SAND2020-4305C

Characterizing Fog at the Sandia Fog Facility

PRESENTED BY

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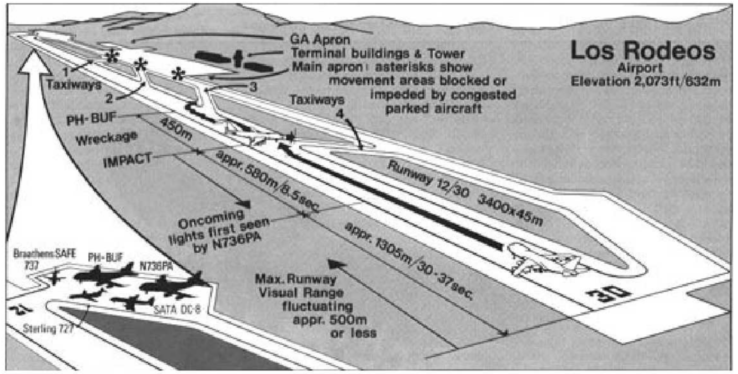
Why do we care about fog?

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

30 to 40 vehicles crash on stretch of foggy Texas interstate Dec 19, 2018



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

Calabasas Helicopter Crash – 9 dead January 26, 2020

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

Huffpost.com

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

- 95-100% RH
- >1km visibility

F. Fuchs

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

R. Montoya

The most common types of fog

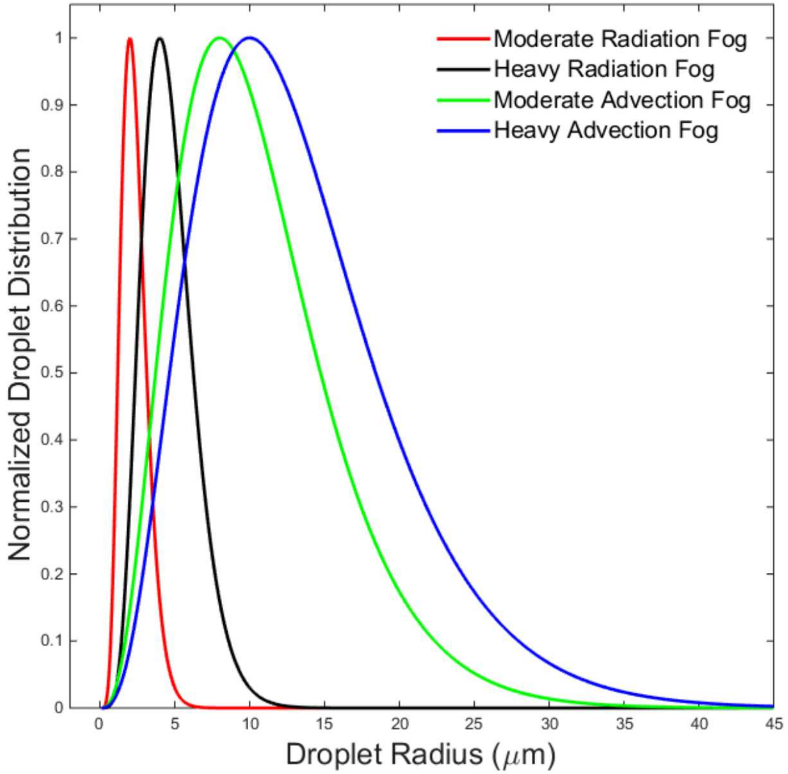
Radiation Fog

Air cooling until the air temperature approaches the dew point.

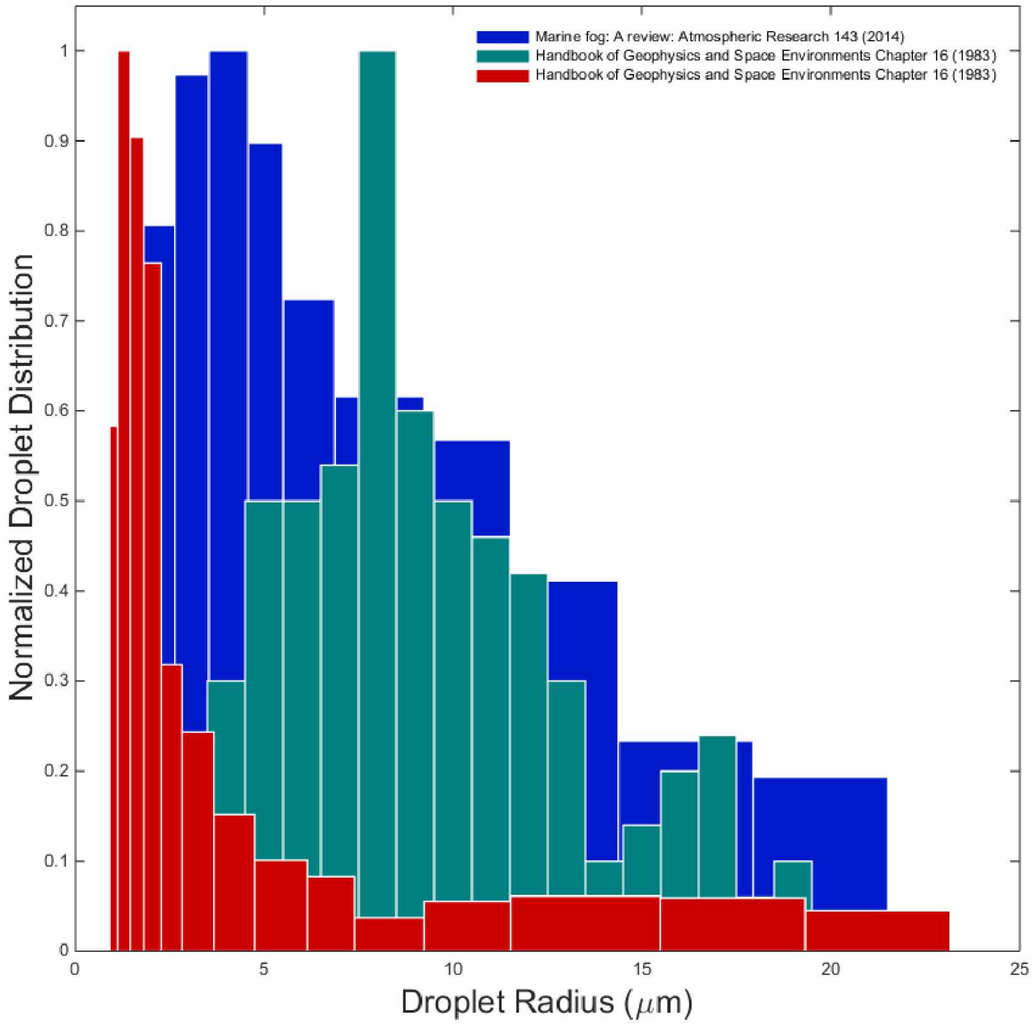
Advection Fog

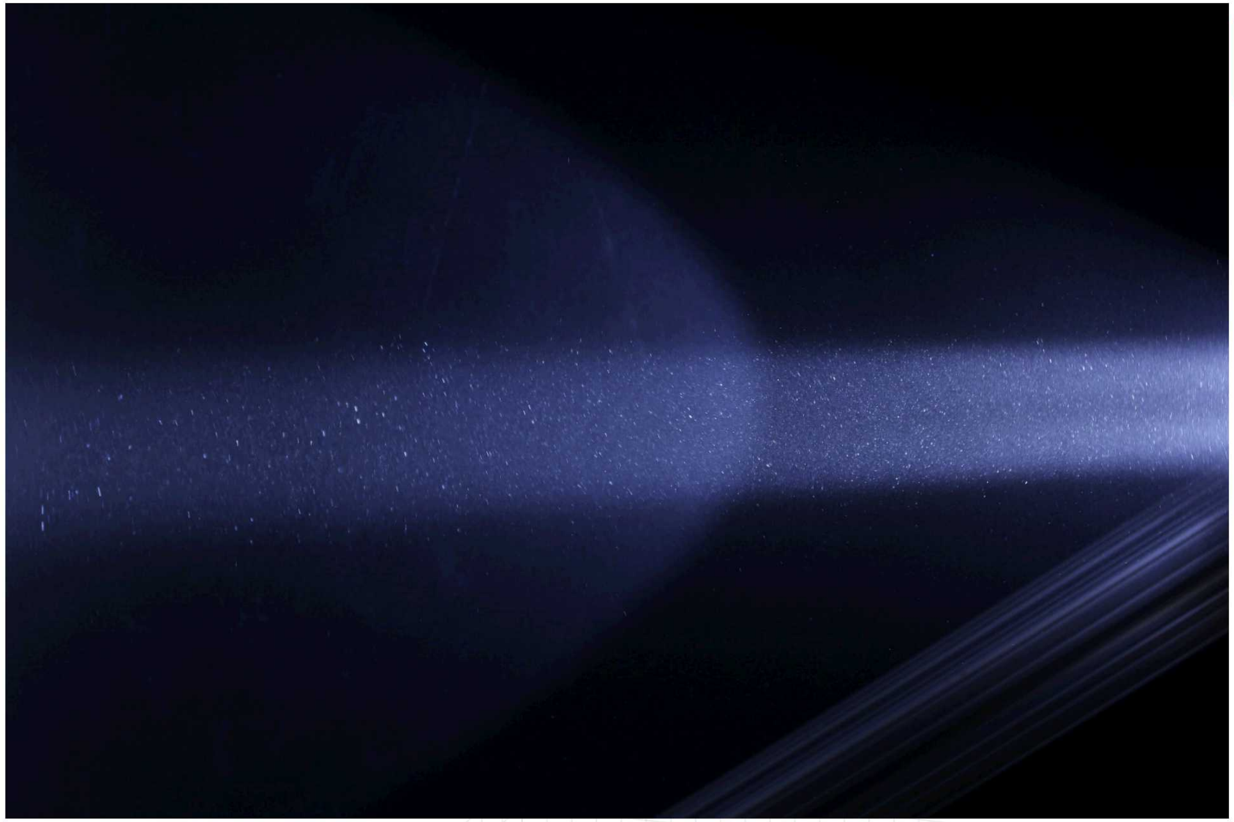
Mixing of air masses with different temperatures and/or humidities.

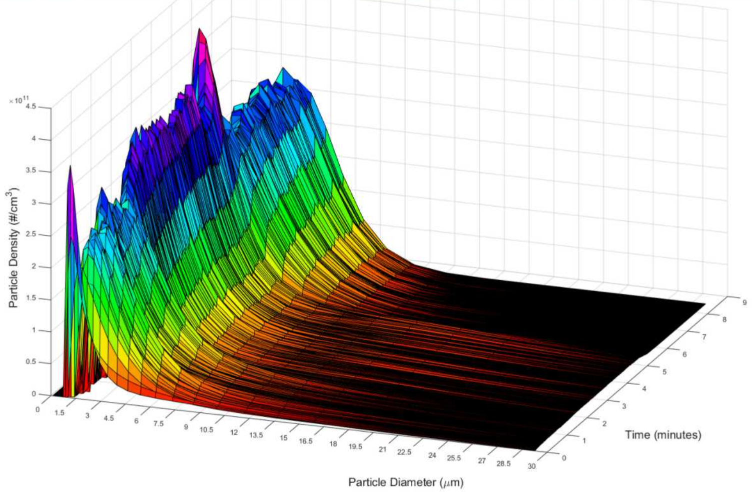
MODTRAN Fog Models



Not all fog is the same







History of Droplet Size Measurements

- 1925 **Kohler** estimated droplet size using freezing wires and frozen droplets and a corona estimation. “His deductions as to the size… …are therefor the variations of the predominant size with time rather than an instantaneous distribution…”

- 1931 **Statton and Houghton** observed that the transmission of light through fog depended on the particle size distribution and the density.

- **Due to experimental setup particles less than 2µm were not identifiable!**

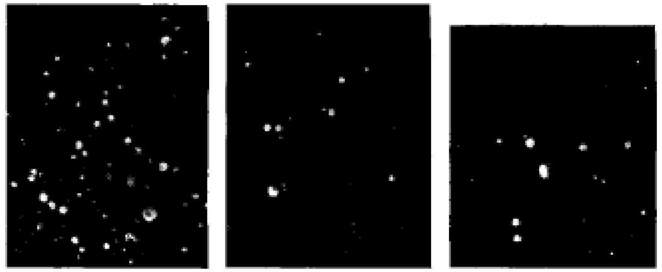
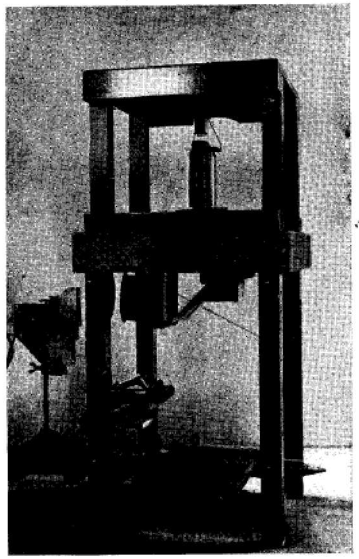


Fig. 3. Photomicrographs of fog particles.



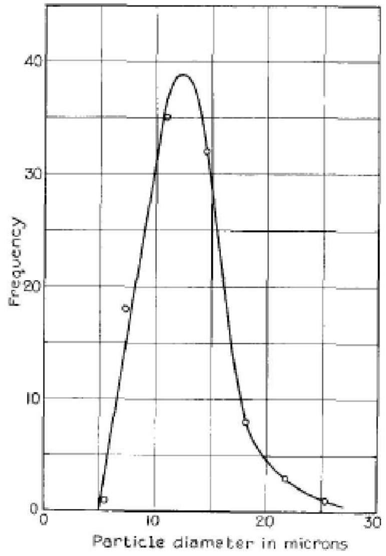


Fig. 4. Size distribution of fog particles at 11:00 A.M. on October 5, 1931. Wind S-10, Baro. 30.15″, Temp. 66°F.

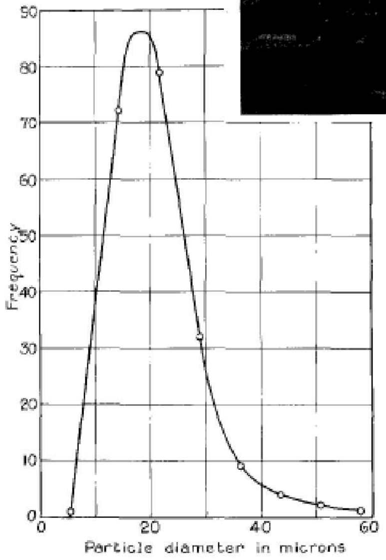
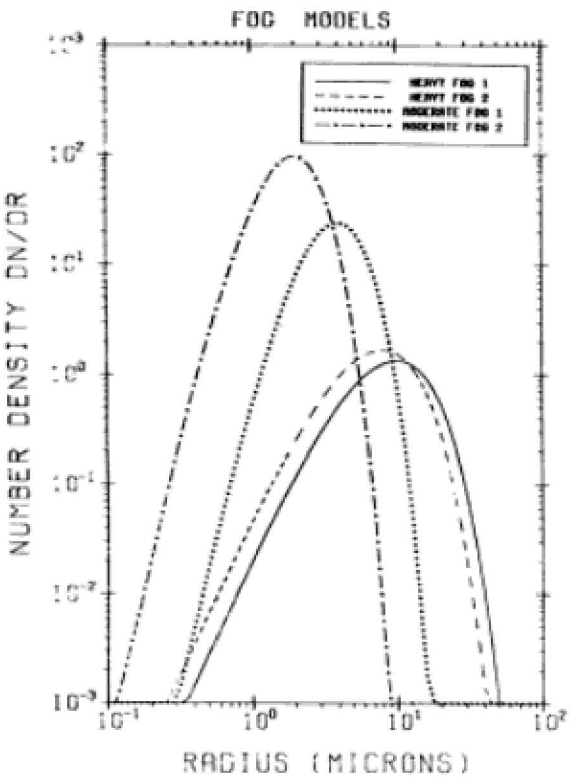
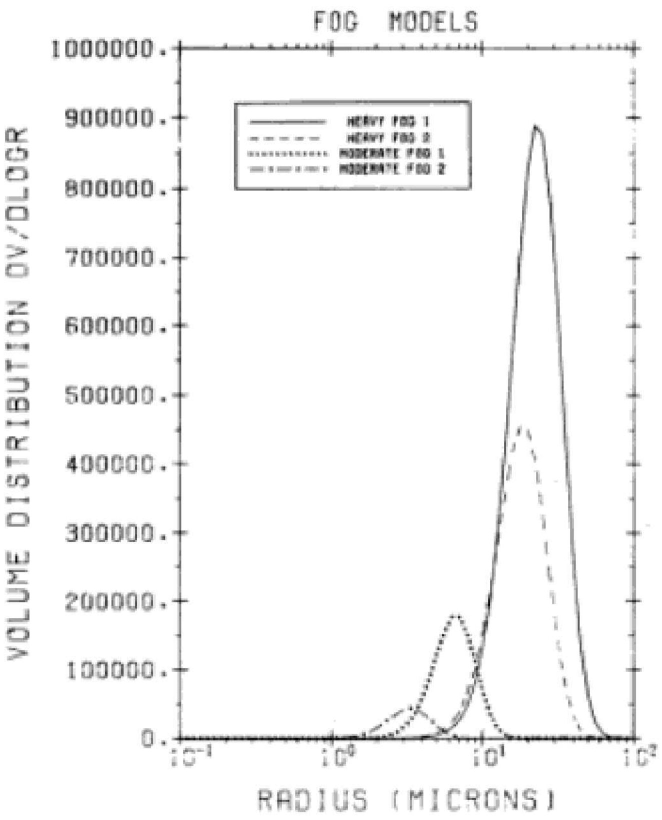


Fig. 5. Size distribution of fog particles at 9:00 A.M. on November 20, 1931. Wind N-7, Baro. 30.50″, Temp. 52°F.

Fog Particle Sizes Shettle and Fenn





$$\frac{dN}{dr} = n(r) = A\, r^{\alpha} \exp(-b r^{\gamma})$$

Models for the Aerosols of the Lower Atmosphere and the Effects of Humidity Variations on Their Optical Properties

ERIC P. SHETTLE
ROBERT W. FENN

"To represent the range of the different types of fog, we use the fog models presented by Silverman and Sprague, [65] following the work of Dyachenko. [66]"

Table 7. Size Distribution Parameters of the Fog Models

Type of Fog	Model	A	α	b	γ	r_{mode} (μ)	$N_o(cm^{-3})$
Advection Fog	1	0.06592	3	0.3	1	10.0	20
	2	0.027	3	0.375	1	8.0	20
Radiation Fog	3	2.37305	6	1.5	1	4.0	100
	4	607.5	6	3.0	1	2.0	200

Shettle, Eric P., and Robert W. Fenn. *Models for the aerosols of the lower atmosphere and the effects of humidity variations on their optical properties*. Vol. 79. No. 214. Air Force Geophysics Laboratory, Air Force Systems Command, United States Air Force, 1979.

Garland - Some fog droplet size distributions obtained by an impaction method

"…revealed large numbers of small droplets which were not visible under phase contrast. In about one third of the fogs studied these droplets, *smaller than 2 μm diameter*, made a large contribution to the optical extinction coefficient."

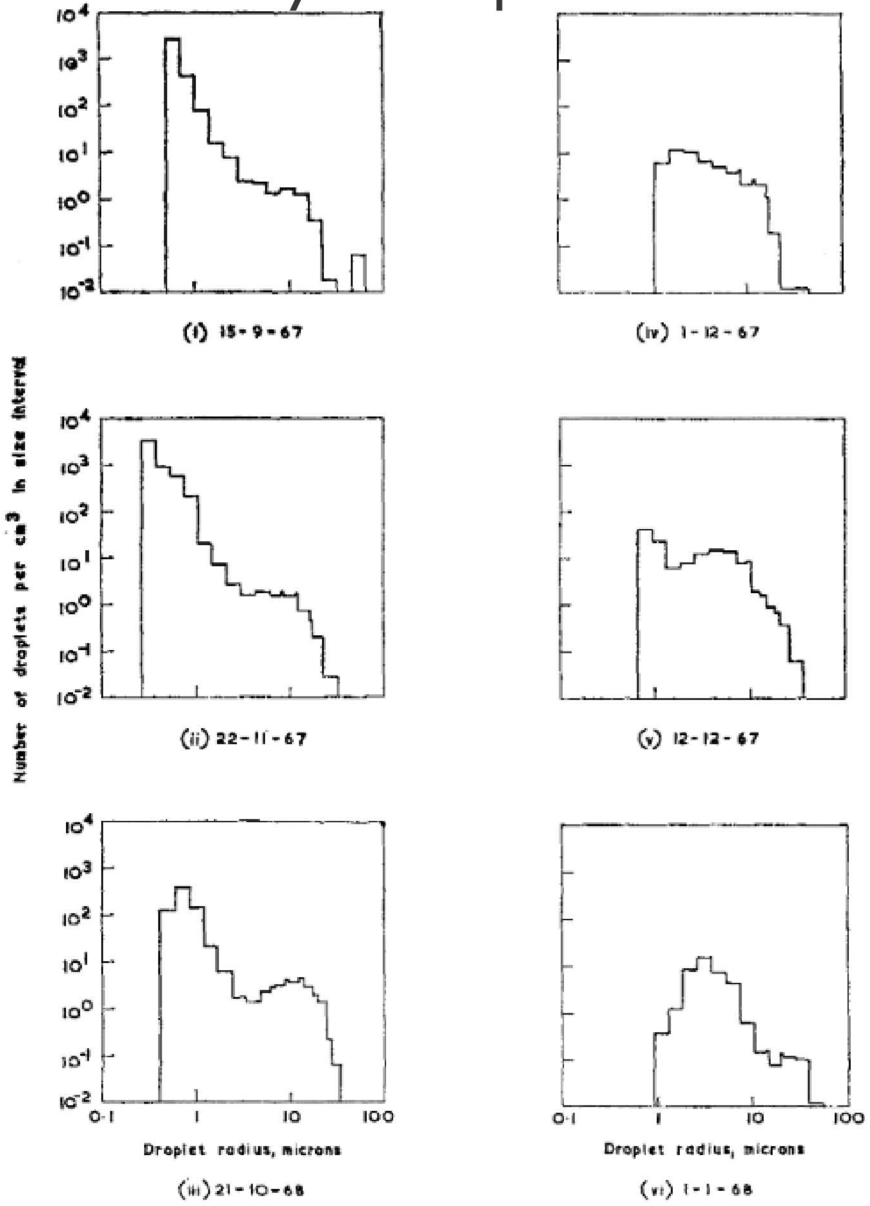
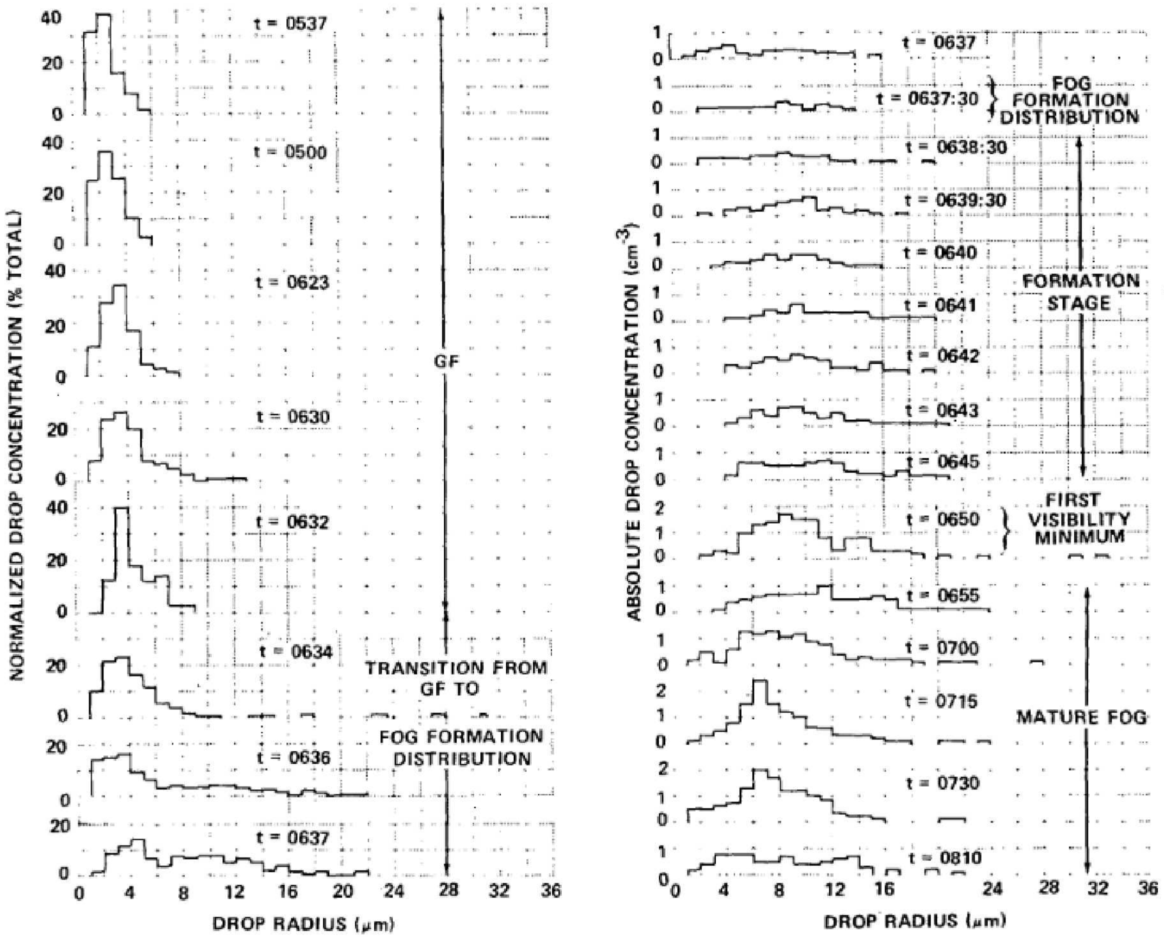


Figure 3. Examples of fog droplet size distributions.

Garland, J. A. "Some fog droplet size distributions obtained by an impaction method." *Quarterly Journal of the Royal Meteorological Society* 97.414 (1971): 483-494.

The Life Cycle of Valley Fog



NOTE: DATA OBTAINED AT 0637 ARE PRESENTED IN NORMALIZED AND ABSOLUTE FORM FOR COMPARISON.

FIG. 1. Drop size distributions for 2 September 1970.

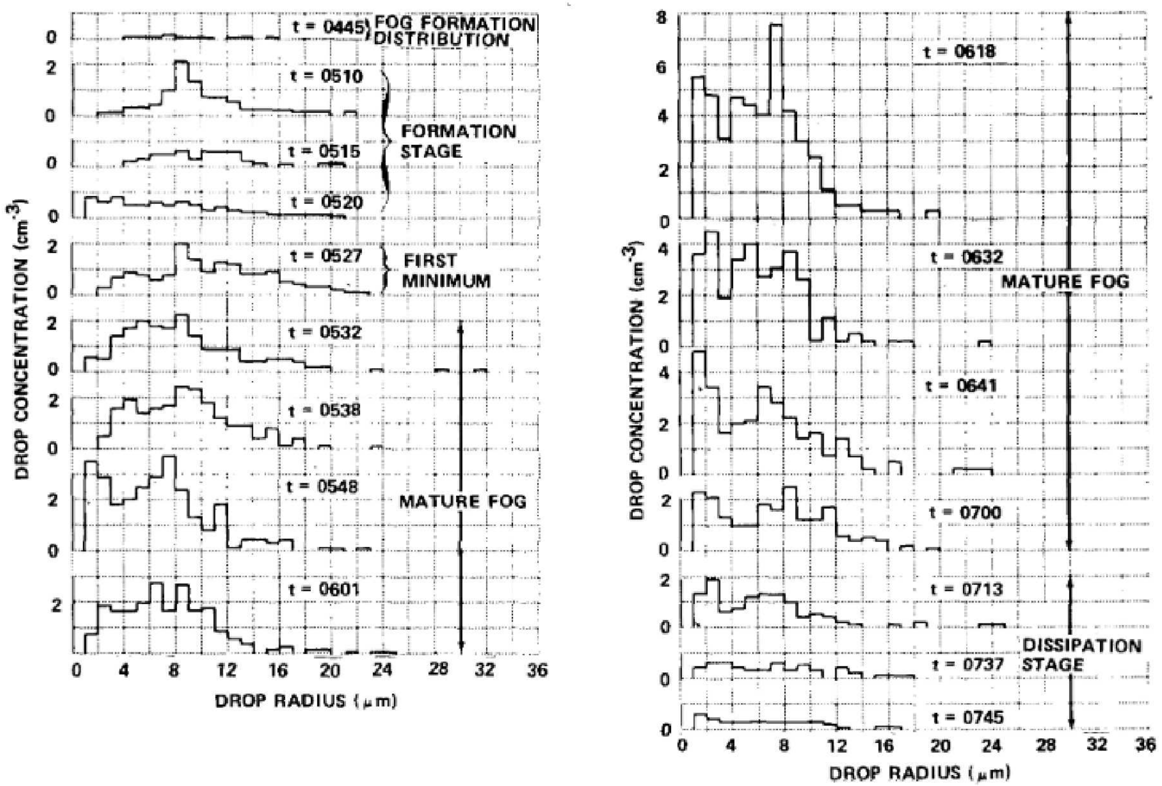


FIG. 2. Drop size distributions for 25 August 1970.

Pilié, R.J., E.J. Mack, W.C. Kocmond, W.J. Eadie, and C.W. Rogers, 1975: [The Life Cycle of Valley Fog. Part II: Fog Microphysics.](#) *J. Appl. Meteor.*, **14**, 364–374

Köhler theory

$$S_{v,w} = \frac{e_a}{e_{sat,w}} = exp\left[\frac{2M_w\sigma_{s/a}}{RT\rho_w a} - \frac{v\Phi_s m_s M_w/M_s}{(4\pi a^3\rho_s/3)\ -\ m_s}\right]$$

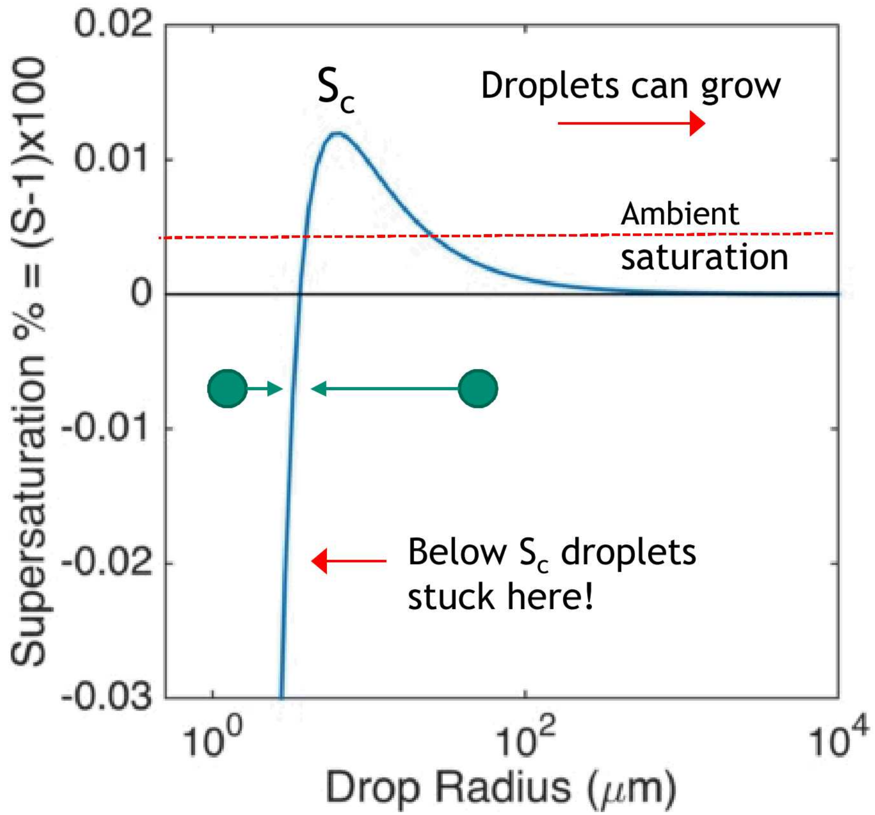
Curvature term

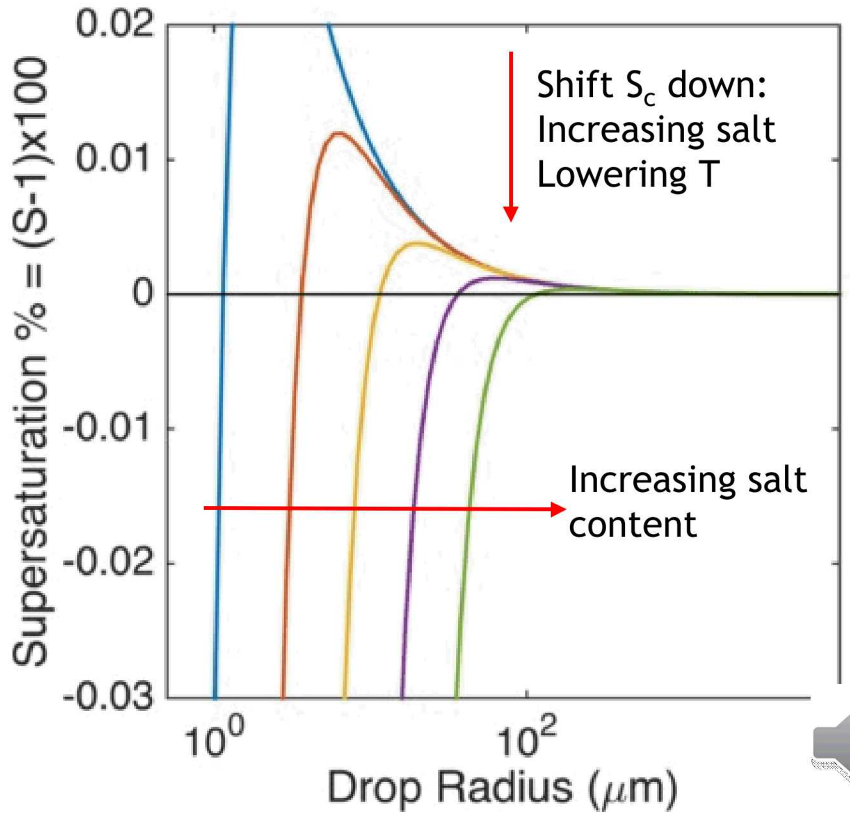
Solute term

Water vapor condenses and from liquid droplets

Activated/Non-activated

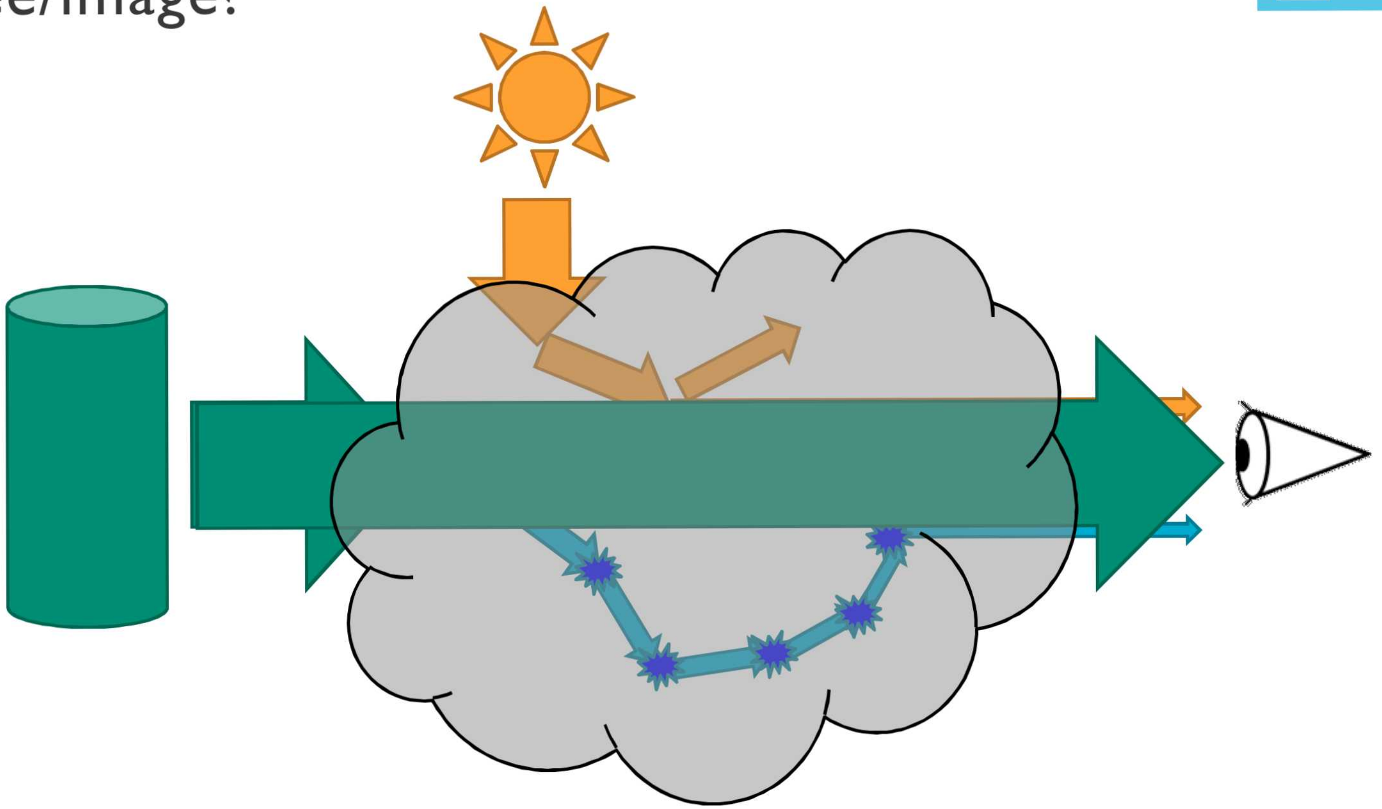
Given a supersaturation value a particle is in
- Equilibrium
- Growth



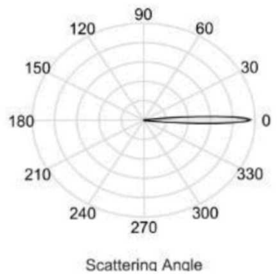


How do particles effect how we see/image?

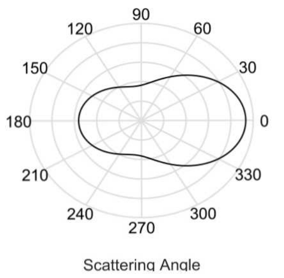
- Loss
  - Scattering
  - Absorption
- Noise
  - Blurring
    - Scattered Light
  - Scattered from background
    - Solar Pedestal
- Dependent on situation
  - Particle size
  - Concentration
  - Wavelength
  - Geometry



Forward scattering

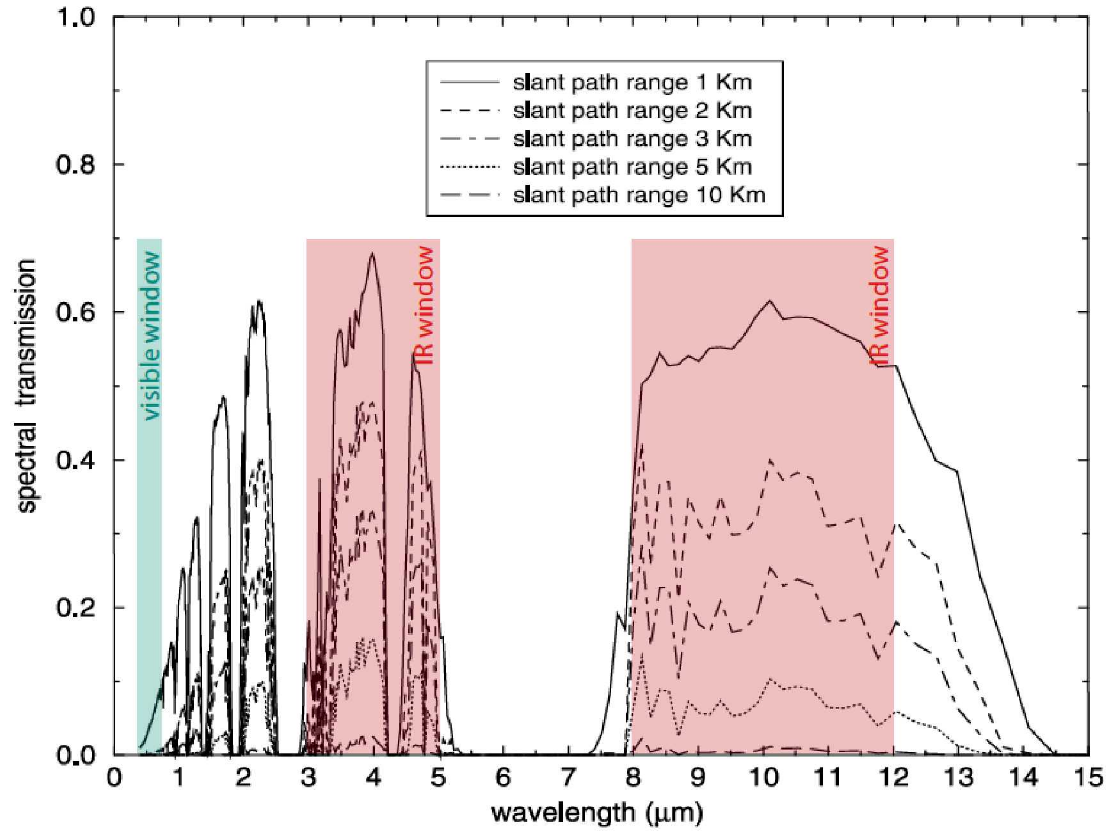


Isotropic scattering



Fog Transmission

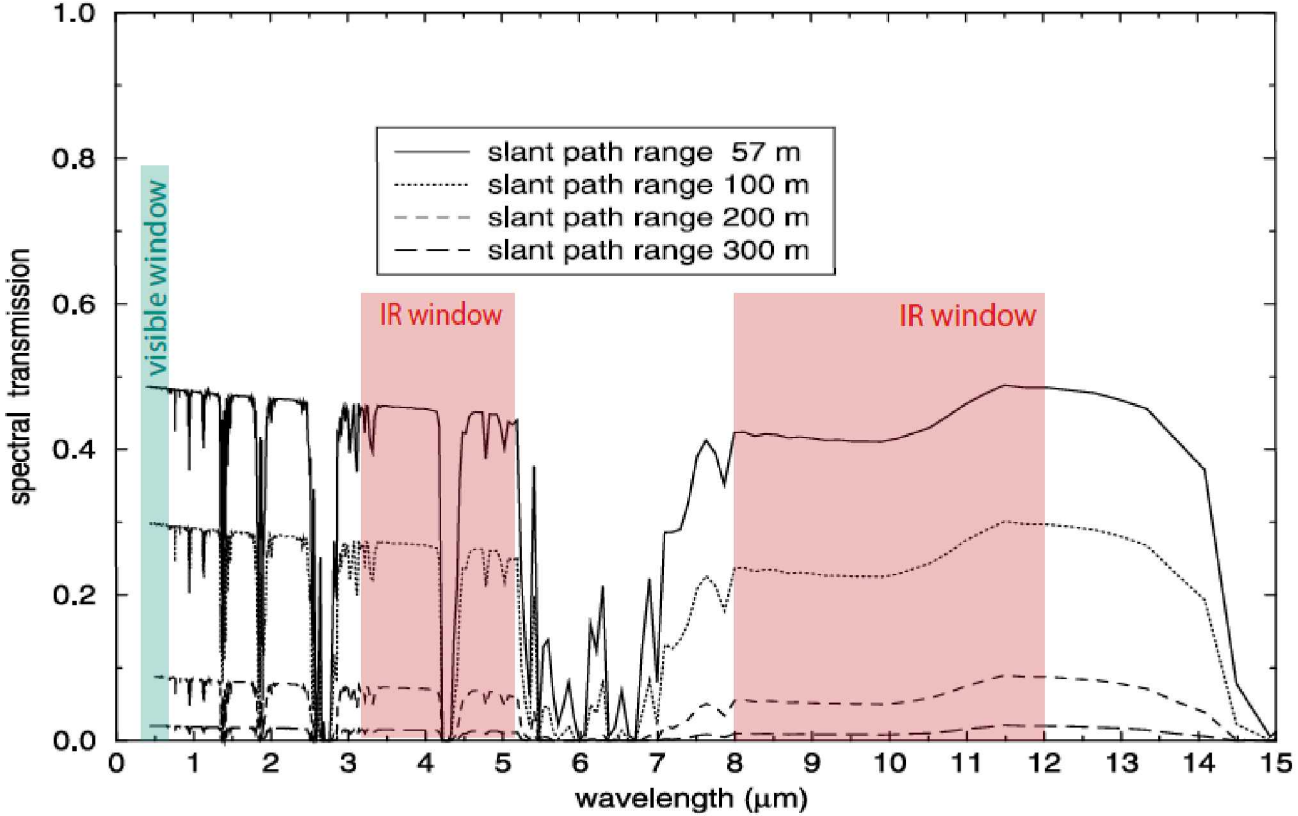
Category 1 fog: visual range 1220 m



[1] C. Petitweg, *Technical Note*, FLIR.

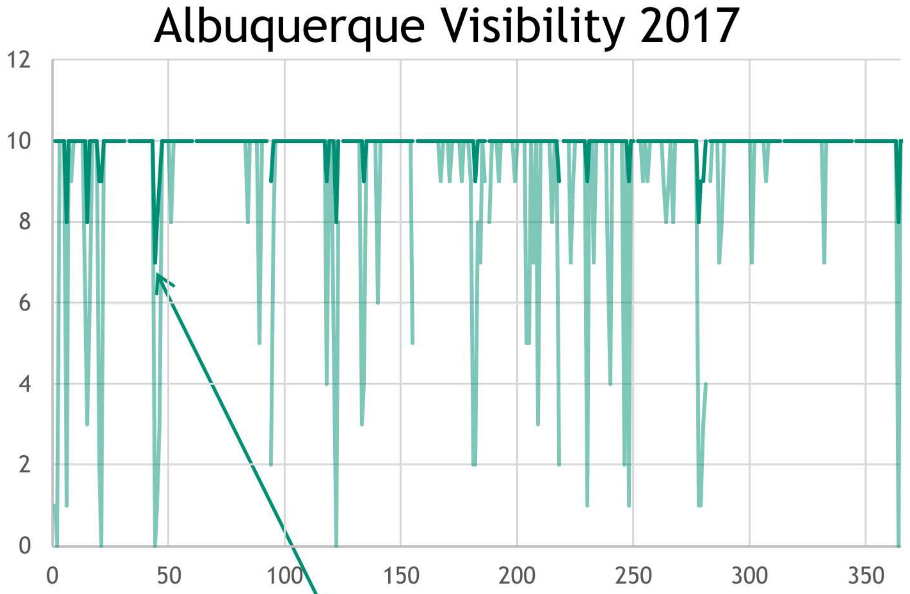
Fog Transmission

Category 3 fog: visual range 92 m



[1] C. Petitweg, *Technical Note*, FLIR.

Weather in ABQ



7 miles lowest average

How do we control the weather?

The Sandia Fog Facility

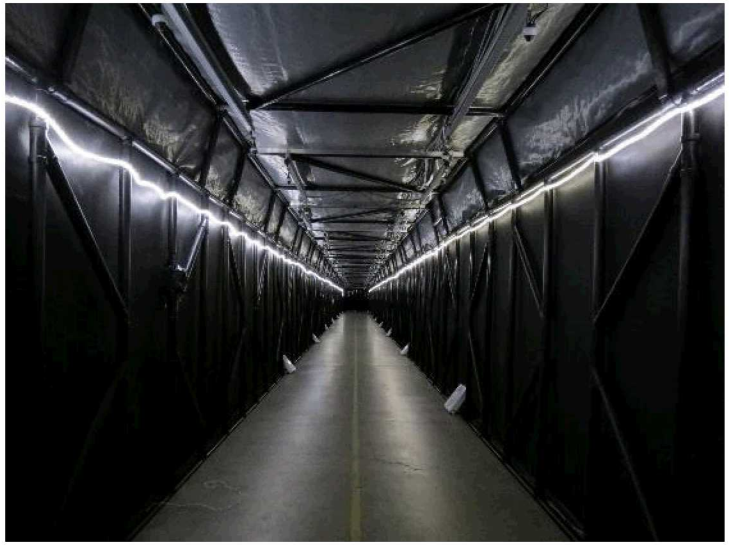
Constructed in 2014

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

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

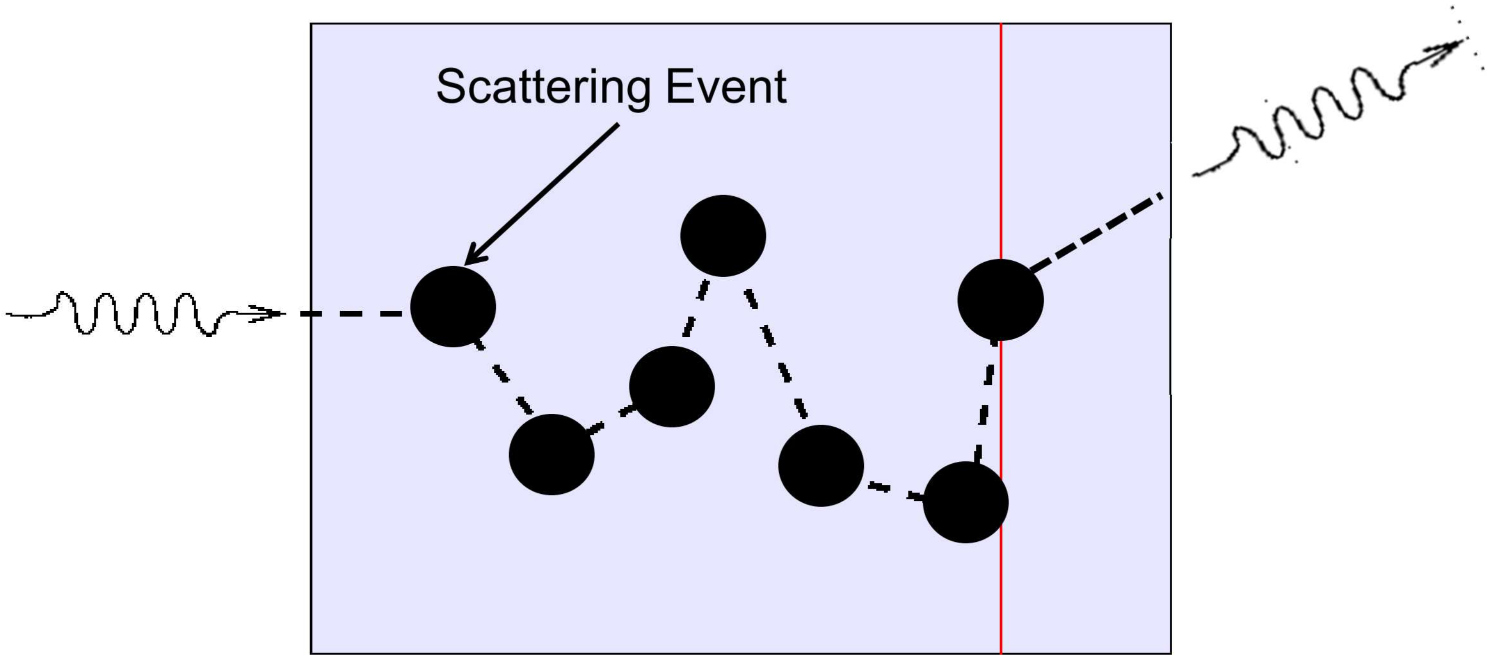
(1) $$LWC = \frac{2\,\beta}{3\sum_i \frac{Q(d_i)\, v(d_i)}{d_i}} \rho_{water}$$

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

$$MOR = \frac{-\ln(}{}$$

Polarization Tracking Monte Carlo

Polarization state of the photon is tracked throughout the scattering environment and modified after each scattering event

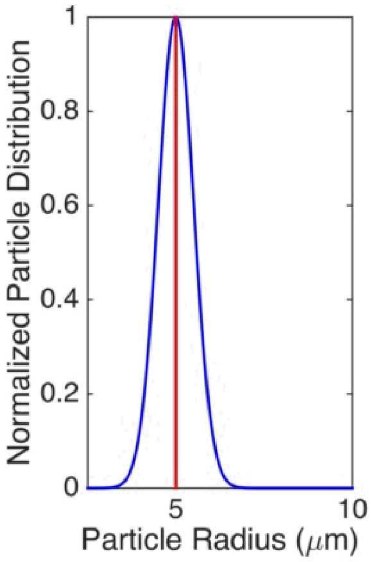


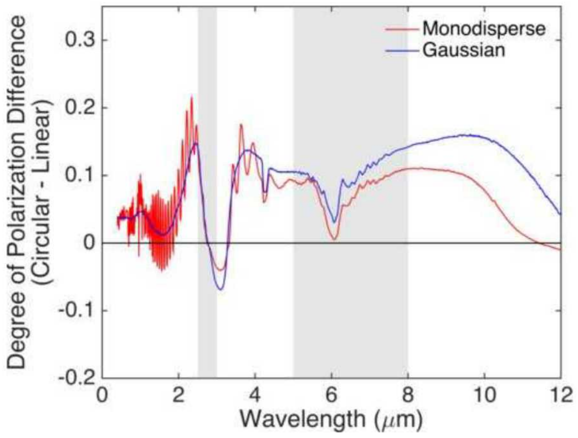
The individual scattering event polarization modifications are cascaded together to determine the final transmitted or reflected Stokes parameters

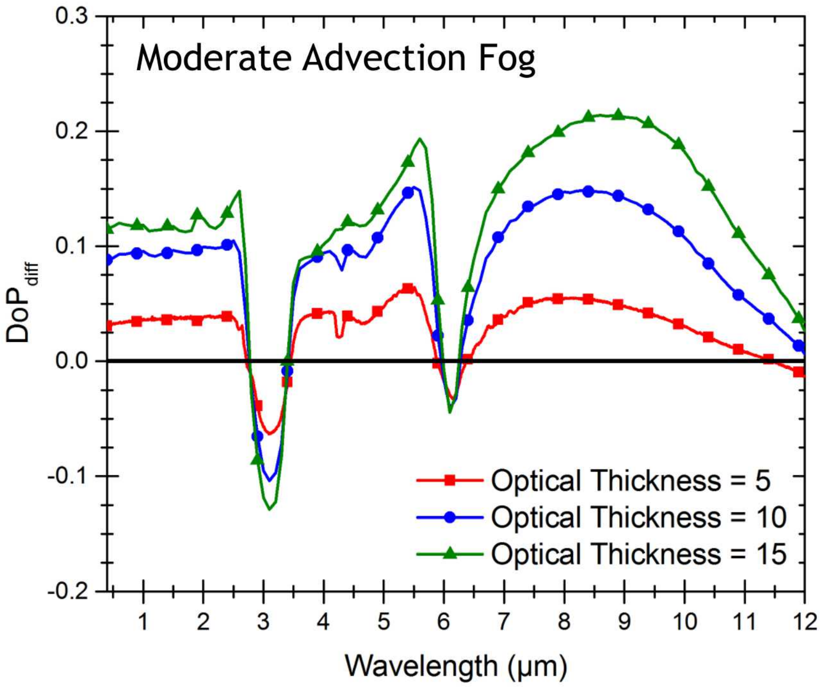
$$\boldsymbol{S}_{scat} = \boldsymbol{R}(-\gamma)\boldsymbol{M}(\alpha)\boldsymbol{R}(\psi)\boldsymbol{S}_{init}$$

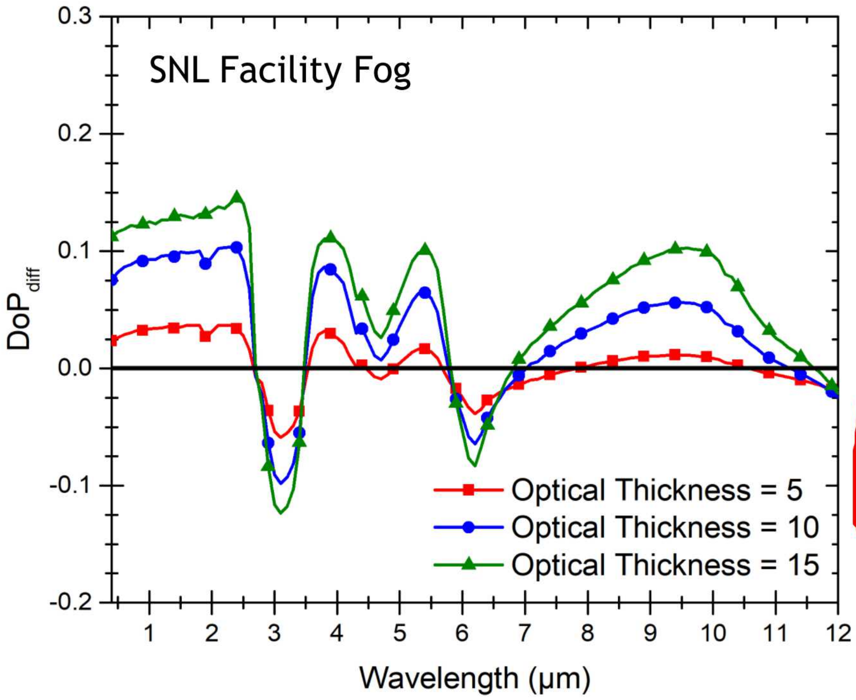
Simulation and modeling capability

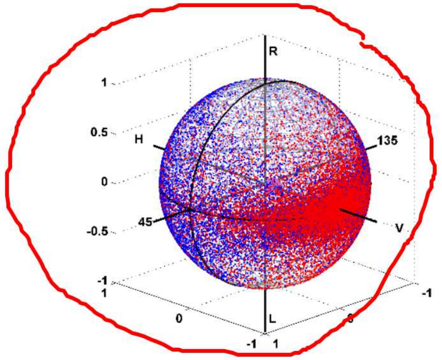
- Simulation can handle arbitrary fog distributions and predict performance of any fog at any optical wavelength
  - Results for various fog models and real-world particle size measurements (published in Applied Optics)
- Supports modeling polarization performance (full stokes)

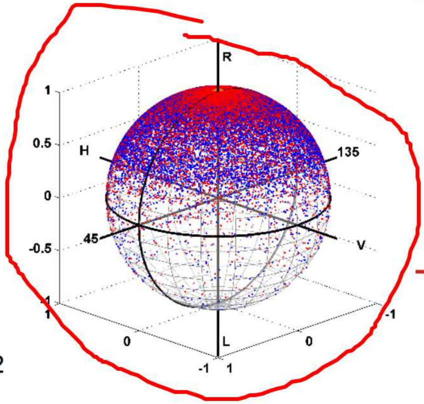


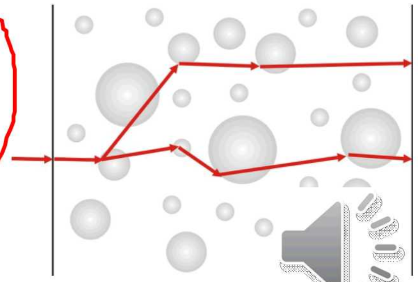








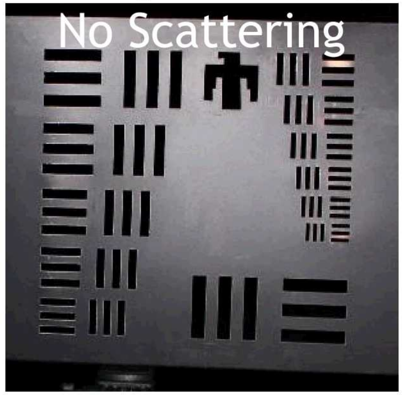




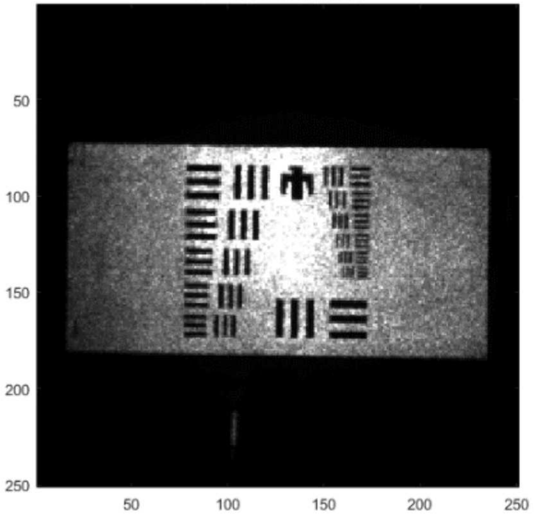
Polarization Measurements Recap

- Our current proof of concept design was assembled with COTS components

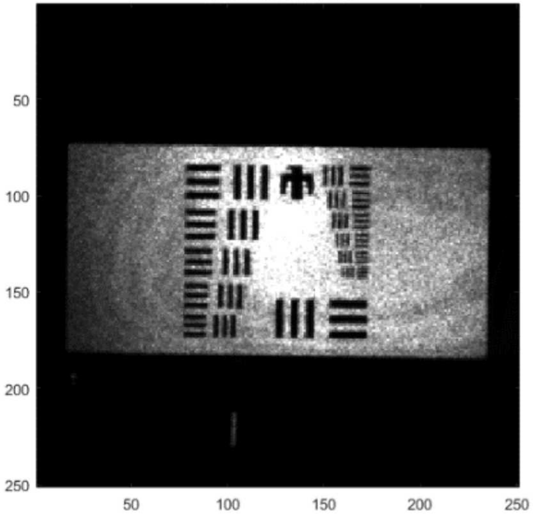
- 1550 nm System: FLIR Tau SWIR
  - Polarization difference imager
    - Linear or Circular polarization configuration



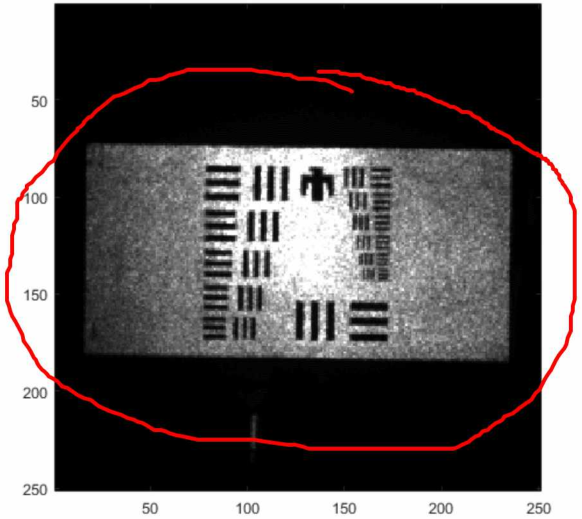
Difference Image:
Circular Polarization



Difference Image:
Linear Polarization

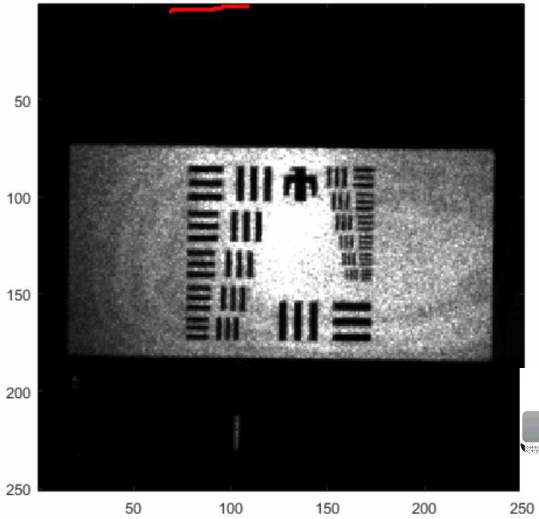


Difference Image:
Circular Polarization

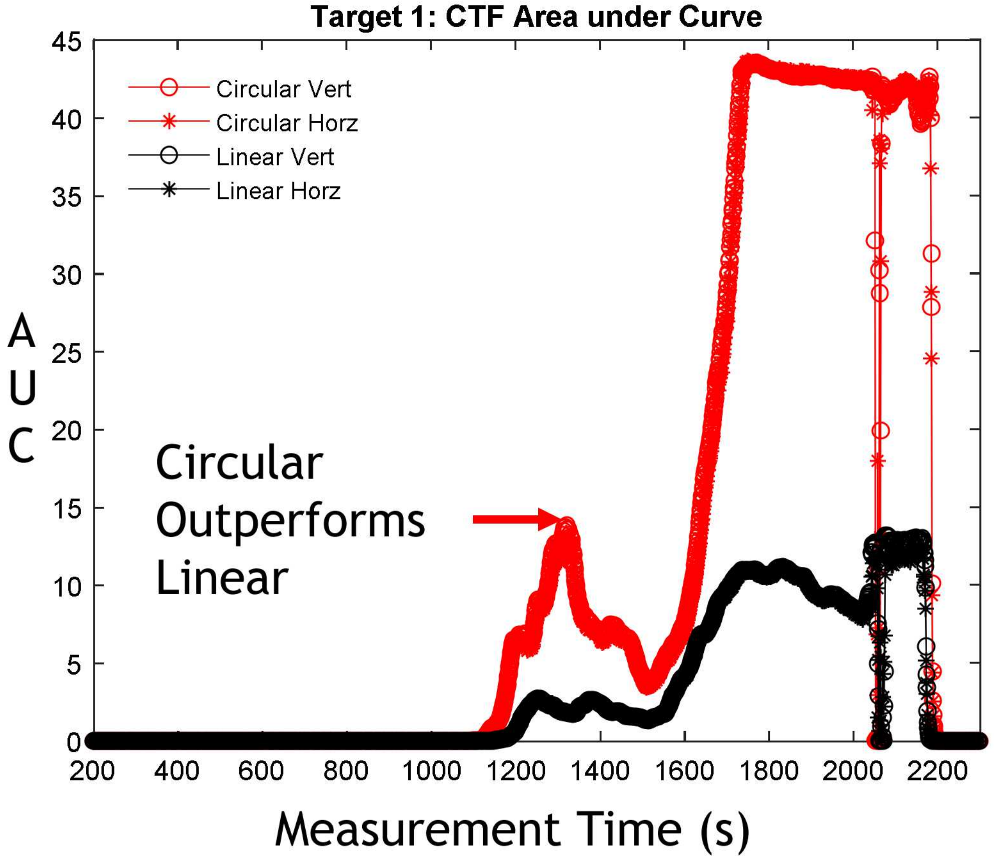


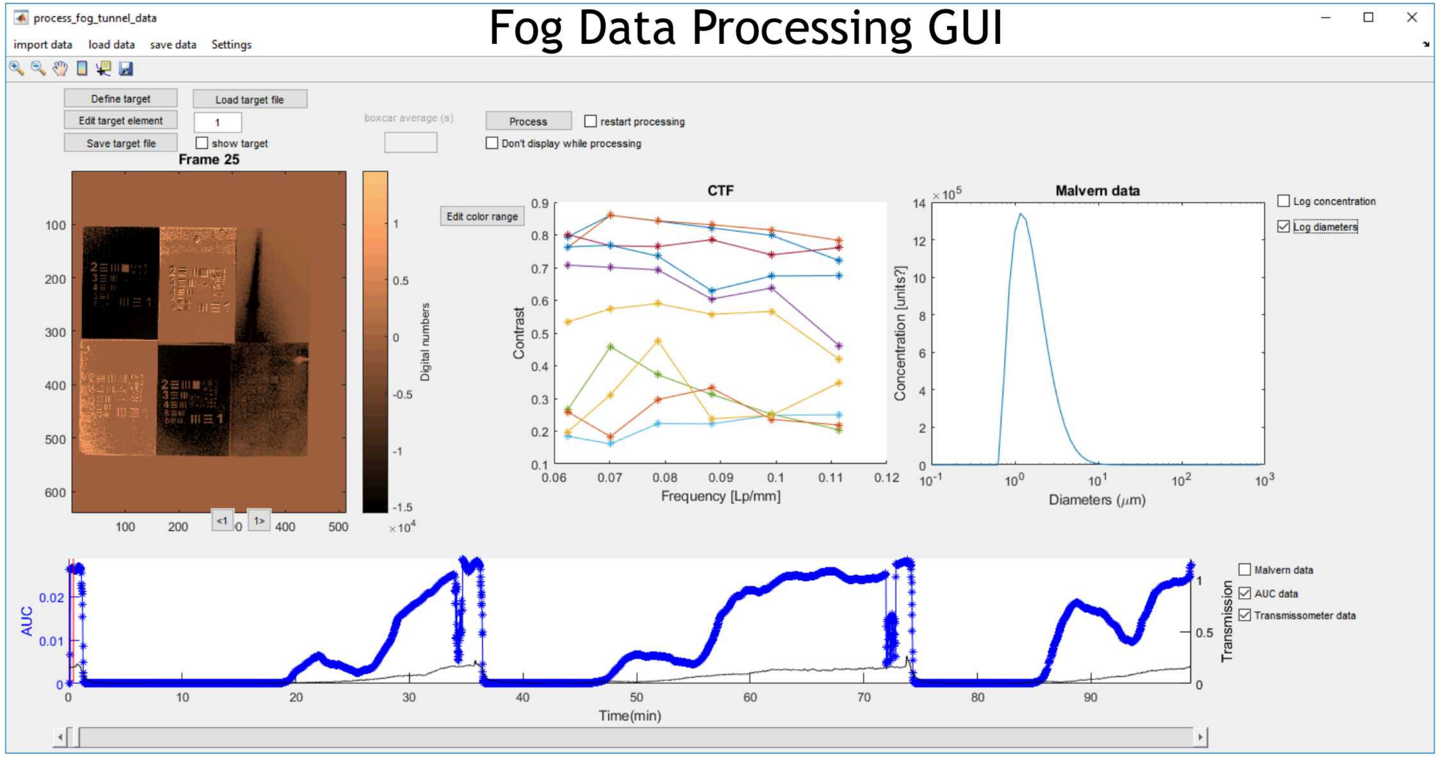
Video

Difference Image:
Linear Polarization



Active imaging of road sign targets at SWIR wavelengths

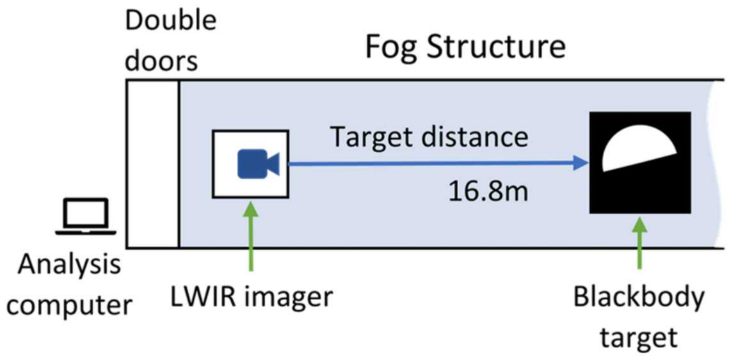


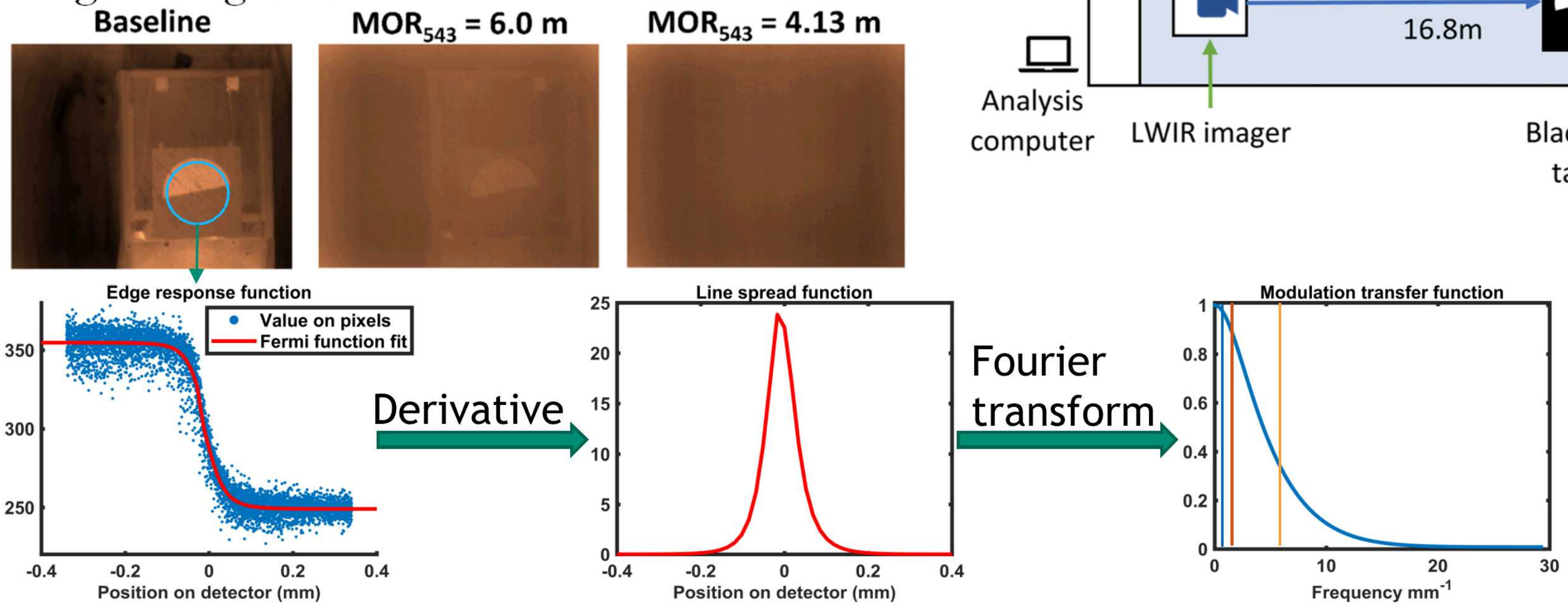


- Active illumination and detection at 1550 nm
- Circular polarized imaging produces much higher contrast compared to linear polarization in the dense fog environment

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

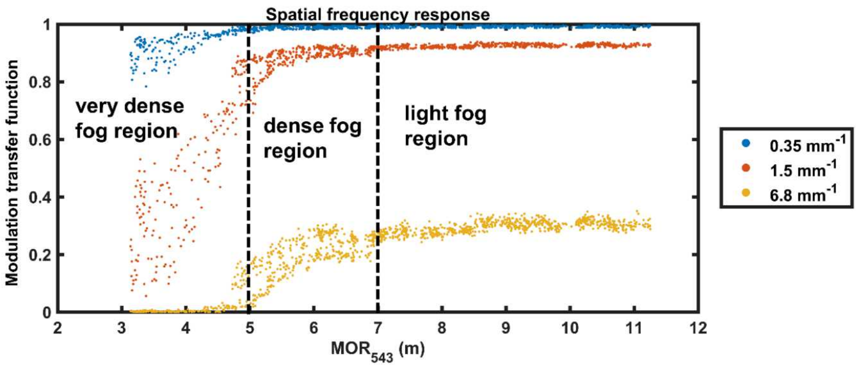
- Slant edge target to measure the resolution over a wide range of fog densities





Repeated for each frame during fog dissipation

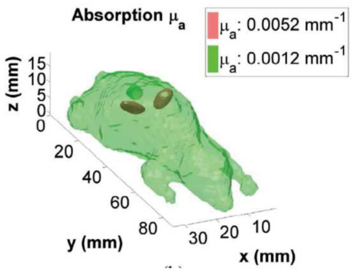
Frequency dependent resolution degradation

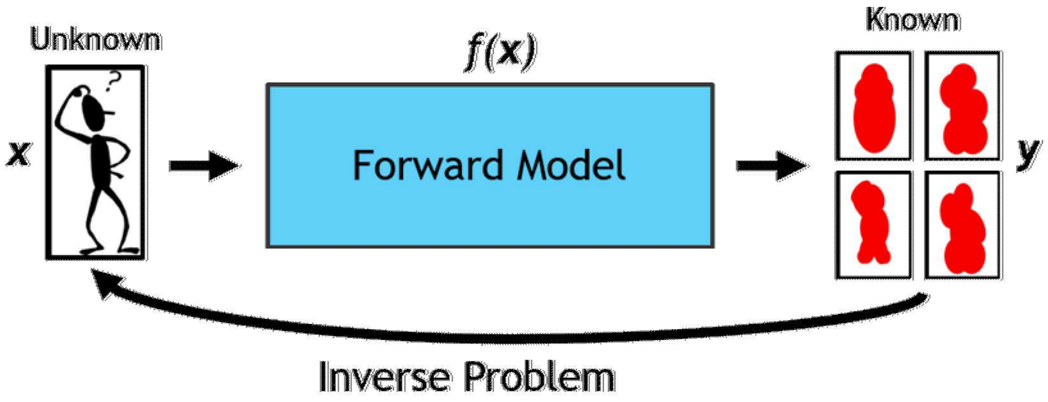


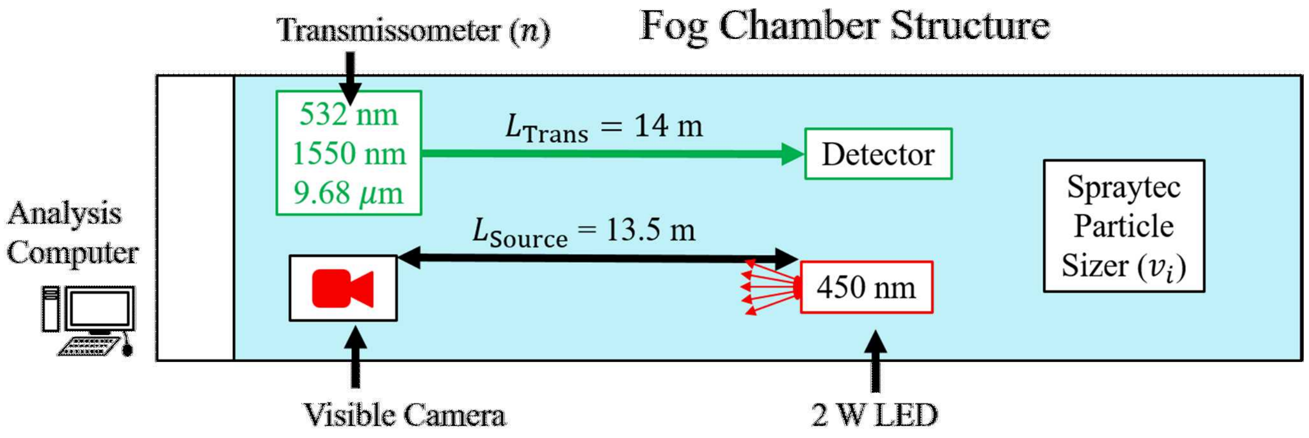
"MEASURING RESOLUTION DEGRADATION OF LONG-WAVELENGTH INFRARED IMAGERY IN FOG" *OPTICAL ENGINEERING*

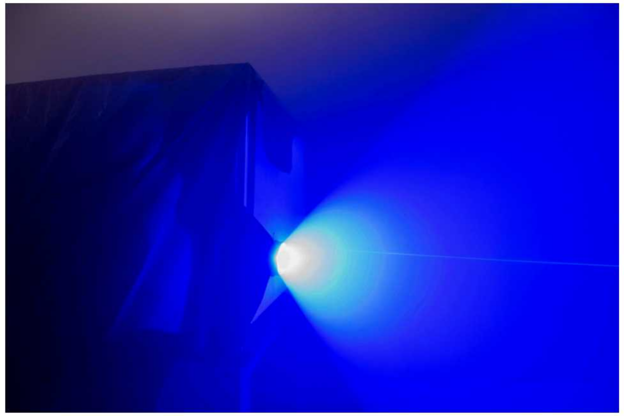
Using Scattered Photons – Computational Imaging

- Diffuse imaging 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 particle motion?**

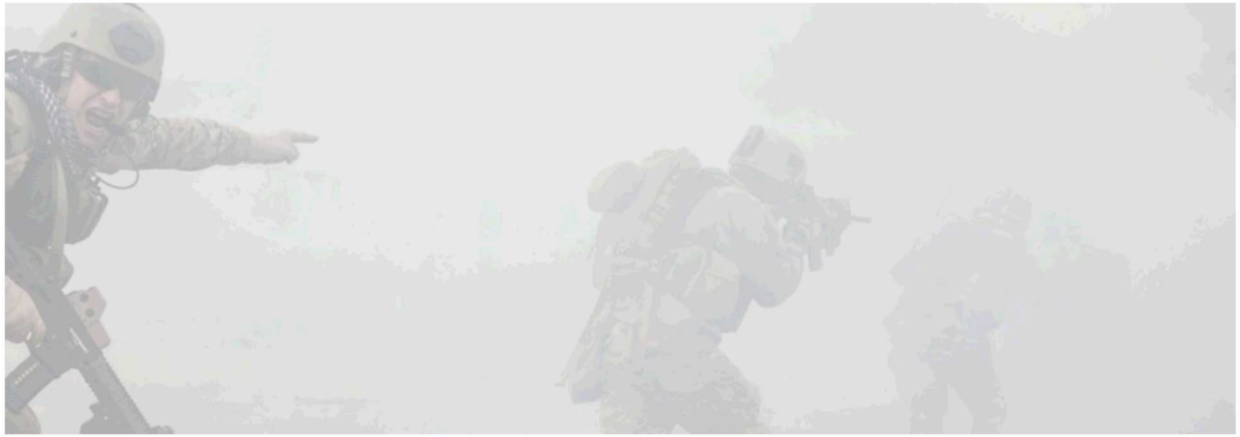








[1] B. Z. Bentz, A. V. Chavan, D. Lin, E. H-R Tsai, and K. J. Webb, *Applied Optics* 55(2), 2016
[2] B. Z. Bentz, D. Lin, and K. J. Webb, *Physical Review Applied* 10, 2018



Thank You

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