# *Extinction and Emission Tomography in Turbulent Sprays and Flames*

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**Acknowledgement: The author acknowledges the support provided by the National Science Foundation and the National Aeronautics and Space Administration for this work.**

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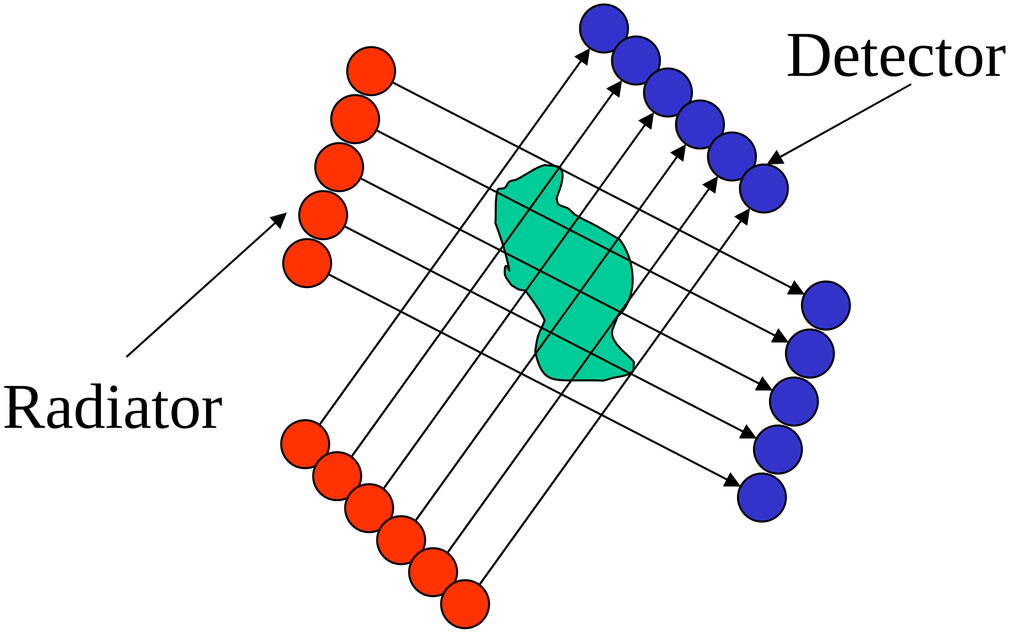
# Outline

- Extinction Tomography
- Emission Tomography
- Concluding Remarks

# Primer on Tomography



- Non-intrusive path-integrated measurement at multiple angles and multiple slices at each angle
- Deconvolute measurements to obtain local properties

# Extinction Tomography

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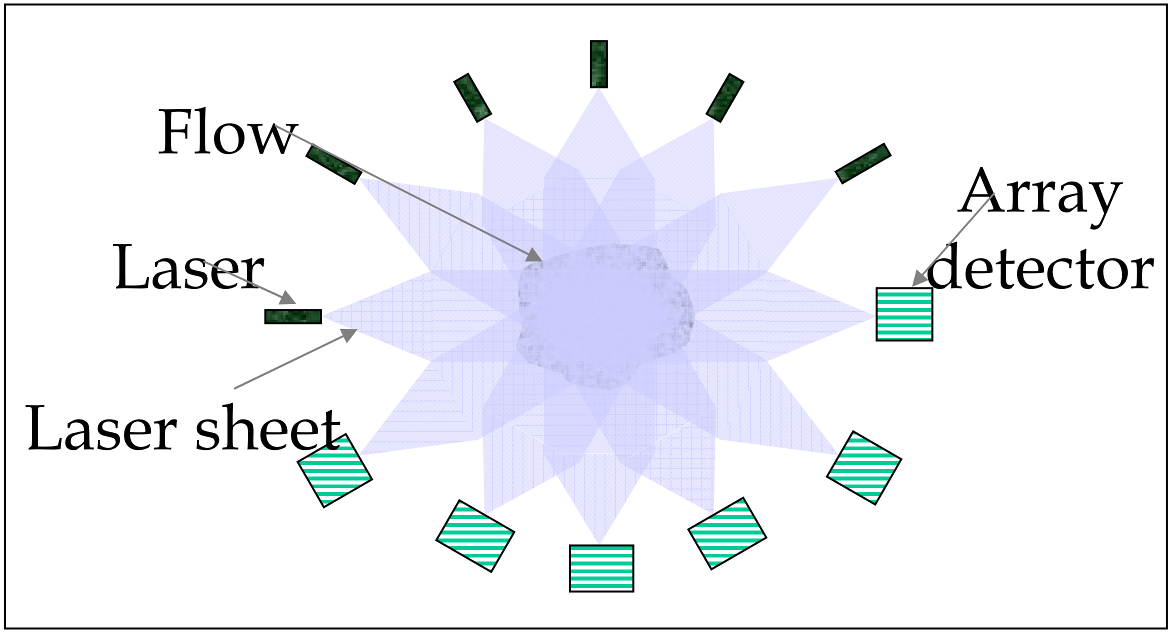
# Extinction Tomography

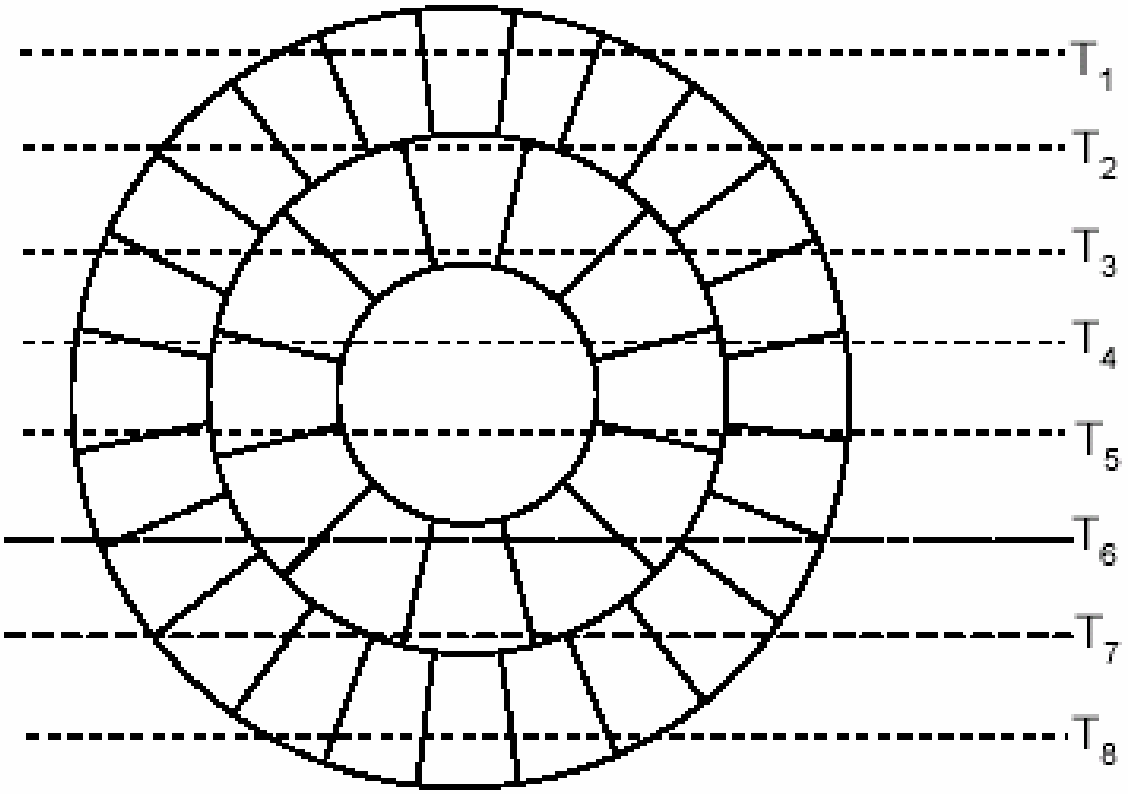


- *Extinction measured at multiple view angles*
- *Deconvoluted using tomography*
- *Challenge is that objects are moving*

# Measurement Considerations

- Multiple view angles for non-axisymmetric flows
- Multiple slices to obtain high spatial resolution
- High speed for transient phenomena
- Extinction should be less than 0.99
- Local extinction coefficient obtained by statistical deconvolution
- Optical access to flow required

# Deconvolution Domain



# Governing Equations

*Equation of radiative transfer for one sample path*

$$\exp(-K_1^1\Delta_1^1 - K_1^2\Delta_1^2 - K_1^3\Delta_1^1) = T_1^1$$

$$K_1^1\Delta_1^1 + K_1^2\Delta_1^2 + K_1^3\Delta_1^1 = -\log(T_1^1)$$

$$E\left\{K_1^1\Delta_1^1 + K_1^2\Delta_1^2 + K_1^3\Delta_1^1\right\} = E\left\{-\log\left(T_1^1\right)\right\}$$

$$\Delta_1^1 E\left\{K_1^1\right\} + \Delta_1^2 E\left\{K_1^2\right\} + \Delta_1^1 E\left\{K_1^3\right\} = E\left\{-\log\left(T_1^1\right)\right\}$$

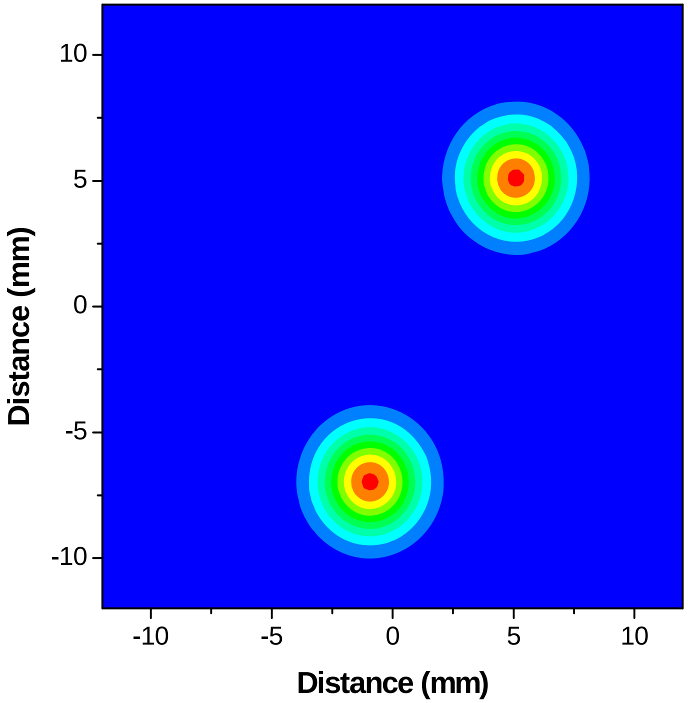
# System of Equations

- For M view angles and N slices, MxN linear equations
- All unknown local extinction coefficients are positive
- LINPOS equations inverted using MLE method
- Method guarantees convergence to optimal solution
- Local extinction coefficient identical to local surface area per unit volume for spherical drops > wavelength of light
- Local extinction coefficient related to volume fraction of particulate for particle < wavelength of light

# Algorithm Steps

- Input geometry of measurements
- Provide initial guess of local extinction coefficients
- Calculate theoretical path integrated transmittance
- Compare theoretical and measured transmittances
- Update local extinction coefficients using MLE method

# Synthetic Data for Algorithm Verification



**2 small highly absorbing region**

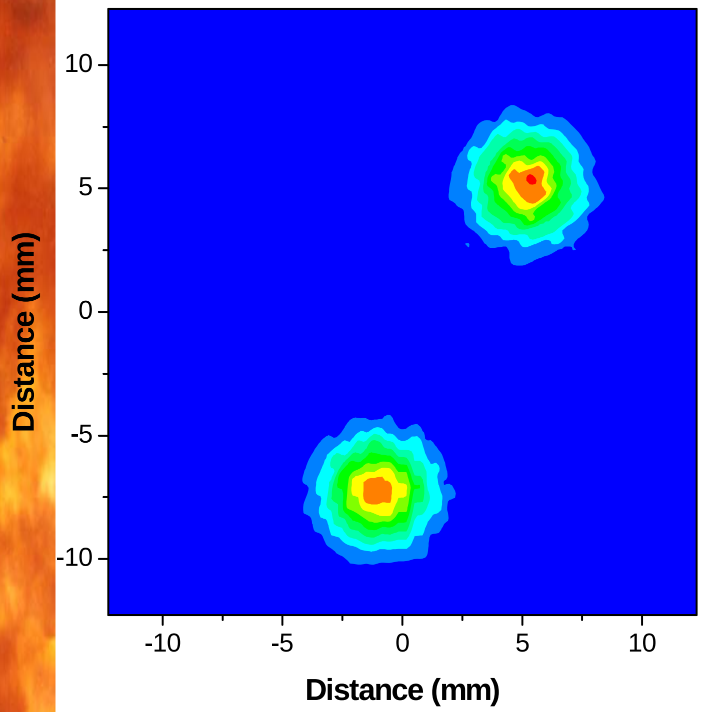
**Minimum transmittance < 0.10**

$$f(r) = \frac{1}{\sigma R\sqrt{2\pi}} \exp(-\left[(r/\sigma R)^2\right]/2)$$

**Very difficult to resolve using alternate methods**

**Rigorous test of the algorithm**

# Output from Algorithm



**Peak local extinction coefficient is 93% of input (6 x 256 array)**

**RMS fitting error defined as:**

$$\mathrm{Err} = \sqrt{\sum_{i=0}^{N} \left(\tau^{i}_{syn} - \tau^{i}_{dec}\right)^{2} / N}$$

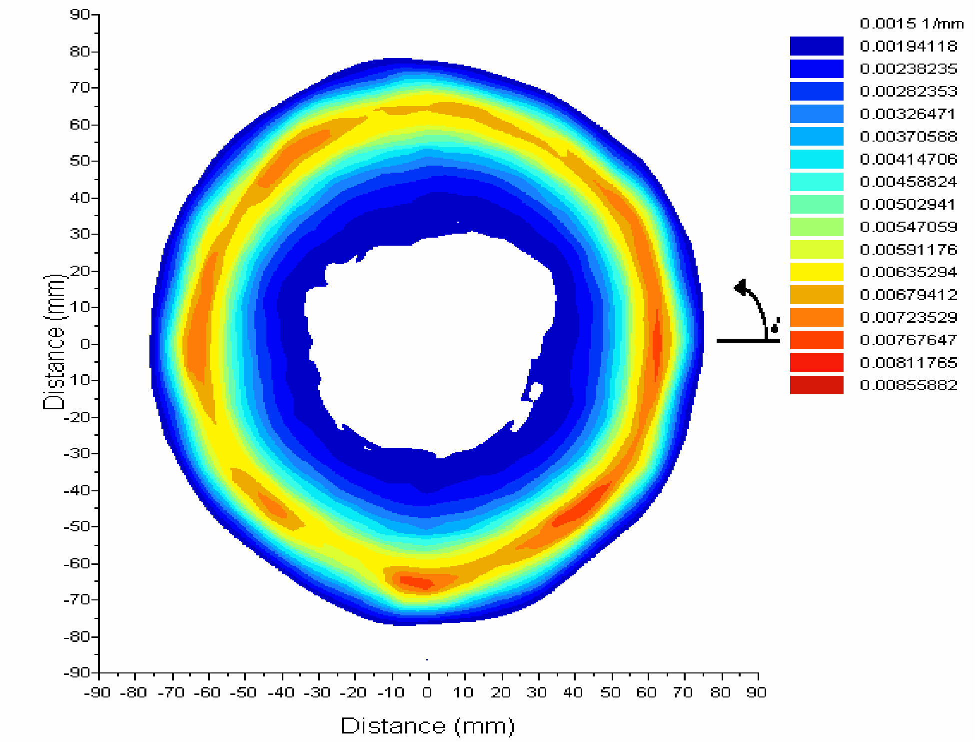
**RMS error is less than 1%**

Jongmook Lim and Yudaya Sivathanu, (2005), “Optical Patternation of a Multihole Nozzle” Atomization and Sprays, vol. 15, pp. 687-698.

# SETscan Patternator

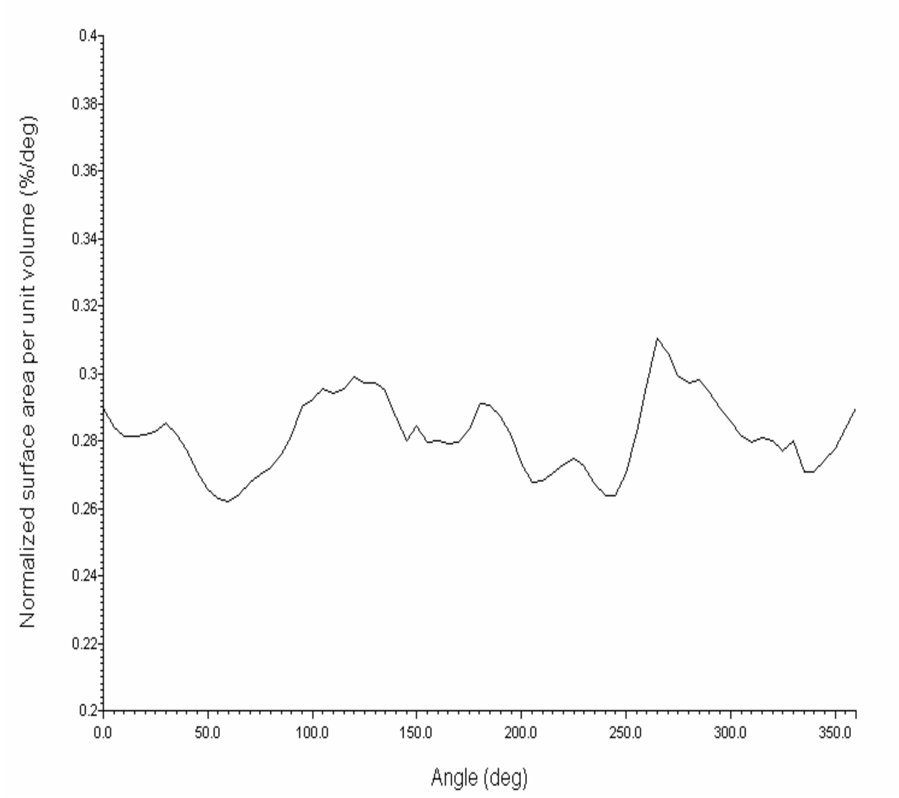
High frequency, optical patternator for sprays

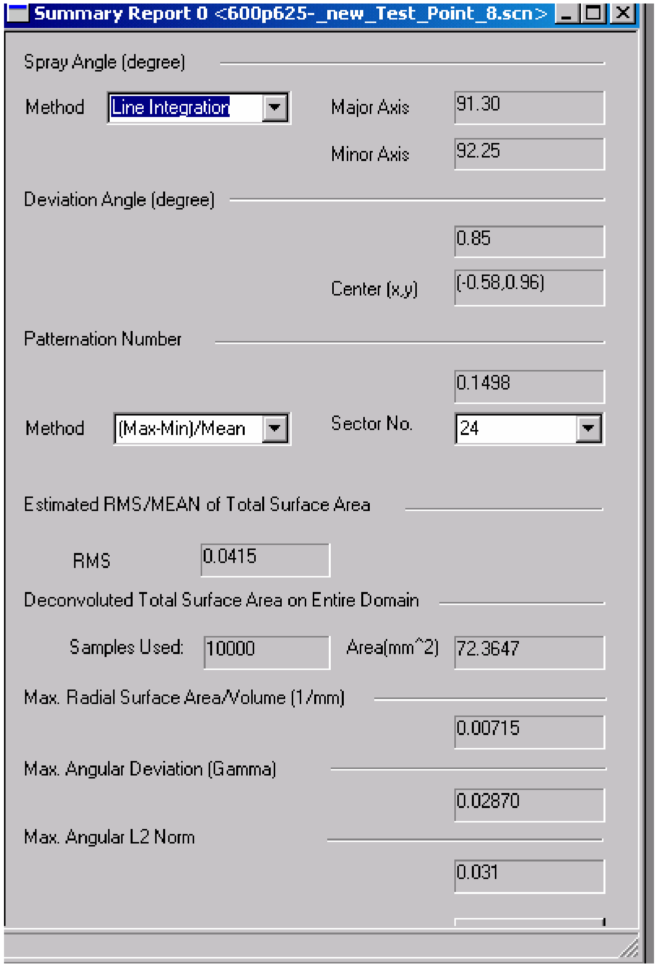
# Sample Result: Aircraft Engine Nozzle



- ➢ Ensemble average of drop surface area density
- ➢ High/low surface area indicates streaks/voids

# Quality Assurance: Aircraft Engine Nozzle





Spray Angle (degree)

Method: Line Integration

Major Axis: 91.30

Minor Axis: 92.25

Deviation Angle (degree)

0.85

Center (x,y): (-0.58,0.96)

Patternation Number

0.1498

Method: (Max-Min)/Mean

Sector No.: 24

Estimated RMS/MEAN of Total Surface Area

RMS: 0.0415

Deconvoluted Total Surface Area on Entire Domain

Samples Used: 10000

Area(mm^2): 72.3647

Max. Radial Surface Area/Volume (1/mm)

0.00715

Max. Angular Deviation (Gamma)

0.02870

Max. Angular L2 Norm

0.031

# Emission Tomography

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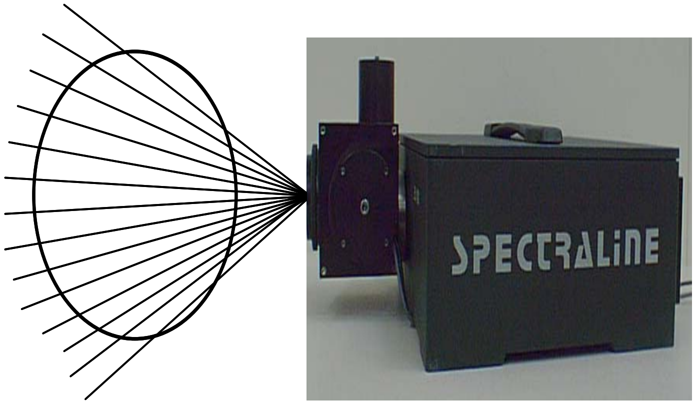
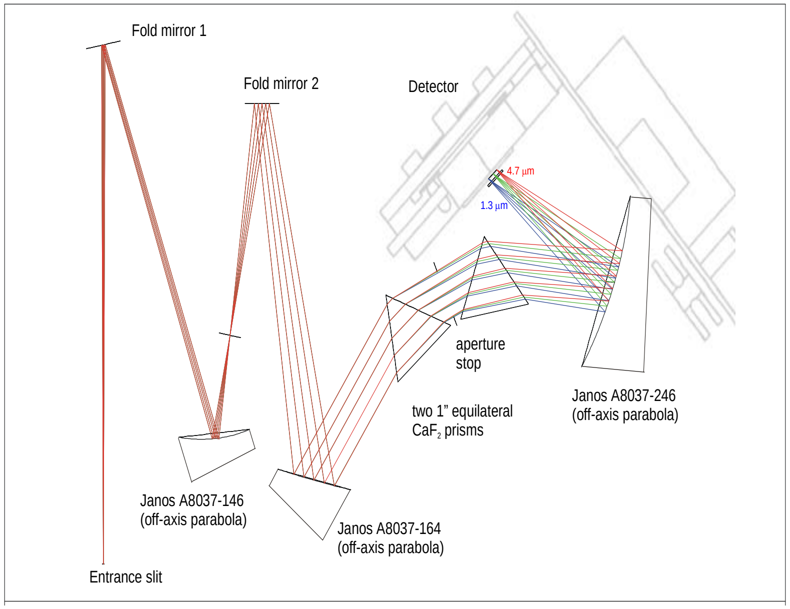
# Typical Experimental Arrangement



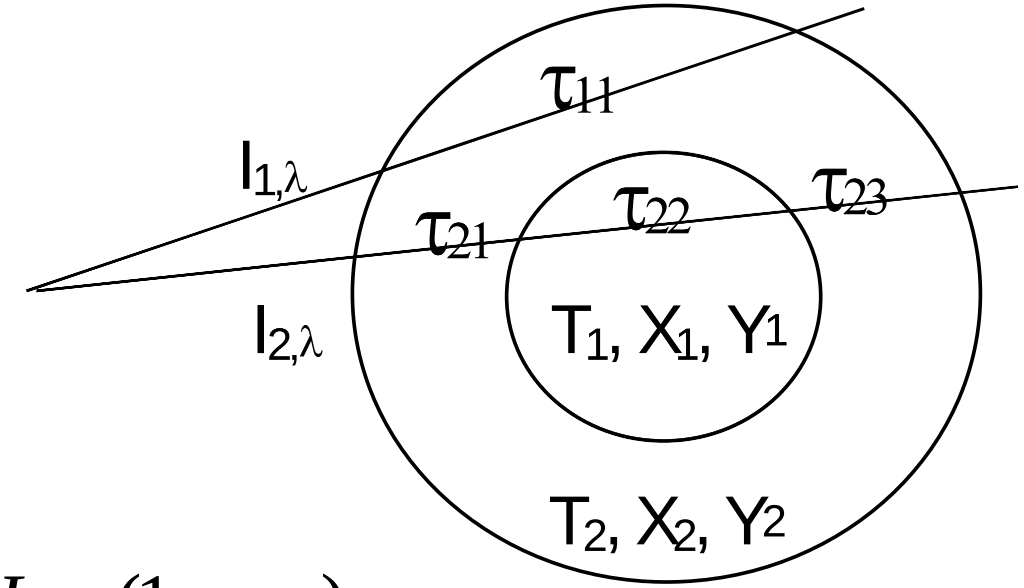


- *Either parallel path or fan beam arrangement*
- *Intensity measured at multiple view angles*
- *Deconvoluted using tomography*

# Measurement Considerations

- High temperature objects (typically flames)
- Intensity is related to temperature and emissivity
- Highly non-linear in temperature
- Emissivity is typically unknown
- Multiple wavelength measurements used
- Self absorption for optically thick systems

# Relevant Equations



$$I_{1,\lambda} = I_{1,b\lambda}(1-\tau_{11})$$

$$\mathrm{I}_{2,\lambda} = \mathrm{I}_{1,b\lambda}\left[(1-\tau_{23})\cdot\tau_{22}\cdot\tau_{21} + (1-\tau_{21})\right] + \mathrm{I}_{1,b\lambda}(1-\tau_{21}).\tau_{21}$$

***Non-linear equations, difficult to solve***

# Linearize Equations

$$I = I_b \cdot (1 - e^{-k\Delta})$$

$$\log(I) = \log(I_b) + \log(1 - \tau)$$

$$\log(I_b) \cong A + BT$$

$$\log(1 - e^{-k\Delta}) = \log(1 - \tau) \cong C + DX + EY + FT$$

$$\log(I) = D \cdot X + E \cdot Y + (B + F) \cdot T + A + C$$

J. Lim, Y. Sivathanu, J. Ji, and J. Gore, (2004), "Estimating Scalars from Spectral Radiation Measurements in a Homogeneous Hot Gas Layer," Combst. Flame, vol. 137, p. 222-229.

# Constants in Equations

From databases such as RADCAL, HITRAN

$$A = -\frac{\partial \log(I_b)}{\partial T} T_0 + \log(I_b(T_0)) \qquad B = \frac{\partial \log(I_b(T_0))}{\partial T}$$

$$C = -\frac{\partial \log(\alpha(X_0, Y_0, T_0))}{\partial X} X_0 - \frac{\partial \log(\alpha(X_0, Y_0, T_0))}{\partial Y} Y_0 - \frac{\partial \log(\alpha(X_0, Y_0, T_0))}{\partial T} T_0 + \log(\alpha(X_0, Y_0, T_0))$$

$$D = \frac{\partial \log(\alpha(X_0, Y_0, T_0))}{\partial X} \qquad E = \frac{\partial \log(\alpha(X_0, Y_0, T_0))}{\partial Y}$$

$$F = \frac{\partial \log(\alpha(X_0, Y_0, T_0))}{\partial T}$$

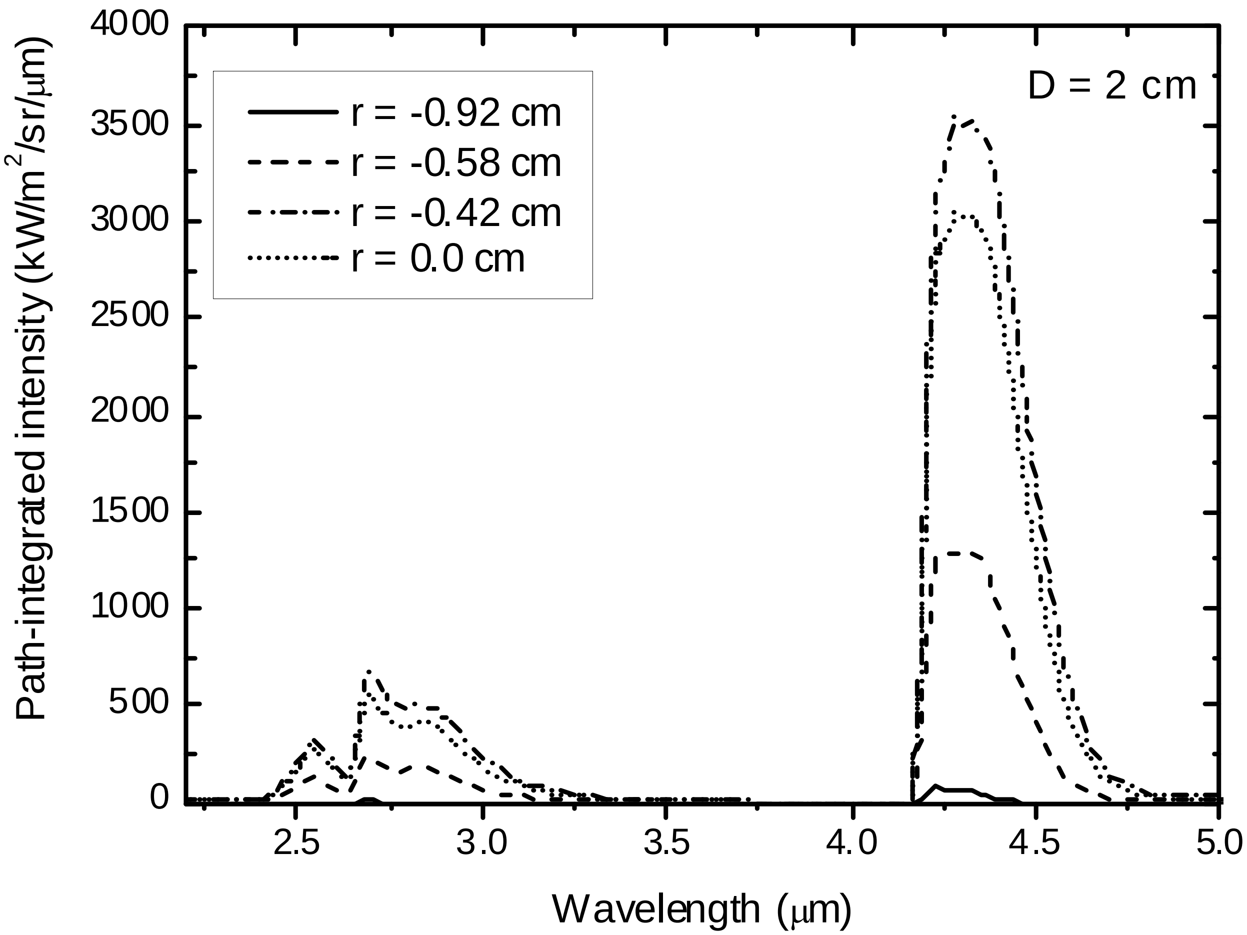
# Flow Chart for Solution

- Linearize equations
- Guess transmittance
- Use MLE to obtain local intensities
- Estimate local properties based on intensities
- Calculate transmittance from local properties
- Utilize transmittance in updated guess
- Continue until convergence achieved

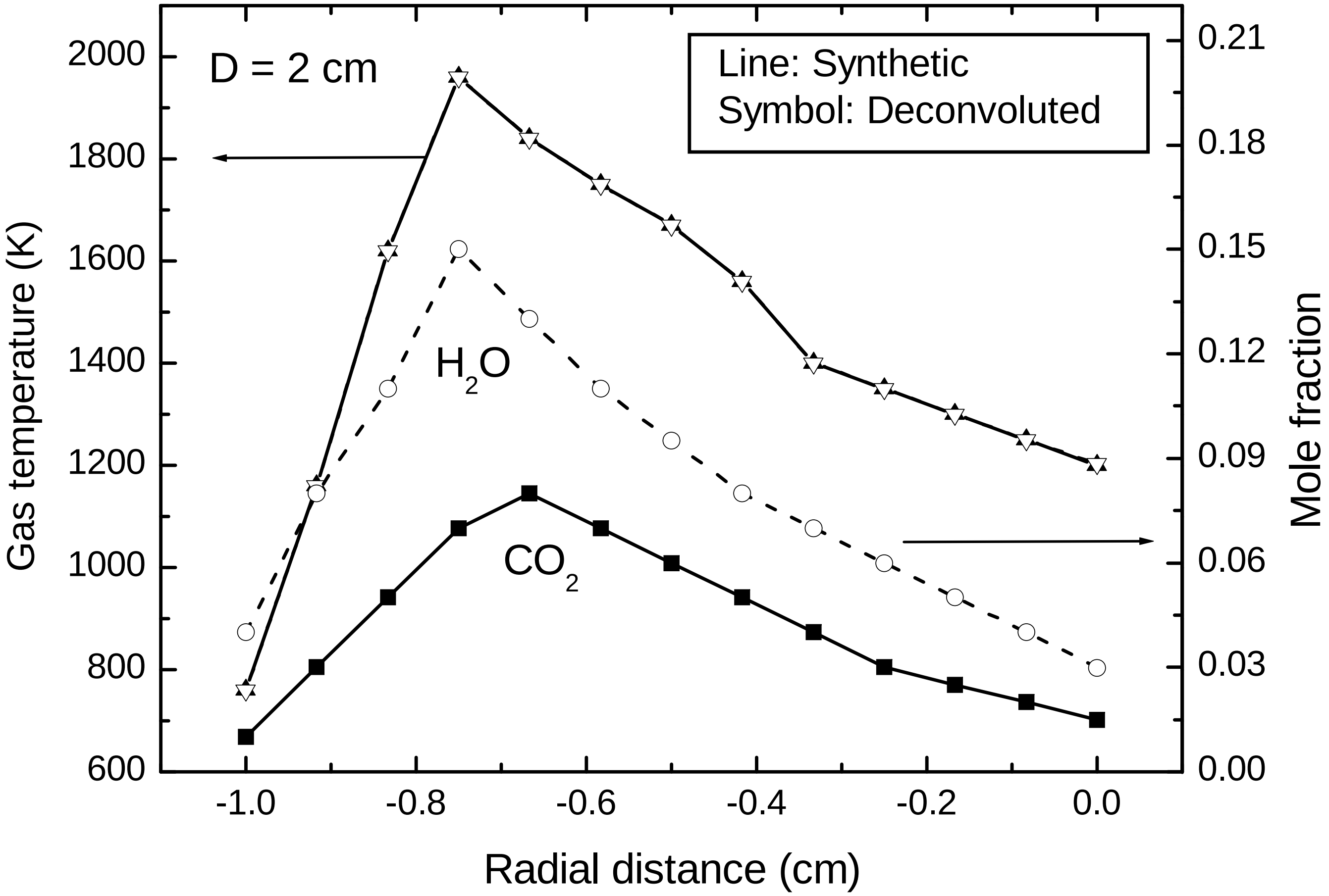
# Validation method

- Use a well characterized flame
- Calculate intensities emitted using equation of radiative transfer
- Use calculated intensities as input to algorithm
- Compare algorithm output with input flame properties

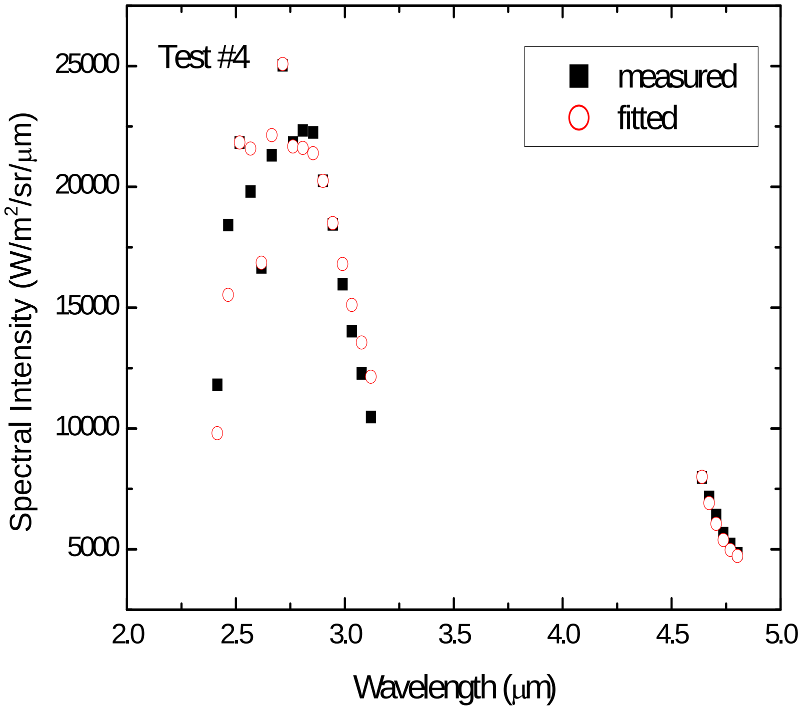
# Calculated Intensities (input to algorithm)

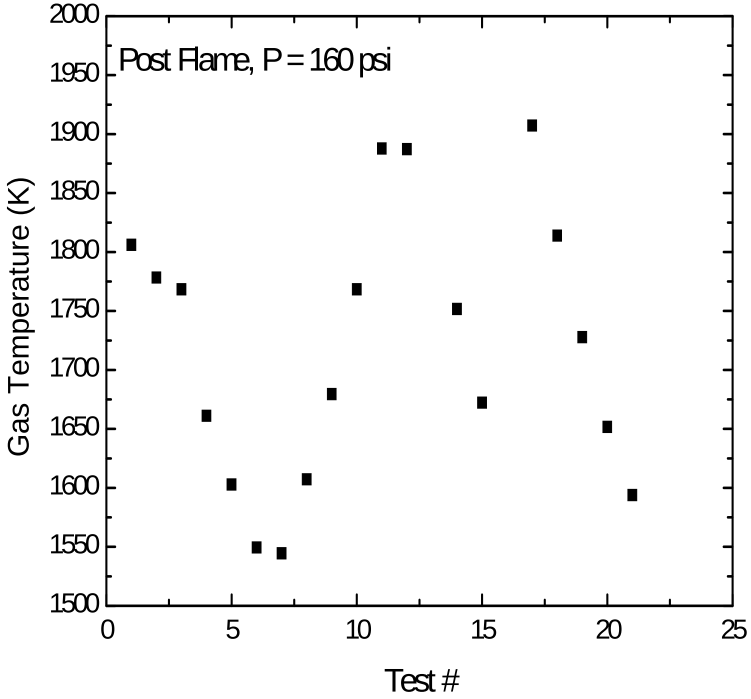


# Converged Properties



# Sample Implementation (Turbine Inlet)



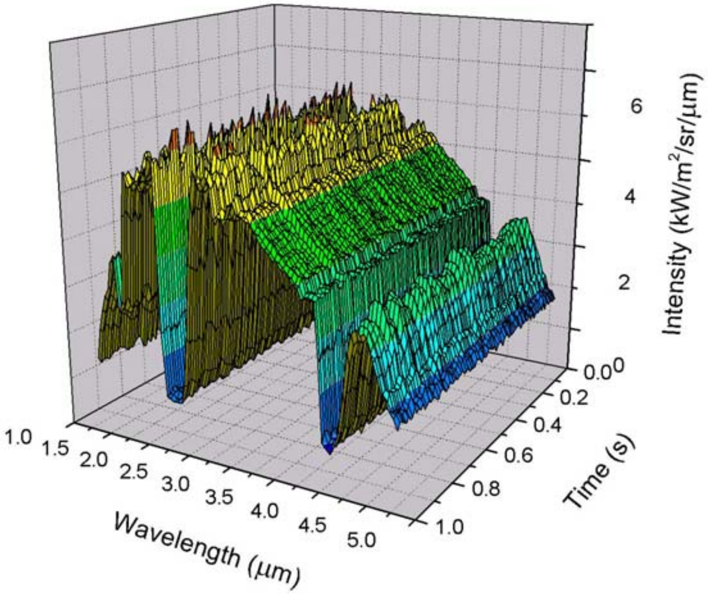


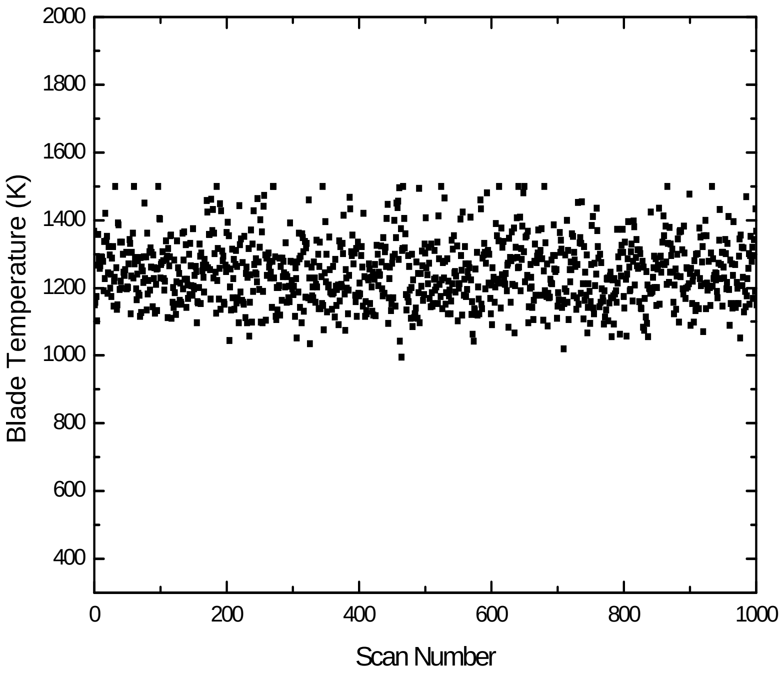
Stochiometry cycled during series of 20 test at ~ 11 bar

Gas temperature successfully estimated by method

Homogeneous layer assumption

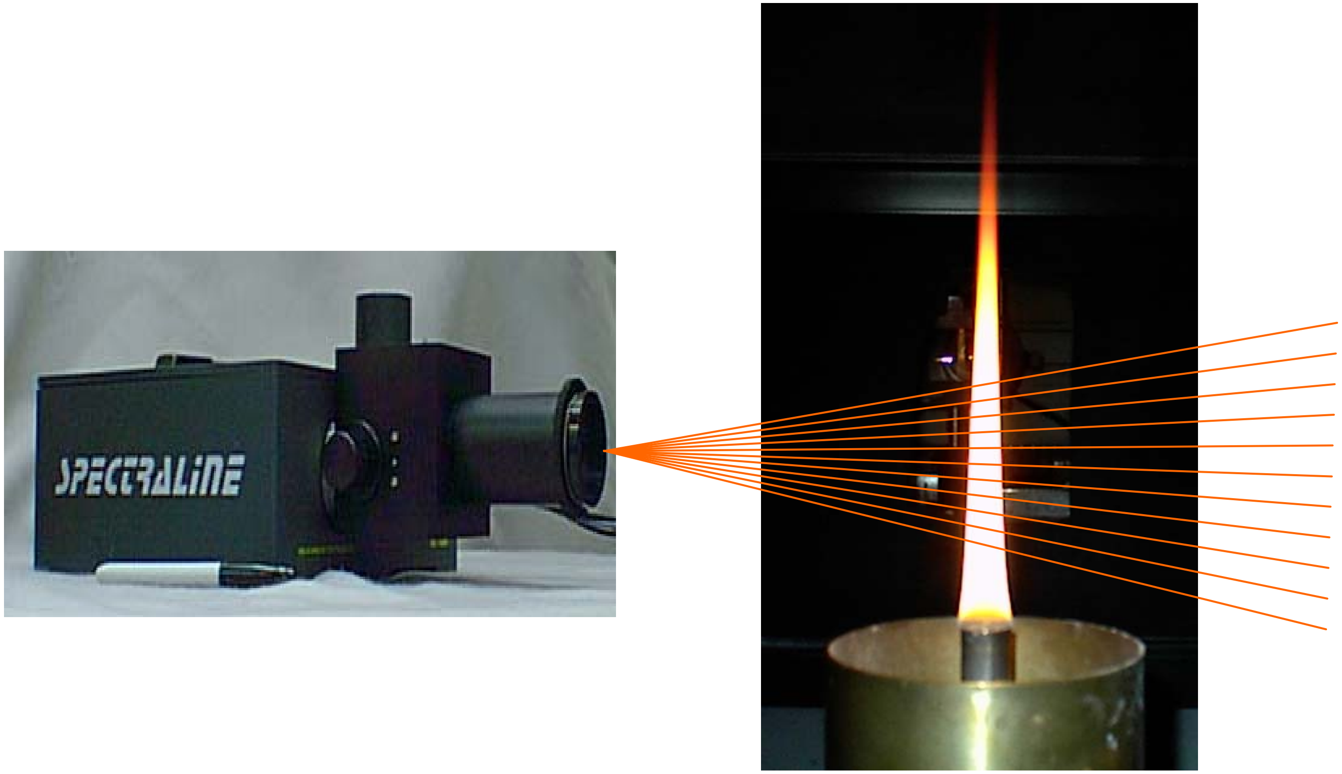
# Sample Implementation (Turbine Blade Temperature)





30 bar power generation turbine, emission from blade
Blade temperature and emissivity (for TBC monitoring)

# Sample Implementation (Axisymmetric system)



Emission measured at 128 view angles

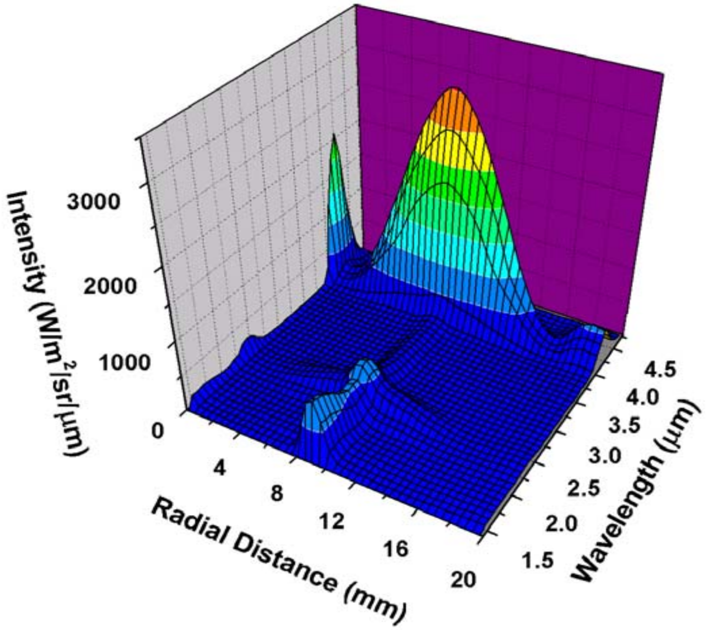
160 wavelengths obtained with ES100 imaging spectrometer

# Evaluation in a Laminar Flame

Incipient Sooting Ethylene Flame

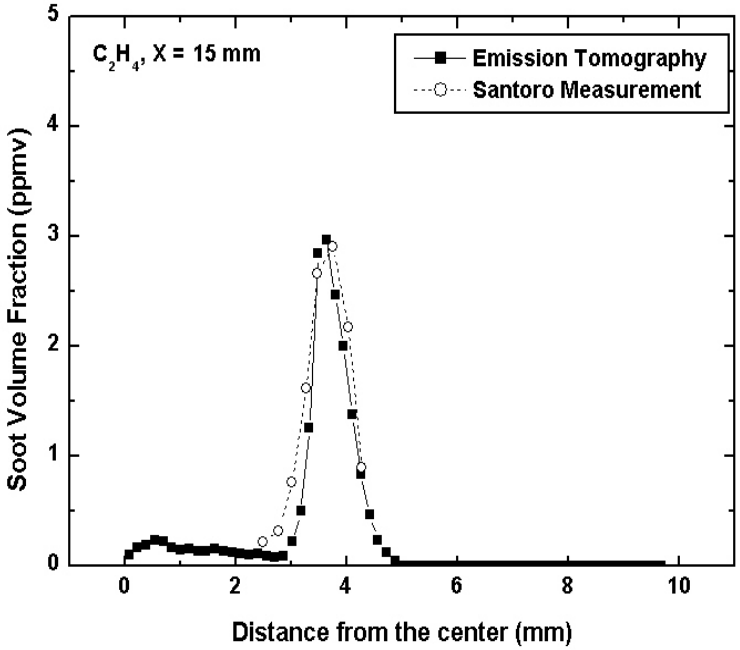
Fuel Flow Rate: 2.30 cm$^3$/sec

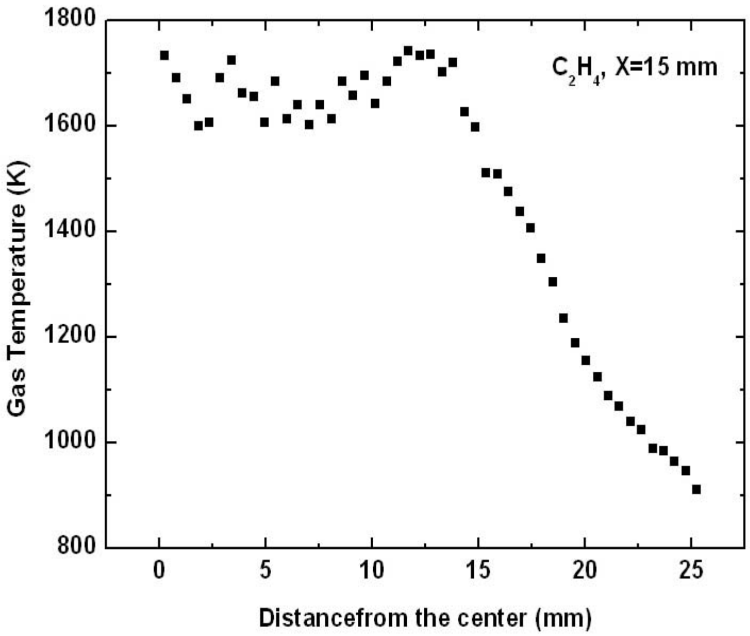
Coflow Air: 713.3 cm$^3$/sec



Measured spectral radiation intensities above burner exit

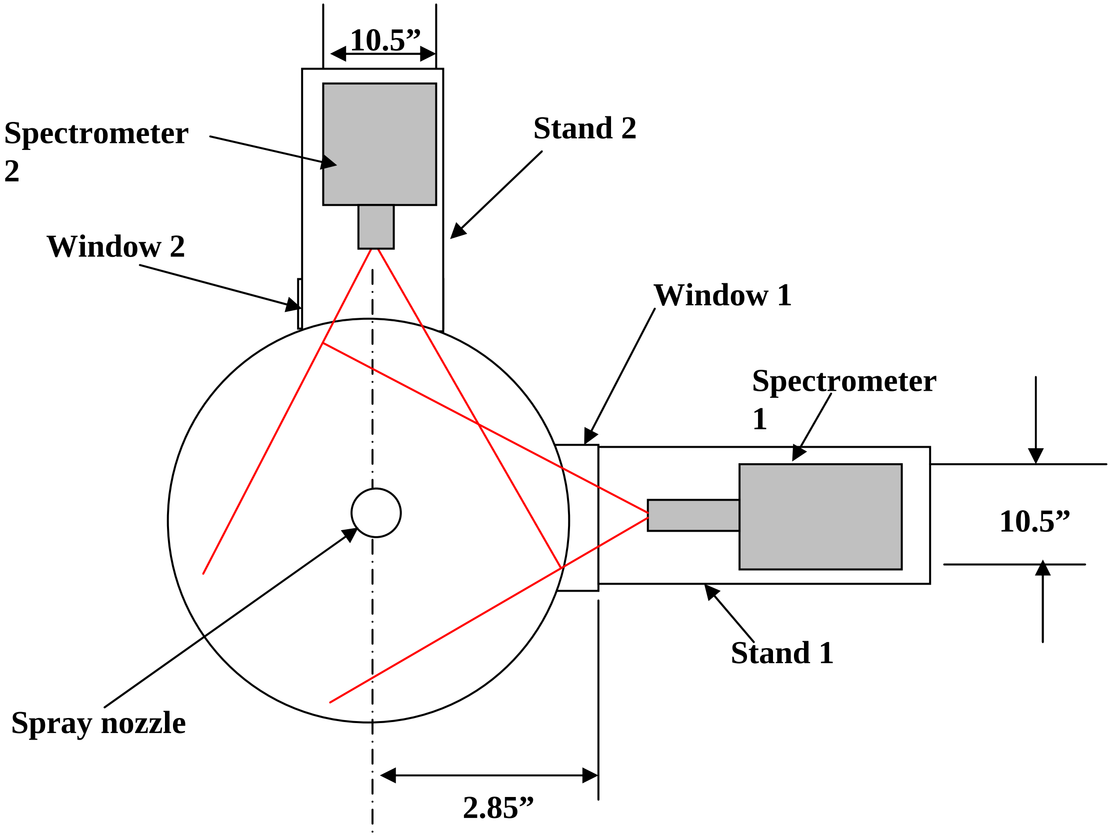
# Sample Results





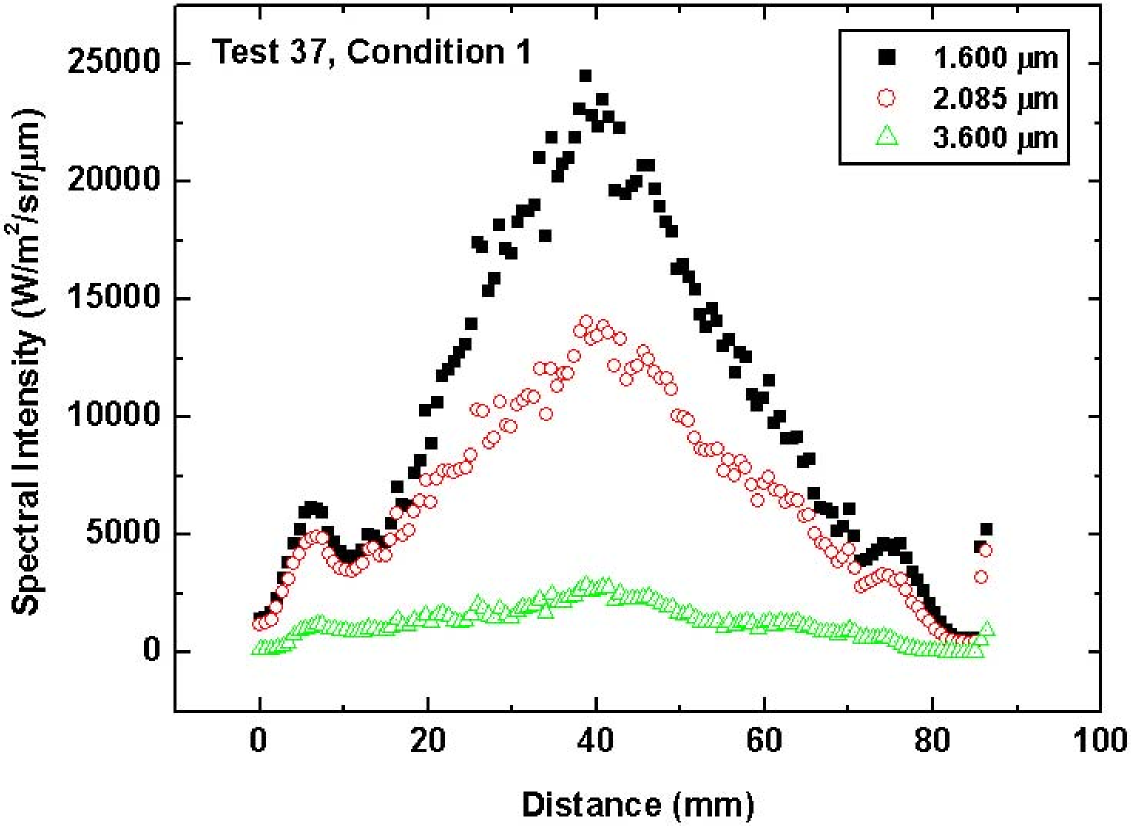
Estimated particulate concentrations, temperatures, and gas concentrations reasonably well

# Sample Implementation (Non-axisymmetric)



Hydrogen/oxygen rocket engine (NASA Marshall-1500 PSI)

# Sample Results



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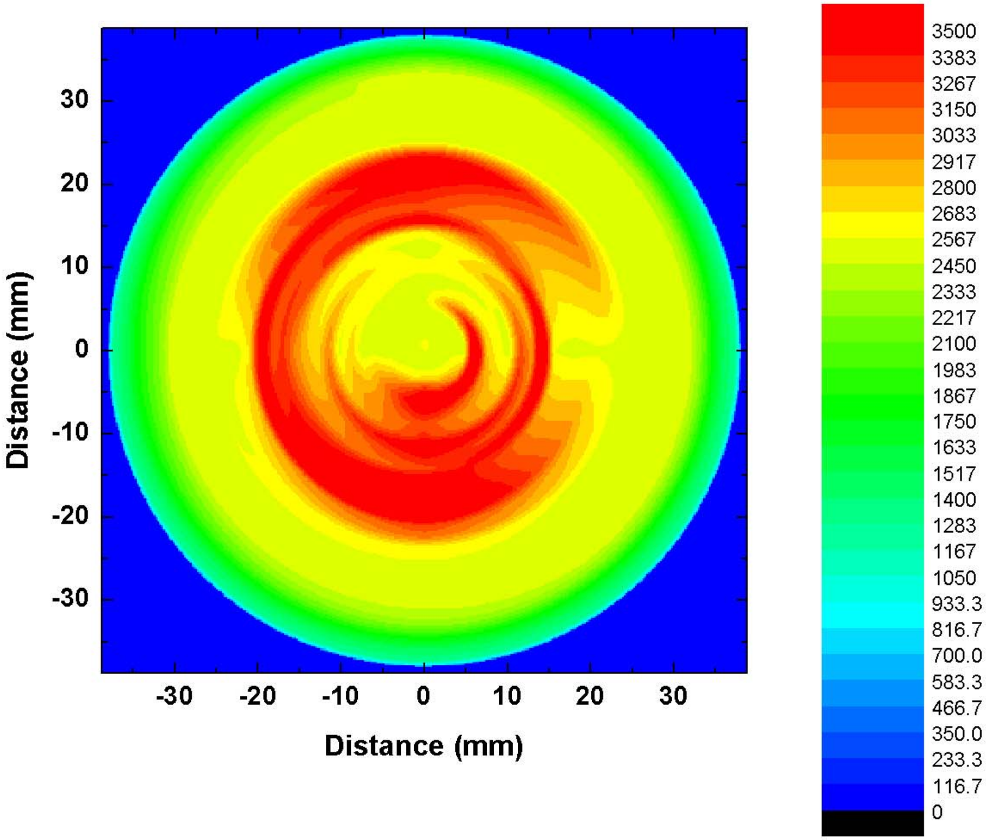
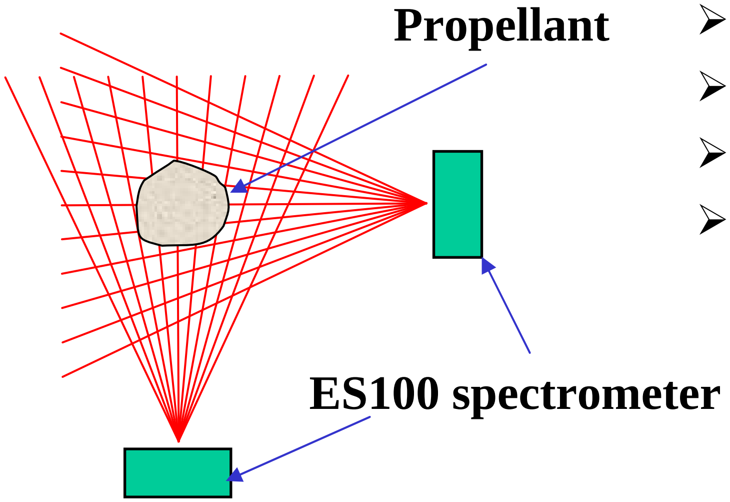
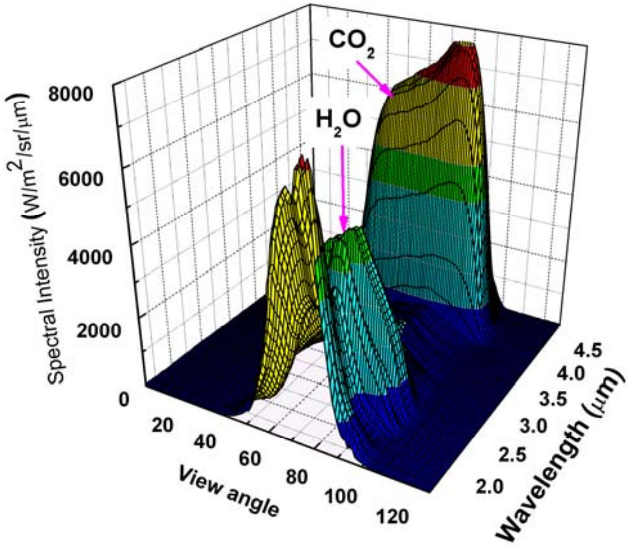
# Sample Temperatures



# Sample Implementation (Solid Propellant Plume)

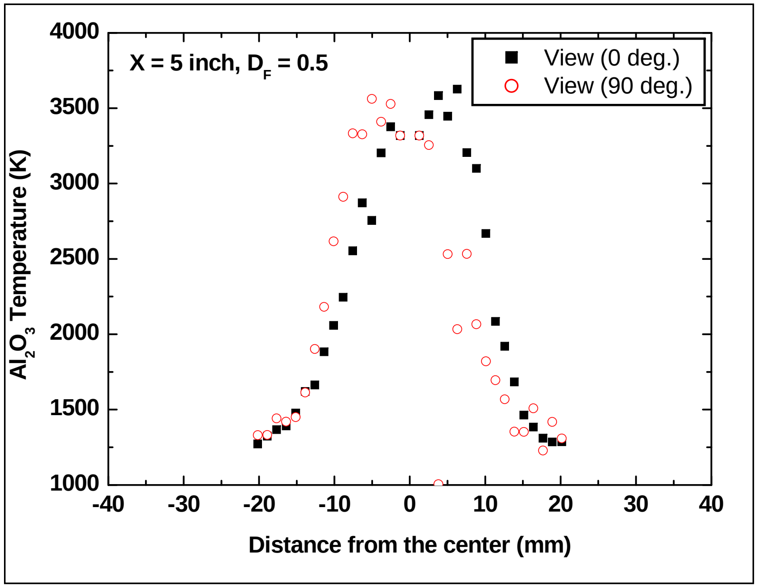


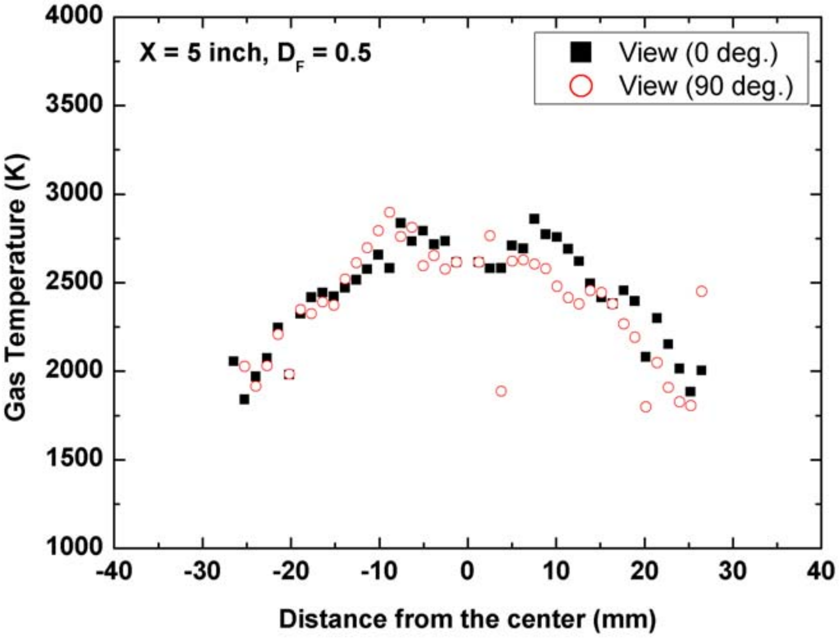
- Two orthogonal spectrometers
- 128 view angles per spectrometer
- 1.3 to 4.8 microns
- 1320 Hz for spectra
- Full planar measurement at 10.3 Hz



Test in solid propellants up to 18 inches in diameter

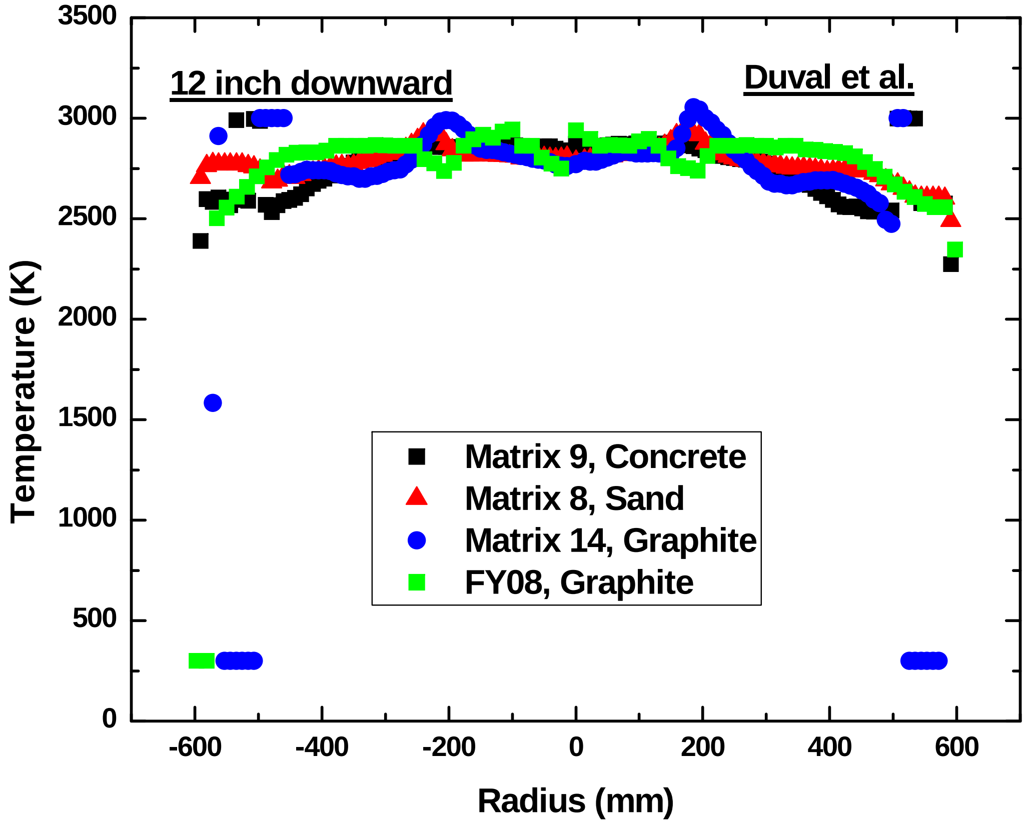
# Solid Propellant Plume Properties





Y. Sivathanu, J. Lim, L. E. Reinhart, and R. C. Bowman, (2007), “Structure of Plumes from Burning Aluminized Propellant Estimated using Fan Beam Emission Tomography,” AIAA Journal, vol. 45, No. 9, pp. 2259-2266.

# Solid Propellant Plume Properties



# Future Directions

- X-Ray based tomography for optically dense flames and sprays
- Engineering for specific applications