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Optical characterization of the Sandia fog facility

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ABSTRACT

Degraded visual environments are a serious concern for modern sensing and surveillance systems. 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. We will present recent results from our work in operating optical systems in our controlled fog experimental chamber. This facility is a 180-foot-long, 10-foot-wide, and 10-foot-tall structure that has over 60 spray nozzles to achieve uniform aerosol coverage with various particle size, distributions, and densities. We will discuss the physical formation of fog in nature and how our generated fog compares. In addition, we will discuss fog distributions and characterization techniques. We will investigate the biases of different methods and discuss the different techniques that are appropriate for realistic environments. Finally, we will compare the data obtained from our characterization studies against accepted models (e.g., MODTRAN) and validate the usage of this unique capability as a controlled experimental realization of natural fog formations. By proving the capability, we 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.

Keywords: scattering, fog, degraded visual environment

1. Introduction

Of the five senses vision is certainly one of our most important. When our visual perception of the world is affected the experience can be disorienting and dangerous. Degraded visual environments (DVE) are an environment in which obscurants perturb transmitted light by scattering, absorption, refraction, or reflection and obscure the physical environment. DVEs are more than a simple nuisance disturbing human vision; they also affect many machine vision systems disrupting numerous industries including security, transportation, remote sensing, surveillance, and more. The defense industry is particularly plagued by DVEs due to their need to operate in all weather conditions in every climate/environment. DVEs are a leading contributor of accidents for airborne platforms, particularly rotor wing, causing reduced operational effectiveness. There are many types of DVEs including smoke,

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rain, brownout, dust, and fog. Fog is of concern to national security and causes significant issues in defense, surveillance, reconnaissance, security. As society relies more upon machine vision for autonomy the economic consequences of DVEs will become more serious. Sandia has made a conscientious investment and a unique capability for testing of optical systems alongside a long history of computational modelling to defeat fog.

Fog and visibility are major sources of weather related accidents in aviation. While wind is the most prevalent cause of accidents, visibility and low ceiling is the second most prevalent cause of accidents [1]. On March 27, 1977, the worst aviation accident in history was caused by fog and low visibility at Tenerife airport in the Canary Islands [2]. Five hundred and eighty-three people were killed when two Boeing 747 passenger jets collided on the runway. Visibility was reported to be between 300 and 2000m. The dangers of fog are not exclusive to aviation. According to the Department of Transportation (DOT), accidents due to fog made up 3.5% of weather related crashes and 9% of weather-related fatalities [3].

Fog is a naturally occurring aerosol consisting of water droplets suspended in air. Fog is commonly formed by the rapid cooling of supersaturated air. This sometimes occurs by atmospheric inversion where warm moist air is settled in a valley and a body of cool air rests above the valley. As the warm air rises the cool air descends causing a rise in the relative humidity, reaching supersaturation. Dissolved solute in the water particles causes the formation of large droplets. This is just one example of fog formation and many other atmospheric phenomena can form fog. Regardless of the exact atmospheric conditions that cause a particular fog; Köhler theory describes the thermodynamics of the droplet formation [4]. The Köhler equation consists of two terms; one describing the thermodynamic equilibrium of the particle based on the curvature of the droplet and another describing the chemical potation of the droplet affected by any dissolved solute that might be present. While the exact description of the Köhler equation is beyond the scope of this manuscript useful insight into how to affect droplet size can be gleaned from the expression. The Köhler equation is given below,

$$S_{v,w} = exp\left[\frac{2M_w\sigma_{s/a}}{RT\rho_w a} - \frac{v\Phi_s m_s M_w/M_s}{(4\pi a^3\rho_s/3)\ -\ m_s}\right] \qquad \text{Eq. 1}$$

where $S_{v,w}$ is the saturation ratio, M_w is the molecular weight of water, $\sigma_{s/a}$ is the droplet surface tension, R is the ideal gas law constant, T is the temperature, ρ_w is the density of water, *v* is the number of dissolved ions, Φ_s is the osmotic coefficient, ρ_s is the density of the aqueous solution, M_s is the molecular weight of the solute, m_s is the moles of solute, and *a* is the droplet radius. A plot of the Kohler equation is shown in Figure 1. This plot shows is the equilibrium radius of the water droplets for a given saturation value of the air. If below peak radius value and inflection point of the curve (termed the critical radius,

R_c), the drops are in equilibrium with their environment and will evaporate or grow until they fall on the curve. Once the saturation reaches high enough level (critical saturation, S_c), the droplets are activated and can coarsen and grow. Below the critical saturation and to the left of the critical radius, the droplets are trapped and can persist in the environment for long times until changes saturation value through temperature or coarsening events

The dissolution of additional solute can also lead to larger particle sizes and greatly changes the critical radius above which particles will tend to grow, as illustrated in Figure 1 for a series of increasing salt content. By dropping the ambient temperature supersaturation can be reached with less water content and should result in more favorable conditions for testing.

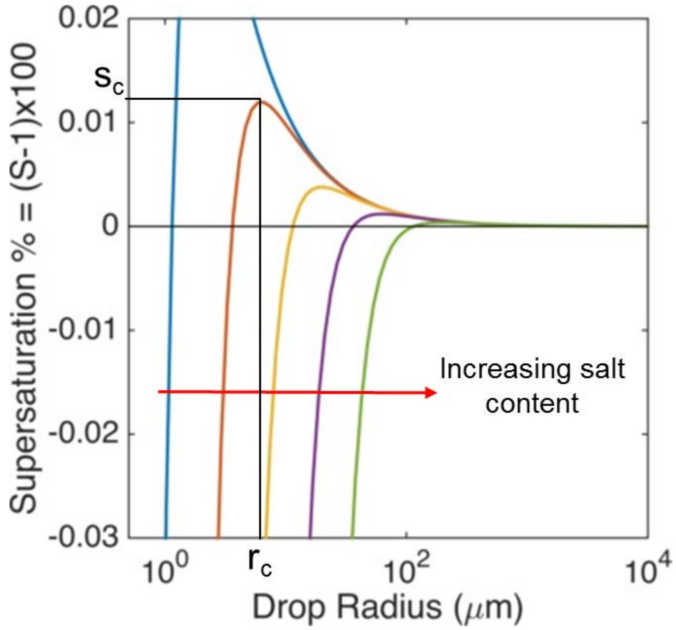

Figure 1. Köhler curves showing the change in the critical diameter as more solute (NaCl) is dissolved in the particle. The critical saturation and critical radius are indicated for the orange curve.

2. Experimental Testing Facility

Sandia has a unique and interesting facility for testing systems (mostly optical) in fog environments. Due to the unreliable nature of weather it is difficult to test equipment and perform optical measurements by relying on spontaneously generated fog. This facility is 180 feet long, 10 feet wide, and has about 10 feet of usable vertical space. Above the usable space are spray nozzles that produce the fog. This facility is enclosed in a class IV laser lab allowing us to investigate high power laser systems like LADARs in a fog environment. The fog is sprayed using a series of nozzles located at the top of the chamber placed along nearly the entire length of the chamber and distributed evenly. This facility is contained indoors and allows for a stable and repeatable testing environment. A picture from inside the tunnel and a diagram of the tunnel layout is shown in Figure 2.

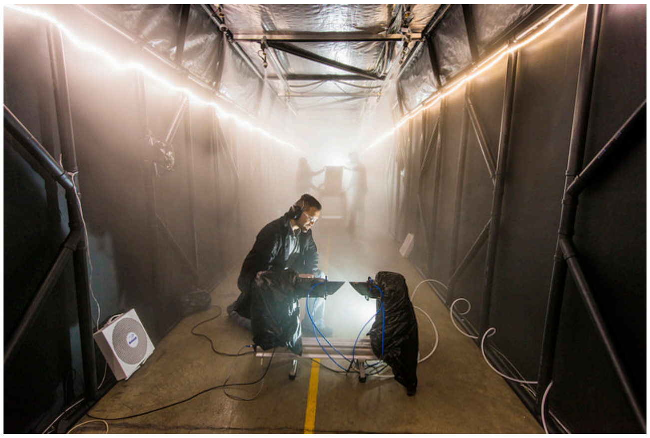

Figure 2. Several staff members work on particle sizing instruments inside the Sandia Fog Facility. The visibility was about 100ft when the photograph was taken.

The fog is produced by dissolving NaCl in water which is then sprayed through 64 industrial agricultural nozzles. The nozzles are arranged in 3 selectable sections so that varying fog conditions can be simulated. The particle size distribution can be affected by changing the amount of NaCl dissolved in the water. We are working to install additional temperature control mechanisms that should allow for the creation of even larger particles reaching fog particle size distributions that are more relevant for advection fog type operations.

3. Measuring Fog

Our team has chosen to use particle sizers to carefully measure the fog we produce in the fog tunnel at Sandia. One of the particle sizers we use is the Spraytec from Malvern Instruments [5]. It uses a laser diffraction system to measure droplet size distributions in real-time and provides time stamped particle size distributions for post processing and correlation with other primary measurements. A schematic of the optical particle sizer is shown in Figure 3. It can be seen in the figure that a laser beam is diffracted by particles. This disturbed beam is incident to an array of detectors that characterize the scattering. This technique allows for a very wide particle range and the Spraytec can size particles from 0.1 µm to 2000 µm in diameter. The Spraytec is not intended for measuring fog which is static, meaning the particles are not moving, so to size particles correctly we use the inhalation cell accessory which draws particles across the detector to simulate the motion of a spray. A low flow rates of 25 liters per minute was used to draw particles across the detection path.

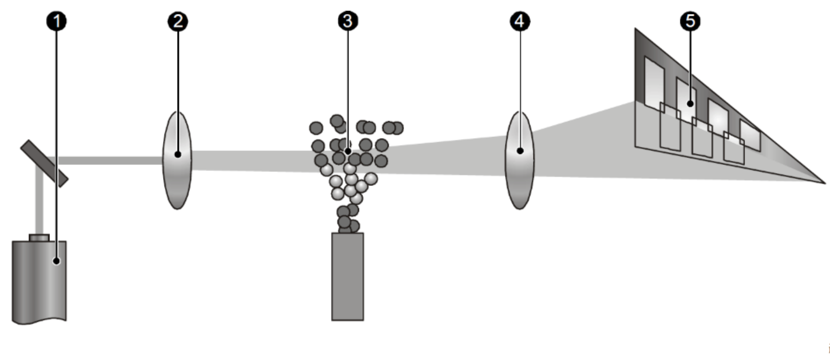

Figure 3. Schematic of the Malvern diffraction system. Light is scattered by an aerosol and the diffraction is characterized by a series of detectors [5].

The measured fog at the Sandia facility is shown in Figure 4. and contrasted against the fog models of MODTRAN [6]. These models are averages of previously reported naturally occurring fogs and are representative of 4-different kind of fogs [7]. It is clear from the figure that the mean particle diameter of the Sandia fog is much smaller than that of the MODTRAN models. Future work at Sandia is focused on increasing the mean particle diameter of our simulative fog. However, this characterized aerosol is highly repeatable and is representative of certain types of light radiation fogs or heavy mists.

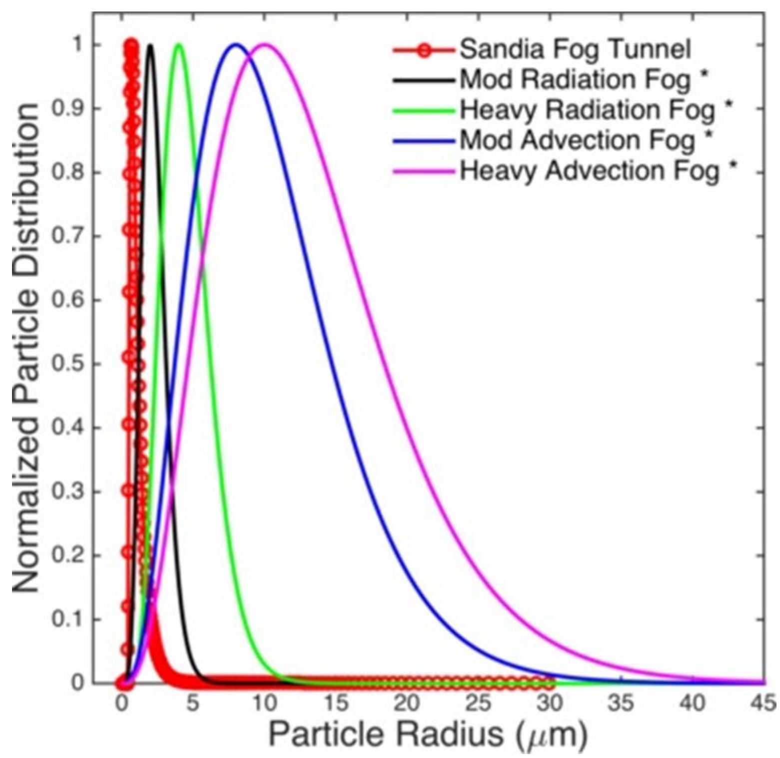

Figure 4. Particle density for the MODTRAN fog models compared to the Sandia fog.

4. Conclusions

Sandia has been engaged in developing an on-demand fog for testing of various systems and for investigating fundamental scattering physics. The current fog we are capable of producing has been well characterized by a particle sizer and is compared to several representative particle distributions. Future work is focused on increasing the size of the particles produced, adding temperature control to the fog chamber, and supporting a growing number of external and internal partners.

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6. References

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