Extinction and Emission Tomography in Turbulent Sprays and Flames

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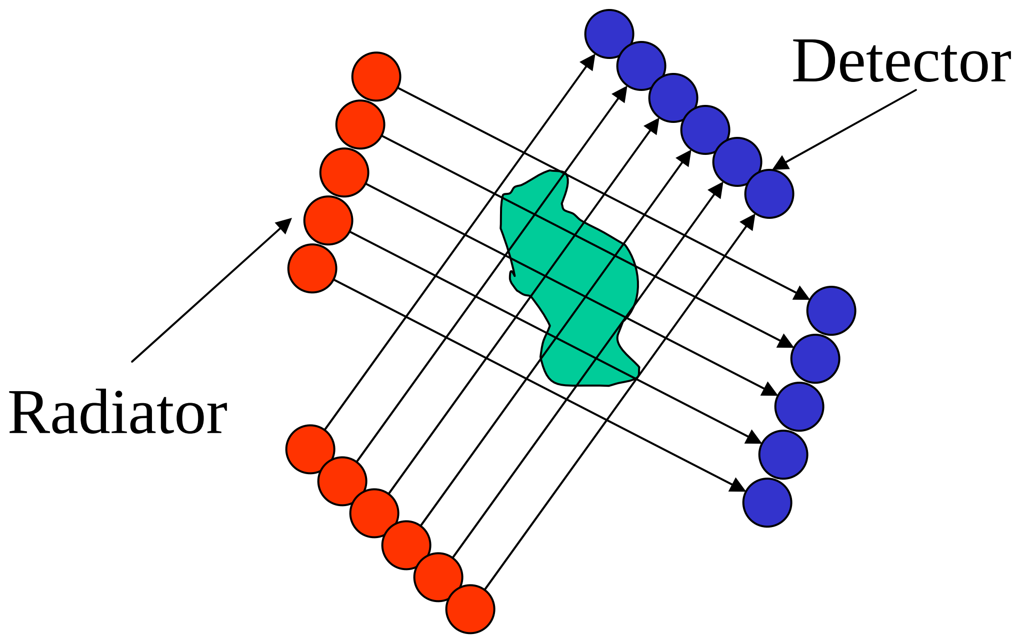
Outline

- 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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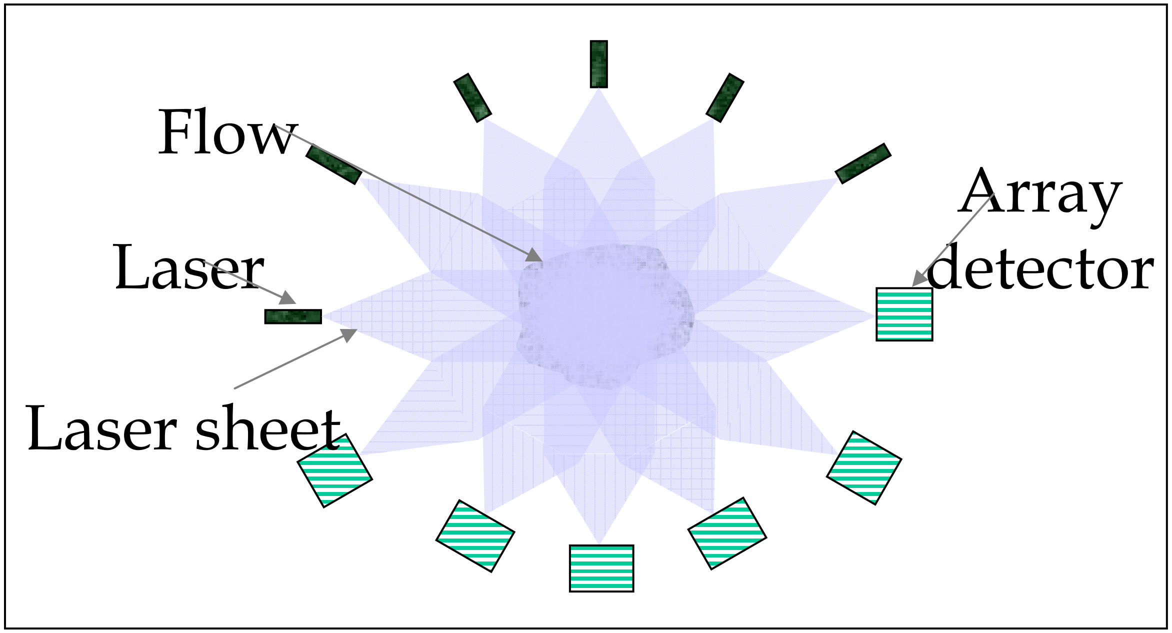
Extinction Tomography

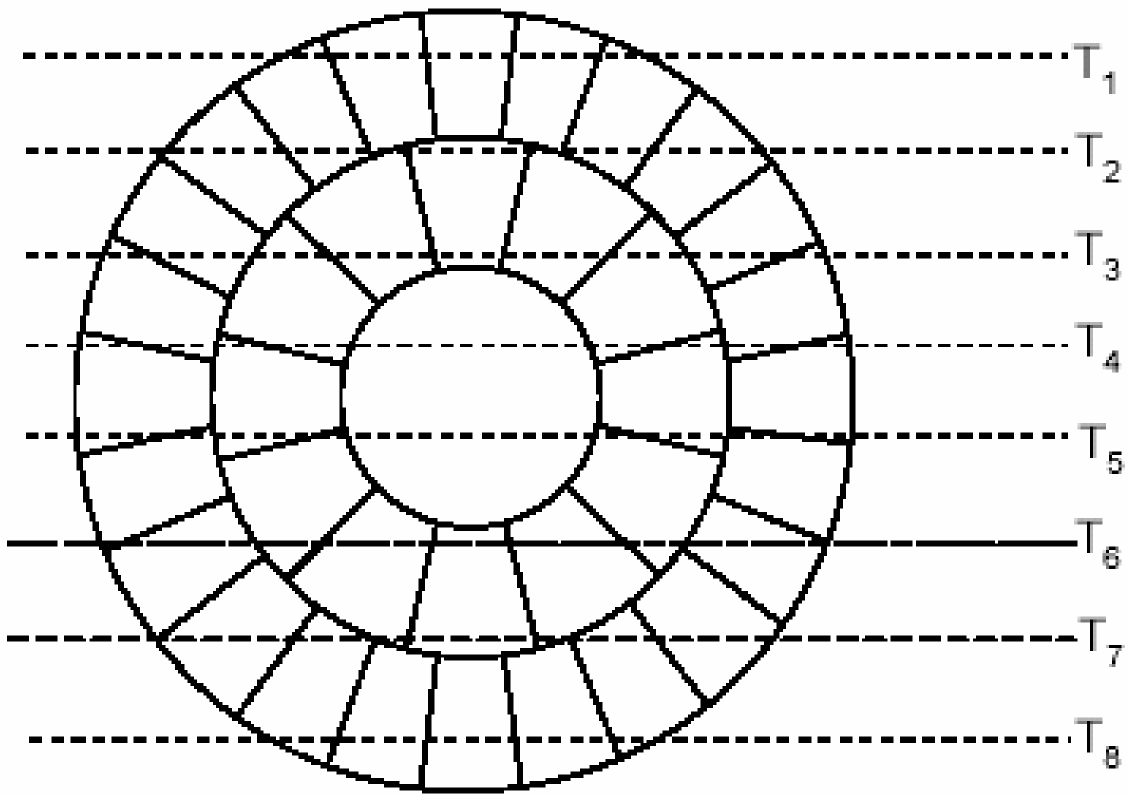


- *Extinction measured at multiple view angles*
- *Deconvoluted using tomography*
- *Challenge is that objects are moving*

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

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

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

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

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

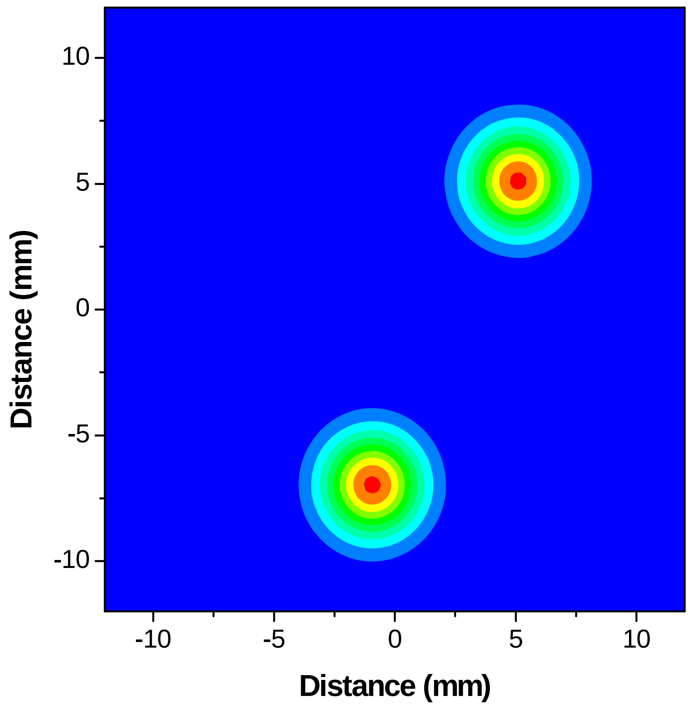
System of Equations

- 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

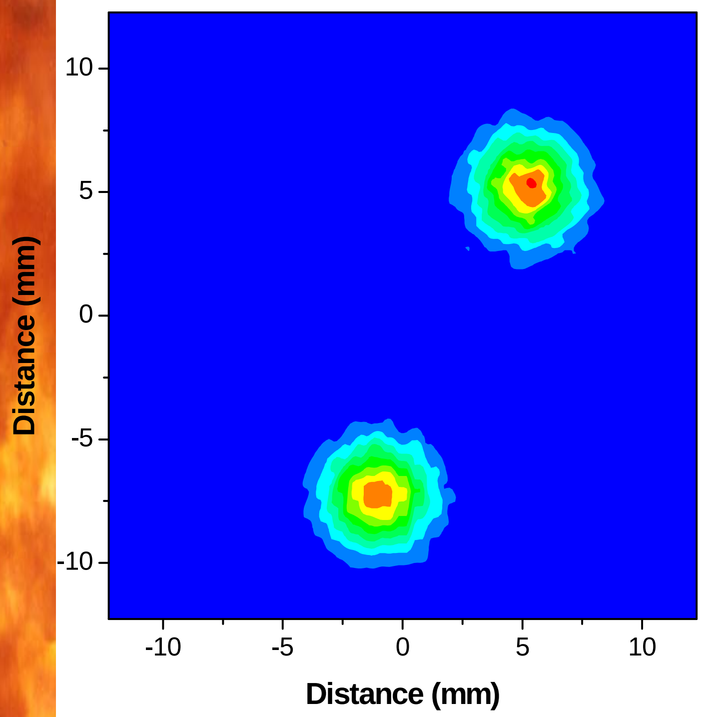
Minimum transmittance < 0.10

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

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:

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

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

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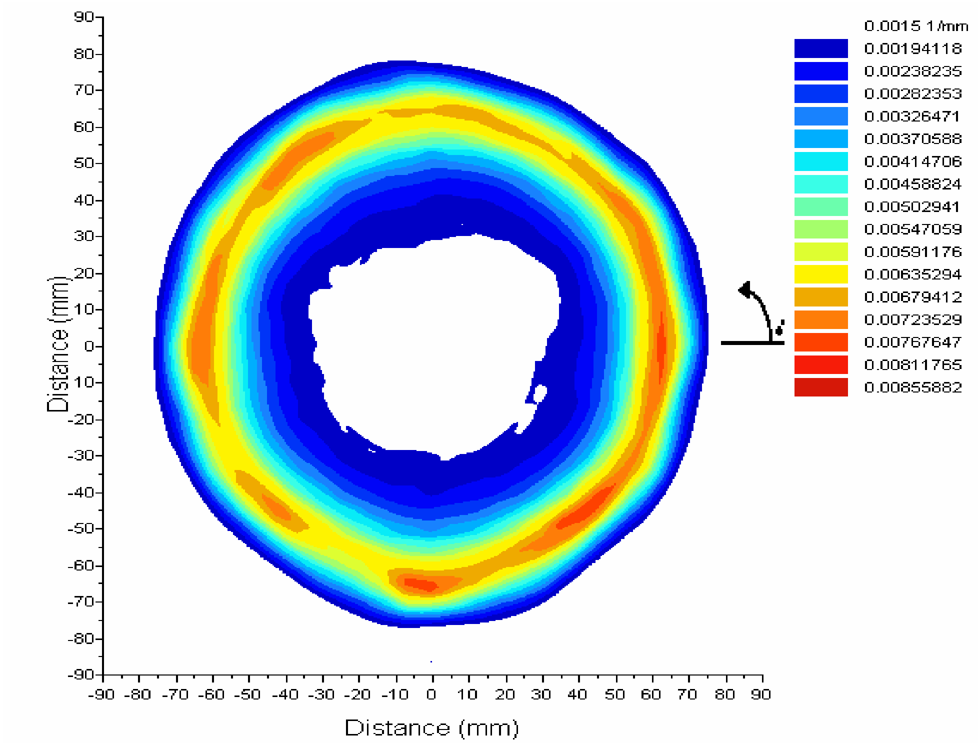
Sample Result: Aircraft Engine Nozzle



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

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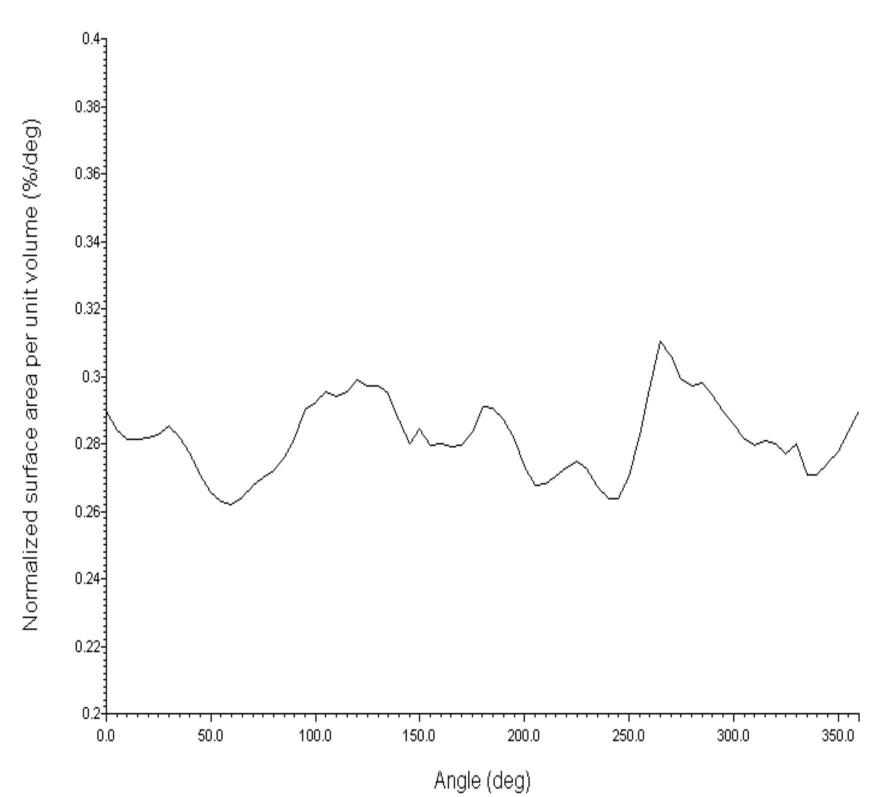
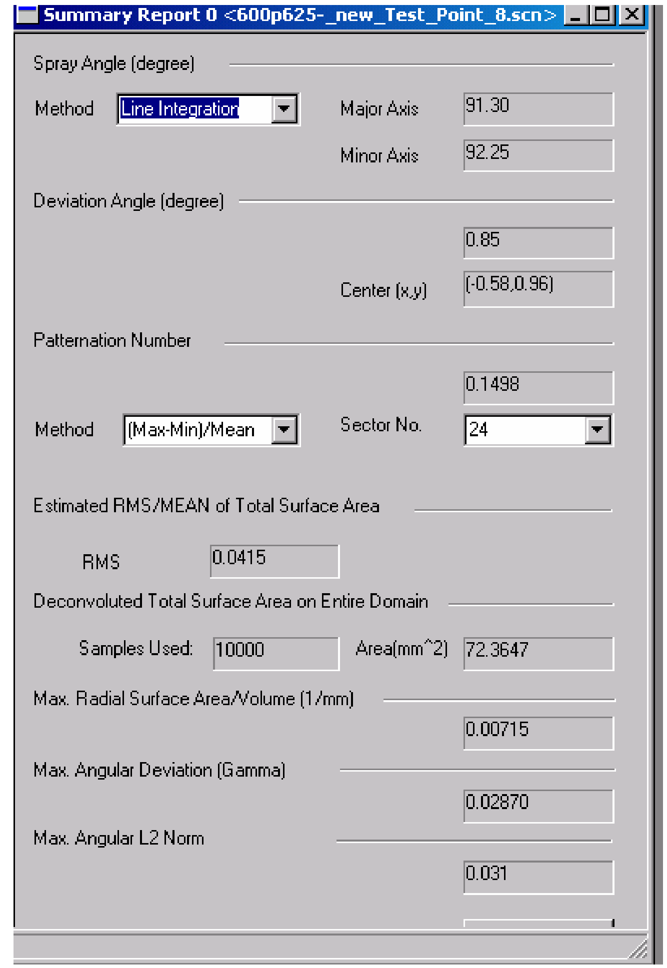
Quality Assurance: Aircraft Engine Nozzle




Summary Report 0 <600p625-_new_Test_Point_8.scn>

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

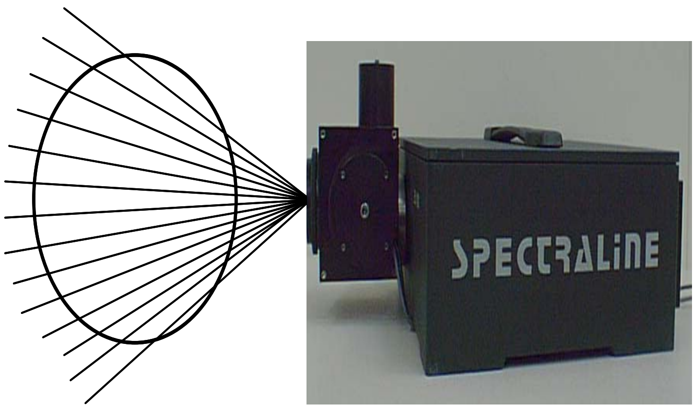
0.031

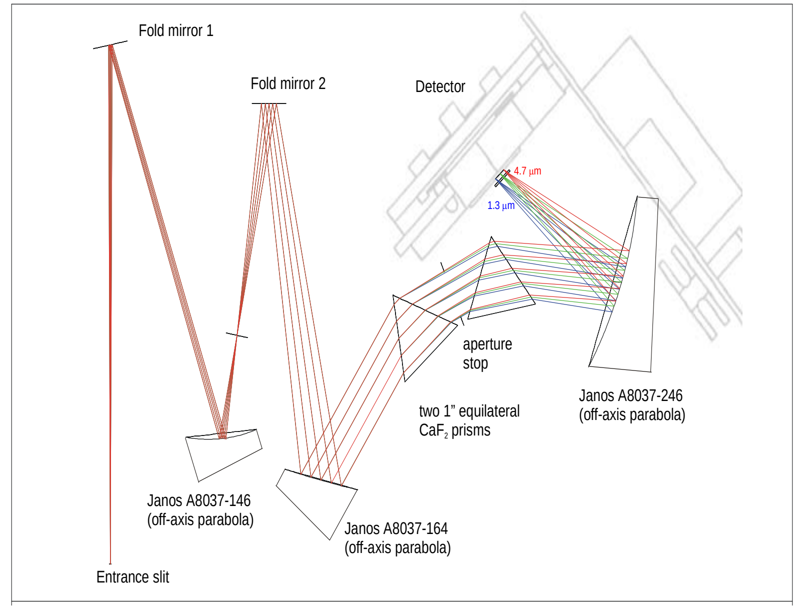
Selected Customers

Abbott	General Motors	Hitachi
Bend Research	Cummins	AVL
Pfizer	Emcom Technologies	FEV
S.C. Johnson & Son	Faurecia	Nordson
Catalytica Energy	Donaldson	Delavan
Delphi	Proctor & Gamble	Woodward
Ricardo	Honeywell	Tenneco
Continental	Bombardier	Synerject
Eaton	Rolls Royce	Danfoss
Columbian Chemical	General Electric	Boston Scientific
United Technologies Aerosapce System	Dow Agrosciences Laboratories	Vertex Pharmaceuticals
Toyota	Bosch LLC.	3M

Emission Tomography

Typical Experimental Arrangement





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

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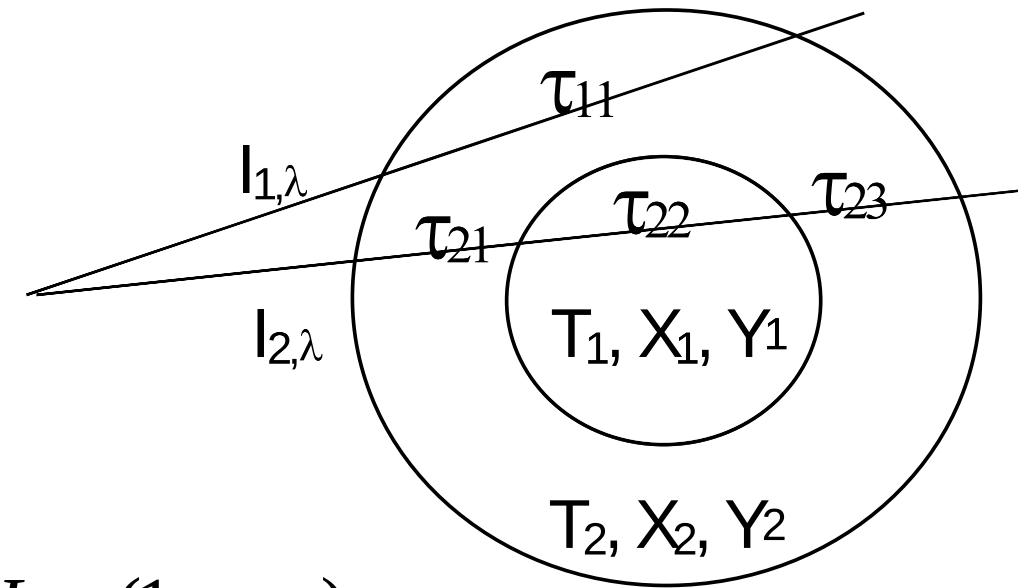
Measurement Considerations

- **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



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

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

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

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

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

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

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

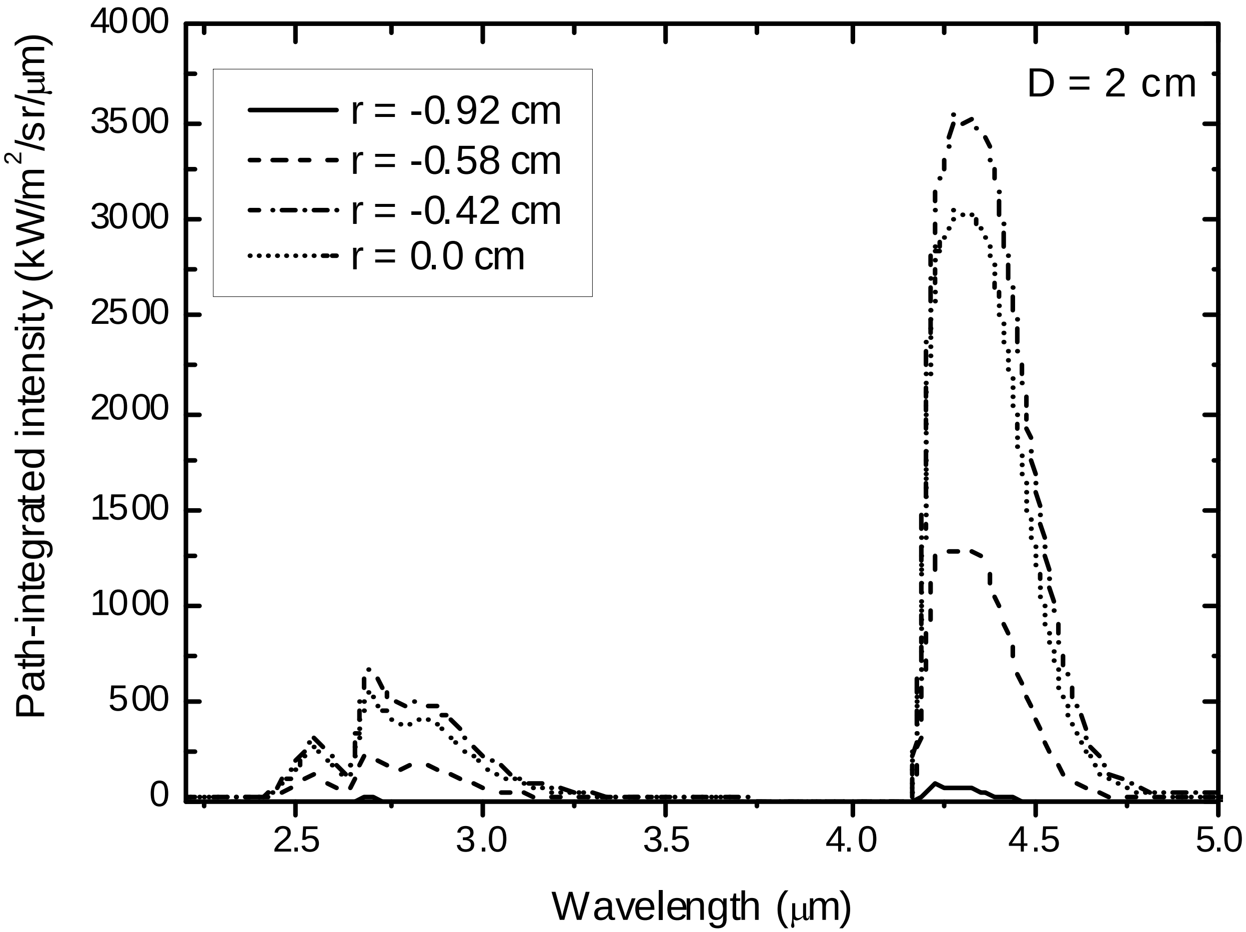
Flow Chart for Solution

- 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

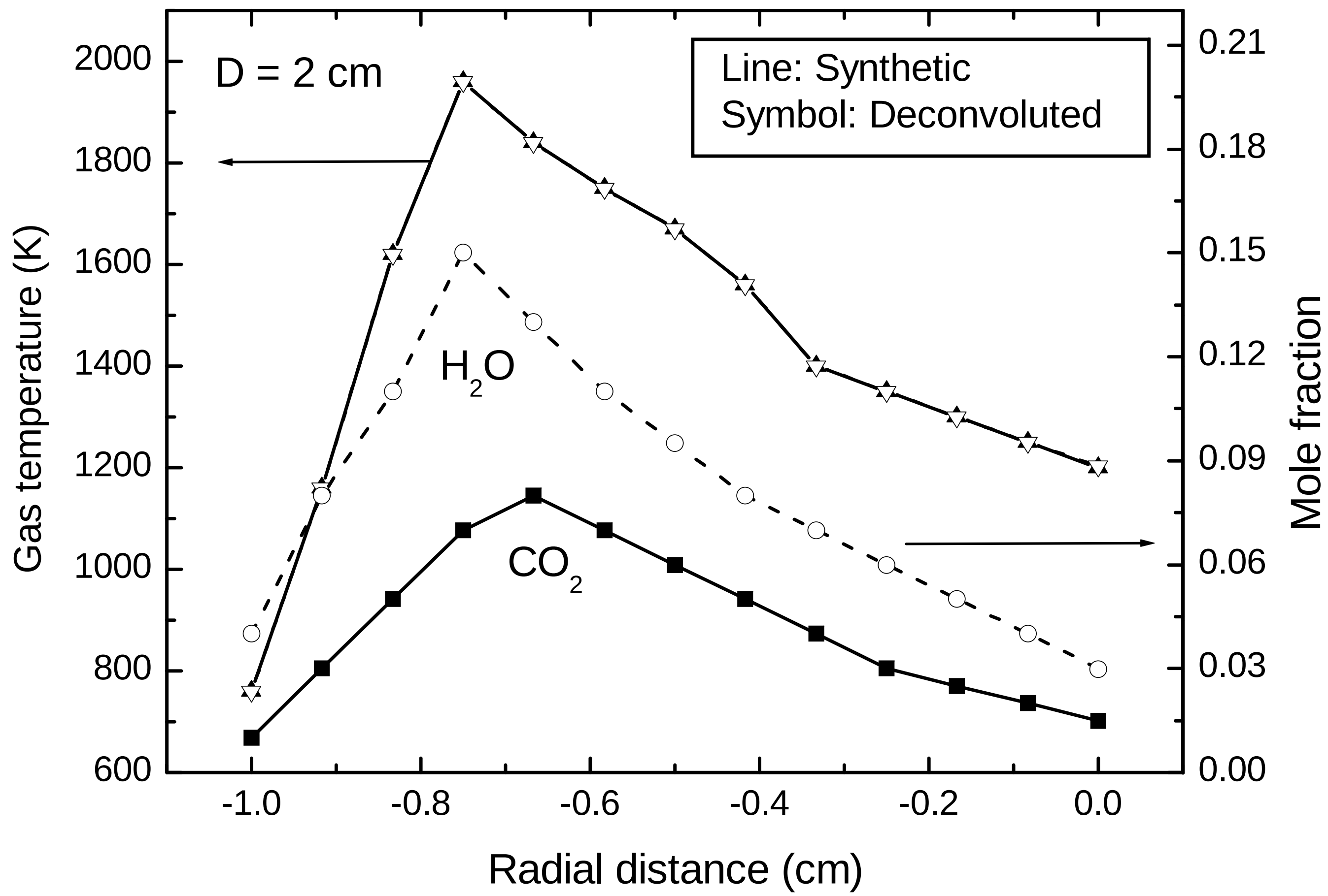
Validation method

- 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



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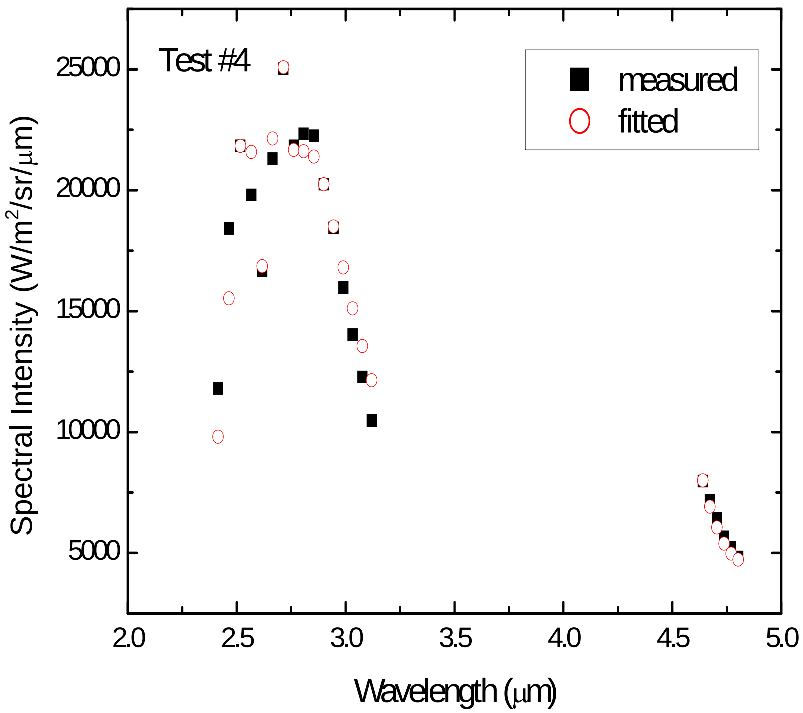
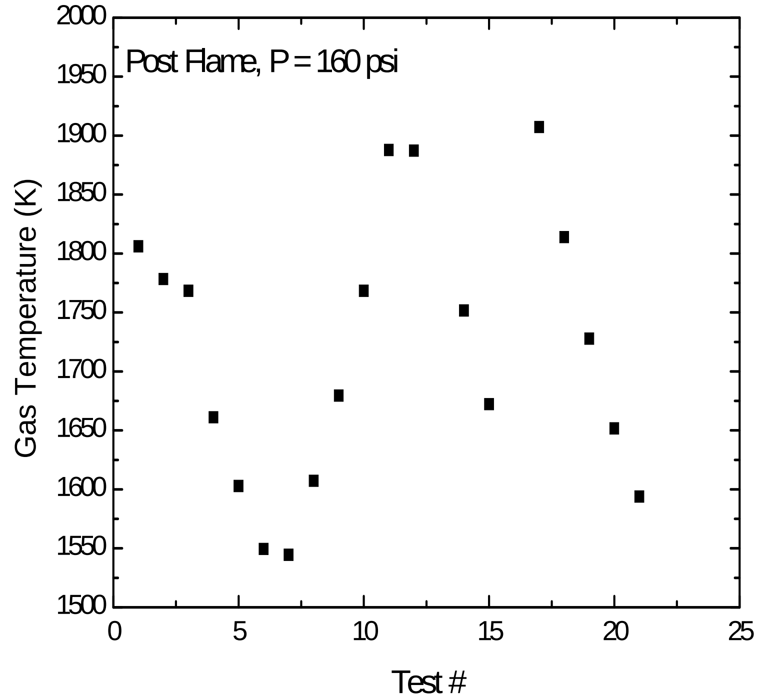
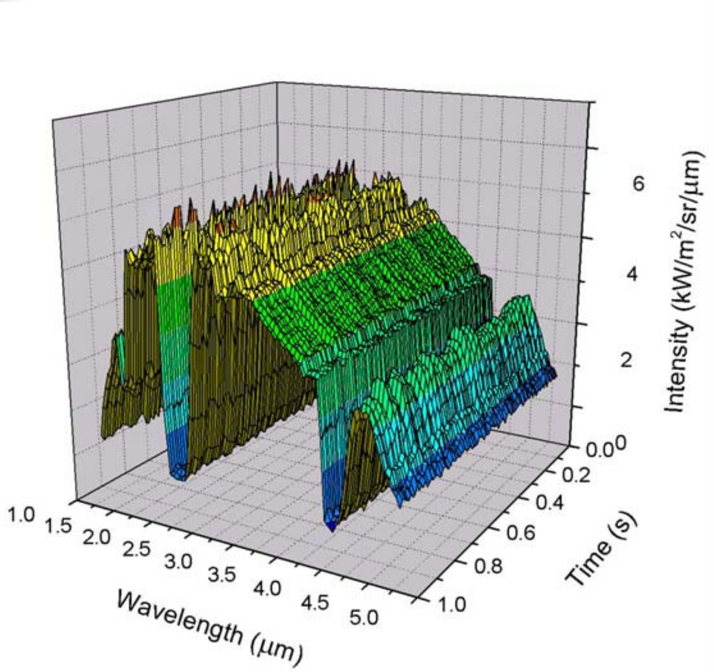
Sample Implementation (Turbine Inlet)

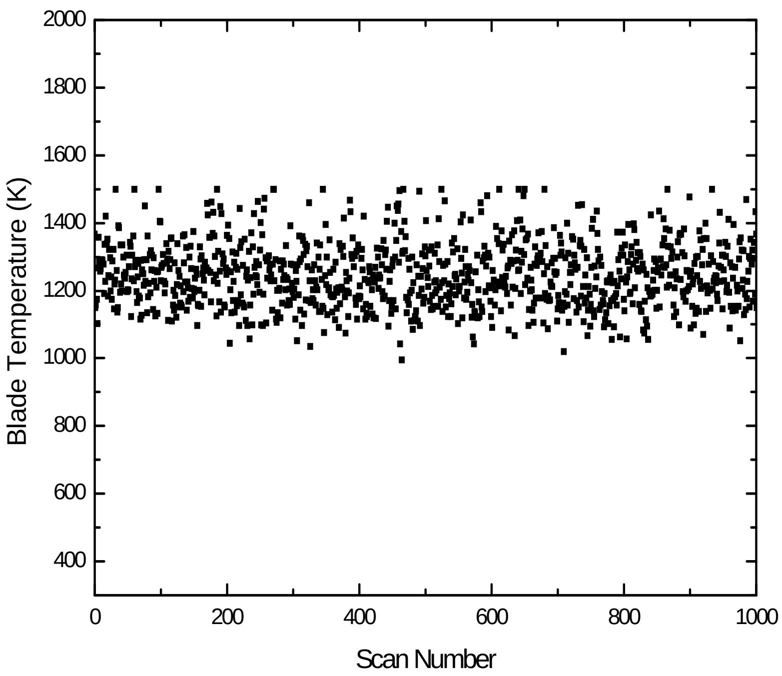




Stochiometry cycled during series of 20 test at ~ 11 bar
Gas temperature successfully estimated by method
Homogeneous layer assumption

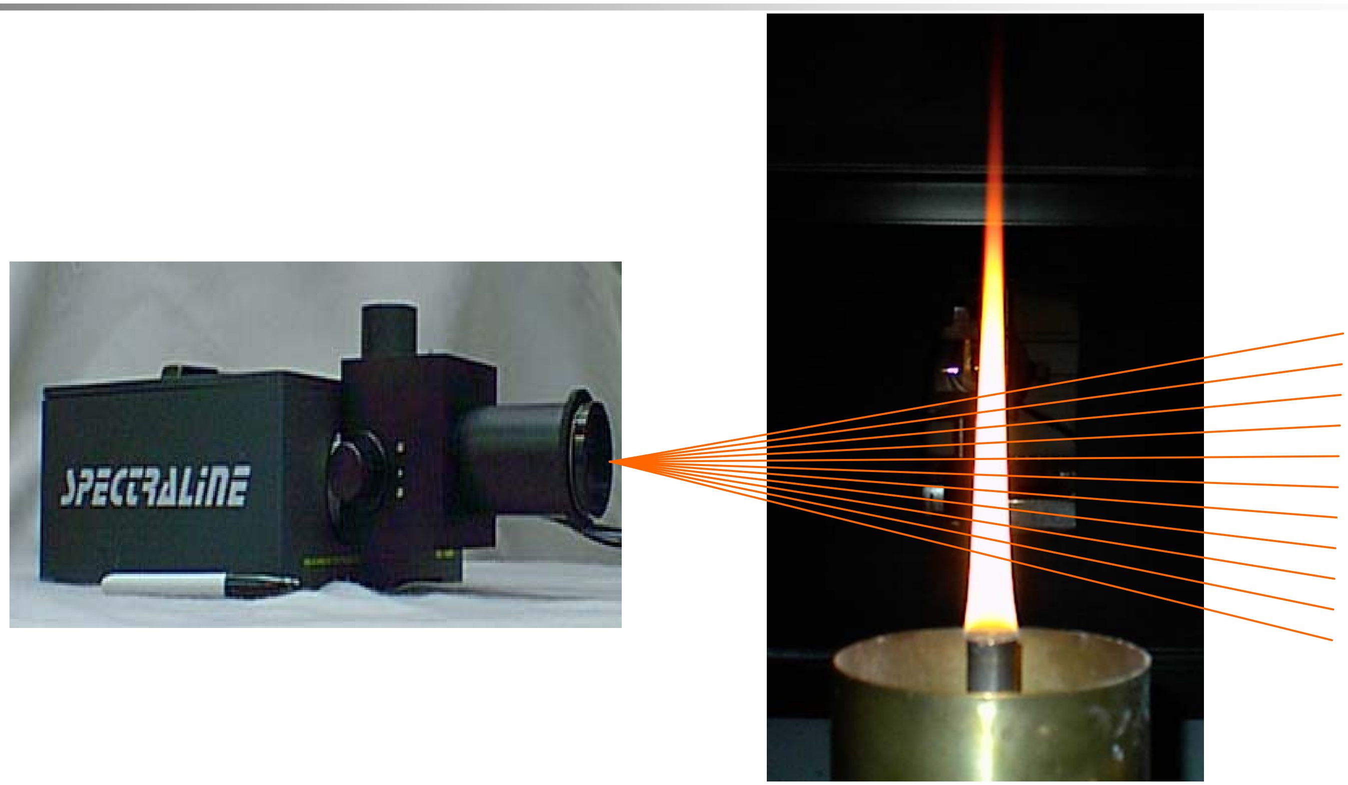
Sample Implementation (Turbine Blade Temperature)





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

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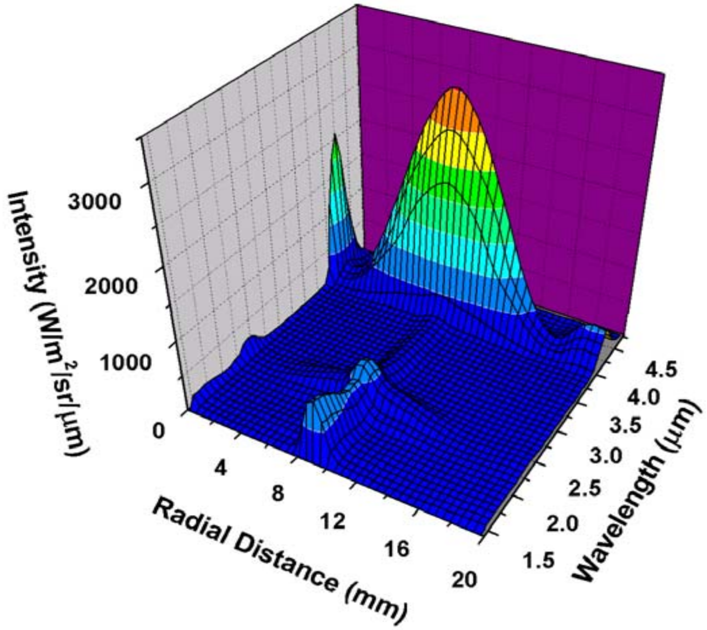
Evaluation in a Laminar Flame

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

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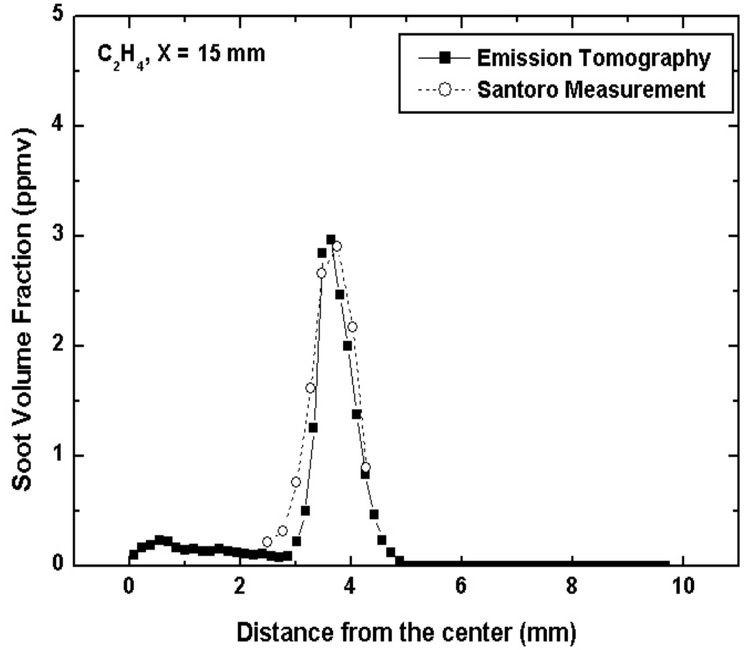
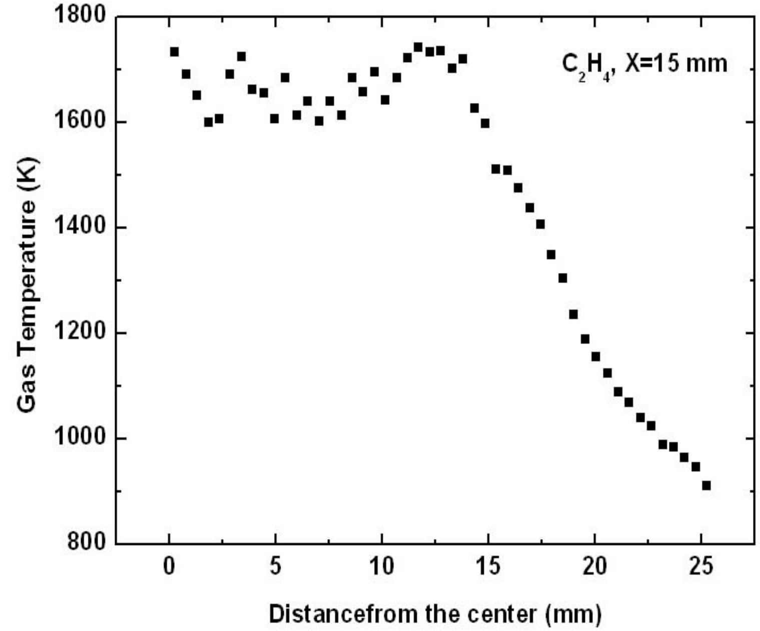
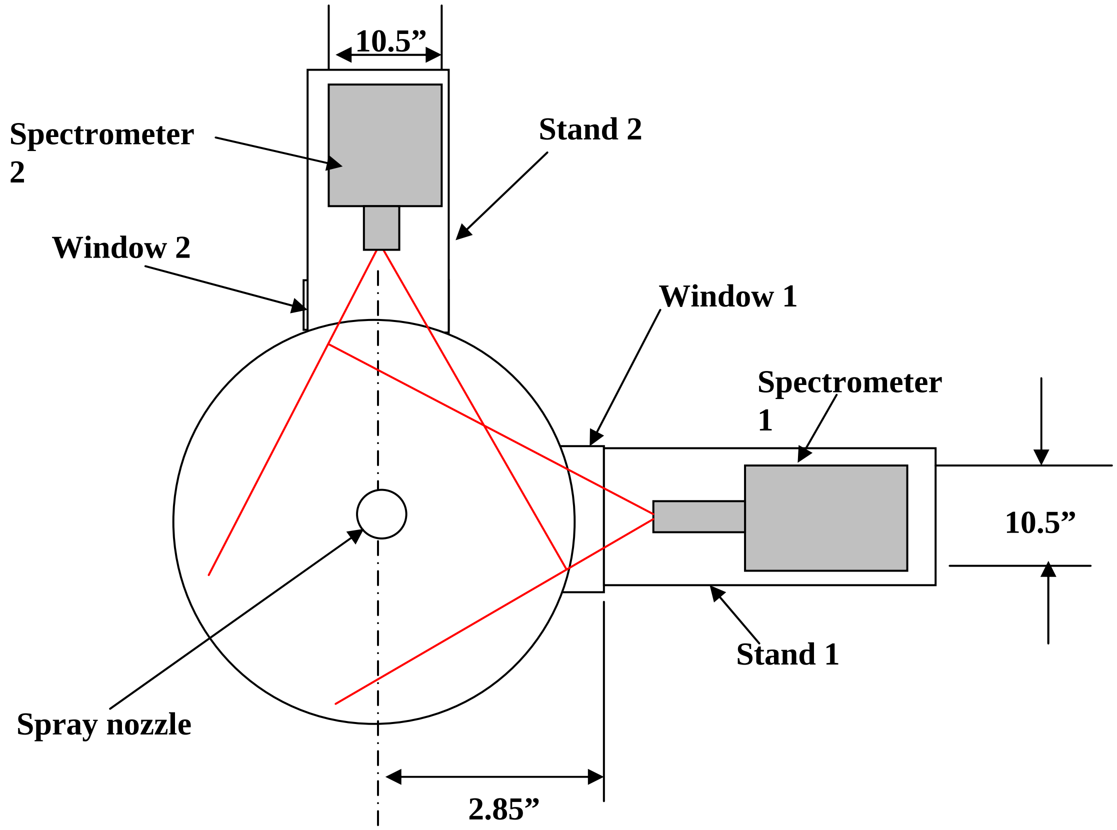
Sample Results





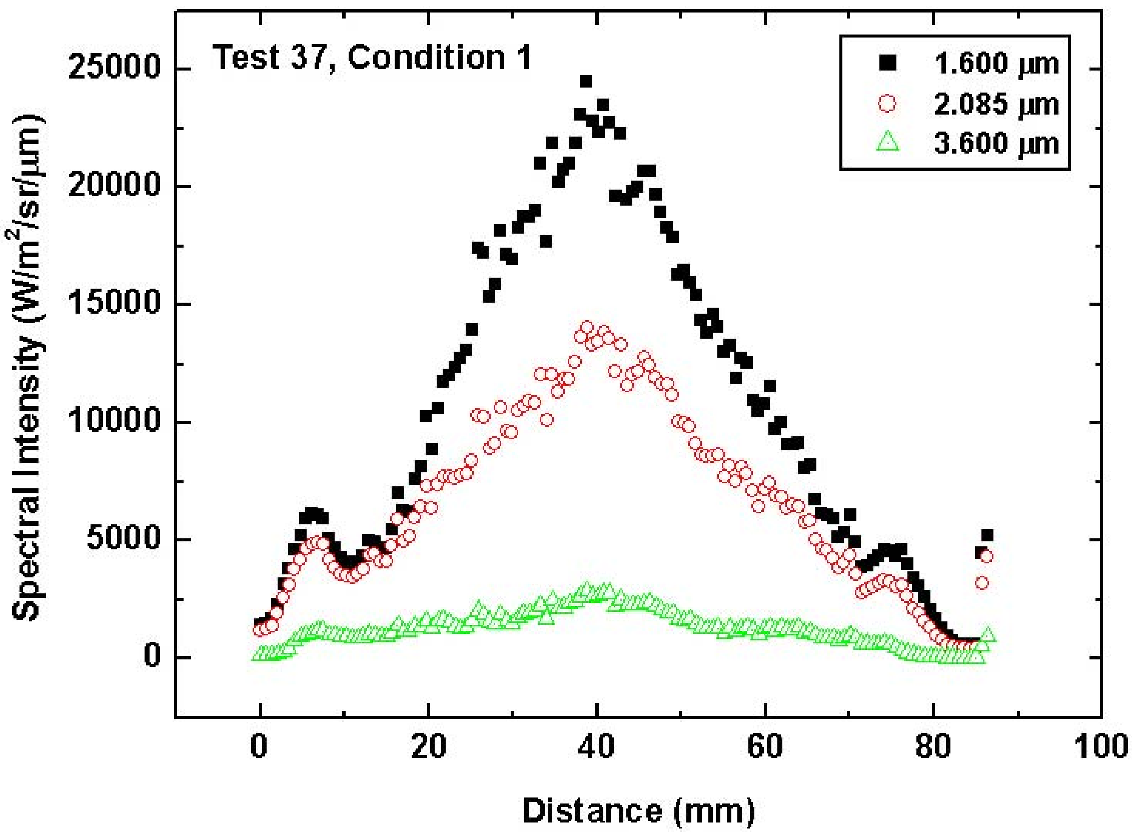
Estimated particulate concentrations, temperatures, and gas concentrations reasonably well

Sample Implementation (Non-axisymmetric)



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

Sample Results



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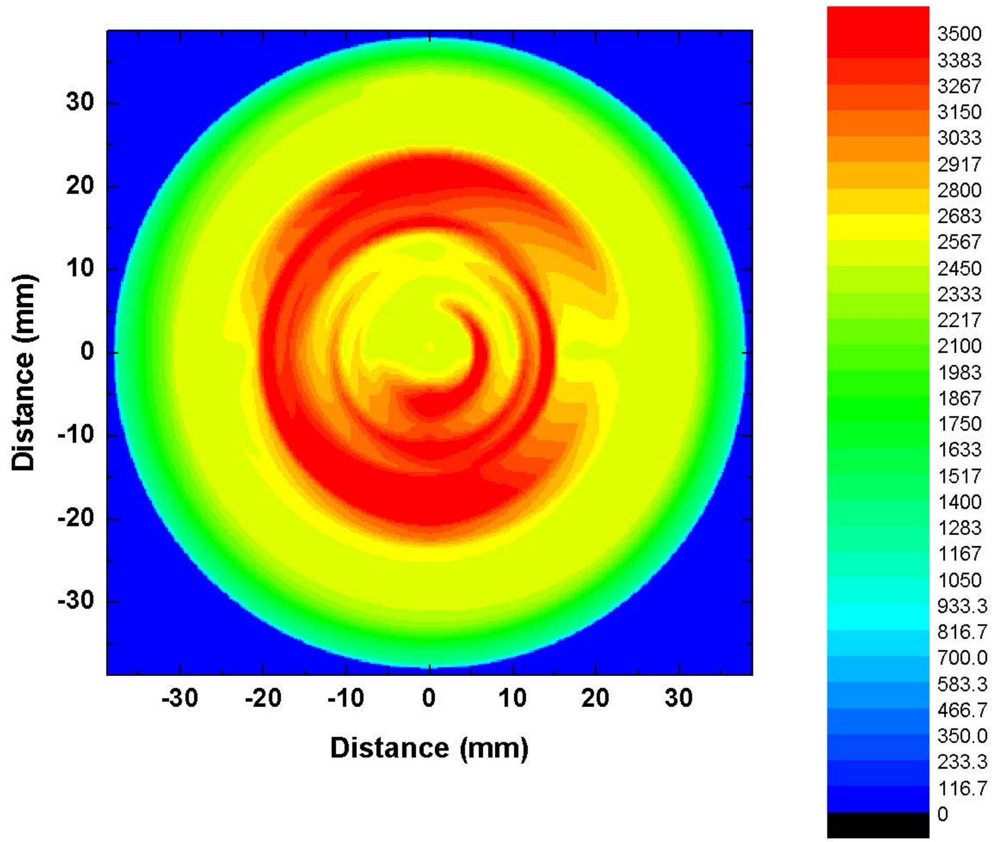
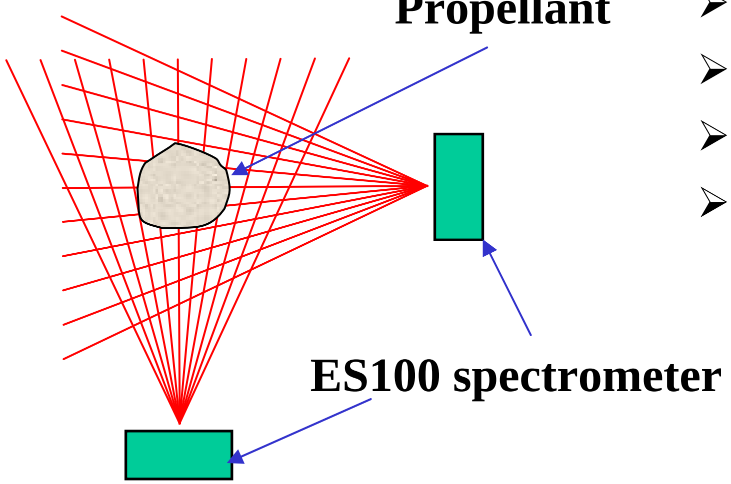
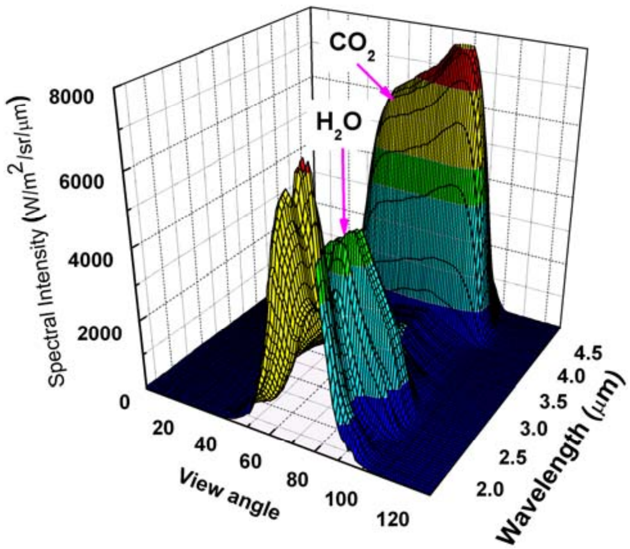
Sample Temperatures



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

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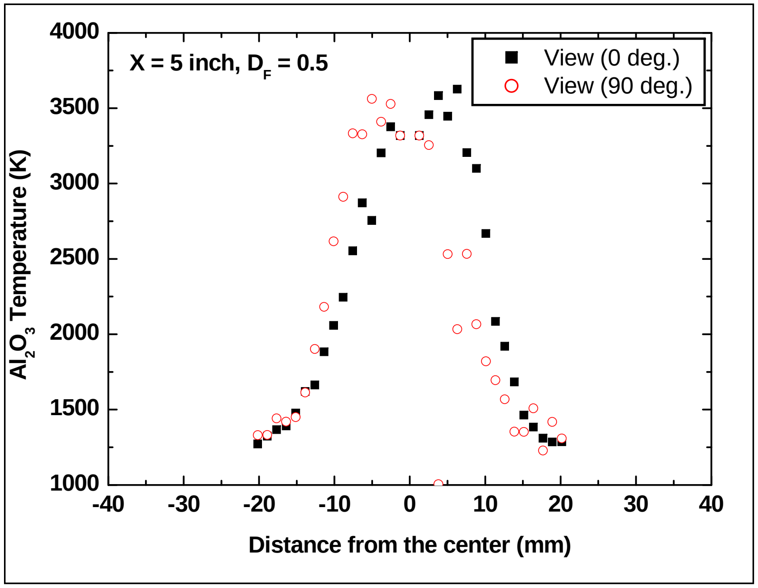
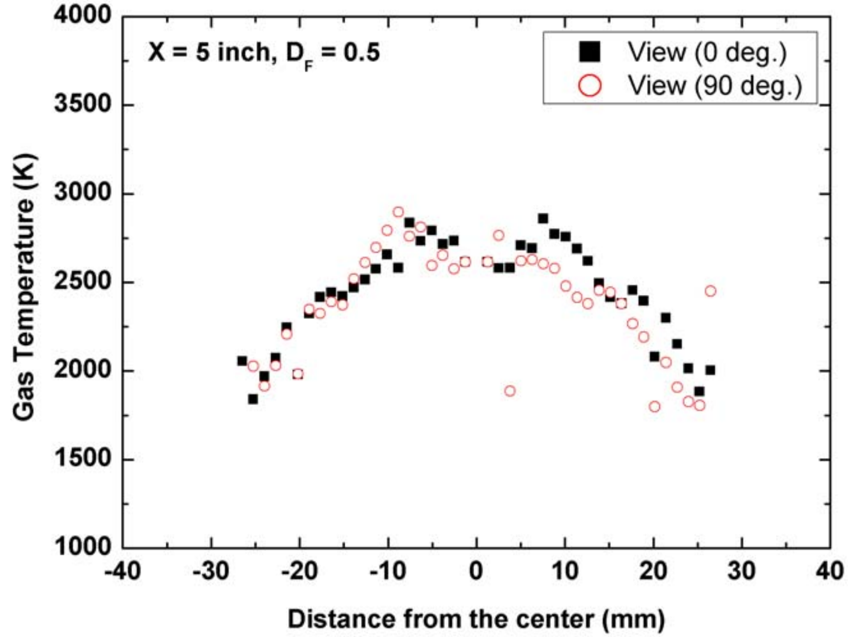
Solid Propellant Plume Properties





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.

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Future Directions

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

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