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Variation of linear and circular polarization persistence for changing field of view and collection area in a forward scattering environment

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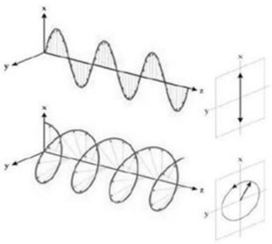
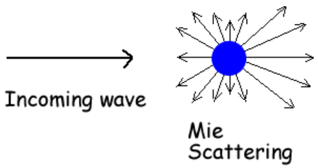
Outline

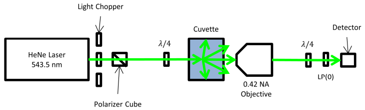
- Motivation

- Background Theory





- Simulation Results
- Experimental Results



- Conclusions
  - $Circular\ DoP_{collected} > Linear\ DoP_{collected}$
  - Circular polarization is more tolerant of collection geometry variations for the forward scattering environments

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Motivation

- Scattering particles change the direction of ambient or active illuminating radiation, reducing the radiation that reaches and ultimately returns from a target of interest
- Scattering environments decrease the ability to distinguish a target from the background

- Our previous research has shown that circular polarization persists superiorly compared to linear polarization in forward scattering environments
  - How does field of view and collection area variations affect this persistence?

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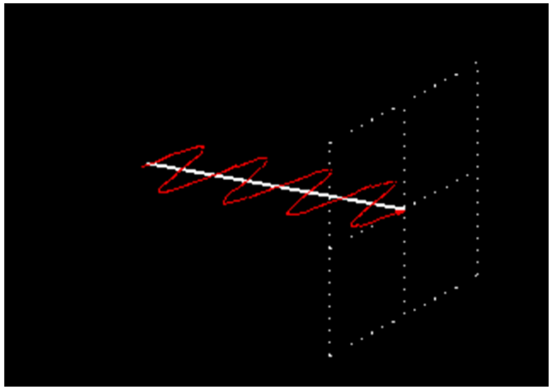
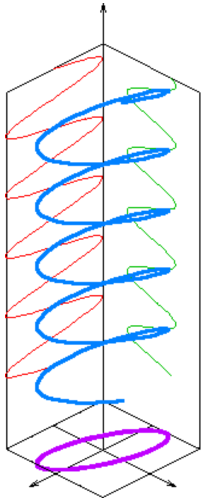
Polarization: Stokes Formalism

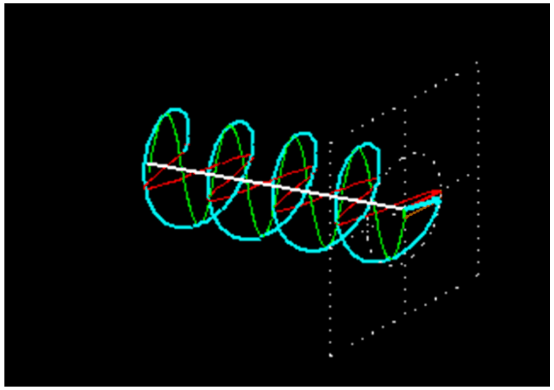
- Polarization defines the oscillation of the electric field in space and time, perpendicular to the light’s propagation direction



Linear Polarization



Elliptical Polarization



Circular Polarization

- Stokes Formalism

$$\vec{\boldsymbol{S}} = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} \langle E_\parallel \, E_\parallel^* + E_\perp \, E_\perp^* \rangle \\ \langle E_\parallel \, E_\parallel^* - E_\perp \, E_\perp^* \rangle \\ \langle E_\parallel \, E_\perp^* + E_\perp \, E_\parallel^* \rangle \\ i \, \langle E_\parallel \, E_\perp^* - E_\perp \, E_\parallel^* \rangle \end{bmatrix} \propto \begin{bmatrix} I_H + I_V \\ I_H - I_V \\ I_{45} - I_{135} \\ I_R - I_L \end{bmatrix} \begin{array}{l} \rightarrow \text{Intensity} \\ \rightarrow \text{Horizontal or Vertical Linear} \\ \rightarrow \text{45 or 135 Degree Linear} \\ \rightarrow \text{Right or Left Circular} \end{array}$$

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

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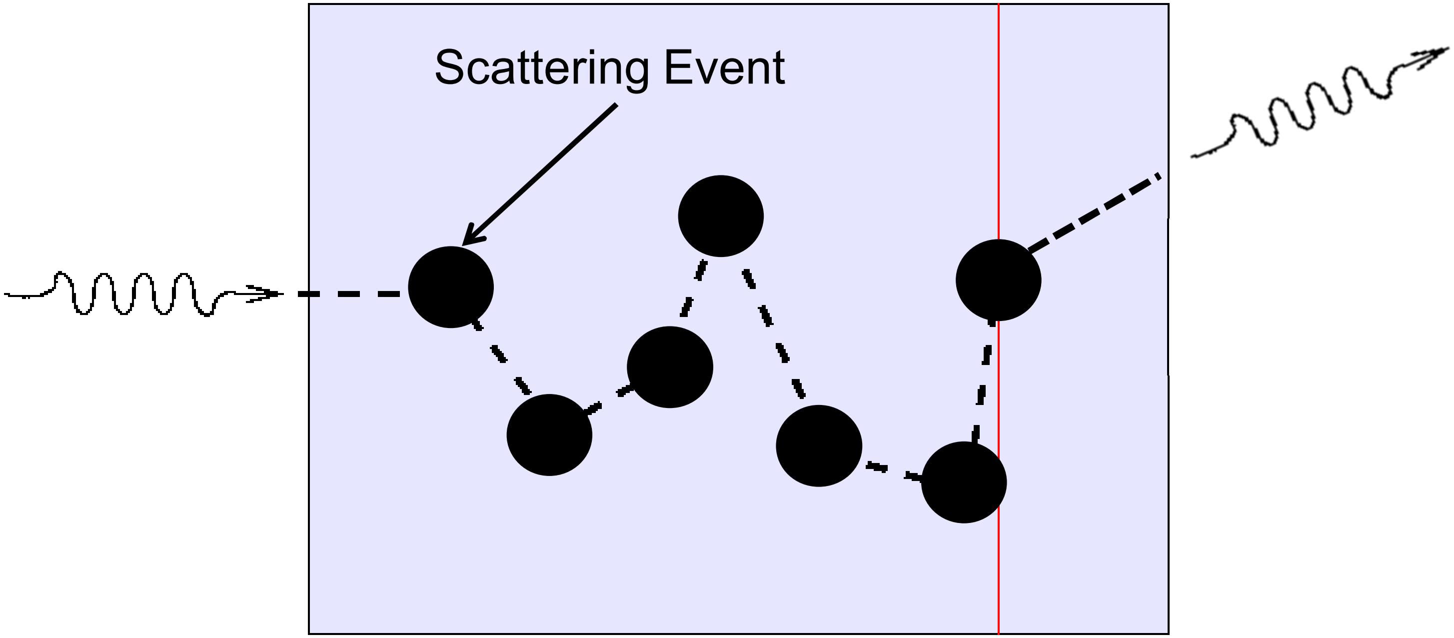
Polarization Tracking Monte Carlo



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

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

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

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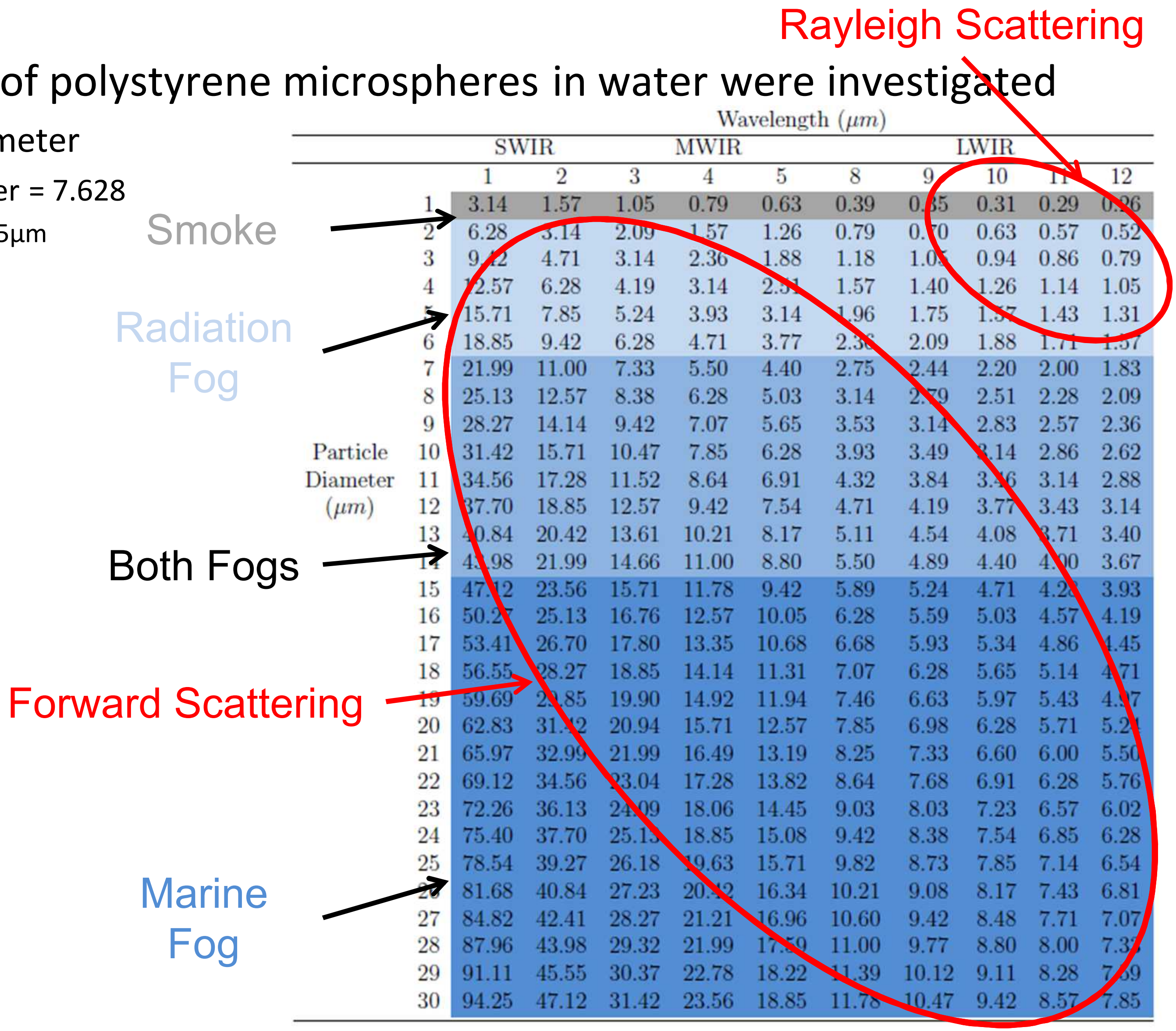
Scattering Environment

- One particle size of polystyrene microspheres in water were investigated
  - 0.99 micron Diameter
    - Size Parameter = 7.628
      - λ=0.5435μm

- Size Parameter

$$x = k\,a = \frac{2\,\pi\,n\,a}{\lambda}$$

- This size parameter corresponds to a forward scattering environment of marine (advection) fog at Long-wave Infrared wavelengths



Rayleigh Scattering

Smoke

Radiation Fog

Both Fogs

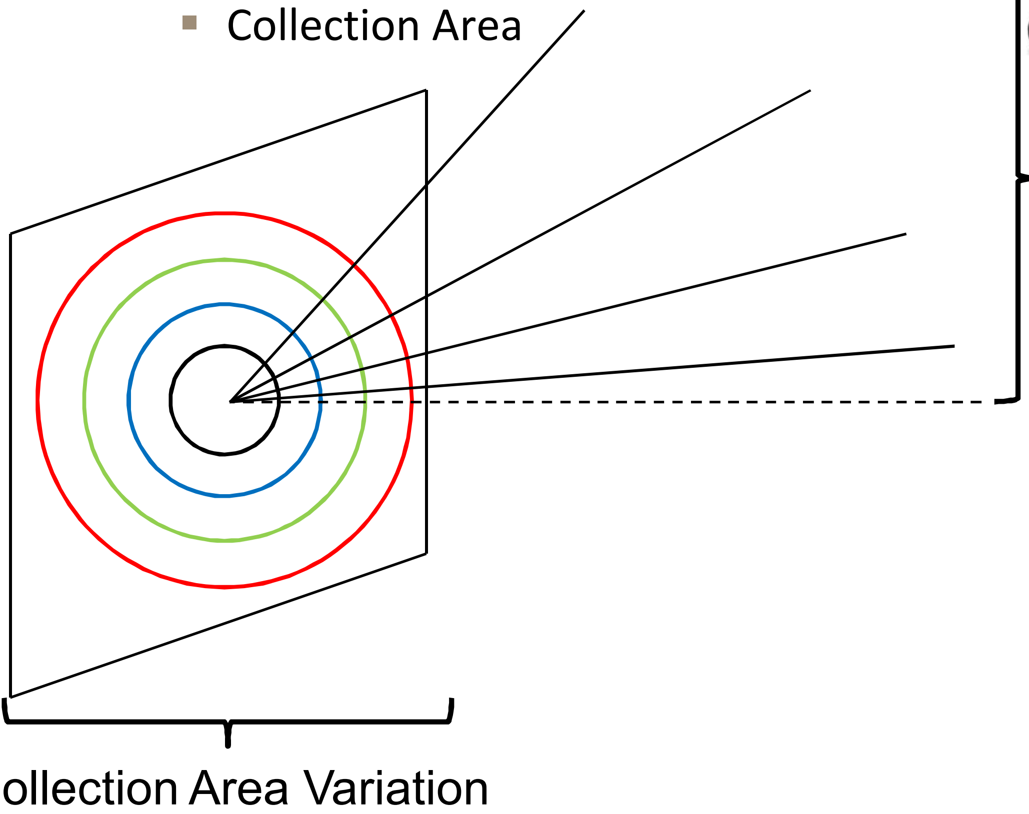
Forward Scattering

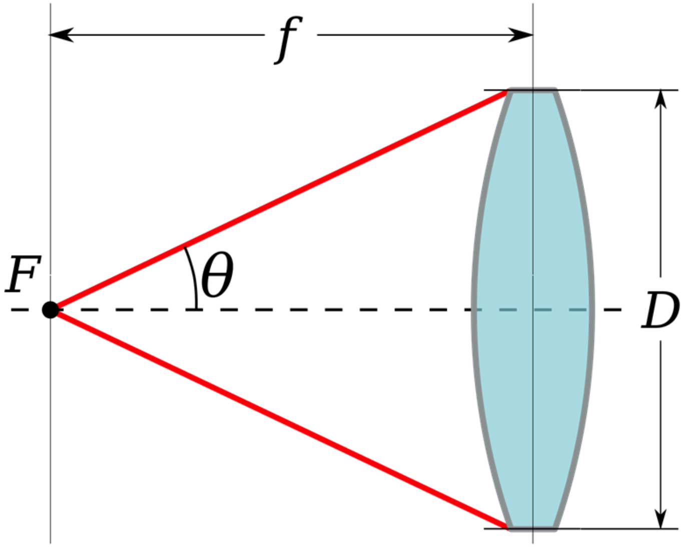
Marine Fog

		Wavelength (μm)									
		SWIR		MWIR			LWIR				
		1	2	3	4	5	8	9	10	11	12
	1	3.14	1.57	1.05	0.79	0.63	0.39	0.35	0.31	0.29	0.26
	2	6.28	3.14	2.09	1.57	1.26	0.79	0.70	0.63	0.57	0.52
	3	9.42	4.71	3.14	2.36	1.88	1.18	1.05	0.94	0.86	0.79
	4	12.57	6.28	4.19	3.14	2.51	1.57	1.40	1.26	1.14	1.05
	5	15.71	7.85	5.24	3.93	3.14	1.96	1.75	1.57	1.43	1.31
	6	18.85	9.42	6.28	4.71	3.77	2.36	2.09	1.88	1.71	1.57
	7	21.99	11.00	7.33	5.50	4.40	2.75	2.44	2.20	2.00	1.83
	8	25.13	12.57	8.38	6.28	5.03	3.14	2.79	2.51	2.28	2.09
	9	28.27	14.14	9.42	7.07	5.65	3.53	3.14	2.83	2.57	2.36
Particle Diameter (μm)	10	31.42	15.71	10.47	7.85	6.28	3.93	3.49	3.14	2.86	2.62
	11	34.56	17.28	11.52	8.64	6.91	4.32	3.84	3.46	3.14	2.88
	12	37.70	18.85	12.57	9.42	7.54	4.71	4.19	3.77	3.43	3.14
	13	40.84	20.42	13.61	10.21	8.17	5.11	4.54	4.08	3.71	3.40
	14	43.98	21.99	14.66	11.00	8.80	5.50	4.89	4.40	4.00	3.67
	15	47.12	23.56	15.71	11.78	9.42	5.89	5.24	4.71	4.28	3.93
	16	50.27	25.13	16.76	12.57	10.05	6.28	5.59	5.03	4.57	4.19
	17	53.41	26.70	17.80	13.35	10.68	6.68	5.93	5.34	4.86	4.45
	18	56.55	28.27	18.85	14.14	11.31	7.07	6.28	5.65	5.14	4.71
	19	59.69	29.85	19.90	14.92	11.94	7.46	6.63	5.97	5.43	4.97
	20	62.83	31.42	20.94	15.71	12.57	7.85	6.98	6.28	5.71	5.24
	21	65.97	32.99	21.99	16.49	13.19	8.25	7.33	6.60	6.00	5.50
	22	69.12	34.56	23.04	17.28	13.82	8.64	7.68	6.91	6.28	5.76
	23	72.26	36.13	24.09	18.06	14.45	9.03	8.03	7.23	6.57	6.02
	24	75.40	37.70	25.13	18.85	15.08	9.42	8.38	7.54	6.85	6.28
	25	78.54	39.27	26.18	19.63	15.71	9.82	8.73	7.85	7.14	6.54
	26	81.68	40.84	27.23	20.42	16.34	10.21	9.08	8.17	7.43	6.81
	27	84.82	42.41	28.27	21.21	16.96	10.60	9.42	8.48	7.71	7.07
	28	87.96	43.98	29.32	21.99	17.59	11.00	9.77	8.80	8.00	7.33
	29	91.11	45.55	30.37	22.78	18.22	11.39	10.12	9.11	8.28	7.59
	30	94.25	47.12	31.42	23.56	18.85	11.78	10.47	9.42	8.57	7.85

Collection Geometry Variations

- How important is the collection geometry for polarization persistence in scattering environments?
  - Variables in the Collection Geometry
    - Angular Field of View
    - Collection Area

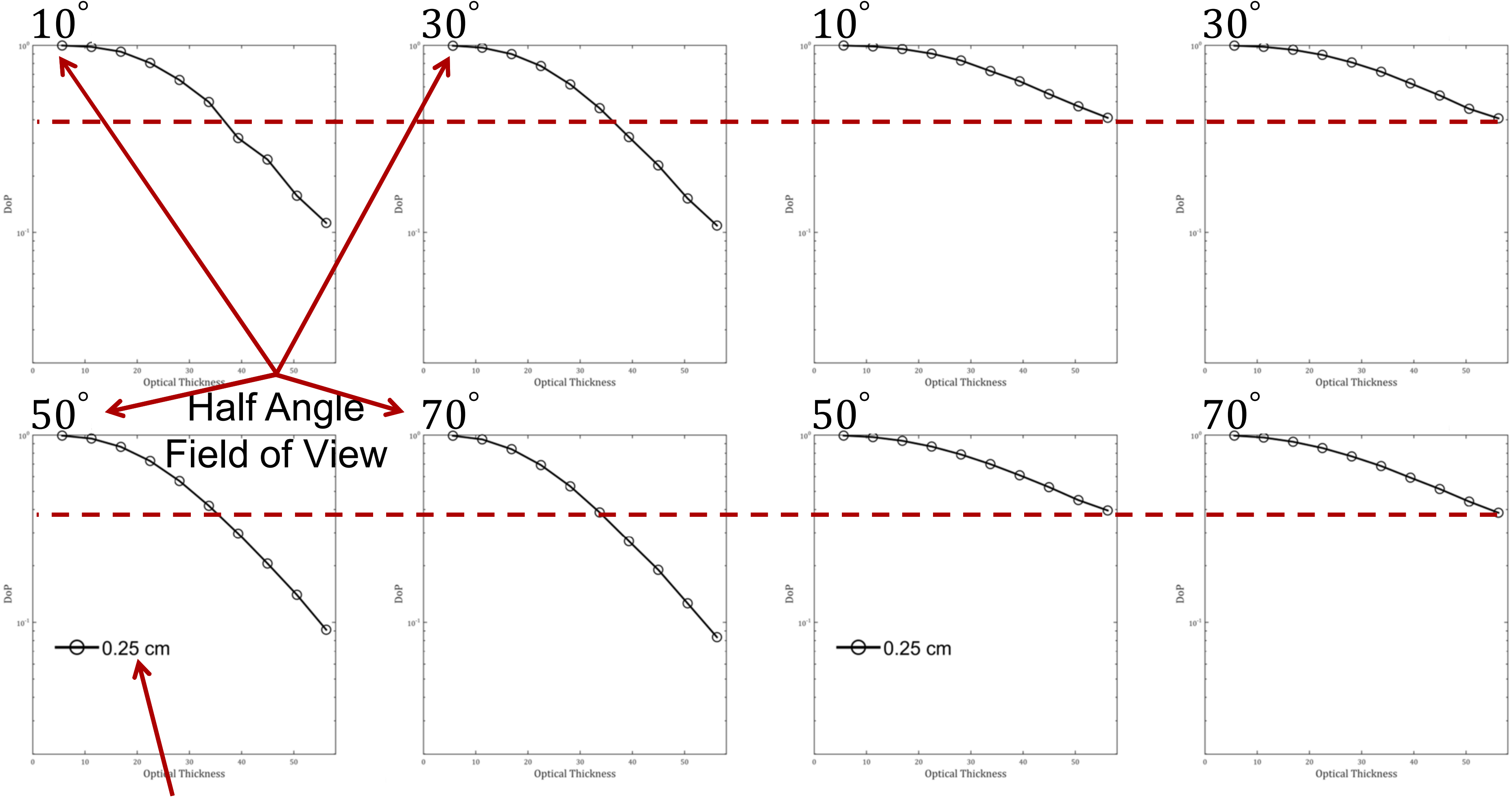




Collection Variation: 0.99 micron particles

Linear Polarization

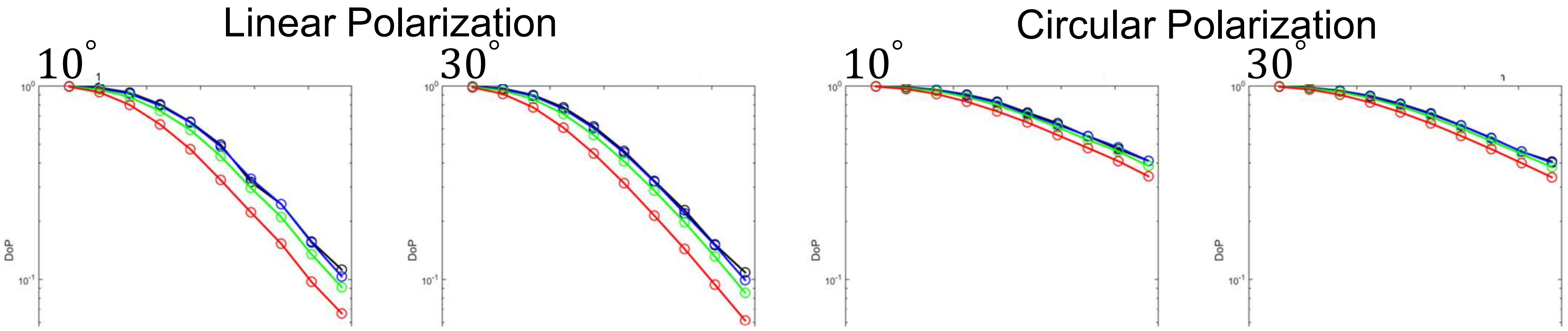
Circular Polarization



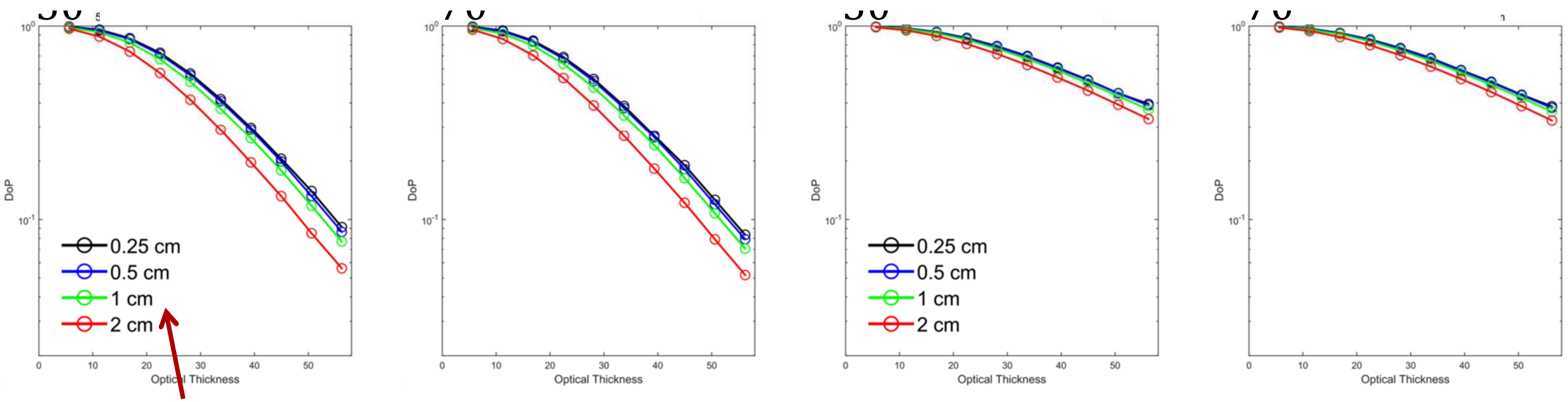
Radius of
Collection Area

Optical Thickness
$\tau = \rho\ \sigma_{ext}\ L$

Collection Variation: 0.99 micron particles



Circular polarization is more tolerant of collection geometry variations for the forward scattering environments

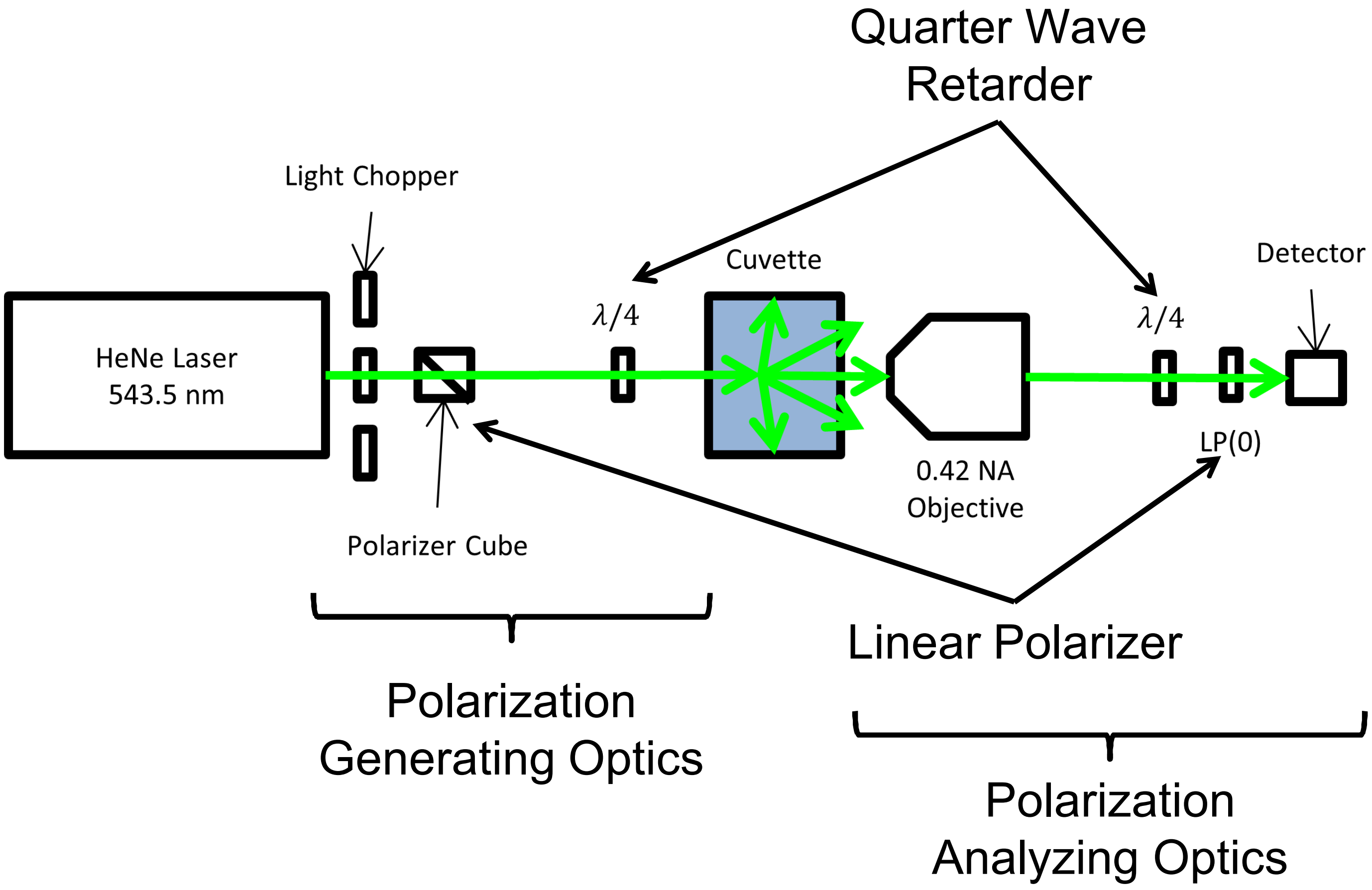


Radius of Collection Area

Optical Thickness

$$\tau = \rho\, \sigma_{ext}\, L$$

Experimental Setup



- Rotating quarter wave retarder, fixed-polarizer polarimeter

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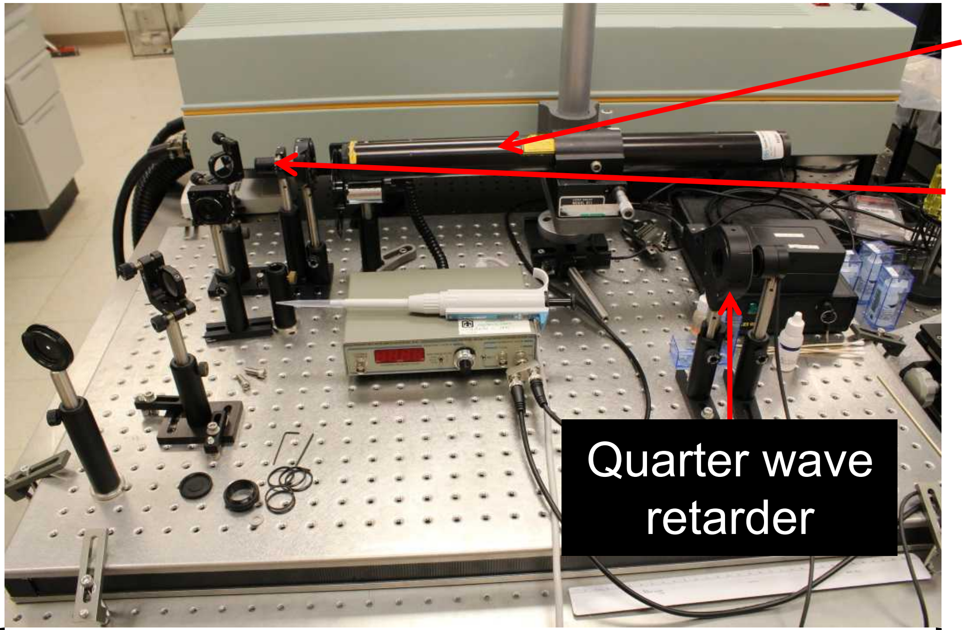
Experimental Setup

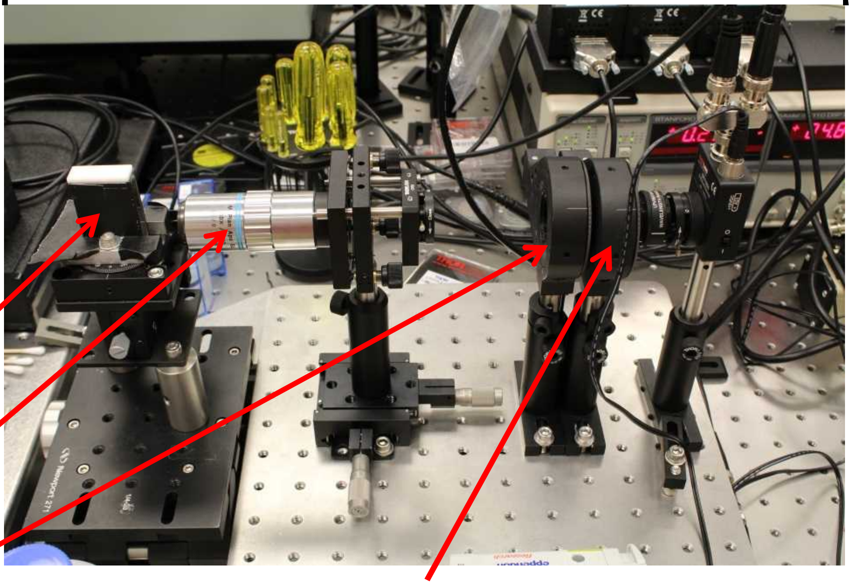


Laser

Polarizing Beam Cube

Polarization Generating Optics

Cuvette and Polarization Analyzing Optics



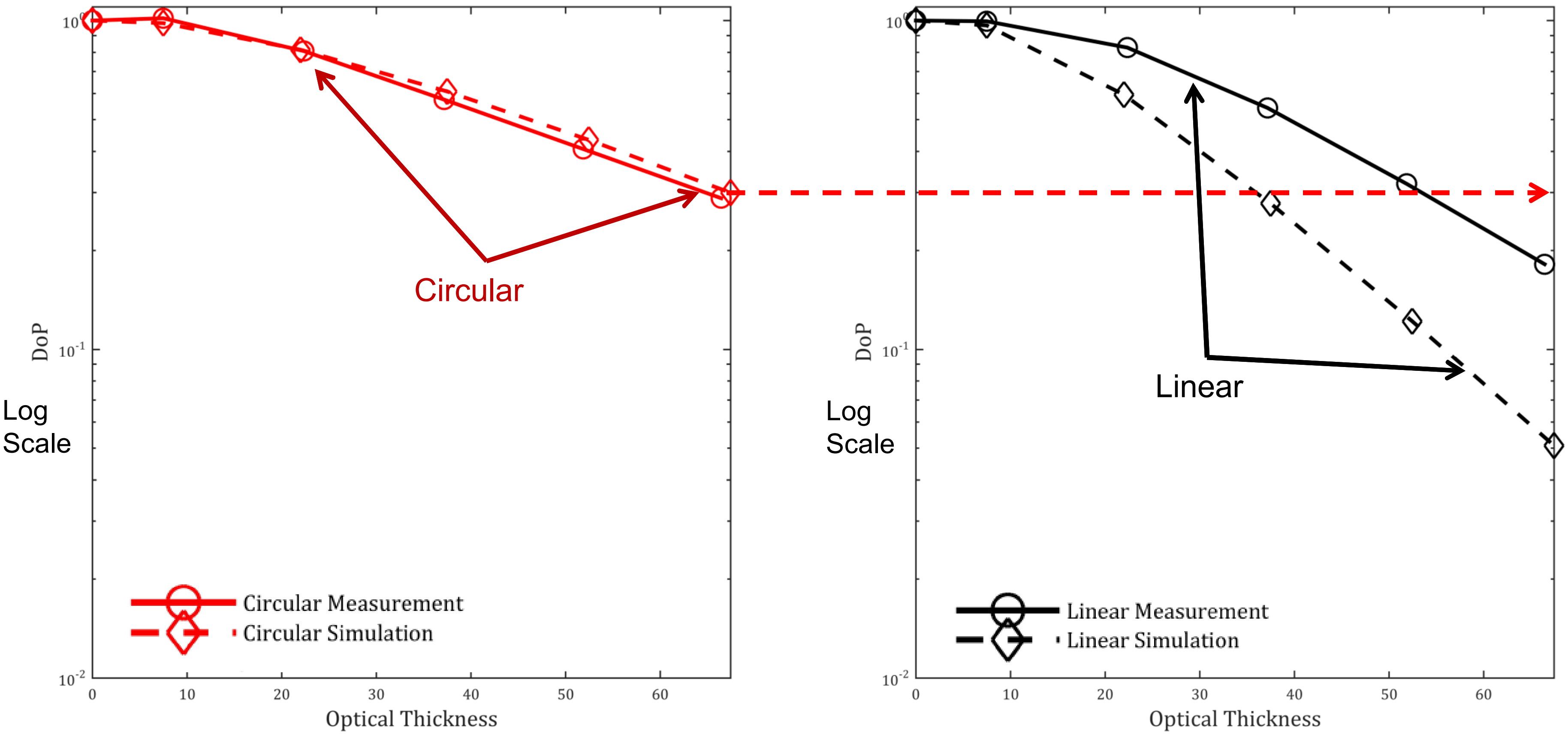
Cuvette

Objective

Quarter wave retarder

Polarizer

Experimental Results: 0.99 micron particles



Circular

Linear

Log Scale

Log Scale

Increasing Density →

Increasing Density →

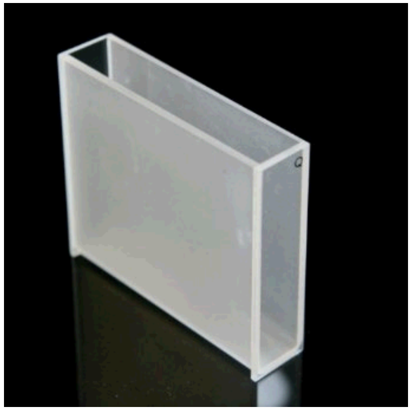
Optical Thickness

$$\tau = \rho\, \sigma_{ext}\, L$$

Simulation collection geometry matches experimental setup

Simulation vs. Experiment

- Monte Carlo simulations currently have an infinite lateral extent for the scattering environment
- Experimental cuvette’s lateral dimensions are limited compared to the simulation
  - Dimensions: 1 cm wide, 3 cm long, 4 cm high



- The cuvette walls can reinject photons that would otherwise be scattered out of the collection geometry
  - The cuvette walls affect linear polarization but circular polarization is unaffected
- Future simulations will take into account the limited lateral extent of the scattering environment and the addition of Fresnel reflections from the glass interface

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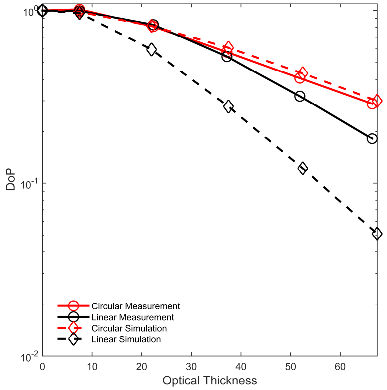
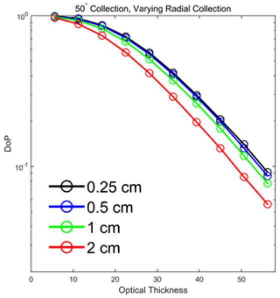
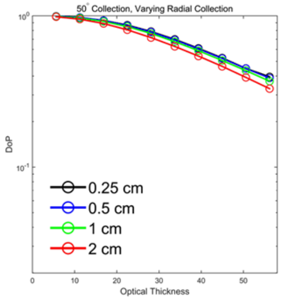
Conclusions

- For the forward scattering environment of 1 µm polystyrene microspheres in water, circular polarization maintains its DoP through increasing optical thickness (range) better than linear polarization



- Circular polarization is more tolerant of collection geometry variations for the forward scattering environments
    - This is significant for implementing circular polarization in optical sensing systems





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