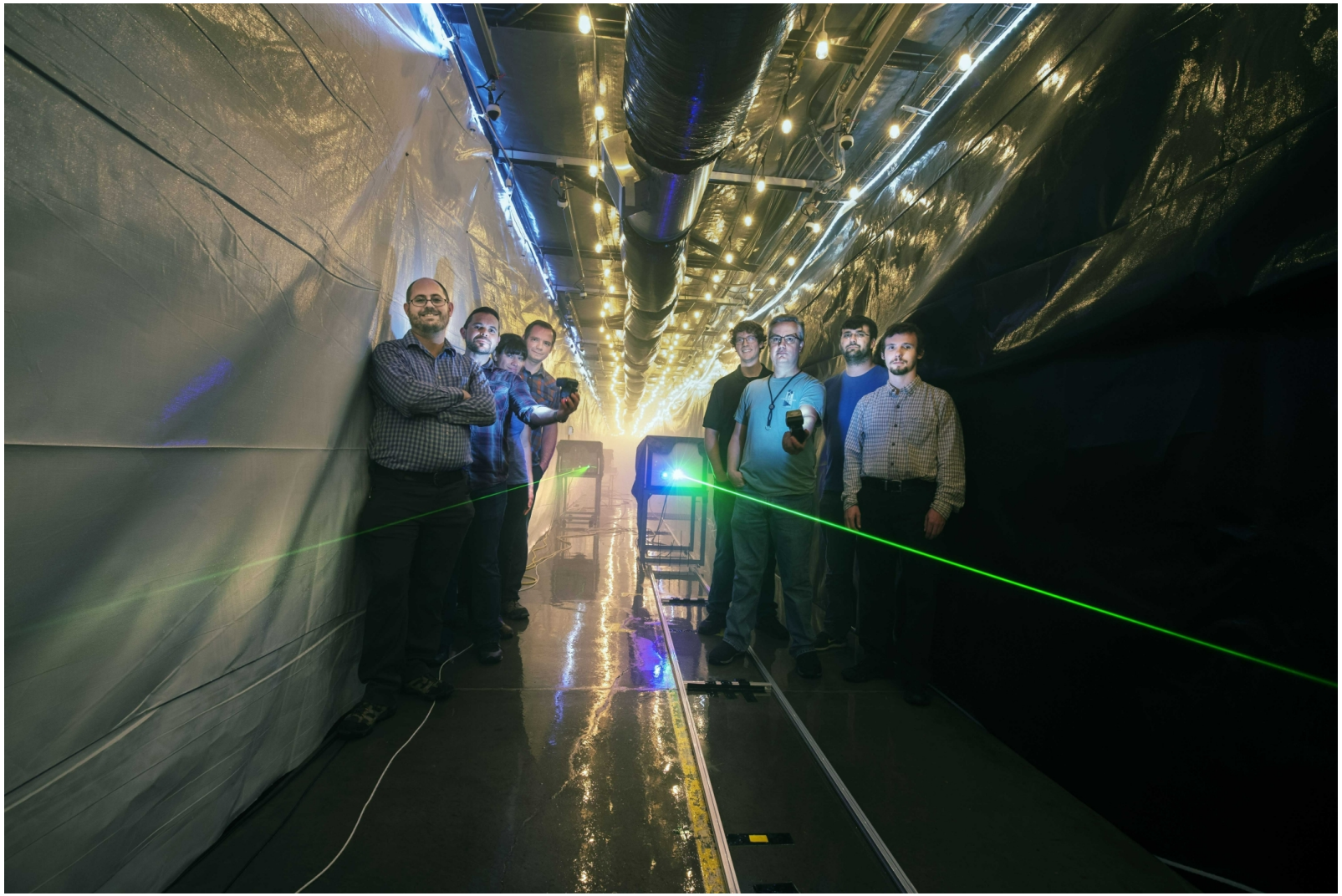
Sandia National Laboratories Fog Team



Multidisciplinary team

- Aerosol scientists
- Optical engineers

Ongoing fog research

- Signal recovery
- Light propagation physics
- Detection, localization, identification
- Machine learning
- Generation
- Systems testing
- Pollution

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What we will be talking about

Introduction

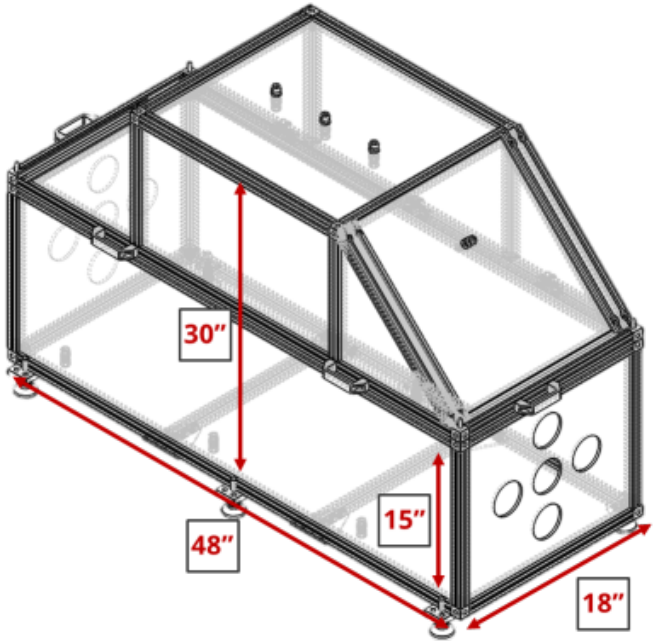
- Why do we care about fog?
- How fog affects imaging
- Common types of fog

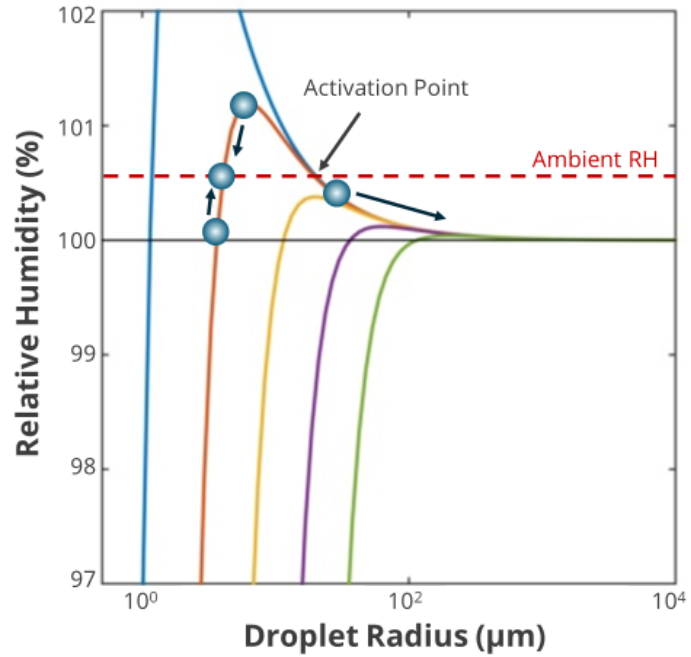
Controlled fog generation testbed

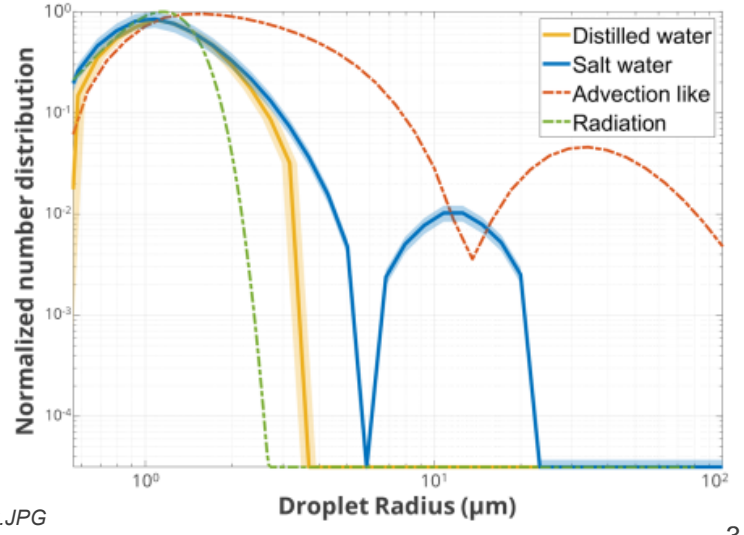
- Current facilities
- Tabletop chamber design
- Fog microphysics
- Tabletop chamber fogs

Applications & future work

- Testbed function
- Future work: machine learning
- Future work: plume analysis







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Trees with fog image: Wikipedia, *https://upload.wikimedia.org/wikipedia/commons/8/83/Sunlight%2C_thin_fog%2C_Jefferson_Park.JPG*
Shuttle with fog image: NASA, *https://www.nasa.gov/sites/default/files/images/576186main_S82-41141_full.jpg*

Why do we care about fog?

Limits how far you can see

- Transportation
- Sensing and detection

Can halt or delay activity

- Lost time, opportunity
- Economic impact

Factor in 25% of vehicle accidents

- Shipping, automobiles, aviation, etc.
- Massive human cost

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Aviation data: **NWS**, *https://www.weather.gov/safety/fog-flying* and **BTS**, *https://www.bts.gov/content/us-general-aviationa-safety-data*
Automobile data: **DOT**, *https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/813266* and *https://ops.fhwa.dot.gov/weather/weather_events/low_visibility.htm*
Image: NASA, *https://www.nasa.gov/sites/default/files/images/576186main_S82-41141_full.jpg*

How does fog affect imaging?

Some light unaffected

- Ballistic light

Light to moderate scattering

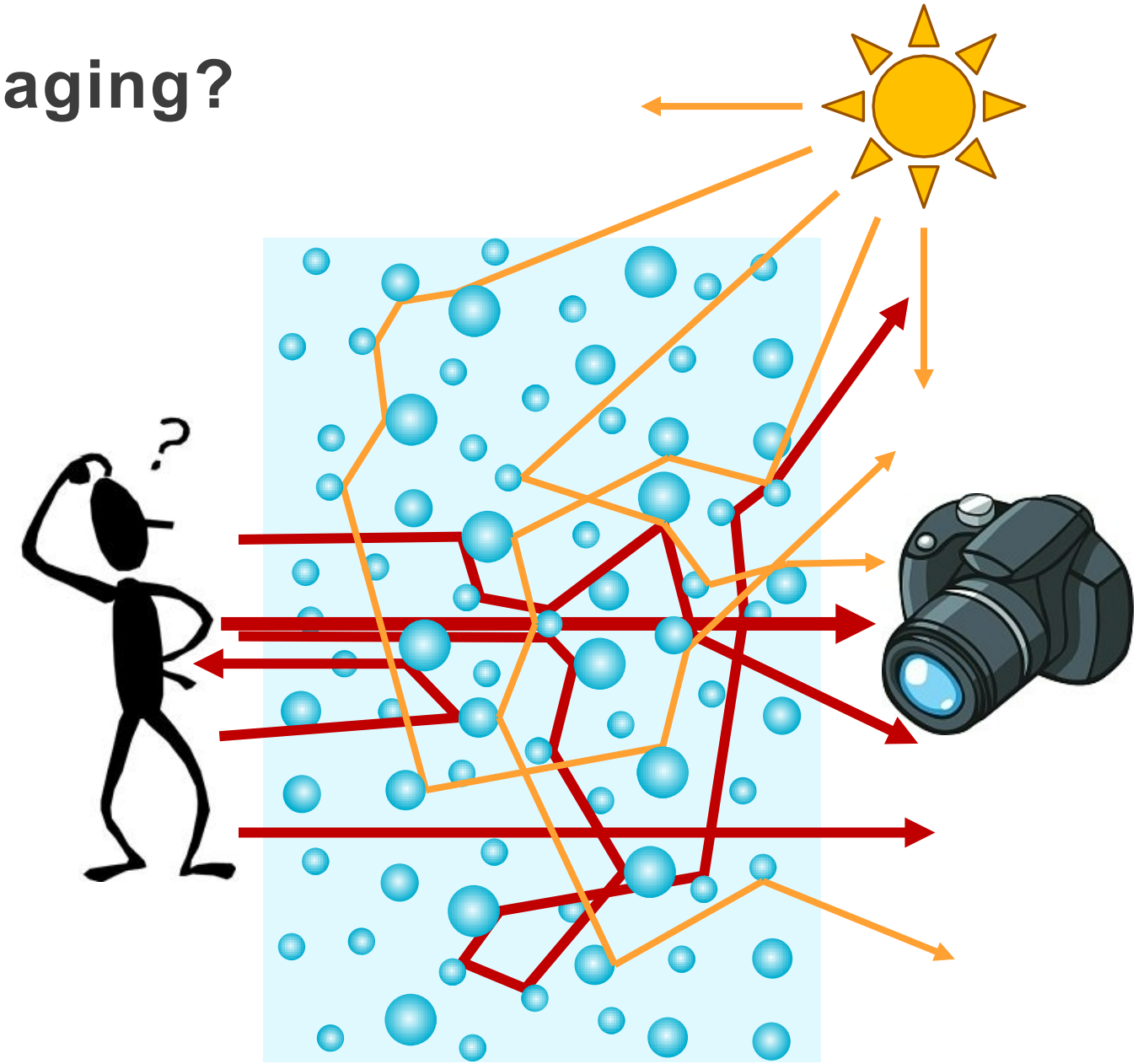
- Causes blurring
- Decreases contrast

Heavy scattering

- Complete scrambling of spatial information
- Backscatter

Background noise

- Light from other sources



How we calculate parameters of interest

Malvern Spraytec

Volume distribution ($\boldsymbol{v}$)

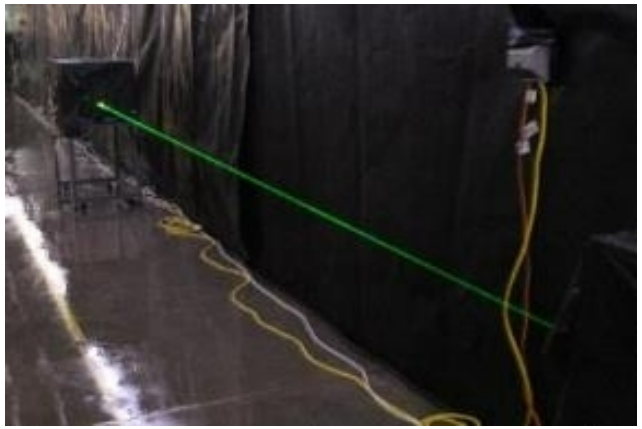
Mie Theory

Scattering efficiency ($\boldsymbol{Q(\theta)}$)

Bulk scattering coefficient ($\boldsymbol{\mu_s}$) and mean scattering angle ($\boldsymbol{g}$)

Transport mean free path ($\boldsymbol{l_t}$) and Meteorological Optical Range ($\boldsymbol{MOR}$)

Number density ($\boldsymbol{N_d}$) and size distribution ($\boldsymbol{N(d)}$)



Transmissometer (532 nm, 1550 nm, 9.68 μm)

Normalized transmission ($\boldsymbol{\Phi_n}$)

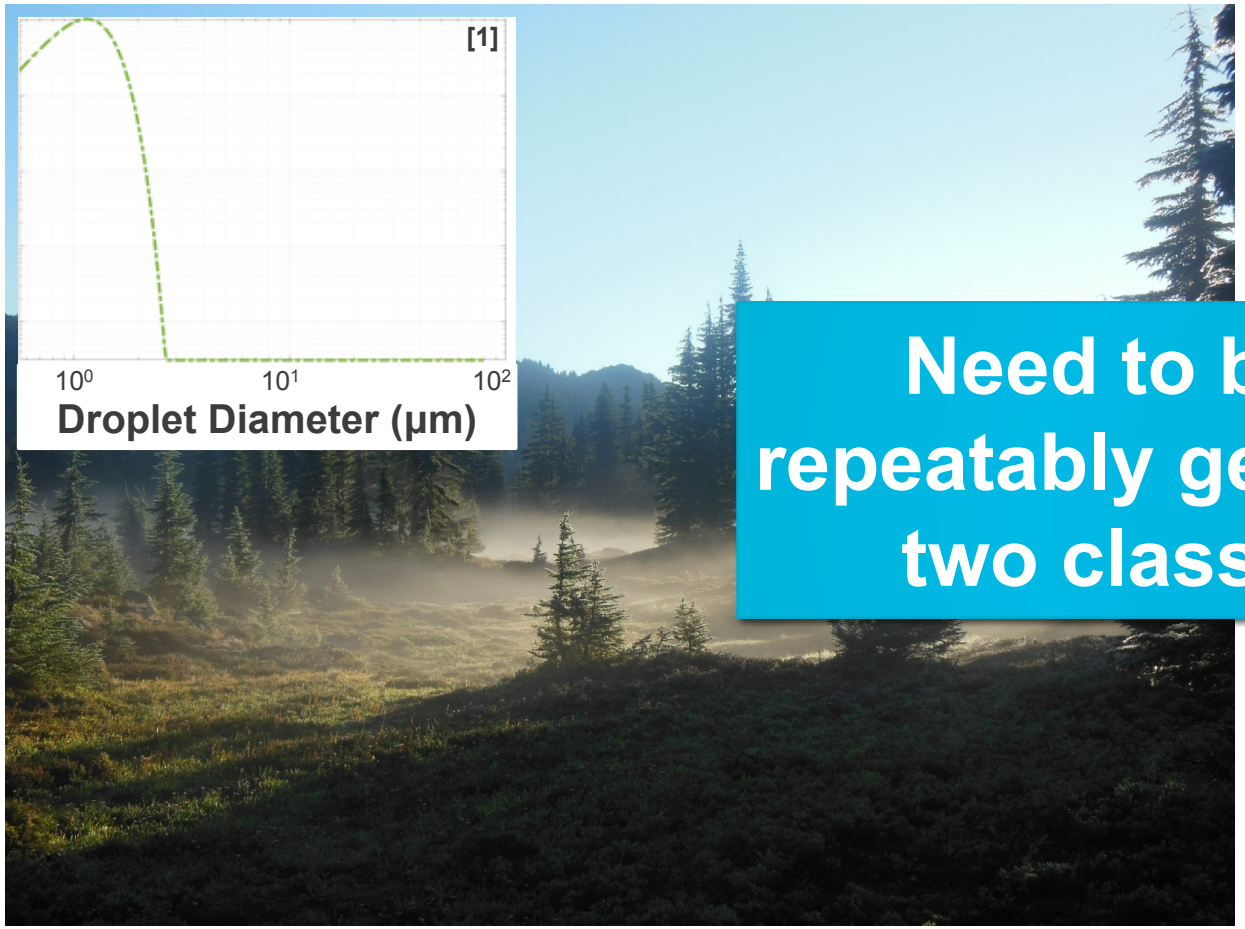
Liquid water content ($\boldsymbol{LWC}$)

$$\boldsymbol{LWC} = \frac{-2\ln(\Phi_n)}{3L\sum_i \frac{Q_i \cdot v_i}{d_i}}\rho_{water} \qquad \boldsymbol{N(d)} = \frac{6v \cdot \mathrm{LWC}}{\pi d^3}$$

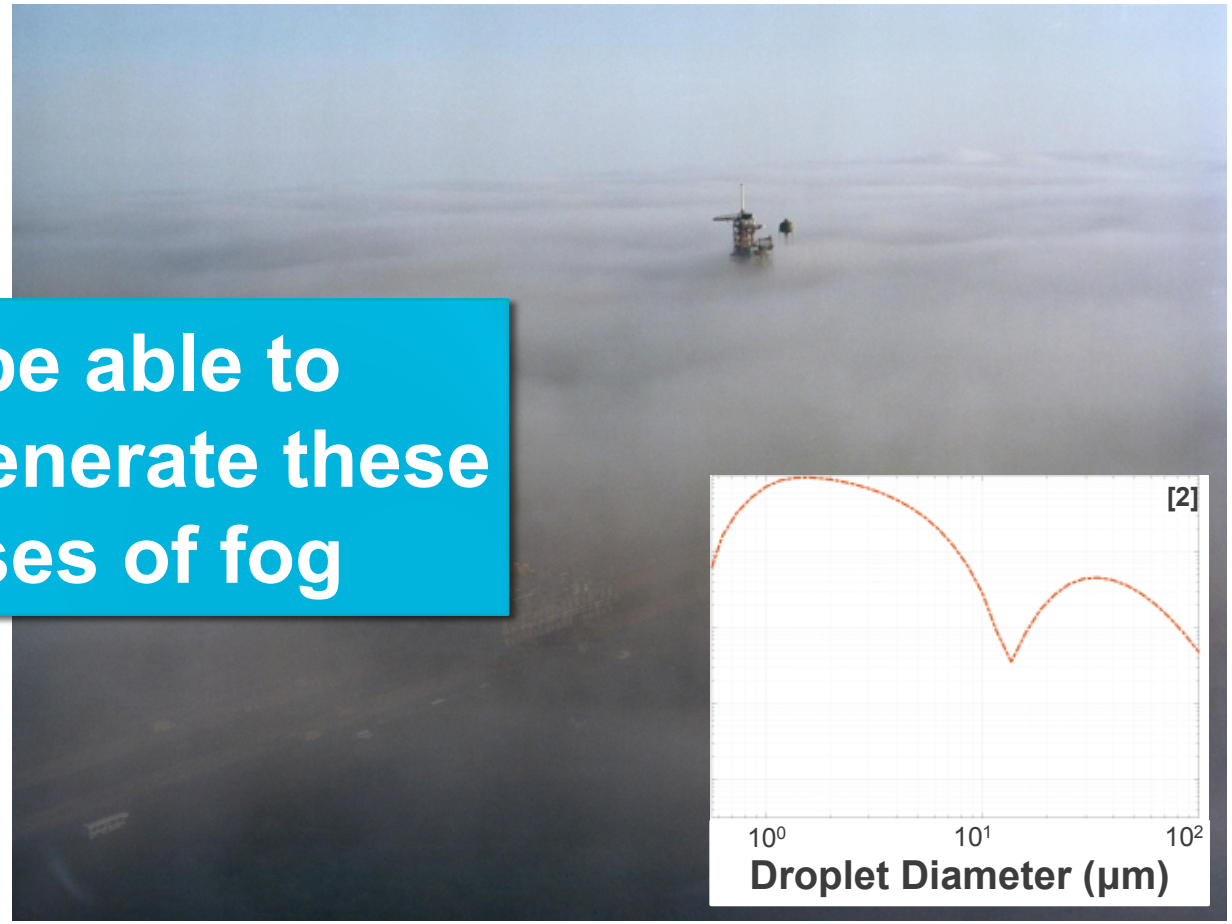
$$\boldsymbol{l_t} = \frac{1}{\mu_s(1-g)} \qquad \boldsymbol{MOR} = \frac{-\ln(0.05)}{\mu_s}$$

[1] J. B. Wright, J. D. v. d. Laan, A. Sanchez, S. A. Kemme, and D. A. Scrymgeour, "Optical characterization of the Sandia fog facility," Proceedings of SPIE 10197 (2017).
[2] B. J. Redman, and J. D. van der Laan, “Measuring resolution degradation of long-wavelength infrared imagery in fog,” Optical Engineering , 58(05), (2019).

Replicate the most common types of fog



Need to be able to repeatably generate these two classes of fog



Radiation fog

Advection fog

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Radiation fog image (left): Wikipedia, *https://upload.wikimedia.org/wikipedia/commons/8/83/Sunlight%2C_thin_fog%2C_Jefferson_Park.JPG*
[1] J. A. Garland, "Some fog droplet size distributions obtained by an impaction method," Quarterly Journal of the Royal Meteorological Society , 97(414), 483-494 (1971).
Advection fog image (right): NASA, https://www.nasa.gov/sites/default/files/images/576186main_S82-41141_full.jpg
[2] B. Z. Bentz, B. J. Redman, J. D. van der Laan, K. Westlake, A. Glen, A. L. Sanchez, and J. B. Wright, "Light transport with weak angular dependence in fog," Optics Express , 29(9), 13231-13245 (2021).

Sandia National Laboratories Fog Chamber

Large scale testing laboratory

- 180’ x 10’ x 10’
- Class IV laser facility
- 64 spray nozzles
- Temperature controls

Instrumentation

- Malvern Spraytec particle sizer
- Multiband transmissometer
- Relative humidity sensors
- Temperature sensors
- Cameras

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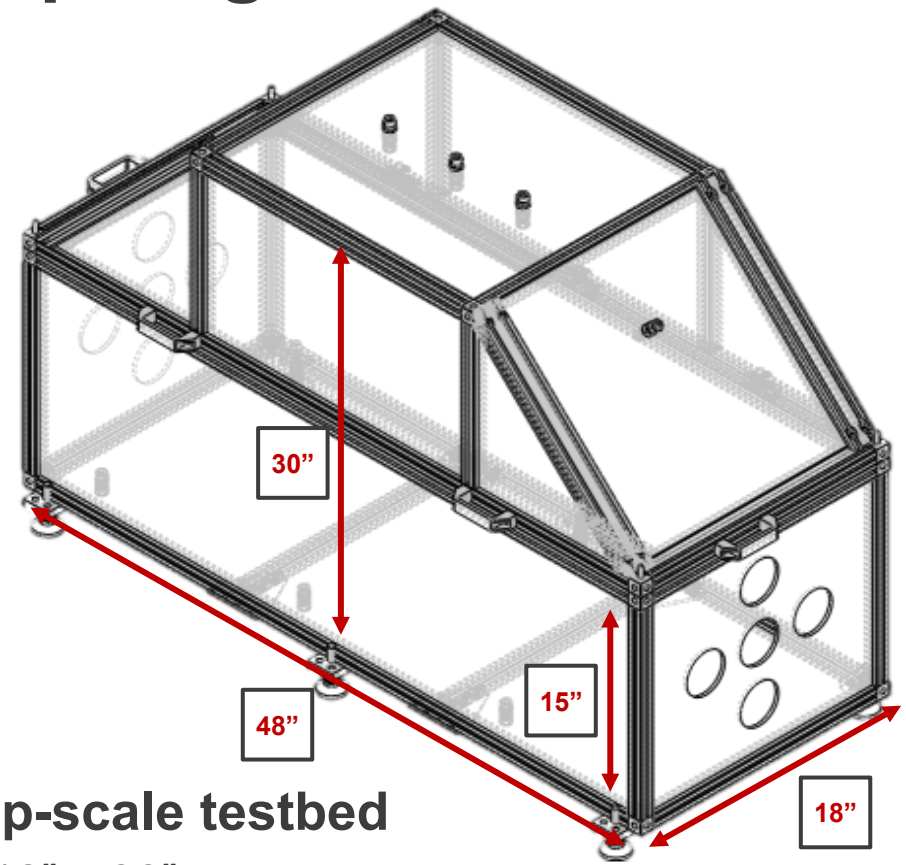
[1] J. B. Wright, J. D. v. d. Laan, A. Sanchez, S. A. Kemme, and D. A. Scrymgeour, "Optical characterization of the Sandia fog facility," Proceedings of SPIE 10197 (2017).

Sandia National Laboratories Tabletop Fog Chamber



Benchtop-scale testbed

- 48” x 18” x 30”
- Single spray nozzle
- Lightweight
- Fully equippable with all SNLFC equipment

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Water droplet formation and growth

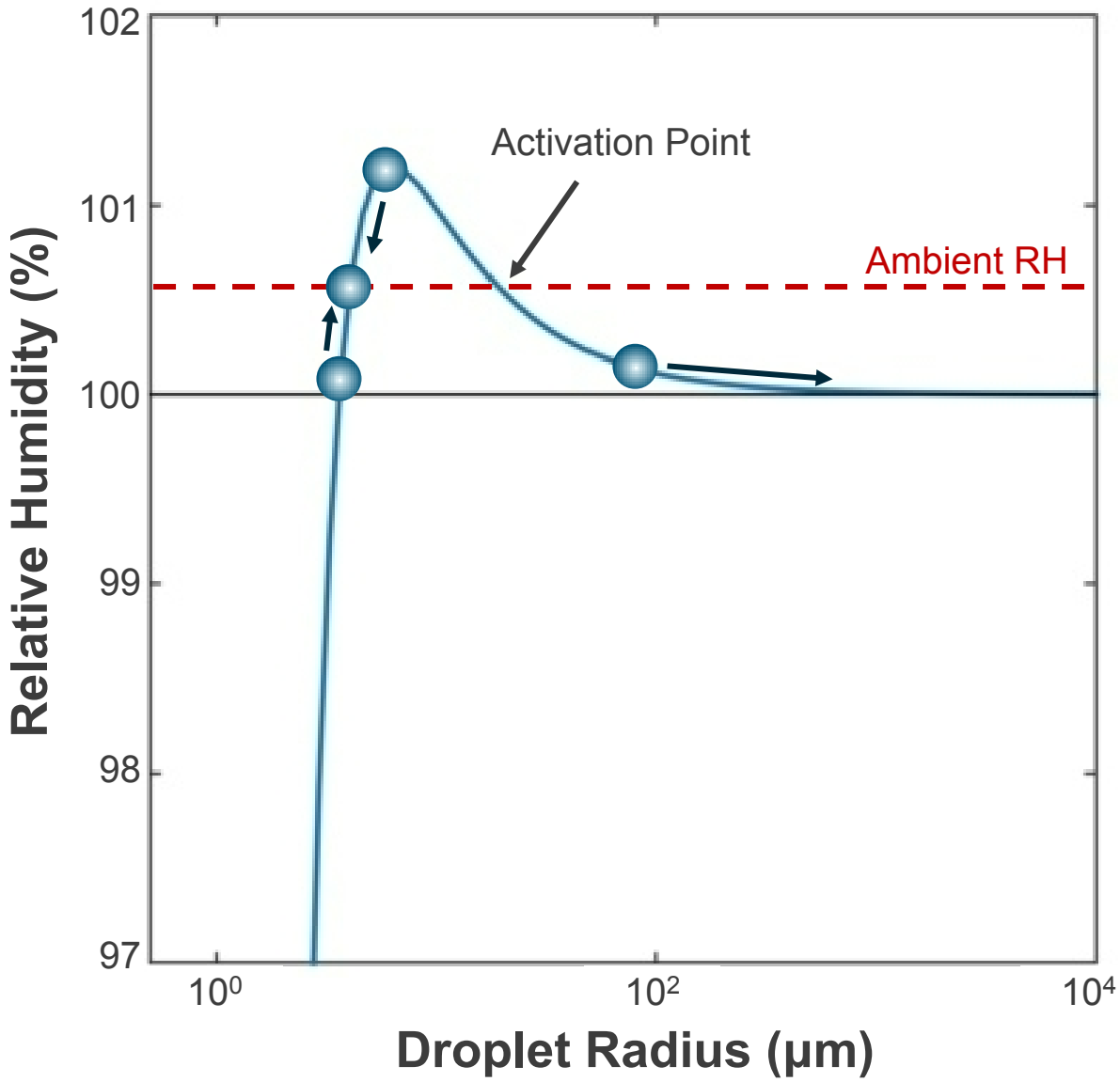
Köhler equation

- Describes the condensation of water vapor into droplets
- Gives relative humidity (RH) of droplets

$$RH = \left[1 + exp\left[\frac{A}{T \cdot r} - B\frac{m_s}{r^3}\right]\right] \cdot 100\%$$

Curvature Term
Driven by surface tension

Solute Term
Driven by chemical potential



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[1] R. Stull, [Practical Meteorology] University of British Columbia, (2020).

Water droplet formation and growth

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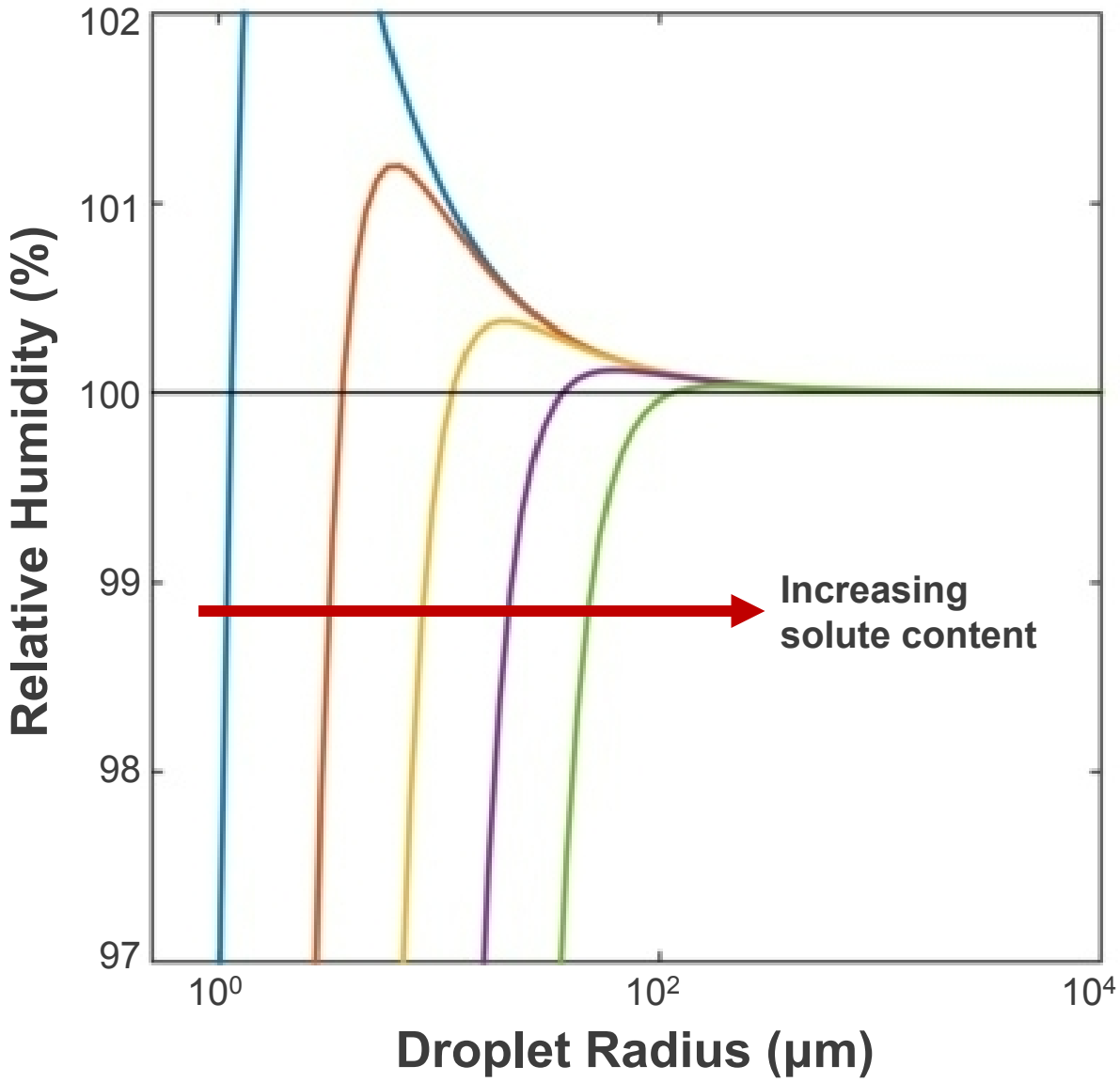
$$RH = \left[1 + exp\left[\frac{A}{T \cdot r} - B\frac{m_s}{r^3}\right]\right] \cdot 100\%$$

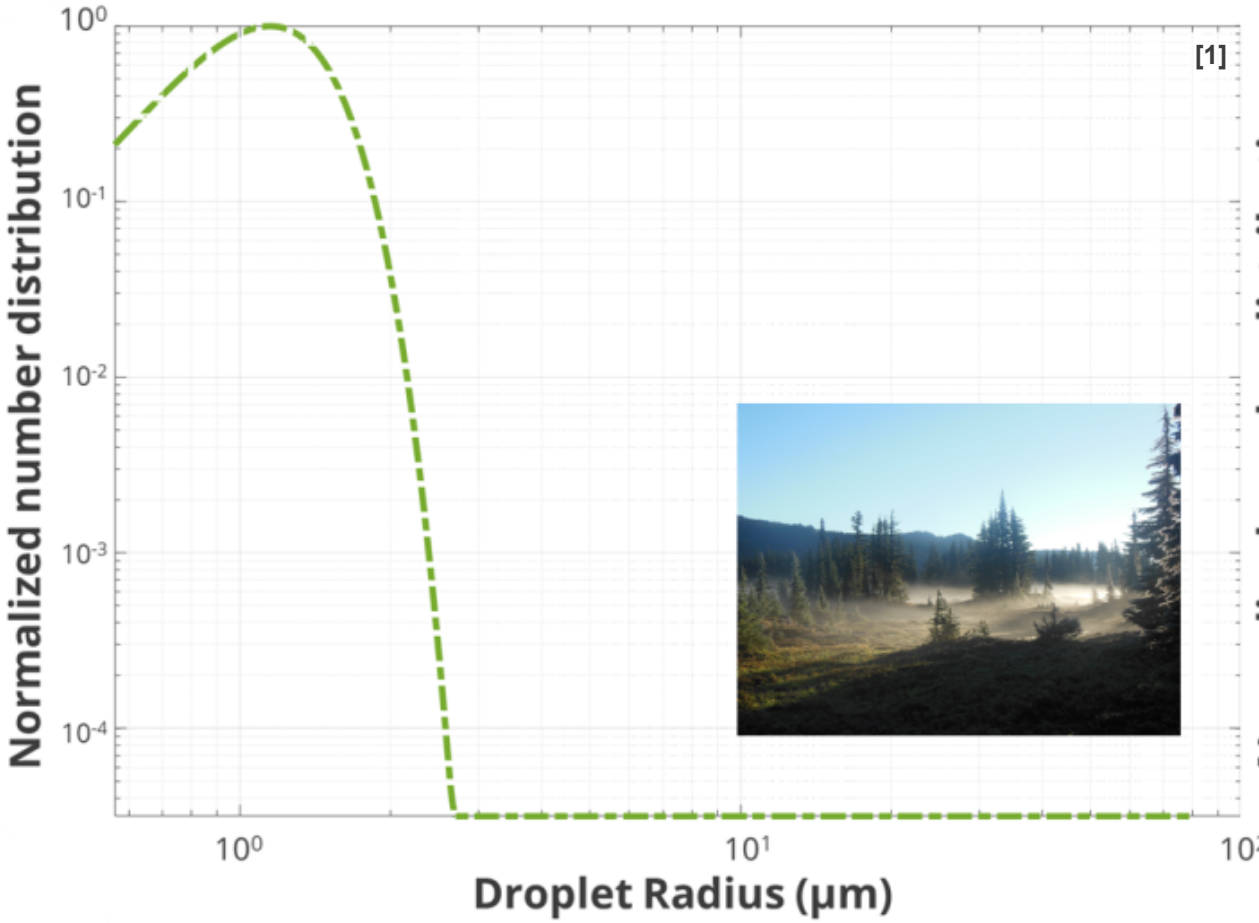
Solute effect

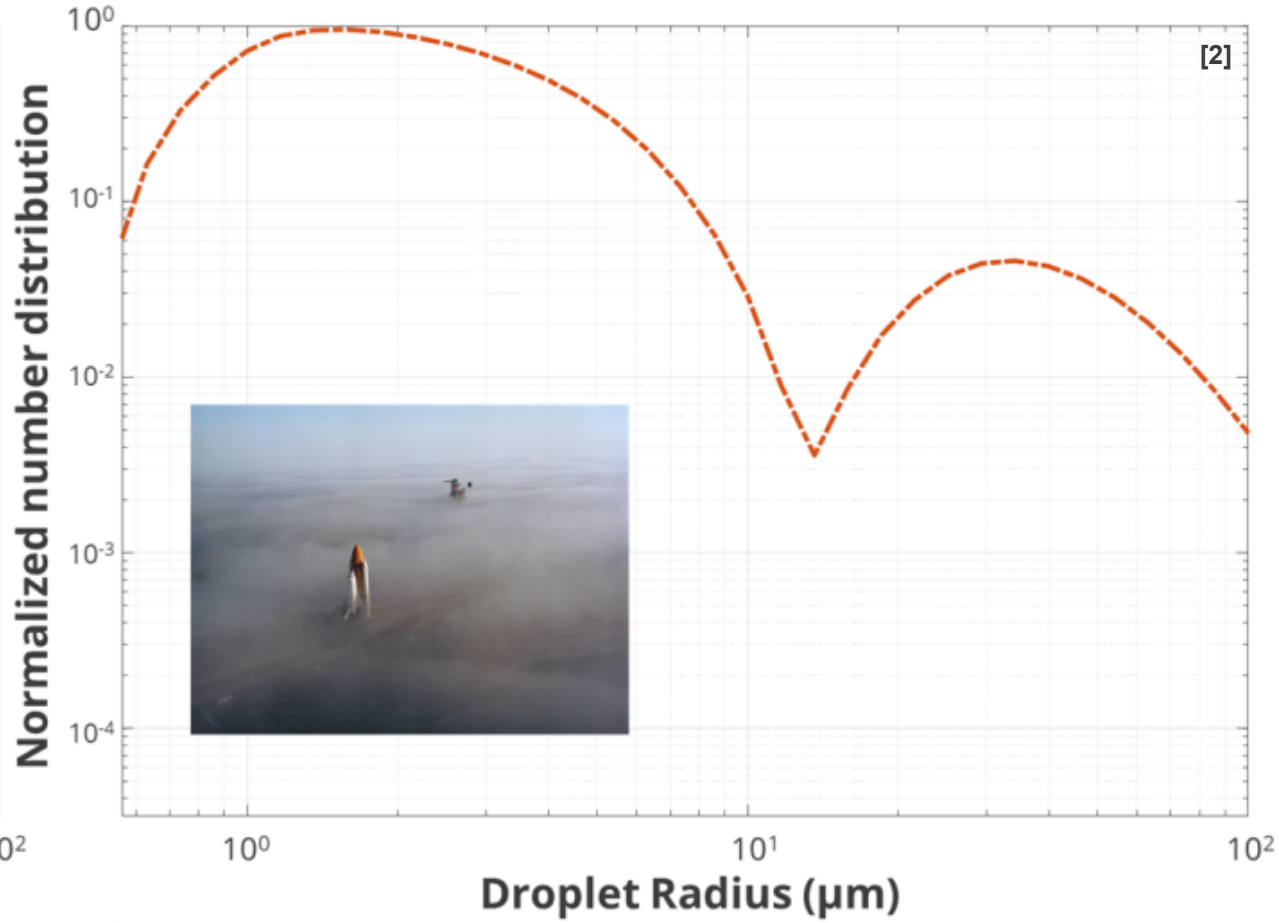
- Hygroscopicity (chemical potential)
- Influences droplet size and count



[1] R. Stull, [Practical Meteorology] University of British Columbia, (2020).

Replicate the most common types of fog





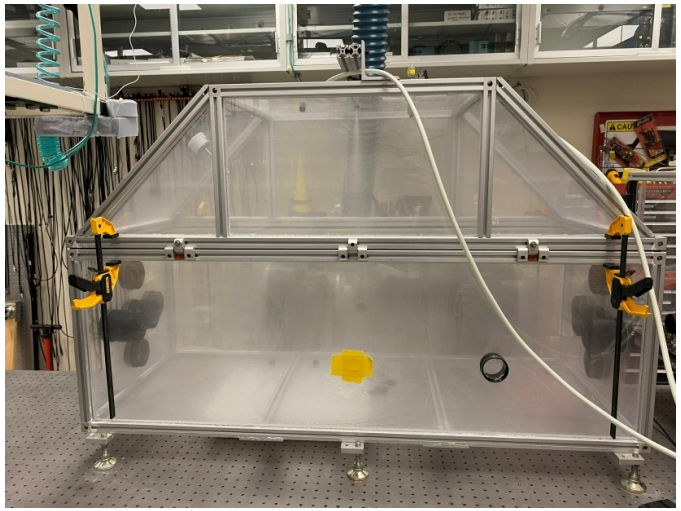
Radiation fog - distilled water only

Advection fog - add solute, 10 g/L salt

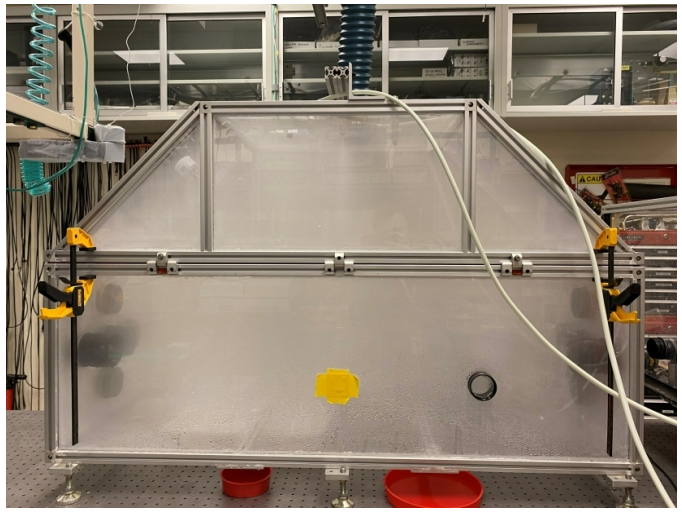
Radiation fog image (left): Wikipedia, *https://upload.wikimedia.org/wikipedia/commons/8/83/Sunlight%2C_thin_fog%2C_Jefferson_Park.JPG*
[1] J. A. Garland, "Some fog droplet size distributions obtained by an impaction method," Quarterly Journal of the Royal Meteorological Society , 97(414), 483-494 (1971).
Advection fog image (right): NASA, https://www.nasa.gov/sites/default/files/images/576186main_S82-41141_full.jpg
[2] B. Z. Bentz, B. J. Redman, J. D. van der Laan, K. Westlake, A. Glen, A. L. Sanchez, and J. B. Wright, "Light transport with weak angular dependence in fog," Optics Express , 29(9), 13231-13245 (2021).

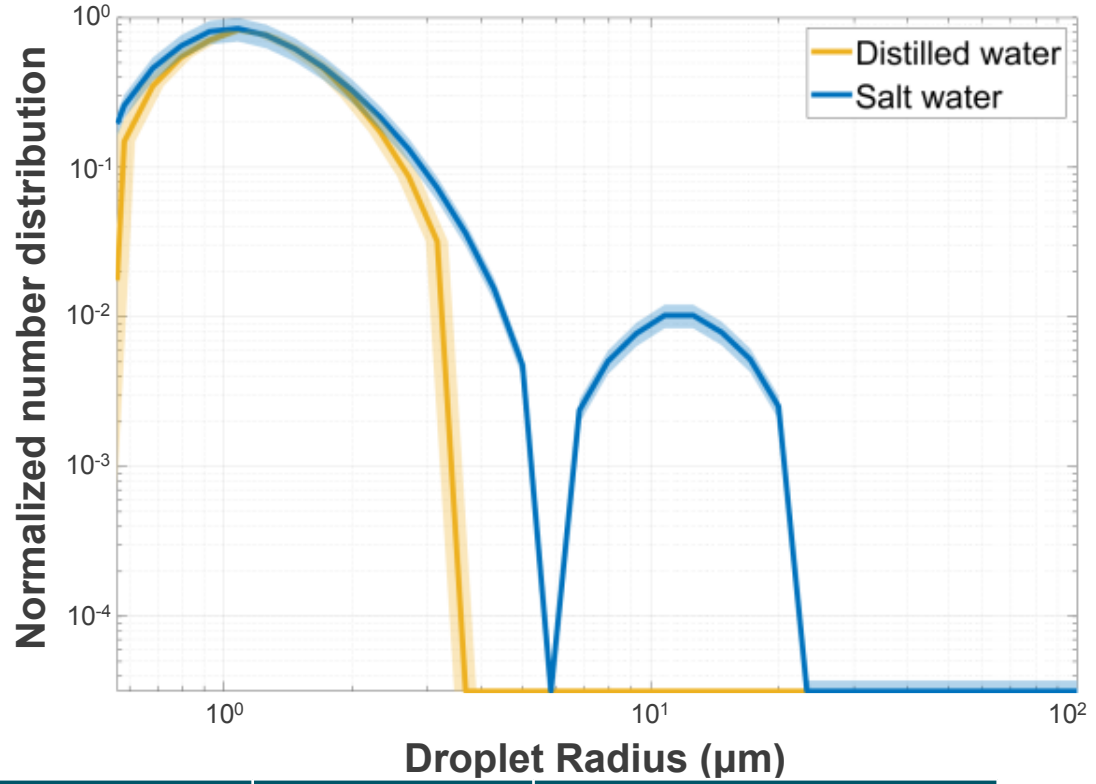
Tabletop chamber fogs

Distilled water



Saltwater





Fog Parameter Set	Mean Droplet Diameter (μm)	Density (#/cm³)		Average MOR (m)	Maximum Equivalent Distance* (m)
		Average	Max		
Distilled water (no solute)	1.58; SD = 0.03	9.8×10^{4}	1.6×10^{5}	1.1	80 m
Saltwater (10 g/L salt)	1.73; SD = 0.13 12.1; SD = 0.09	2.0×10^{5}	4.2×10^{6}	0.49	180 m

***in ICAO Category IIIc conditions**[1]

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[1] J. B. Wright, J. D. v. d. Laan, A. Sanchez, S. A. Kemme, and D. A. Scrymgeour, "Optical characterization of the Sandia fog facility," Proceedings of SPIE 10197 (2017).
[2] B. J. Redman, and J. D. van der Laan, "Measuring resolution degradation of long-wavelength infrared imagery in fog," Optical Engineering , 58(05), (2019).

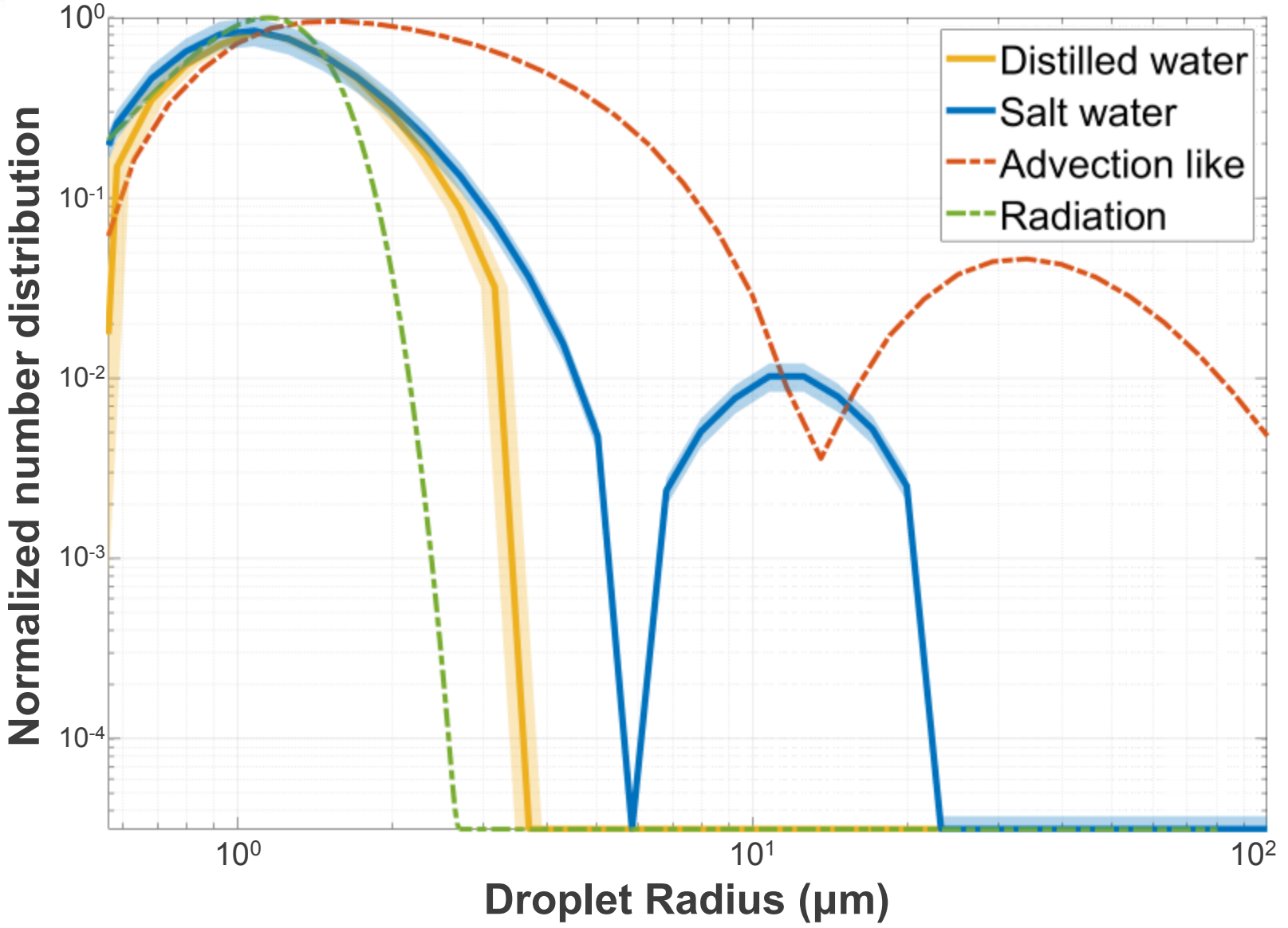
Successful generation of radiation & advection like fogs

Optical testbed for fog

- Well-characterized
- Highly repeatable conditions
- Sensitive to controls
- Atmospheric relevance

Future work & applications

- Optics testing
- Machine learning data development
- Atmospheric microphysics studies
- Add environmental controls



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Future work: Physics-Informed Deep Learning (PIDL)

Elihu Deneke, Ph.D.

Research goals

- Develop PIDL model to image in light scattering media like fog
- Verify and validate models with repeatable and well-characterized fogs
  - SNL Tabletop Fog Chamber and Fog Chamber facility

Physics-driven

(+) Interpretable, generalizes well

(-) Difficult to formulate, limited data utilization

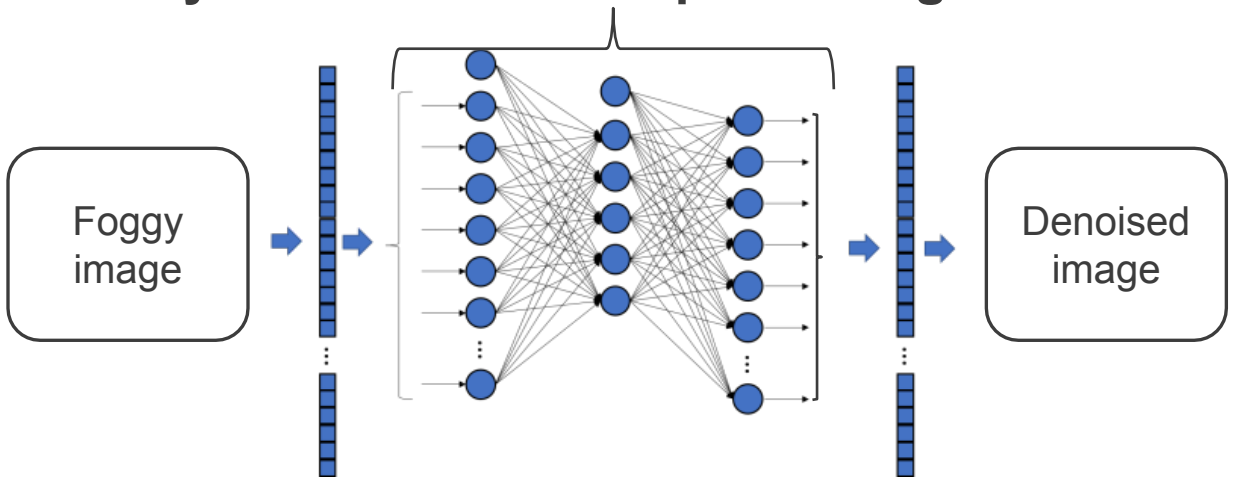
+

Data-driven (Deep Learning)

(+) Utilizes big data easily, high functionality

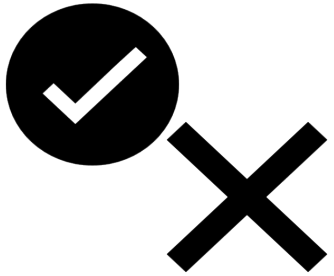
(-) Bias to training conditions, difficult to interpret

Physics-Informed Deep Learning model

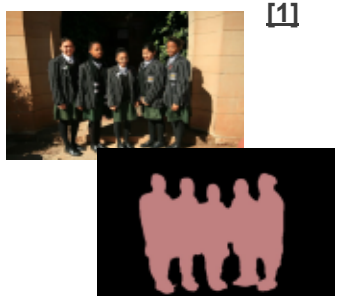


Target and Event Sensing

Denoising
(Can we see?)

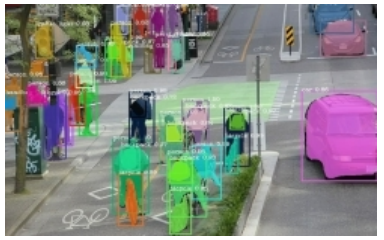


Detection
(Is it there? / Did it happen?)



[1]

Segmentation
(Where is it? / Where did it occur?)



[2]

Recognition
(What is it? / What happened?)

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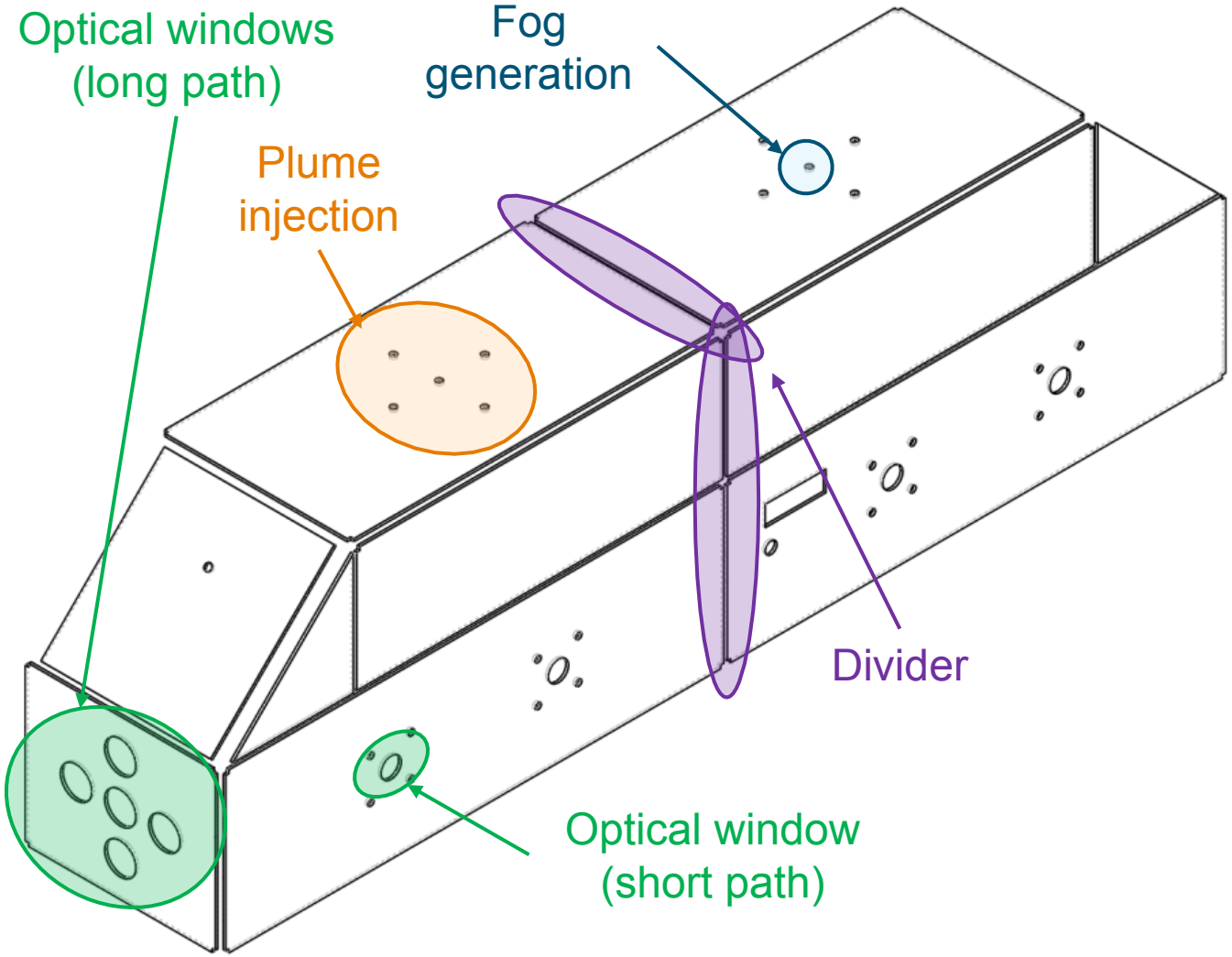
Image [1]: Wikipedia, *https://commons.wikimedia.org/wiki/File:Jeppe_high_for_girls.jpg*
Image [2]: Wikipedia, *https://commons.m.wikimedia.org/wiki/File:Dunsmuir_Separated_Bike_Lanes_104.jpg*

Future work: Stand-off plume analysis in fog

Lekha Patel, Ph.D.



Pollutants in the atmosphere

- Mimic mixing of chemical plumes with atmospheric aerosols (clouds, fogs, etc.)
- Inform stand-off analysis

Building fog diffusion chamber

- Longer path length for longer equivalent distances
- Divided into two sections for diffusion studies
- **Direct chemical injection of hazardous plumes**

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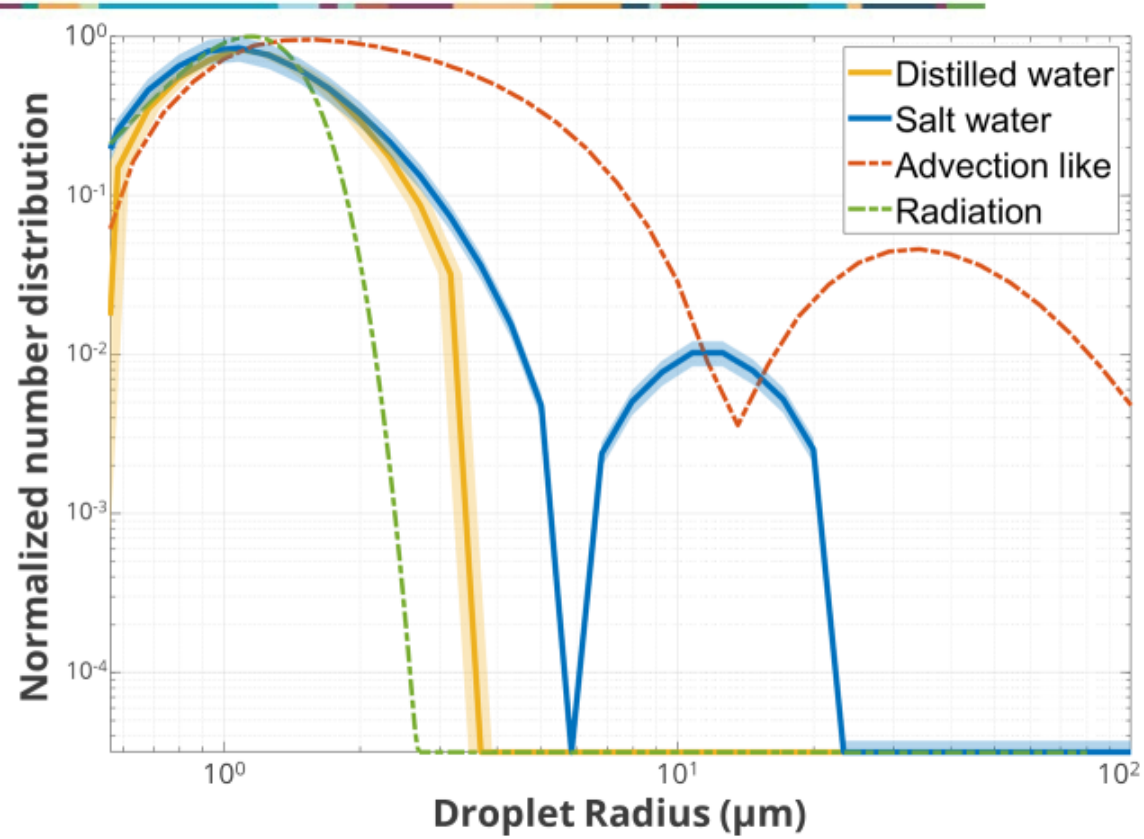
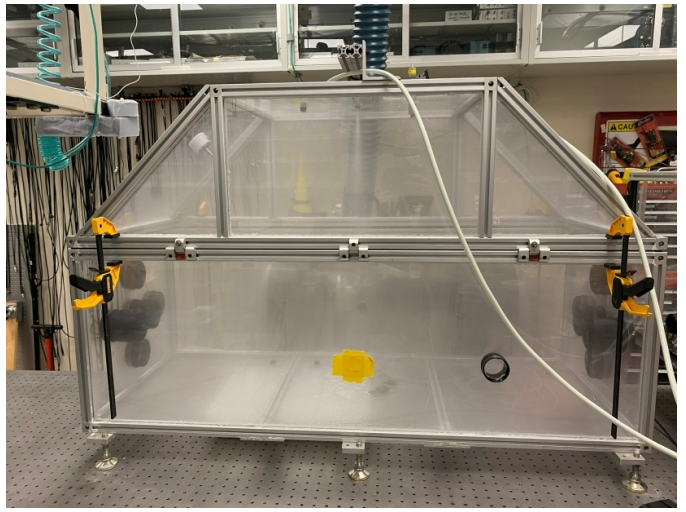
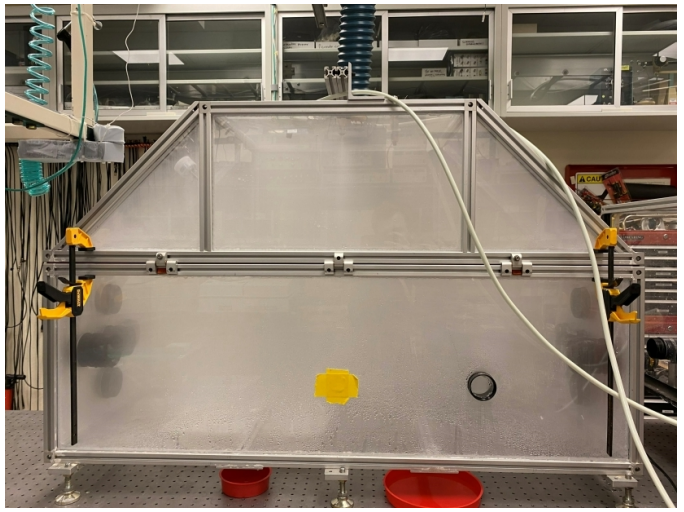
Summary



Distilled water



Salt water



Fog Type	Mean Diameter (μm)	Max Density (#/m^3)	ICAO Cat. IIIc distance (m)
Distilled water (no solute)	1.58; SD = 0.03	1.6 x 10^5	Up to 80 m
Salt water (10 g/L salt)	1.73; SD = 0.13 12.1; SD = 0.09	4.2 x 10^6	Up to 180 m

Applications

- Testbed for optics in fog / cloud environments
- System for studying atmospheric aerosol microphysics

Achievements

- **System generates highly repeatable conditions**
- Good agreement with theory
- Generates relevant, real-world aerosols

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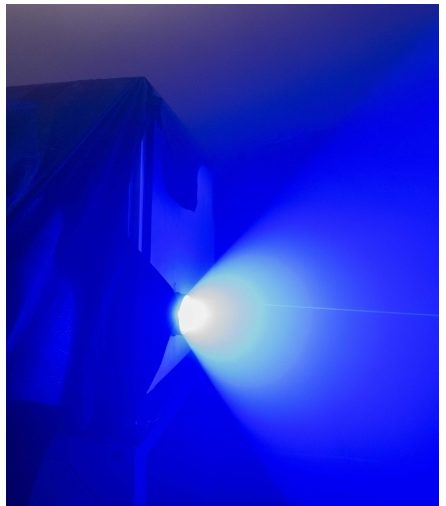
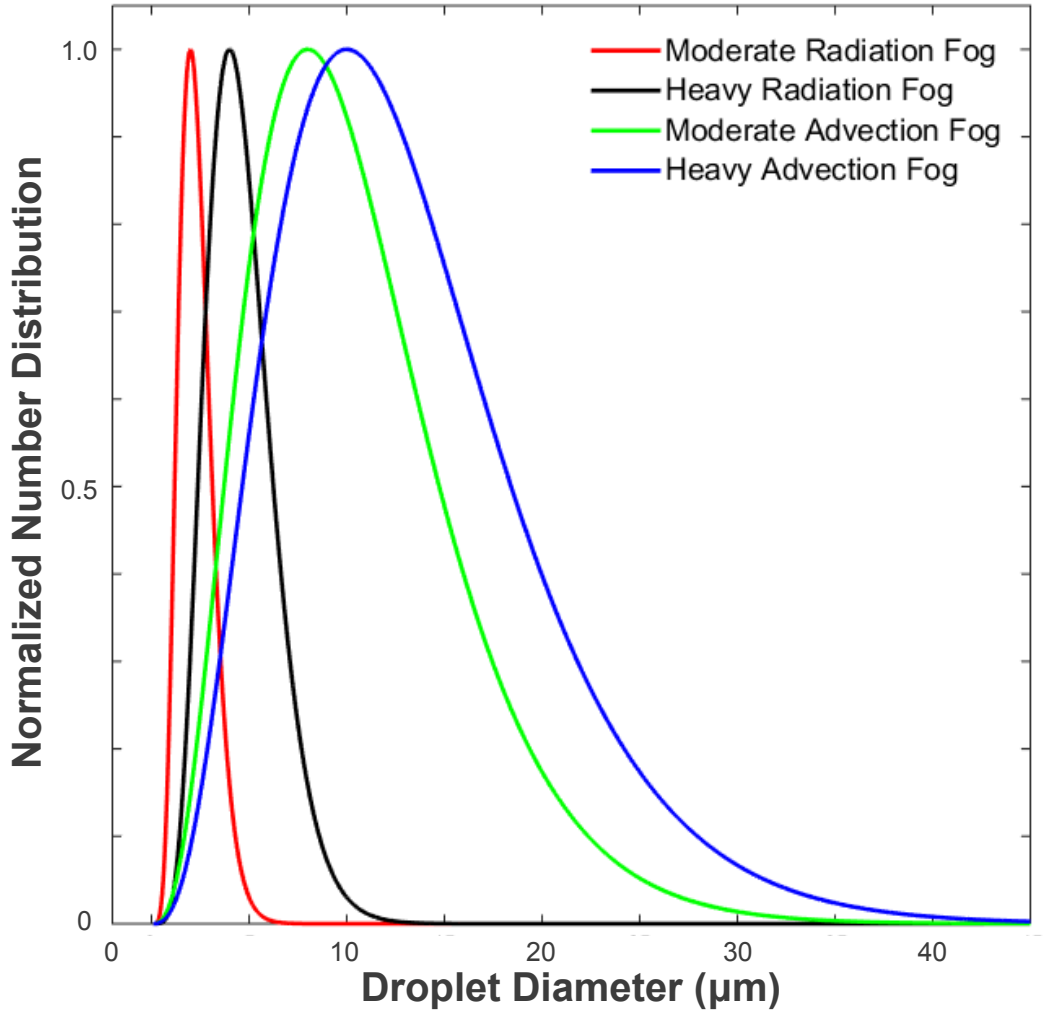
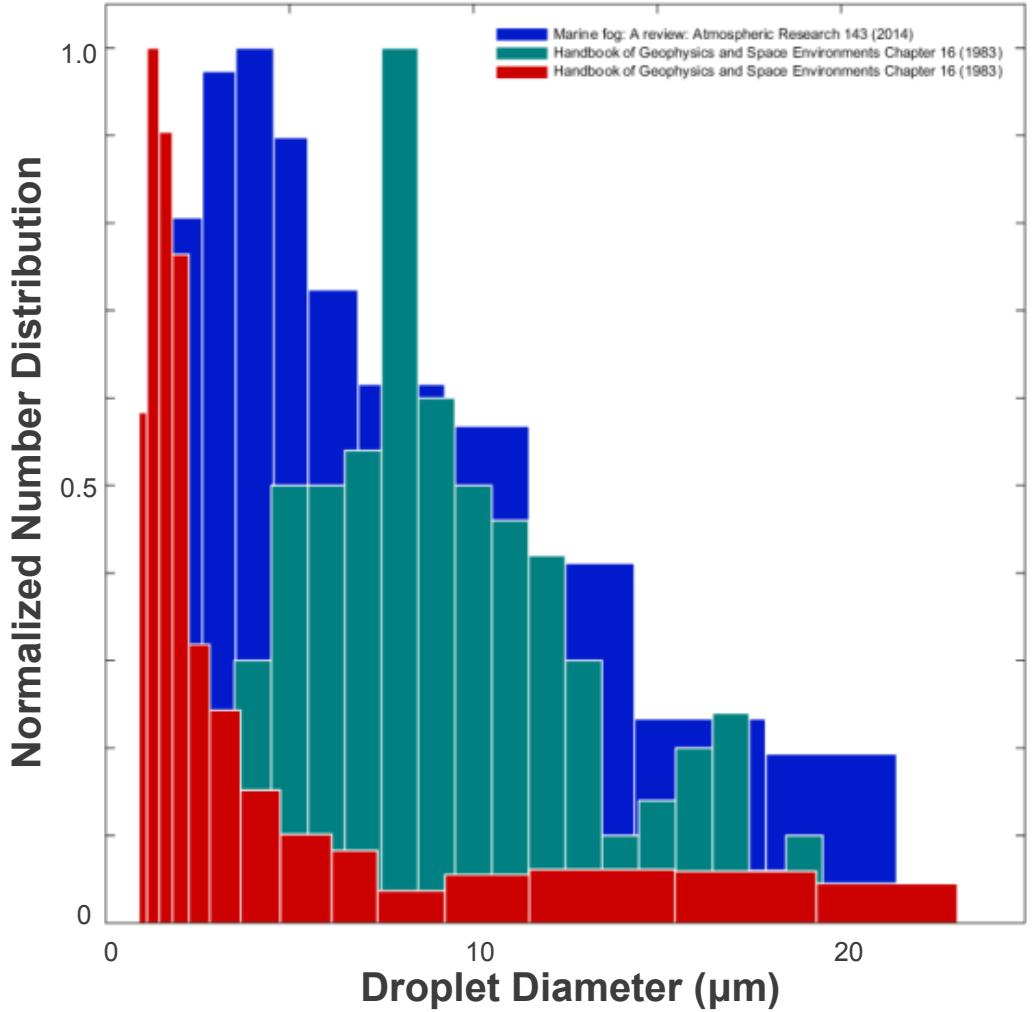


MODTRAN





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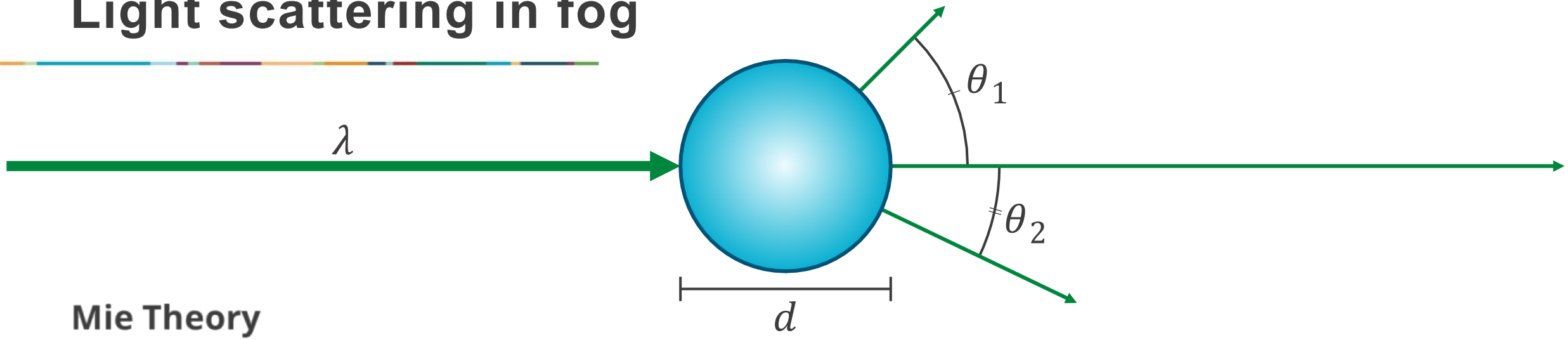
MODTRAN

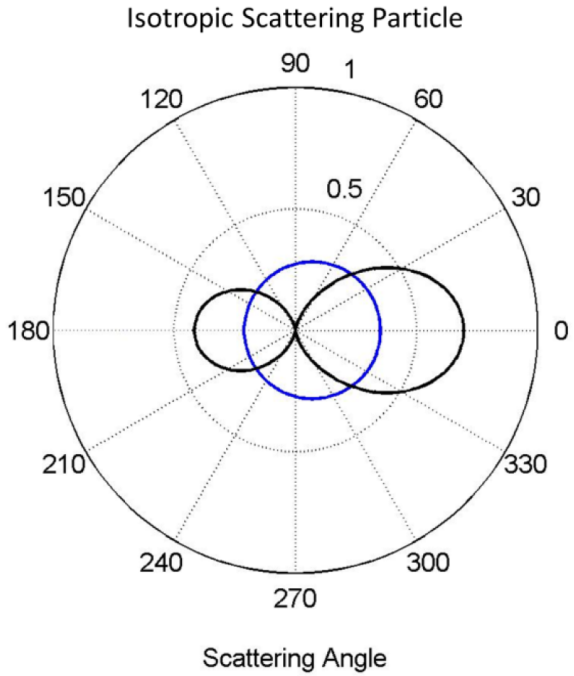
Real-world fogs

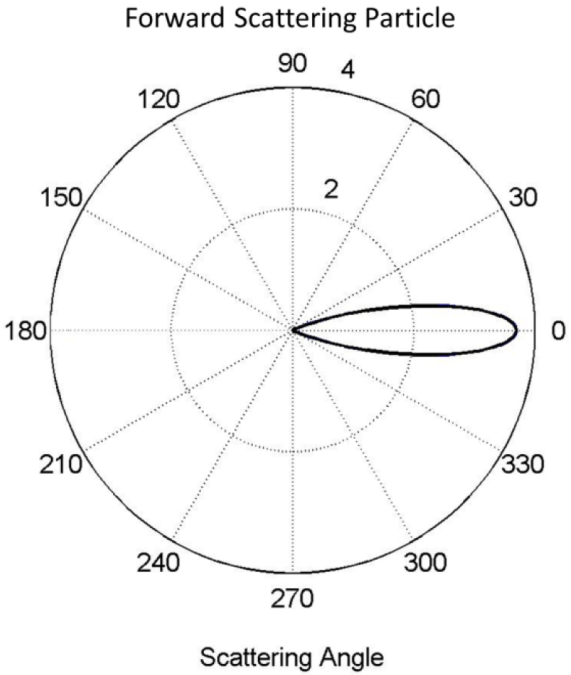
Light scattering in fog



Mie Theory

- Describes scattering and absorption of light by spherical droplets
- Input
  - Droplet diameter (d)
  - Wavelength of light (λ)
  - Droplet refractive index
- Output
  - Bulk scattering coefficient (μ_s)
  - Bulk absorption coefficient (μ_a)
  - Scattering angle (θ)





[1] J. D. van der Laan, J. B. Wright, S. A. Kemme, and D. A. Scrymgeour, "Superior signal persistence of circularly polarized light in polydisperse, real-world fog environments," Applied Optics, 57(19), 5464-5473 (2018).