Gas Sensing Based on Tunable Diode Laser (TDL) Absorption

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- TDL absorption fundamentals
- Example applications
  - T for arcjet flow-facility characterization
  - Inlet mass flux for aeroengines
  - T & X_{H_2O} in aeroengine combustors:
    - gas turbine & scramjet
  - T, X_{H_2O}, & X_{fuel} in pulse detonation engines
  - T & X_{H_2O} in IC-engines
- Combustion control
- The future of TDL sensing
  - Many wavelengths for non-uniformities
  - Differential absorption for HC fuels
Role of Optical Diagnostics in Combustion/Propulsion Research

- Characterize test facilities
- Evaluate simulations and models
- Understand complex reactive environments

Optical Diagnostics

- TDL Sensing in SCRAMJET @ WPAFB, OH
- TDL Sensing in IC Engine @ Sandia, Livermore, CA
- PLIF imaging of H₂ jet in model SCRAMJET
- PLIF in plume of Titan IV at Aerojet

Demonstrated applicability in large-scale systems as well as laboratories
**What is Tunable Diode Laser Absorption?**

Wavelength-Multiplexed TDL Sensing Fundamentals

- 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

  \[ \tau_\nu \equiv \frac{I}{I_0} = \exp(-k_\nu \cdot L) \]

- 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

  \[ \frac{k_{\nu_1}}{k_{\nu_2}} = \frac{S_1(T) \cdot \Phi_1(T, P, \chi_i)}{S_2(T) \cdot \Phi_2(T, P, \chi_i)} \approx f(T) \]

- T and \( k_\nu \) yield \( \chi_i \) (species mole fraction)

- *Many-line* ratios for non-uniform T(x), \( \chi_i(x) \)

- \( V \) from Doppler shift

- Mass and momentum flux from \( \rho \) and \( V \)
TDLs Available from the Visible to the Mid-IR

Many important combustion species can be detected by TDL absorption

- Telecommunications TDLs robust, high-power, fiber-coupled, readily available
- Visible TDLs available for selected wavelengths
- NIR TDLs at wavelengths longer than telecom are becoming available
- TDL-driven DFG (difference frequency generation) lasers are emerging (NovaWave and NEL announced products at SPIE 2007)
Many Combustion Species Absorb Light in the NIR

- Small combustion species $\text{H}_2\text{O}$, $\text{CO}_2$, and $\text{CO}$ have structured discrete spectra from overtone and combination bands in the NIR.
- Other species monitored in the NIR include:
  
  $\text{NH}_3$, $\text{CH}_4$, $\text{C}_2\text{H}_2$, $\text{C}_2\text{H}_4$, $\text{C}_3\text{H}_8$, $\text{H}_2\text{CO}$, $\text{HCN}$, $\text{HF}$, $\text{HBr}$, $\text{HCl}$, $\text{NO}$, $\text{H}_2\text{S}$, ….
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**
  - O₂ mass-flux sensor (1989)

- **777-845 nm**
  - Plasma \( n_e, T, O, N, Xe, Ar \) diagnostics (1990)

- **1.34, 1.39 \( \mu m \)**
  - H₂O mass- and momentum-flux sensor (1992)

- **1.55-2.00 \( \mu m \)**
  - Multiplexed sensors for T, H₂O measurements (1993)

- **1.3-1.4 \( \mu m \)**
  - High-pressure H₂O measurements (1996, 2003-6)

- **1.65, 2.3 \( \mu m \)**
  - Fast-sampling and *in situ* emissions (CO, CO₂, NO, NO₂, NH₃, UHC) (1996-9)

- **In situ** CO measurements (1999-2002)

- **1.3-1.8 \( \mu m \)**

- **1.3-1.4 \( \mu m \)**
  - Measurements in pulse detonation engines of H₂O, \( T_{gas} \) (1999); soot (2000); velocity (2002-5); NIR fuel (2002-5)

- **777-845 nm**
  - Gas temperature for practical propulsion engine ground test (2003-present)

- **0.5-10 \( \mu m \)**
  - Atoms for population temperature in NASA Ames arcjet (2002-4)

- **1.3-1.4 \( \mu m \)**
  - Multi-wavelength diagnostics for two phase flow (2003-present)

- **3.4 \( \mu m \)**
  - Gas temperature in IC-engines (2003-5)

- **2.7 \( \mu m \)**
  - Hydrocarbon fuel measurements in mid-IR w/TDL driven DFG (2006-present)

- **H₂O using fundamental bands and CO₂ with first overtone (2007)**
My main message today is that:
TDL Absorption is Practical for Ground Testing

- CW absorption can yield species, T, P, V, & m 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:
  - Arcjets, aero-engine inlets, gas turbine combustors, scramjets, pulse detonation engines, IC engines, coal-fired combustors, shock tunnels and shock-heated flows
- Utilizes cheap, robust and portable near-IR TDL light sources and fiber optics
- Potential use in control of practical systems
- Extension to uv and mid-IR for hydrocarbon fuels and trace species

Arcjet at NASA Ames

SCRAMJET at AFRL WPAFB

PDE at NPS

Chris Brophy, NPS

S. Kim et al., AIAA 2005-0900
TDL Sensing in High-Enthalpy Ground Test Facilities
Example: NASA Ames Arcjet-Driven Hypersonic Tunnel

- **Goals:**
  1. Time-resolved temperature sensing in the arc heater: O or N (to infer T)
  2. Electrode health monitor: Copper from electrode erosion

- **Challenges:** Extreme Conditions T=6000-8000K, P= 2-8 bar
  
  Difficult access (mechanical, optical, and electrical)
Fiber Optics Solves Difficult Optical Access Issues

- 60MW Arcjet facility is electrically isolated
- Plasma is confined in a stack of Cu rings
- Fiber-coupled telescopes provide access
  - via 3mm holes in Cu rings
T Sensing Based on Excited-State Concentrations of N, O

Equilibrium assumption and measurement of excited-state N or O atom concentration sufficient to determine T

Even the small (ppb) concentrations lead to strong absorption in heater (L~15cm)

- 100 ppb of excited O/total O ~50% absorption for arc-heater flow
- 20 ppb of excited N/total N ~ 4% absorption for arc-heater flow
T Sensor Provides Sensitive Monitor of Arc-Heater Performance

- TDL sensor monitors excited O-atom population via NIR absorption
- Equilibrium temperature inferred from measurement of \( ^5S_0^2 \) population
- Measurements versus time monitor arc-plasma performance
- Second TDL sensor for Cu monitors electrode erosion
Cu Sensor Monitors Electrode Erosion

Electrode erosion: (1) maintenance problem
(2) contamination

- Increased erosion seen at high power
- Enables maintenance scheduling
Sensors can target performance of individual engine components

- Inlet: mass flux
- Combustor/augmentor: temperature, species concentration
  - Exhaust: temperature, species, mass flux & thrust, engine health
- Potential for real-time combustion control
TDL Mass Flux Sensor: Full-Scale Aero-Engine Inlet

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

- Air density $\rho$ from measured absorbance of O$_2$
- Use *direct absorption* to integrate absorbance by scanning an oxygen transition with $S(T) \propto 1/T$

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

$A \propto \rho_{O_2} \propto \rho_{air}$

- Use *wavelength modulation spectroscopy, WMS-2f*, to measure velocity from Doppler shift

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

Oxygen $b^1\Sigma^+_g - X^3\Sigma^-_g$ absorption spectrum
- Bellmouth installed on inlet of commercial engine (Airbus 318)
- Sensor hardware remotely operated in control room
- TDL beams mounted in engine bellmouth
TDL data agrees well (1.2% in V and 1.5% in \( \rho \)) w/ test stand instrumentation

Flow model employed to account for non-uniformities

Success in non-uniform flow suggests other potential applications
High temperature/pressure fiber optic probes were custom designed to provide optical access through the pressure vessel and combustor wall.
Gas Turbine Results: T at the Combustor Exit Plane

- First diode laser absorption measurements in a gas turbine combustor facility
- Data confirms the feasibility of using water absorption features to infer temperature and water vapor concentration
- Potential for measurements of temperature at kHz rates
- Potential for real-time control applications
Time-resolved $T$ and $\chi_{H_2O}$ at kHz rates with 4 multiplexed lasers

Hybrid de-multiplexer enables 4 laser signals using two detectors
Multiple Transitions Provide T Sensitivity Over Wide Range

- $E''$, lower state energy, determines temperature dependence of absorption
- Temperature from ratio of measured absorption
- Availability of four wavelengths (with $E''=80-3000\text{cm}^{-1}$) allow accurate measurements over wide range in temperature
Sensor Captures Start-up Transients and Steady Combustion

- Ethylene + Air Operation, $\phi=0.7$
- 16.5 cm upstream of combustor exit
- Steady Combustion

- Sensor has 2kHz temperature bandwidth, yet allows long data records (>10s)
- Captures initial T, autoignition, flame attachment and steady combustion
- Allows evaluation of combustor performance versus injector and/or flame holder
- Provides ability to identify disruptions
Sensor Captures Unstart Event in SCRAMJET

Unstart event evident in temperature trace
Unstart confirmed with pressure sensor data

Ethylene + Air Unstart Event, $\phi=0.85$
16.5 cm upstream of combustor exit
TDL Sensors for Pulse Detonation Engines

- PDE advantages:
  - High specific impulse, high thermal efficiency, mechanical simplicity
  - TDL diagnostics important for performance evaluation, simulation validation
    - Sensors have measured: $T$, $\chi_{\text{fuel}}$, $\chi_{\text{H}_2\text{O}}$, $V$, $P$, soot and aerosol loading
  - Field measurements at: NPS, GE, Pratt (China Lake NAWC), WPAFB
  - PDEs provide challenging measurement environment
- Variable pulse rate (ramped to 40 Hz)
- Total test time 15 seconds
- Time-resolved measurements of $C_2H_4$ fuel loading
- Time-resolved measurements of $H_2O$ for gas T and $X_{H2O}$
Wavelength-Multiplexing for Multiple-Parameter Sensing: Pulse Detonation Engine Example

Combine multiple lasers

Example data from one transition

- Wavelength-multiplexing combines several lasers each scanned in $\lambda$
- Each laser scans one (or more transitions)
- Simultaneous measurements of multiple system parameters
- Potential for: $T$, $v$, $X_{\text{fuel}}$, $X_{\text{O}_2}$, $X_{\text{H}_2\text{O}}$, $X_{\text{CO}_2}$
Simultaneous TDL Sensing of Fuel and Gas Temperature @40Hz

Time-resolved fuel measurements critical to set valve timing
Time-resolved temperature critical to validate performance and simulations
T Sensor Captures Engine Failure Mode

- 1\textsuperscript{st} PDE cycle
  - successful detonation, blow-down
- 2\textsuperscript{nd}, 3\textsuperscript{rd} PDE cycle
  - flame-holding, main-tube
- 4\textsuperscript{th} cycle:
  - flame-holding, main-tube and initiator
    - T provides sensitive indicator of failure mode
    - T sensor used to optimize purge air flows to avoid failure

40Hz, C\textsubscript{2}H\textsubscript{4}-air, $\phi=1$
reduced initiator purge air
TDL Sensors for IC-Engine Applications: Potential for Multi-Parameter Measurements

Motivation: Aid evaluation of new engine concepts and designs

Challenges:
- limited optical access, time-varying T & P, and soot and droplet scattering

Strategy:
- Wavelength-multiplexed absorption for T, species, and non-uniformities

Applications: Inlet, exhaust, and in-cylinder

Examples:
- Cross-cylinder temperature and H$_2$O measurements in optical engine for HCCI (Homogeneous charge compression ignition)
- Short-path (point) temperature and H$_2$O measurements (near spark plug) for SCSI (Stratified charge spark ignition)
Stanford TDL Sensor Used a Diesel-Like HCCI Engine @ Sandia National Laboratory

- State-of-the-art optical engine facilities for sensor validation and test (1hr commute)
- TDL-based $T$ and $X_{H_2O}$ sensor used to investigate HCCI engine operation
- Fiber-coupled lasers and detectors enable use within limited space
  - HCCI operation with well-mixed iso-octane/air
Cylinder-center path reduces effects from cold boundary layer, line-of-sight temperature non-uniformities and beam steering

Flat-head Diesel enables measurement at all crank angles
Diesel-Like HCCI Engine: 3-Cycle Average Fired-Engine

Sensor successfully measures temperature even during combustion

- Temperature from ratio of two line absorbance
- Temperature used to infer $X_{H2O}$
- Water mole-fraction data reveals rise due to combustion
  - Plateau value useful for assessing efficiency
- Sensor could be utilized to investigate engine operation
  - Combustion phasing
  - Combustion efficiency
  - EGR effects
  - Valve-timing effects

Data from November 4, 2005: with J. Dec, M. Sjoberg, and W. Hwang
Nissan/PSI/Stanford TDL Sensor for Spatially-Resolved T in IC-Engines

- Nissan: Developed fiber-coupled optical probe in a working spark plug (6mm gap)
- Stanford: Developed two-color wavelength modulation (WMS-2f) ratio concept for temperature with time-varying pressure during the cycle
- PSI: Developed synchronous 2f data system and portable TDL sensor
Spatially-Resolved Temperature Results in a Production Engine

- Production specification, single-cylinder engine at Nissan Motor Company

- WMS-2f, two-line ratio, successful for intake air w/50% relative humidity
- Temperature measurements near the spark during compression
- Practical tool for test stand evaluation of production engines
- Current work aimed at new species
Gas Temperature Sensor for Coal-Fired Power Plants

Motivation:
- *In situ* sensors can improve combustion efficiency
  - Efficiency increase of 1% reduces GHG by 1% and saves $1M/year in fuel (coal) costs for a 600 MW boiler
  - Path-integrated sensing allows optimization of over-fire-air addition
- Sensors can optimize maintenance
  - Identify burner malfunction from temperature profile

Challenges:
- Long path, nearly opaque, vibration and thermal movement

Strategy:
- Sensors developed at Stanford tested in coal combustors in Colorado and TVA in collaboration with Zolo Technologies:
  - Provides fiber technology to enable practical implementation
  - Provides access to power plants to test measurement concepts
Swirl-stabilized combustor
Fuel: propane

Phase-delay feedback control strategy:
Modulate the intake air flow w/pressure

- Two-line ratio with single TDL provides scanned-wavelength T at 2kHz
- TDL sensor compared with pressure sensor (microphone) and chemiluminescence
TDL T Sensor Offers Advantages over Traditional P Sensor for Combustion Instabilities

- Instability is monitored via FFT of T (power spectrum of 2kHz T data)
- Instability suppressed by the phase-delay feedback control
- Advantages of T sensor: better spatial resolution & improved noise immunity
- First application of laser-based sensor in control of swirl-stabilized flames
Flame structure varies from stable combustion to near LBO.

- Near LBO, quenching by flame stretch becomes more important.
- Less anchorage to ORZ makes flame unstable.
  - Low-frequency T fluctuations
  - TDL sensor can be used to characterize LBO process
  - Flame structure suggests best location for line-of-sight.
TDL Temperature Sensor to Prevent Lean Blowout

Propane/air swirl flame

- Steady combustion ($\phi-\phi_{LBO}=0.4$)

- Near LBO ($\phi-\phi_{LBO}=0.02$)

 FFT of temperature provides warning of incipient LBO

- Near LBO => increase in *low-frequency T-fluctuations*

- These low-frequency fluctuations *can be used as control variable*

- No need for knowledge of the LBO stoichiometry
Demonstration of LBO Suppression using FFT of T

- Air flow constant
- Main fuel programmed
- Control fuel to suppress LBO

Conclusions

- TDL sensor detects incipient LBO with improved SNR vs microphone
- LBO is suppressed during fuel turndown without knowing the LBO stoichiometry
A Practical Example: Control of Laboratory and Prototype Incinerators with TDL Gas Temperature Sensors

5-kW Forced Combustor
HTGL, Stanford University

50-kW Forced Combustor
NAWC, China Lake, CA
Wavelength-Multiplexed Sensors: $T$, $H_2O$, $CO$, and $C_2H_4$

- Fast-sampling system located near combustor for rapid emissions measurements

- $T$, $X_{H2O}$ determined from laser transmission signals (1.34 $\mu$m, 1.39 $\mu$m)
- Magnitude of oscillations at forcing frequency, $T_{rms}(f_0)$, calculated from $T(t)$
- Control system varies phase $\theta$, amplitude $A_{air}$, and frequency $f_0$ to maximize $T_{rms}(f_0)$
Active Control Reduces Emissions

- Optimized acoustic forcing maximizes $T_{\text{rms}}$
- Unburned fuel and CO emissions significantly reduced
- Demonstrates potential of TDL sensors for process control
The Future of TDL Sensing: Broad-Spectrum Wavelength-Multiplexed TDL System

- System based entirely on room-temperature TDLs
- UV/visible for NO, O₂, radicals, and plasma species
- NIR for H₂O, T, V, m → use of many wavelengths for non-uniform flows
- Mid-IR for hydrocarbon fuel, CO, CO₂, pollutants → differential absorption for probing multi-phase fuel flows
Use Many Multiplexed Wavelengths for:
T Sensing in Uniform & Non-uniform Gas Medium

Two different strategies to interpret the data

- Profile fitting:
  - Use known information about the distribution to postulate a T-profile, constrain with other measurements and fit the unknowns: \( T(x) = f(T_{\text{char}}, L_{\text{char}}, x) \)

- Temperature binning:
  - Determine the column density for a set of temperature bins yielding the PDF \((X_{\text{abs}} L)\)

Measurement of attenuation on each laser yields a line-of-sight path integral

\[
A_i(\lambda_i) = P \int_0^L X_{\text{abs}}(x) S_i[T(x)] dx
\]
Exploit Known Constraints: Profile Fitting Strategy

- Postulate T distribution profile: $T(x) = f(T_{\text{char}}, L_{\text{char}}, x)$

\[
\begin{align*}
A_1 &= P \int_0^L g(X_{\text{char}}, L_{X\text{char}}, x) \cdot S_1 \left( f(T_{\text{char}}, L_{T\text{char}}, x) \right) dx \\
A_2 &= P \int_0^L g(X_{\text{char}}, L_{X\text{char}}, x) \cdot S_2 \left( f(T_{\text{char}}, L_{T\text{char}}, x) \right) dx \\
&\vdots \\
A_m &= P \int_0^L g(X_{\text{char}}, L_{X\text{char}}, x) \cdot S_m \left( f(T_{\text{char}}, L_{T\text{char}}, x) \right) dx
\end{align*}
\]

\[
\min_{T_{\text{char}}, L_{T\text{char}}, X_{\text{char}}, L_{X\text{char}}} \sum_{i=1}^m \left( P \int_0^L g(X_{\text{char}}, L_{X\text{char}}, x) \cdot S_i \left( f(T_{\text{char}}, L_{T\text{char}}, x) \right) dx - A_i \right)^2
\]
Obtain PDF from: Temperature Binning Strategy

\[
\begin{bmatrix}
S_1(T_1) & S_1(T_2) & \cdots & S_1(T_n) \\
S_2(T_1) & S_2(T_2) & \cdots & S_2(T_n) \\
\vdots & \vdots & \ddots & \vdots \\
S_m(T_1) & S_m(T_2) & \cdots & S_m(T_n)
\end{bmatrix}
\begin{bmatrix}
(X_{absL})_1 \\
(X_{absL})_2 \\
\vdots \\
(X_{absL})_n
\end{bmatrix}
= \begin{bmatrix}
\tilde{A}_1 \\
\tilde{A}_2 \\
\vdots \\
\tilde{A}_m
\end{bmatrix}
\]

\[\min \sum_{i=1}^{m} \left( \sum_{j=1}^{n} \left( S_i(T_j) \cdot (X_{absL})_j - \tilde{A}_i \right) \right)^2 \]

- The solution (column density) is the PDF of the absorbing species
- Mole fraction constant: column density \( \Rightarrow \) the fraction of path length \( (f_j) \)

PDF solution sufficient for monitoring and control applications with goals of minimizing or maximizing the non-uniformities

Potential for characterizing channel flows, e.g., in process control
Difference-frequency-generation of mid-IR with robust NIR components

- Tuning of telecommunications NIR laser tunes mid-IR wavelength $\sim 100 \text{ cm}^{-1}$
- Wavelength tunability enables optimization for specific application
- Stanford multiplexes the tunable DFB to provide alternating output wavelengths
- Multi-wavelength absorption enables detection of hydrocarbon fuels (broad features)
Fuel distribution is critically important for propulsion testing, yet difficult to measure.

C-H stretch vibrations have strong, blended absorption near 3000 cm\(^{-1}\) (3.3 μm).

Differential absorption enables species selectivity and suppression of interferences.

**Dual-Wavelength Differential Absorption (DWDA)**

- Measure extinction at two colors \(\lambda_1\) and \(\lambda_2\) and take difference.
- Rejects common-mode interference, i.e.

  \[
  \text{if: } \tau_{\text{interference}}(\lambda_1) = \tau_{\text{interference}}(\lambda_2) \text{ then: } \ln(I/I_0)_{\lambda_1} - \ln(I/I_0)_{\lambda_2} = \{\beta(\lambda_2) - \beta(\lambda_1)\} X_i PL
  \]

Example for n-dodecane detection with scattering interference.
Suppression of Droplet Interference: Example of DWDA in a Shock-Heated Aerosol

Experiment Details:
- Shock-heated n-dodecane aerosol
  - Pre-shock: room temperature aerosol
  - Post-shock: isentropically compressed mixture (droplets evaporate)
- Vapor $X_{\text{dodecane}}$ obtained before and after shock arrival
DWDA Measurements of Dodecane Vapor Formed by Evaporation from Shock-Heated Aerosol

- DWDA successful even with large droplet extinction
  - Note 50% attenuation of near-IR beam before shock; 80% after shock
  - NIR signal yields temporal evolution of droplet loading
- Good potential for application to practical (liquid-fueled) combustors

Shock conditions:
- $P_2 = 0.78$ atm
- $T_2 = 436$ K

Pre-Shock:
- $P_1 = 0.22$ atm
- $T_1 = 298$ K

Dodecane vapor pressure @ 300 K
The JP-10 absorption depends on temperature

**DWDA for JP10**: Measure extinction at two colors $\lambda_1$ and $\lambda_2$

- Ratio of absorbance provides $T$
- $T$ and either absorbance measurement provides fuel concentration
- Modify mid-IR DFG laser to provide two colors
**Mid-IR JP-10 Fuel Measurements (@NPS)**

**Goal:** Need time-resolved JP-10 measurements in NPS valveless PDE for valve timing and fuel/air stoichiometry

- Fiber delivery of mid-IR
- Detector mounted directly to engine
- Inlet $T = 450 \text{ K} – 550 \text{ K}$ (vitiated air)
- Fill $P = 1.2 – 2.5 \text{ atm (abs)}$
- Time-resolved fuel loading enables optimization of valve timing, injector design, ignition scheduling and calibration of fuel delivery
- Sensor shows that cooling from liquid fuel vaporization does not significantly alter the vitiated PDE input gas conditions
- Note PDE thermocouple $T$ has 1s time constant, and TDL $T$ has 200$\mu$s time constant
Summary and Future Opportunities

- TDL-based sensors proven useful for $T$, $X_i$, $V$, and $\dot{m}$ in many applications for system understanding, optimization and control
  - Pulse detonation engines (NPS, P&W, GE, WPAFB, Stanford)
  - Arcjet-driven hypersonic flow facility (NASA Ames & Calspan)
  - Aero-engine mass flux (P&W)
  - Gas Turbine Engine (WPAFB, P&W)
  - SCRAMJET facility (WPAFB)
  - Piston engines (Sandia and Nissan)
  - Coal-fired power plants (Zolo)

- Potential for the future:
  - Applications to maintenance and control of ground-test facilities
    - Hypersonic mass flux (NASA)
  - Valuable research tool to develop new combustion concepts
    - Flame stability in augmented aeroengines (AF/P&W)
  - Flight applications
  - New wavelengths (UV and mid-IR) for new species and increased sensitivity
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