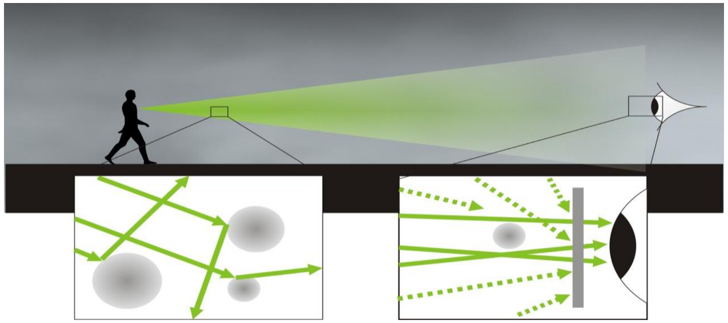
Exceptional service in the national interest

Sandia National Laboratories



Harnessing polarization for signal persistence in generated and natural fog environments

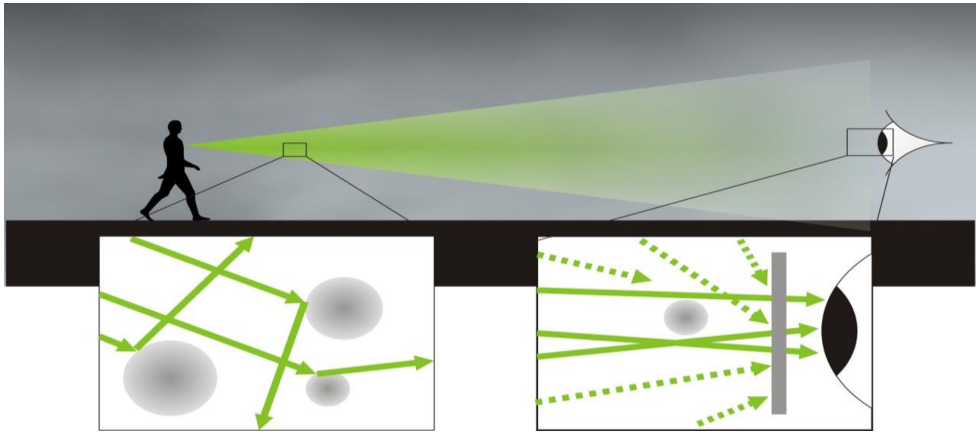
David A. Scrymgeour, Jeremy B. Wright, John D. van der Laan, Andres Sanchez, Karl Westlake, Shanalyn A. Kemme

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. SAND2017-SAND2017-5448 C

dscrymg@sandia.gov

Target detection and ranging is inhibited by degraded visual environments (fog)

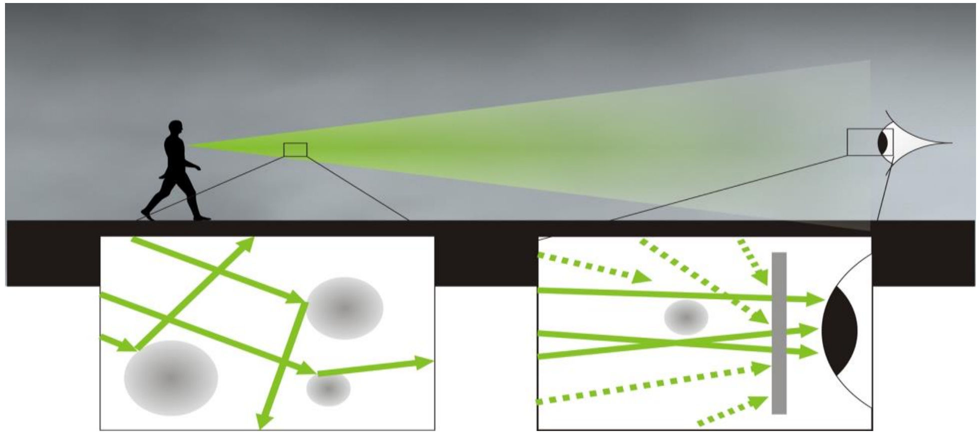


- Scattering particles change the direction of ambient or active illuminating radiation
- Scattering environments decrease the ability to distinguish a target from the background
- Polarization helps SNR in variety in DVEs

- Circular polarization persists superiorly compared to linear polarization in forward scattering monodisperse environments
  - "Detection range enhancement using circularly polarized light in scattering environments for infrared wavelengths," Appl. Opt. (2015) DOI: 10.1364/AO.54.002266
  - "Evolution of circular and linear polarization in scattering environments," Opt. Express. (2015) DOI: 10.1364/OE.23.031874

dscrymg@sandia.gov

Target detection and ranging is inhibited by degraded visual environments (fog)

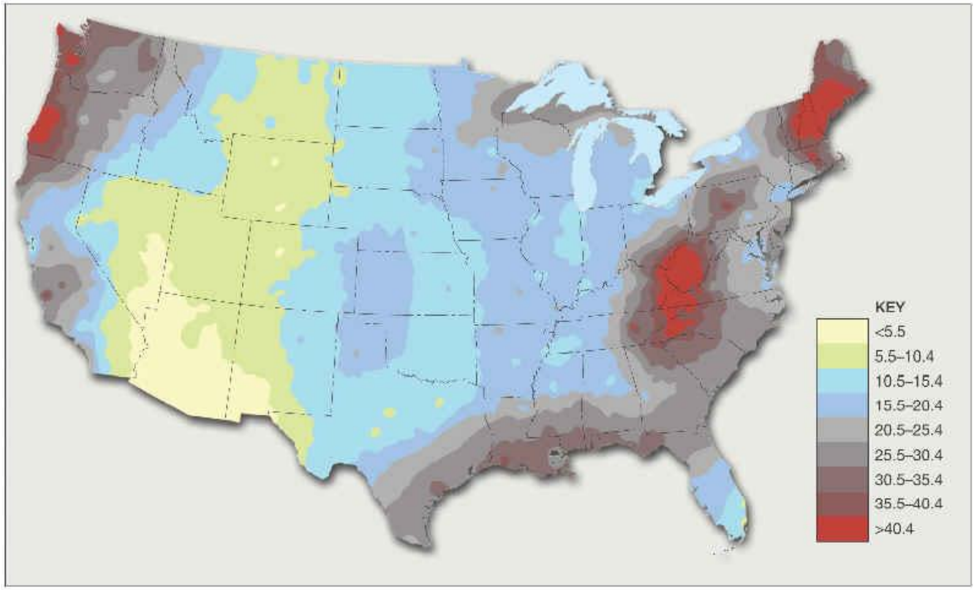


- Sandia National Labs Fog Tunnel Facility
  - Ideal test bed for testing optical systems in reproducible environment

- Discuss wavelength & polarization dependent persistence in fog
  - Simulations & experiments
  - For most fog droplet distributions circular polarization persists better than linear polarization for visible and infrared regimes

Weather related crashes and transportation delays cost $50B annually

Annual days with heavy fog visibility (<.4 km)



Adapted from Bulletin American Meteorological Society 96, (2015)

11 dead in helicopter crash of Florida Coast due to thick fog: WINK News, 3/11/15

What is fog?

Thick cloud of tiny water droplets suspended in the atmosphere at or near the earth's surface with < 1km visibility

Radiation Fog (Inland Fog)

- Moist air is cooled near the ground causing supersaturation
- Generally smaller droplet size (mean radii < 10 µm)

Advection Fog (Maritime)

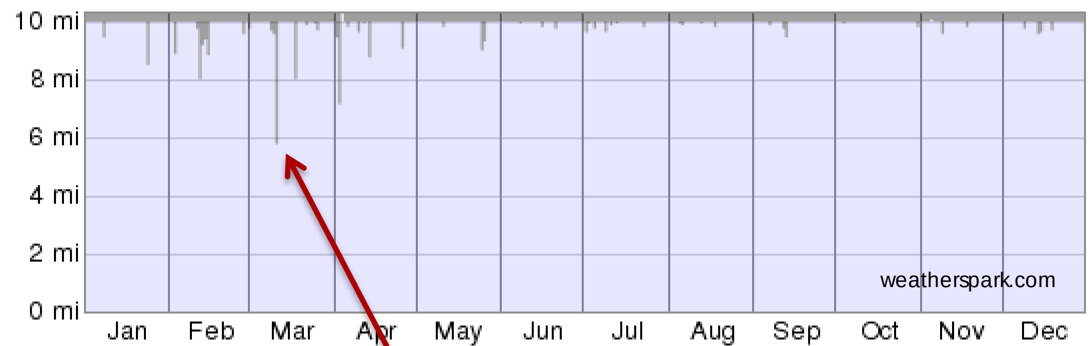
- Moist air passing over cool surface (water/land)
- Generally larger droplet size (mean radii > 10 µm)

dscrymg@sandia.gov

Studying fog in the high desert

Sandia National Laboratories

Visibility in 2012



5.8 miles lowest average

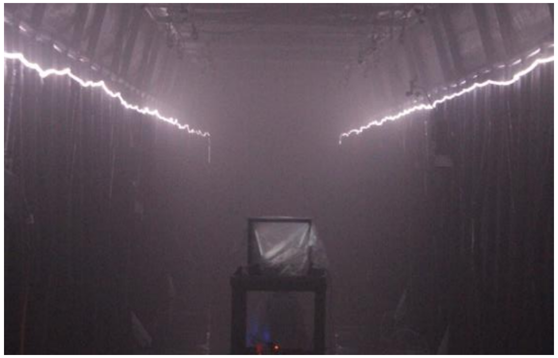
Sandia Fog Tunnel creates controlled fog events for study

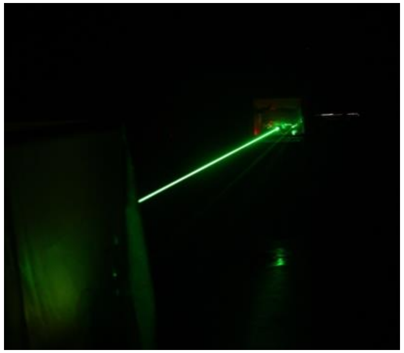
- Constructed in 2014
- Navy Research Funded
- 10’ x 10’ x 180’
  - 6% grade (no pooling)
- 64 spray nozzles
  - 3 selectable sections
- Indoors
  - Stable Environment
  - With maintenance, fog persistent for > 8 hours

dscrymg@sandia.gov

Continuing to upgrade facility capability

- Class IV laser operation (FY16)
- Positive Pressure Dry Boxes (FY16)
- Instrumentation (time correlated)
  - Particle Sizers
    - Malvern
    - Droplet Measurement Technologies
  - Temperature, Humidity, Dew Point
- Temperature Control (soon)

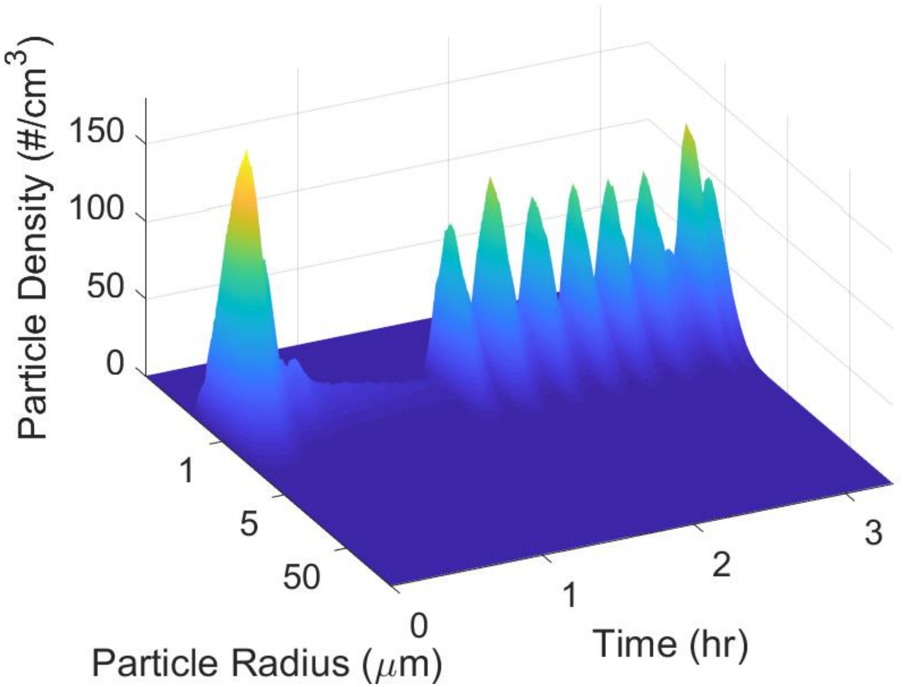


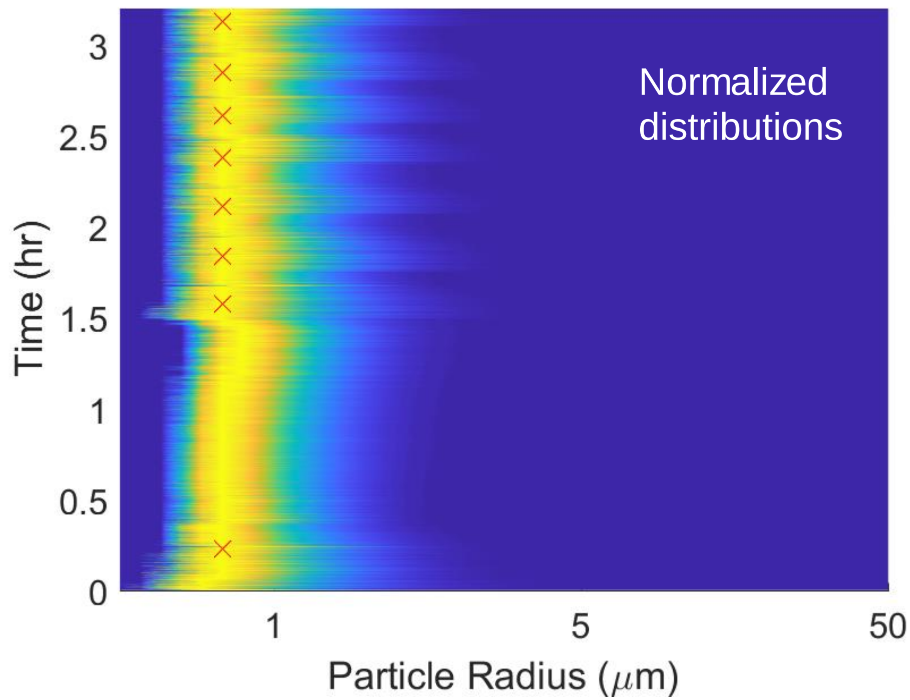


dscrymg@sandia.gov

Fog tunnel generates consistent distributions for experiments

Humidity and droplet distributions maintained by cyclic spraying



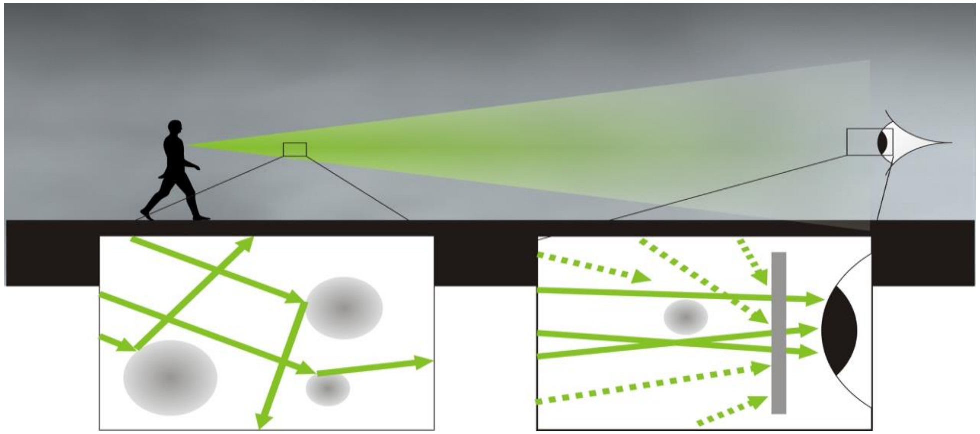


Malvern Spraytec – laser diffraction

Salt concentration: 10 g/L

dscrymg@sandia.gov

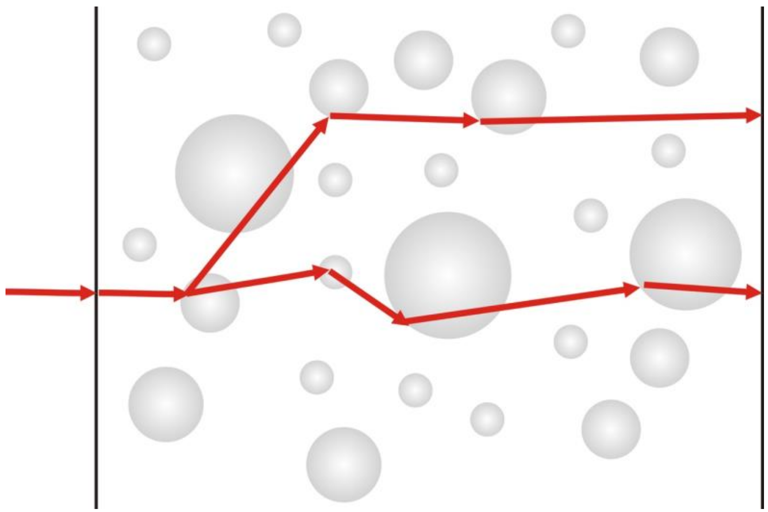
Target detection and ranging is inhibited by degraded visual environments (fog)



- Sandia National Labs Fog Tunnel Facility
  - Ideal test bed for testing optical systems in reproducible environment

- Discuss wavelength & polarization dependent persistence in fog
  - Simulations & experiments
  - For most fog droplet distributions circular polarization persists better than linear polarization for visible and infrared regimes

Polarization Tracking MC Simulation to propagate photons through DVEs

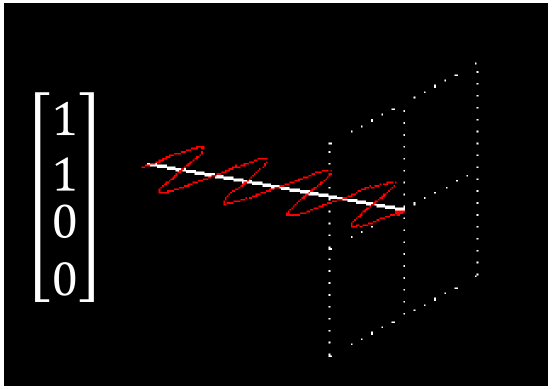


- Unique ability to study DVEs effect on polarization state
- Simulate millions of photons → Mie Scattering Theory
- Individual scattering event polarization modifications are cascaded together to determine the final transmitted Stokes parameters

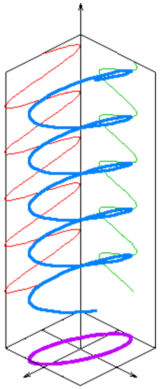
dscrymg@sandia.gov

Stokes Vectors and Degree of Polarization

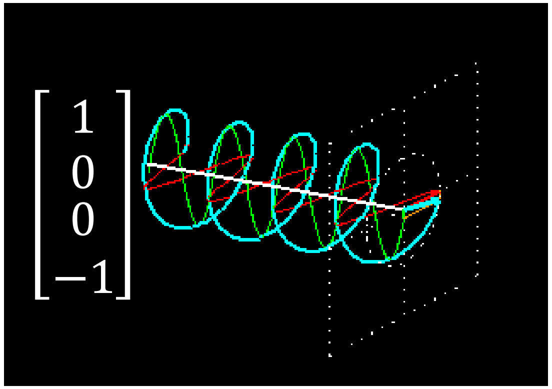
- Polarization defines the oscillation of the electric field in space and time, perpendicular to the light's propagation direction



Linear Polarization



Elliptical Polarization



Circular Polarization

- Stokes Formalism

$$\vec{\boldsymbol{S}} = \begin{bmatrix}S_0\\S_1\\S_2\\S_3\end{bmatrix} = \begin{bmatrix}I\\Q\\U\\V\end{bmatrix} = \begin{bmatrix}\langle E_\parallel\, E_\parallel^* + E_\perp\, E_\perp^*\rangle\\ \langle E_\parallel\, E_\parallel^* - E_\perp\, E_\perp^*\rangle\\ \langle E_\parallel\, E_\perp^* + E_\perp\, E_\parallel^*\rangle\\ i\,\langle E_\parallel\, E_\perp^* - E_\perp\, E_\parallel^*\rangle\end{bmatrix} \propto \begin{bmatrix}I_H + I_V\\ I_H - I_V\\ I_{45} - I_{135}\\ I_R - I_L\end{bmatrix}$$

- $I_H + I_V$ → Intensity
- $I_H - I_V$ → Horizontal or Vertical Linear
- $I_{45} - I_{135}$ → 45 or 135 Degree Linear
- $I_R - I_L$ → Right or Left Circular

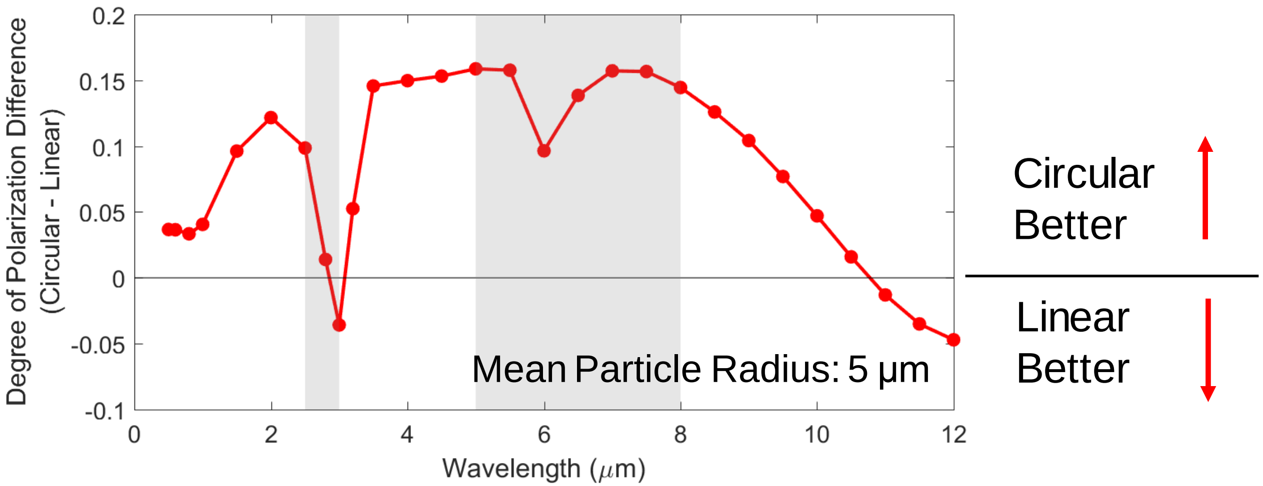
$$DoP = \frac{\sqrt{{S_1}^2 + {S_2}^2 + {S_3}^2}}{S_0}$$

dscrymg@sandia.gov

Degree of Polarization Difference shows which polarization has superior signal persistence

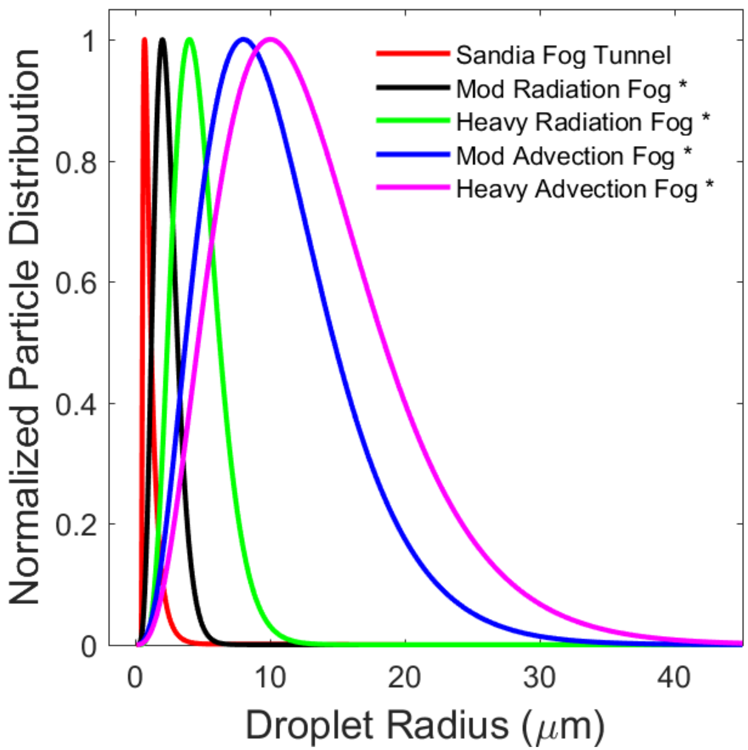
- DOP_{diff} defines the difference between transmitted DoP when circularly polarized light is incident versus when linearly polarized light is incident
- Calculated for scattering environments (fog)
- Figure of merit defined by:

$$DoP_{diff} = DoP_{circular} - DoP_{linear}$$



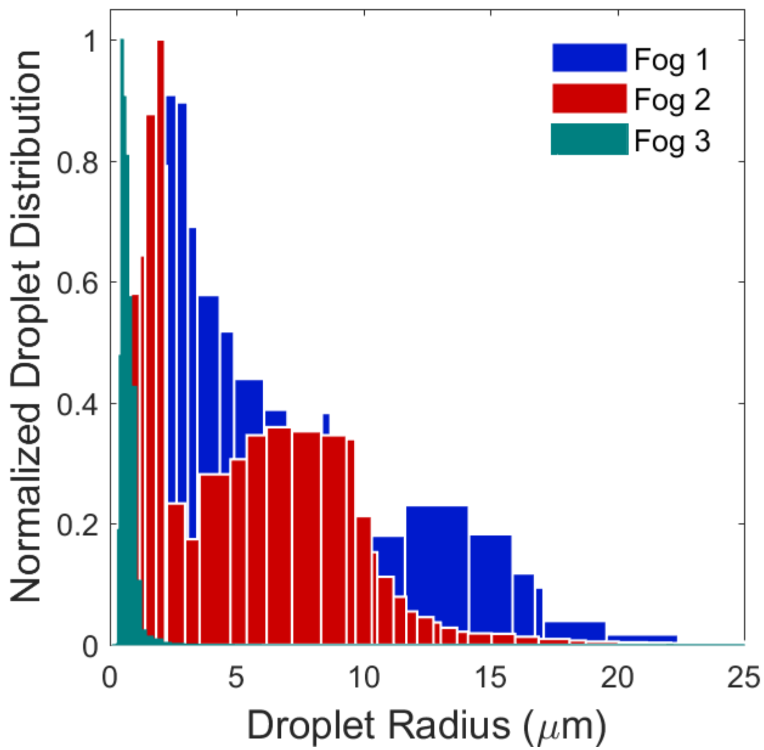
dscrymg@sandia.gov

Model and environmental fog



= inland

= maritime

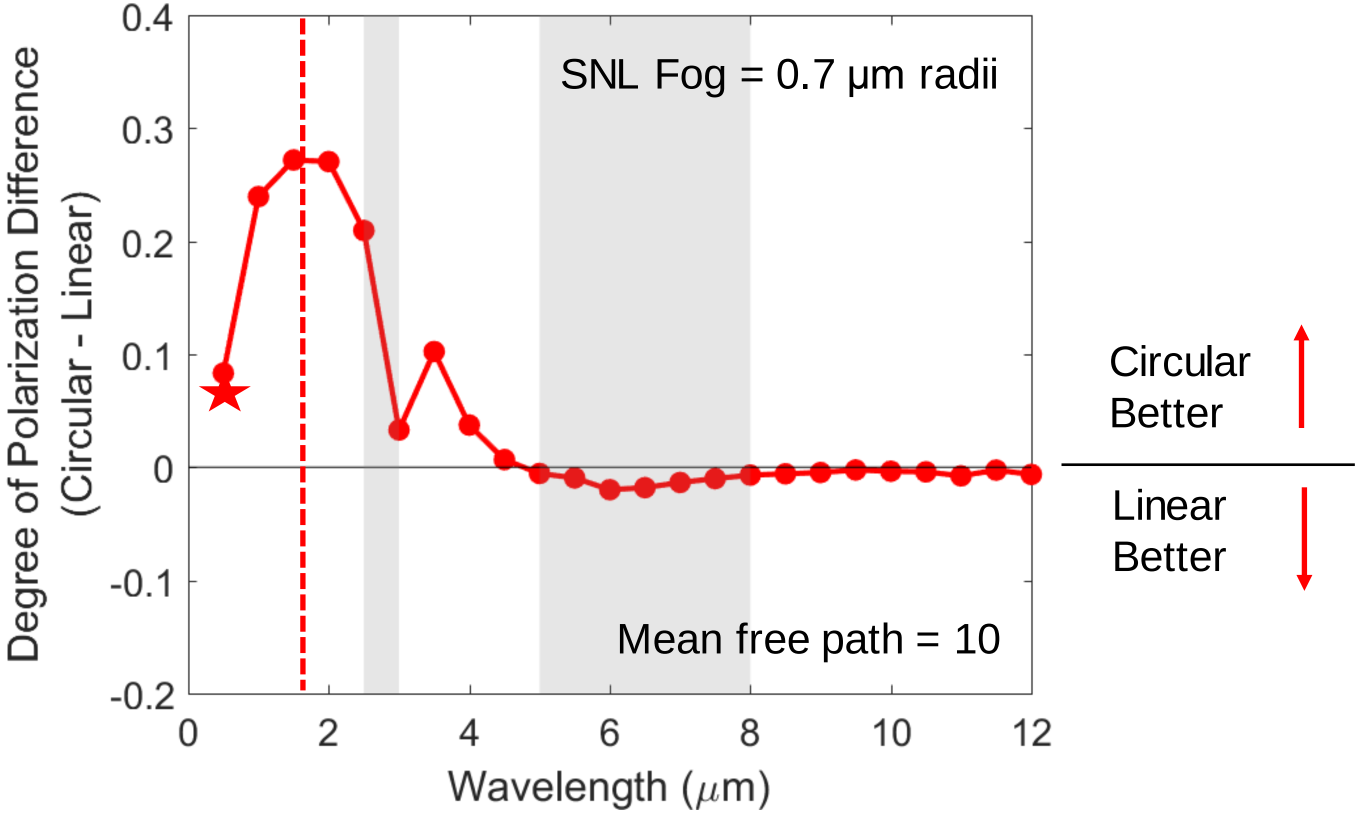


- MODTRAN "Industry Standard"
- Averaged from historical records (1970s)

Fog 1:
Marine fog: A review; Atmospheric Research 143 (2014)
Fog 2&3:
Handbook of Geophysics and Space Environments; Chapter 19 (1983)

Tailor wavelength and polarization to the specific fog

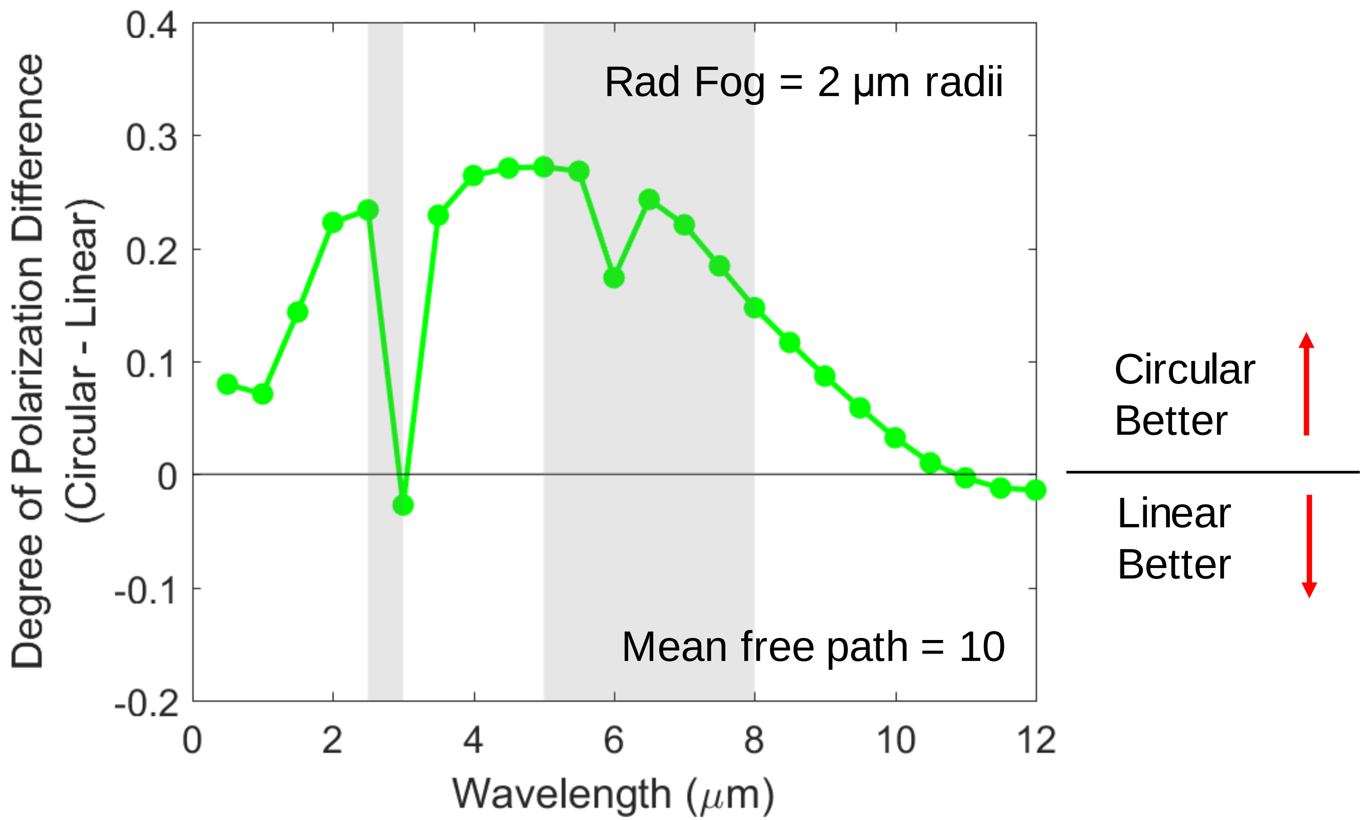
Sandia National Laboratories



Circular polarization outperforms linear for visible and SWIR regimes

dscrymg@sandia.gov

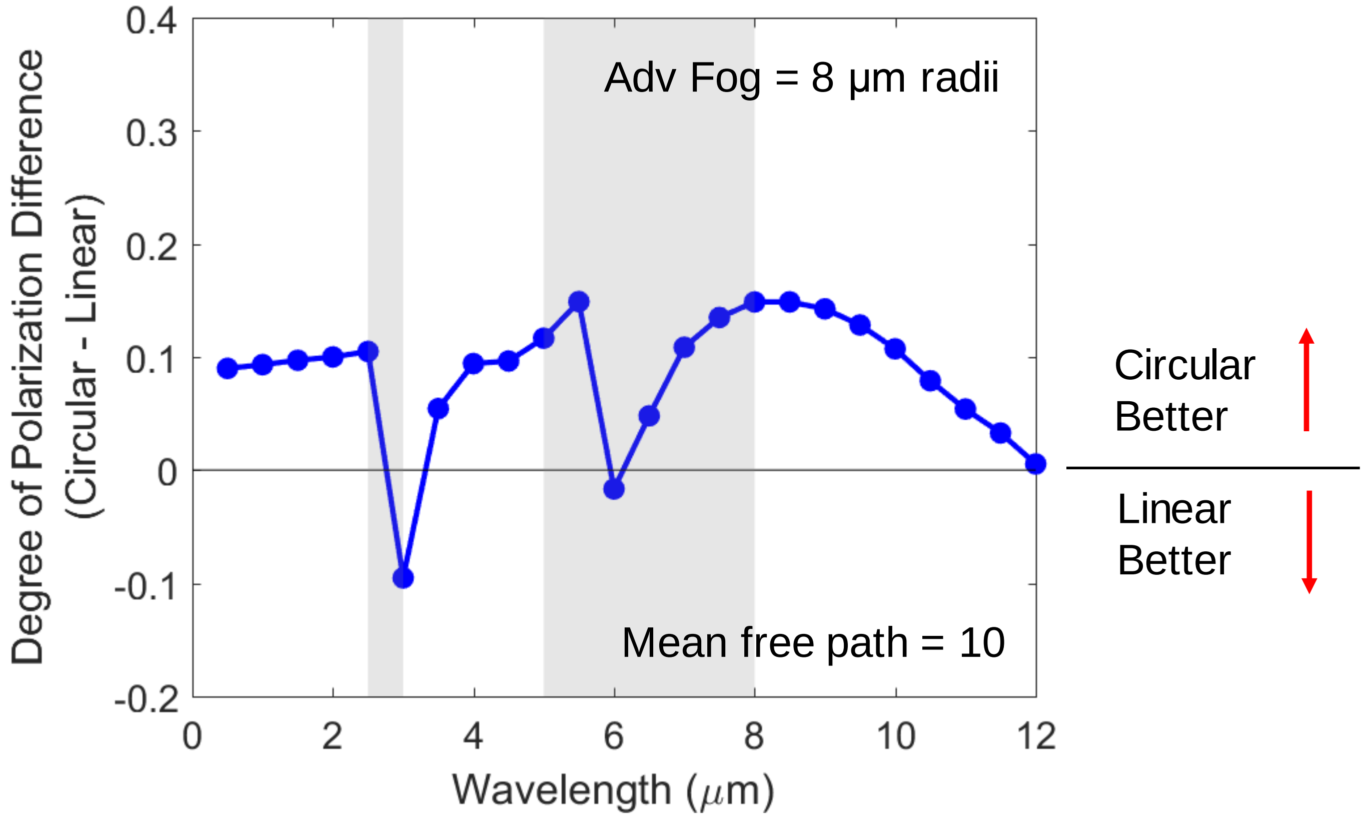
Tailor wavelength and polarization to the specific fog



Circular polarization outperforms linear for visible and MWIR regimes

dscrymg@sandia.gov

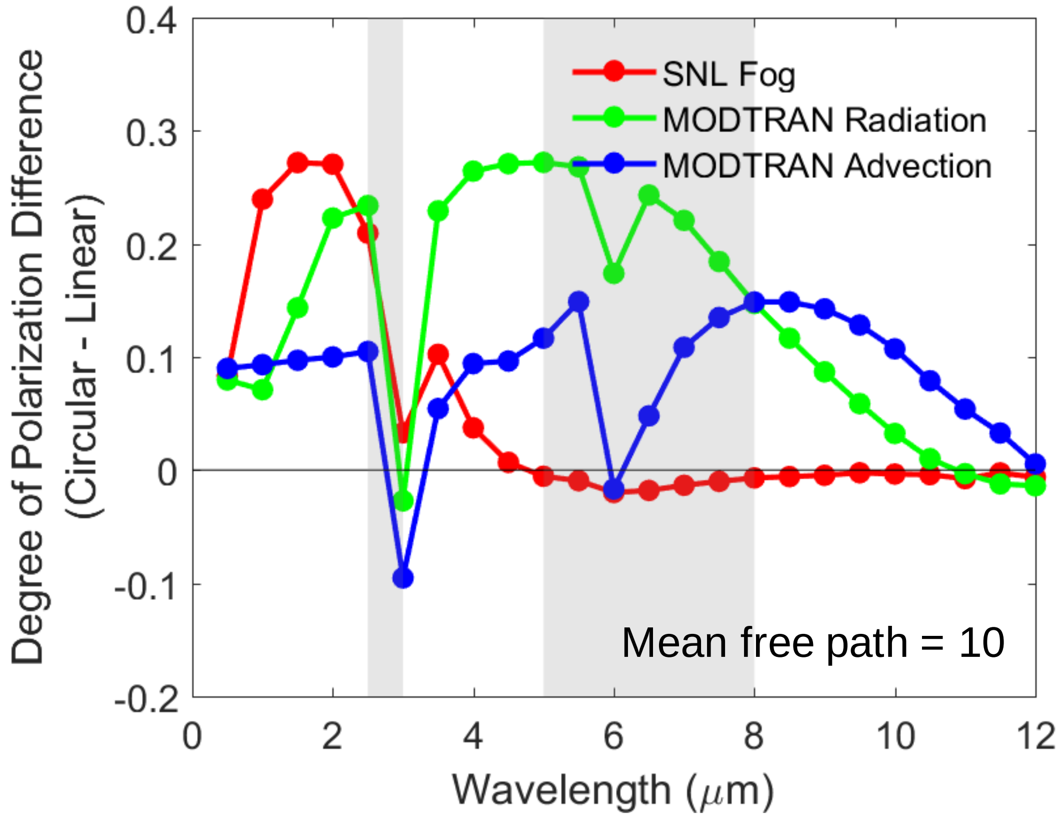
Tailor wavelength and polarization to the specific fog



Circular polarization outperforms linear for visible and IR regimes

dscrymg@sandia.gov

Tailor wavelength and polarization to the specific fog



Mean Particle Radii:
SNL Fog 0.7 μm
Rad Fog 2 μm
Adv Fog 8 μm

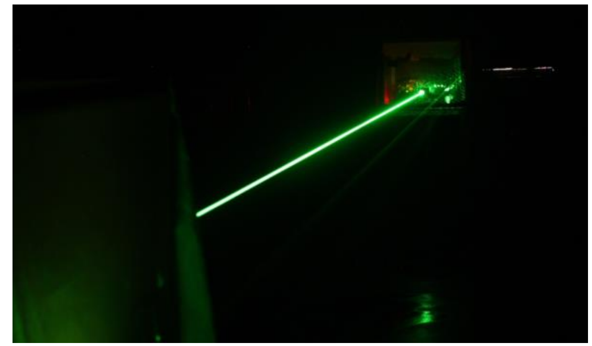
Circular Better

Linear Better

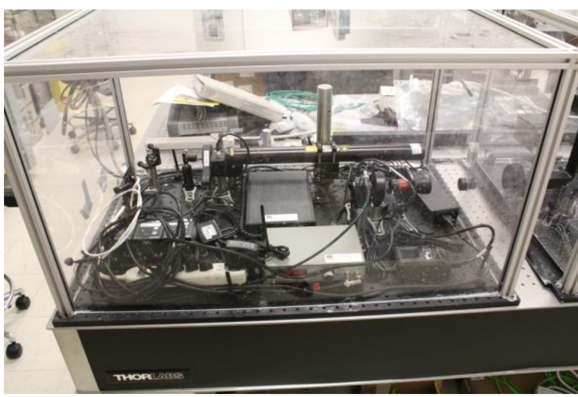
dscrymg@sandia.gov

Experimental work focused on validating simulation work

- Live DOP measurements
- Simultaneous fog characterization
- In visible (532 nm) and IR (1550 nm)



Transmit Box



Vary:
Distance between boxes

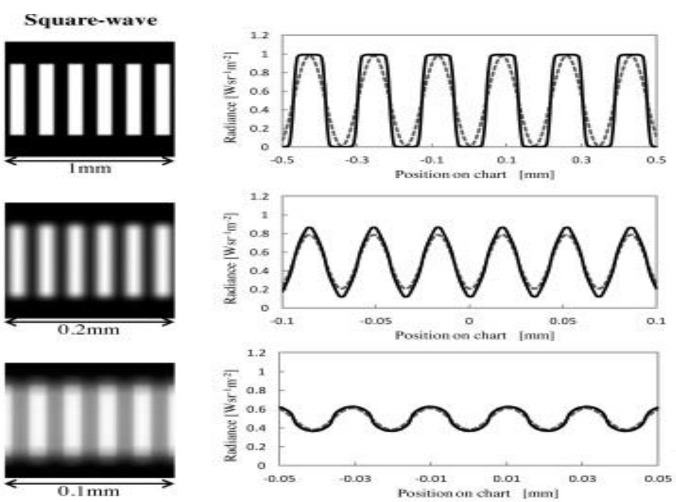
10’, 20’, 30’, 40’

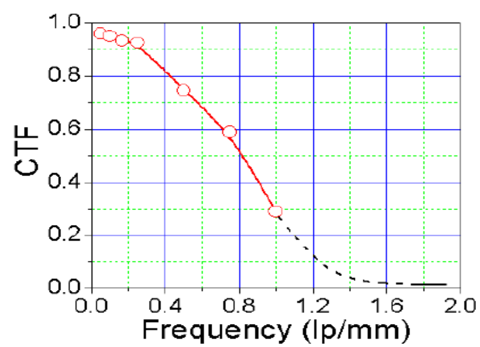
Receive Box

dscrymg@sandia.gov

Future Work

Preliminary imaging experiments using visible transmisometers





We want to quantify how polarization affects imaging in fog

Conclusions

- Sandia Fog Facility controlled reproducible environment for optical testing in fog
- Circular polarization persists through fog scattering environments better than linear polarization for broad wavelengths and broad fog particle distribution parameters
  - Utilizing this offers the ability to increase range in fog environments
- Small mean particle size distributions:
  - Visible and SWIR wavelengths
- Mid/Large mean particle size distributions:
  - Visible to LWIR wavelengths

dscrymg@sandia.gov

The End

Harnessing polarization for signal persistence in generated and natural fog environments

Authors: David A. Scrymgeour, Jeremy B. Wright, John D. van der Laan, , Shanalyn A. Kemme

Symposium on "9th NATO Military Sensing Symposium " (SET-241) :

Abstract:

Degraded visual environments (DVEs) are a serious concern for modern sensing and surveillance systems. In particular, fog is of interest due to the frequency of its formation along our coastlines disrupting border security and surveillance. Fog presents hurdles in intelligence and reconnaissance by preventing data collection with optical systems for extended periods. Our previous work has shown promise for increasing signal and range utilizing polarized light, specifically circular polarization, for DVEs such as fog and dust in the visible, mid-wave, and long-wave infrared spectrums. These promising results show us that intentionally tailoring both the illumination wavelength and the polarization state can used to extend range and increase signal to noise in DVEs.

The utility of harnessing polarization is clear from many diverse systems (tissue imaging, environmental imaging) but the lack of reproducible environmental testing facilities has rendered systematic investigation of environmental conditions difficult. Here we present recent results from our work in operating optical systems in our controlled fog experimental chamber. The Sandia National Laboratories facility for controlled fog experiments is a 200 foot long, 10 foot wide, and 10 foot tall structure that has over 60 spray nozzles to achieve uniform aerosol coverage. We will discuss the characterizations of fog distributions and how we characterize the aerosol at our facility. We will show simulation examining polarization transmission for our experimentally measured fog distributions as well as a range of realistic fog conditions. We systematically explore the effect of particle size, particle distribution, and other distribution variables on the polarization transmission through fog DVEs. These simulation results validate the usage of this unique capability as a controlled experimental realization of natural fog formations, and will enable the testing and validation of future fog penetrating optical systems and providing a platform for performing optical propagation experimentation in a known, stable, and controlled environment. Finally, we will show that circular polarization persists better than linear polarization for most variations of the fog distributions - a promising approach to improving sensing in all DVEs.

20 minute talk

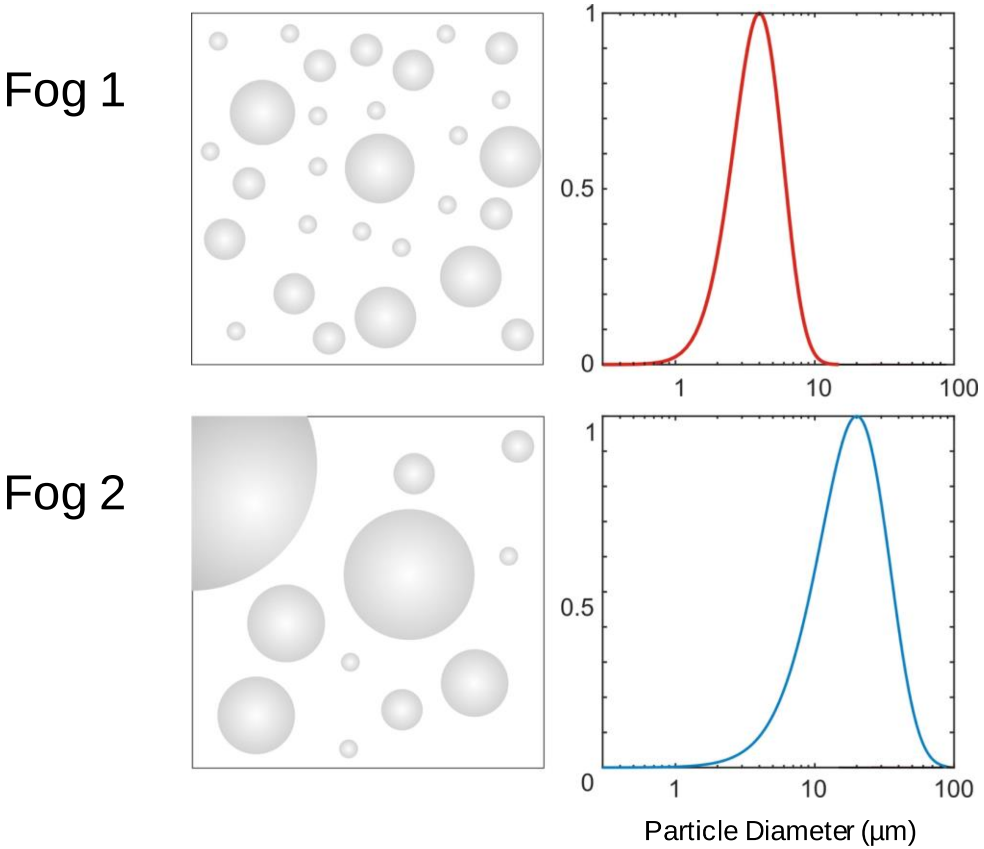
Develop and characterize fog analogs

Description of fog:

- Particle distribution
- Particle density

Depends on:

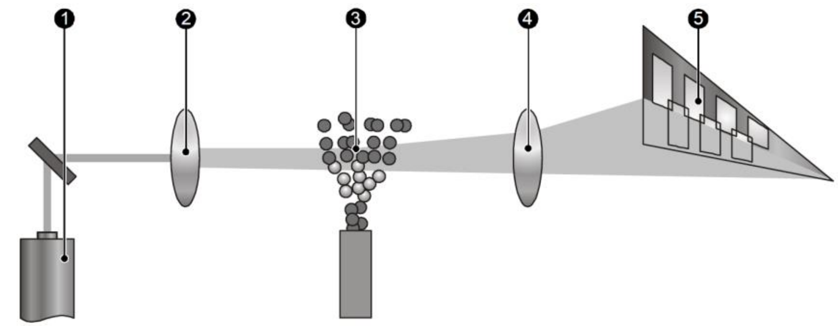
- Relative Humidity
- Temperature
- Nucleating species

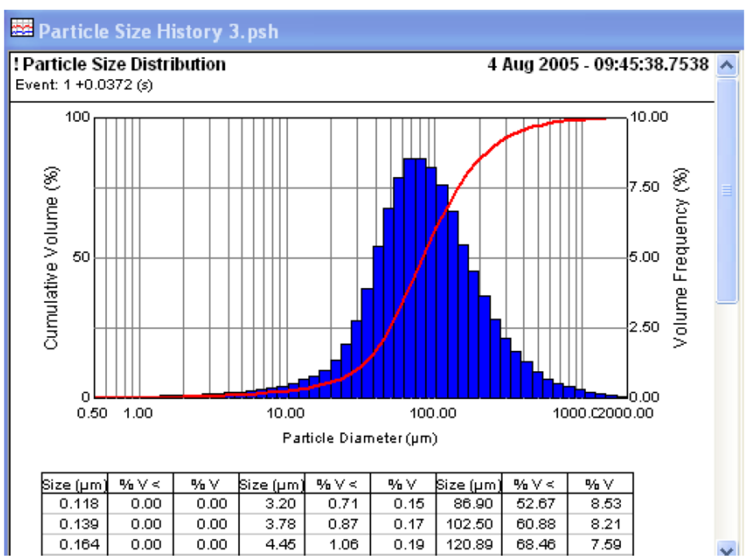


dscrymg@sandia.gov

Malvern- Spraytek

- Laser diffraction system
- Large particle range
  - 0.1 – 900 microns
- Multiple Scattering Model
- 1Hz Continuous

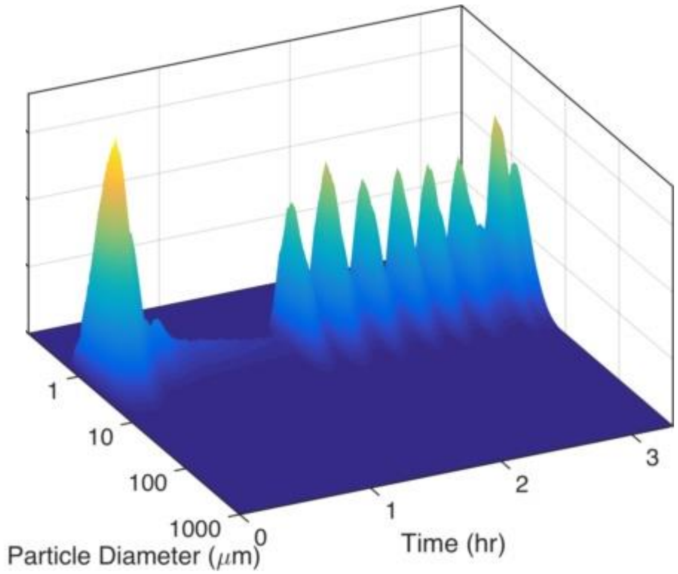




Size (μm)	% V <	% V	Size (μm)	% V <	% V	Size (μm)	% V <	% V
0.118	0.00	0.00	3.20	0.71	0.15	86.90	52.67	8.53
0.139	0.00	0.00	3.78	0.87	0.17	102.50	60.88	8.21
0.164	0.00	0.00	4.45	1.06	0.19	120.89	68.46	7.59

Using the Spraytek

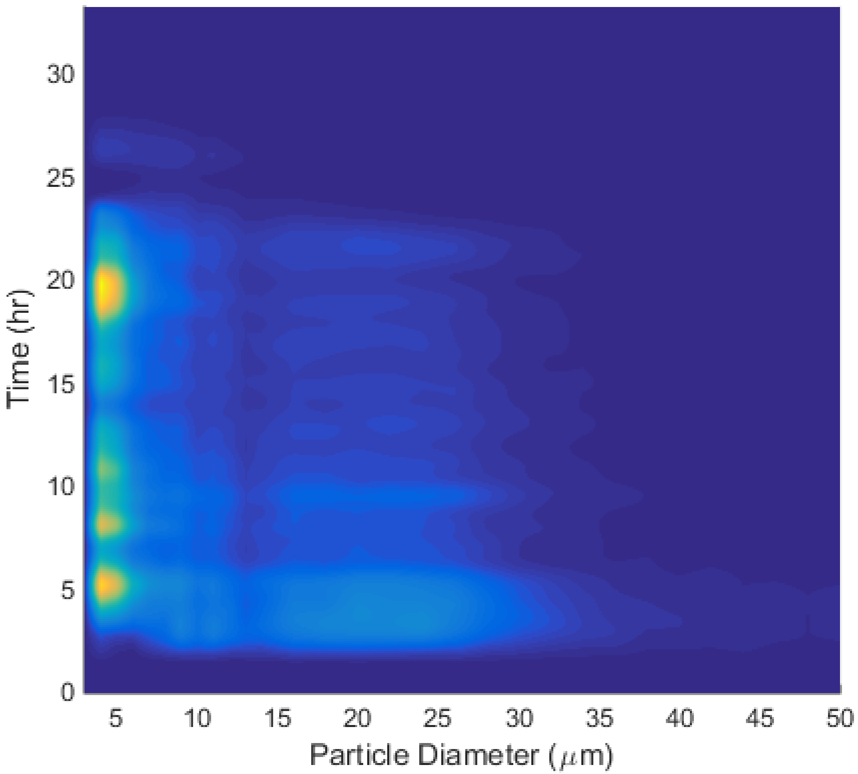
- Inhalation Cell
  - Moving particles
  - Flow Rate
- Number Concentration

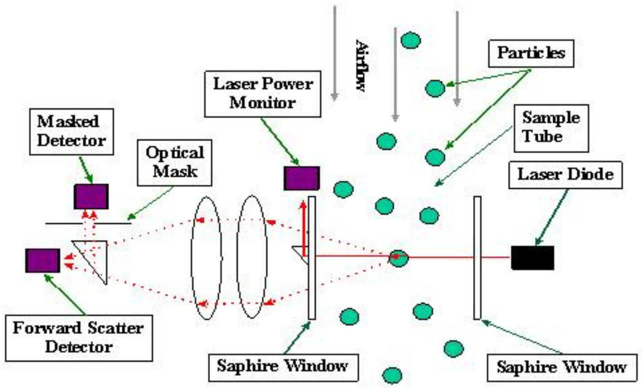


dscrymg@sandia.gov

Droplet Measurement Technologies - FM-120

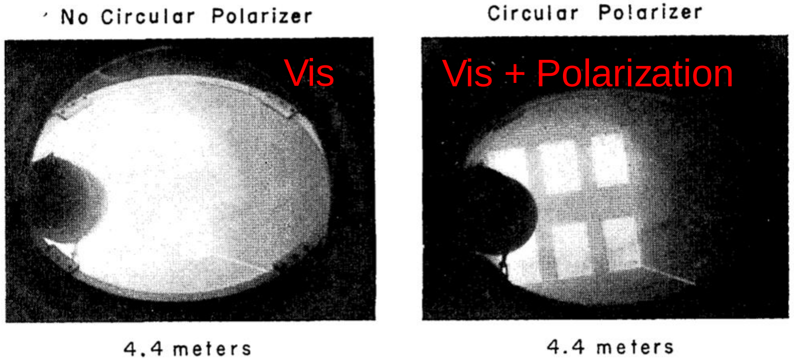
Particle sizing > 2µm



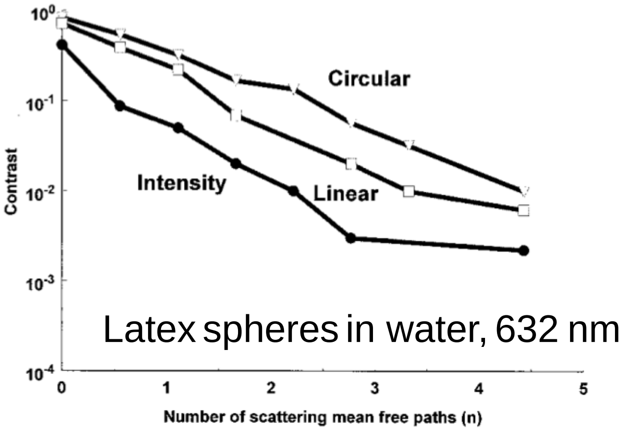


Polarization increases performance compared to intensity based optical techniques

Painted Al targets in seawater



Gilbert, G.D., Applied Optics, 6(4), (1967)



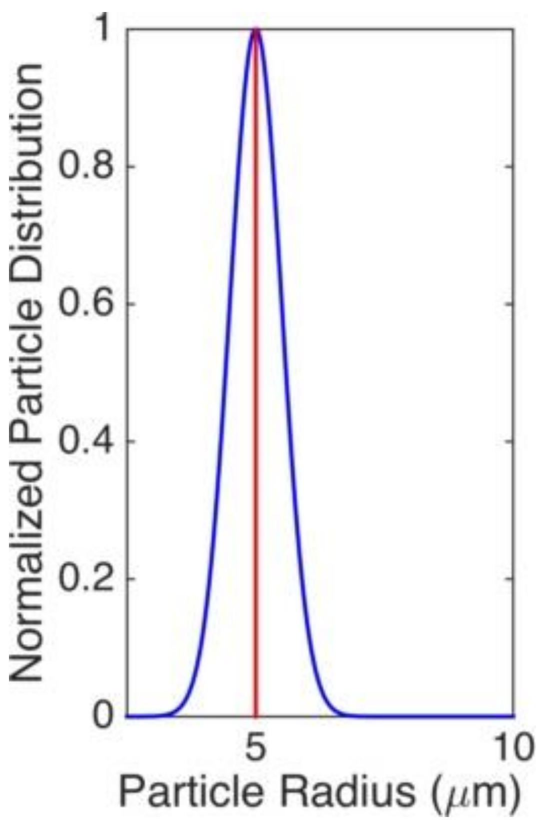
Lewis et al, Applied Optics, 38, 18, (1999)

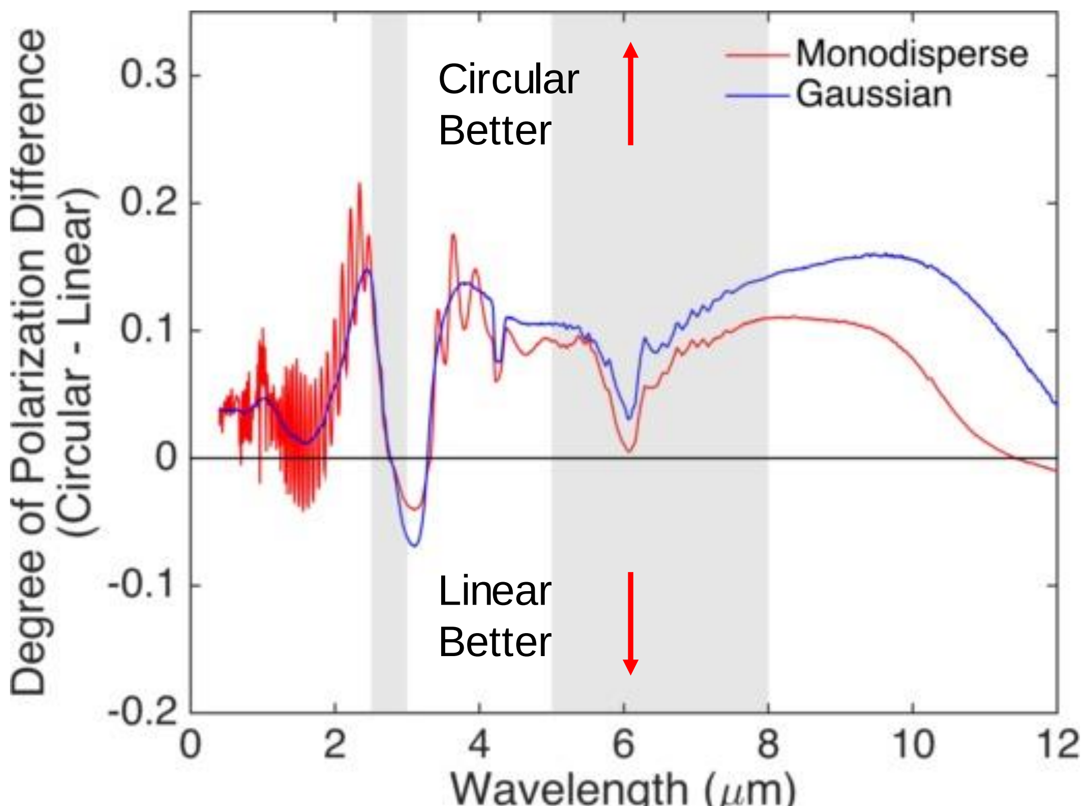
- Polarization boosts contrast in wide variety of optical applications
- Previous work has shown that wide wavebands in both MWIR and LWIR that show preferential persistence of polarized signals
- Tailored polarization + wavelength = enhanced range and persistence

dscrymg@sandia.gov

Monodisperse vs Gaussian distributions of droplets

- Distributions remove the large resonant behavior from monodisperse Mie scattering





dscrymg@sandia.gov