Description of the Laser Doppler Velocimetry Method For Flow Characterization

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Company Information

Artium Technologies, Inc.:

- Founded in 1998 by former Aerometrics key employees
- Focus on optical diagnostics development
- Supported by: NASA, U.S. Navy Office of Naval Research, U.S. Air Force, U.S. Army, U.S. Environmental Protection Agency (EPA), NIST, California Air Resources Board (CARB)

Areas of Expertise:

- Particle light scattering and imaging optical system design and development
- Laser Doppler Velocimeter and Phase Doppler Interferometer Instrument development and manufacturing
- Fluid dynamics research and experimentation
- Atomization and Sprays research
- Spray combustion research and experimentation
- Aircraft icing and atmospheric cloud instrumentation for research and development
- Laser Induced Incandescence instrument development for nvPM emissions monitoring

Outline of Presentation:

- Background and features of LDV instruments
- Description of the measurement principle
- Signal detection and processing
- Optical Configurations
- Flow seeding with particles
- Particle response characteristics
- Applications examples

Laser Doppler Velocimetry

Background and Capabilities:

- First HeNe laser developed at Bell Labs. 1962
- Originated in 1964 by Yeh and Professor Cummins
- Measurements made non-intrusively and in situ
- Velocity measured precisely and with high accuracy
- No calibration required, other than measuring the beam intersection angle
- Small measuring volume, high spatial resolution
- Very high velocity range – mm/s to 600 m/s
- Requires particles in the fluid to scatter light
- Method is highly developed and refined

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Laser Doppler Velocimeter Method: Key Advantages

- Measurements are *based on the wavelength of laser light* that is known to high precision and accuracy, does not change over time or due to environmental conditions
- *Signals have a unique sinusoidal character* making them easily detectable with high reliability using digital techniques
- *Simultaneously measures the velocity to three components* and forms a direct measurement of the velocity distribution to obtain mean and turbulence intensity
- *High spatial and temporal reso*lution allows detailed turbulence measurements

Typical LDV 200 Transceiver System

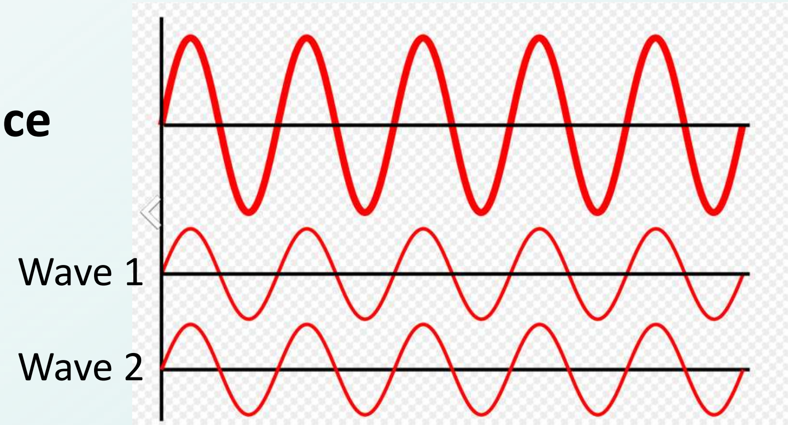
- Built-in DPSS lasers
- Large optics available for larger working distances
- Fully automatic setup of signal processor parameters

Light Interference

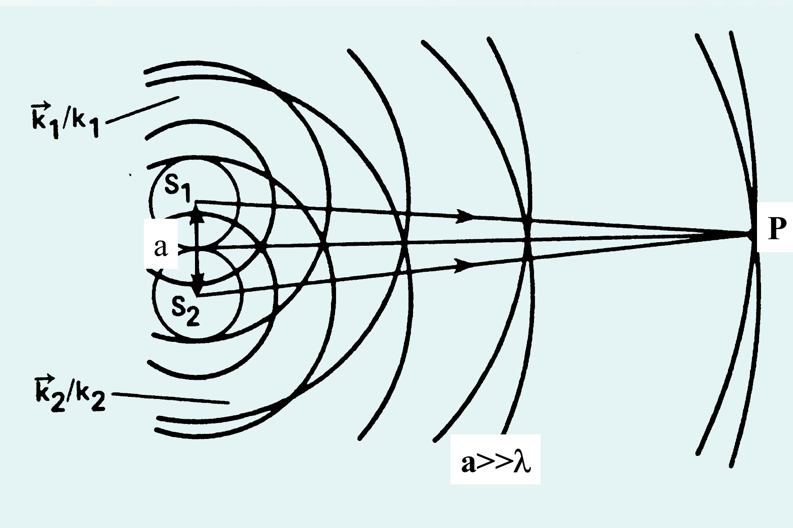
LDV Method is based on light interference

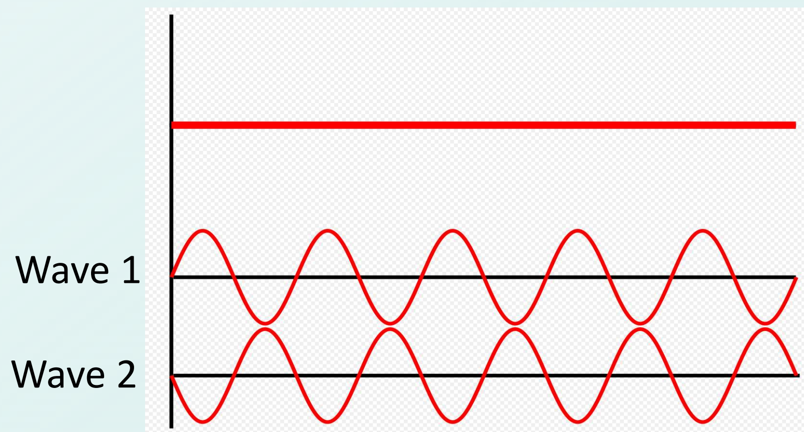
Requirements:

1. Single wavelength, single frequency, coherent light generally provided by lasers
2. Parallel linear polarization
3. Equal or nearly equal light intensities



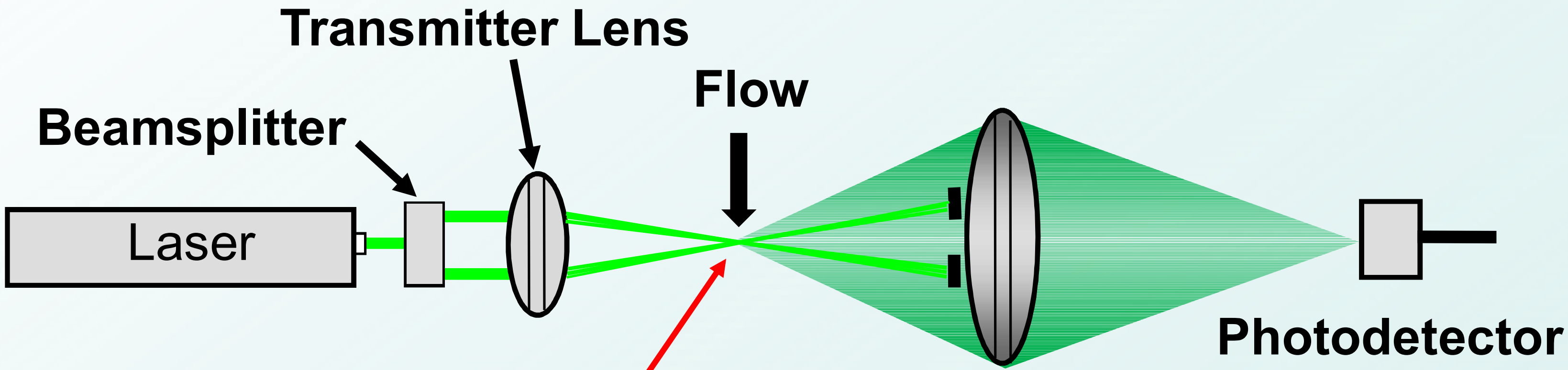
In phase, constructive interference

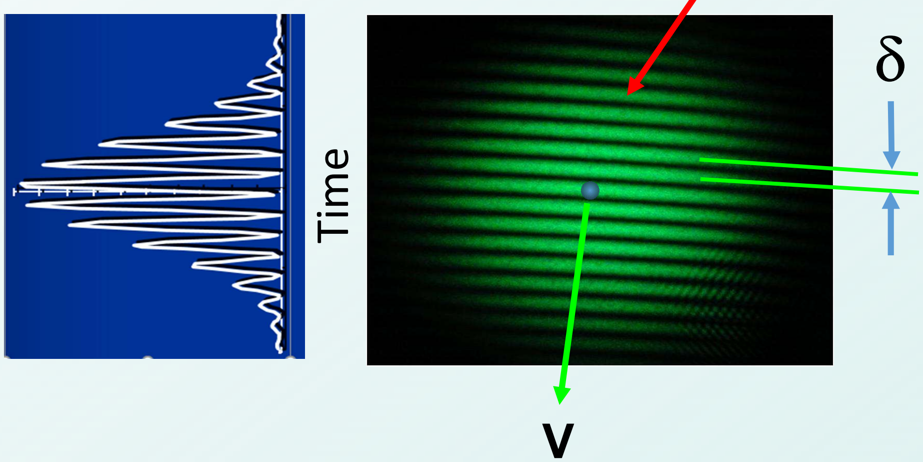




Out of phase, destructive interference

Interference and the Fringe Model





$$\delta = \lambda / 2 \sin(\gamma / 2)$$

$$V = f \cdot \delta$$

Fringe Pattern at the Laser Beam Intersection

- λ - Laser wavelength
- f - Doppler difference frequency
- δ - Fringe spacing
- γ - Beam intersection angle

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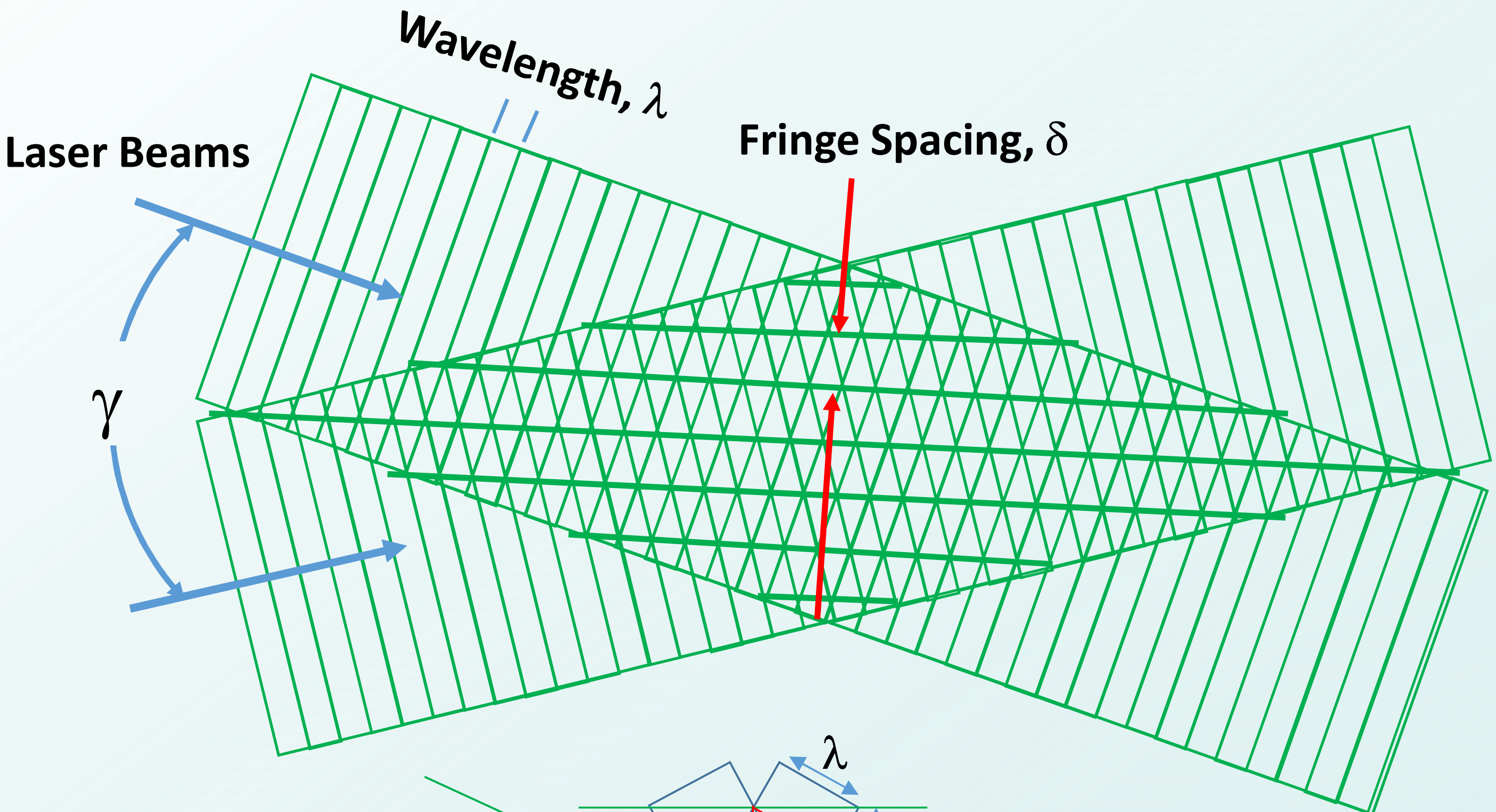
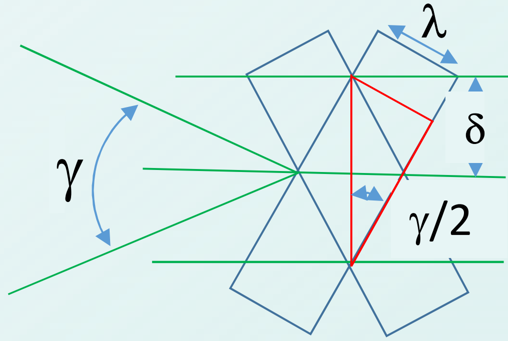
Formation of Interference Fringes at the Laser Beam Intersection



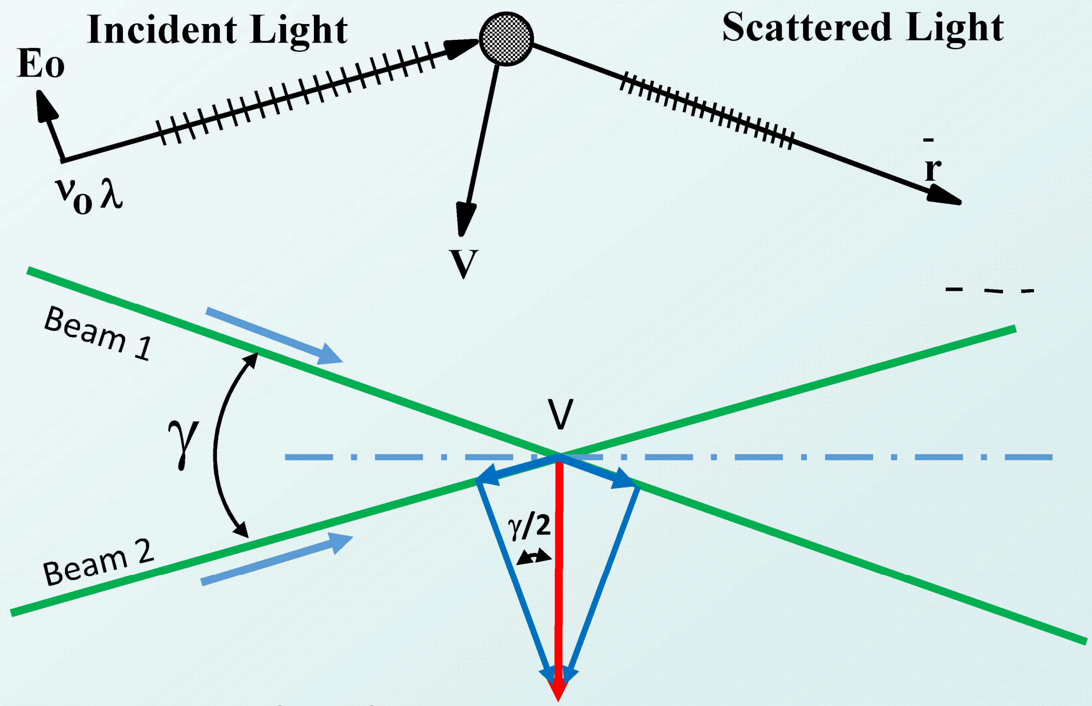
Calculation of the interference fringe spacing



$2\delta = \lambda / \sin \gamma/2$

Λ – laser wavelength is known, γ is measured

Doppler Shift Model



Description:

- Light frequency shifted by velocity component along the beams
- Frequency shifted up on one beam and down on the other
- Expression shows the resultant Doppler difference frequency
- Fringe model gives the same result
- Fringe spacing $\delta = \lambda/2\sin\gamma/2$
- $V = f * \delta = f * \lambda/2\sin\gamma/2$
- Light scattered to the receiver is shifted in frequency but does not affect the difference frequency

V – particle velocity

$f = c/\lambda$, c – speed of light, λ – light wavelength

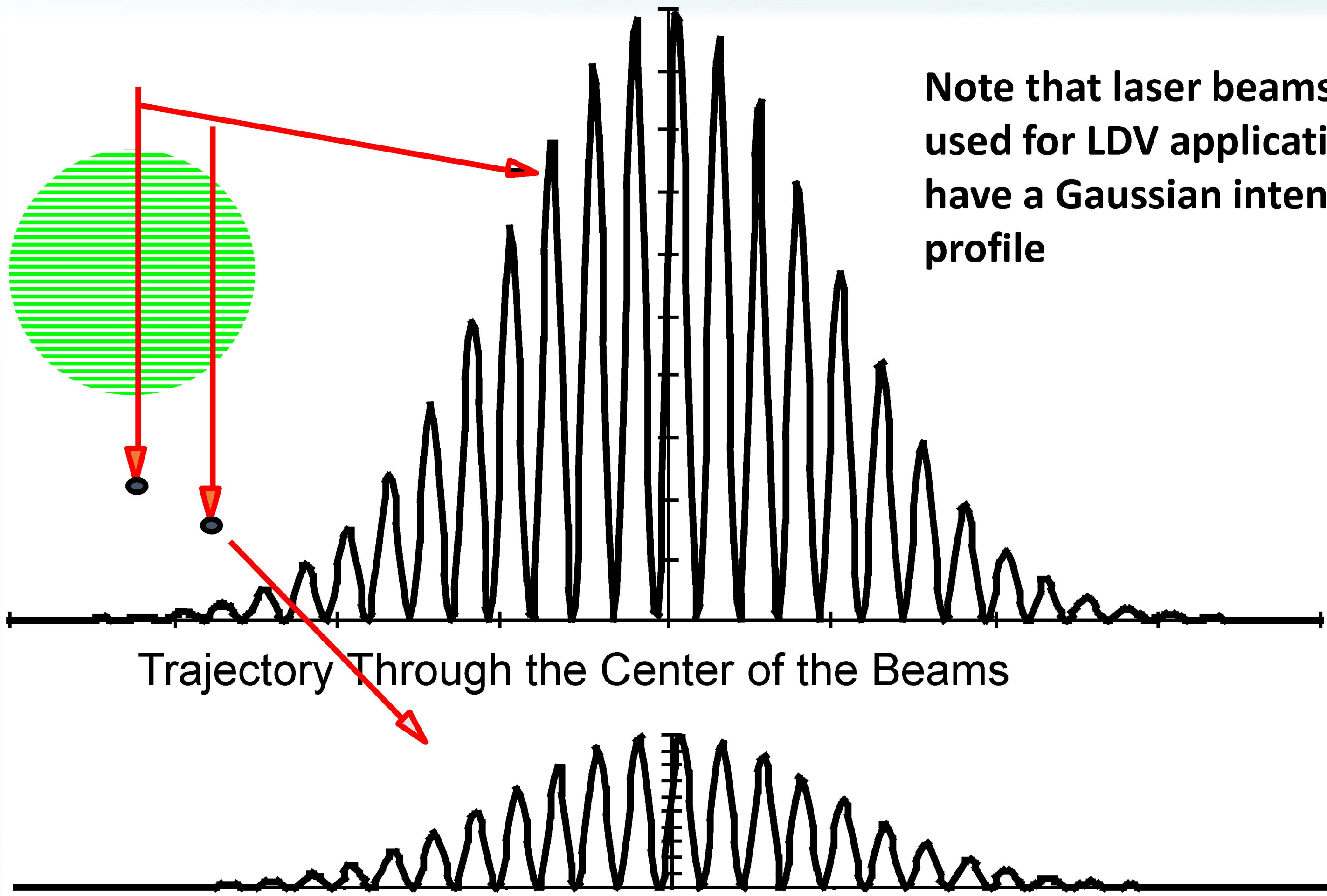
$f_{diff} = f_1 - f_2$

$f_{diff} = 1/\lambda((c + V\sin\gamma/2) - (c - V\sin\gamma/2))$

$f_{diff} = 1/\lambda\ 2V\sin\gamma/2$

$V = f * \lambda/2\sin\gamma/2$

Effect of Trajectory Through the Gaussian Beam on the Signal Amplitude

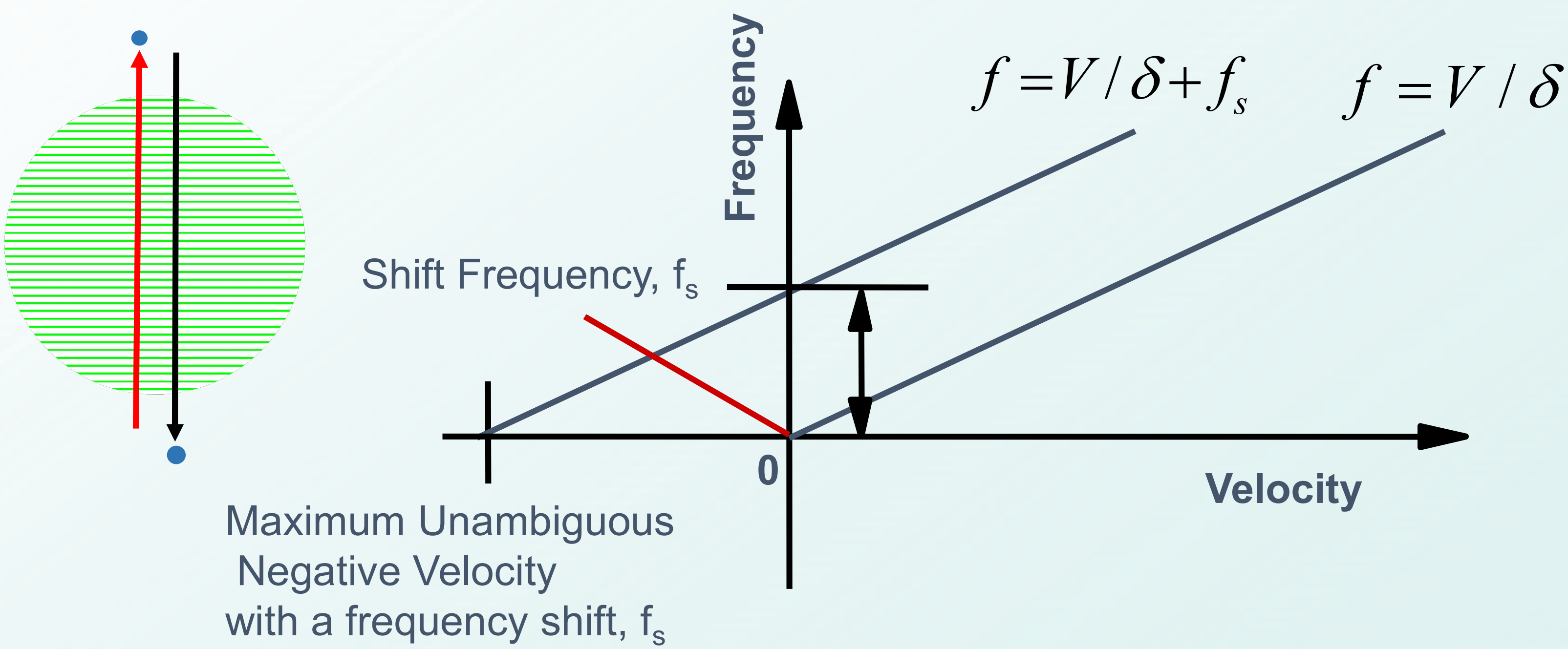


Note that laser beams used for LDV applications have a Gaussian intensity profile

Trajectory Through the Center of the Beams

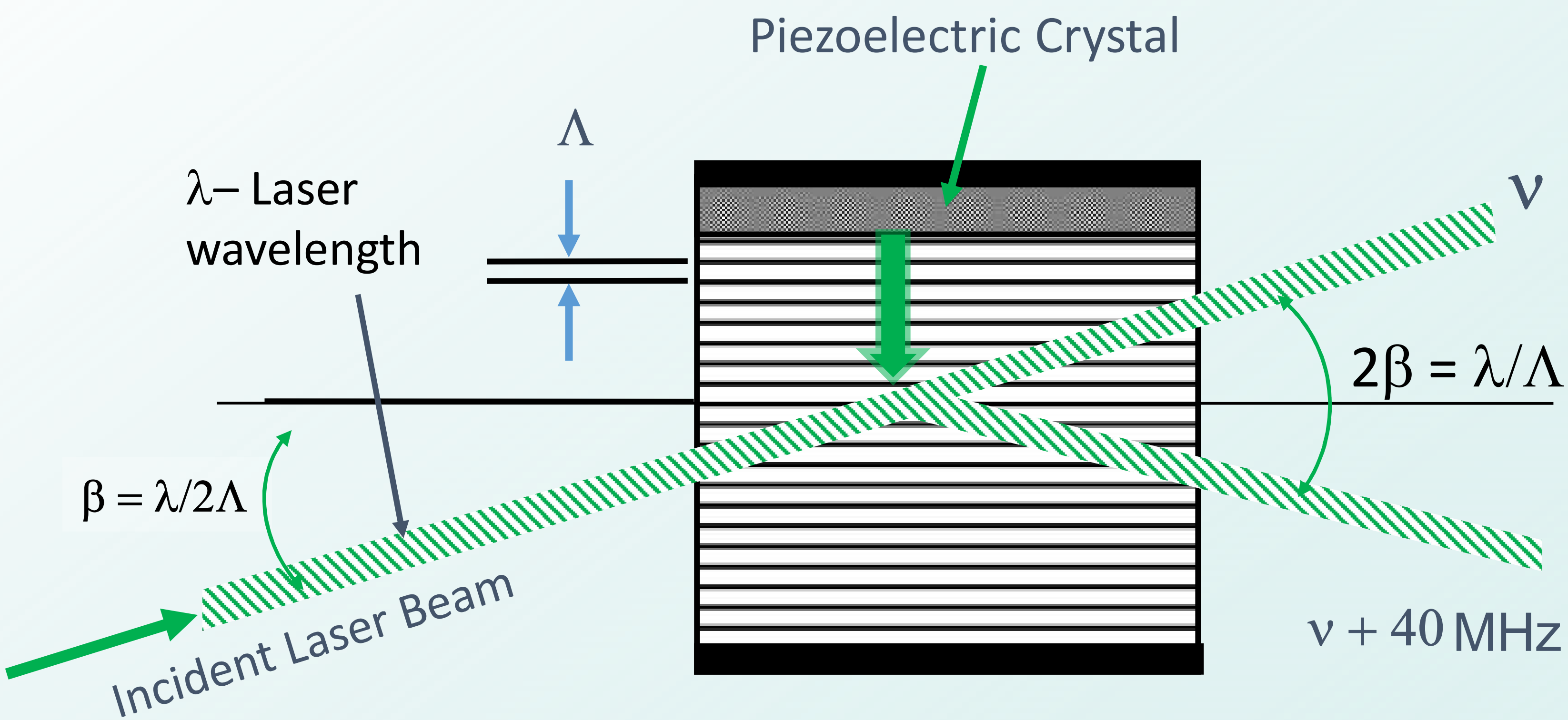
Trajectory Away from the Center of the Beams

Directional Ambiguity and Frequency Shifting



- Particles moving in either the forward or reversed direction generate identical signals
- Introducing a frequency shift into one beam relative to the other will cause the interference fringes to appear to move at the shift frequency.
- Note that with frequency shifting, negative velocities can be distinguished from positive velocities

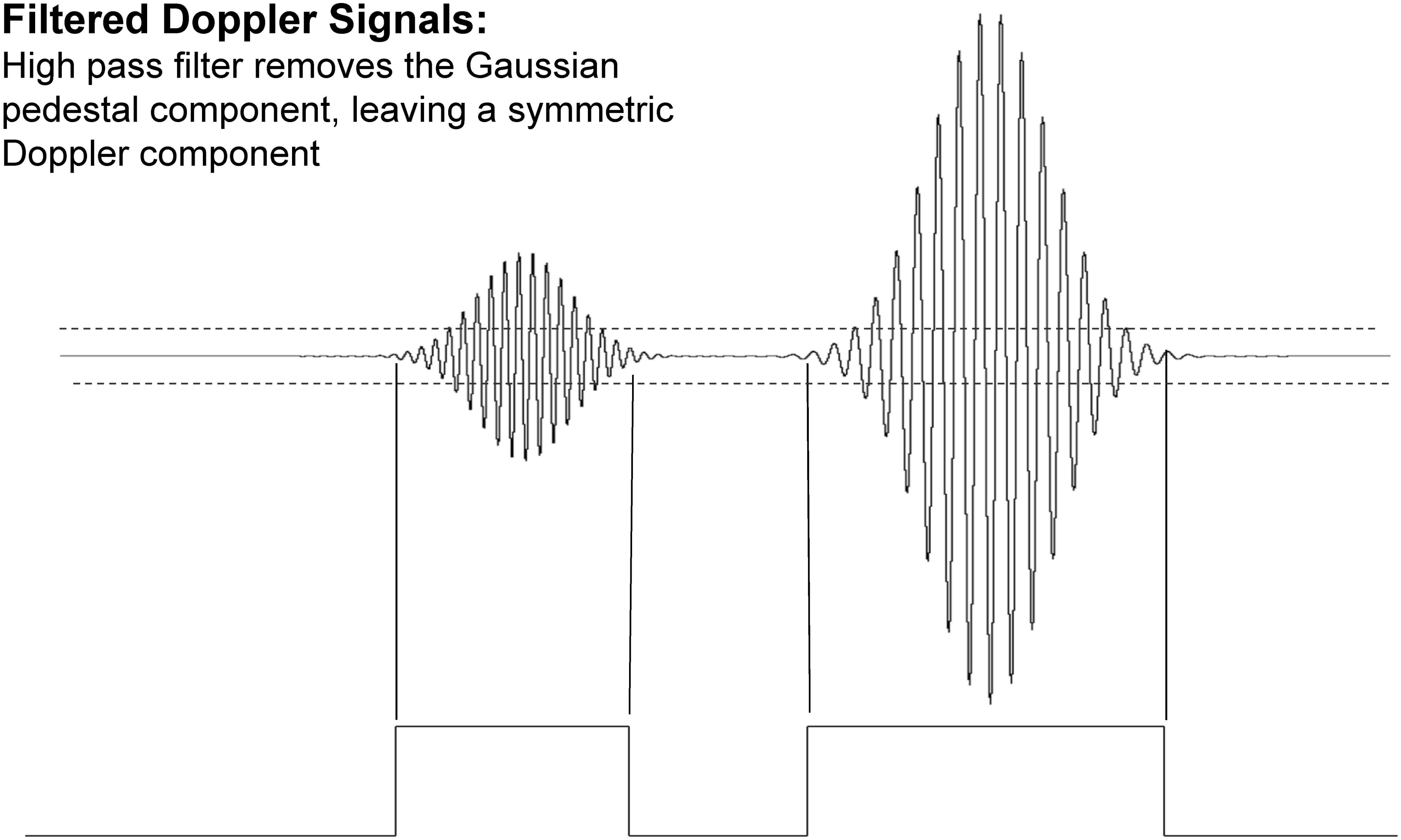
Bragg Cell: Acousto-optical Frequency Shifting



Λ - Wavelength of the acoustic wave in the crystal

Doppler burst Detection based on Sinusoidal Character of the Signal

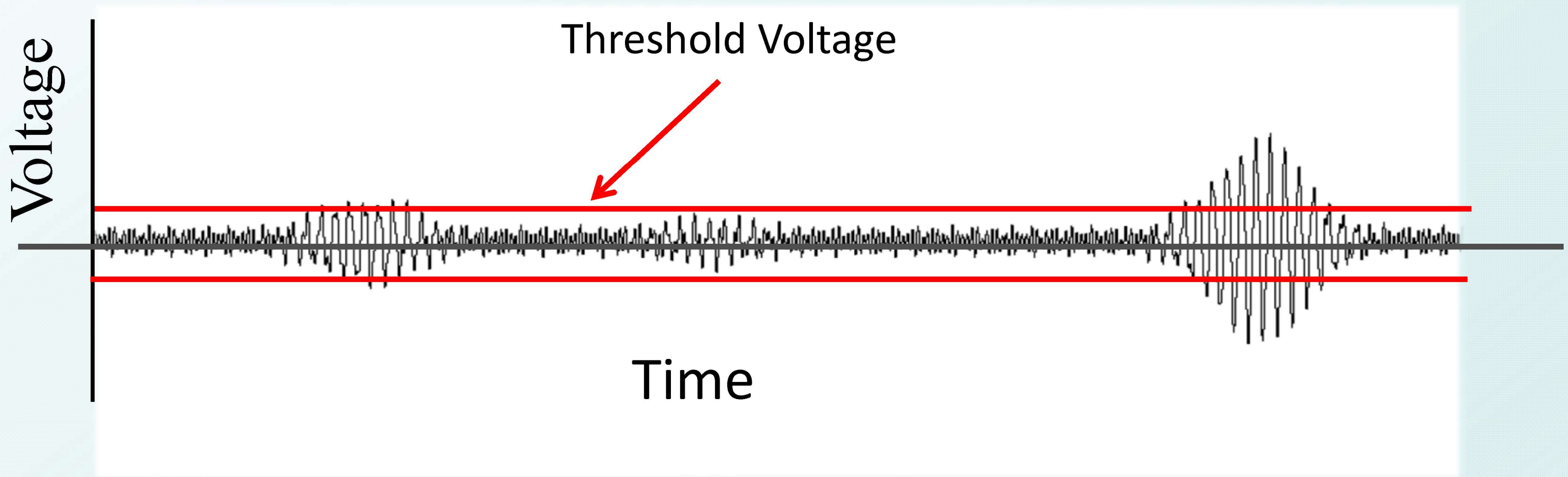
Filtered Doppler Signals:
High pass filter removes the Gaussian pedestal component, leaving a symmetric Doppler component



Signal Detection

Noisy Signals

- Old signal detection method (still used by others) requires setting a voltage threshold detection level to find the signals.
- This can be very challenging when the SNR is low and variable.



Signal Detection based on Sinusoidal Character And Signal to Noise Ratio (SNR) of the Signal

Doppler Burst Signal Detection

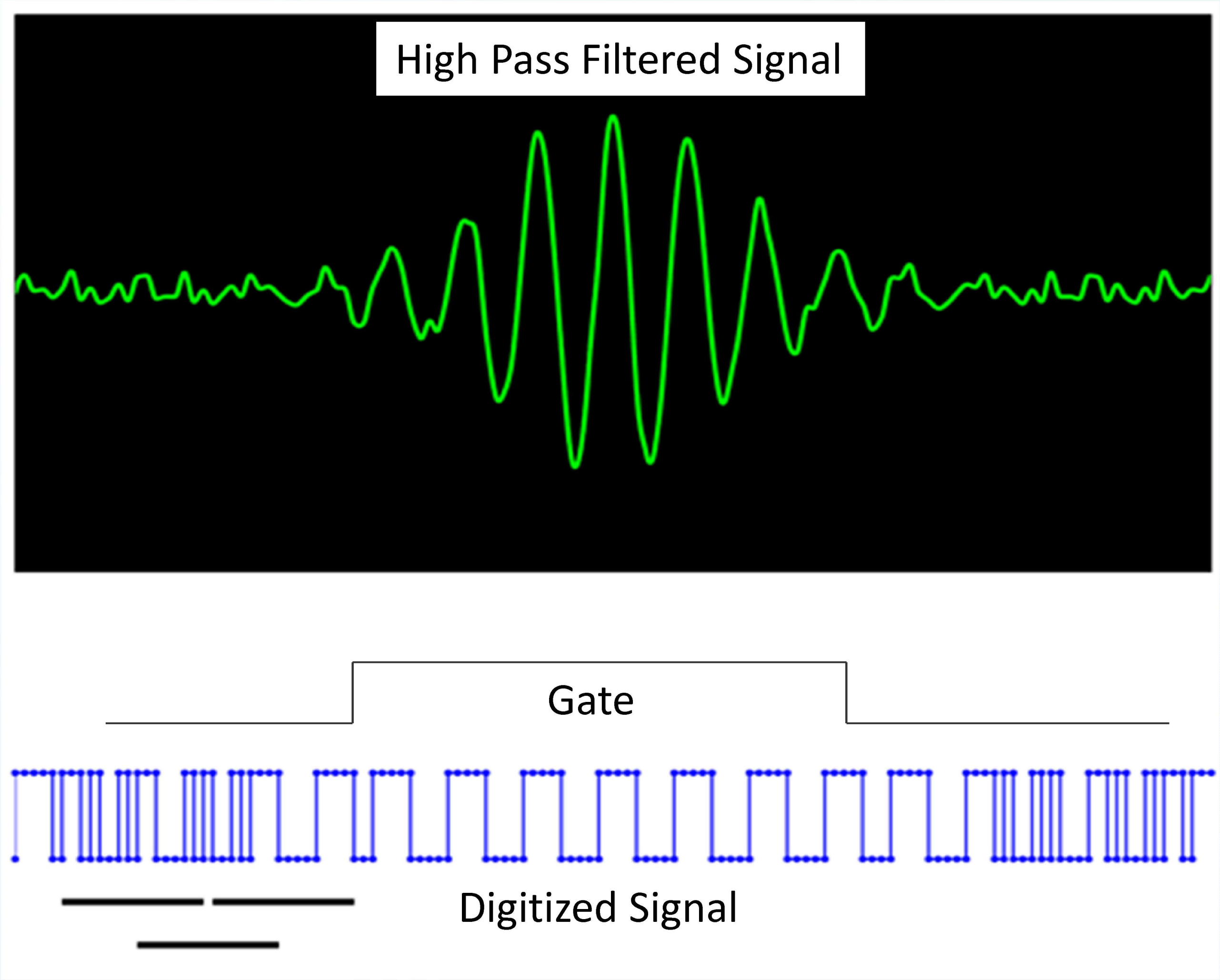
- Important Component Required by LDV Methods
- Critical For Detection of Small Particles In LDV Applications

Advanced Signal Detection Methods

- Based on the *Sinusoidal character of the signal*
- Uses *patented Digital Detection method and SNR* for detection/rejection
- *Requires no adjustment*
- Reliably separates signal from noise
- *Capable of 10 million detections per second*
- No part of the incoming record is missed

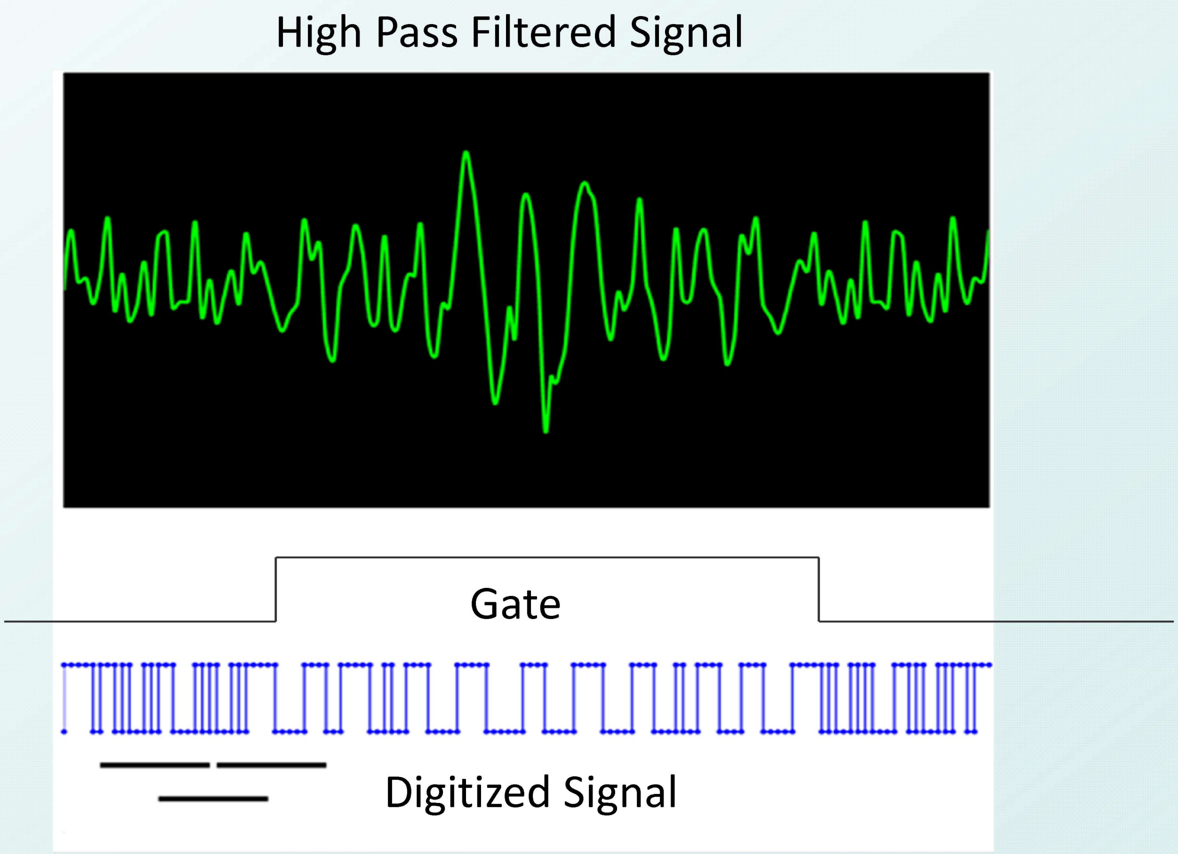
Digital Signal Burst Detection

For single frequency signals, one bit sampling is sufficient



ASA Digital Signal Burst Detection

Even noisy signals can be easily detected and processed reliably to obtain the particle velocity.



Signal Processing and the Fourier Transform

- A transform takes one function (or signal) and turns it into another function (or signal)
- Continuous Fourier Transform:

$$H(f) = \int_{-\infty}^{\infty} h(t) e^{2\pi i f t} dt$$

$$h(t) = \int_{-\infty}^{\infty} H(f) e^{-2\pi i f t} df$$

- The Fast Fourier Transform (FFT) is a very efficient algorithm for performing discrete Fourier transform calculations
- Frequency Measurements Using The **Discrete Fourier Transform**
  - Requires high speed ADC's to sample the signals
  - Signal Frequency is Determined From the Sampled Signal using the DFT

$$f(s) = \sum_{k=0}^{N-1} x(k) \left[\cos\frac{2\pi sk}{N} - i \sin\frac{2\pi sk}{N} \right]$$

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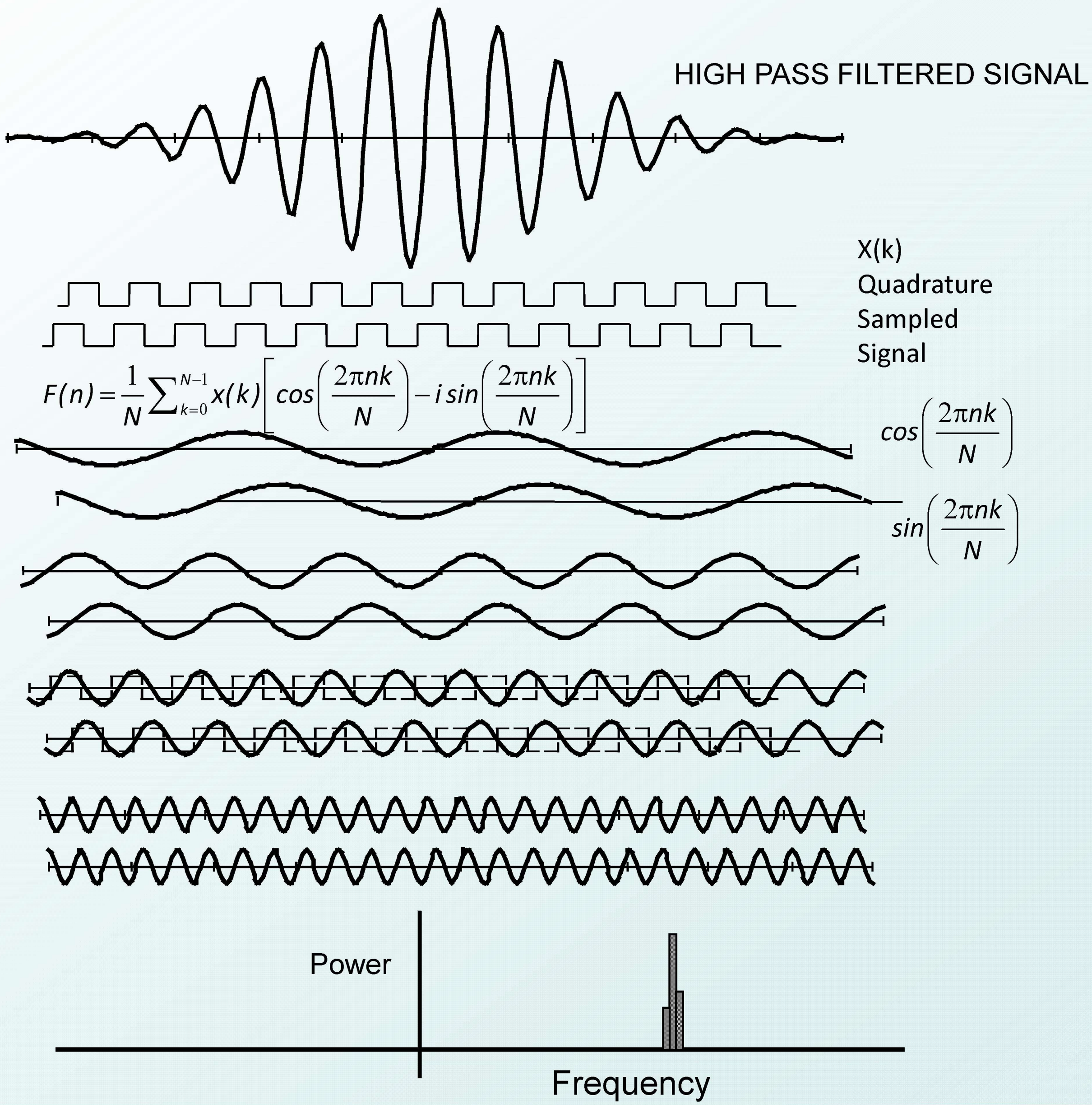
Schematic Describing the Discrete Fourier Transform (DFT)



- Signal is recorded using 1-bit quantization
- Recorded signal consists of a series of 1's and 0's
- Discrete Fourier Transform is applied which essentially correlates the sampled signal with pure sine waves
- Up to 16,384 frequencies are used in the correlations

Advanced Signal Analyzer (ASA)

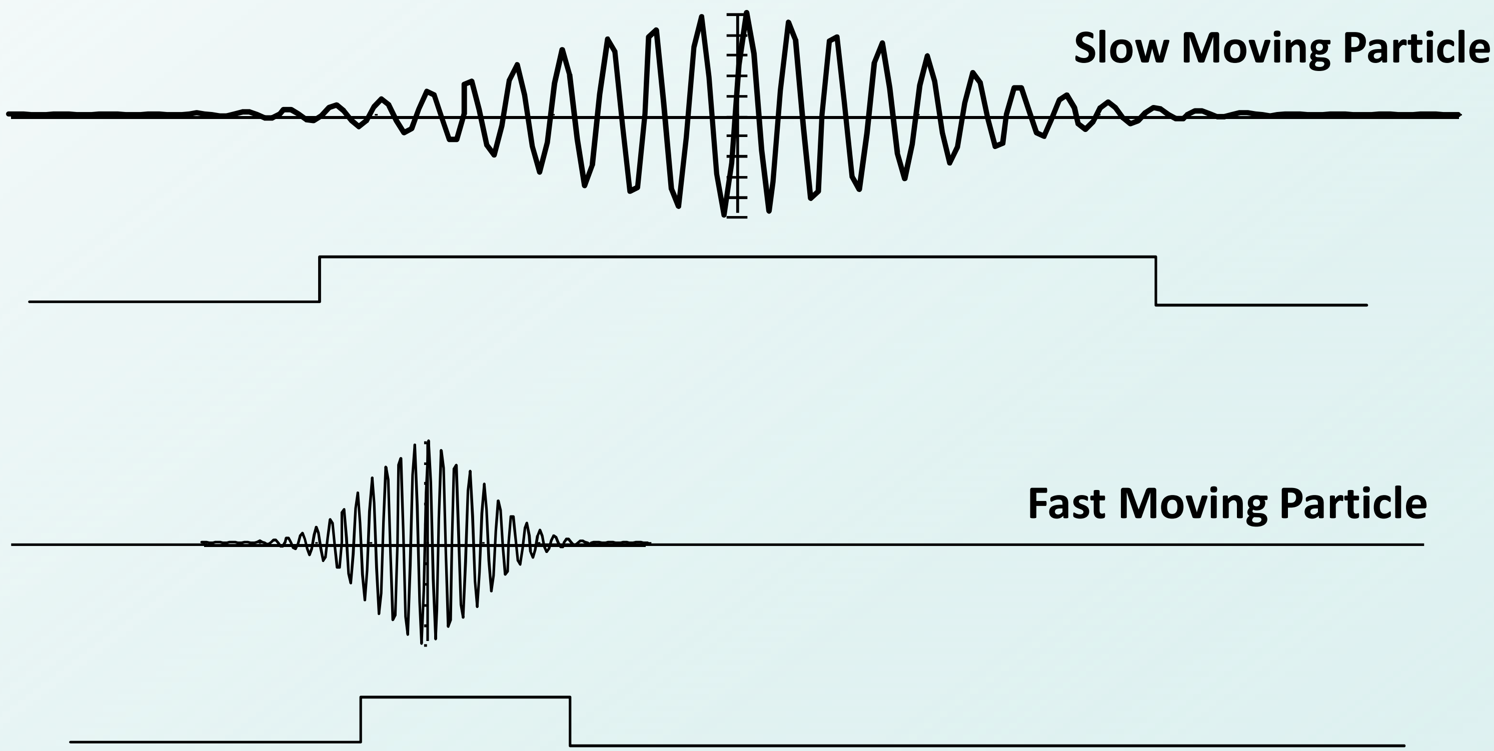
- Uses of the discrete Fourier transform (DFT) to improve performance by up to 100 times that of the earlier counter or autocorrelation plus counting methods
- Critical features of the ASA:
  - Uses high speed ADC’s (to 500 MHZ) to sample the signals in quadrature (real and imaginary components) to 250 MHz (Nyquist criterion)
  - Doppler signals vary in time due to differences in the particle velocities, particle size, and trajectory through the beam
  - Sampling capable of up to 100,000 ADC readings to adapt to any signal length
  - Signal processing (DFT) is computed in the high-speed computer using software
  - Provides greater flexibility, advanced signal validation, and ease of upgrades
  - Highly reliable in discriminating noisy signals and providing high resolution and accuracy

Advanced Signal Analyzer

Signal sampling time directly affects measurement precision and accuracy

<u>ASA Adaptive Burst Length Sampling</u>

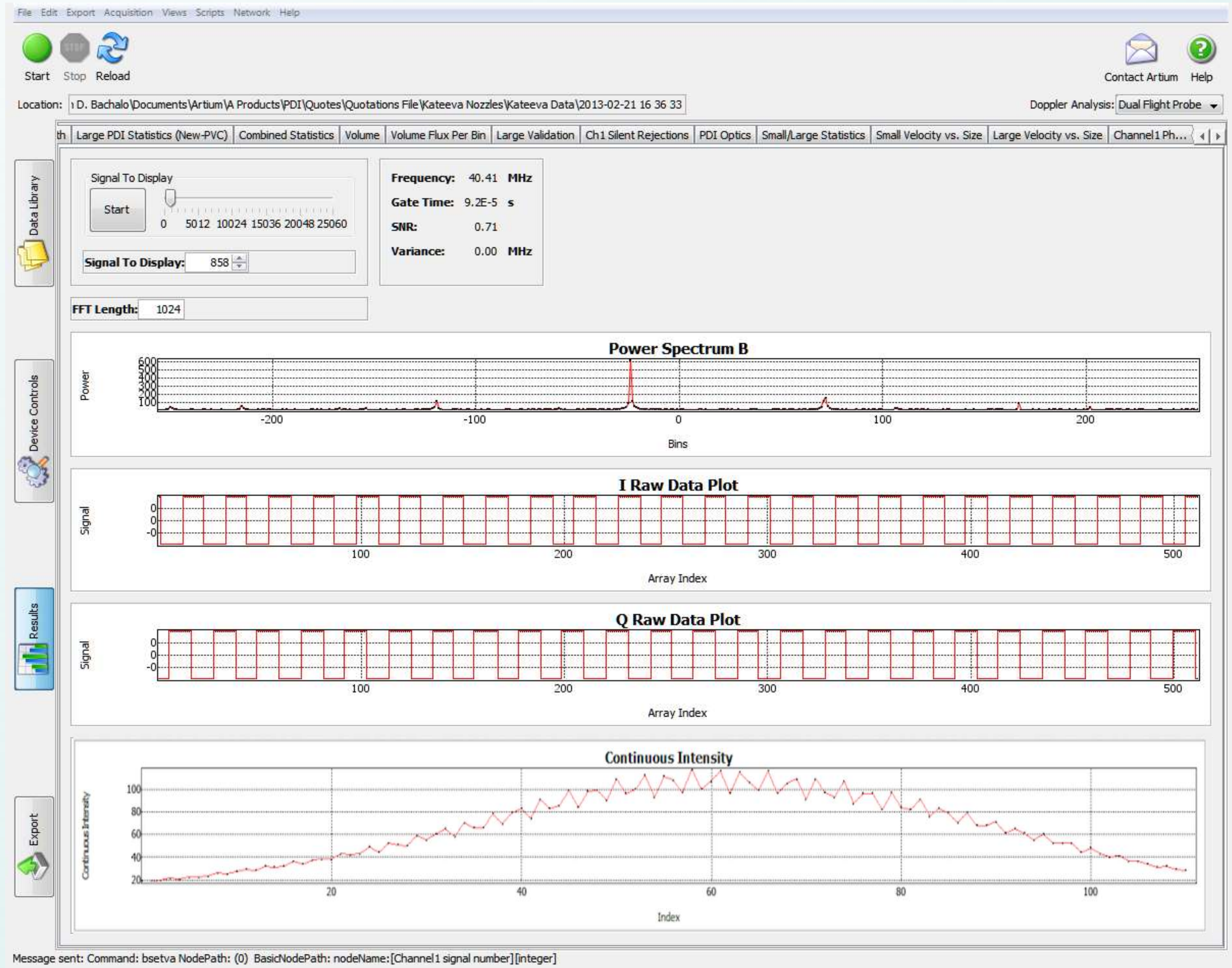
Doppler Burst Signals



Artium’s Processor Showing Sampled Signals and Doppler Frequency Spectrum

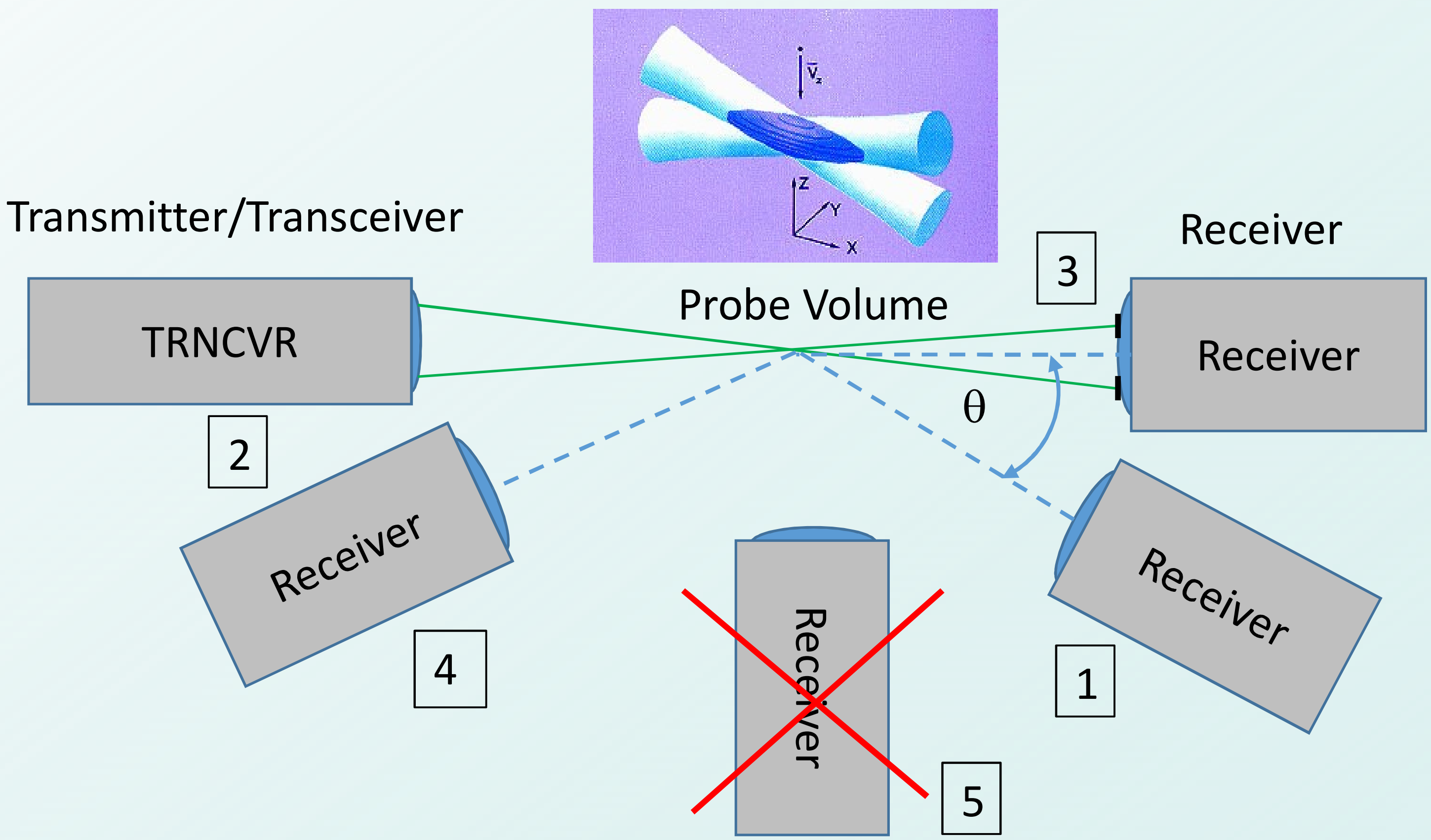
Artium’s ASA Processors and AIMS software allow the display of each sampled Doppler signal and the frequency spectrum.

ASA instruments also show the signal amplitude with 12- bit resolution.



Possible Locations of the LDV Receiver Optics

1. Off-axis forward scatter, good signal quality, sample volume definition
2. Transceiver detects backscatter light, lower signal, convenient, lower scattered light intensity, poorer sample volume definition
3. On-axis forward scatter, best signals, poorer sample volume definition
4. Off-axis backscatter, lower signal, good sample volume definition
5. 90° light scatter detection, very low light scatter, do not use



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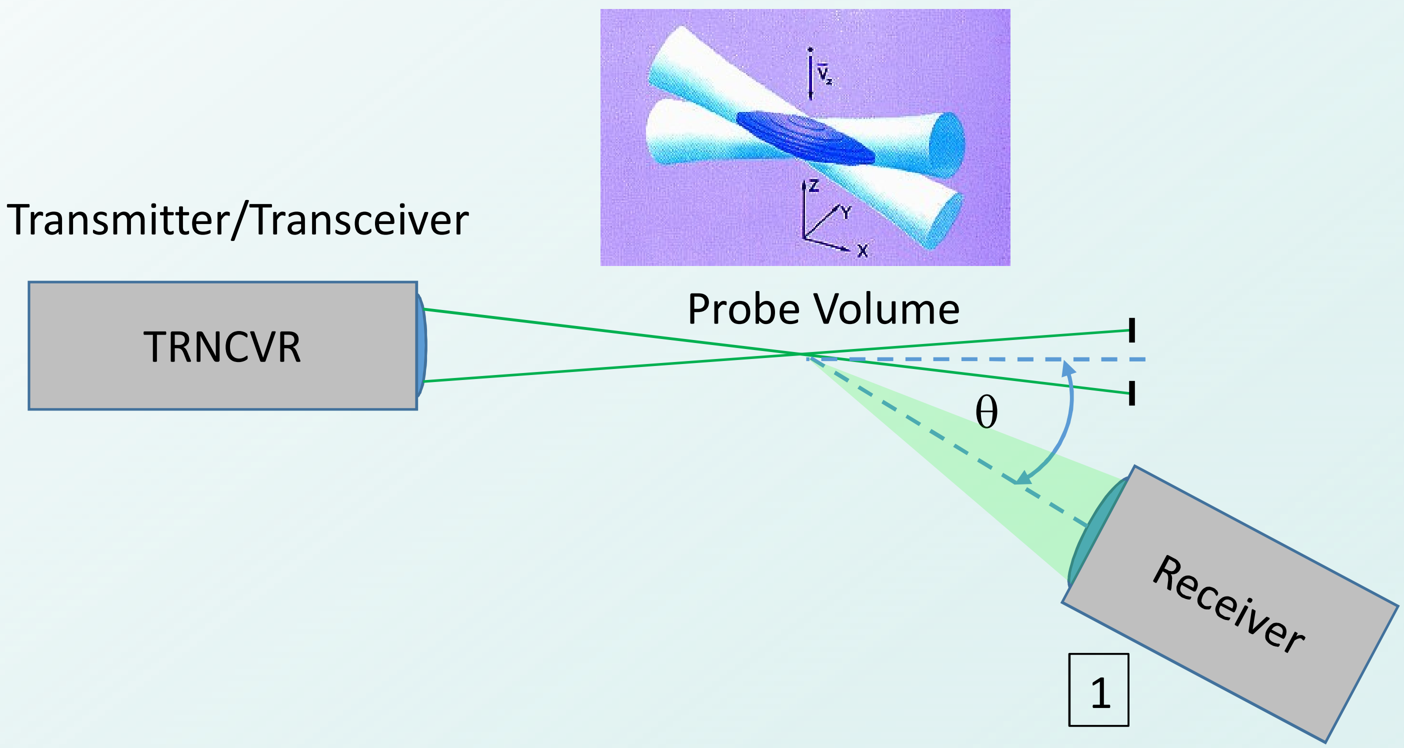

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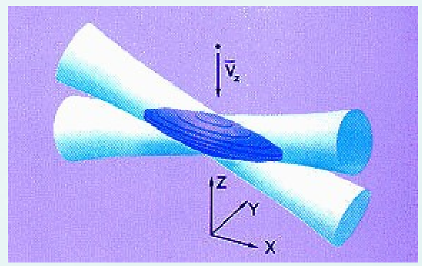

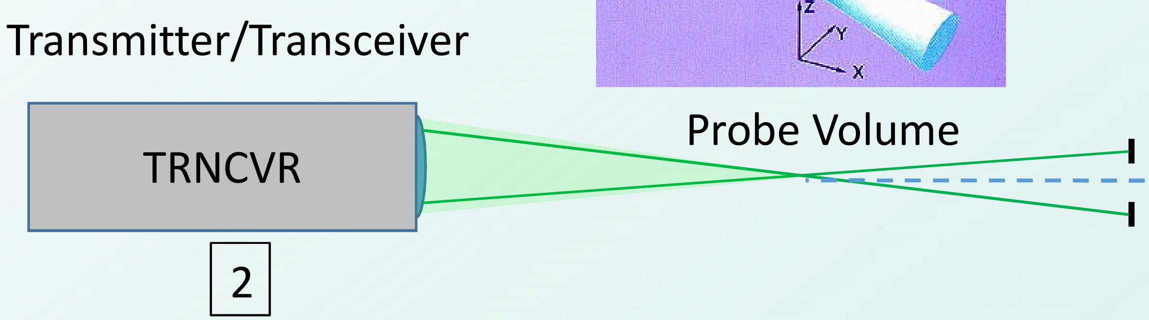

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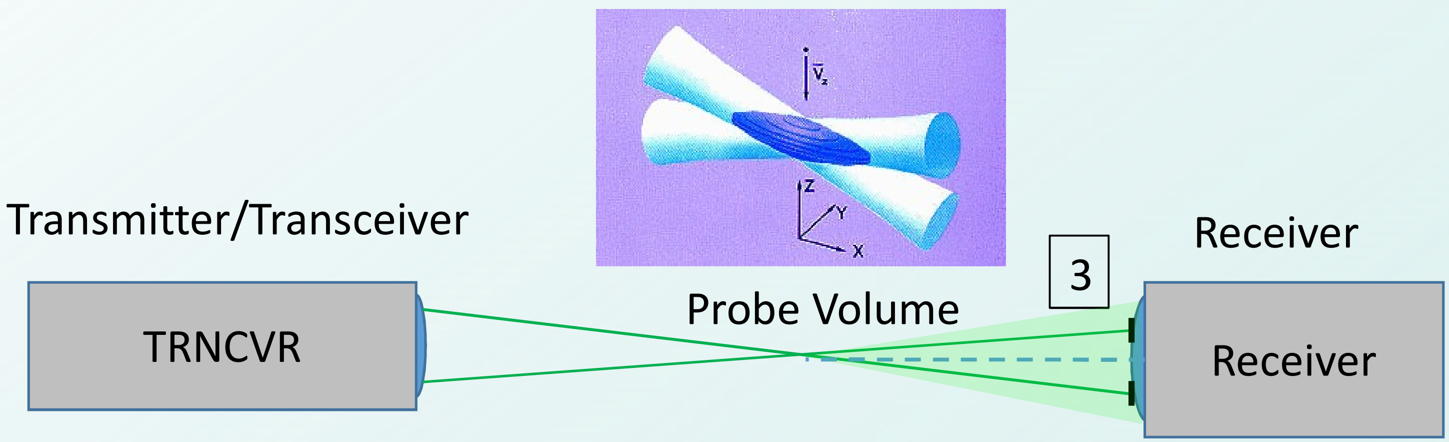

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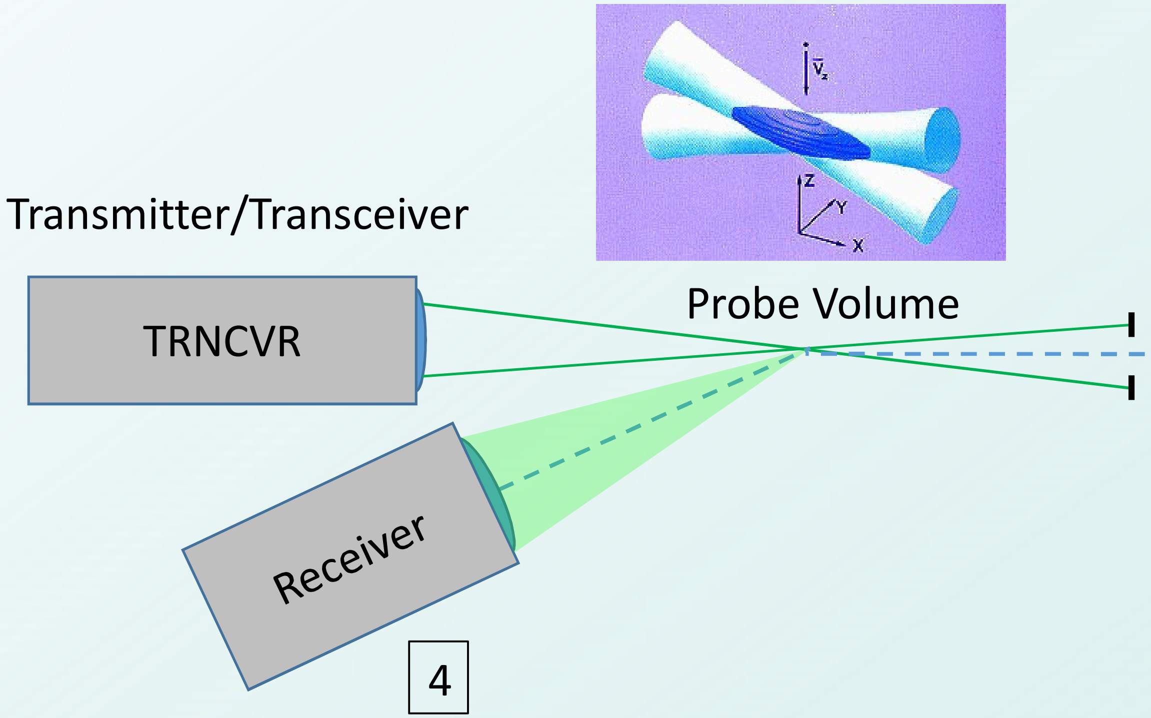
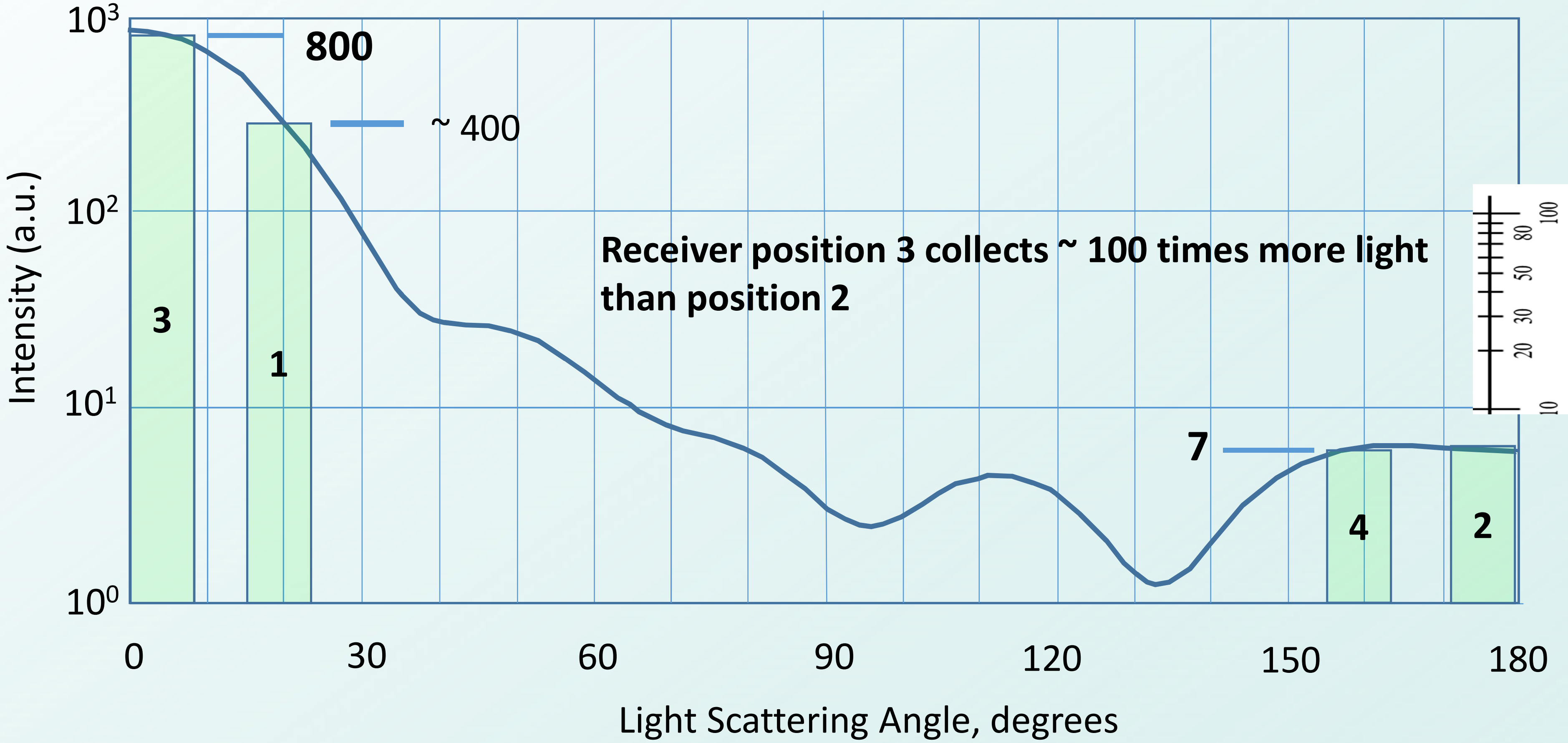
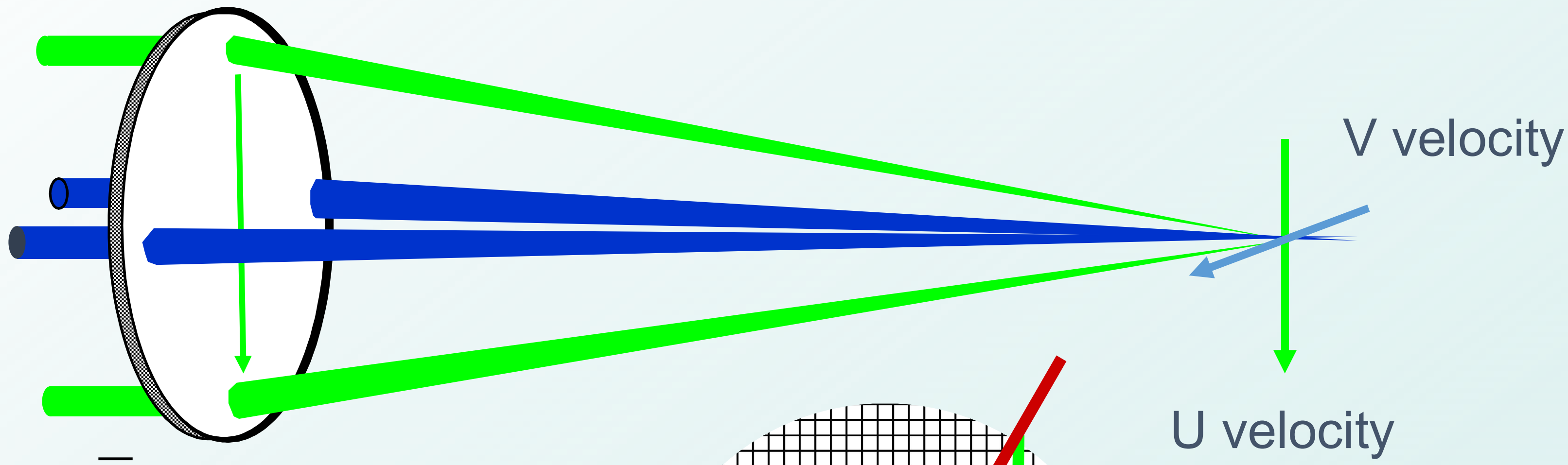


Example of Light Scattering Intensity Versus Detection Angle

- Particle diameter 1 μm
- 0.532 wavelength
- Index of refraction 1.4

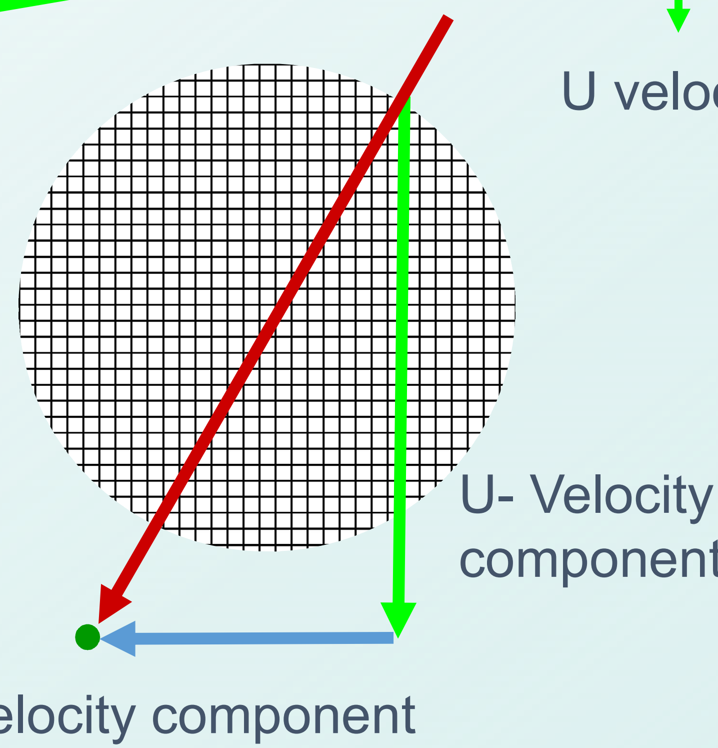


Two-Component Laser Doppler Velocimeter

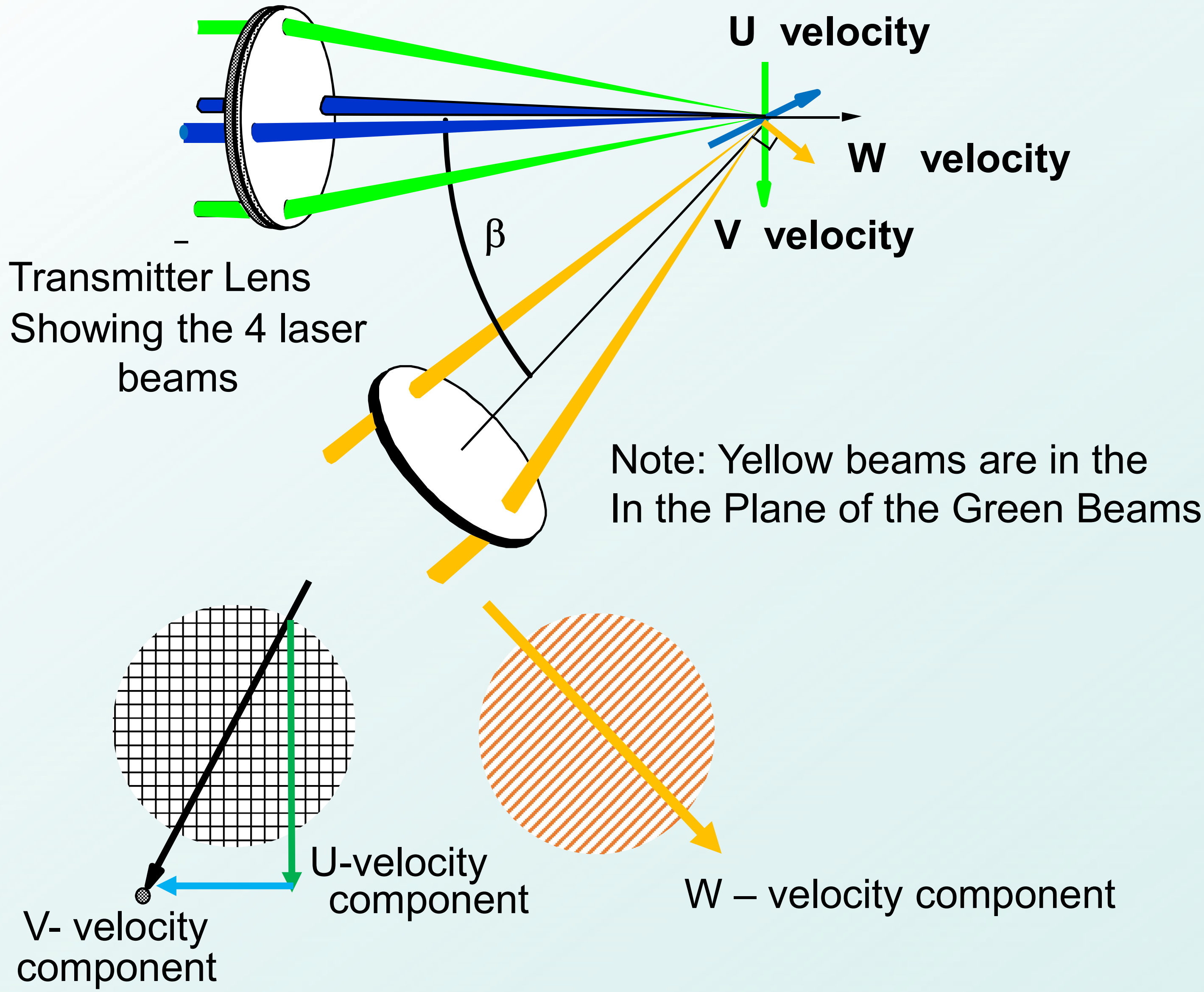


Transmitter Lens
Showing the 4 laser beams

Velocity component measured
is in the plane of the two beams



Transmitting Optics for a Three-Component System



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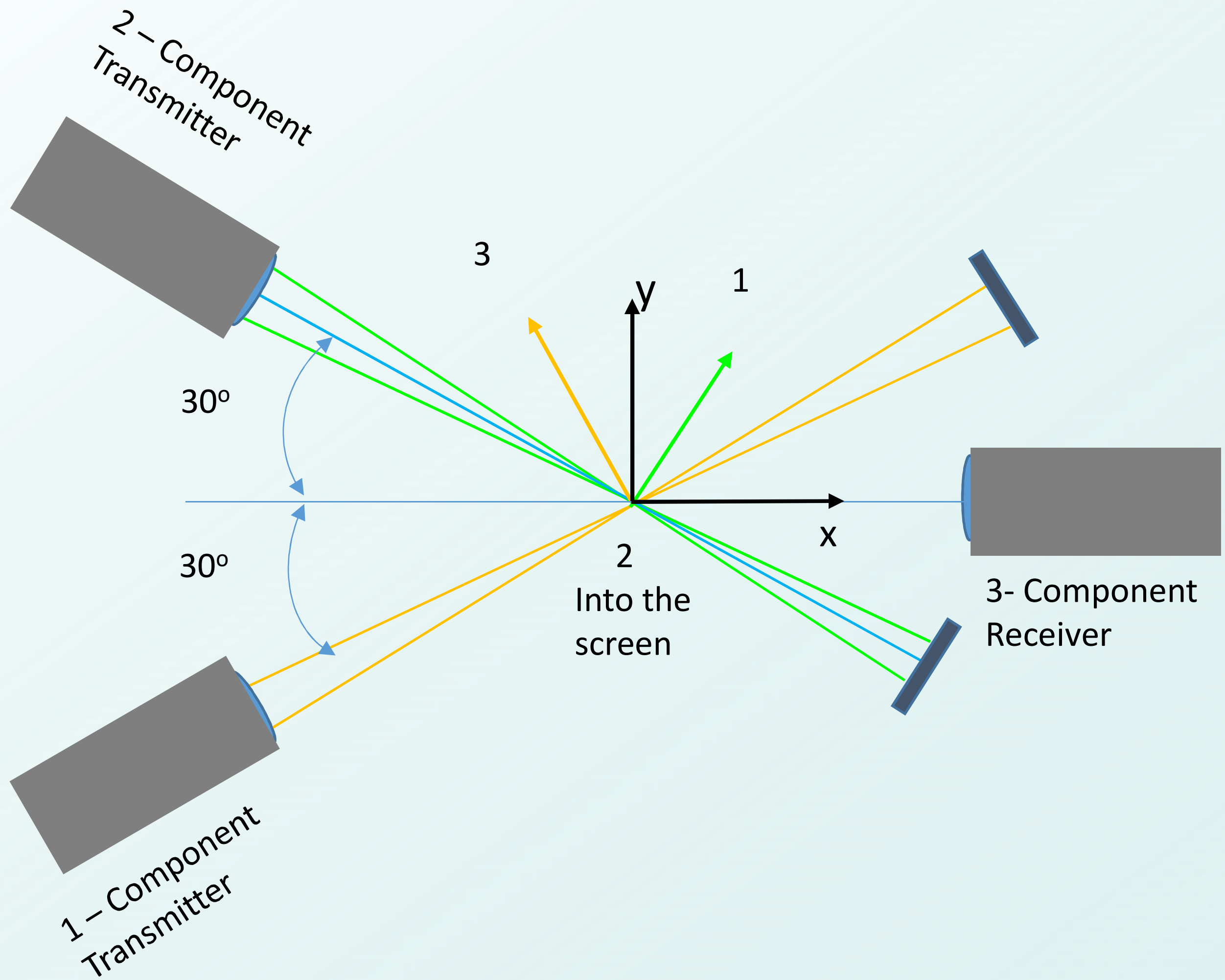
Preferred Arrangement of 3 - Component LDV Optics



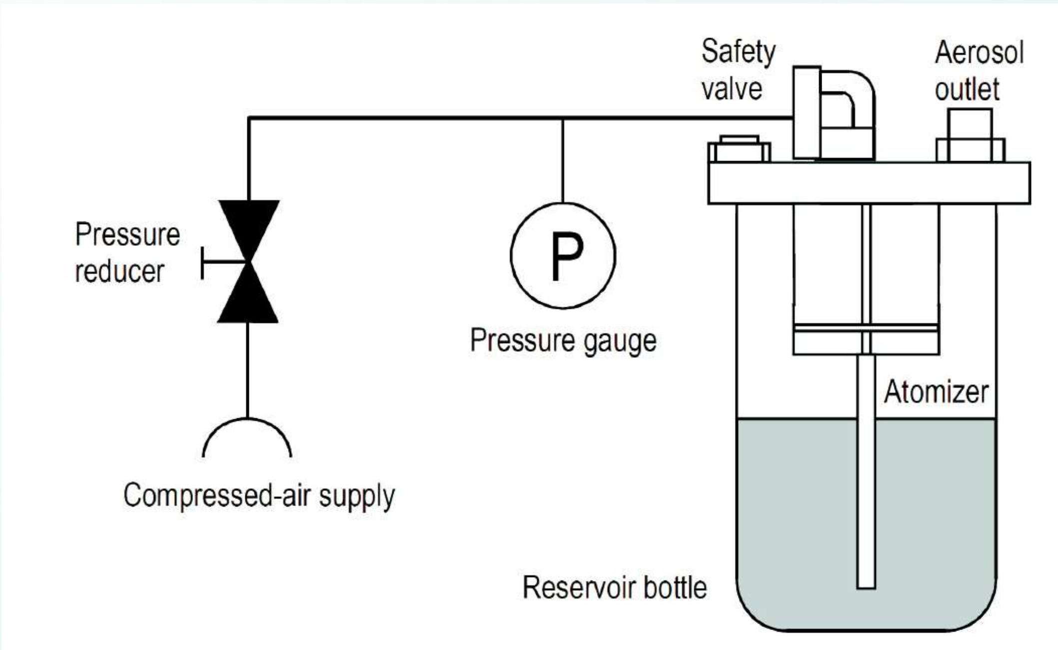
Flow Seeding and Seed Particles

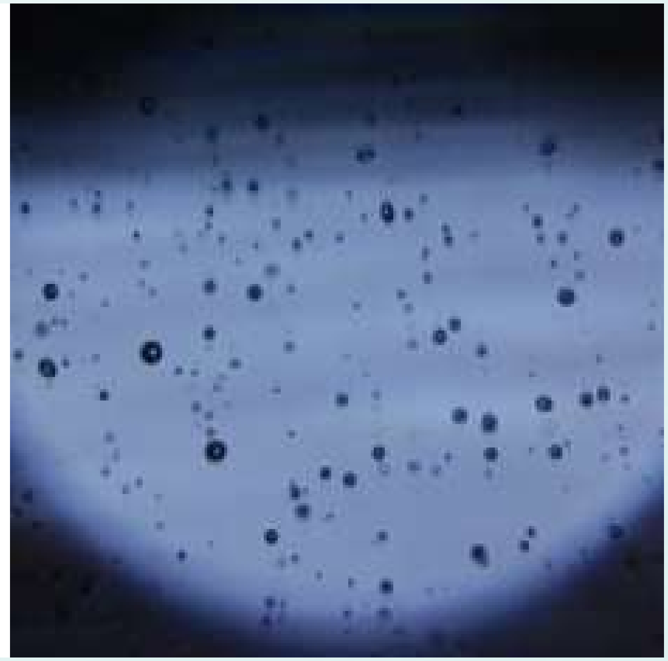
- Particles must be added to flow to scatter light to the detectors
- Seed particles must adequately respond to the flow to measure mean velocity and turbulence
- Seed particle concentration distribution must be uniform, or measurement bias will occur
- Considerations for Seed Particle Selection
  - Size - Mean and Distribution
    - Too Small - Low Signal Intensity, SNR
    - Too Big - Particles Lag The Flow
  - Material Density, particle **mass** is important
  - Means Available for Dispersing In Flow Facility
  - Window Contamination

Seeding Materials and Methods

- Water droplets from atomizers – 0.5 to 5 μm
- Mineral oil or other light oils from atomizers – 0.5 to 3 μm
- Incense smoke – 0.3 to 2 μm
- Alumina particles dispensed from a fluidized bed
- Polystyrene latex spheres, PSL dispersed with fine water spray, water evaporates – 0.5 to 3 μm
- Smoke formed by heating oil – 0.3 to 3 μm
- Heating and condensing glycol of “Fog Juice”
- Refractory seed particles are needed in high temperature environments

Aerosol Generator for Seed Particle Production





LaVision Seed Generator

The solid particle generator **Particle Blaster 100** generates particles in the micrometer range. In combination with our **FlowMaster** (LaVision`s PIV systems) it is designed to measure velocities in air flow for pressure up to 2 bar.

LaVision Seed Generator

The solid particle generator **Particle Blaster 200** generates particles in the micrometer range. In combination with our **FlowMaster** (LaVision`s PIV systems) it is designed to measure velocities in air flow for pressure up to 20 bar.

- aerodynamics
- wind tunnel
- turbomachinery
- engine flows
- reactive flow fields
- industrial flow systems (pumps, mixers)
- life science flow phenomena
- flames

Particle Dynamics and Response

The particle response equation is:

$$\frac{\rho_p \pi d_p^3}{6}\frac{du_p}{dt} \cong C_D \frac{\rho_g \pi d_p^2}{8}(u_g - u_p)\left|u_g - u_p\right|$$

and for a Stokes flow, $C_D = 24/Re_p$ and where u_p and u_g are the particle

$$Re_p = \rho_g \frac{\left|u_g - u_p\right|}{\mu_g} d_p$$

and gas phase velocities, ρ_p and ρ_g are the particle and gas densities, d_p is the particle diameter, and μ and ν are the dynamic and kinematic viscosity.

Temporal rate of change of the particle velocity is given as

$$\frac{du_p}{dt} = \frac{18\nu\rho_g}{d_p^2 \rho_p}(u_g - u_p)$$

Relaxation time τ for a unit density particle in air (p=1 atm, T=20°C)

g – acceleration of gravity

$u_t = \tau g = \rho_P d^2 g/18\mu$ – terminal velocity of particle

τ – relaxation time for particle

Diameter, μm	$u_t = \tau g$	τ (sec)	Stop Distance u_o = 1m/s	Stop Distance u_o=10m/s
0.05	0.39 μm/s	$4x10^{-8}$	0.04 μm	$4x10^{-4}$ mm
0.1	0.93 μm/s	9.15^{-8}	0.092 μm	$9.15x10^{-4}$ mm
0.5	10.1 μm/s	$1.03x10^{-6}$	1.03 μm	0.0103 mm
1	35 μm/s	$3.57x10^{-6}$	3.64 μm	0.0357 mm
5	0.77 mm/s	$7.86x10^{-5}$	78.6 μm	0.786 mm
10	3.03 mm/s	$3.09x10^{-4}$	309 μm	3.09 mm
50	7.47 cm/s	$7.62x10^{-3}$	7.62 mm	76.2 mm

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Spray Interactions With Turbulence

- **Observation:** Turbulent flows contain a continuum of length and time scales from the large-scale eddies down to the Kolmogorov microscales.
- Particle response is determined by the bounds set forth in our analysis
- Axisymmetric Jet, D = 2.0 mm:

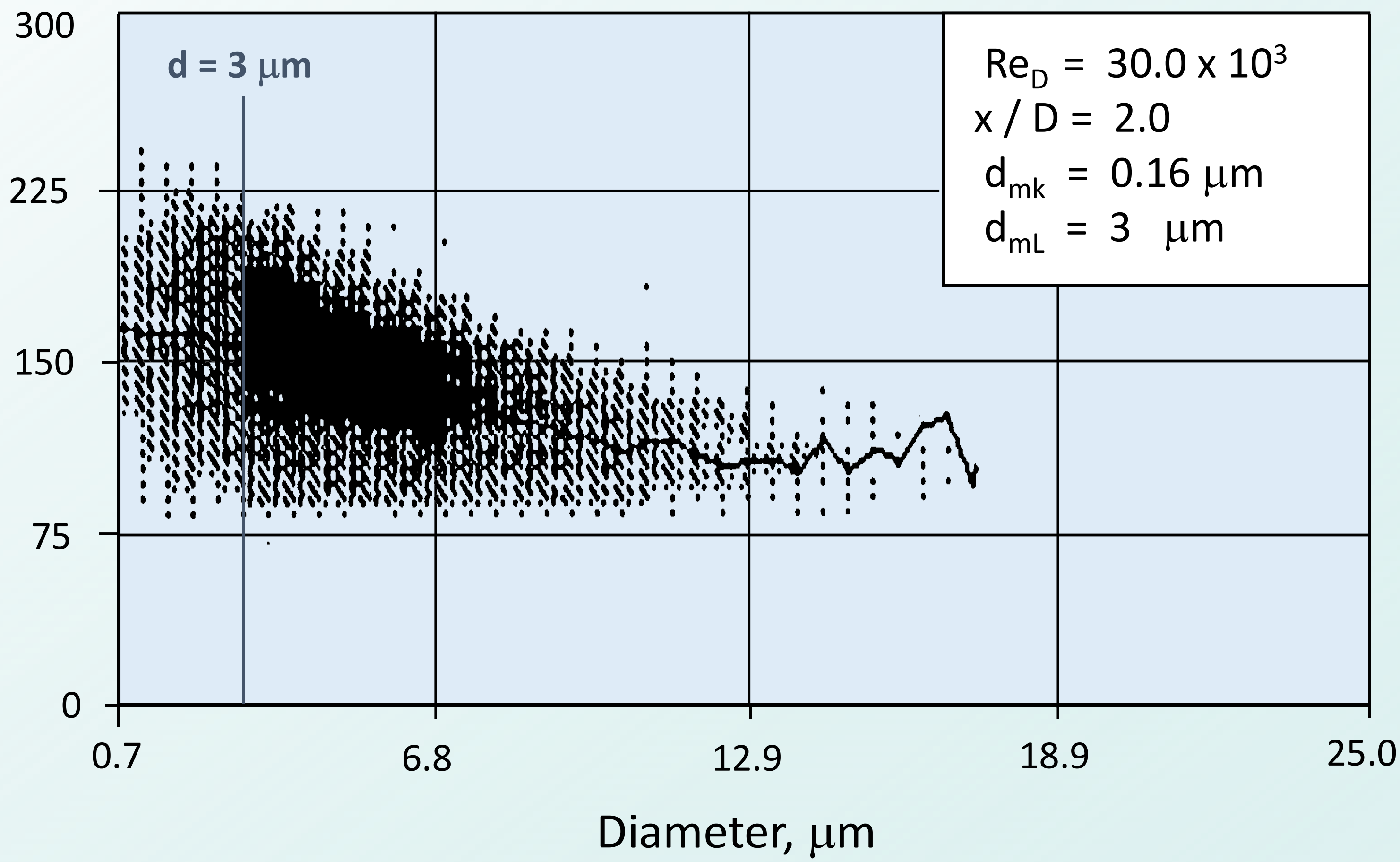
Re_D	d_{pk} (μm) Kolmogorov	d_{pL} (μm) Large Scales
8.3×10^3	0.42	5.4
12.6×10^3	0.30	4.5
20.6×10^3	0.20	3.5
36.0×10^3	0.14	2.6
50.0×10^3	0.10	2.2

Conclusion:

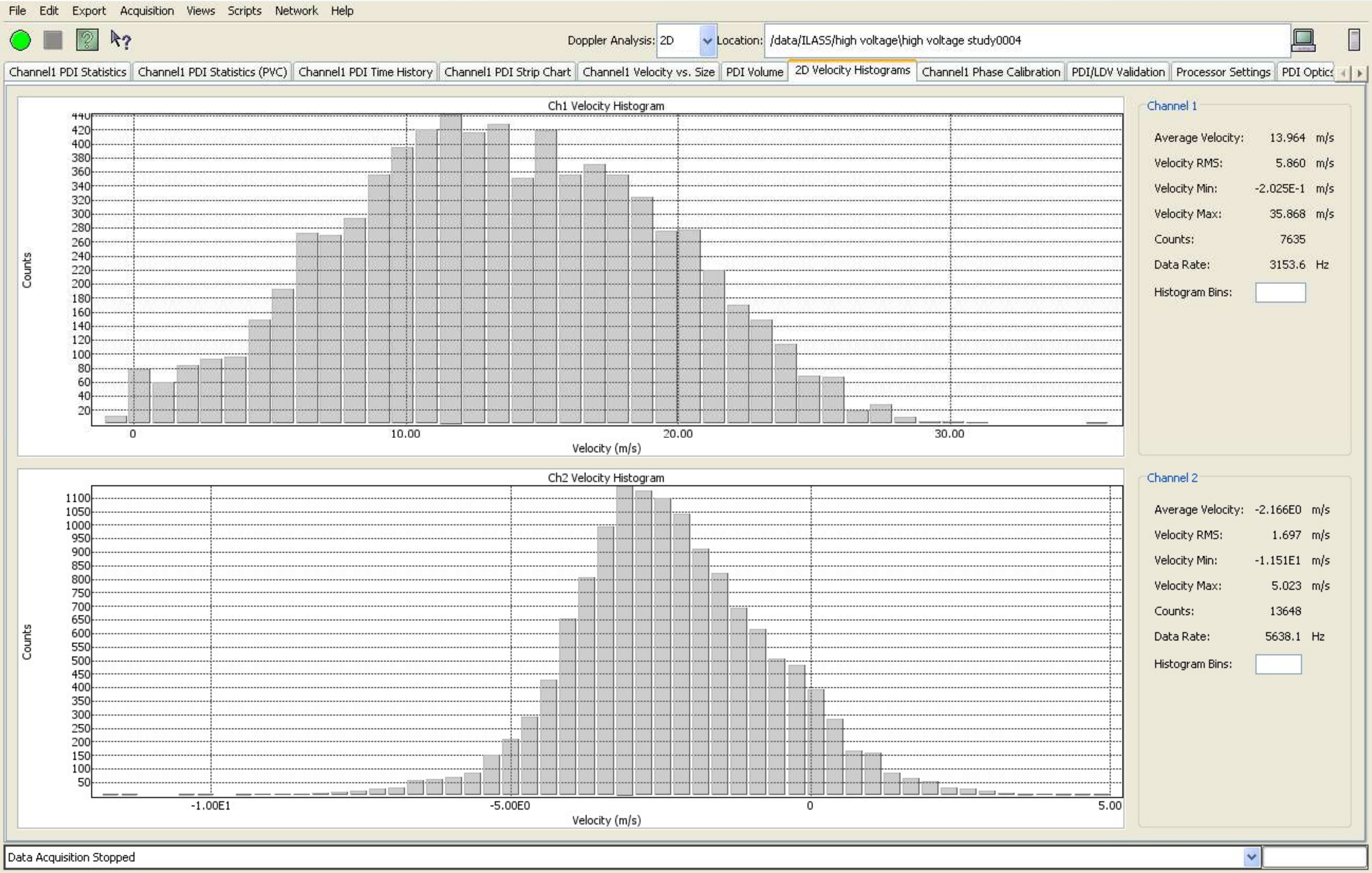
Larger particles will not equilibrate to even large turbulence scales (eddies).

Particle Interactions With Turbulence

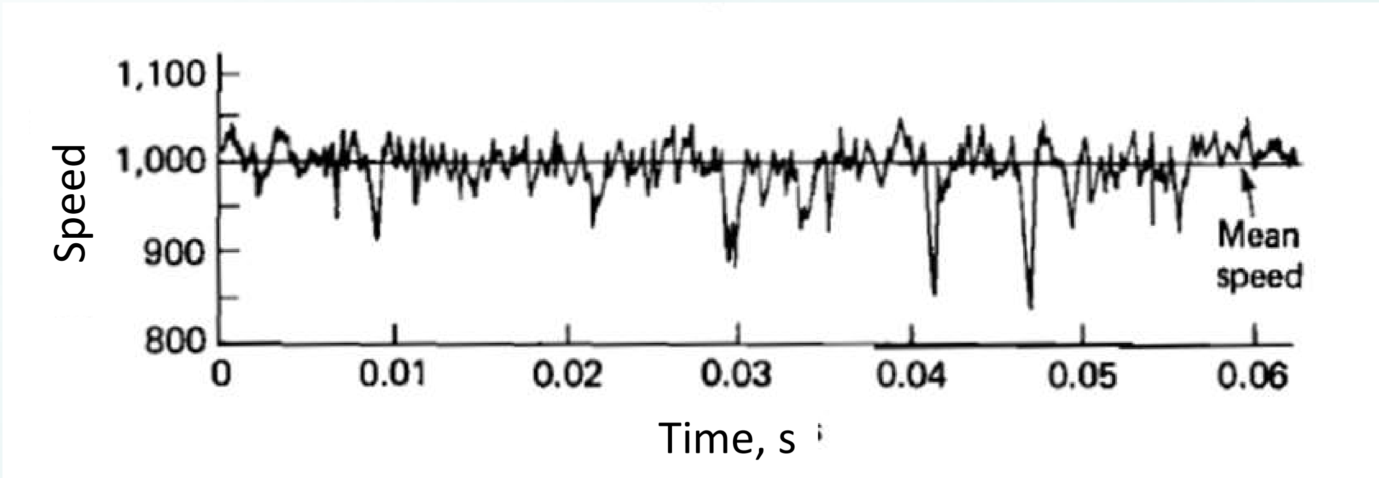
Size - Velocity Correlation, simultaneous measure of particle velocity and size for a sonic jet



Histograms of Measured Two Velocity Components



Mean and fluctuation velocity components



$$u(t) = \overline{u} + u'(t)$$

$$v(t) = \overline{v} + v'(t)$$

$$w(t) = \overline{w} + w'(t)$$

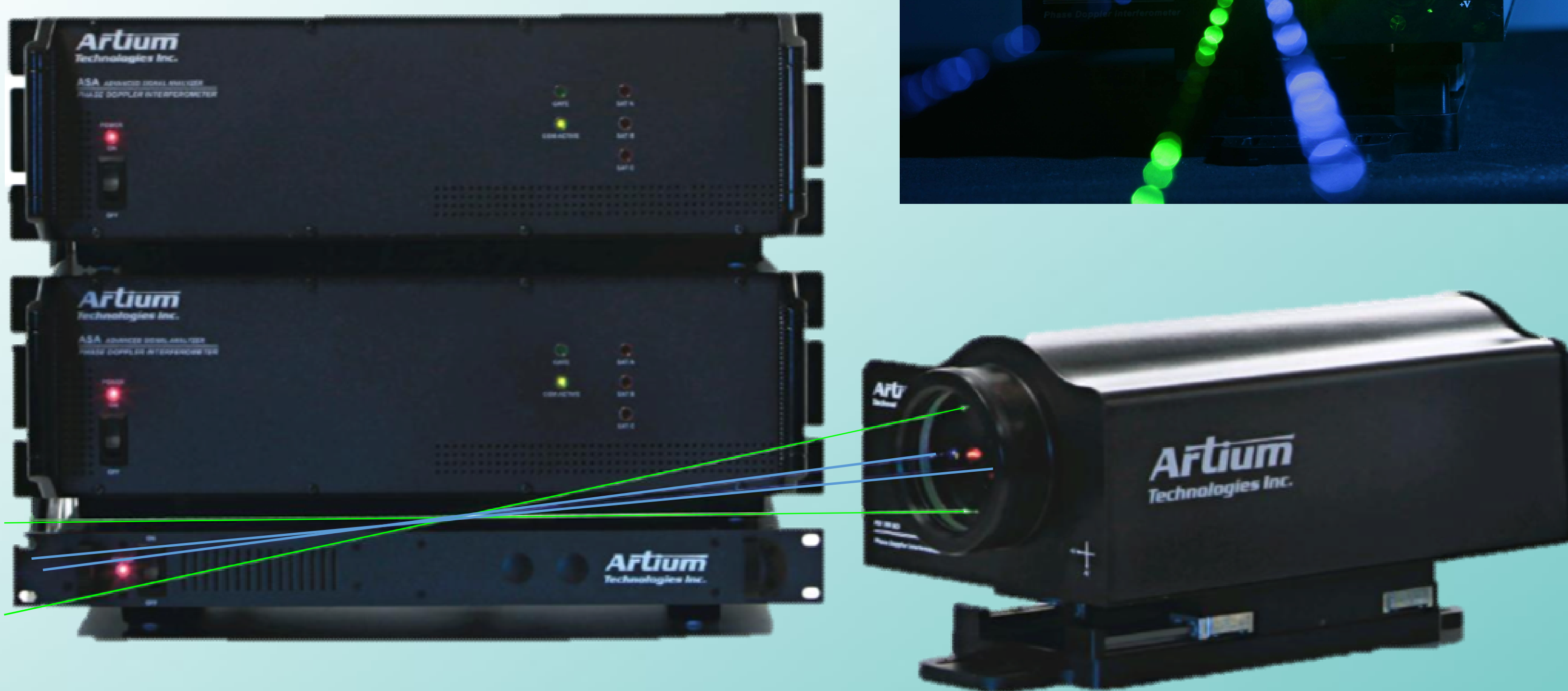
Mean and fluctuation velocity components

- For statistically stationary systems, ensemble average is equal to the time average
- Considered an ergodic ensemble

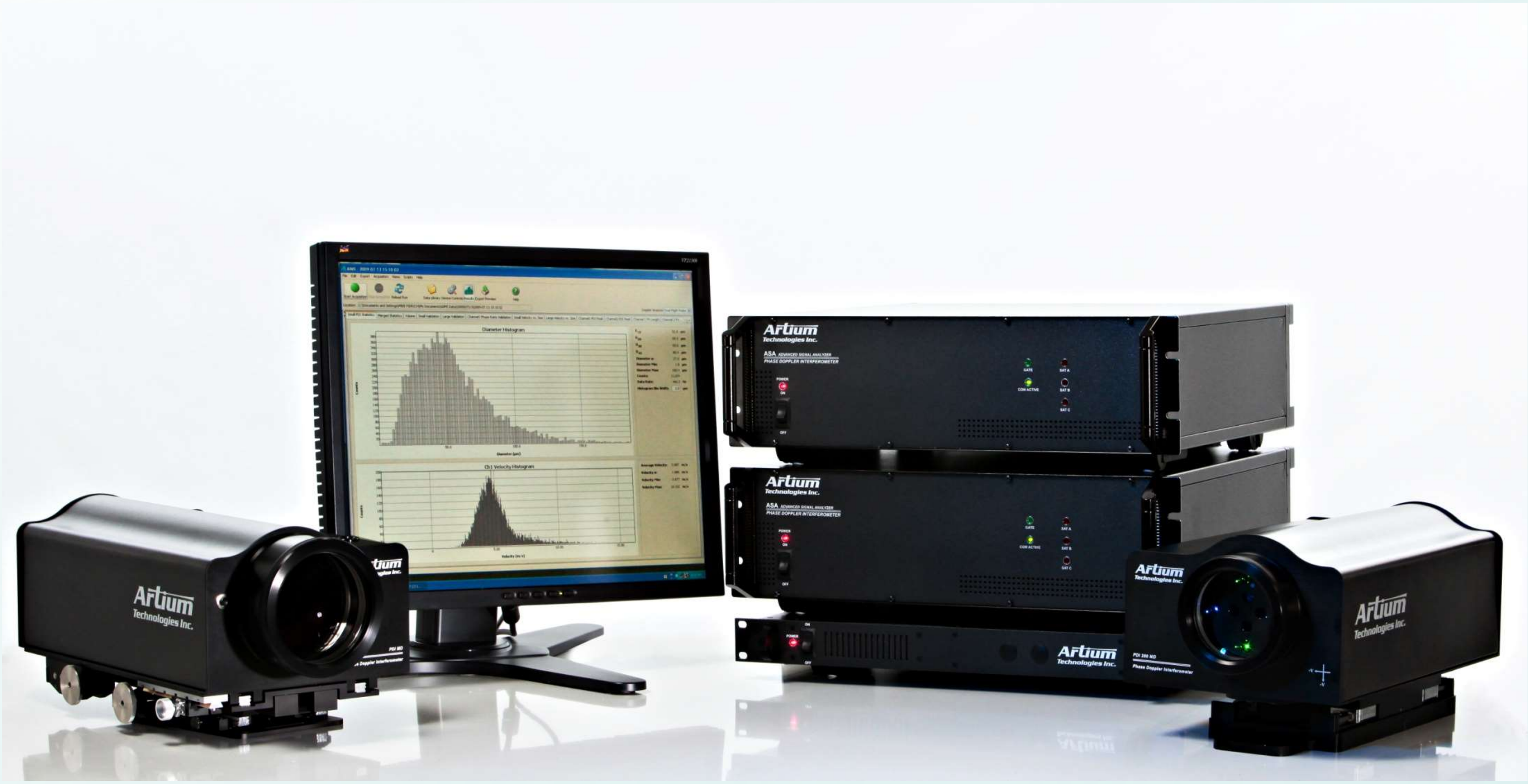
- Mean velocity: $$\overline{u} = \frac{1}{T}\int_0^T u(t)dt \qquad \overline{u} = \frac{1}{T}\sum_{i=1}^{N} u_i \Delta t = \frac{1}{N}\sum_{i=1}^{N} u_i$$
- Fluctuating velocity: $$rms_u = \sqrt{\overline{u'^2}} = \left[\frac{1}{T}\int_0^T \left(u(t) - \overline{u}\right)^2 dt\right]^{1/2} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(u_i - \overline{u})^2}$$
- Cross-Correlations: $$\overline{u'v'} = \frac{1}{T}\int_0^T u'v'dt = \frac{1}{N}\sum_{i=1}^{N}\left(u_i - \overline{u}\right)\left(v_i - \overline{v}\right)$$

Typical LDV 200 Transceiver System

- Built-in DPSS lasers
- Large optics available for larger working distances
- Fully automatic setup of signal processor parameters

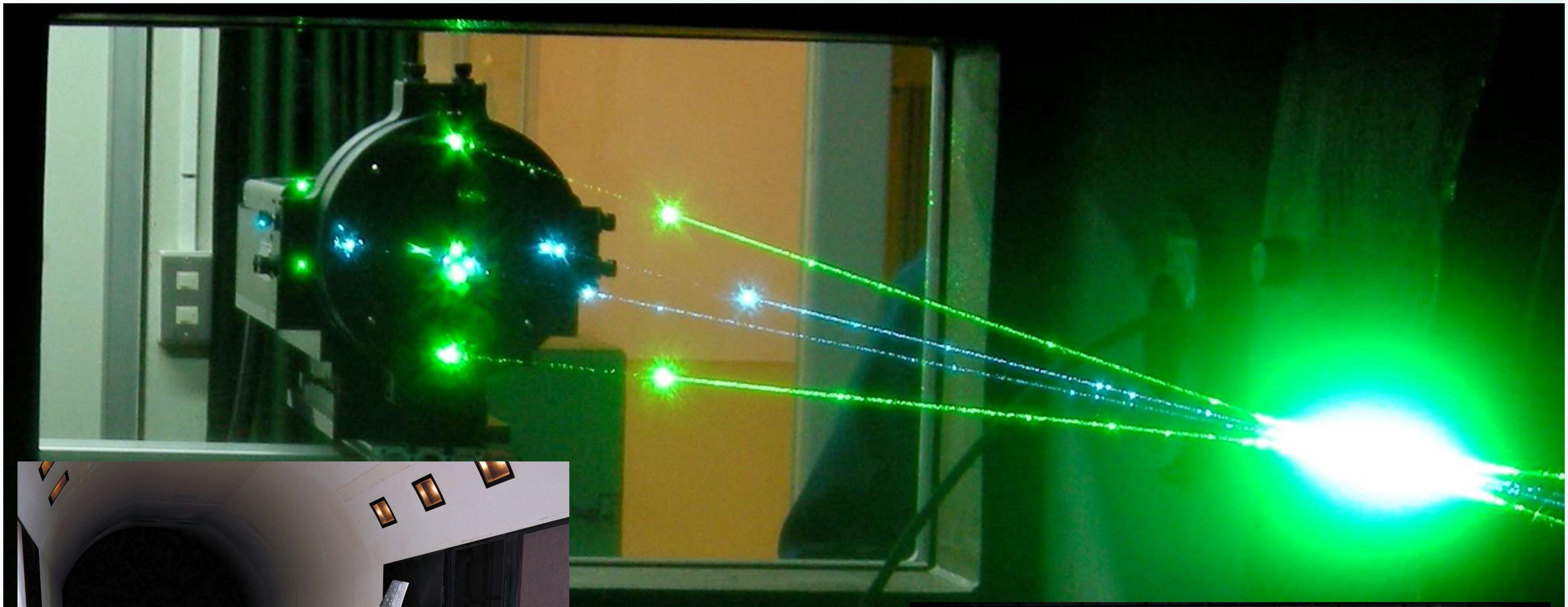


Artium's
2D and 3D PDI and LDV MD Systems



3D LDV with Computer Controlled Traverse

Transmitter system with a large beam spacing beam expander for use as a modular LDV for large scale flow fields



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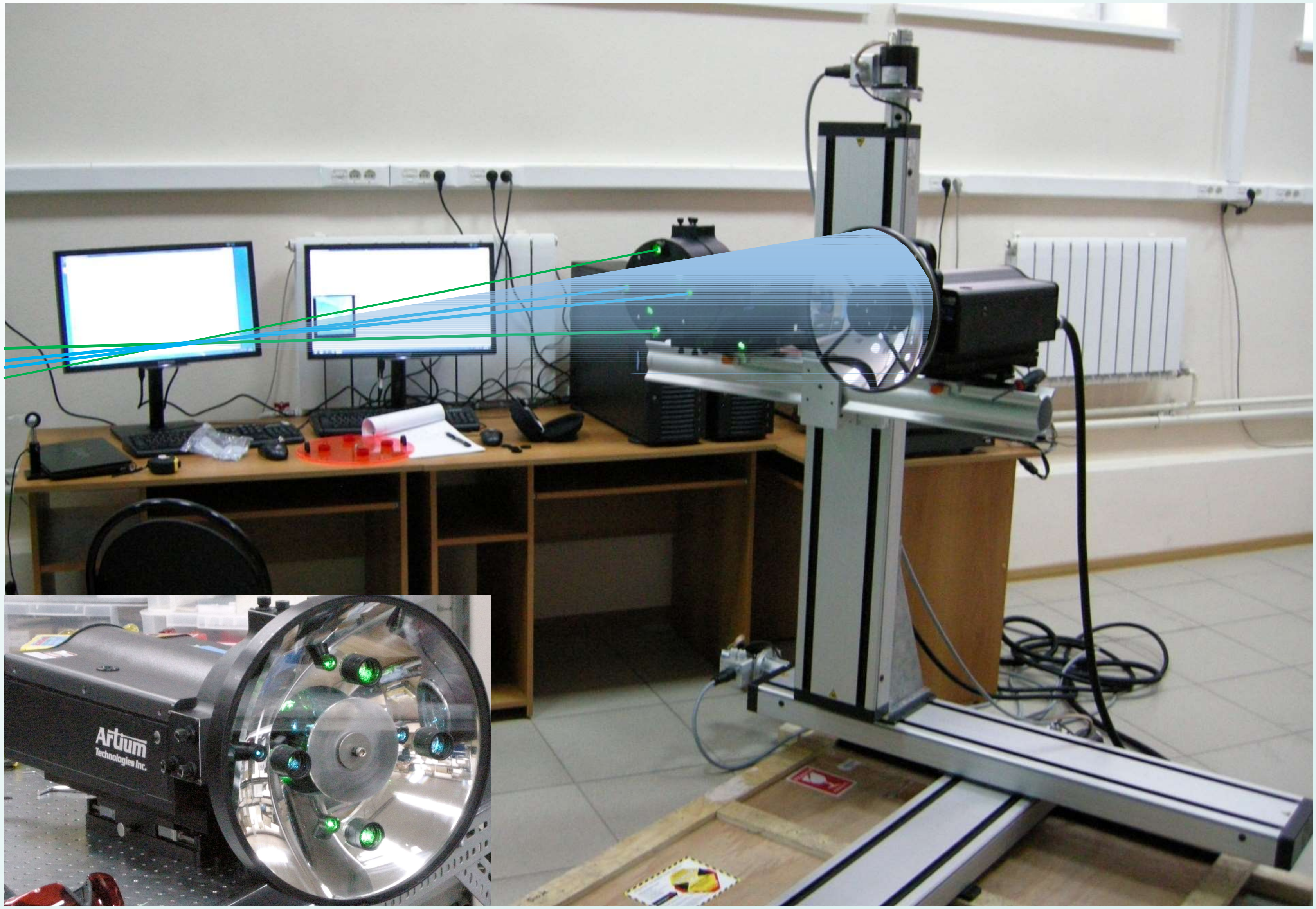
Large Scale LDV Systems for Automotive and Architectural Wind Flow Investigations



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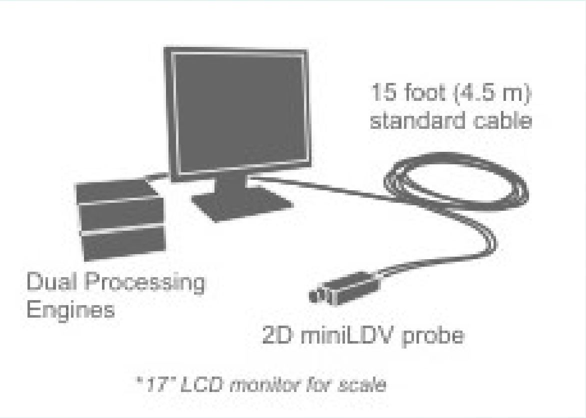
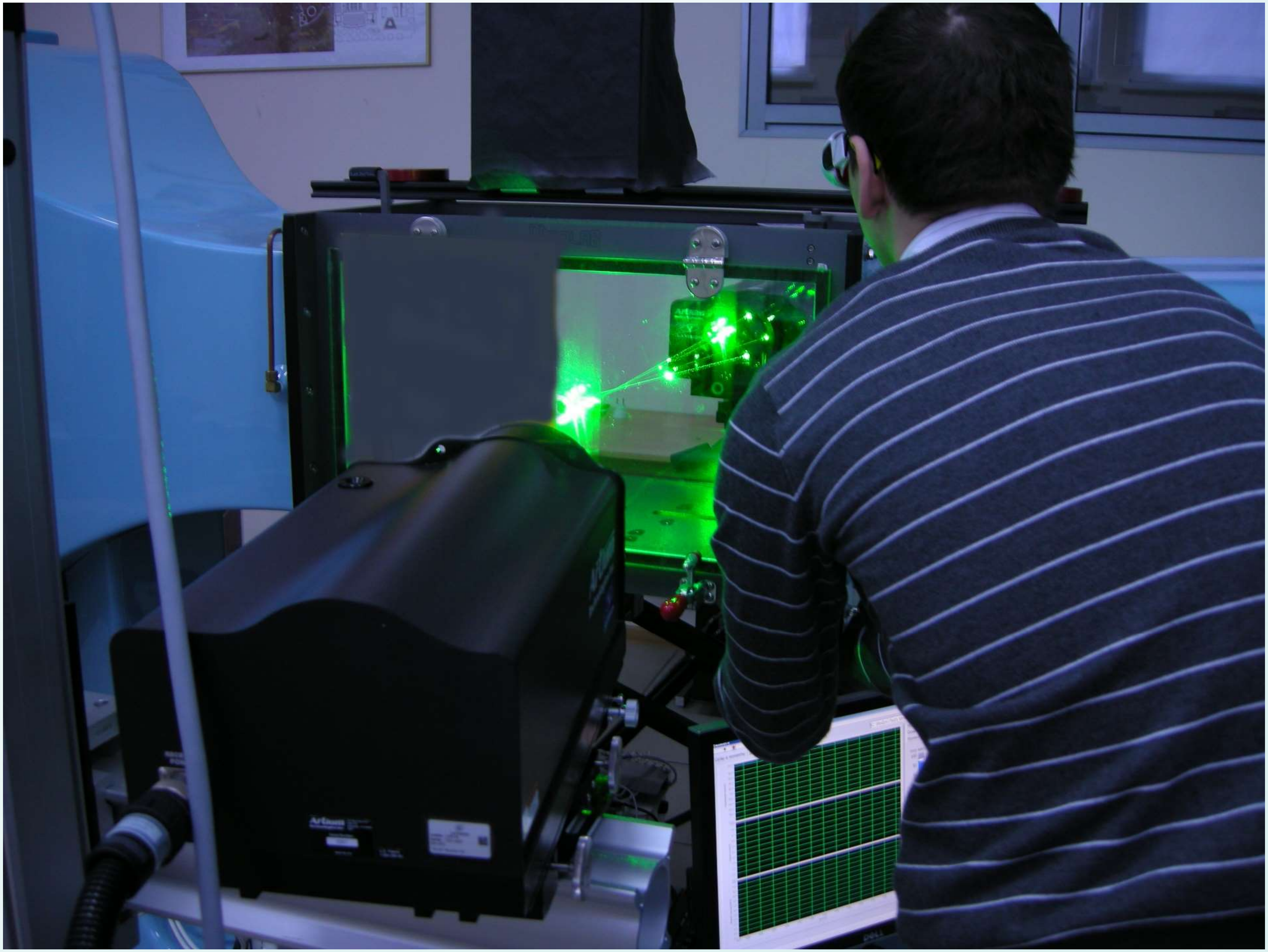
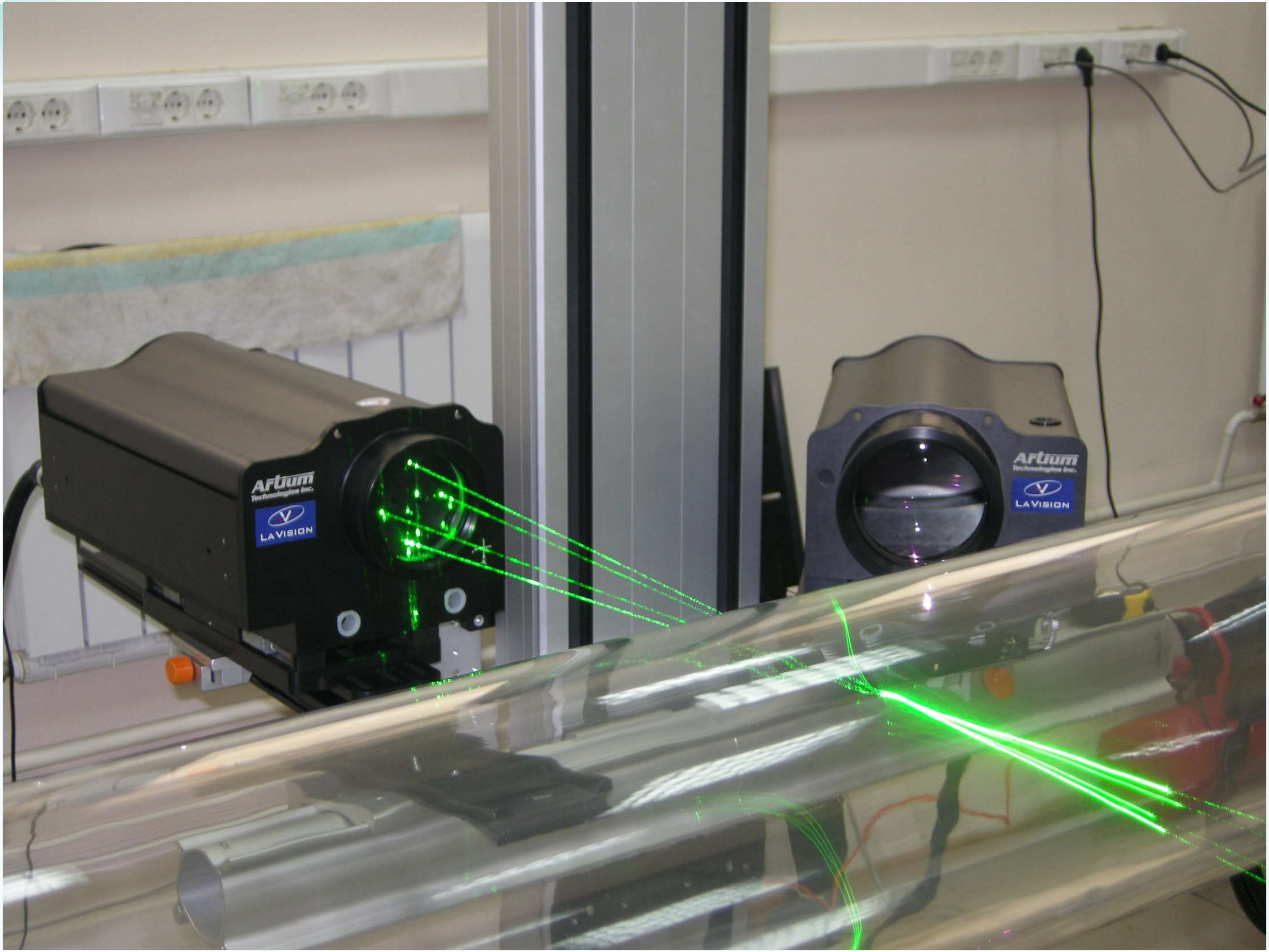
Miniature LDV Systems

Small LDV systems built by MSE and represented by Tesscorn



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Summary

- LDV is the most reliable and accurate means for measuring flow and particle velocity
- Requires coherent light source to produce high quality scattered light interference
- Measures mean and fluctuating velocities
- Large velocity range capability, up to hypersonic speeds
- Requires no calibration after manufacture of the optical system
- Modern solid-state lasers, electronics signal processors, and computers have resulted in near turnkey systems
- Basis for the phase Doppler interferometer (PDI) for particle sizing

Questions and Discussion