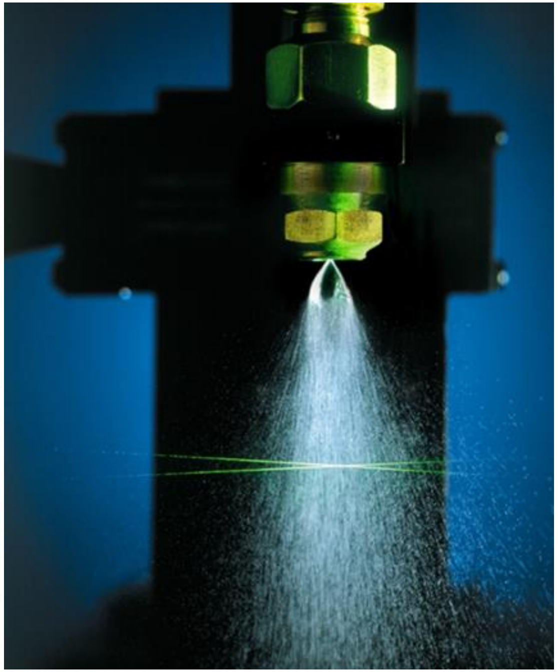
TSI FLUID MECHANICS WEBINAR SERIES

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

May 26th, 2021



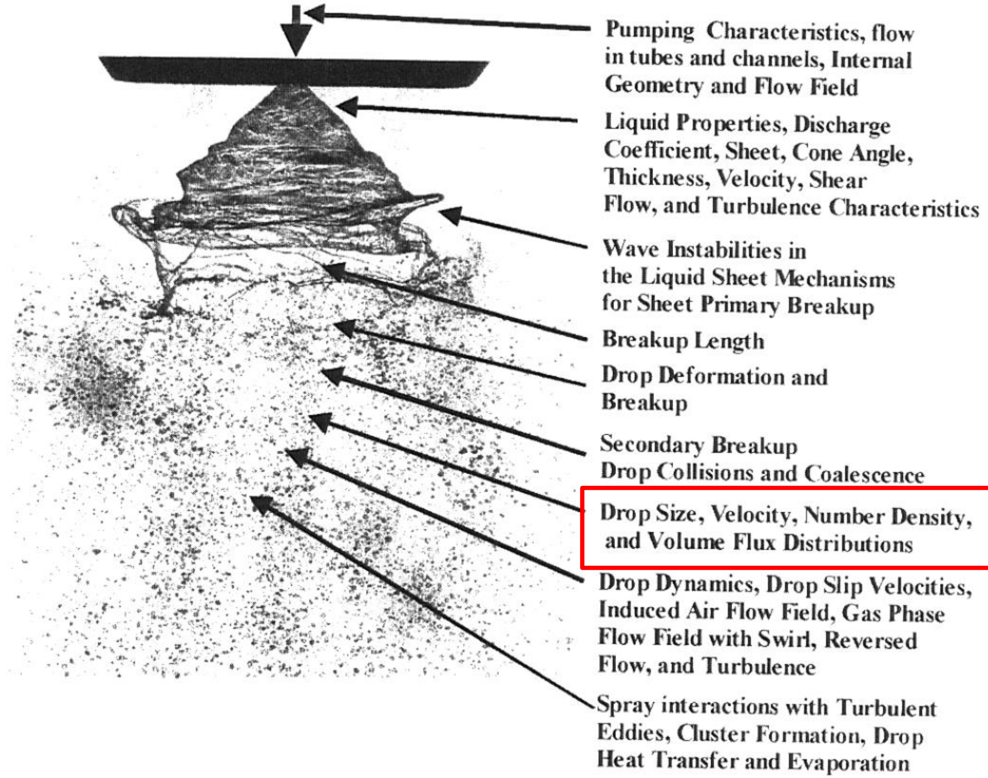
Introduction

+ 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

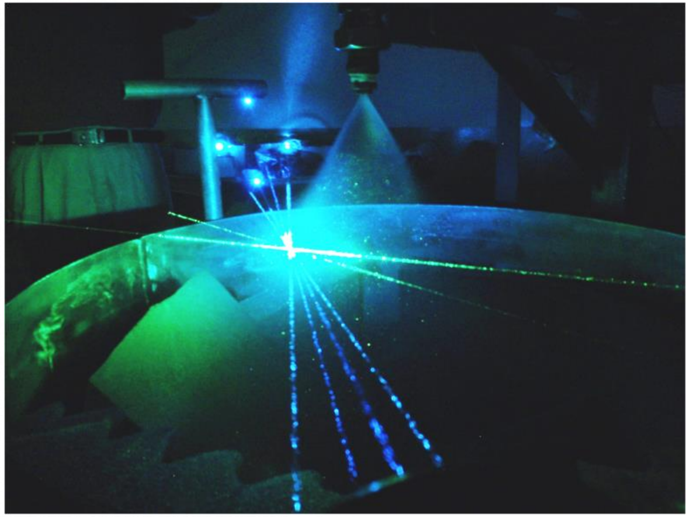
Spray Characterization



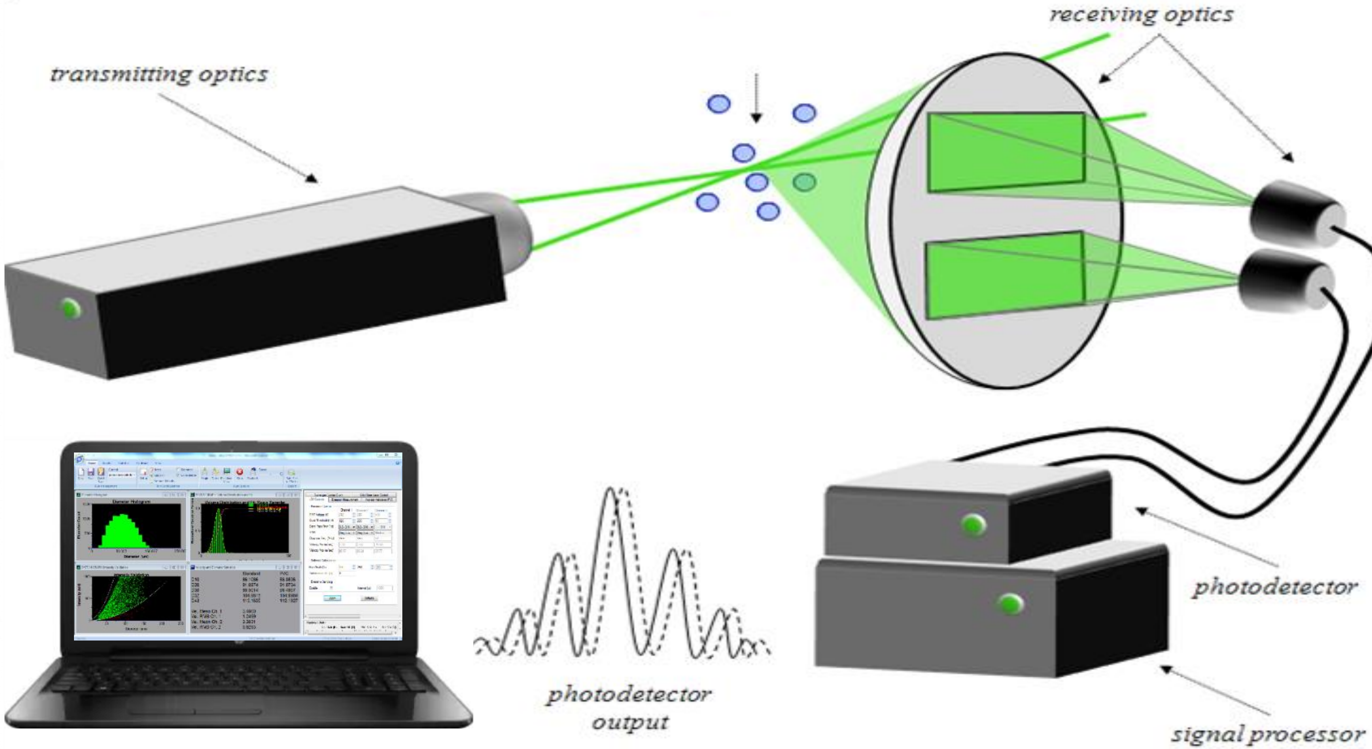
Bachelo (2000) Spray Characterization for 20th Century

Phase Doppler Particle Analysis (PDPA)

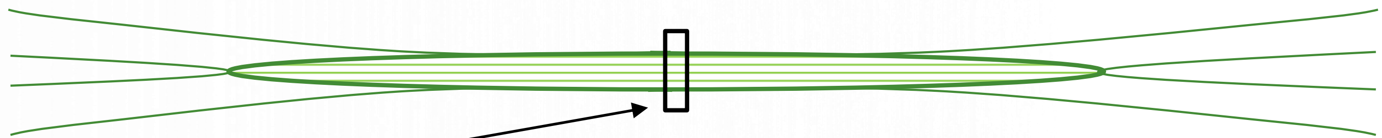
+ Derive Particle Size information by measuring the same laser Doppler signal scattered by particles passing through a single point from several distinct locations in space

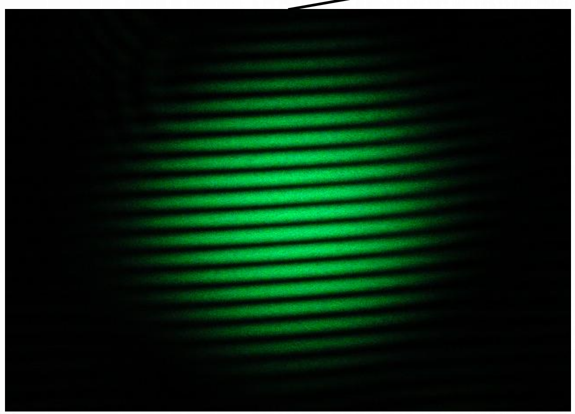


PDPA Schematic

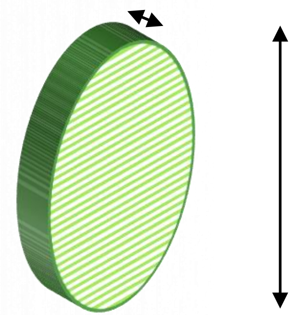


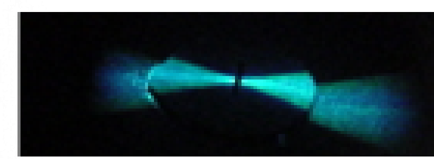
PDPA Measurement Volume





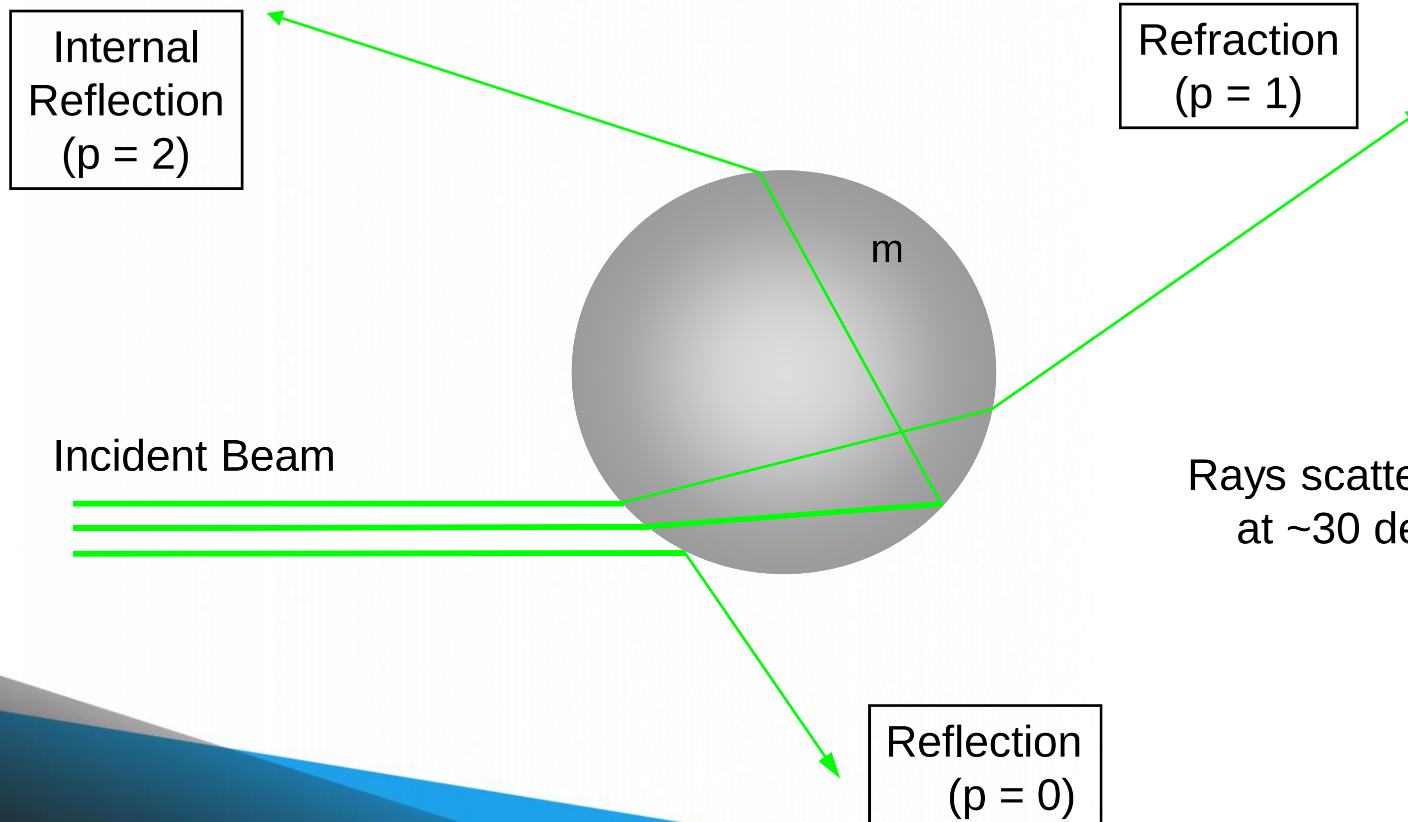
Fringe Pattern at the center of the beam crossing





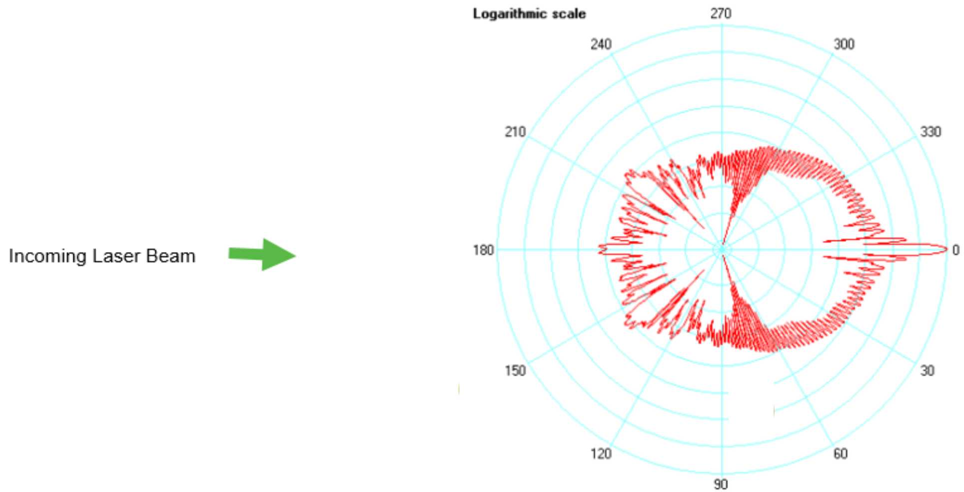
(Actual Receiver Slit)

Light Scattering by a Droplet



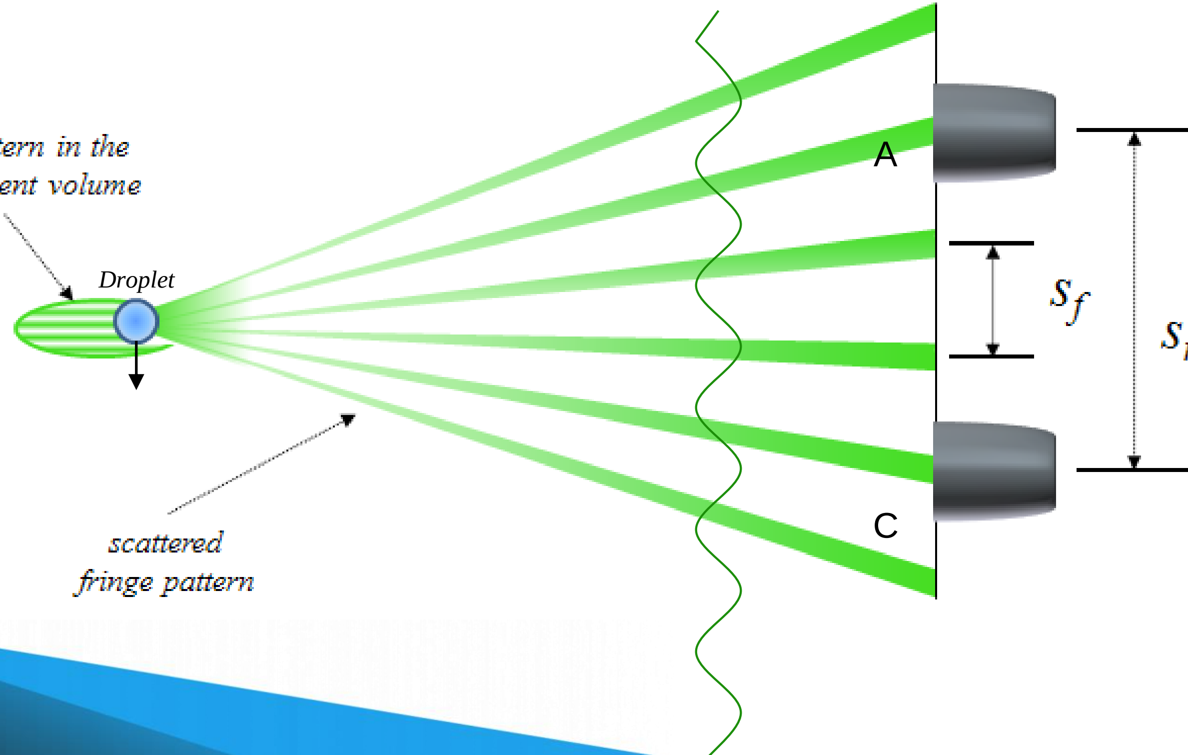
Mie Scattering

+ 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

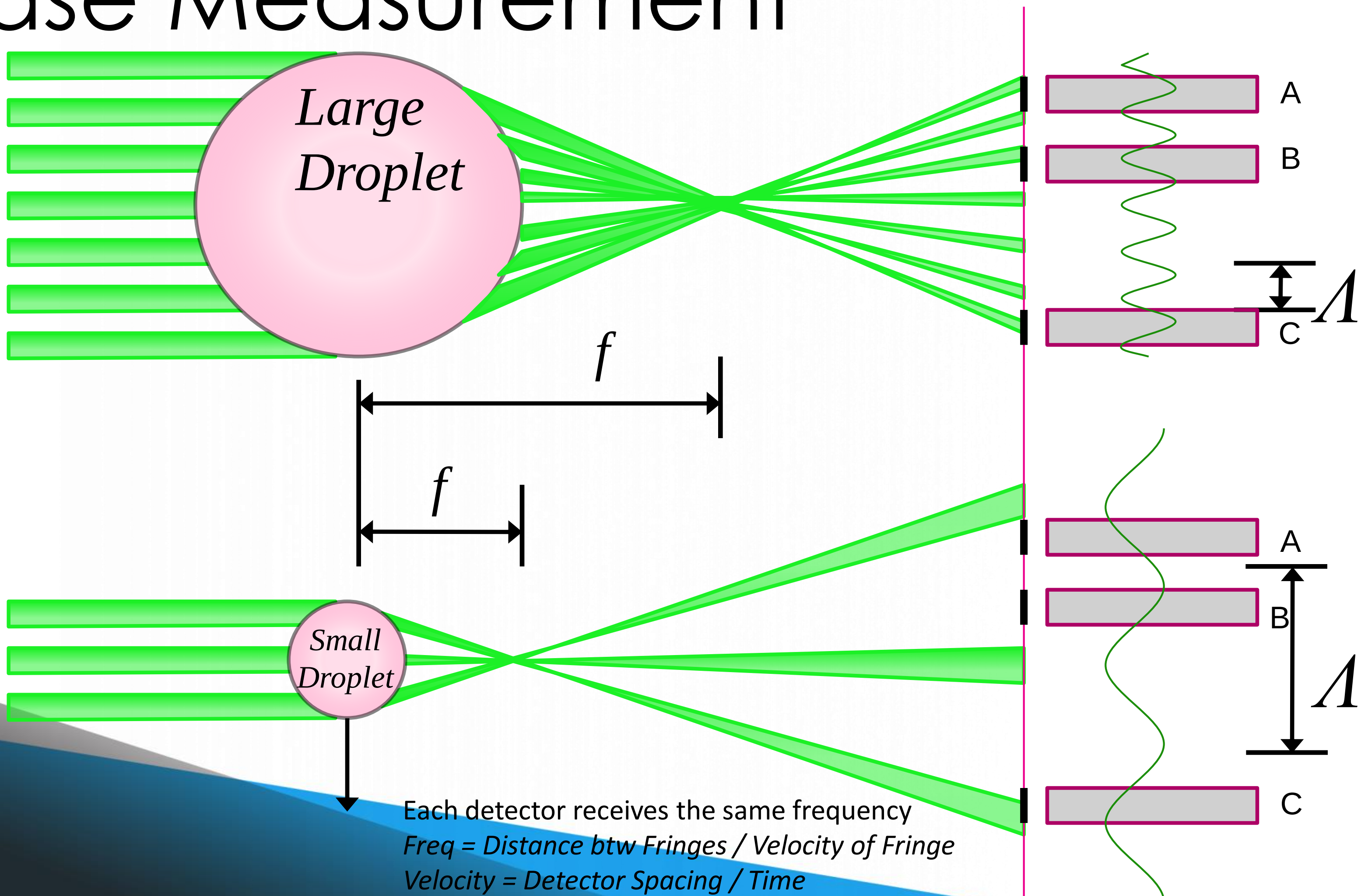


PDPA Scattered Light Signal

Droplet acts like a lens



Phase Measurement

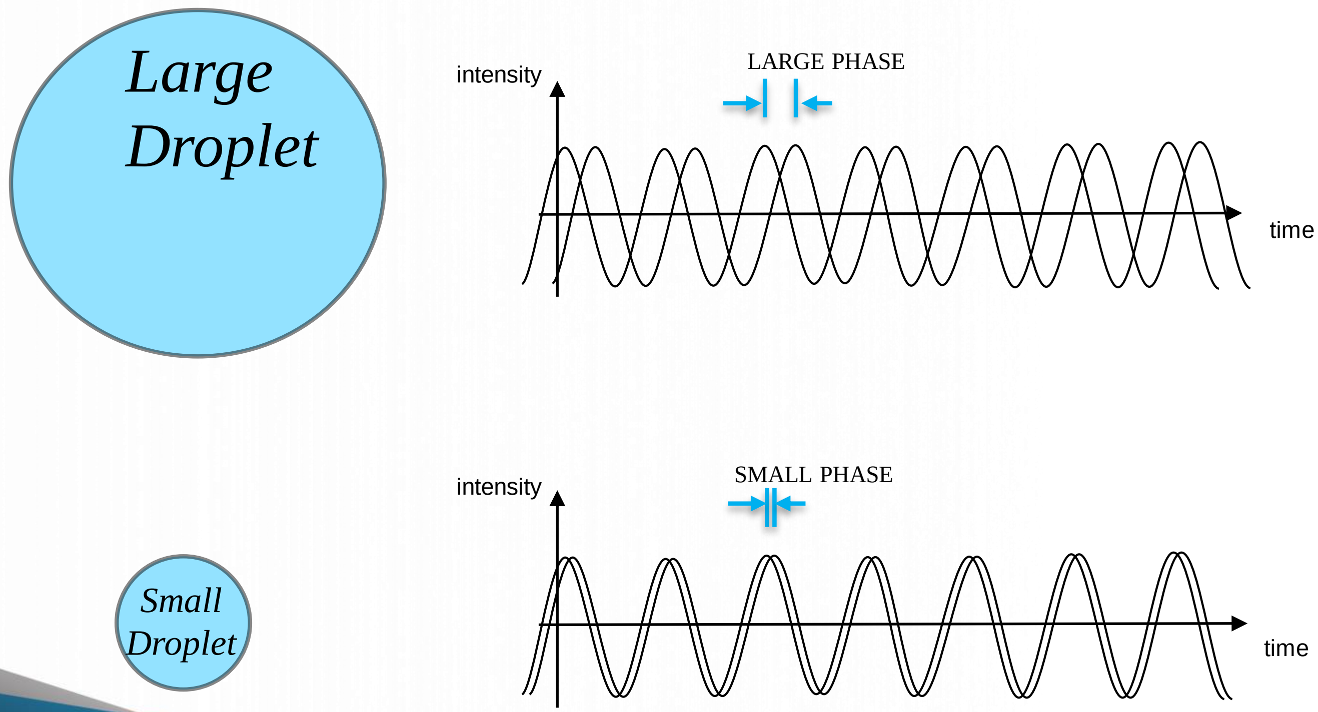


Each detector receives the same frequency

Freq = Distance btw Fringes / Velocity of Fringe

Velocity = Detector Spacing / Time

Diameter – Phase Relationship



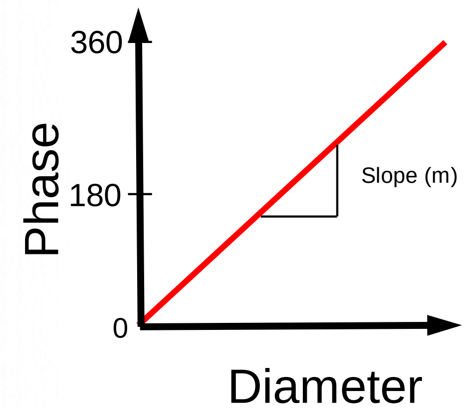
Note: in this example, the frequency (and thus, velocity) is the same for the large and small drop, only the phase shift changes based on diameter…

Diameter – Phase Relationship

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

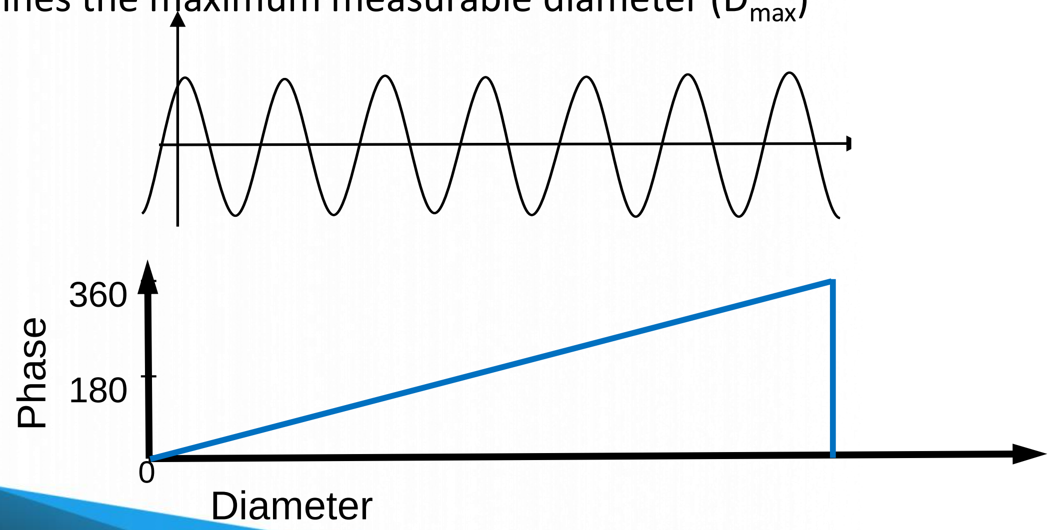
+ Phase – Measured by the PDPA system

+ 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…)



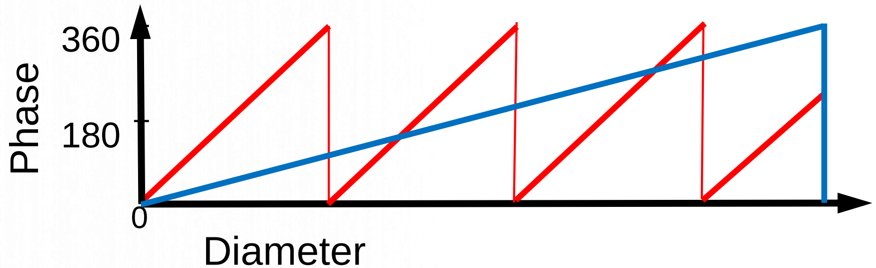
Maximum Measurable Diameter (D_{max})

+ 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

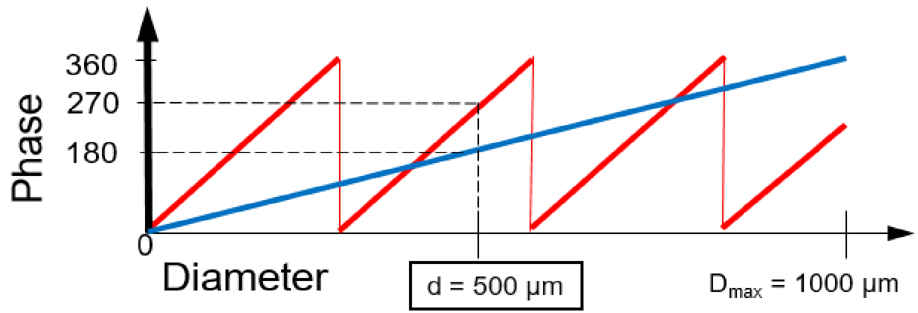
+ Using 3 detectors gives us 2 independent phase measurements with different resolutions
  - AB – Low Resolution, Large Dynamic Range
  - AC – High Resolution, Small Dynamic Range
+ We use AB phase to tell us which AC line we are on
+ We use AC to determine the diameter with high degree of resolution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

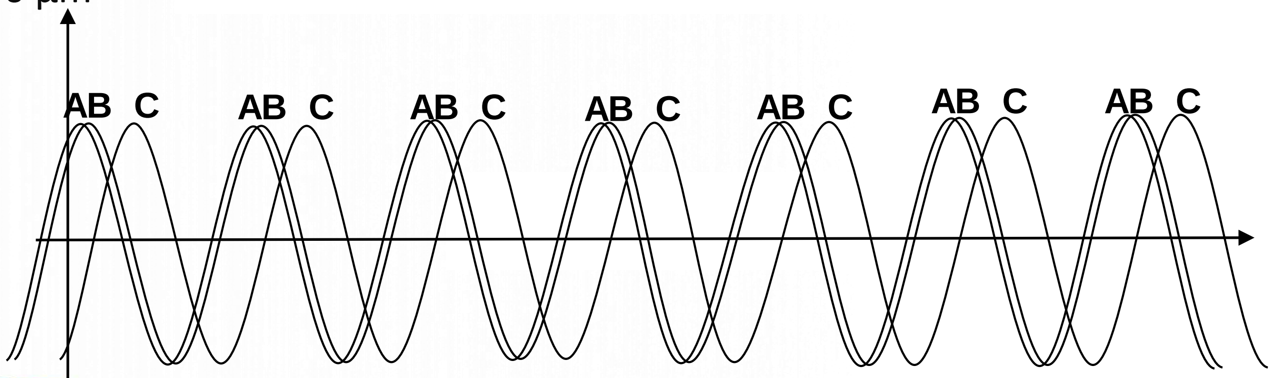


Receiver – 3 Detectors

+ Typical Ratio is 3.5
+ Example
  - Phase AB = 180
  - Phase AC = 270

  - Diameter (d) = 500 µm

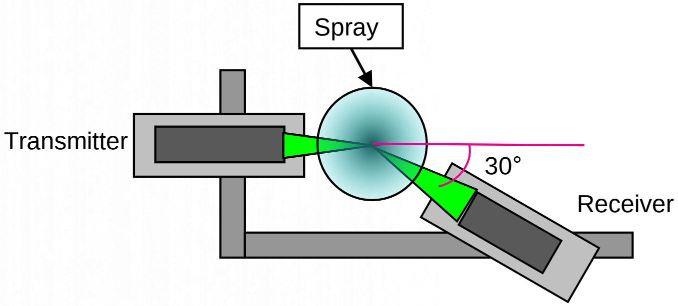




PDPA System Common Layouts

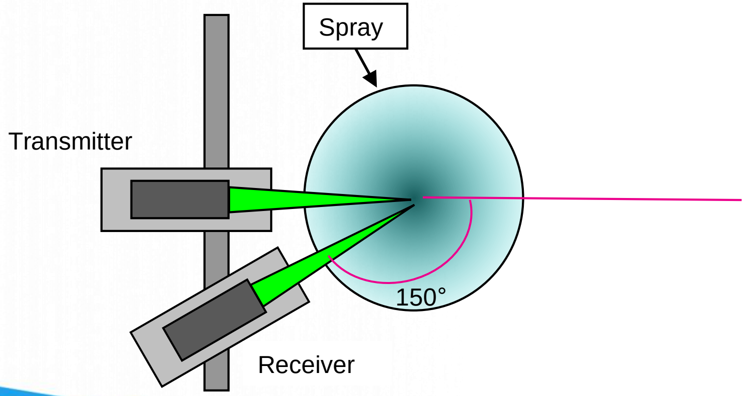
Forward Scatter Refraction

- 30° Receiver Angle
- Generally Transparent Droplets



Back Scatter Reflection

- 150° Receiver Angle
- Opaque Droplets

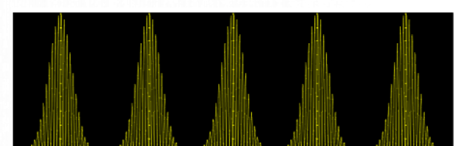


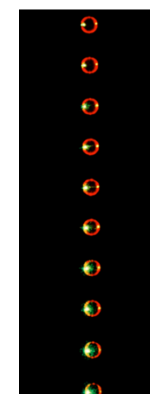
Receiver Calibration

+ 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.

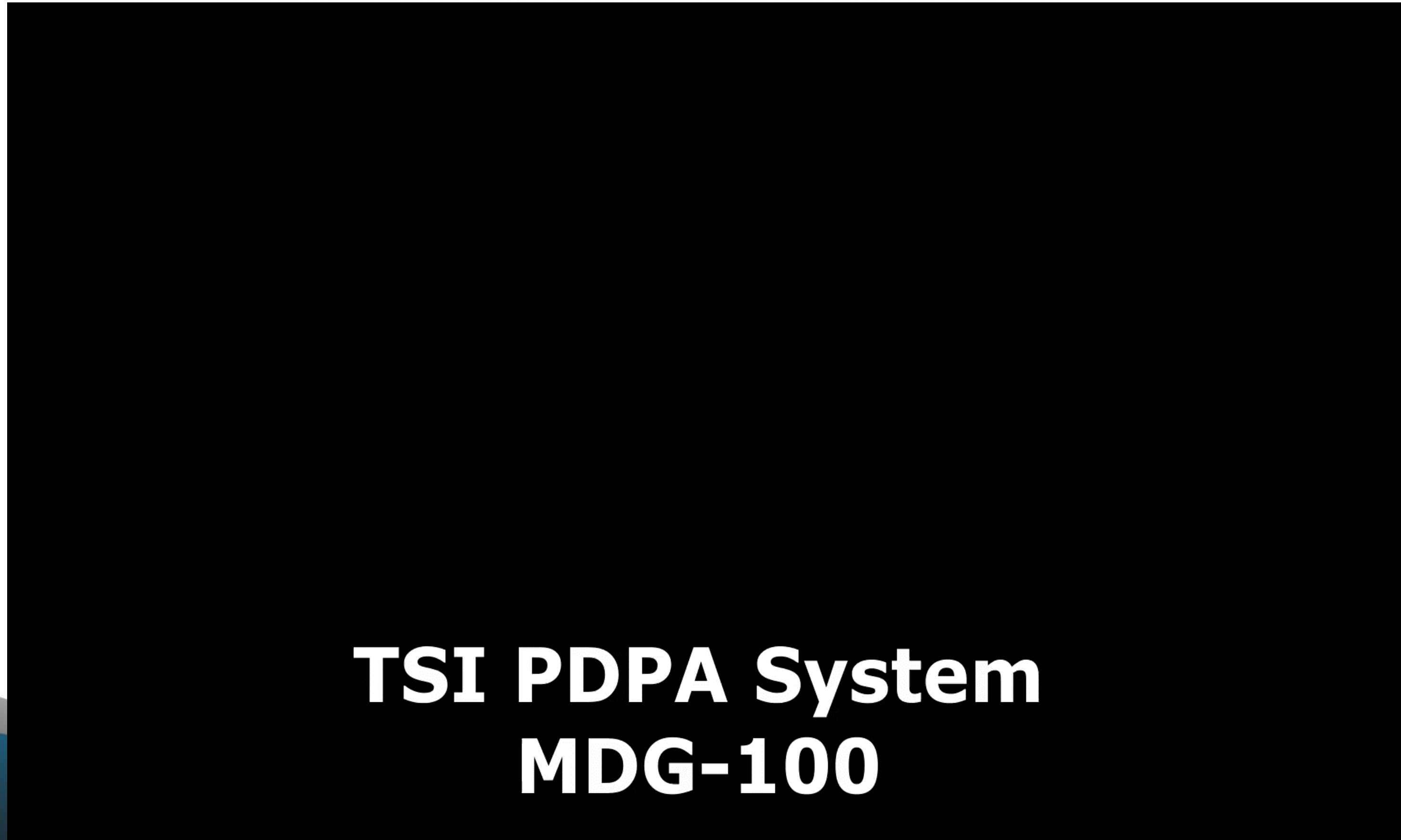
$$\frac{\pi D^3}{6} = \frac{Q}{f} \text{ or } D = \left[\frac{6Q}{\pi f}\right]^{\frac{1}{3}}$$

$$D = 317\left[\frac{Q_{(cc\,/\,min)}}{f_{(kHz)}}\right]^{\frac{1}{3}}$$

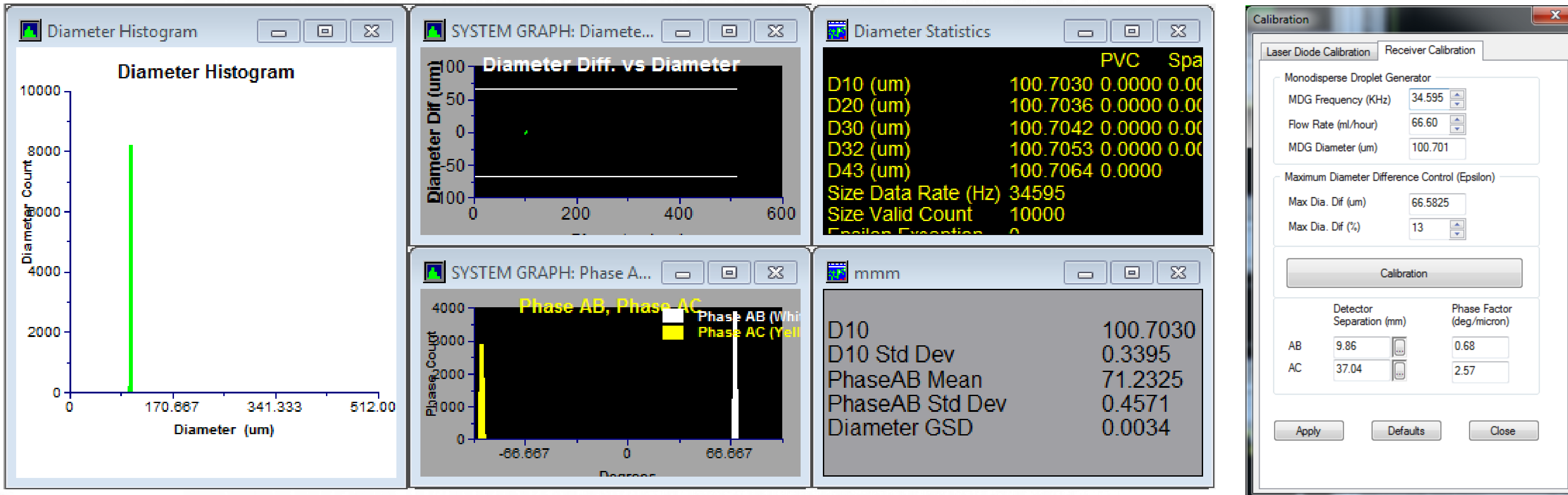




Receiver Calibration

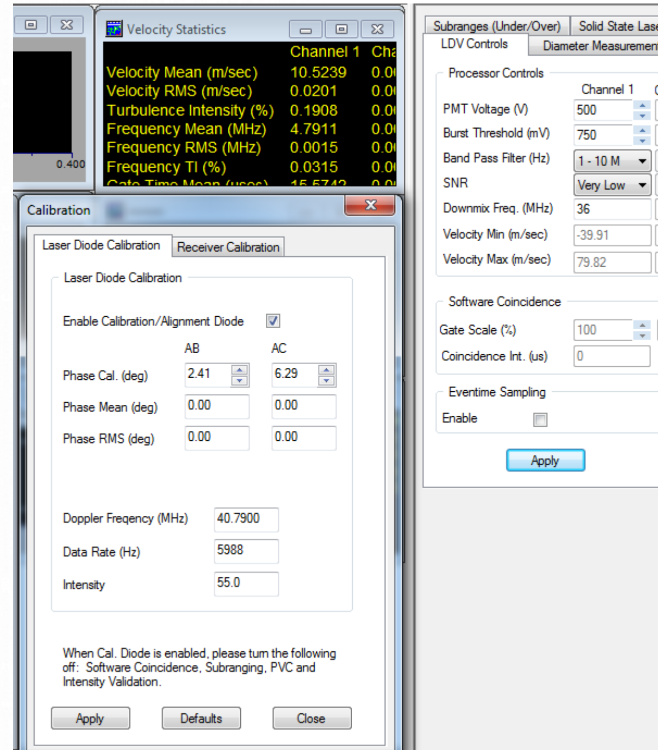


Receiver Calibration



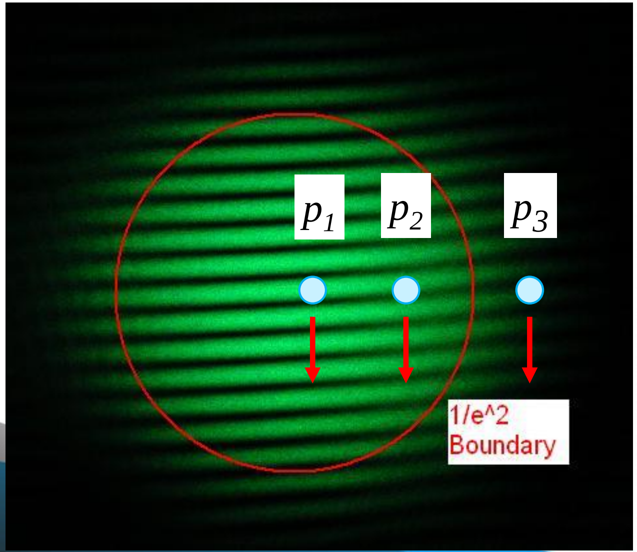
Phase Calibration

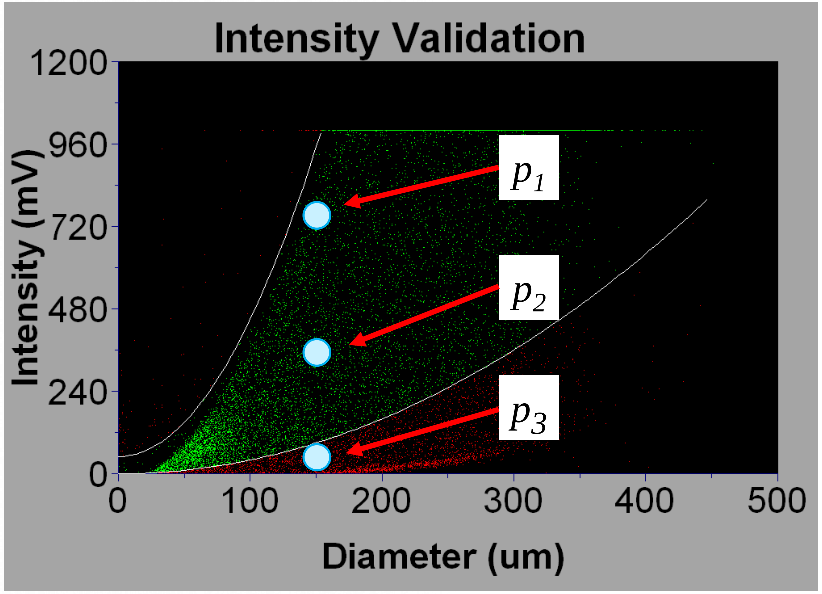
- Remove Electronic Timing Delays from Signal
  - Produce a ‘known’ signal
  - Apply the offset
- Use Calibration Diode in the processor to simulate signal



Intensity Validation

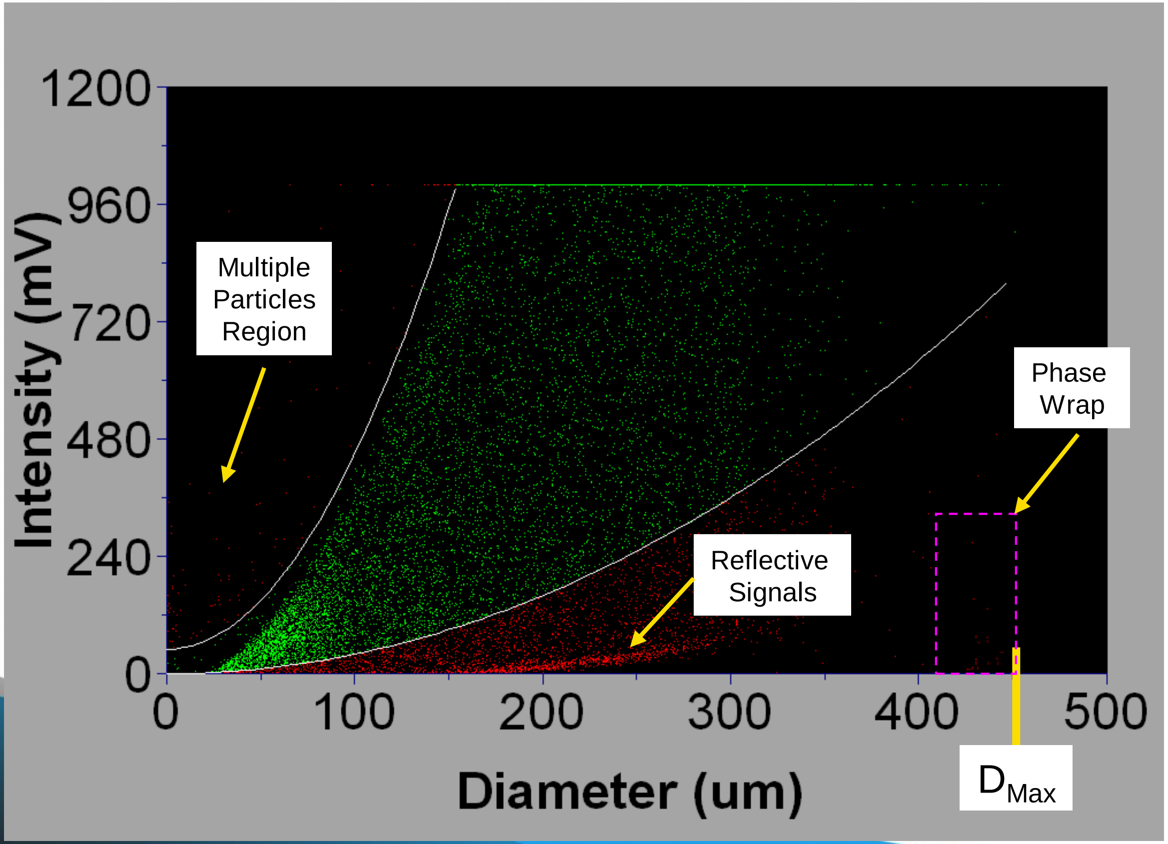
Intensity Validation allows us to validate *where* particles cross the measurement region





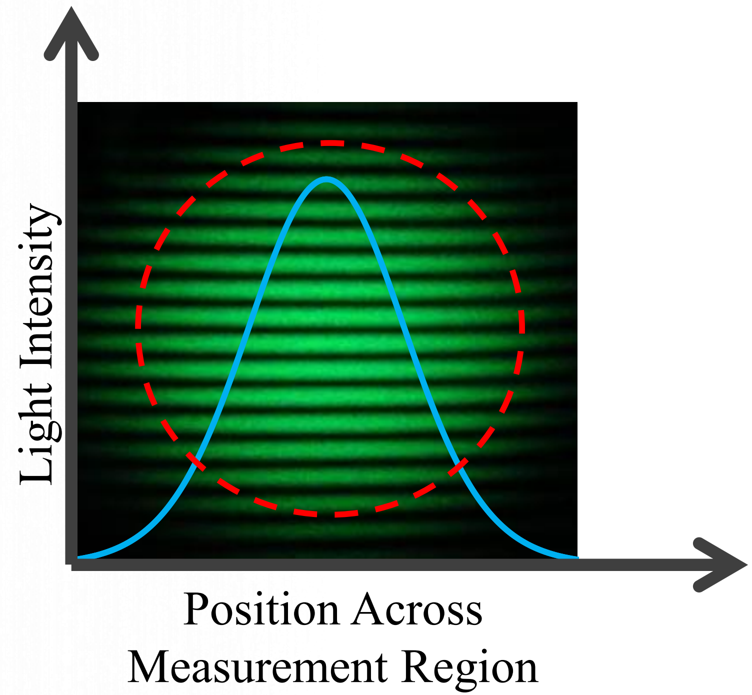
Intensity ~ d^2

Intensity Validation



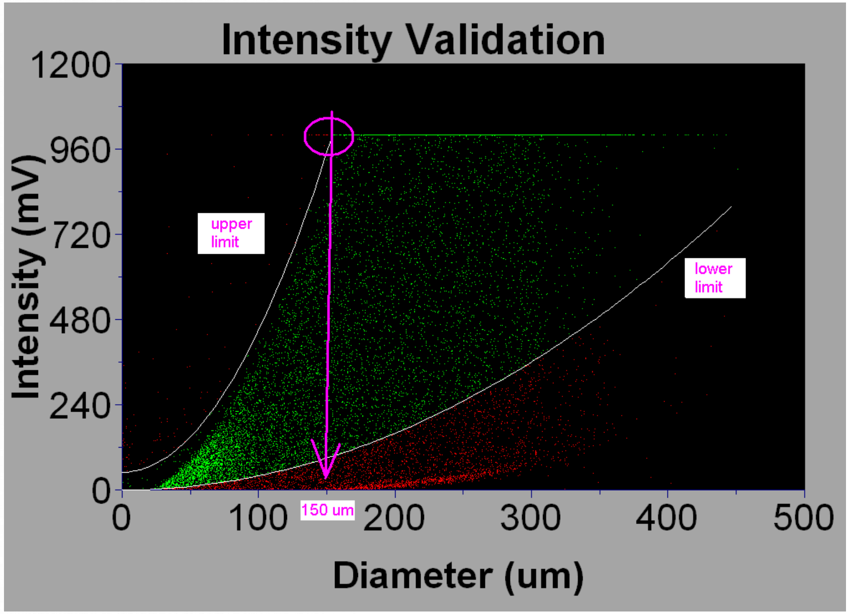
Intensity Validation

+ 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

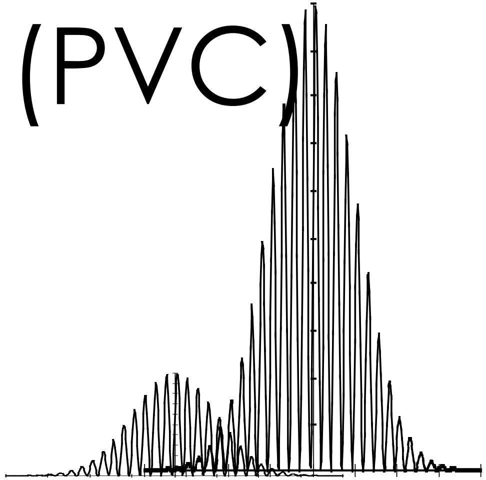


Intensity Validation – 1/3 D_{max} Rule

+ 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 $1/e^2$ (~0.1) of Upper Limit Slope

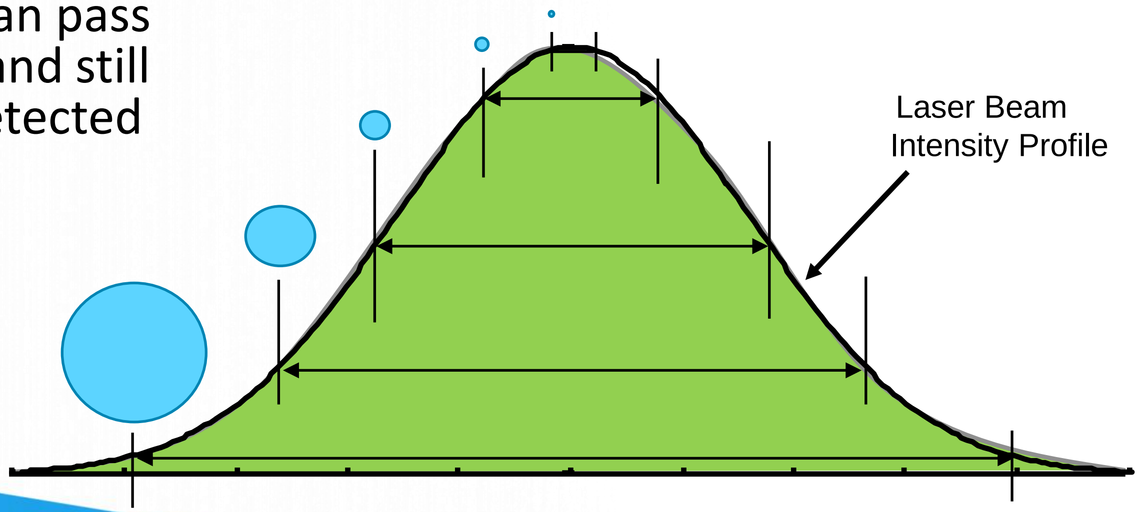


Probe Volume Correction (PVC)

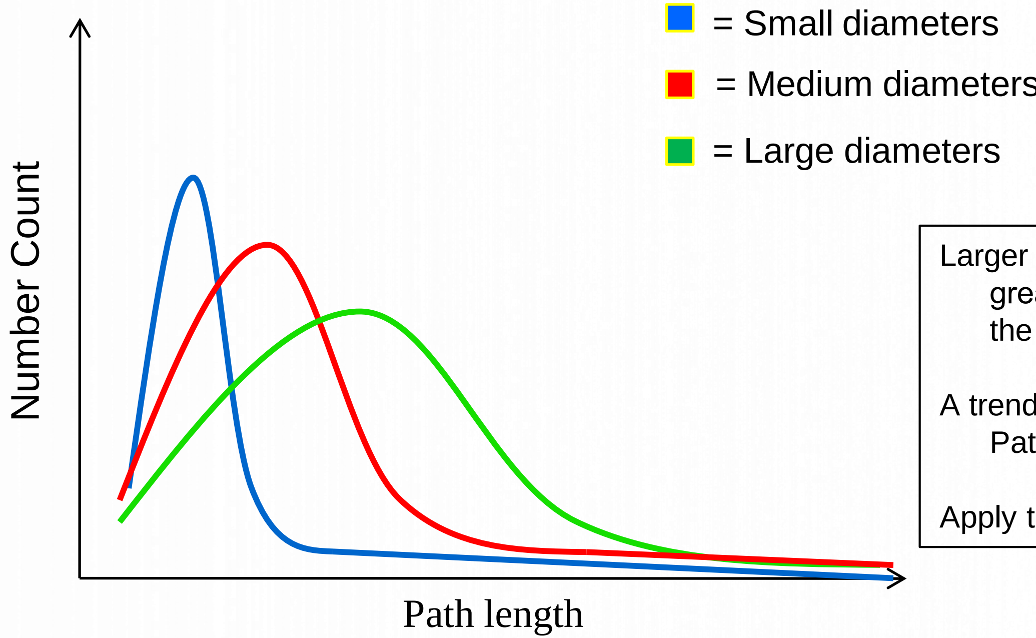


+ Why does the sample volume depend on measured drop size?
  - Scattered Light Intensity

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



Probe Volume Correction (PVC)



Larger Particles Travel through a greater 'detectable' range of the probe volume

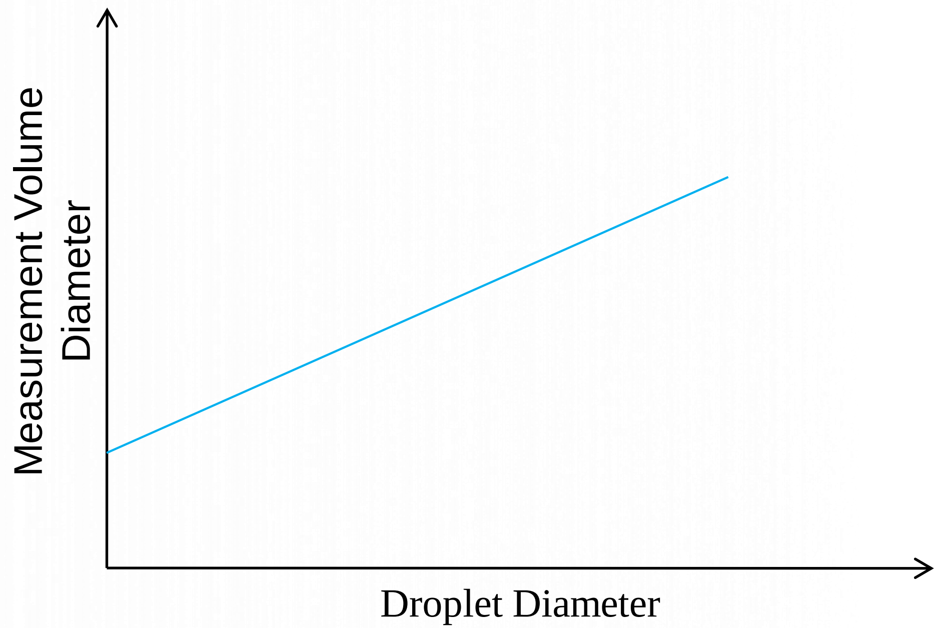
A trend can be determined WRT Path length vs. Diameter

Apply trend to remove bias

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

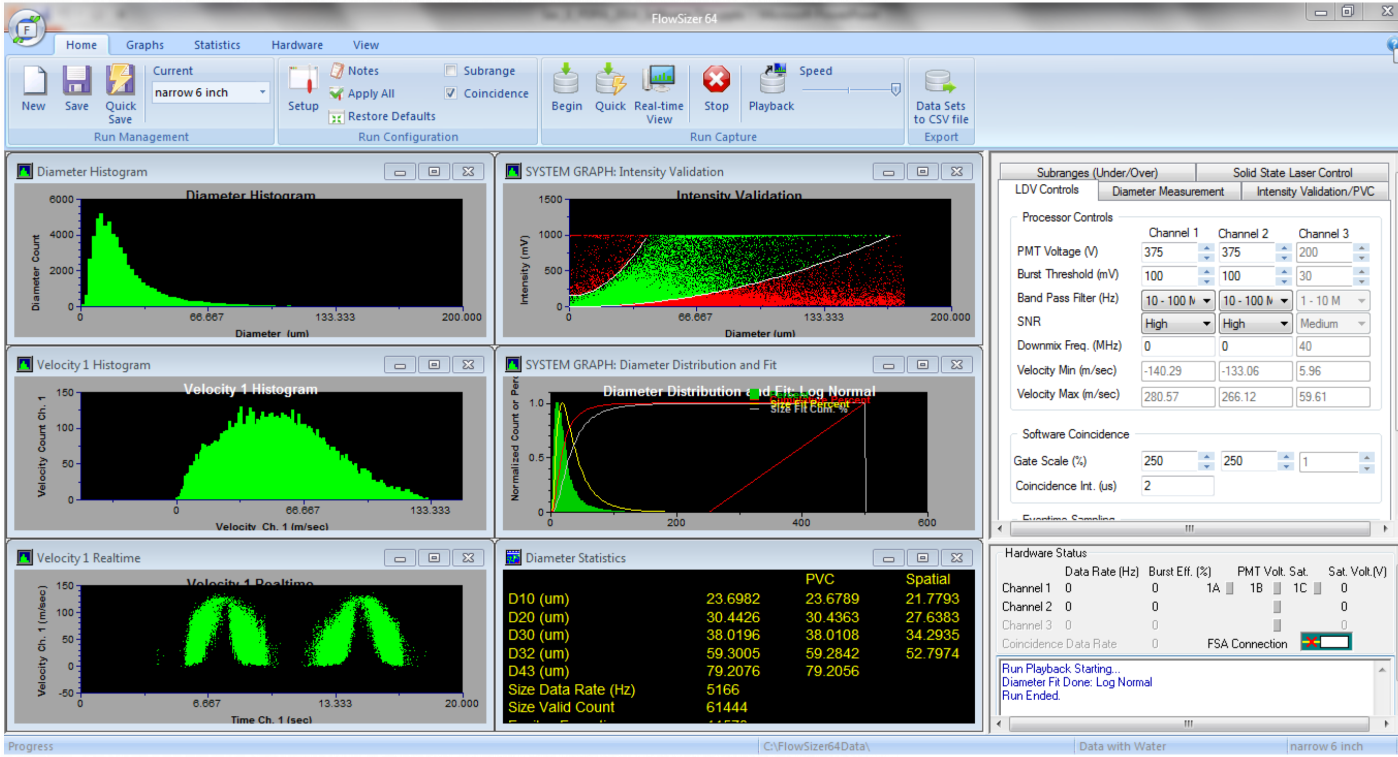
*Path Length = Gate Time x Velocity

Probe Volume Correction (PVC)

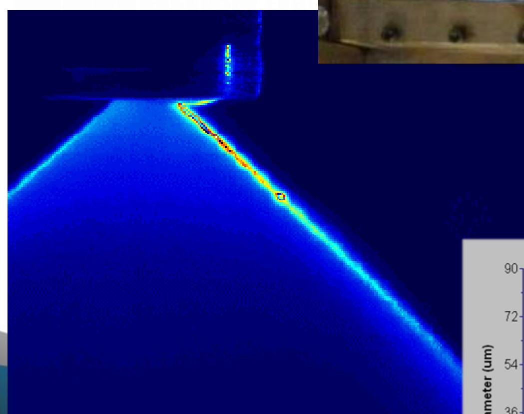


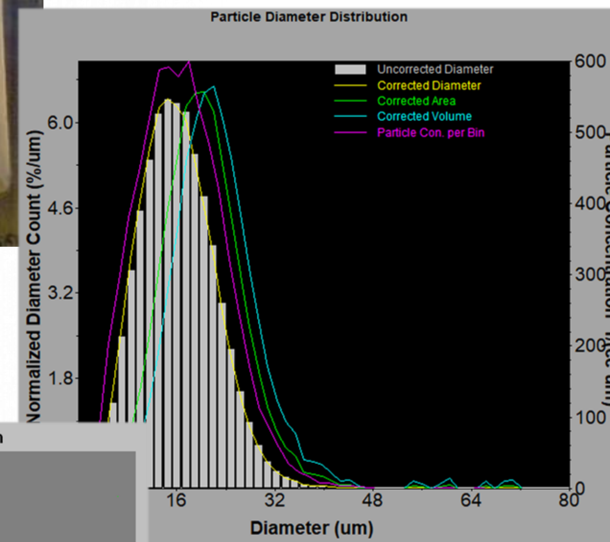
Fandrey, Naqwi, Shakal, Zhang (2000) A Phase Doppler System for High Concentration Sprays.

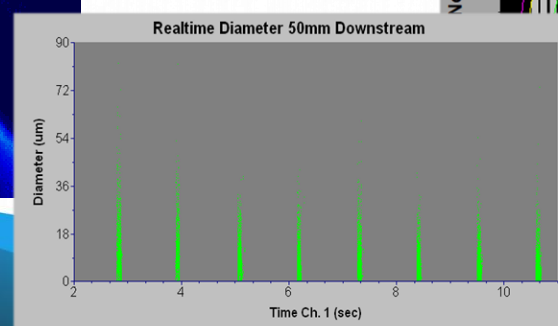
Ideal PDPA Data



Case Study : Combustion spray







Case Study: Fire Suppression Spray

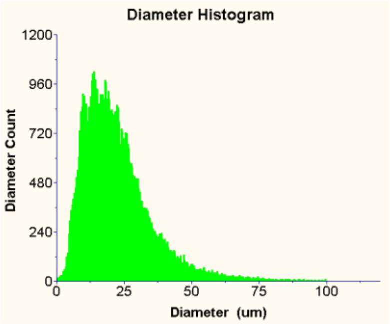
Water Spray

Water, 30cm downstream, Edge Location

Foam Spray

3% Surfactant, 30cm downstream, Edge Location

Water Spray
D10 = 24.9 um
D32 = 59.7 um
DV50 = 77.1 um



Foam Spray
D10 = 23.0 um
D32 = 46.4 um
DV50 = 54.4 um

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
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