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Increasing Detection Range and Minimizing Polarization Mixing with Circularly Polarized Light through Scattering Environments

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ABSTRACT

We present both simulation and experimental results showing that circularly polarized light maintains its degree of polarization better than linearly polarized light in scattering environments. This is specifically true in turbid environments like fog and clouds. In contrast to previous studies that propagate single wavelengths through broad particle-size distributions, this work identifies regions where circular polarization persists further than linear by systematically surveying different wavelengths through monodisperse particle diameters. For monodisperse polystyrene microspheres in water, for particle diameters of 0.99 and 1.925 microns and varying optical depths, we show that circular polarization's ability to persist through multiple scattering events is enhanced by as much as a factor of four, when compared to that of linear polarization. These particle diameters correspond to size parameters found for infrared wavelengths and marine and continental fog particle distributions. The experimental results are compared to Monte Carlo simulations for all scattering environments investigated.

Keywords: Circular polarization, polarization, scattering, polarization mixing, Mie Theory, Monte Carlo, fog

1. INTRODUCTION

This work presents results from both simulations and experiments showing circularly polarized light maintains its degree of polarization better than linearly polarized light. Over the past decade there has been an increased interest in circular polarization and its uses in imaging and sensing in scattering environments. [Ishimaru, Bicout, Lewis, etc.] In monodisperse polystyrene microspheres in water, for particle diameters of 0.99 and 1.925 microns and varying optical thicknesses, we show that circular polarization's ability to persist through multiple scattering events is enhanced by as much as a factor of four, when compared to that of linear polarization. These particle diameters correspond to size parameters found for infrared wavelengths and marine and continental fog particle distributions. Ishimaru, et. al. and similarly Bicout, et. al. showed simulation results for polystyrene microspheres in water where circularly polarized light maintains its degree of polarization better than linearly polarized light in the forward and backward direction. Both authors report large separation of degree of polarization for circular and linear polarization. We expand on these simulation results and show the variation of the degree of polarization when collection angles are changed. Using polarization tracking Monte Carlo simulations, we show that results similar to Ishimaru and Bicout are achieved only for the limited case where all exit angles are included. However, for our results, the degree of polarization difference between circular and linear will be modified with realistic collection angles.

2. BACKGROUND

Polarization is defined as the movement of the electrical field vector in space and time; characterized by the Stokes vector. The four Stokes parameters define the irradiance of the light (S0), the horizontal or vertical linear nature of the light (S1), the 45 or 135 degree nature of the light (S2), and finally the right or left circular nature of the light. Equation (1) shows the definition of the Stokes vector.

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$$\vec{\boldsymbol{S}} = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} I_H + I_V \\ I_H - I_V \\ I_{45} - I_{135} \\ I_R - I_L \end{bmatrix} \tag{1}$$

Throughout our analysis we use the Degree of Polarization (DoP), defined by Equation (2), which calculates the percentage of the total intensity that is purely polarized. A general Stokes vector can be comprised of a purely unpolarized and purely polarized portion as in Equation (3).

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

$$\vec{\boldsymbol{S}} = \vec{\boldsymbol{S}}_{\boldsymbol{polarized}} + \vec{\boldsymbol{S}}_{\boldsymbol{unpolarized}} = \begin{bmatrix} \sqrt{{S_1}^2 + {S_2}^2 + {S_3}^2} \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} + \begin{bmatrix} S_0 - \sqrt{{S_1}^2 + {S_2}^2 + {S_3}^2} \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{3}$$

The DoP of light transmitted through a scattering medium is of particular interest because the use of polarization difference imagers depends on the difference between the polarization state of the light reflected from the scattering medium and light that persists to the target. [Tyo] Detection range has been shown to increase by a factor of two or three using this technique [Tyo ref 31,32] and recently contrast improvements of X10 have been observed for limited scattering environments. [Miller]

Ishimaru et. al. and Bicout et. al. showed that circularly polarized light maintains its DoP better than linear for simulations of monodisperse polystyrene microspheres. These results were for an entire hemisphere of forward scatter. We show in Figure 1, simulation results performed with a polarization tracking Monte Carlo which are consistent with the work of Ishimaru and Bicout. The simulations are for monodisperse polystyrene particles with diameter of 1.05 micron in water with an illumination wavelength of 0.53 microns. The simulations look at the transmitted DoP as the optical thickness increases. The simulations use all exiting photons, regardless of exit angle and location, to determine the resulting DoP. These results show a large difference between circularly and linearly polarized signals.

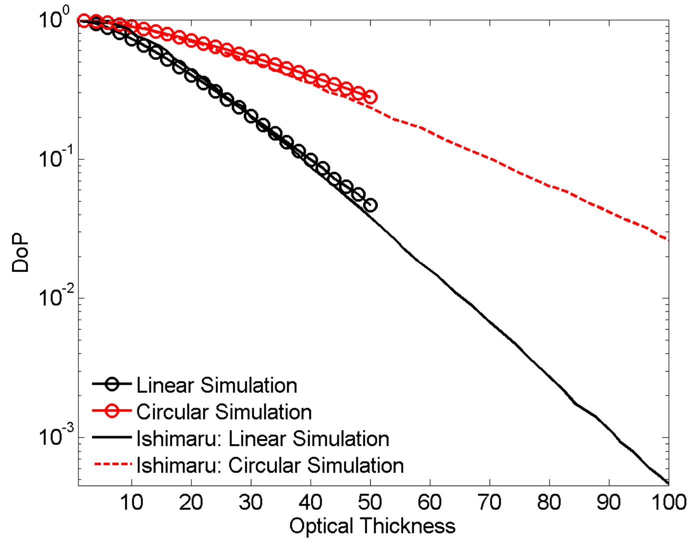

Figure 1. Ishimaru simulation results from reference X versus our consistent simulation results for 1.05 micron diameter polystyrene particles in water with an illumination wavelength of 0.53 microns

The simulations results in Figure 1 show circularly polarized light maintains its DoP by a factor of 6 or 8 dB better than linearly polarized light at an optical thickness of 50. An optical thickness of 50 is similar to very milky water and is a highly scattering environment. The optical thickness of a solution is defined in Equation (4), where C_{sca} is the particles scattering cross-section defined by Mie scattering theory, ρ is the particle volume density, and L is the length of the cuvette. The optical thickness is a unitless quantity.

$$\tau = \rho \bullet C_{sca} \bullet L \tag{4}$$

3. EXPERIMENTAL SETUP FOR 0.99 AND 1.925 MICRON DIAMETER BEADS IN WATER

We show experimental results of polystyrene microsphere solutions in water where a collection lens permits a set range of angles in the forward scattering direction. The variation of collection angles can drastically affect the overall DoP measured for both linearly and circularly polarized light.

The experimental setup for circularly polarized light and linearly polarized light investigation were the same. A He-Ne laser with a wavelength of 543.5 nm was used as the source. The laser beam entered a polarizing beam splitter which acted as a polarizer. The TM polarized beam after exiting the beam splitter was linearly polarized vertical to the table. The beam was expanded using a 10x objective and a 100 mm focal-length lens. Following the beam expander, the beam had a 1 cm cross section. Light then transmitted through the polarization generating optics. The polarization generating optics consisted of a half-wave retarder (HWP) followed by a quarter-wave retarder (QWP). The HWP was mounted in a rotation stage while the QWP was placed in a stationary mount with its fast axis set to 90 degrees from the horizontal. To generate linearly polarized light the HWP's fast axis was aligned with the QWP's fast axis. To generate circularly polarized light the HWP's fast axis was aligned to +22.5 degrees from the QWP's fast axis. At this point, a part of the beam was picked off by a 3 degree wedge to monitor any fluctuations in the incident laser power. A detector was used to monitor the beam incident to the scattering medium. The beam then passed through the scattering solution. The solution was held in a glass cuvette. The cuvette holds up to 12 mL of solution and has a front face area of 1x4 cm and a length of 3 cm. After passing through the solutions, the light was collected with a 150 mm focal-length f/5 lens. The collected scattered light proceeded to the polarization analyzing optics and the final second detector. The polarization analyzing optics included a QWP mounted in a rotation stage and a fixed linear polarizer with fast axis horizontal. The resulting Stokes vector transmitted through the medium was measured by the rotating QWP polarimeter. The experimental setup is shown below in Figure 2.

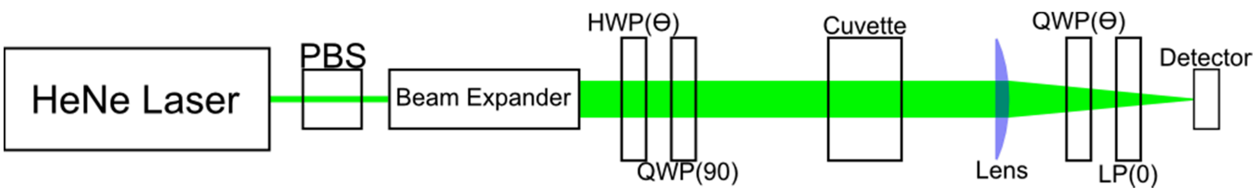

Figure 2. Experimental Setup for 0.99 and 1.925 micron diameter polystyrene beads in water.

For each measurement 1000 intensity values were taken from each detector at a sampling rate of ??. These samples were averaged and the relative value between the incident and transmitted intensity was calculated. This process occurred for each angular position of the rotating QWP polarimeter. A data reduction matrix was then used to calculate the resulting transmitted Stokes vector.

The scattering environments of interest were mono-disperse polystyrene microspheres in water. The polystyrene sphere solutions came in ?? volume percent microspheres for each mean particle diameter of 0.99 and 1.925micron (PolySciences). The size parameter is given by k*r where k is the wavenumber and r is the radius of the particle. The size parameter corresponding to the investigated particle solutions in water with the illumination wavelength of 543.5 nm are 5.72, 11.13, and 17.34. These size parameters correspond to marine fog particles with infrared wavelengths. The total volume in the cuvette for each measurement was 6 mL. Densities of microsphere solutions were increased for each subsequent measurement by adding a fixed amount of the microsphere solution to DI water in the cuvette. To compare the polarization properties for the different sized microsphere solutions the optical thickness was calculated.

Table 1 shows the solutions added to water for each measurement and the resulting optical thickness.

0.99 micron diameter particle solution											
Total Solution Added (μL)	0	10	20	30	40	50	60	70	80	90	100
Optical Thickness	0	5.62	11.24	16.86	22.481	28.101	33.721	39.341	44.961	50.58	56.2
1.925 micron diameter particle solution											
Total Solution Added (μL)	0	10	20	30	40	50	60	70	80	90	100
Optical Thickness	0	2.16	4.319	6.479	8.639	10.799	12.959	15.118	17.278	19.438	21.598
Total Solution Added (μL)	110	120	130	140	150						
Optical Thickness	23.758	25.917	28.08	30.24	32.397						

4. EXPERIMENTAL MEASUREMENTS FOR 0.99 AND 1.925 MICRON DIAMETER BEADS IN WATER

Experimental results for the 0.99 micron particle solutions are shown in Figure 3. The DoP for linearly and circularly polarized light depolarize initially simultaneously until an optical thickness of 15. After an optical thickness of 15, circularly polarized light consistently maintains its DoP better than linear. At an optical thickness of 30, the DoP is a factor of 0.1 or 0.5 dB. The greatest difference in DoP between circularly polarized and linearly polarized light is a factor of 0.6 or 7 dB.

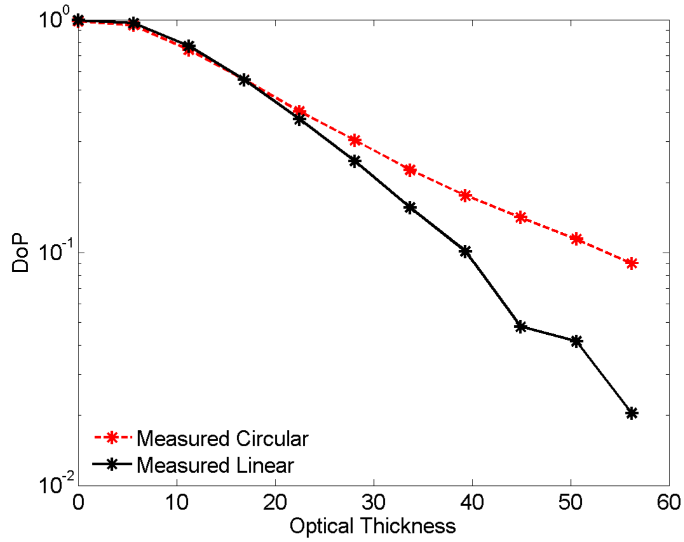

Figure 3. Experimental Results for 0.99 micron diameter polystyrene beads in water with an illumination wavelength of 0.5435 micron.

Experimental results for the 1.925 micron particle solutions are shown in Figure 4. Similar to the 0.99 micron particle, circularly polarized light depolarize initially simultaneously until an optical thickness of 11. After an optical thickness of 11, circularly polarized light maintains its DoP better than linear. At an optical thickness of 30, the DoP is a factor of 0.7. The greatest difference in DoP between circularly polarized and linearly polarized lights is 4dB. At the largest optical thickness of 32 there is an increase in the DoP for linearly polarized light. This is most likely due to noise in the measurement at the large optical thickness and a low signal.

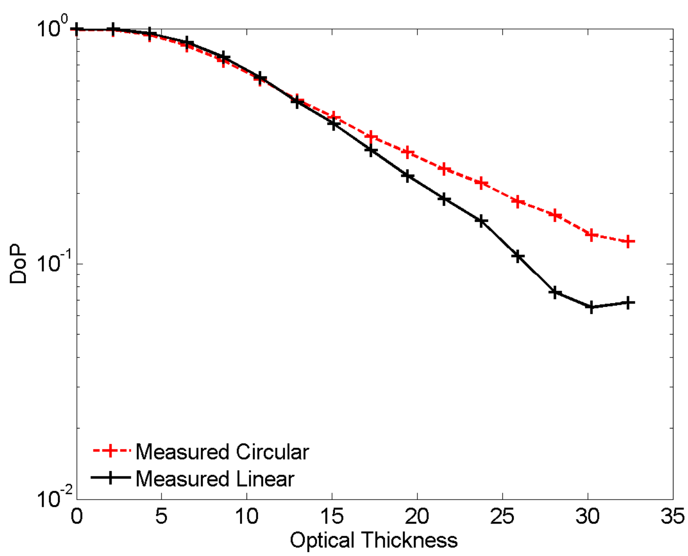

Figure 4. Experimental Results for 1.925 micron diameter polystyrene beads in water with an illumination wavelength of 0.5435 micron.

In order to compare both scattering configurations, the sets of experimental results are plotted on the same axes as simulation results in Figure 5 and 6. We see that for both particle sizes there is an inflection point around an optical thickness of 15 where circularly polarized light begins to maintain its DoP better than linearly polarized light. For these scattering environments we show that circularly polarized light outperforms linearly polarized light and that the DoP contrast is larger for the 2 micron beads compared to the 1 micron beads for the same incident wavelength light. For all simulation results all exiting angles are collected and the resulting Stokes vector is calculated.

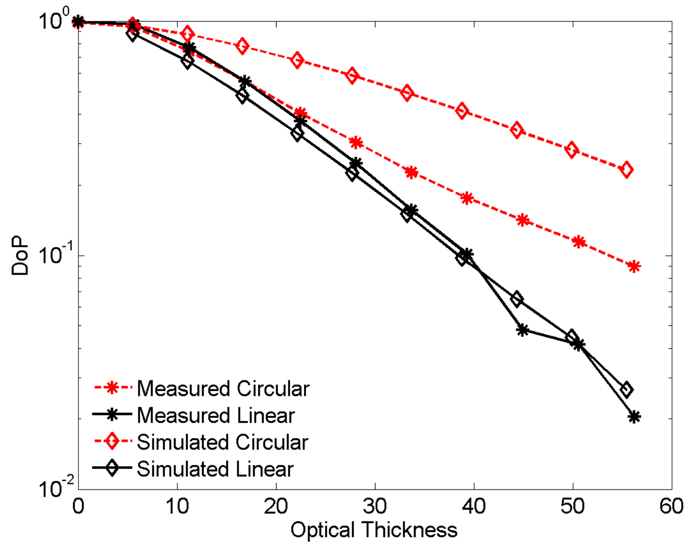

Figure 5. Experimental and Simulation results for 0.99 micron particles in water.

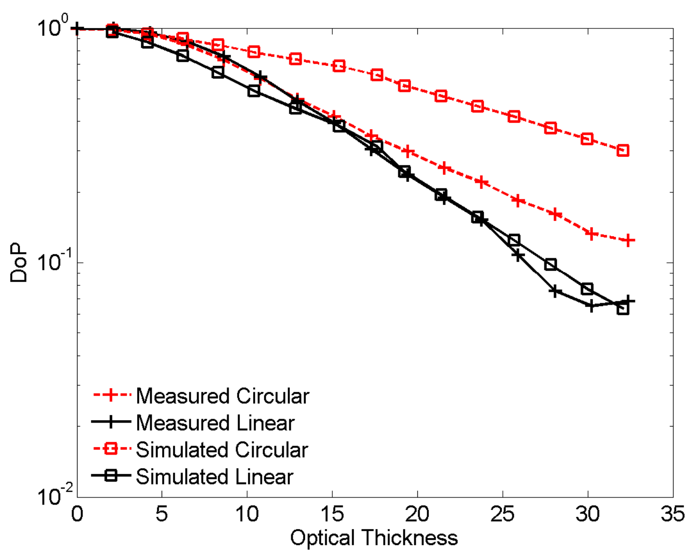

Figure 6. Experimental and Simulation results for 1.925 micron particles in water.

In contrast, our experimental results collect a limited range of angles. We verified that Ishimaru and Bicout showed simulation results when all angles in the forward scattering hemisphere are collected. Circularly polarizared light outperforms linearly polarized light for experiments but not to the extent that Ishimaru, Bicout, and our simulations showed. The change in angle ranges in the forward scattering direction changes the resulting performance of circularly and linearly polarized light. Collecting the full hemisphere of forward scatter increases the number of photons and therefore the DoP is larger versus collecting a defined cone of angles. Figure 7 below shows the difference between the forward scattering hemisphere versus a collection cone of angles.

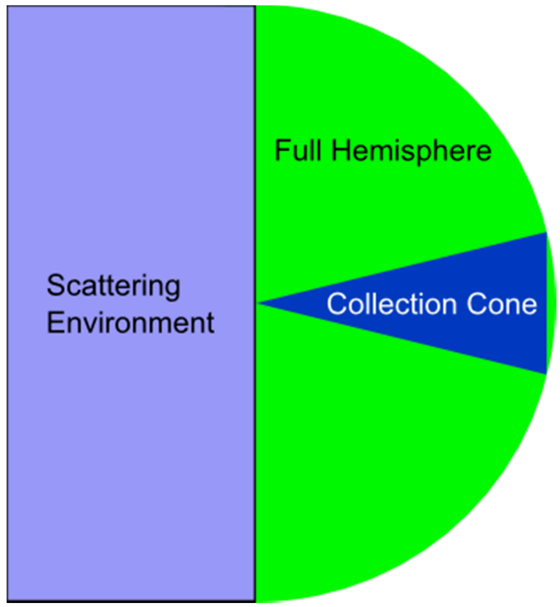

Figure 7. Forward scattering hemisphere of angles for simulation results versus a collection cone of angles for experimental results.

5. CONCLUSION

We show that circular polarization persists longer through multiply scattering environments by a factor of four when compared to linear polarization. Ishimaru and Bicout showed a large separation in simulations of DoP for circular and linearly polarized light in the forward hemispherical direction. We confirmed these results with our own simulations, collecting for the entire forward hemisphere. We continued this work with experimental measurements using 0.99 and 1.925 micron diameter polystyrene particles in water with an illumination wavelength of 0.5435 microns. Our experimental measurements again showed that circularly polarized lights DoP outperformed linearly polarized light, but not to the extent predicted by Ishmaru and Bicout. We hypothesize that this difference can be explained by the described difference in collection angle. Circularly polarized imaging and sensing systems can increase range and contrast in scattering environments but careful consideration should be taken when investigating the environments of interest as collection angle will greatly vary the resulting DoP observed.

REFERENCES