Application of Extinction and Emission Tomography to Structure Determination in Aircraft and Rocket Engines

Yudaya Sivathanu
En'Urga Inc.
1291-A Cumberland Avenue
West Lafayette, IN 47906

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

En'Urga Inc.

Outline

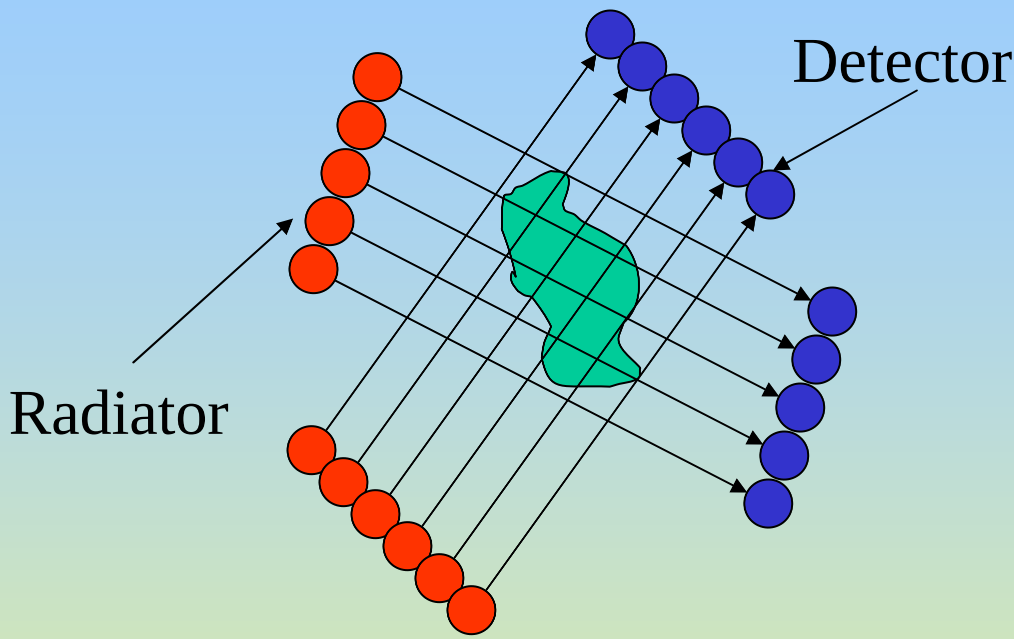
- Background
- Extinction Tomograpy
- Emission Tomography
- Concluding Remarks

En'Urga Inc.

Background

En'Urga Inc.

Primer on Tomography



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

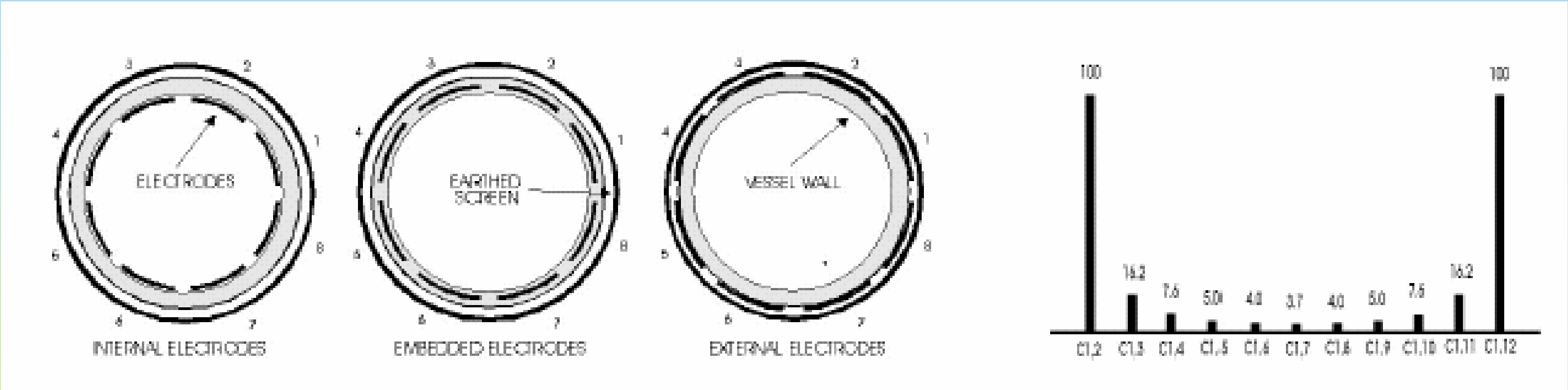
En'Urga Inc.

Common Non-Optical Techniques

- Capacitance
- Resistance (Conductance)
- Microwave
- Acoustic

Electrical Capacitance Tomography

- Measures capacitances between pairs of electrodes
- Distribution of permittivity



REINECKE N. and MEWES D., (1996), Recent developments and industrial/research applications of capacitance tomography, Meas. Sci. Technol. 7 pp 233-246

En'Urga Inc.

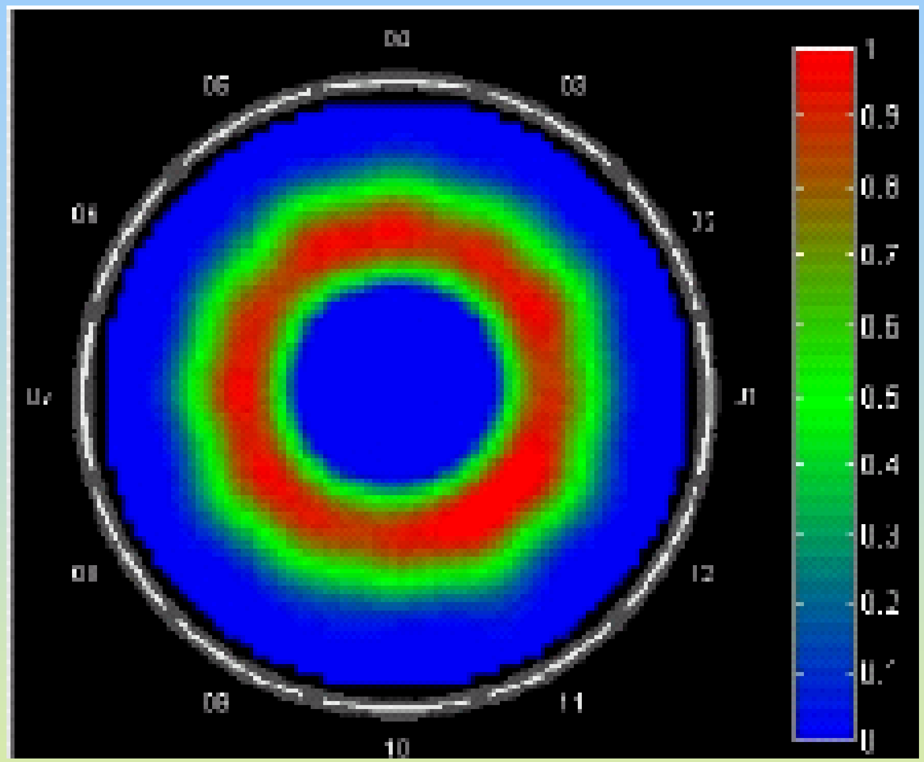
Measurement Characteristics

Frequency	**100 Hz**
Resolution	**~ 150 points (8 electrode system)**
Materials	**Non-conducting**
Accessibility to flow	**Not required**
Algorithm	**Back Plane Projection**
Applications	**Oil pipelines** **Fluidized beds** **Cryogenic flow**

REINECKE N. and MEWES D., (1996), Recent Developments and industrial/research applications of capacitance tomography, Meas. Sci. Technol. 7 pp 233-246

En'Urga Inc.

Sample Result



Byars, M., 2001, “Developments in electrical capacitance tomography,” 2nd World Congress on Industrial Process Tomography, Hannover, Germany.

En’Urga Inc.

Electrical Resistance Tomography

- Measures resistance between pairs of electrodes
- Distribution of conductivity/impedance
- Similar arrangement to internal capacitance probe
- Combination of both types used

Wang, M., Mann, R., and Dickin, F. J., (1999), Electrical resistance tomographic sensing systems for industrial applications', *Chem. Eng. Comm.*,Vol. 175, pp.49-70

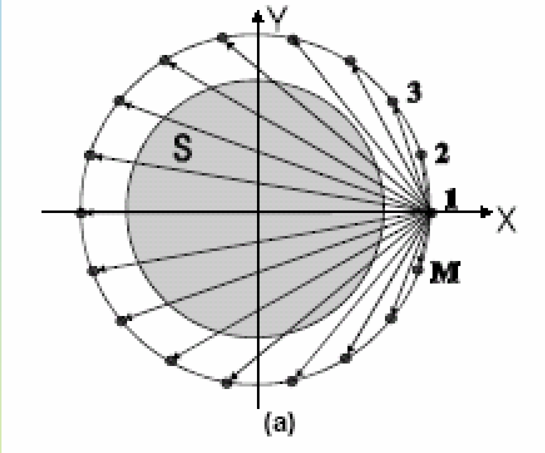
Measurement Characteristics

Frequency	**100 Hz**
Resolution	**~ 150 points (8 electrode system)**
Materials	**Conducting**
Accessibility to flow	**Required**
Algorithm	**Back Plane Projection**
Applications	**Water/oil mixtures** **Molten metal processing** **Concentration in mixers**

En'Urga Inc.

Microwave tomography

- *Electromagnetic scattering by a dielectric object*
- *Antennas act as radiation and receiver*
- *Distribution of dielectric constant*



Wu, Z., Boughriet, A., McCain, H., Davis, L. E., and Nugroho, A. T., 2000, "Investigation of microwave tomographic imaging techniques for industrial processes," Proc. SPIE Conf. on Process Imaging for Automatic Control, p151-158.

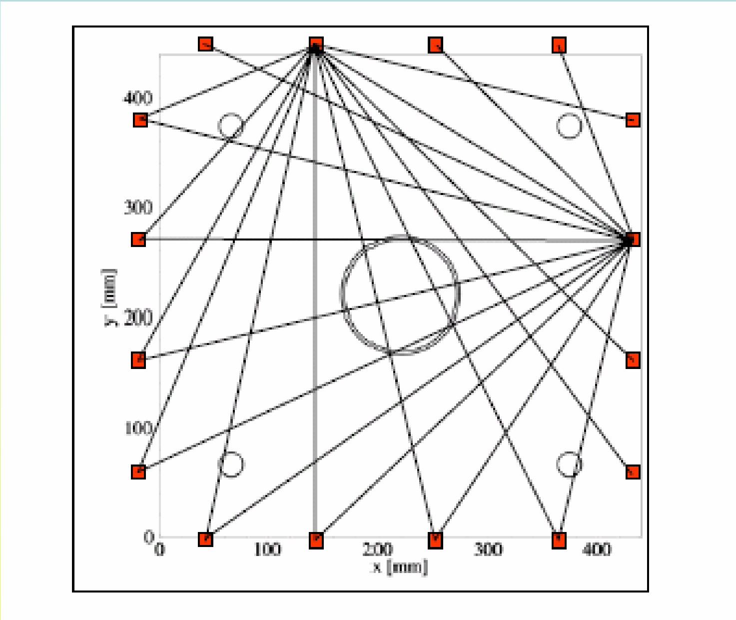
En'Urga Inc.

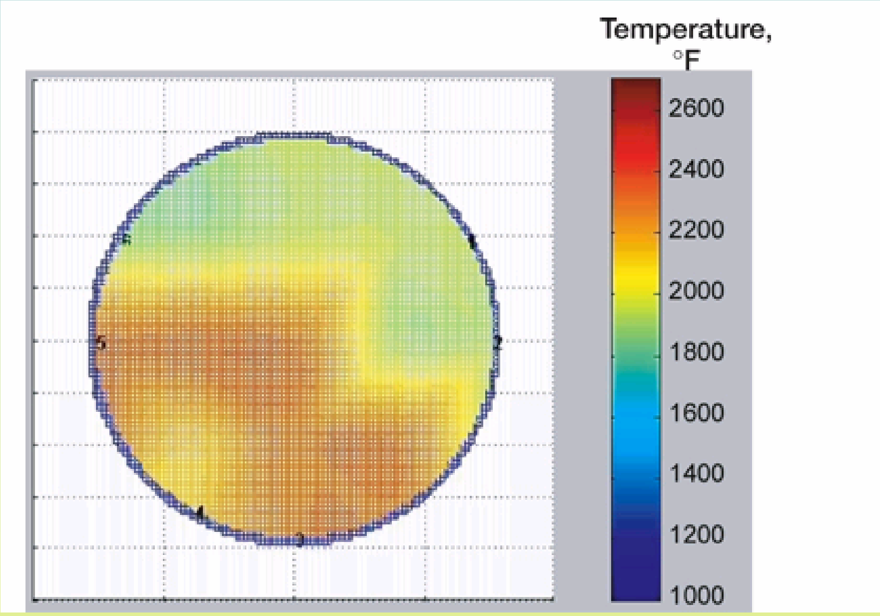
Measurement Characteristics

Frequency	20 Hz (with microwave array)
Resolution	~ 1000 points (32 x 32 array)
Materials	Dielectric material
Accessibility to flow	Not required
Algorithm	Back Plane Projection
Applications	Medical field Wood, paper, textiles Oil/water mixtures

Acoustic Tomography

- Acoustic waves send through an object at many different angles
- Attenuation or wave speed in transmission tomography
- Acoustic impedance mismatch in reflection tomography





NASA Glenn high pressure combustor

En'Urga Inc.

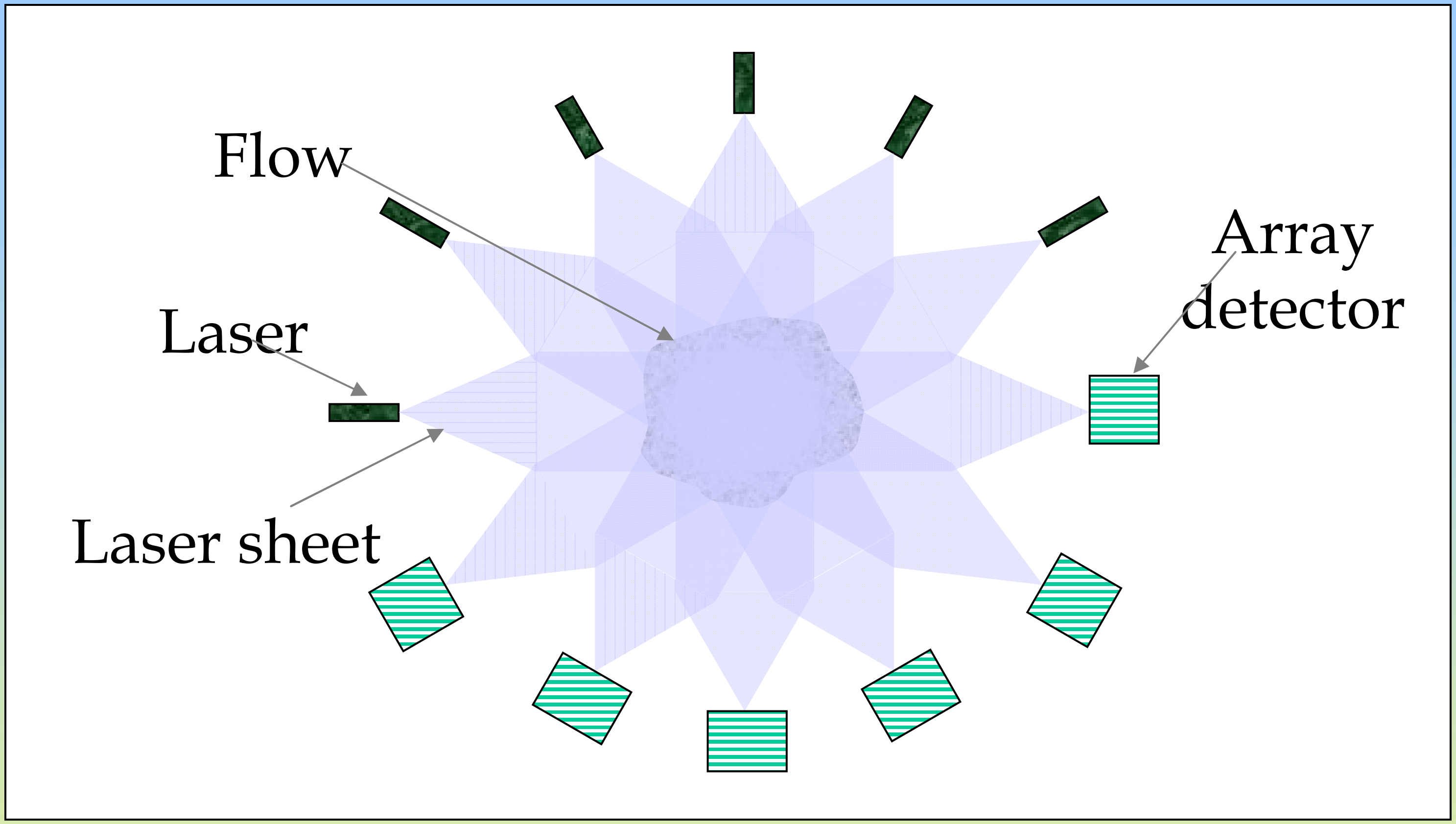
Measurement Characteristics

Frequency	10 Hz
Resolution	Medium
Materials	Speed of sound variation
Accessibility to flow	Not required
Algorithm	FFT, Algebraic reconstruction
Applications	Weld inspection Two-phase flows Oceanography (temperature)

Extinction Tomography

En'Urga Inc.

Extinction Tomography



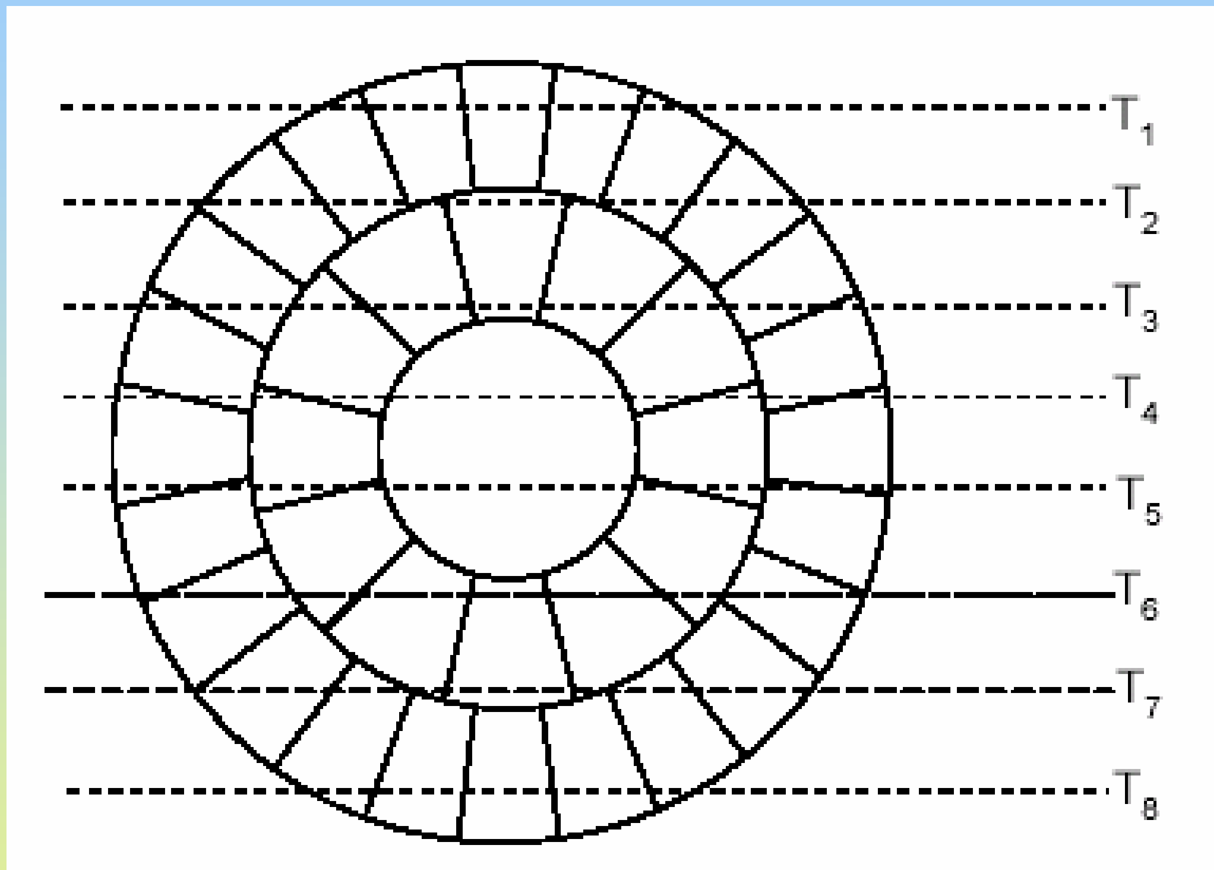
- *Extinction measured at multiple view angles*
- *Deconvoluted using tomography*
- *Challenge is that objects are moving*

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

En'Urga Inc.

Deconvolution Domain



En'Urga Inc.

Governing Equations

Equation of radiative transfer for one sample path

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

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

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

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

En'Urga Inc.

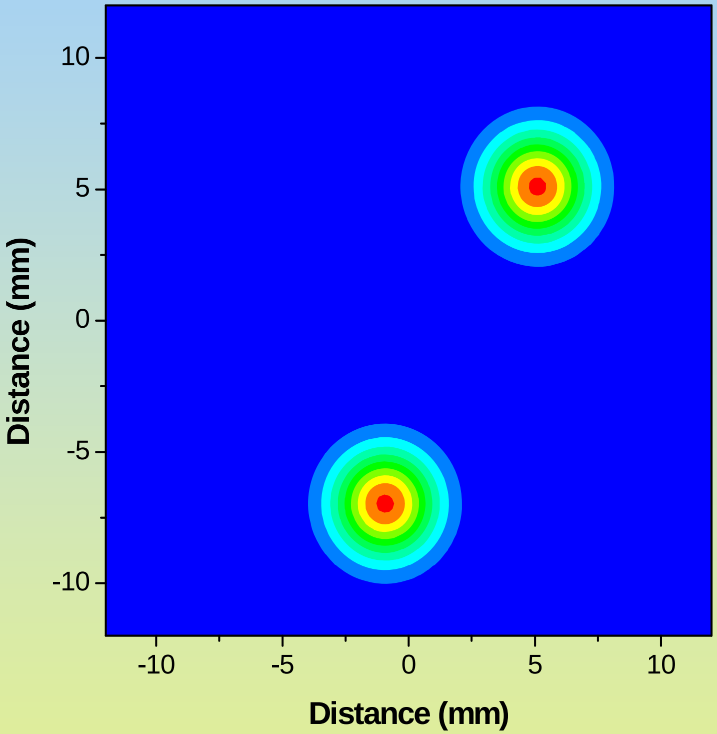
System of Equations

- 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

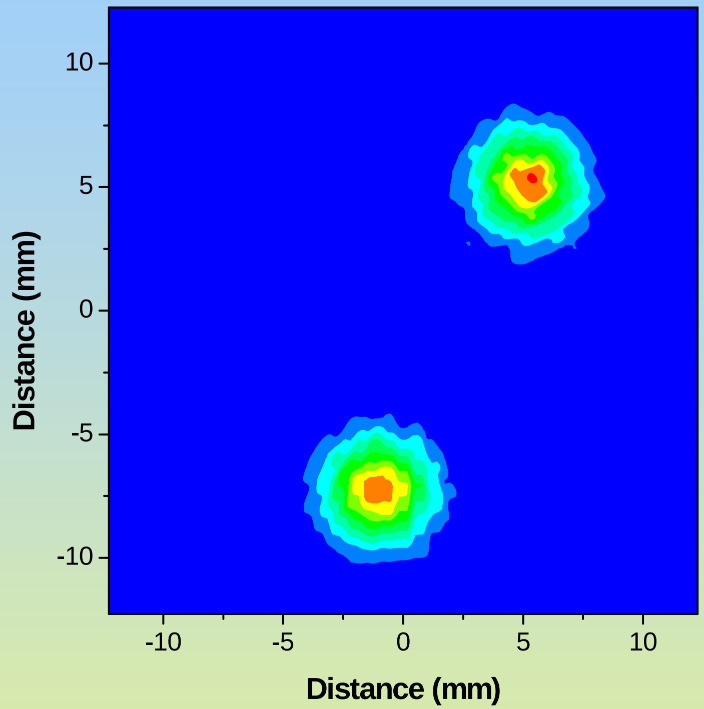
$$f(r) = \frac{1}{\sigma R\sqrt{2\pi}} \exp(-\left[(r/\sigma R)^2\right]/2)$$

Very difficult to resolve using alternate methods

Rigorous test of the algorithm

En'Urga Inc.

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.

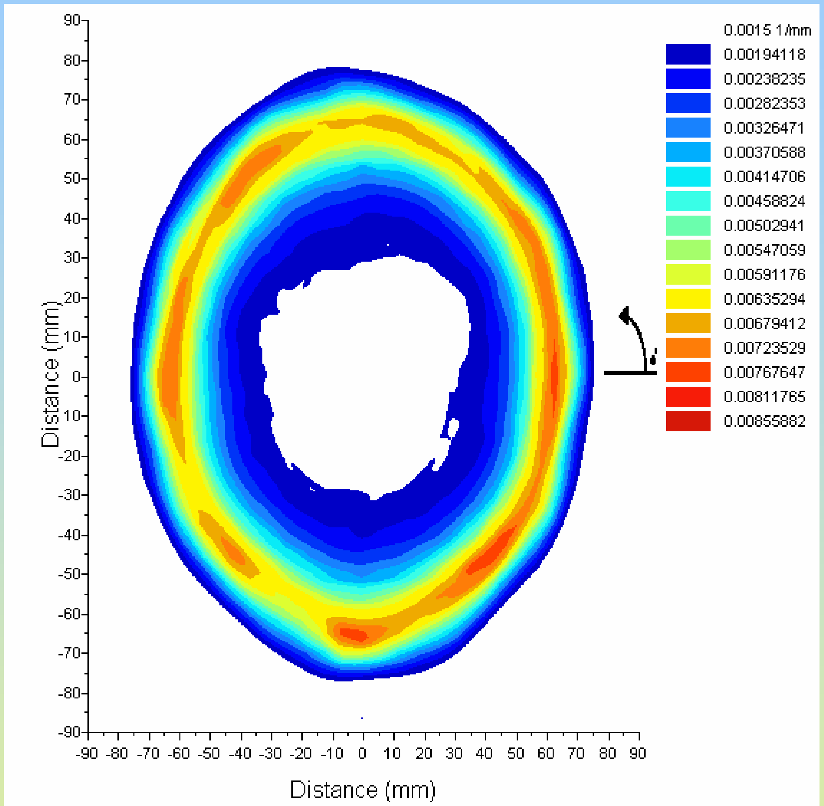
En'Urga Inc.

SETscan Patternator

High frequency, optical patternator for sprays

En'Urga Inc.

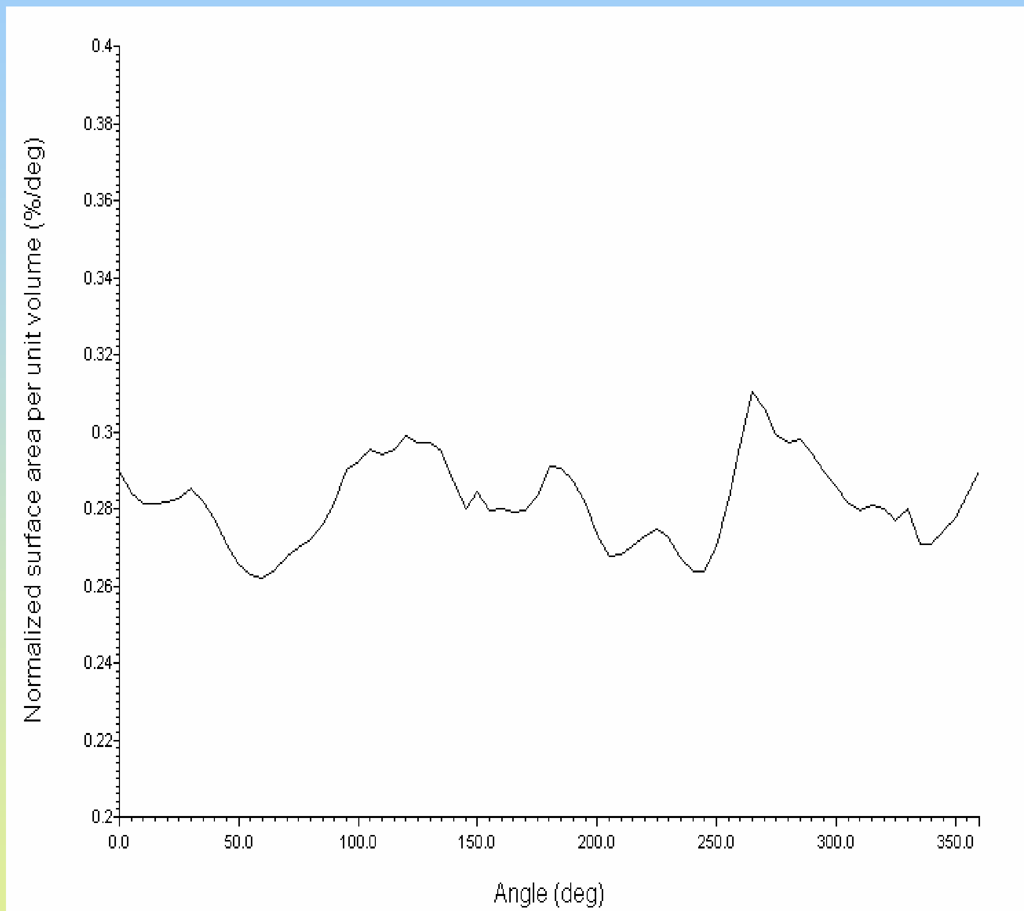
Sample Result: Aircraft Engine Nozzle

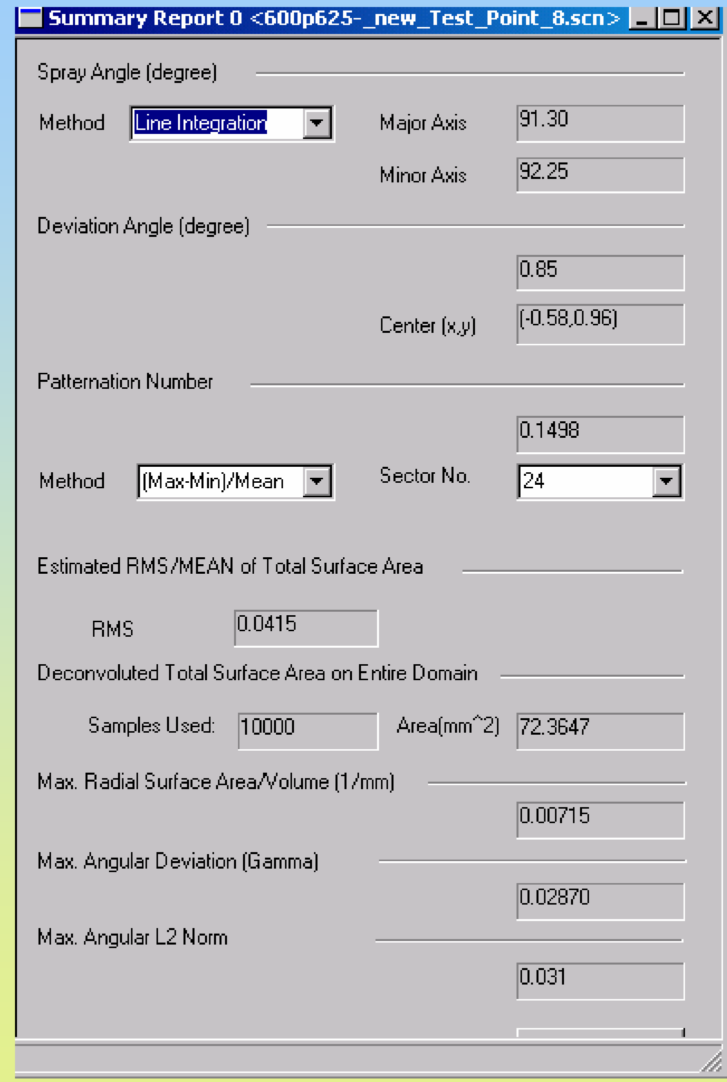


- Ensemble average of drop surface area density
- High/low surface area indicates streaks/voids

En'Urga Inc.

Quality Assurance: Aircraft Engine Nozzle



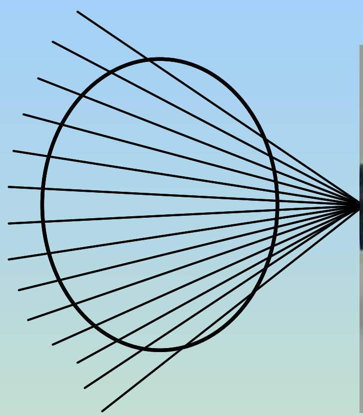


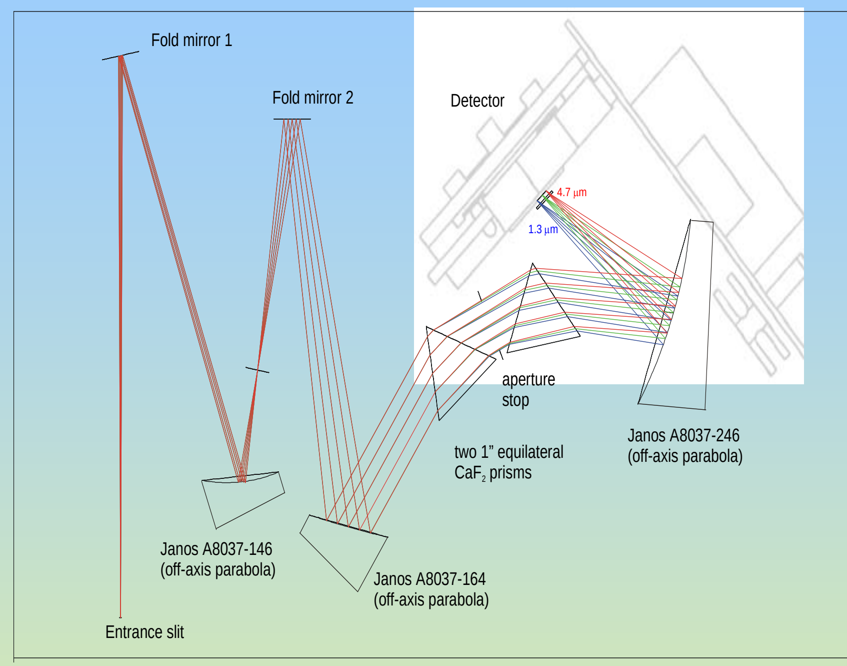
En'Urga Inc.

Emission Tomography

En'Urga Inc.

Typical Experimental Arrangement





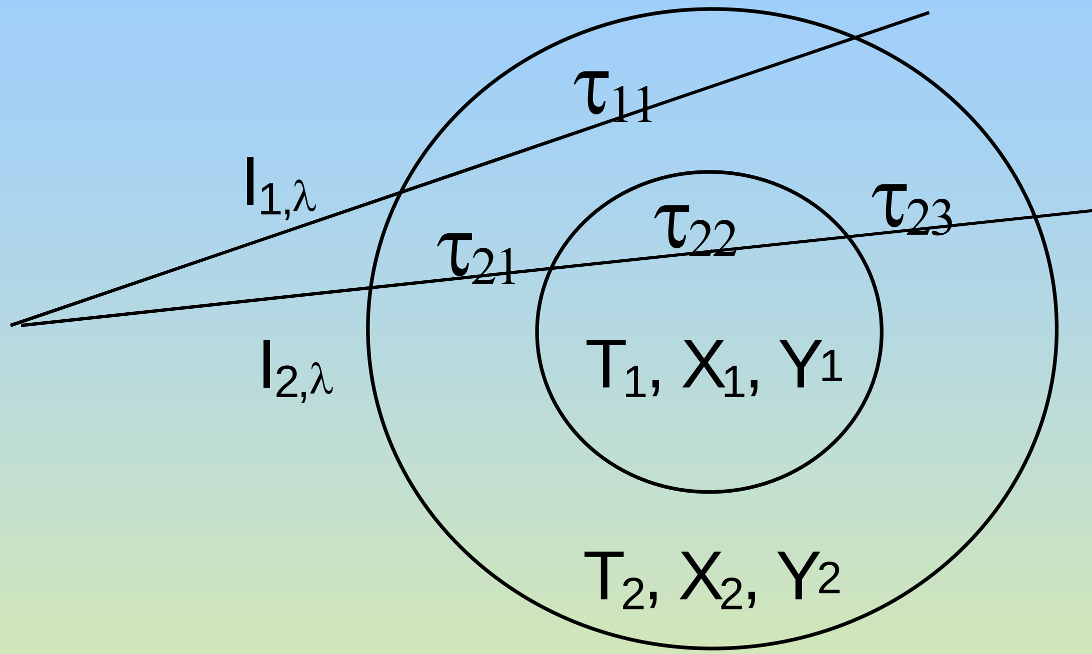
- *Either parallel path or fan beam arrangement*
- *Intensity measured at multiple view angles*
- *Deconvoluted using tomography*

En'Urga Inc.

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

En'Urga Inc.

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.

En'Urga Inc.

Constants in Equations

From databases such as RADCAL, HITRAN

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

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

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

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

En'Urga Inc.

Flow Chart for Solution

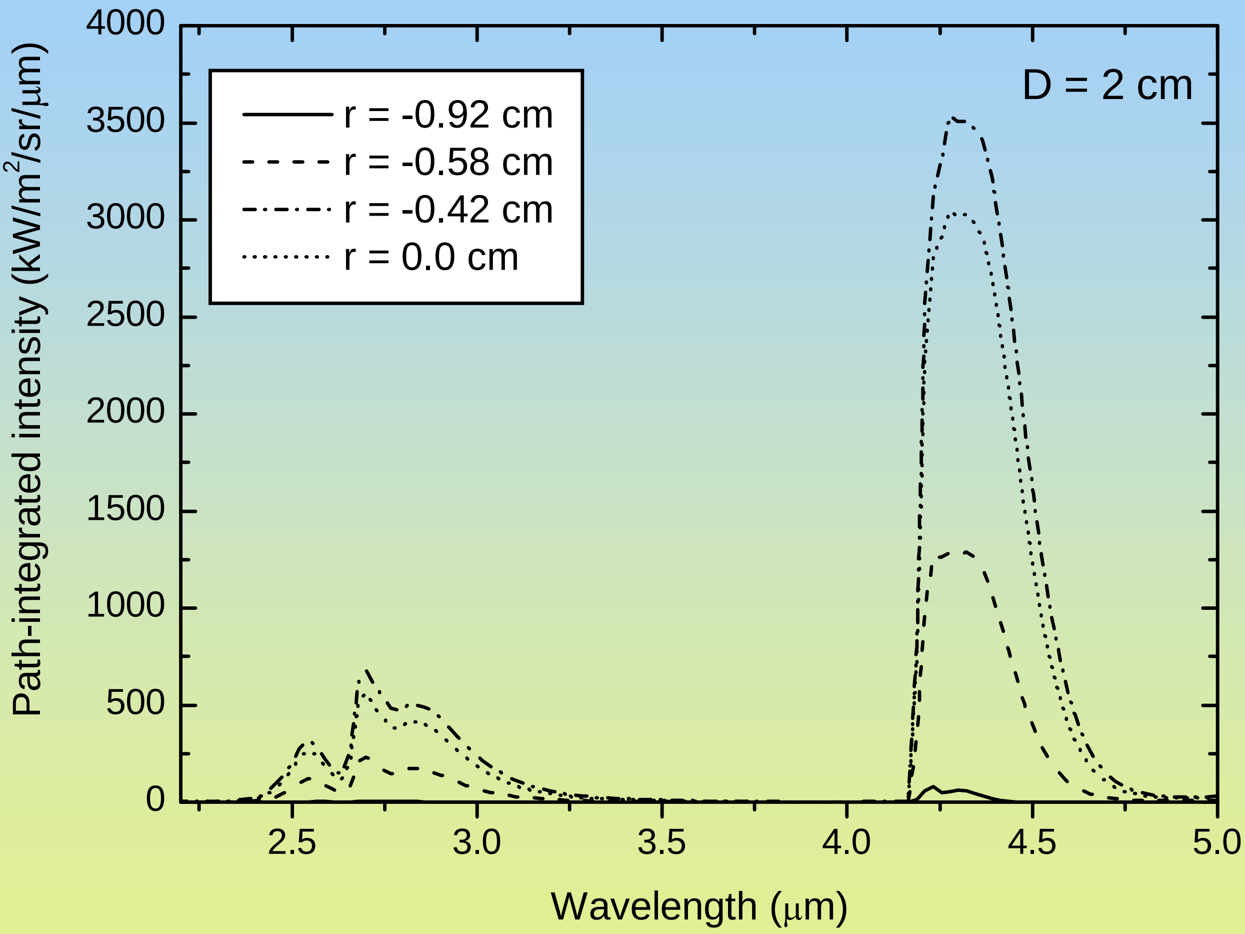
- **Linearize equations**
- **Guess transmittance**
- **Use MLE to obtain local intensities**
- **Estimate local properties based on intensities**
- **Calculate transmittance from local properties**
- **Utilize transmittance in updated guess**
- **Continue until convergence achieved**

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

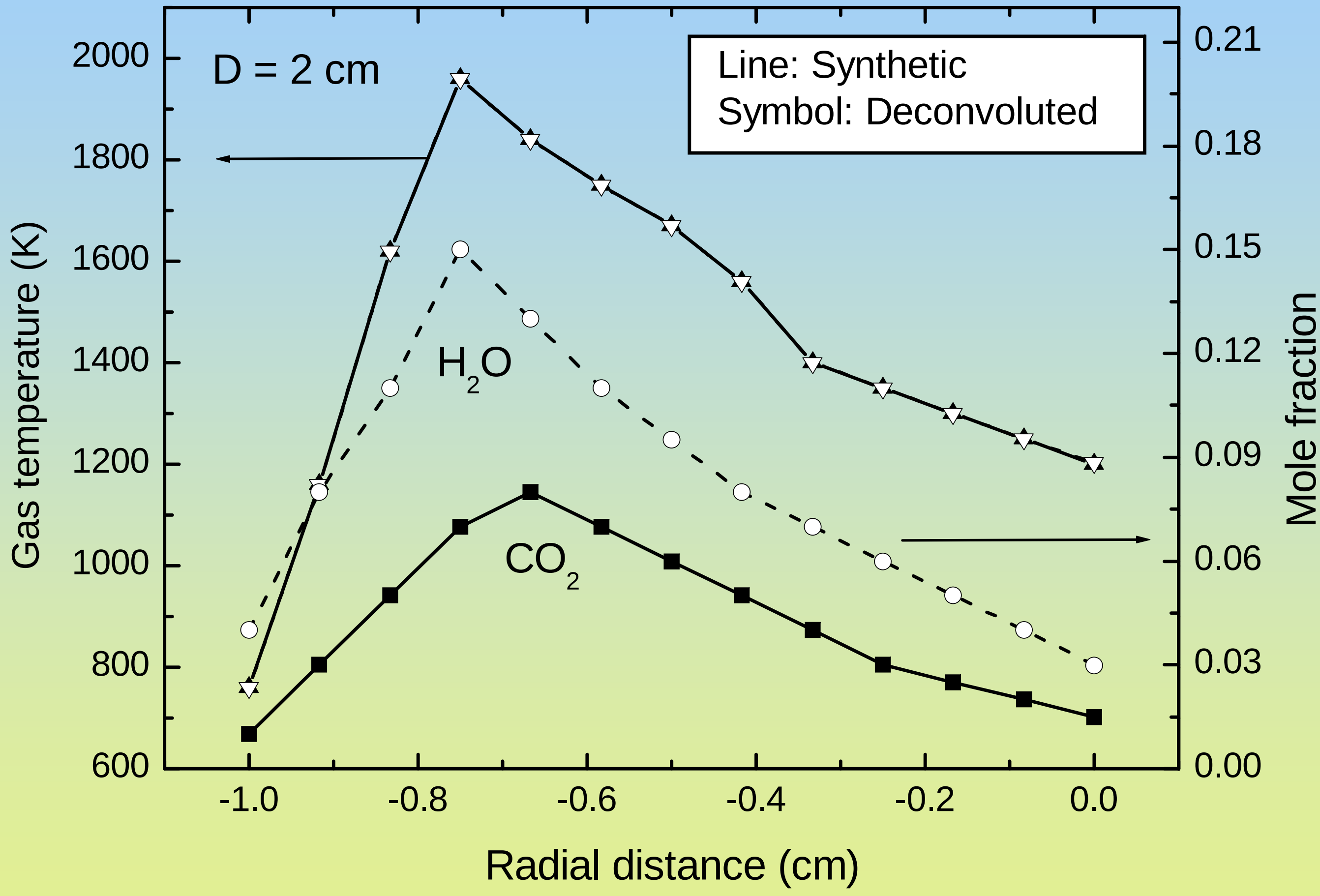
En'Urga Inc.

Calculated Intensities (input to algorithm)



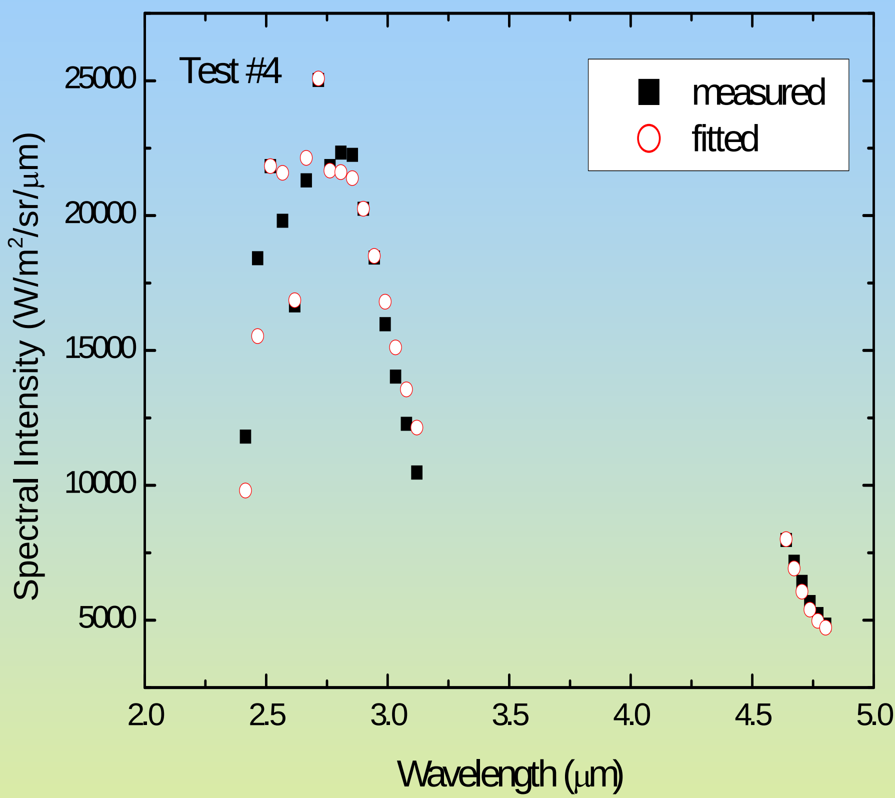
En'Urga Inc.

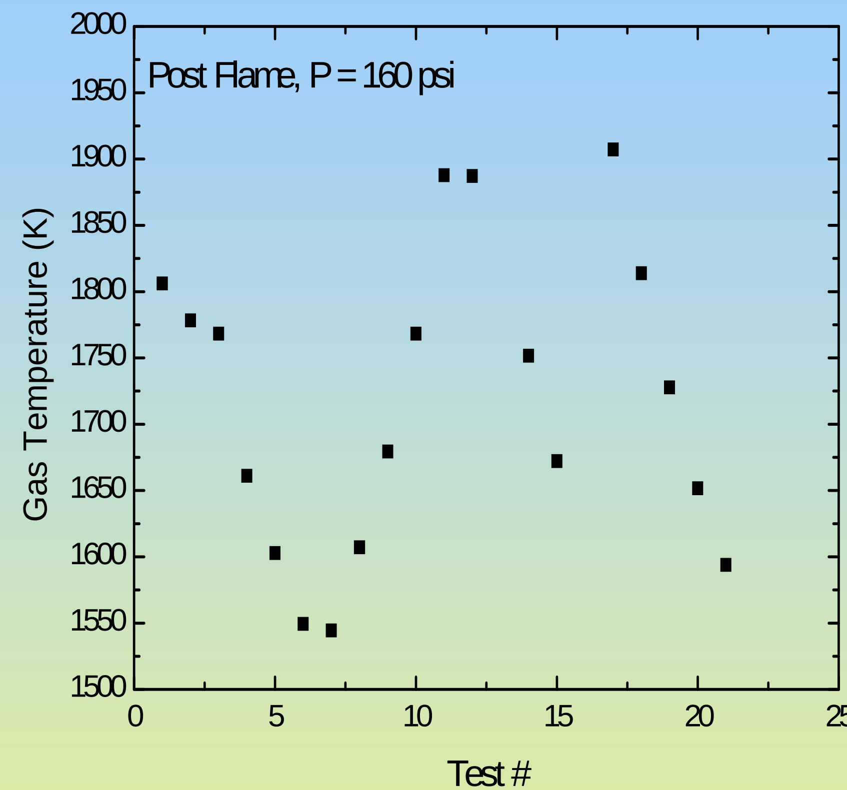
Converged Properties



En'Urga Inc.

Sample Implementation (Turbine Inlet)





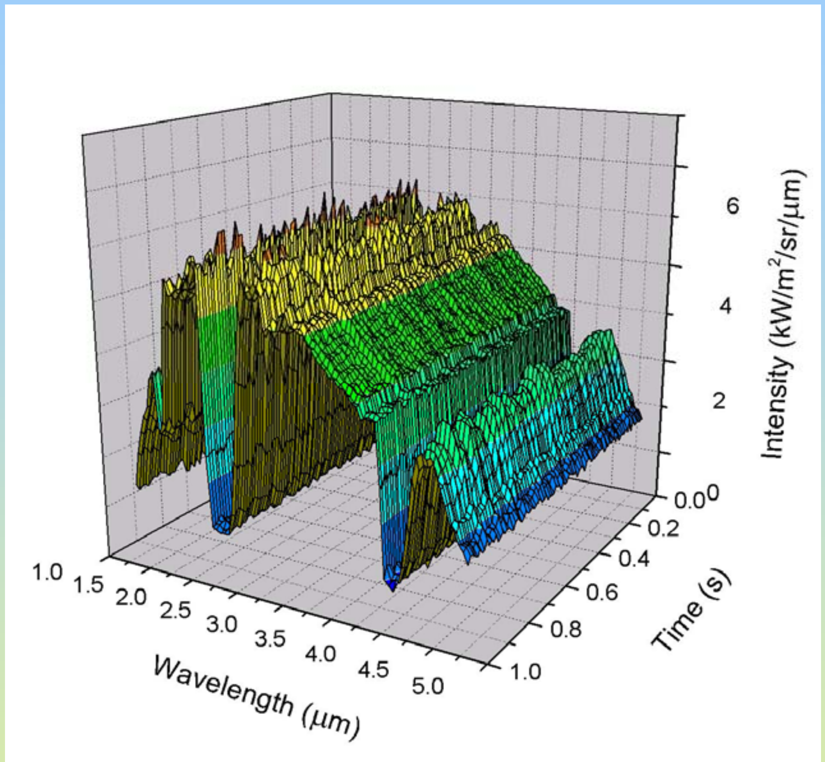
Stochiometry cycled during series of 20 test at ~ 11 bar

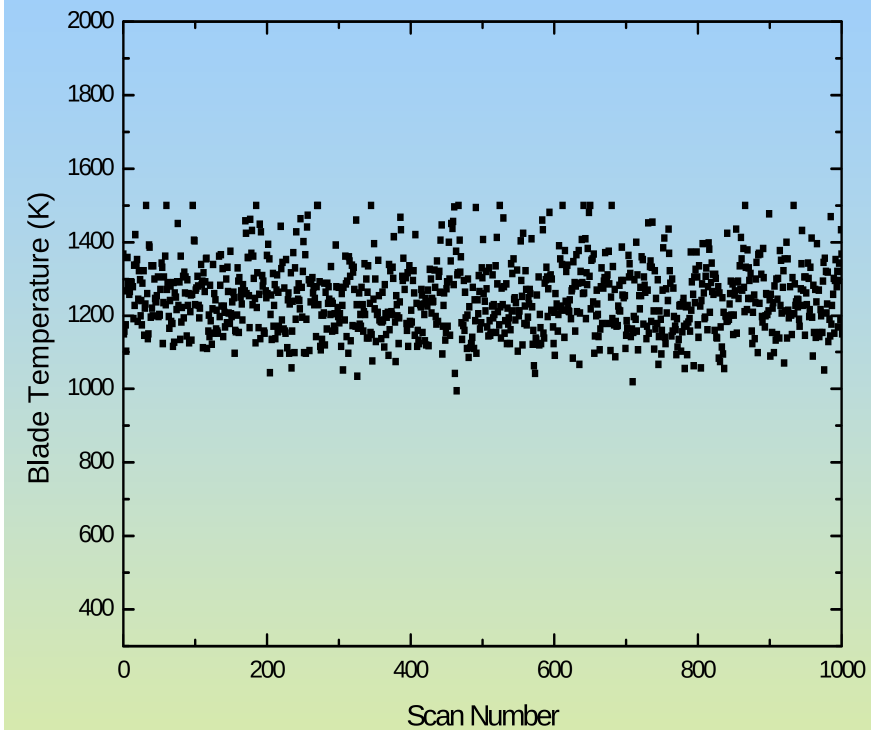
Gas temperature successfully estimated by method

Homogeneous layer assumption

En'Urga Inc.

Sample Implementation (Turbine Blade Temperature)

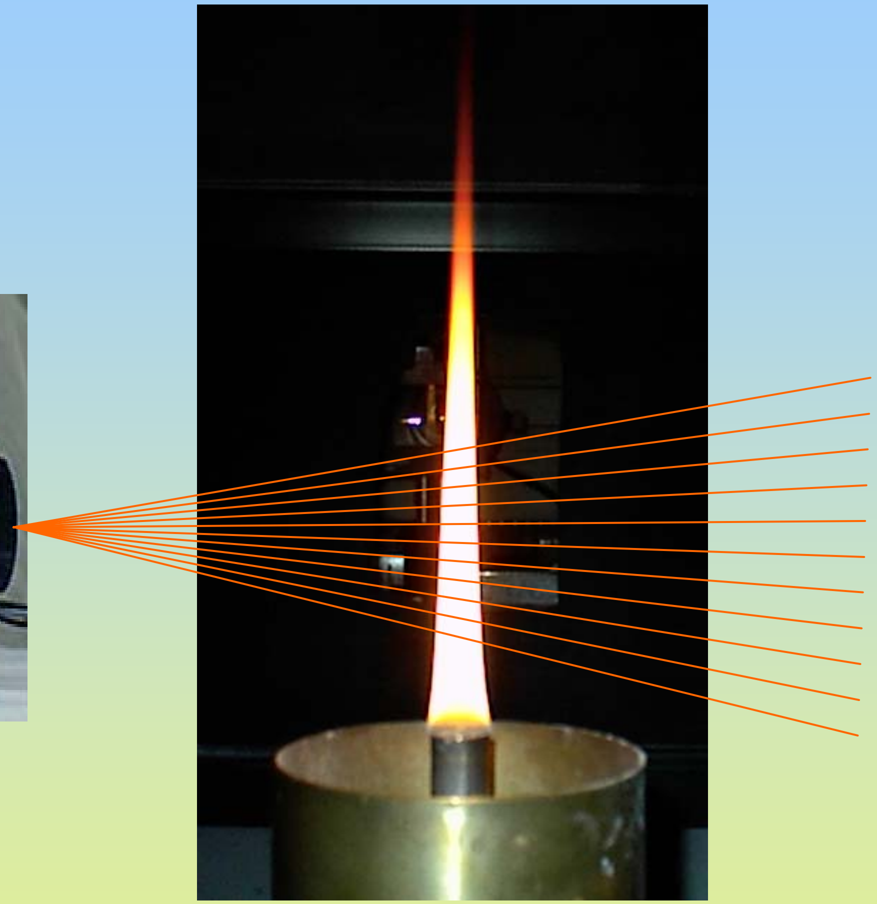




30 bar power generation turbine, emission from blade
Blade temperature and emissivity (for TBC monitoring)

En'Urga Inc.

Sample Implementation (Axisymmetric system)



Emission measured at 128 view angles
160 wavelengths obtained with ES100 imaging spectrometer

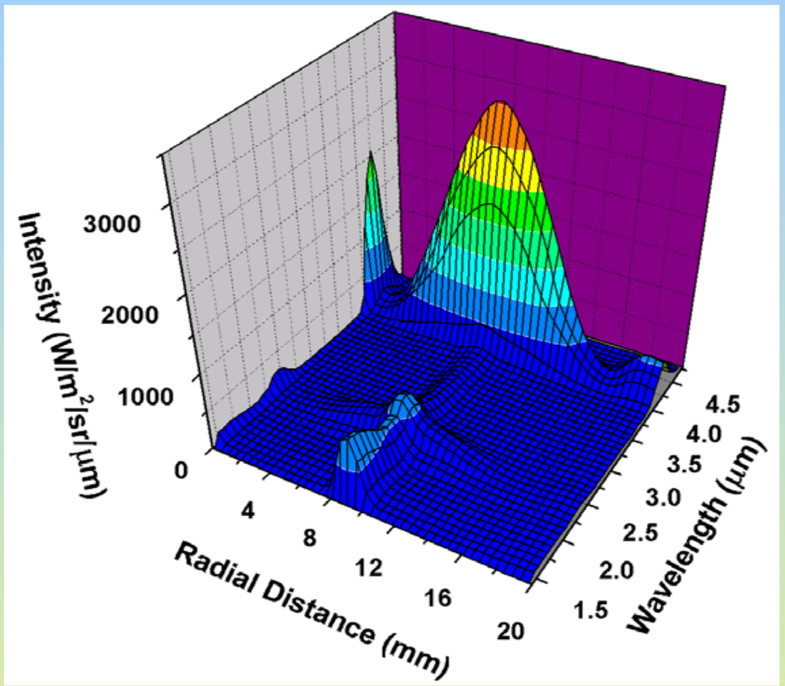
En'Urga Inc.

Evaluation in a Laminar Flame

Incipient Sooting Ethylene Flame

Fuel Flow Rate: 2.30 cm^3/sec

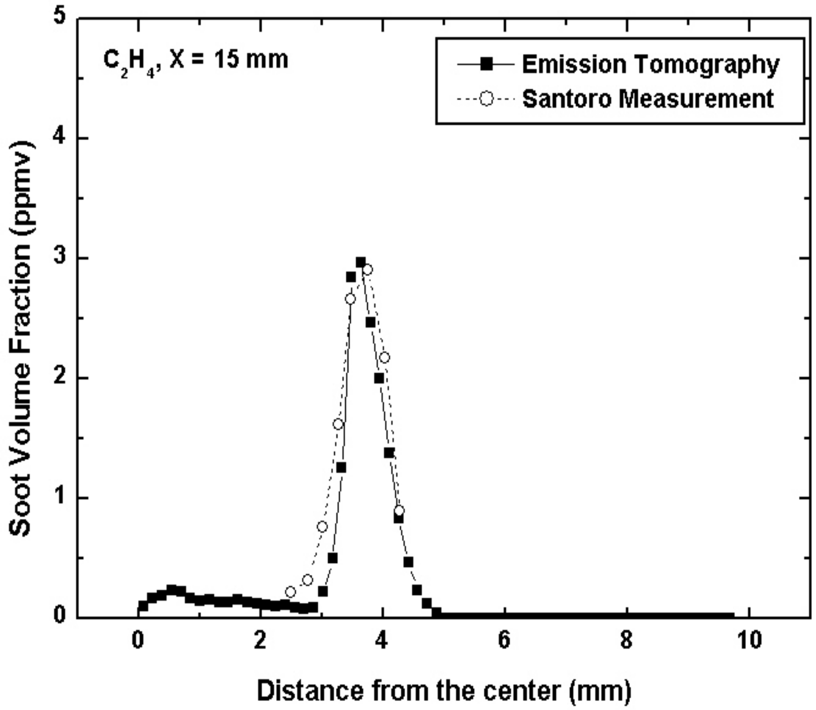
Coflow Air: 713.3 cm^3/sec

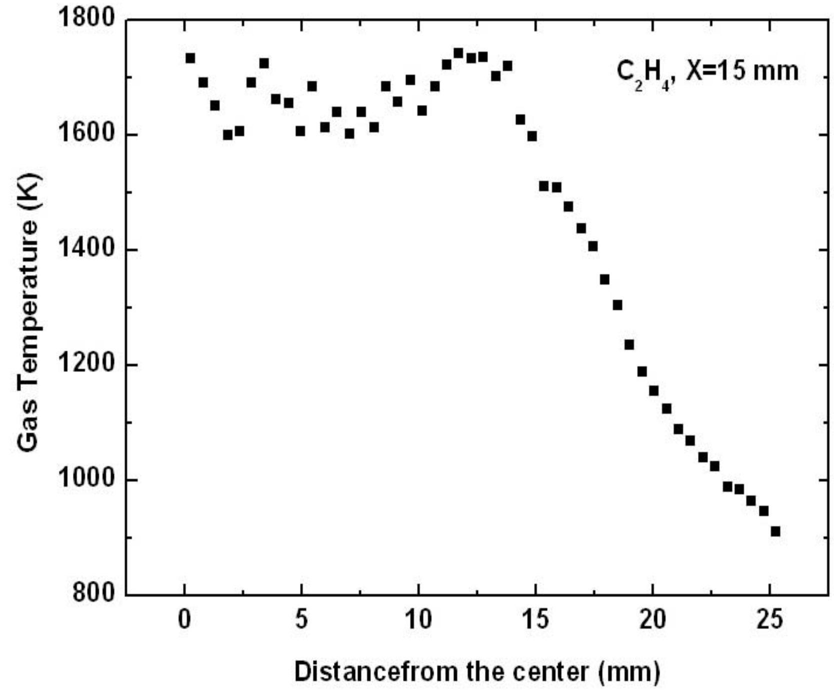


Measured spectral radiation intensities above burner exit

En'Urga Inc.

Sample Results



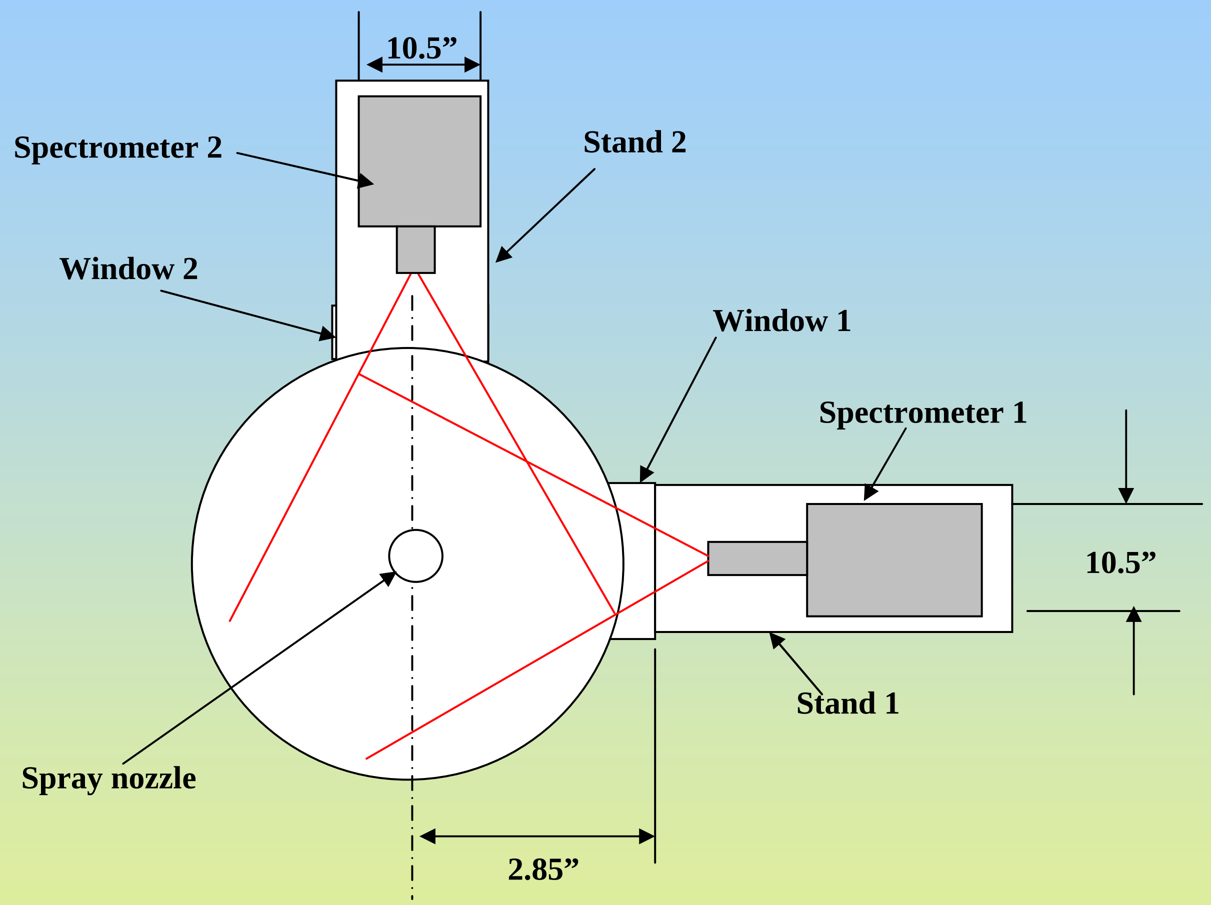


Estimated particulate concentrations, temperatures, and gas concentrations reasonably well

En'Urga Inc.

Sample Implementation (Non-axisymmetric)

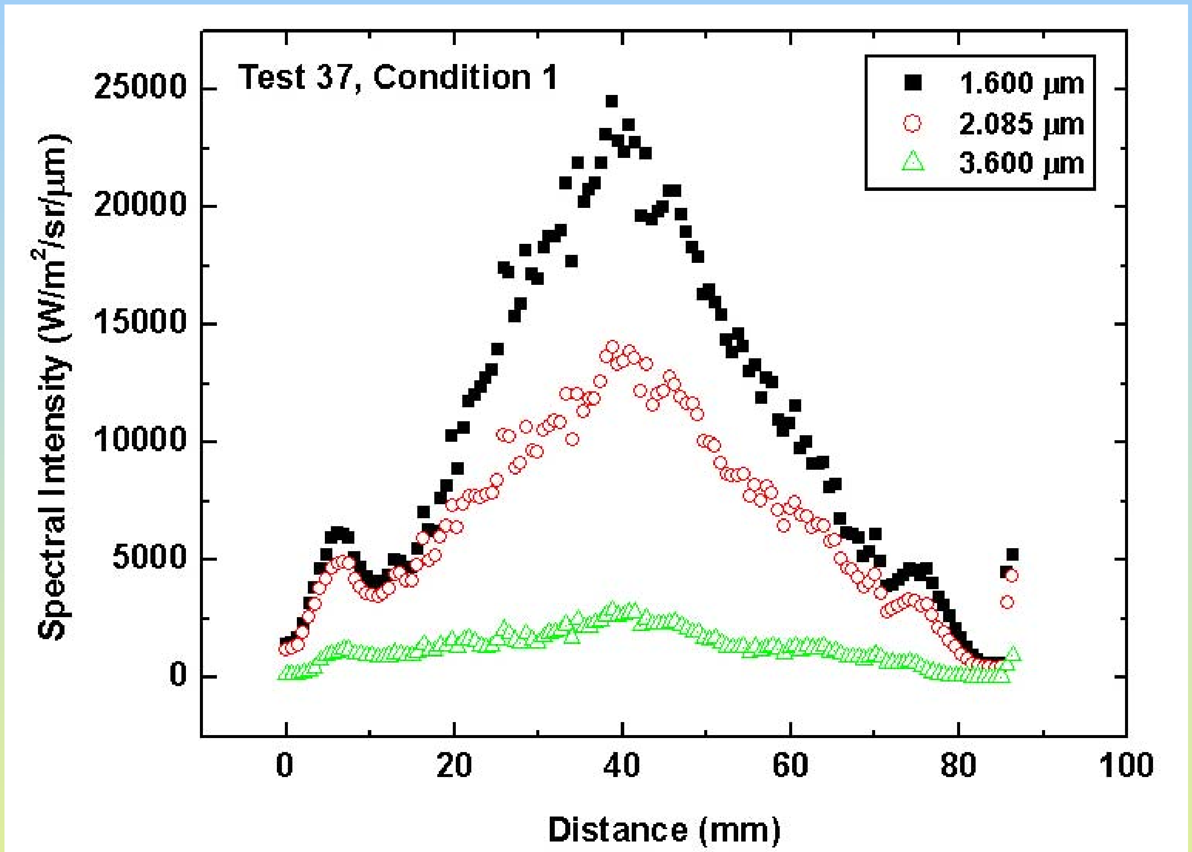
-



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

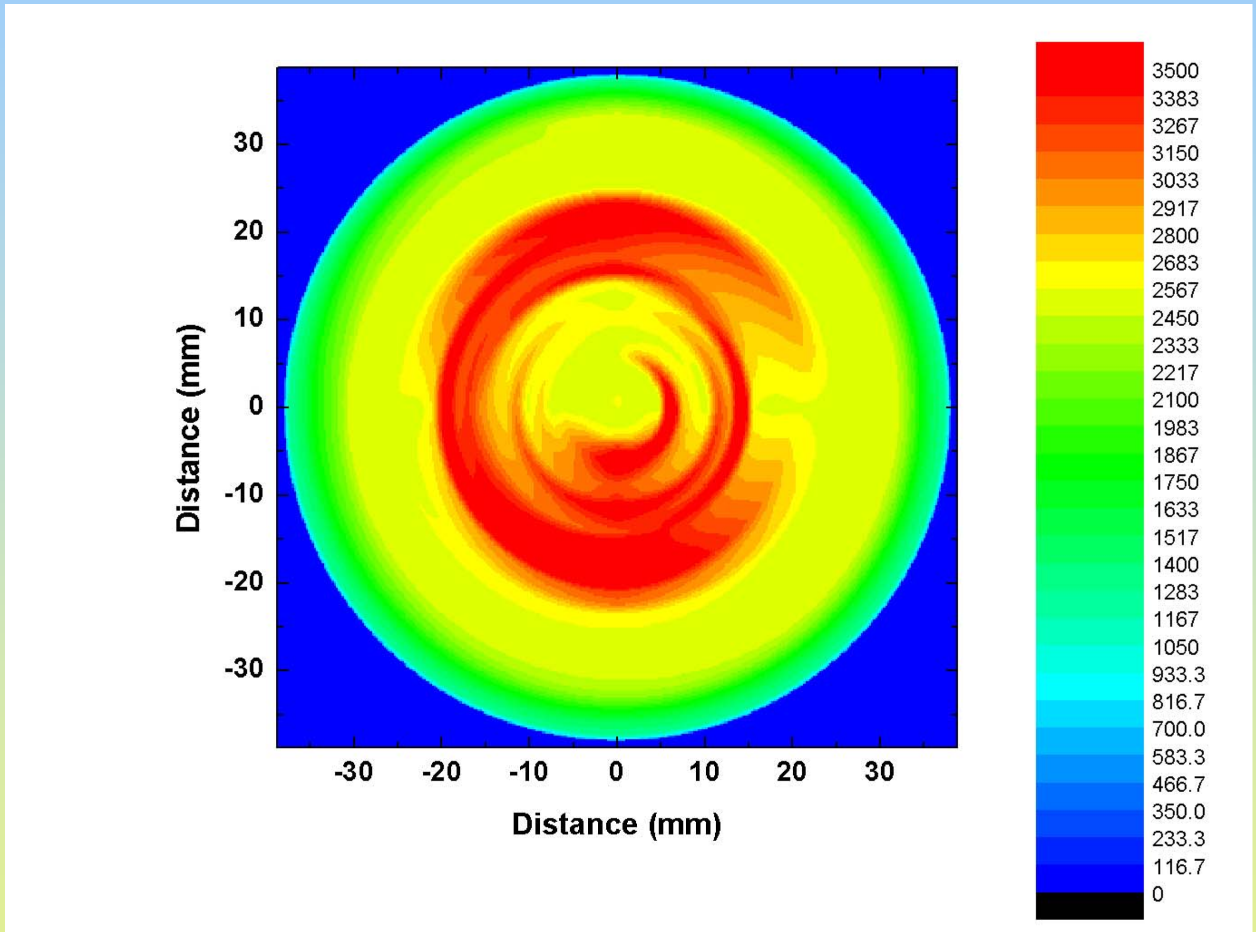
En’Urga Inc.

Sample Results



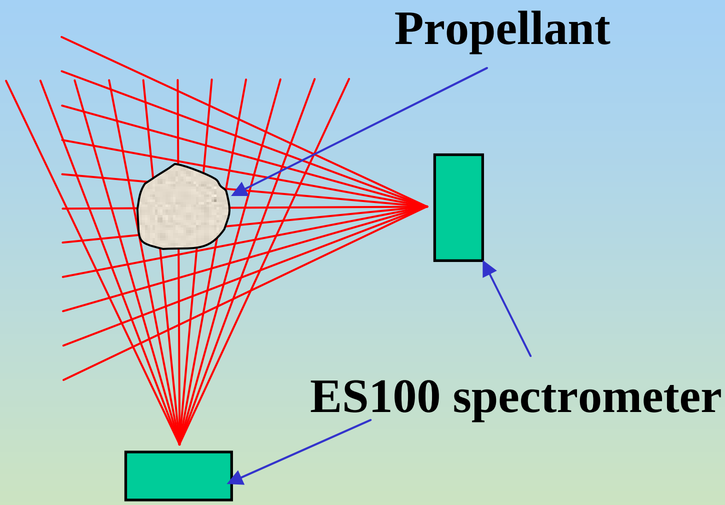
En'Urga Inc.

Sample Temperatures

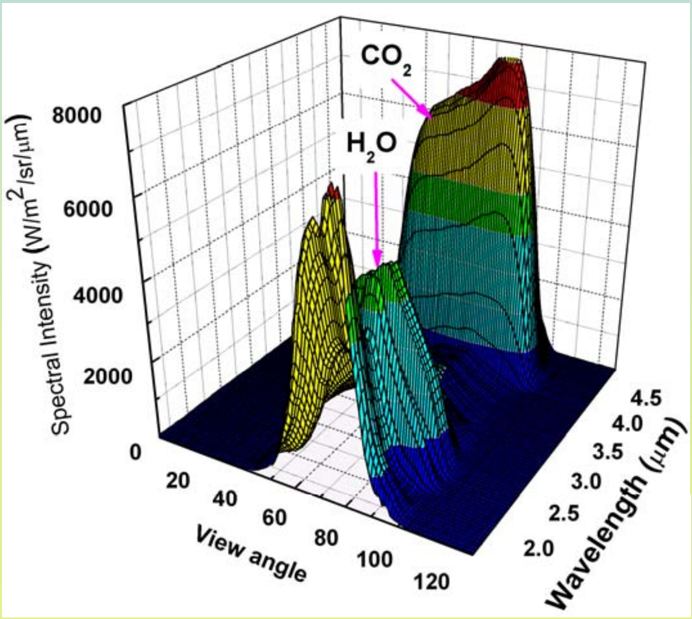


En'Urga Inc.

Sample Implementation (Solid Propellant Plume)



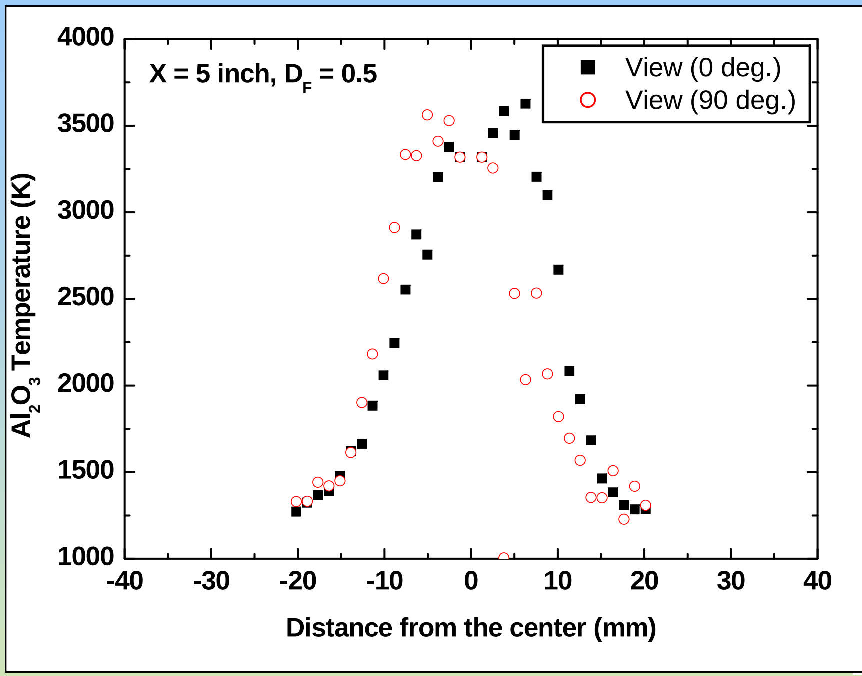
- Two orthogonal spectrometers
- 128 view angles per spectrometer
- 1.3 to 4.8 microns
- 1320 Hz for spectra
- Full planar measurement at 10.3 Hz

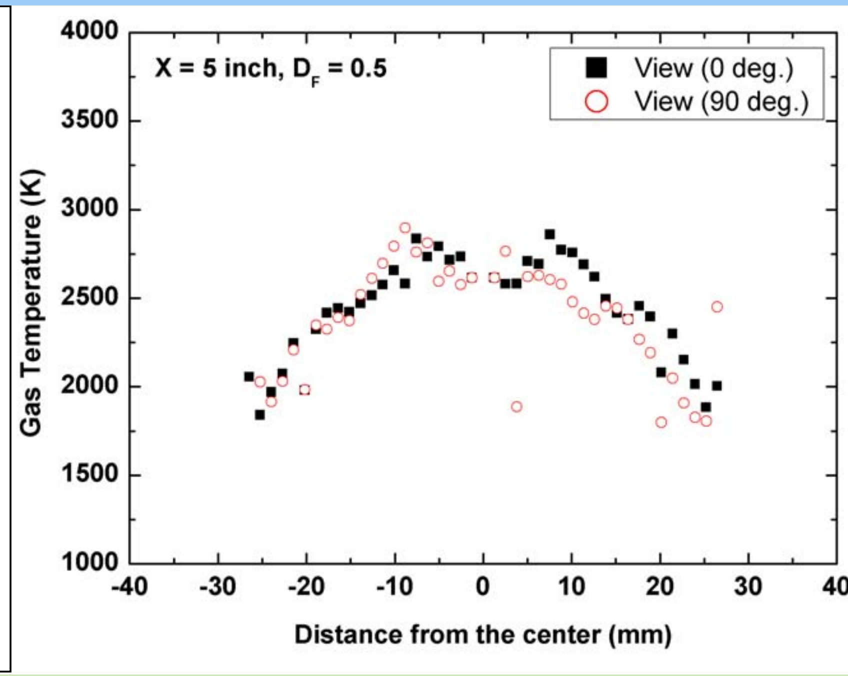


Test in solid propellants up to 18 inches in diameter

En'Urga Inc.

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.

En’Urga Inc.

Future Directions

- X-Ray based tomography for optically dense flames and sprays
- Engineering for specific applications
- Process control based on selected features of the deconvoluted results
- Velocity estimation using Statistical Pattern Imaging techniques

En'Urga Inc.