Hypersonic Mass-Flux Sensing with Fiber-Coupled Tunable Diode Lasers for Ground Test Applications and Flight Evaluation

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NASA Fundamental Aeronautics 2007 Annual Meeting

- Goals
- Technical background
- Prior accomplishments
  - Inlet mass flux sensor for ground test of PW6000 aeroengine
- Sensor for NASA facility
  - Sensor design and spectroscopy
  - Sensor validation at Stanford
- Work plan

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Goal, Background, and Approach

Goal: Develop an experimentally validated tunable diode laser (TDL) absorption sensor for hypersonic ground-test applications and evaluate potential for flight use

Background: Build on Stanford's long history in development of TDL sensors for robust and fast sensing in propulsion devices

- Previous demonstration of prototype sensor for mass flux measurements in the inlet of a PW6000 aeroengine during ground test
  - Hybrid architecture using wavelength-modulation spectroscopy for velocity and direct absorption for density
  - Optimal spectroscopic line selection minimizes influence of temperature
  - Real-time data update at 1 Hz

Approach

- Diode laser absorption of H_2O for combustion driven flow facility
- Velocity from Doppler shift of absorption between to optical paths
- Density from line-of-sight absorption
- Gas temperature from ratio of two absorption features

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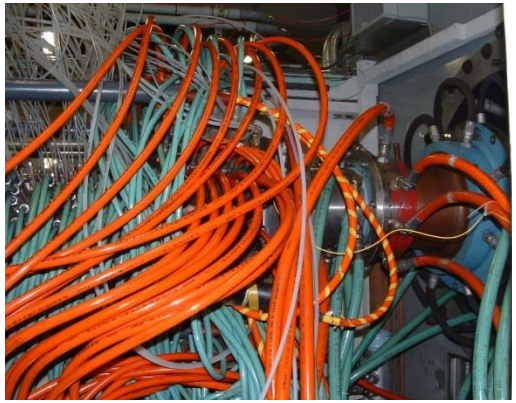
Technical Background: History of Successful Use of TDL Absorption Sensors in Harsh Environments

- CW absorption can yield species, T, P, V, in real-time at extreme conditions
  - T to 8000K, P to 50 atm, V to 15km/sec, multiphase flows, overcoming strong emission, scattering, vibration, and electrical interference
- Proven in harsh environments and large-scale systems:
  - Pulse detonation engines, arcjets, scramjets, shock tunnels, gas turbine combustors, aero-engine inlets, IC engines, coal-fired combustors
- Utilizes cheap, robust and portable TDL light sources and fiber optics
- Extension to UV and mid-IR for explosives, agents, bio-hazards, ……

Arcjet at NASA Ames



S. Kim et al., AIAA 2005-0900

SCRAMJET at AFRL WPAFB

J.T.C. Liu, *et al.*, *Applied Optics* (2005)

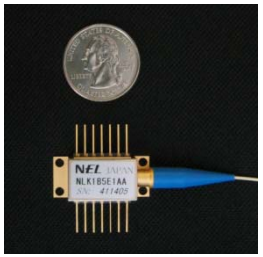
PDE at NPS

Chris Brophy, NPS

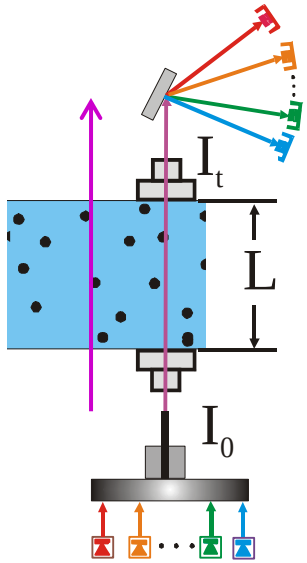
Technical Background: Wavelength-Multiplexed Absorption Fundamentals for Gases with Resolved Spectra

- Provides non-intrusive, time-resolved line-of-sight absorption measurements

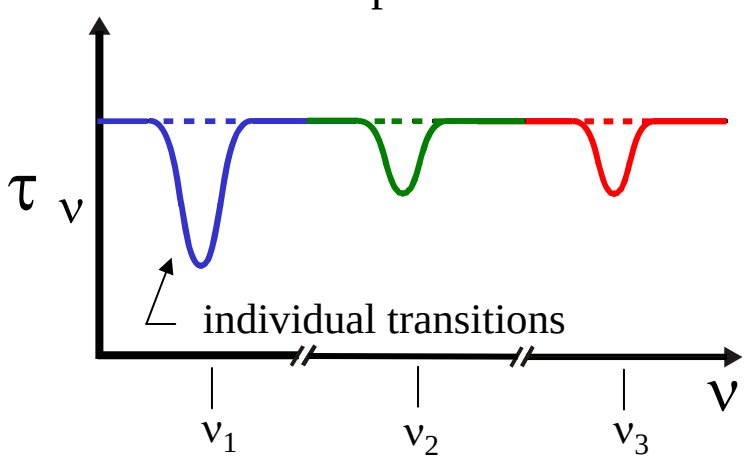
Fiber-coupled lasers are small and robust



Visible & near-IR λ's



Multiplexed-lasers



- Beer - Lambert Relation

$$\tau_\nu \equiv \frac{I}{I_o} = \exp(-k_\nu \cdot L)$$

- Spectral absorption coefficient

$$k_\nu = S(T) \cdot \Phi(T, P, \chi_i) \cdot \chi_i \cdot P$$

- Wavelength-multiplexing for *many parameters*
- Two-line ratio yields T

$$\frac{k_{\nu 1}}{k_{\nu 2}} = \frac{S_1(T) \cdot \Phi_1(T, P, \chi_i)}{S_2(T) \cdot \Phi_2(T, P, \chi_i)} \approx f(T)$$

- *Many-line* ratios for non-uniform T, species
- T and k_ν yield χ_i (species mole fraction)
- V from Doppler shift
- Mass and momentum flux from ρ and V

Technical Background: Stanford Milestones in TDL Sensing

- Pioneered use of mid-IR, lead salt TDLs in the 1970s (cryogenic cooling)
- Many applications of visible/near-infrared TDLs from 1989-present (room T)

760 nm	O_2 mass-flux sensor for NASA (1989)
777-845 nm	Plasma (n_e, T, O, N, Xe, Ar) diagnostics (1990)
1.34, 1.39 μm	H_2O mass- and momentum-flux sensor (1992)
	Multiplexed sensors for T, H_2O measurements (1993)
	High-pressure H_2O measurements (1996, 2003-6)
1.55-2.00 μm	Fast-sampling and *in situ* emissions (CO, CO_2, NO, NO_2, NH_3, UHC) (1996-9)
1.3-1.4 μm	Laser-based combustion control (1998-2006)
1.65, 2.3 μm	*In situ* CO measurements (1999-2002)
1.3-1.8 μm	Measurements in pulse detonation engines of H_2O, T_{gas} (1999); soot (2000); velocity (2002-5); NIR fuel (2002-5)
	Gas temperature for practical propulsion engine ground test (2003-present)
777-845 nm	Atoms for population temperature in NASA Ames arcjet (2002-4)
0.5-10 μm	Multi-wavelength diagnostics for two phase flow (2003-present)
1.3-1.4 μm	Gas temperature in IC-engines (2003-5)
760 nm	Mass flux measurements in PW6000 ground test (2005)
3.4 μm	Hydrocarbon fuel measurements in mid-IR w/TDL driven DFG (2006-present)
2.7 μm	H_2O using fundamental bands and CO_2 with first overtone (2007)

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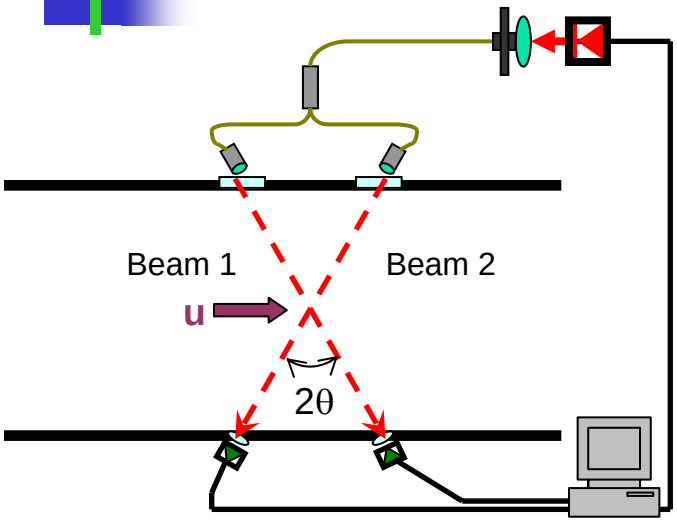
Concept: TDL Mass Flux Sensor for High-Speed Flows

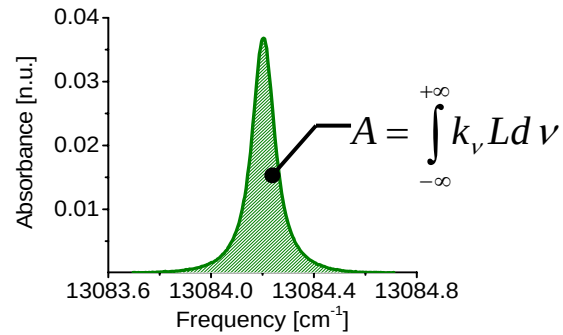


Mass Flux = (Air Density) × (Inlet Velocity)

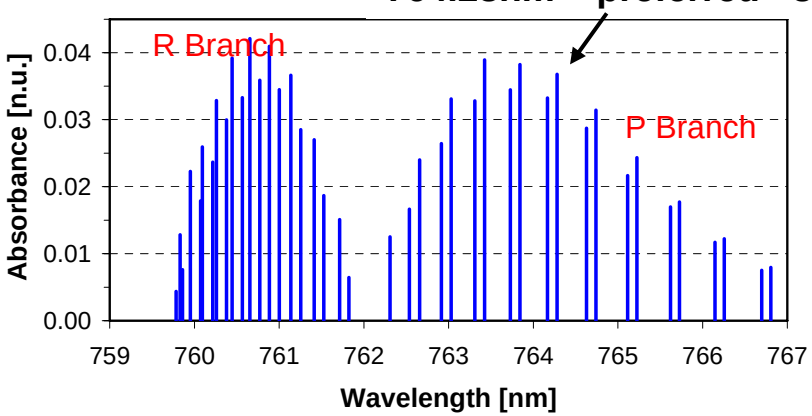
- Air density ρ from measured absorbance of O_2
- Measure integrated absorbance on selected oxygen transition with S(T) ∝1/T :

$$A = S(T)\cdot P_{O_2}\cdot L = \rho_{O_2}\cdot S(T)\cdot (RT)\cdot L$$

$$A \propto \rho_{O2} \propto \rho_{air}$$

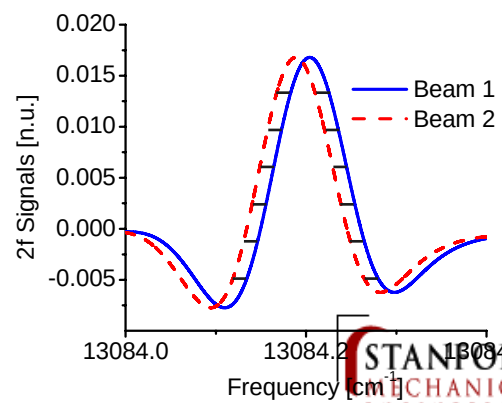


764.28nm – preferred ~300K



- Velocity u from Doppler shift:

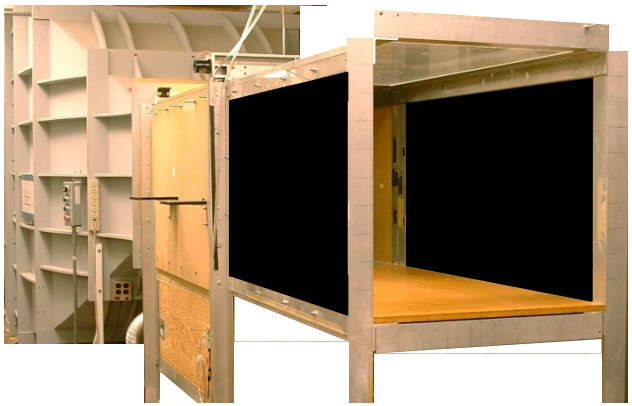
$$\Delta\nu = \nu_0 (2\sin\theta)\frac{u}{c}$$

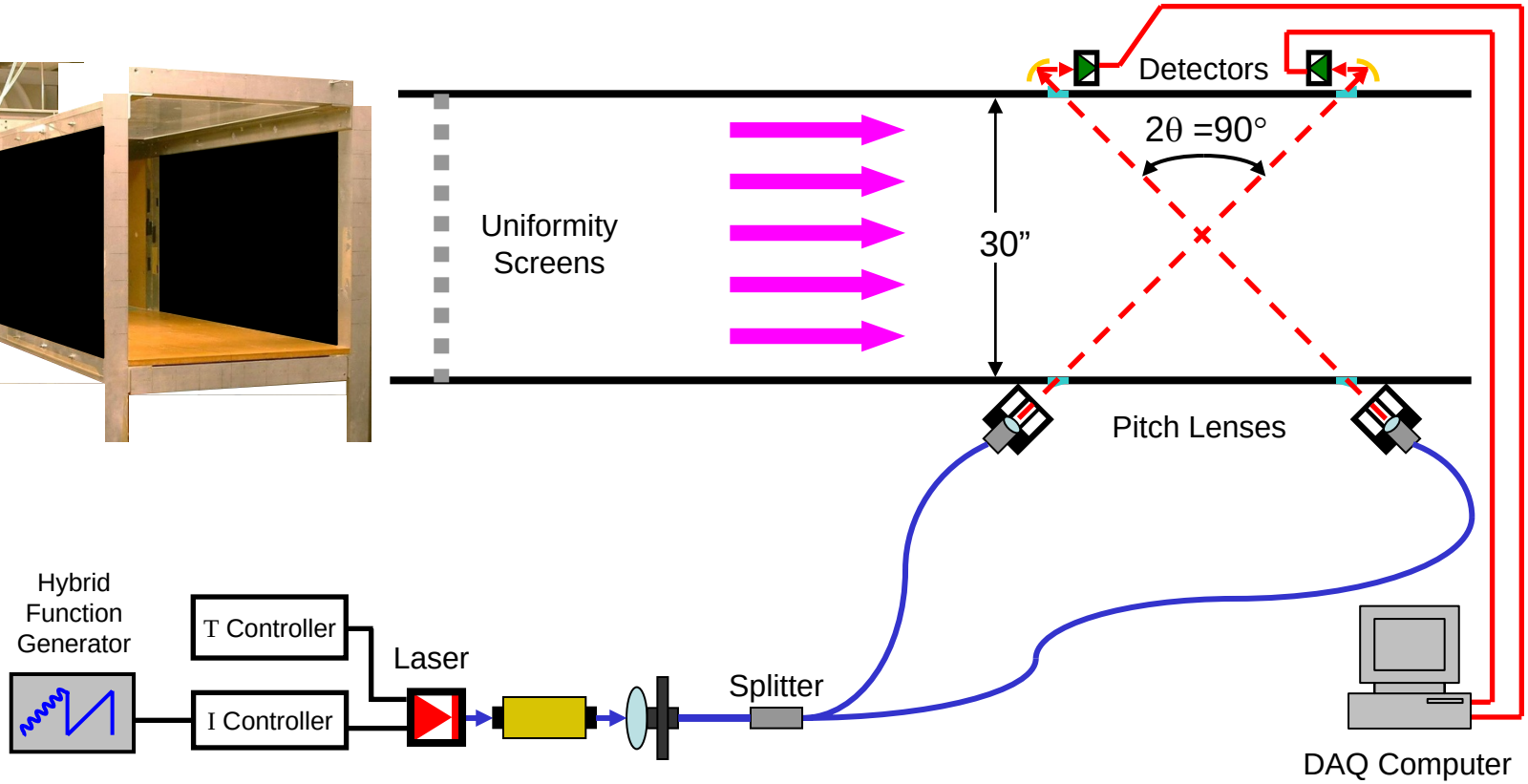


Note for optimum sensor design:

1. Line selection depends on range of static temperature
2. Desire 2θ near 90° or as large as possible

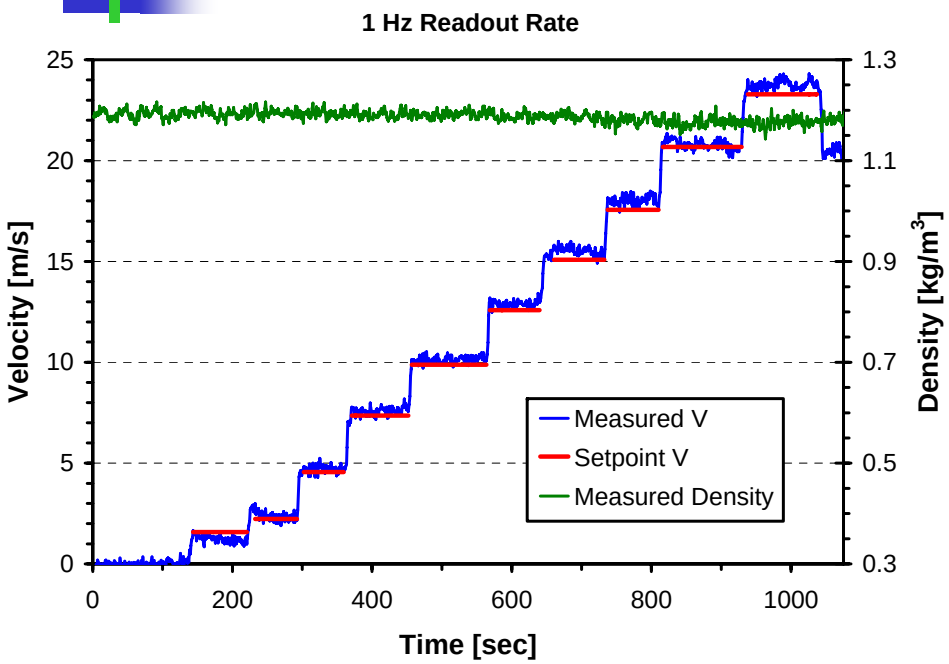
Sensor Installation in Stanford Wind Tunnel

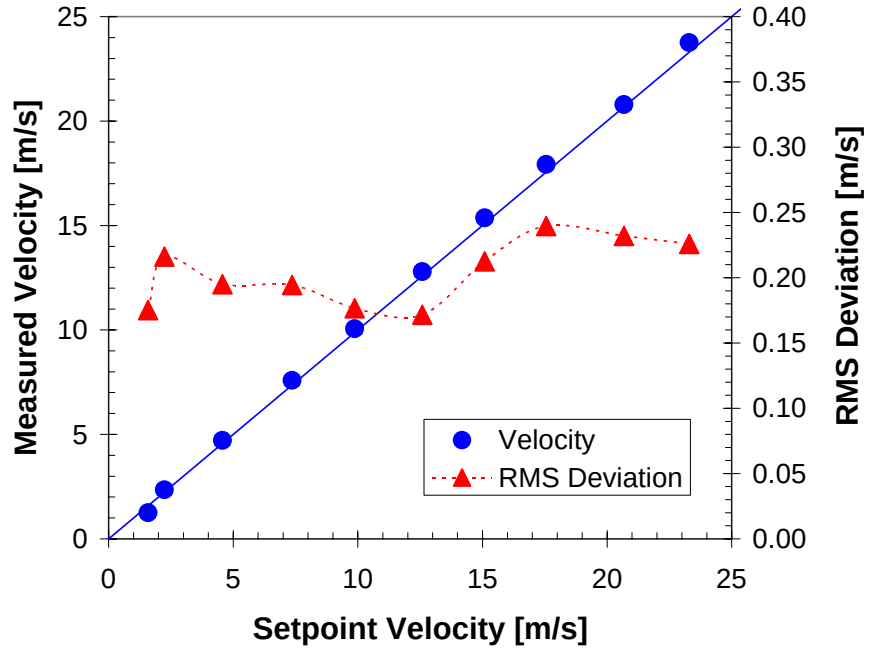




- Stanford wind tunnel flows up to ~ 25 m/s
- V via WMS-2f & ρ via direct absorption on alternate scans @50Hz
- Measurement rate at 1Hz

Validation Measurements in Stanford Wind Tunnel





- Real-time 1Hz measurements of mass flux using scanned-2f strategy
- RMS deviation <0.25m/s for 1Hz measurements
- Average deviation between average sensor data and set point is 0.4m/s
- Can be used with non-uniform flow when suitable model is available
- Potential for flight systems

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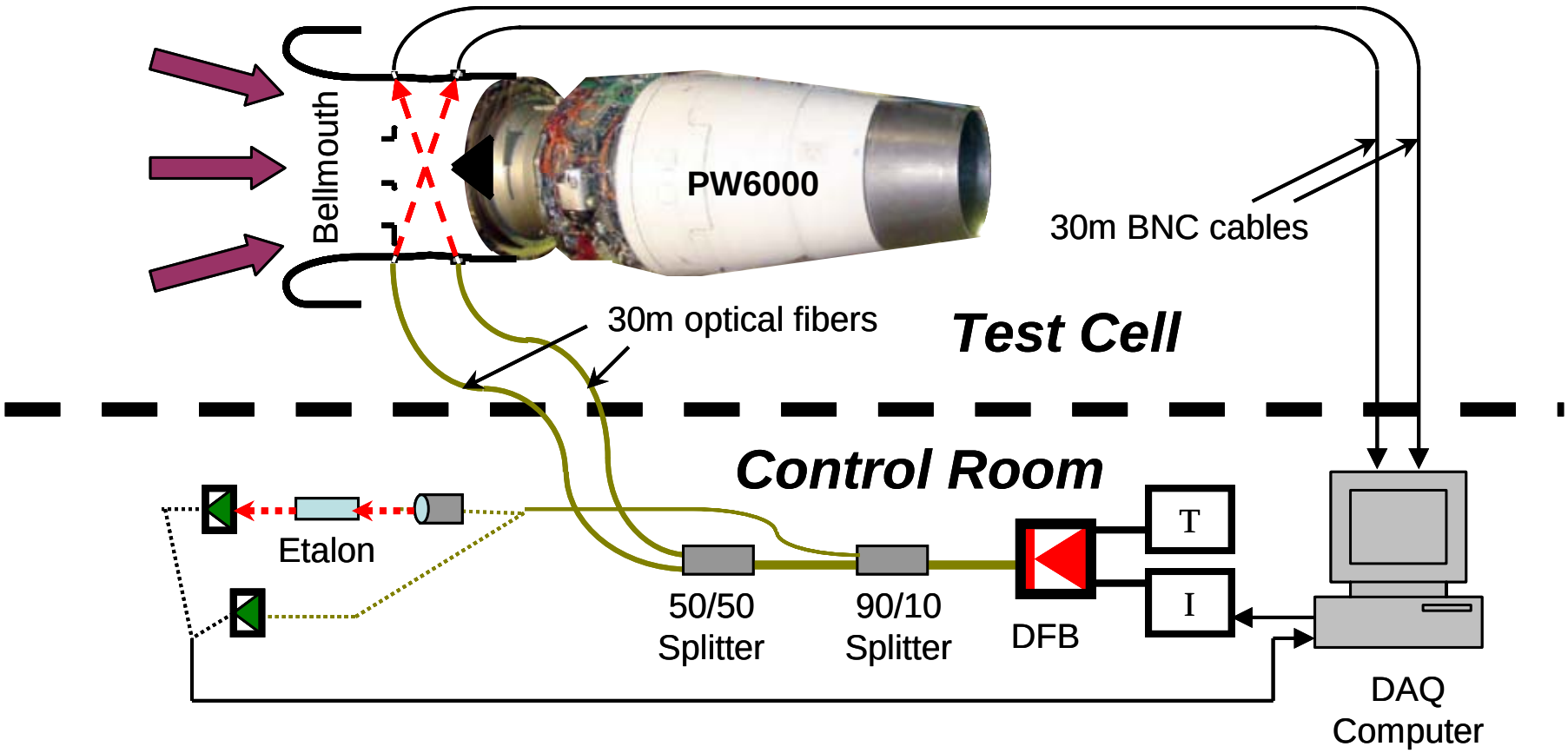
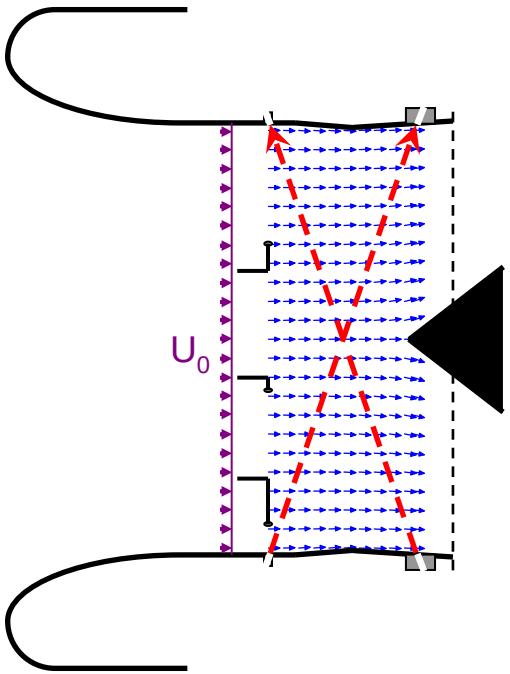
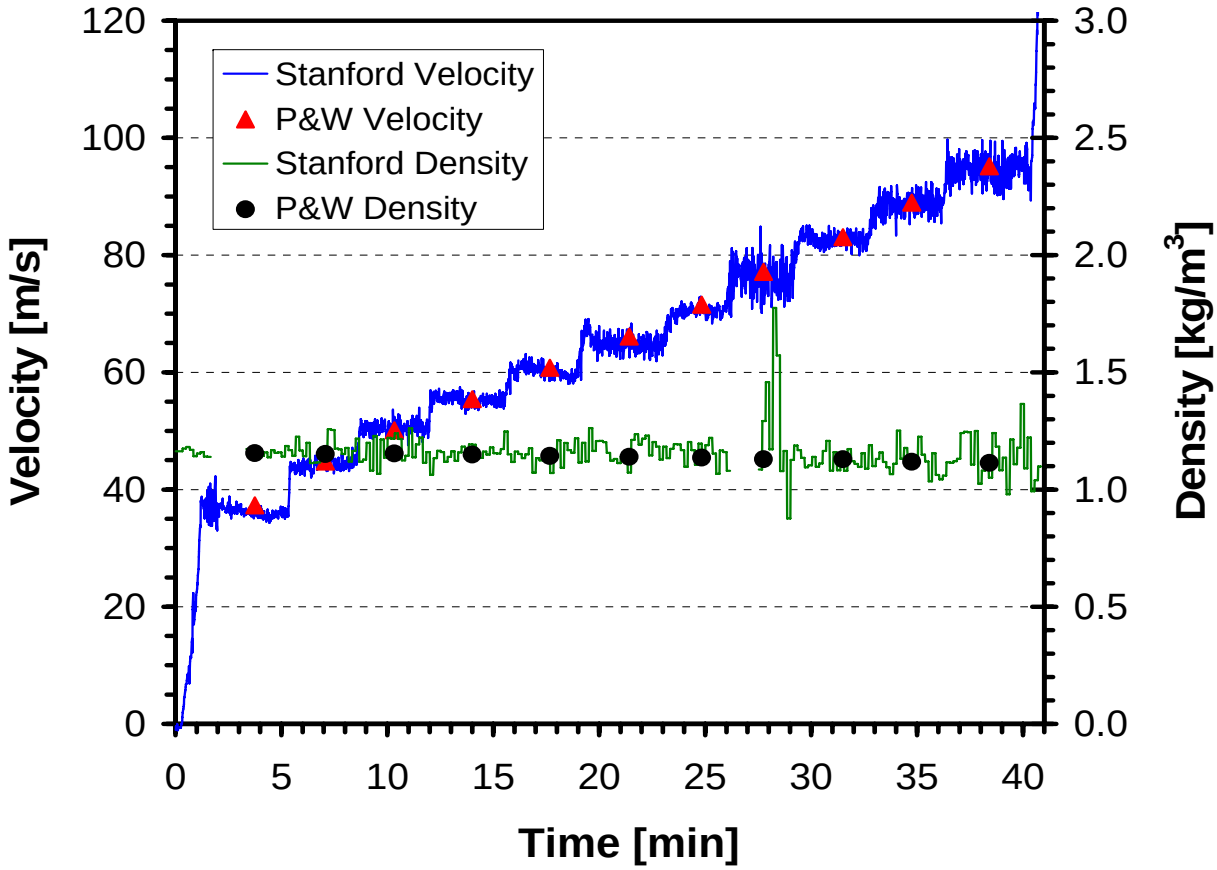
Sensor Tests in Pratt and Whitney Engine Inlet



- Bellmouth installed on inlet to PW6000 commercial engine (Airbus 318)
- Sensor hardware remotely operated in control room
- TDL beams mounted in engine bellmouth

P&W Mass Flux versus TDL Sensor Measurements





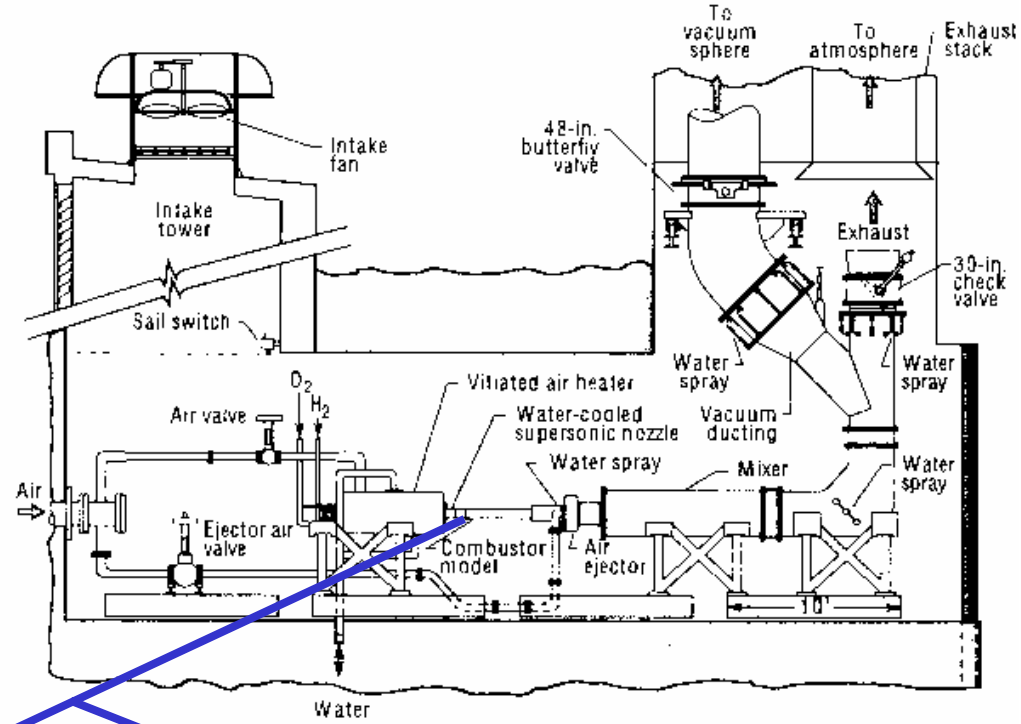
- Mounting constraints required correction for non-uniform flow
- Mounting constraints limited 2θ to 37°
- TDL measurements agree well with test stand instrumentation
- Average deviations 1.2% in V and 1.5% in ρ

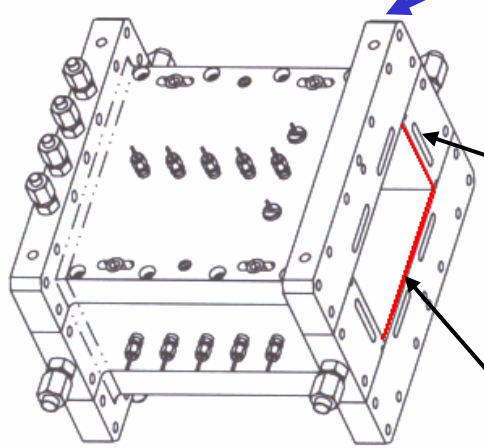
Develop a TDL-Based Mass Flux Sensor for NASA

- Identify test facility for proof-of-concept validation testing
  - Direct-Connect Supersonic Combustion Test Facility (DCSCTF)
  - Combustion driven (choice of O_2 or H_2O as TDL absorption target)
  - Determine velocity via Doppler shift of absorption line (transition)
  - Determine gas density via temperature from ratio of two absorption lines and the well known static pressure in the facility
- H_2O is ideal target for absorption measurement
  - Many strong absorption lines (transitions)
  - Absorption in the region 1.3-1.7μm
    - Mature, robust, available, easy to use telecommunications TDLs
    - TDL fiber optics technology to couple sensor to rig
- Select lines optimum for test facility conditions (P, T, pathlength, etc)

Langley Facility for Sensor Demonstration: Direct-Connect Supersonic Combustion Test Facility (DCSCTF)

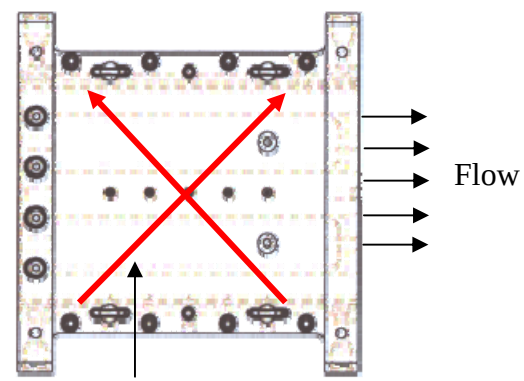
- Simulates atmospheric supersonic and hypersonic flight conditions
  - Nozzles for M2 and M2.7
- Select absorption line for conditions
  - T_{static} ~ 650 K for M2
  - T_{static} ~ 915 K for M2.7
  - $0.5 < P_{static} < 2$ atm





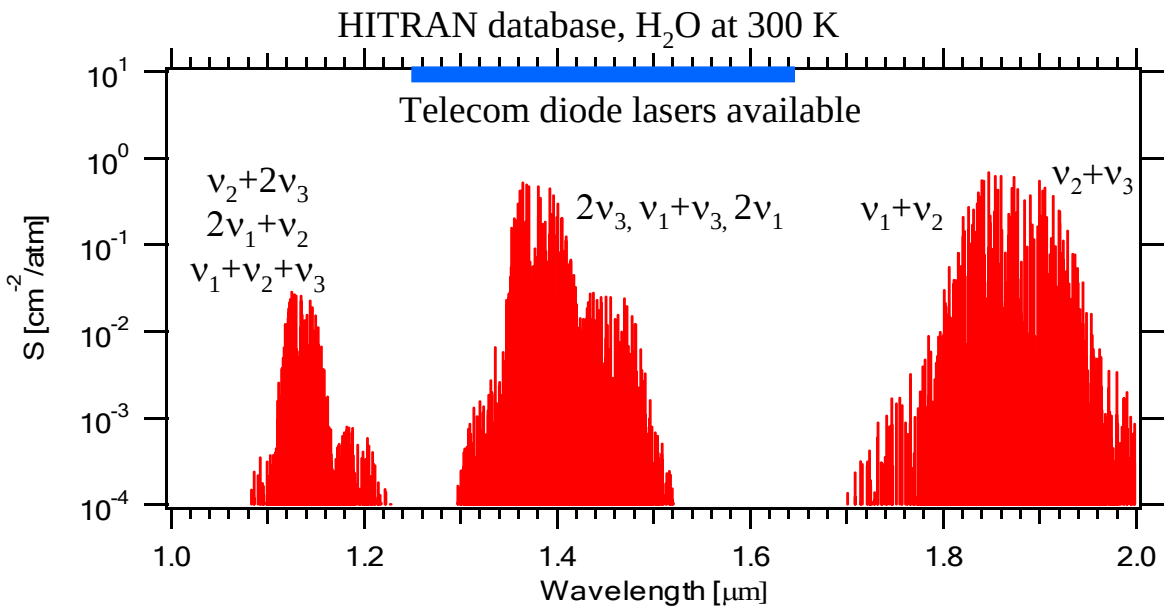
M 2.0 = 1.52”
M 2.7 = 1.5”

M 2.0 = 3.52”
M 2.7 = 6.69”



Potential laser paths

Large χ_{H2O} in Combustion Gases: Chose H_2O Lines for DCSCTF



- HITRAN 2004 database lists 2632 lines in telecommunications region
- Criteria for line selection
  - Sufficient absorbance for good SNR
    - Absorbance > 0.1 for P, χ_{H2O}, and L (202 of 2632 lines qualify)
  - Temperature insensitive signal (need S(T)~1/T) for 600<T<1000 K
    - Ground state internal energy 730 cm^{-1} < E" < 1118 cm^{-1} (10 lines qualify)
  - Single line separated from neighboring transitions
    - Need > 0.3 cm^{-1} from nearest neighbor (2 lines qualify)
      - 7378.7 cm^{-1} (1355.3 nm)
      - 7413.7 cm^{-1} (1348.9 nm)

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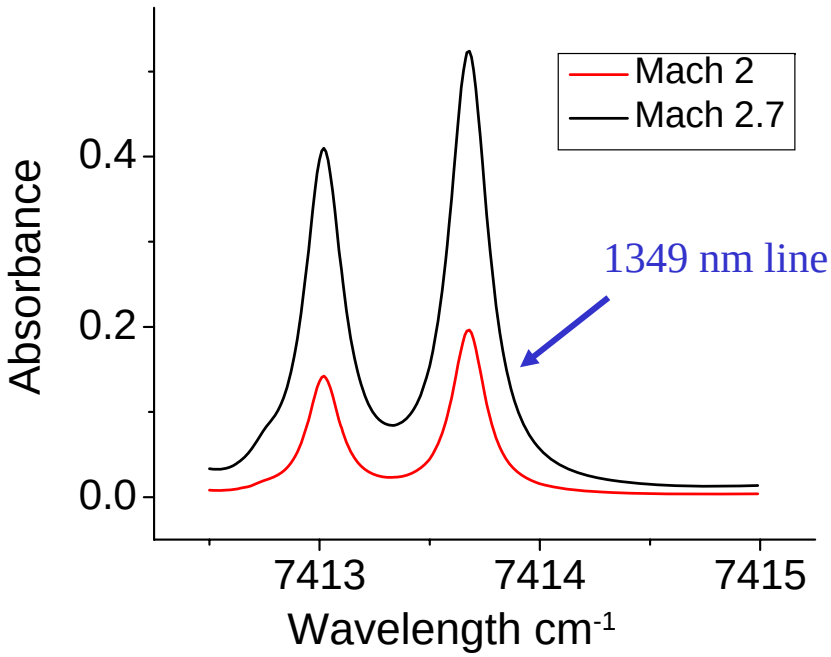
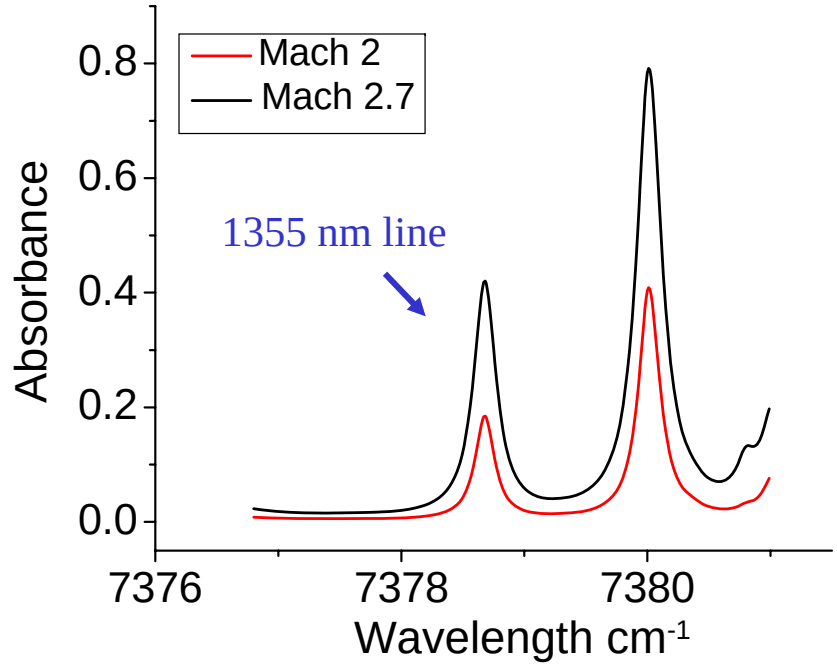
HITRAN Simulations at DCSCTF Conditions

Simulation conditions: Mach 2 nozzle: T=651K, P=138kPa, L=12.43cm, and X_{H2O}=0.13

Mach 2.7 nozzle: T=915K, P=145kPa, L=24.03cm, and X_{H2O}=0.26





- Signal range excellent for good SNR
- Sufficient separation for Doppler shift measurement ($\Delta\nu_D$~ 0.038cm^{-1}@M2 and 0.055cm^{-1}@M2.7)

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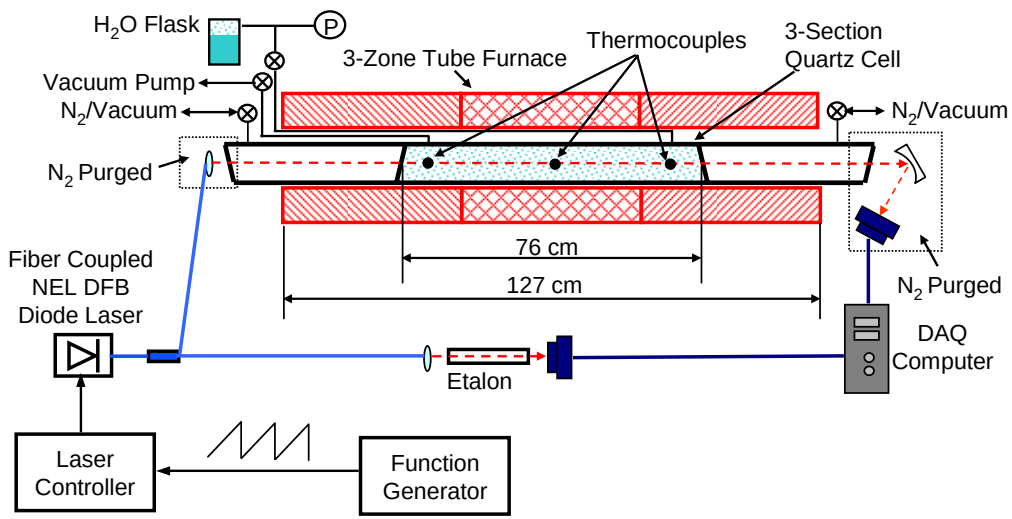
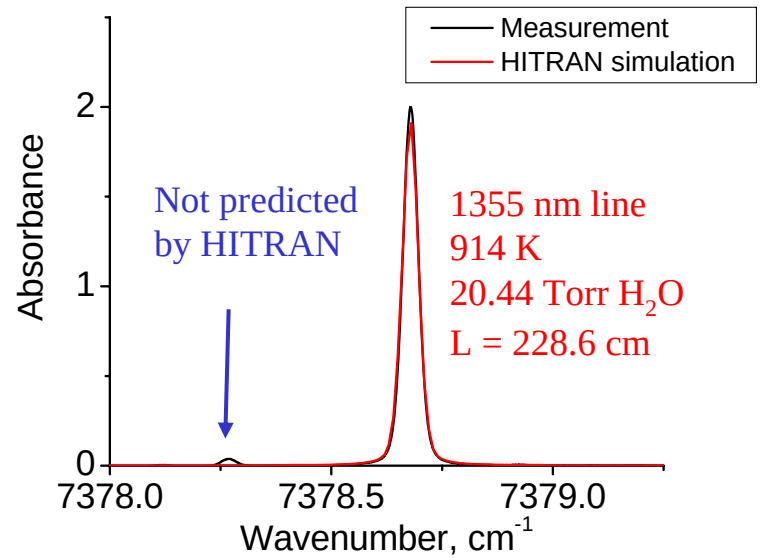
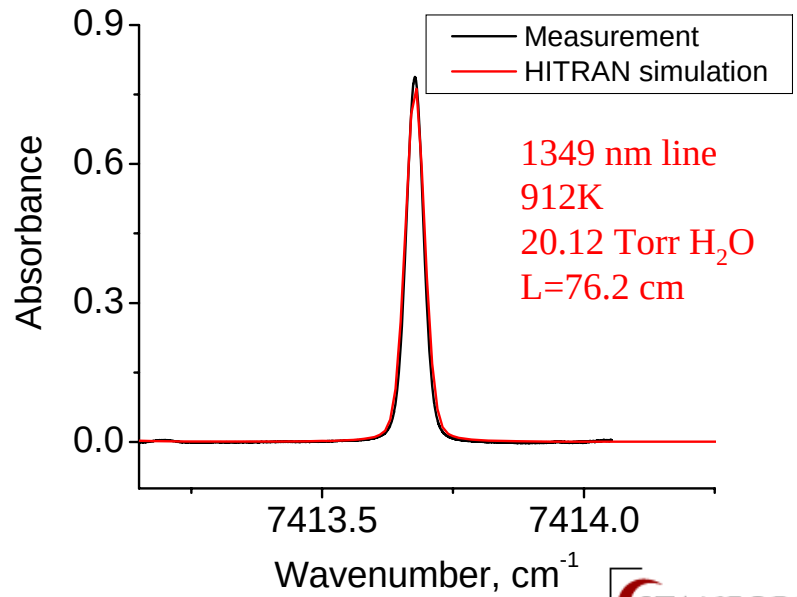
Spectroscopy Must Be Validated



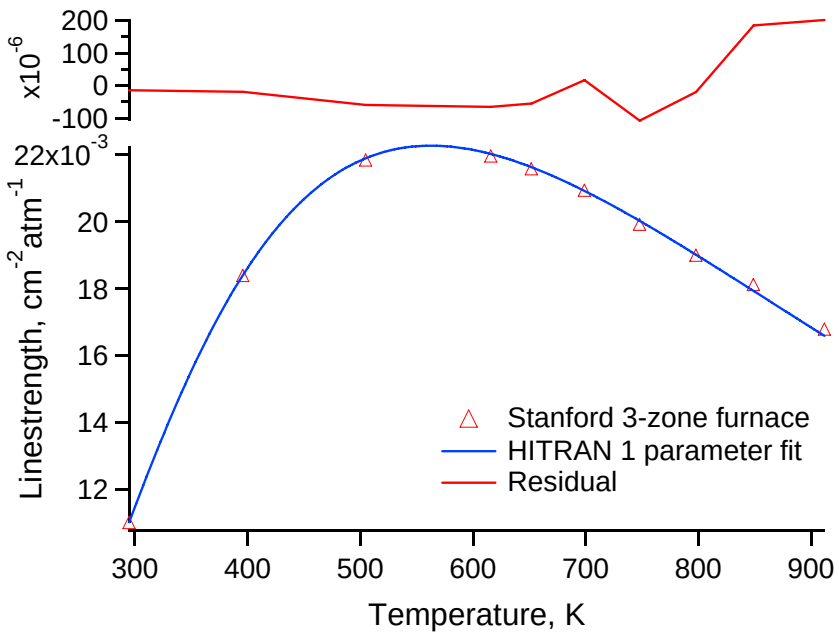




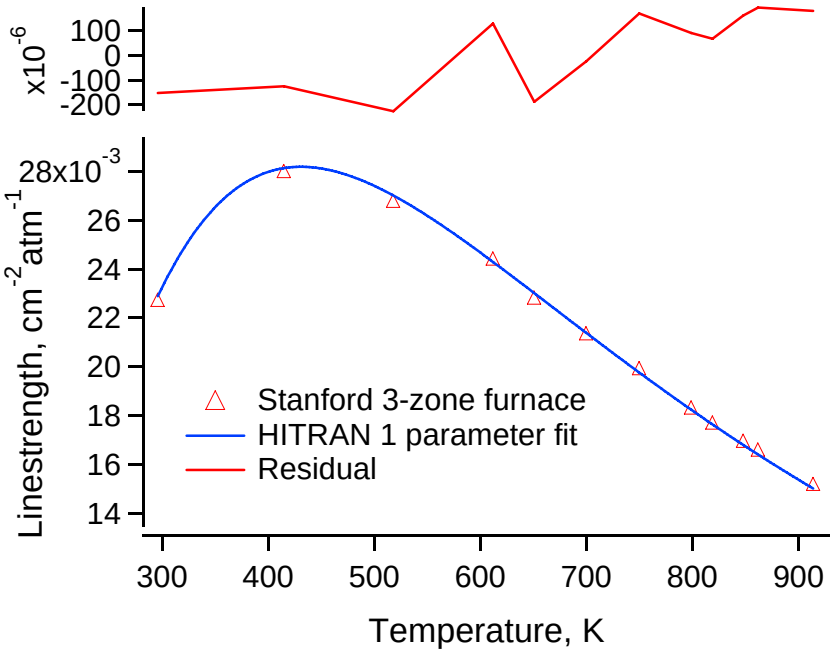
- Well controlled T and P
- Pure H_2O at low pressure
- Investigate unpredicted features near transition
- Quantitatively measure S(T), S(298K)
- Measure pressure broadening 2γ (air & self)

New Linestrength Data for Candidate H_2O Lines

S(T) for 1348.8 nm line



S(T) for 1355 nm line



- Measure absorption as function of T
- Two-parameter fit to S(298) and E”
  - If $E''_{Fit} \sim E''_{HITRAN}$ line assignment is correct
- Fit to S(298) and E''_{HITRAN}
- Stanford S(298) uncertainty <3%
  HITRAN uncertainty 5-10%
- High E” line selected for two-color temperature measurement
- Measurements of line broadening underway

	$S_{measured}$ (cm^{-1}/atm)	S_{HITRAN} (cm^{-1}/atm)
1348.86 nm	1.11 $(10)^{-2}$	1.28 $(10)^{-2}$
1355 nm	2.29 $(10)^{-2}$	2.41 $(10)^{-2}$

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Extension of Mass Flux Sensing to NASA Flow Facilities: Crucial Research Questions

- How do flow nonuniformities influence the apparent measurement result?

1. What design strategies can be used to *minimize* the influence of nonuniformities?
2. What design strategies can be used to *maximize* the influence of nonuniformities so that the nonuniformity can be monitored?

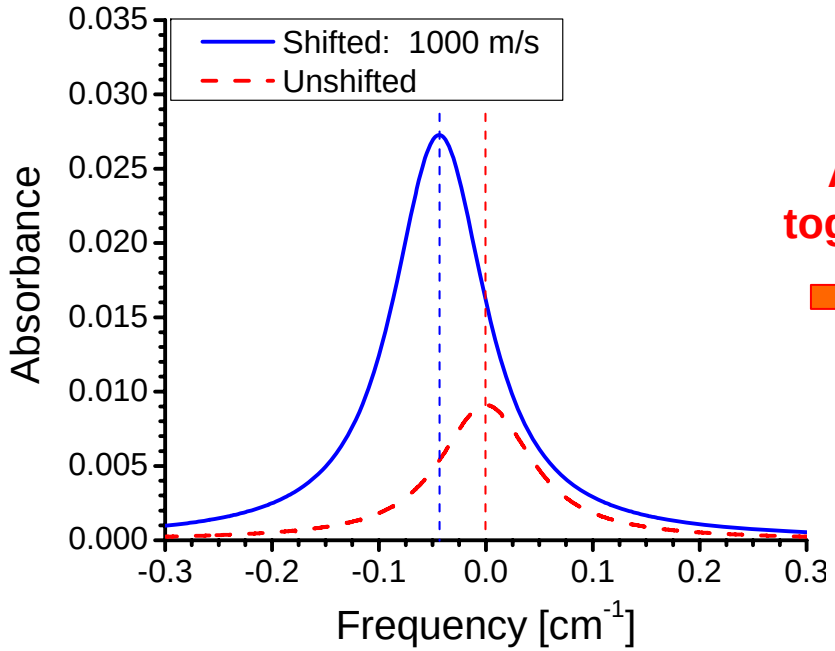
- What data acquisition and analysis algorithms enable optimum measurement bandwidth and minimum sensor uncertainty?

- Are there interesting fluctuations in the flow, and at what frequencies do the interesting fluctuations appear in target facility ?

  (establishes the data rates required for sensor)

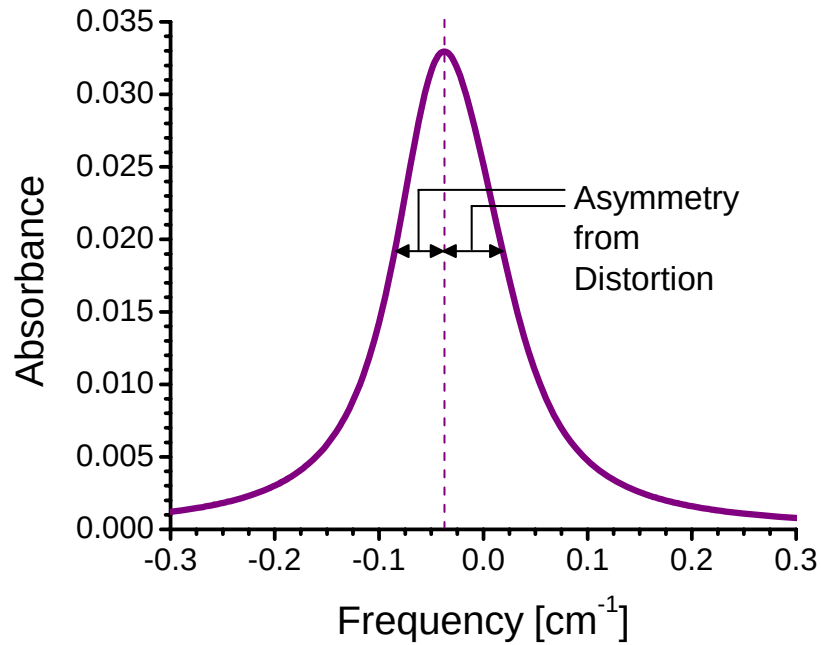
Example of Lineshape Distortion by Nonuniform Flow

Two Doppler-shifted direct absorption segments



Add together

Resulting distorted lineshape



- Velocity non-uniformities (e.g. boundary layers or stagnant regions) distort lineshape
- Asymmetric lineshape distortion may introduce error into Doppler shift analysis
- Need to understand & quantify effect of non-uniformities on V measurement

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Validation and Testing of Sensor

- Test environments available at SU
  - Low-velocity wind tunnel (V<25m/s) used to test aero-engine inlet sensor
  - Shock-tube with optical test section for low M# test conditions
  - Shock-driven expansion tube with variable lengths for driver, driven and expansion sections to enable a wide range of high M# test conditions
- Stronger line strength of H_2O absorption compared to O_2 can compensate for shorter path length in shock-driven test facilities
- Preliminary temperature measurements via two-color diode laser absorption of H_2O illustrate feasibility of sensor testing in expansion tube

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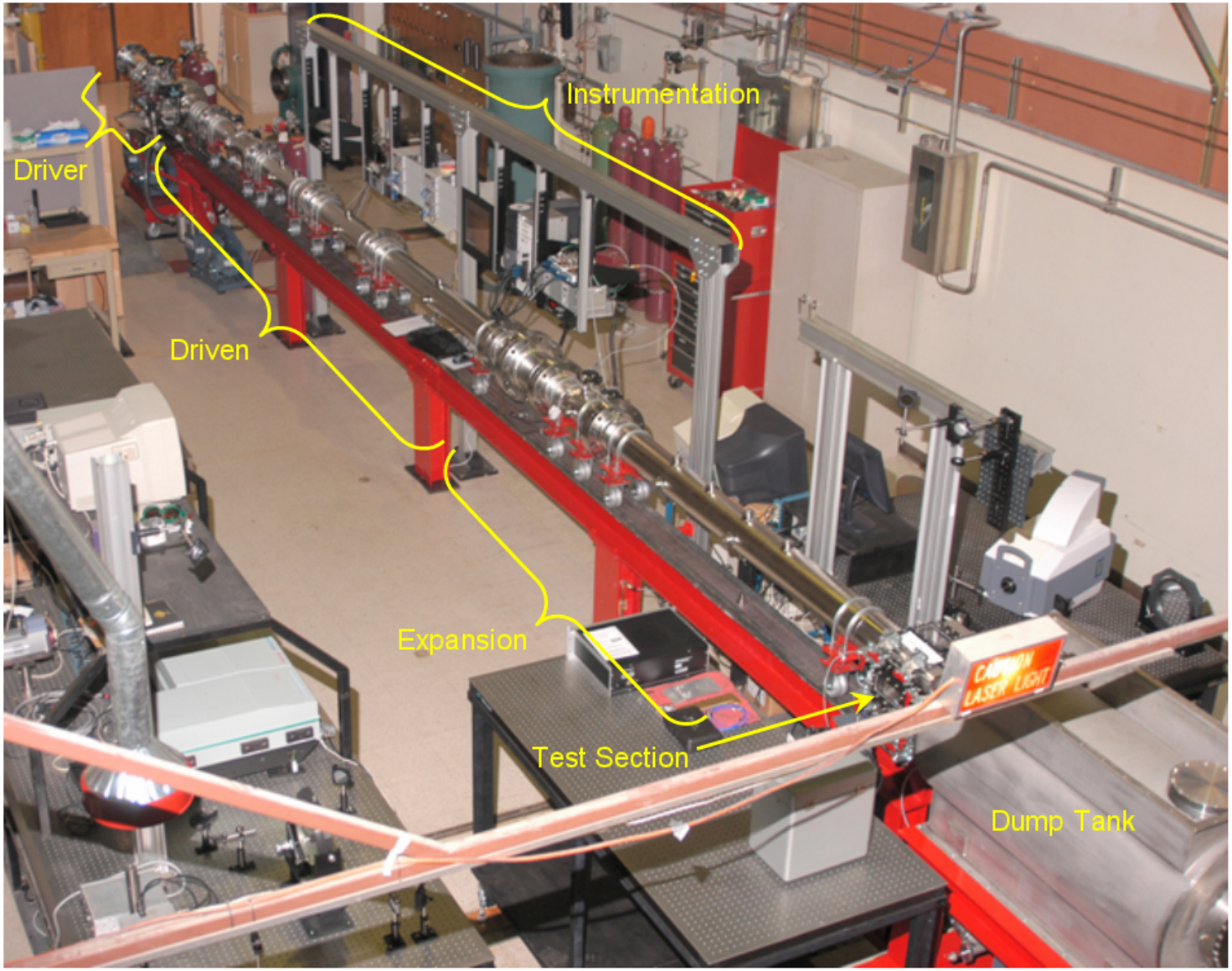
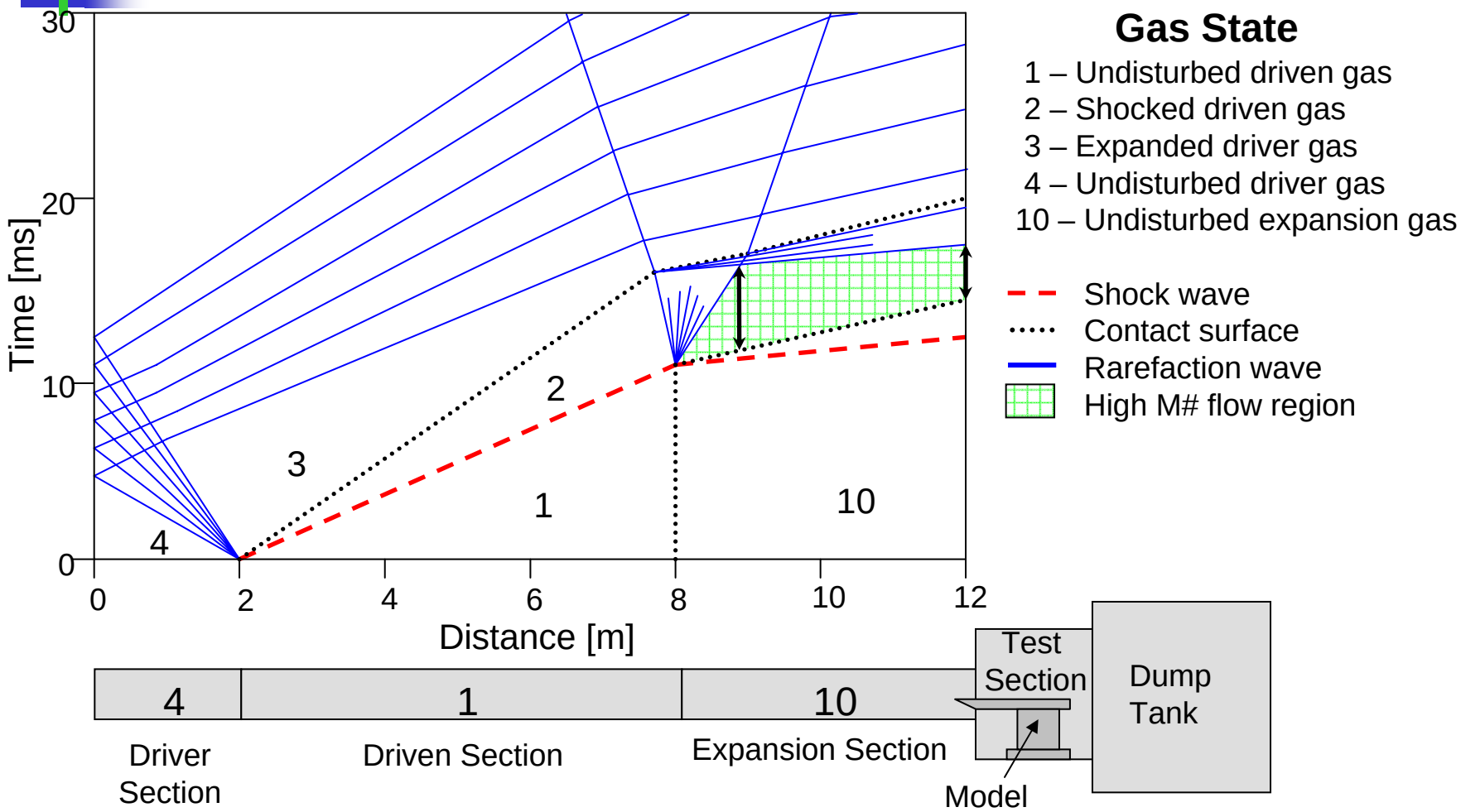
Expansion Tube Facility Available for Sensor Testing to M=5

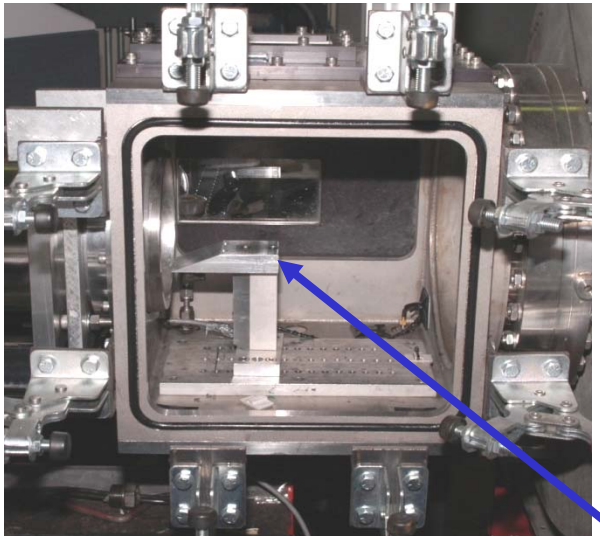


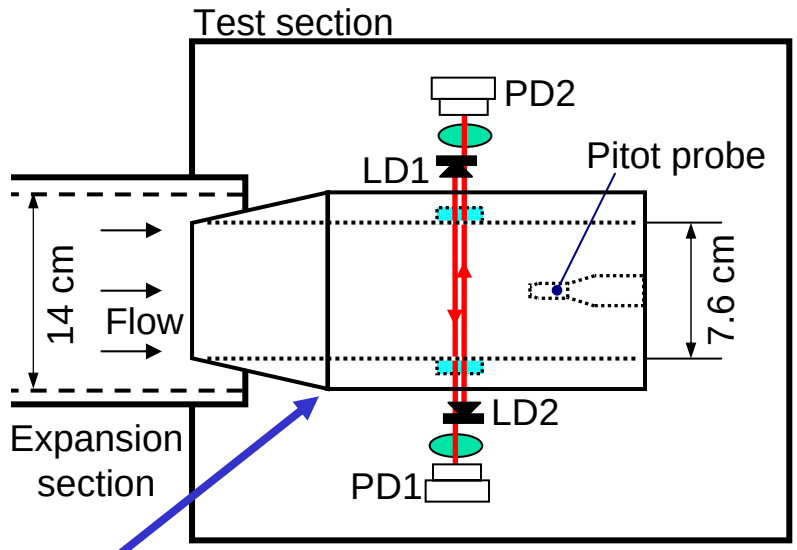
Stanford Expansion Tube Provides Wide Range of Flow Velocities



- Adjustable lengths of driver, driven and expansion sections enable variation of test time
- V up to 2km/s should be feasible

Test Model for Diode Laser Sensor Temperature Measurements in the Expansion-Tube Facility





Model

- Shock driven air expansion with H_2O at 50% relative humidity
- Two color TDL measurements at 100 kHz
- Ratio of TDL absorption of H_2O provides gas temperature
- Test rig will be modified for velocity measurements

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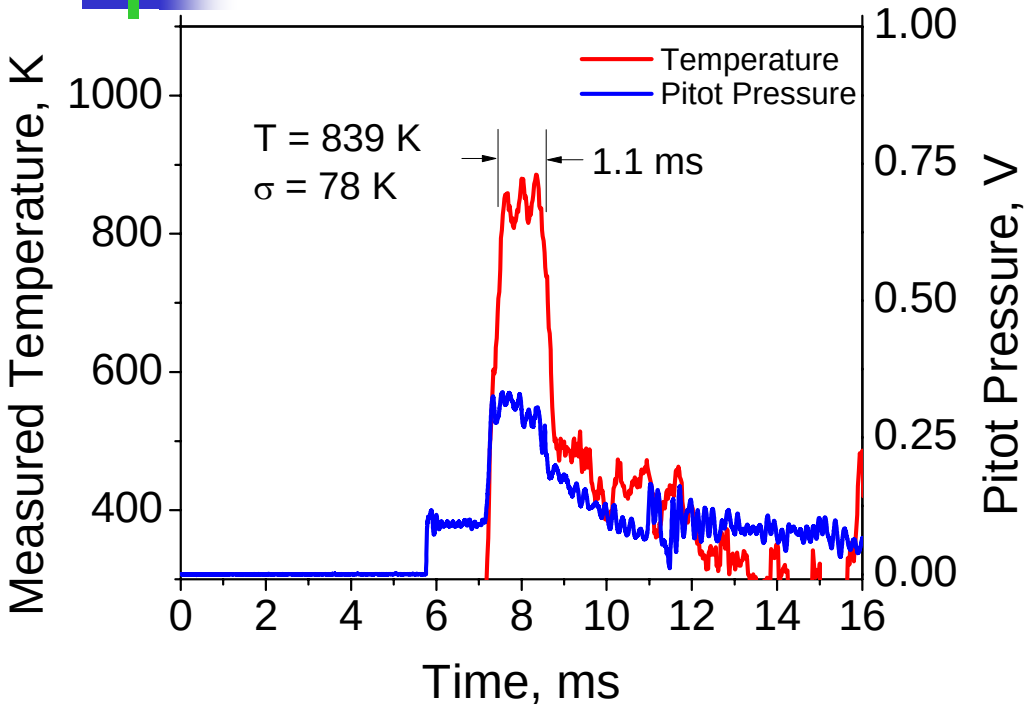
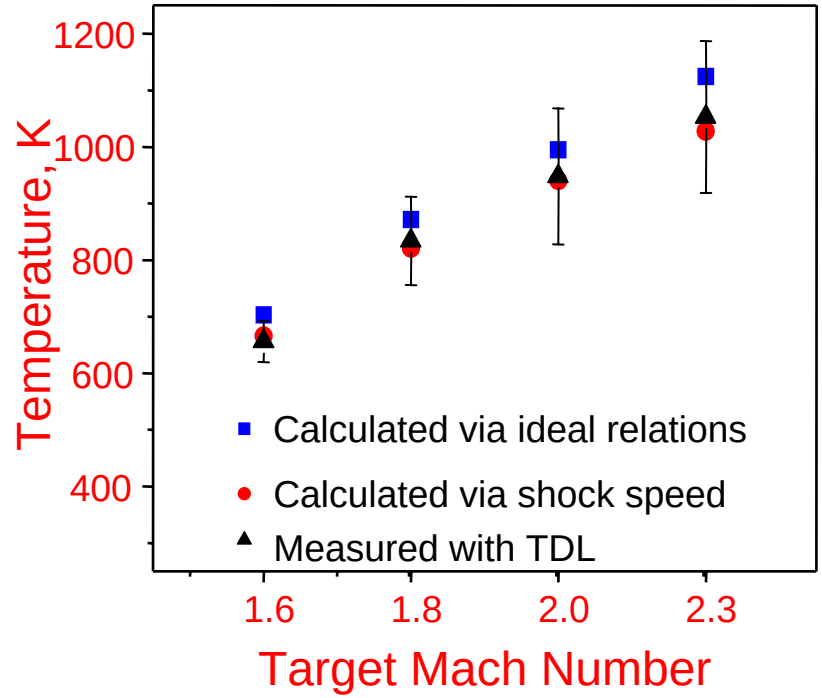
Preliminary TDL Measurements in Expansion Tube





- Two color diode laser measurements of water temperature illustrate feasibility of validation testing of mass flux sensor design, sensor software, and all hardware except for O_2 lasers

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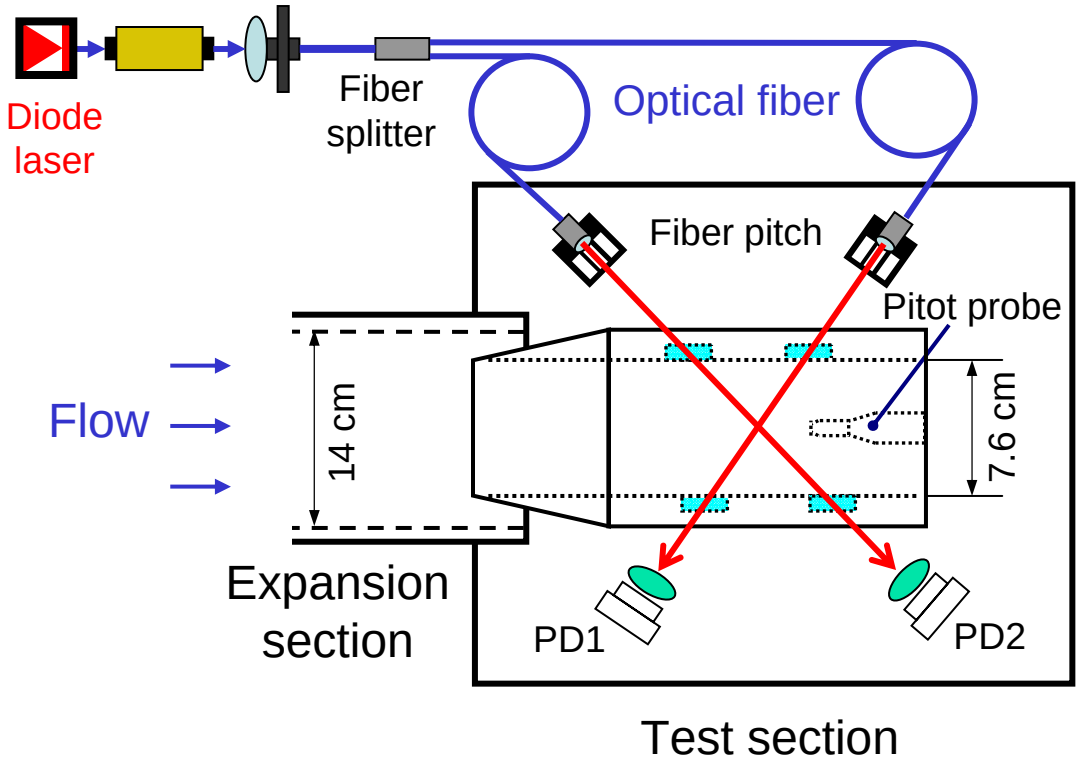
Modify Model for TDL V Sensing in Expansion Tube



- Velocity measurements in the expansion tube use a modified model with one diode laser and two beam paths
- Flow uniformity/non-uniformity can be measured with pitot probes

Progress and Ultimate Goal of This Research

Progress:

- Initial design of laser-based mass flux sensor specific to NASA facility
- Precision measurements of the supporting spectroscopy nearly complete
- Engineering and assembly of prototype sensor underway
- Validation tests planned at Stanford
- Planning begun for sensor tests in year 2 at NASA

Goal: Develop an experimentally validated tunable diode laser (TDL) absorption sensor for hypersonic ground-test applications and evaluate potential for flight use

Proposed Work Plan Year 1

- ✓ Select range of target flow conditions based on consultation with NASA personnel
- ✓ Optimum line selection requires S(T)~1/T to reduce sensitivity on T
  - ✓ Two H_2O lines selected for prototype sensor
- ✓ Investigate fiber-coupling strategies and develop method to split the laser into two or more paths without introducing intensity modulation into the two beams
- ✓ Acquire and fiber-couple lasers for prototype mass flux sensor and determine their frequency/intensity modulation characteristics
- ✓ Develop first-generation data-logging sensor software

1. Estimate the nonuniformities in the target flows to assess impact
2. Simulate signal lineshapes and strengths for a variety of WMS modulation conditions in a uniform flow (✓) and in a flow with the expected nonuniformities
3. Visit target NASA flow facilities to understand optical access options and determine the number of locations desirable for sequential/simultaneous measurements (visit planned)
4. Construct first-generation laboratory prototype sensor and test in Stanford expansion tube facility

- **Milestone Year 1:** Prototype sensor tests in Stanford high-speed flow facility

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Proposed Work Plan Year 2 and 3

Year 2:

- Refine/modify first-generation sensor design based on lessons learned
- Develop second-generation sensor software/hardware in preparation for field measurements at a NASA test facility
- Conduct validation experiments in Stanford test facilities
- Conduct field test(s) of sensor in NASA flow facility(ies) to evaluate sensor performance

Milestone Year 2: Test second-generation mass flux sensor at NASA

Year 3:

- Refine/modify second-generation sensor hardware/software based on lessons learned during NASA field test
- Finalize sensor design for ground testing applications
- Conduct field test(s) of sensor in NASA flow facility(ies) targeting mass flux ground test measurements (i.e. provide mass flux for ongoing ground test measurements)
- Develop design for potential flight sensor

Milestone Year 3: Report performance for TDL sensors in ground test applications and proposed design for flight sensor, and recommend further research requirements