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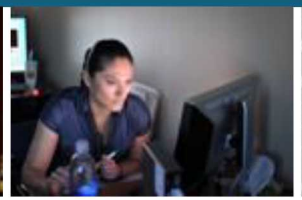
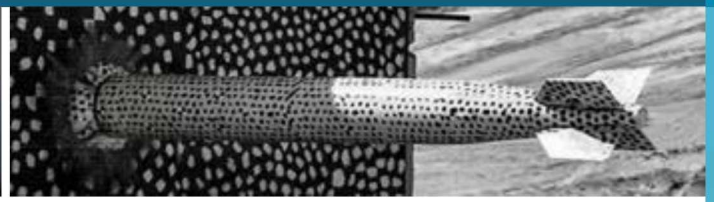
SAND2019-4124C

Sandia National Laboratories

Testing active polarimetric imagers in fog





PRESENTED BY

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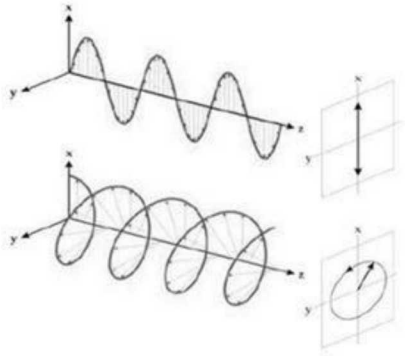
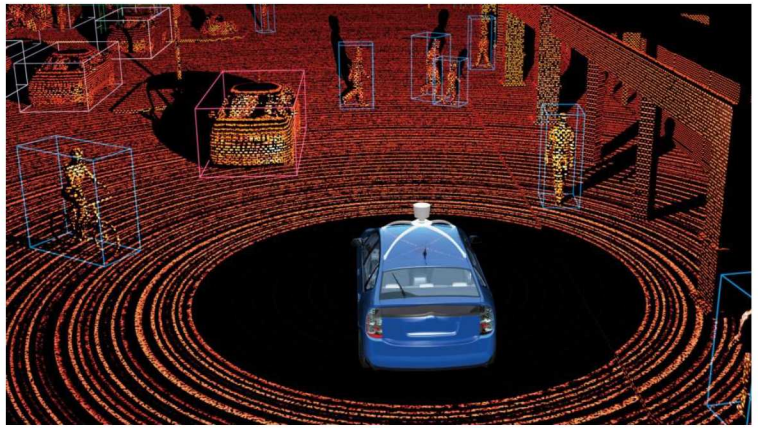
Polarimetric Imagers in Realistic Fog

- Motivation/Background
  - Sensing in degraded visual environments
  - Previous Simulation Predictions
    - Circular polarization persists better than linear polarization
  - Bio-inspired Imagers
- Real Fog Testing Environment
  - Sandia's Fog Facility
- Polarization Overview
- Polarimetric Imager Design
  - Visible and Short-wave Infrared (SWIR)
  - Linear and Circular polarization
- Experimental Setup
- Experimental Results
  - Circularly polarized imaging outperforms linearly polarized imaging



Motivation:
Increased signal through fog with polarized light

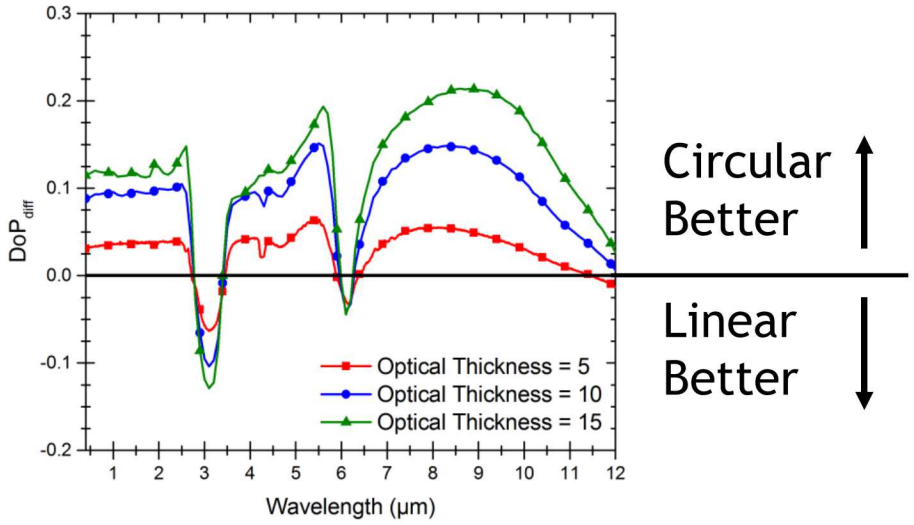
- Autonomous systems will need a multifaceted solution to sensing in fog



- Scattering environments decrease the ability to distinguish a target from the background

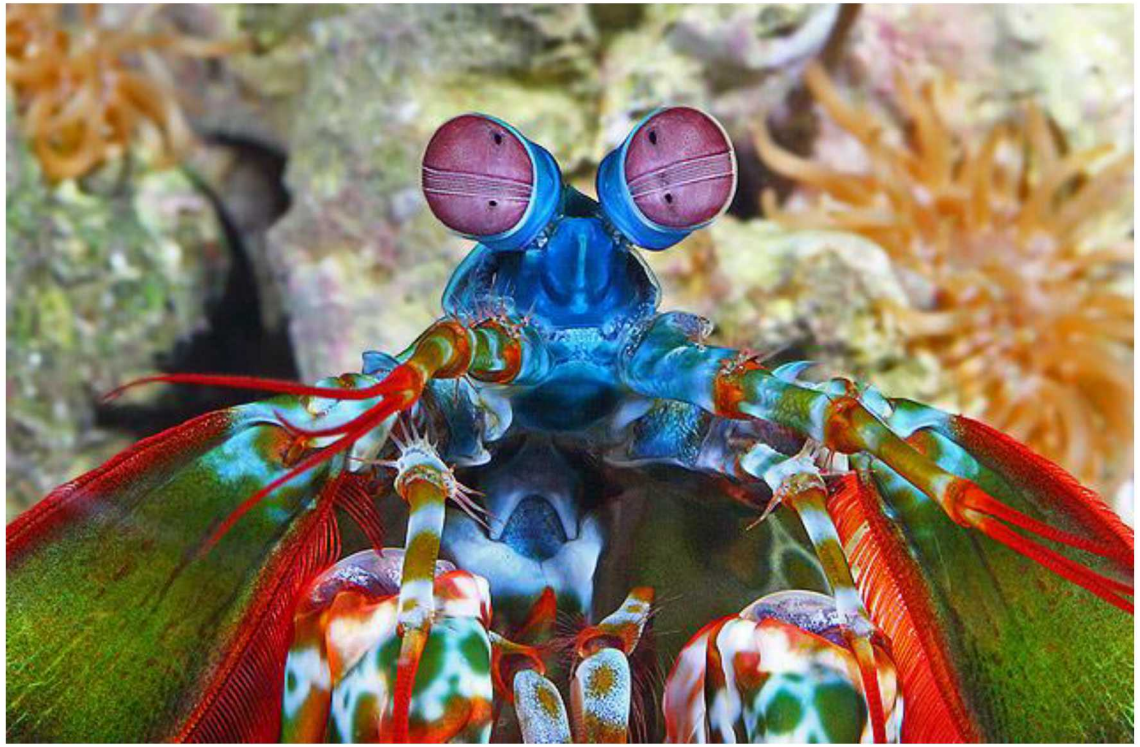
- Previous and ongoing research
  - Circular polarization persists superiorly compared to linear polarization in real-world forward-scattering fog environments

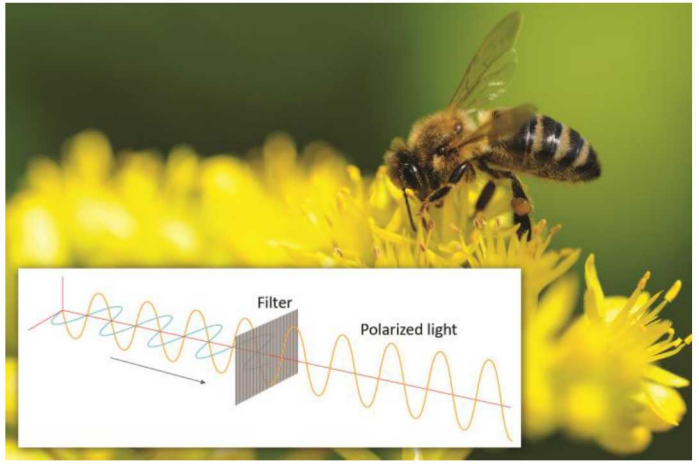
van der Laan, et. al, "Superior signal persistence of circularly polarized light in polydisperse, real-world fog environments," Appl. Opt. **57**, 5464-5473 (2018).



Motivation: Bio-inspired Imaging Systems

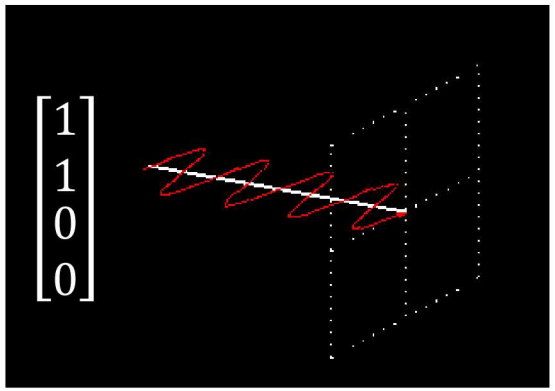
- Nature has evolved to see polarized light
- Insects use polarized vision for navigation
- Mantis shrimp can see both linear and circular polarizations
  - Likely used to find fellow mantis shrimp and prey in murky coastal waters
- Polarization difference imagers mimics biological imaging systems



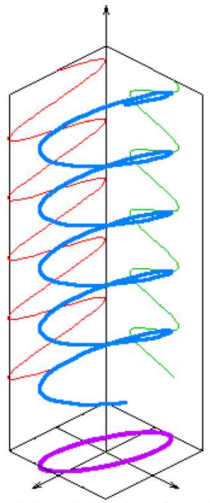


What is Polarized Light?

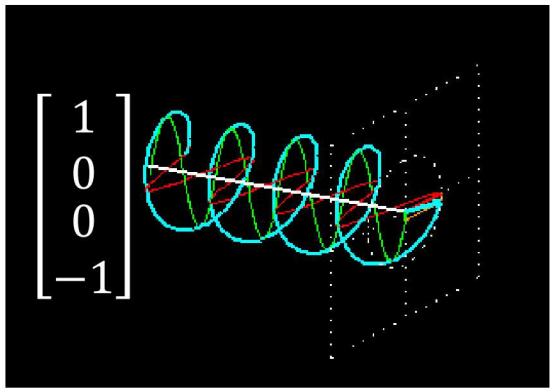
- Polarization defines the oscillation of the electric field in space and time, perpendicular to the light's propagation direction



Linear Polarization



Elliptical Polarization



Circular Polarization

- Stokes Vector

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

$I_H + I_V$ → Intensity

$I_H - I_V$ → Horizontal or Vertical Linear

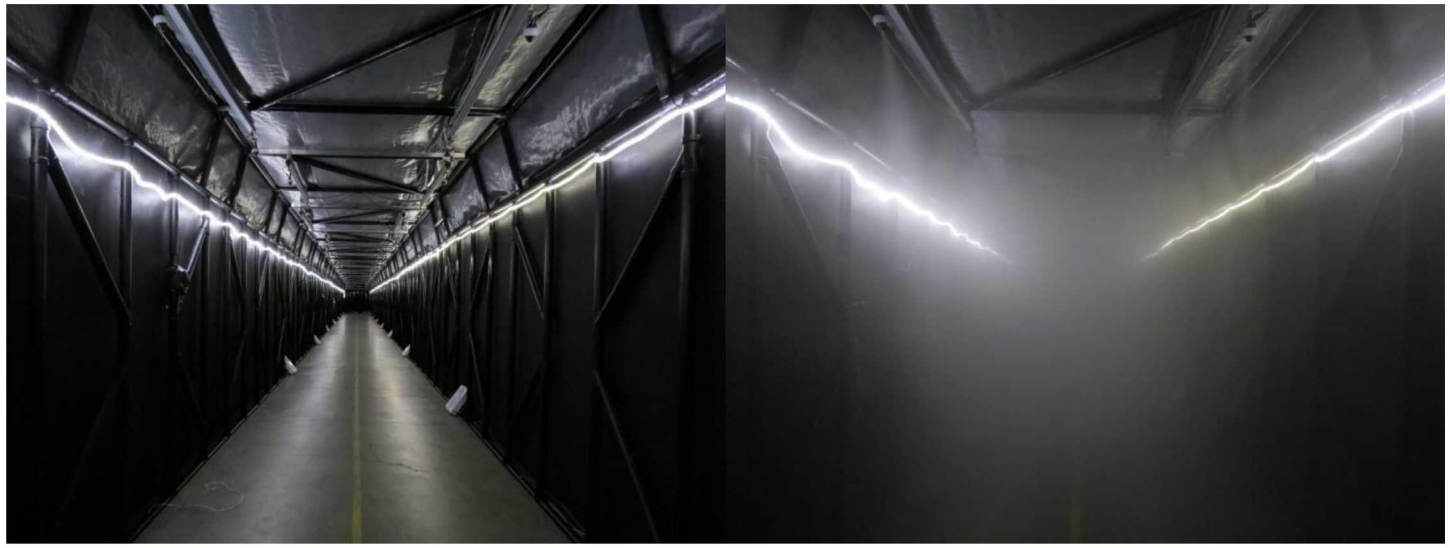
$I_{45} - I_{135}$ → 45 or 135 Degree Linear

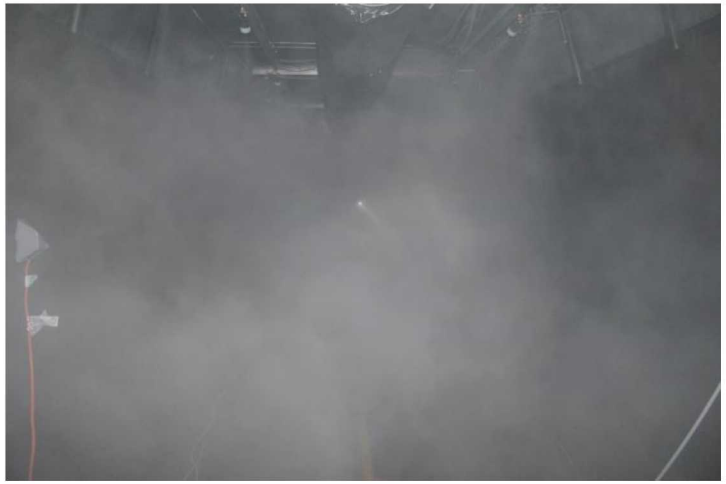
$I_R - I_L$ → Right or Left Circular

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

Fog Testing at Sandia's Fog Facility: Repeatable, measured fog environment

- Sandia Fog Facility:
  - Sandia has a unique fog generating test facility
  - Constructed in 2014 with Navy funds
  - Facility Dimensions: 10x10x180 feet
  - 64 spray nozzles
    - 3 controllable sections: 24, 24, 16 nozzles in each
  - Completely indoors – stable environment
  - Temperature control through A/C unit
  - Realistic fog particle size generation
- Continuously measured scattering parameters





Polarimetric Difference Imager Design: Similar design for SWIR and Visible Wavelengths

Visible Imager

- Images S_1 Stokes Value (Linear: Horizontal – Vertical)
- Images S_3 Stokes Value (Circular: Right – Left)
  - Addition of quarter waveplate

- Laser
  - SpectraPhysics, 532 nm, 200 mW

- Detectors:
  - Basler acA2440
    - 2448x2048, 3.45 µm pixels

- Lenses:
  - Navitar Vis 50 mm f/1.4
- Polarizing Beam Splitter:
  - Thorlabs, 2 inch, visible AR coating

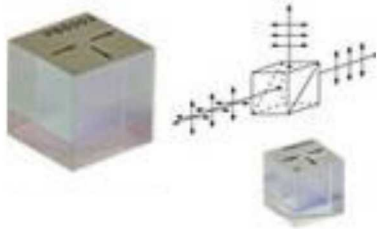
- Quarter Waveplate:
  - Thorlabs, 532 nm Zero Order

SWIR Imager

- Images S_1 Stokes Value (Linear: Horizontal – Vertical)
- Images S_3 Stokes Value (Circular: Right – Left)
  - Addition of quarter waveplate

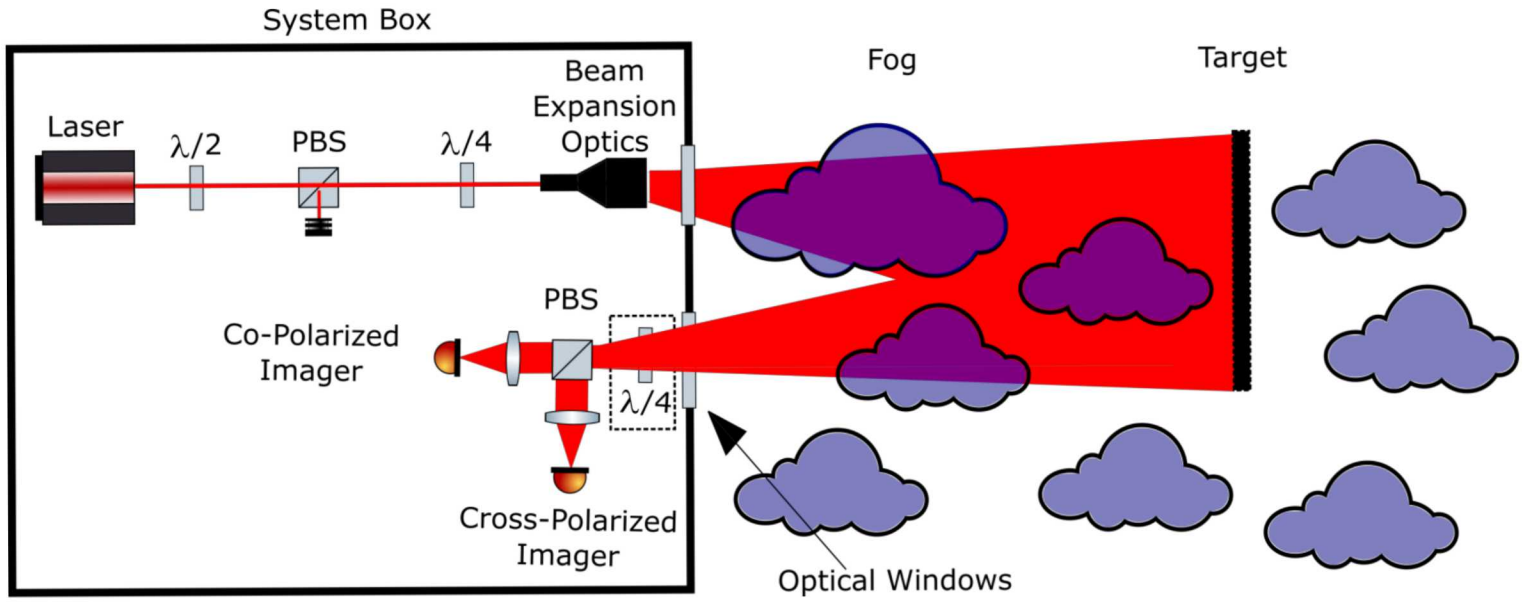
- Laser:
  - Thorlabs, 1550 nm, Single mode, 40 mW

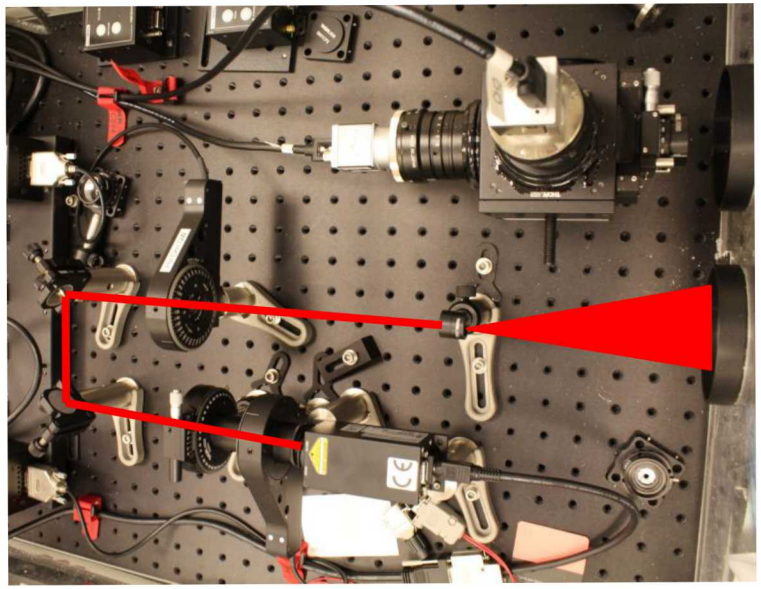
- Detectors:
  - FLIR Tau SWIR
    - 640x512, 15 µm pixel
- Lenses:
  - Navitar SWIR 50 mm f/1.4

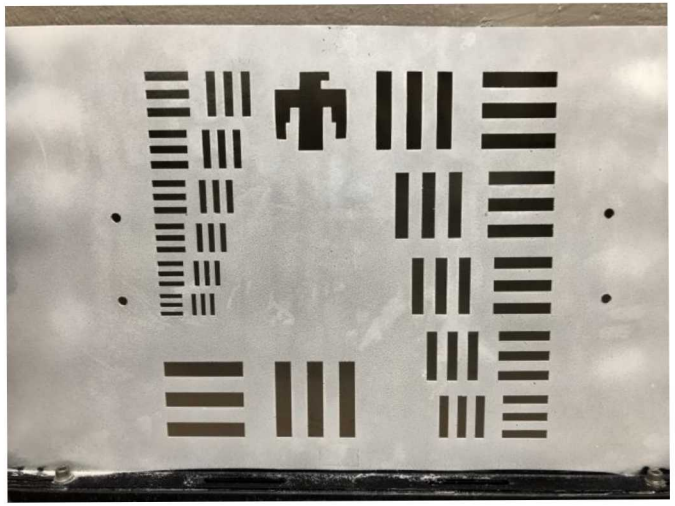


- Polarizing Beam Splitter:
  - Thorlabs, 2 inch, SWIR AR coating
- Quarter Waveplate:
  - Thorlabs, 1550 nm Zero Order

Experimental Setup: Imaging a Diffuse Resolution Target in Fog





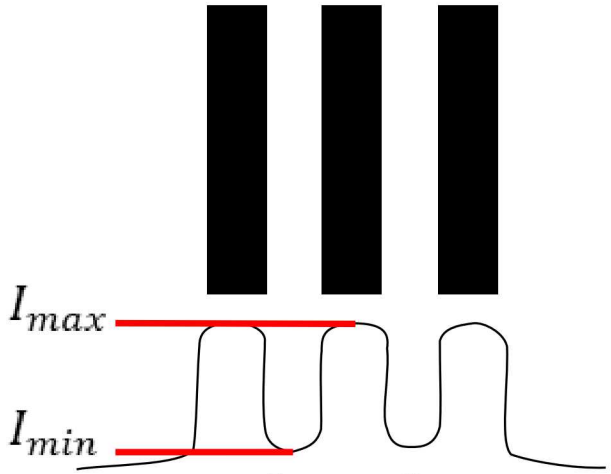


- Target:
  - Cutout aluminum with diffuse TiO2 paint
  - Additional targets tested (future publication)
    - Street sign materials
- Target Distance: 25 ft

Stokes Parameter Difference Imagers: Contrast measurements with varying fog density

- Visible and SWIR imagers are run at the same time with the same polarization settings
- Co and cross-polarized images are collected for a number of spray pulses
- The difference image is created from each co and cross-polarized image
  - Output: Linear Stokes image S_1, Circular Stokes image S_3

- Contrast Transfer Function (CTF)
  - Measured from each difference image
- Area Under the Curve (AUC)
  - Integration of the CTF curve



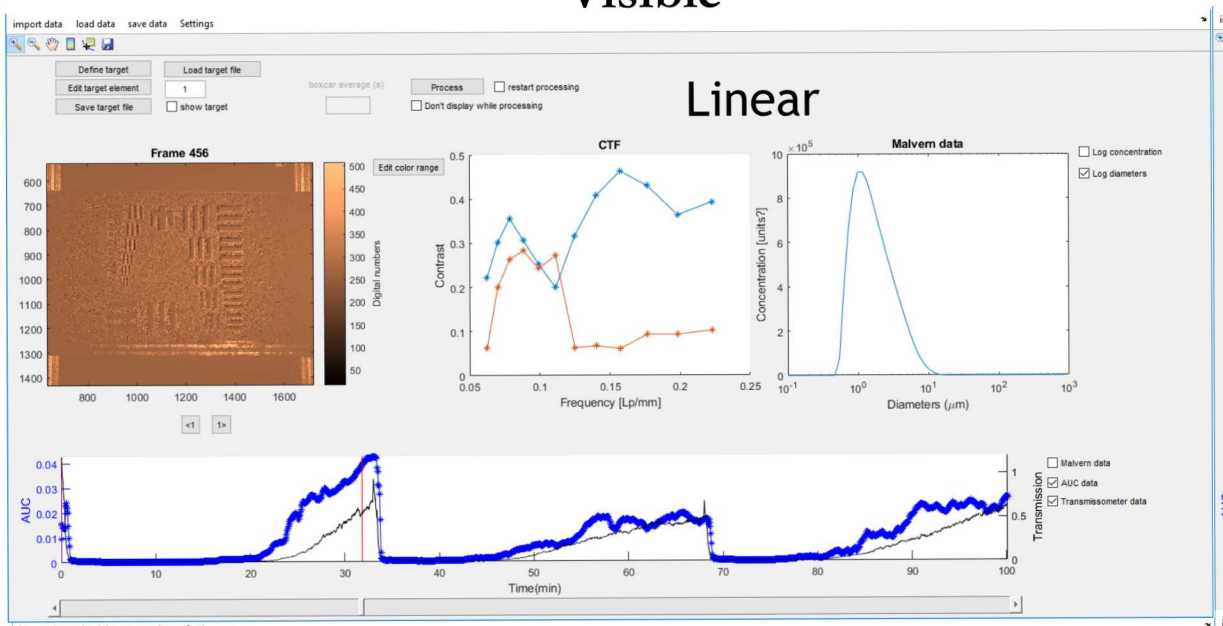
$$C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

Combining Multiple Fog Pulses

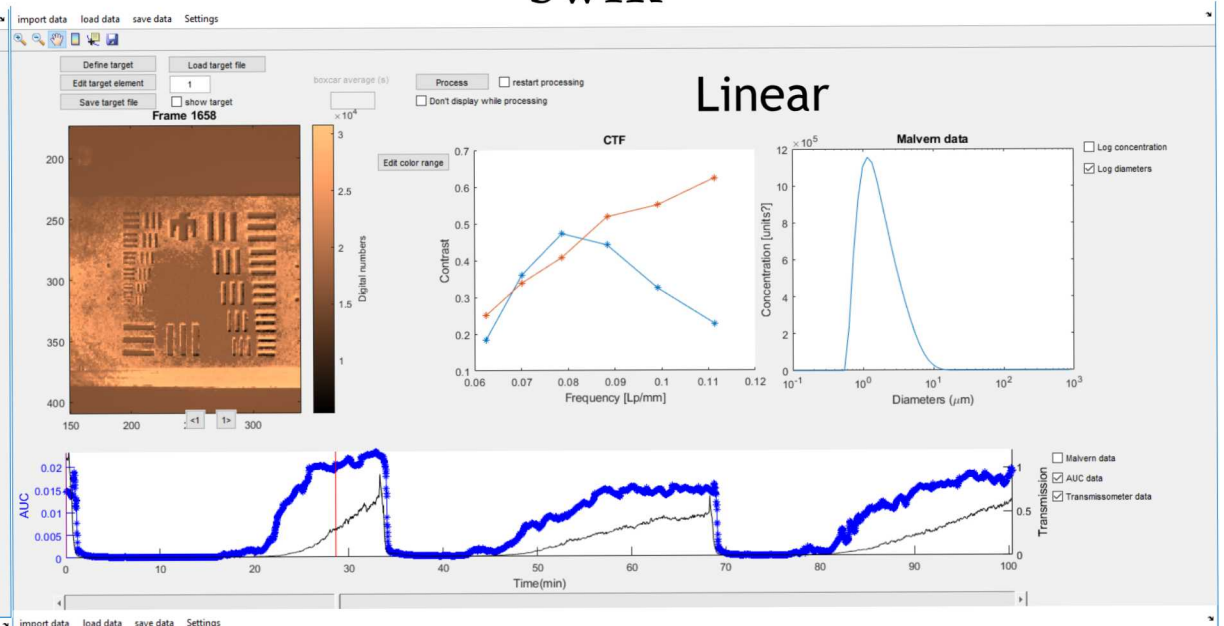
Visible

SWIR

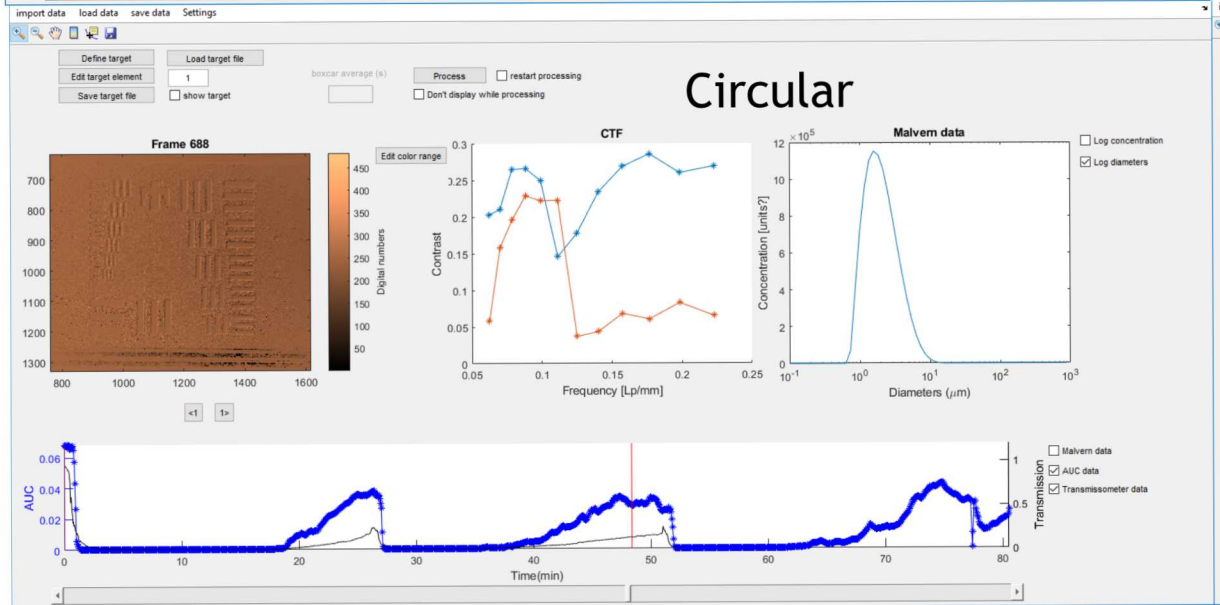
Linear



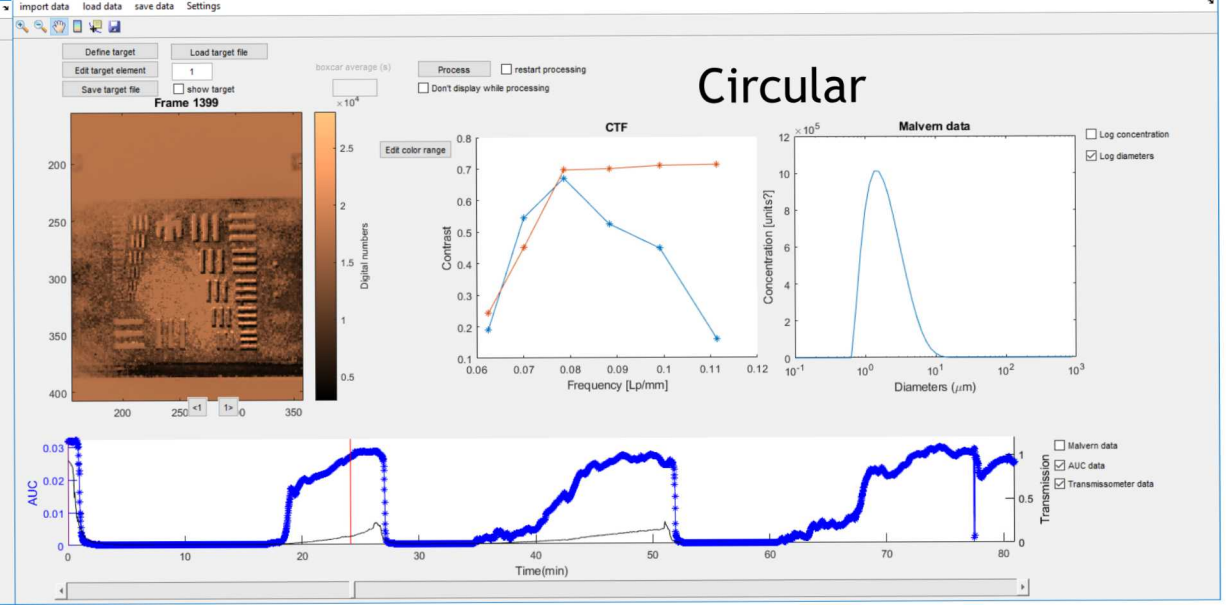
Linear



Circular

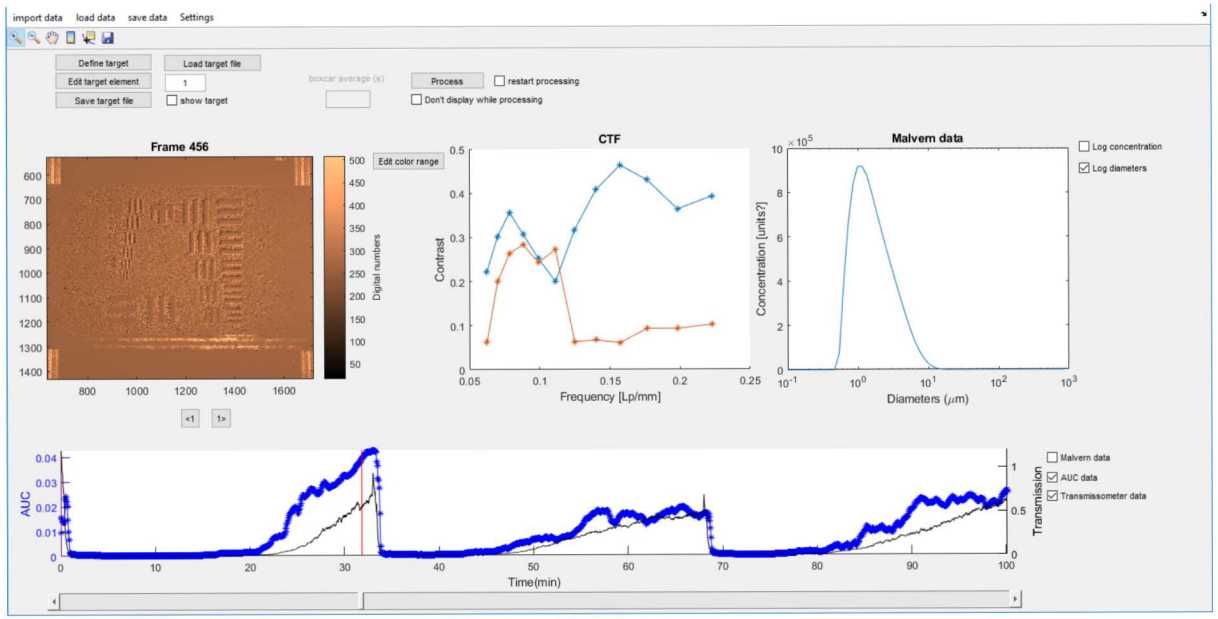


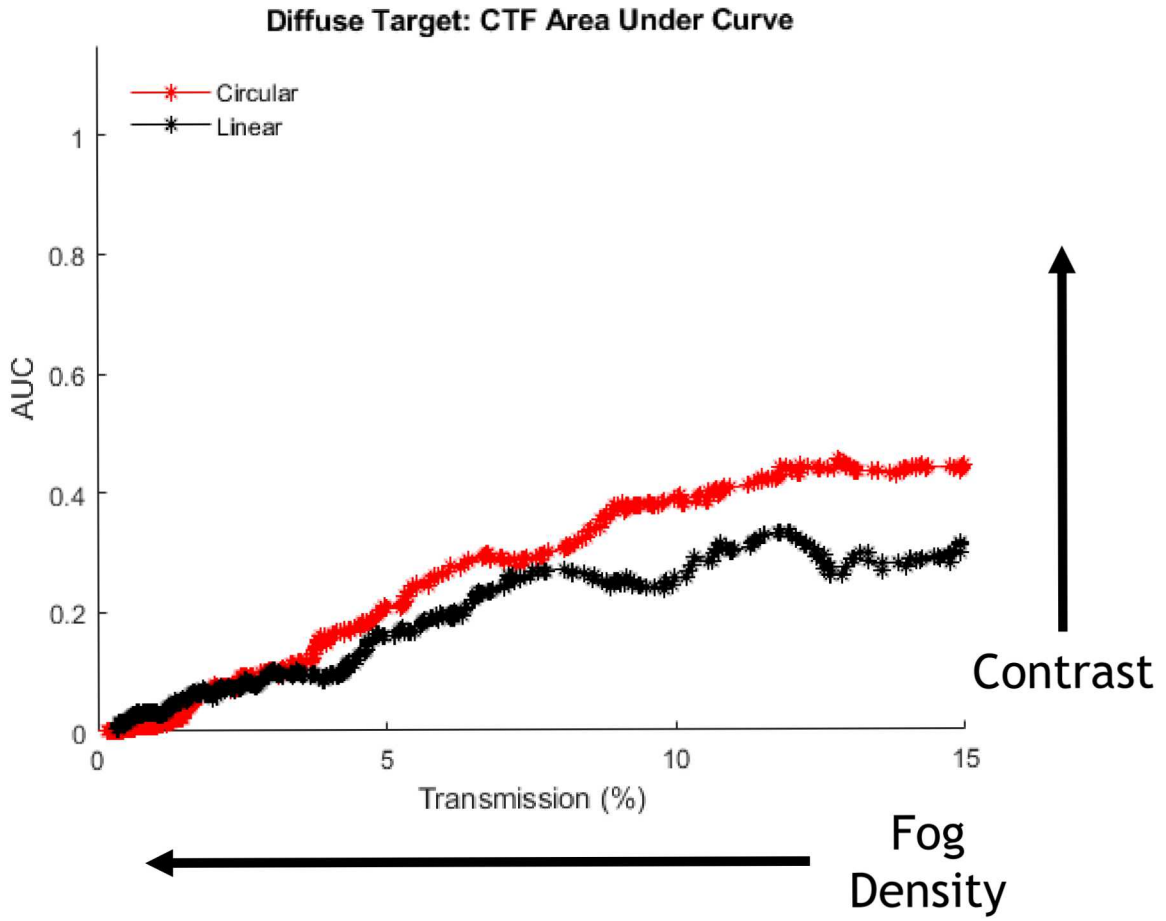
Circular



Experimental Results: Visible Imager Higher Contrast with Circularly Polarized Light

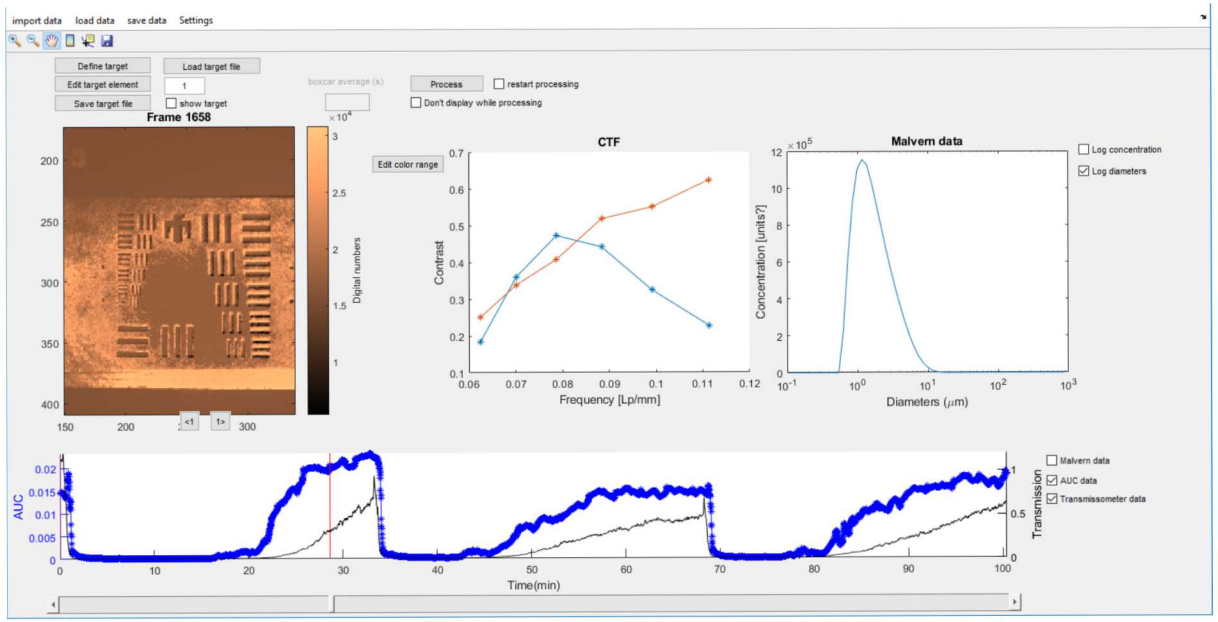
- CTF AUC values are normalized by the no fog baseline
- AUC organized based on transmission value
- Circular polarization has increased contrast compared to linear polarization for all but the densest fog environments

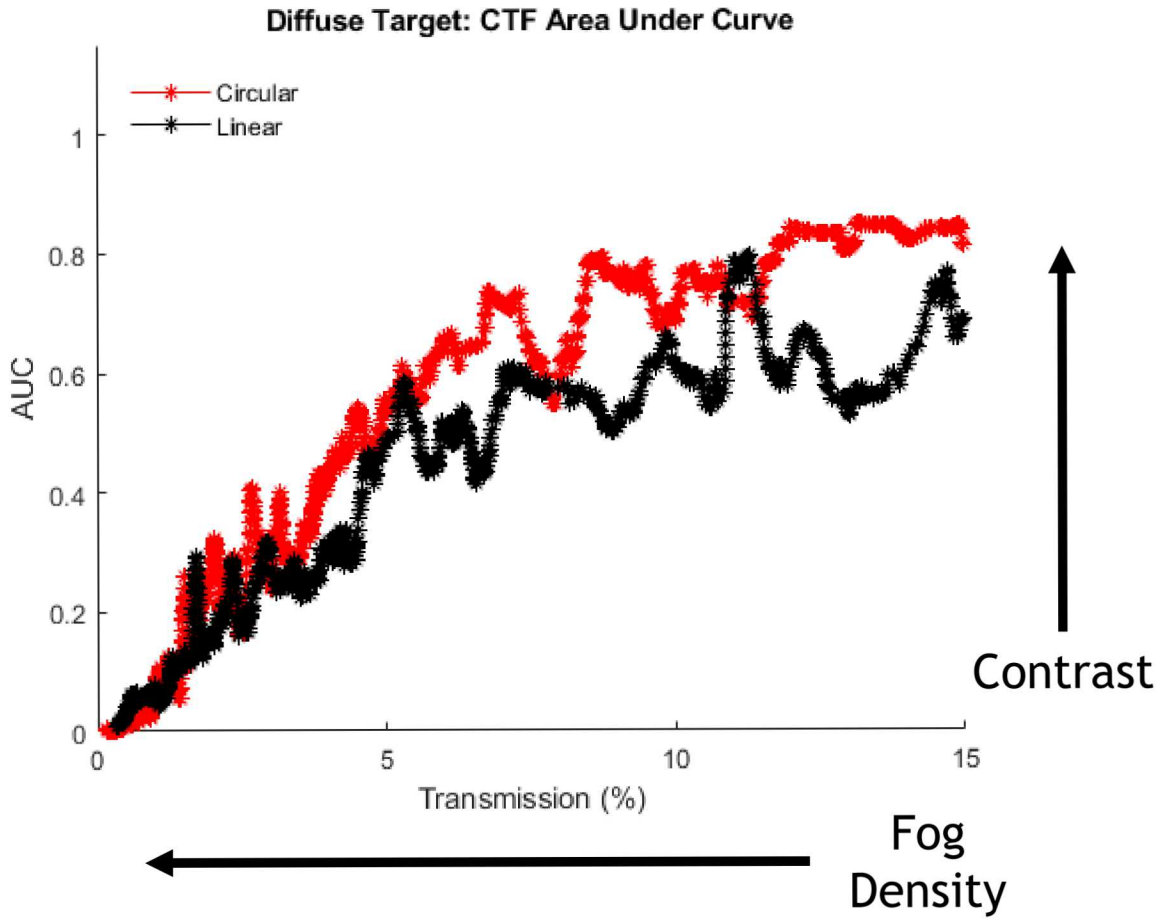




Experimental Results: SWIR Imager Higher Contrast with Circularly Polarized Light

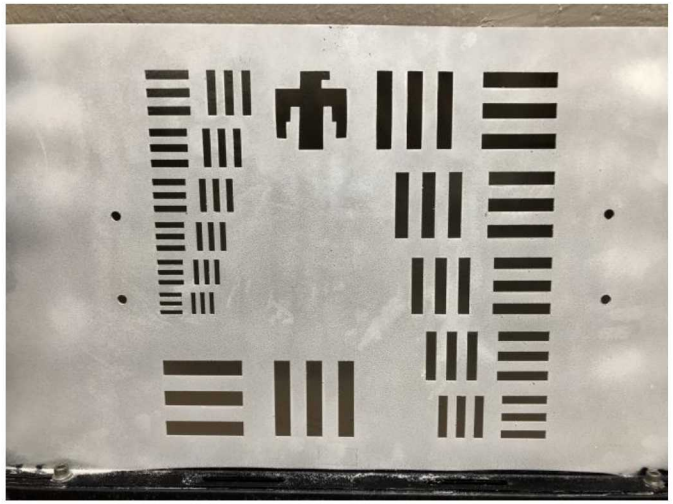
- CTF AUC values are normalized by the no fog baseline
- AUC organized based on transmission value
- Circular polarization has increased contrast compared to linear polarization for all but the densest fog environments
- SWIR has higher contrast than Visible

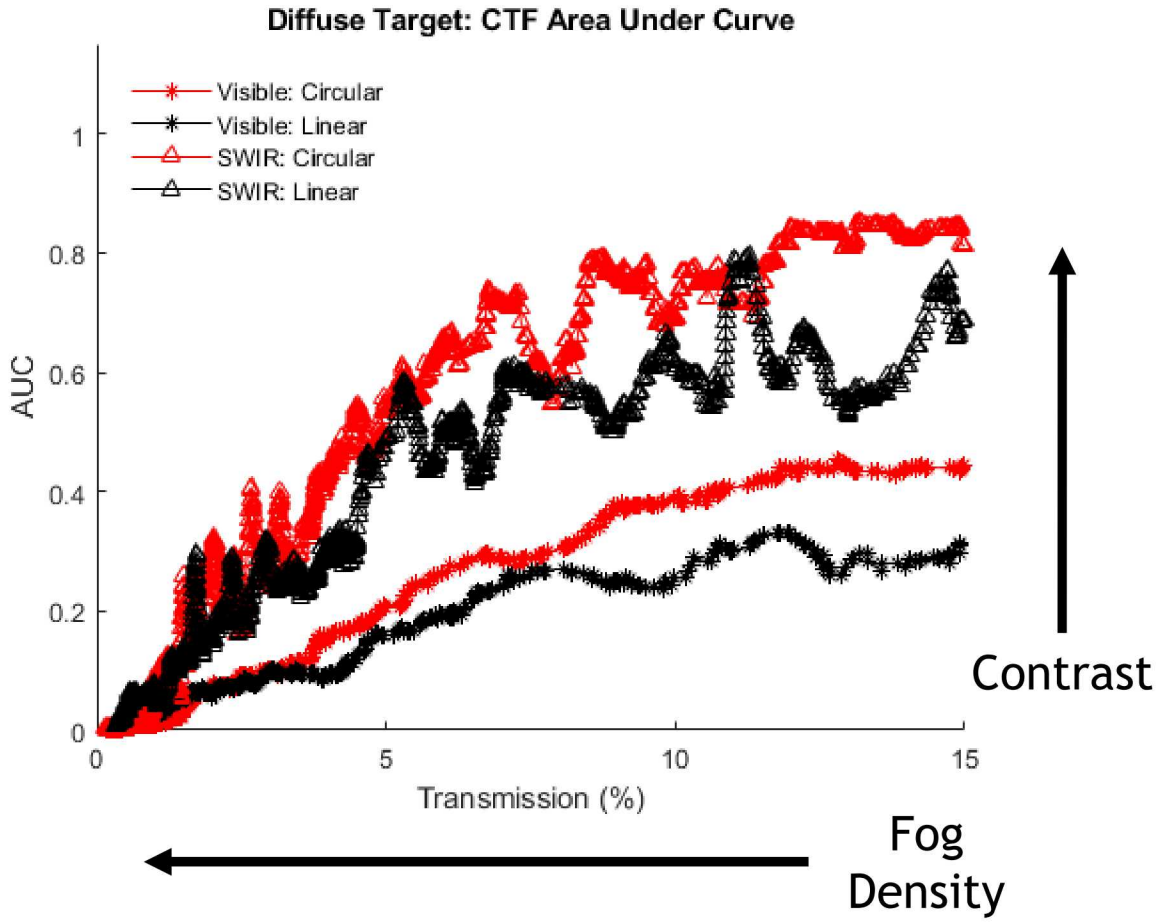




Comparison: Visible vs SWIR Wavelengths

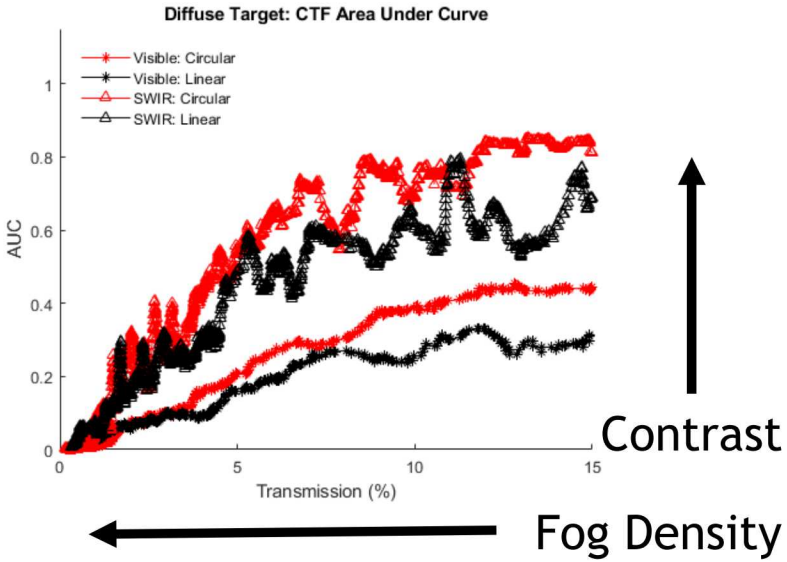
- SWIR imager shows **2-3x** contrast compared to visible imager
- SWIR results are noisier than the visible results
  - Likely due to reduced resolution and lower laser output power
  - More susceptible to small variations in the fog density
- SWIR penetrates fog better than visible with this diffuse target

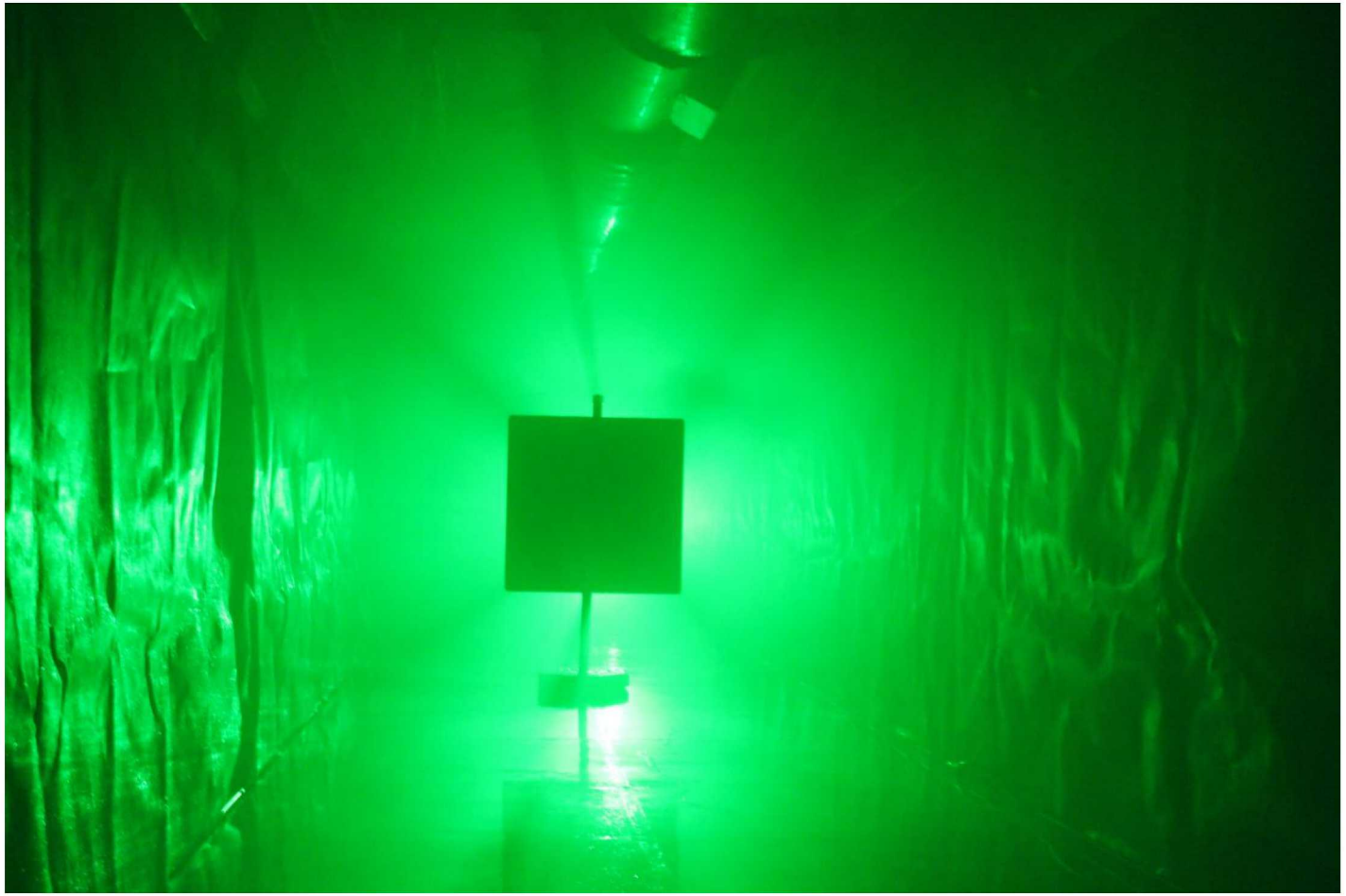




Circular polarization outperforms linear polarization in realistic fog environments

- Tested active polarimetric difference imagers in realistic fog environments
- Circular polarization outperforms linear polarization for both SWIR and visible systems
- SWIR imaging system has higher contrast than the visible imaging system
- Ongoing work will present results from reflective targets (future publications)





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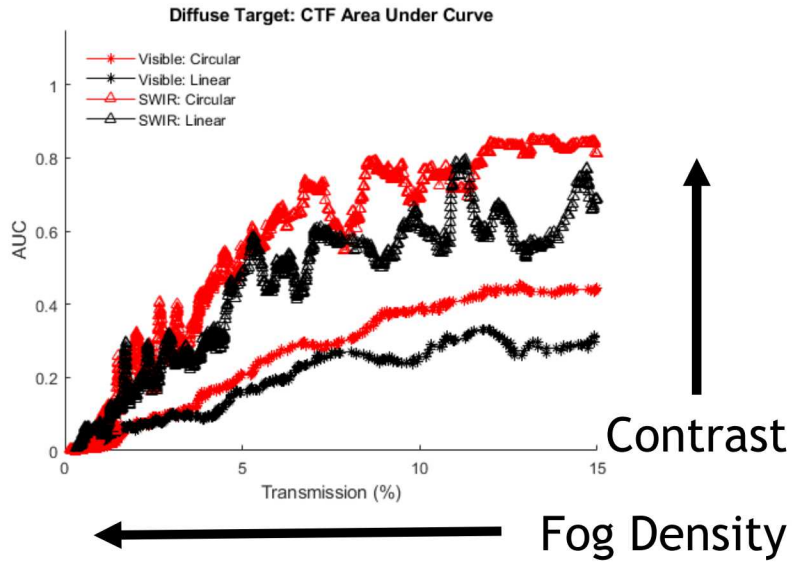

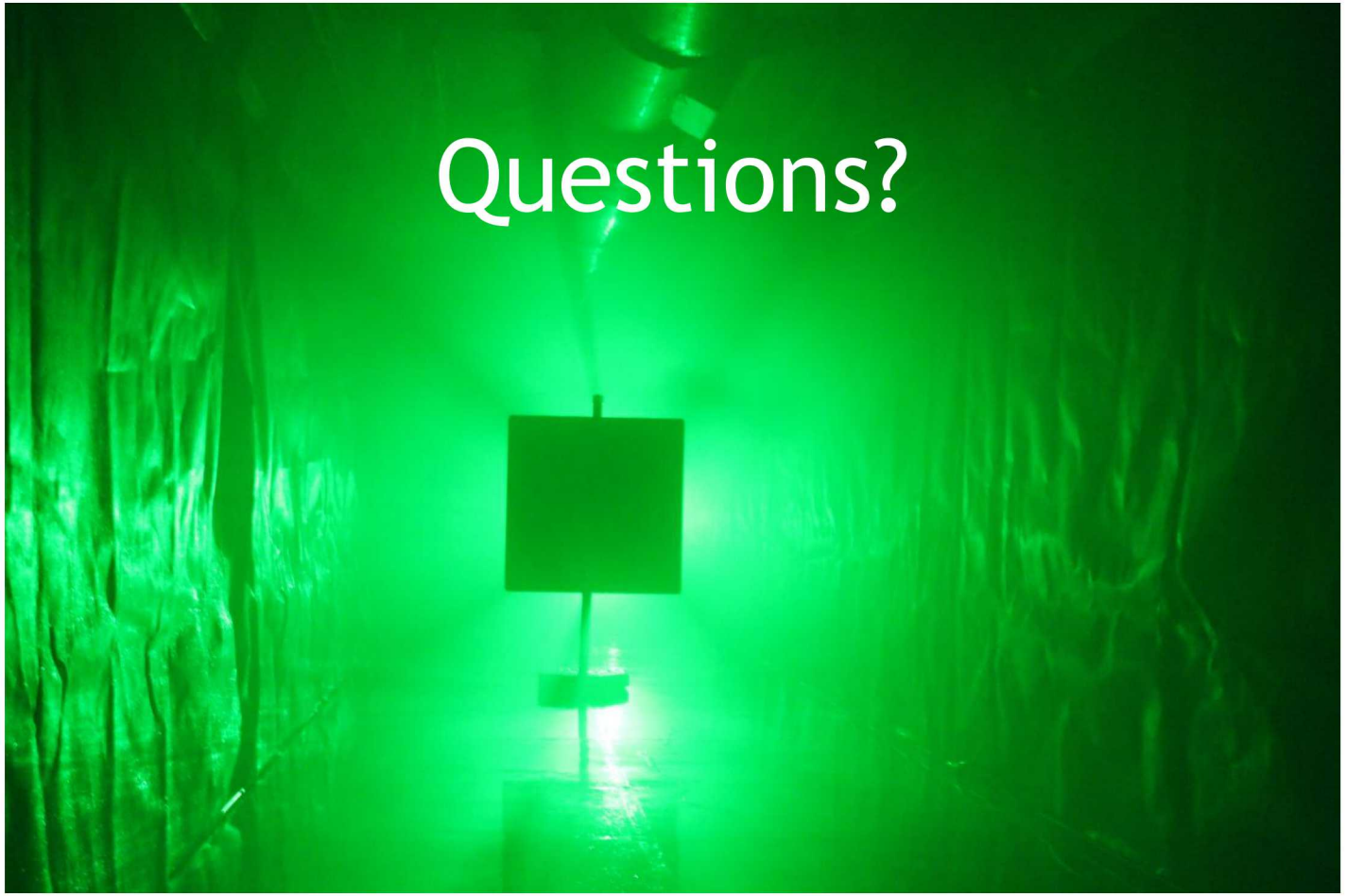

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