Non-intrusive sensing of air velocity, humidity, and temperature using TDLAS

TDLAS: Tunable Diode Laser Absorption Spectroscopy

Suhyeon Park
Mechanical Engineering, Virginia Tech

Advisor
Dr. Lin Ma
Aerospace and Ocean Engineering
Mechanical Engineering Adjunct
Virginia Tech

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Outline

- **Introduction:**

  Concept of TDLAS measurement

- Velocity measurement

- Temperature measurement and non-uniform distribution analysis

- Water concentration tomographic inversion

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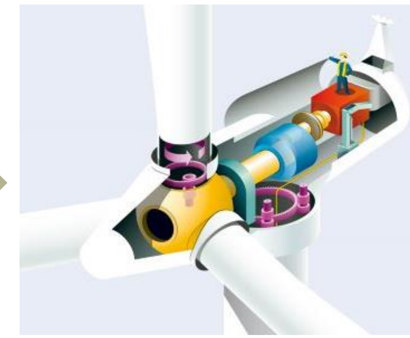
TDLAS for wind energy

Research instrument

TDLAS sensor
Real-time
monitoring

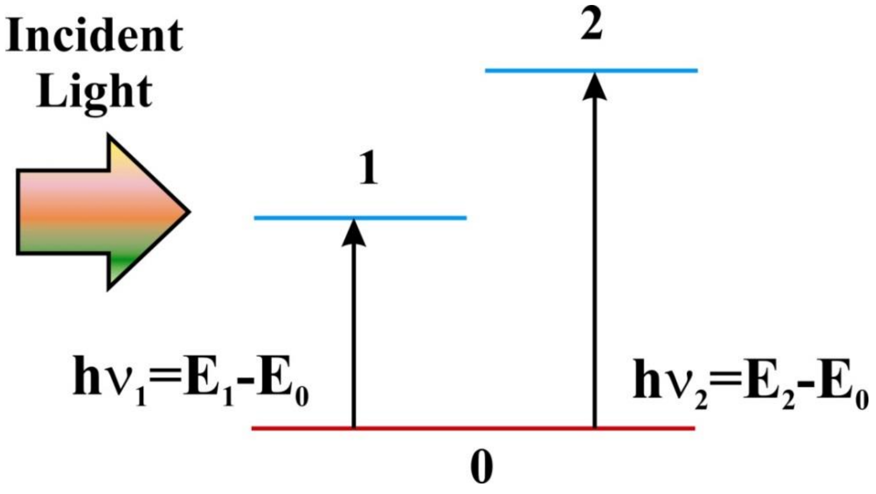
Flow info →

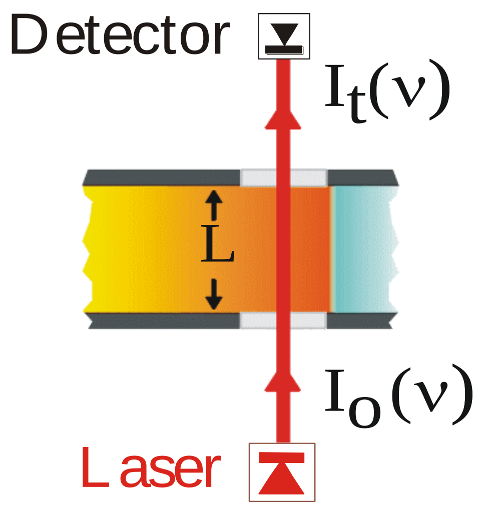


Active control of wind turbines

- Velocity, humidity and temperature - simultaneous measurement
- Non-intrusive in-situ real-time monitoring without particle seeding
- Calibration-free accurate measurement
- Low cost, low maintenance

Fundamental theory of absorption spectroscopy

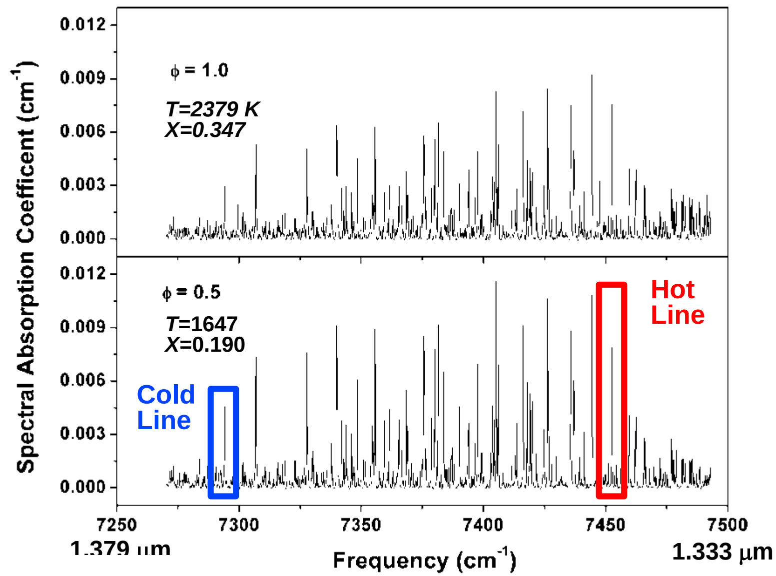


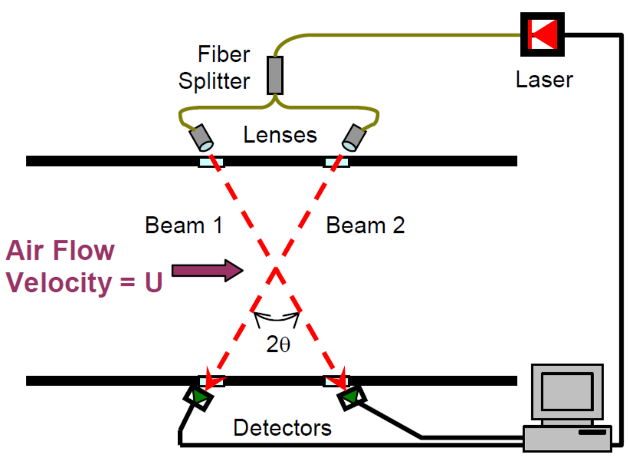


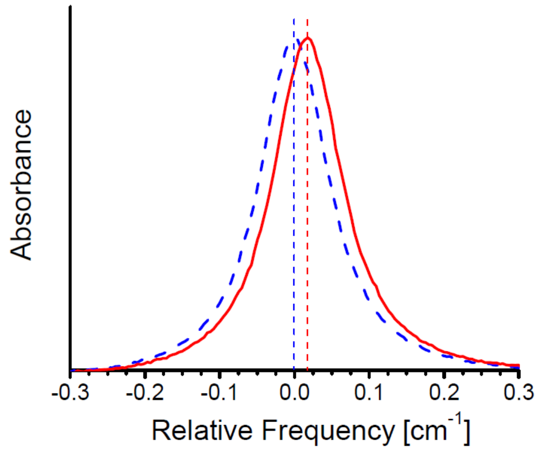
- Beer - Lambert relation: $\tau(\nu) = \frac{I_t(\nu)}{I_o} = \exp[-k_\nu \cdot L]$
- Measure k_ν and *P* to infer *T* and *X* : $k_\nu = f(T, X, P)$

Principle of TDLAS measurement

- T – temperature : inferred from the shape of spectra (the relative absorption strengthen of a “cold” and a “hot” line)
- X – H_2O concentration : inferred from the magnitude of the spectra after T)
- V – flow velocity : inferred from Doppler shift between two beams with an angle







$$\Delta \nu = \frac{(2\sin\theta)U}{c}\nu_0$$

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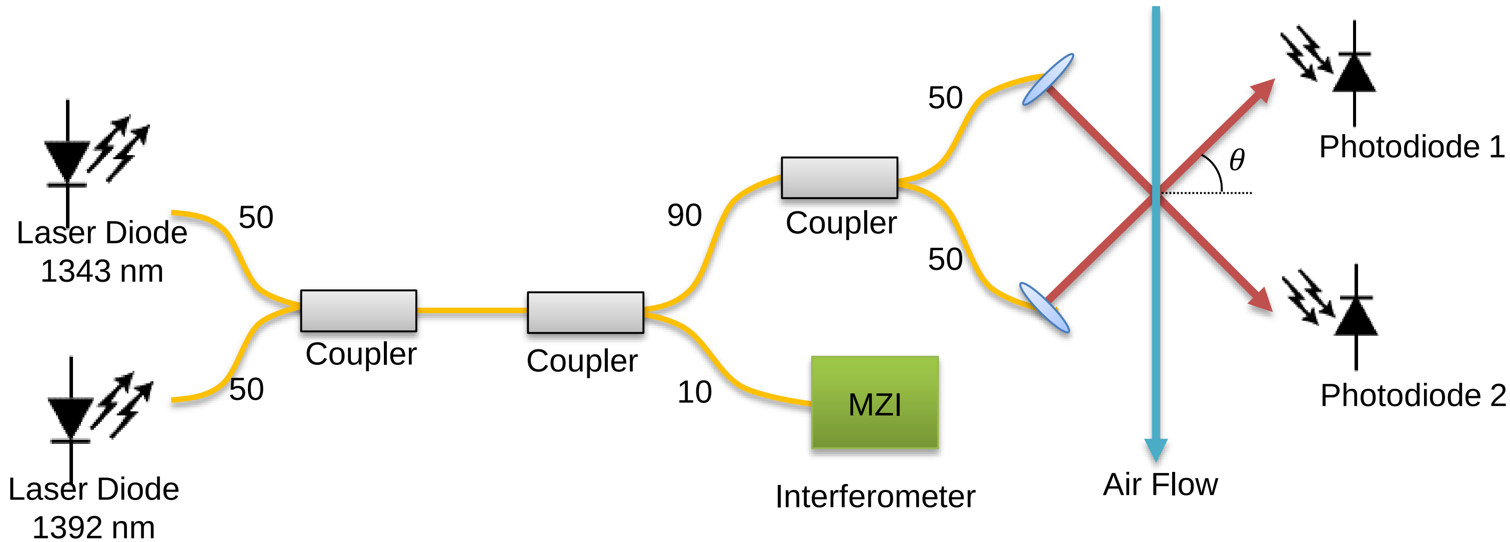
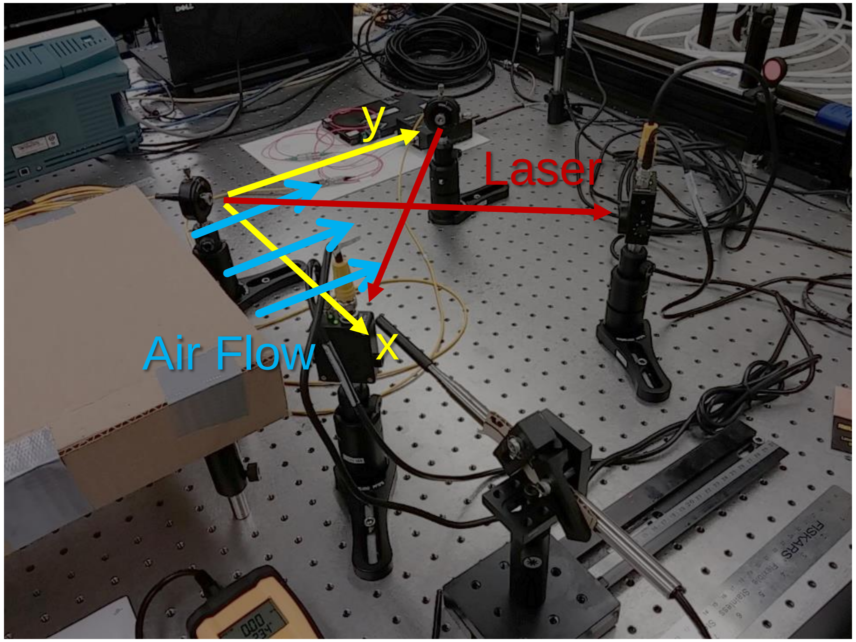
TDLAS Doppler velocimetry setup



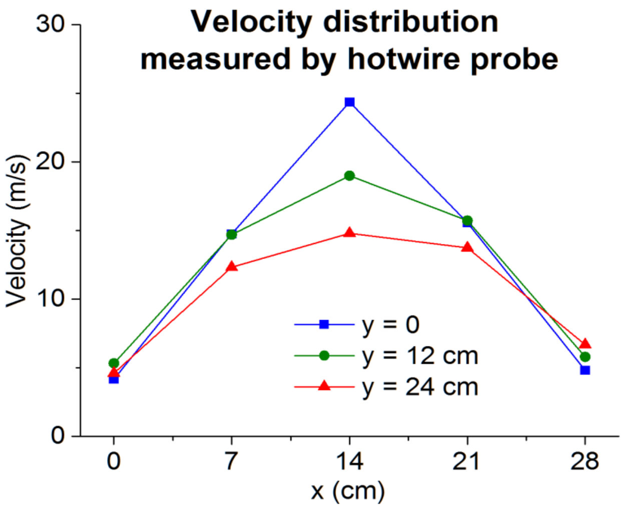
Schematic of H_2O absorption velocity measurement

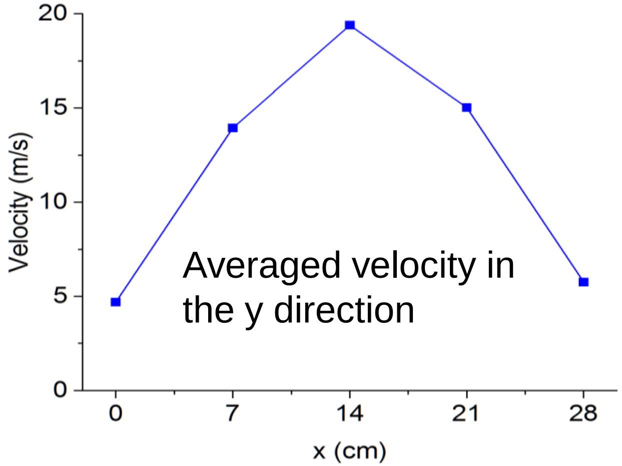
- Tunable diode laser scans across optical frequency
- Mach-Zehnder interferometer converts time series data into frequency spectrum
- Two beams cross at angle 2θ and Doppler shift is measured

TDLAS velocity measurement demonstrated in a simple duct



Experimental setup of TDLAS velocity measurement





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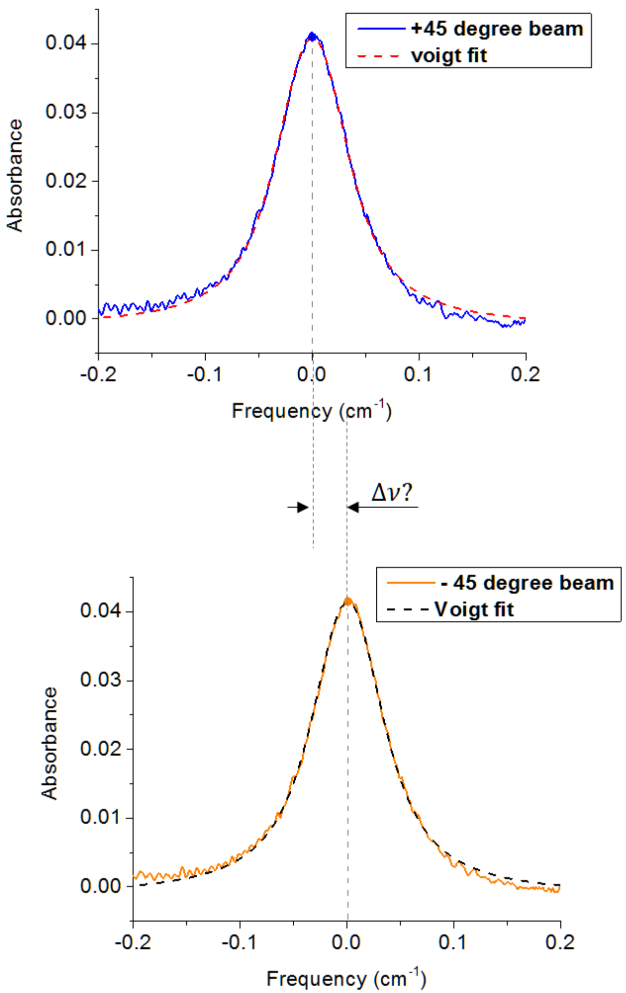
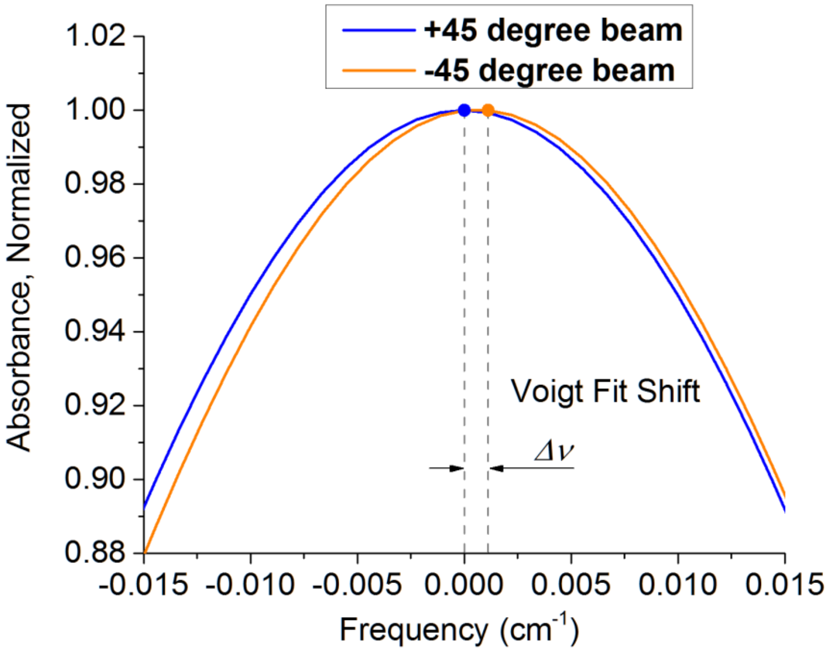
Measured Doppler shift by TDLAS





Voigt Fitting Parameters

	Voigt 1	Voigt 2
y_0, offset	-1.2264E-03	-1.3770E-03
x_c, center	**-1.6779E-03**	**-1.2582E-03**
A, area	4.5947E-03	4.6043E-03
w_G, Gaussian width	-3.6193E-02	-3.4506E-02
w_L, Lorenzian width	6.5980E-02	6.7691E-02

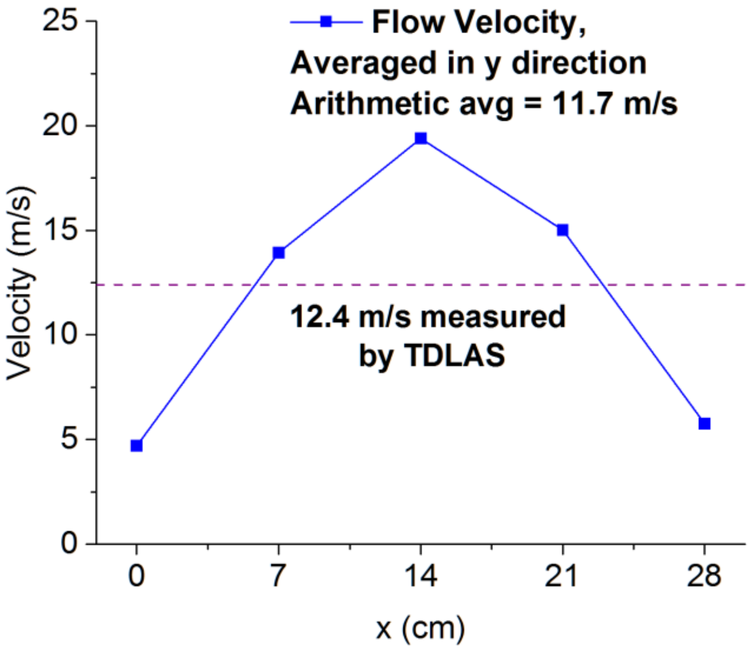
TDLAS measured velocity in agree with hot wire velocity

$$\Delta \nu = \frac{2\sin(\theta)\, V}{c} \cdot \nu_0$$

$$V = \frac{c}{2\sin(\theta)} \cdot \frac{\Delta \nu}{\nu_0}$$

$$\Delta \nu = |x_{c2} - x_{c1}| = 4.1975 \times 10^{-4}\ (\mathrm{cm}^{-1})$$

$$V = \frac{3 \times 10^{8}}{2\sin(45°)} \times \frac{4.1975 \times 10^{-4}}{7185} = 12.39\ (\mathrm{m/s})$$



- TDLAS velocity agrees well with "averaged" hot-wire velocity
- "Averaging" (i.e., effects of flow non-uniformity) will be more thoroughly investigated in the future

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Ambient air temperature measurement

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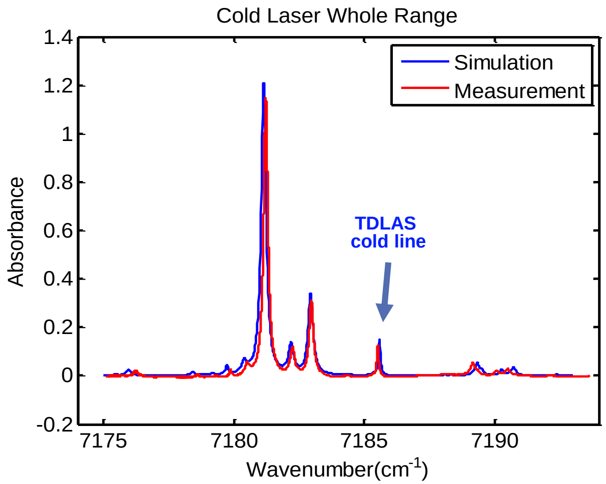
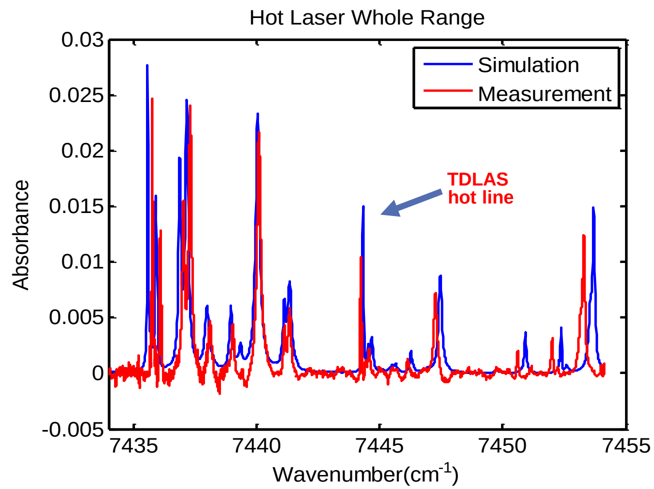
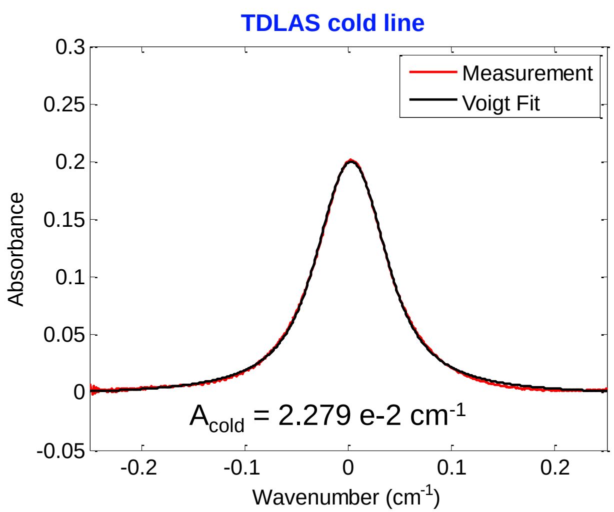


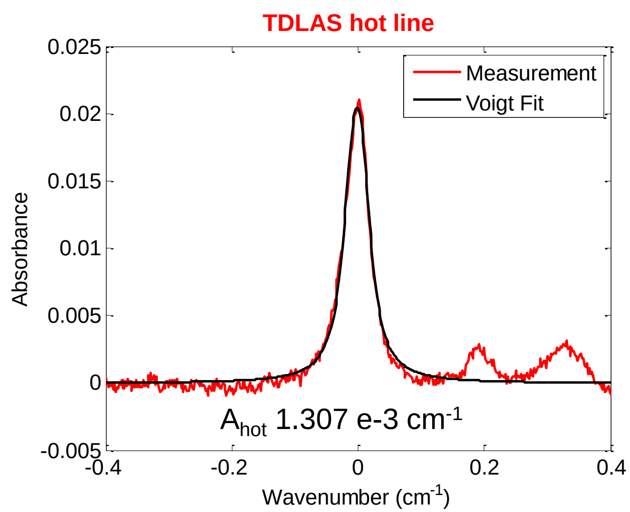


Identification of target lines

Laser controller setting:

- Diode temperature
  $T_{case,cold}$ = 27.2° C
  $T_{case,hot}$ = 26.2° C
- Drive current control
  V_{mod} = 1.7 $V_{pp,}$ ramp signal

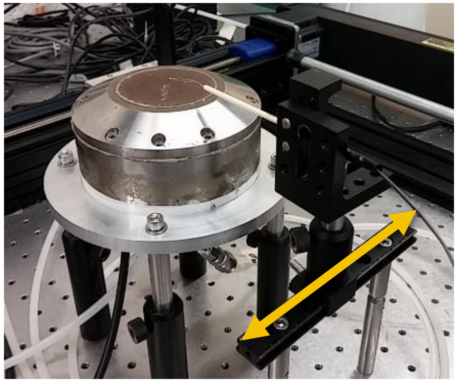




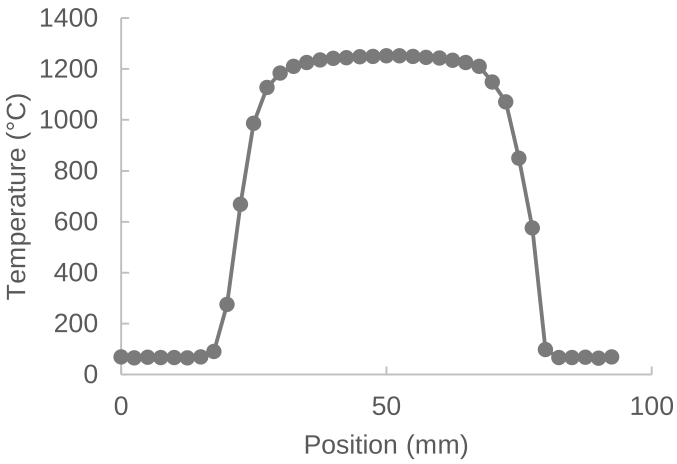
Temperature sensing

- Room condition
  T = 23° C
- Measured temperature
  T_M = 25° C
  (error = +2 K)

Thermocouple measurement of flame temperature

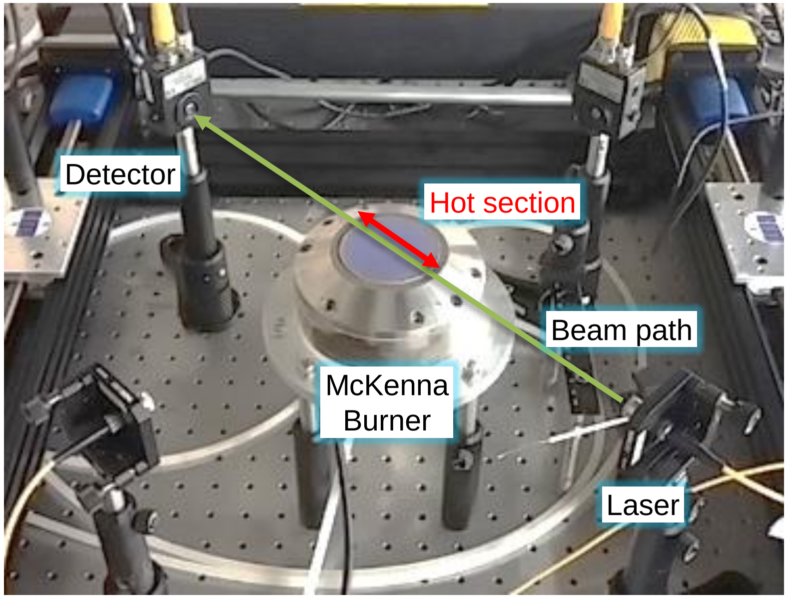


McKenna Burner and flame temperature measurement



- Thermocouple was manually traversed through a stable flat flame from a McKenna burner
- McKenna burner flame temperature was about 1200 °C.

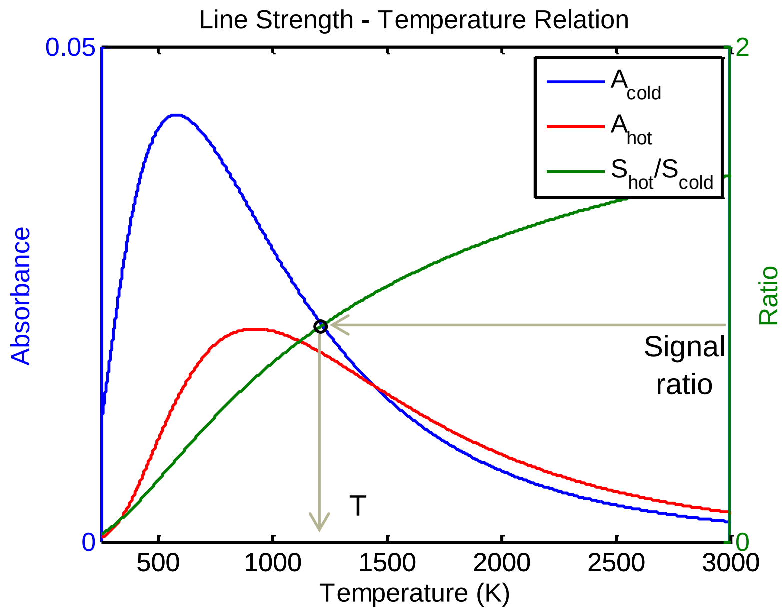
Setup to demonstrate non-uniform temperature distribution



Non-uniform temperature distribution setup

- TDLAS measurement was conducted for premixed burner flame
- Goal: To see if TDLAS can resolve the non-uniform temperature and water concentration in the laser beam path
  - Hot section: flame
  - Cold sections: ambient air

Line-of-sight TDLAS measurement of Flame Temperature

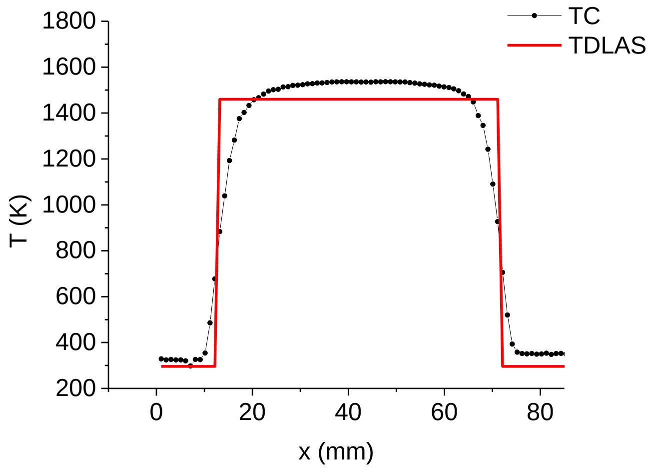


T = 1209 K = 936 °C

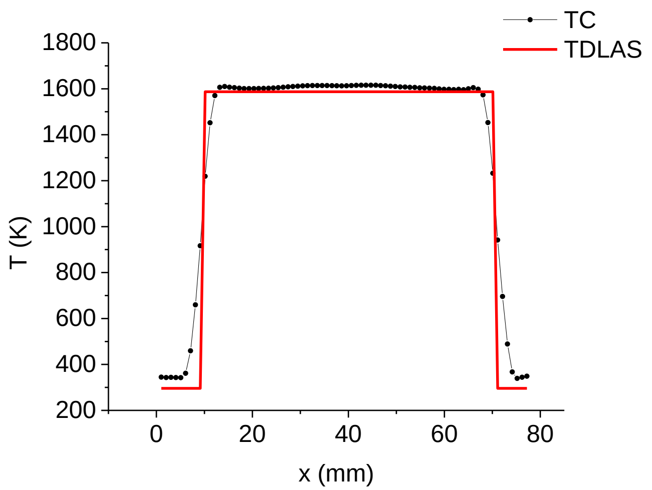
- TDLAS measured temperature was 936 °C
- Discrepancy is due to temperature non-uniformity in the beam path
- Possible solutions include non-uniform analysis or tomographic inversion.

Flame temperature distribution by TDLAS non-uniform analysis

Case 1
TDLAS 1460 K
TC 1489 K



Case 2
TDLAS 1587 K
TC 1588 K



- Non-uniformly distributed temperature is found by thermocouple (TC) and TDLAS measurement
- TDLAS measured temperature distribution agrees with TC measurement

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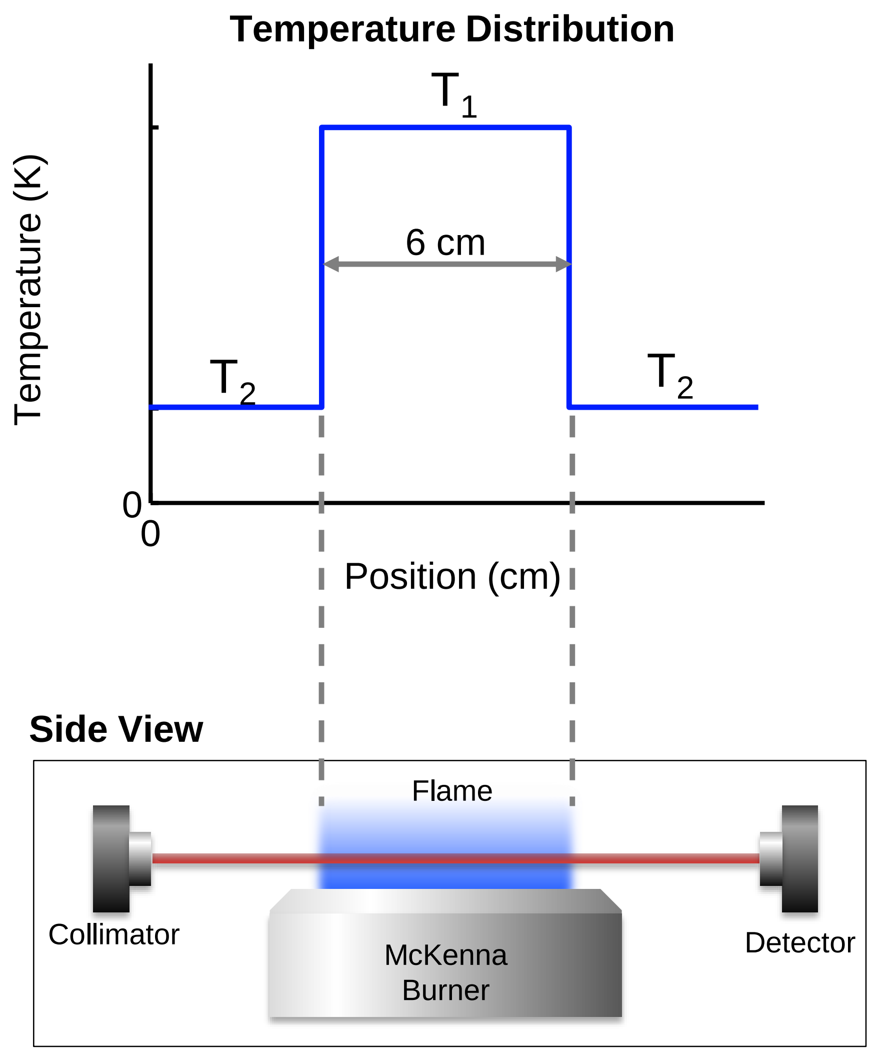
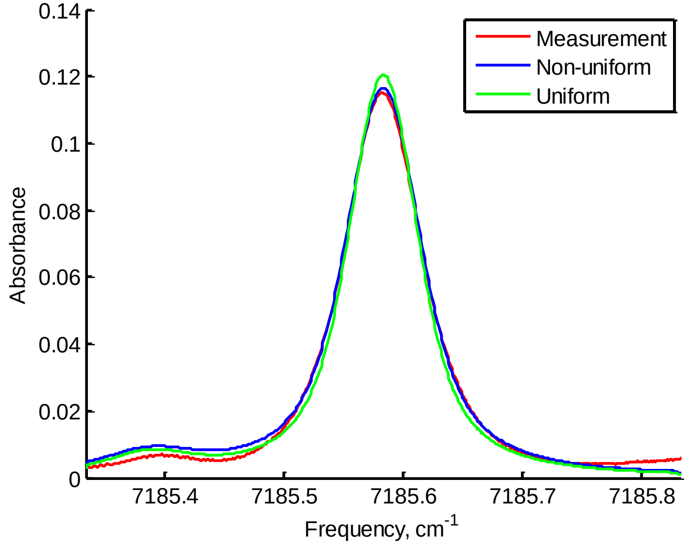
Non-uniform fitting procedure

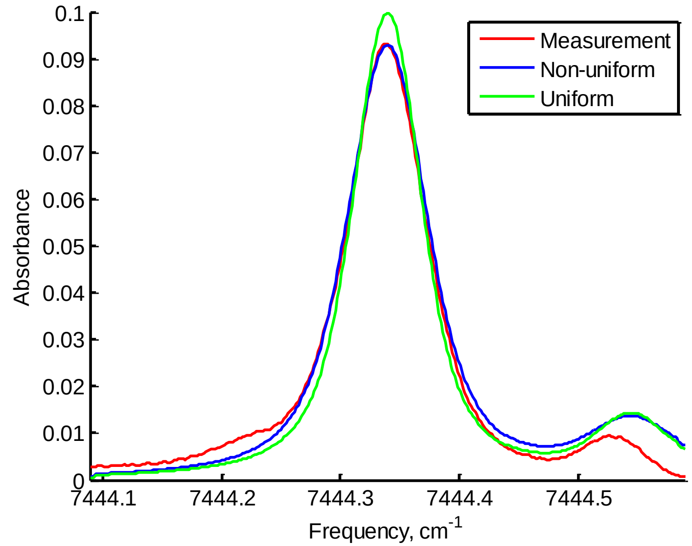


- Fitting procedure demonstrated to find T1, X1, T2, X2 in hot section and cold sections
- Valuable for practical implementation
  - Practical flows are non-uniform
  - Undesirable/difficult to mount sensors near hot flows

Example results from the fitting procedure

TDLAS absorption spectrum T_1 = 1587 K, X_1 = 0.117





- Our method exploits the shape (i.e., all the data points on the absorption lines) to obtain distribution information in non-uniform flows

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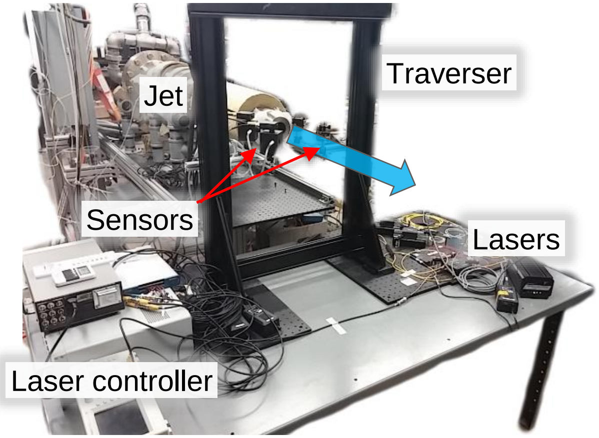
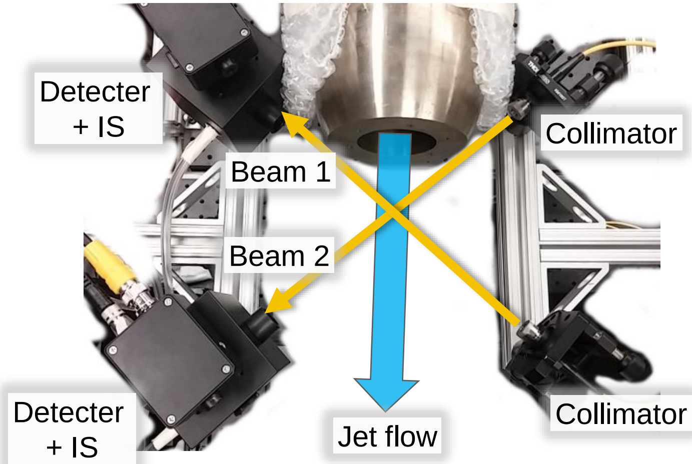
TDLAS setup in high speed jet measurement



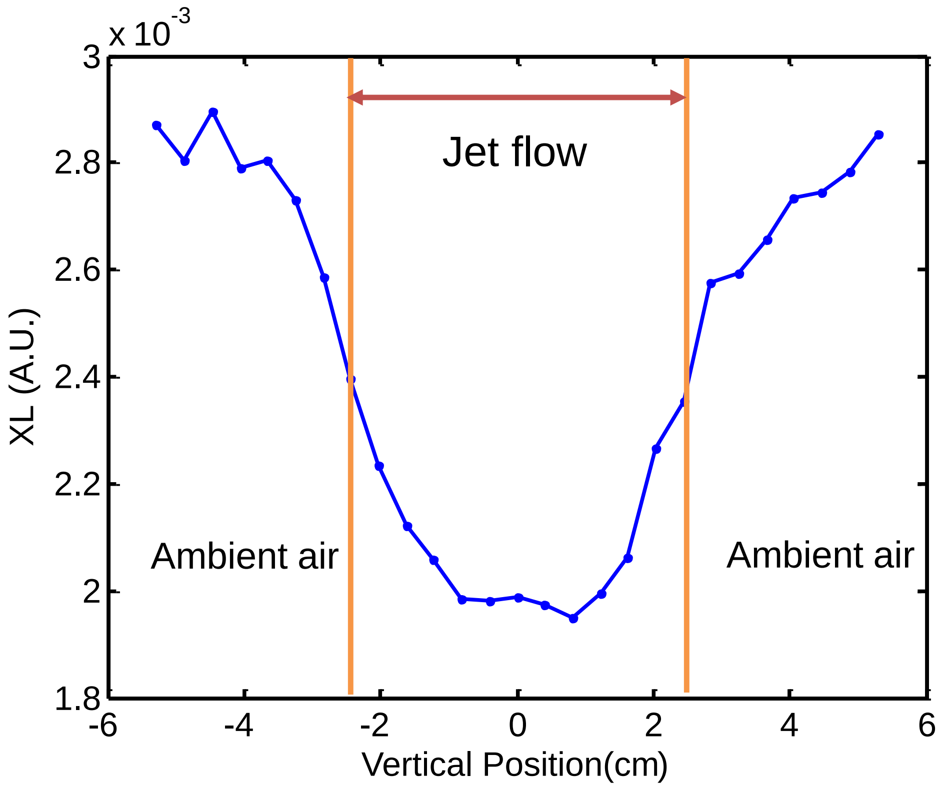
TDLAS setup installed at the high speed jet facility



TDLAS sensors located at the jet

- TDLAS measurement system is installed for high speed jet measurement
- Laser beams cross at the jet for TDLAS velocity measurement with Doppler effect
- Sensors are installed on a vertical traverser

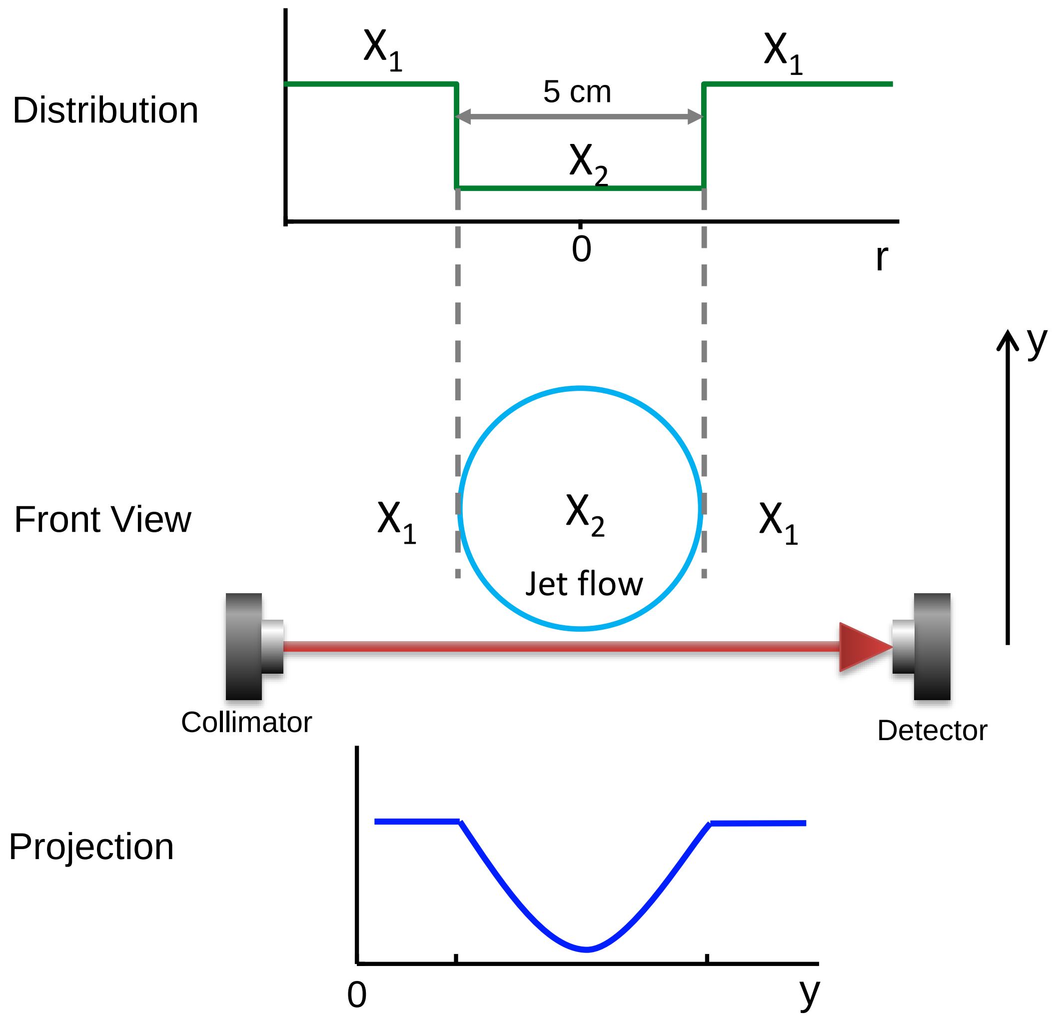
Water density of high speed jet obtained by traversing TDLAS



TDLAS measurement in the high speed jet at Mach 0.65

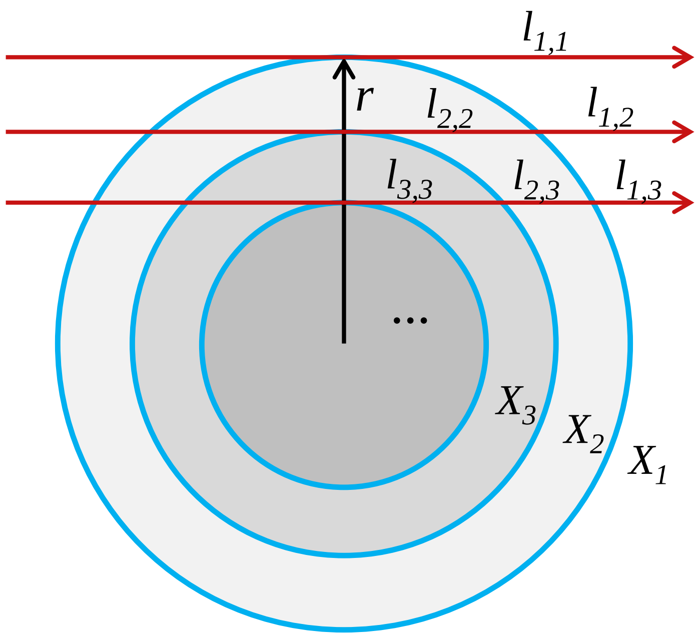
- Line-of-sight averaged water concentration measured by traversing the TDLAS sensor
- Conditions
  - Ambient air:
    25 °C, X = 0.010
  - Compressor supplied air:
    17 °C, X = 0.008
  - Traversing step : 0.4 cm

Projection of non-uniform distribution



- TDLAS measurement by traversing is a projection of non-uniform distribution
- Water density projection should be reconstructed to distribution by tomography

Introduction to Abel inversion (Tomography in 1D)



$$\mathbf{X} = \mathbf{A}^{-1}\mathbf{P}$$

X - Distribution
A - Geometry
P - Projection

- Abel inversion is used in axially symmetric geometry
- The jet is divided into layers with different water density (X_1, X_2, X_3 ...)
- Distribution can be obtained from TDLAS measured projection by Abel inversion

1D tomography applied to TDLAS jet measurements

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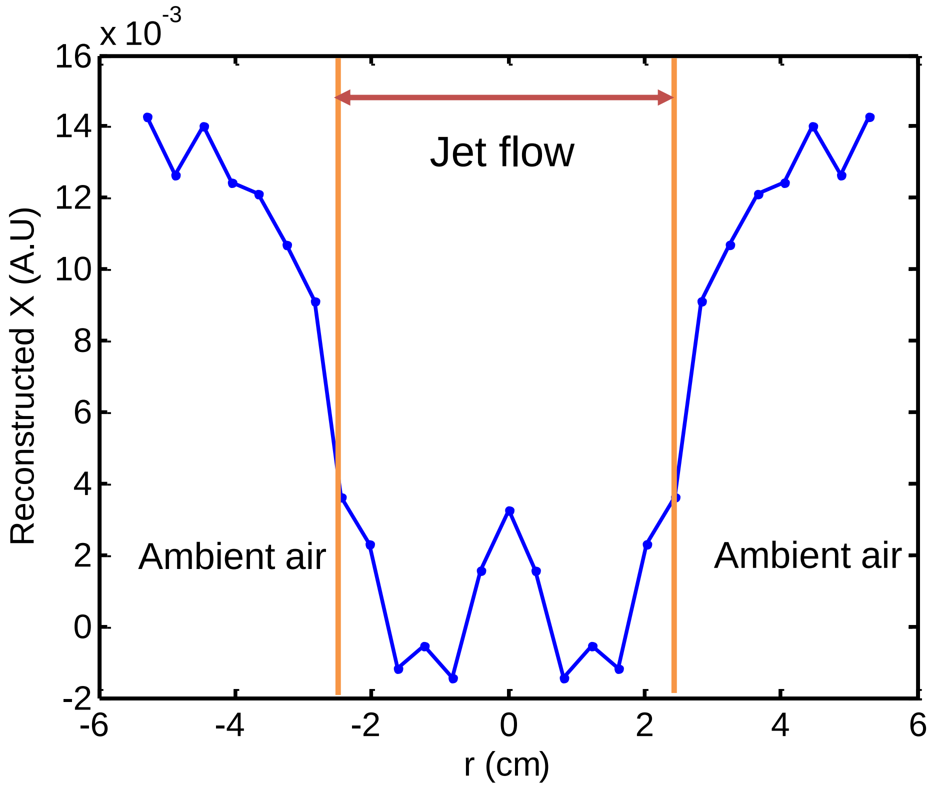

Spatial distribution of water density in the high speed jet at Mach 0.65

- Abel inversion is applied to TDLAS jet measurements
- Spatial distribution of water density in the jet is obtained

Conclusion

- TDLAS measurement of temperature, velocity, water concentration was demonstrated simultaneously

- Non-intrusive instantaneous measurement capabilities of TDLAS sensor can be utilized in research facilities and practical monitoring system of wind energy

Thanks !

Q&A

Suhyeon Park
Department of Mechanical Engineering
Virginia Tech, Blacksburg, 24060, VA
Tel: (540)750-1559
Email: spark11@vt.edu