A Plenoptic Multi-Color Pyrometer

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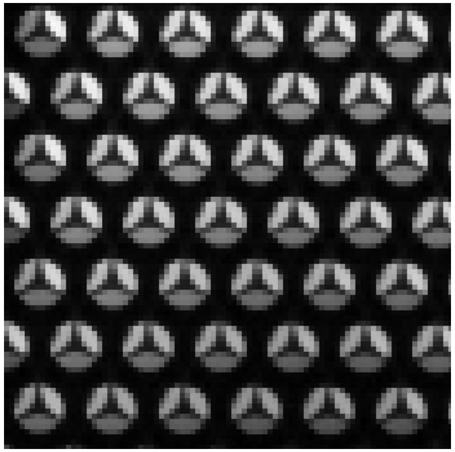

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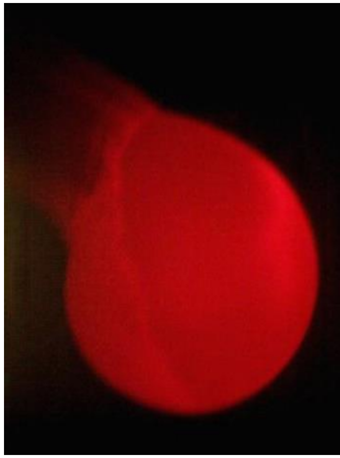
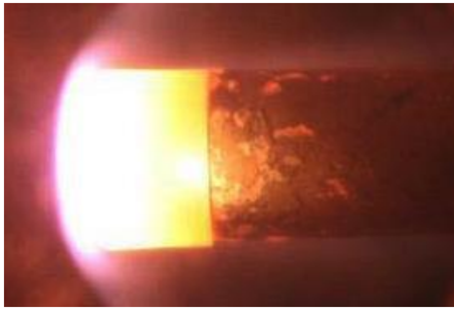
Outline

- Motivation and Background
  - Pyrometers
  - Plenoptic cameras
- Description of Apparatus
- Calibration Experiments
- Example Applications
- Conclusions
- Future Work

Motivation

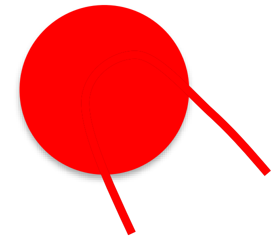
- What are typical NASA applications?
  - Pyrometers are used in numerous industrial and scientific application such as…
    - Boron Nitride Nanotube (BNNT) production
      - Inman et al. "Optical Pyrometry for Study of BNNT Generation," AIAA 2014-2526, Aviation 2014.
    - Welding, machining
  - HYMETS materials testing:
    - Temperature and emissivity of materials
      - Data needed for radiation budget, modelling
      - Splinter et al. "Comparative measurements of Earth and Martian entry environments in the NASA Langley HYMETS Facility." *AIAA 2011-1014*, 2011.





Background: Pyrometers

- What other types of pyrometers are there?
  - “Disappearing” filament comparison
  - Single color, 2D imaging
  - 2 color point or 2D imaging
  - Multi color point or line imaging



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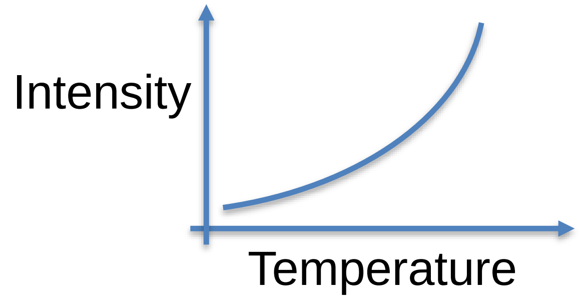

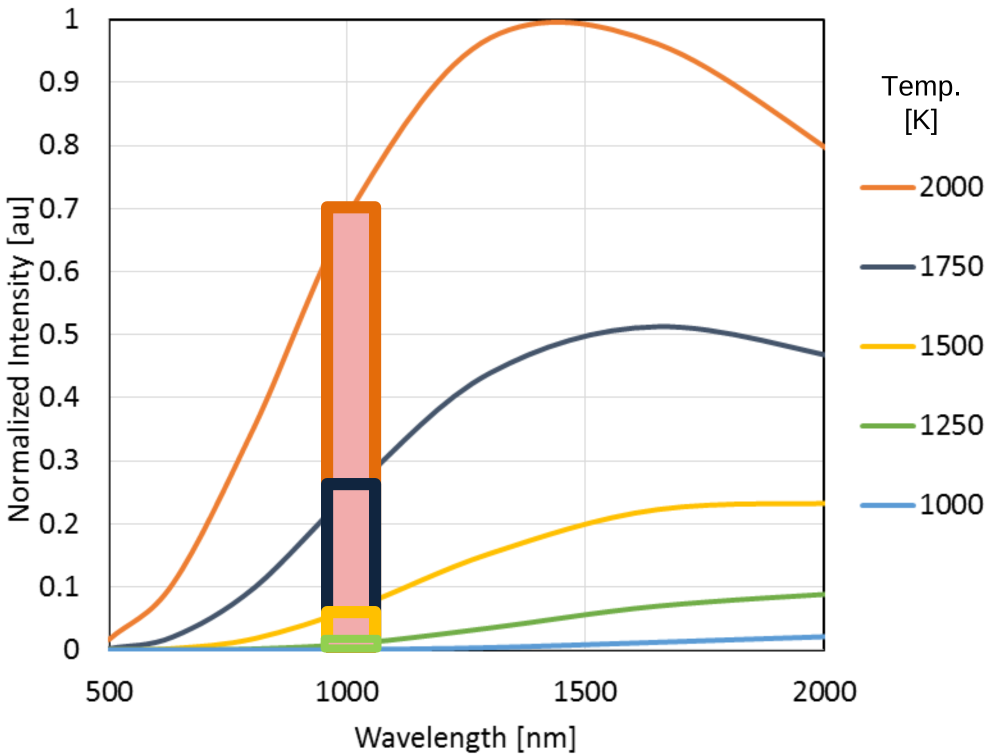

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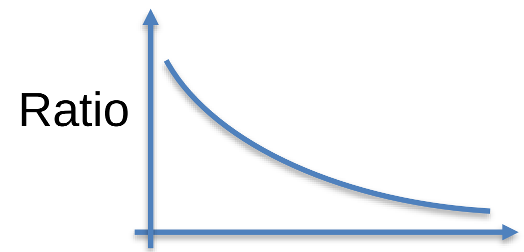
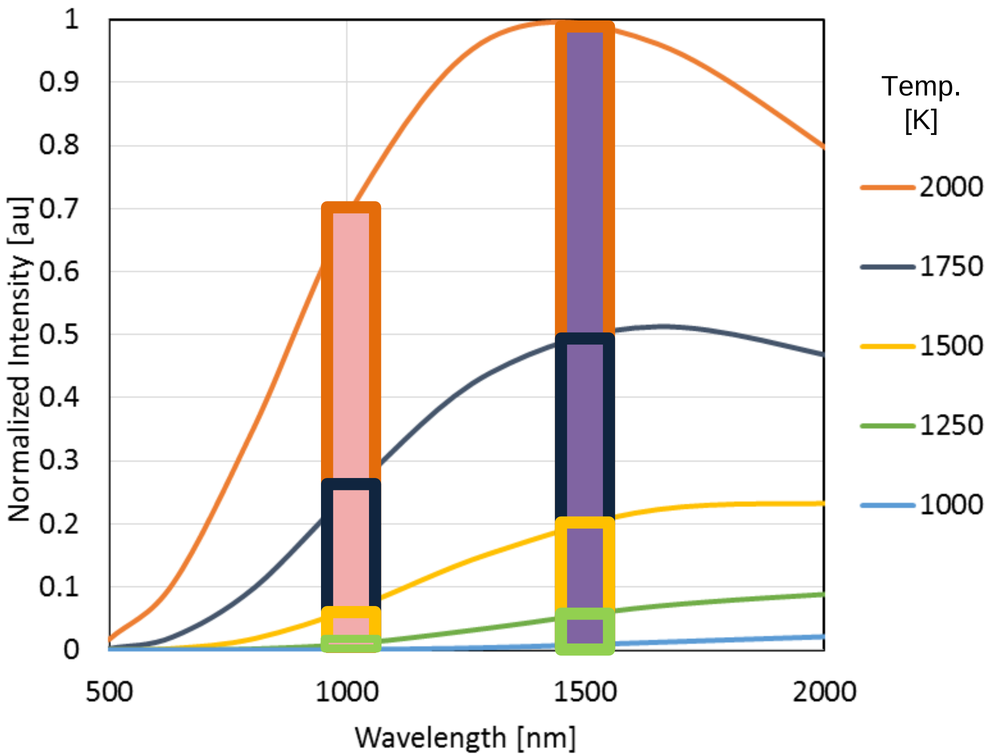
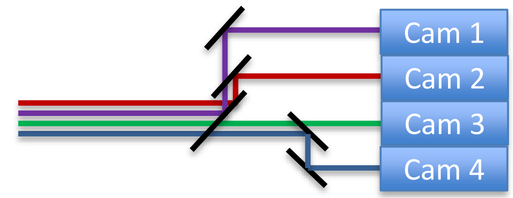


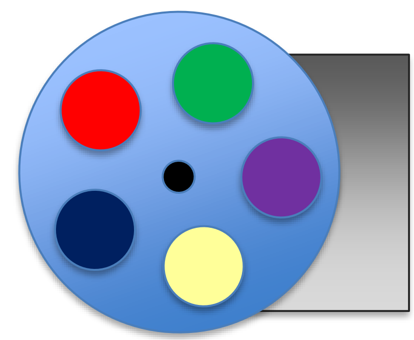


Background: Multi-Color Imagers

- We want to image multiple colors, not just 2
  - Can use beam splitters and get ~4
    - Expensive, bulky



  - Can use a filter wheel
    - Limited number of colors
    - Non-simultaneous (transient events)

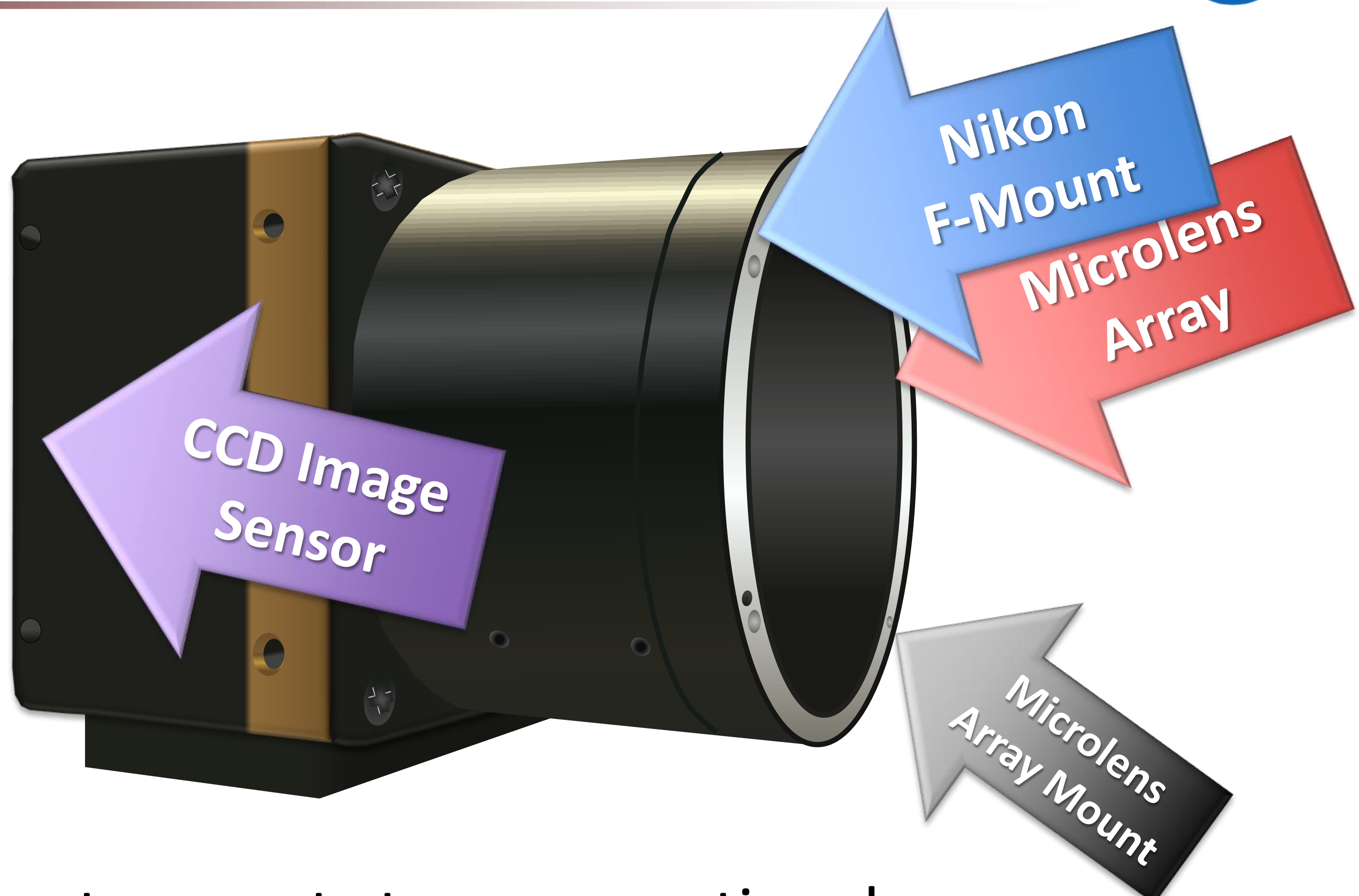


  - Other "hyperspectral" devices developed
    - Reviewed by Hagen and Kudenov, Opt. Eng., 2013
    - Fibers, grating, beam splitters, clever optical devices...

Background: Plenoptic Cameras

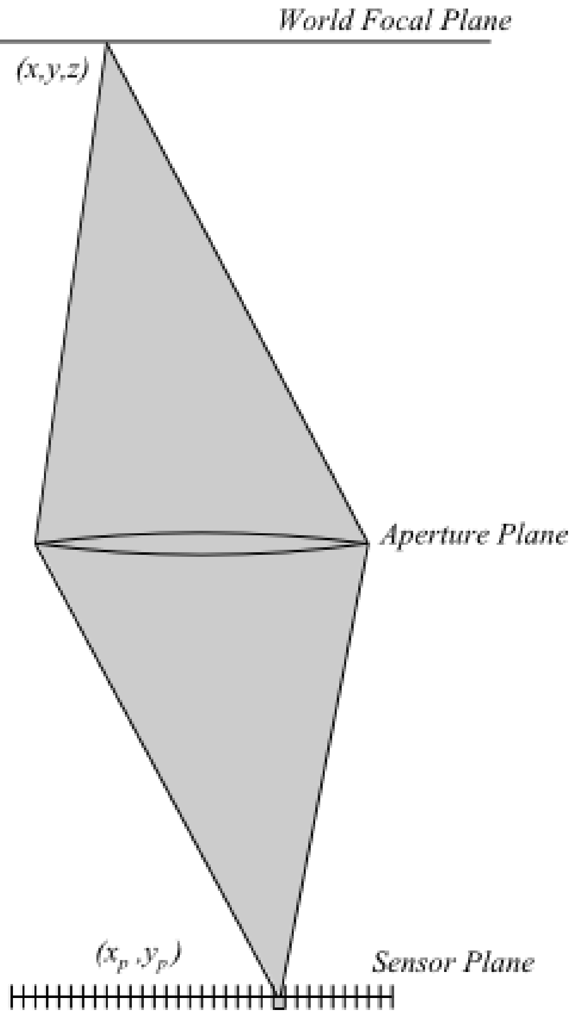
- Plenoptic camera technology or ‘light field imaging’ measures image brightness as well as the direction of the light rays to enable new imaging capabilities
  - Can refocus acquired image to different depths
  - View same scene from slightly different directions (perspectives)
  - Recently used for single-camera tomographic particle image velocimetry (PIV) and background oriented schlieren (BOS)
    - Fahringer, Lynch, Thurow. "Volumetric particle image velocimetry with a single plenoptic camera." Measurement Science and Technology 26.11 (2015).
    - Klemkowsky, Thurow, Mejia-Alvarez. "3D Visualization of Density Gradients Using a Plenoptic Camera and Background Oriented Schlieren Imaging.“ AIAA 2016-1047, 2016

The Plenoptic Camera

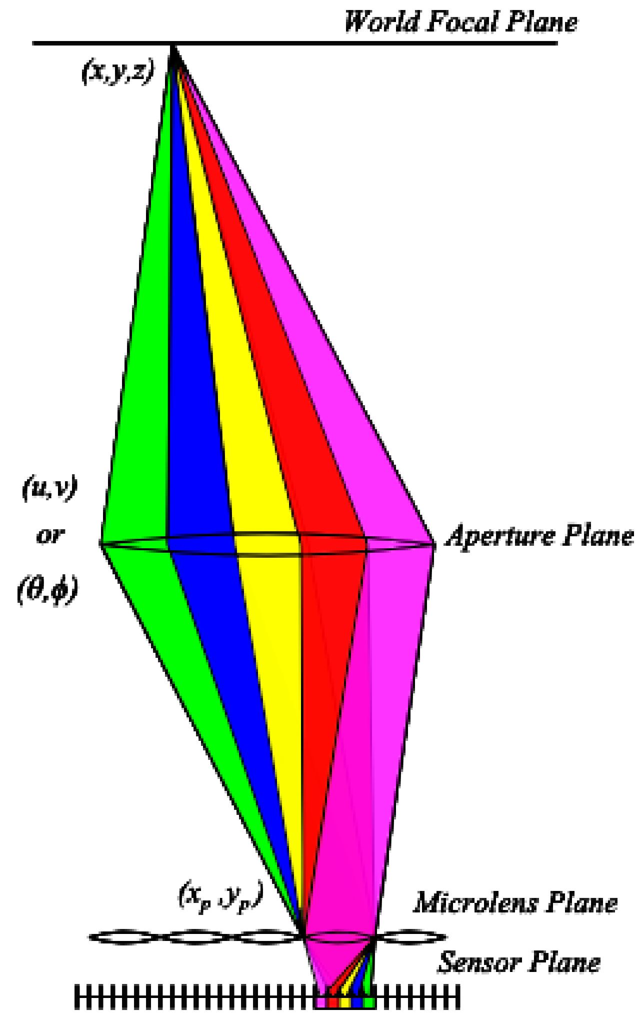


- Similar in most respects to a conventional camera
- Key difference is the insertion of an array of microlenses

Plenoptic Camera Operation



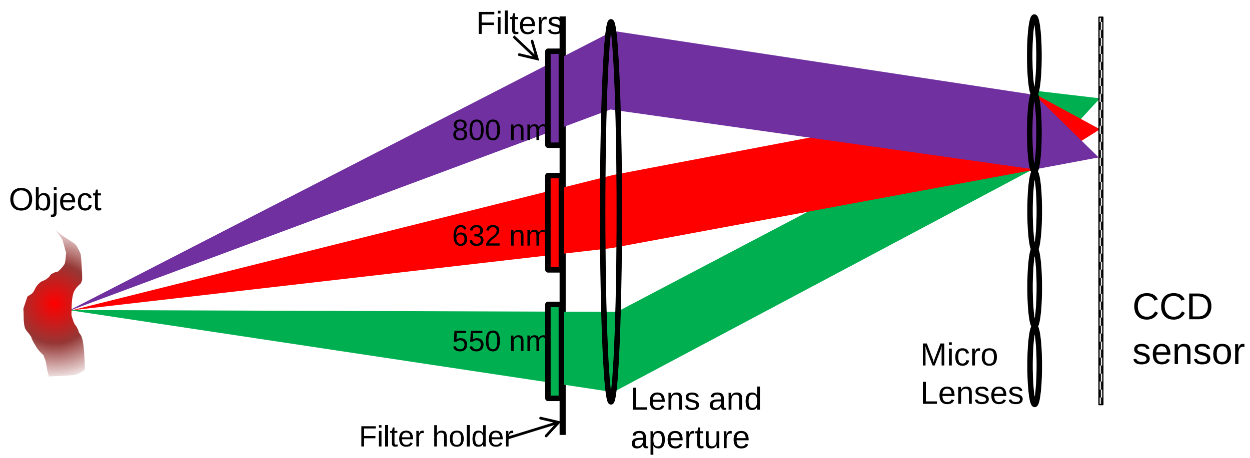
Conventional Camera



Plenoptic Camera

Plenoptic Spectra Imager (PSI) Concept

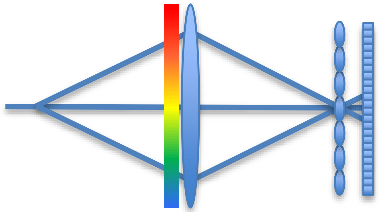
- Inserted color filters near aperture plane



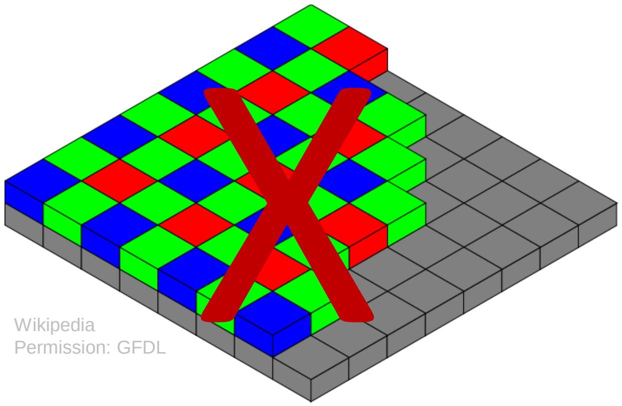
- Microlenses form image of the aperture plane on CCD.
- Horstmeyer et al, SPIE, 2009, (Stanford) used spectral filters in conjunction with plenoptic camera technology to identify different colored objects in a scene.
- We are using this approach for quantitative metrology applications, including pyrometry, for the first time.
- Could use discrete filters or rainbow filter or combination thereof

What the technique is NOT.

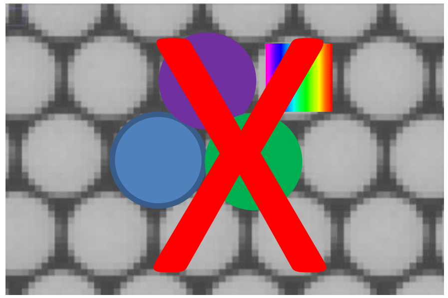
- We put the filter in the aperture plane.



- We are not putting filters on the camera pixels:



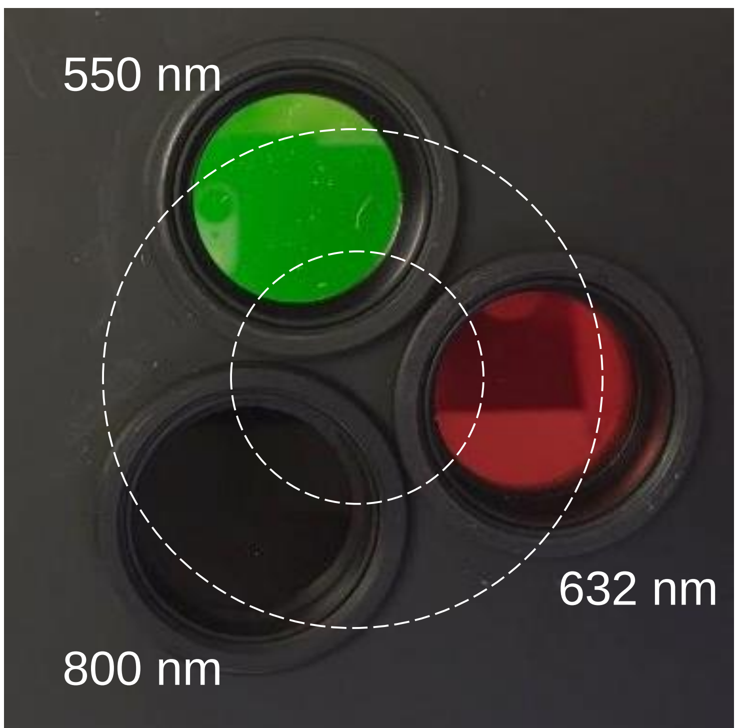
- We are not putting filters on the micro lens array:

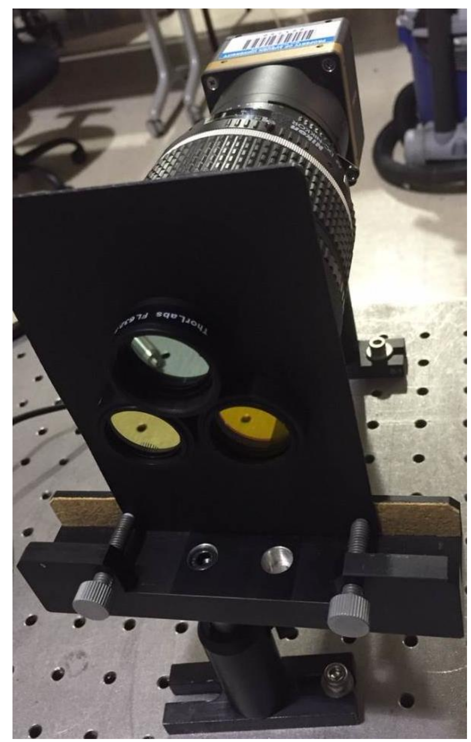


- These latter two would be expensive and inflexible.

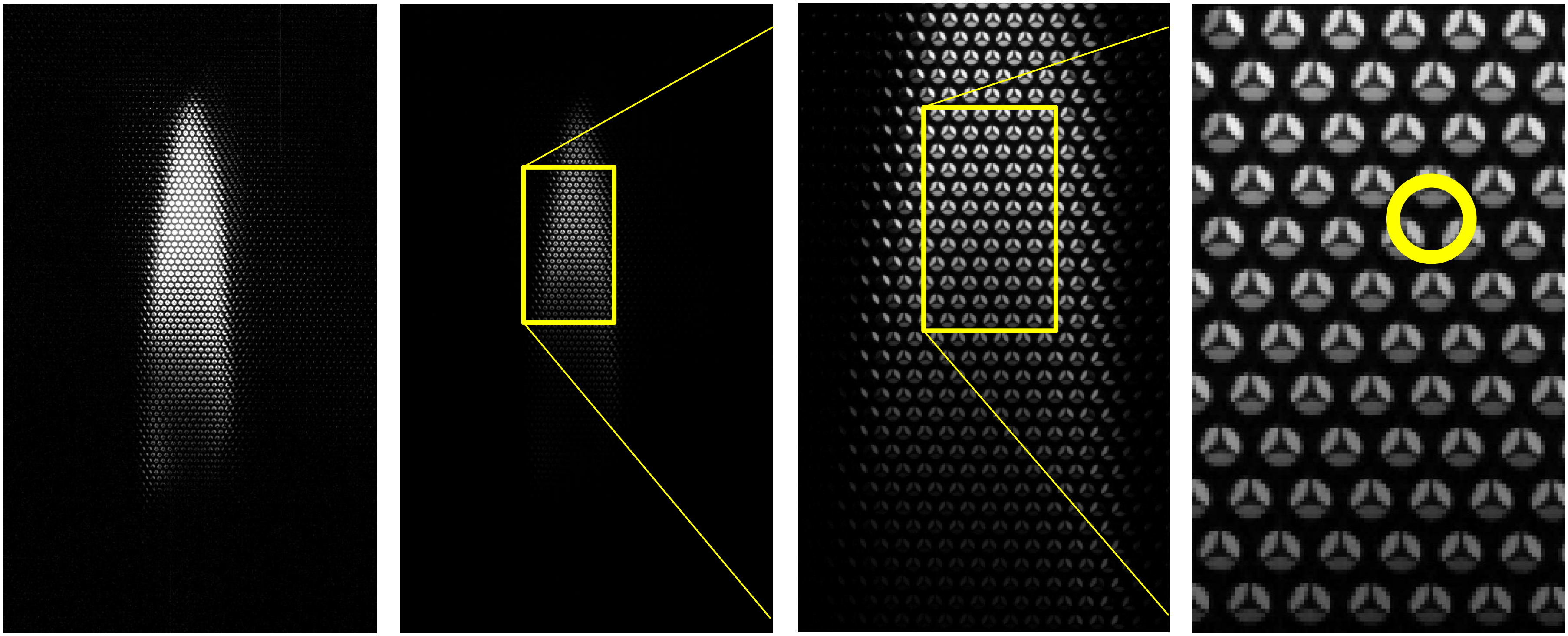
Description of PSI Camera Setup

- Use 3 spectral filters previously characterized by Inman et al.
  - Inner dashed circle: f/4.5 aperture; outer circle: f/2
  - Added ND 0.5 filter to 800 nm channel to attenuate
- Adapt filter holder to existing Plenoptic Camera assembled by and used by Auburn in prior work (PIV and BOS)



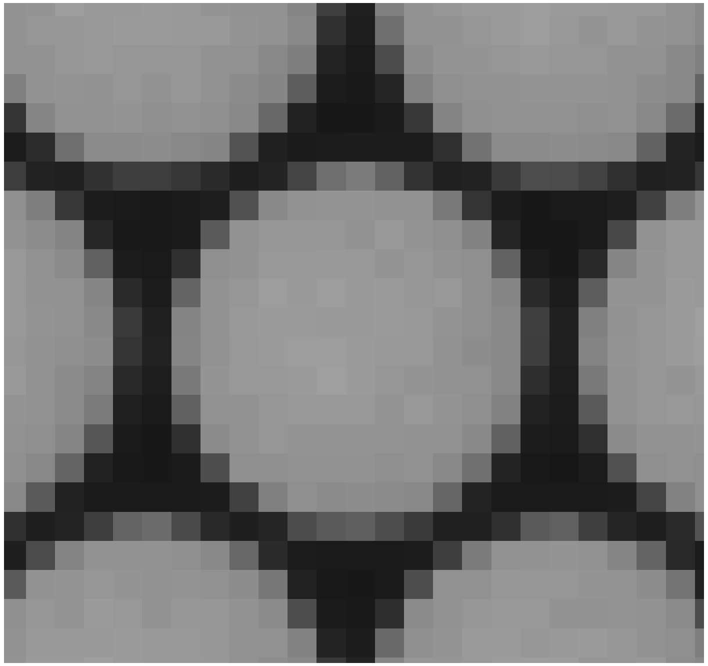


View of a burning match

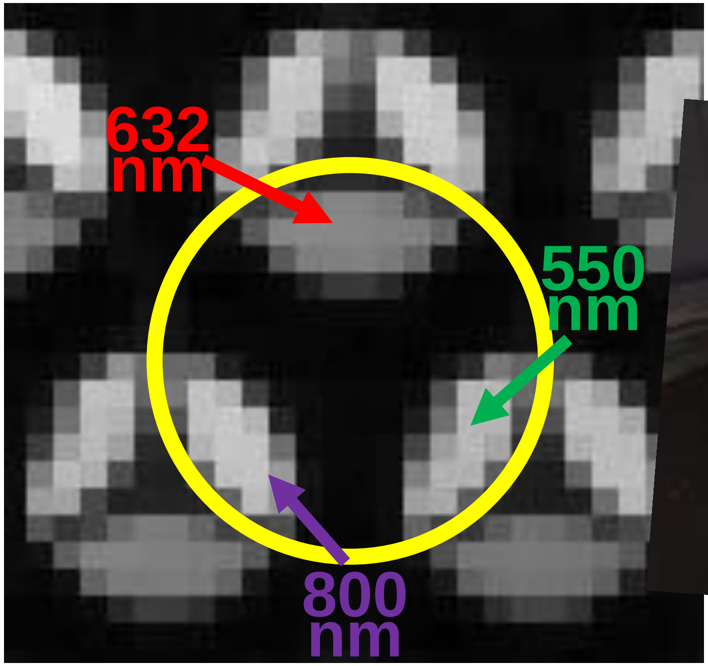


- Raw images displayed with different intensity scalings and magnifications

Single Microlens Images



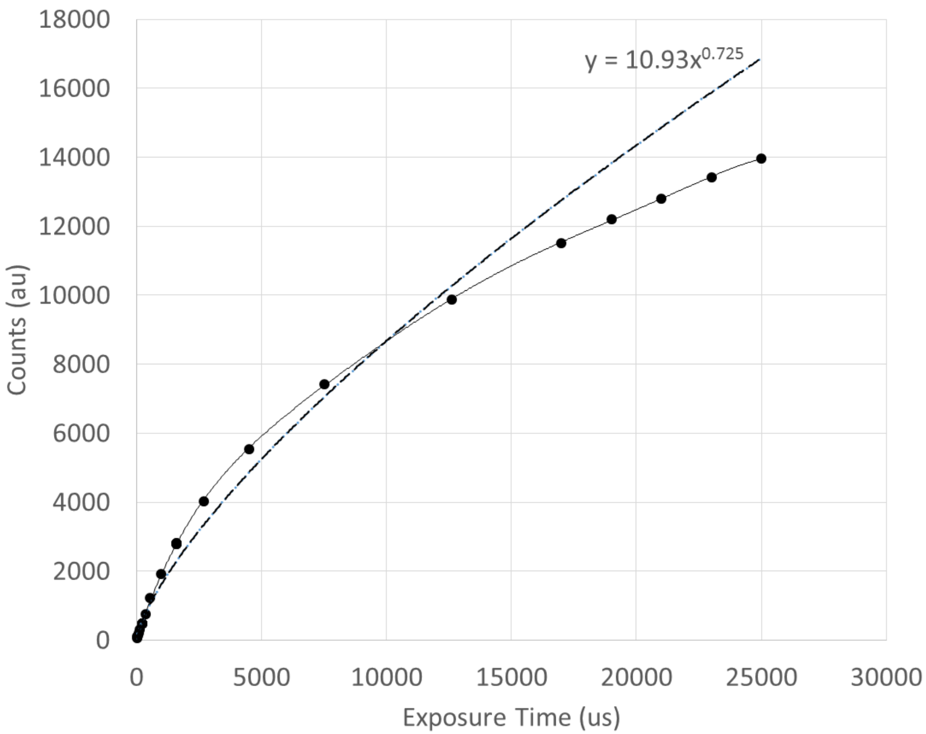
Unfiltered Image

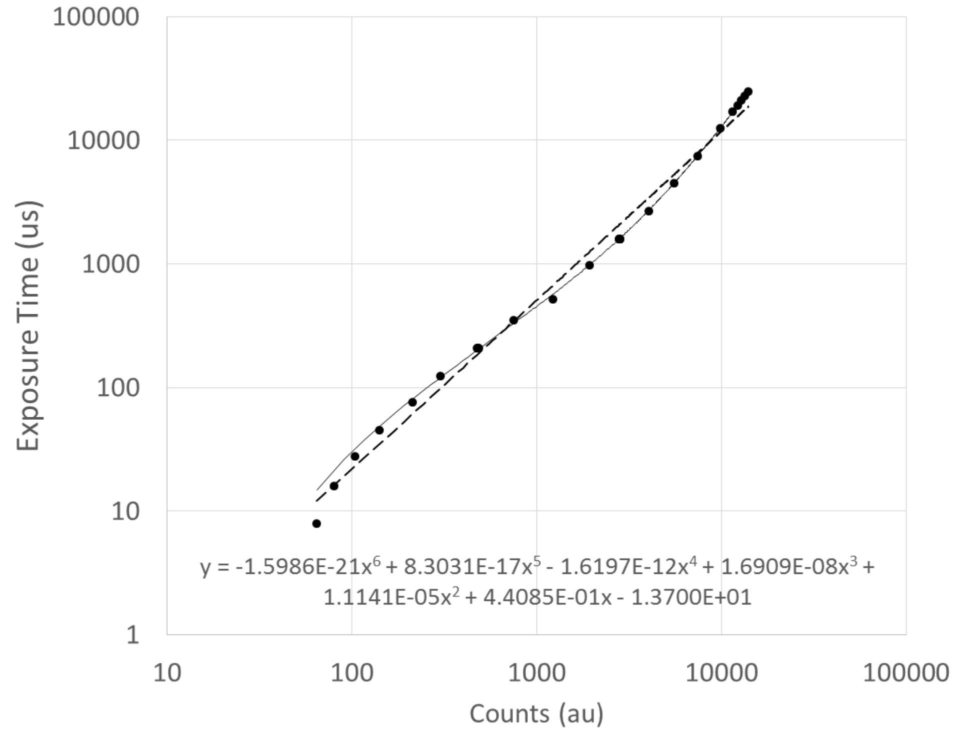


Filtered image

Filter Arrangement

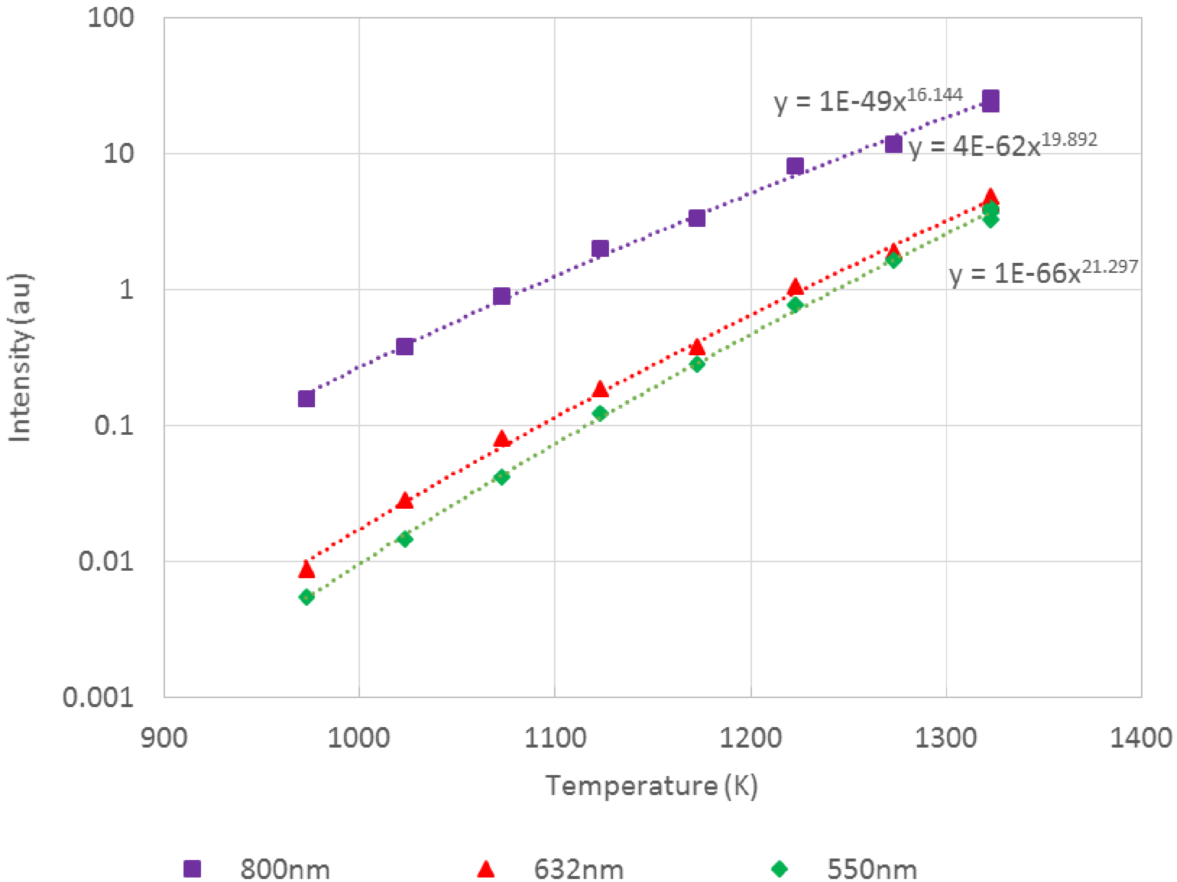
Camera Nonlinearity Correction





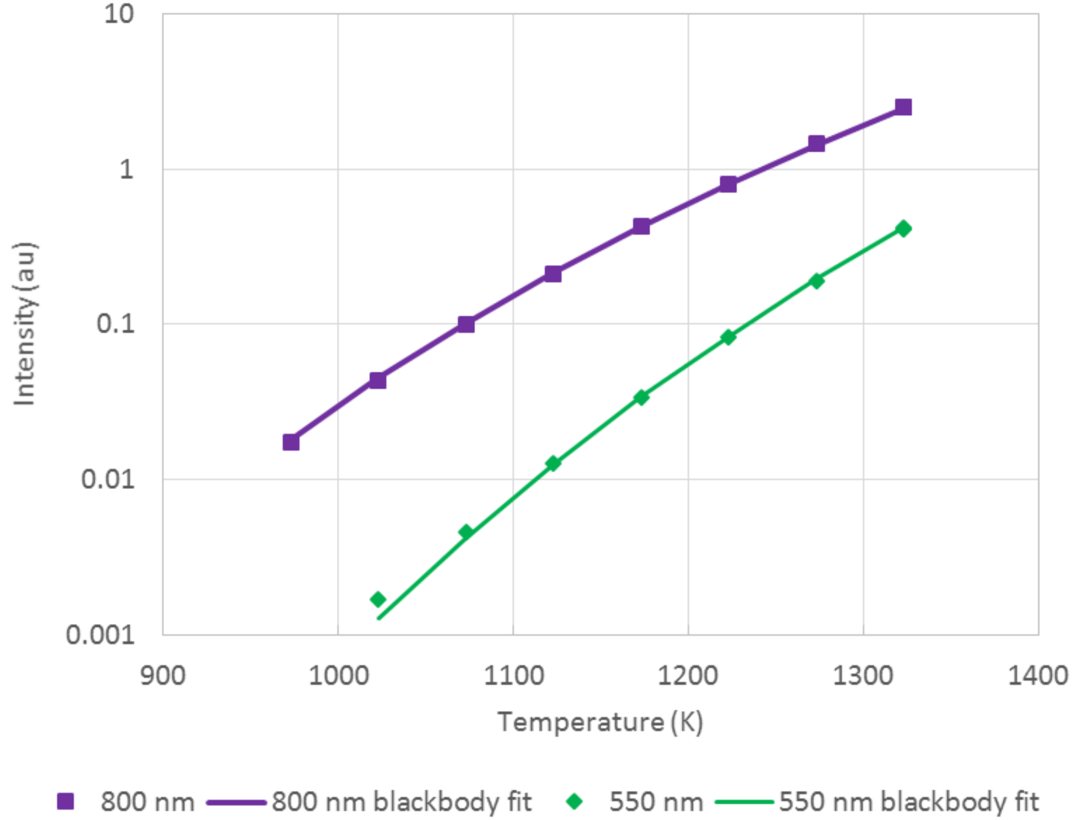
- Camera was observed to exhibit nonlinearity
  - Varied exposure time and imaged constant intensity source
  - Nonlinearity helpful to extend camera dynamic range
- Inverted axes (right figure) and fit with polynomial.

Raw Signal Intensity vs. Temperature



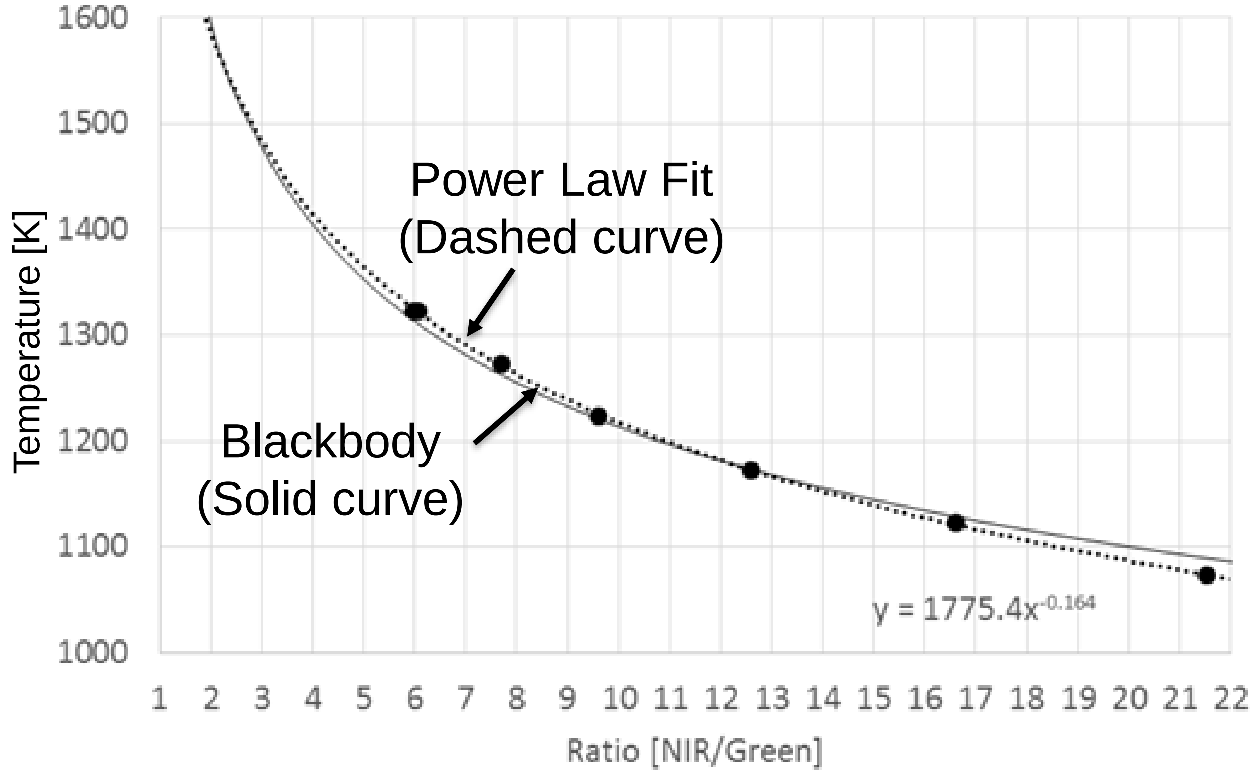
- Obtained in a calibrated blackbody furnace at known, variable temperature. Various exposure times used.
- The signal increases dramatically with temperature. O(10^{20})
  - Requires high dynamic range detector

Signal Intensity vs. Blackbody Theory



- Blackbody computed at known temperature and then least-squares fit was performed for an amplitude scaling factor for both curves.
- The scaling factors for 550 nm and 800 nm differed by a factor of 12.9
  - The sensor for the camera is 4.2x more sensitive to 550 nm than 800 nm light
  - There was a 0.5 ND filter making the signal 3.02x dimmer in the 800 nm range
  - These two account for a 12.7x difference in the constants which agrees to 1.5%

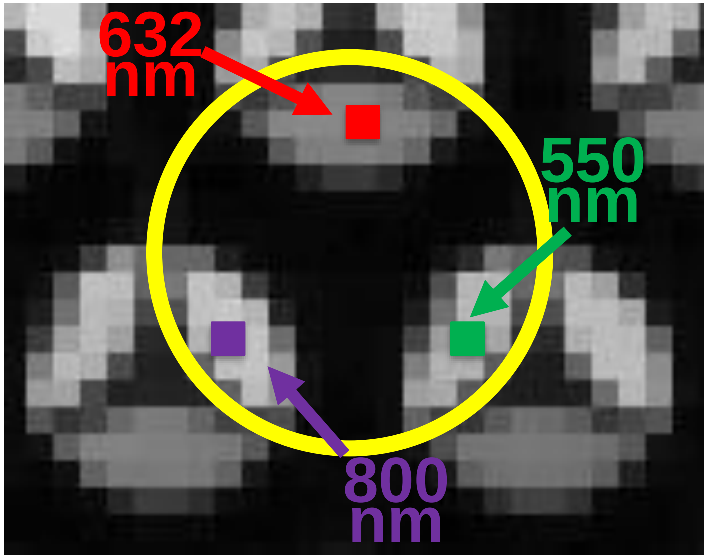
NIR/Green versus Temperature



- Points are ratio of data from previous chart.
- NIR-Green Ratio changes monotonically with temperature.
  - Use to measure temperature.
- NIR-Green Ratio chosen due to their wide spectral separation, giving a more accurate result

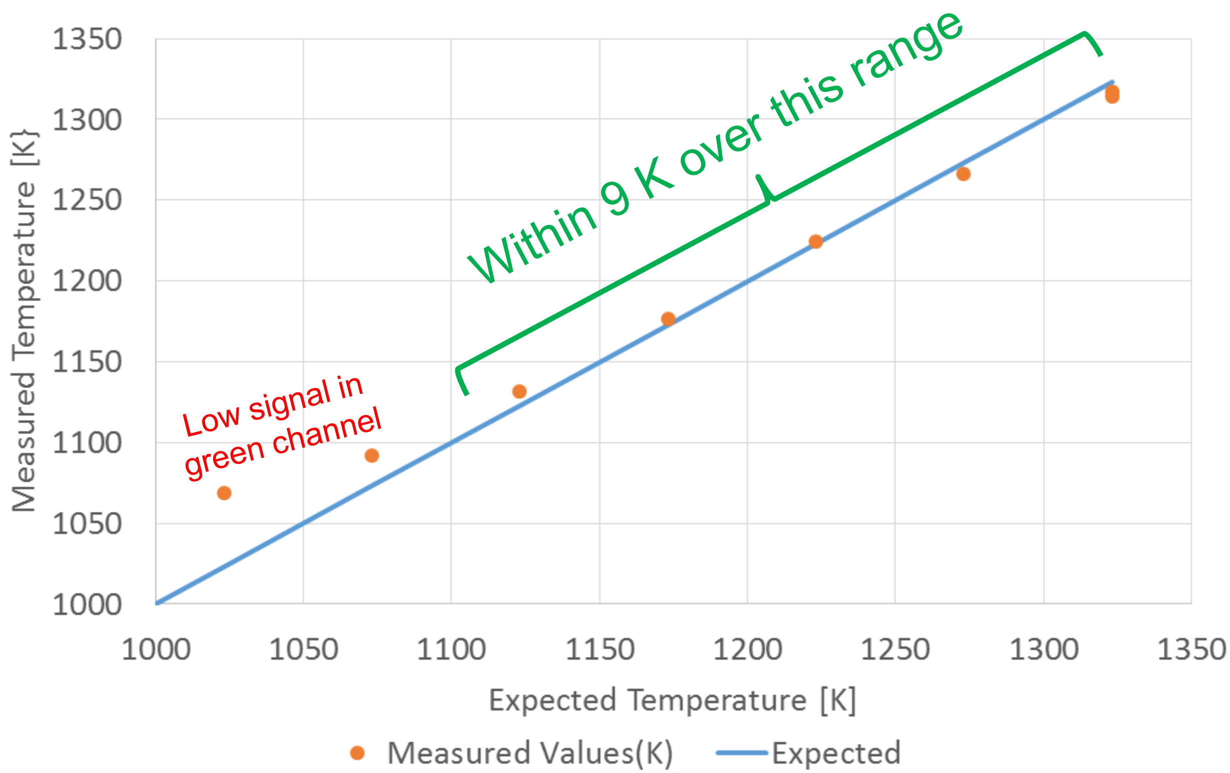
Plenoptic Image Processing

- Used Auburn's program
- Chose one point from each filter
- Produced 3 new images
  - 550 nm, 632 nm, 800 nm
- There were edge artifacts
  - Repeatable, were corrected
- Custom ImageJ code written
  - Imported 550 and 800 nm images, corrections and ratio-temperature curve fit
  - Produced temperature images



Accuracy and Precision

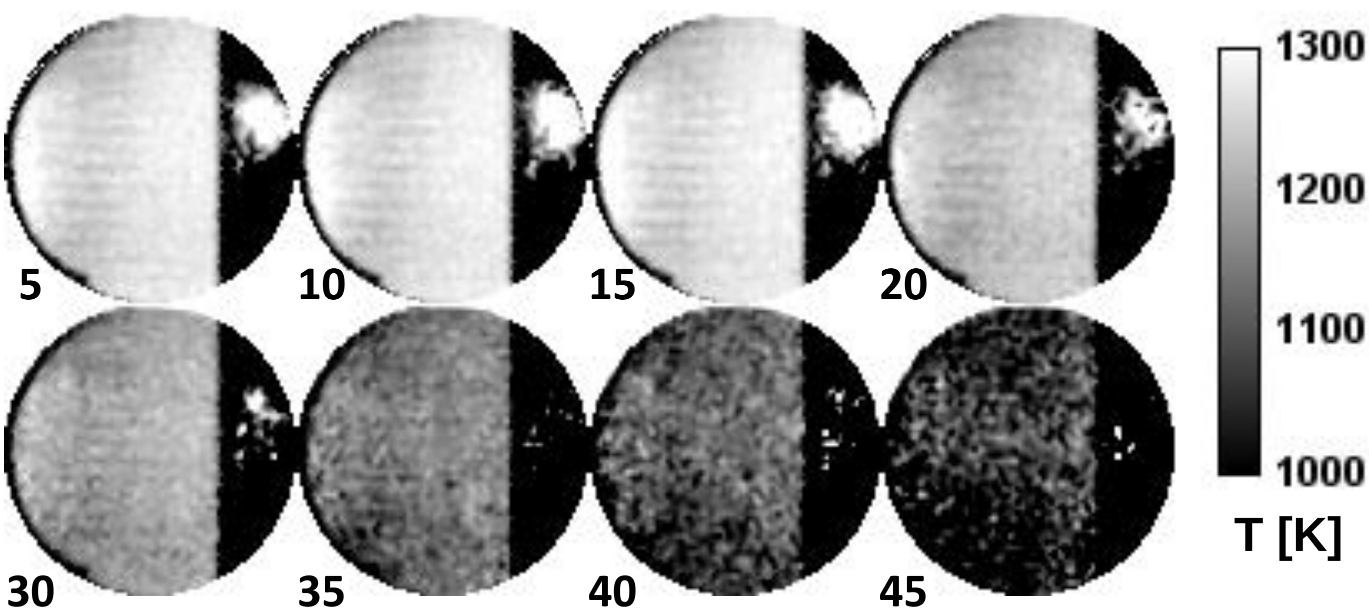
- Reprocess calibration data with ImageJ code
- **Accuracy**: deviation from known temperature
  - Within 9K over 1123-1323 K
  - 6 K avg deviation
  - Systematic error at lower T where 550 nm counts are low

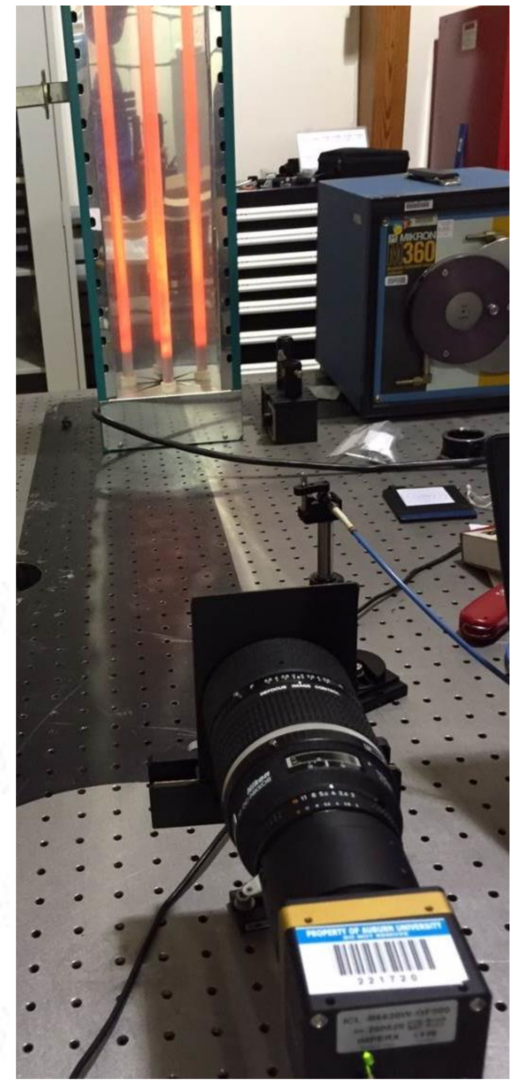


- **Precision**: 1 σ variation in temperature over a uniform area: typically 5-10 K.

Sample Application:

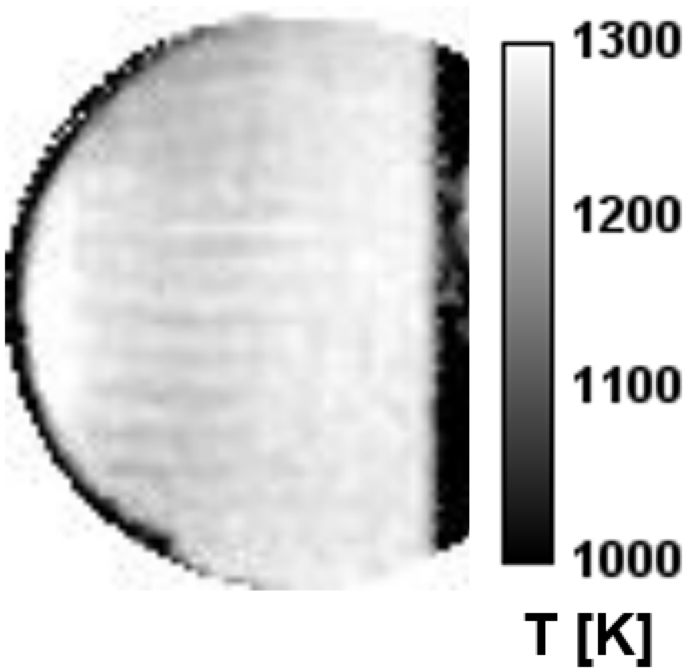
- Image the cool down of a paint-drying radiation heater.
  - Constant camera settings.
  - Neglect variation of emissivity with color and temperature.
- Heater turned off after frame 15.
  - Acquired data at ~0.3 Hz.



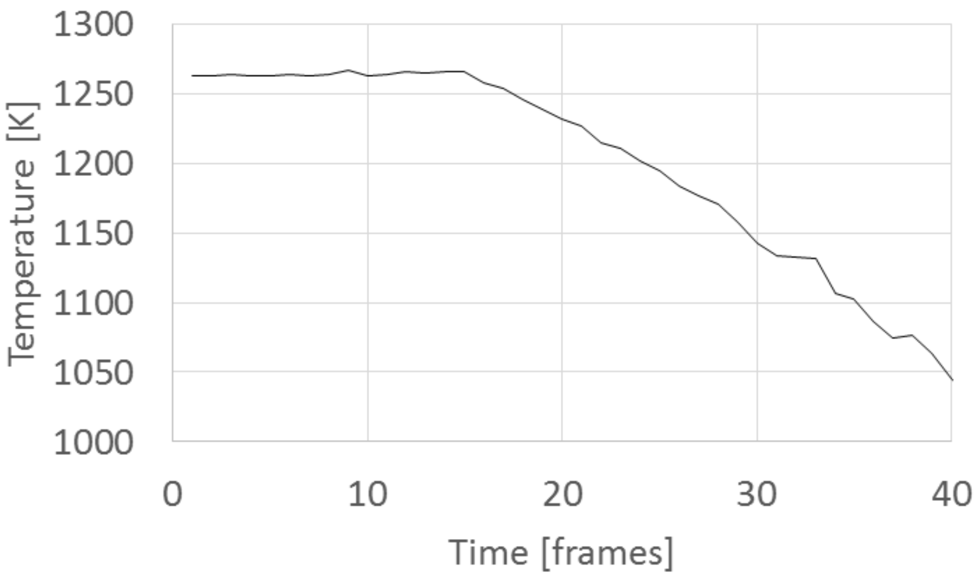


Cool-down of heater

- Data from previous chart



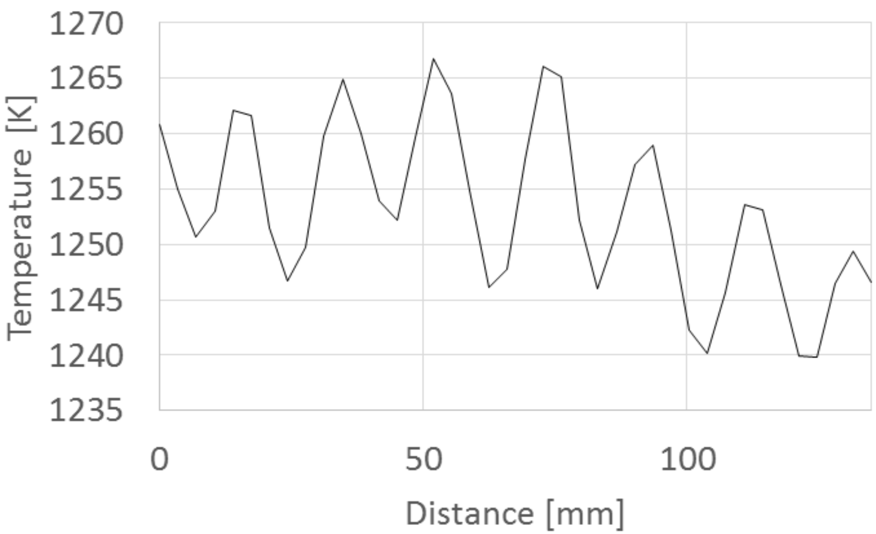
Animation of temperature image

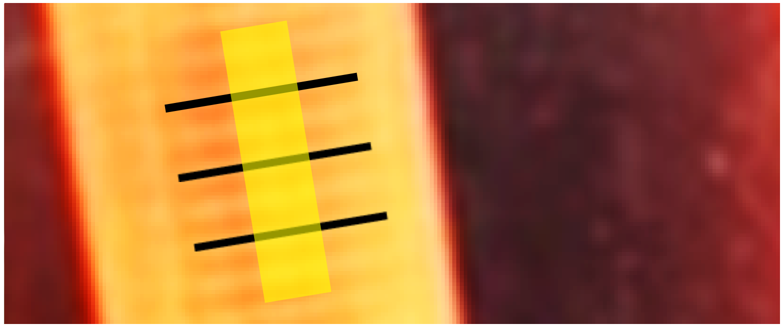


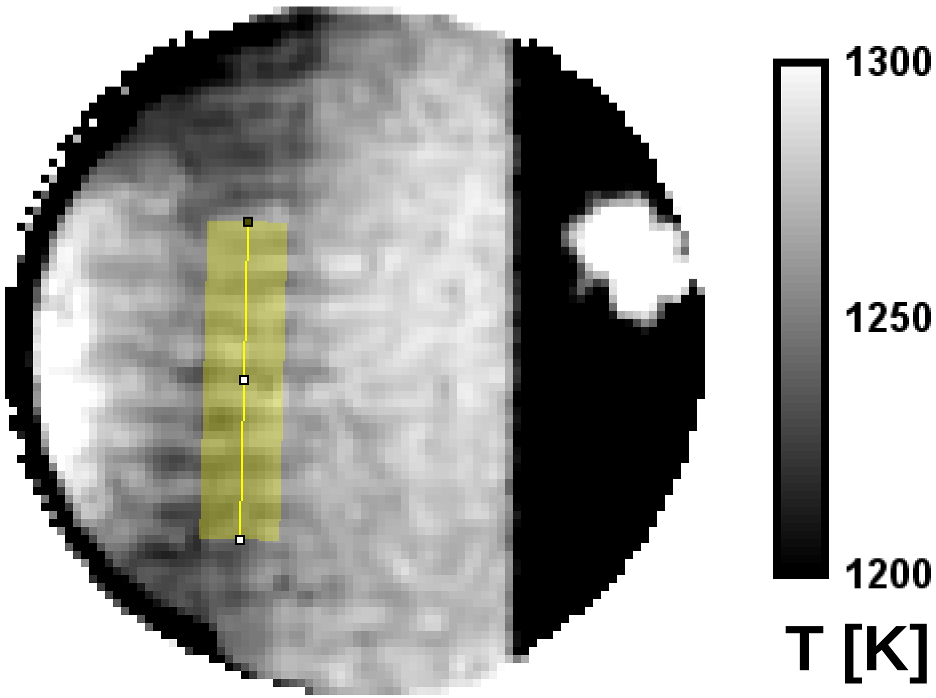
Spatial average versus time

- Temperature map becomes noisy below 1100 K

Spatial Variation in T Detected

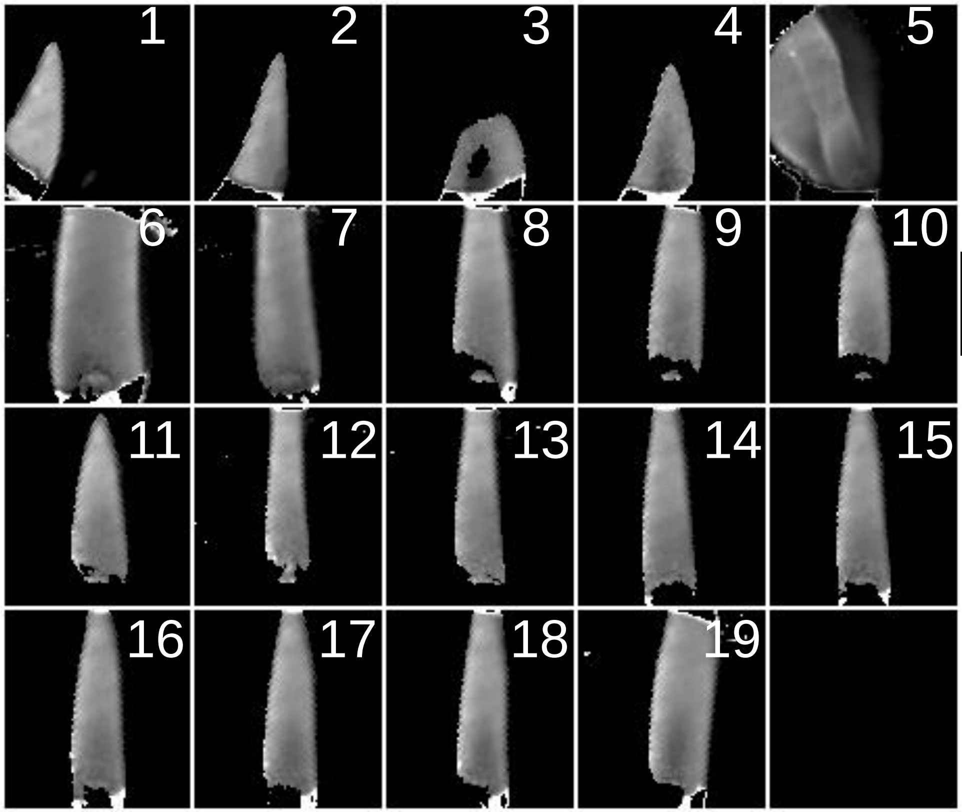


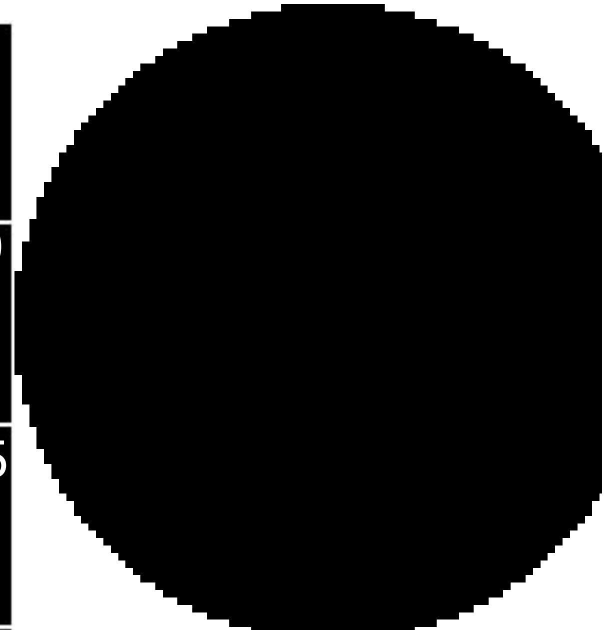


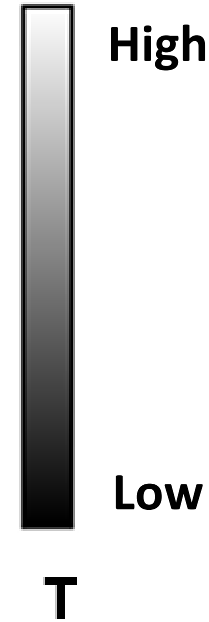


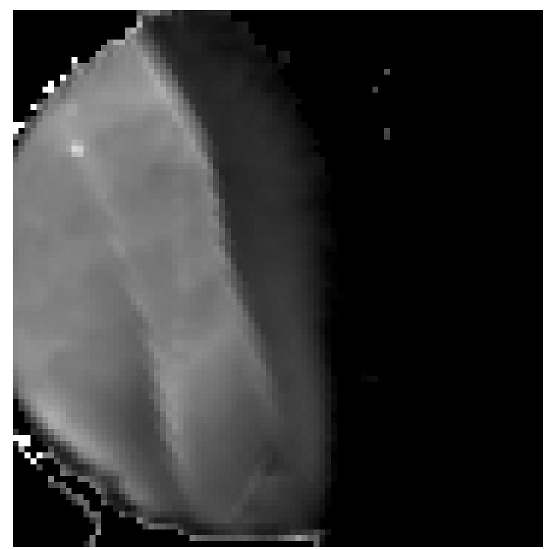
- Can resolve temperature oscillations of 20-30 K with good resolution→ wire coils
- Spatial resolution of ~5 mm demonstrated

Measurement in a Flame









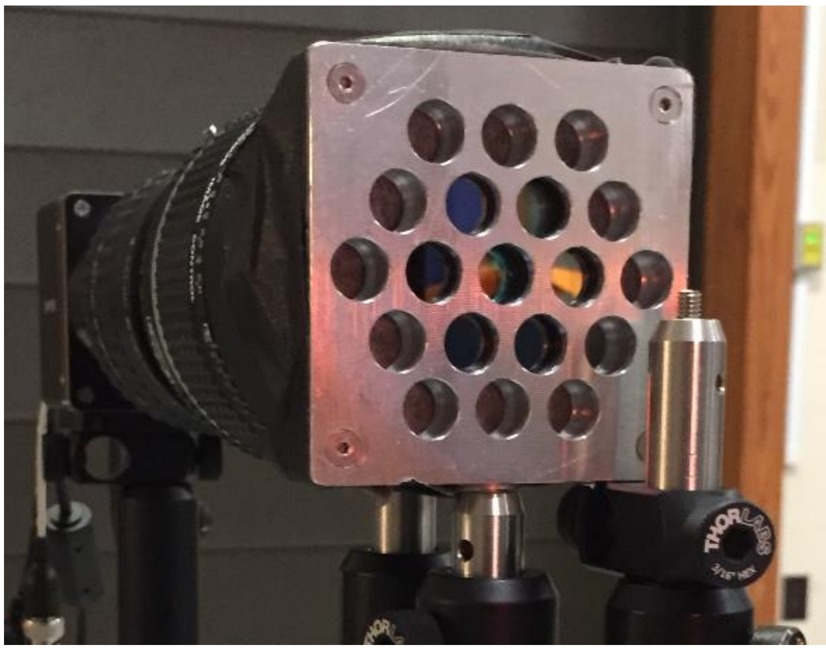
- Butane lighter used to ignite a match
  - Detecting soot emission.
- Image 5: explosive ignition of the match
- Need to understand soot emissivity to determine temperature

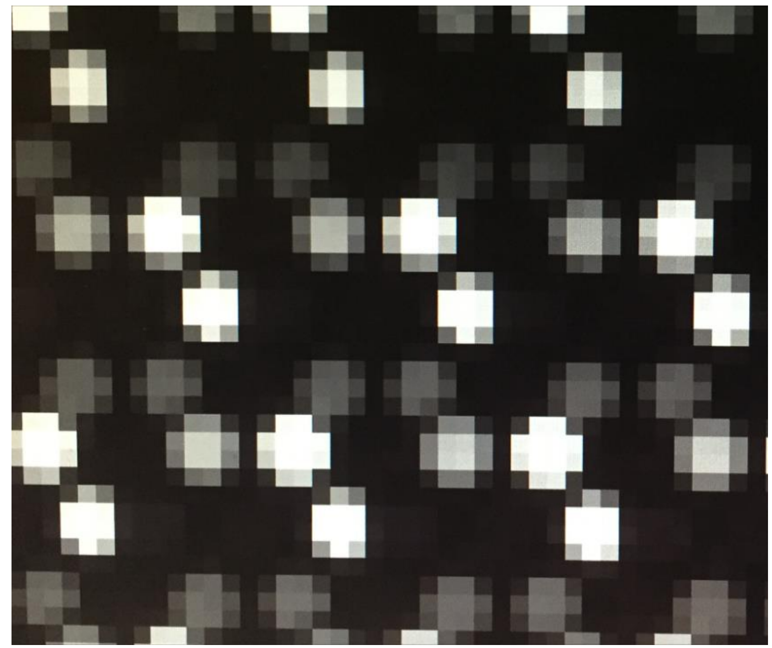
Conclusions

- The instrument shows promise for accurate (6-9 K) and precise (5-10 K) temperature measurement at two wavelengths
  - Dynamic range limited, especially without changing exposure settings (T^{20} dependence)
- Two demonstration experiments: heating element and butane flame lighting a match
- Future instrument could have more accurate and precise temperature measurement with a wider dynamic range using a more advanced setup and improved analysis code.

Future Work

- Flame temperature measurement from soot.
- Improve system to measure more colors (7, 19):





- Use more colors in temperature measurement
  - Curve fit through all colors instead of simple ratio.

Thanks for your attention!

Masking technique

- LFIT program (Auburn) shows artifacts when measurements are made on edges of the micro lens image
  - artifacts are repeatable
  - we normalized and corrected for them