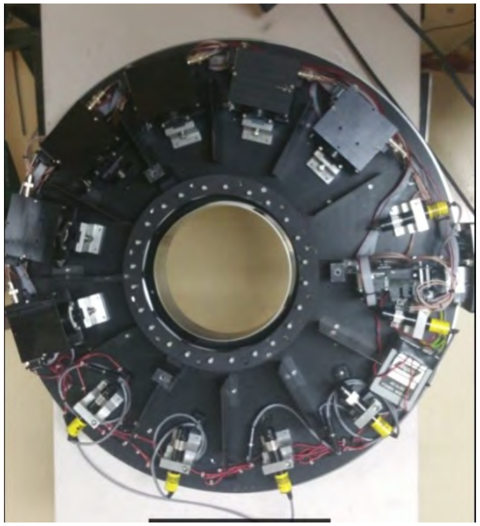
PODScan: Planar Drop Sizer

An Overview of the PODScan dropsizer



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Outline

- SMD measurement Techniques
- Scattering and Extinction Tomography
- Mathematical Procedure
- Result and Discussion
- Conclusions and Future Works

Single Point SMD

- PDPA – Velocity + Drop Size at the same time for a point

– combine LDV and drop size capability

- Planar measurement is time consuming.

- Diffraction

- Malvern Instrument
- Uses Mie theory to relate the scattering phase function to the drop size
- Line of sight measurement, multiple scattering effect are significant for a dense spray due to high FOV optical arrangement

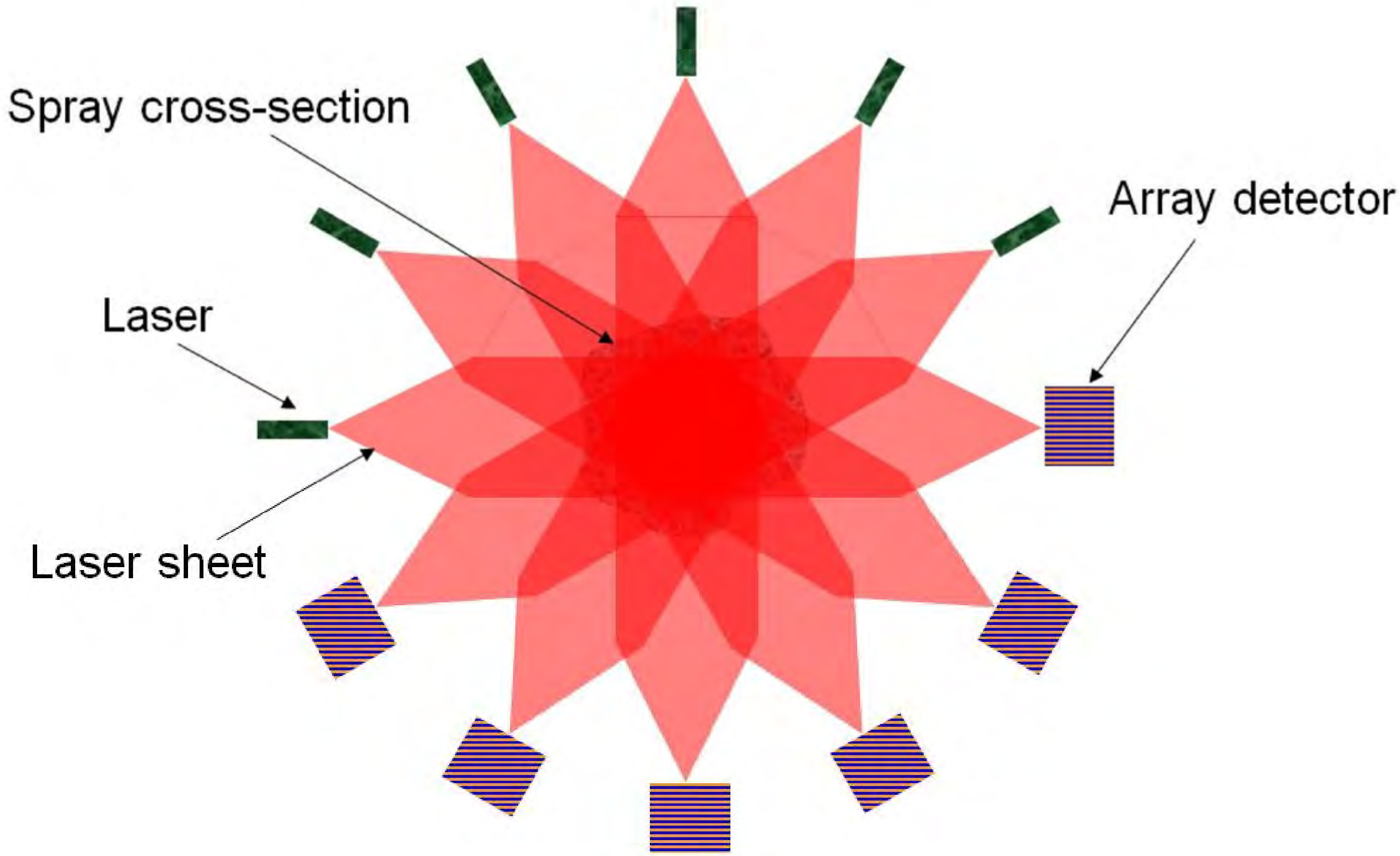
Planar SMD - LIF/MIE

- Yeh (1993), Sankar (1997) and Domann (2003), Commercially available system
- Fluorescence intensity is proportional to volume of droplet and scattering intensity is to the surface area of droplets

$$\frac{S_{LIF}}{S_{MIE}} = \frac{C_{LIF}. \int D^3 P(D) dD}{C_{MIE}. \int D^2 P(D) dD} = C \cdot SMD$$

- Fluorescence dye is necessary for water and liquid fuel, and calibration procedure is involved. For dense spray, the method suffers from multiple scattering effects.
- Multiple scattering effects are corrected with structured laser illumination (Mishra et. al.,2014)

Extinction Tomography for Local Surface Area



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Extinction Tomography for Local Surface Area

- Path integrated extinction of laser sheets
- 6-Axis measurement with 512 linear array
- Local extinction coefficients obtained by statistical extinction tomography using MLE method
- For liquid sprays, the local extinction coefficients is equal to the surface area of the droplets
- No correction or calibration is required other than geometrical arrangement.
- No multiple scattering effects – applicable to near opaque spray

Scattering/Extinction Tomography

- Provide planar SMD distribution,
- Simple modification to extinction tomography system,
- Inherit benefit of extinction tomography – quantitative measurement, no correction is necessary.
- Minimal multiple scattering effects with Small FOV.
- No fluorescence dye is necessary, attractive in production setting.
- No calibration is necessary for scattering phase function as long optical efficiency of the sensors are uniform.
- Provides second order SMD (width of PDF) as well as first order (mean) SMD.

Radiative Transfer Equation with Scattering

$$I_\lambda^2 = \frac{S_\lambda}{\beta_\lambda} * \left(1 - \exp\left(-\beta_\lambda \cdot \Delta\right)\right) + I_\lambda^1 \cdot \exp\left(-\beta_\lambda . \Delta\right)$$

$$S_\lambda = \sigma_\lambda \int_\Omega \cdot I_s \cdot \Phi(\theta) d\Omega$$

$$\beta_\lambda \cong \sigma_\lambda$$

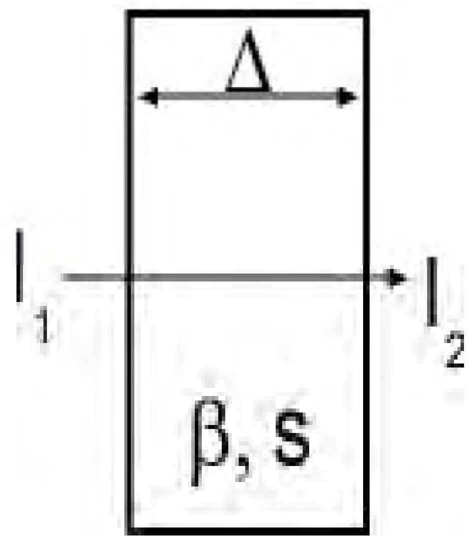
$\Phi(\theta) = scattering\ phase\ function$

$\beta_\lambda = extinction\ coefficient$

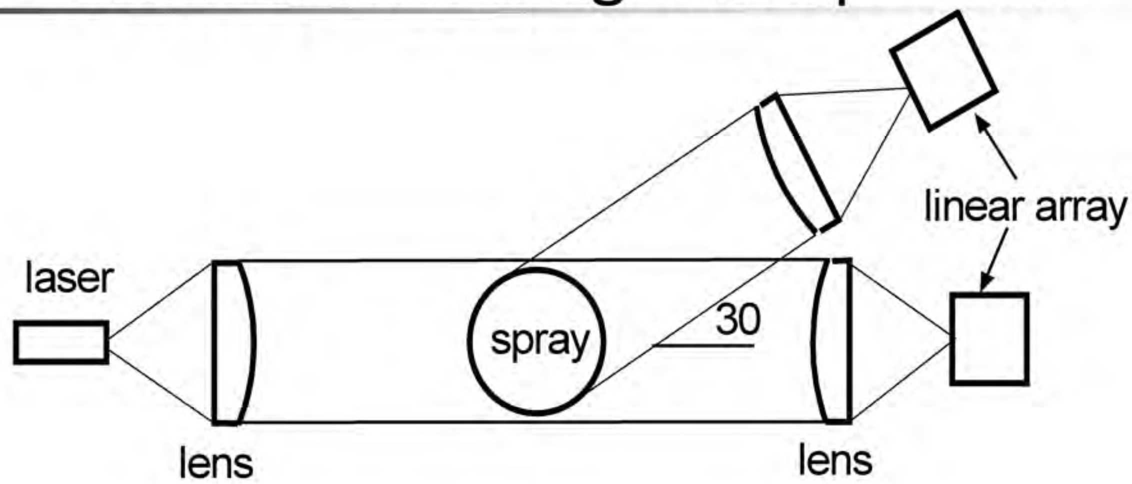
$\sigma_\lambda = scattering\ coefficient$

$\Delta = path\ length$

$S_\lambda = radiation\ source\ from\ scattering$

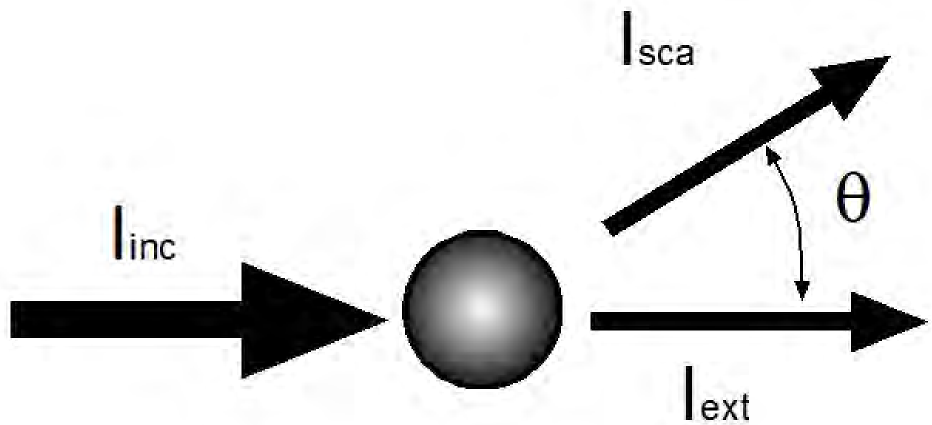


Geometrical Arrangement per Axis



- Inline axis measures the extinction caused by the drops
- 30 degree off axis measures the scattered intensity
- There are 6 axis of measurement of the scattering intensities and the extinction for the tomography system
- Optical system with a narrow aperture measures only in-plane light for both extinction and scattering (small FOV).

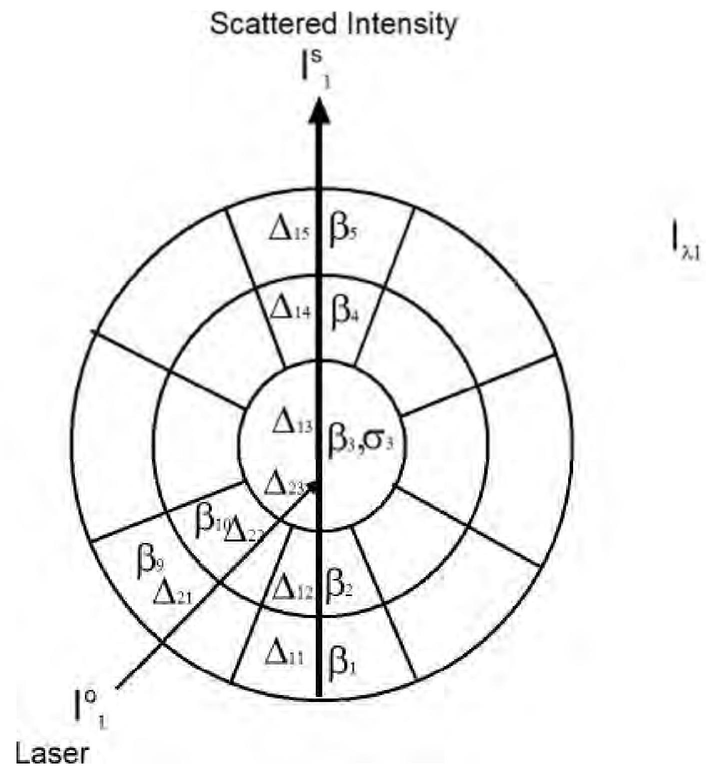
What is scattering phase function?



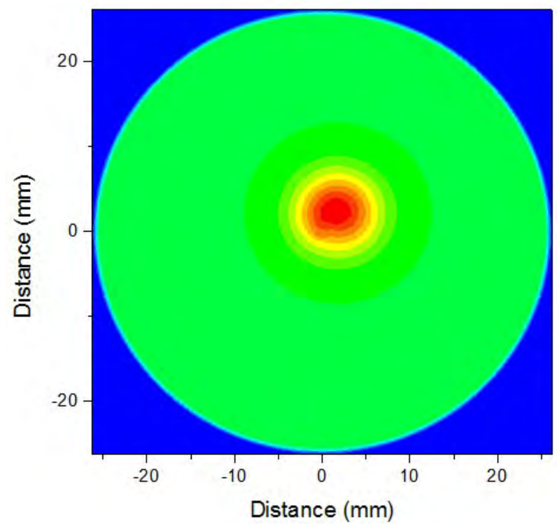
For spherical droplet $$\Phi(\theta) = \frac{I_{sca}}{I_{inc}}$$

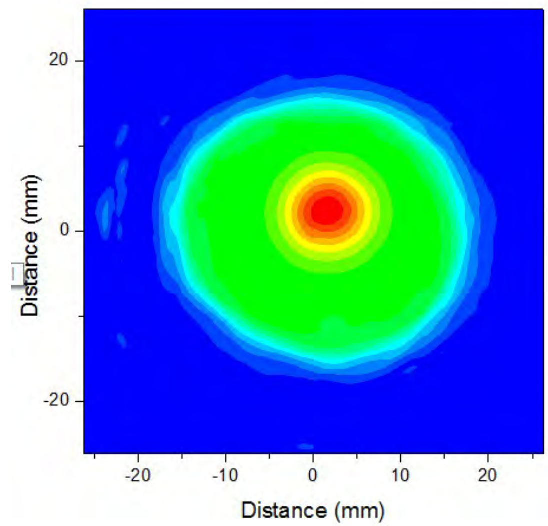
Scattering/Extinction Tomography

- Only single scattered light is accounted for in system
- Multiply scattered light is too small to be detected with the current optical arrangement.
- Scattered light at 30 degree is typically 1000 or 10000 less than incident light because of our narrow aperture for the sensor.
- All parallel lines of incident light contributes to a scattering measurement.



Numerical Validation for Tomography





- Forward Scattering Phase Function – Clipped Gaussian, Peak Value= 0.40.
- Reconstructed Scattering Phase Function – Peak Value= 0.393
- Recovery was excellent with given resolution of the tomography system

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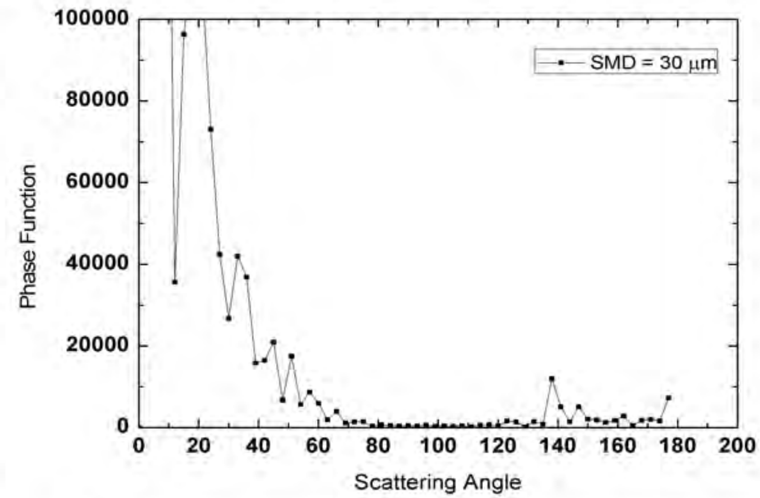
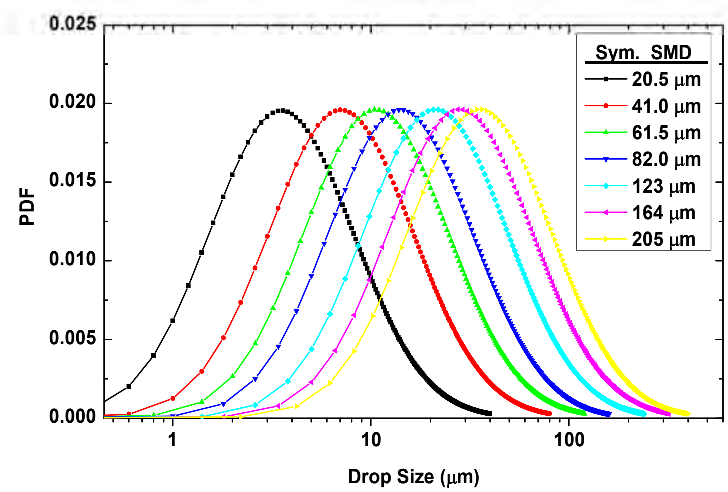
Scattering Phase Function and SMD

- Phase Function is directly related to the SMD if the droplet is spherical.
- Mie simulation will used for the phase function.
- For the mono-disperse droplet, the phase function is extremely spiky.
- A log-normal distribution of drop size is used for the Mie simulation to smooth out.





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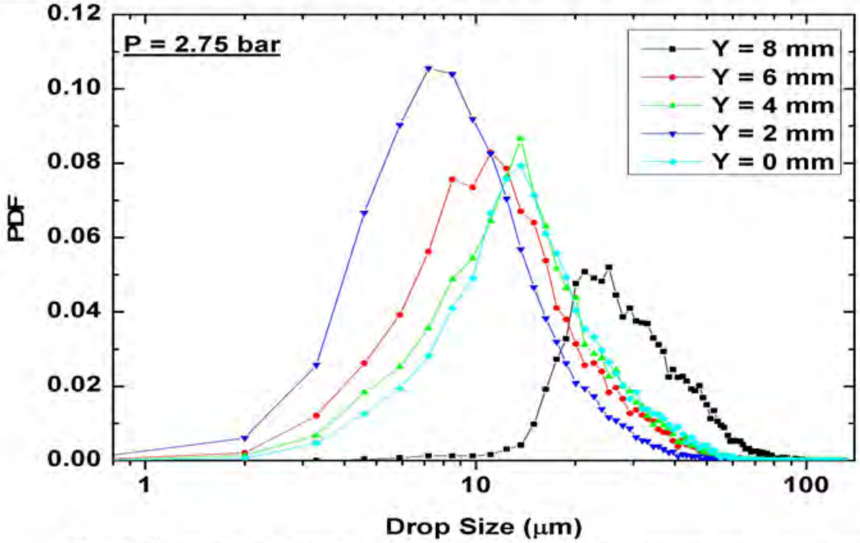
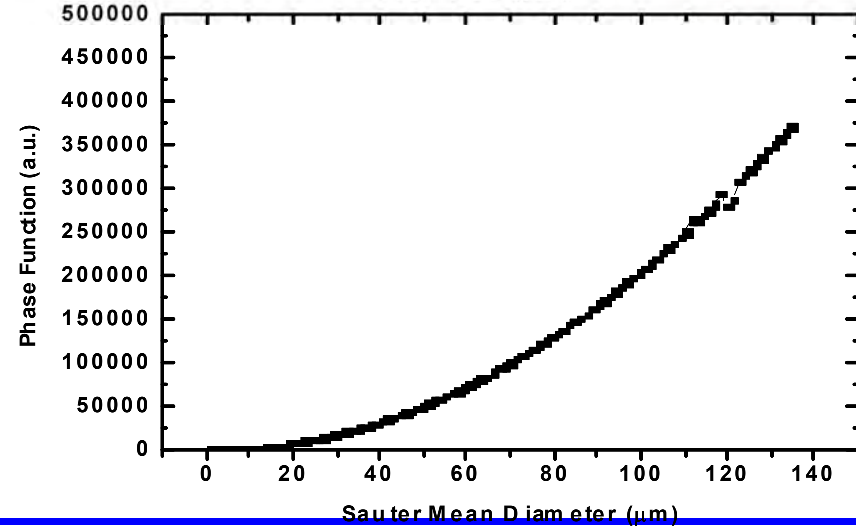
Scattering Phase Function and SMD

- PDF shape with PDPA measurement are all similar and shapes are log-normal distribution.

- Phase function is proportional to the SMD of spray.





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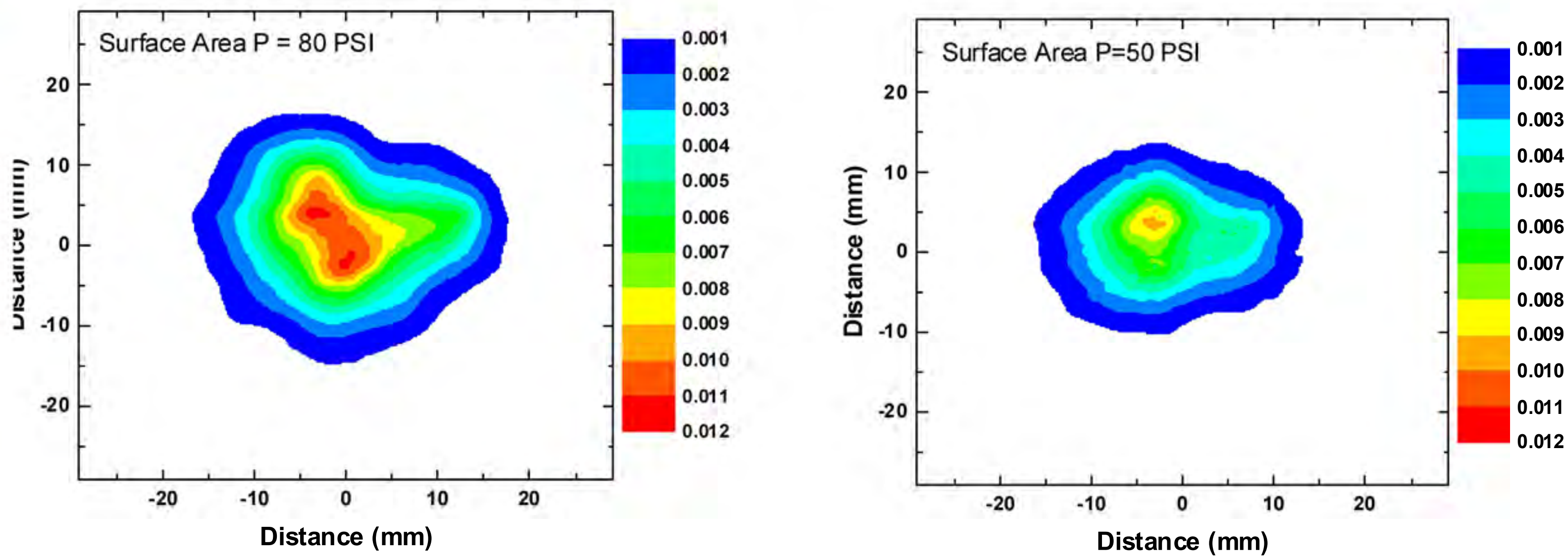
Results and Discussions



- Only 30 degree scattering signal is strong enough.
- Scattering signal is ~1/10000 smaller than extinction signal
- Neutral density filter were removed for the scattering measurement to increase sensitivity
- Peak extinction coefficient is at the center (high number density)

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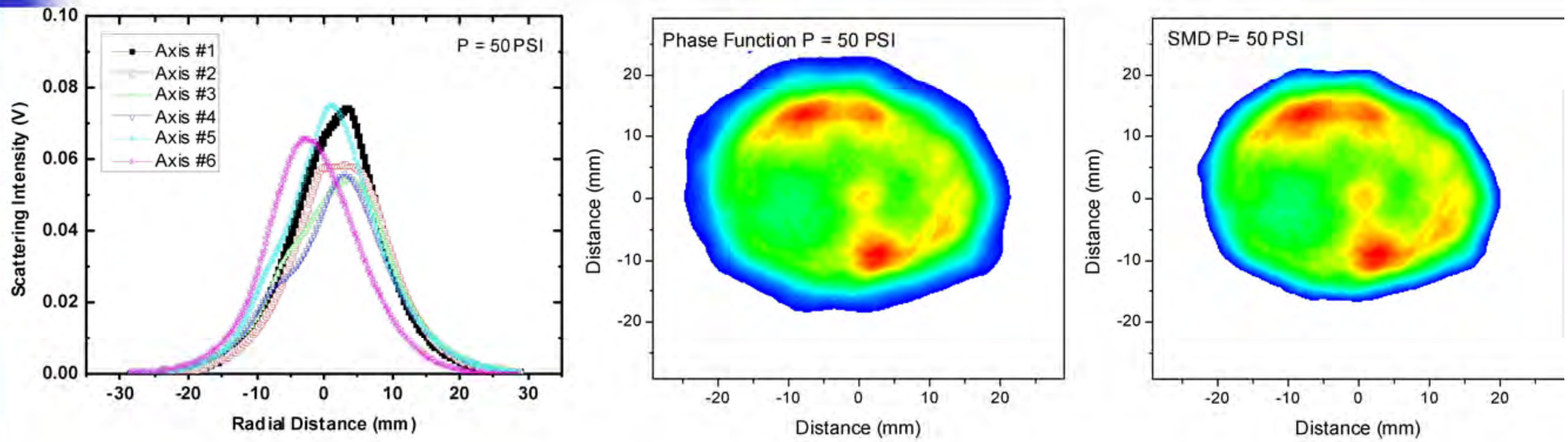
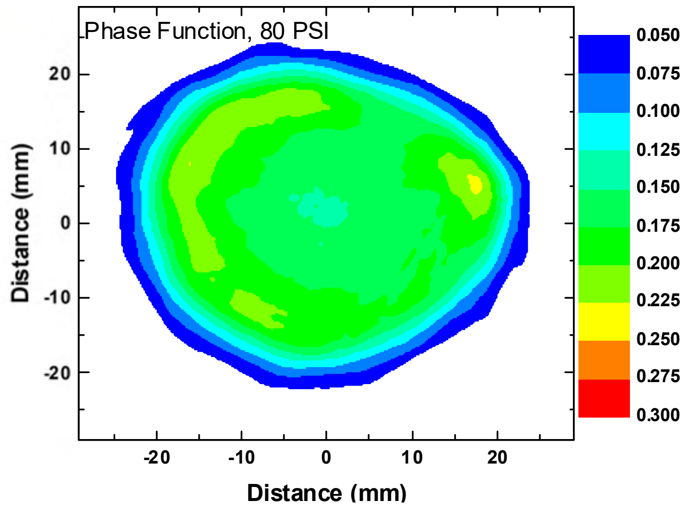
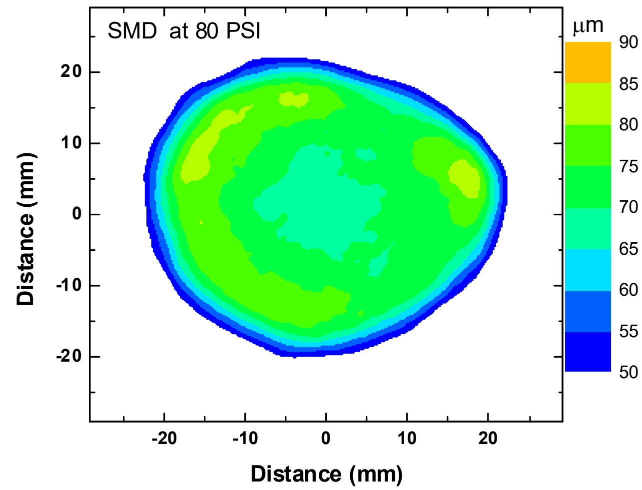
Deconvoluted SMD at P = 50 PSI



- The peak scattering intensity is very similar for all axis
- The high phase function at the periphery, which indicated the drop size are larger at the periphery
- SMD is almost linearly proportional to the Phase Function

Deconvoluted SMD at P = 80 PSI





- **At higher pressures, drop sizes are more uniform**
- **SMD is almost linearly proportional to the Phase Function**
- **Measurements agree with PDI method**

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Conclusions

- A scattering/extinction tomography system was developed to estimate planar SMD distribution
- The scattering tomography system does not involve any calibration constants (other than accounting for the non-uniformity of sensors)
- The system is free of multiple scattering effects.
- Once the non-uniformity in optical efficiency of sensors are measured, the scattering phase function can be directly converted to SMD distribution.
- Second order SMD (width of PDF) as well as first order SMD (mean) and are available at the same time from the scattering/extinction tomography system.