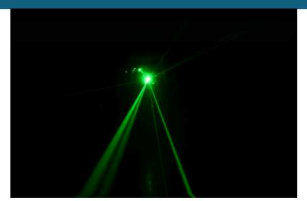
SAND2019-4093C

Polarimetry for extended persistence and range in fog



PRESENTED BY

Jeremy B. Wright

John D. van der Laan, Brian Bentz, Andres Sanchez, Steve Storch, Laura Lemieux, Taylor Settecerri, Karl Westlake, Brian Redman, Julian Medina, Jacob Segal, Shanalyn A. Kemme, David A. Scrymgeour

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What is fog?

Fog - a thick cloud of tiny water droplets suspended in the atmosphere at or near the earth's surface that obscures or restricts visibility.

- Dewpoint temperature spread is <3 °C
- <1km of visibility
- Low Elevation

Mist – Between fog and haze particles less than 5µm.

- 95-100% RH
- >1km visibility

Haze – Does not contain activated droplets according to Köhler theory.

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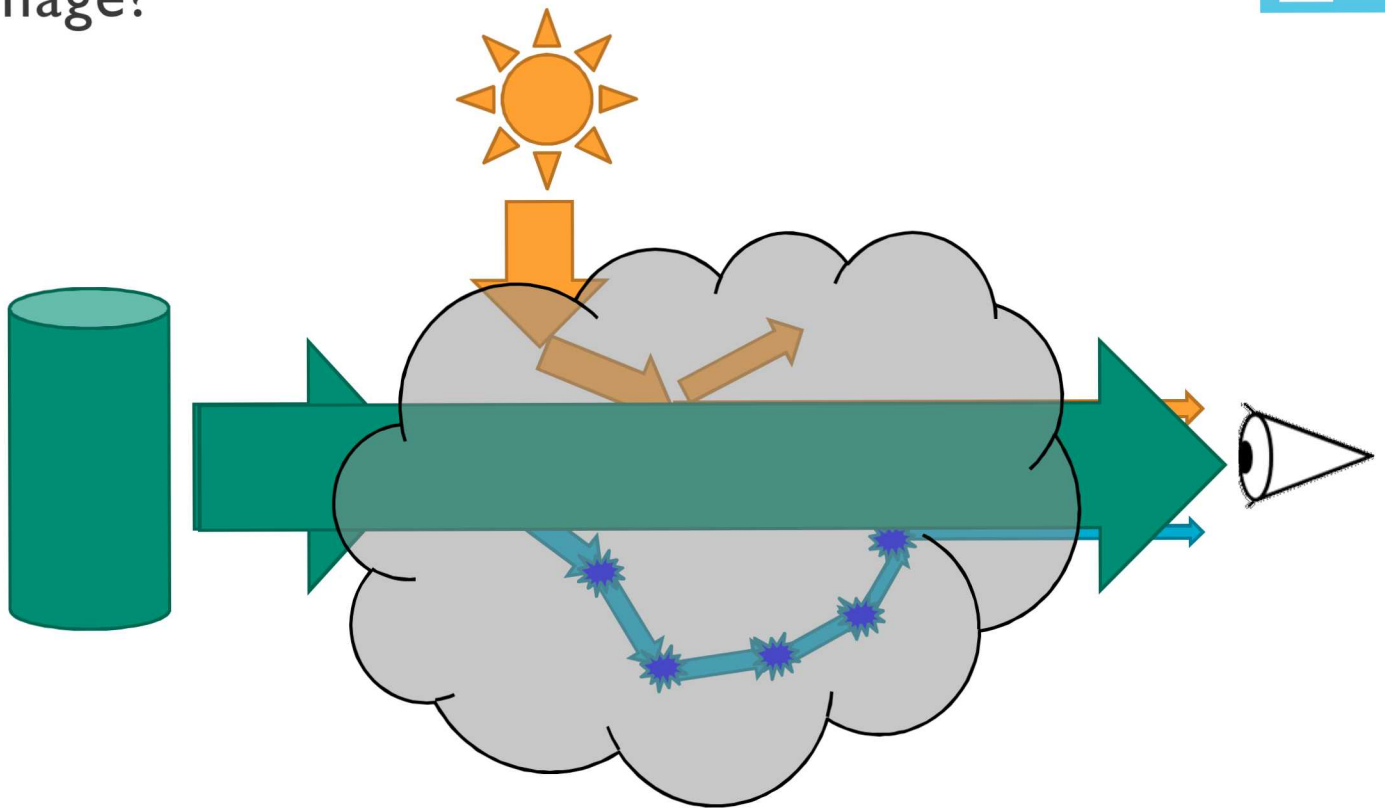
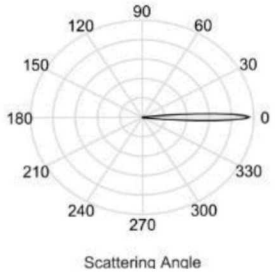
How does fog effect how we see/image?

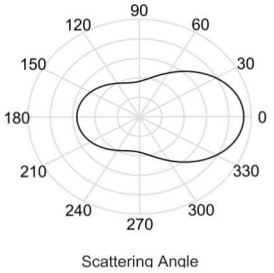
- Loss
  - Scattering
  - Absorption
- Noise
  - Blurring
    - Scattered Light
  - Scattered from background
    - Solar Pedestal
- Dependent on situation
  - Particle size
  - Concentration
  - Wavelength
  - Geometry



Forward scattering

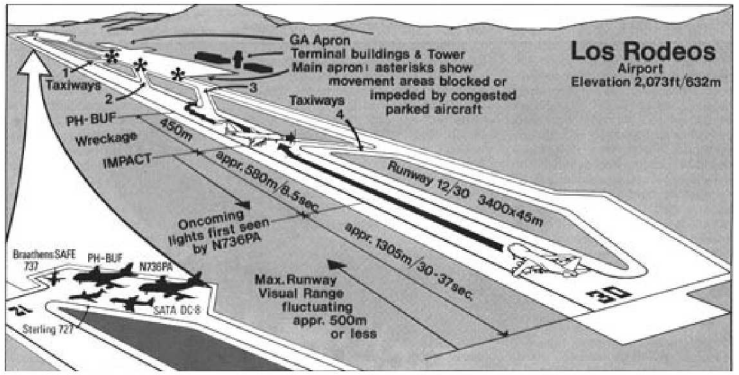


Isotropic scattering



Why do we care about fog?

11 dead in helicopter crash off Florida Coast due to thick fog: WINK News, March 11, 2015



Tenerife Airport Disaster –Fog a major contributor- 583 dead March 27,1977

30 to 40 vehicles crash on stretch of foggy Texas interstate

Dec 19, 2018

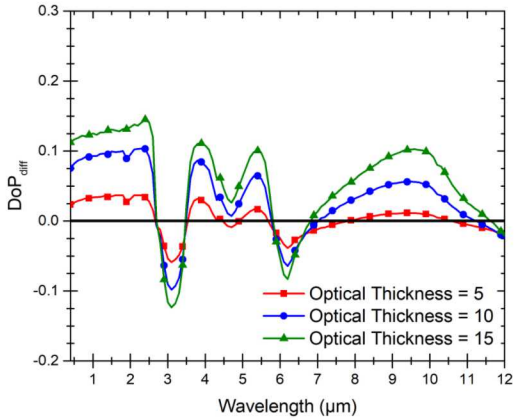
Sandia's Approach to fog

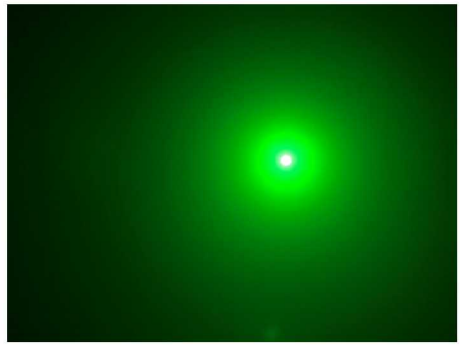
Sandia Fog Facility

How we characterize fog

Polarimetry

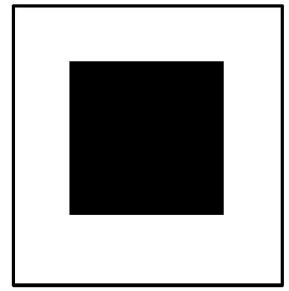
Future work



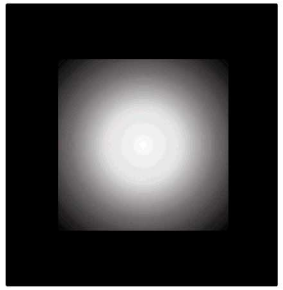


Describing visibility in fog

- Visibility
  - Distance that an object can be seen
- Koschmieder (2-5% transmission)
  - Dark object against light background
  - Daytime contrast against the sky
- Allard's Law
  - Transmission of point source
  - Night visibility of beacon
- Meteorological optical range
  - Distance to attenuate a collimated beam
  - 5% transmission



Koschmieder Equation



Allard's Law

..for detectability, a new system is required to provide visual ranging for commonly encountered objects, especially under harsh weather conditions… Journal of Atmospheric Sciences Lee and Shang 2016

The most common types of fog

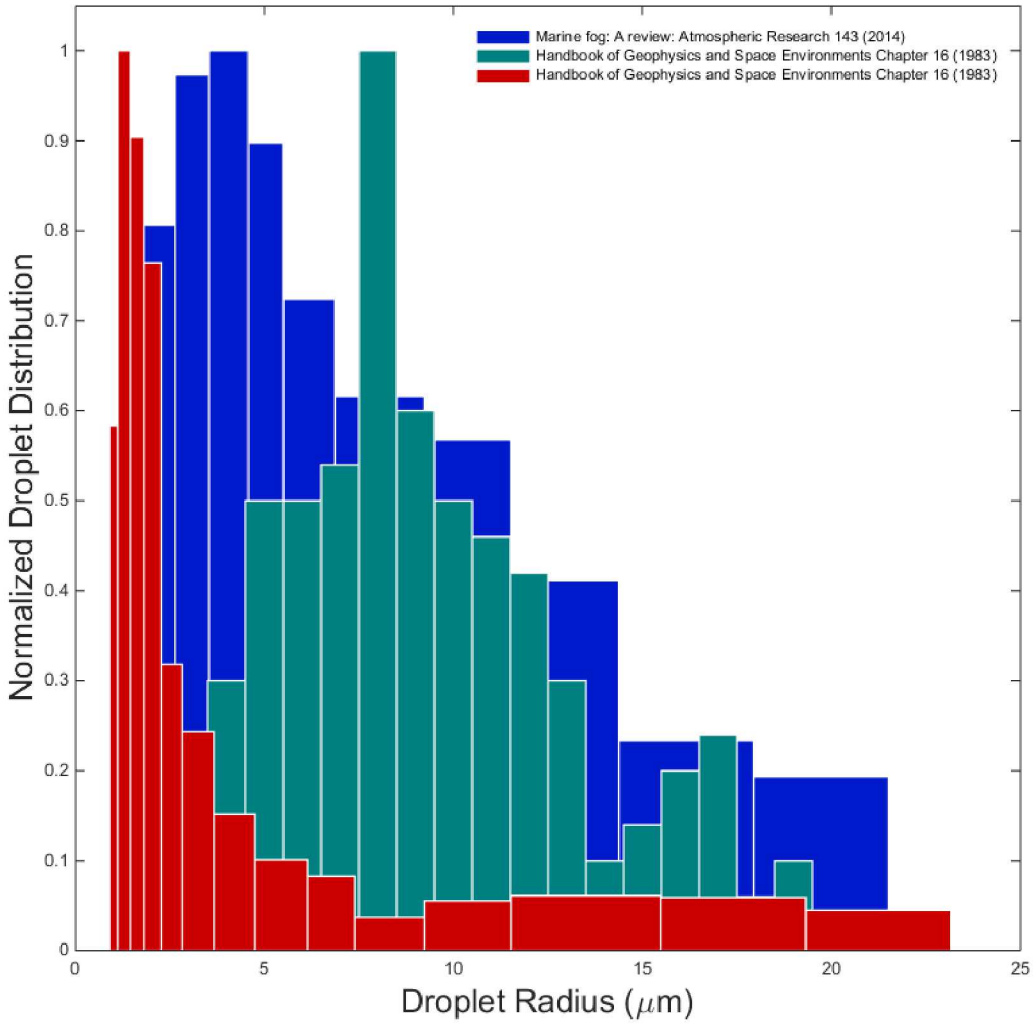
Radiation Fog – Most Common

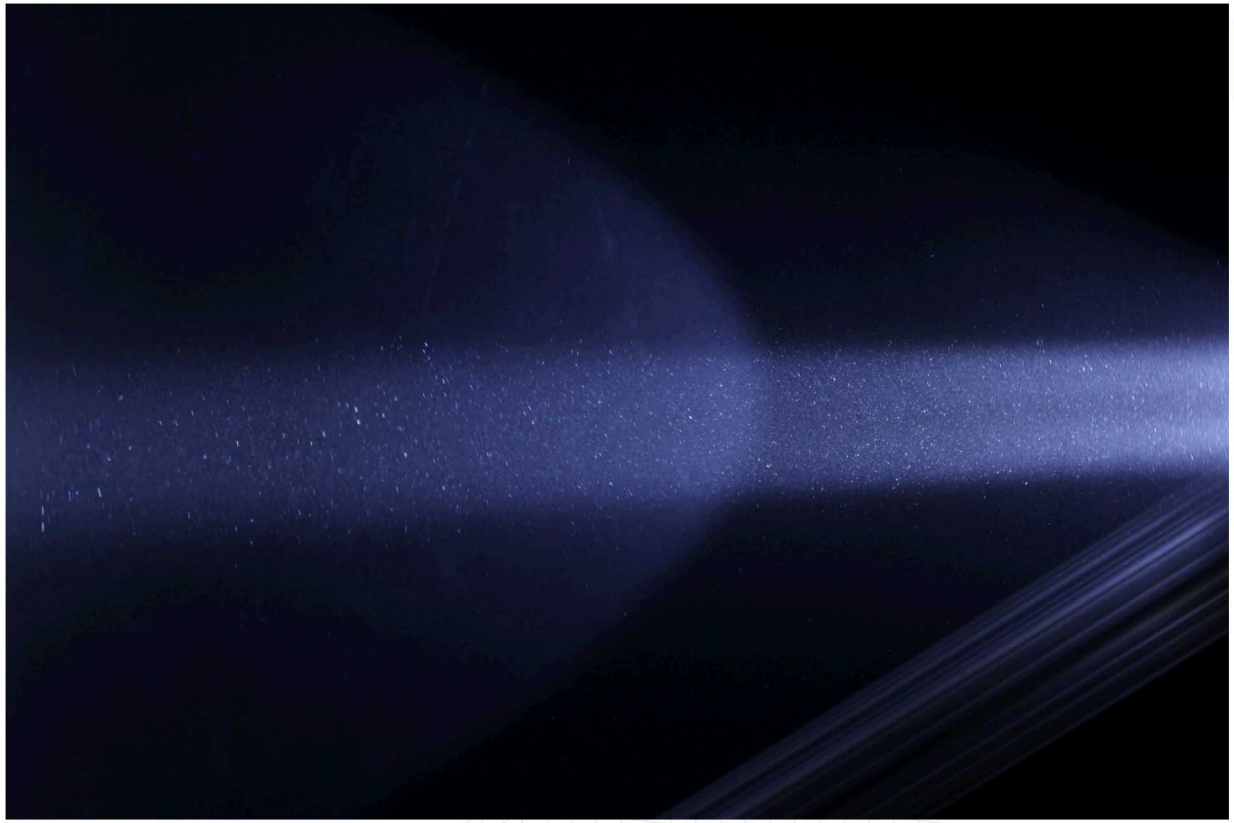
Moist air is cooled near the ground causing supersaturation

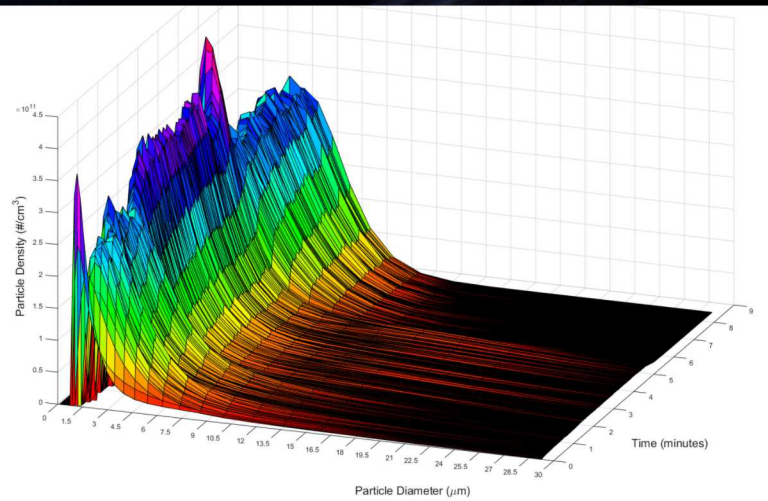
Advection Fog – More Prevalent in Coastal Climates

Atmospheric patterns play more of a role than radiation fog

Not all fog is the same







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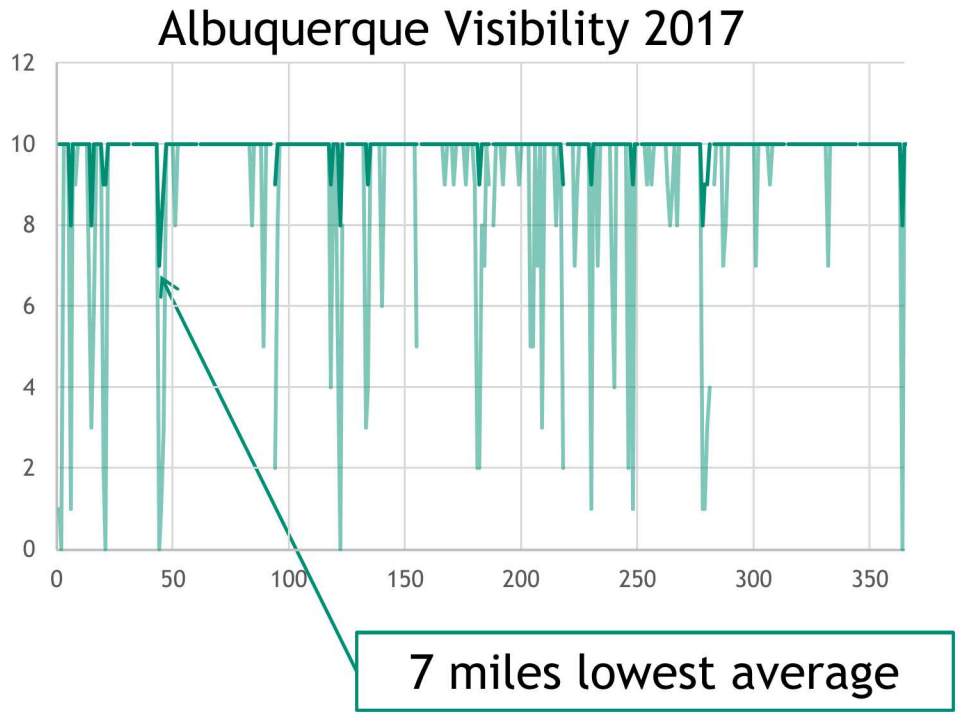
Weather in ABQ



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How do we control the weather?

The Sandia Fog Tunnel

Constructed in 2014

10’ x 10’ x 180’
- 6% grade (no pooling)

64 spray nozzles
- 3 selectable sections

Indoors
- Stable Environment

LDRD Funded improvements

Temperature Control

Plastic Sheeting

Roll Doors

Instrumentation (time correlated)

Visibility (MOR)

Particle Sizers

Temperature, Humidity

Class IV lasers

Positive Pressure Dry Boxes

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Measuring fog droplet distribution

- Malvern Spratec
  - Narrow separation
  - Inhalation cell
- Transmissometer
  - Transmission, T
  - Extinction coefficient β
  - Long distance
- Mie scattering theory
  - Wavelength dependent
  - Particle size dependent
- Products
  - Liquid water content, LWC
  - Droplet concentration Nd
  - Number of droplets N(d)
  - Meteorological optical range, MOR

Droplet

Nd

N(d)

MOR

Equivalent distances through MOR=100m (ICAO) CATIIIc fog

Example case	Fog facility MOR (m)	Target distance (m)	Equivalent Distance to ICAO CATIIIc
Passive Imaging Discussed in this Presentation			
Thick fog	3	9 m	300 m
Moderate fog	6	9 m	150 m
Thin fog	15	9 m	60 m
Full Length of Facility			
Thick fog	3	55 m	1833 m
Moderate fog	6	55 m	917 m
Thin fog	15	55 m	367 m

Capable of very long equivalent distances

(1) $$LWC = \frac{2\,\beta}{3\sum_i \frac{Q(d_i)\,v(d_i)}{d_i}}\rho_{water}$$

(2) $$N(d) = \frac{\mathrm{LWC}\,v(d)}{\frac{4\pi}{3}\left(\frac{d}{2}\right)^3}$$

$$MOR = \frac{-\ln(0.05)}{\beta}$$

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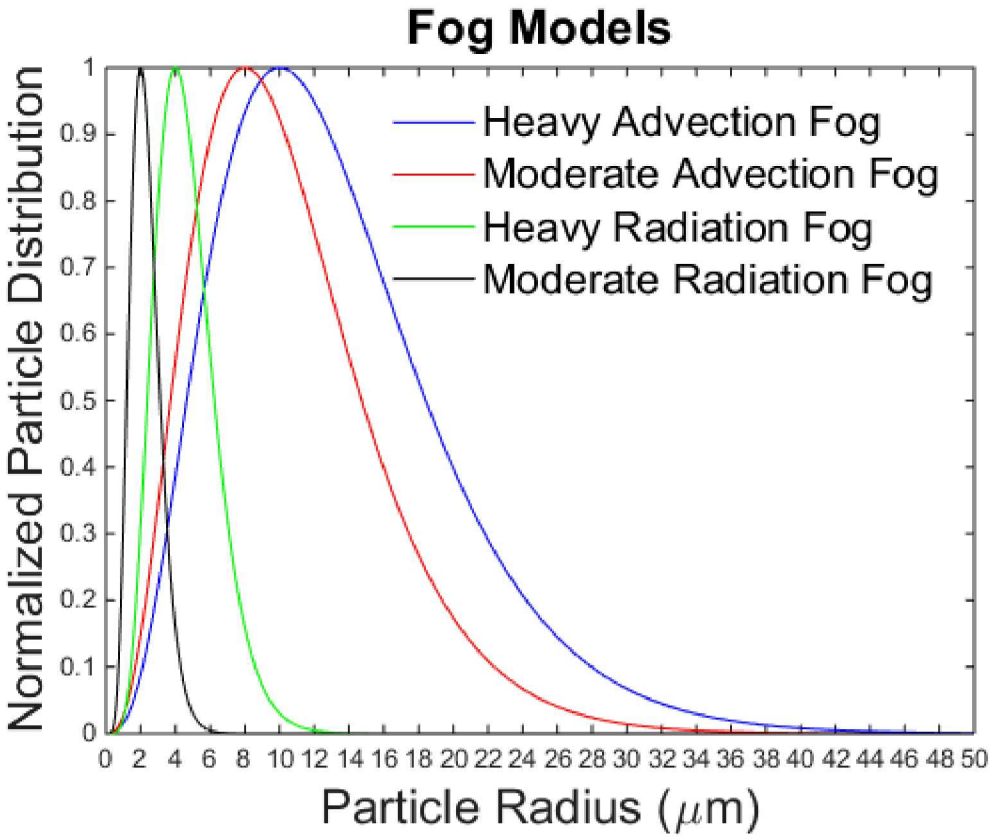
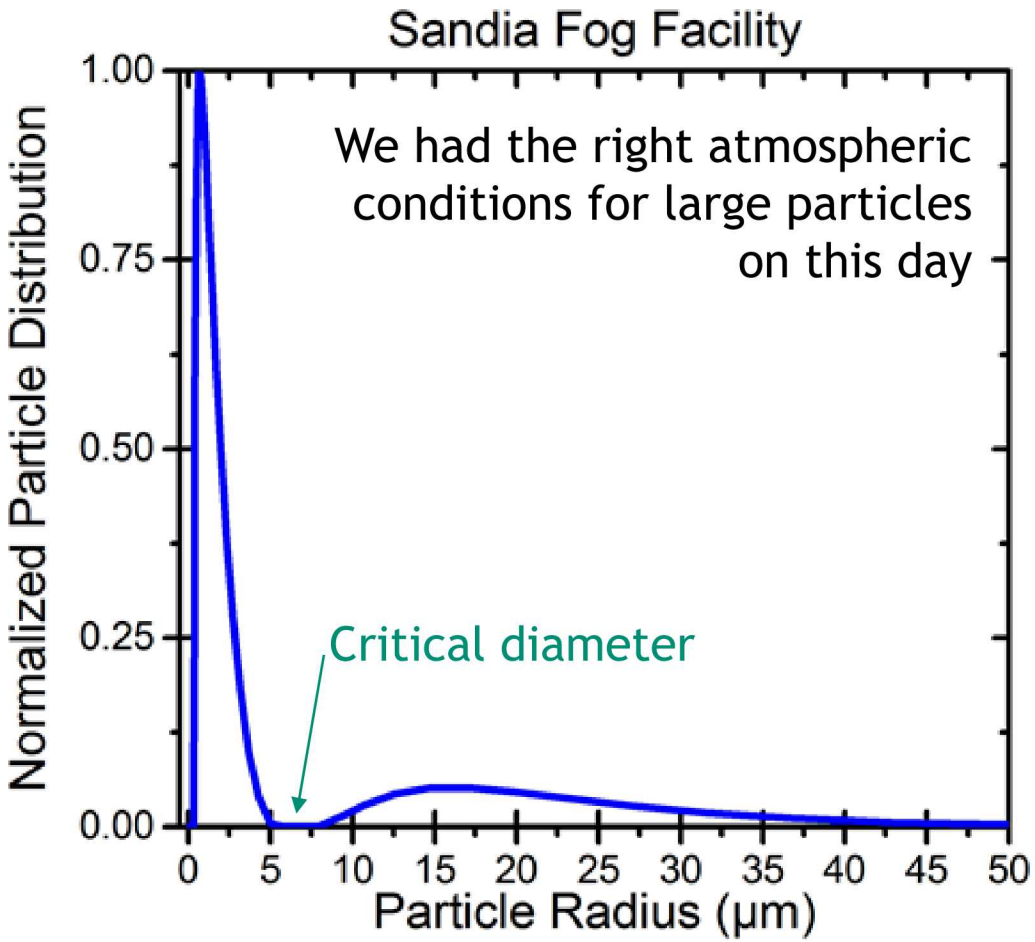
Developing and Characterizing Fog Analogs

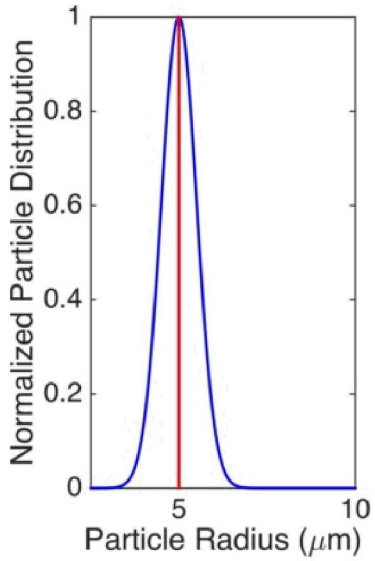
Modtran

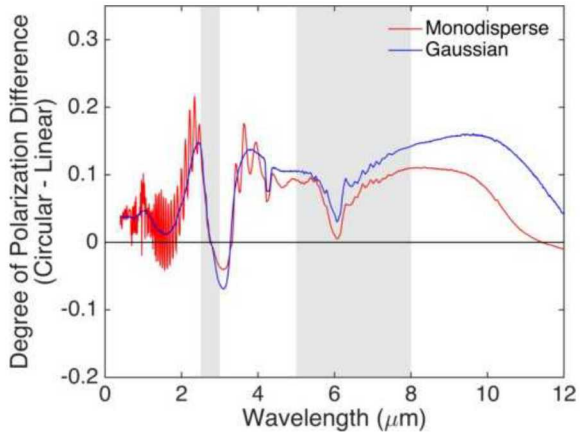


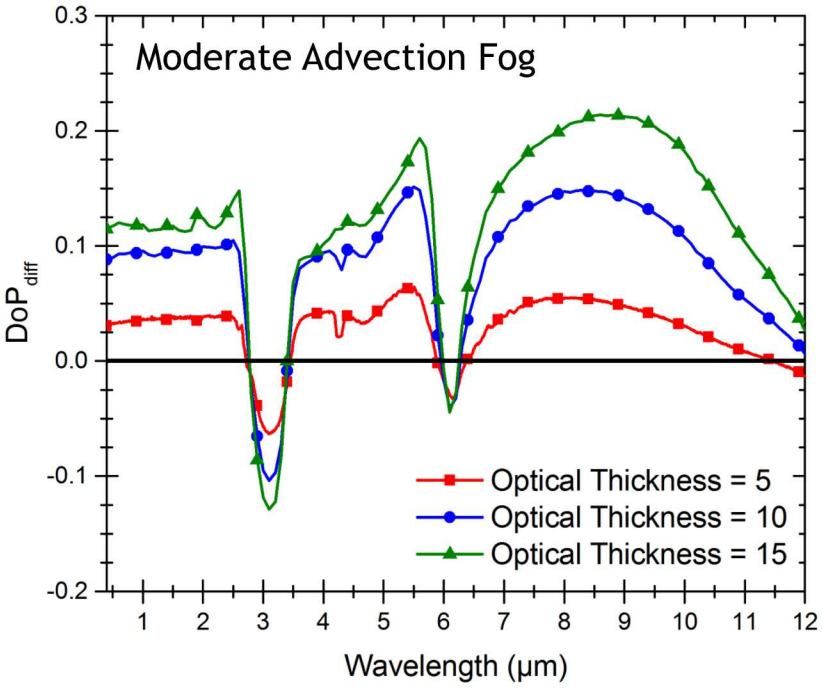


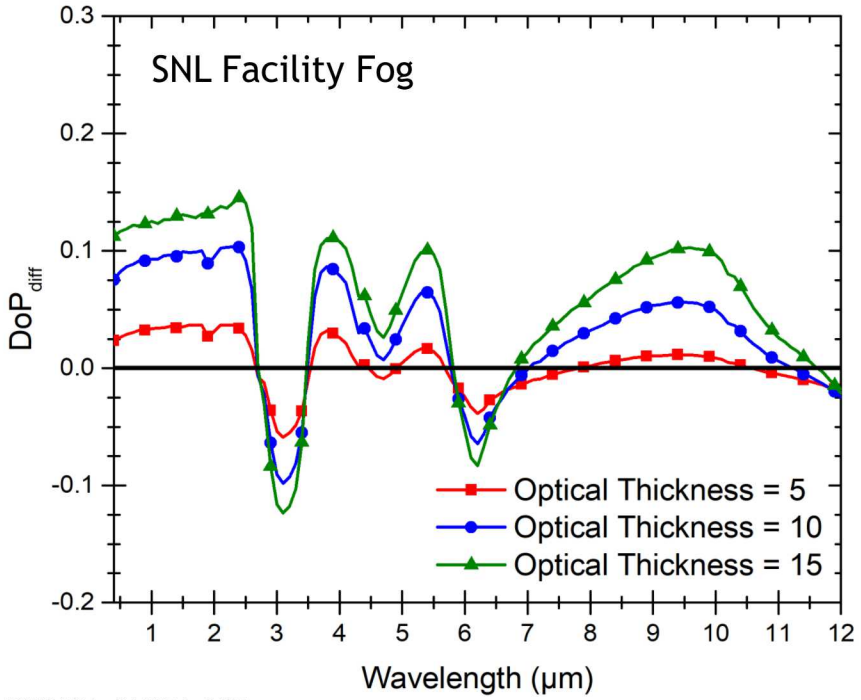
Simulation and modeling capability

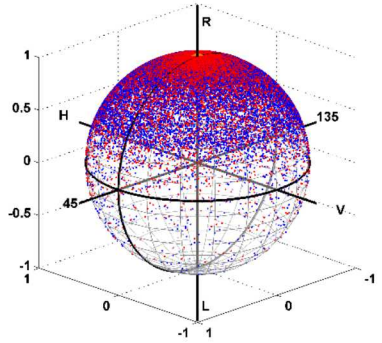
- Simulation can handle arbitrary fog distributions and predict performance of any fog at any optical wavelength
  - Results for various fog models and real-world particle size measurements (published in Applied Optics)
- Supports modeling polarization performance (full stokes)

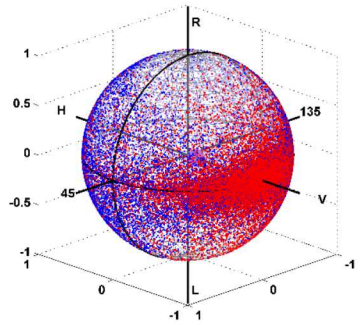


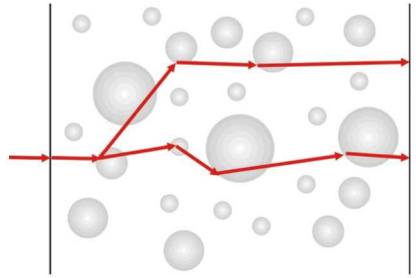






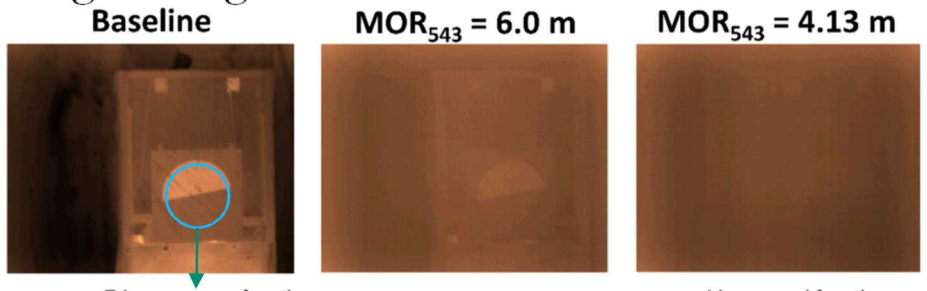


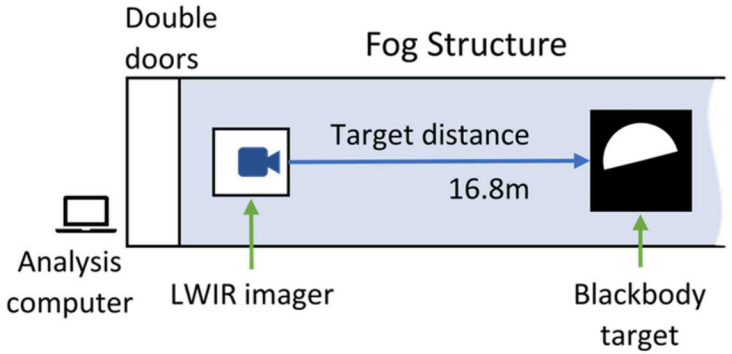


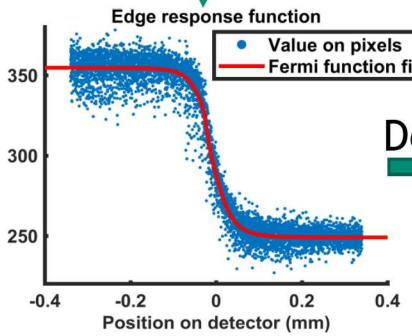


Measuring resolution degradation of passive long-wavelength infrared imagery in fog

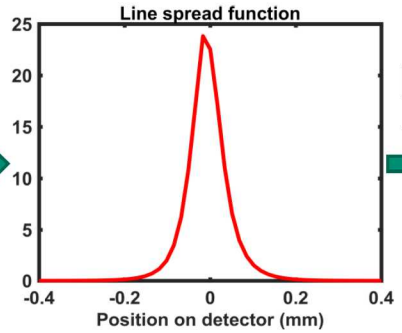
- Slant edge target to measure the resolution over a wide range of fog densities



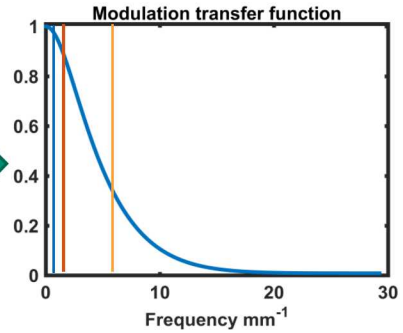




Derivative

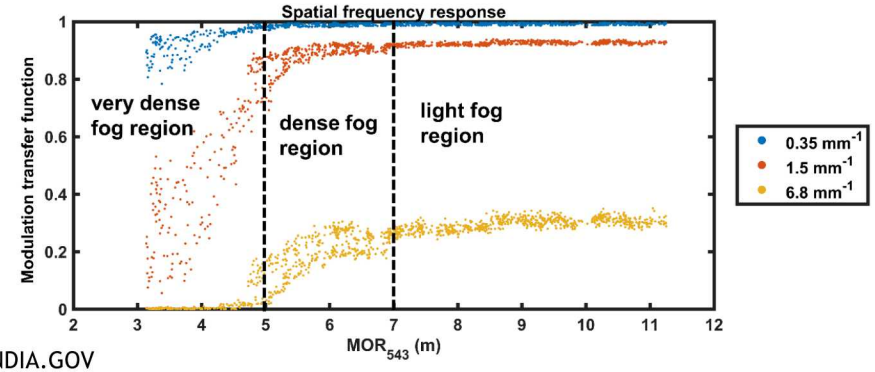


Fourier transform



Repeated for each frame during fog dissipation

Frequency dependent resolution degradation



"MEASURING RESOLUTION DEGRADATION OF LONG-WAVELENGTH INFRARED IMAGERY IN FOG" *OPTICAL ENGINEERING*

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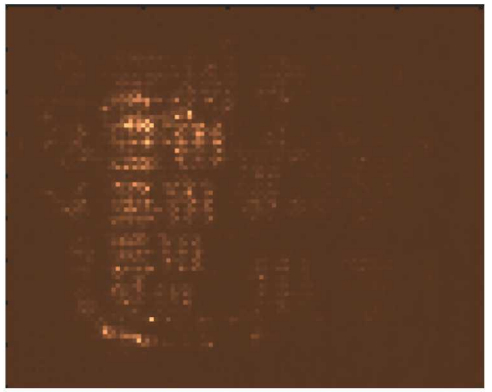
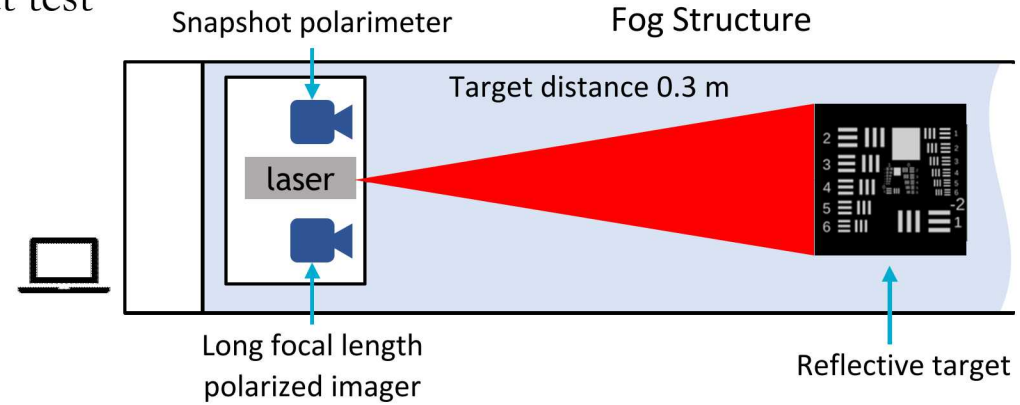
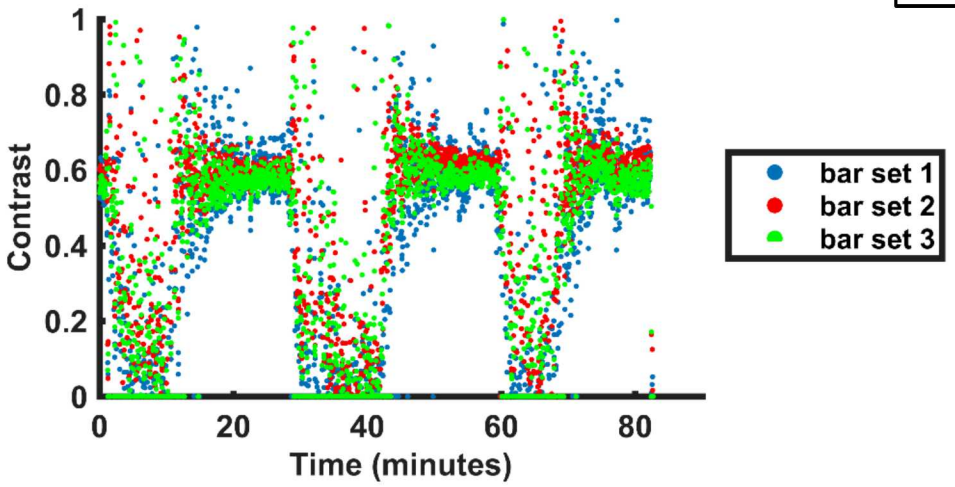
Active illumination of reflective target to measure polarizations effect on long-wavelength infrared resolution degradation caused by fog

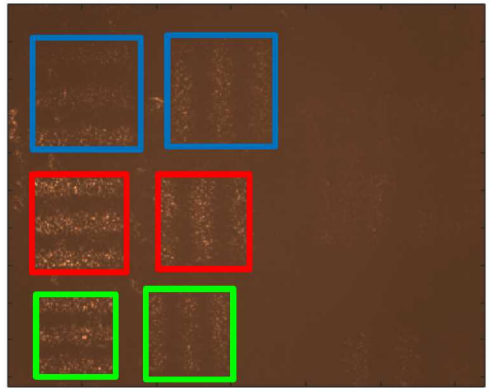
- Two instruments measuring simultaneously
  - Multiple polarization states simultaneous, low resolution
  - Polarizer same angle as laser, higher resolution
- Measuring contrast from bars of USAF1951 target
- Laser shuttered to measure background throughout test
- Data processing ongoing
  - difficultly measuring contrast with speckle



Fog Structure







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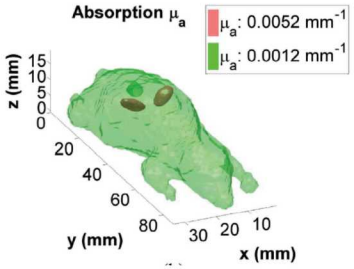
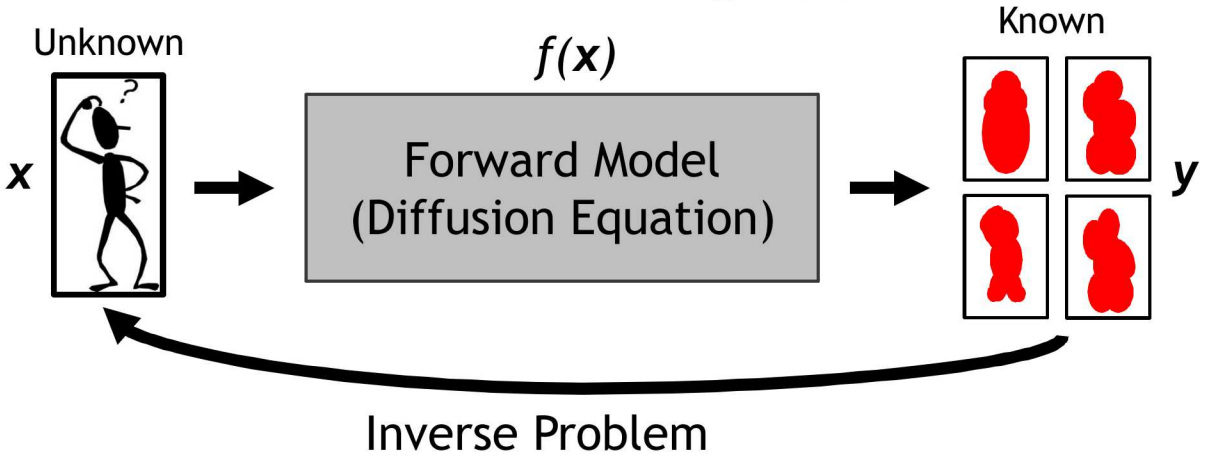
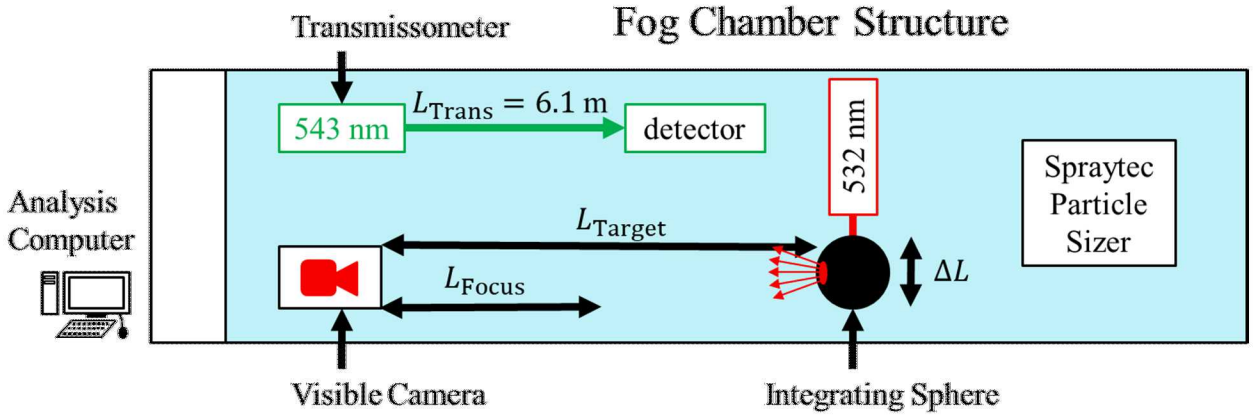
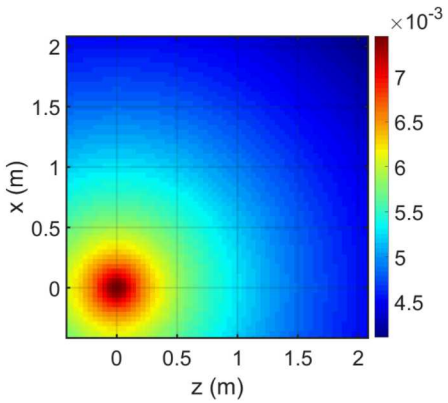
Diffusion equation – computational imaging

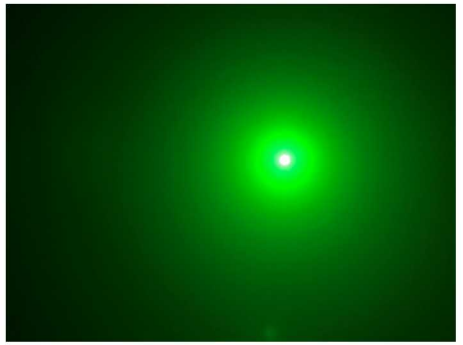
- These methods have been used for biomedical applications [1,2]
- Information **10 times deeper** in tissue
- Can employ inexpensive COTs sources and detectors
- **Key question: will this work for fog with Brownian motion?**











[1] B. Z. Bentz, A. V. Chavan, D. Lin, E. H-R Tsai, and K. J. Webb, *Applied Optics* 55(2), 2016
[2] B. Z. Bentz, D. Lin, and K. J. Webb, *Physical Review Applied* 10, 2018

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Thank You

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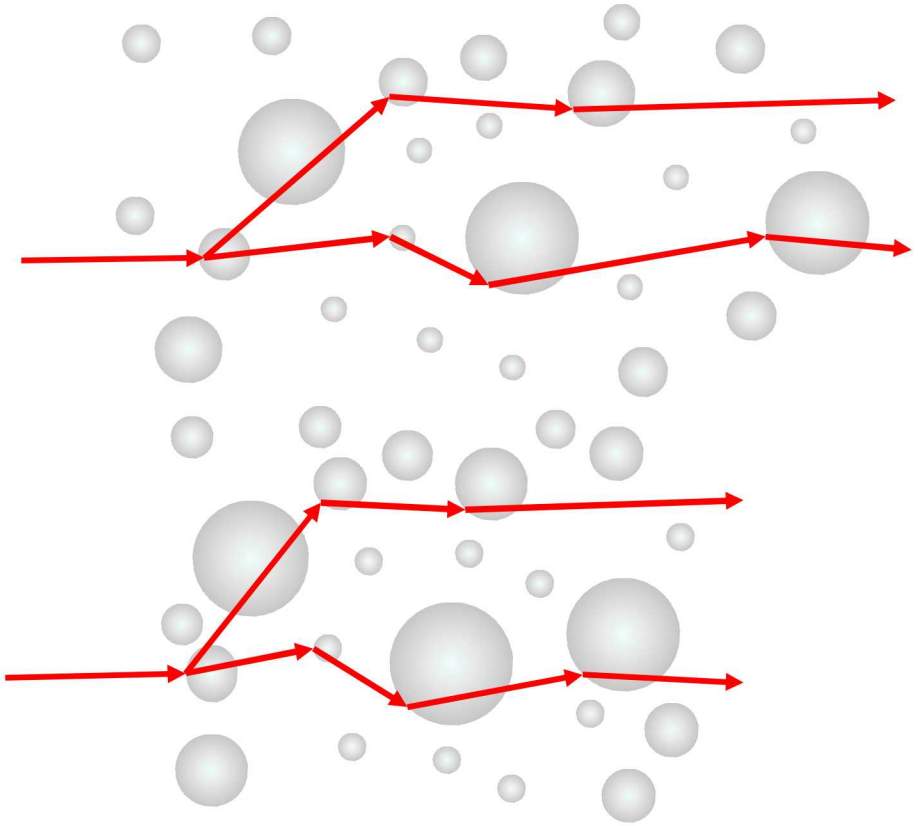
Thick fog for long distance equivalent

- Scattering probability
  - Probability of hitting a droplet
- Beer-Lambert Law
  - Optical Thickness
  - Short distance through thick fog
  - longer distance through thinner fog
- Very dense particle concentration



Equivalent distances through MOR=100m (ICAO) CATIIIc fog

Example case	Fog facility MOR (m)	Target distance (m)	Equivalent Distance to ICAO CATIIIc
Passive Imaging Discussed in this Presentation			
Thick fog	3	9 m	300 m
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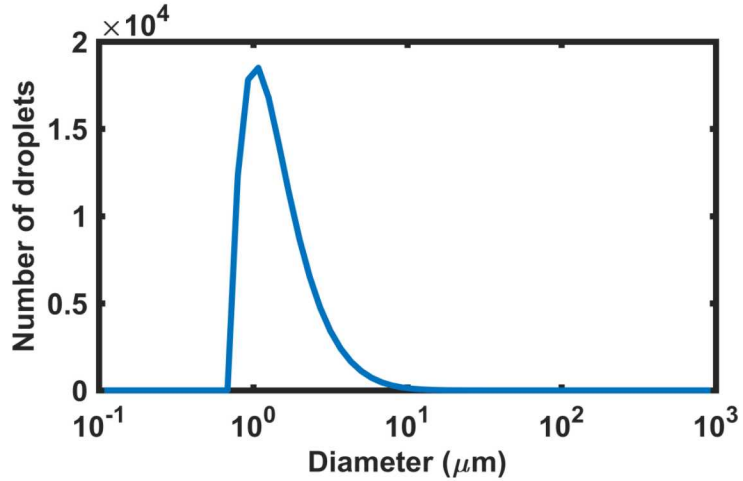
Capable of very long equivalent distances



Brian J. Redman, et al., "Measuring resolution degradation of long-wavelength infrared imagery in fog," Opt. Eng. 58(5) 051806 (2019)

Defining Visibility

Visibility
a measure of the distance at which an object or light can be clearly discerned. It is reported within surface weather observations and METAR code either in meters or statute miles, depending upon the country.

Wikipedia

Visibility
a) the greatest distance at which a black object of suitable dimensions, situated near the ground, can be seen and recognized when observed against a bright background;
b) the greatest distance at which lights of 1,000 candelas can be seen and identified against an unlit background.

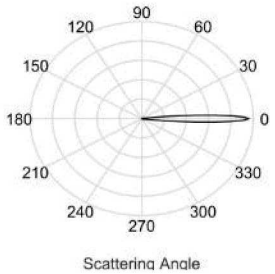
International Civil Aviation Organization

Visibility
the length of path in the atmosphere required to reduce the luminous flux in a collimated beam from an incandescent lamp, at a color temperature of 2700 K, to 5 per cent of its original value, the luminous flux being evaluated by means of the photometric luminosity function of the International Commission on Illumination. For aeronautical purposes, the surface MOR is measured at a height of 2.5 m above the surface.

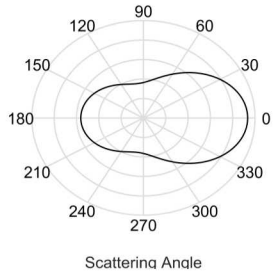
World Meteorological Organization

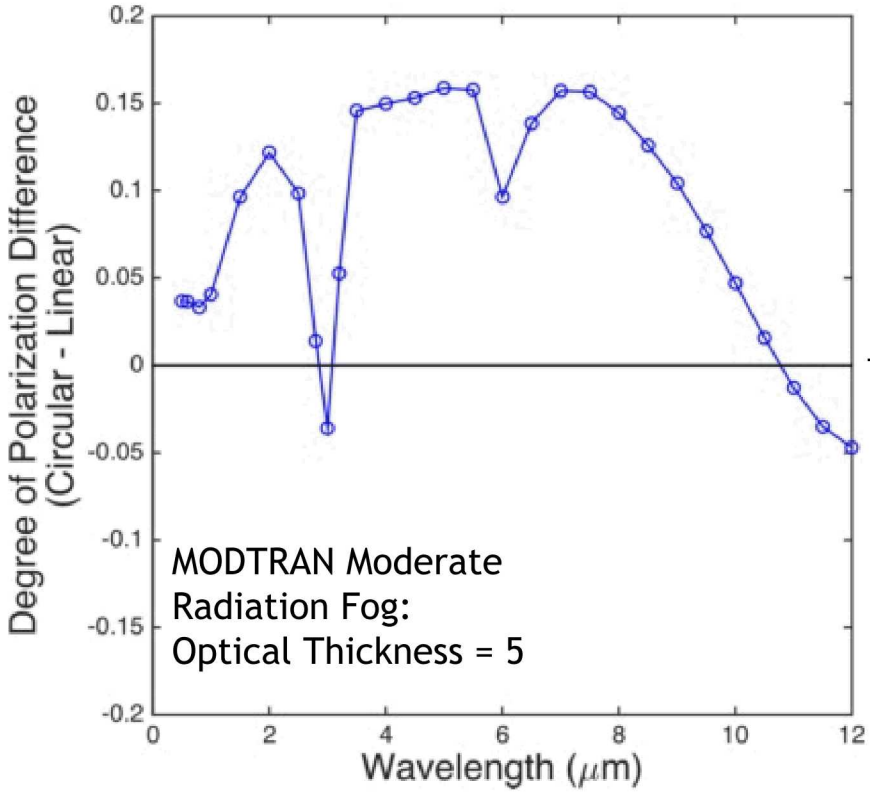
Why Fog Particle Size Matters

Forward scattering



Isotropic scattering



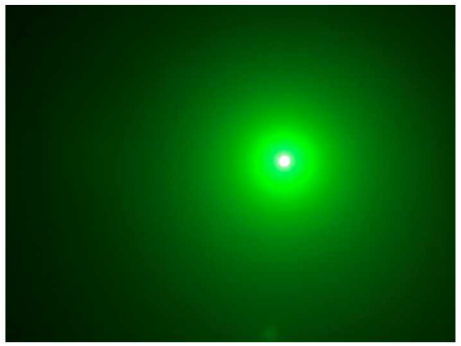


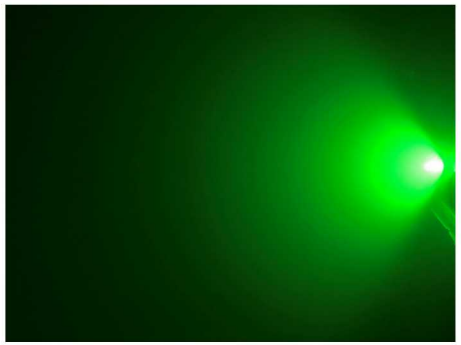
Circular Better

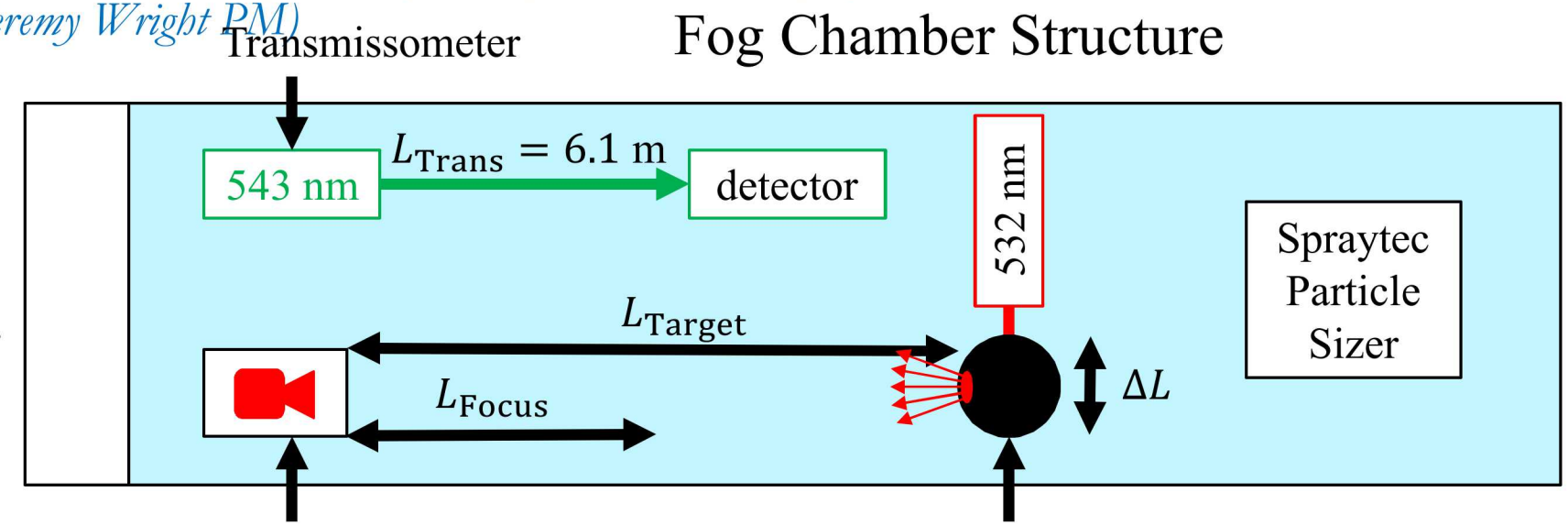
Linear Better

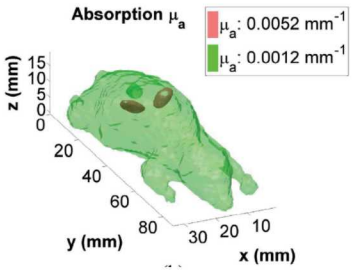
Future Work

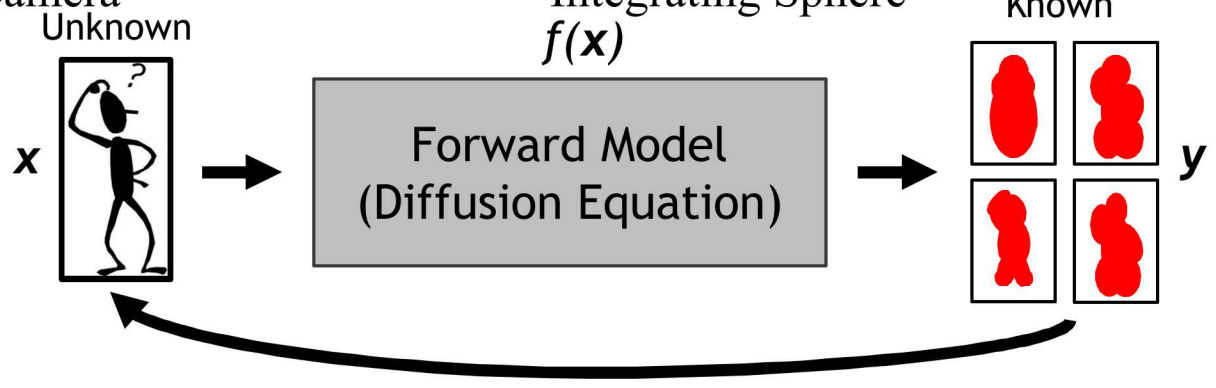
SAIL LDRD FY19 – Diffuse Imaging in Fog "Utilizing Highly Scattered Light for Intelligence through Aerosols" (Brian Bentz PI / Jeremy Wright PM)











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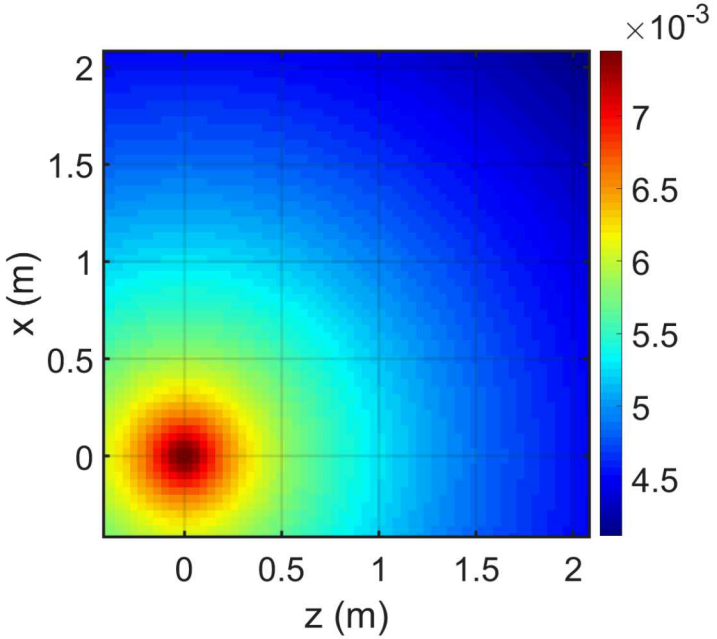
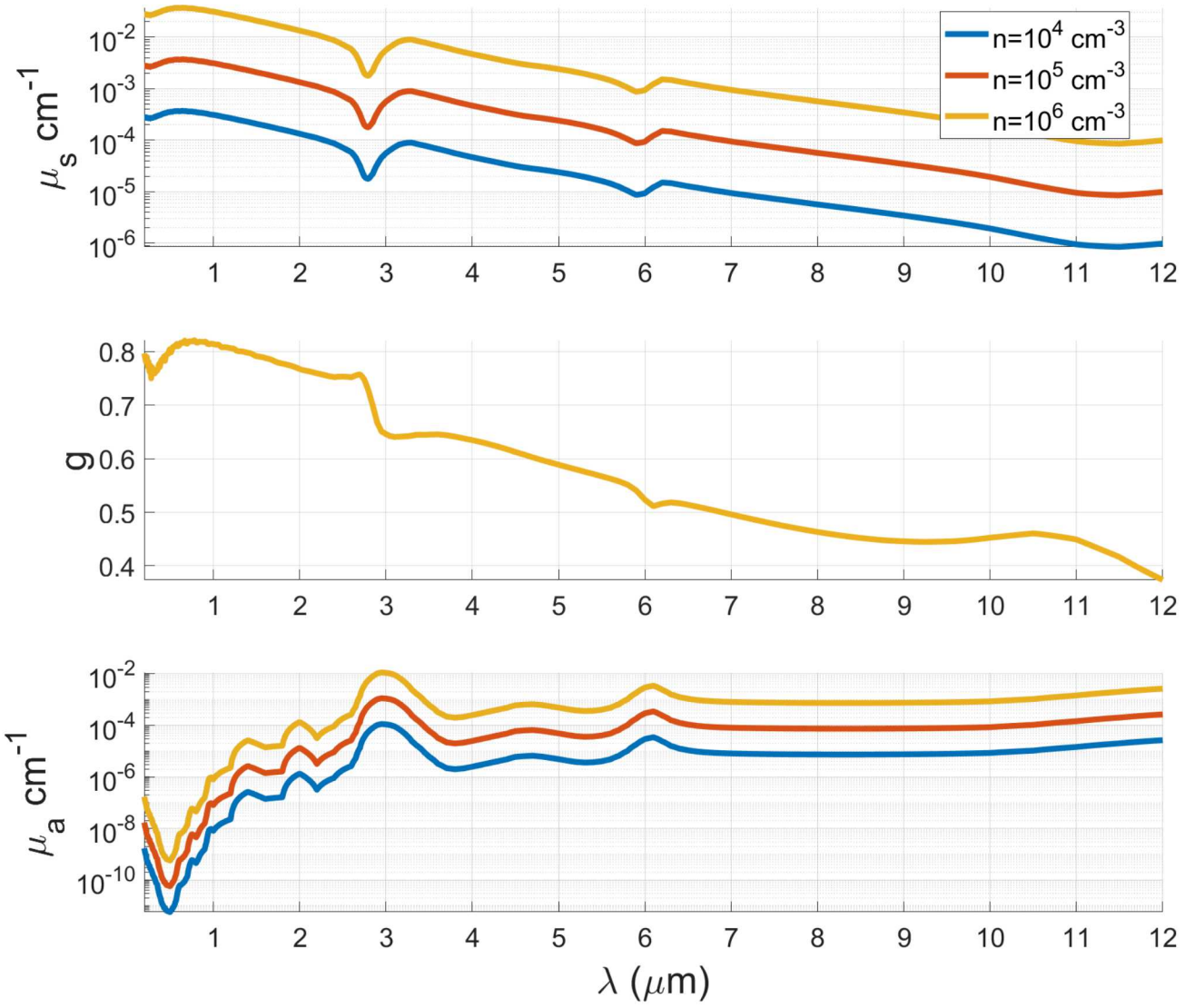
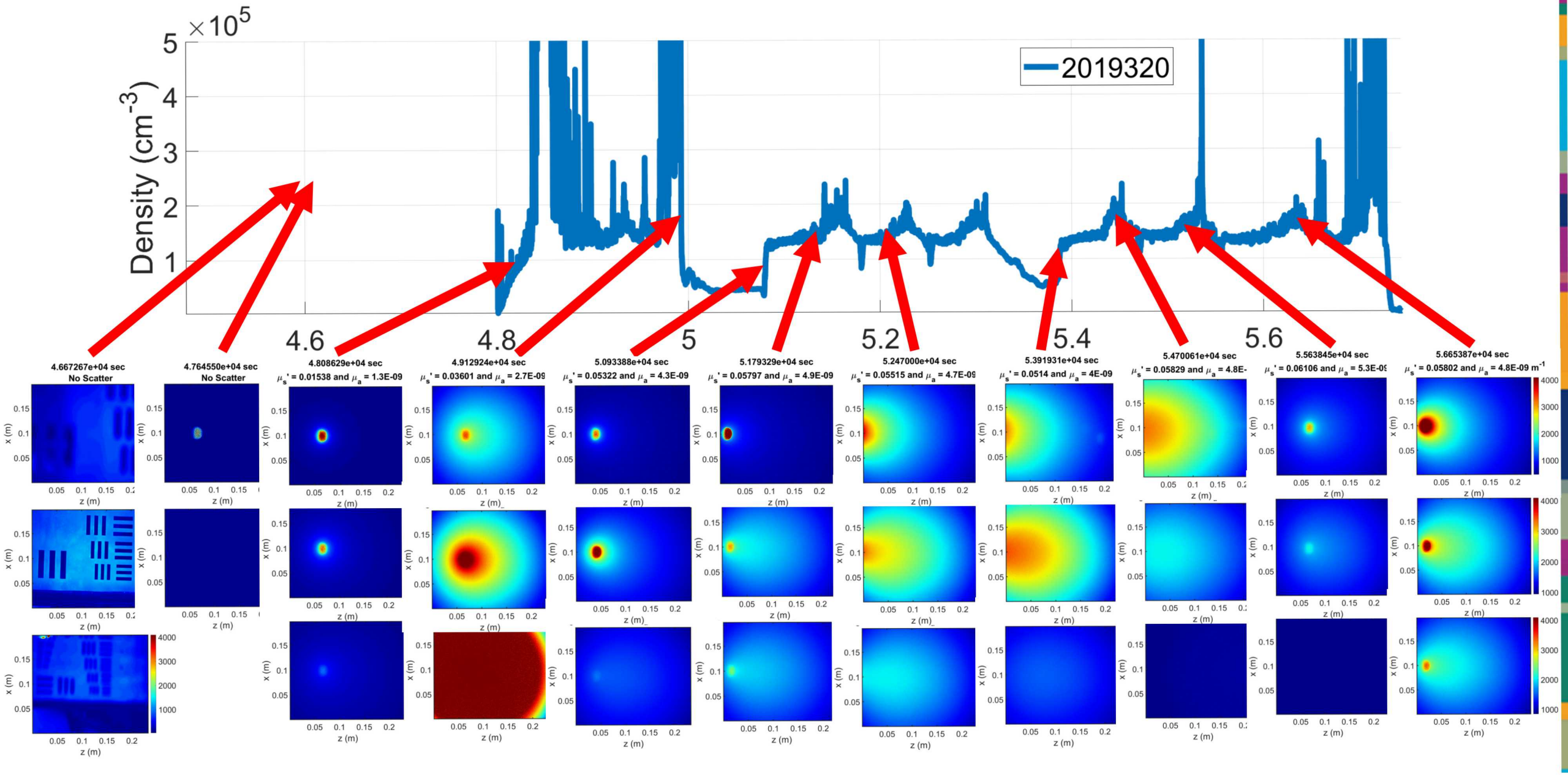
- $\mu_s = \sigma_s n_s$ is the scattering coefficien (cm^{-1})
- g is anisotropy (mean cosine of the scattering angle)
- $\mu_a = \sigma_a n_a$ is the absorption coefficient (cm^{-1})





Initial Experimental Results

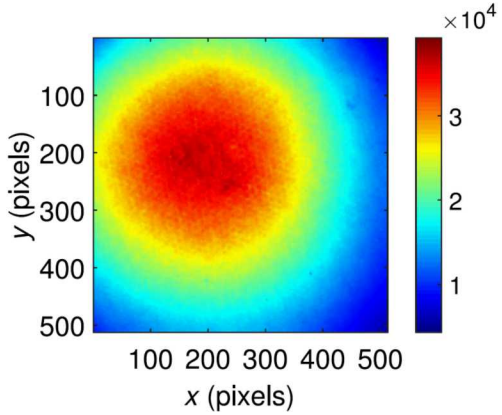


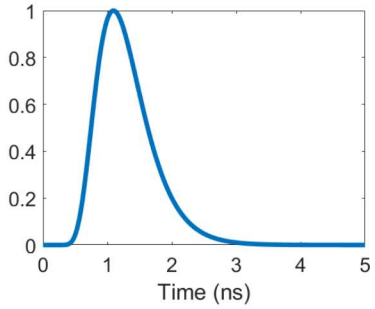
Diffusion Model

- In a scattering medium the photon flux density ϕ (W/m^2) satisfies [1]

$$\frac{1}{c}\frac{\partial}{\partial t}\phi(\boldsymbol{r},t) - D\nabla^2\phi(\boldsymbol{r},t) + \mu_a\phi(\boldsymbol{r},t) = S(\boldsymbol{r},t)$$

- D is the diffusion coefficient, μ_a is the absorption coefficient, and S is the source term
- Approximation to the radiative transfer equation (RTE)
- Solutions can be computed faster than with the RTE
- There is evidence that the RTE and diffusion approximation hold in clouds [2]





[1] M. S. Patterson, B. Chance, and B. C. Wilson, *Applied Optics* 28(12), 1989
[2] A. B. Davis and A. Marshak, *Journal of the Atmospheric Sciences* 59(18), 2002
[3] B. Z. Bentz, D. Lin, and K. J. Webb, *Physical Review Applied* 10, 2018