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CBT-TCS: the New Temperature and Soot Loading Measurement Technique in a Laminar Diffusion Flame

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Outline

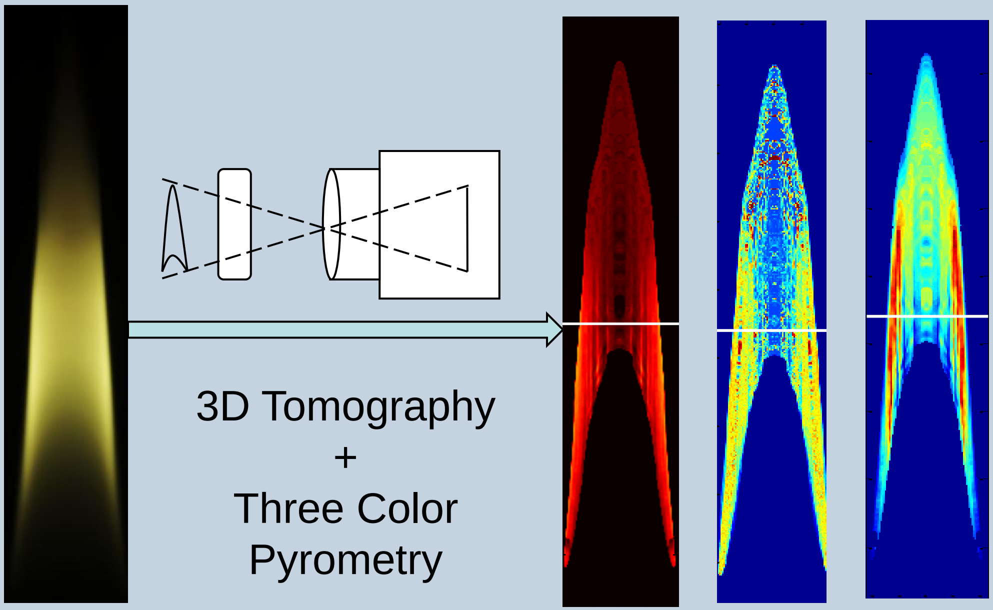
- Introduction
- Experiment Setup and Software Packages
- Accuracy Improvement Techniques
- Sample Data and Assumptions
- Conclusions

Motivation

- Sub-micron particulate matter is of concern to human health
- Legislation places limits on the particulate emissions
- For model validation, a simple flame is needed
- Spatially resolved non-intrusive measurement is needed of:
  - Flame temperature
  - Soot volume fraction
  - Soot particle diameter

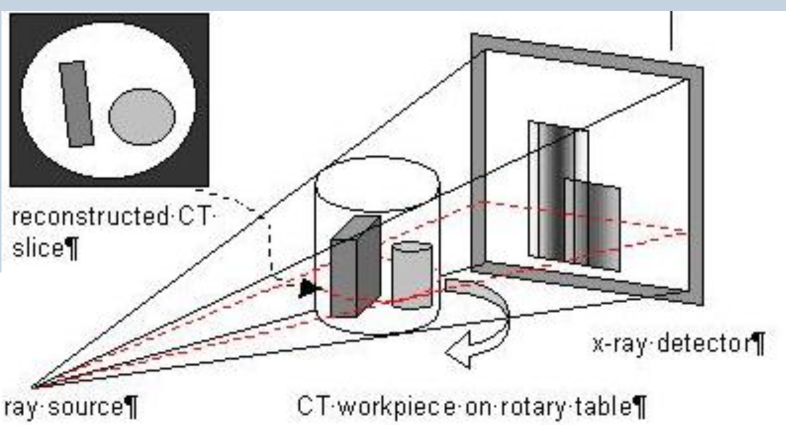
Introductions to CBT-TCS

(Cone Beam Tomographic Three Colour Spectrometry)



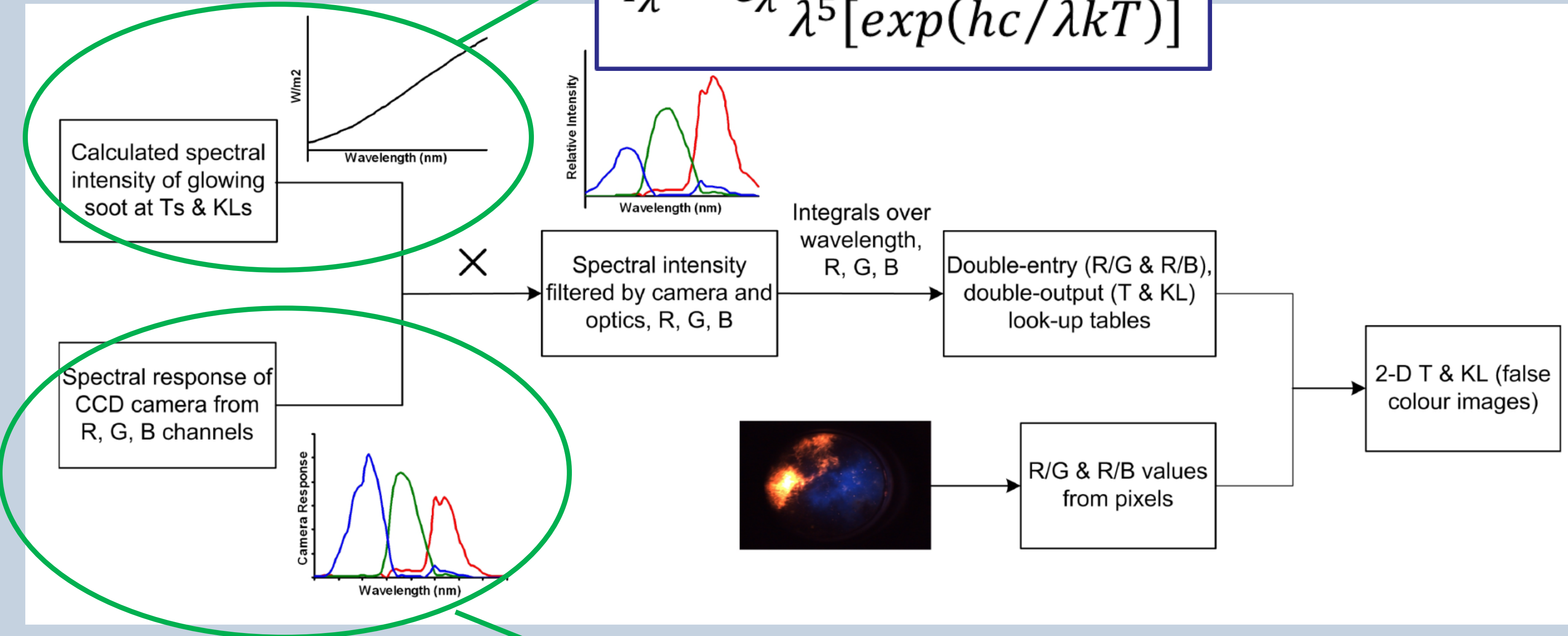
- Optical diagnostic techniques used to measure the 3D temperature, soot diameter and soot volume fraction distributions

- Combination of three colour pyrometry and 3D tomography technique



Three Colour Pyrometry - Strategy

$$I_\lambda = \varepsilon_\lambda \frac{2\pi hc^2}{\lambda^5[exp(hc/\lambda kT)]}$$



Calibration of the spectral response of the Camera Sensor

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Three Colour Pyrometry
- emissivity & scattering models (1/2)

- Energy balance (Kirchhoff's Law)

⇨ Emissivity (ε) = Absorption efficiency (*Qabs*)

- Different Scattering Models
  - Rayleigh-Gans Theory (*X* [$x = \pi d/\lambda$] < 0.3);

    d - diameter; *T* and *fv* - Soot volume Fraction

$$\varepsilon = Q_{abs}^{R} = 4xIm\left\{\frac{m^2-1}{m^2+2}\right\}$$

Where *m* = *n* - *ik* is the complex refractive index

  - Rayleigh-Gans Theory with Penndorf extension (*x* < 0.8; *T, D* and *fv*)

$$\varepsilon = Q_{abs}^{P}$$

$$= Q_{abs}^{R} + 2x^2[N_1\left(\frac{1}{15}+\frac{5}{3}\frac{1}{M_4}+\frac{6}{5}\frac{M_5}{M_1^2}\right)+\frac{4}{3}\frac{M_6}{M_1^2}x] - Q_{sca}^{R}[1+2\frac{x^2}{M_1}\left(\frac{3}{5}M_3-2N_1x\right)]$$

Three Colour Pyrometry
- emissivity & scattering models (2/2)

- Mie Scattering Theory (analytical solution; *T*, *D* and *fv*)

$$\varepsilon = Q_{abs}^{M} = \frac{2}{x^2}\sum_{n=1}^{\infty}(2n+1)Re(a_n + b_n) - \frac{2}{x^2}\sum_{n=1}^{\infty}(2n+1)(|a_n|^2 + |b_n|^2)$$

where a_n and b_n are scattering coefficients and are functions of x and m

- Hottel and Broughton Correlation (Empirical correlation; *T*, *KL*)

$$\varepsilon = 1 - \exp\left(-\frac{KL(s)}{\lambda^{\alpha}}\right)$$

where *KL* is proportional to the soot volume fraction and α is a constant

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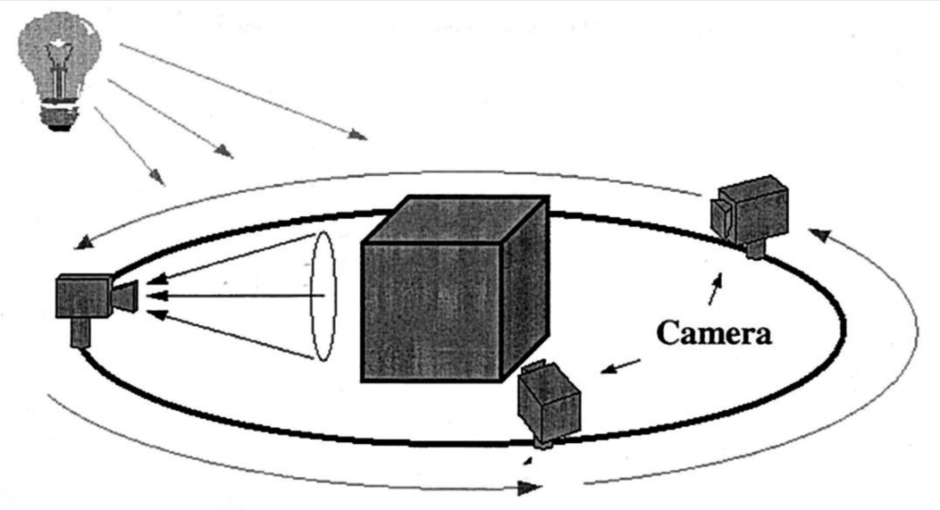
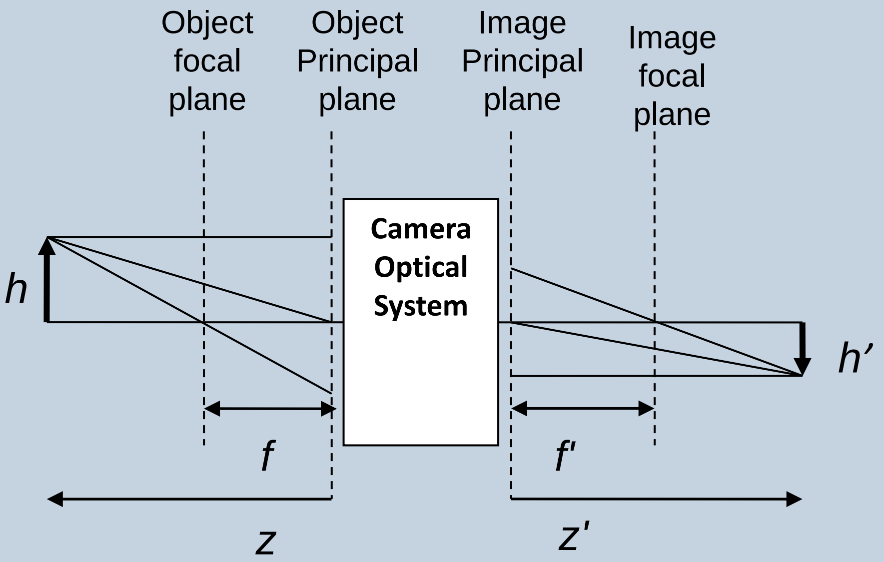
Cone-Beam Tomography – Cone-Beam System



- Need only one projection for axis-symmetric object (e.g. laminar diffusion flame)



Newton's Lens Formula:

$$h'/h = f/(z + f) = (z' + f')/f'$$

$$\Rightarrow \quad h'/z' = -(f/f')(h/z)$$

Constant: (f/f')

Cone-Beam Tomography
– Filtered Backprojection Algorithm

Fourier Slice Theory: FT of Projection = FT of the Field

Step 1 Filtered Projection

$$R_\beta'(p,\zeta) = R_\beta(p,\zeta)\frac{D_{SO}}{\sqrt{D_{SO}^2 + \zeta^2 + p^2}}$$

$R_\beta(p, \zeta)$: Projection Data

$$Q_\beta(p,\zeta) = \mathrm{IFFT}\left(\mathrm{FFT}\left(R_\beta'(p,\zeta)\text{with } ZP\right) \times H(p,\zeta)\right)$$

$H(p, \zeta)$: Window Function

IFFT: Inverse Fast FT; and FFT: Fast FT; ZP: Zero Padding

Step 2 Backprojection

$$g(t,s,z) = \int_0^{2\pi} \frac{{D'_{SO}}^2}{\left(D'_{SO} - s'\right)^2} Q_\beta\left(\frac{D_{SO}t}{D_{SO} - s}, \frac{D_{SO}z}{D_{SO} - s}\right) d\beta$$

g(t,s,z): the property field in Cartesian coordinate

References: Kak, A. C., Slaney, M. (1999), Principles of Computerized Tomographic Imaging, IEEE press, New York

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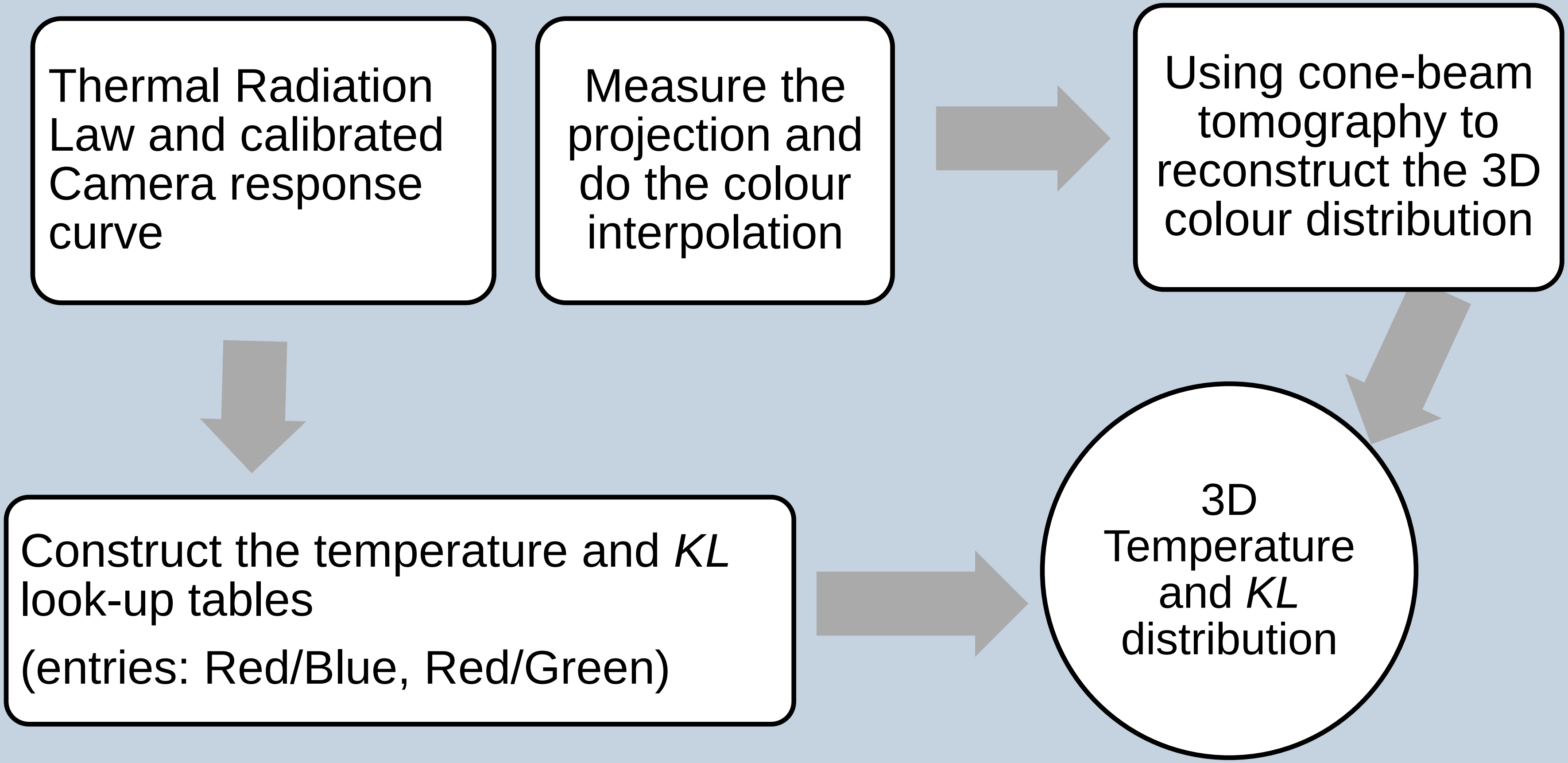
Cone-Beam Tomographic Three Colour Spectrometry (CBT-TCS) - Strategy



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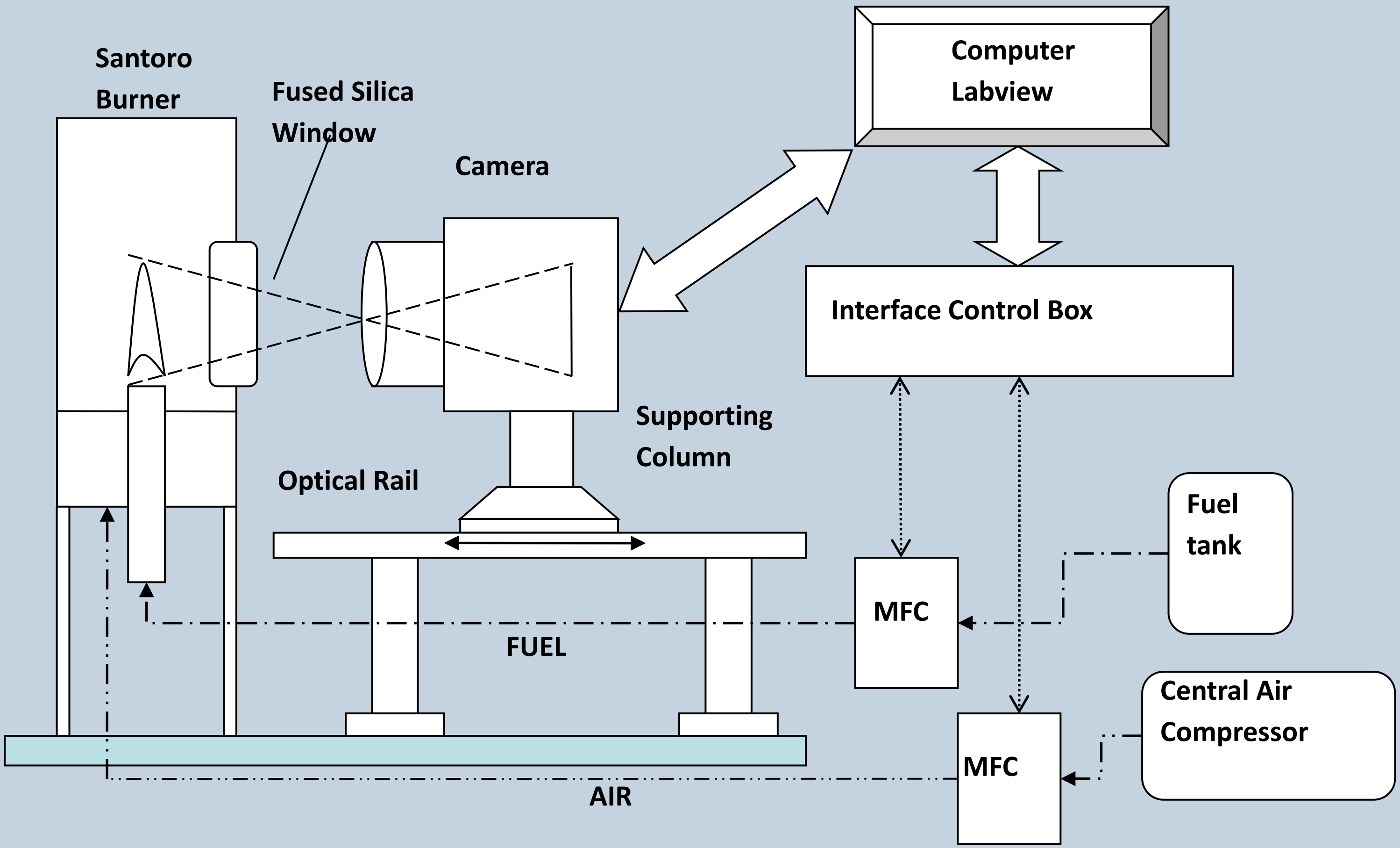
Experiment Setup - Diagram



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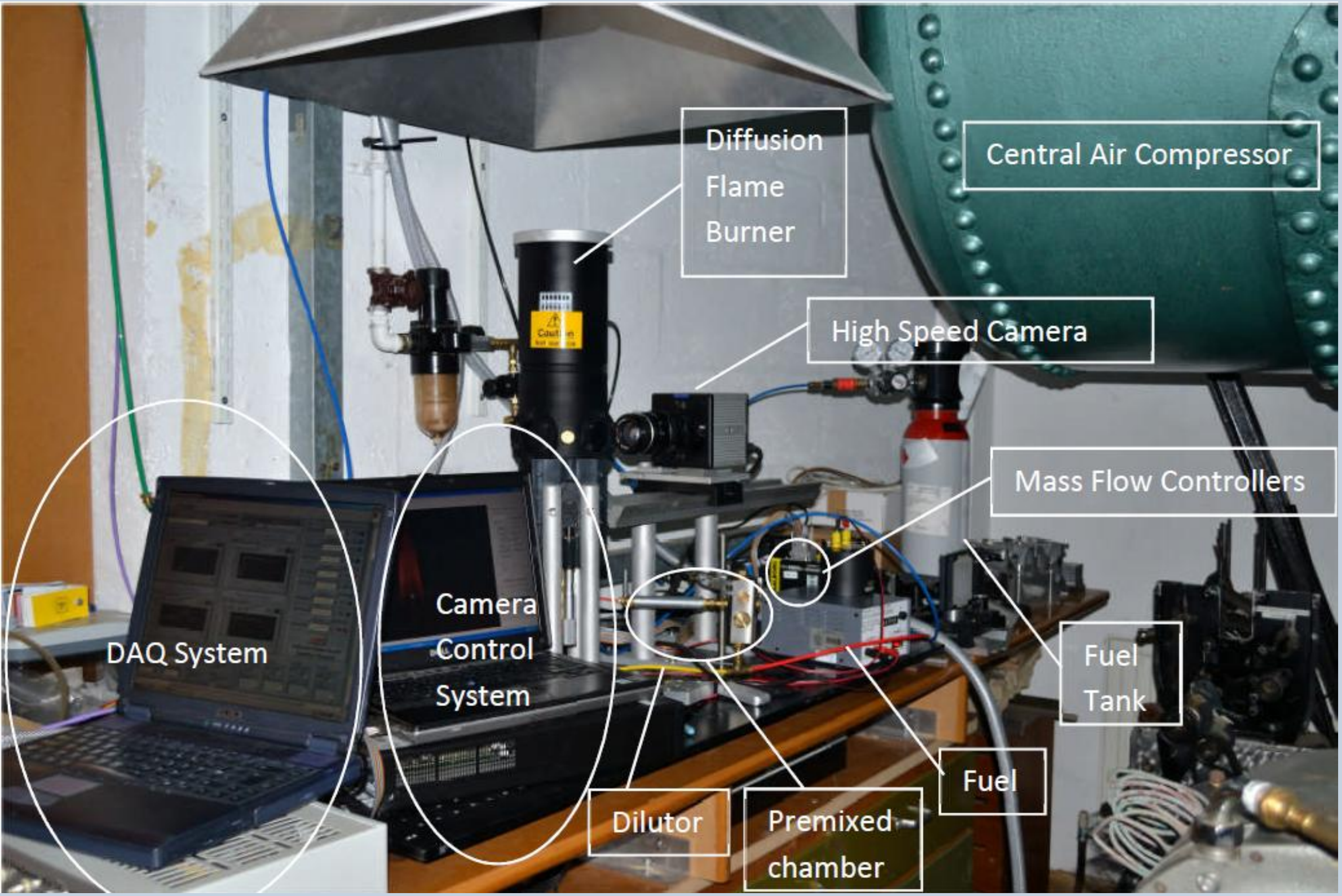
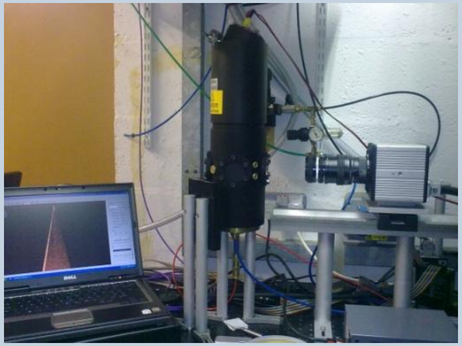
Experiment Setup - Photos





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Software Package – Original OSCaR

- Open source tomography code

  OSCaR source code URL: www.cs.toronto.edu/~urezvani/OSCaR.html

- Three MATLAB GUIs

- Functions of original code:

  - Predefine parameters to do the tomography

  - Implementing the 3D filtered backprojection algorithm to X-ray images from different gantry angles by using different window functions

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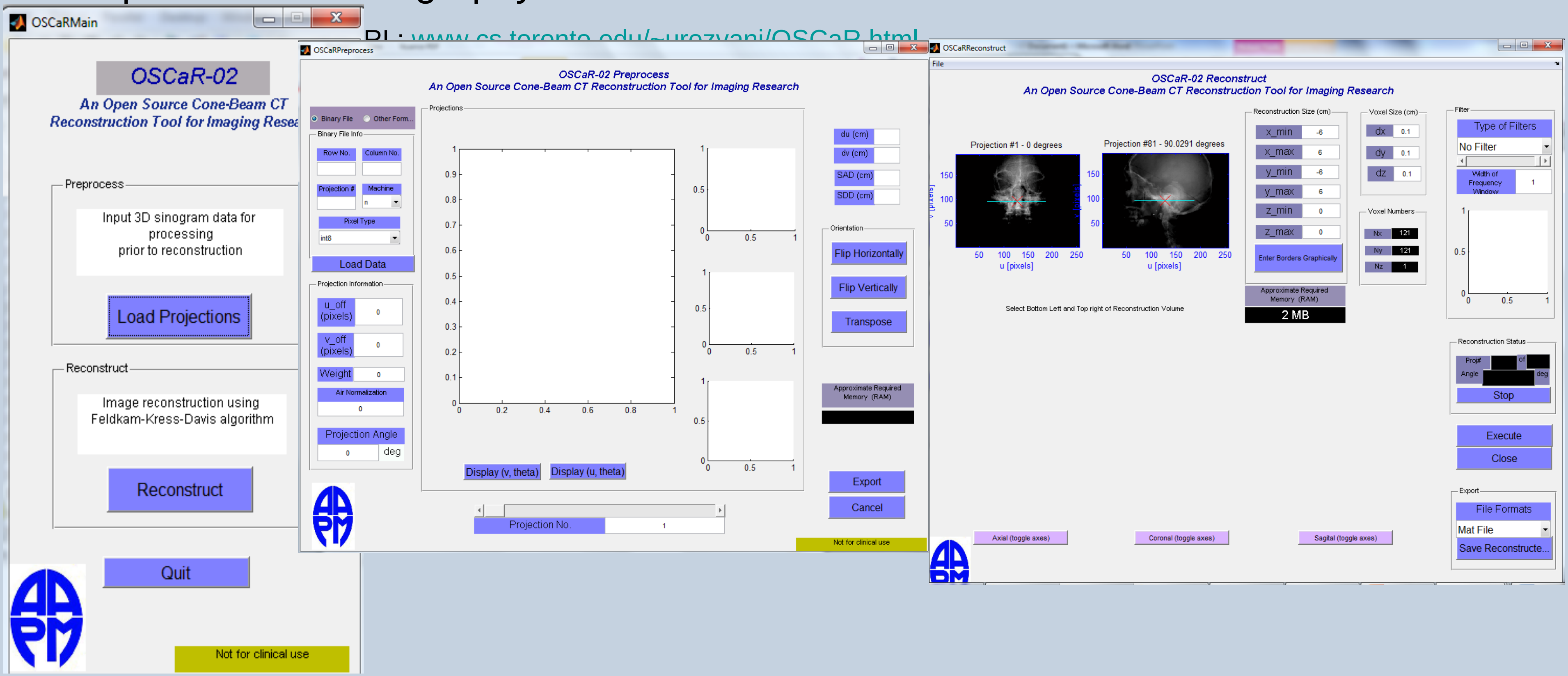
Software Package – Original OSCaR

- Open source tomography code

RL : www.cs.toronto.edu/~urezvani/OSCaR.html

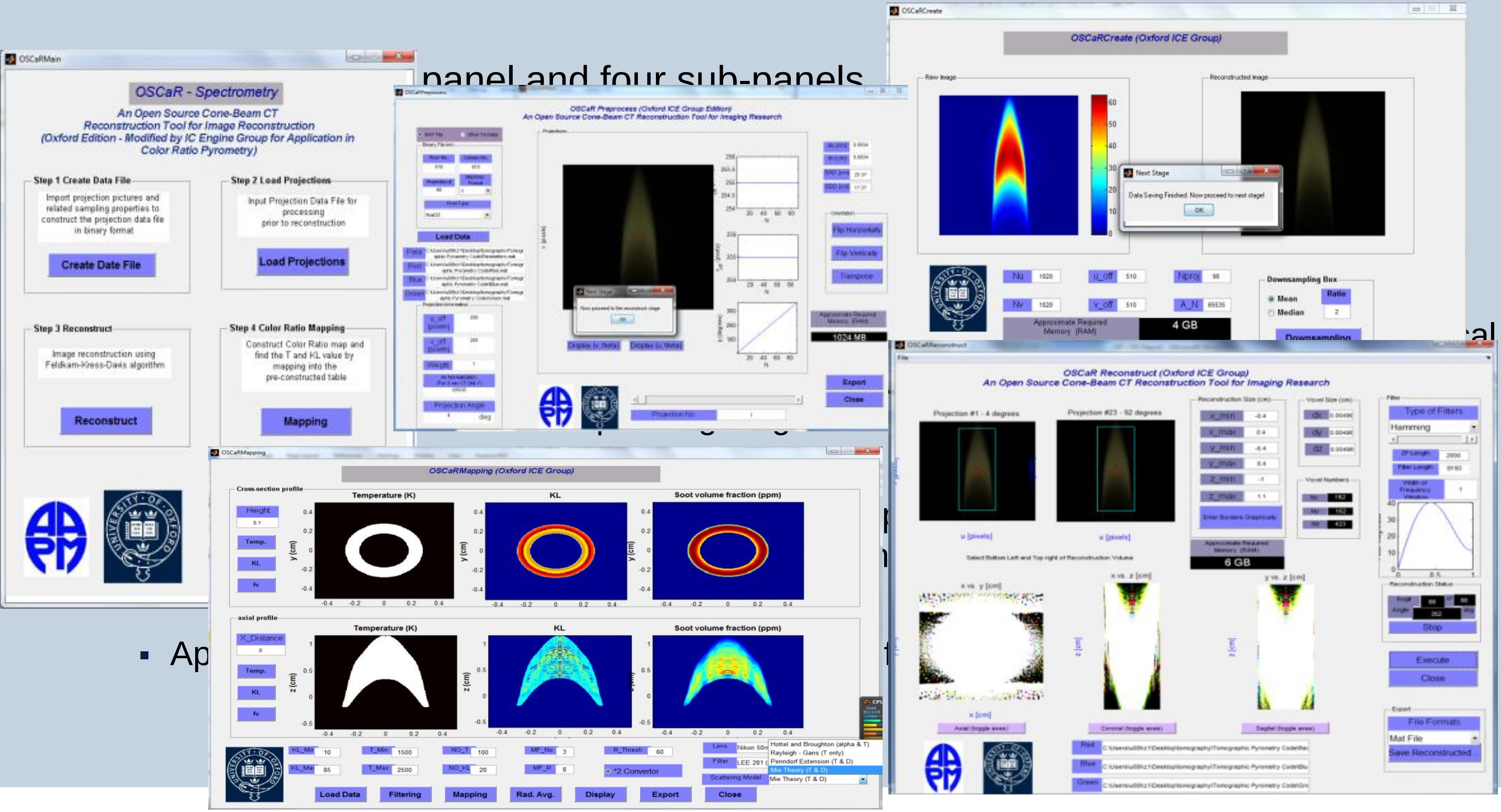


Software Package – Modified OSCaR

- Including one main panel and four sub-panels
- Extended functions:
  - Read projection images, do the colour demosaicing and the downsampling
  - Modified the 3D filtered backprojection algorithm to make it applicable to current optical setup and apply this algorithm to individual colour channels by using different window functions with different zero-padding lengths
  - Applying 3D median filter, construct the look-up table and do the mapping to find *T*, *D* and *fv* according to the selected optical components and scattering model
  - Apply a circumferential average and export the final data matrix

Software Package – Modified OSCaR

panel and four sub-panels



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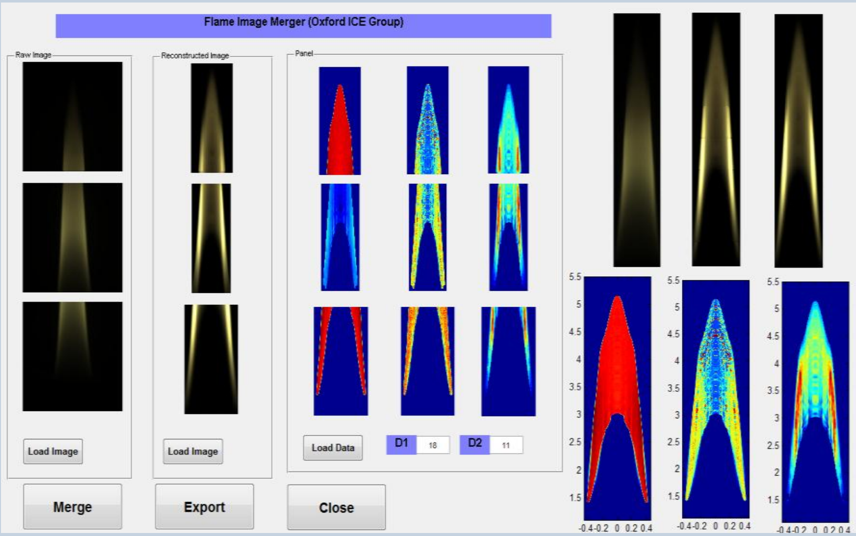
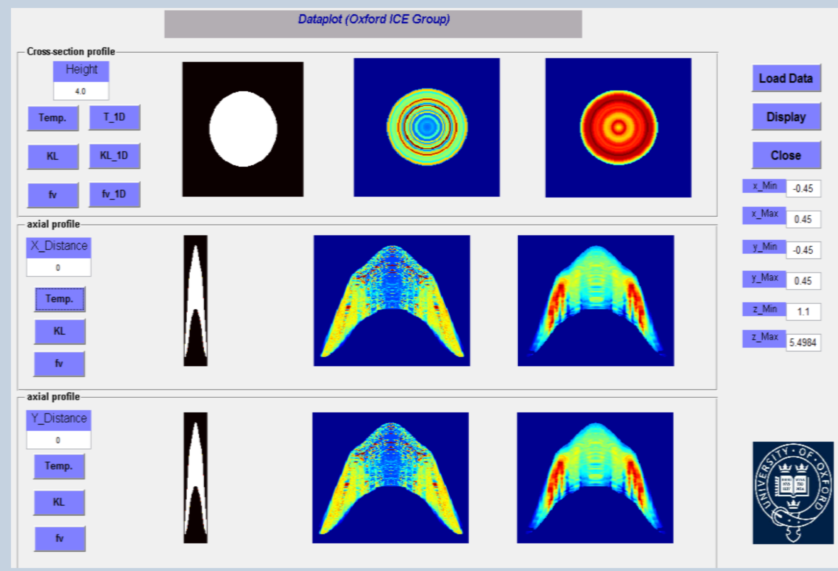
Software Package – Post-processing

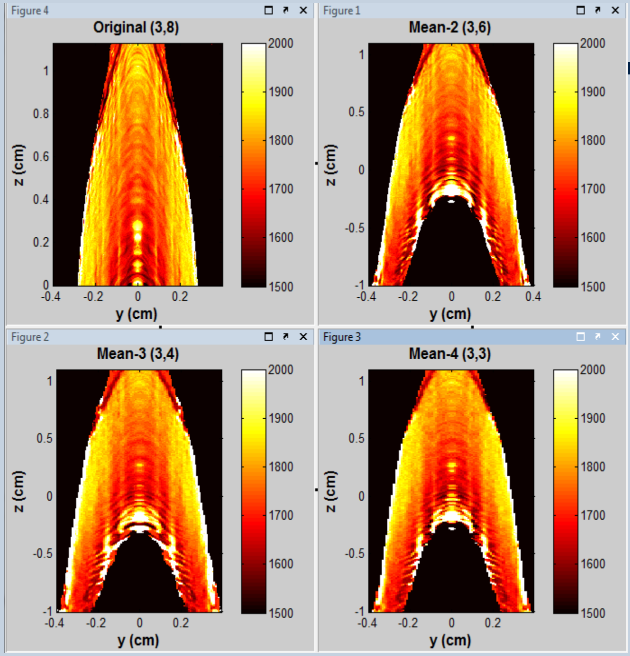


- Merging data from different portions of the flame

- Display and save the selected data



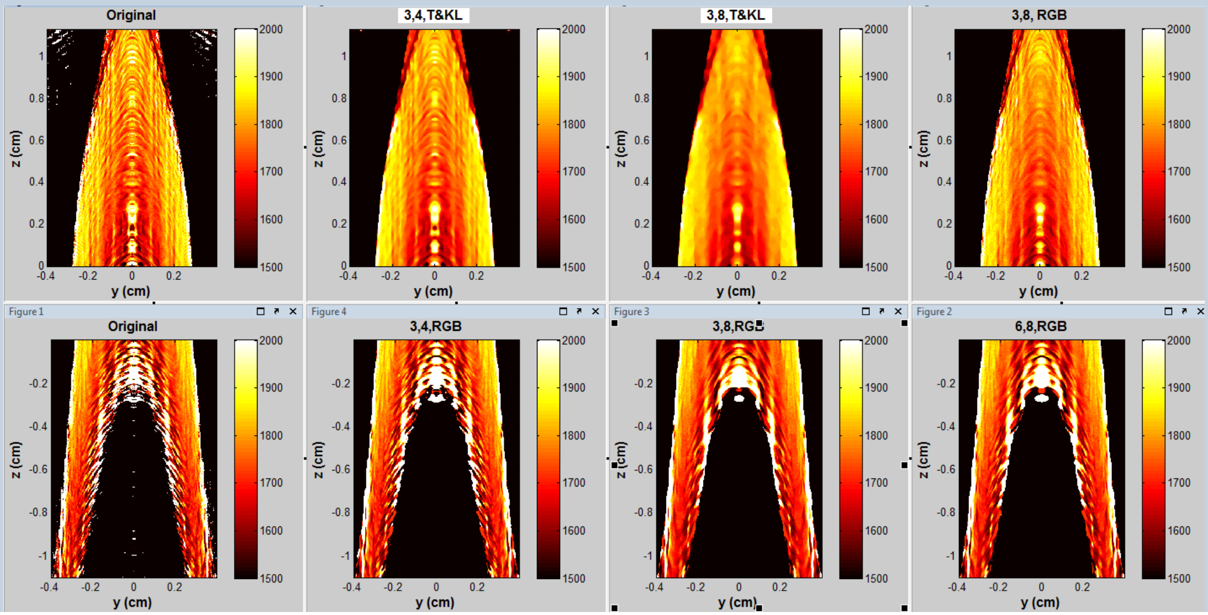
Accuracy Improvement Techniques (1/2)



- Downsampling

Trade-off between accuracy and spatial resolution:

smaller pixel width ⇨ smaller difference between two adjacent projections, if the difference is comparable to the background noise poor accuracy but good spatial resolution



- 3D Median Filter

apply to the *T*, *D*, or *KL* data

Blur the image

apply to the reconstructed RGB colour map

Enhance the smoothness

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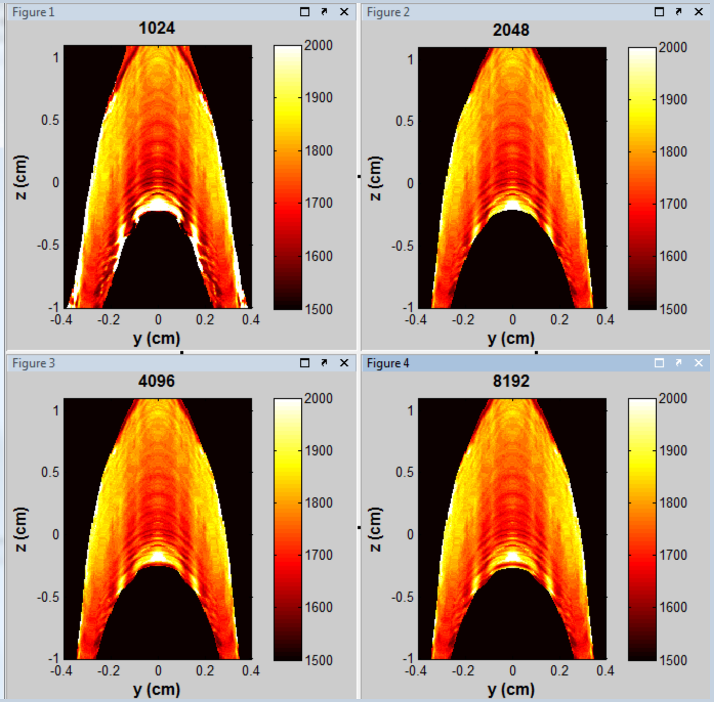
Accuracy Improvement Techniques (2/2)



- Increase the zero-padding length when using the fast Fourier transform so as to increase the resolution in the frequency domain

- Other techniques
  - Circumferential averaging for axis-symmetric flame
  - Using optical filters to make more use of the dynamic range of different colour channels (especially the blue)

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Sample data – ethylene co-flow laminar diffusion flame

- Test Condition
  - Fuel flow rate: 143 mL/min;
    Air flow rate: 45 L/min
  - Camera setup:

    Frame rate: 60 frames/sec

    Aperture size: *f*/32 (with 2* convertor)

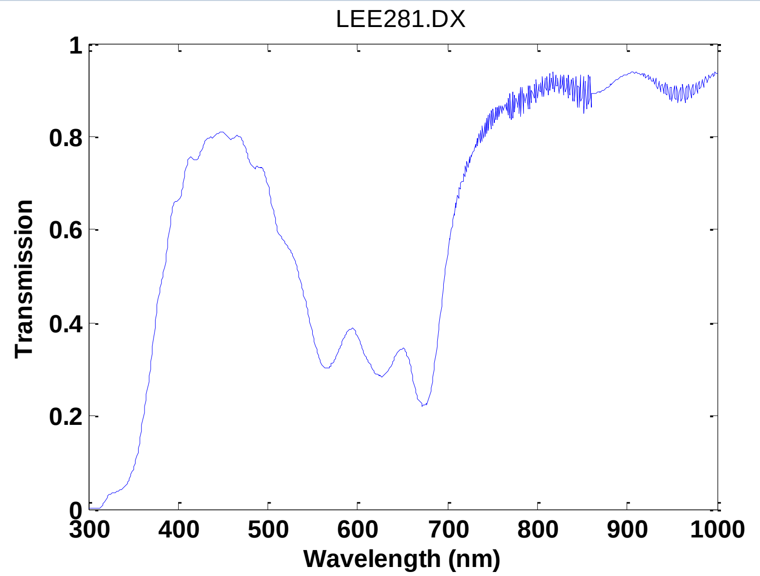
    Focus length: 100mm

    Object to lens distance: 23.6 cm

    Lens to detector distance: 17.4 cm
  - Optical component

    Lens: Nikon 50mm lens with 2* convertor

    Filter: LEE E281 filter (around 0.4 transmission efficiency for red and green light and 0.8 for blue light)



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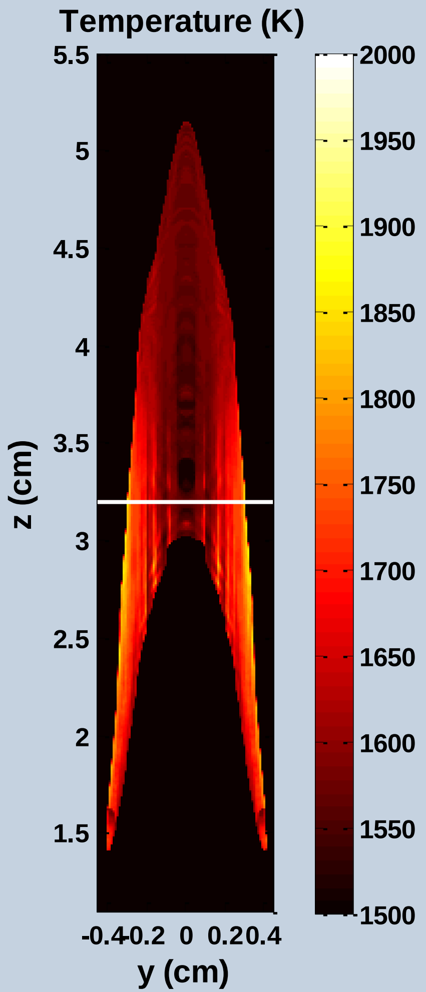
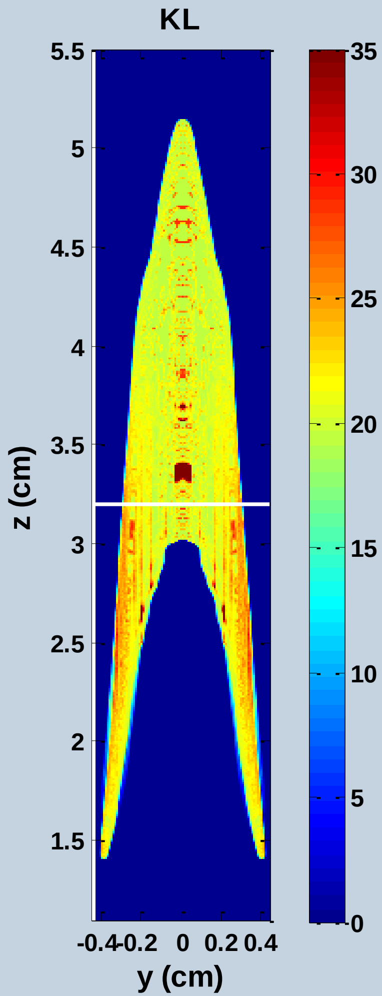
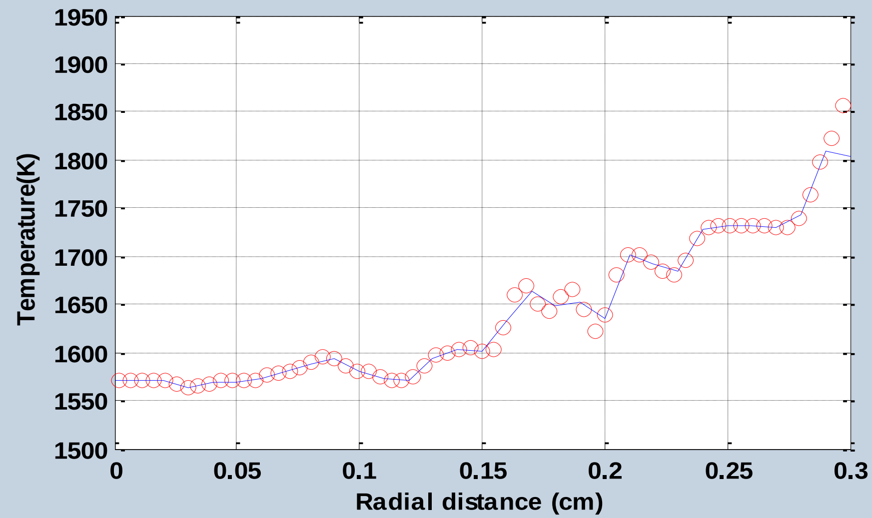
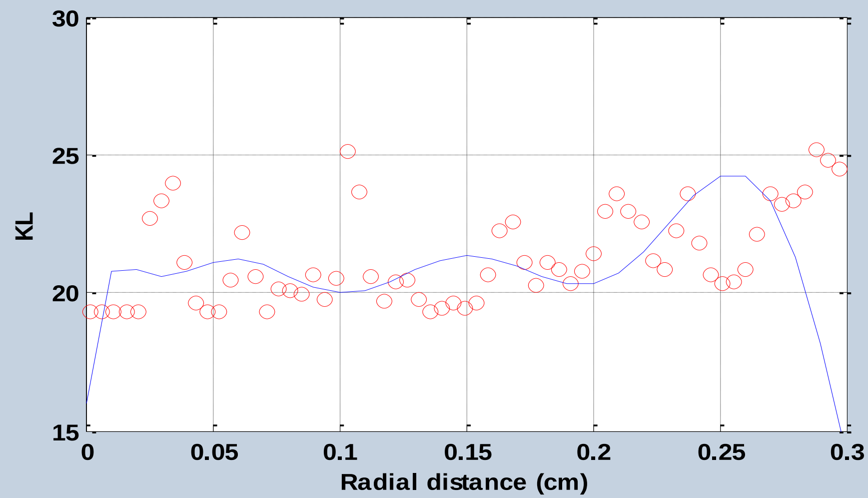
Sample Data (1/4) – Hottel and Broughton









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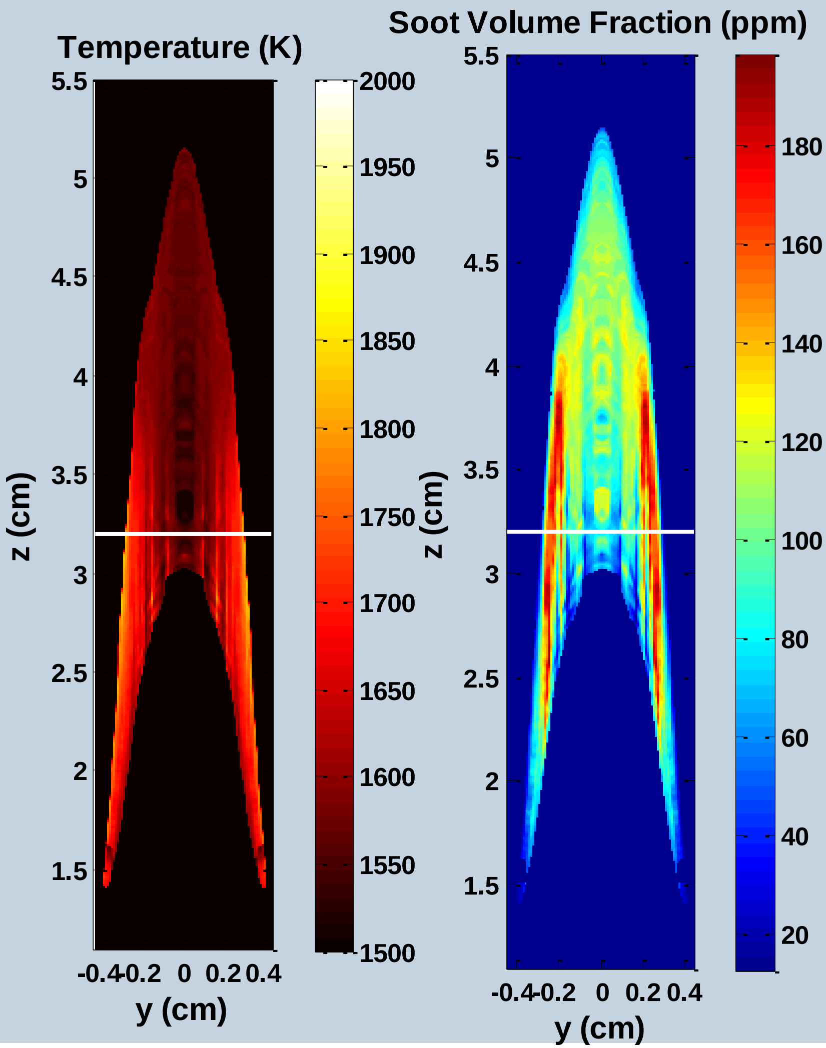
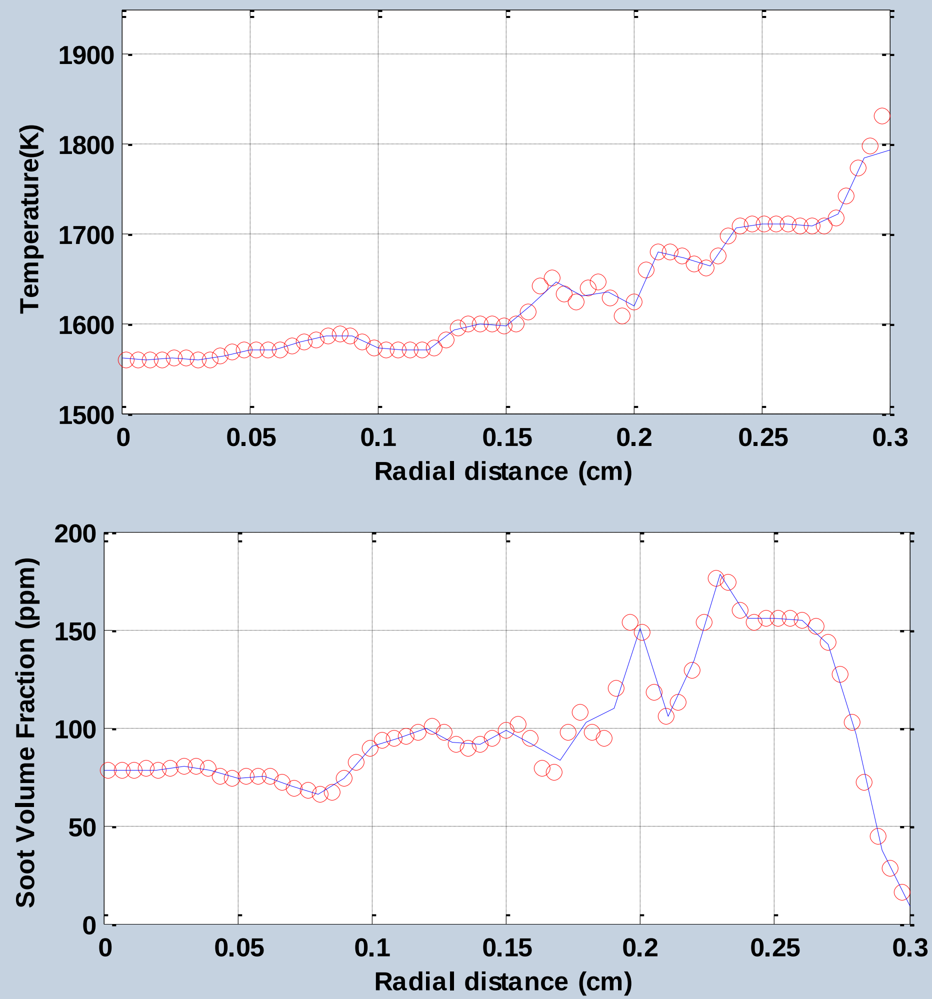
Sample Data (2/4) – Rayleigh-Gans Theory





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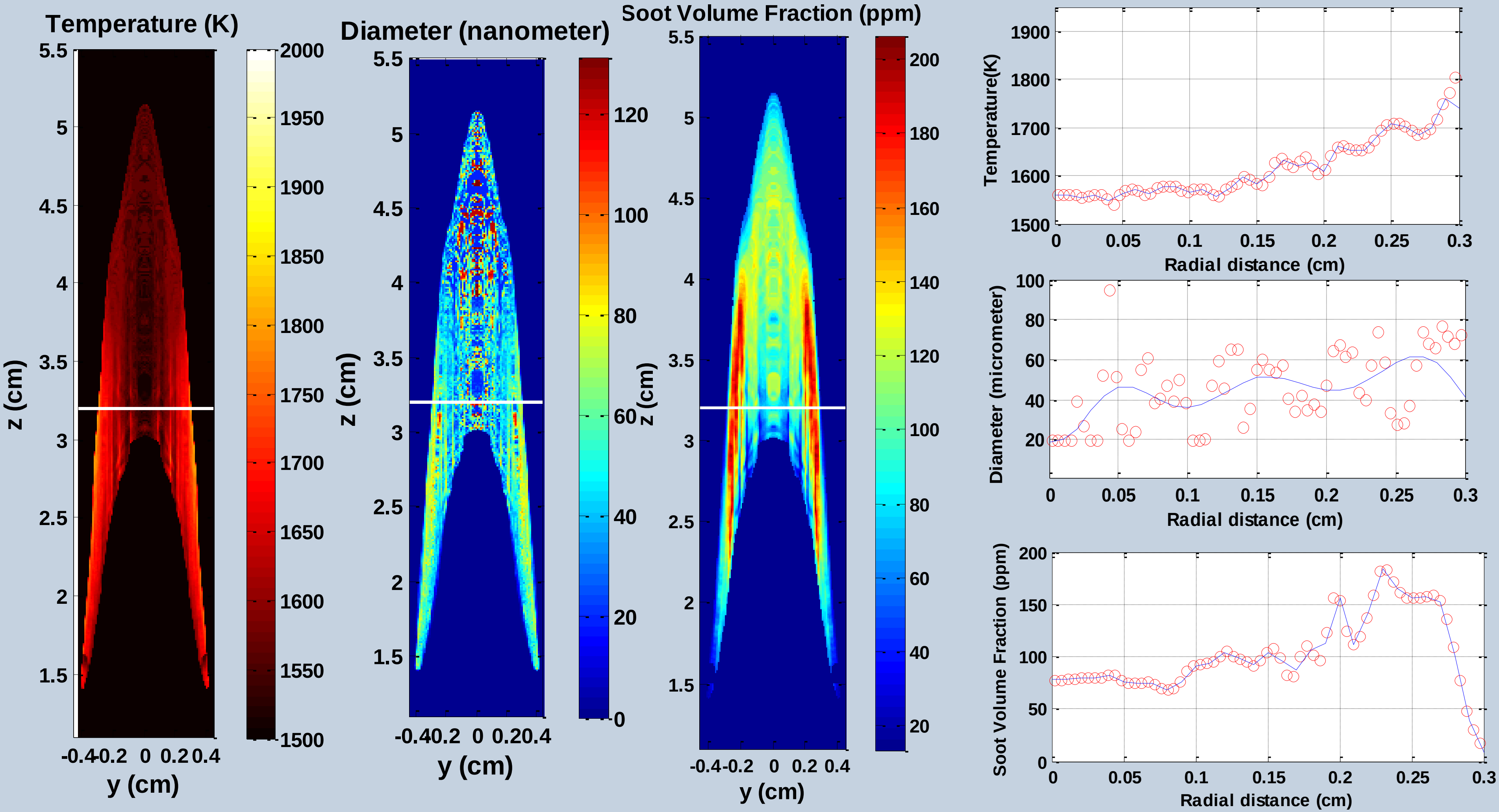
Sample Data (3/4) – Rayleigh-Gans-Penndorf



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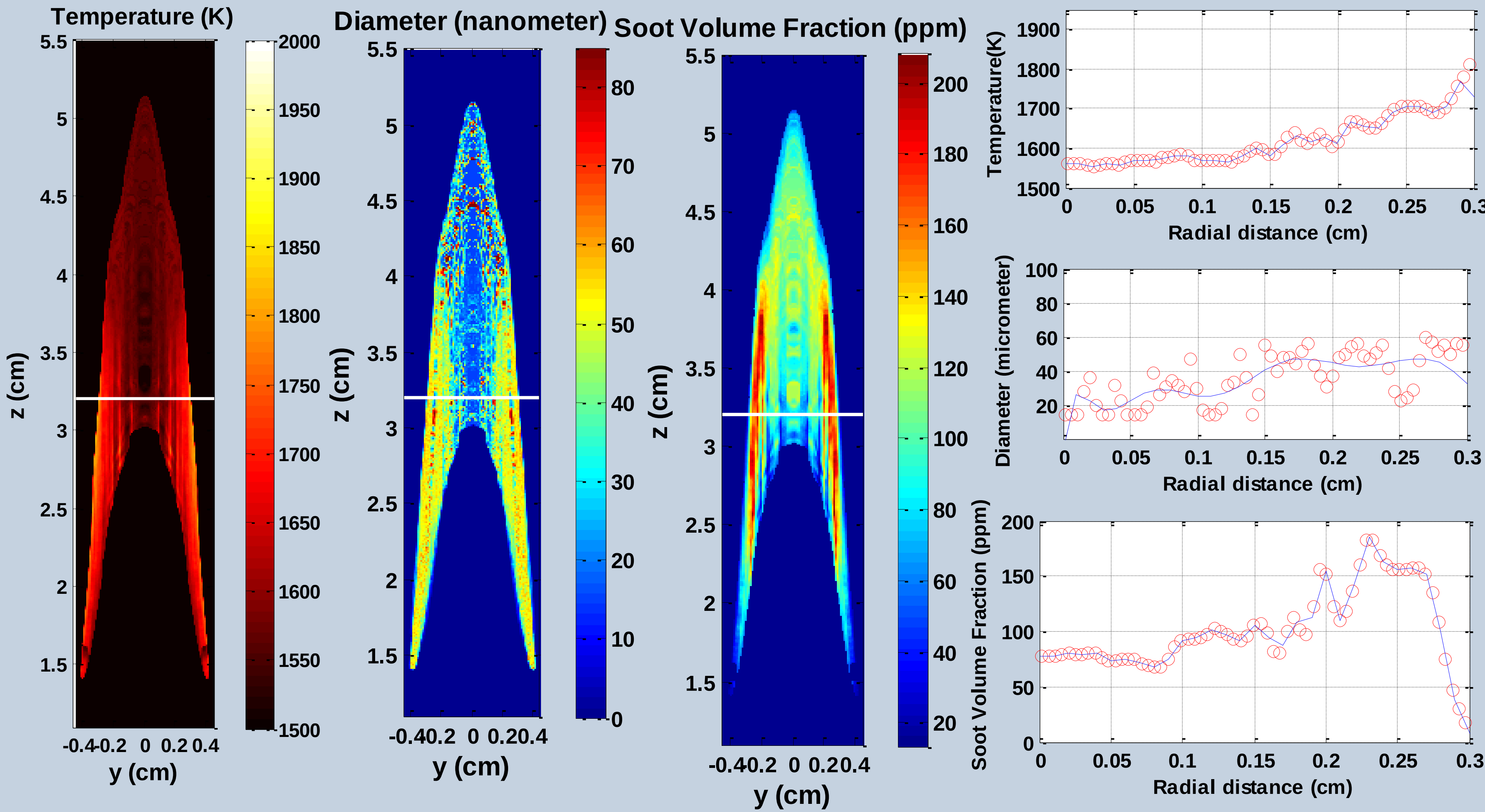
Sample Data (4/4) – Mie Scattering



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Assumptions (1/2)

- Particulate temperature is the same as local flame temperature
- Thermal radiation from other species are negligible compared to soot particles
  - CO_2: 2.0, 2.7, 4.3, 9.4, 10.4 and 15 µm
  - H_2O: 1.38, 1.87, 2.7, and 6.3 µm
  - Chemilluminescence from radicals is negligible except from the circumferential base of the flame

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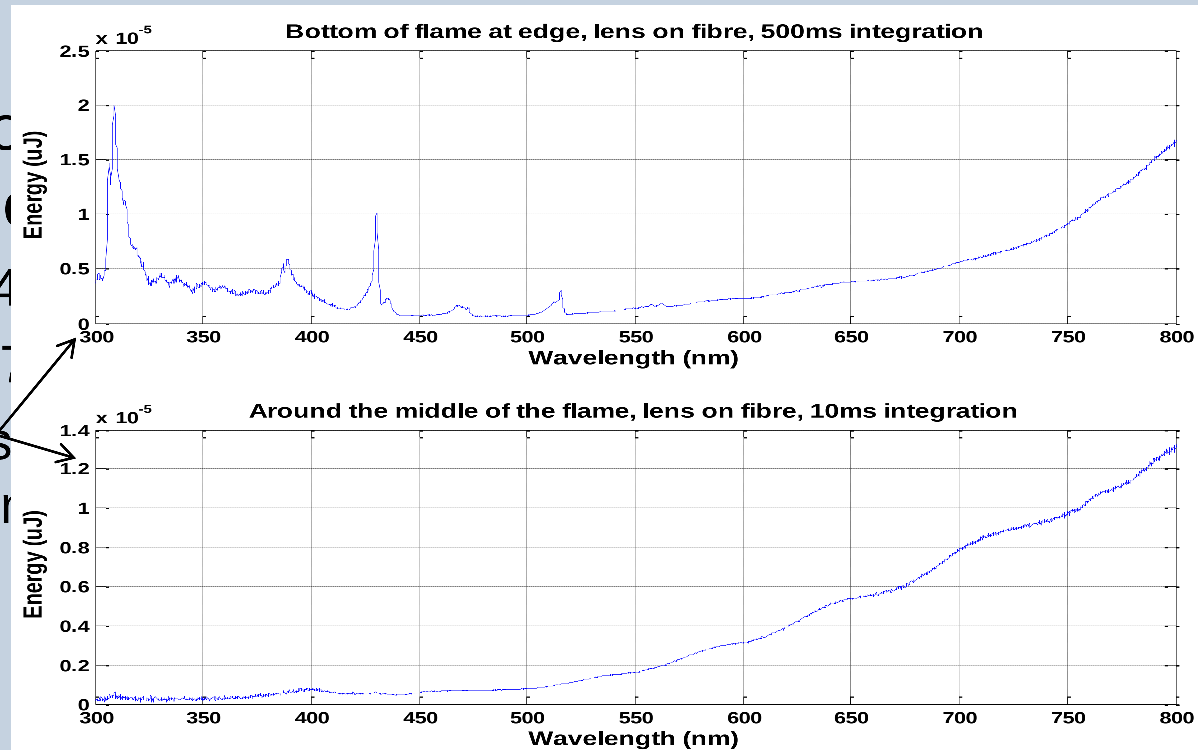
Assumptions (1/2)

- Particulate temperature is the same as local flame temperature

- Ther diatic comp o so
  - C 2.7, 4
  - H , 1.87
  - C mines th nferer



Assumptions (2/2)

- The radiation attenuation along the optical path is negligible (optical-thin approximation)
  - Not clear at this point
  - Can be partially corrected by using an iterative method suggested by Lu et al. (2009)
  - Need to be corrected by introducing certain scattering models in the future

Conclusions

- The CBT-TCS technique is an effective and convenient optical diagnostic method to measure the spatially distributed temperature, soot diameters and soot volume fraction for an axi-symmetric flame

- The optical-thin assumption may need to be addressed in the future to increase its accuracy

- CBT-TCS can be applied to asymmetric flames by using multiple images

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Thanks for Your Attention ~~

Q & A