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Towards Structured PLIF Excitation for Probing Harsh Environments

Technique Development and Ongoing Work

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Motivation and Overview

-Planar Laser Induced Fluorescence (PLIF) excitation an oft-used combustion diagnostic

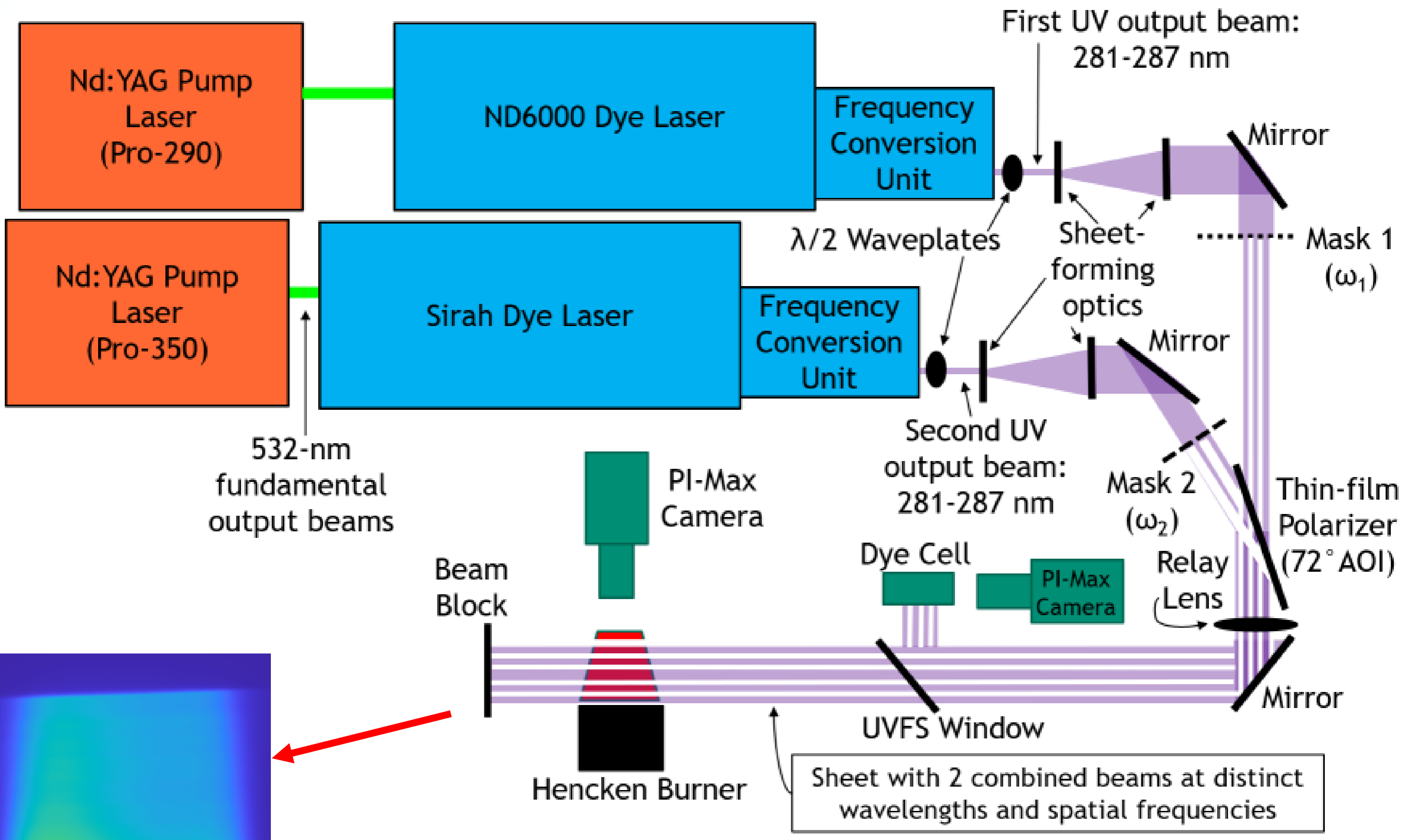
-Typically requires ensemble-averaged background subtraction of extraneous light

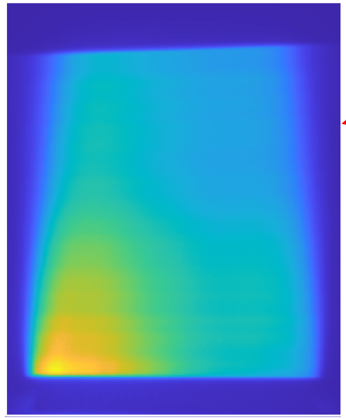
-In harsh environments background subtraction is difficult to quantify, if not impossible

-Structured illumination provides a way to perform background subtraction

-Regimes inaccessible for conventional diagnostics now accessible, such as two-color OH PLIF thermometry

Experimental Setup Used in this Study





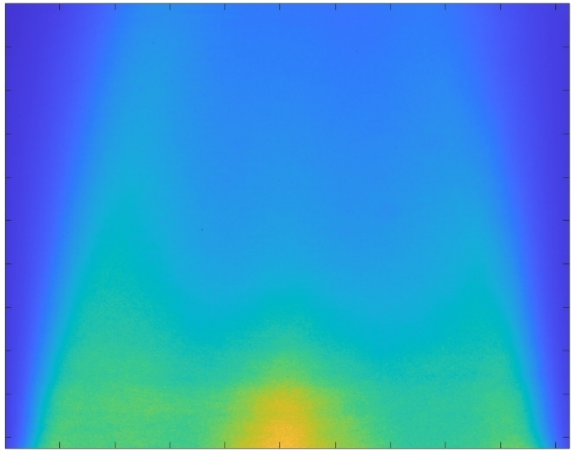
Representative PLIF Image in H_2-Air Hencken Burner Flame

- Nd:YAG-pumped dye laser system
- Dye output frequency doubled to 281-287 nm for OH LIF Excitation
- Laser sheets co-aligned into the measurement volume
- Wavelengths used here were 282.75 nm and 286.46 nm

Technique Basics of Structured Illumination: Motivating Visuals

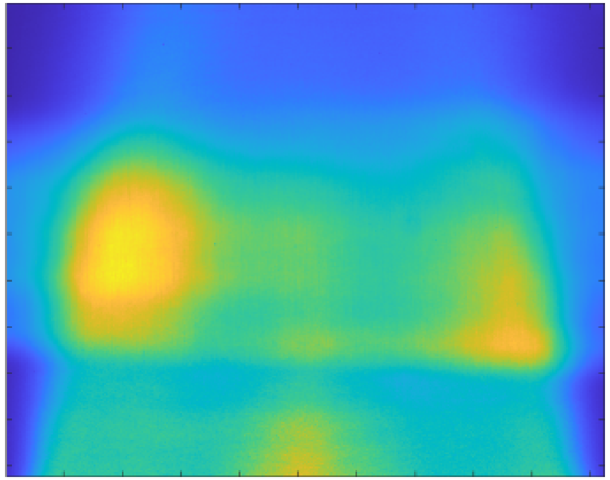
- Consider the following example which simulates a harsh environment (highly transient, luminous background)

Background Illumination (Long Camera Exposure of Flame, Laser off)



Turn Laser On

PLIF Sheet Apparent in Flame, But Mixed with Background



Now What?

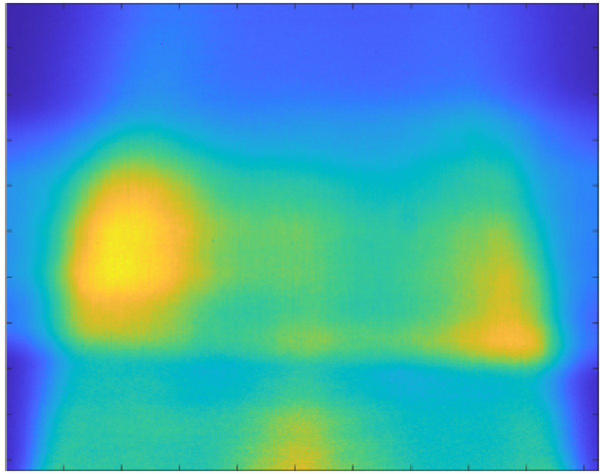
- <u>In conventional PLIF:</u>
- Subtract background from PLIF sheet image
- Requires ensemble-averaging of signal and background
- Visualize quasi-steady behavior

- In examining highly transient (requiring single shot measurements), luminous environments ensemble-averaged background subtraction is not possible.
- Signal and background luminosity both vary rapidly, cannot perform accurate subtraction of single-shot image with an averaged background image
- Another method is required to remove background while capturing features of interest

Technique Basics Cont'd. : Another Dimension

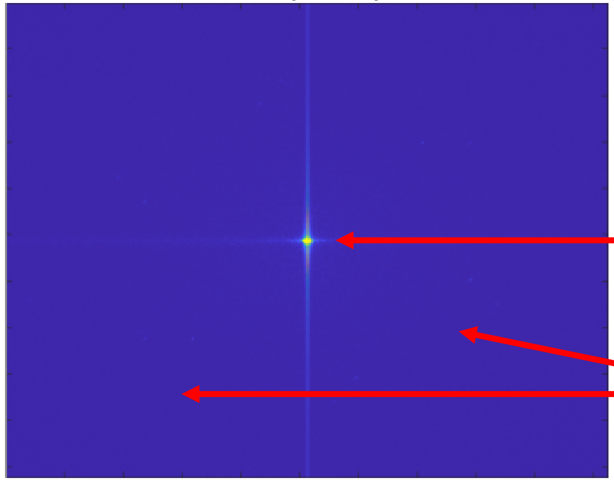
- How to remove unwanted background signal in transient environments?
- Must remove the *true* background luminosity, not an *averaged* luminosity
- Need a method of filtering out the background: enter the Fourier (complex) dimension

Previous image with signal and background



Apply 2D Fourier Transform

PLIF flame image represented in the complex plane

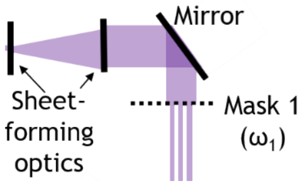


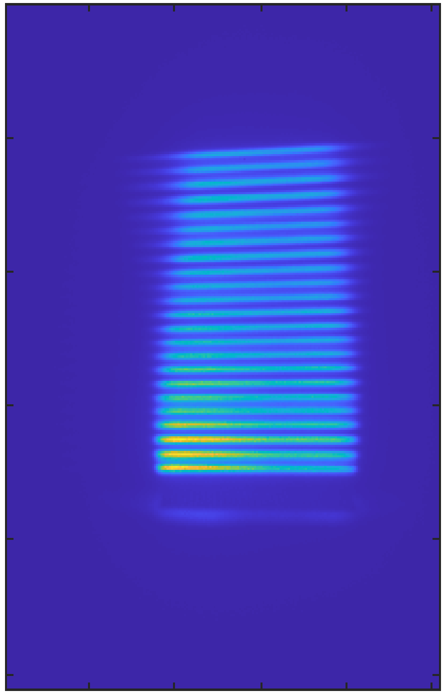
- DC signals appear in the center of the complex plane
- Virtually all information in PLIF image has DC or near-DC frequencies!
- No information at higher frequencies!

- Need to encode PLIF sheet information in flame image such that it shows up in unused portions of the Fourier (complex) domain, enabling filtering.

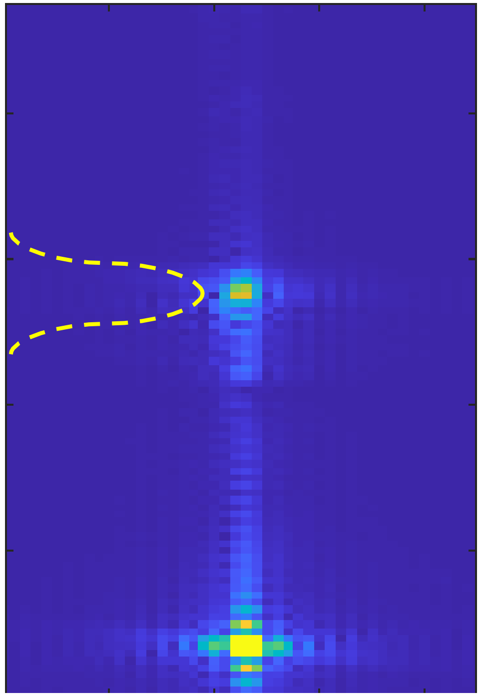
Technique Basics Cont'd. : Imposing Structure and Filtering

- Recall the optical setup: masks

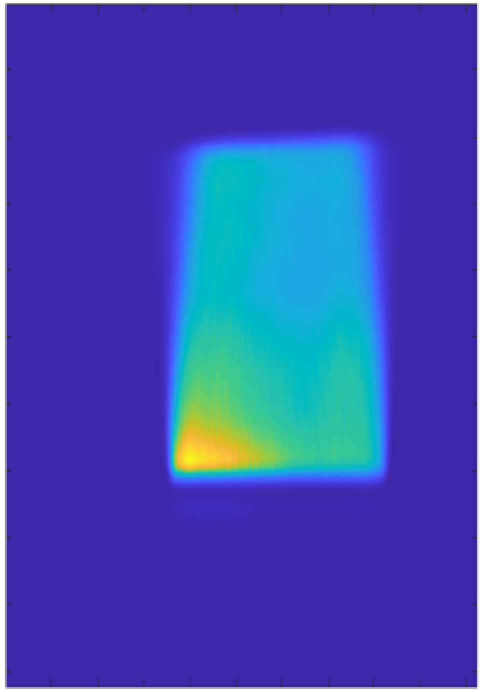




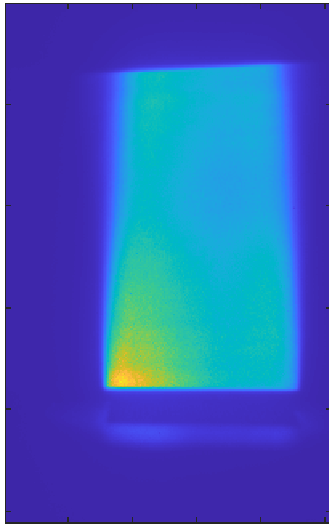
Impose known spatial frequency (structure) via masks



Fourier transform to complex plane and apply gaussian filter (yellow dashed line)



Inverse Fourier transform to real plane to recover original image

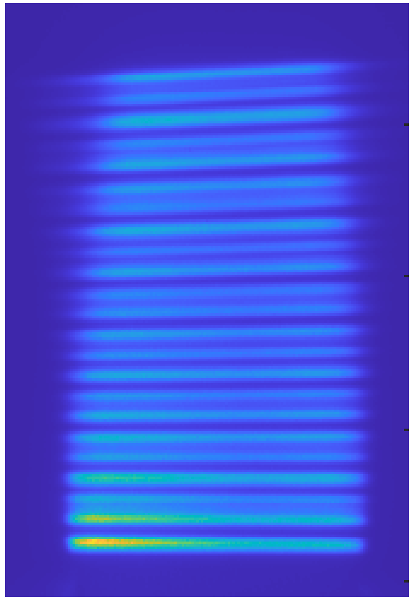


Compared to unmasked PLIF flame image, always have some loss of resolution

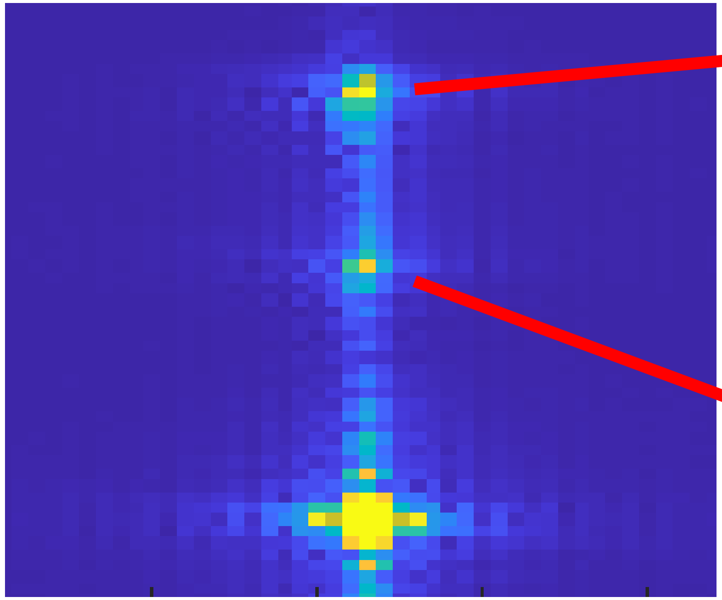
Extension to Multiple Channels

- Complex plane certainly big enough to accommodate multiple frequencies (semi-infinite)
  - Extension to multiple measurement channels is relatively trivial from analysis standpoint

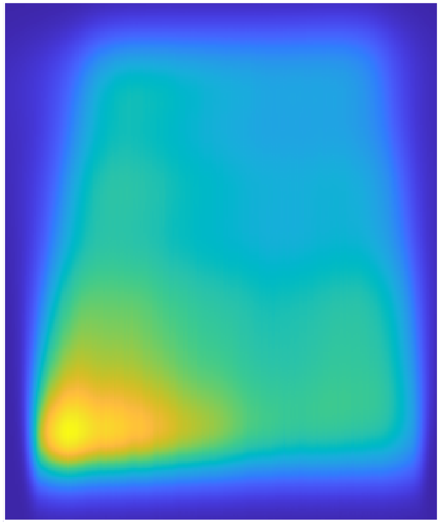
- Multi-channel structured illumination enables access to regions previously inaccessible for conventional diagnostics, such as two-color OH PLIF

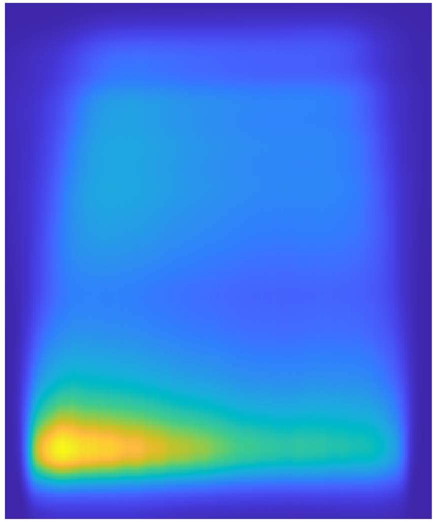


PLIF flame with 2 PLIF sheets combined in single beam, Each with Distinct Spatial Frequency



Fourier plane showing DC (bottom), low (middle) and high (top) spatial frequencies, respectively



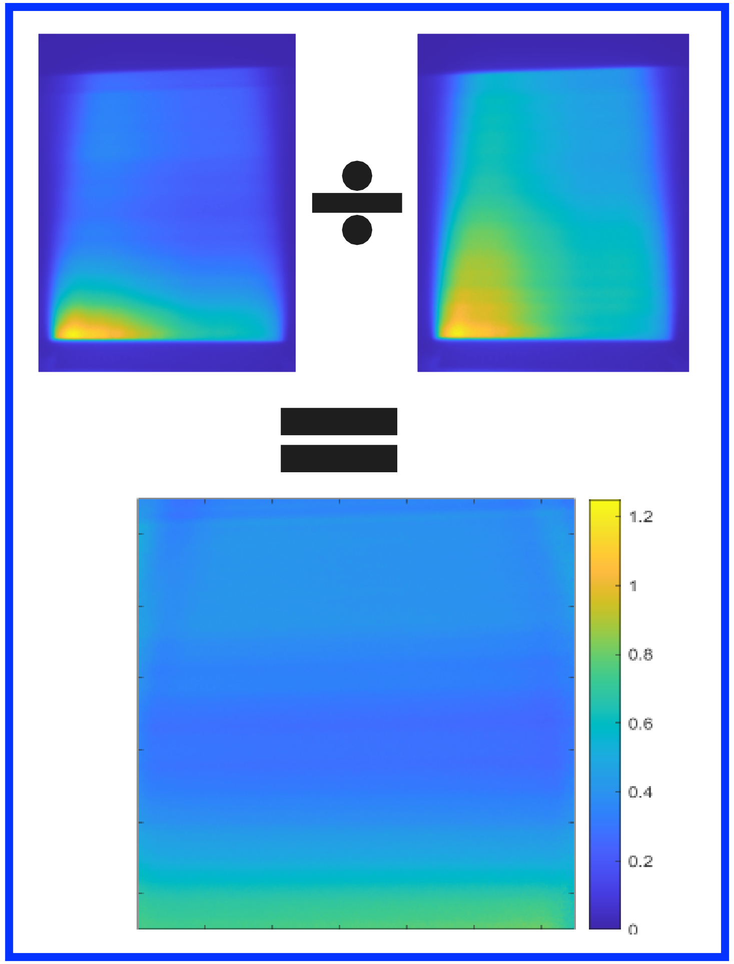


Extracting Multiple Channels for Measurement

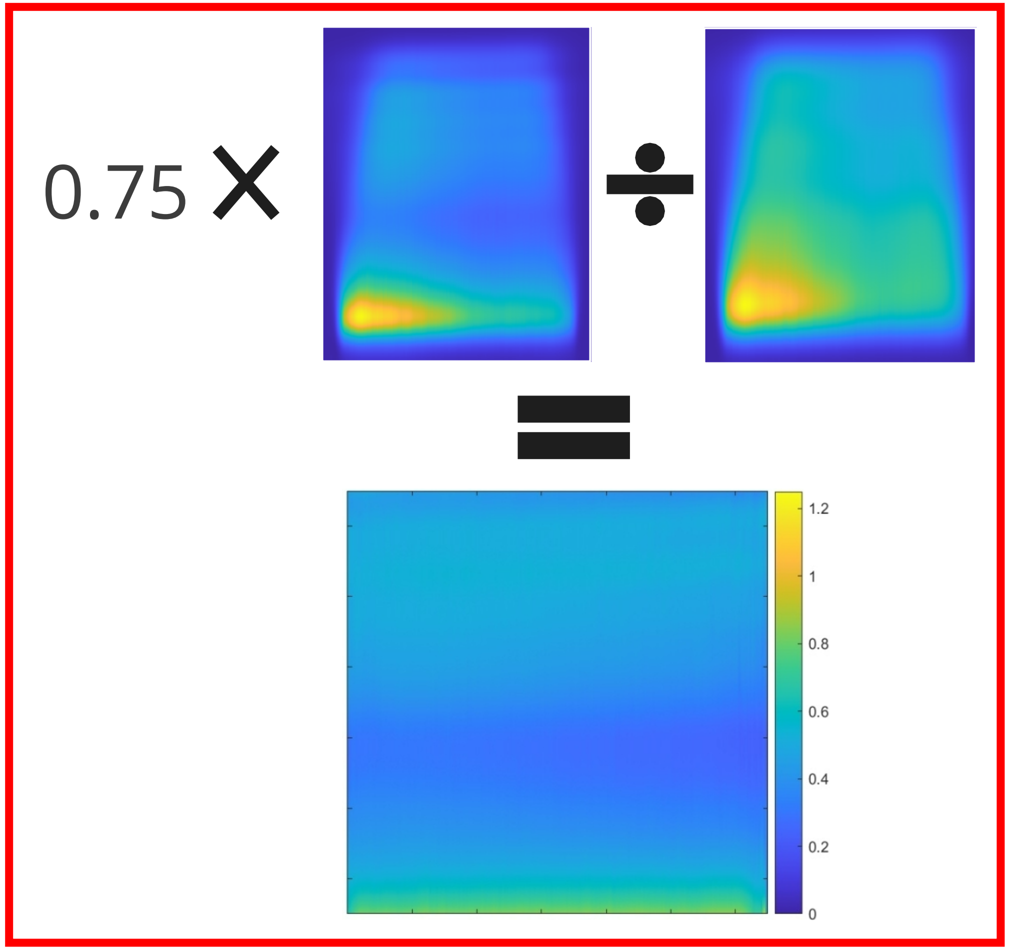
- PLIF thermometry (ratio of 2 images) was mentioned previously, so a question is:
- How well can we utilize structured illumination to create accurate ratio maps of the flame?

$$R = \frac{I_{f1}}{I_{f2}}$$

Conventional Ratios

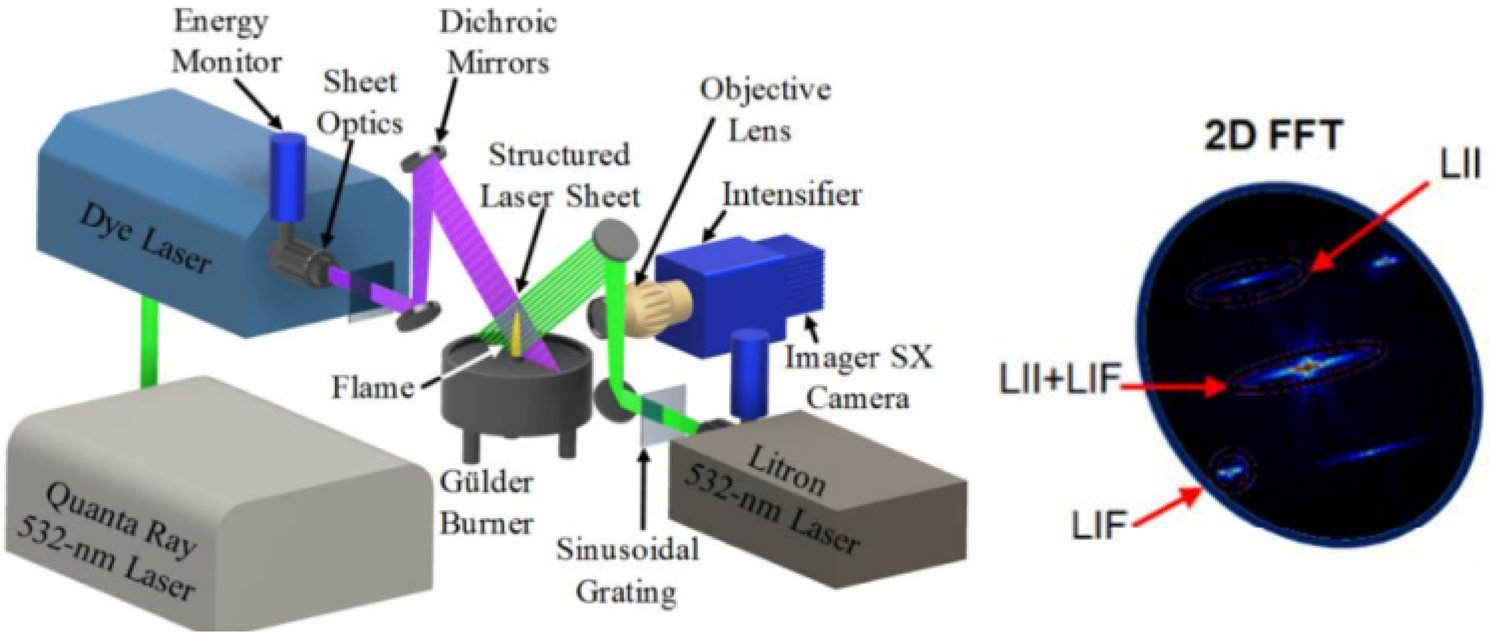


Structured Ratios



- Structured ratios replicate relative behavior of conventional ratios with reasonable accuracy
- Resolution needs improvement, however
- Apply higher spatial frequency:
- Decrease magnification of optical setup; increases spatial frequency of masked PLIF sheet at probe volume

A Brief Aside: Beam Alignment



Mishra, Y. N., Boggavarapu, P., Chorey, D., Zigan, L., Will, S., Deshmukh, D., & Rayavarapu, R. (2020). Application of FRAME for Simultaneous LIF and LII Imaging in Sooting Flames Using a Single Camera. *Sensors (Basel, Switzerland)*, *20*(19), 5534. https://doi.org/10.3390/s20195534

- Refresher: Beams co-aligned in present configuration

- Easier Fourier filtering, less signal interference if beams not co-aligned

- Present experimental application involves detonation blast chamber with limited optical access
    - Need beams co-aligned for now
    - Use polarization optics, thin-film polarizer to combine beams

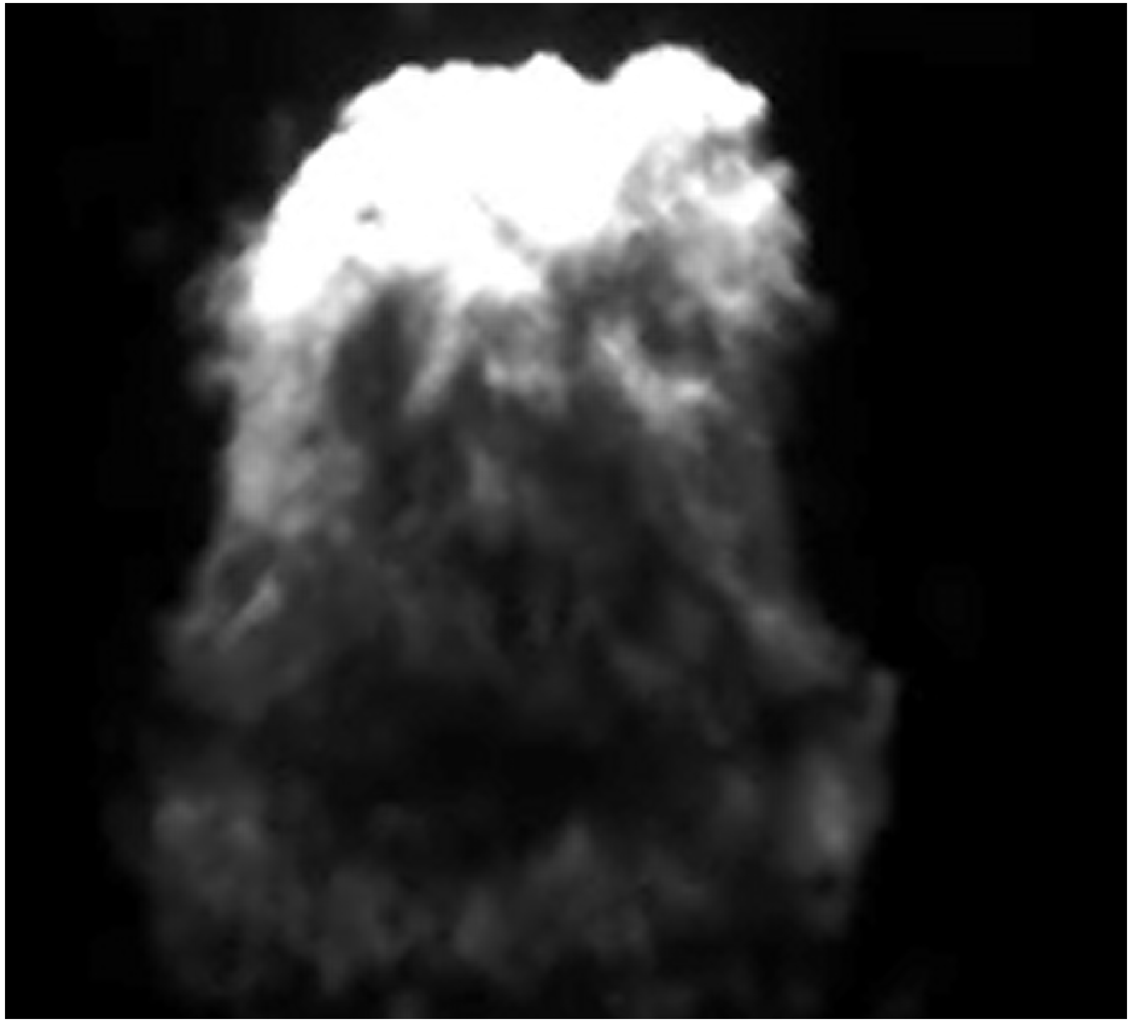
- Regardless of beam orientation, signals require adequate separation in Fourier space

Combining Two-Color OH PLIF and Structured PLIF

- Ultimate goal: Perform two-color OH PLIF thermometry utilizing structured illumination

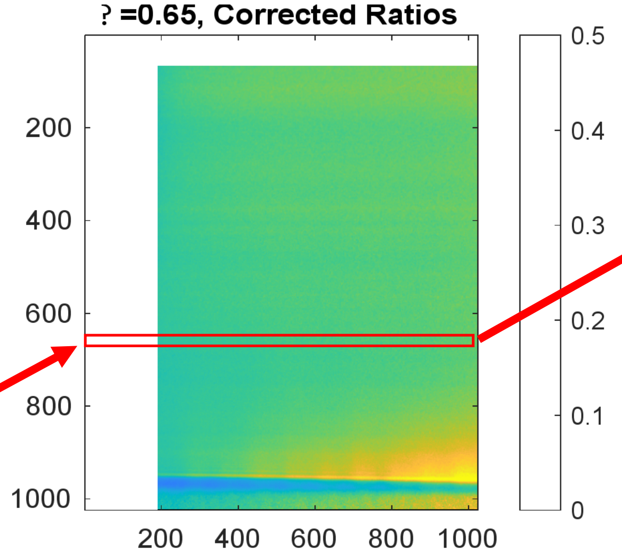
- Applied to post-detonation fireball environments

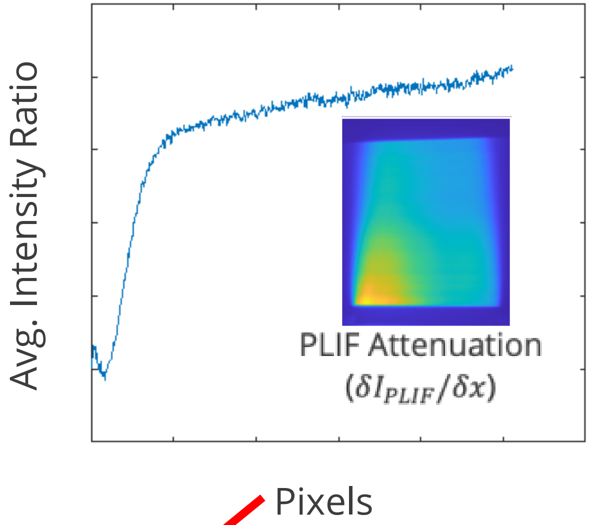
- Demonstrate conventional two-color PLIF thermometry before applying structured illumination

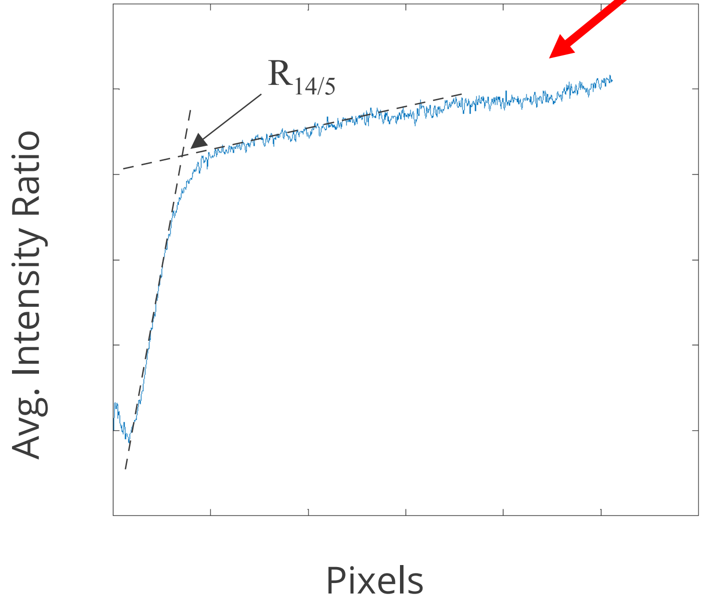


Conventional Two-Color OH PLIF Thermometry: Calculating Ratios

- Laser power set ~ 0.40 mJ/pulse (linear regime)
- Image $Q_1(5)$ & $Q_1(14)$ PLIF sheets separately
- Correct for background, flat field distortion
- Ratio the images: Define region of Interest
    - 10 pixels high, 1 cm above surface
    - Average values vertically and plot
- Ratio not constant across image
- Beam attenuation=PLIF attenuation
- Differing $Q_1(5)$ & $Q_1(14)$ concentrations and absorption coefficients
    - Beer-Lambert Law
- Define $R_{14/5} = Q_1(14) / Q_1(5)$ with slope-intercepts

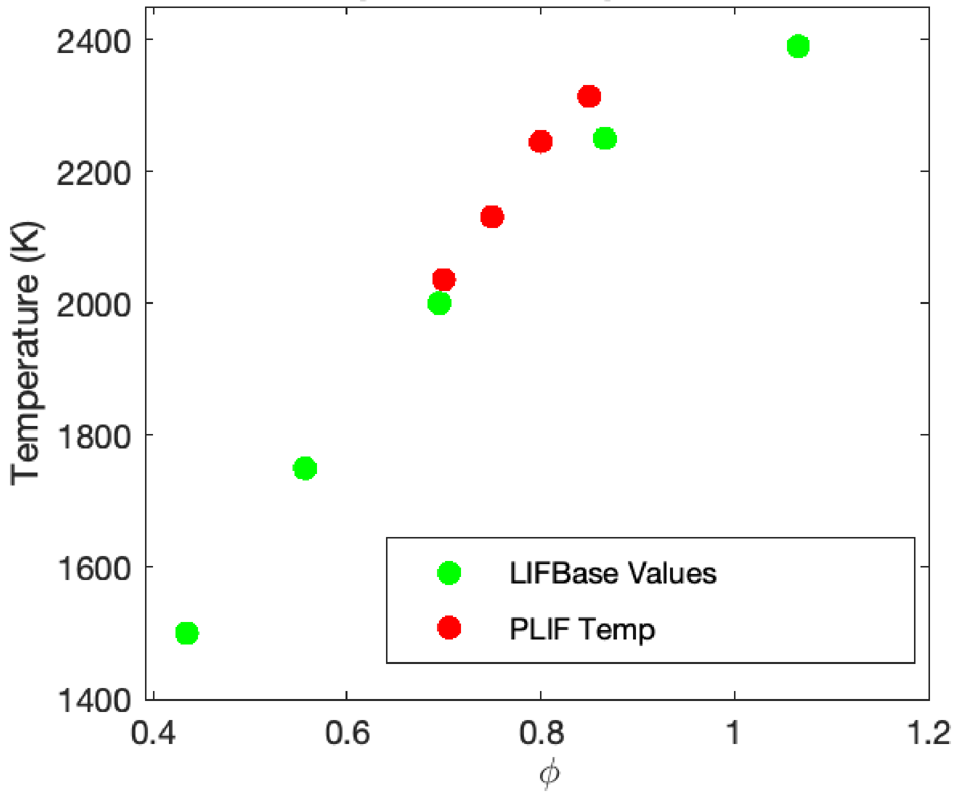


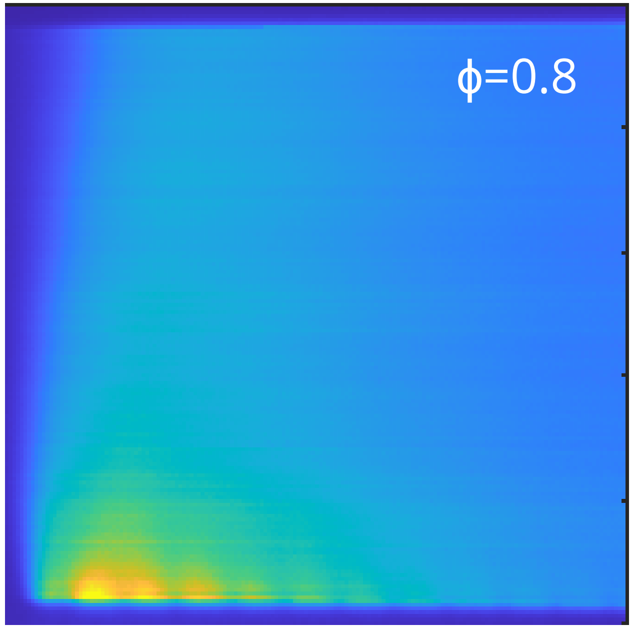


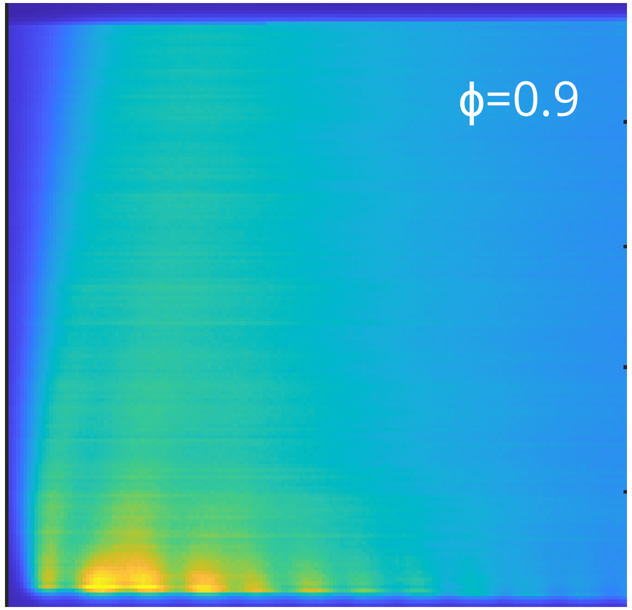


Conventional Two-Color OH PLIF Thermometry: Results and Discussion

- PLIF signal ratios converted to temperature and compared to theoretical LIFBASE values
- Reasonable agreement at lower equivalence ratios
- As ϕ increases, less agreement of measurement/theory temperatures
- Diffusion flame skews results: No co-flow in burner (left edge of flame below)







Conclusions

- Potential of structured Illumination technique successfully demonstrated
- Modifications to optical setup needed (decrease magnification, mentioned previously)
- Acquire burner with co-flow to eliminate diffusion flame
- Incorporate analysis for PLIF sheet attenuation: Beer-Lambert corrections

Future Work: Additional Considerations

- Re-take conventional two-color OH PLIF thermometry data after Beer-Lambert corrections

- Collect two-color structured OH PLIF thermometry data, compare to conventional data

- Conduct two-color structured OH PLIF thermometry measurements in post-detonation fireballs