Harnessing Polarization for Signal Persistence in Generated and Natural Fog Environments

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ABSTRACT

Degraded visual environments (DVEs) are a serious concern for modern sensing and surveillance systems. Fog is of particular 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 (LWIR) spectrums. These promising results show us that intentionally tailoring both the illumination wavelength and the polarization state can be 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 discuss the characterizations of fog distributions in our unique 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. The usage of this unique capability allows a controlled experimental realization of environmental fog formation, 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 show that circular polarization persists better than linear polarization for simple model fog distributions with a median size of 5 µm for wavelengths from visible to LWIR - a promising approach to improving sensing in all DVEs.

1.0 BACKGROUND

1.1 Utilizing polarization for scattering environments

Objects hidden in obscuring environments like fog are very difficult to interrogate because the light scatters off suspended particles and at each interaction the direction and polarization of each photon is changed. The exact details of the scattering interaction are a complex interplay between the index of refraction of the medium and the scattering particle, the particle size, the incident wavelength, and the photon's polarization state. We seek to understand the physics of the interaction in scattering environments to better exploit any potential gains.

Utilizing polarization has been shown to improve contrast[1-5] and signal persistence[6,7] in many obscuring environments both in the atmosphere and underwater. For example, an early paper by Gilbert and Pernicka showed circular polarization increases both range and contrast in turbid water by a factor of two.[8] More recently, Lewis et al has shown that a target illuminated with circularly polarized light showed greater contrast than either linear or unpolarized light when imaging through polystyrene spheres in water.[3]

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Our past work has shown that *specific* polarizations at *specific* wavelengths are often favored in certain environmental scattering conditions, which should allow the tailoring the polarization state for additional benefit in specific scattering conditions.[9] In coupled simulation and experimental work we have demonstrated the greater persistence of circularly polarized light over linearly polarized light in scattering environments (i.e. polystyrene beads in water).[10] We have recently shown in systematic simulation work the greater persistence of circularly polarized light over linearly polarized light in the midwave (3-5 µm) and longwave (8-13 µm) infrared wavebands traveling through dust and fog.[9] This work indicates that through most of the mid-wave infrared (MWIR) and long-wave infrared (LWIR) bands there is more circularly polarized light indicating that circularly polarized light persists for longer distances. Our current simulation and experimental work is focused on extending these results to real-world fog conditions, a critical need for many national security applications.

1.2 Fog Distributions and Sandia's Fog Generating Facility

Fog is suspended water particles at or near the earth's surface and is composed of a mixture of micron-size haze particles and larger droplets reaching tens of microns in size.[11,12] The formation of fog is complex, and generally involves high relative humidity conditions, temperature gradients, and condensation nuclei such as hygroscopic solutes (i.e. salt), ice, or dust. Advection or coastal fog is formed when warmer moist air passes over a cool surface like water or land, while radiation or inland fog is formed when a cooling ground causes moisture to condense (atmospheric inversion). In general, advection fog is nucleated with salt and has a larger particle distribution (mean droplet distribution >10 µm) compared to inland fogs which are nucleated on dust or other particulates and has smaller particle distributions (mean droplet distribution <5 µm).

Fog is characterized by two aspects that are of interest to the optical experiments and simulations performed as part of this work: (1) by the size distribution of droplet radii and (2) the total droplet density given in terms of droplet number per volume (#/cm^3). Some commonly accepted models of fog are included in the Moderate Resolution Propagation Model (MODTRAN) atmospheric radiative transfer code created and supported by the United States Air Force.[13] These models were determined by averaging atmospheric data sets collected at various times at different sites in work dating to the early 1970's. The MODTRAN droplet size distributions are shown in Figure 1(a).[14]

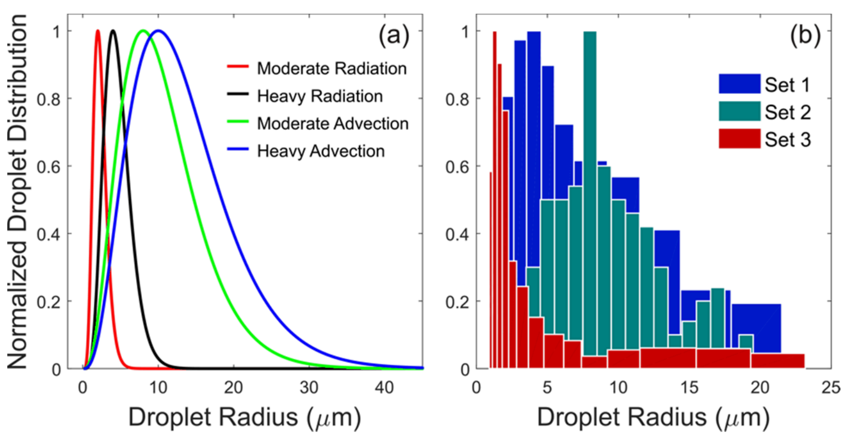

Figure 1: (a) sample fog distributions taken from MODTRAN models and (b) examples of environmental fog adapted from references 15 (set 1 and 2) and 16 (set 3).

However, environmental fog distributions can be very complex and depend upon the turbulent mixing, thermal history, relative humidity, and nucleating particles. While the MODTRAN fog models are commonly accepted in the optical literature, these models represent averaged particle distributions and often lack the complexity seen in environmental fog. Several examples of environmental fog adapted from the literature is shown in Figure 1(b).[15,16] It is unclear how sensitive the propagation of polarization is to specific droplet distributions as you move from smoothly varying distributions to the distributions of actual environmental fog.

One of the challenges associated with performing transmission research in naturally occurring environmental fog is an absence of controlled conditions. The Sandia Fog facility was developed to simulate the natural conditions that would be found in environmental fog within a contained and controlled environment. Seed particles mimicking the composition of environmental seed particles are introduced into a controlled temperature and humidity-environment. These seed particles, combined with simulated atmospheric mixing, relative humidity and temperature, allow the fog droplet to both form and persist. This facility offers a unique capability to systematically create and reproduce fog mixtures for controlled environment research and development.

1.3 Polarization tracking simulation of scattering environments

In our previous work, we employed a polarization tracking Monte Carlo code which uses Mie theory to track the interaction of photons traveling through a slab of scattering particles such as fog.[17,18] A pencil beam of one million photons is sent into a slab of scattering droplets. The polarization state for each photon is tracked individually throughout the scattering process until the photon is transmitted out of the slab or absorbed (photons reflected out of the slab are ignored). The polarization state of the light can be defined by the Stokes parameters as:

$$\vec{\boldsymbol{S}} = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} \langle E_\parallel E_\parallel^* + E_\perp E_\perp^* \rangle \\ \langle E_\parallel E_\parallel^* - E_\perp E_\perp^* \rangle \\ \langle E_\parallel E_\perp^* + E_\perp E_\parallel^* \rangle \\ i \langle E_\parallel E_\perp^* - E_\perp E_\parallel^* \rangle \end{bmatrix} \propto \begin{bmatrix} I_H + I_V \\ I_H - I_V \\ I_{45} - I_{135} \\ I_R - I_L \end{bmatrix} \quad \text{Equation 1}$$

where || terms correspond to the parallel and $\perp$ perpendicular component of the electric field, *E*, respectively. The complex conjugate of the electric field is noted as *. The total intensity of the light is given by S_0, with S_1 indicating horizontal or vertical linearly polarized light, S_2 indicating 45 or 135° linearly polarized light, and finally S_3 indicating right or left circularly polarized light. Light can vary from purely polarized (S = 1) to completely unpolarized (S = 0). The Degree of Polarization (*DoP*) defines the percentage of light that is purely polarized,

$$DoP = \frac{\sqrt{{S_1}^2 + {S_2}^2 + {S_3}^2}}{S_0}, \quad \text{Equation 2}$$

where the sum of the squares of the S_1, S_2, and S_3 terms must always be less than or equal to the square of the S_0 parameter. The DoP can vary from 0 for completely unpolarized light, to 1 for purely polarized light.

In our work, we are mainly interested in the signal persistence of circularly polarized light versus linearly polarized light after traversing the slab of scattering droplets. We define the degree of polarization difference, DoP_{diff} as

$$DoP_{diff} = DoP_{circular\ incident} - DoP_{linear\ incident}, \quad \text{Equation 3}$$

where $DoP_{circular}$ and DoP_{linear} incident is the collected *DoP* for transmitted circularly and linearly polarized light, respectively. The DoP_{diff} is then the measure of the strength and type of polarization that persists after traversing the scattering environment. If $DoP_{diff} > 0$, circularly polarized light is depolarized less by the scattering media, so that more circularly polarized photons survive to be collected. Similarly, if $DoP_{diff} < 0$, linear polarization is favored. If DoP_{diff} is zero, each polarization state is depolarized the same. After simulating each polarization state, the Stokes parameters are combined and the cumulative transmitted DoP is calculated along with the DoP_{diff} value.

For the simulation in this paper, a slab of scattering fog media was defined as 1000 cm in length and infinite in lateral extent. The density of droplets in the slab was defined to have optical thickness of 5 for all wavelengths, i.e. 1000 cm path length corresponds to 5 mean free paths. The optical thickness is defined as,

$$\tau = \rho \sigma_{ext} L \qquad \text{Equation 4}$$

where ρ is the particle volume density, σ_{ext} is the extinction cross-section defined by Mie scattering theory, and L is the slab length. The index of the droplets was set to that of water for the simulation wavelength, and the atmospheric absorption over the 1000 cm path length for each wavelength was determined using MODTRAN. [13,19]

2.0 RESULTS AND DISCUSSION

2.1 Experimental fog generation

Sandia has a unique facility for testing optical systems in generated fog environments. The facility is 180 feet long, 10 feet wide, and 10 feet tall with a series of 60 nozzles located at the top of the chamber placed evenly along the entire length of the chamber. This facility is enclosed in a class IV laser lab allowing us to investigate high power laser systems in a fog environment. A picture from inside the facility is shown in Figure 2. When in operation, the fog can be very dense and prevent one from seeing one's own feet.

Figure 2: Image of fog facility after the completion of a fog generation.

This facility is contained indoors with temperature and humidity control to allow for a stable and repeatable testing environment. Shown in Figure 3(a) is a normalized fog distribution showing a >3 hour testing window versus the droplet diameter as measured with a Malvern Instruments Spraytec particle size analyser.[20] The number density is normalized at each time stamp to allow for the easy comparison of the mean particle size as a function of time. The particle densities vary from ~100 to over $5\text{x}10^4$ #/cm^3, and vary as a function of time from the most recent charging spray. After a spray, the fog density decreases with time as droplets are removed the through gravity and evaporation as indicated in Figure 3(b). The red x's in Figure 3(a) indicate when the spray nozzles were activated, and show the highest particle densities (the peaks in Figure 3(b)). In the later part of the tests, the fog was recharged at 30 minute increments to yield a stable ~20 minute increments to conduct experiments. The sprayed solution is a salt water mixture (NaCl) of 10 g/L concentration.

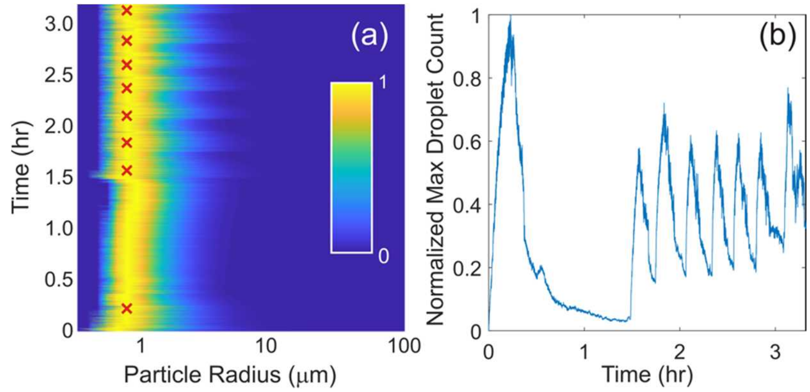

Figure 3: (a) Normalized fog distribution as a function of time highlighting the facilities ability to generate consistent and stable fog mixtures. The red x's indicate when the sprayers were activated to regenerate the fog density. (b) the normalized maximum droplet counts as a function of time. The peaks correspond to the x's in (a).

As clearly shown in Figure 3, the Sandia Fog facility can generate a stable and repeatable mixture for optical experiments. Having a well characterized fog mixture (size distribution and particle density) that can be reproducibly and repeatedly created is a remarkable benefit to the optical study of fog distributions. Combined with the ability to do up to Class IV laser operation, we offer a state-of-the-art facility to do optical experiments in degraded optical environments. We have started optical characterization of polarization persistence through the Sandia Fog facility, and are currently experimenting with generating different fog distributions by changing the salt concentration and modifying the humidity and temperature of the facility.

2.2 Simulation of nominal fog mixtures

To test the sensitivity of the polarization persistence of light traveling through fog to the specifics of the droplet size distribution, we performed Monte Carlo simulations on a model fog of environmentally relevant particle size shown in Figure 4(a). Two different Gaussian distributions with a mean size of 5 μm and variances of 0.005 and 0.5 were compared to an unphysical but simple monodisperse particle size of 5 μm.

Shown in Figure 4(b) is the results of the Monte Carlo simulation of transmission polarization persistence. Plotted is the transmitted DoP_{diff} versus the wavelength for the three different distributions shown in Figure 4(a). These results show that for both the monodisperse and Gaussian distributions, circular polarization persists longer ($DoP_{diff} > 0$) through the model mixture for virtually all wavelengths from visible through LWIR. The effect is especially pronounced in the LWIR, where the size of the wavelength is larger than the mean particle radius of 5 μm. This indicates that if ranging or imaging in this fog model using circularly polarized light, one would have more information carrying signal (circularly polarization light) than if one used linear or unpolarized light.

We can also notice that on changing the distribution width from a delta function to a Gaussian distribution slightly affects the overall performance of circular polarization versus linear polarization. The responses diverge for longer wavelengths and increase the DoP_{diff} for circular polarization due to the Gaussian distributions containing larger particles than the monodisperse mixture. We know from previous work, that there is oscillatory behavior of the response at shorter wavelengths, so the dips seen below 2 μm are likely due to an under sampled oscillatory response.[9] The dips above 2 μm are due to atmospheric absorption.

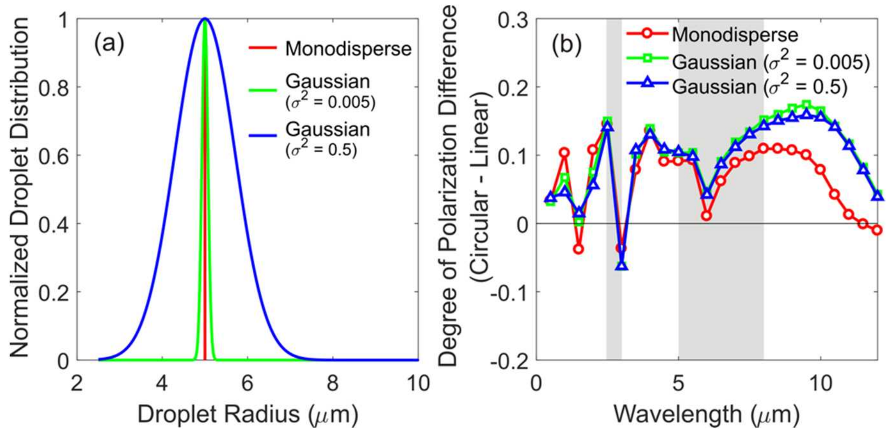

Figure 4: (a) distribution of a monodisperse and Gaussian distributions with variance of σ^2=0.005 and 0.5 for mean particle size 5 µm and (b) Transmission DoP_{diff} results versus wavelength from visible to LWIR. A horizontal black line for $DoP_{diff} = 0$ delineates where linear polarization performs better (negative values) and where circular polarization performs better (positive values). Gray boxes represent regions where transmission through atmosphere is minimal.

Moving forward, we will be using our simulation tool to assess the sensitivity of the polarization persistence to different fog models (such as the MODTRAN models) as well as specific environmental fog mixtures. The responses simulated here seem to indicate that the individual distribution is not as important as the mean particle size relative to the wavelength of the light. This will hopefully show that general approaches to ranging and imaging in fog can be established by properly selecting both the wavelength and polarization properly.

3.0 CONCLUSIONS

We reported here on the demonstration of the Sandia Fog facility. We can generate a stable and repeatable fog mixture in a large testing facility (over 180' long) inside a Class IV laser enclosure that can enable multiple optical studies of environmental fog distributions. We showed that we could generate a sustained fog mixture with the same nominal size distribution for greater than 3 hours. This facility will enable the testing of scientific apparatus to understand the scattering of light and the testing of system solutions for real-world defence applications.

We showed that for a model fog mixture with mean particle size of 5 µm, that circularly polarized light maintains its polarization more than linear polarized light for much of the wavelengths from visible to the LWIR. Simultaneously, we are further developing our polarization tracking Monte Carlo code to enable the simulation of polarization persistence in different fog mixtures and wavelengths.

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