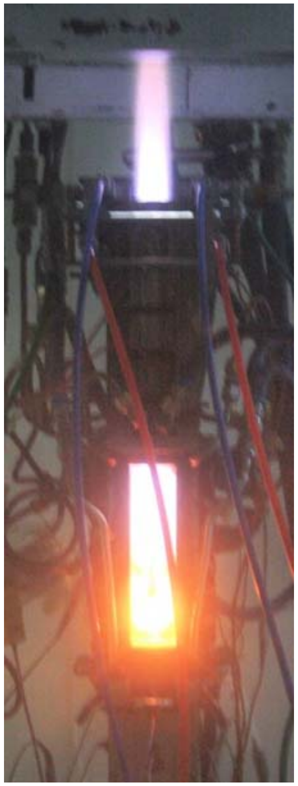
Quantitative Laser Diagnostics for Combustion Chemistry and Propulsion

Lecture 9: Tunable Diode Laser Absorption (TDLAS)

1. History and vision – for aeropropulsion
2. Absorption fundamentals
3. Absorption sensor strategies
4. Wavelength access – lasers/detectors
5. Example applications – combustion
6. Example applications - aerospace
7. 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…

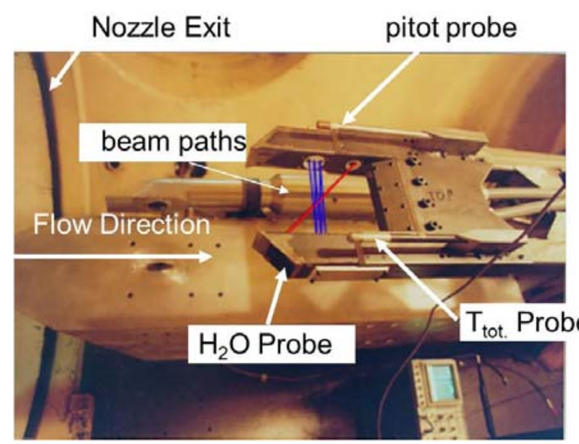
T/species in Shocktube

Hanson, *Appl Opt* (1977)

SCRAMJET @ WPAFB

Rieker, *Proc Comb Inst* (2009)

Facility @ CALSPAN



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2012 – TDL absorption in scramjet flight tests

T/species in Shocktube

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SCRAMJET @ WPAFB

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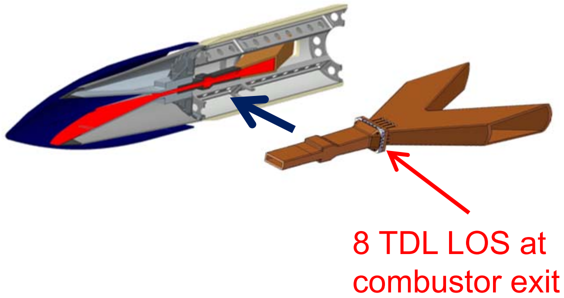
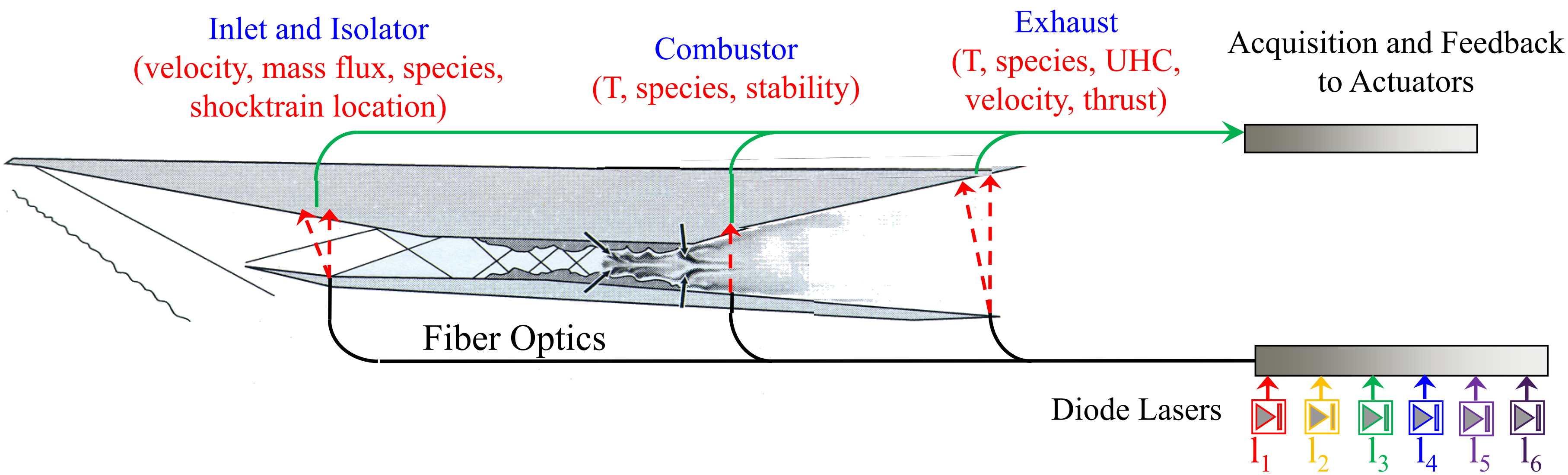
HiFire-2 Scramjet Flight Test



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

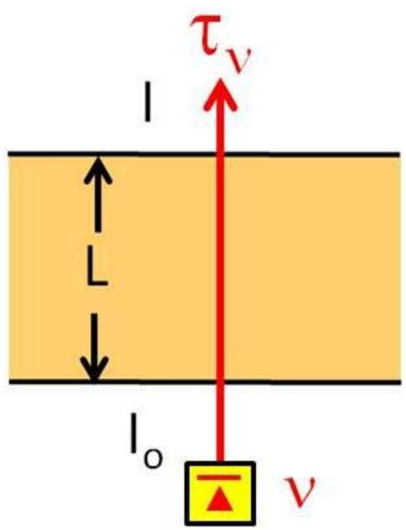


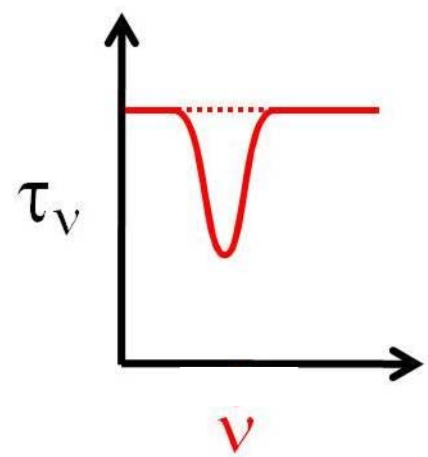
- Sensors developed for T, V, H_2O, CO_2, O_2, & other species
- Prototypes tested and validated at Stanford
- Several successful demonstrations in ground test facilities
- Opportunities emerging for use in flight

Now for some absorption fundamentals

2. Absorption Fundamentals: The Basics

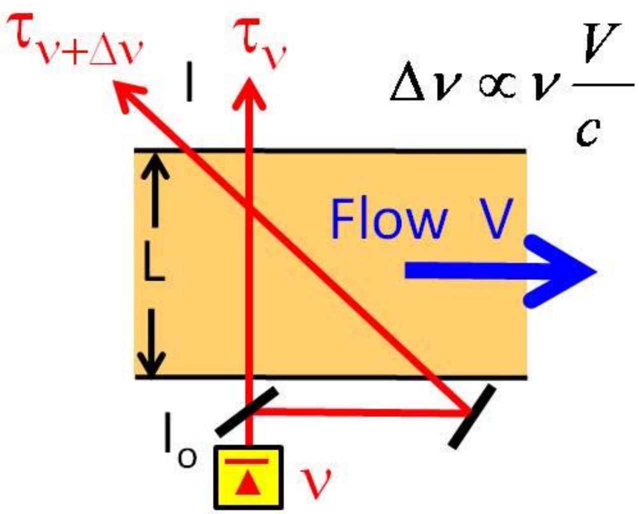
Absorption of monochromatic light

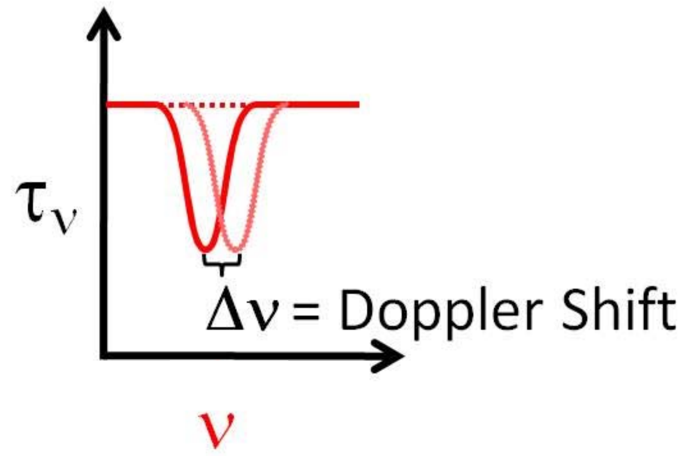




- **Scanned-wavelength *line-of-sight* direct absorption**
  - **Beer-Lambert relation** $\tau_\nu \equiv \frac{I_t}{I_o} = \exp(\underbrace{-k_\nu \cdot L}_{\text{absorbance}}) = \exp\left(-n_i \cdot \sigma_\nu \cdot L\right)$
  - **Spectral absorption coefficient** $k_\nu = S(T) \cdot \Phi(T, P, \chi_i)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

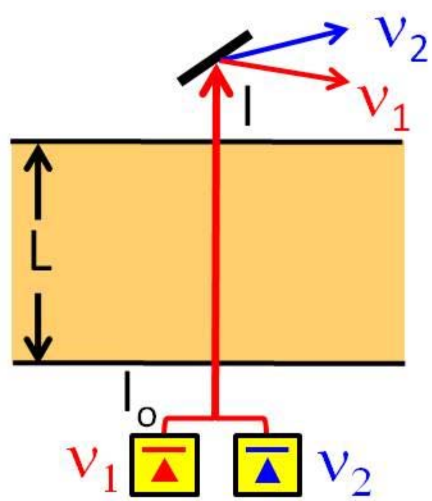
2. Absorption Fundamentals: The Basics

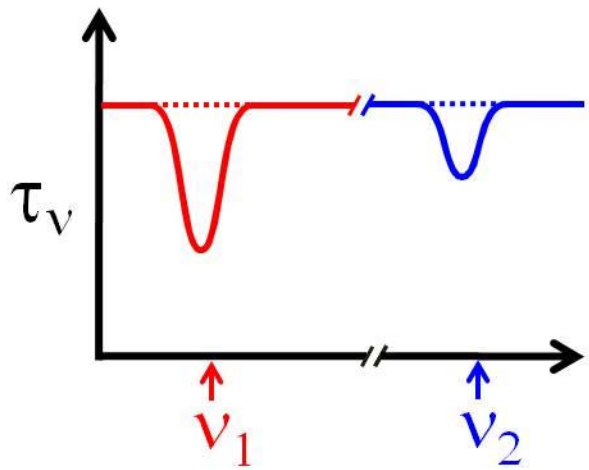




- **Shifts & shape of Φ contain information (T,V,P,χ_i)**

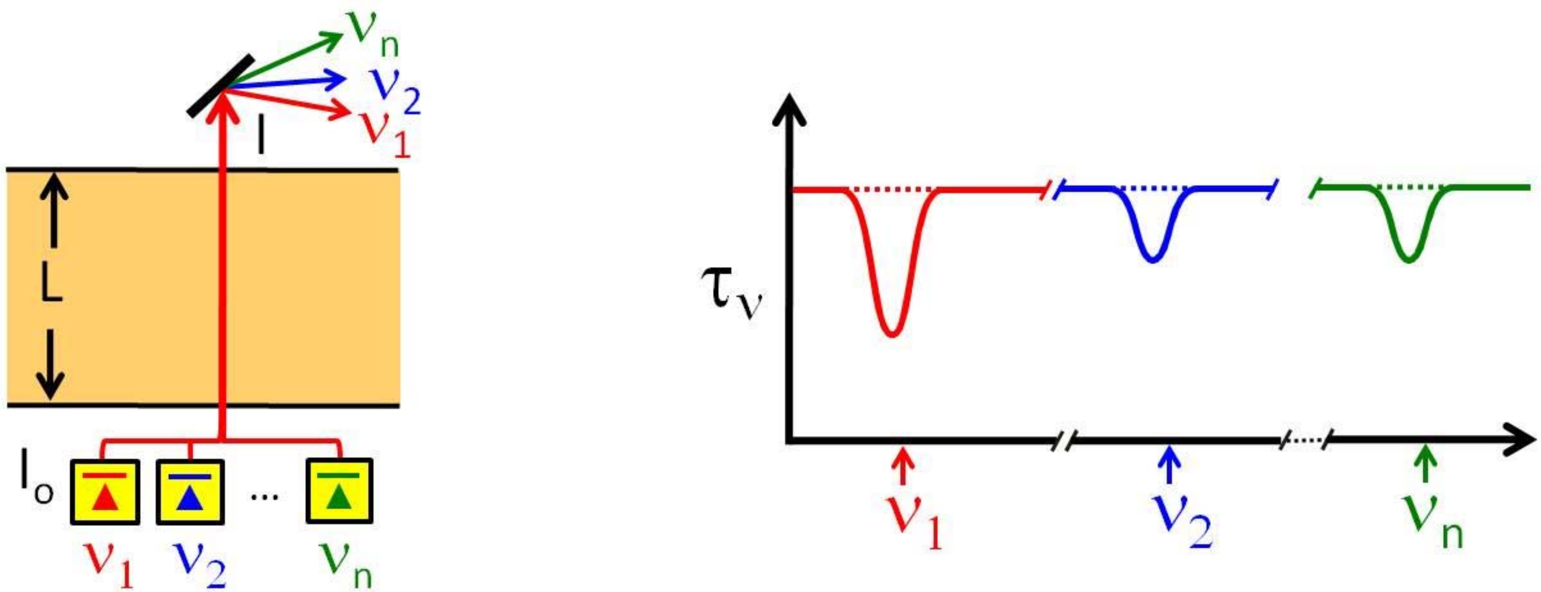
2. Absorption Fundamentals: The Basics





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

2. Absorption Fundamentals: Summary

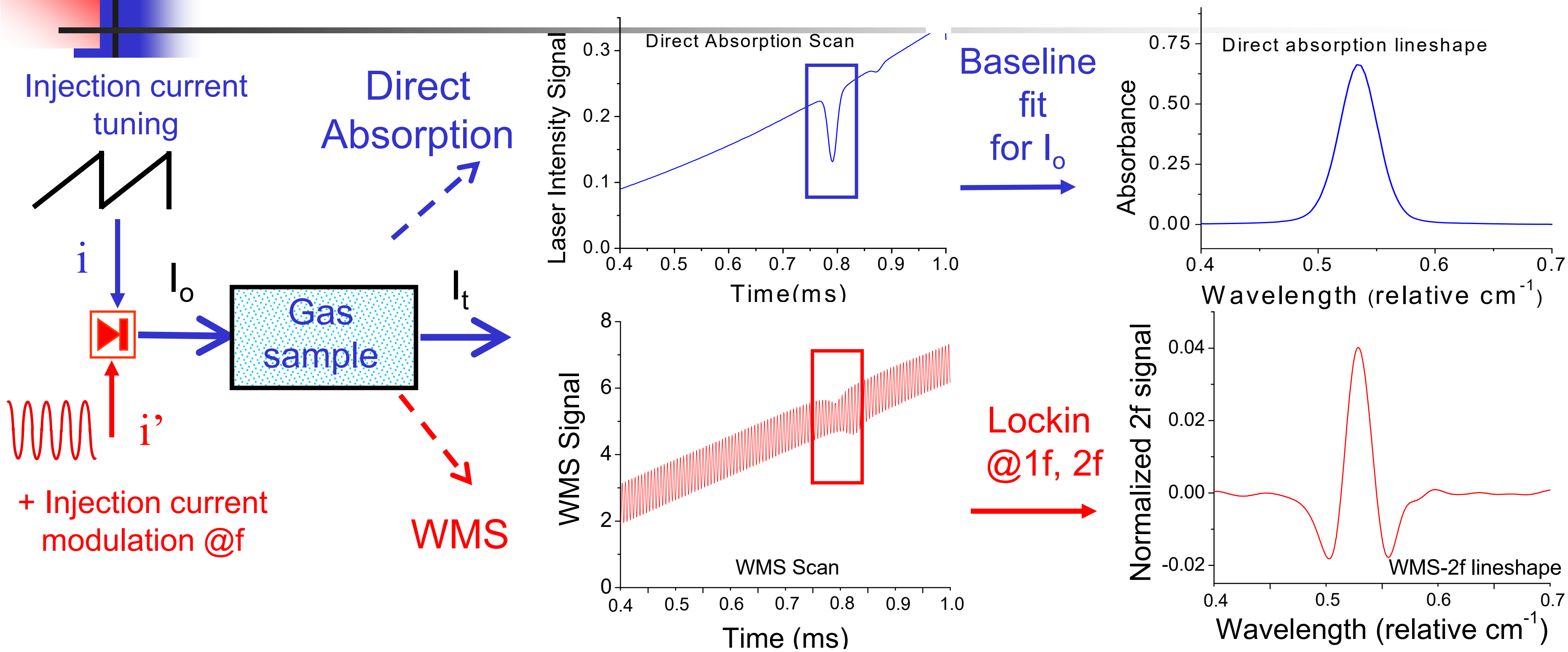


- **Wavelength multiplexing is also effective**
  - **To monitor multiple parameters or species**
  - **To assess non-uniformity along line-of-sight**

Two primary strategies for absorption measurements

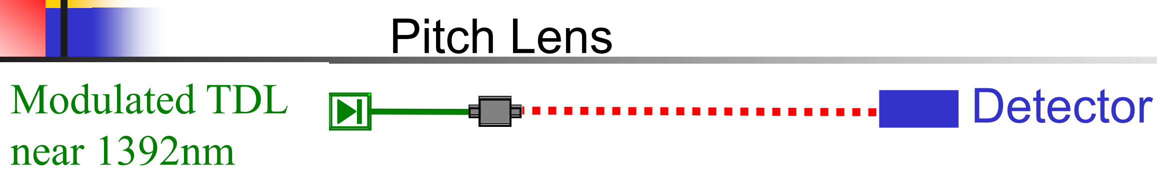
3. Absorption Sensor Strategies:

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

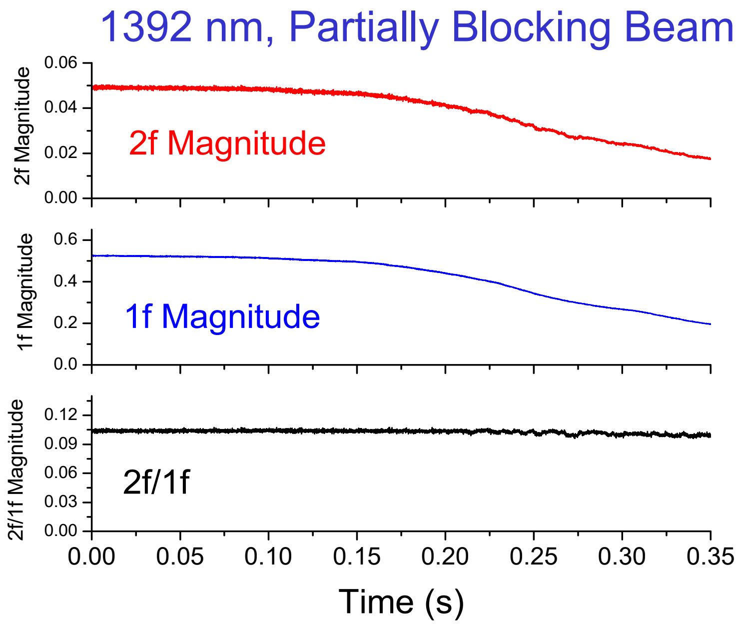


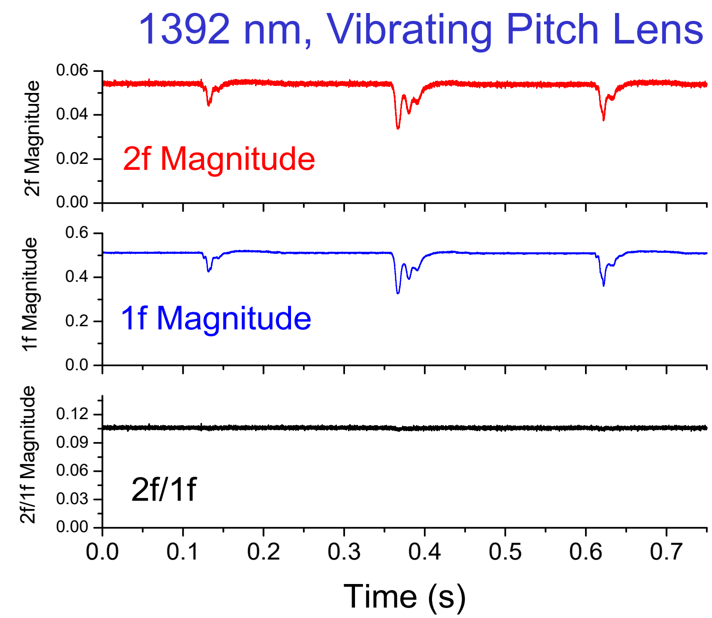
- **Direct absorption: Simple, if absorption is strong enough**
- **WMS: More sensitive especially for small signals (near zero baseline)**
  - **WMS with TDLs improves noise rejection**
  - ***Normalized WMS, e.g. 2f/1f* cancels scattering losses!**

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)



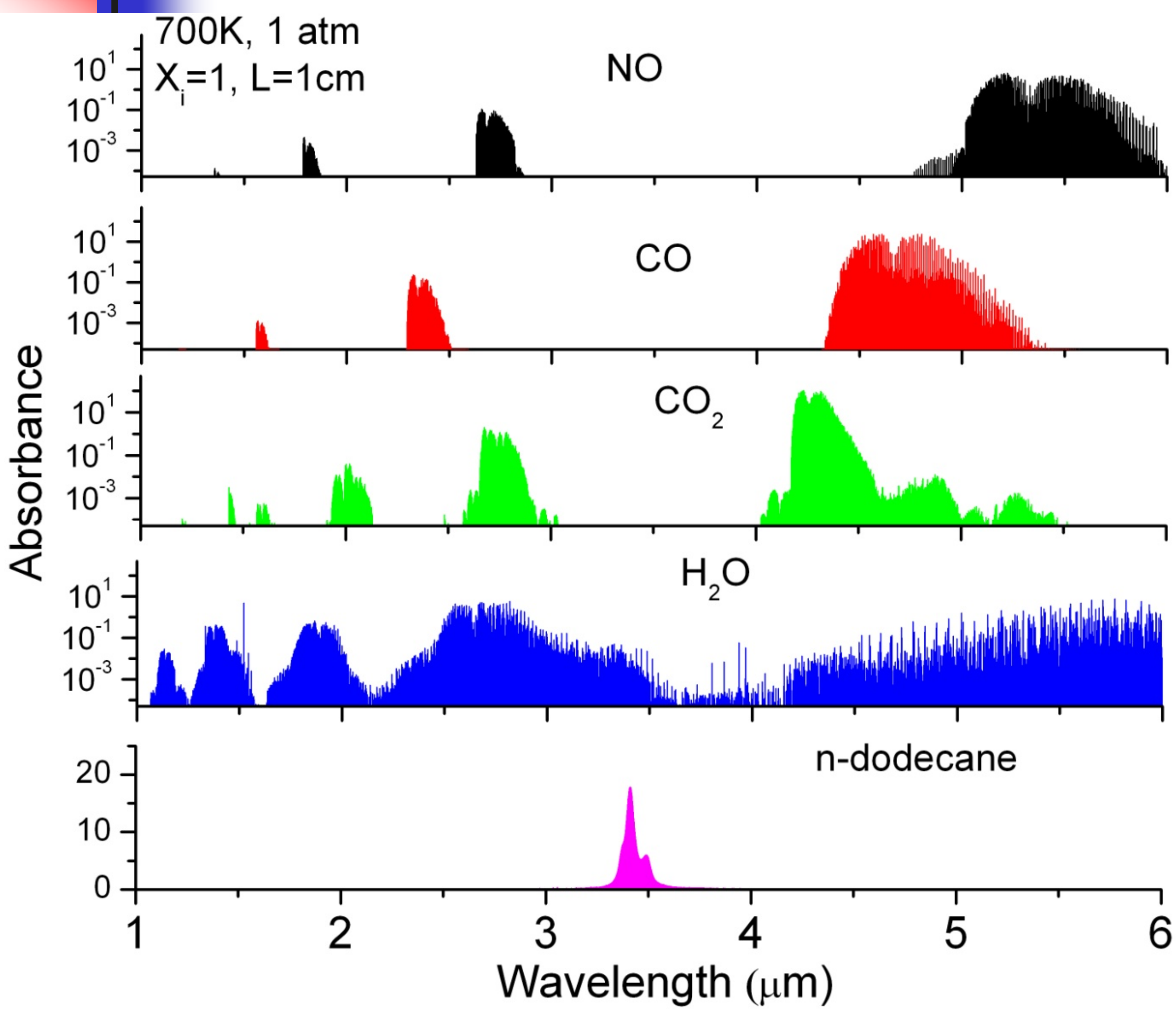


- **Demonstrate normalized WMS-*2f/1f* in laboratory air**
  - **2f/1f unchanged when beam attenuated (e.g., scattering losses)**
  - **2f/1f unchanged when optical alignment is spoiled by vibration**

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

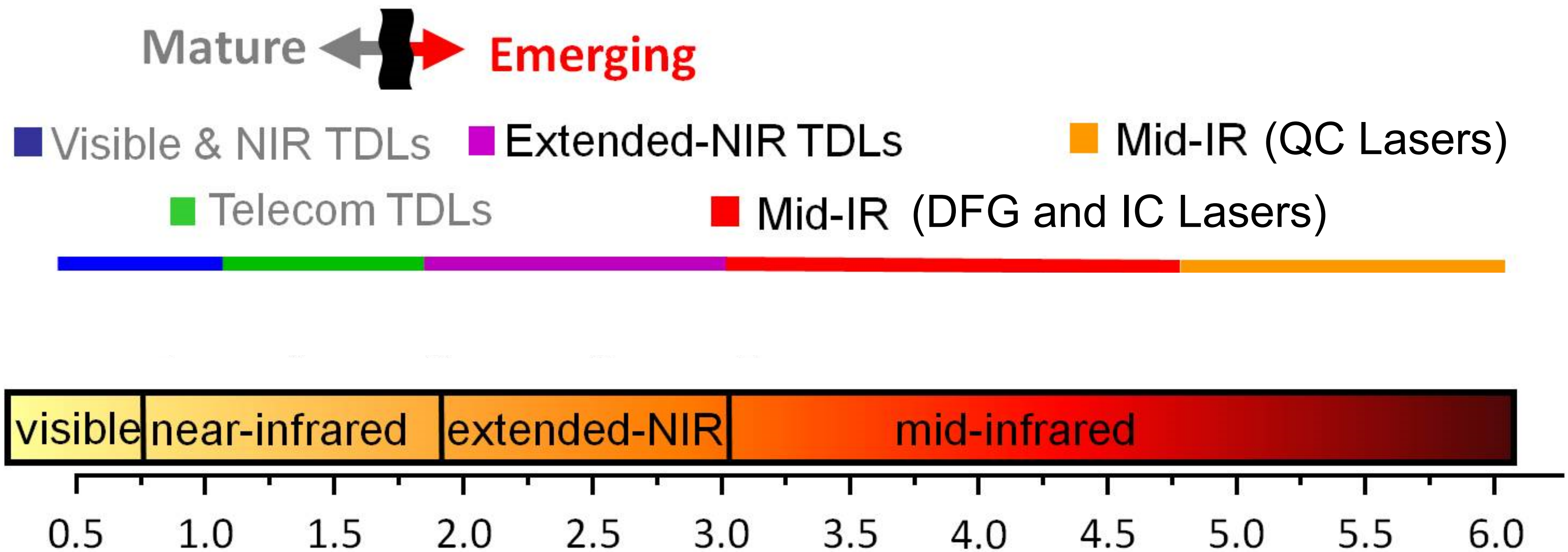
What species/wavelengths can we access?

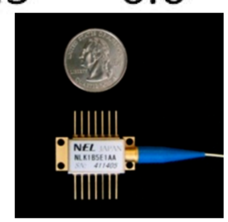
4. Wavelength Access: A Wide Range of Combustion Species/Applications using Wavelengths in the IR



- 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:
Laser Access Visible to Mid-IR



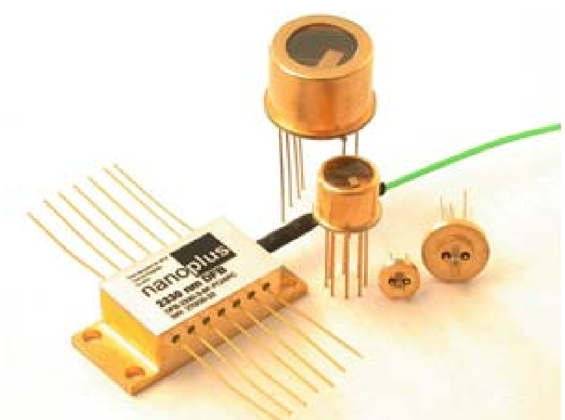


- Allows access to many atoms and molecules
- Visible and telecom TDLs can be fiber-coupled
- TDLs at wavelengths > telecom are emerging rapidly

Now lets consider hardware: lasers and detectors

4. Wavelength Access - Lasers

- Sources – Semiconductor lasers
  - 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

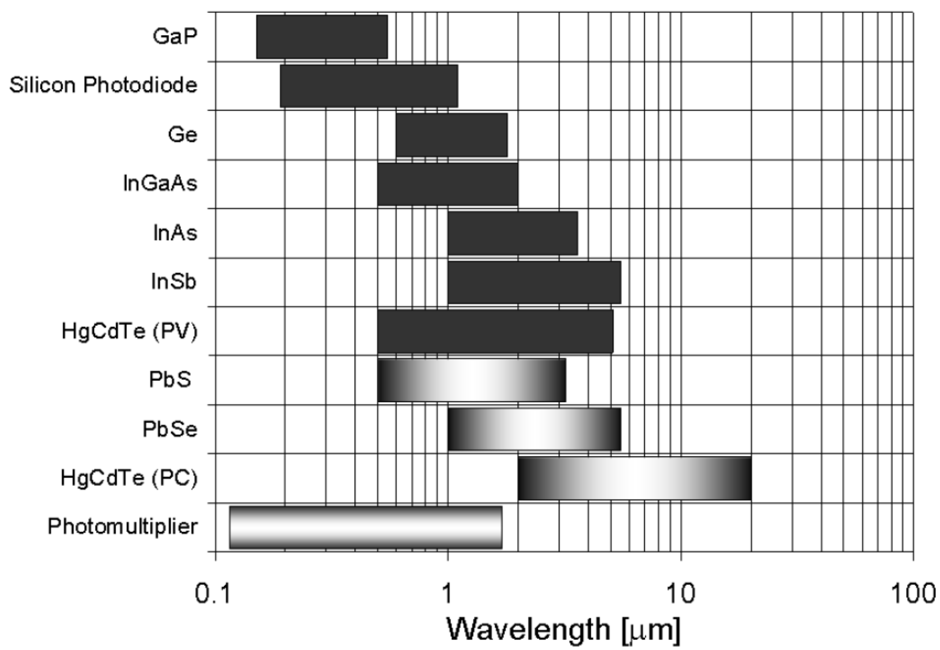
- Detectors – Photodiode/Photovoltaic detectors
  - A photodiode is a semiconductor that generates voltage or current when light is incident on it
  - Like photoconductors, they have a minimum photon energy associated with the bandgap energy of the semiconductor
  - Source of noise: Johnson noise (not 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

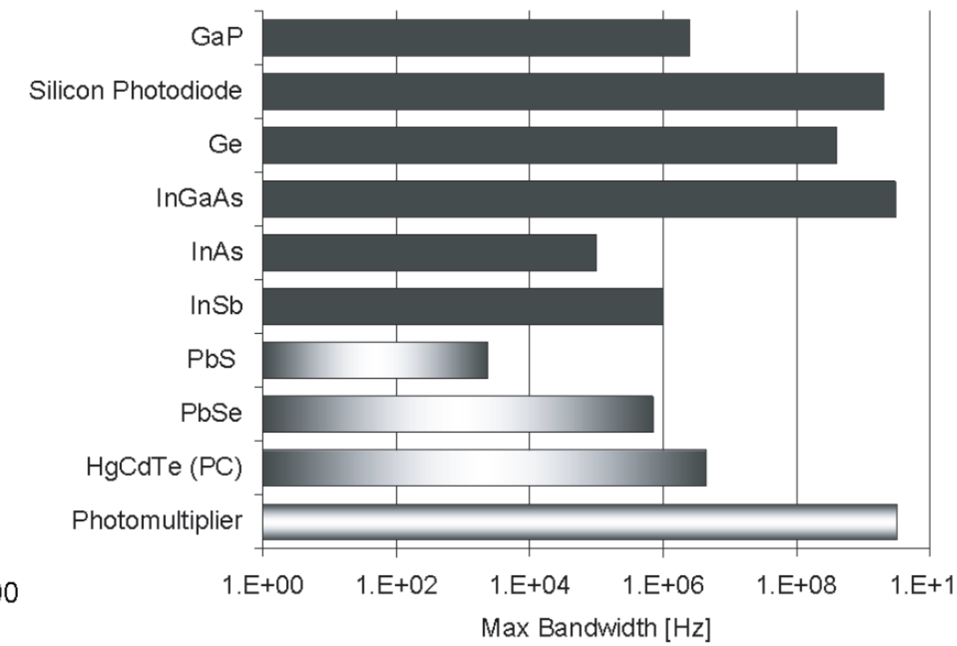
4. Wavelength Access - Detectors

- Detectors – Select a detector
  - **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 – Select a detector
  - 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

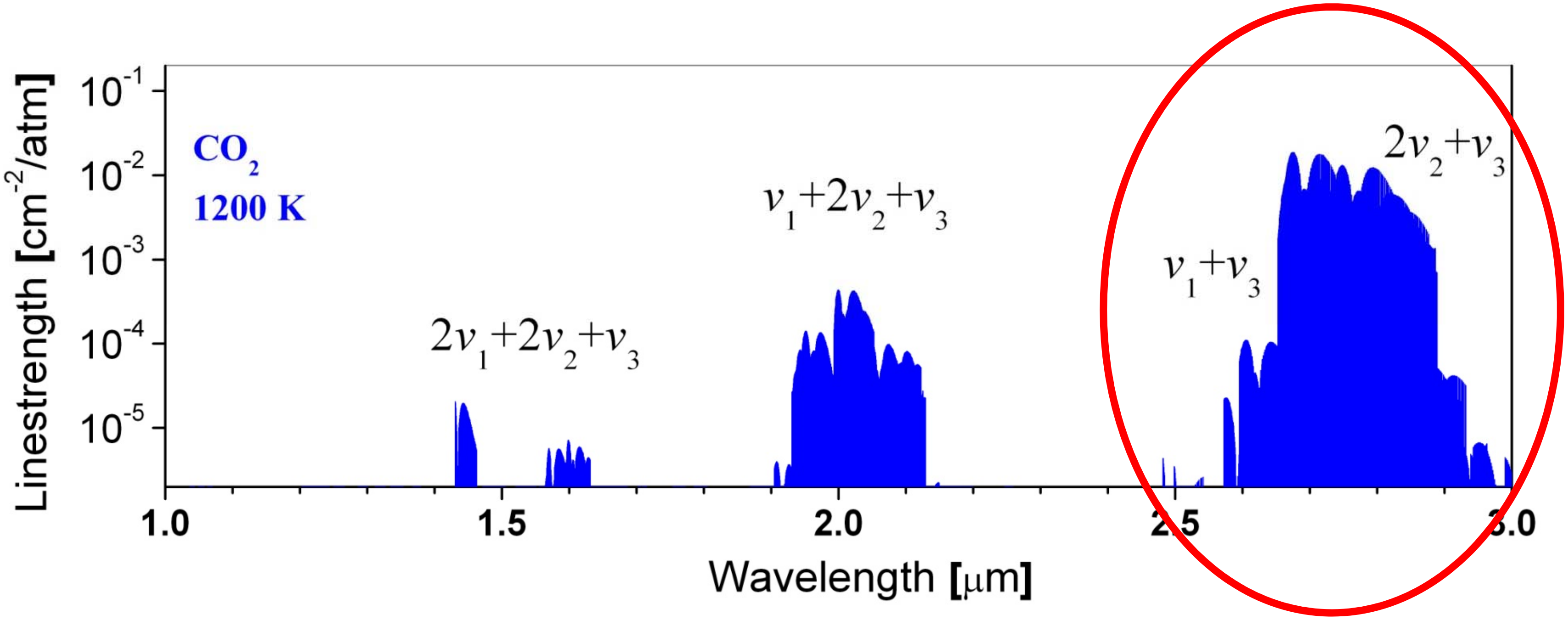
5. Example TDL Applications – Combustion

1. Extended NIR provides stronger CO_2 absorption
2. Exploit strong CO_2 absorption near 2.7μm for precision T
3. Exploit 1f-normalized WMS-2f for T with aerosol present

5.1 CO_2, T Sensor Using Extended-NIR

Extended NIR Enables Large Increase in Sensitivity

- Access to CO_2 enabled by new DFB lasers for λ >2.5 μm
- The band strength near 2.7 μm is orders of magnitude stronger than NIR

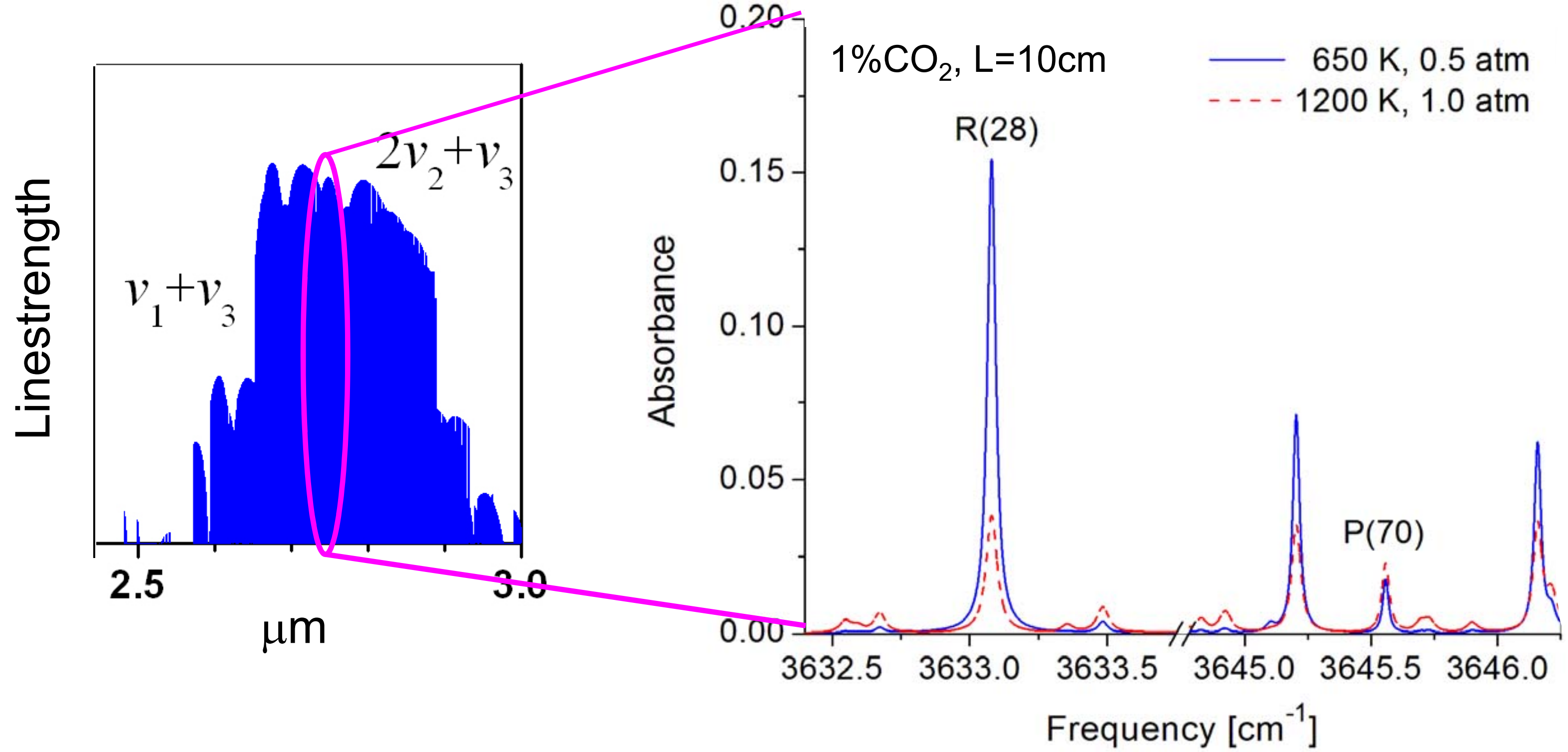


- **Many candidate transitions for optimum line pair (depending on T)**

Next: Line selection in $2\nu_2+\nu_3$ band

5.1 Extended-NIR Sensor for CO_2, T

Strategy: Sense T by ratio of absorption by two CO_2 transitions



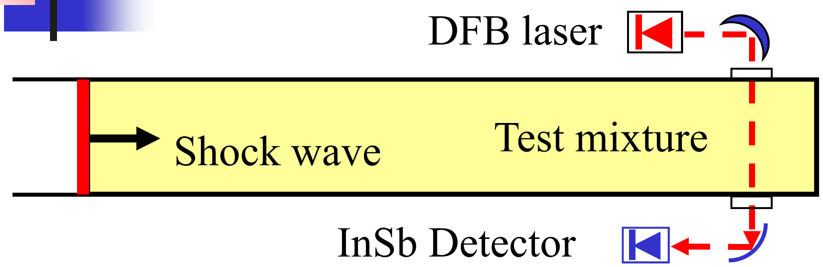
- A near optimum line pair R(28) and P(70) selected
  - Strong, isolated from H_2O, wide separation in E"

Validate in shock tube to demonstrate achievable precision

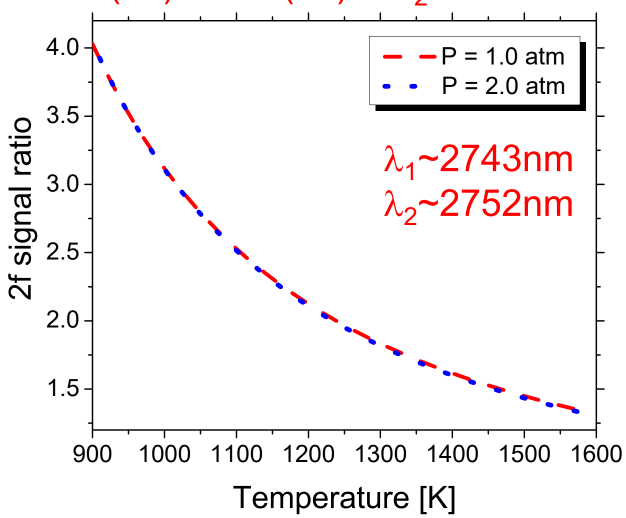
5.2 Shock-Tube Validation of Extended NIR CO_2, T Sensor

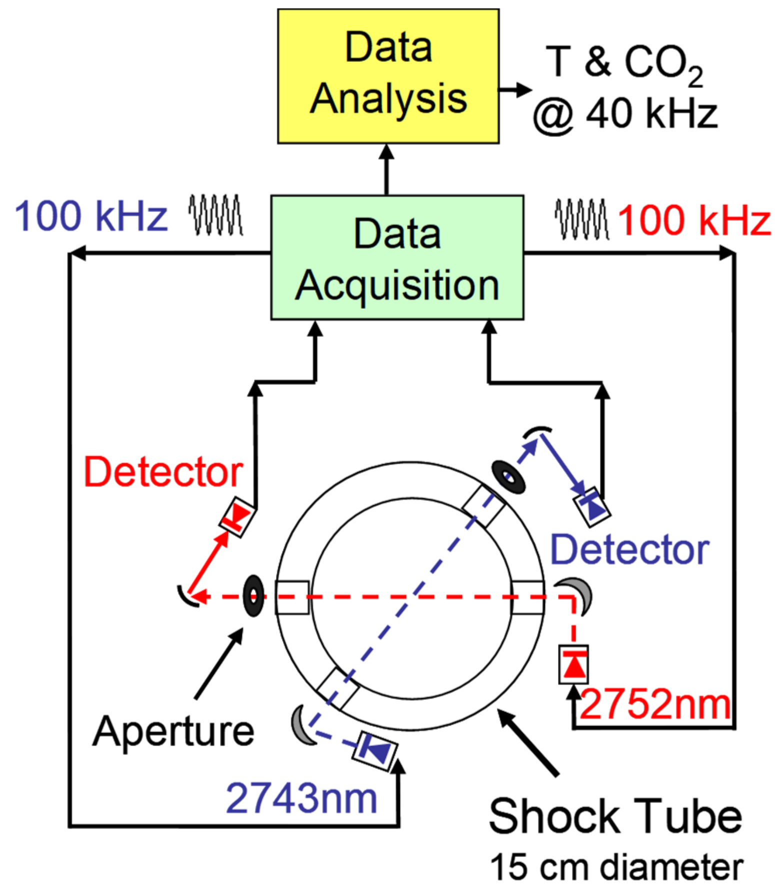
Precision Time-Resolved T from WMS-2f/1f of CO_2

Validate fast, sensitive strategy for CO_2, T using a shock tube



Ratio of WMS-2f/1f signals for R(28) and P(70) CO_2 transitions





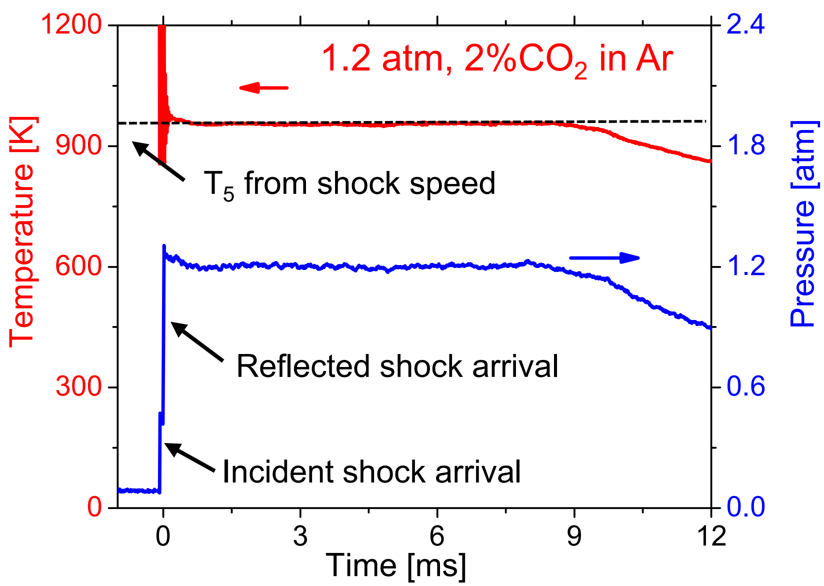
- **Ratio of WMS-2f signals sensitive to temperature**

Next: Measured accuracy and precision

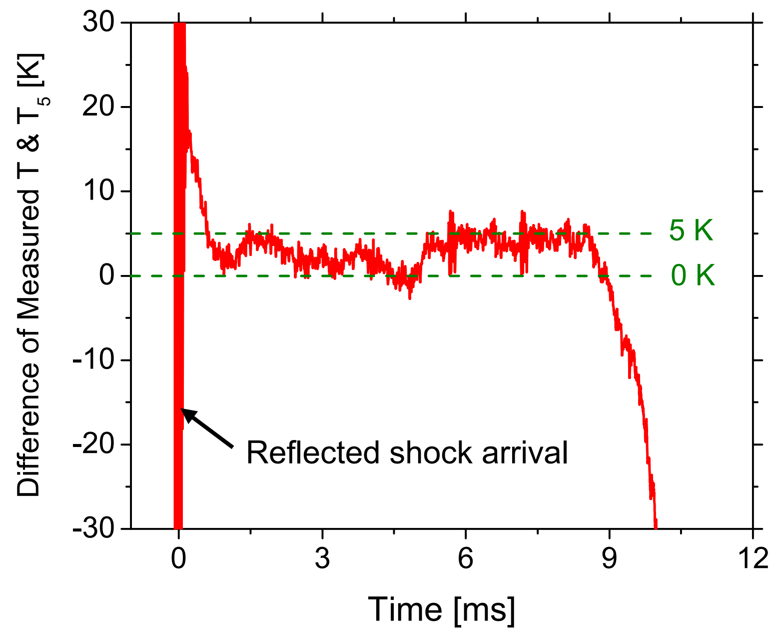
5.2 Shock-Tube Validation of Extended NIR CO_2, T Sensor

Temperature vs Time in Shock-Heated Ar/CO_2 Mixtures

Accuracy



Precision



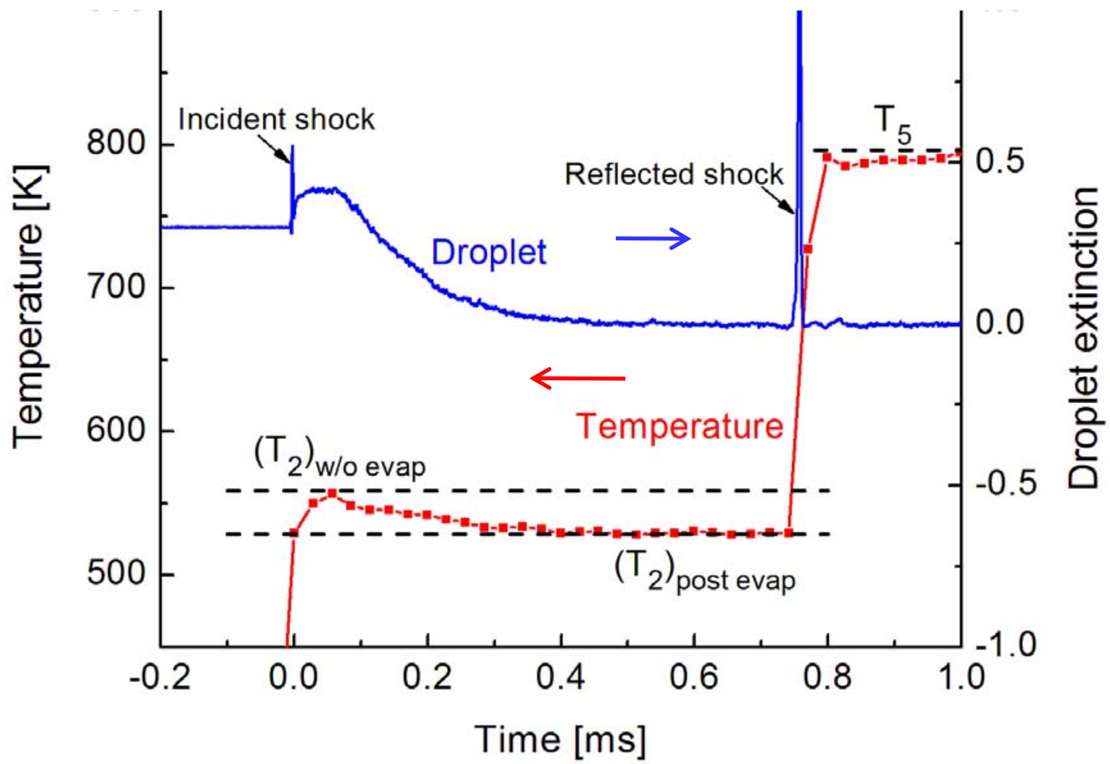
- **Temperature data agree with T_5 determined from ideal shock relations**
- **Temperature precision of ±3 K demonstrated!**
- **Unique capability for real-time monitoring of T in reactive flows**

Next: High potential for multi-phase flows, e.g., droplet evaporation

5.3 1f-Normalized WMS-2f for CO_2 with Scattering

Validate in Aerosol-Laden Gases

- Aerosol shock tube experiment: 2% CO_2 /Ar in n-dodecane aerosol
  - L=10 cm, P_2=0.5 atm; P_5=1.5 atm



- **2f/1f TDL sensor successfully measures T in presence of aerosol!**

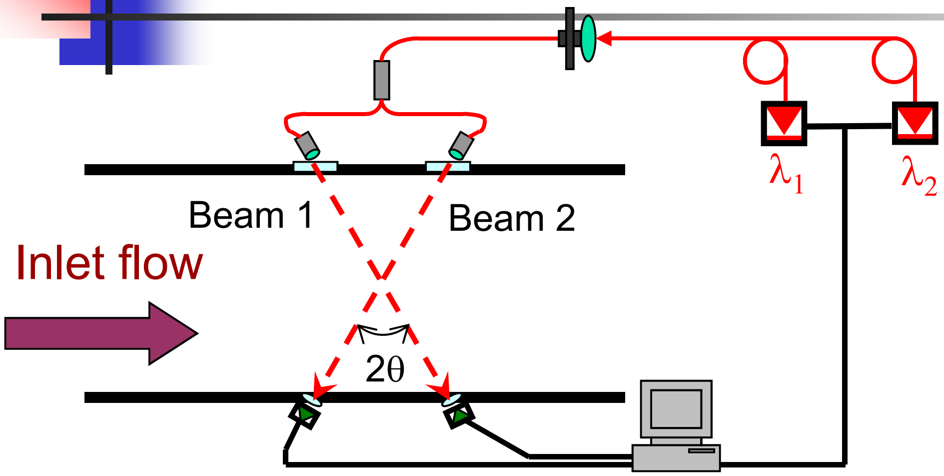
Next example: Detection of gasoline in IC-engines

6. Example TDL Applications - Aerospace

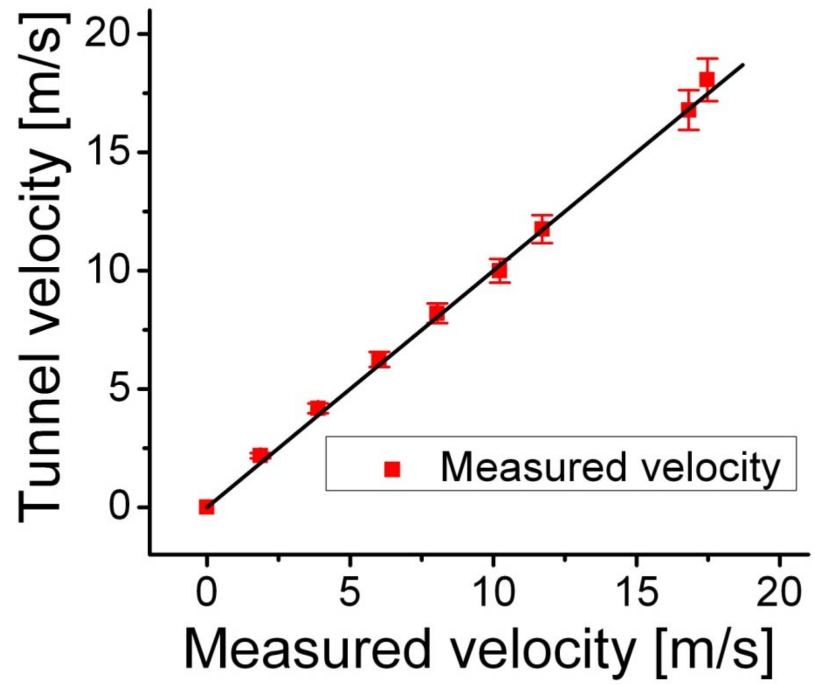
1. Subsonic velocity in a laboratory wind tunnel @SU – ambient H_2O
2. Supersonic velocity in a test facility @NASA – H_2O from vitiation
3. Supersonic combustion @UVa
   - Exploit mid-IR absorption for strong signals
   - H_2O, CO, and CO_2 measurements to compare with CFD
   - Scramjet unstart monitor

6.1 Subsonic Velocity @ SU:

TDLAS Sensors in Wind Tunnel



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

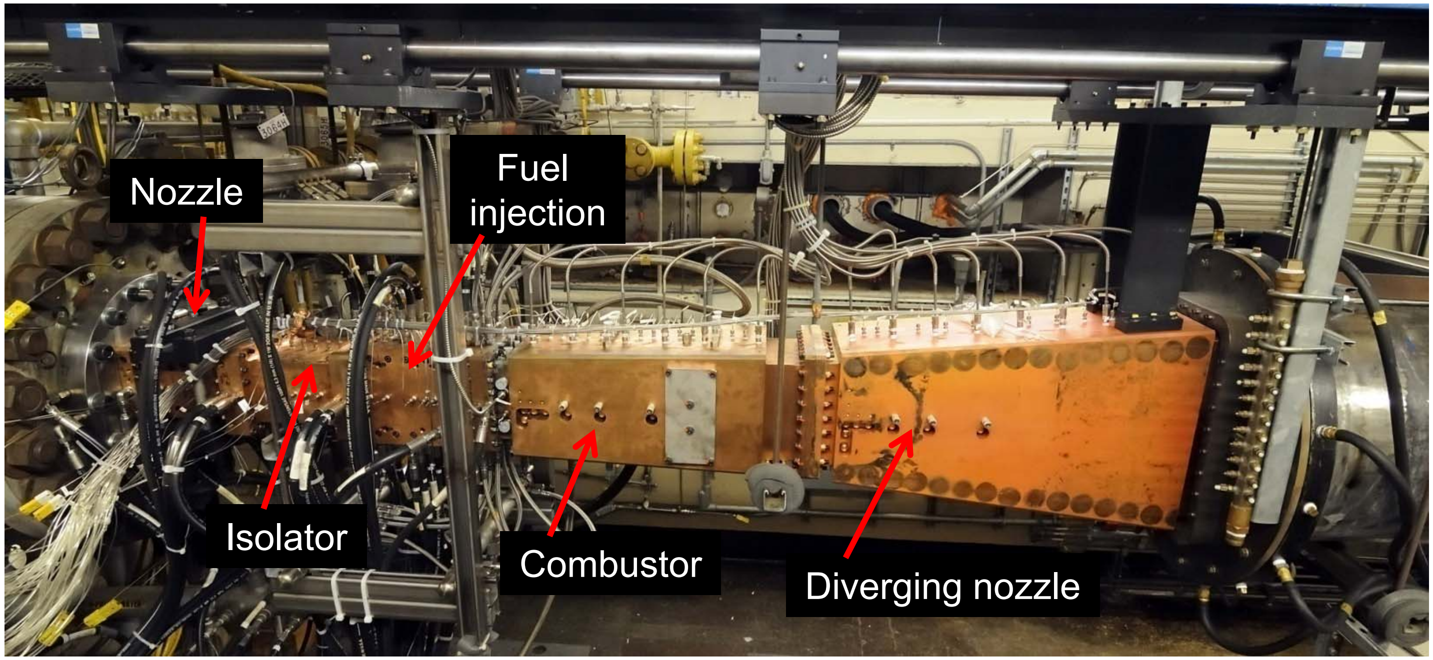


- TDL sensor of mass flux based on H_2O absorption
- Velocity from Doppler shift of absorption wavelength
- Validate sensor in subsonic wind tunnel w/ ambient H_2O @ Stanford
- 0.5 m/s precision for V in uniform subsonic flow

Next: Test in supersonic-flow facilities at NASA Langley

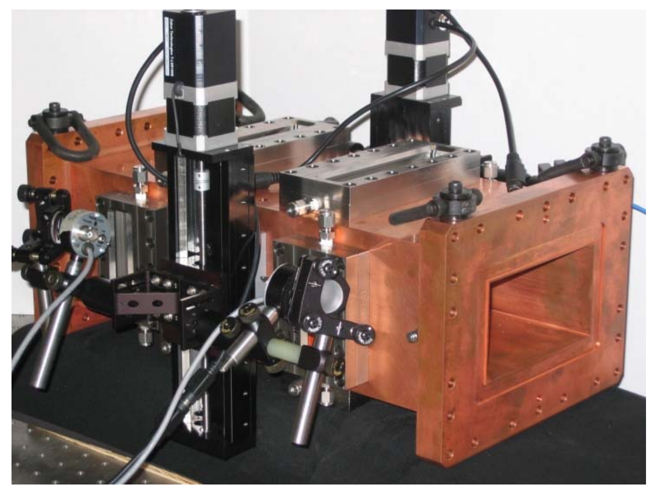
6.2 Supersonic Velocity@NASA Langley via TDLAS: Direct-Connect Supersonic Combustion Test Facility

Vitiated inlet air



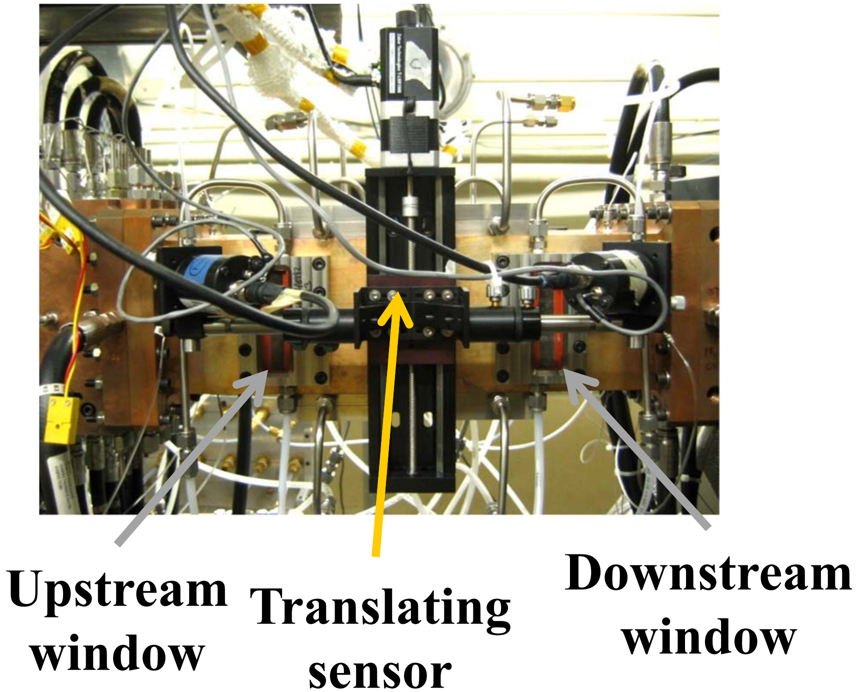
DCSCTF: Simulates atmospheric supersonic and hypersonic flight conditions

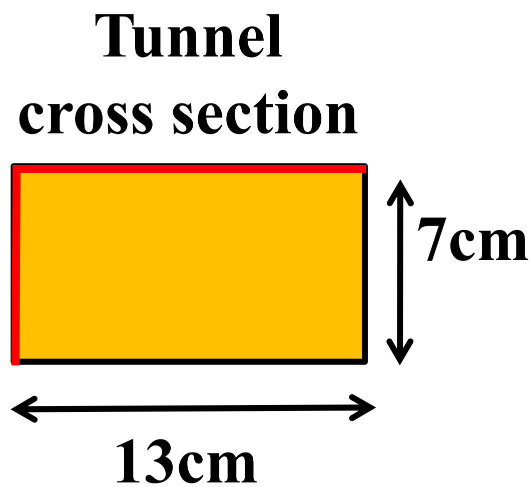
- M=2.65 nozzle with T_{static}~ 990K and P_{static}~ 0.7 atm; simulates M=5 flight
  - Add optical access to isolator
  - Measure V, T, mass flux



6.2 Supersonic Velocity @NASA via TDLAS

Supersonic test facility at NASA Langley (2009)





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

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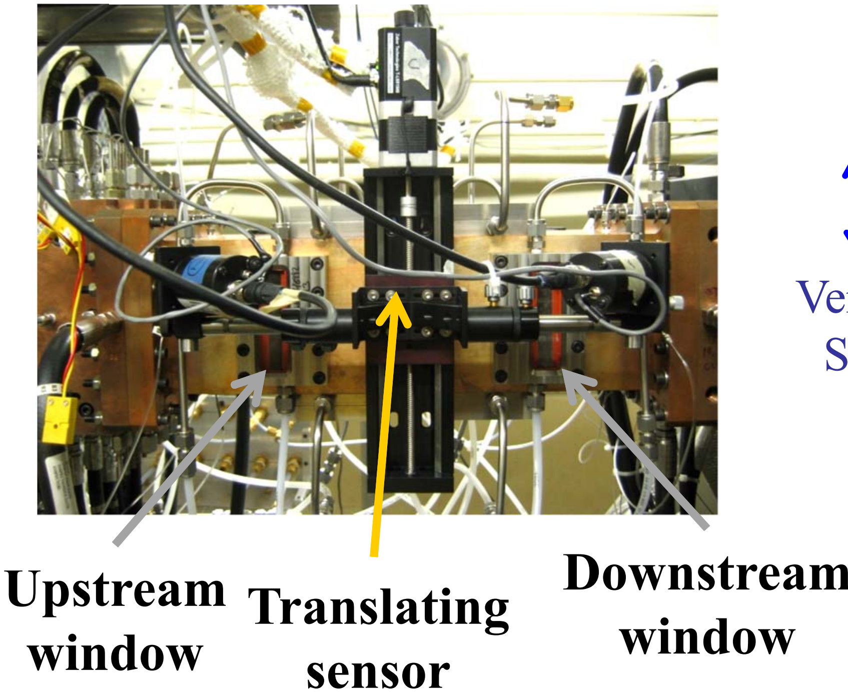
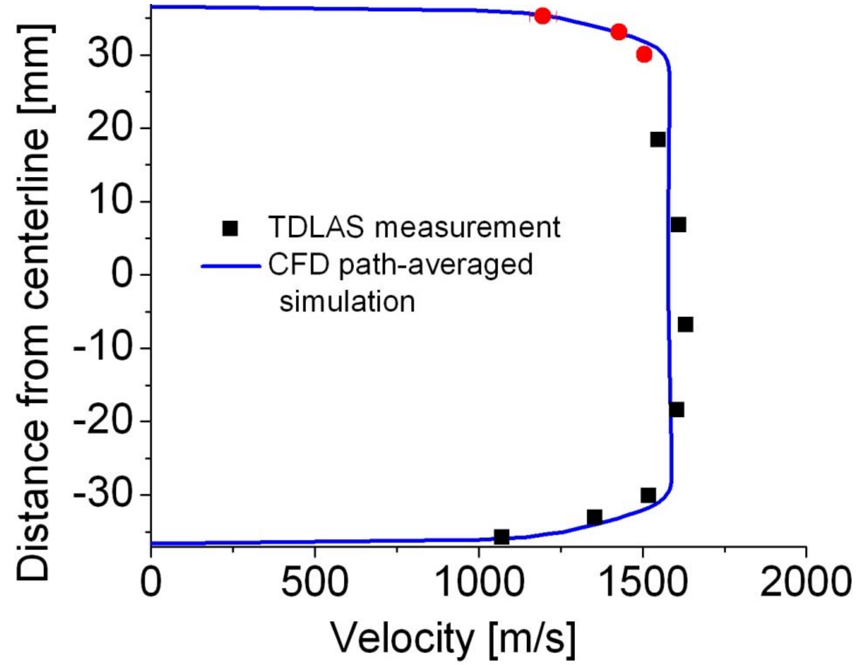
Supersonic test facility at NASA Langley (2009)



Vertical Scan



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

Chang et al., AIAA, 2011

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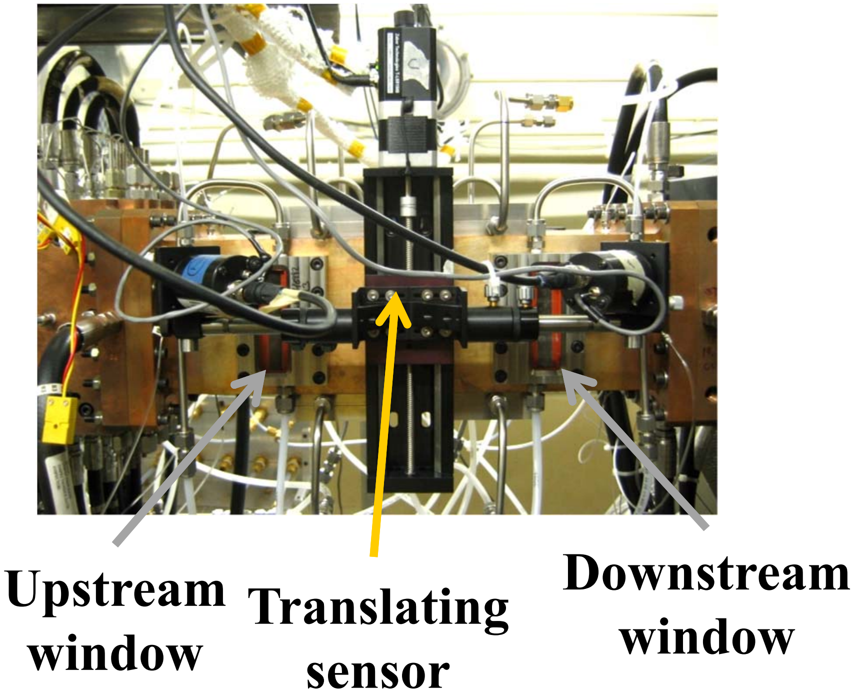
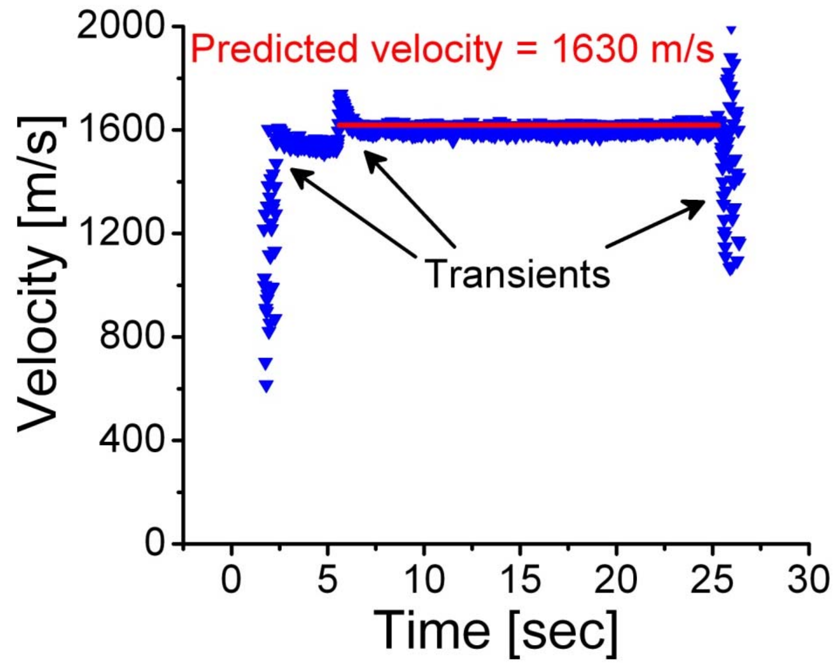
Supersonic test facility at NASA Langley (2009)





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

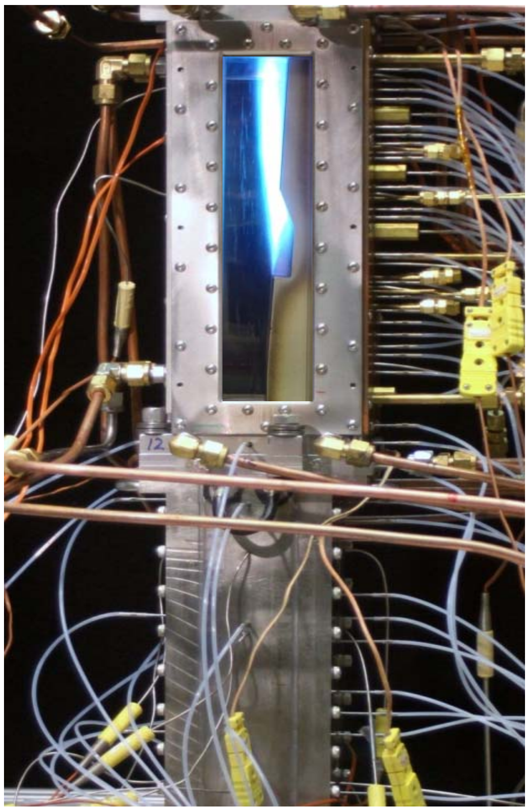
Next: A supersonic combusting flow @ UVa

Chang et al., AIAA, 2011

6.3 Mid-IR absorption sensing in scramjet flows

Goal: Spatially-resolved CO, CO_2 and H_2O in supersonic combustion

Mach 5 flight condition
Mach 2 in combustor
C_2H_4/Air, $\phi \approx 0.15$

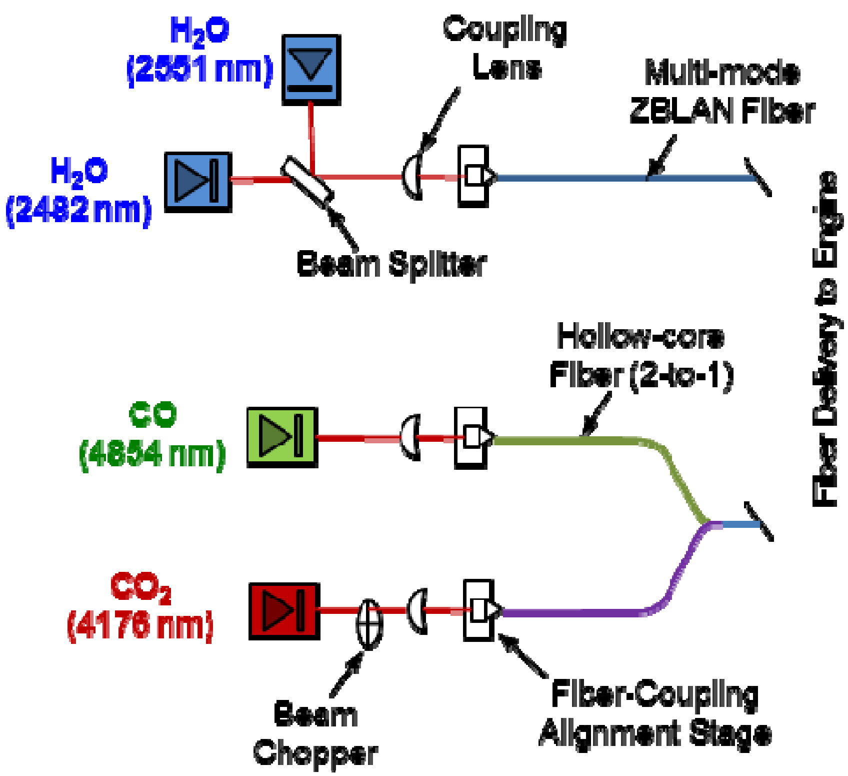


UVa Supersonic Combustion Facility
Charlottesville, VA

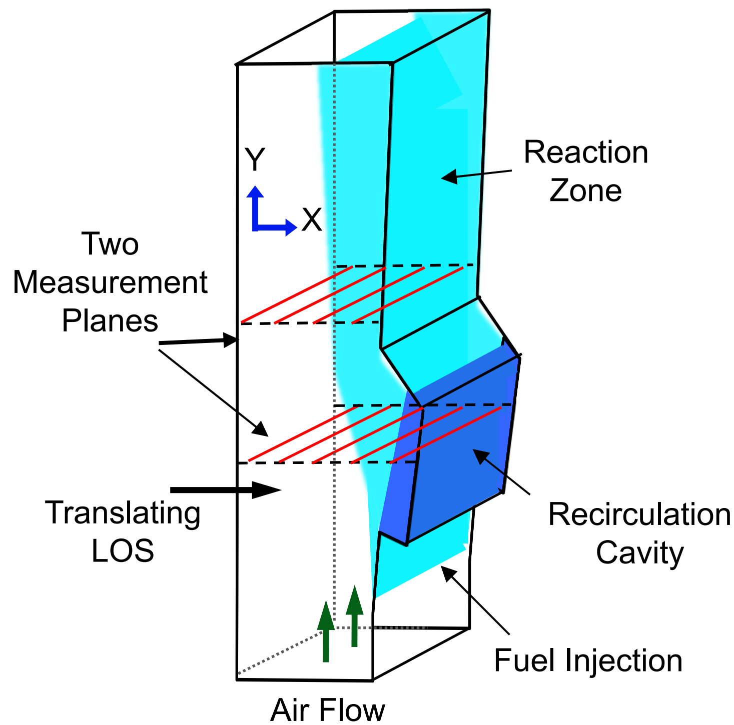
6.3 Mid-IR absorption sensing in scramjet flows

Optical Setup: Translating LOS

Four lasers
Two for H_2O and T
One for CO and one for CO_2



SIDE VIEW
Supersonic flow path



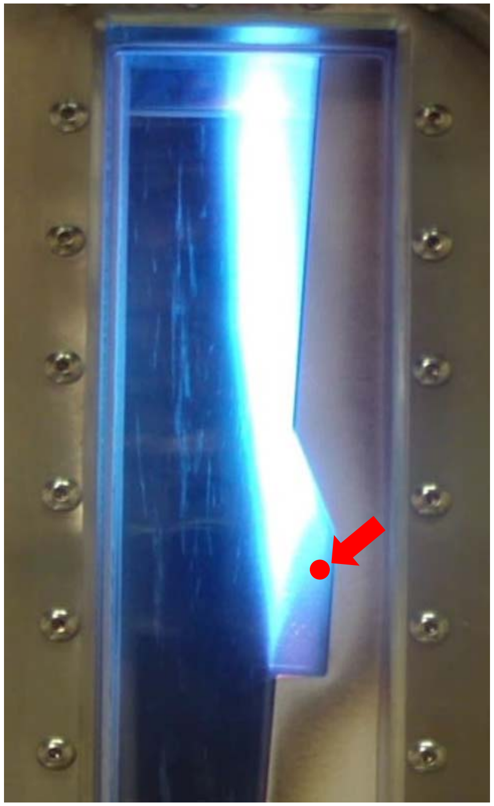
- **First use of fiber-coupled Mid-IR for aero-applications**

6.3 Mid-IR absorption sensing in scramjet flows

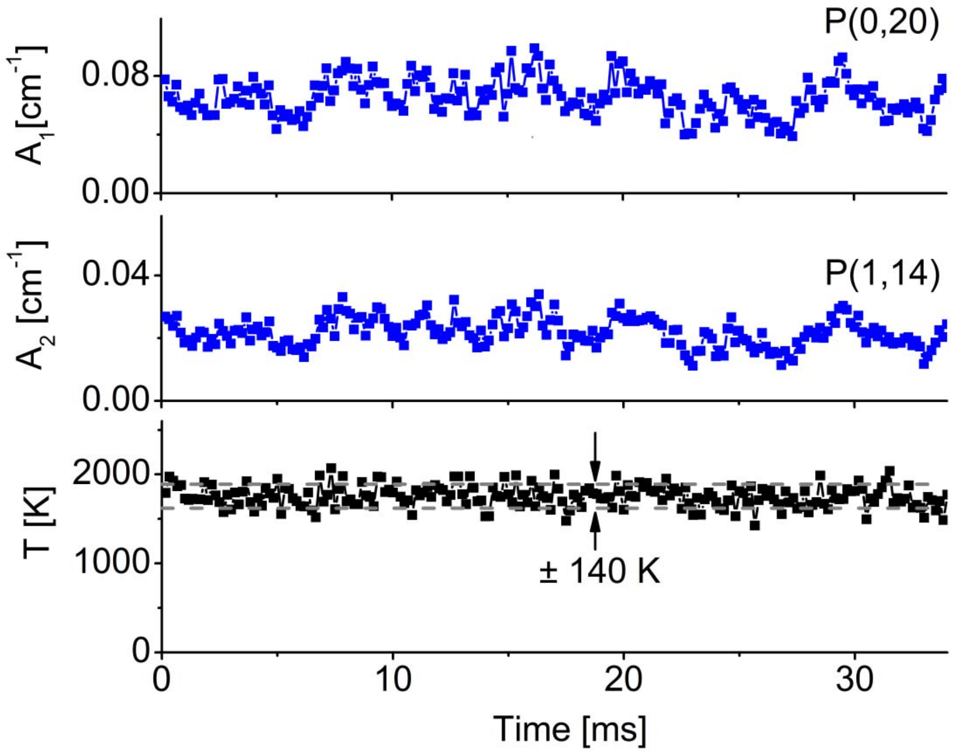
Time-resolved CO and T Measurements

UVa Combustor

C_2H_4 + Air: $\phi \approx 0.15$



Two-line CO T measurement @ 6 kHz



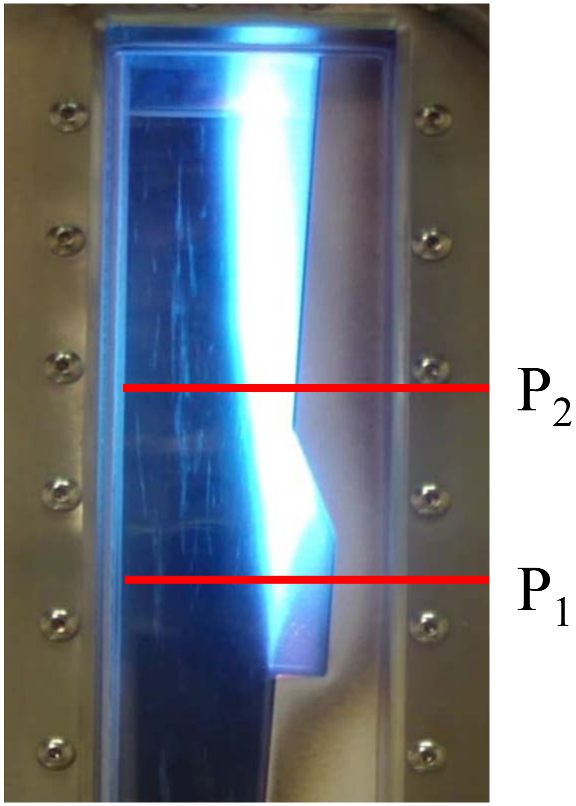
- **TDL sensor captures flow fluctuations**

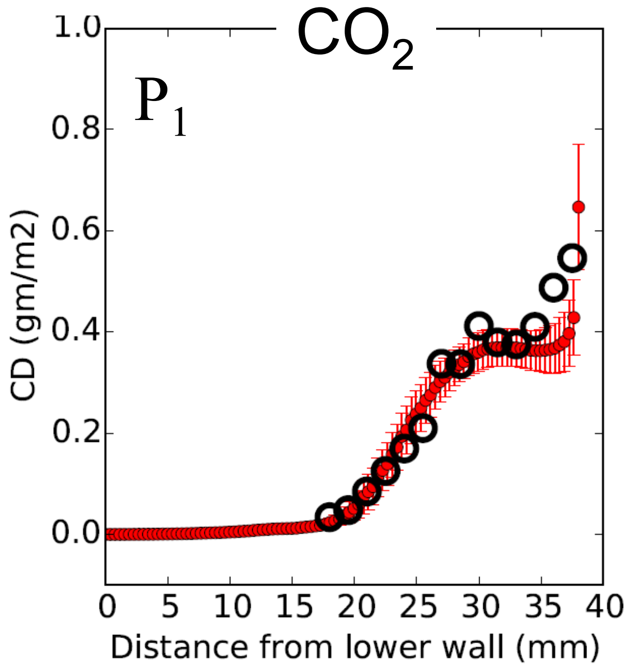
6.3 Mid-IR absorption sensing in scramjet flows

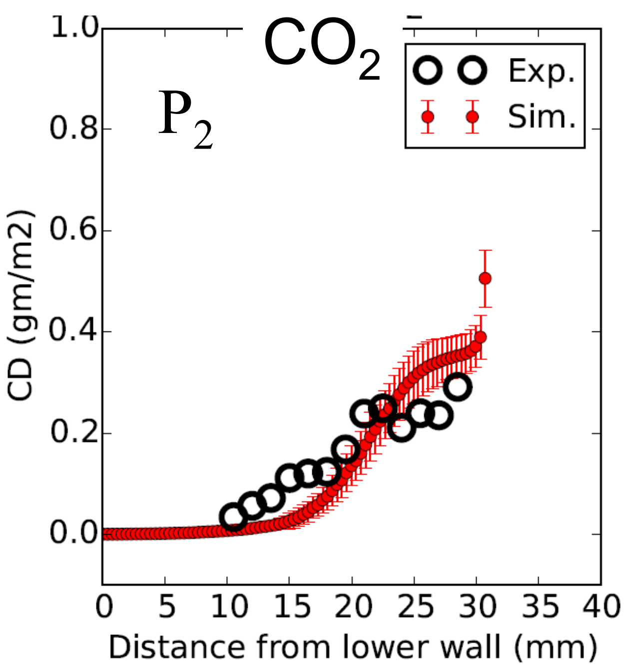
Comparison of TDL Data with CFD (NCSU)

UVa Combustor

C_2H_4 + Air: $\phi \approx 0.15$





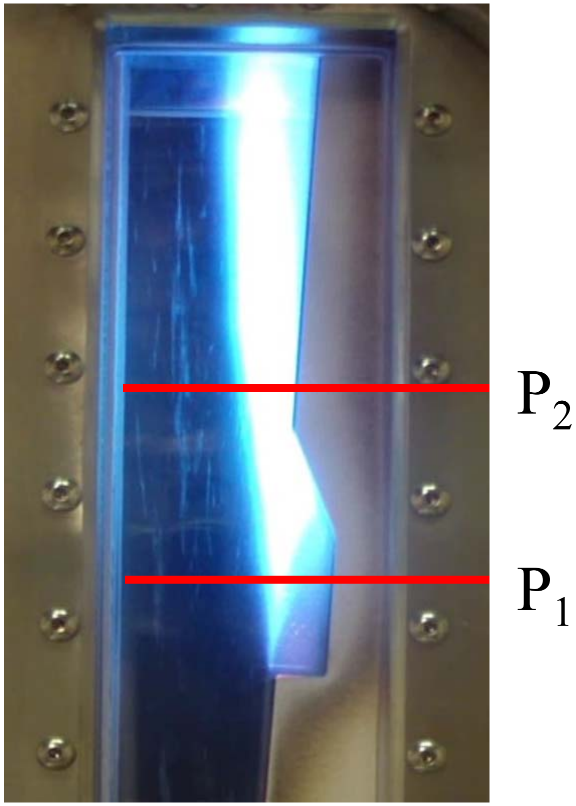


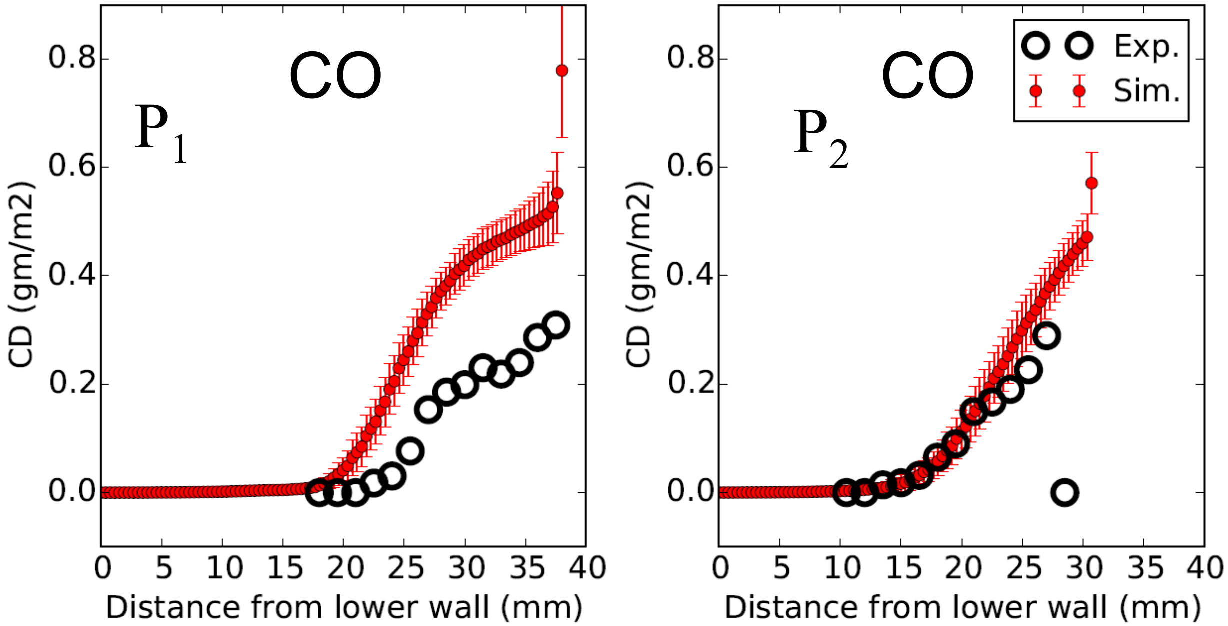
Measured and CFD CO_2 in good agreement

6.3 Mid-IR absorption sensing in scramjet flows
Comparison of TDL Data with CFD (NCSU)

UVa Combustor

C_2H_4 + Air: $\phi \approx 0.15$

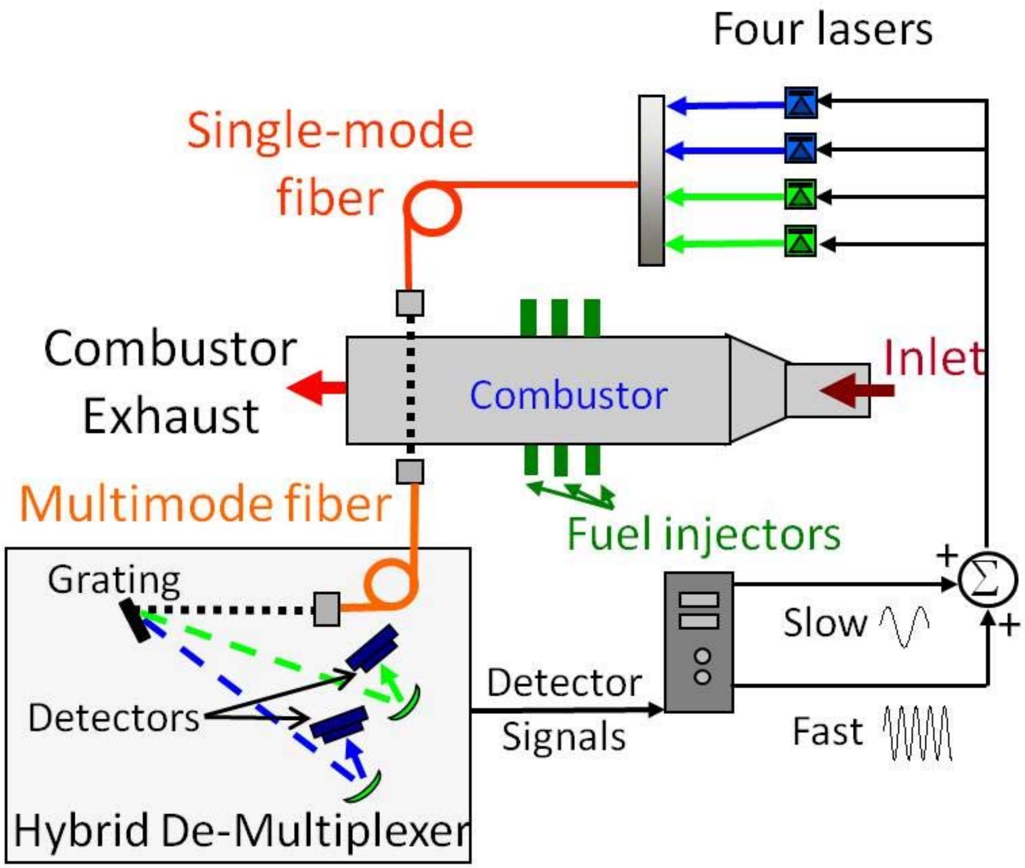




CFD overpredicts CO in cavity

6.4 Scramjet Unstart Monitor

Example: Fluctuations in T Uniformity via TDLAS

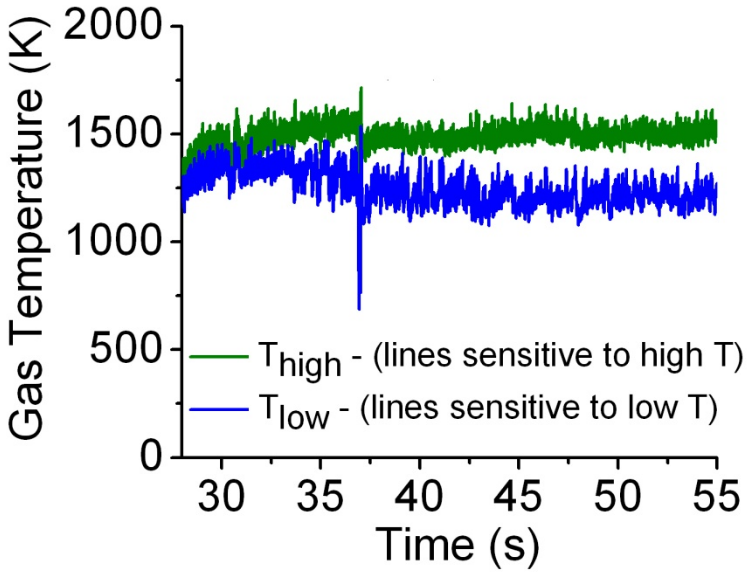


2007

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

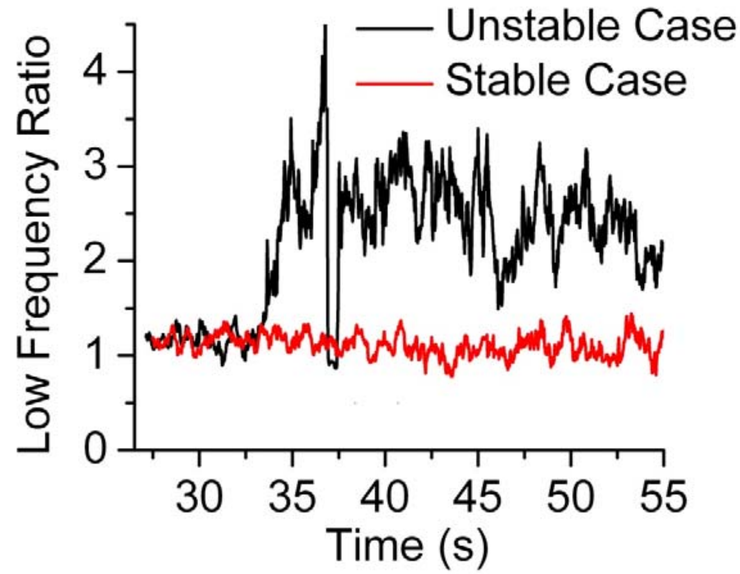
6.4 Scramjet Unstart Monitor

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

7. Future trends for TDLAS Sensing

- Portable TDL-based aerospace sensors useful for T, V, species and mass flux over wide range of conditions, facilities
- Robust TDL-based sensors for long term monitoring of energy systems

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

    → CO, CO_2, HC's, radicals, NO, NO_2
  - Research in advanced energy and propulsion concepts

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