

TSI FLUID MECHANICS WEBINAR SERIES

# SIMULTANEOUS VELOCITY AND DIAMETER MEASUREMENTS USING PDPA : KEY STEPS AND BEST PRACTICES

May 26th, 2021



# Introduction

- + Presenters:
  - Wing Lai, TSI
  - Dan Troolin, TSI
- + To limit feedback and noise, audio from attendees will be muted during the presentation
- + Questions and Answer period at the end of the presentation
- + Please use Q & A box to submit your questions

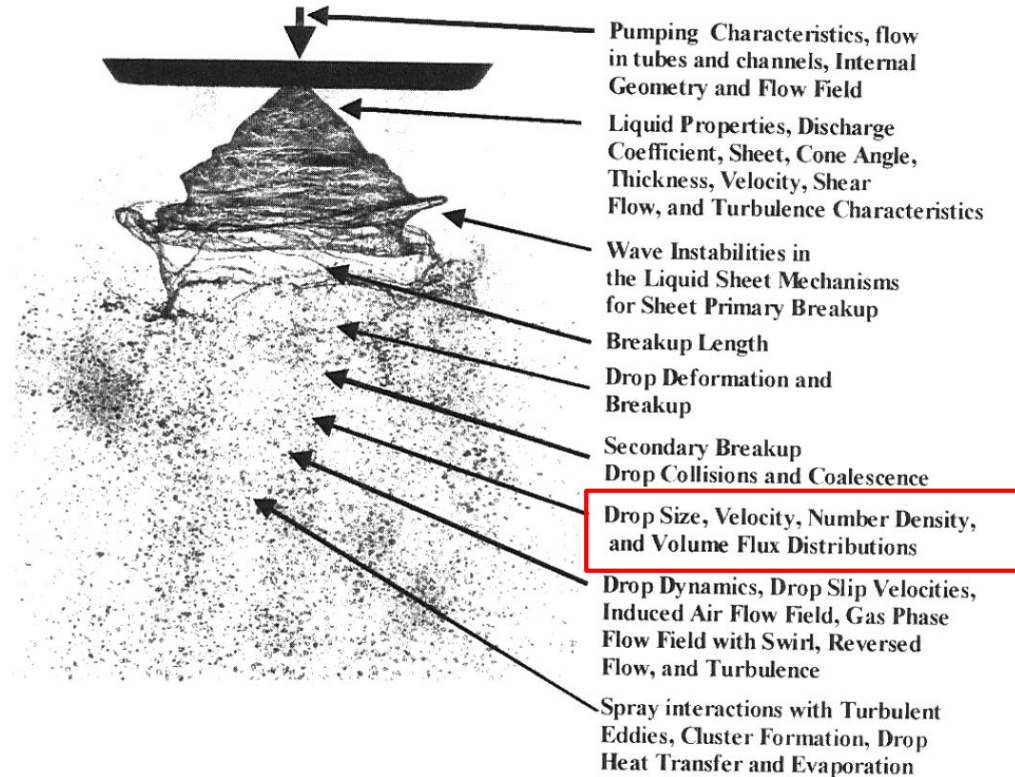


# Agenda

- + Phase Doppler Particle Analysis (PDPA)
  - Scattered Light Signal
  - Phase Measurements
  - Diameter – Phase Relationship
  - Maximum Measurable Diameter
  - Receiver – 3 Detectors
- + Diameter Measurements
  - Phase Calibration
  - Intensity Validation
  - Probe Volume Correction
- + Application examples
- + Q&A



# Spray Characterization

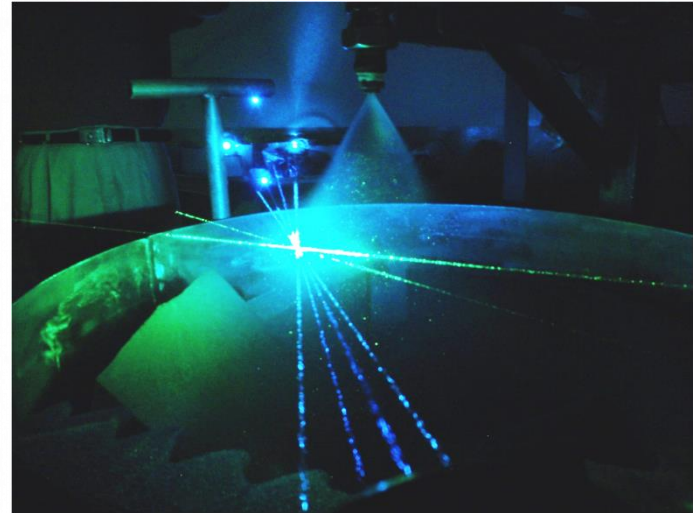


Bachelo (2000) Spray Characterization for 20th Century



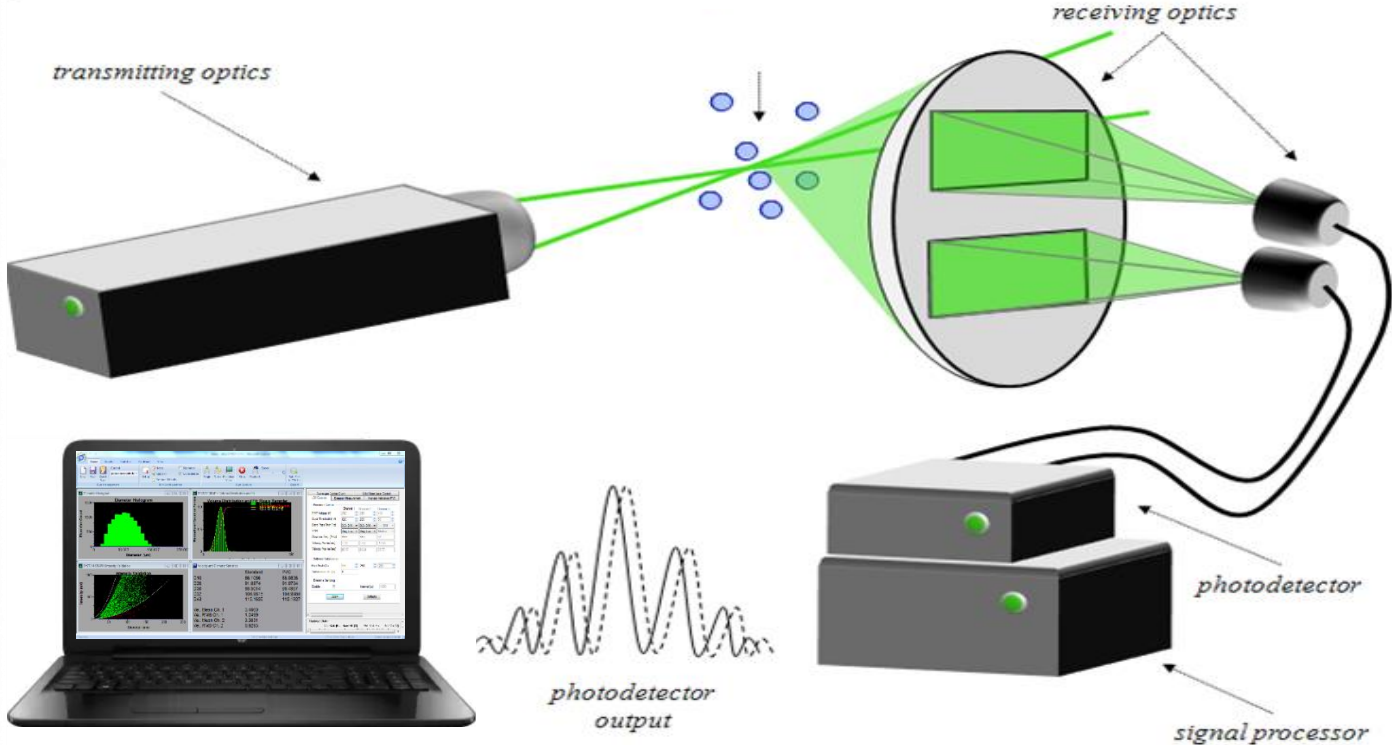
# Phase Doppler Particle Analysis (PDPA)

- + Derive Particle Size information by measuring the same laser Doppler signal scattered by particles passing through a single point from several distinct locations in space

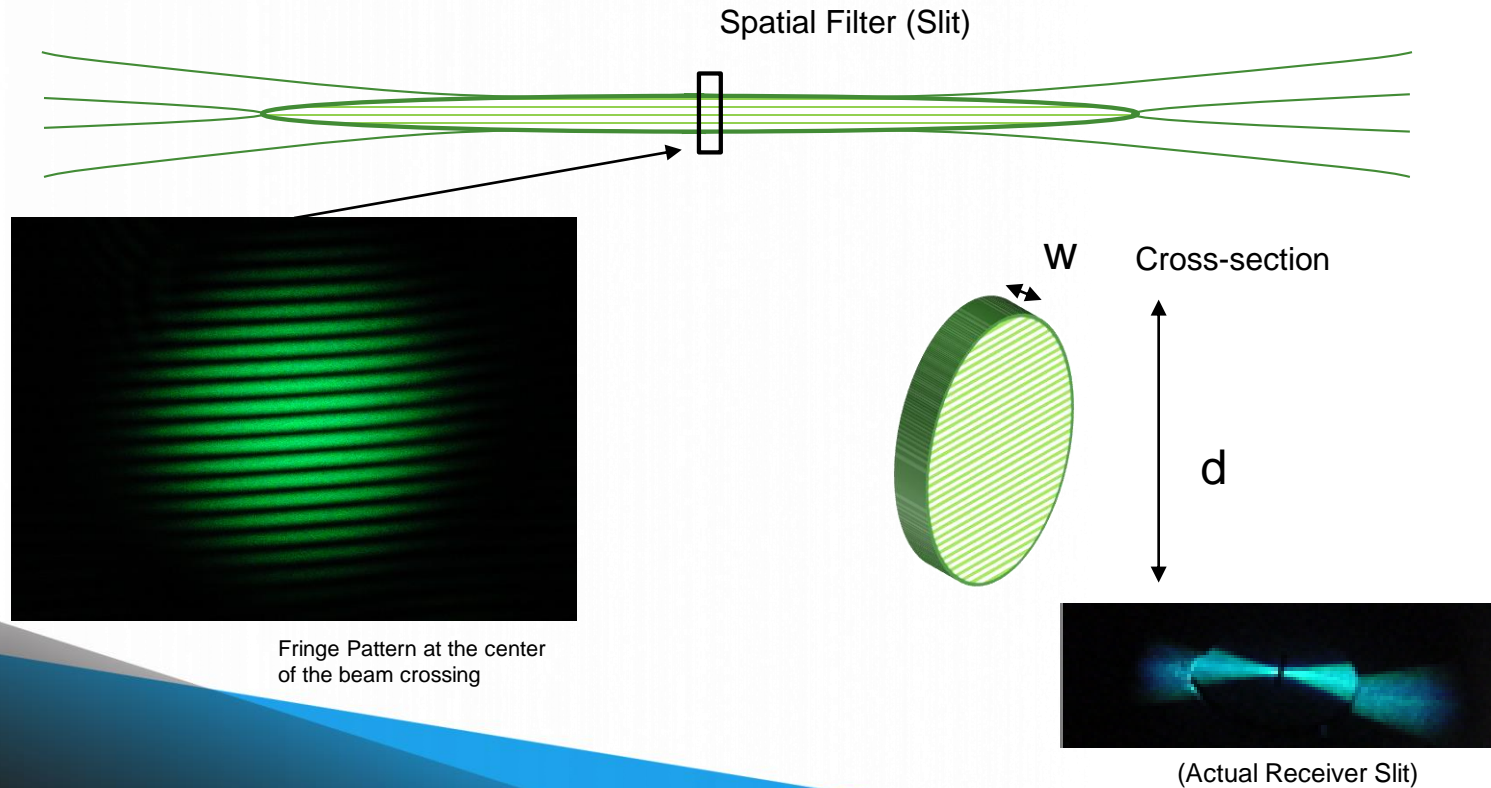




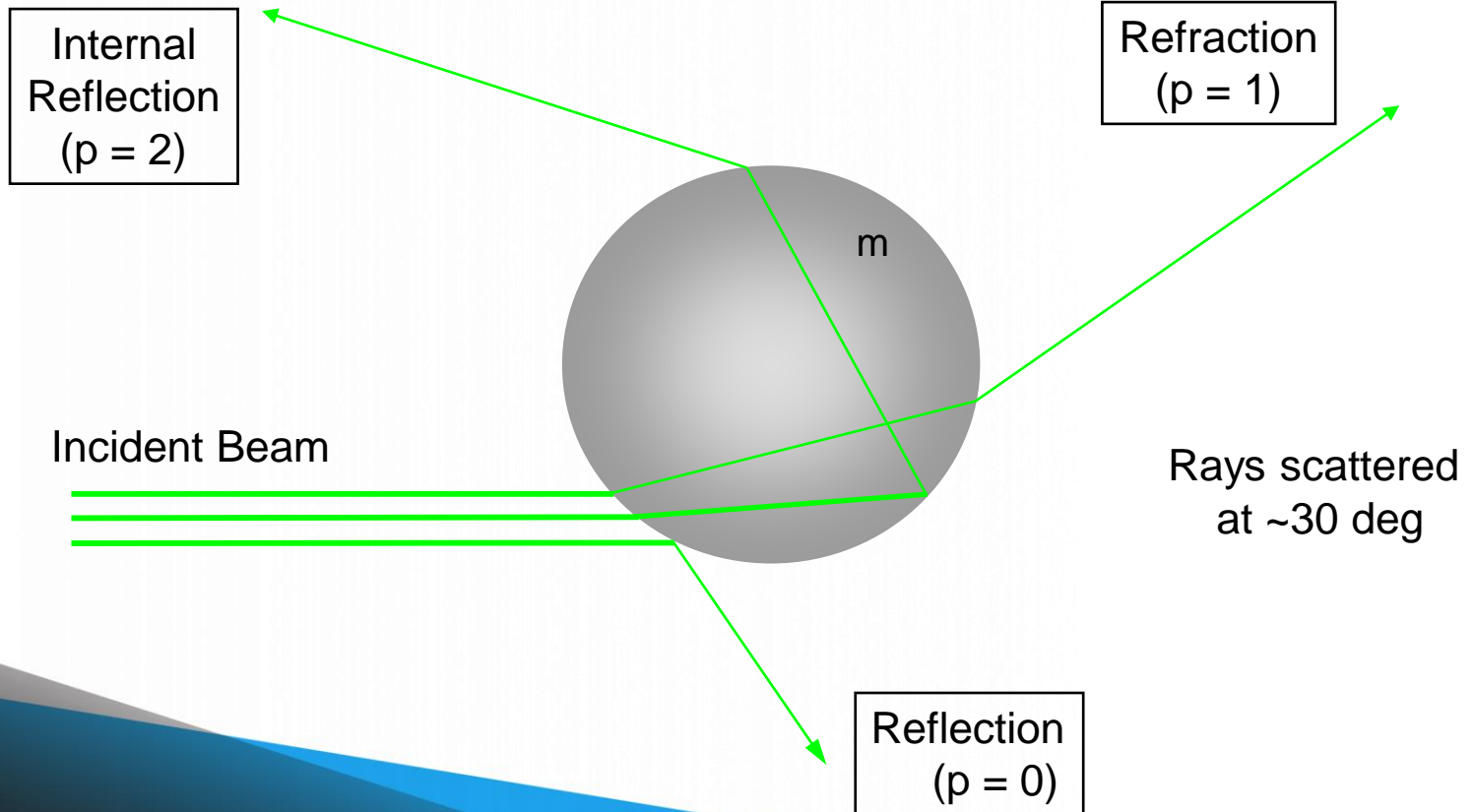
# PDPA Schematic



# PDPA Measurement Volume



# Light Scattering by a Droplet

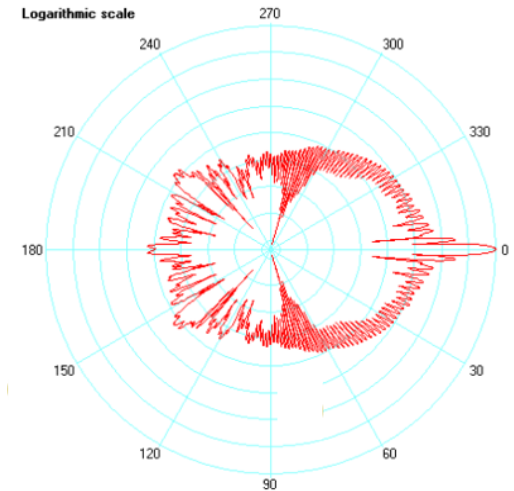




# Mie Scattering

- + Solution to Maxwell's equation
  - Lorenz-Mie, Lorenz-Mie-Debye
- + Scattering of an electromagnetic plane wave by a homogeneous sphere
  - How light scatters (reflects/refracts) off of droplets
- + PDPA mostly uses scattering modes:
  - $p = 0$ : Reflection
  - $p = 1$ : Refraction
  - $p = 2$ : Internal Reflection

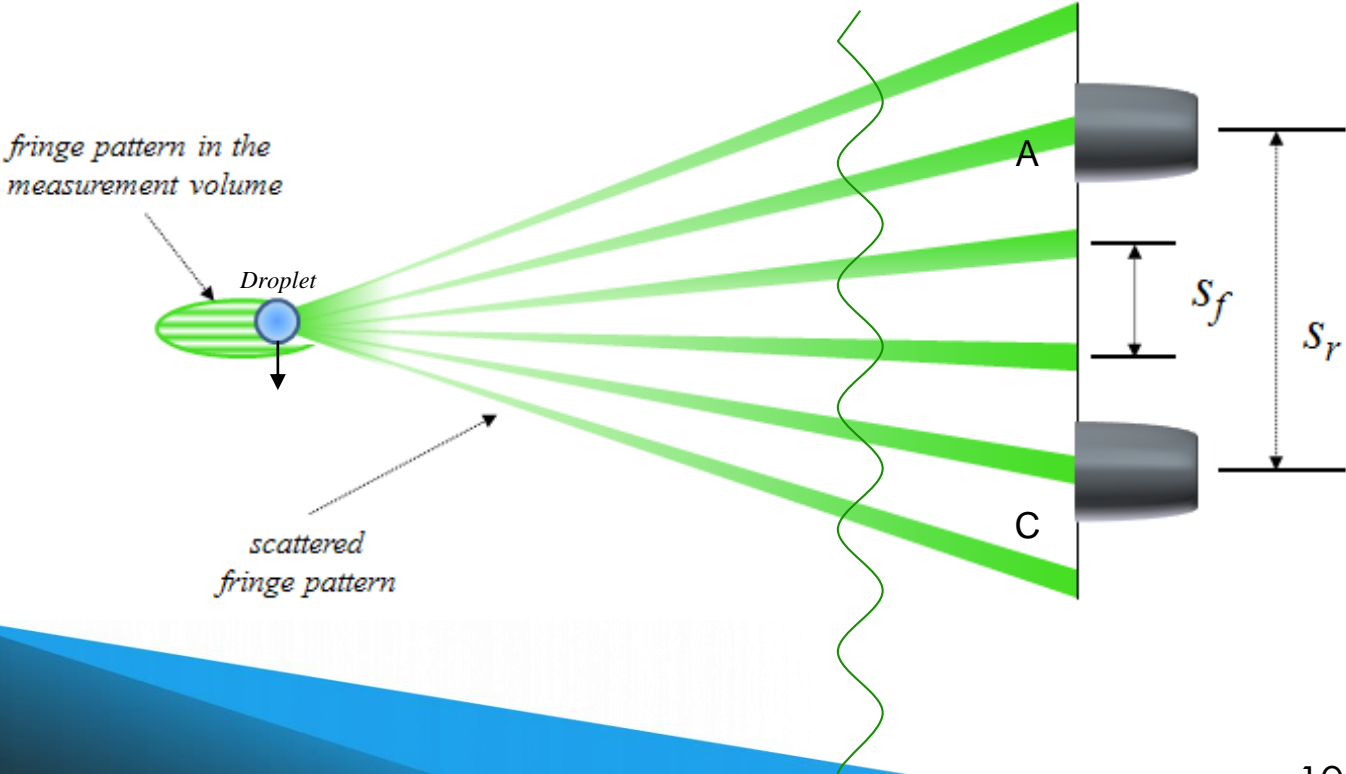
Incoming Laser Beam →



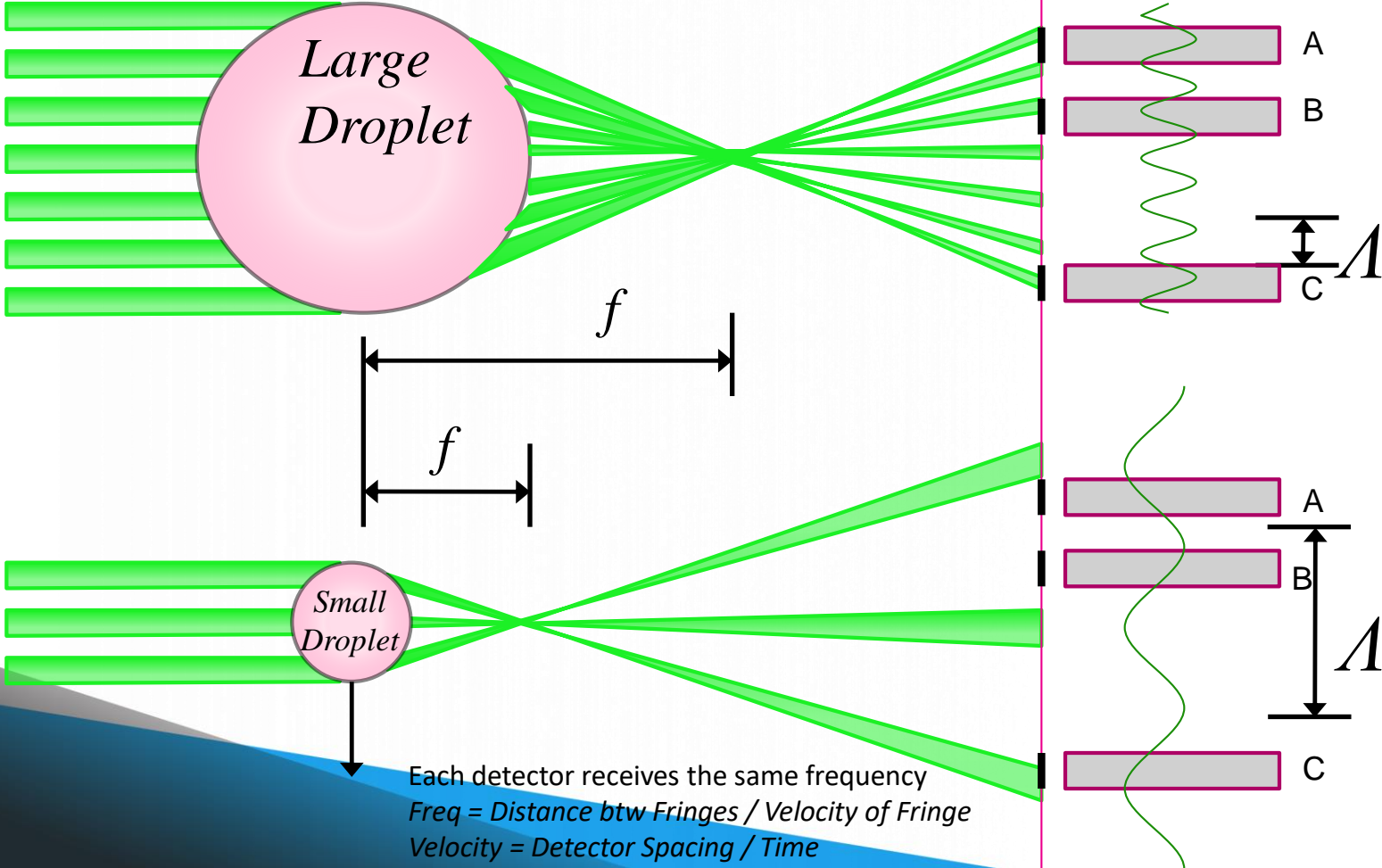
# PDPA Scattered Light Signal



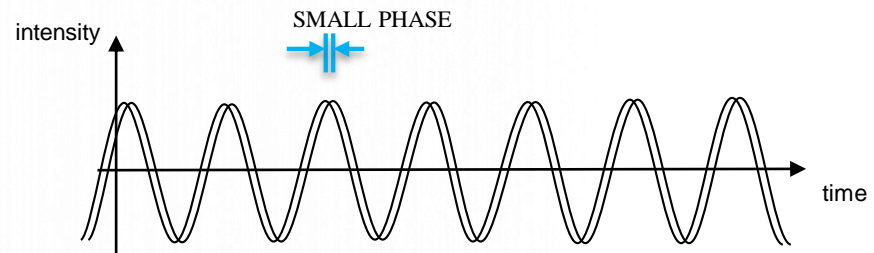
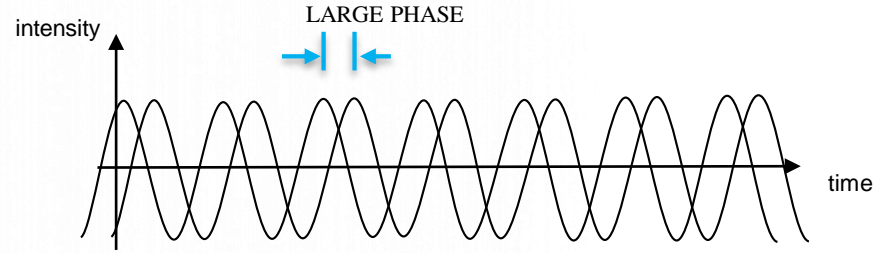
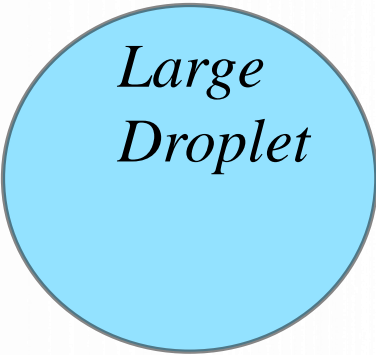
Droplet acts like a lens



# Phase Measurement



# Diameter – Phase Relationship



Note: in this example, the frequency (and thus, velocity) is the same for the large and small drop, only the phase shift changes based on diameter...



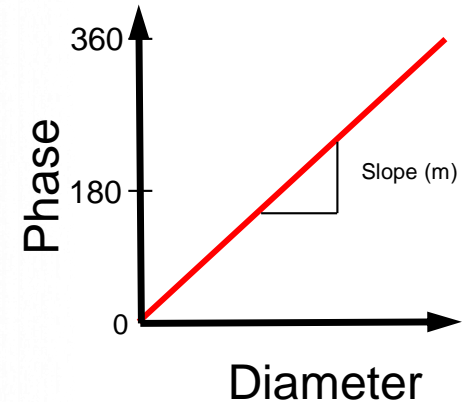
# Diameter – Phase Relationship

$$Diameter = \frac{Phase}{360^\circ} \times \frac{Fringe\ Spacing}{slope} \times \frac{Receiver\ Focal\ Length}{Detector\ Separation}$$

+ Phase – Measured by the PDPA system

+ Constants for a given medium and arrangement:

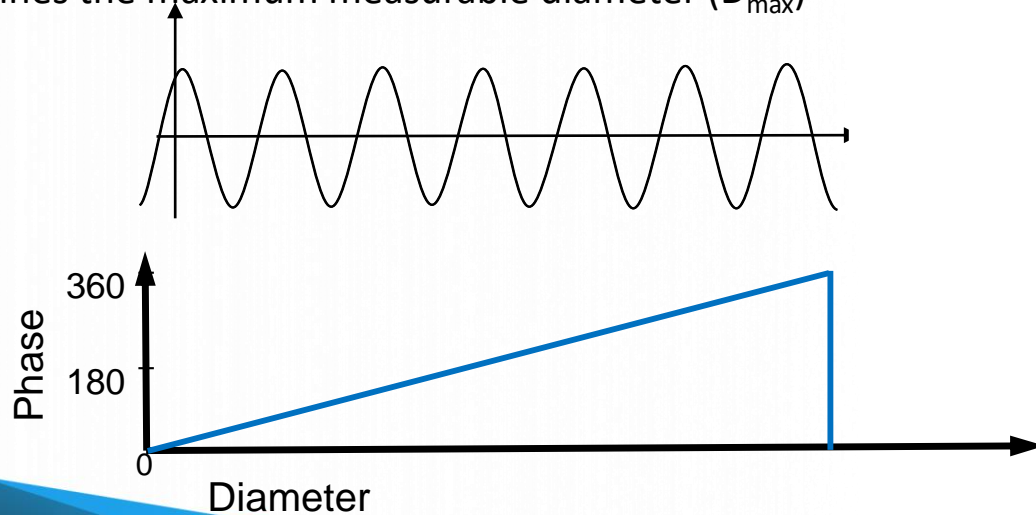
- Fringe Spacing – Determined by Optical Arrangement
- Receiver F.L. – Determined by Lens
- Detector Sep – Design of Receiver
- Slope – Calculated based on Mie Scattering (R.I., etc...)





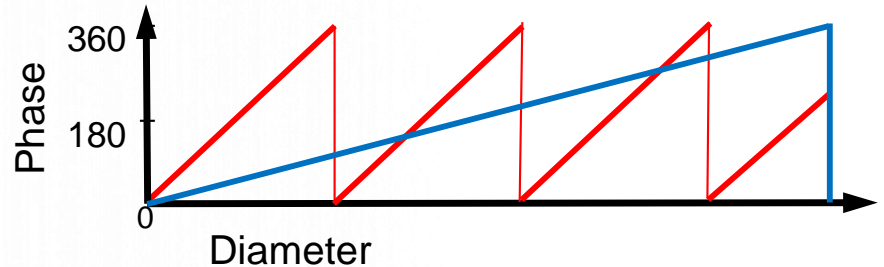
# Maximum Measurable Diameter ( $D_{\max}$ )

- + As the diameter increases, there becomes a point where the phase 'wraps around'
  - This phenomena is called "Phase Wrap"
- + This determines the maximum measurable diameter ( $D_{\max}$ )



# Receiver – 3 Detectors

- + Using 3 detectors gives us 2 independent phase measurements with different resolutions
  - AB – Low Resolution, Large Dynamic Range
  - AC – High Resolution, Small Dynamic Range
- + We use AB phase to tell us which AC line we are on
- + We use AC to determine the diameter with high degree of resolution
- + Validate droplet sphericity



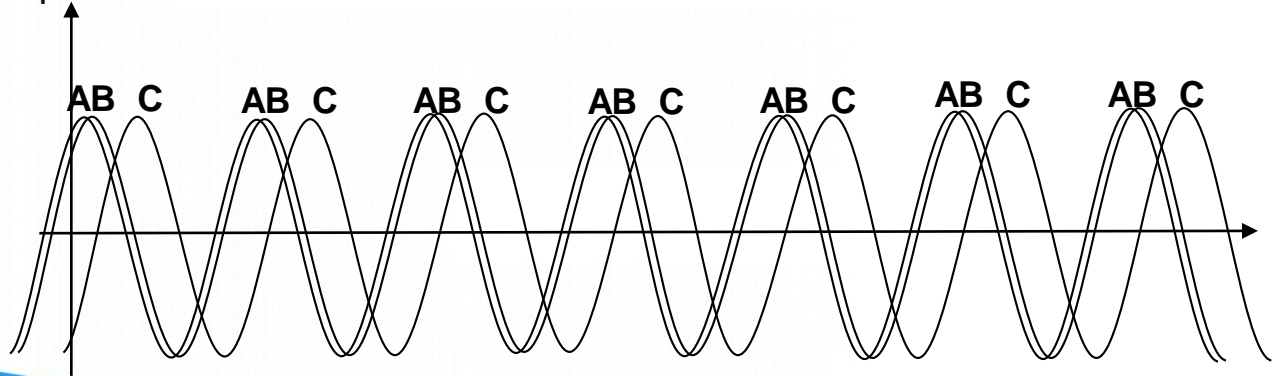
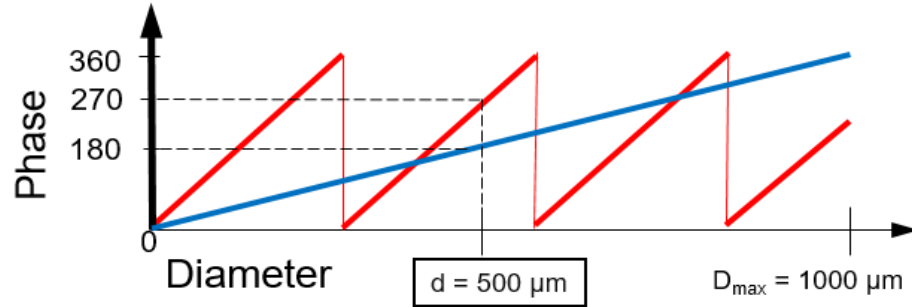
# Receiver – 3 Detectors

+ Typical Ratio is 3.5

+ Example

- Phase **AB** = 180
- Phase **AC** = 270

- Diameter ( $d$ ) = 500  $\mu\text{m}$

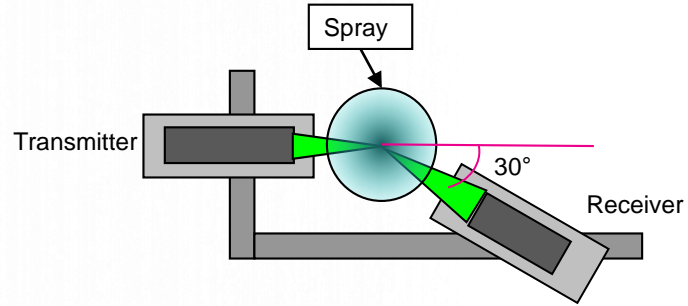


# PDPA System Common Layouts

## Forward Scatter Refraction

30° Receiver Angle

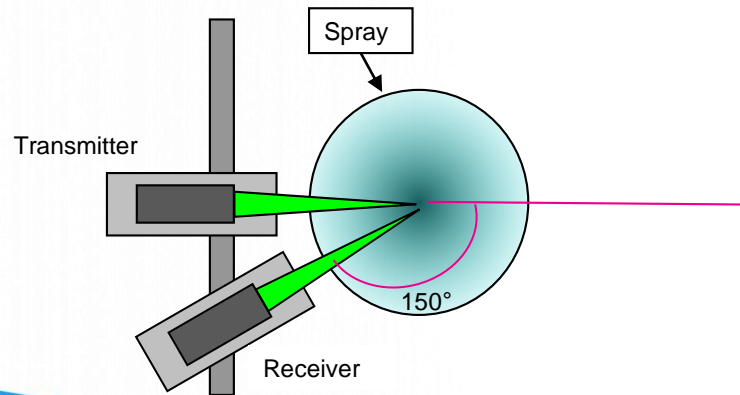
Generally Transparent Droplets



## Back Scatter Reflection

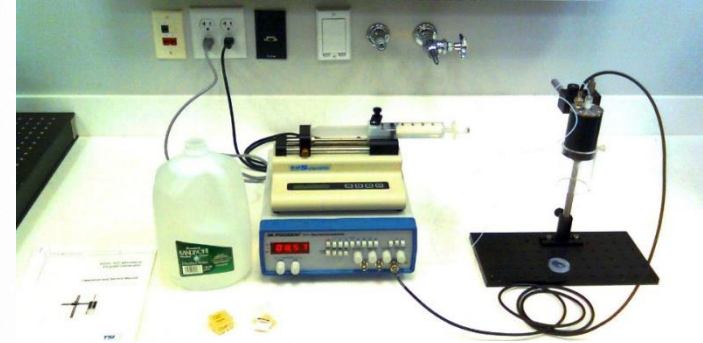
150° Receiver Angle

Opaque Droplets



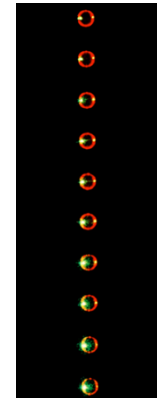
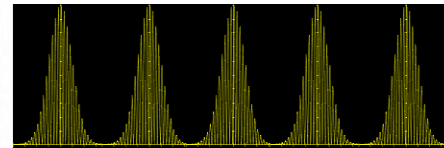
# Receiver Calibration

- + Monodisperse Droplet Generator (MDG-100)
  - Provides a stream of droplets with known diameter
  - where  $Q$  is the liquid flow rate and  $f$  is the excitation frequency.
  - For convenience, the expression will be reduced to allow direct input of the flow rate read from the syringe pump in cc/min and the frequency in kilohertz.



$$\frac{\pi D^3}{6} = \frac{Q}{f} \text{ or } D = \left[ \frac{6Q}{\pi f} \right]^{\frac{1}{3}}$$

$$D = 317 \left[ \frac{Q (\text{cc} / \text{min})}{f (\text{kHz})} \right]^{\frac{1}{3}}$$



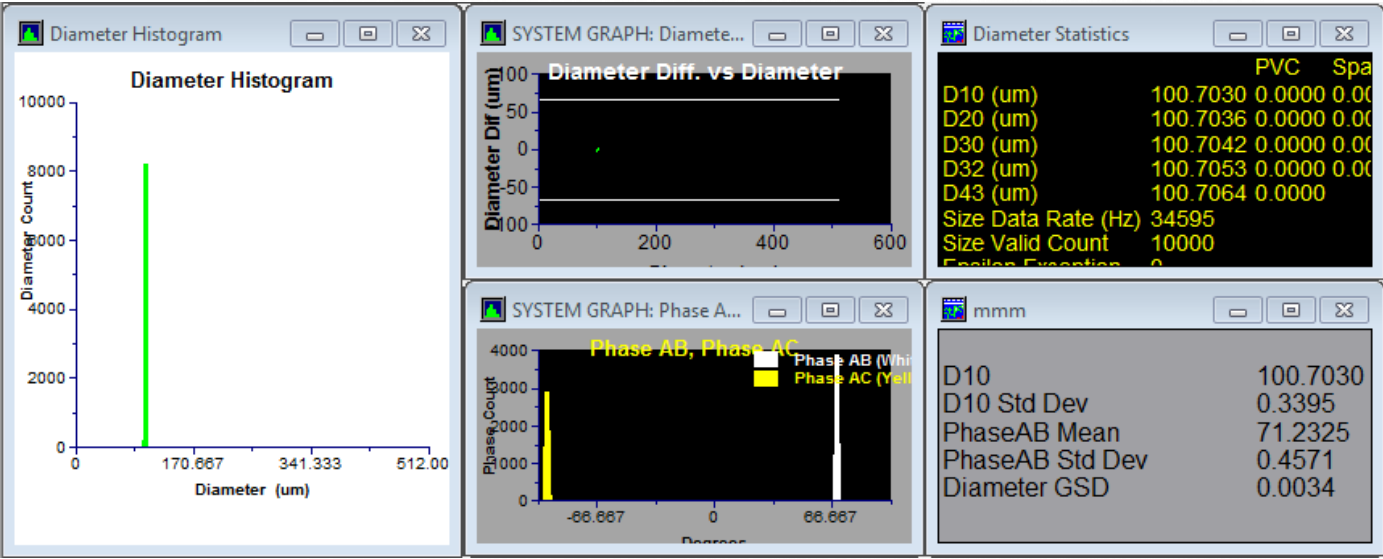


# Receiver Calibration

**TSI PDPA System  
MDG-100**



# Receiver Calibration



The 'Calibration' dialog box is shown with the 'Receiver Calibration' tab selected. It contains the following settings:

- Monodisperse Droplet Generator:**
  - MDG Frequency (KHz): 34.595
  - Flow Rate (ml/hour): 66.60
  - MDG Diameter (um): 100.701
- Maximum Diameter Difference Control (Epsilon):**
  - Max Dia. Dif (um): 66.5825
  - Max Dia. Dif (%): 13
- Calibration:** A button to execute the calibration.
- Detector Separation (mm) and Phase Factor (deg/micron):**

Detector	Separation (mm)	Phase Factor (deg/micron)
AB	9.86	0.68
AC	37.04	2.57

Buttons for 'Apply', 'Defaults', and 'Close' are located at the bottom.



# Phase Calibration

- + Remove Electronic Timing Delays from Signal
  - Produce a 'known' signal
  - Apply the offset
- + Use Calibration Diode in the processor to simulate signal

The screenshot displays three overlapping windows from the TSI software interface:

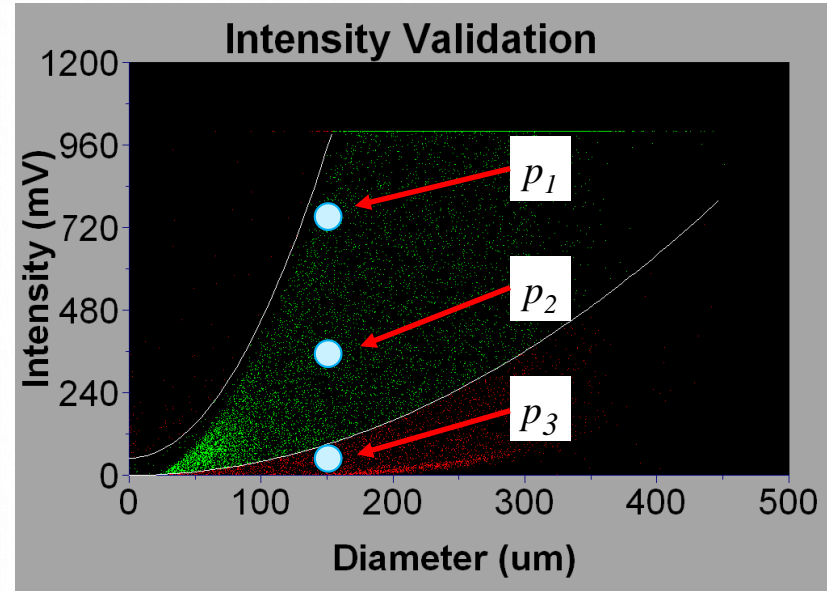
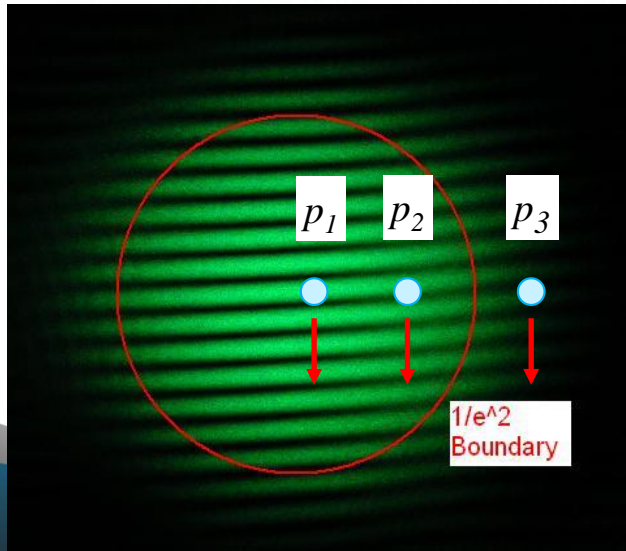
- Velocity Statistics:** A table showing measurement data for Channel 1 and Channel 2. The data is as follows:

	Channel 1	Channel 2
Velocity Mean (m/sec)	10.5239	0.00
Velocity RMS (m/sec)	0.0201	0.00
Turbulence Intensity (%)	0.1908	0.00
Frequency Mean (MHz)	4.7911	0.00
Frequency RMS (MHz)	0.0015	0.00
Frequency TI (%)	0.0315	0.00
Data Time Mean (μsec)	45.5749	0.00
- Calibration:** A dialog box with two tabs: "Laser Diode Calibration" (selected) and "Receiver Calibration". Under "Laser Diode Calibration", there are fields for "Phase Cal. (deg)" (2.41 for AB, 6.29 for AC), "Phase Mean (deg)" (0.00), "Phase RMS (deg)" (0.00), "Doppler Frequency (MHz)" (40.7900), "Data Rate (Hz)" (5988), and "Intensity" (55.0). A checkbox "Enable Calibration/Alignment Diode" is checked. A note at the bottom states: "When Cal. Diode is enabled, please turn the following off: Software Coincidence, Subranging, PVC and Intensity Validation." Buttons for "Apply", "Defaults", and "Close" are at the bottom.
- Processor Controls:** A panel on the right with various settings for "Channel 1" and "Channel 2". Key settings include: "PMT Voltage (V)" (500), "Burst Threshold (mV)" (750), "Band Pass Filter (Hz)" (1 - 10 M), "SNR" (Very Low), "Downmix Freq. (MHz)" (36), "Velocity Min (m/sec)" (-39.91), "Velocity Max (m/sec)" (79.82), "Gate Scale (%)" (100), and "Coincidence Int. (us)" (0). An "Apply" button is at the bottom.



# Intensity Validation

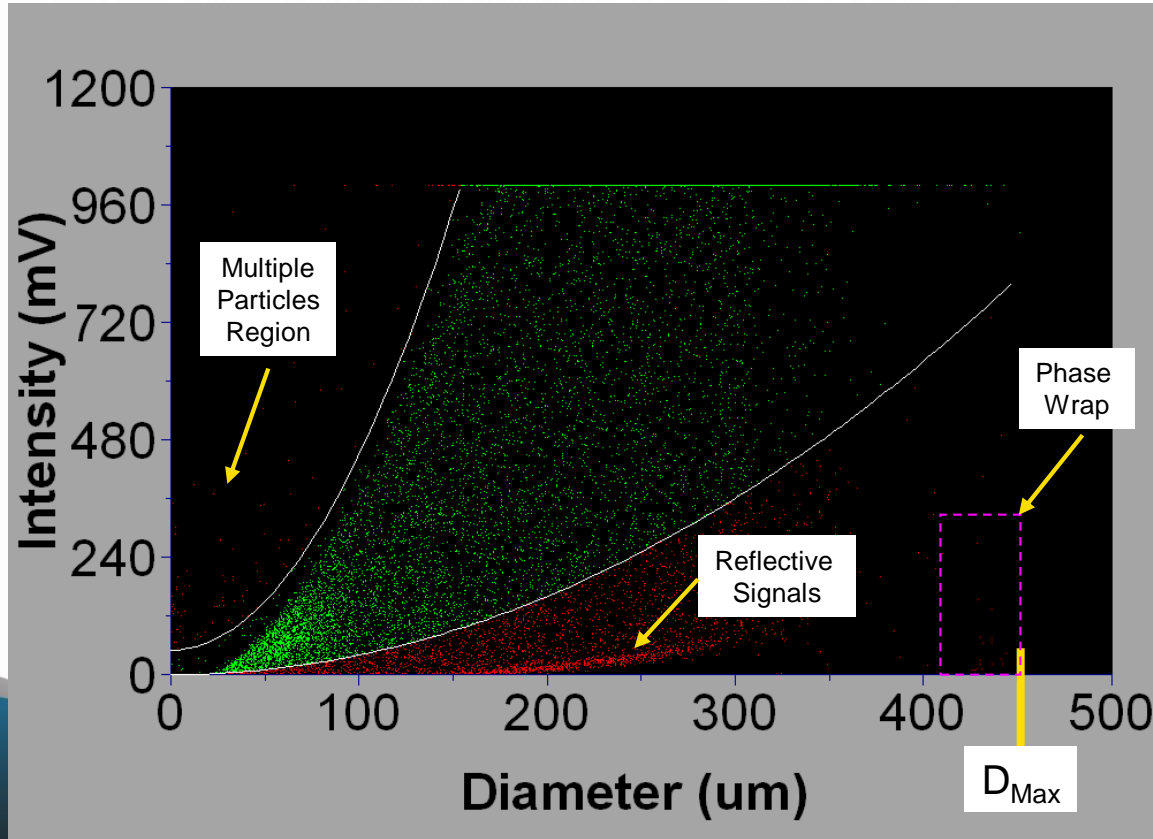
Intensity Validation allows us to validate *where* particles cross the measurement region



$$\text{Intensity} \sim d^2$$



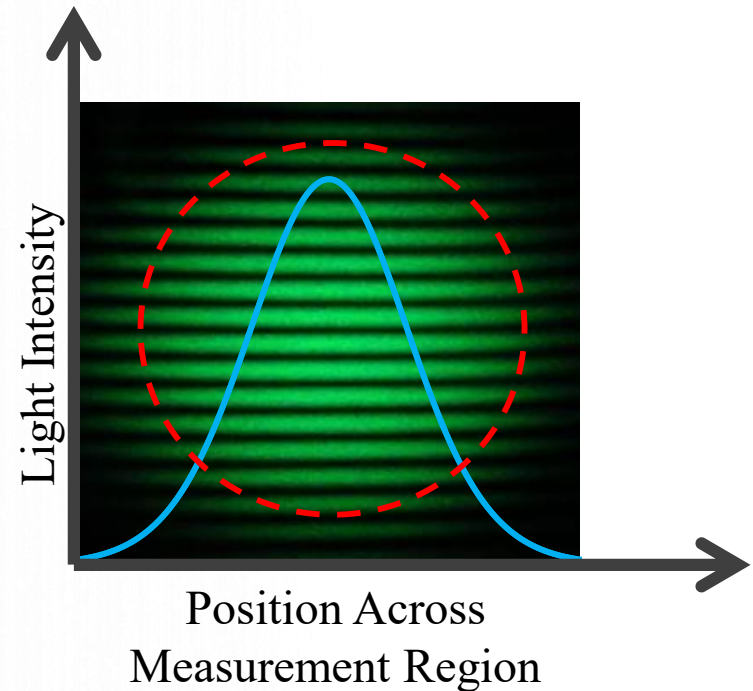
# Intensity Validation





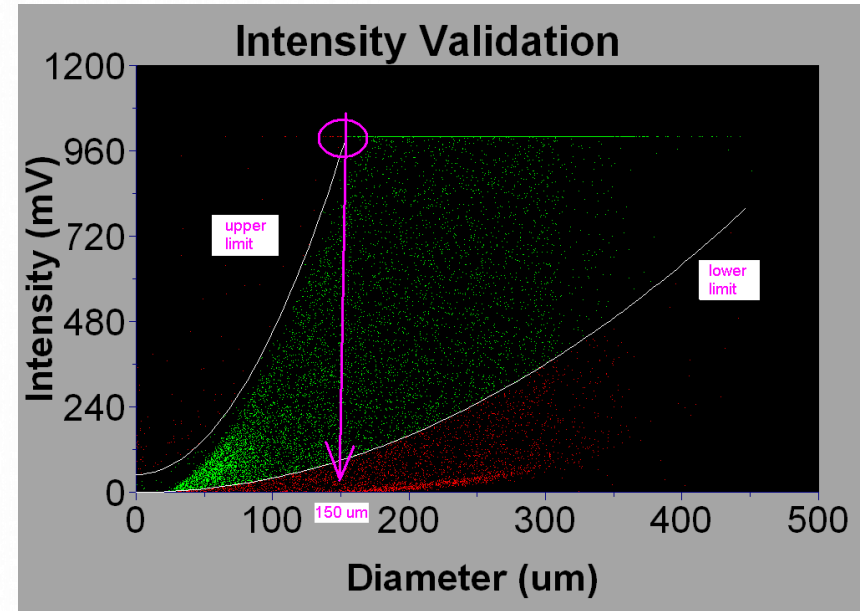
# Intensity Validation

- + Gaussian distribution of light intensity through fringe volume
- + Larger particles traveling past edges will scatter enough light for signal
  - Small particles will not
  - This would bias results toward larger particles
- + Intensity Validation imposes “physical limits” on the data to eliminate this bias



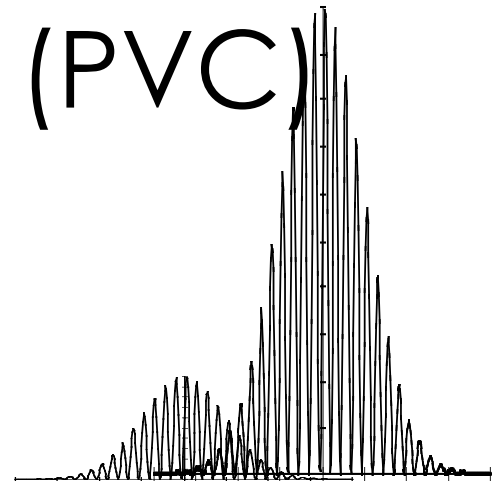
# Intensity Validation – $1/3 D_{\max}$ Rule

- + Find  $D_{\max}$  from optics setup
- + Arrow indicates  $1/3$  of  $D_{\max}$
- + Set slope of upper limit so that it intersects intensity saturation (1000mV) at  $1/3 D_{\max}$
- + PMT voltage & laser power are adjusted so that the data comes close to upper limit
- + Slope of Lower Limit is set to  $1/e^2$  ( $\sim 0.1$ ) of Upper Limit Slope

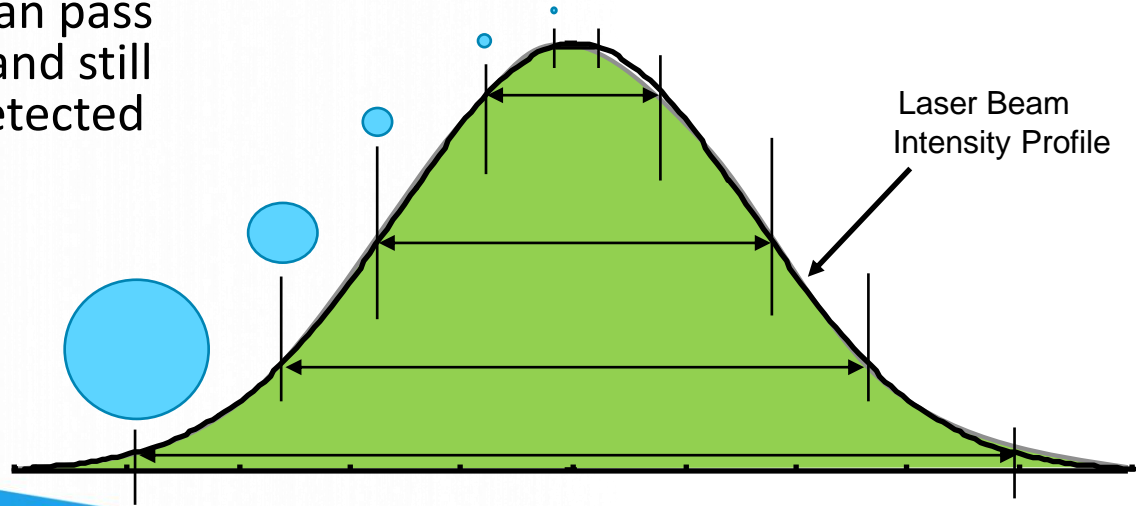


# Probe Volume Correction (PVC)

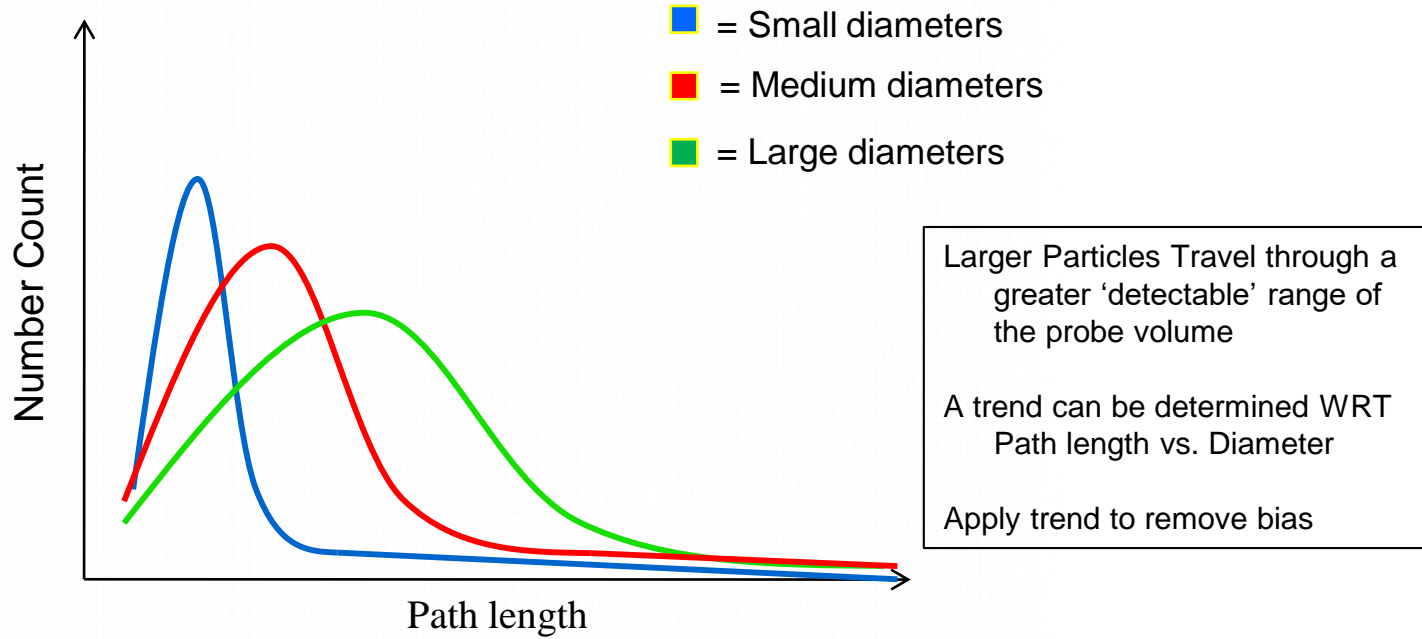
- + Why does the sample volume depend on measured drop size?
  - Scattered Light Intensity



- + Notice how the larger drops can pass through the beam anywhere and still produce enough light to be detected



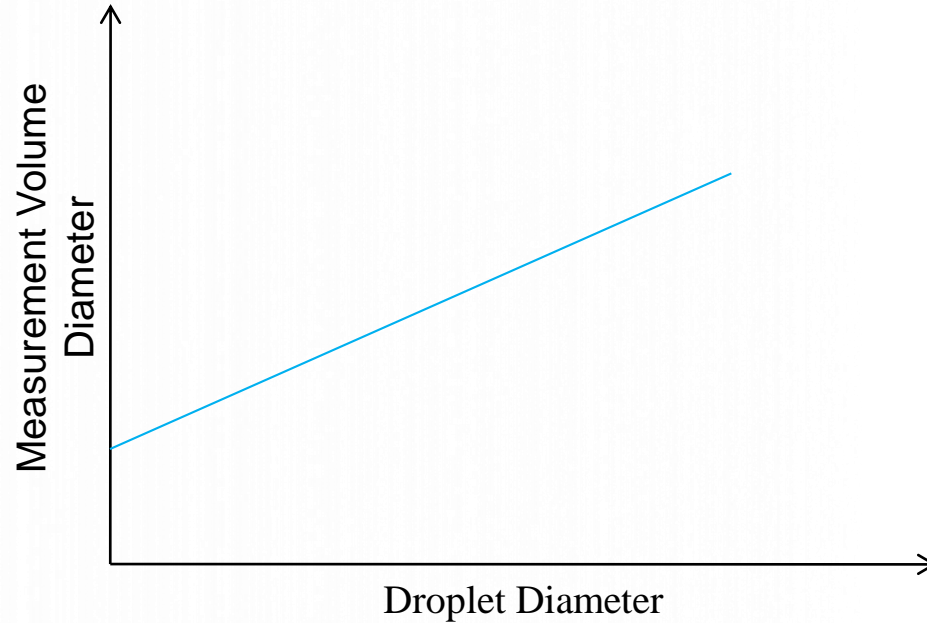
# Probe Volume Correction (PVC)



\*Path Length = Gate Time x Velocity

Fandrey, Naqwi, Shakal, Zhang (2000) A Phase Doppler System for High Concentration Sprays.

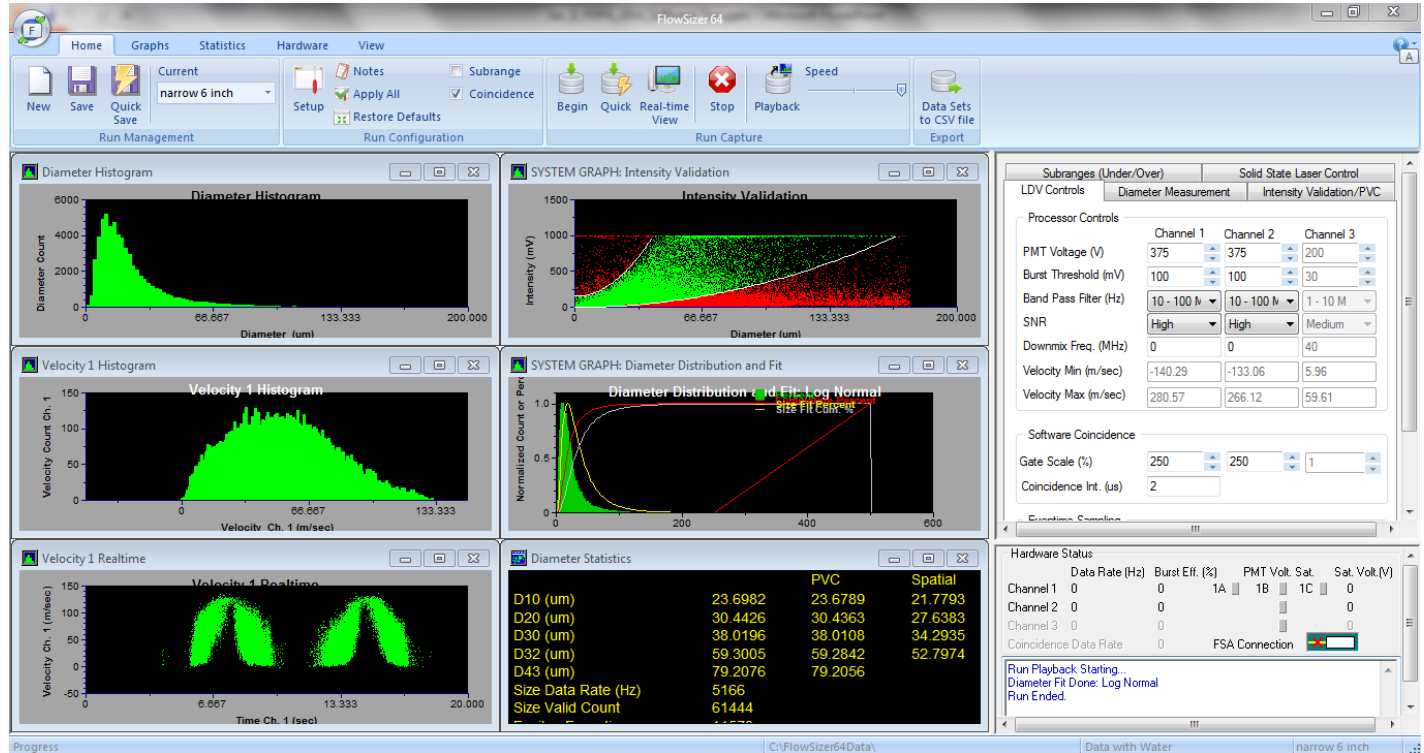
# Probe Volume Correction (PVC)



Fandrey, Naqwi, Shakal, Zhang (2000) A Phase Doppler System for High Concentration Sprays.

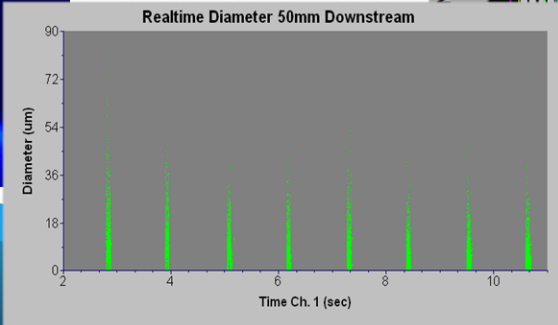
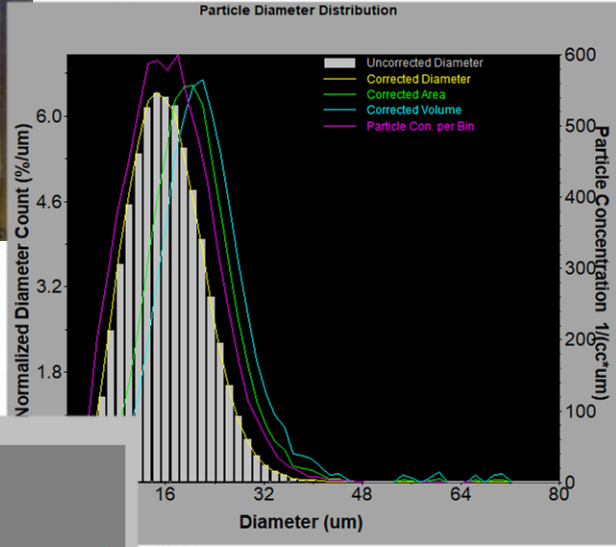
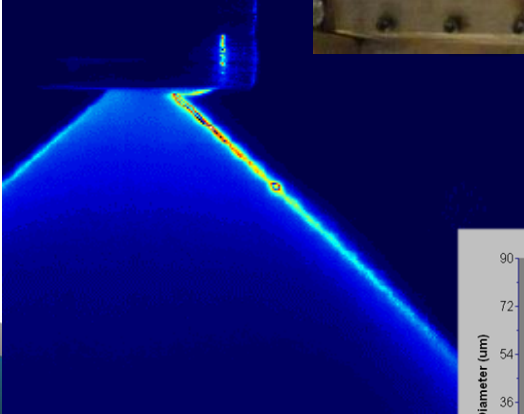
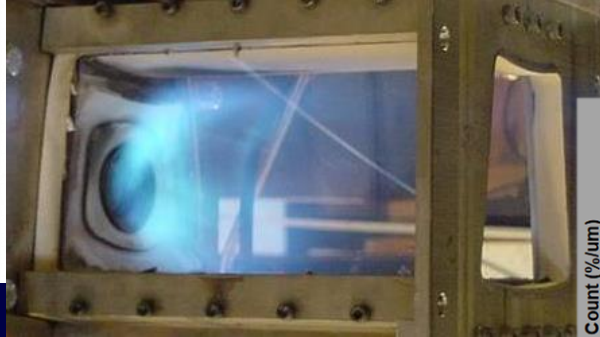


# Ideal PDPA Data





# Case Study : Combustion spray



# Case Study: Fire Suppression Spray

Water Spray



Water, 30cm downstream, Edge Location

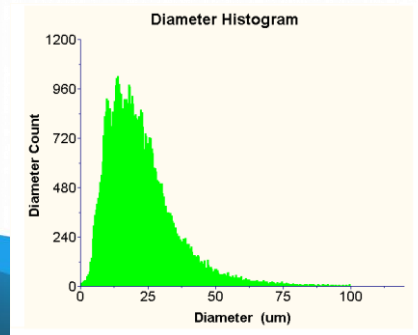
Water Spray  
D10 = 24.9  $\mu\text{m}$   
D32 = 59.7  $\mu\text{m}$   
DV50 = 77.1  $\mu\text{m}$

Foam Spray



3% Surfactant, 30cm downstream, Edge Location

Foam Spray  
D10 = 23.0  $\mu\text{m}$   
D32 = 46.4  $\mu\text{m}$   
DV50 = 54.4  $\mu\text{m}$



# Conclusions

## + Phase Doppler Particle Analysis (PDPA)

- Powerful technique to provide simultaneous velocity and diameter of droplets in Spray
- 3-detector approach eliminates ambiguity of Phase Wrap and gives better size resolution

## + Steps for good measurements

- Phase Calibration
  - Remove electronic timing delay from signal
- Intensity Validation
  - Imposes “physical limits” on the data to eliminate bias of large particle travelling on the edge of the measurement volume
- Probe Volume Correction



# Thank You for Attending!

+ Questions and Answers

+ Email address:

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