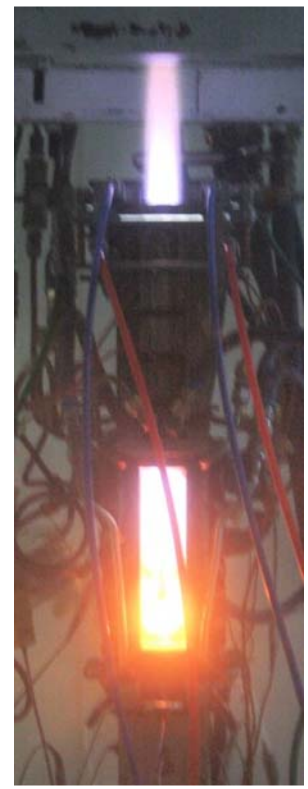
Quantitative Laser Diagnostics for Combustion Chemistry and Propulsion

Lecture 9: Tunable Diode Laser Absorption (TDLAS)

1. History and vision – for aeropropulsion
2. Absorption fundamentals
3. Absorption sensor strategies
4. Wavelength access – lasers and detectors
5. Example applications – aerospace
6. Future trends for aerospace



Direct-connect scramjet combustor
at UVa flow facility

1. The History of TDL Absorption for Aeropropulsion:
35 Years: From the Laboratory to Flight

1977 – TDL absorption in shock tube flows and flames

1989 – Mass flux sensor using O_2 absorption

1993 – Multiplexed measurements of H_2O, T and momentum flux

1998 – Combustion control (lab flames, incinerator)

2001 – Multi-species in flames: CO, CO_2, NH_3, H_2O

1996-present – Applications to flow facility characterization: arcjets, hypersonic flow tunnels, gas turbine engine sector rigs…

1998-present – Applications for engine tests: scramjet combustors, commercial aircraft engines, ic-engines, pulse detonation engines, gas turbines, augmentors…

2012 – TDL absorption by AFRL for T and combustion efficiency in scramjet flight test

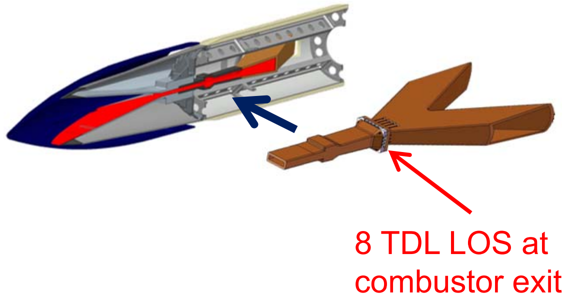
T/species in Shocktube

Hanson, *Appl Opt* (1977)

SCRAMJET @ WPAFB

Rieker, *Proc Comb Inst* (2009)

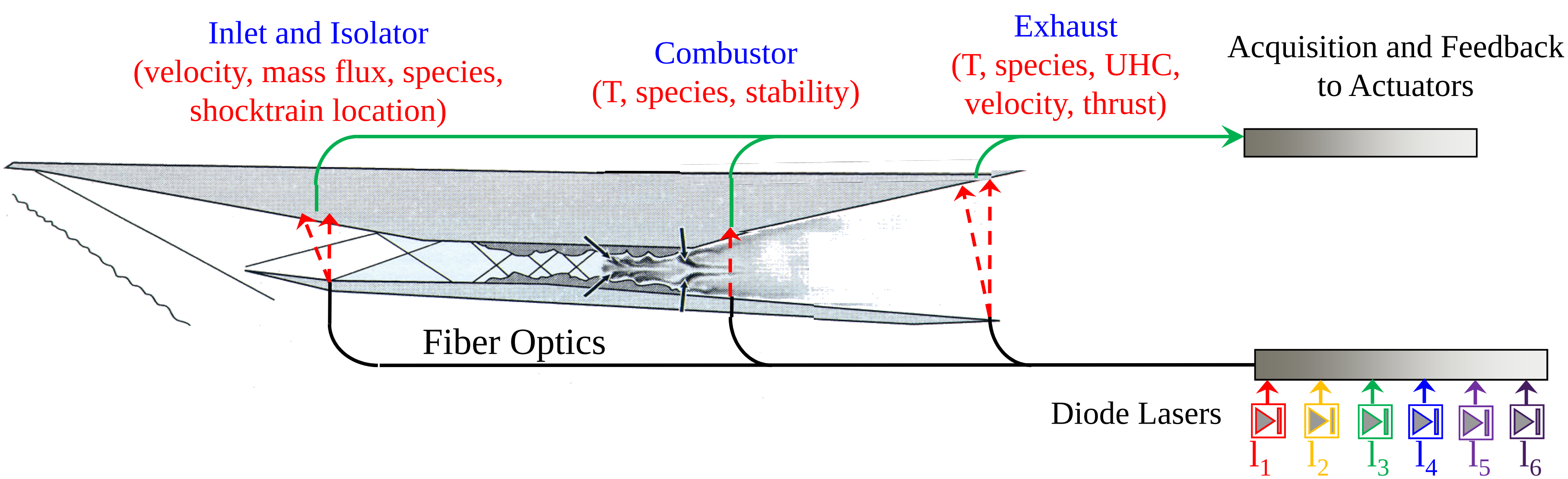
HiFire-2 Scramjet Flight Test



AFRL WPAFB: scheduled 2012

1. Vision for TDLAS Sensors for Aeropropulsion

– Diode laser absorption sensors offer prospects for time-resolved, multi-parameter, multi-location sensing for performance testing, model validation, feedback control

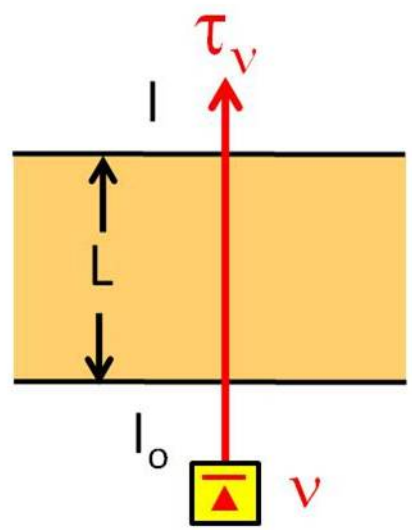


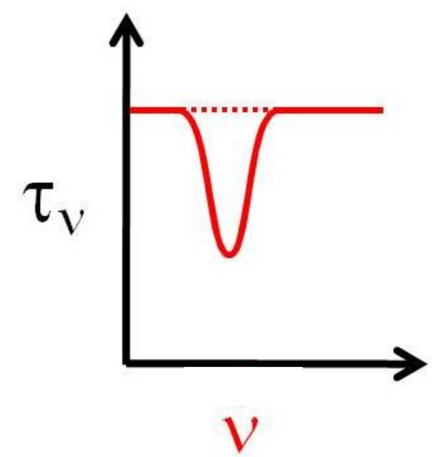
- Sensors developed for T, V, H_2O, CO_2, O_2, & other species
- Prototypes tested and validated at Stanford
- Several successful demonstrations in ground test facilities
- Opportunities emerging for use in flight

Now for some absorption fundamentals

2. Absorption Fundamentals: The Basics

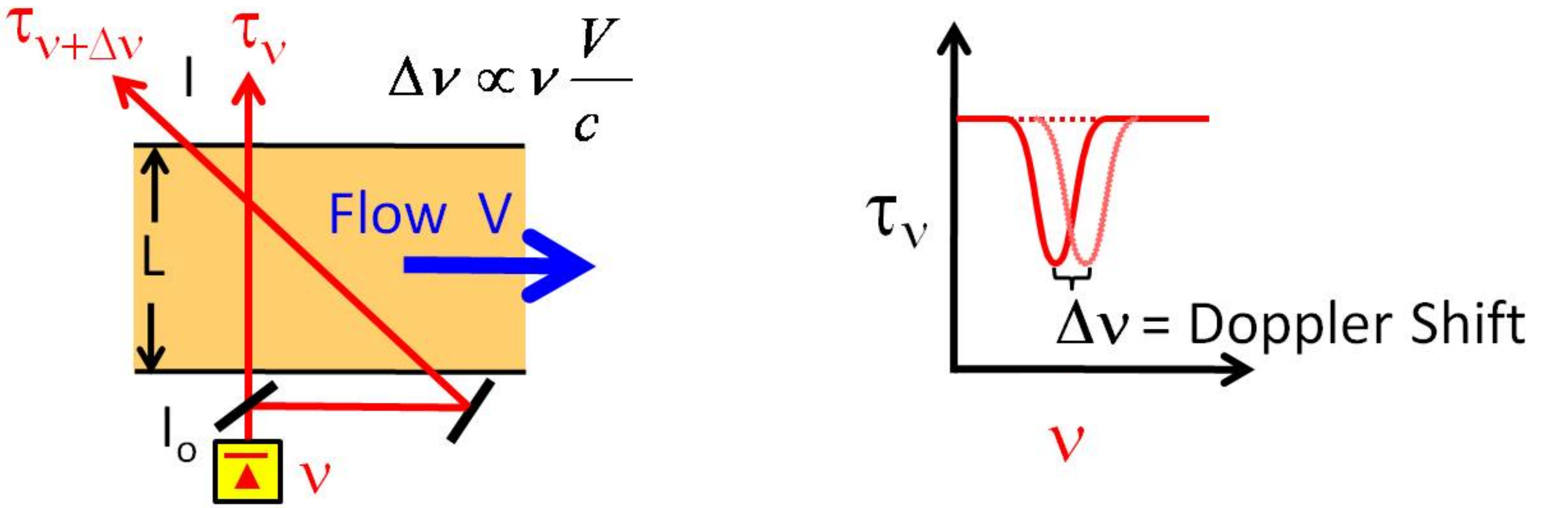
Absorption of monochromatic light





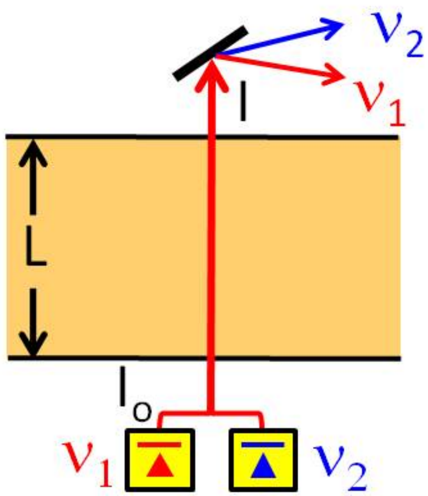
- **Scanned-wavelength *line-of-sight* direct absorption**
  - **Beer-Lambert relation** $\tau_\nu \equiv \dfrac{I_t}{I_o} = \exp(\underbrace{-k_\nu \cdot L}_{\text{absorbance}}) = \exp\left(-n_i \cdot \sigma_\nu \cdot L\right)$
  - **Spectral absorption coefficient** $k_\nu = S(T)\cdot\Phi(T,P,\chi_i)\cdot\chi_i\cdot P$

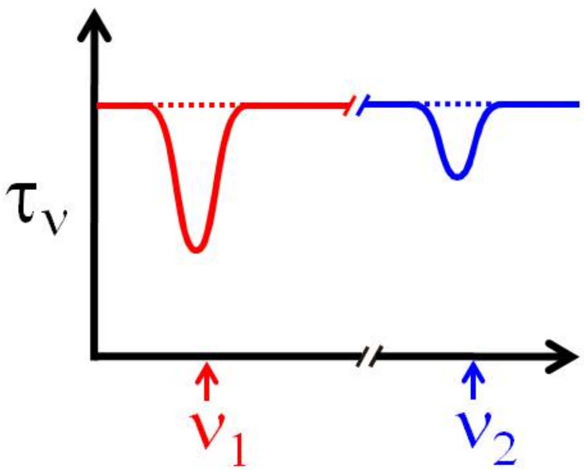
2. Absorption Fundamentals: The Basics



- **Shifts & shape of Φ contain information (T,V,P,χ_i)**

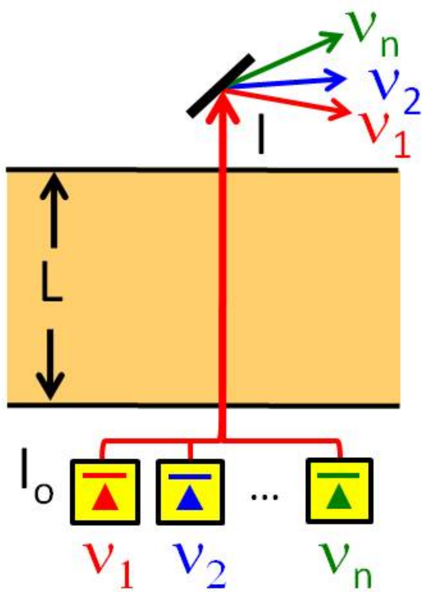
2. Absorption Fundamentals: The Basics

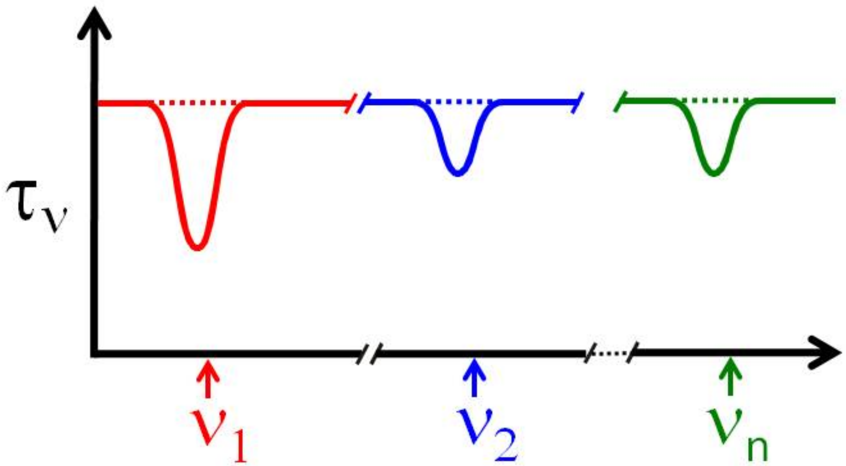




- **T from ratio of absorption at two wavelengths**

2. Absorption Fundamentals: Summary



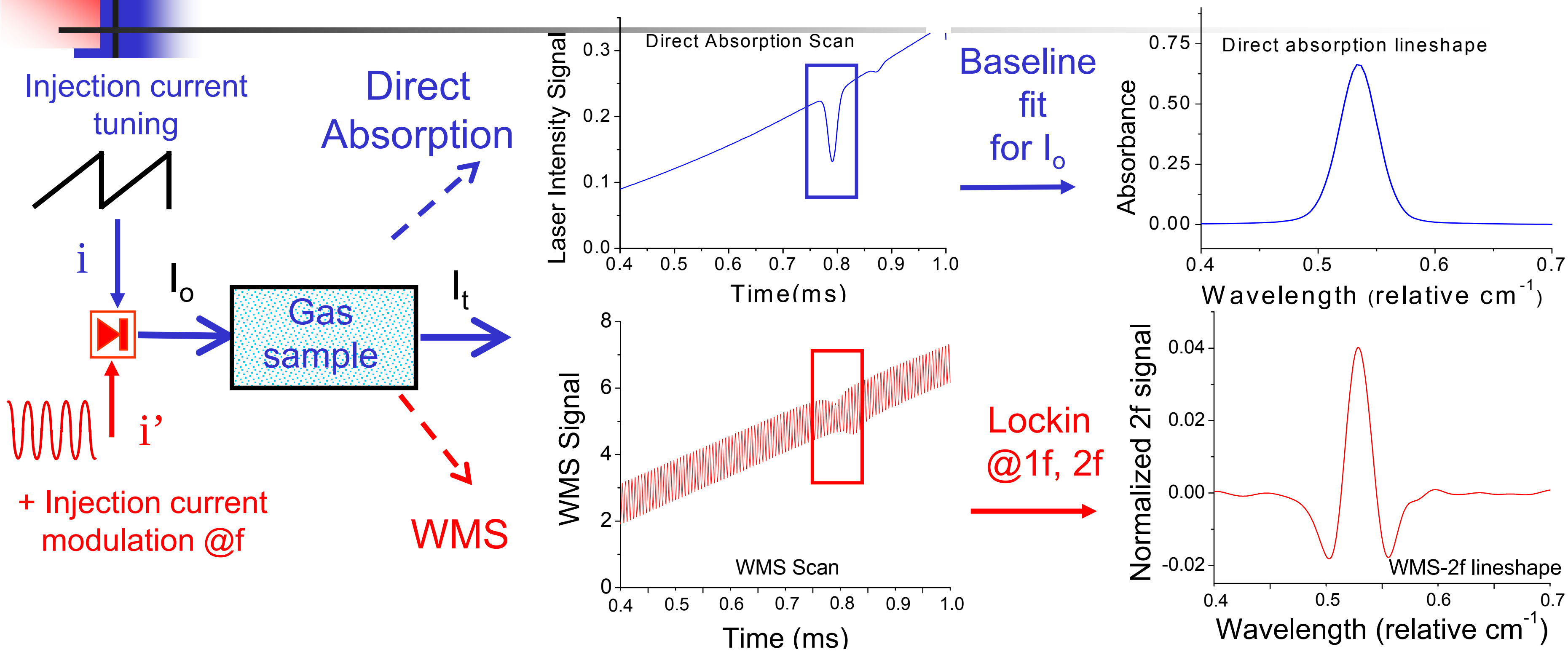


- **Wavelength multiplexing is also effective**
  - **To monitor multiple parameters or species**
  - **To assess non-uniformity along line-of-sight**

Two primary strategies for absorption measurements

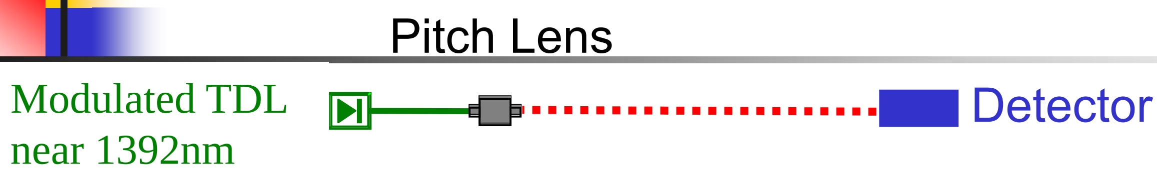
3. Absorption Sensor Strategies:

Direct Absorption (DA) & Wavelength Modulation Spectroscopy (WMS)

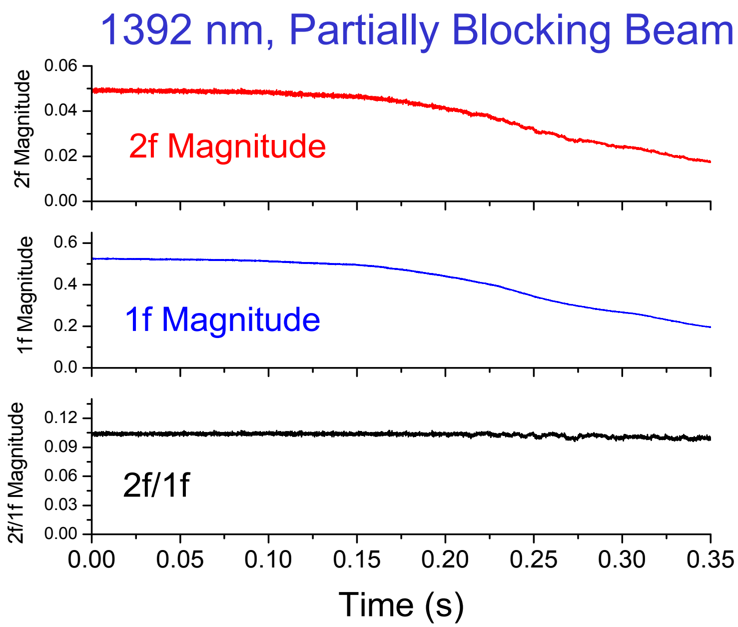


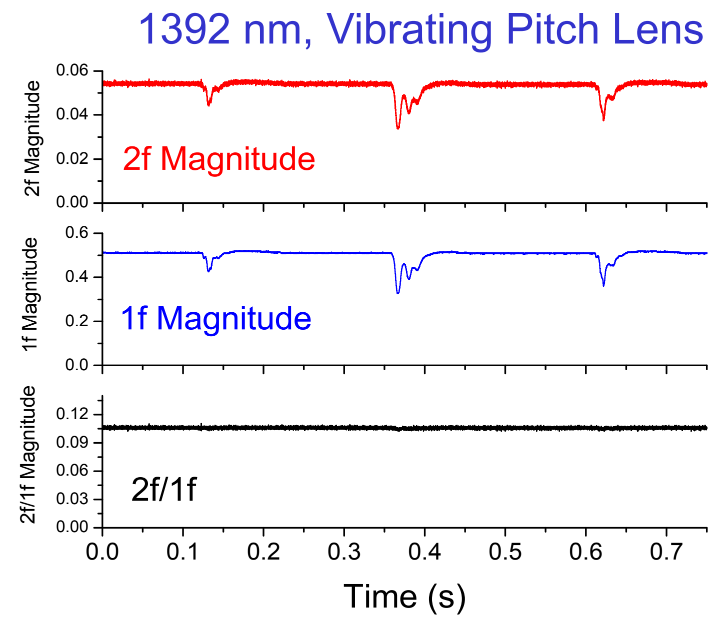
- **Direct absorption: Simple, if absorption is strong enough**
- **WMS: More sensitive especially for small signals (near zero baseline)**
  - **WMS with TDLs improves noise rejection**
  - ***Normalized WMS, e.g. 2f/1f* cancels scattering losses!**

3. Absorption Sensor Strategies:
WMS-2f/1f Accounts for Non-Absorption Losses



- Fixed λ WMS-*2f/1f*
- Ambient H_2O (T=296 K, 60% RH)
- L=29.5 cm, ~6% absorbance)



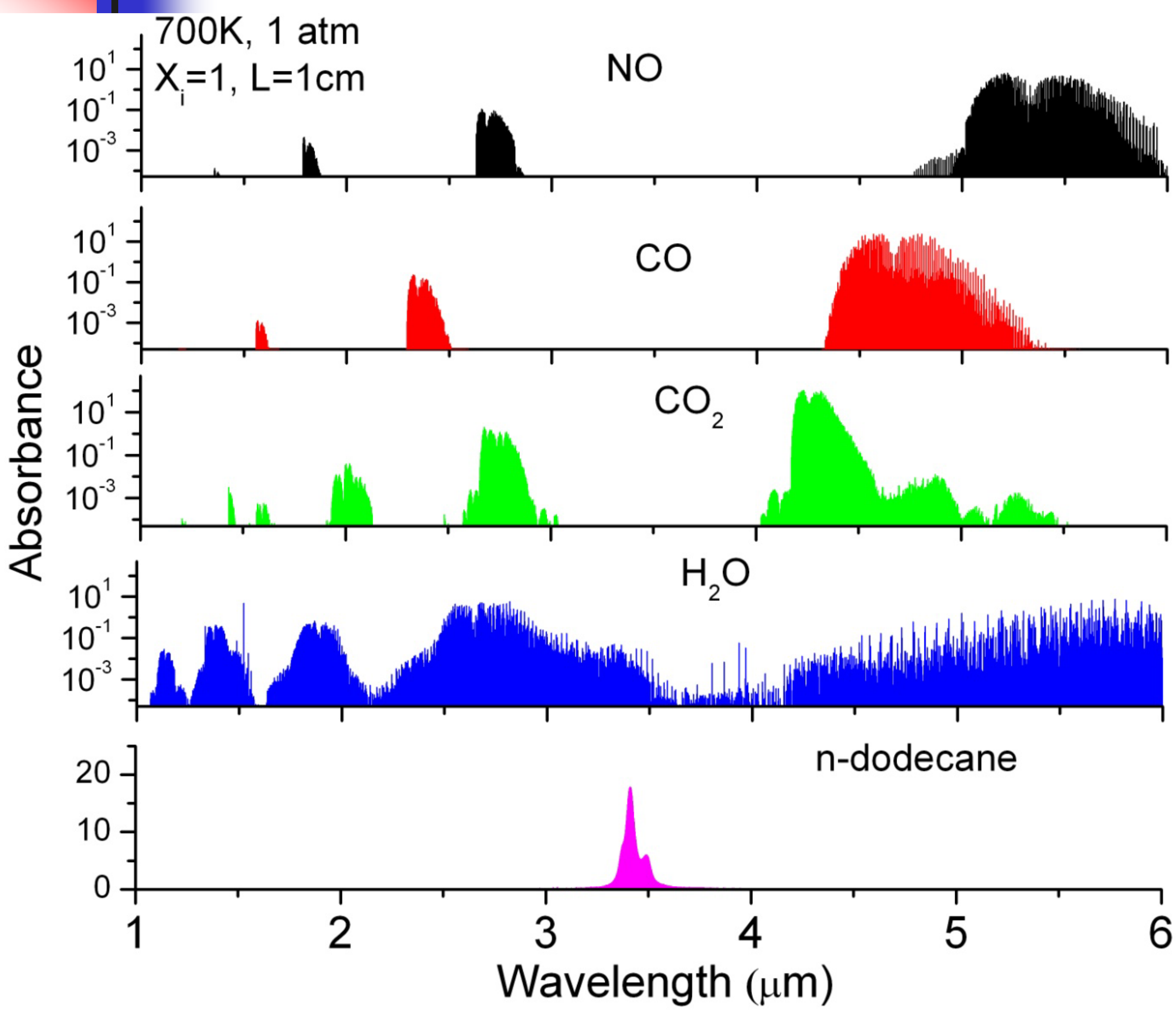


- **Demonstrate normalized WMS-*2f/1f* in laboratory air**
  - **2f/1f unchanged when beam attenuated (e.g., scattering losses)**
  - **2f/1f unchanged when optical alignment is spoiled by vibration**

WMS-*2f/1f* signals free of window fouling or particulate scattering

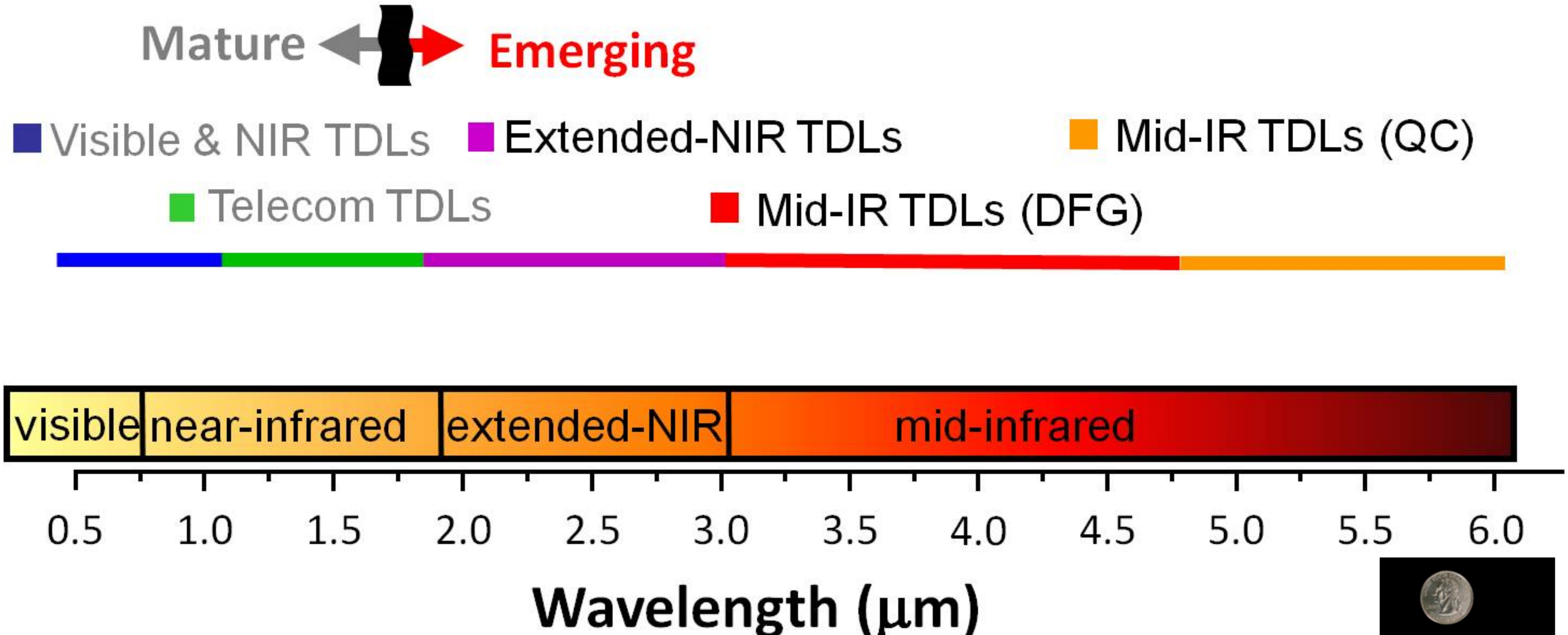
What species/wavelengths can we access?

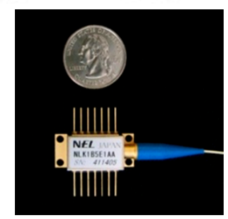
4. Wavelength Access: A Wide Range of Combustion Species/Applications using Wavelengths in the IR



- Small species such as NO, CO, CO_2, and H_2O have discrete rotational transitions in the vibrational bands
- Larger molecules, e.g., hydrocarbon fuels, have blended features
- Different strategies used to monitor discrete lines or blended absorption features

4. Wavelength Access:
TDLs Access Visible to Mid-IR



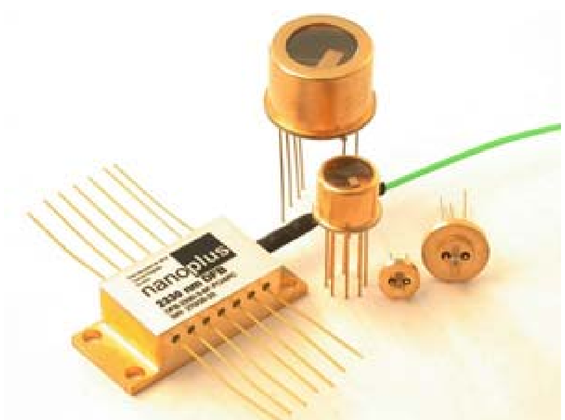


- Allows access to many atoms and molecules
- Visible and telecom TDLs can be fiber-coupled
- TDLs at wavelengths > telecom are emerging rapidly

Now lets consider hardware: lasers and detectors

4. Wavelength Access - Lasers

- Sources – <u>Semiconductor lasers</u>
  - Available from the near UV (375 nm) to the far-IR (~ 11 μm)
    - Power: ~ 1 to 500 mW
    - Low power restricts their application to absorption experiments
  - Near-IR lasers are compact, rugged, and fiber-coupled
  - DFB lasers can be rapidly tuned over several wavenumbers by changing the injection current or laser temperature
    - External cavity diode lasers can be tuned more than 100 cm^{-1}



Diode lasers, near- to extended-near-IR
($1000 - $6000)
Fiber-coupled up to 2.3μm

QC lasers, mid-IR (~$40,000)

4. Wavelength Access - Detectors

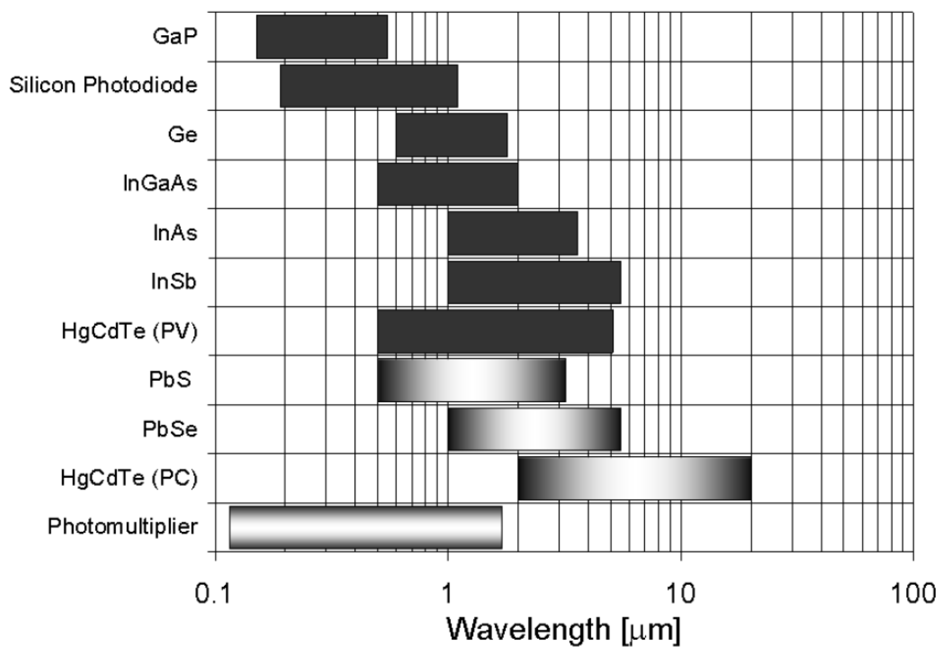
- Detectors – Photodiode/Photovoltaic detectors
  - A photodiode is a semiconductor that generates voltage or current when light is incident on it
  - Like photoconductors, they have a minimum photon energy associated with the bandgap energy of the semiconductor
  - Source of noise: Johnson noise (not shot-noise limited)
  - A variation is avalanche photodiode, signal (volts) = constant x intensity

Detector material	λ [μm]
Si	0.2 – 1.1
Ge	0.4 – 1.8
InAs	1.0 – 3.8
InSb	1.0 – 7.0
InSb (77K)	1.0 – 5.6
HgCdTe (77K)	1.0 – 25.0

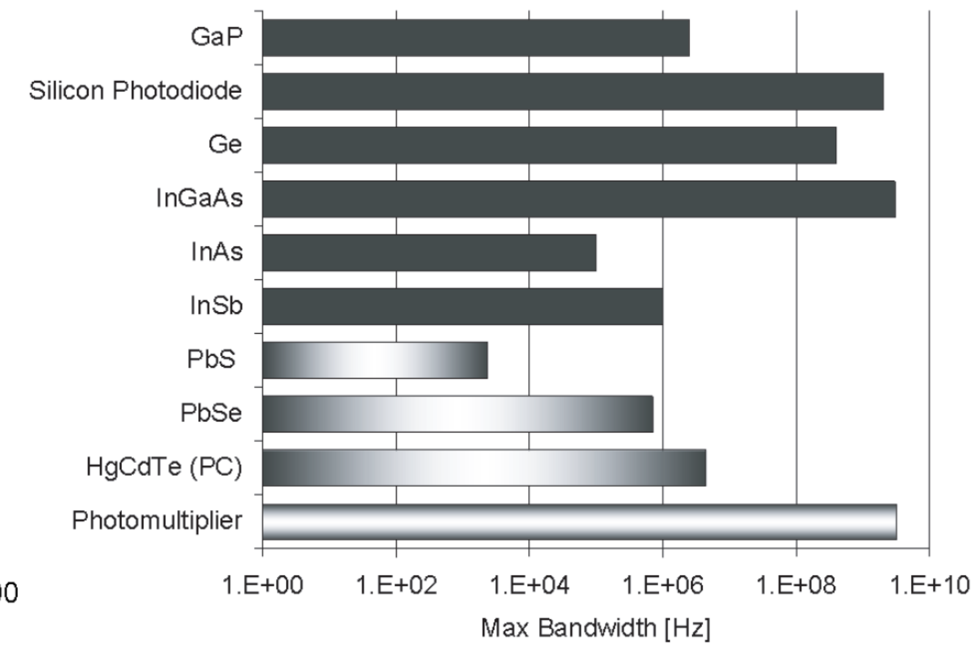
4. Wavelength Access - Detectors

- Detectors – <u>Select a detector</u>
  - **Criteria**: wavelength, time response, noise, simplicity, cost …

Wavelength



Bandwidth



  - Frequency bandwidth is important for time-resolved measurements
  - Bandwidth depends on the detector area, material, temperature, and pre-amplifier gain

4. Wavelength Access - Detectors

- Detectors – <u>Select a detector</u>
  - Detector noise is characterized by the detectivity, ***D****

$$D^* = \frac{\sqrt{A_{\text{Detector}}\Delta f}}{\text{NEP}}$$

    - Δf = bandwidth
    - NEP = noise equivalent power: the amount of the optical power required to equal the magnitude of the detector noise
    - D* is improved at lower temperatures (cooling)
  - The signal-to-noise ratio (SNR) for a measurement dominated by the detector noise can be calculated using:

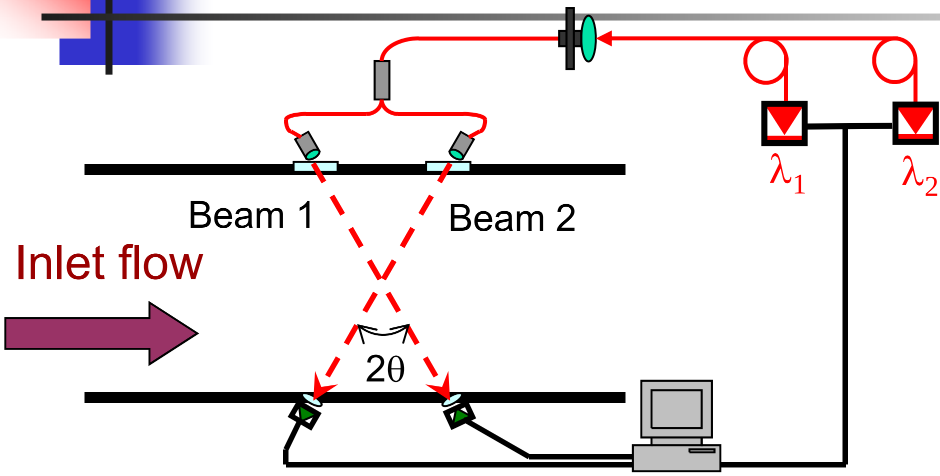
$$\text{SNR} = \frac{P_{\text{incident}}}{\text{NEP}} = \frac{P_{\text{incident}} D^*}{\sqrt{A_{\text{Detector}}\Delta f}}$$

  - Cost and complexity are also important considerations
  - Spatially uniform responsivity is also important
    - Smaller and cooled detectors are more uniform

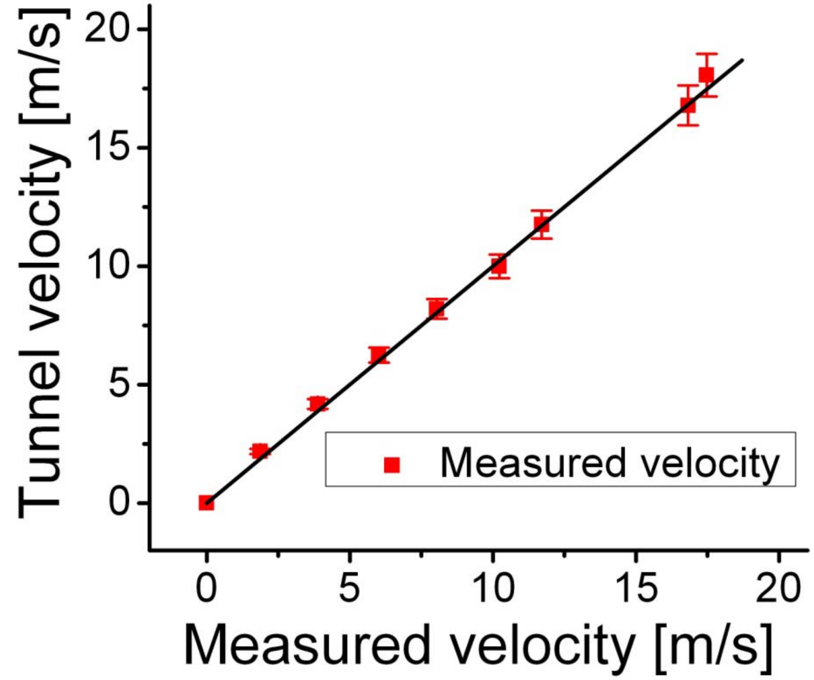
5. Example TDL Applications - Aerospace

1. Subsonic velocity in a laboratory wind tunnel @SU – ambient H_2O
2. Supersonic velocity in a test facility @NASA – H_2O from vitiation
3. Supersonic combustion @UVa – non-uniform T and species on LOS
   - Solutions for non-uniformities (column density and species weighted T)
   - Measurements in H_2 fueled combustor of H_2O column density and T_{H2O}
   - Velocity in H_2 fueled combustor
4. Supersonic combustion @ATK – M10 flow capture by model scramjet
5. Scramjet unstart monitor @AFRL

5.1 Subsonic Velocity @ SU:
TDLAS Sensors in Wind Tunnel



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



- TDL sensor of mass flux based on H_2O absorption
- Velocity from Doppler shift of absorption wavelength
- Validate sensor in subsonic wind tunnel w/ ambient H_2O @ Stanford
- 0.5 m/s precision for V in uniform subsonic flow

Next: Test in supersonic-flow facilities at NASA Langley

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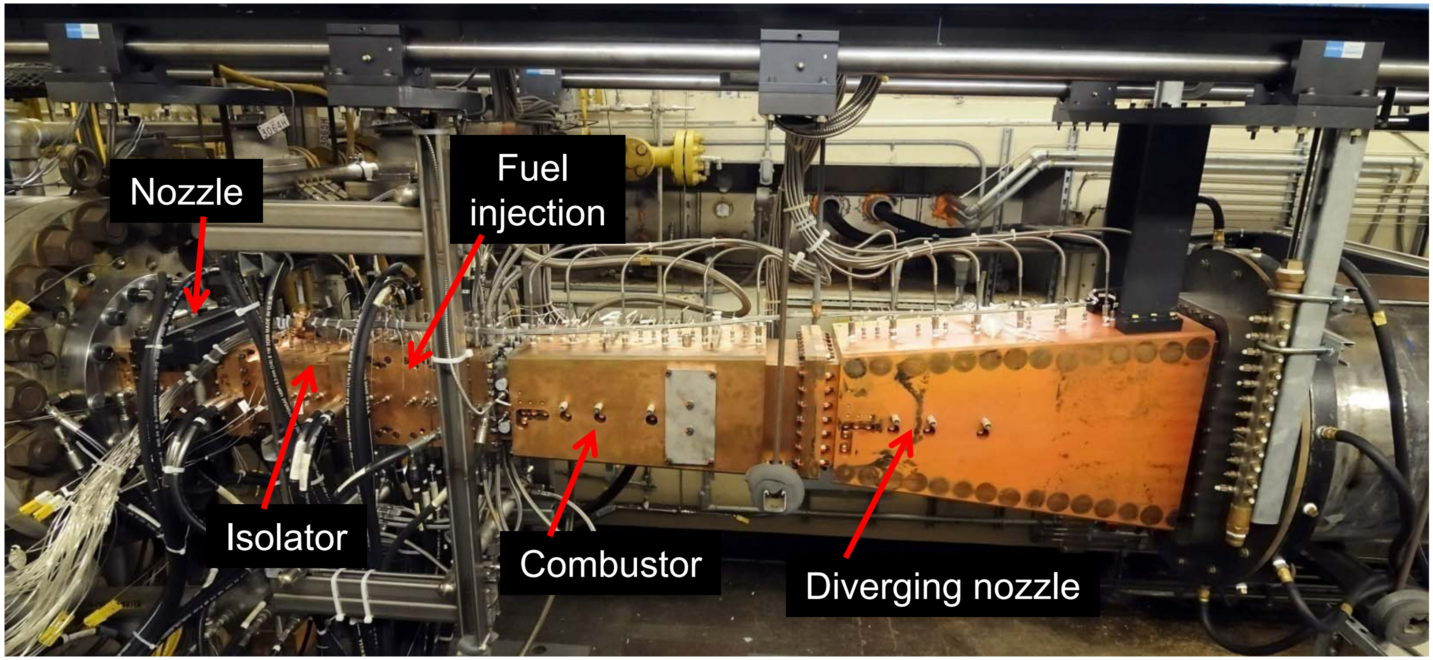
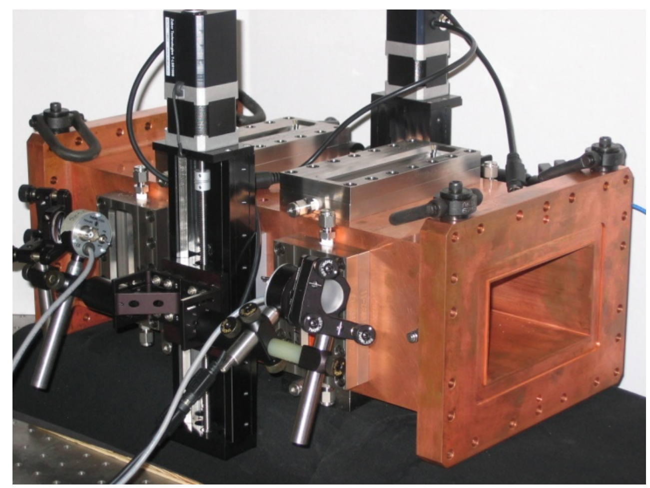
5.2 Supersonic Velocity@NASA Langley via TDLAS:
Direct-Connect Supersonic Combustion Test Facility

Vitiated inlet air



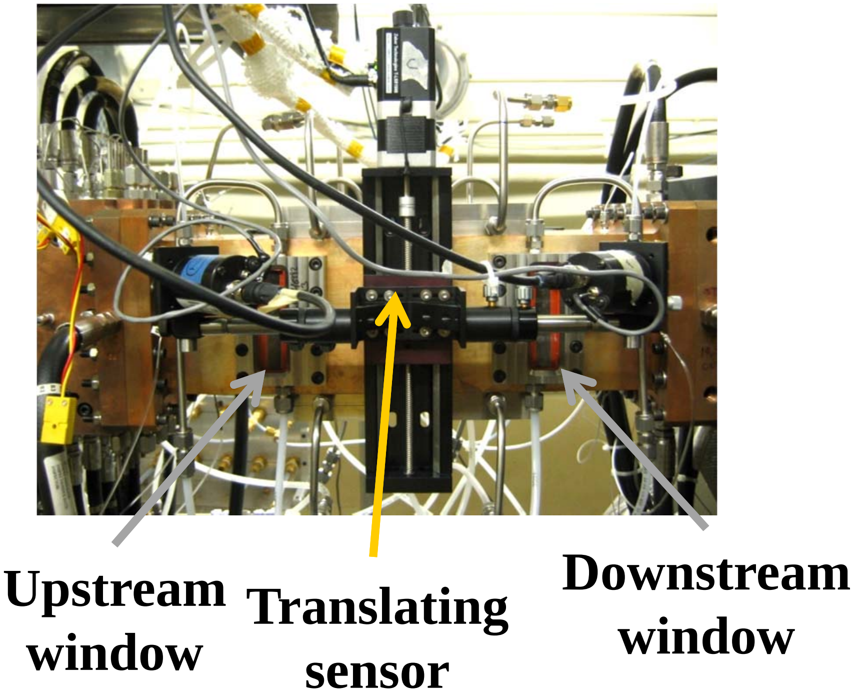
DCSCTF: Simulates atmospheric supersonic and hypersonic flight conditions

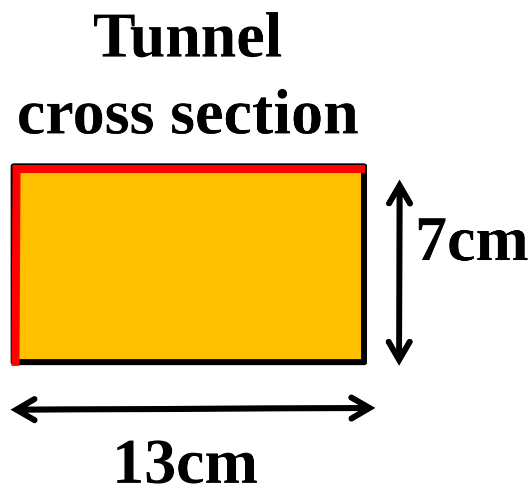
- M=2.65 nozzle with T_{static}~ 990K and P_{static}~ 0.7 atm; simulates M=5 flight
  - Add optical access to isolator
  - Measure V, T, mass flux



5.2 Supersonic Velocity @NASA via TDLAS

Supersonic test facility at NASA Langley (2009)





- Sensor translates to probe vertical and horizontal planes

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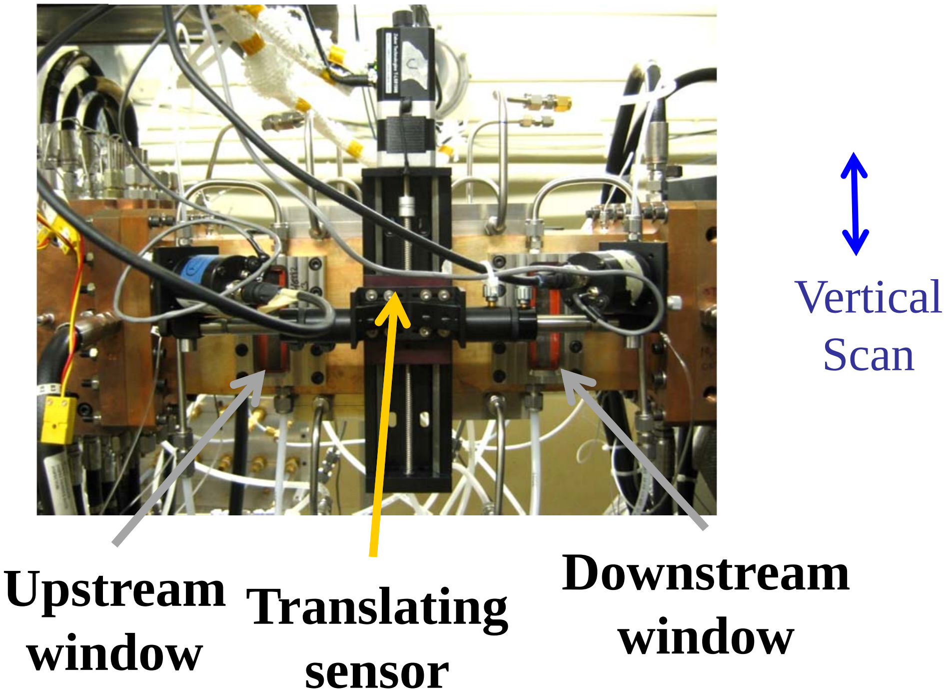

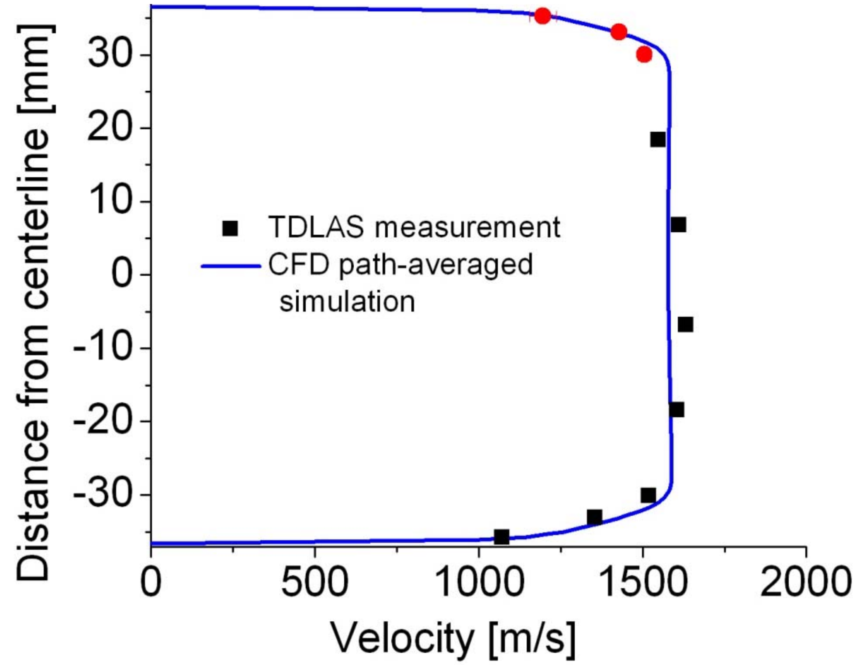

- **Sensor translates to probe vertical and horizontal planes**

Chang et al., AIAA, 2011

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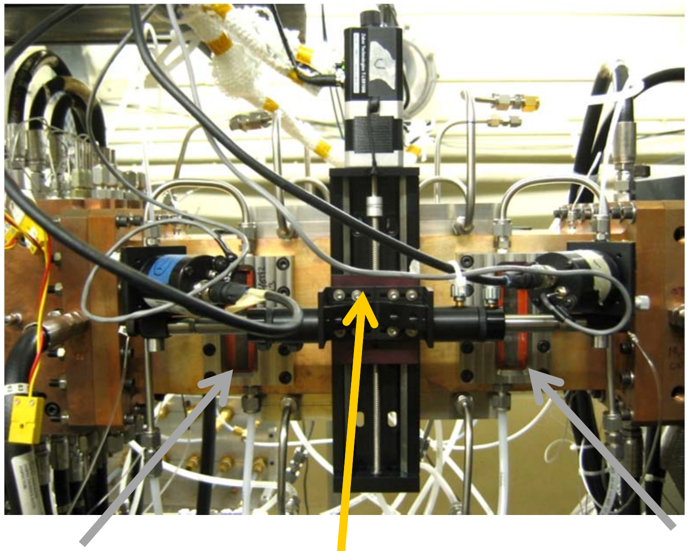
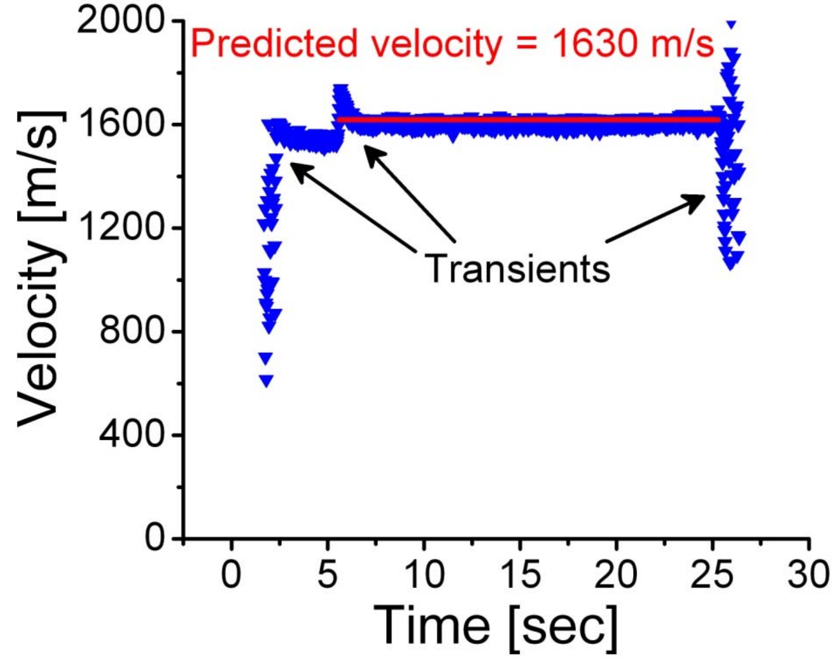




- **Sensor translates to probe vertical and horizontal planes**
- **Fast sensor captures start-up transients in V and T**

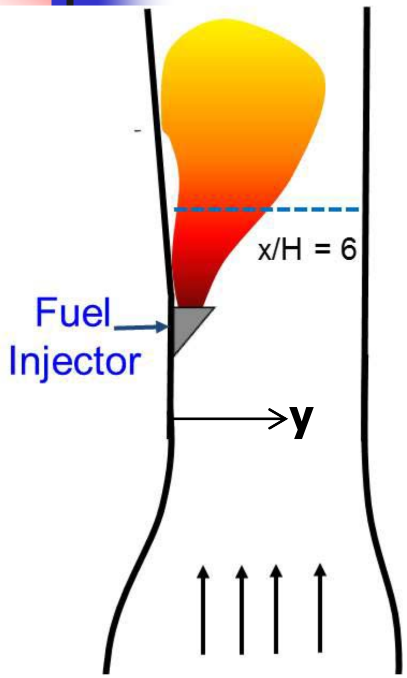
Next: A supersonic combusting flow @ UVa

Chang et al., AIAA, 2011

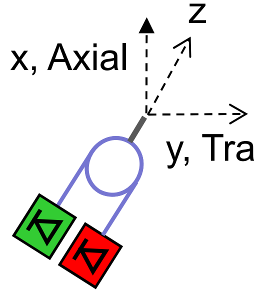
5.3 Supersonic Combustion @ Uva

CFD Predicts Non-Uniform H_2O Products of Combustion

UVa Combustor

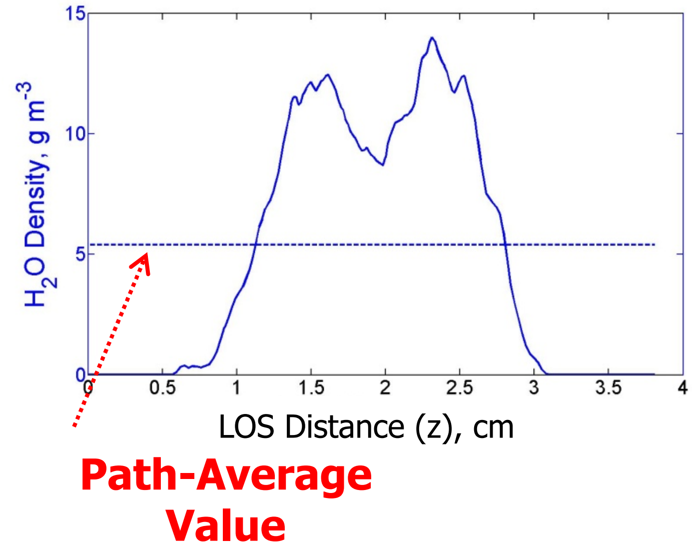


Two-color TDL Sensor for T and H_2O



NCSU CFD along TDLAS LOS @ x/H=6

Φ=0.17, y= 0.4” from injector wall

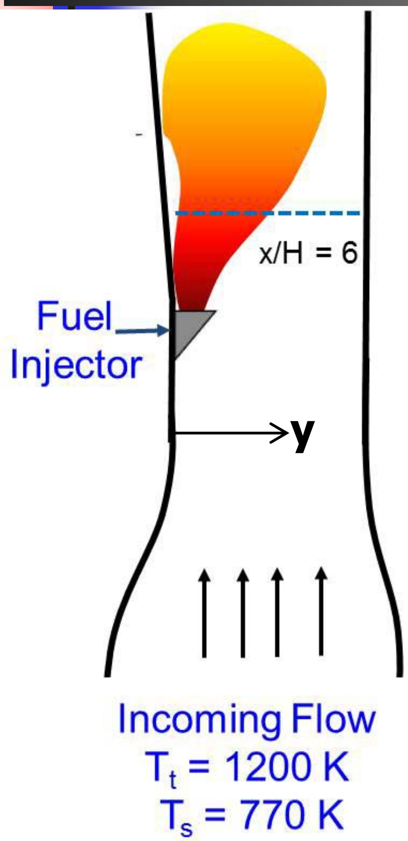


- Combustion of jet in supersonic cross flow produces non-uniform distribution
- Two-color sensor is scanned transverse to flow to give f(y) data
- But what about variations along LOS(z)?
  - Predicted H_2O density not uniform

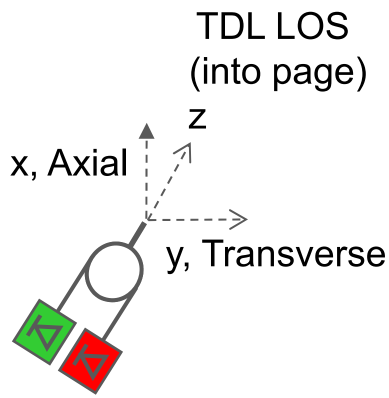
5.3 Supersonic Combustion @ Uva

CFD Predicts Non-Uniform H_2O Products of Combustion

UVa Combustor



Two-color TDL Sensor for T and H_2O



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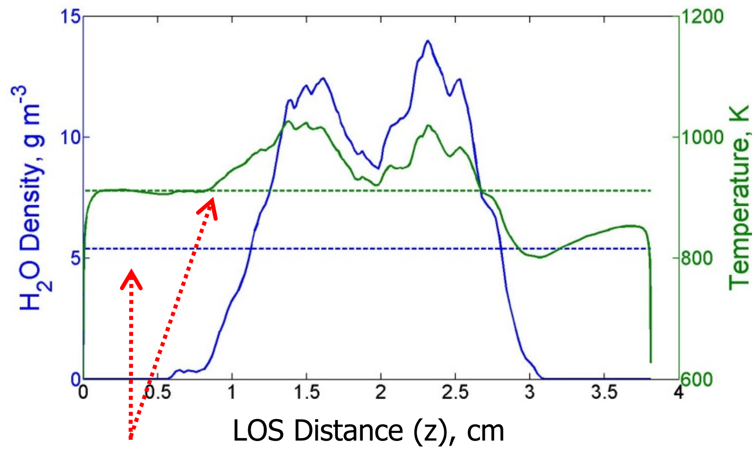


Path-Average Values

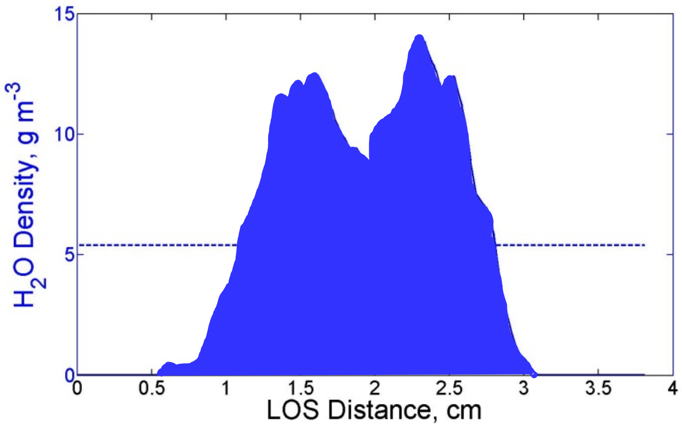
- But what about variations along LOS(z)?
  - Predicted H_2O density and temperature are both not uniform

What can be done for this problem?

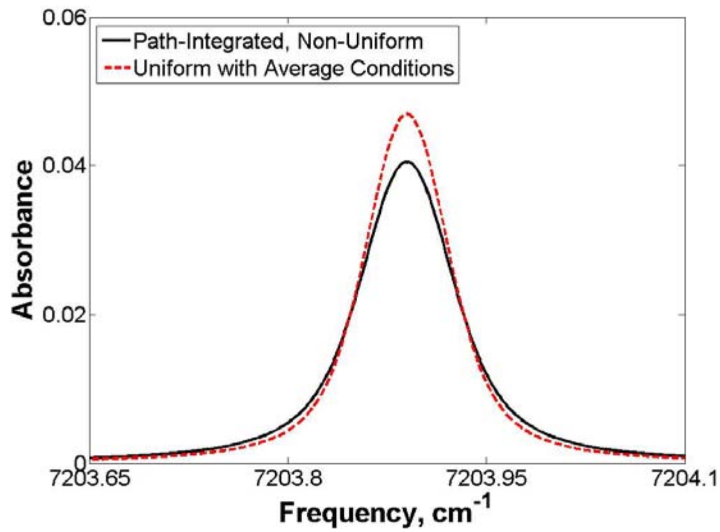
5.3 Supersonic Combustion @ Uva

Non-Uniform T and H_2O Affect Absorption

NCSU CFD along TDLAS LOS @ x/H=6



Simulated absorbance



- **Non-uniformity impacts values of absorbance**

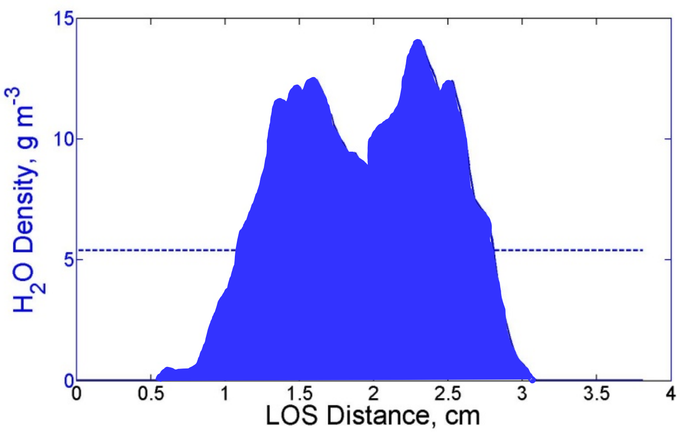
Solution for non-uniform H_2O: Introduce column density σ_{H2O}

-Allows direct comparison with CFD

5.3 Supersonic Combustion @ Uva

Non-Uniform T and H_2O Affect Absorption

NCSU CFD along TDLAS LOS @ x/H=6



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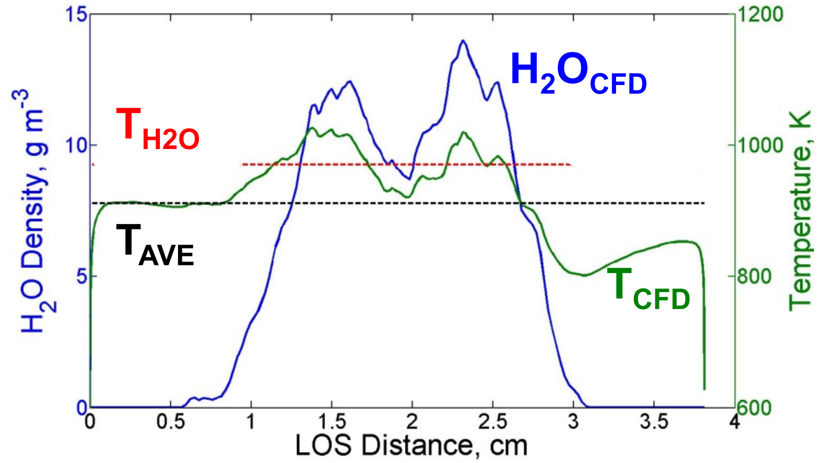


- **Non-uniformity impacts values of absorbance**

Solution for non-uniform H_2O: Introduce column density σ_{H2O}

-Allows direct comparison with CFD

Solution for non-uniform T: 1. Optimize the line selection

2. Measure species-specific T_{H2O}

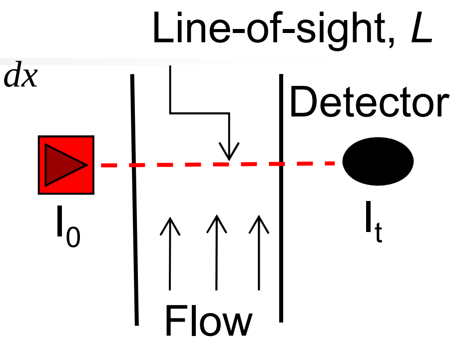
-Extend to multi-species; e.g., T_{CO2}

-Another metric for new tests of CFD

5.3 Supersonic Combustion @ Uva

Column Density: New Paradigm to Test CFD

- **Problem: k_ν is not constant along LOS,** $\tau_\nu = \dfrac{I_t}{I_o} = e^{-\int_0^L k_\nu dx}$
  - **Why:** *T*, χ_{H2O}, and ρ are **not** uniform
  - **New Approach:** Write absorbance α in terms of ρ_{H2O}



$$\alpha_\nu = \int_0^L k_\nu dl = \int_0^L S(T)\Phi_\nu(T,\rho,\chi)\rho_{H_2O}R_{H_2O}Tdl$$

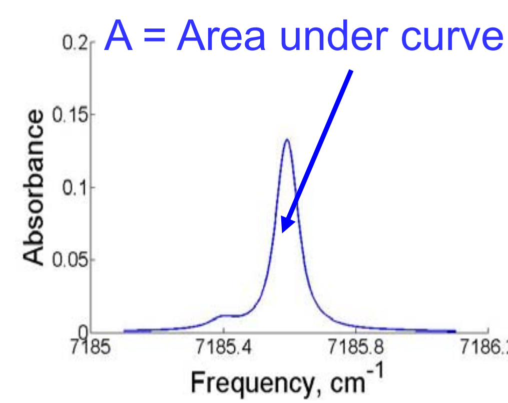
- **Strategy:**

1. Intelligent line selection ($S(T) \propto 1/T$)

   Thus, α_ν insensitive to non-uniform T

   and integrated absorbance (A) becomes

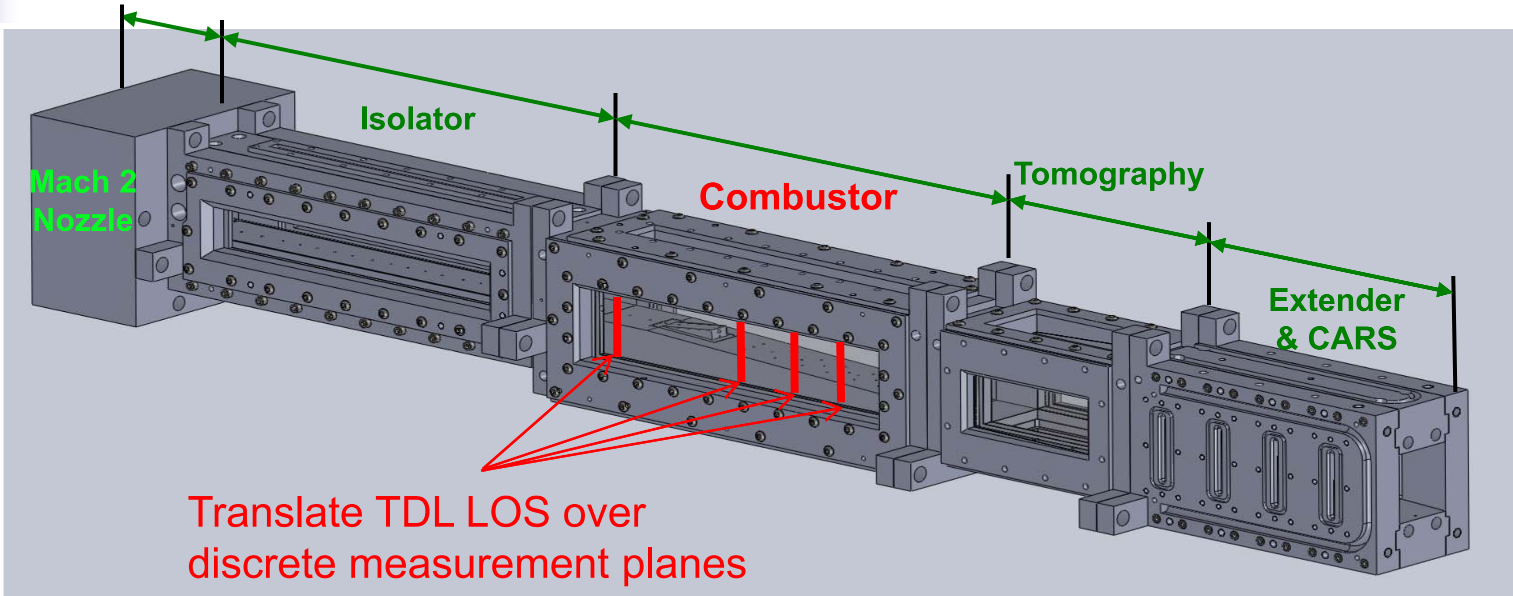
$$A = \int_{-\infty}^{\infty} \alpha_\nu d\nu = c\int_0^L \rho_{H_2O} dl = c \times \sigma_{H_2O}$$



2. Integrated absorbance yields column density $\sigma_{H_2O} \equiv \int_0^L \rho_{H_2O} dl$
3. Measured σ_{H2O} new direct test of CFD
4. T_{H2O} determined by ratio of absorbance on two H_2O lines

   also new test of CFD

5.3 Supersonic Combustion at UVa (H_2 Fueled)



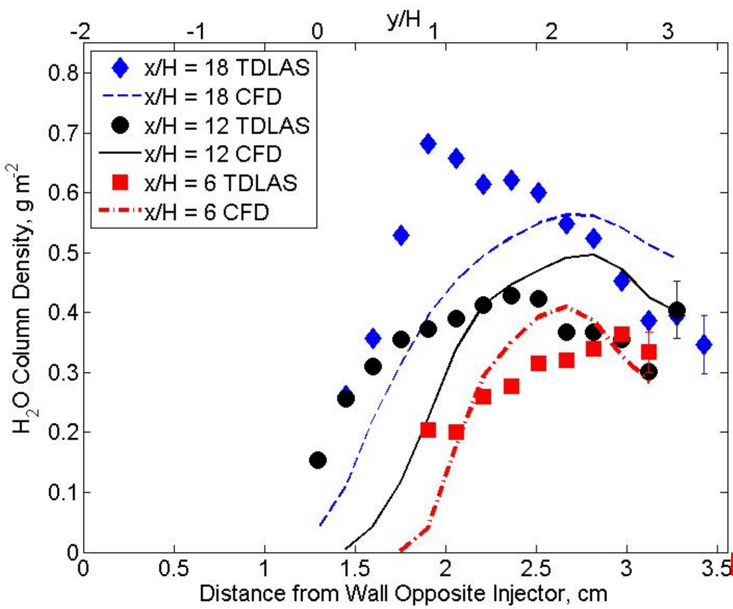
- Two-color NIR sensor developed for H_2O and tested at Stanford
  - Confirmed tunnel static temperature and inflow condition for CFD
  - σ_{H2O}, T_{H2O} & V_{H2O} data to compare with CFD at three measurement planes downstream of fuel injector

Now lets look at an example of the data compared to CFD

5.3 Supersonic Combustion @UVa

TDLAS Results vs CFD

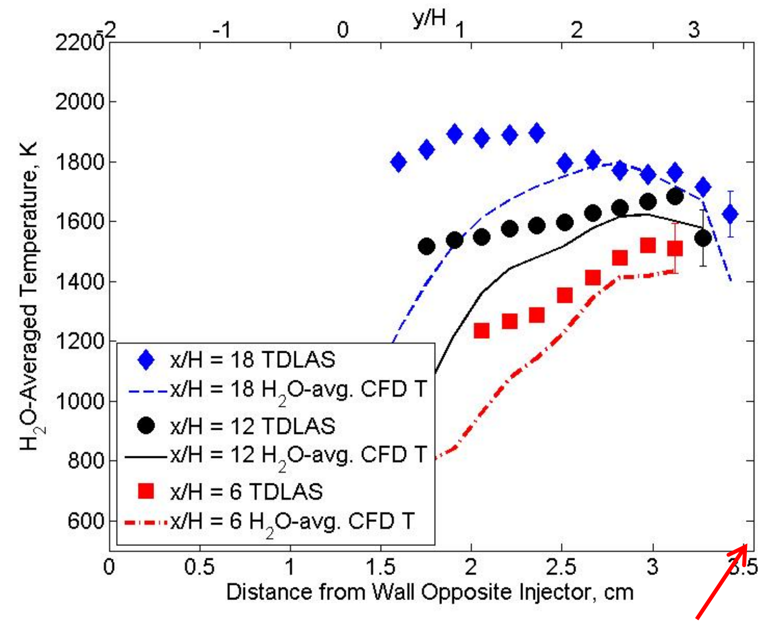
Column Density



ϕ=0.17

Injector side

Temperature



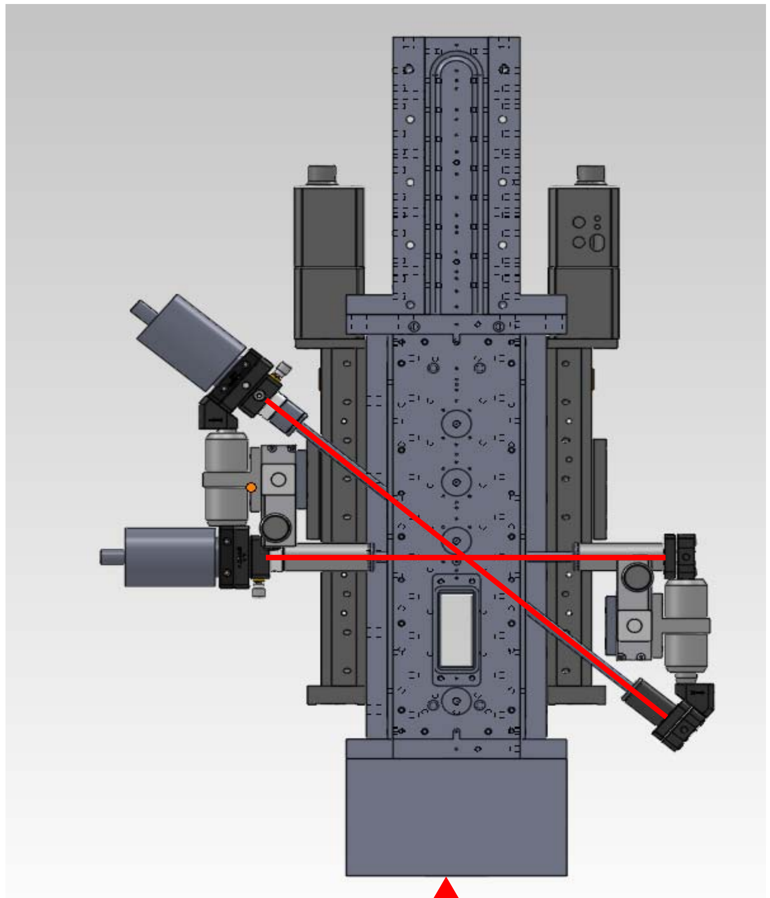
Injector side

- Measured σ_{H2O} in best agreement with CFD at x/H=6
  - TDLAS suggest greater fuel penetration than CFD predicts
- Measured T_{H2O} in similar agreement with CFD at all x/H
  - Good agreement near injector wall, higher measured T further from wall

Next: Velocity in this combusting flow

5.3 Supersonic Combustion @UVa

TDLAS Velocity via Doppler Shift



Flow

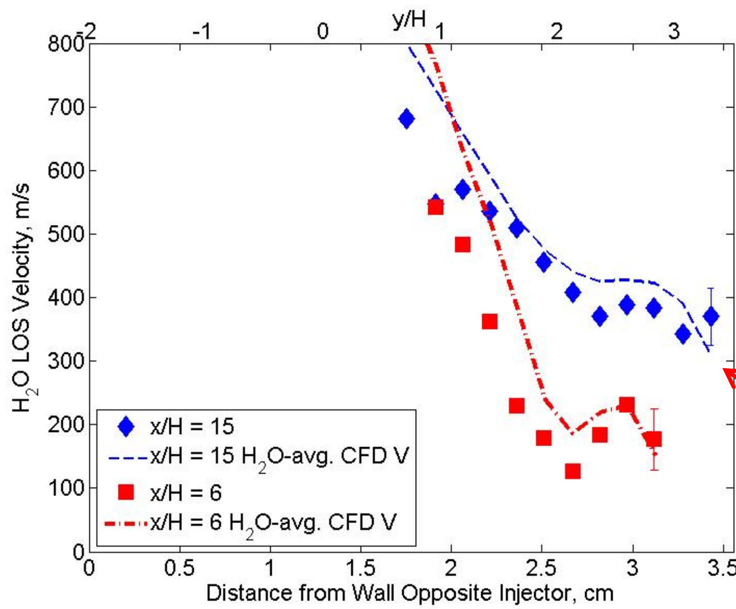
5.3 Supersonic Combustion @UVa

TDLAS V_{H2O} vs CFD for Combusting Flow

Axial Velocity

Core flow velocity
~950m/s

ϕ=0.17



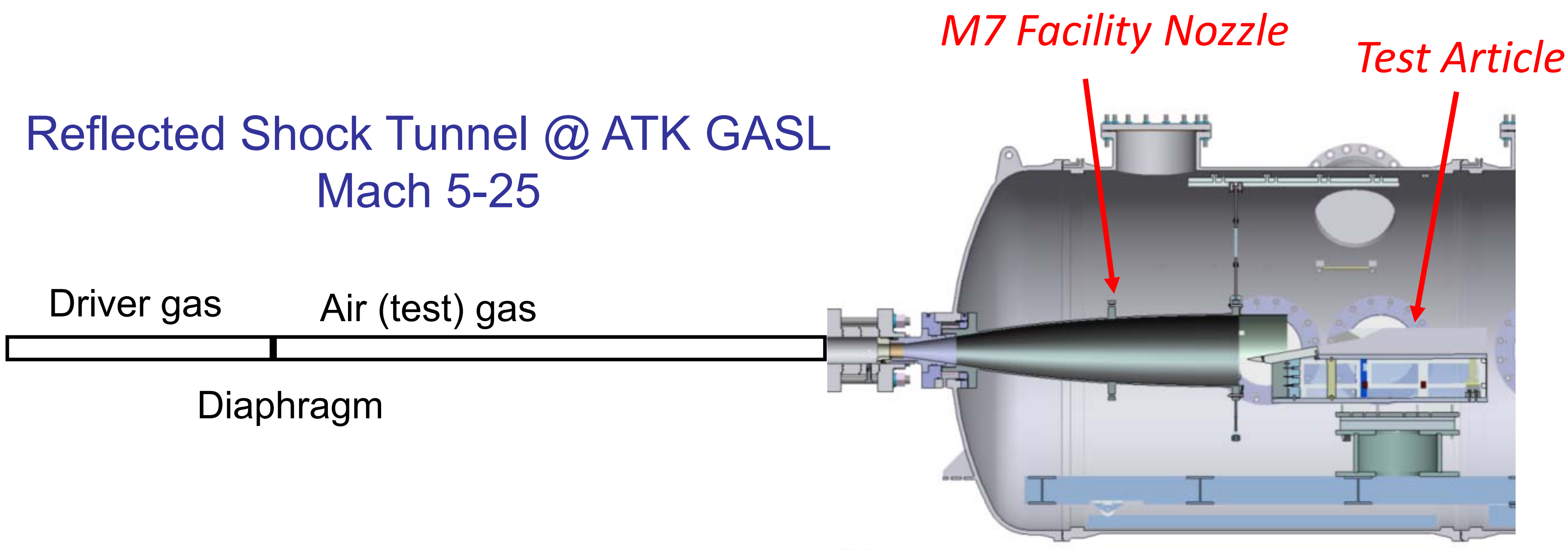
Injector side

- H_2O only present as combustion product (thus no V_{H2O} far from injector wall)
- Large decrease in core-flow velocity near wall, as predicted by CFD
  - Significantly reduced axial velocity due to addition/mixing of fuel
  - Excellent CFD-TDLAS agreement in shape and magnitude

Next: Measurements in an impulse facility

5.4 Supersonic Combustion @ATK

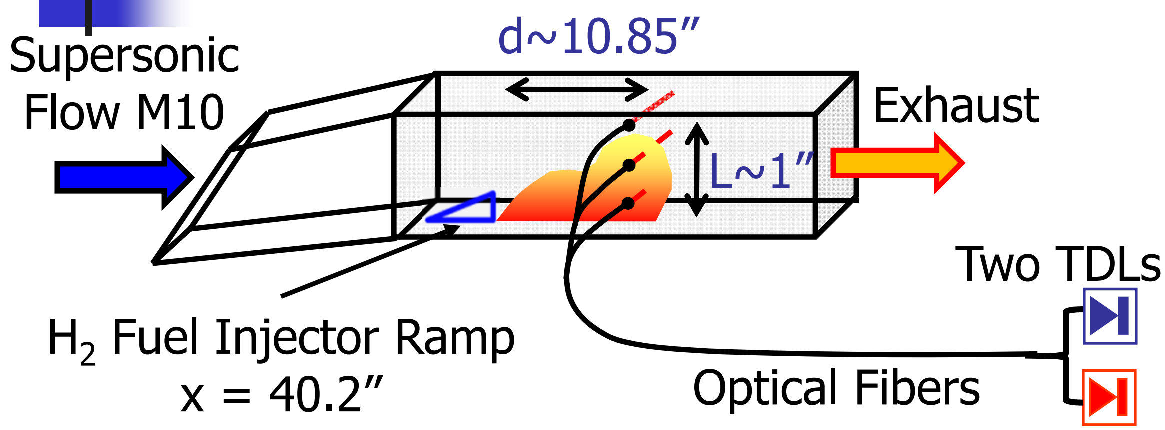
TDLAS in a Model Scramjet @M10

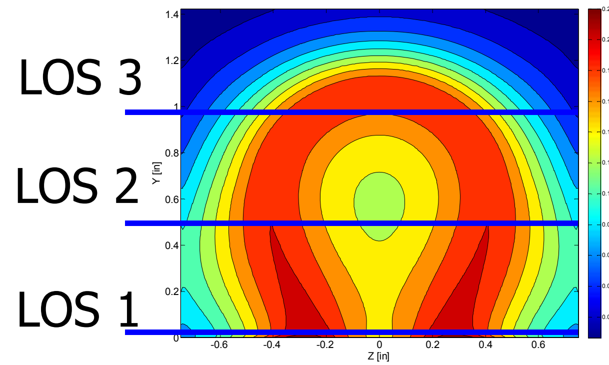


- High-speed flow produced by expansion of detonation driven shock wave
- Impulse facility produces a short test time of steady flow (~3ms at M10)
- Tests conducted at M=10 flight condition for H_2 combustion at ϕ~1

5.4 Supersonic Combustion @ATK

NIR H_2O Sensor for Model Scramjet





NCSU CFD of χ_{H2O} at TDLAS Measurement Plane, AoA =7.5°

Setup:

- 2-color, 3-LOS, fiber-coupled sensor mounted on model

Goals:

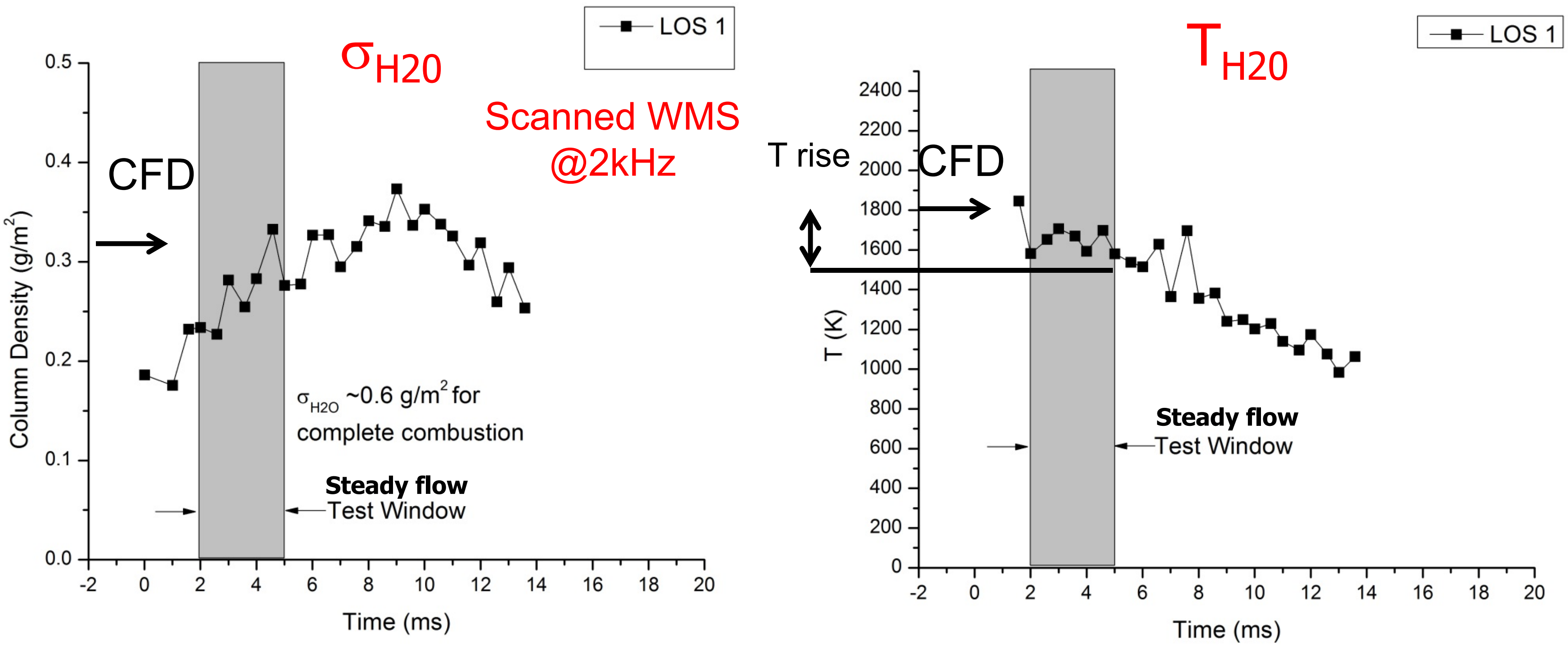
- Characterize model capture @M10 in ATK tunnel (TARE run)
- Provide data for H_2 combustion in model to compare with CFD

Results:

- Determined time-resolved T_{H2O} and σ_{H2O} to compare with CFD

5.4 Supersonic Combustion @ATK

M10 Combustion: φ = 1.03, AoA = 7.5°



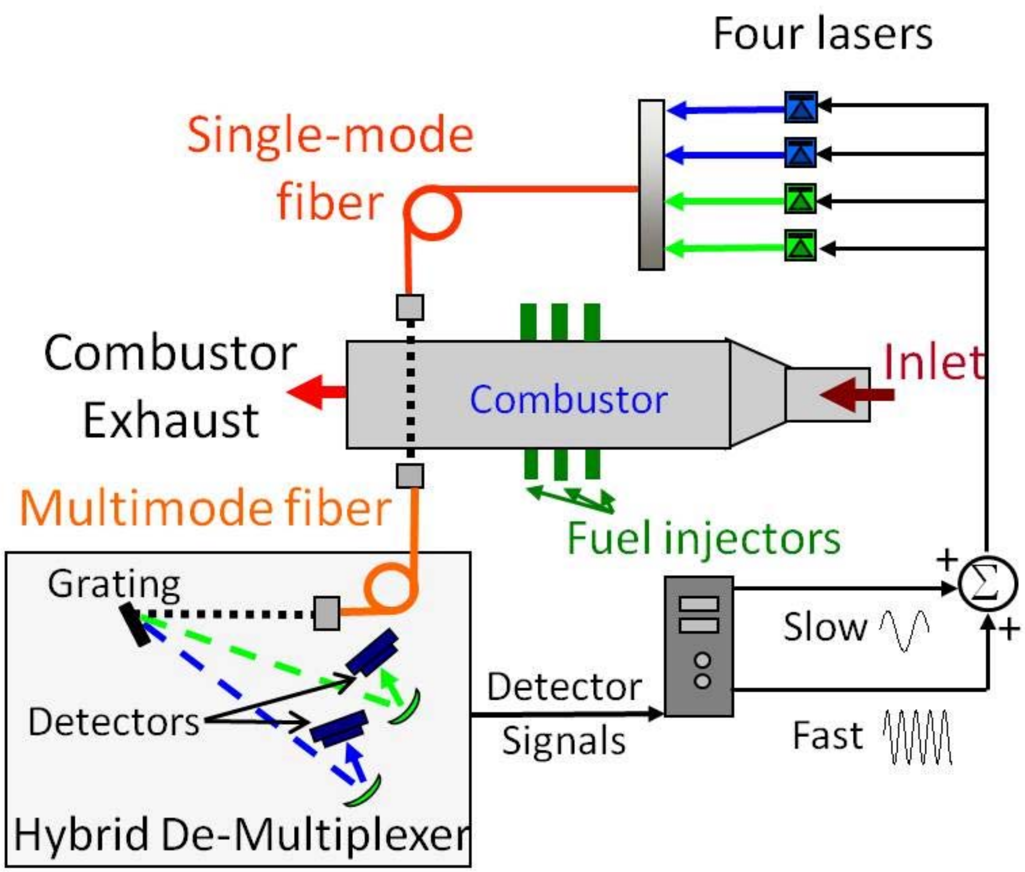
Key Results

- Significant combustion product H_2O observed prior to steady test time
  - Evidence of prompt ignition (before steady flow developed)

Next: Can we learn about flow from signal fluctuations?

5.5 Scramjet Unstart Monitor @AFRL

Example: Fluctuations in T Uniformity via TDLAS

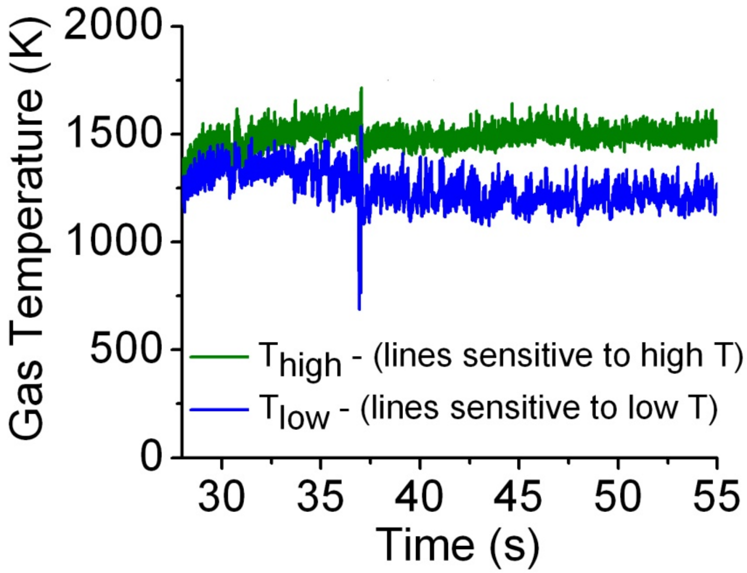


AFRL, WPAFB, 2007

- Simultaneous measurements on 4 H_2O lines
  - Two lines for T_{low} and two lines for T_{high}

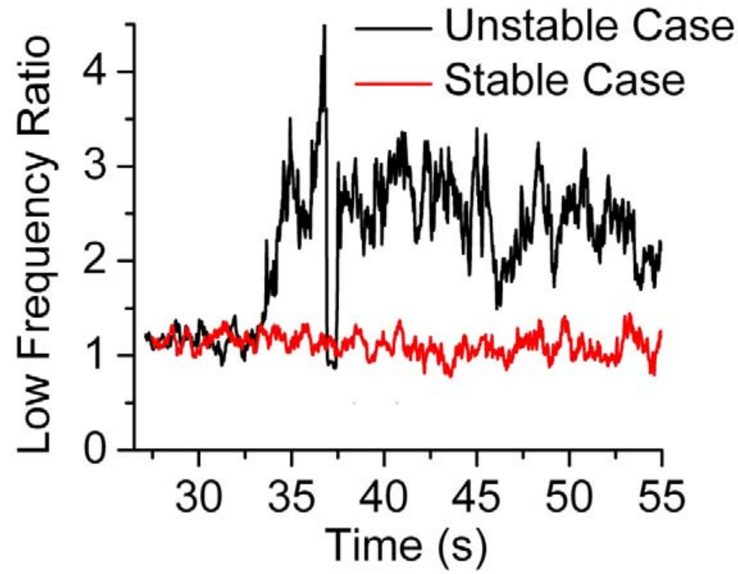
5.5 Scramjet Unstart Monitor @AFRL:

Sensor Monitors Time-Resolved T_{low} vs T_{high}



Running FFT of T_{low} & T_{high}

Ratio low-frequencies



- **$T_{low} \neq T_{high}$ indicates temperature is not uniform**
- **Low-frequency fluctuations anticipate inlet unstart**
- **Fluctuation sensing : A new paradigm for control!**

Rieker et al., Proc Comb Inst, 2008

6. TDLAS for Aeropropulsion – Future Trends

- Portable TDL-based sensors useful for T, V, species and mass flux over wide range of conditions, facilities

- Current and future topics:
  - Characterization/maintenance/control of ground-test facilities
  - Emerging applications in flight systems
  - Extension to UV and mid-IR to access new species

    → CO, CO_2, HC's, radicals, NO, NO_2
  - Advanced propulsion concepts: scramjets, detonation engines, rockets

Next Lecture

TDLAS Applications to Energy Conversion

1. Fuel in IC engines – fuel and T
2. H_2O and T in slagging coal gasifier
3. H_2O in NCCC coal gasifier
4. NO and CO in coal-fired boiler exhaust