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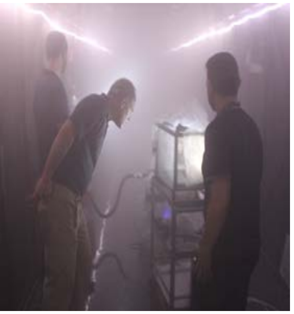

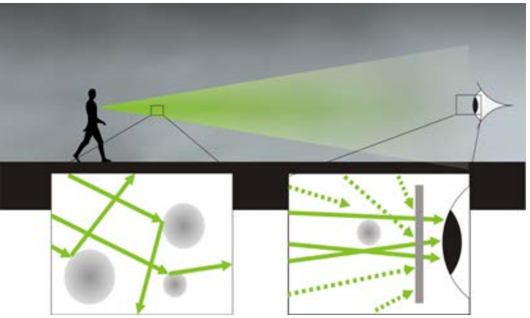

Optical Characterization of the Sandia Fog Facility

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SOF and Tactical Physics

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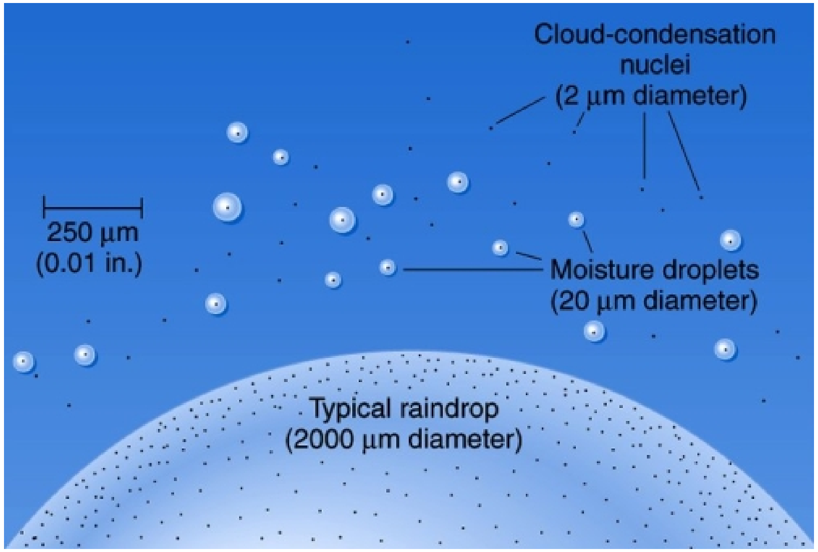
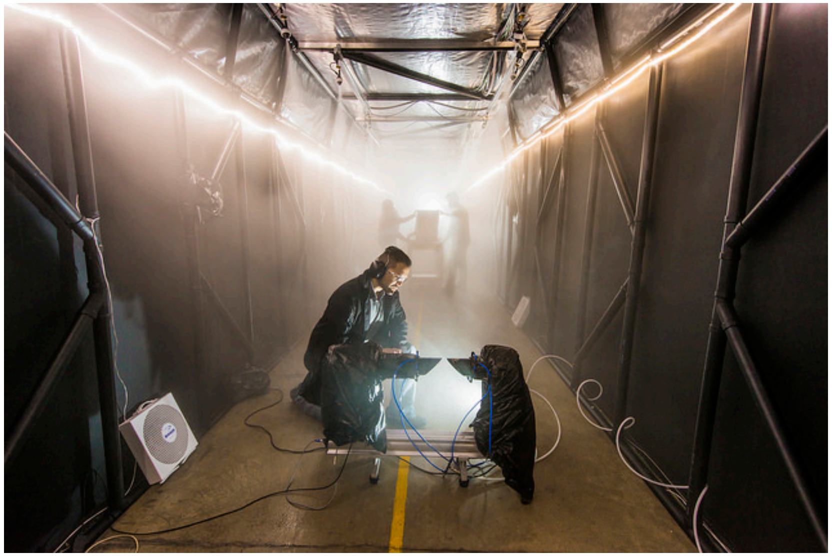
Outline

- What is Fog, Why do we care?
- Sandia Fog Tunnel Overview
- How we characterize fog
- Current and Future work





What is fog?

- Fog - a thick cloud of tiny water droplets suspended in the atmosphere at or near the earth's surface that obscures or restricts visibility.
  - Dewpoint temperature spread is <3 °C
  - <1km of visibility
  - Low Elevation

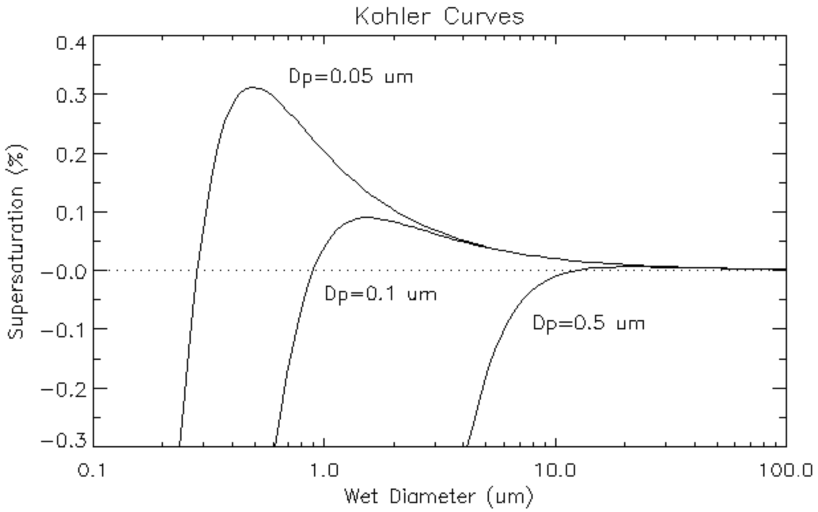
- Mist – Between fog and haze particles less than 5µm.
  - 95-100% RH
  - >1km visibility

- Haze – Does not contain activated droplets according to Köhler theory.

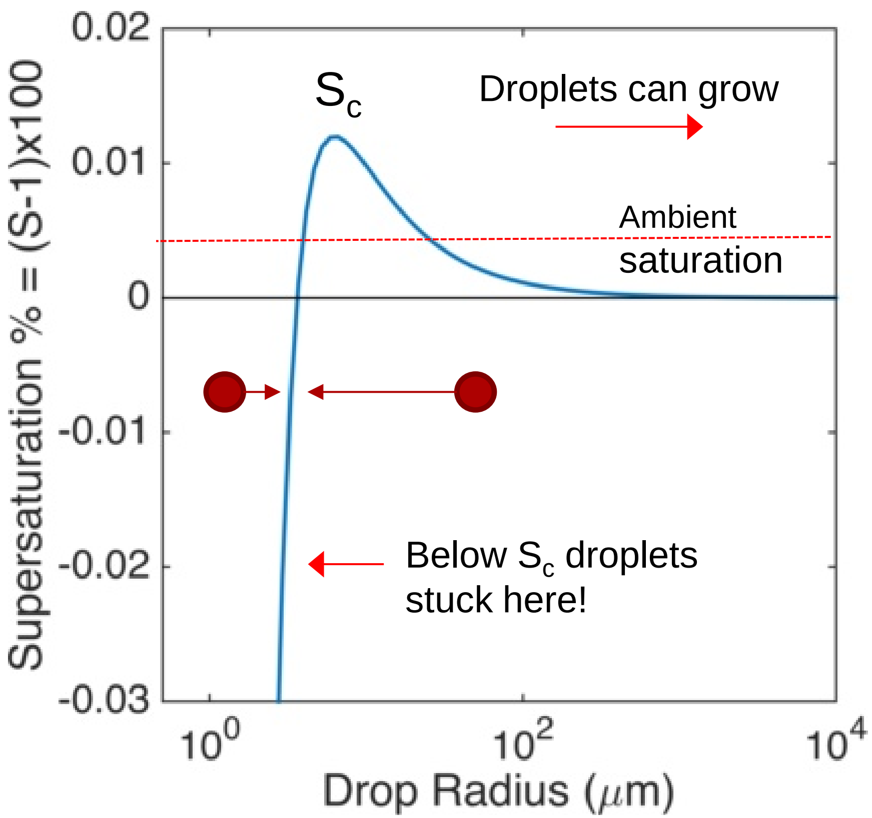
Köhler Theory – Cloud Physics

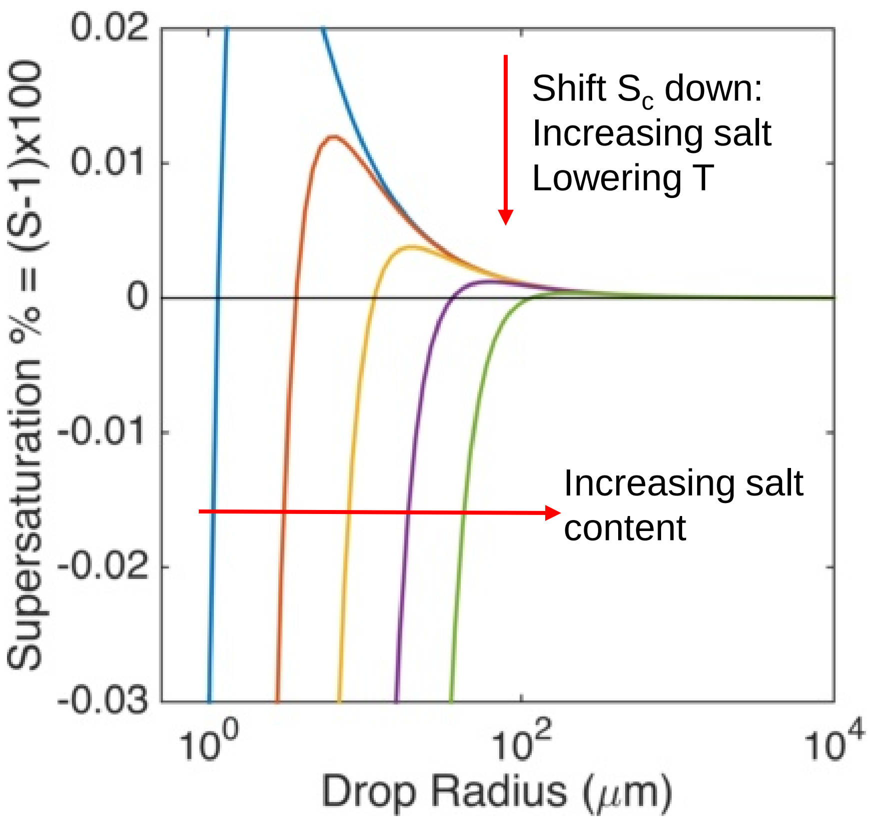
- Water vapor condenses and from liquid droplets
- Curvature term and Solute term
- Given a supersaturation value a particle is in
  - Equilibrium
  - Growth

$$\ln\left(\frac{p_w(D_p)}{p^0}\right) = \frac{4M_w\sigma_w}{RT\rho_w D_p} - \frac{6n_s M_w}{\pi\rho_w D_p^3}$$



Droplet microphysics (Kohler Equation)



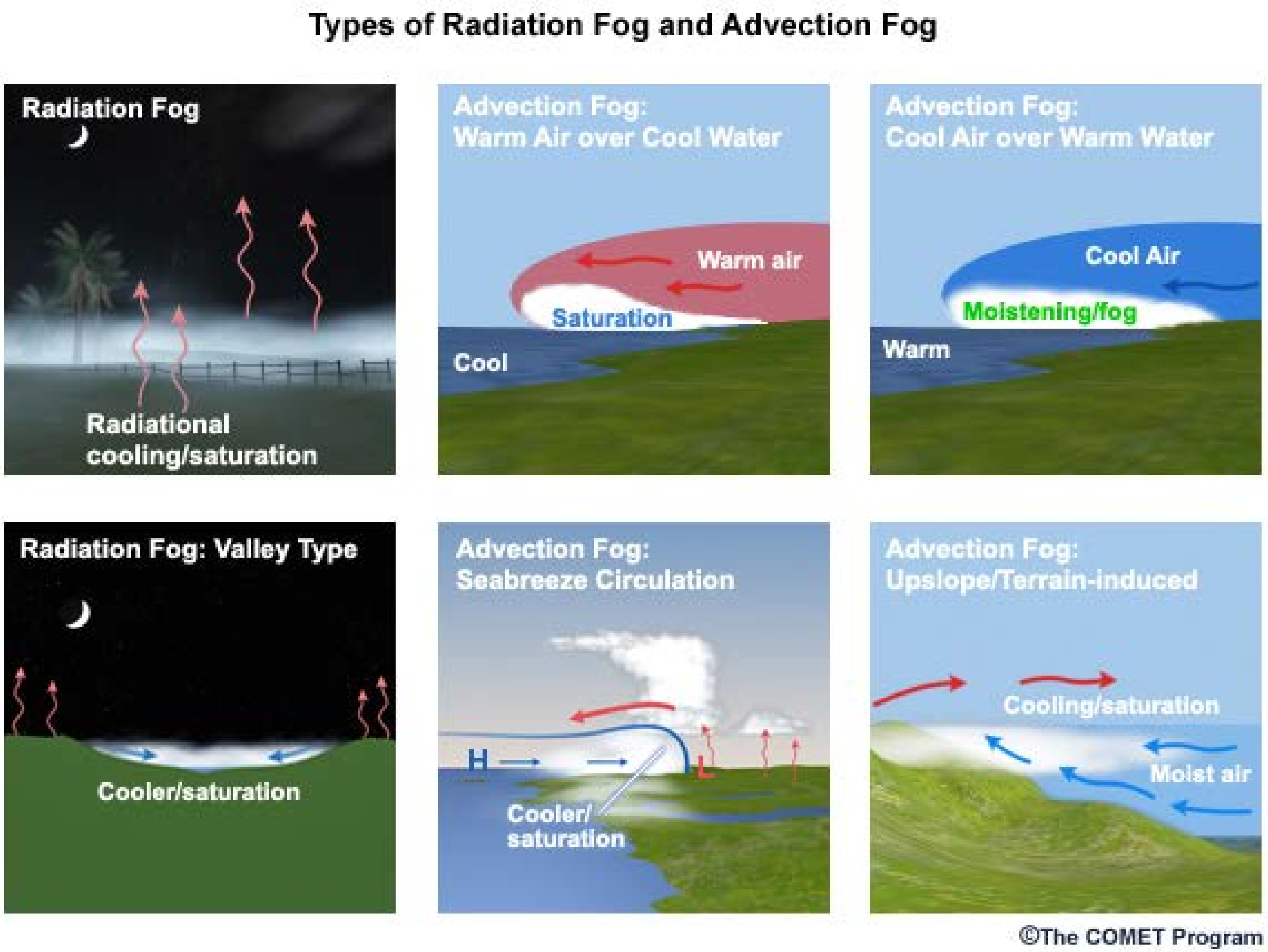


The most common types of fog

- Radiation Fog – Most Common
- Moist air is cooled near the ground causing supersaturation

- Advection Fog – More Prevalent in Coastal Climates
- Atmospheric patterns play more a role than radiation fog

Advection Fog – Many Flavors



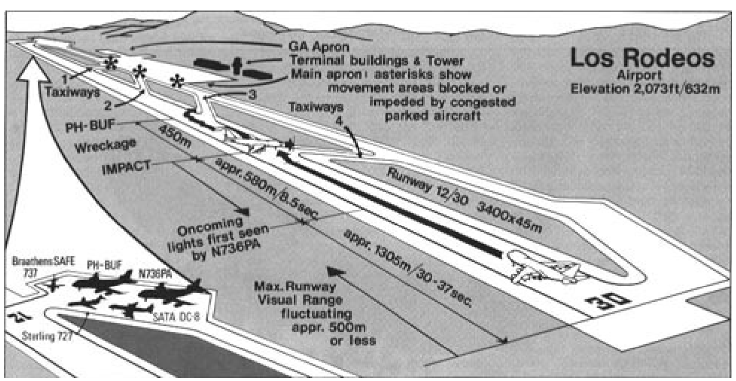
Less common type of fog

- Precipitation fog
  - Rain falling into dry air
- Freezing Fog
  - Condensed droplets freeze
- Ice fog
  - Suspended droplets ice

- Super fog
  - Smoke and moisture mix
  - <10 ft visibility
- Pea Soup Fog
  - Soot particulate
  - Sulfur Dioxide

Why do we care about fog?

11 dead in helicopter crash off Florida Coast due to thick fog: WINK News, March 11, 2015



Tenerife Airport Disaster –Fog a major contributor- 583 dead March 27,1977

2 separate accidents 90 vehicles 2 dead. Tule Fog SFGATE Feb 5, 2002

Defining Visibility/MOR

In **meteorology**, visibility is a measure of the distance at which an object or light can be clearly discerned. It is reported within surface weather observations and METAR code either in meters or statute miles, depending upon the country.

Wikipedia

Visibility

a) the greatest distance at which a black object of suitable dimensions, situated near the ground, can be seen and recognized when observed against a bright background;
b) b) the greatest distance at which lights of 1,000 candelas can be seen and identified against an unlit background.

ICAO

Visibility

the length of path in the atmosphere required to reduce the luminous flux in a collimated beam from an incandescent lamp, at a colour temperature of 2700 K, to 5 per cent of its original value, the luminous flux being evaluated by means of the photometric luminosity function of the International Commission on Illumination. For aeronautical purposes, the surface MOR is measured at a height of 2.5 m above the surface.

World Meteorological Organization

Contrast and visbility

To define visibility the case of a perfectly black object being viewed against a perfectly white background is examined. The visual contrast, $C_V(x)$, at a distance x from the black object is defined as the relative difference between the light intensity of the background and the object

$$C_V(x) = \frac{F_B(x) - F(x)}{F_B(x)}$$

where $F_B(x)$ and $F(x)$ are the intensities of the background and the object, respectively. Because the object is assumed to be perfectly black, it must absorb all of the light incident on it. Thus when $x=0$ (at the object), $F(0) = 0$ and $C_V(0) = 1$.

Between the object and the observer, $F(x)$ is affected by additional light that is scattered into the observer's line of sight and the absorption of light by gases and particles. Light scattered by particles outside of a particular beam may ultimately contribute to the irradiance at the target, a phenomenon known as multiple scattering. Unlike absorbed light, scattered light is not lost from a system. Rather, it can change directions and contribute to other directions. It is only lost from the original beam traveling in one particular direction. The multiple scattering's contribution to the irradiance at x is modified by the individual particle scattering coefficient, the number concentration of particles, and the depth of the beam. The intensity change dF is the result of these effects over a distance dx. Because dx is a measure of the amount of suspended gases and particles, the fraction of F that is diminished is assumed to be proportional to the distance, dx. The fractional reduction in F is

$$dF = -b_{\text{ext}} F dx$$

where b_{ext} is the attenuation coefficient. The scattering of background light into the observer's line of sight can increase F over the distance dx. This increase is defined as $b' F_B(x)\, dx$, where b' is a constant. The overall change in intensity is expressed as

$$dF(x) = [b' F_B(x) - b_{\text{ext}} F(x)]\, dx$$

Since F_B represents the background intensity, it is independent of x by definition. Therefore,

$$dF_B(x) = 0 = [b' F_B(x) - b_{\text{ext}} F_B(x)]\, dx$$

It is clear from this expression that b' must be equal to b_{ext}. Thus, the visual contrast, $C_V(x)$, obeys the Beer–Lambert law

$$\frac{dC_V(x)}{dx} = -b_{\text{ext}} C_V(x)$$

which means that the contrast decreases exponentially with the distance from the object:

$$C_V(x) = \exp(-b_{\text{ext}} x)$$

Lab experiments have determined that contrast ratios between 0.018 and 0.03 are perceptible under typical daylight viewing conditions. Usually, a contrast ratio of 2% ($C_V = 0.02$) is used to calculate visual range. Plugging this value into the above equation and solving for x produces the following visual range expression (the Koschmieder equation):

$$x_V = \frac{3.912}{b_{\text{ext}}}$$

with x_V in units of length. At sea level, the Rayleigh atmosphere has an extinction coefficient of approximately 13.2×10^{-6} m^{-1} at a wavelength of 520 nm. This means that in the cleanest possible atmosphere, visibility is limited to about 296 km.

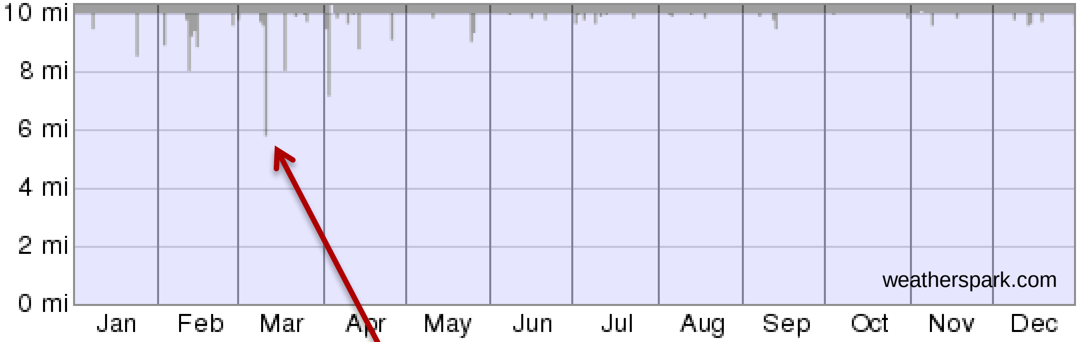
Visibility perception depends on several physical and visual factors. A realistic definition should consider the fact that the human visual system (HVS) is highly sensitive to spatial frequencies, and then to use the Fourier transform and the contrast sensitivity function of the HVS to assess visibility.[1]

Foggy morning road

On clear days, Tel Aviv's skyline is visible from the Carmel mountains, 80km north

Weather in ABQ

Visibility in 2012



5.8 miles lowest average

Dec. 23, 2016 30 flights delayed due to thick fog!

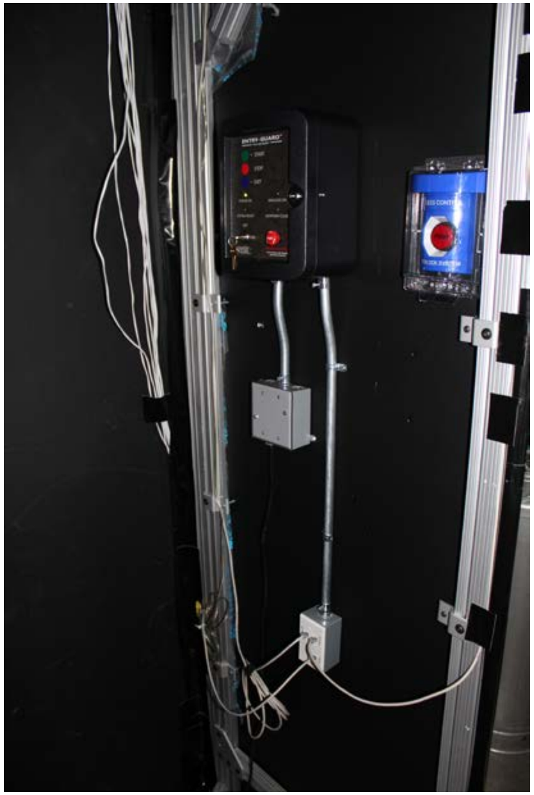
No Fog

HOW DO WE CONTROL THE WEATHER?

The Sandia Fog Tunnel

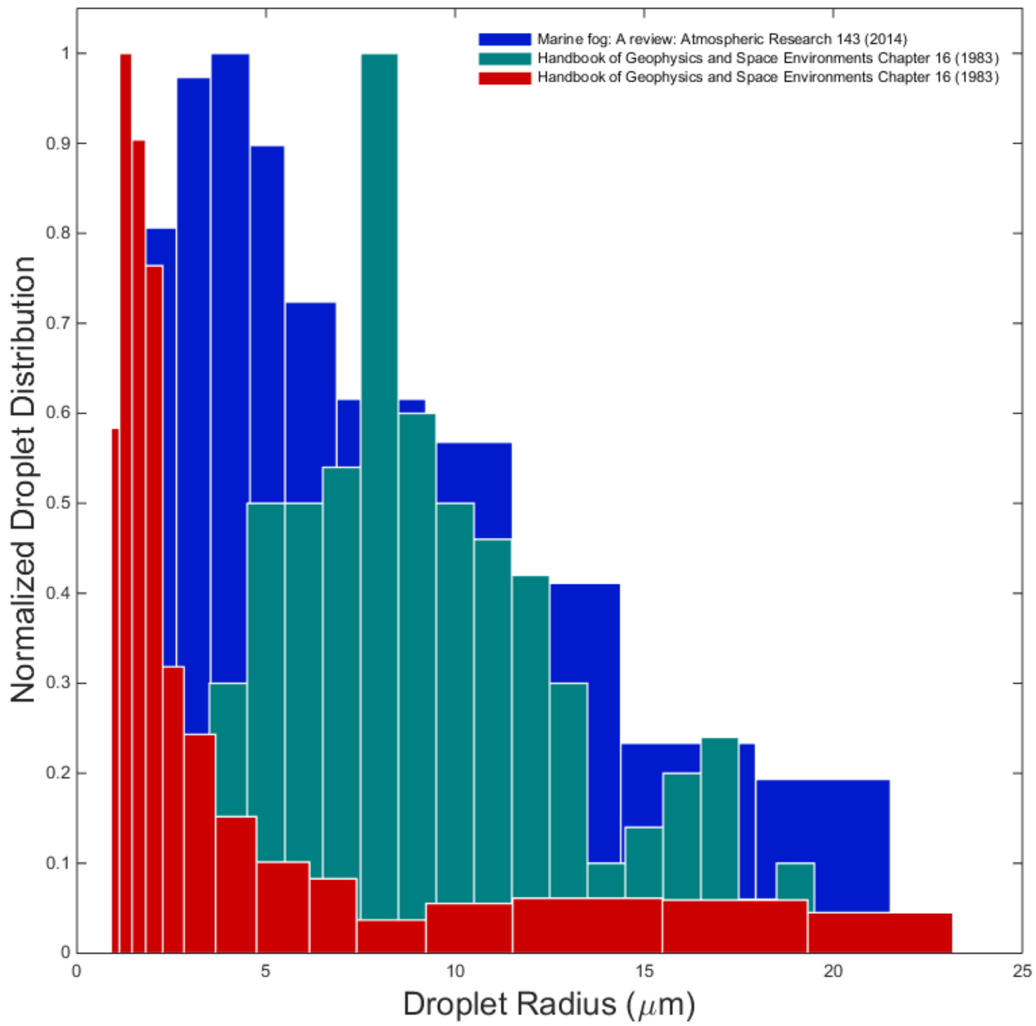
- Constructed in 2014?
- Navy Research Funded
- 10’ x 10’ x 180’
  - 6% grade (no pooling)
- 80 spray nozzles
- Indoors – Controlled Environment

Sandia Fog Tunnel – Living Laboratory

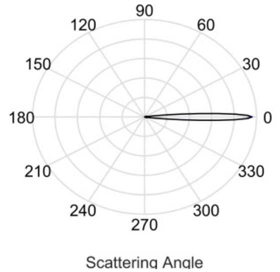


- Continue to upgrade
  - Temperature Control (soon)
  - Instrumentation (time correlated)
    - Visibility (MOR)
    - Particle Sizers
      - Malvern
      - Droplet Measurement Technologies
      - Temperature, Humidity, Dew Point
- Customer inspired upgrades
  - Additional Power
  - Class IV lasers
  - Positive Pressure Dry Boxes

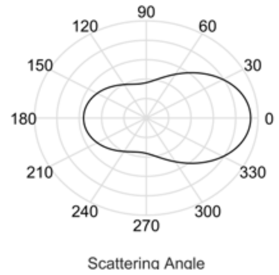
Not all fog is the same



Forward scattering



Isotropic scattering



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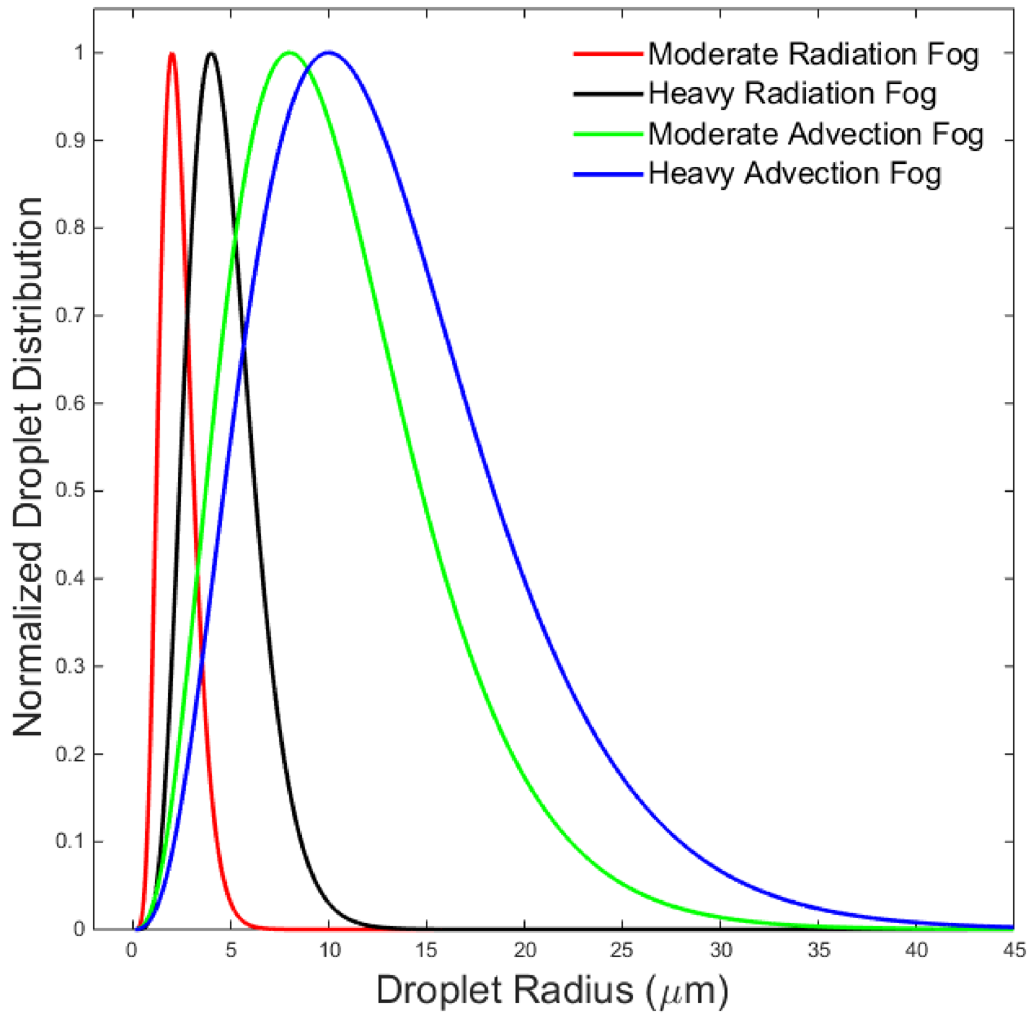
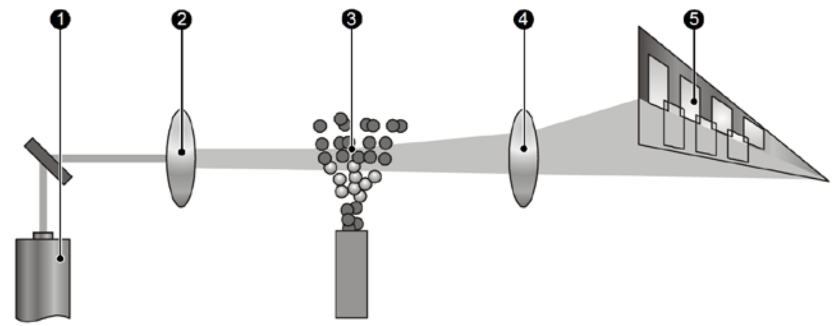
MODTRAN Fog Models

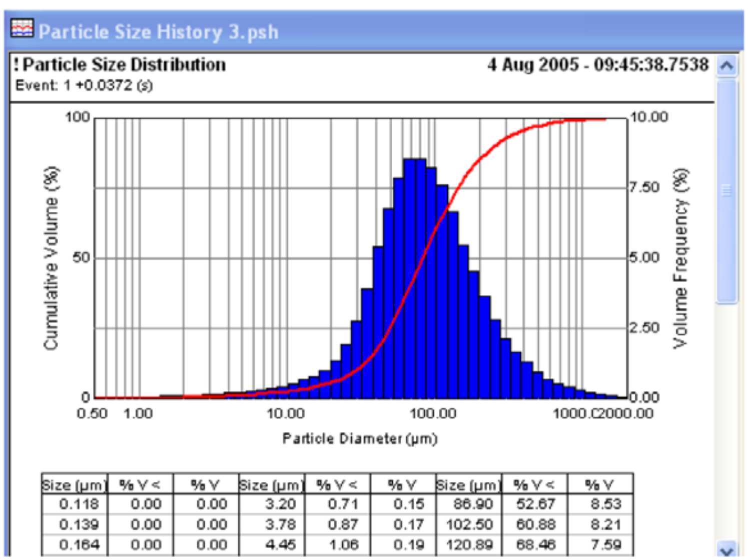
- “Industry Standard”
- Averaged from historical records



Malvern- Spraytek

- Laser diffraction system
- Large particle range
  - 0.1 – 900 microns
- Multiple Scattering Model
- 1Hz Continuous

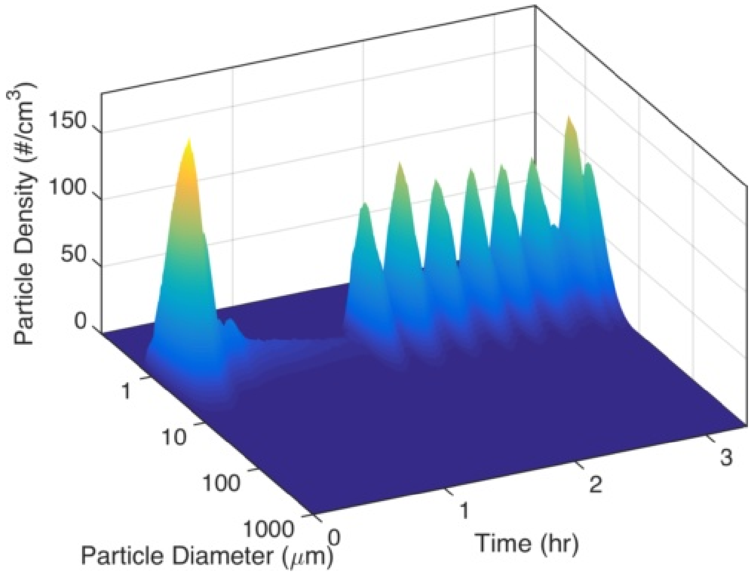




Size (μm)	% V <	% V	Size (μm)	% V <	% V	Size (μm)	% V <	% V
0.118	0.00	0.00	3.20	0.71	0.15	86.90	52.67	8.53
0.139	0.00	0.00	3.78	0.87	0.17	102.50	60.88	8.21
0.164	0.00	0.00	4.45	1.06	0.19	120.89	68.46	7.59

Using the Spraytek

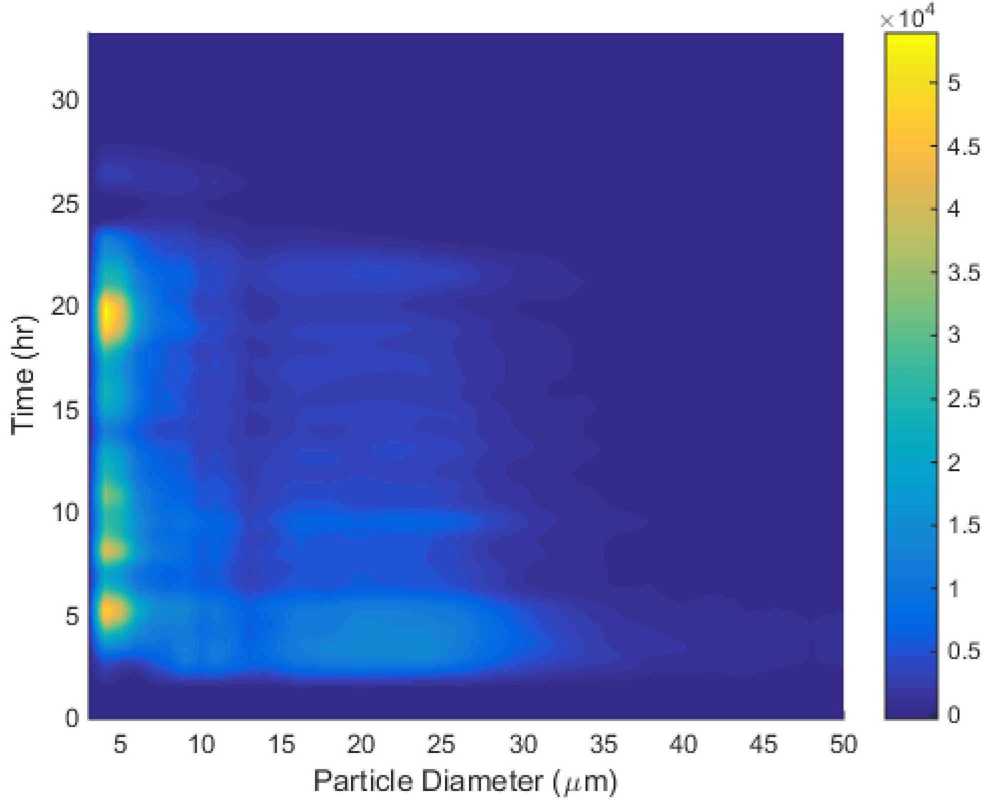
- Inhalation Cell
  - Moving particles
  - Flow Rate
- Number Concentration

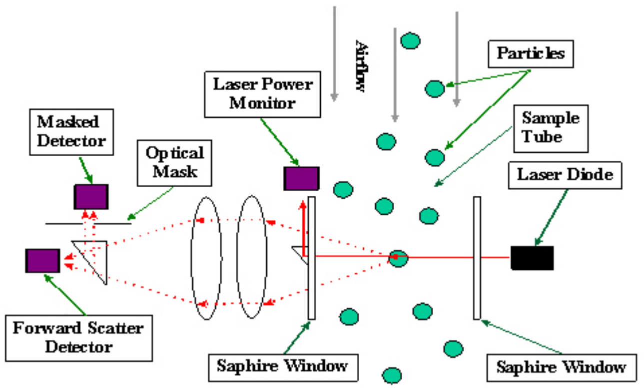


- More Words?

Droplet Measurement Technologies - FM-120

Particle sizing > 2µm

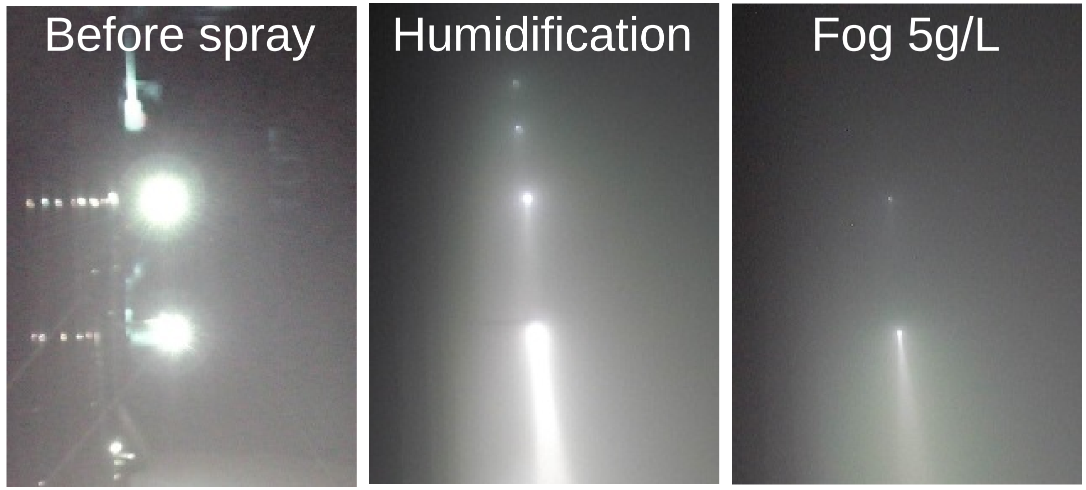


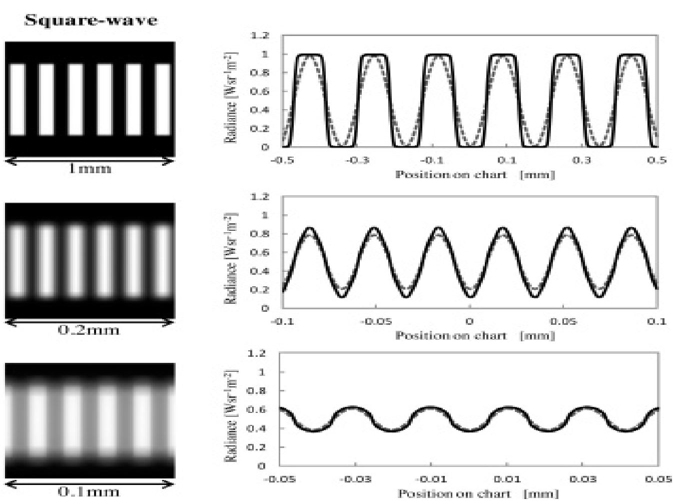


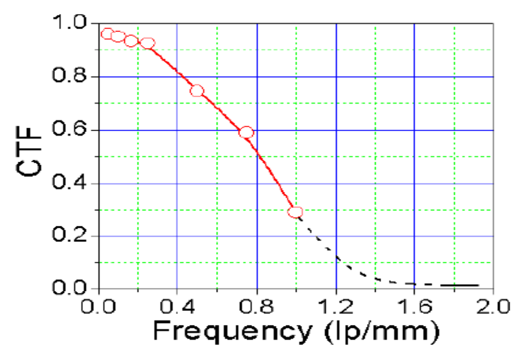
Future Work

Preliminary imaging experiments

- 40’ standoff
- 30’
- 20’
- 10’





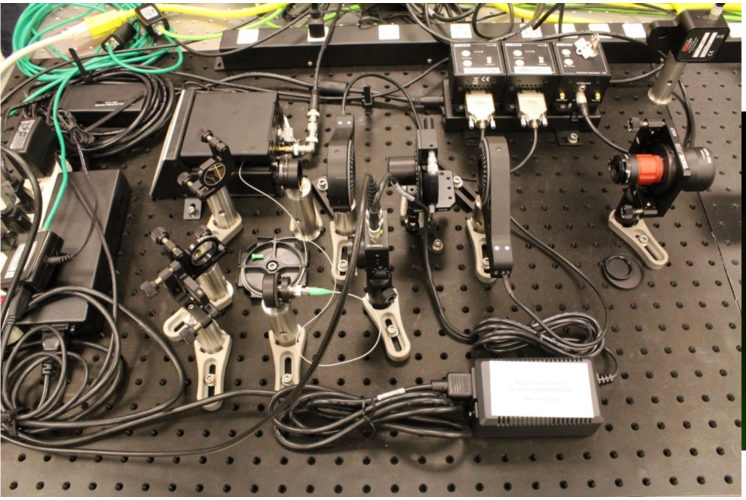


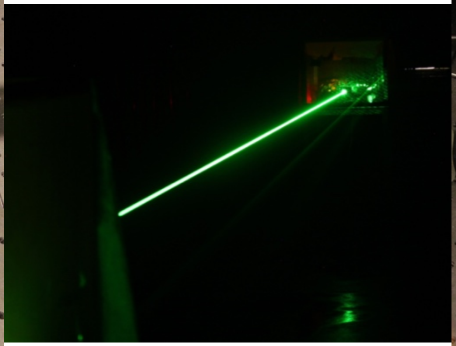
We want to quantify how polarization affects **imaging**; and compare results in both simulation and measurement

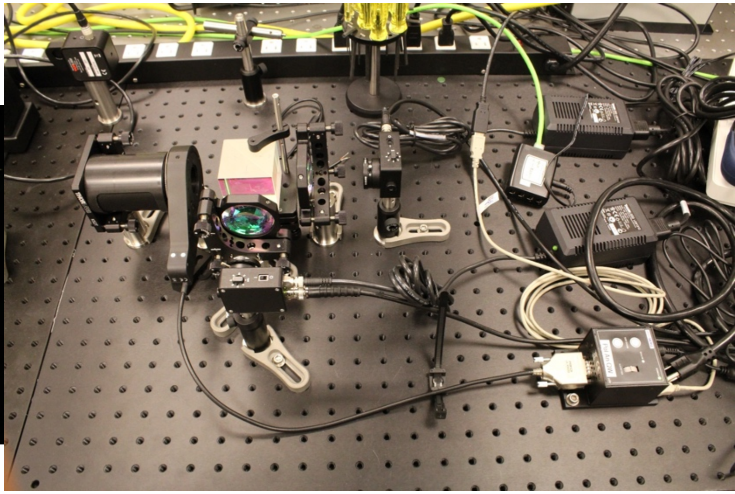
Current Work

Transmit Box

Receive Box

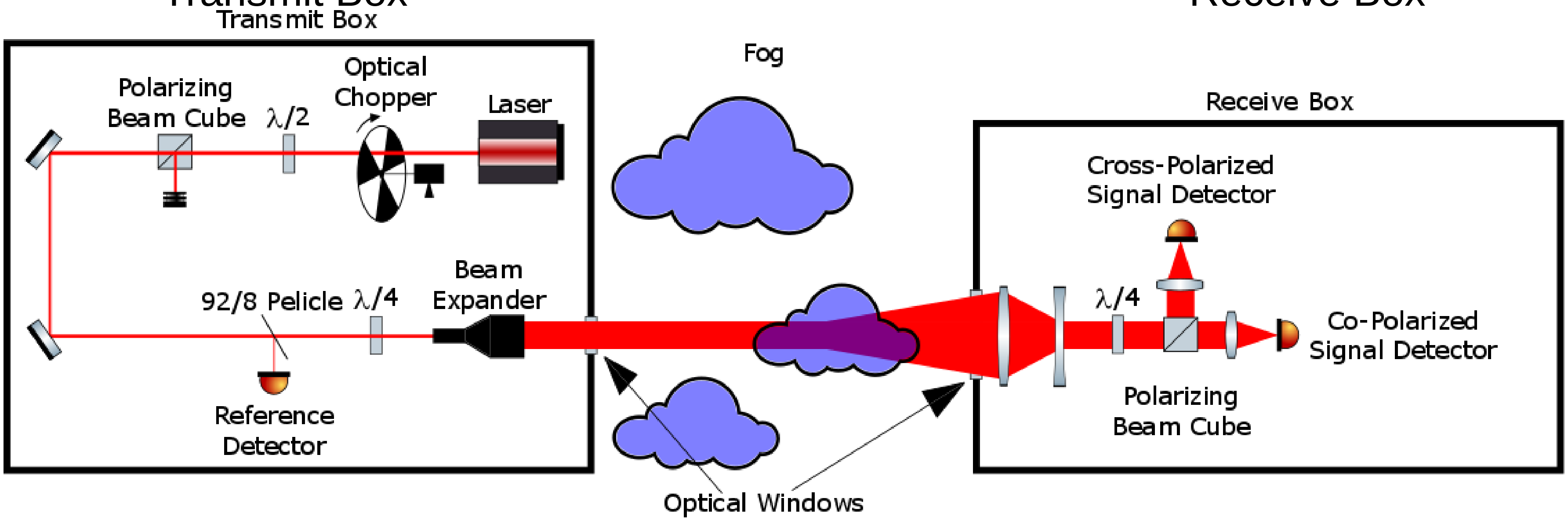




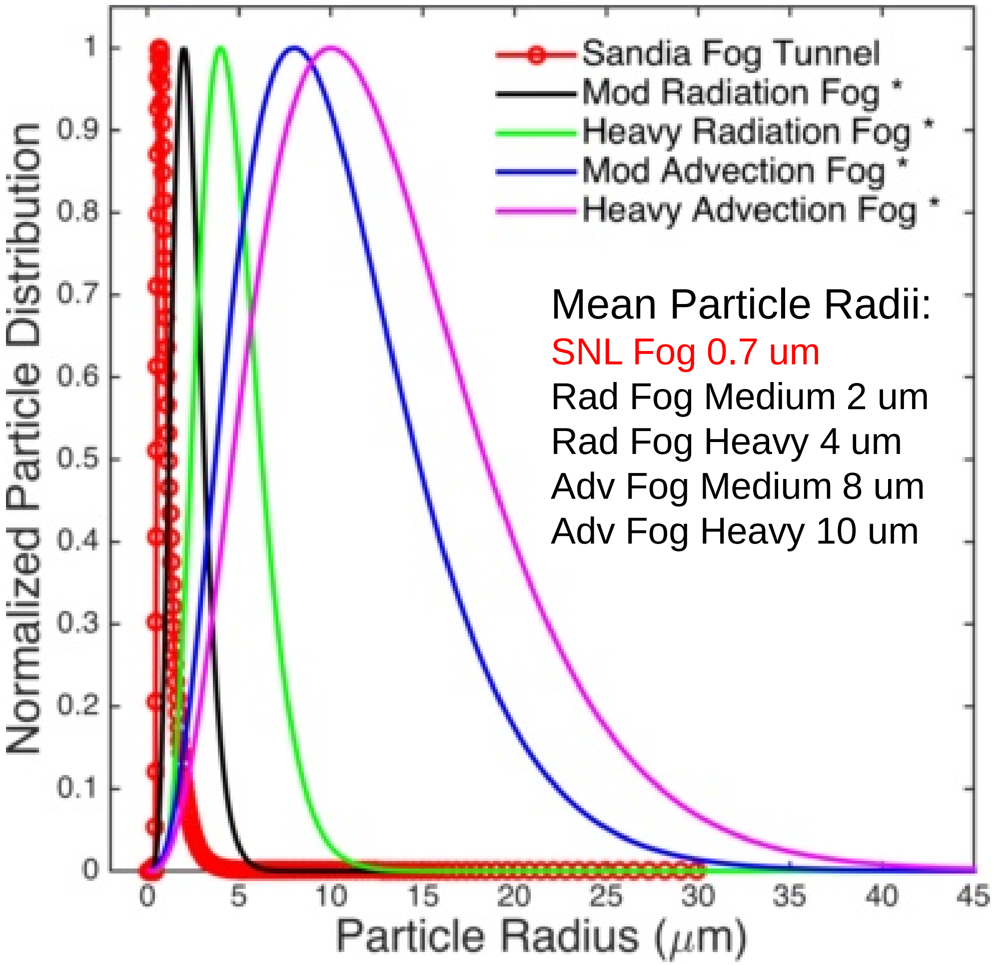


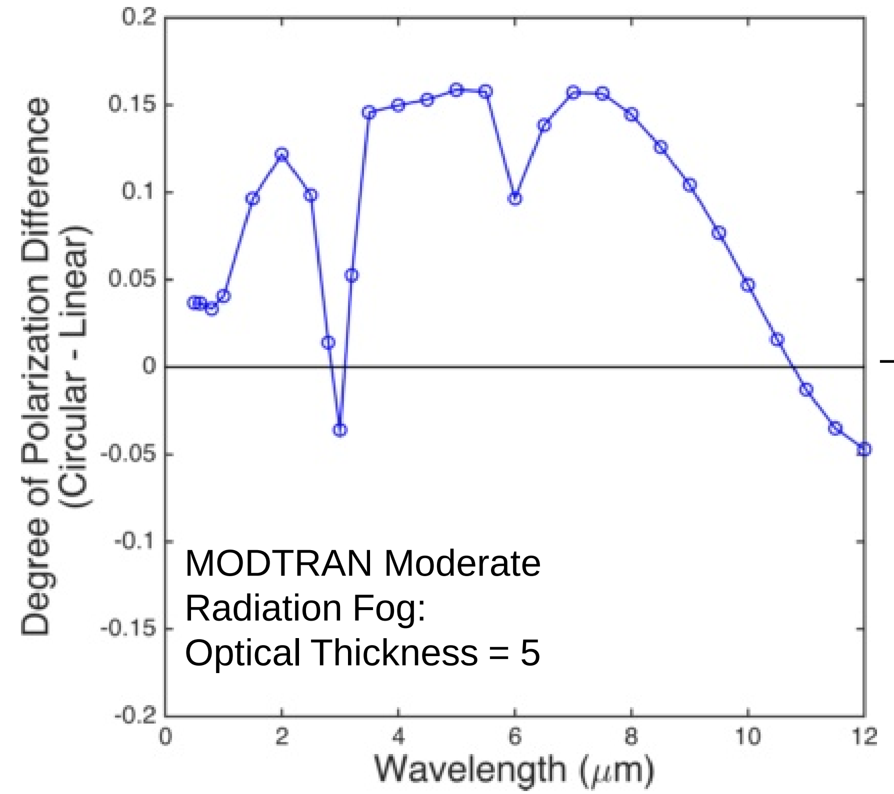
Transmit Box

Receive Box



Develop and Characterize Fog Analogs





John’s Talk: 10197-4 Right Here, Next!

Any Questions?

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FAA Rules for visibility (VFR)

Altitude	Type of Airspace	Flight Visibility	Cloud Clearance
10,000 MSL	E	5 statute miles	111 ✈1,000 below, ✈1,000 above, ✈1 sm horizontal
Below 10,000 MSL	C	3 statute miles	152 ✈ 500 below ✈1,000 above ✈2,000 horizontal
	D		
	E		
	B	3 statute miles	Clear of clouds
1,200 AGL or higher	G (night)	3 statute miles	152 ✈ 500 below ✈1,000 above ✈2,000 horizontal
	G (day)	1 statute mile	152 ✈ 500 below ✈1,000 above ✈2,000 horizontal
Below 1,200 AGL	G (night)	3 statute miles	152 ✈ 500 below ✈1,000 above ✈2,000 horizontal
	G (day)	1 statute mile	Clear of clouds

Kohler Equation

Behavior of salt water droplets

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

In cgs units

$S_{v,w} = \frac{e_a}{e_{sat,w}}$	Saturation ratio with respect to plane water surface
M_w , M_s	Molecular weight water, salt
$\sigma_{s/a}$	Surface tension, salt water in air
R	Ideal gas law constant
T	Temperature in K
ρ_w	Density of water
a	Radius of droplet

v	# ions salt dissolves into
Φ_s	Practical osmotic coefficient ≈ 1
m_s	Mass of salt (g)
ρ_w	Density of aqueous salt solution

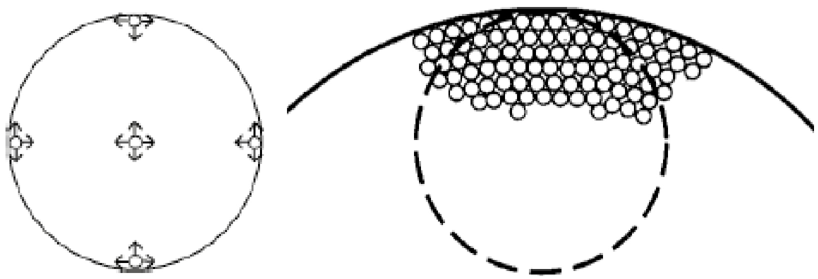
Taken from “Microphysics of Clouds and Precipitation” 2nd edition, H. R. Pruppacher and James D. Klett, Kluwer Academic Publishers 1997
Chapter 6: Equilibrium behavior of cloud drops and ice particles

Kohler Equation

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

Curvature term   Solute term

Curvature term (Kelvin equation) – equilibrium vapor pressure is larger over a droplet than plane surface



Easier to evaporate from surface than from bulk, and the probability that a molecule evaporates from the surface is higher for curved surfaces.

A curved surface is in equilibrium with water phase at higher pressure than plane surface

For a given supersaturation value, particle size determines if a droplet can exist/grow

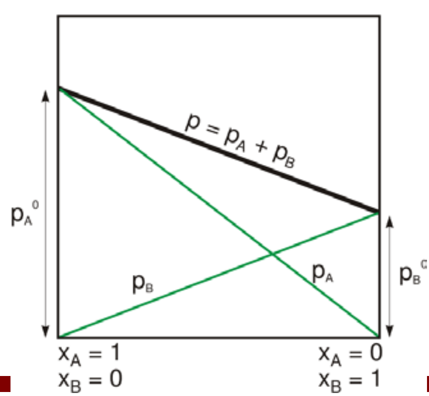
Kohler Equation

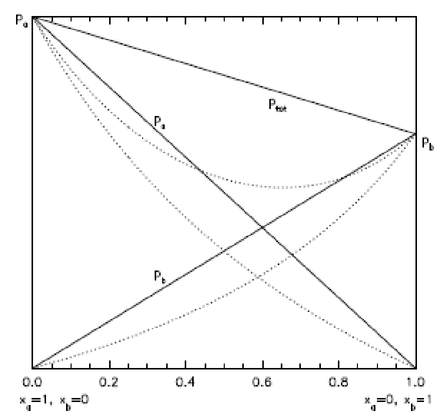
$$S_{v,w} = \frac{e_a}{e_{sat,w}} = exp\left[\frac{2M_w\sigma_{s/a}}{RT\rho_w a} - \frac{v\Phi_s m_s M_w/M_s}{(4\pi a^3\rho_s/3)\ -\ m_s}\right]$$

Curvature term

Solute term

Solute term (Raoult's Law) – the vapor pressure of a solution of a non-volatile solute is lower than the pure solvent. Salt interacts with water and more tightly binds it, so it costs more energy to evaporate water out of salt water bulk





Dotted lines = solute disassociate into 3 components

Kohler Equation

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

If dilute salt solution $m_s << m_w$, $\sigma_{s/a} \approx \sigma_{w/a}$, $\Phi_s \approx 1$, and close to saturation ($e_a/e_{sat,w} \approx 1$)

$$S_{v,w} = \frac{e_a}{e_{sat,w}} = 1 + \frac{A}{a} + \frac{B}{a^3}$$

$$\frac{A}{a} = \frac{2M_w\sigma_{w/a}}{RT\rho_w a} \approx \frac{3.3x10^{-5}}{Ta}$$

$$\frac{B}{a^3} = \frac{3vm_sM_w}{4\pi M_s\rho_w a^3} \approx \frac{4.3vm_s}{M_s a^3}$$

Curvature term

Solute term