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14. ABSTRACT
Modulated absorption-emission thermometry (MAET) is a non-intrusive, radiometric technique for measuring line-of-sight average temperature in high-temperature gases. The technique uses alternating measurements of emission and transmission to obtain the emissivity and the radiative intensity of the gas over a spectral band. The temperature is then calculated from the Planck function. The technique does not involve the measurement of spectral features such as line widths or strengths and therefore is suitable for high-pressure environments where spectral lines are broadened and merged. It is also suitable for environments where broadband emitters such as soot are present.

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A Method for Eliminating Beam Steering Error for Modulated Absorption-Emission Thermometry

AIAA SciTech2015

5-9 Jan 2015

Edward B. Coy

Thermal Management Group

AFRL/RQRC

Integrity ★ Service ★ Excellence

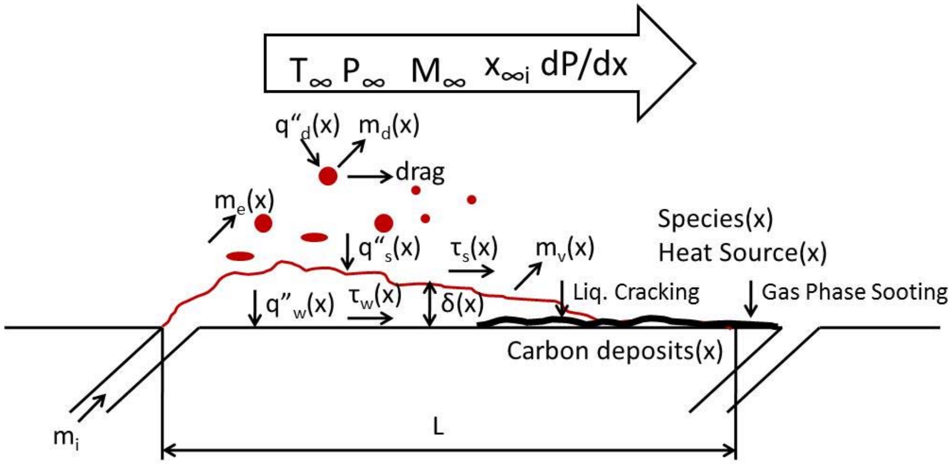
Outline

- Motivation for fuel film cooling studies
- Challenges of optical diagnostics for liquid rocket engine combustion chambers
- Limitations of basic one-color MAET
- Assumptions and theory of two-color MAET
- Prevention of window fouling
- Data Reduction
- Summary of Results

Motivation

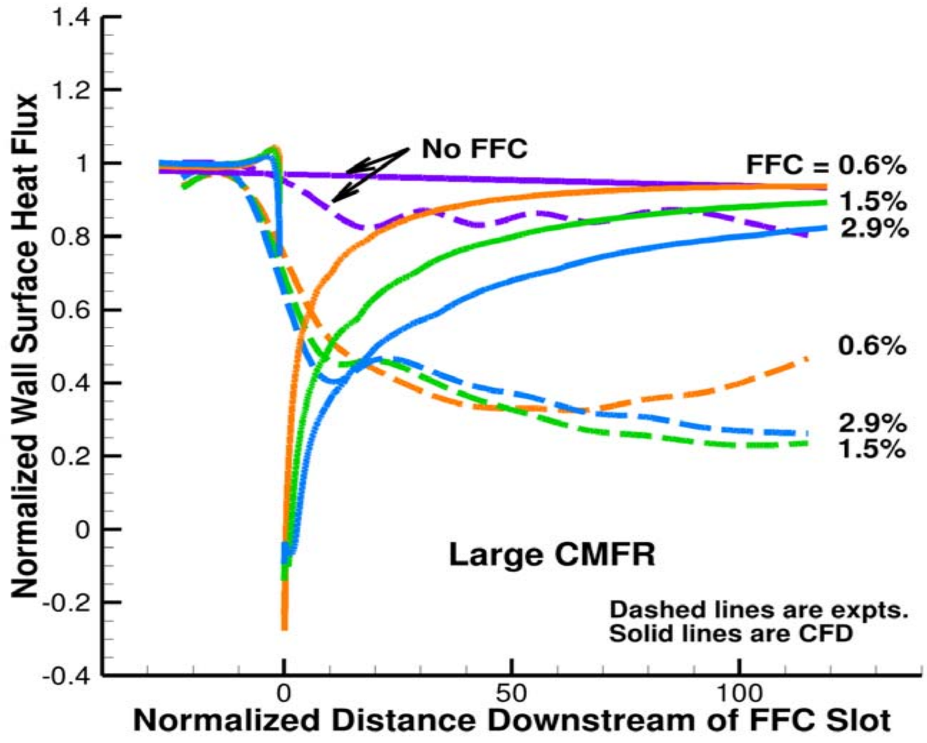
- **Fuel Film Cooling is a critical Technology for high performing ORSC engines**
  - **Need to reduce heat load on regenerative cooling channels in order to meet pressure drop and pressure design limits**
  - **Reduced pressure budget for cooling channels reduces pump horsepower and turbine inlet temperature**

- Reduces adiabatic wall temperature
- Adds thermal barrier coating



Status of Modeling and Simulation

- Existing data set for film cooling effectiveness consists of wall heat flux measurements
- CFD predictions are inaccurate
- Data on gas conditions in boundary layer will help

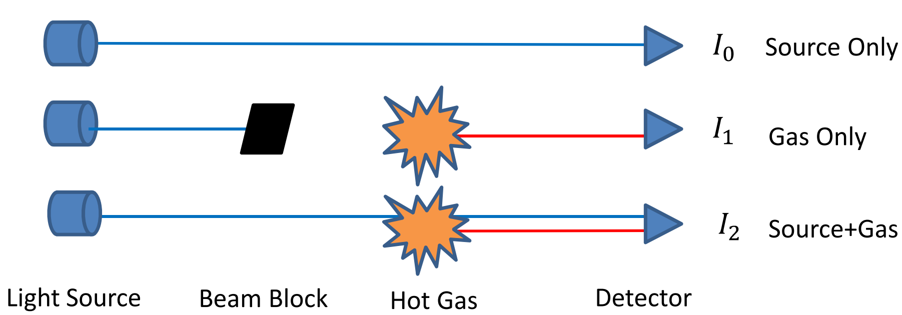


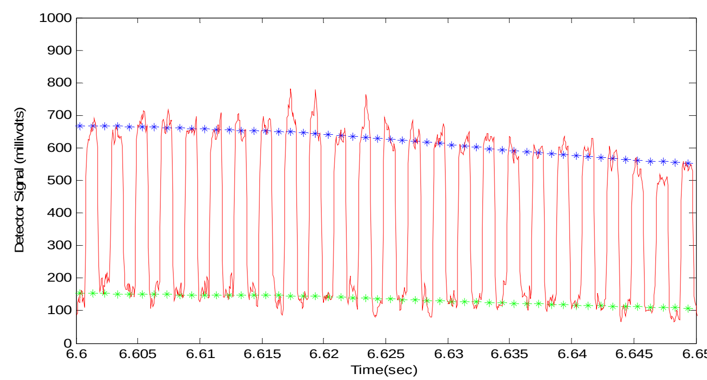
Technical Challenges

- Challenges for optical diagnostics at LRE relevant conditions (50-200 atm / 800-3600K)
  – Line broadening
  – Beam steering
  – Scattering
  – Luminosity
  – Soot absorption and emission
  – Window fouling
  – Test stand environment

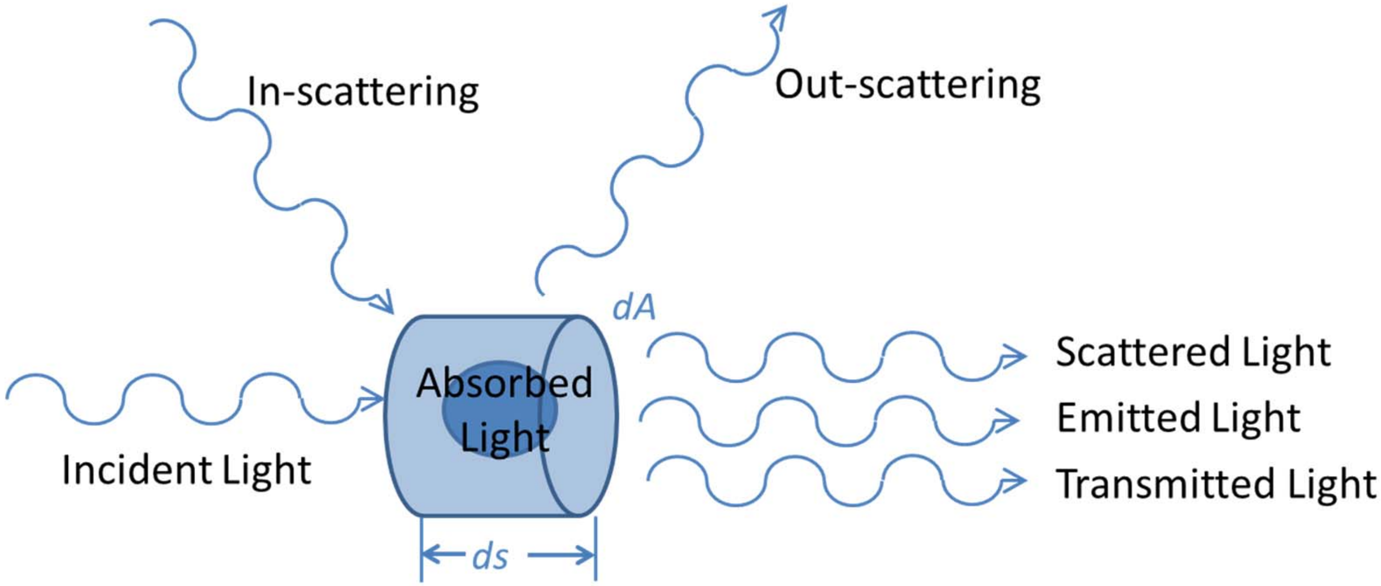
Modulated Absorption-Emission

- **Radiometric technique for line-of-sight temperature and species in high temperature gas**
- **Uses alternating measurements of absorption and emission to obtain emissivity and radiative intensity over a band**
- **Does not require spectral data for temperature**
- **Temperature is calculated based on Planck function**
- **Species and soot concentrations based on absorption**





Radiative Transfer Equation



$$\frac{dI_\lambda}{ds} = \kappa_\lambda I_{b\lambda} - \beta_\lambda I_\lambda + \frac{\sigma_\lambda}{4\pi}\int_0^{4\pi} I_\lambda(s_i)\Phi(s_i, s)\,d\Omega$$

Basic MAET

- **Assumptions**
  - Scattering is negligible
  - Beam steering is negligible
  - Absorptivity=Emissivity (Kirchhoff's Law)

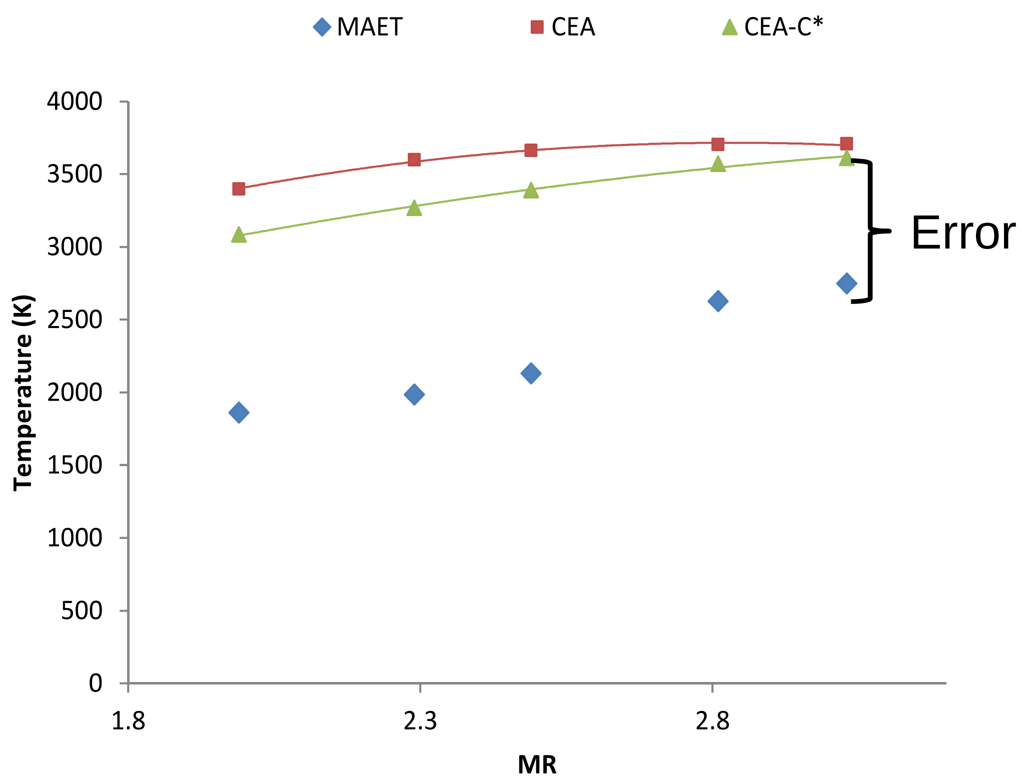
$$\epsilon_\lambda = \frac{I_{0,\lambda} + I_{1,\lambda} - I_{2,\lambda}}{I_{0,\lambda}}$$

$$I_{b\lambda} = I_{1,\lambda}/\epsilon_\lambda$$

$$T_{gas} = \frac{hc_0}{\lambda k_b ln\left[\frac{2hc_0^2}{I_{b\lambda}\lambda^5} + 1\right]}$$

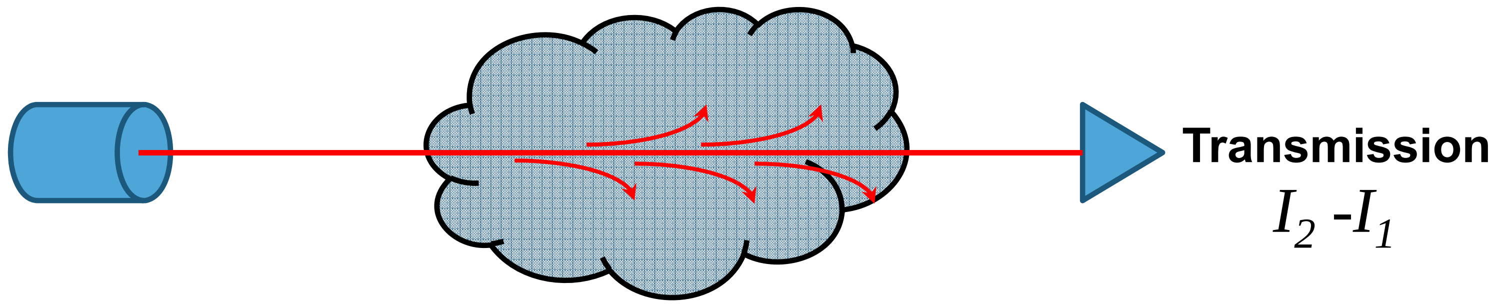
Basic MAET

RP-2/O_2 MR=2.8 P_c=750 psi



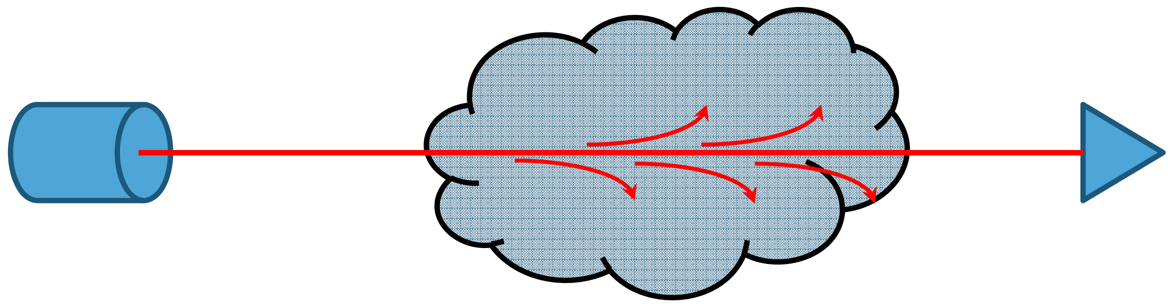
Beam Steering and Scattering are not Negligible

Scattering Assumptions



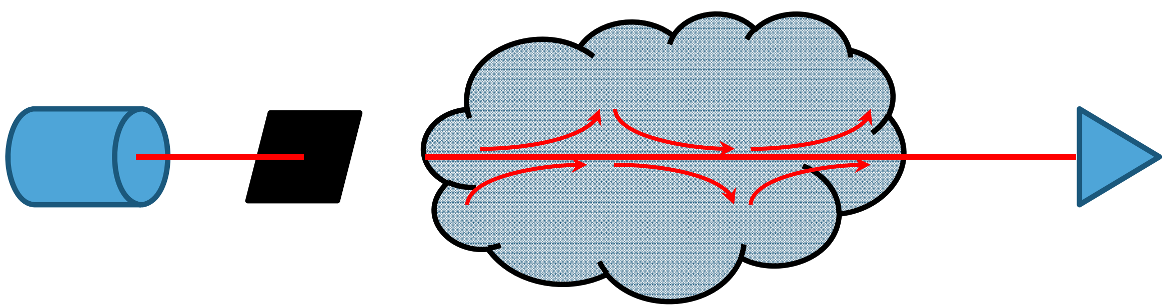
Out-scattering Only

Scattering Assumptions



Transmission, $I_2 - I_1$

Out-scattering Only

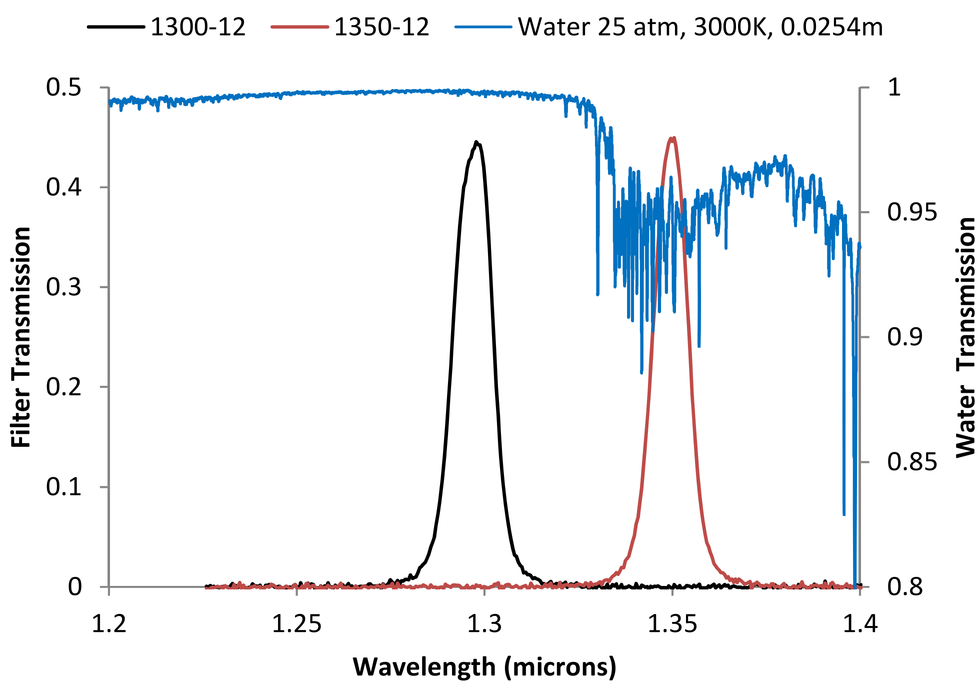


Emission, I_1

Out-scattering = In-scattering

Beam Steering Assumptions

- **Beam steering is a weak function of wavelength**
- **Use 2-wavelength detection to cancel effects of beam steering**



Two-wavelength Formulation

- **Transmissivity depends on the extinction coefficient,** $\beta = \bar{\kappa} + \Delta\kappa_g + \sigma$

$$\tau_\lambda = e^{-\beta_\lambda L} = \frac{I_{2,\lambda} - I_{1,\lambda}}{I_{0,\lambda}}$$

- **Scattering and broadband absorption cancel from the transmissivity ratio**

$$\frac{\tau_{\lambda_1}}{\tau_{\lambda_2}} = \frac{\boldsymbol{e}^{-(\bar{\boldsymbol{\kappa}}+\boldsymbol{\Delta\kappa_g}+\boldsymbol{\sigma})\boldsymbol{L}}}{\boldsymbol{e}^{-(\bar{\boldsymbol{\kappa}}+\boldsymbol{\sigma})\boldsymbol{L}}} = \boldsymbol{e}^{-\Delta\kappa_g L}$$

- **Emission ratio also depends only on** $\Delta\kappa_g$

$$\frac{1 - I_{1,\lambda_1}/I_{b,\lambda_1}}{1 - I_{1,\lambda_2}/I_{b,\lambda_2}} = \boldsymbol{e}^{-\Delta\kappa_g L}$$

Fundamental Equations of MAET

- **Solve for temperature implicitly**

$$\frac{\tau_{\lambda_1}}{\tau_{\lambda_2}} = \frac{1 - I_{1,\lambda_1}/I_{b,\lambda_1}}{1 - I_{1,\lambda_2}/I_{b,\lambda_2}}$$

- **For this study we assume $\Delta\kappa_g$ is due to water only**

$$\Delta\kappa_g = -\frac{1}{L} ln\left(\frac{\tau_{\lambda_1}}{\tau_{\lambda_2}}\right)$$

- **We also assume that broadband absorption, $\bar{\kappa}$, is due to soot only**

$$\bar{\kappa} = \frac{-1}{L} ln\left(1 - \frac{I_{1,\lambda}}{I_{b,\lambda}}\right) - \Delta\kappa_g$$

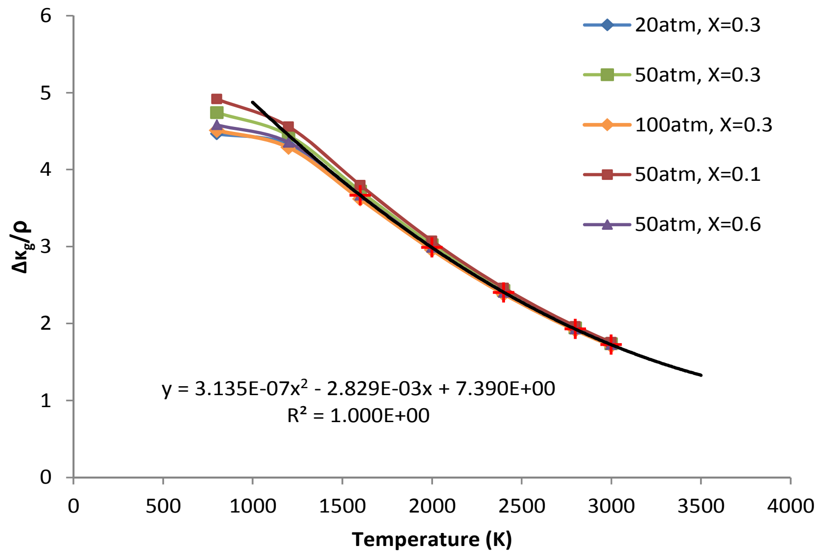
Soot Volume Fraction and Water Concentration

- **Mie theory result for soot volume fraction for particles smaller than wavelength**

$$\bar{\kappa} = -Im\left\{\frac{m^2-1}{m^2+2}\right\}\frac{6\pi f_v}{\lambda}$$

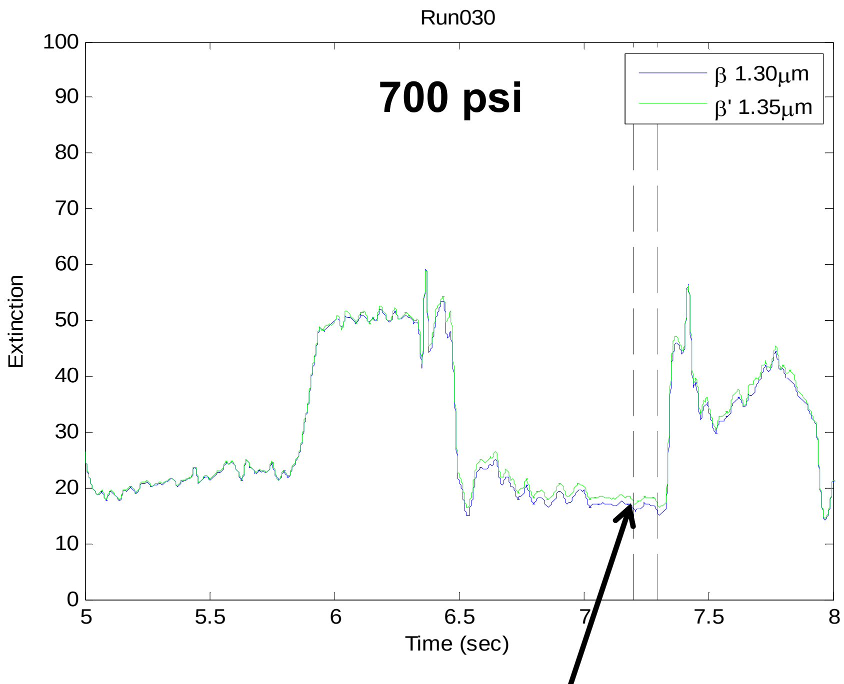
- **HiTemp-based polynomial fit for water density**

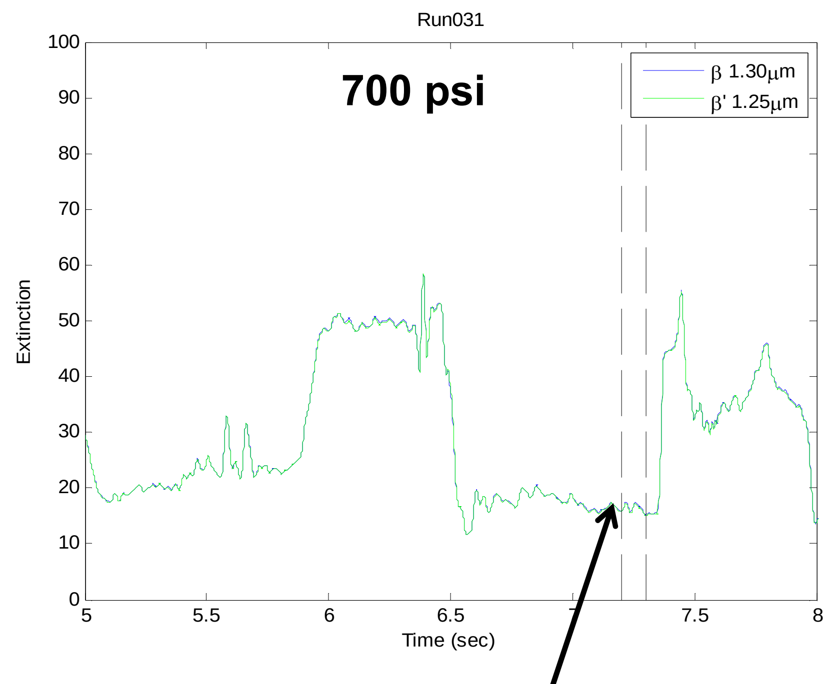
$$\Delta\kappa_g = \rho_w \mathbf{P}(\mathrm{T})$$



Extinction Measurements

- **Extinction at 1.25 and 1.30 microns are identical**
- **Supports assumption that scattering and beam steering are weak functions of wavelength**





Difference is due to water absorption

Negligible difference. No absorption

Window Fouling

Optimal Momentum Flux for Purge Flow

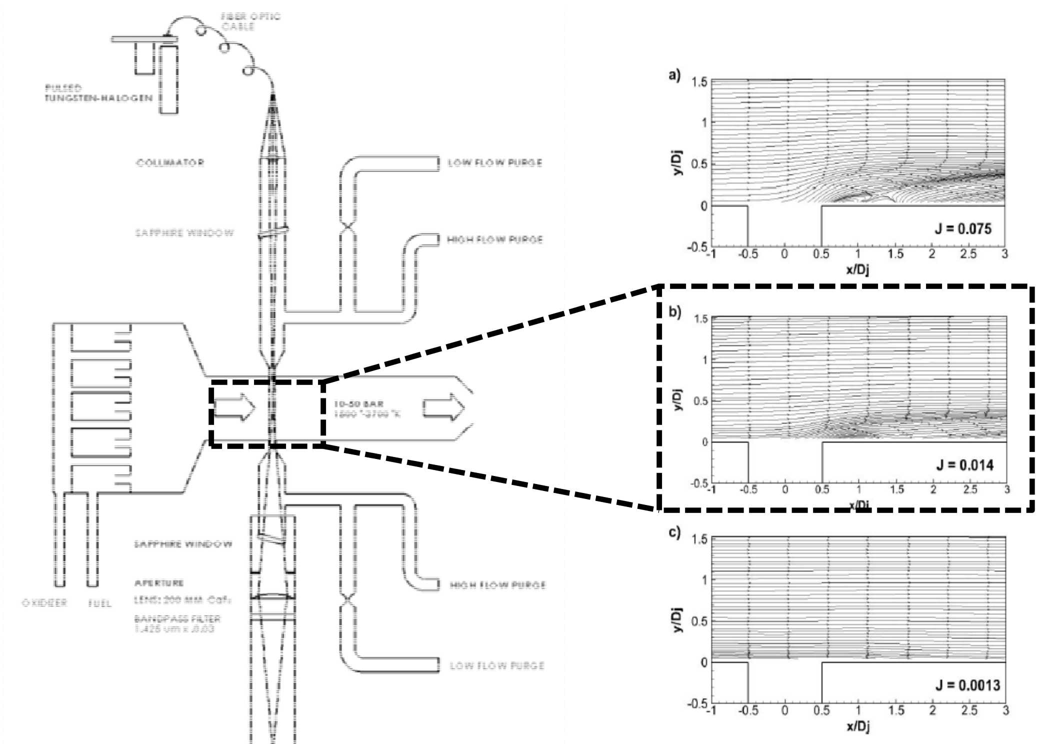


Figure 6. Streamlines of the mean velocity

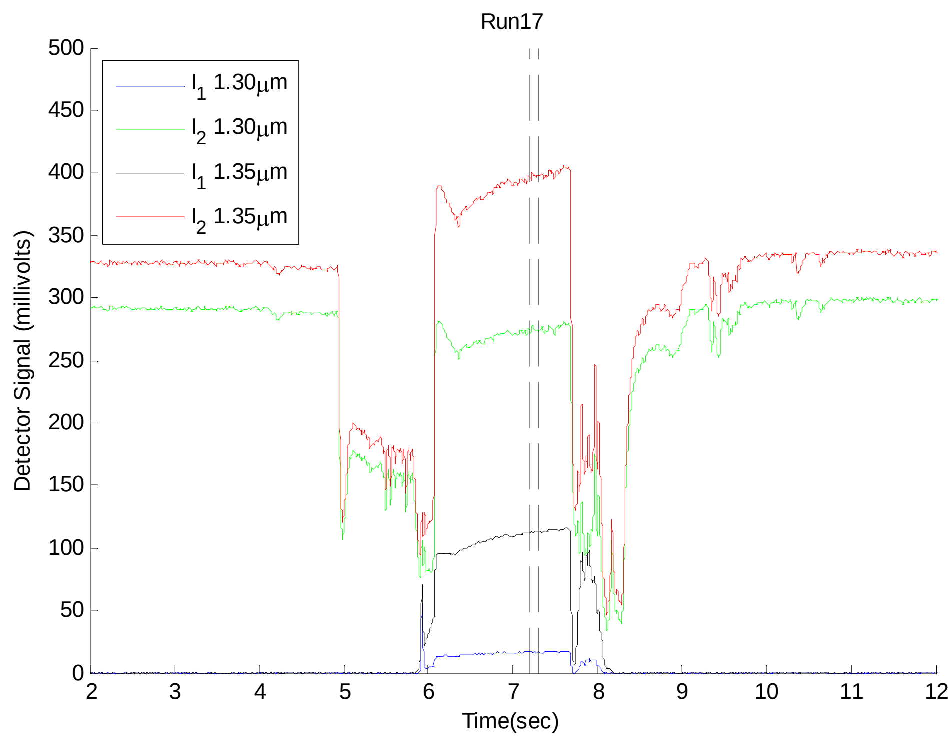
PIV Results

- **Mean velocity fields**
- **Mean Vorticity**
- **Mean Turbulence Vel.**
- **Reynold's Stress**
- **Jet Penetration**
- **Power Spectral Density**
- **Pulsing phenomena**

D. Salazar, D. Forliti, K. Kuzmich, E. Coy, "Near-Wall Velocity Field Measurements of a Very Low Momentum Flux Transverse Jet," PA (Public Affairs) Clearance Number 14344.

Data Reduction – Step 1

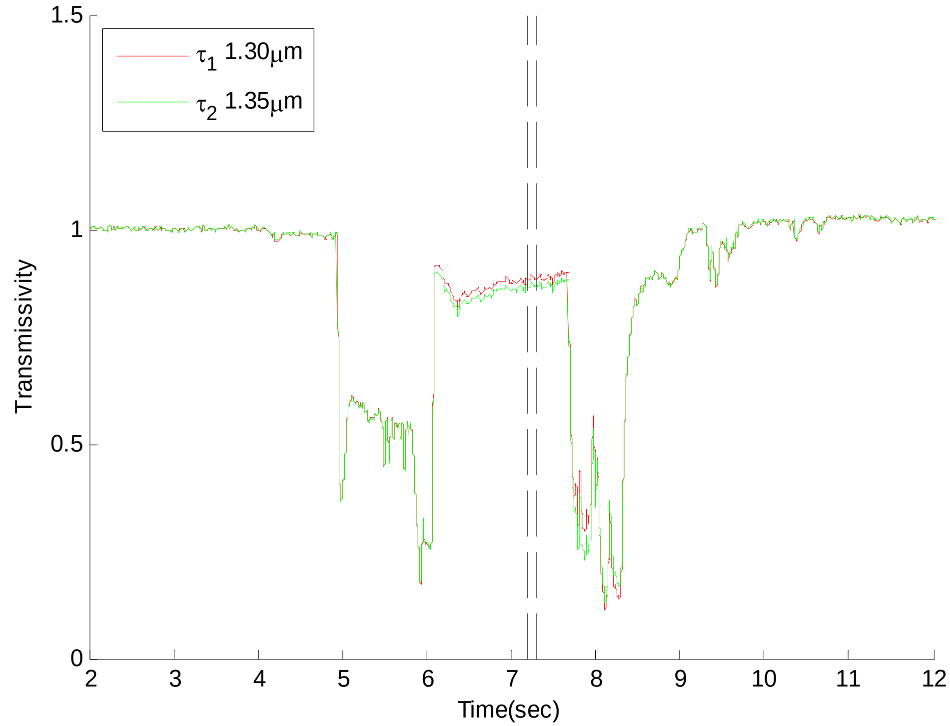
- **Detector signals after conditional sampling and smoothing**



Data Reduction – Step 2

- **Transmissivity at 1.30 and 1.35 microns**
- **Includes effects of scattering, beam steering and broadband absorption**

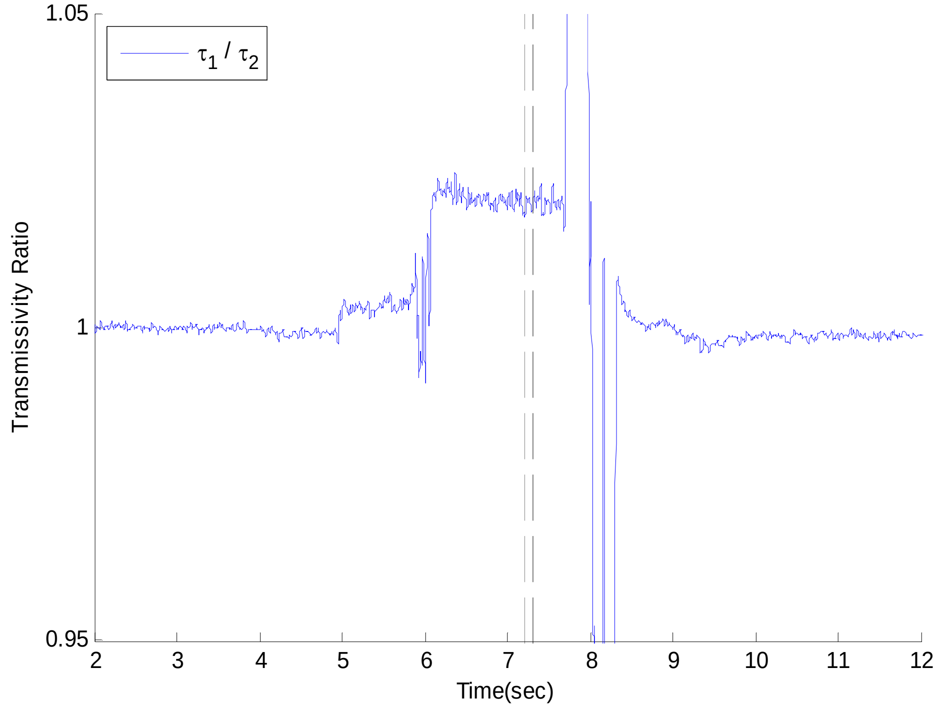
$$\tau_\lambda = e^{-\beta_\lambda L} = \frac{I_{2,\lambda} - I_{1,\lambda}}{I_{0,\lambda}}$$



Data Reduction – Step 3

- **Transmissivity ratio**
- **Scattering, beam steering and broadband absorption are eliminated. Depends only on $\Delta\kappa_g$**

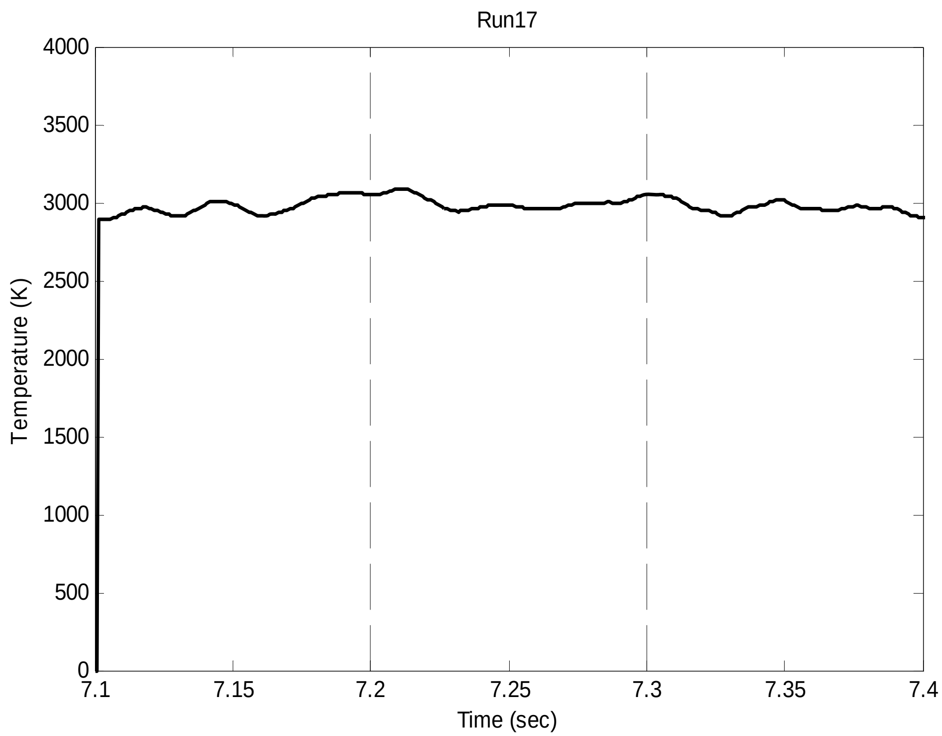
$$\frac{\tau_{\lambda_1}}{\tau_{\lambda_2}} = \frac{e^{-(\bar{\kappa}+\Delta\kappa_g+\sigma)L}}{e^{-(\bar{\kappa}+\sigma)L}} = e^{-\Delta\kappa_g L}$$



Data Reduction – Step 4

- **Solve for temperature that satisfies the MAET governing equation**

$$\frac{\tau_{\lambda_1}}{\tau_{\lambda_2}} = \frac{1 - I_{1,\lambda_1}/I_{b,\lambda_1}}{1 - I_{1,\lambda_2}/I_{b,\lambda_2}}$$



Data Reduction – Step 5

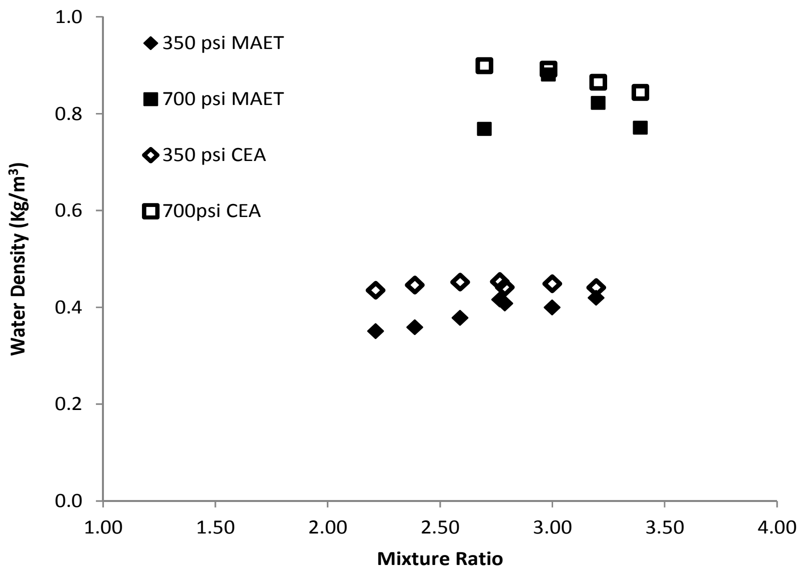
- **Calculate water and soot concentrations**

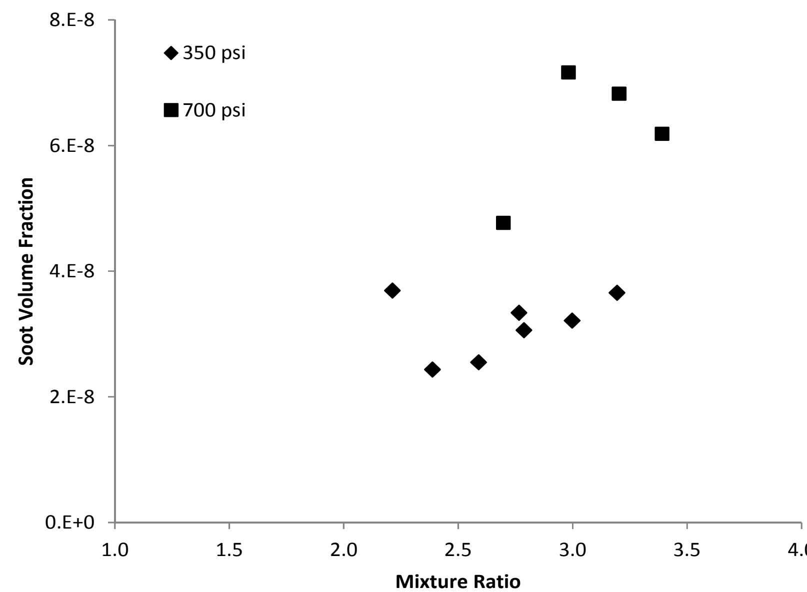
$$\Delta\kappa_g = -\frac{1}{L} ln\left(\frac{\tau_{\lambda_1}}{\tau_{\lambda_2}}\right)$$

$$\rho_w = \mathbf{P}(\mathrm{T}) / \Delta\kappa_g$$

$$\bar{\kappa} = \frac{-1}{L} ln\left(1 - \frac{I_{1,\lambda}}{I_{b,\lambda}}\right) - \Delta\kappa_g$$

$$f_v = \lambda\bar{\kappa}/6\pi \; Im\left\{\frac{m^2-1}{m^2+2}\right\}$$





Conclusion

- **Two-wavelength MAET is well-suited for LRE relevant conditions (50-200 atm / 800-3600K)**
- **All of the major technical challenges have been addressed**
  - ✓ **Line broadening**
  - ✓ **Beam steering□**
  - ✓ **Scattering**
  - ✓ **Luminosity**
  - ✓ **Soot absorption and emission**
  - ✓ **Window fouling**
  - ✓ **Test stand environment**