Some Advanced Laser Diagnostics for High-Speed Turbulence

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- Recent advances in optical, photo-detection, and data acquisition hardware provide low uncertainty time-dependent 3-component laser-Doppler velocimeter experimental data for high-speed turbulent flows, using only one access window.

- The innovation of using both parallel and diverging fringe patterns (Comprehensive LDV) determines the particle position within 10 microns uncertainty and provides velocity profiles over a focal volume length.

- Small sub-micron seeding particles follow the high-speed turbulent eddies.

- A survey of applications of these advances to high-speed complex flows will be presented, including subsonic, transonic, supersonic, and hypersonic flows. Miniature portable probe heads are being used inside wind tunnel models. Galvanometer scanners can be used to survey large flow areas.

Some Desired Features of a Turbulent Flow Measurement Method

- Is non-intrusive –no physical probes in the flow
- Does not affect the flow behavior or interfere with the flow
- Measures <u>3-velocity components</u> at multiple locations without traversing
- Requires only one small wall area access location
- Produces valid high data rate or time-dependent data up to the highest frequency motions
- Has high spatial resolution
- Can obtain data near walls to determine skin friction
- Can obtain data for high temperature flows

The Comprehensive laser-Doppler velocimeter has been proven to be able to provide such data.

Recent Advances in Optical, Photo-detection, and Data Acquisition Hardware

Lasers – small diode lasers with adequate coherency – 1.5W; need 2 beams from same laser for one fringe pattern.

Bragg cells – splits incident laser beam into multiple beams, each with a known frequency shift $\mathbf{f_s}$ from the incident beam; Interfering fringe pattern moves at shift frequency $\mathbf{f_s}$, e.g., between 200MHz to 500MHz.; moves signal to higher frequencies with less 1/f noise. Miniature units available.

Polarization preserving fiber optics – provides flexible optical design features; can transmit incident laser power over 40m or more at a power loss; AUR fiber treatment method reduces losses.

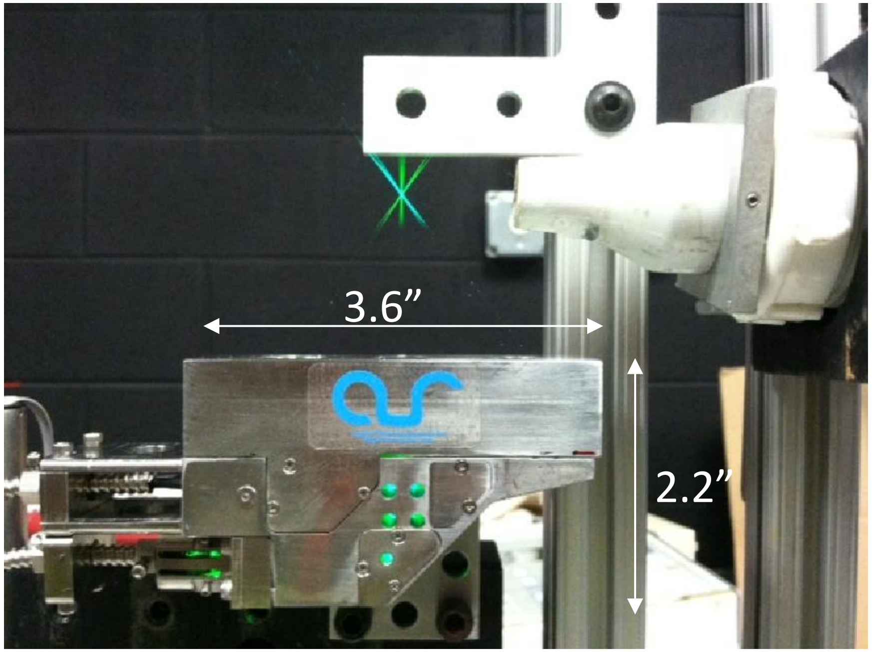
Recent Advances in Optical, Photo-detection, and Data Acquisition Hardware (cont.)

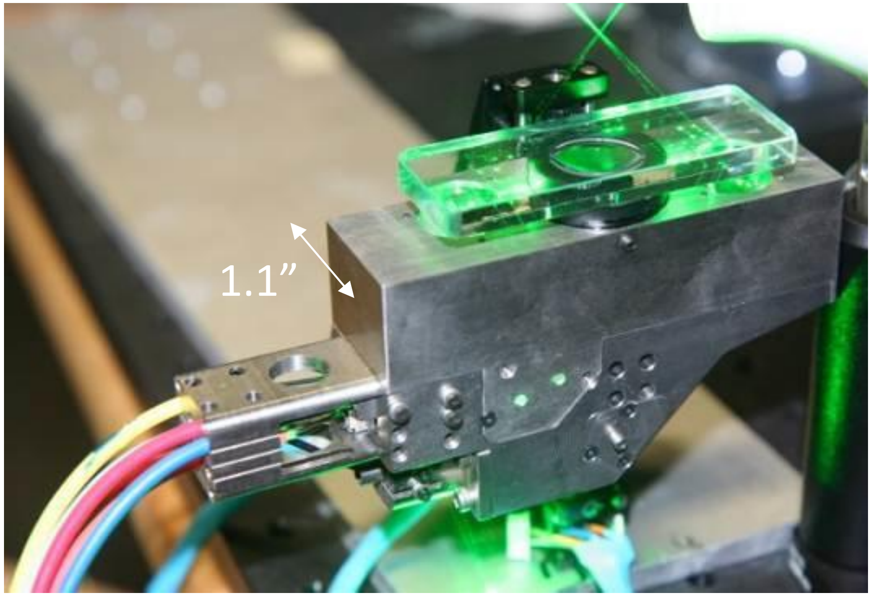
Photomultiplier tubes (PMT):

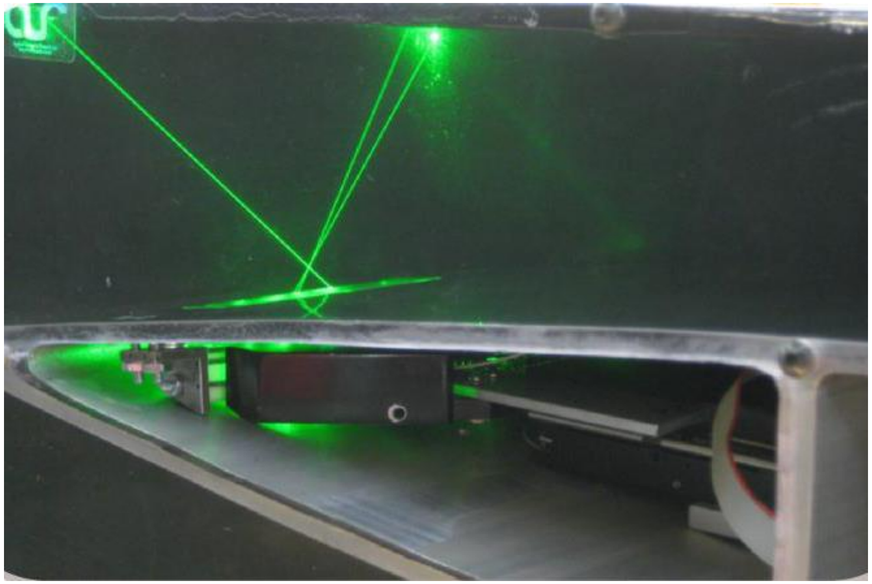
- Improved sensitivity, time response, and signal-to-noise ratio (SNR) provide an opportunity for LDV data from small sub-micron particles, e.g., 30nm.
- **Two matched PMTs:** Multiple off-axis backscatter receiving lens permit collection of more light.
- The PMTs have different noise. This permits one to cross-correlate, multiply, add and subtract, and perform a cross-spectral analysis of the 2 signals and further improve the signal-to-noise ratio (SNR)
- Phase Doppler velocimetry possible to determine particle size for larger particles.

Data Acquisition and Storage: 2GHz analog to digital converters; Multiple TB real-time data storage.

Sub-miniature LDV

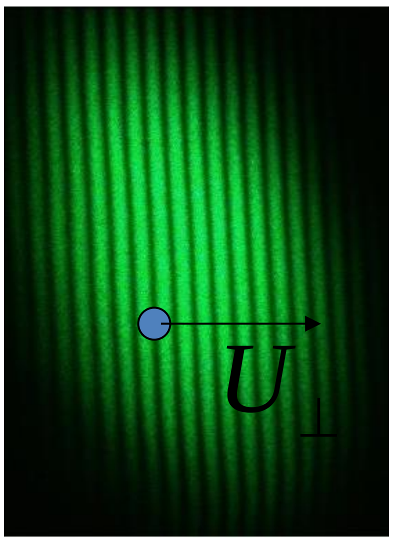




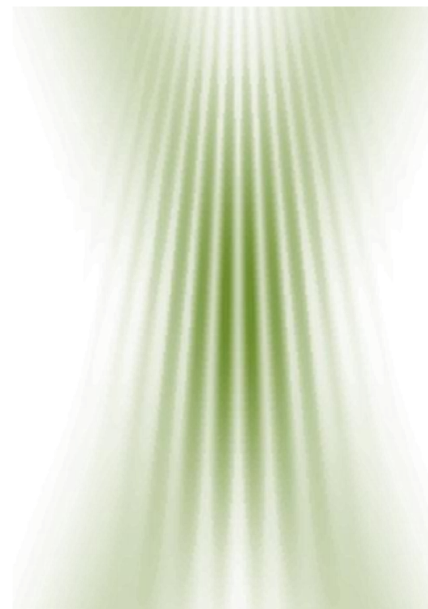


Superimposed Parallel and Converging Fringe Patterns

(Comprehensive LDV) *determines the particle position within 10 microns uncertainty* and provides velocity profiles over a focal volume length.

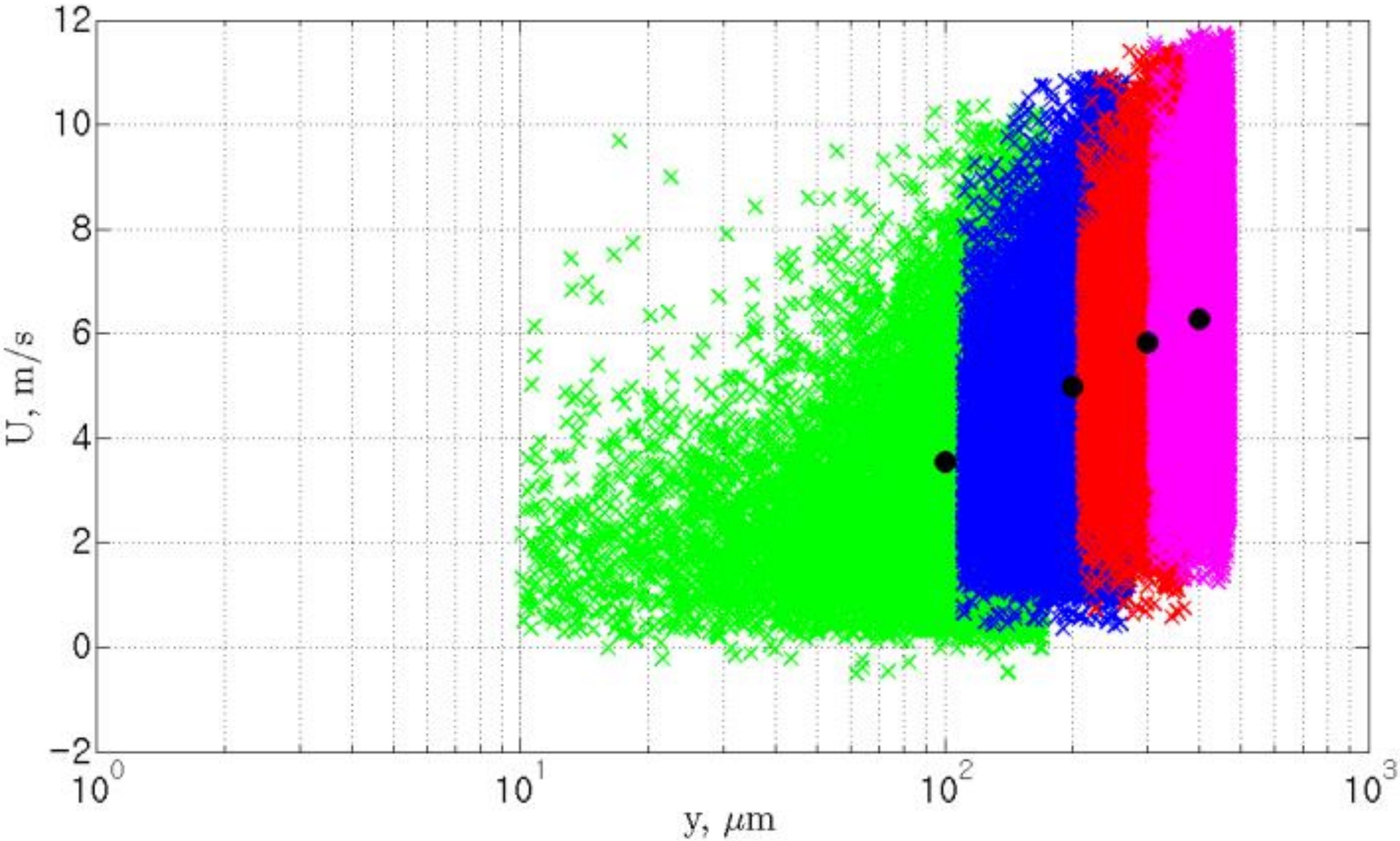


One parallel fringe pattern volume for LDV measures the velocity component perpendicular to the fringes.



Converging fringe volume formed for CompLDV. When superimposed on the LDV volume, both velocity and particle position along fringes are determined.

Low-speed Shear-layer Flow



Each color shows the data from one stationary measurement volume; • mean velocity. Note data at y ≥ 10μm above the wall.

What do particle trajectory measurements provide users?

- **Instantaneous direct measurements (2nd order trajectory measurements expanded around the arrival time):**
  - **3 components of velocity**
  - **3 components of particle position**
  - **3 components of acceleration**
- **Instantaneous calculated quantities:**
  - **Reynolds stress tensor**
  - **Triple product tensor**
  - **Velocity gradient tensor**
  - **Vorticity tensor**
  - **Rate-of-strain tensor**

What do particle trajectory measurements provide users (cont)?

- **Velocity-acceleration fluctuation tensor**
- **Anisotropic Dissipation rate tensor**
- **Skin friction velocity**
- **Total derivatives (1st and 2nd) of Reynolds stresses (noise applications)**
- **Additionally, the velocity-pressure gradient fluctuation tensor is determined using time-averaged quantities**

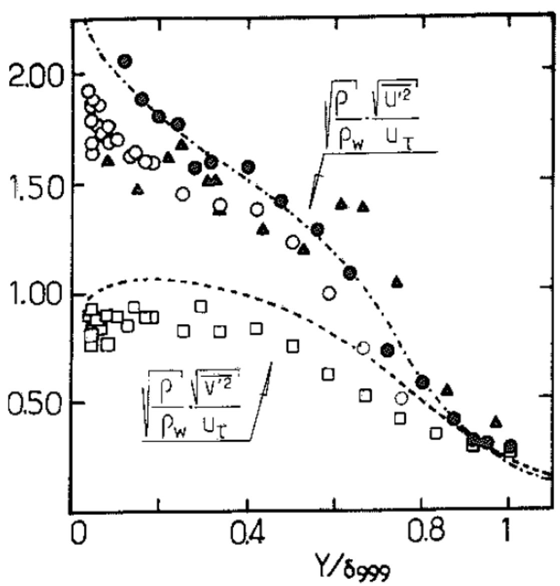
Particles for High Speed Flow

- All particles lag the flow unsteadiness to some degree.
- Commonly used 0.5 to 1 micron and larger particles have a large time lag and low frequency response.
- Need to use as small as possible and low-mass particles to reduce lag effects – some porous particles available.
- “Green” bio-degradable known-size particles are available.
- Need to know particle size in order to correct the data for particle lag.
- Size of clean condensing and evaporating particles – large size hard to control; may cause data bias when they evaporate during tests.
- Solid fluidized 30nm to 200nm high temperature TiO_2 and other particles available.

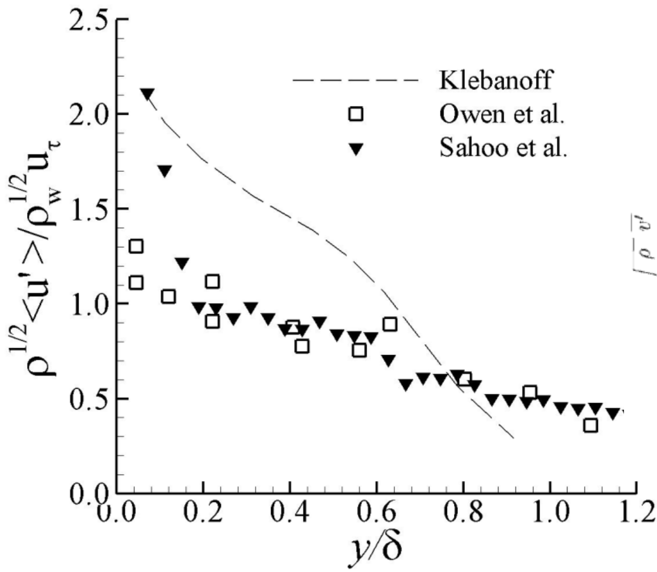
Particle Lag Effects on Tracer Particle Data

In experiments with tracer particles in supersonic turbulent boundary layers <u>the turbulent stress quantities are low</u>.

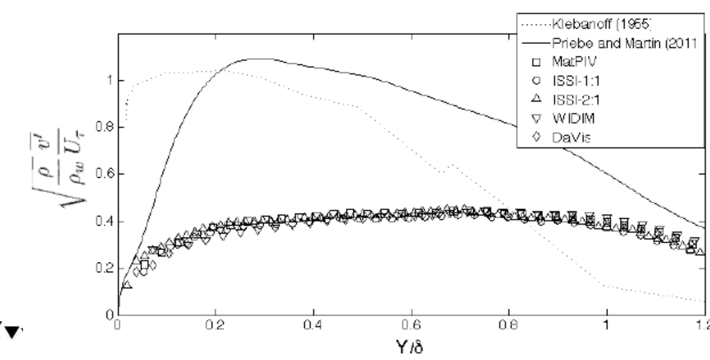
Strong evidence exists that *experimental data* gathered in high speed flows using particle-based techniques exhibit *significant particle lag effects* on magnitudes of turbulence quantities compared with low speed TBLs.



El'ena and Lacharme
(1988, Re_θ = 4,700, M = 2.3, LDV)

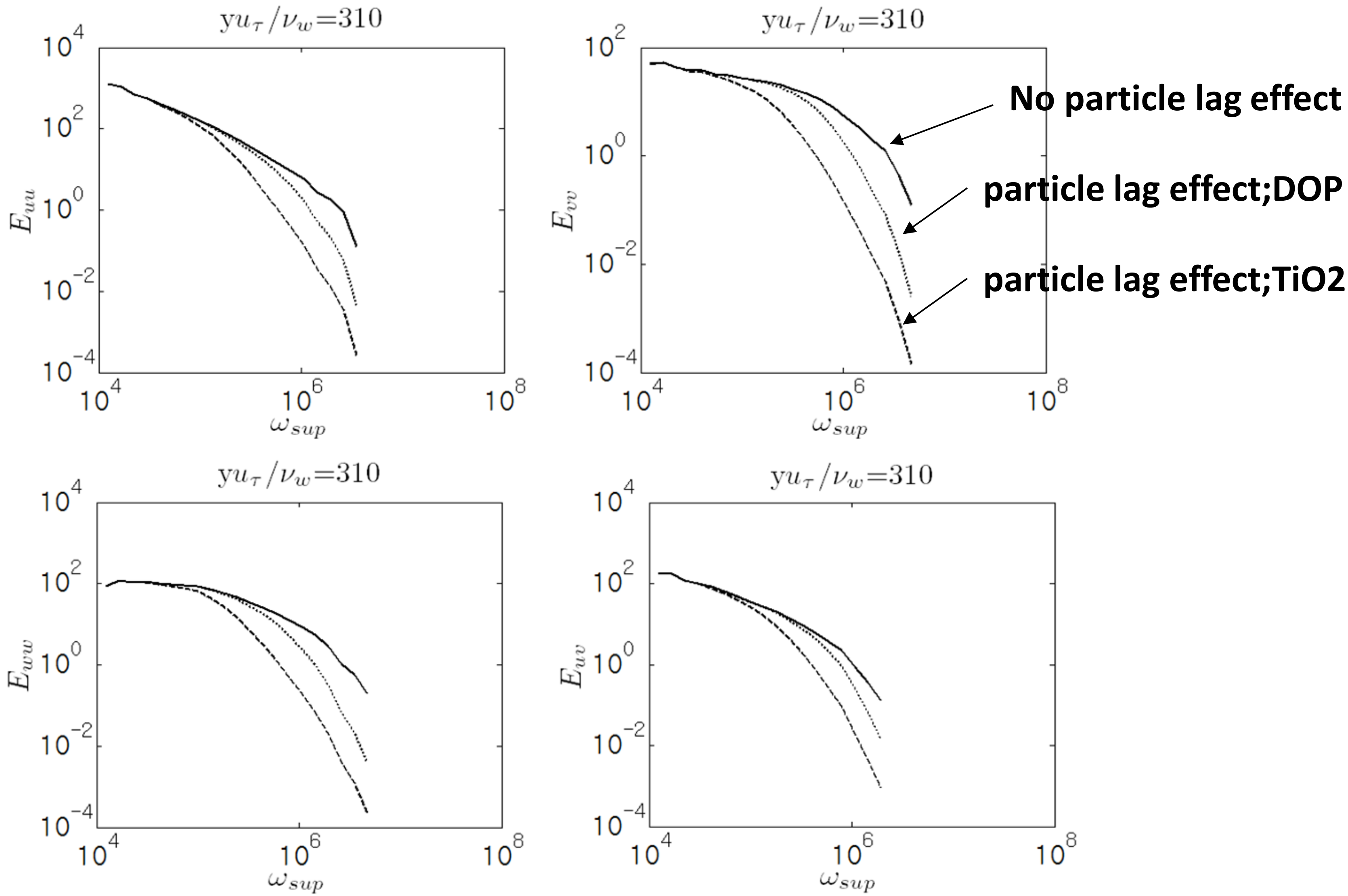


Sahoo et al.
(2009, Re_θ=3,600, M=7.2, PIV)



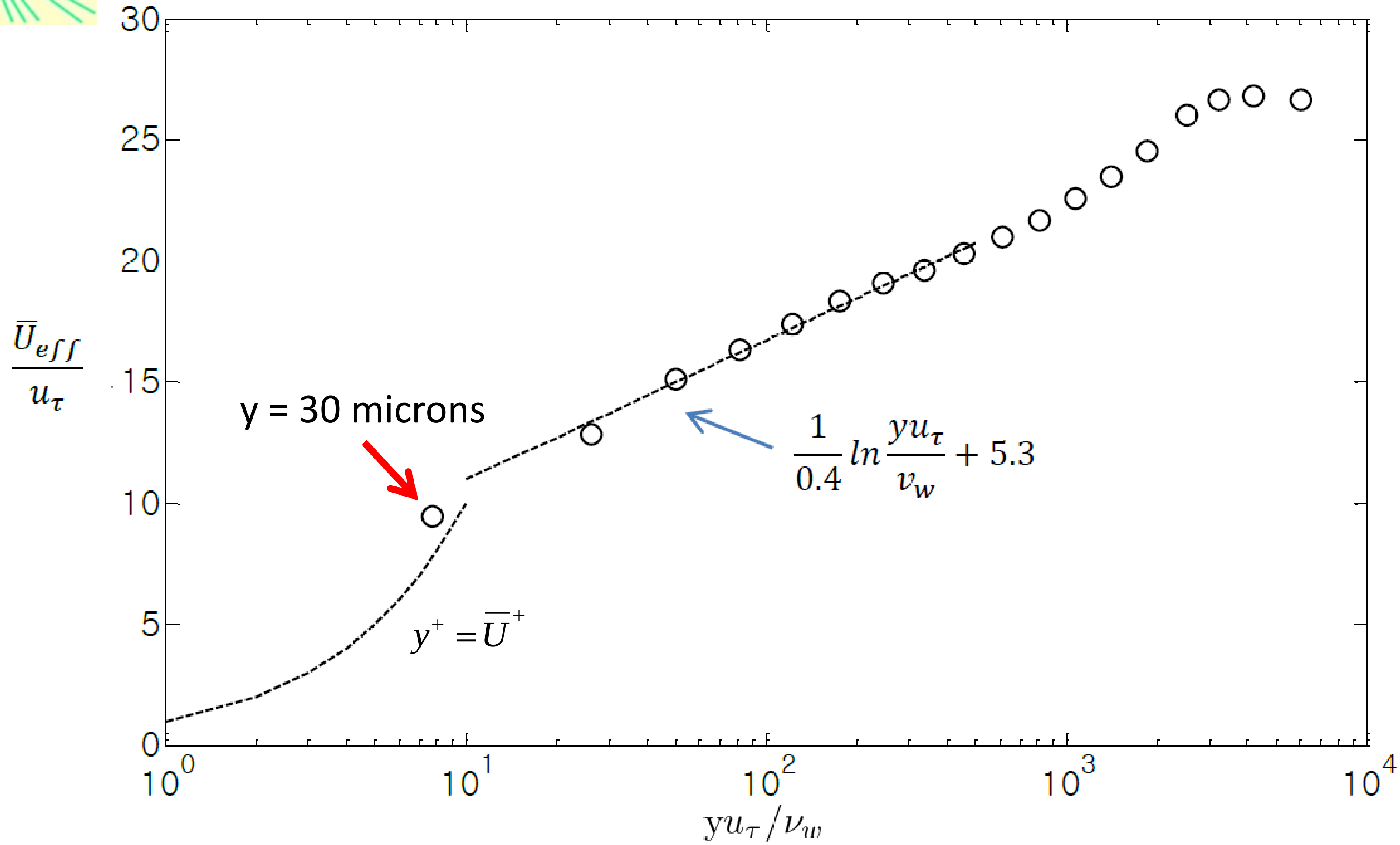
Williams and Smits, 2012,
Re_θ = 5,153, M = 7.38, PIV)

Corrected Spectral Shapes of Reynolds Stresses for Mach 2 Supersonic TBL



DOP (0.6μm, ρ = 1g/cm³) and TiO2 (0.6 μm, ρ = 4.2g/cm³).

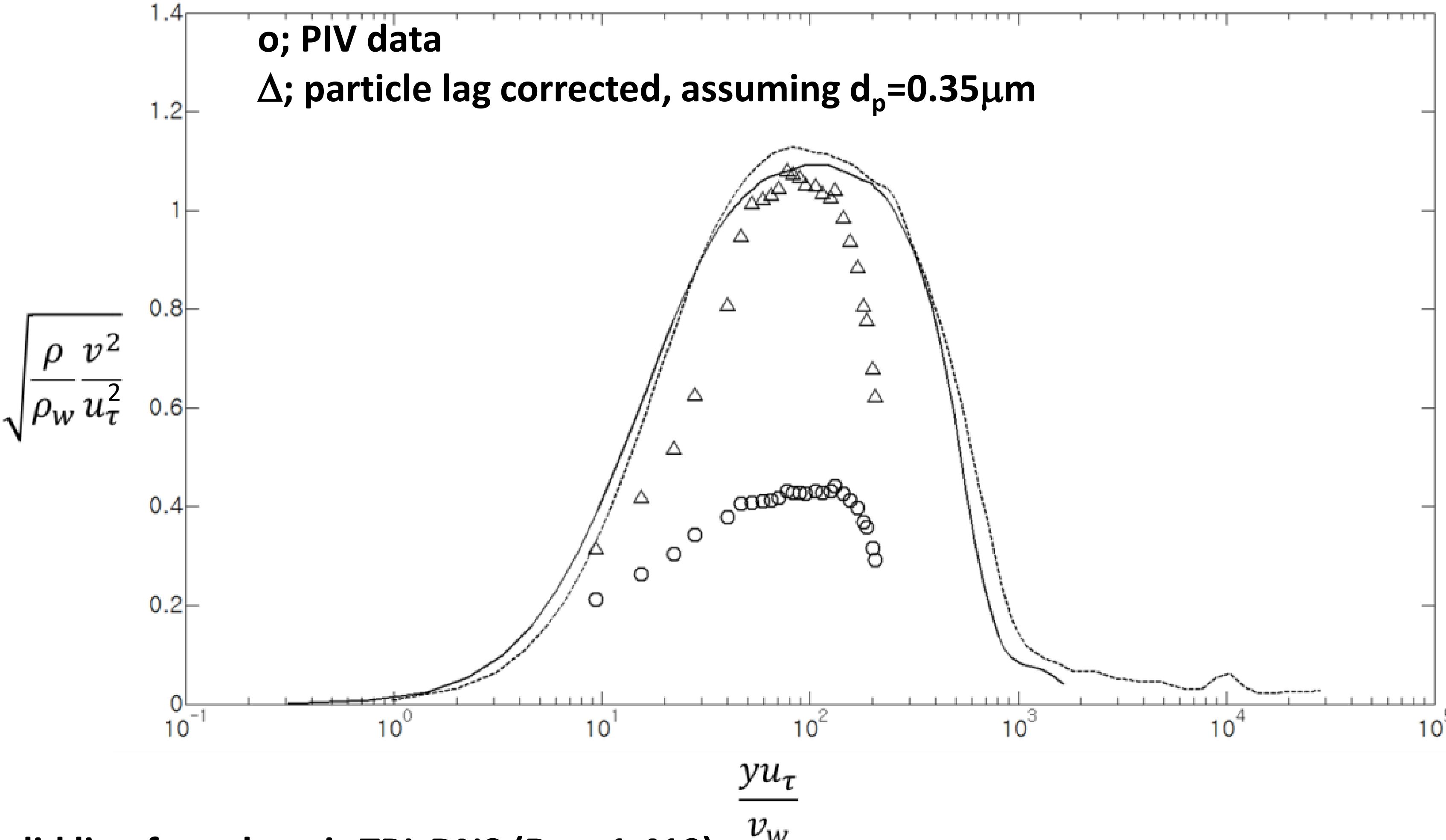
Particle Lag Corrected Results Mach 2 TBL



Transformed stream-wise velocity. u_τ is determined by particle lag corrected LDV results. **Byun, Lowe, Simpson (2012)**

Application of Particle Lag Correction M= 7.38

Williams and Smits (2012) presented their PIV data (TiO2) for a hypersonic TBL (Re_θ = 5,153 and M = 7.38)



solid line for subsonic TBL DNS (Re_θ =1,410)
dashed line for supersonic TBL DNS (Re_θ =3,600)

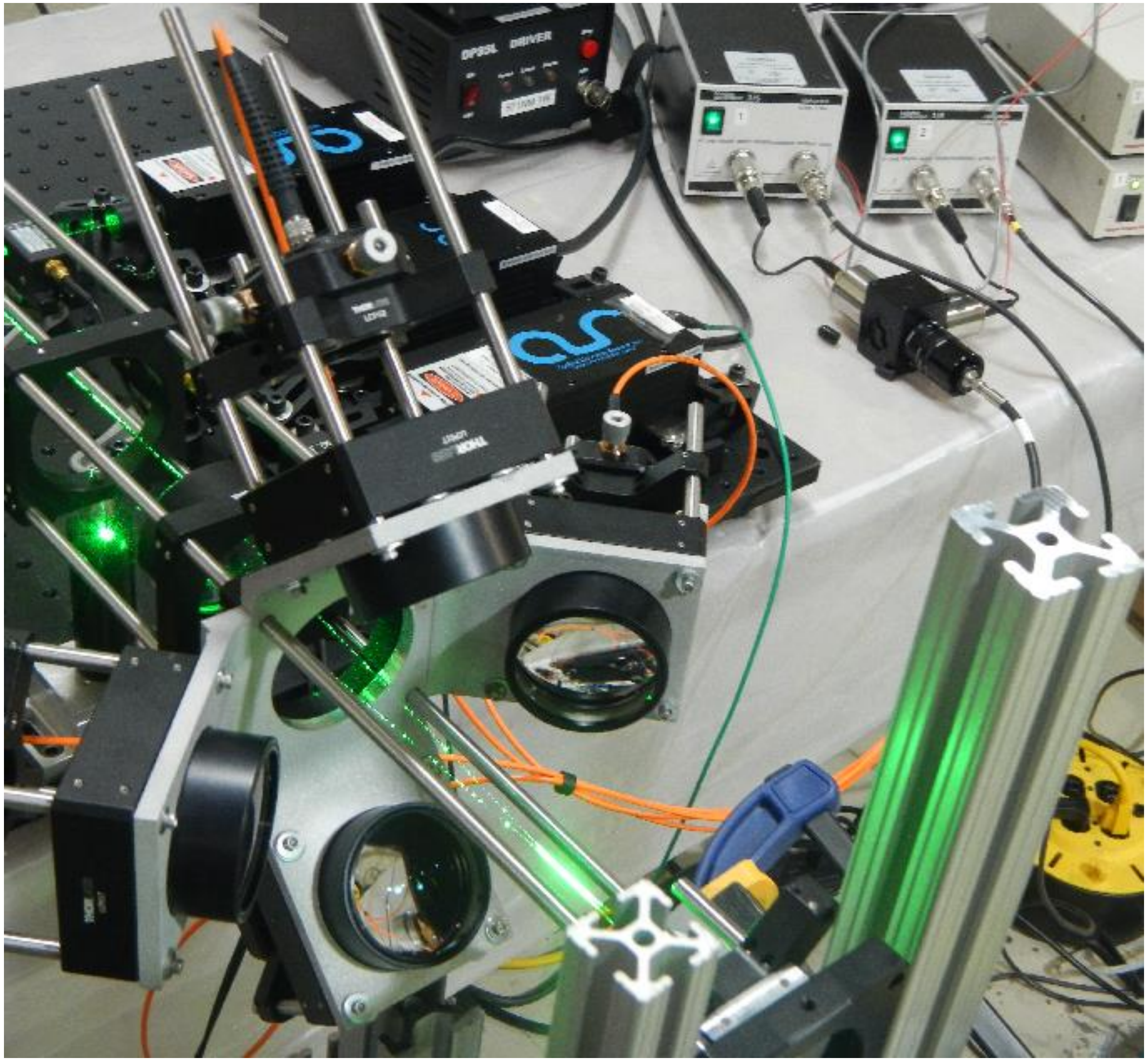
Received Scattered Light Power Affected by Particle Size

$$\frac{RL}{I} = \frac{CD^2(d_p)^6}{b^2L^2F(\phi)}$$

RL is the received scattered light power,
I is the incident laser power,
C is a constant derived from light scattering theory,
D is the diameter of the light receiving lens,
d_p is the diameter of the seeding particle,
b is the diameter of the fringe pattern at its waist,
L is the distance from the measurement volume to the receiving lens,
F(Φ) is a function of the scattering angle.

Multi-Receiving heads LDV

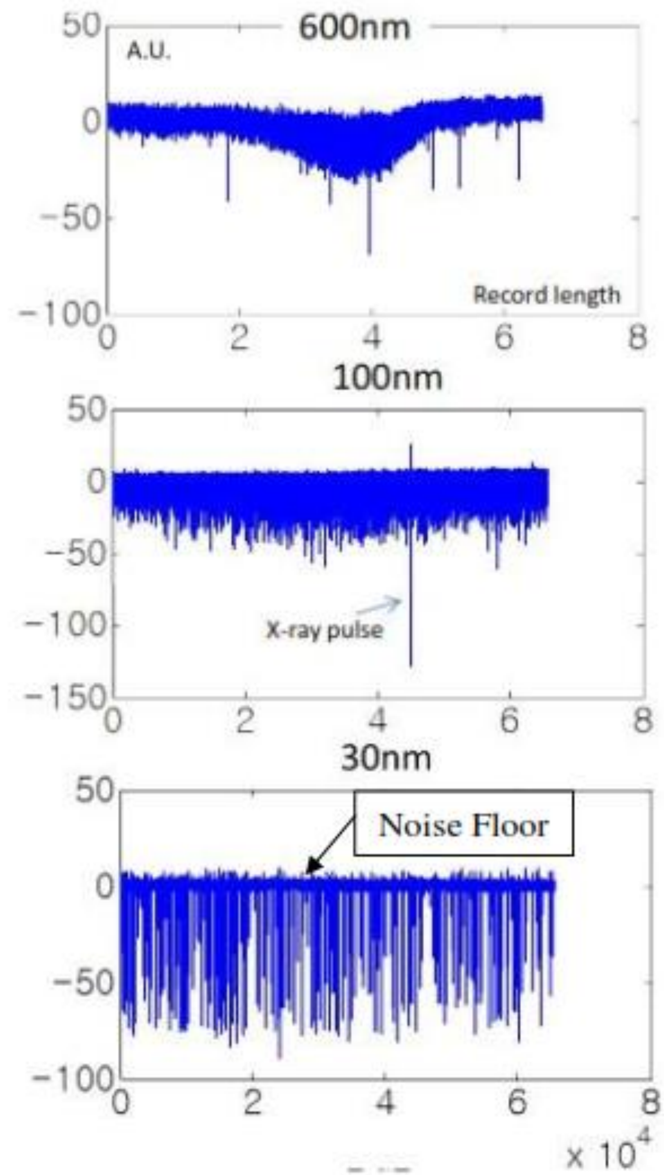
To detect very low scattered light, 4 receiving heads are used.
Also useful for Phase-Doppler measurement of larger particle size

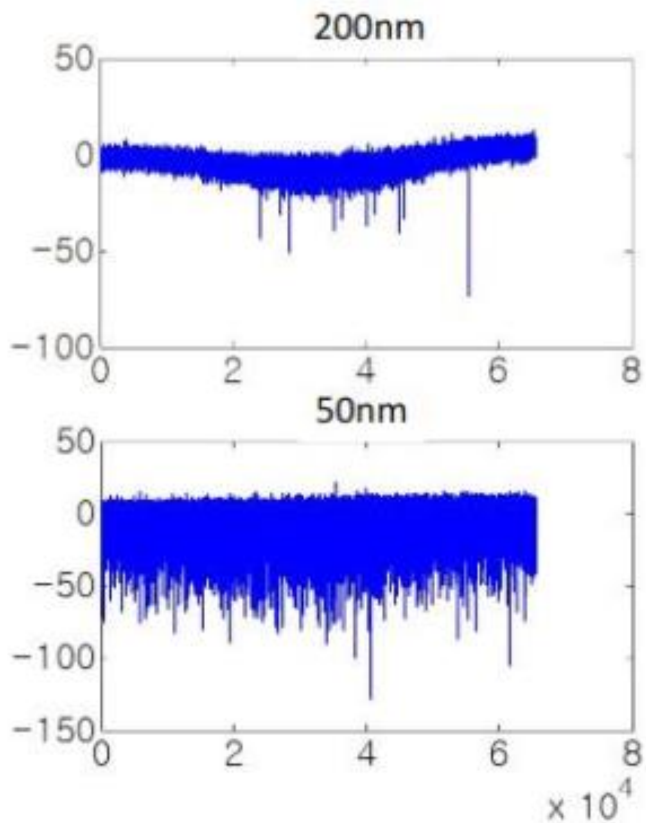


Signal Processing –Various-sized Particles

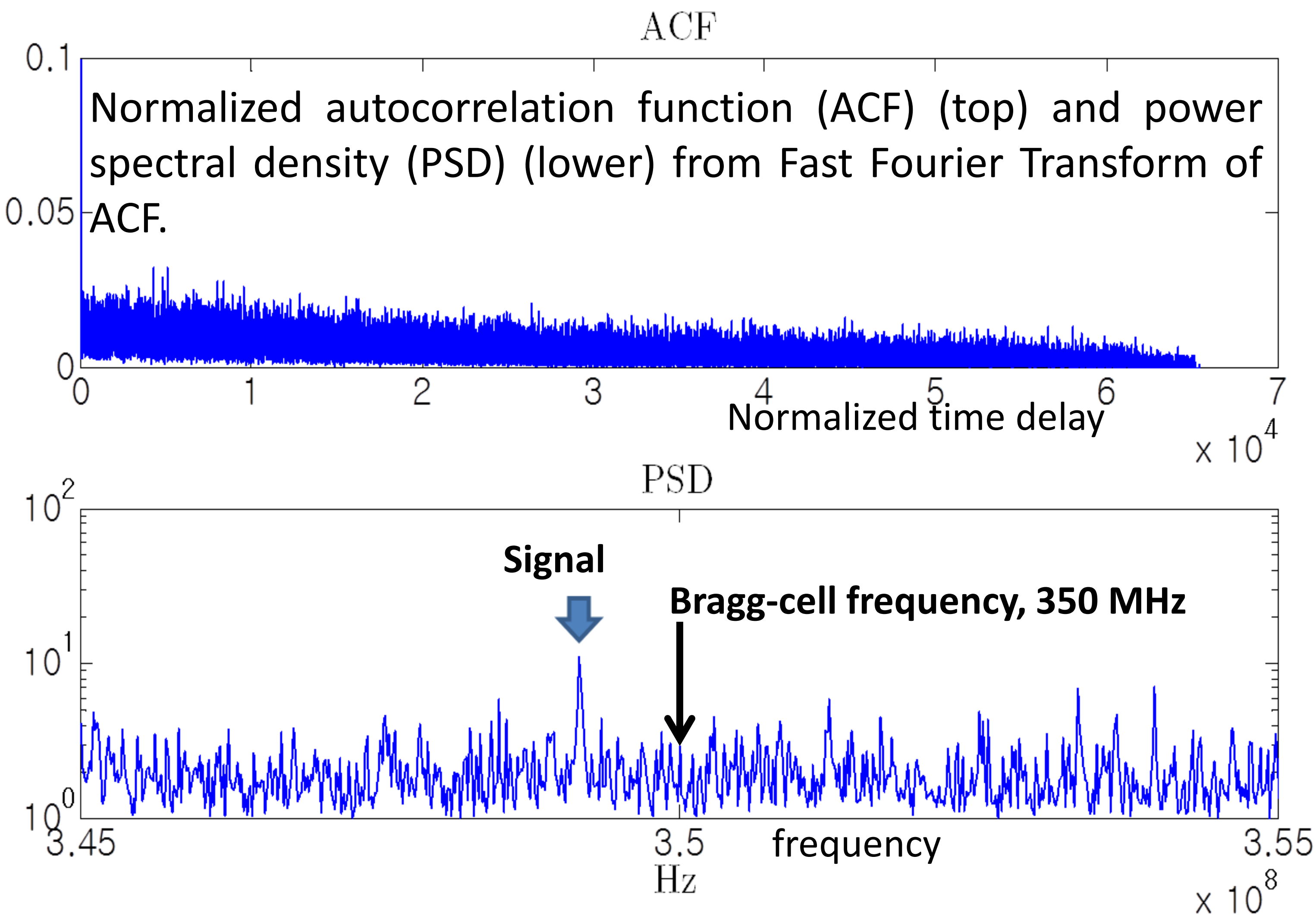
AUR Studio^{TM} Fast-Fourier-Transform (FFT) produces low uncertainty velocities for larger particles.

Shinpaugh, Simpson et al. (1992)





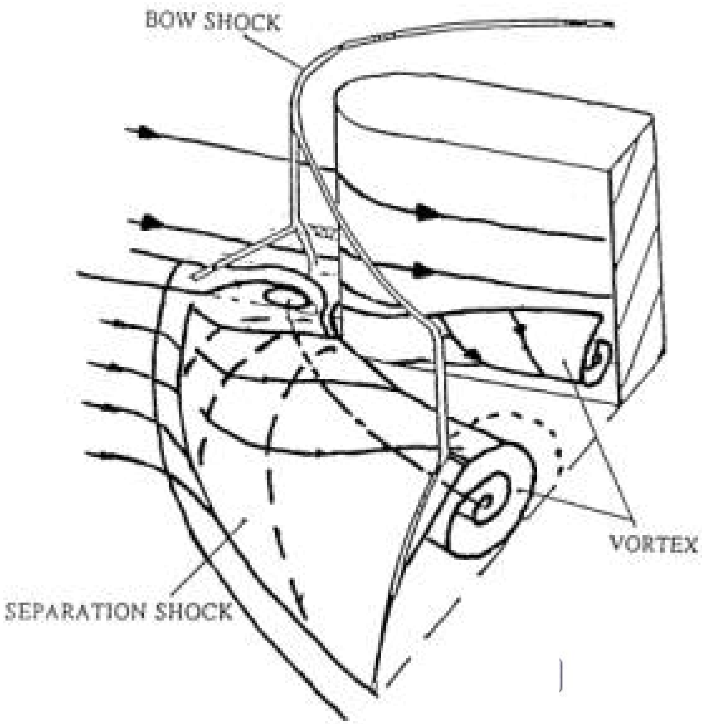
Photon Correlation Method Required to Process 30nm Particle Signals

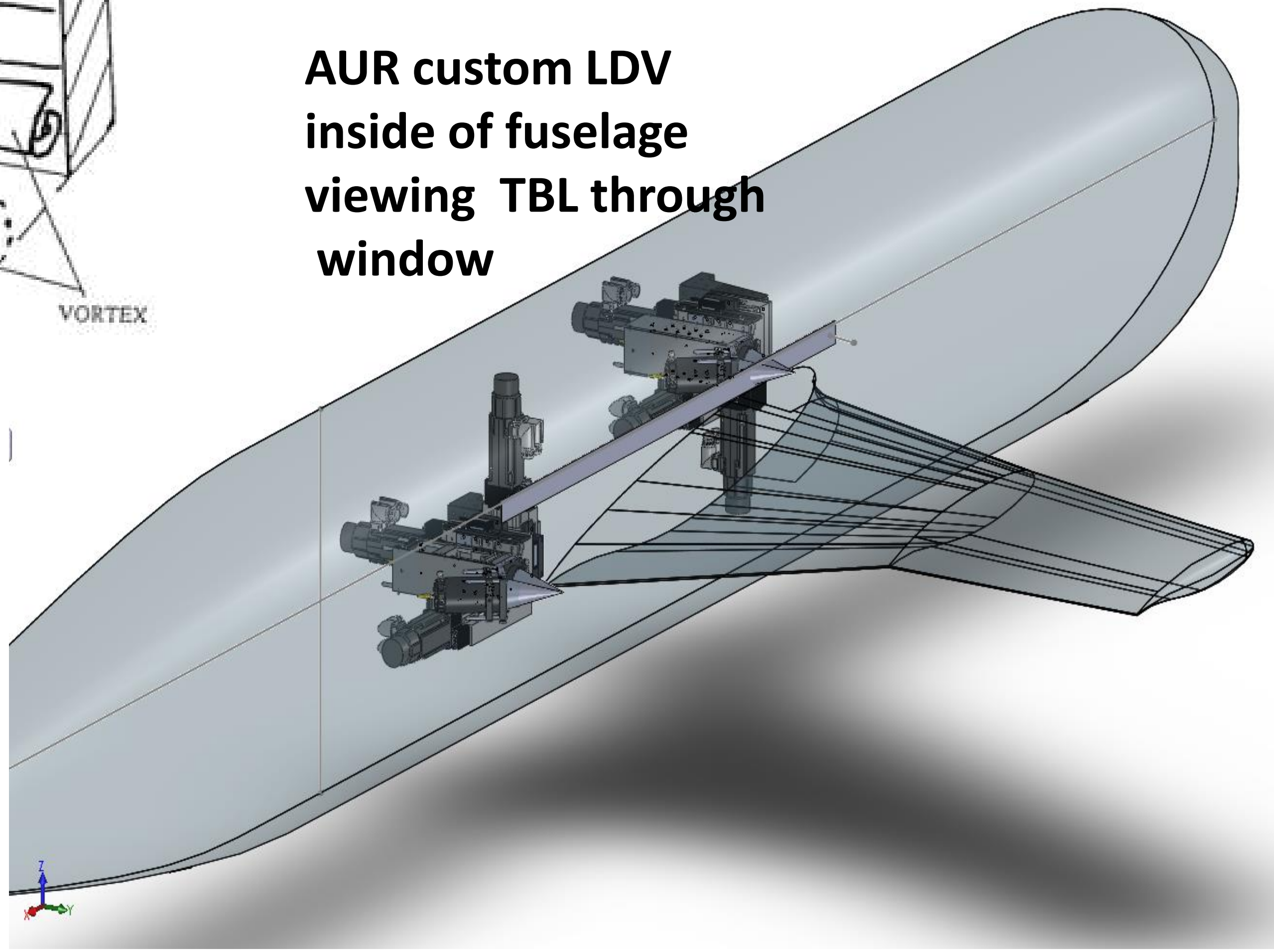


Normalized autocorrelation function (ACF) (top) and power spectral density (PSD) (lower) from Fast Fourier Transform of ACF.

APPLICATIONS

Current NASA Juncture Flow Program for Wing-Fuselage Junction Turbulent Data for Code Verification and Validation





AEDC Hypervelocity Wind Tunnel 9
White Oak near Silver Spring, Md.

> Requires free-stream turbulence frequencies up to 1 MHz for useful data for boundary layer transition.

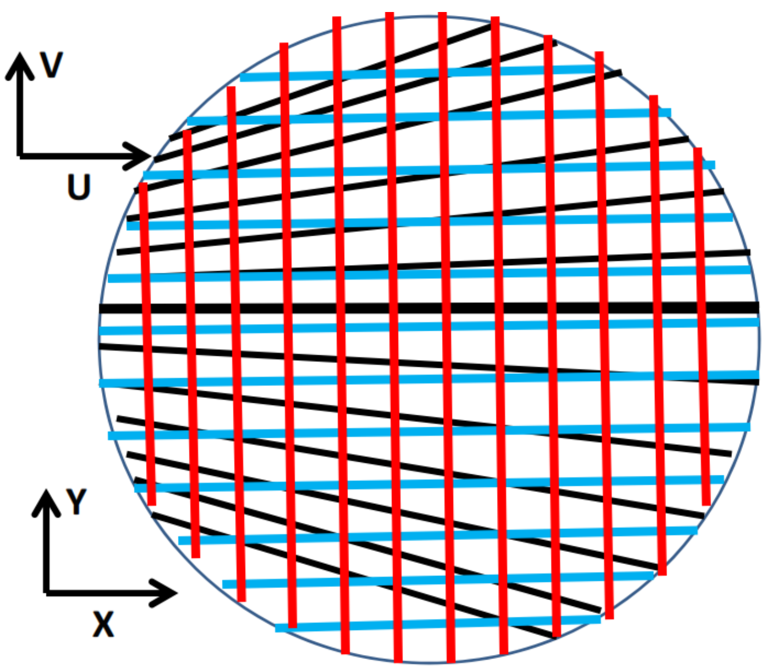
> Multiple point measurements to obtain turbulence length scale and convection velocity magnitudes and directions.

> Several (~20) simultaneous point measurements without traversing the instrument, to characterize turbulence across a boundary layer in a single run.

> The measurement volume for each point should be less than 1 mm in size

AUR CompLDV Hypersonic Flow Design

- Sketch of 3 measurement volume fringe patterns.
- Vertical red fringe pattern 1 measures U;
- Horizontal green pattern 2 measures V;
- Black diverging fringe pattern 3 and patterns 1 and 2 measure X, Y location of particle in 1mm diameter volume.



- Fringe pattern can be rotated to measure boundary layers
- Colors shown just for illustration. All actual laser beams are 532nm green. Bragg cells at 200MHz to 500MHz cause all fringes to sweep through volume.

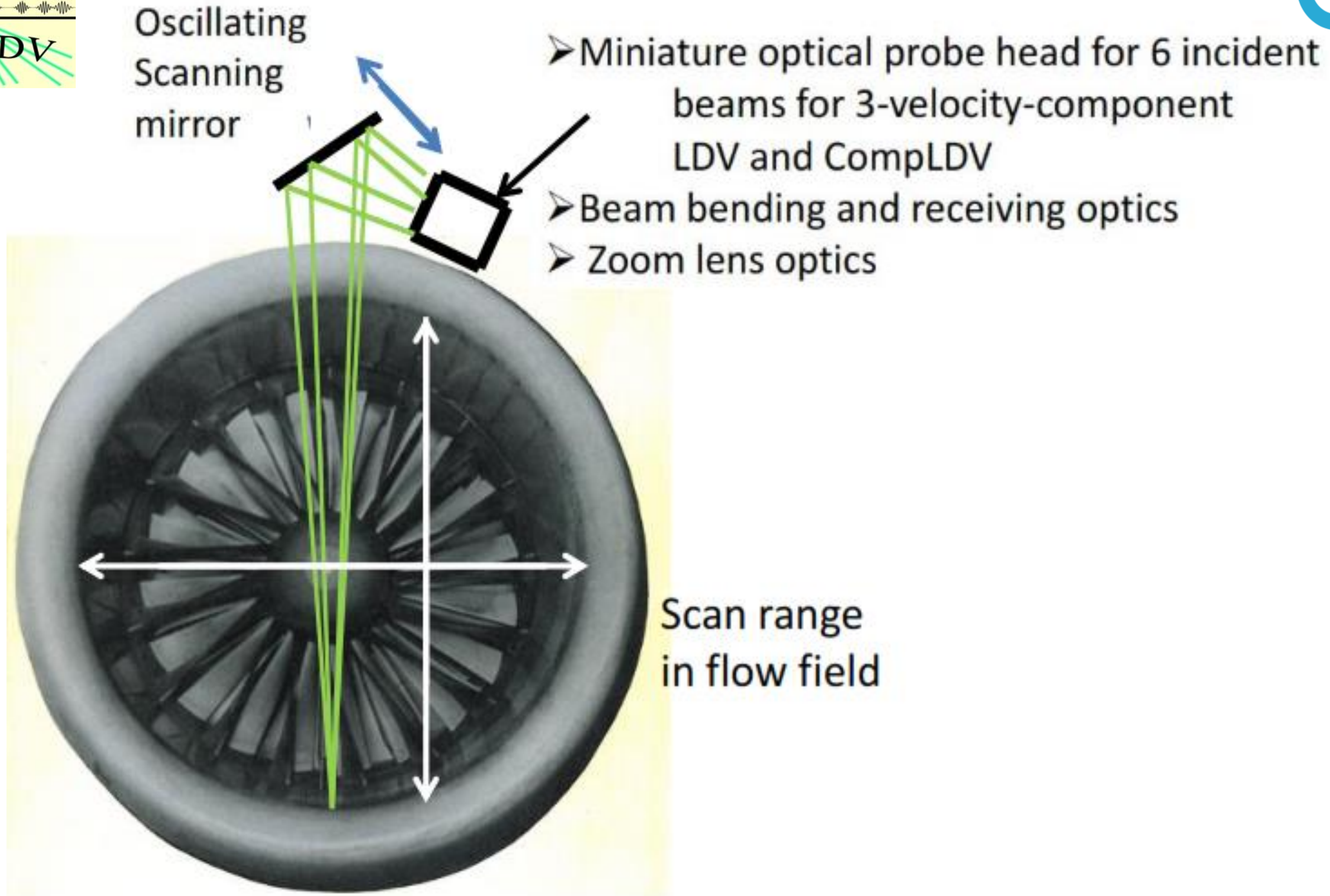
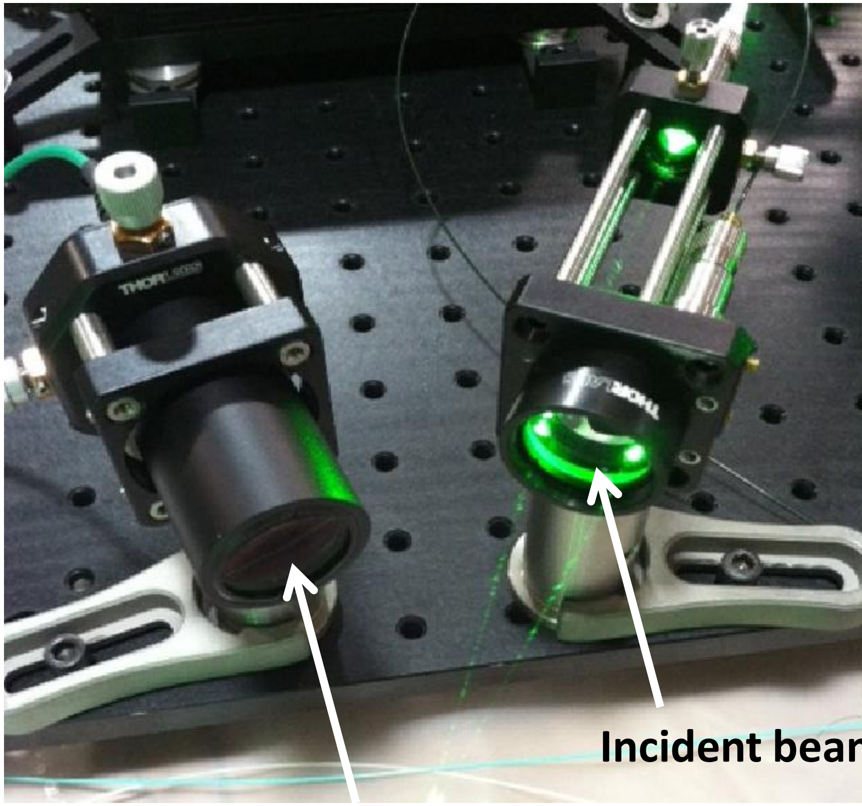


Diagram for the scanning three-velocity component particle-position-resolving LDV/CompLDV for measuring the inflow of a turbomachine.

AGILE CompLDV – Next Generation



Using new technologies:

-More compact design with smaller components

-Much easier to align

-Robust alignment

-Much easier to stabilize the beam polarization axis a with rotatable collimator

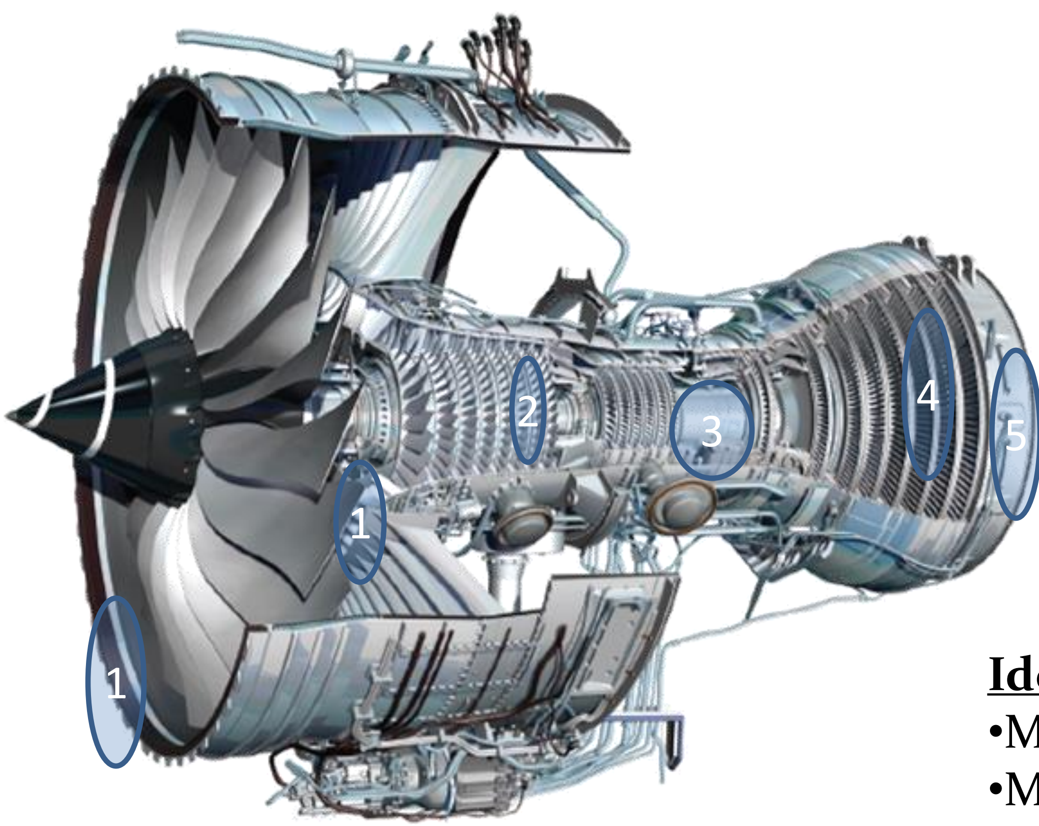
-Much better Gaussian beam profile due to improved collimator

-Approximately 2000/s valid data rate

Advanced laser-Doppler velocimetry for High Reynolds Number, high speed wall-bounded flows

- Three-velocity-component near-wall data are crucial for understanding flow physics
- Effective and useful measurement of this region requires
  - **Fine spatial resolution**
  - **Large velocity dynamic range**
  - **Ability to mitigate flare** from surfaces being measured
- LDV (Yeh and Cummins 1964)
  - **10000:1 dynamic range possible**
  - **Off-axis optical designs and through-the-wall access greatly reduces wall flare**
  - **Standard LDV has up to 30 micrometer resolution, Comprehensive LDV can resolve 2 micrometers.**
  - **High laser powers and sensitive detectors allow the use of small particles**
- Digital Particle image velocimetry (Willert and Gharib 1991 Lisbon meeting)
  - 200:1 dynamic range is crippling in the near wall region of HRN, high speed flows
    - "2 digit voltmeter"—R. Adrian, pioneer of digital PIV
- Molecular filter-based Doppler velocimetry (DGV, PDV; Komine 1990 US Patent 4,919,536)
  - Quickly obtain high quality measurements at many points.
  - Dynamic range limited by the experimental setup due to finite transition width of molecular filters
  - Extremely near wall measurements have not yet been achieved.
- **Conclusions:**
  - **LDV is the only existing technique for effectively measuring high speed flows within 10's of micrometers from boundaries.**
  - **Advanced LDV offers unparalleled combinations of attractive features.**

Turbomachinery applications



1. Inlet flow boundary layer: Inlet noise and proper computations
2. Compressor blade measurements: Flow performance
3. Combustor flow behavior
4. Turbine blade measurements: Flow and heat transfer performance
5. Nozzle boundary layer: Jet noise

Ideal uses for Advanced LDV!

- Miniature packages
- Multipoint measurements without traversing
- Extreme velocity range
- Possibility for in-situ measurements!

Rolls-Royce Trent 1000 engine for the Boeing 787
Source: Rolls-Royce website

Conclusions

Comprehensive Laser-Doppler Velocimetry can provide much desired data for turbulent flows, including high-speed turbulent flow.

This is due to (1) the overlapping parallel and converging fringe patterns, (2) advances in optical, fiber-optics, photo-detection, and data acquisition hardware, and (3) AUR Studio™ Fast-Fourier-Transform (FFT) and photon correlation signal processing, accounting for small sub-micron particle lag effects.

Miniature optical probe heads (AGILE LDV) can be inserted into practical flow equipment for in situ measurements, using small sub-micron particles.