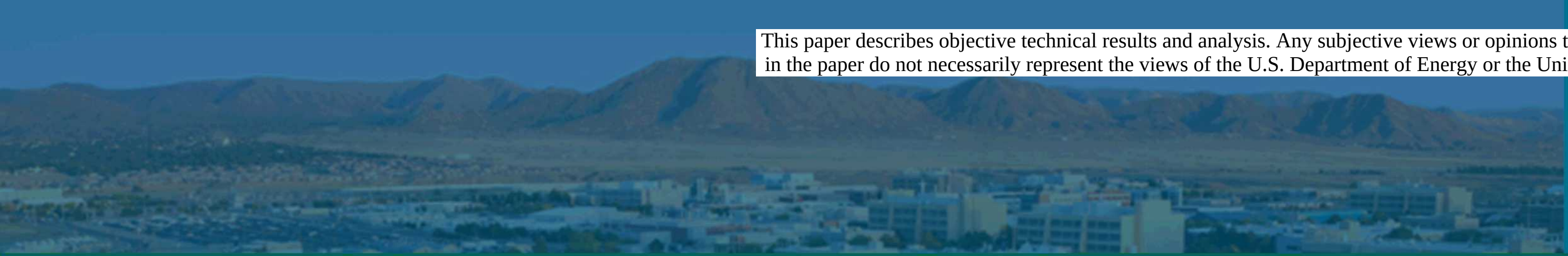
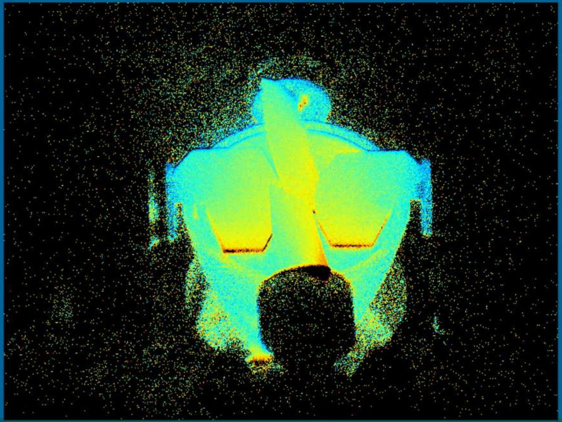


SAND2020-0099C

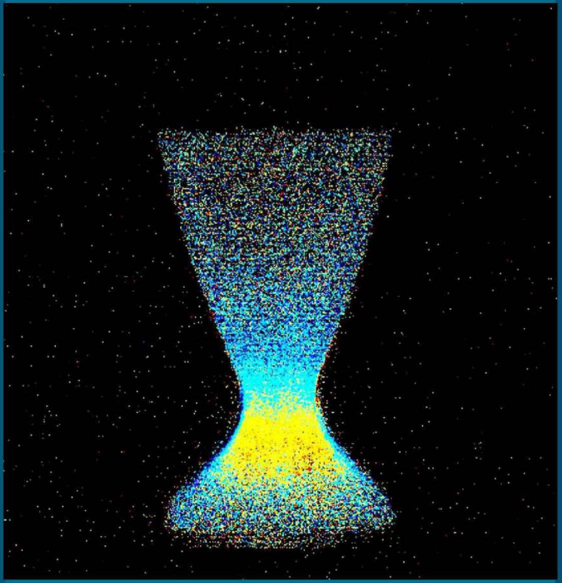
Spatially-Resolved Surface Temperature Measurements of a Rocket Motor Nozzle using an Acousto-optic Modulator



Ellen Yi Chen Mazumdar[1,2], Justin L. Wagner[1], Donald J. Frederick[1], Daniel R. Guildenbecher[1], Terry L. Hendricks[3]

[1]Sandia National Laboratories
[2]Georgia Institute of Technology
[3]Exo-Atmospheric Technologies, LLC

AIAA SciTech
Orlando, Florida, January 6th-10th, 2020



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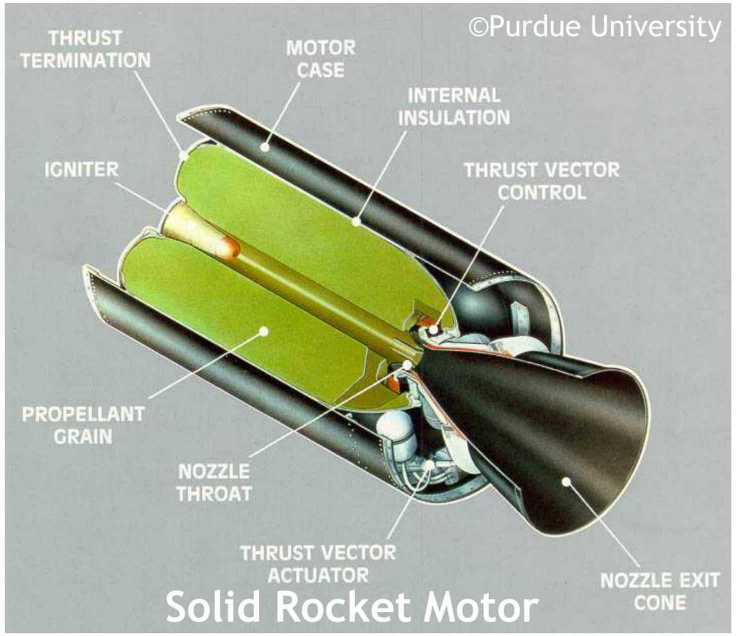
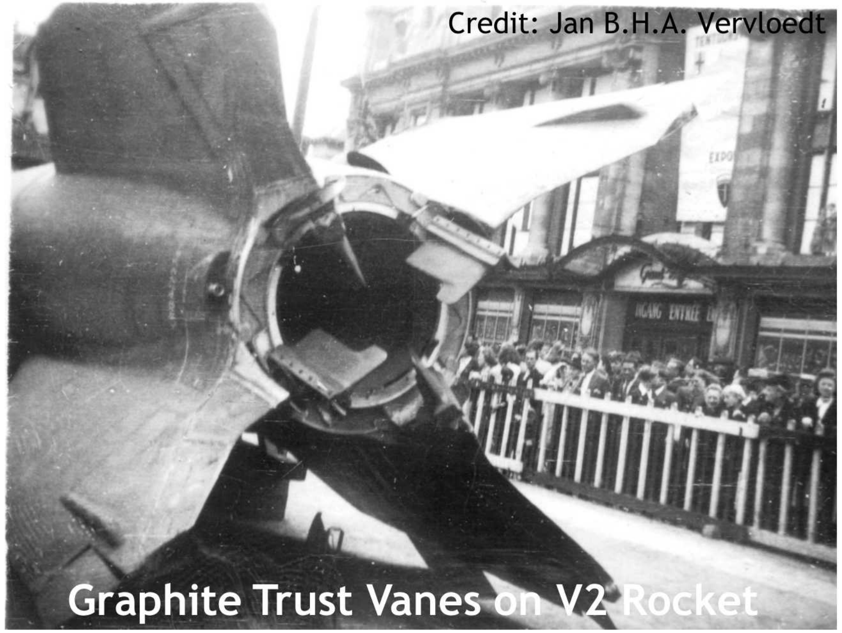
Motivation

- Solid rocket motor components (nozzles and thrust vanes) need to withstand high temperatures.
- Temperature, material properties, and flow properties determine erosion rates.
- Measuring 2D temperature under realistic testing conditions, even at small scales, is challenging.
  - Long experiments and large flow rates are needed to simulate a full grain burn.
  - Large vacuum chamber is needed to simulate full grain burns at high altitudes.



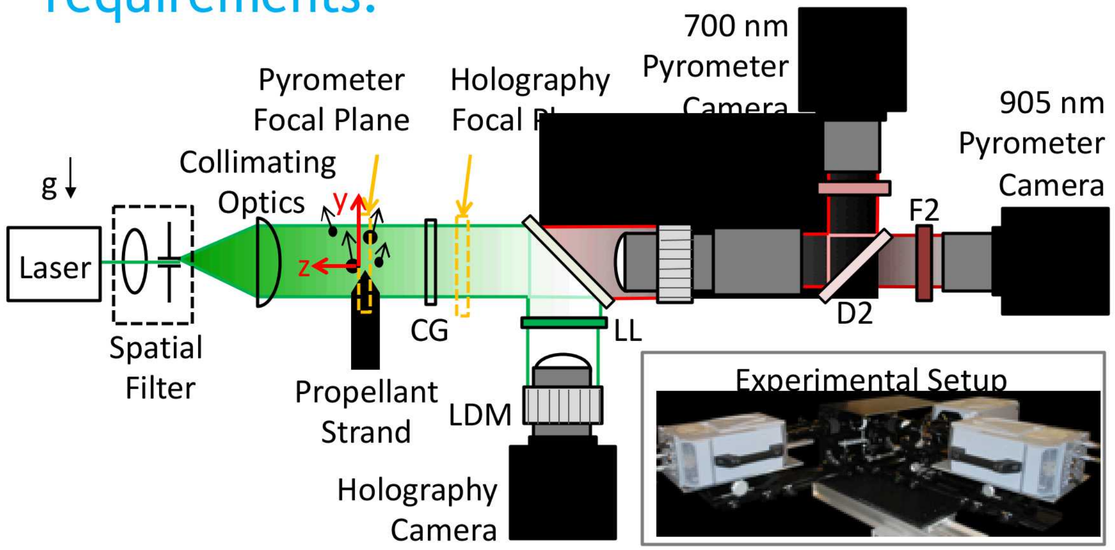
Solid Rocket Motor

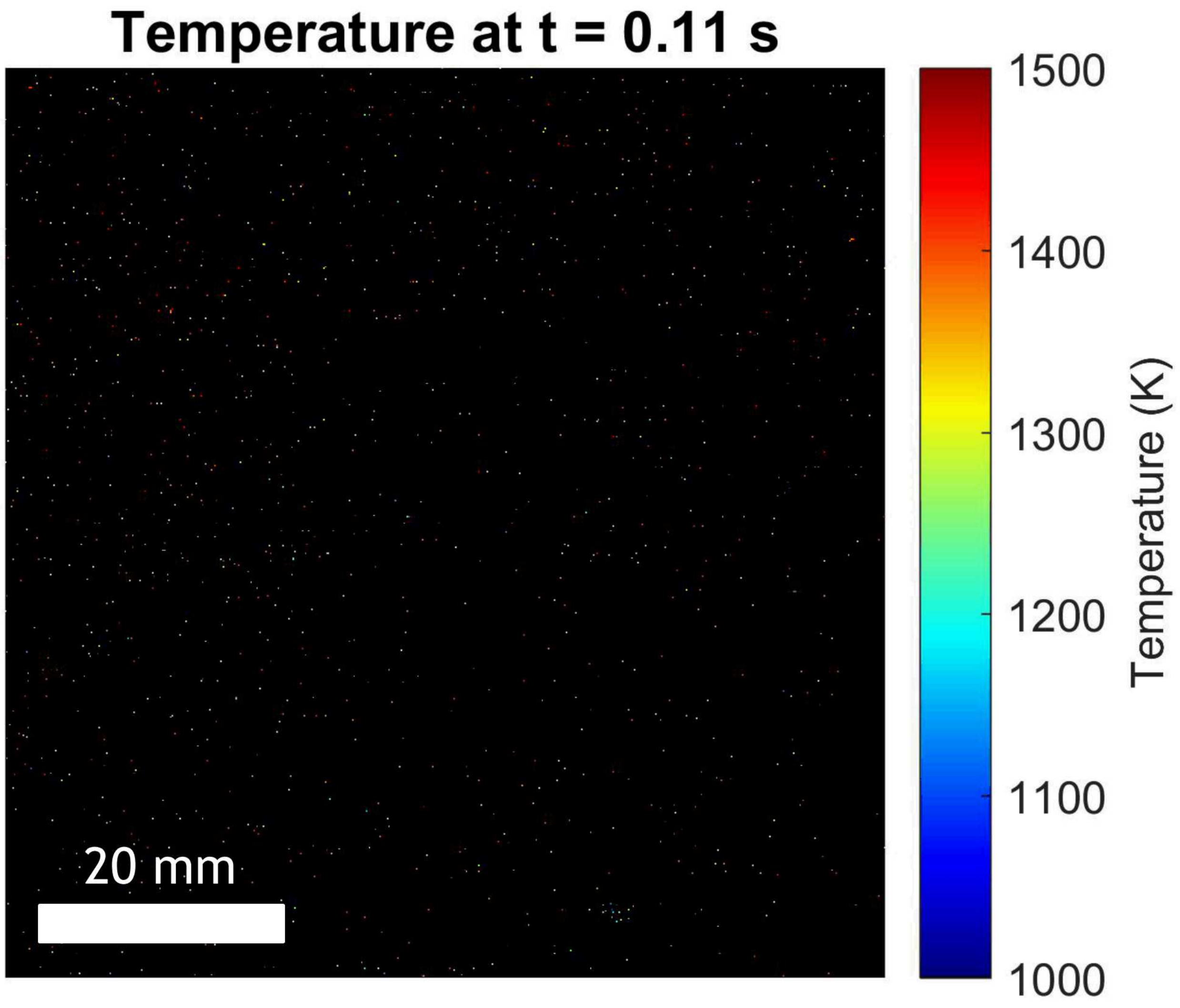

Credit: Jan B.H.A. Vervloedt
Graphite Trust Vanes on V2 Rocket


©LACO Technologies
LACO Vacuum Chamber

Overview

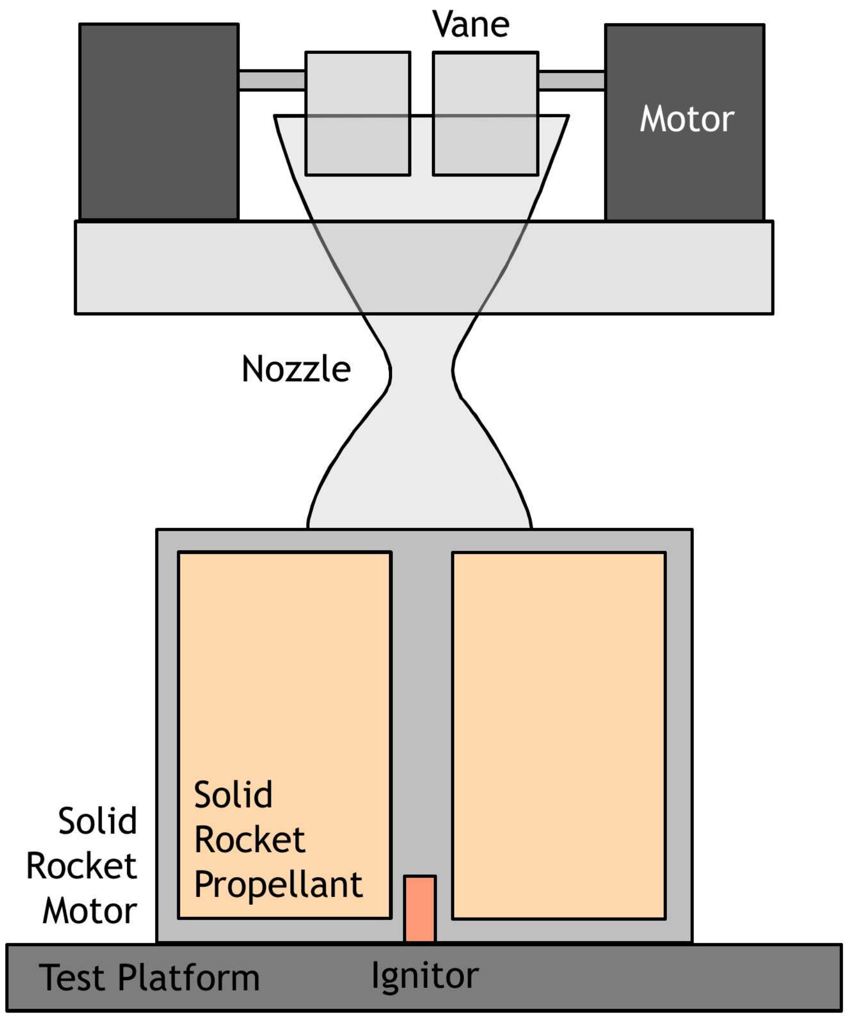
- Imaging pyrometry can estimate surface temperatures and visualize erosion.
- Existing imaging pyrometry methods use multiple cameras, require careful alignment, and need image registration.
- Proposed Solution: Develop compact imaging pyrometry system with low-realignment requirements.





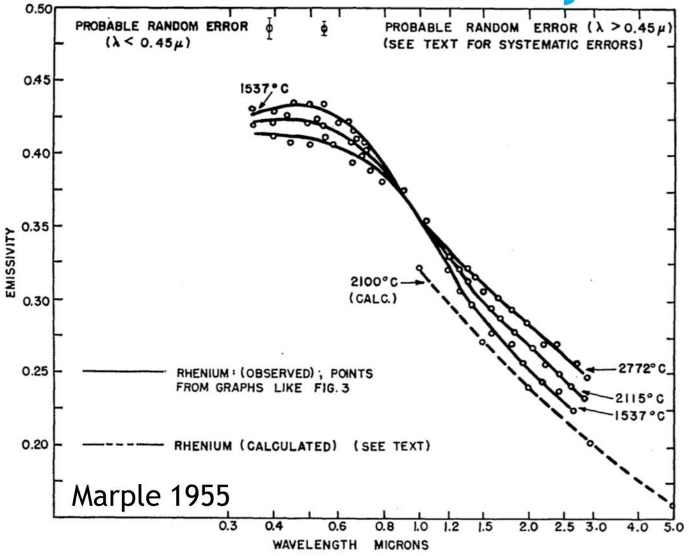
AOTF Imaging Pyrometry of Rocket Motor Nozzle

Rocket Motor System

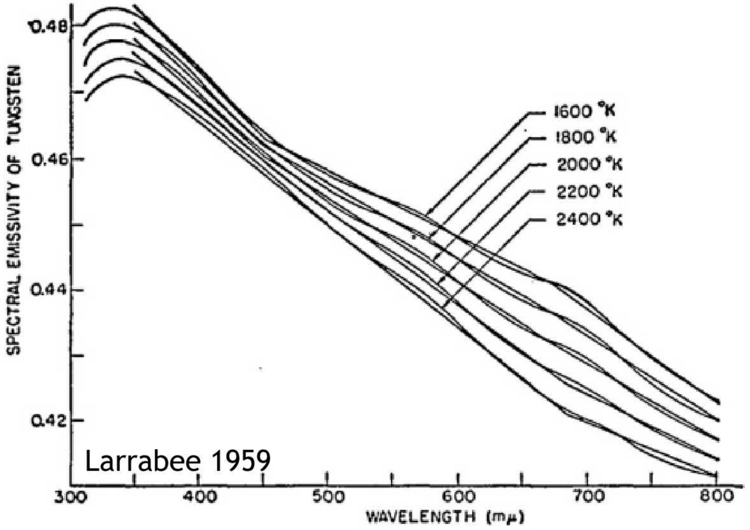


- Propellants (non-metalized) with 10 to 45 second burn times
- Thrust vanes reduce efficiency but provide ability to steer
- Materials
  - Rhenium, melting temperature ~3458K
  - Tungsten, melting temperature ~3695K
- Diagnostics
  - Temperature sensitive paint – May not survive the higher temperatures, would change the vane geometry
  - Fluorescence or absorption – External illumination needed.
  - Emission spectroscopy or Pyrometry – Can be measured with the same technique if materials are gray or similar.

Rhenium Emissivity



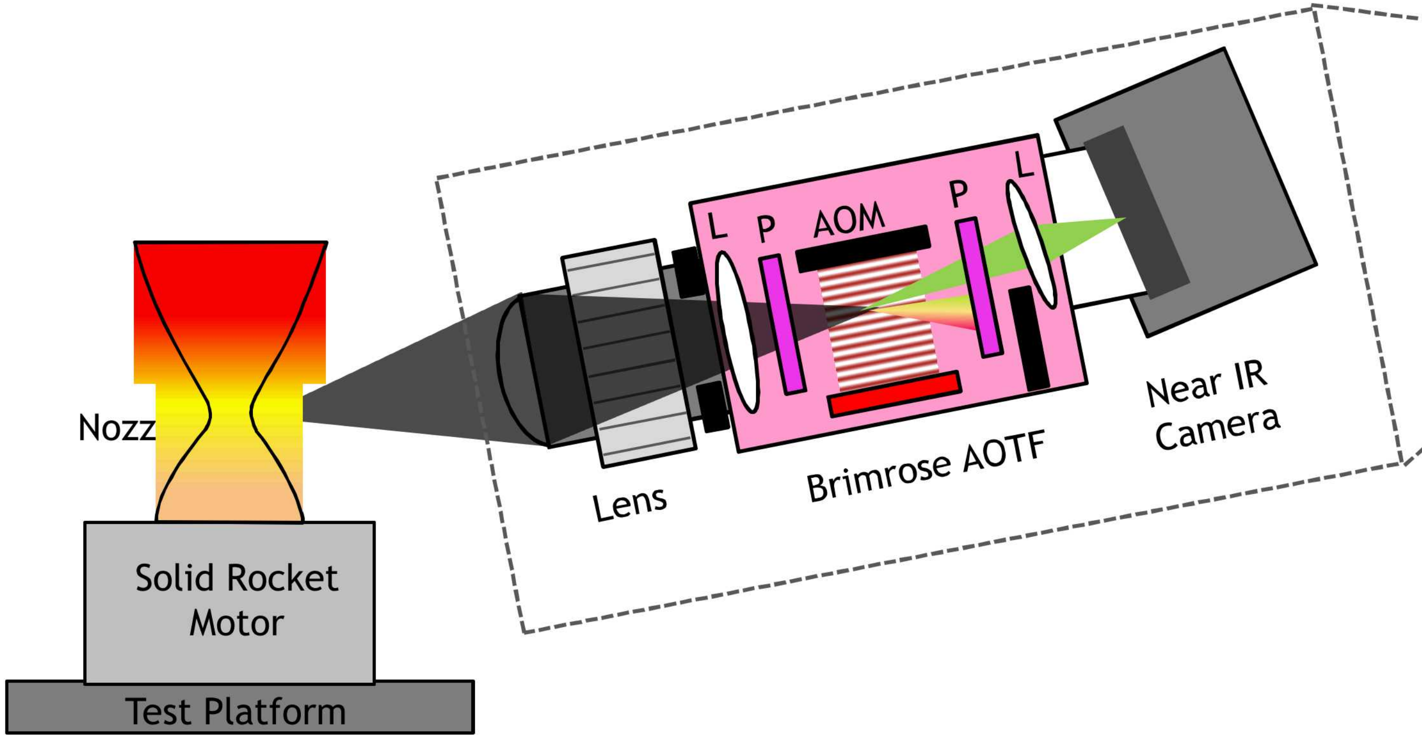
Tungsten Emissivity



Sandia National Labs High Altitude Chamber (HAC) Facility

- 27-foot (~8 m) diameter vacuum sphere
- 1 of 3 vacuum spheres for SNL hypersonic wind tunnel
- Simulate altitudes ≤230,000 feet (70,000 m, 35 mTorr)
- ~20 min to pump down
- Applications:
  - Explosive and pyrotechnic testing
  - Ejection, inflation, and free-fall testing
  - Testing centrifuge to 600 rpm
  - Test articles up to 1-ton and 60” diameter

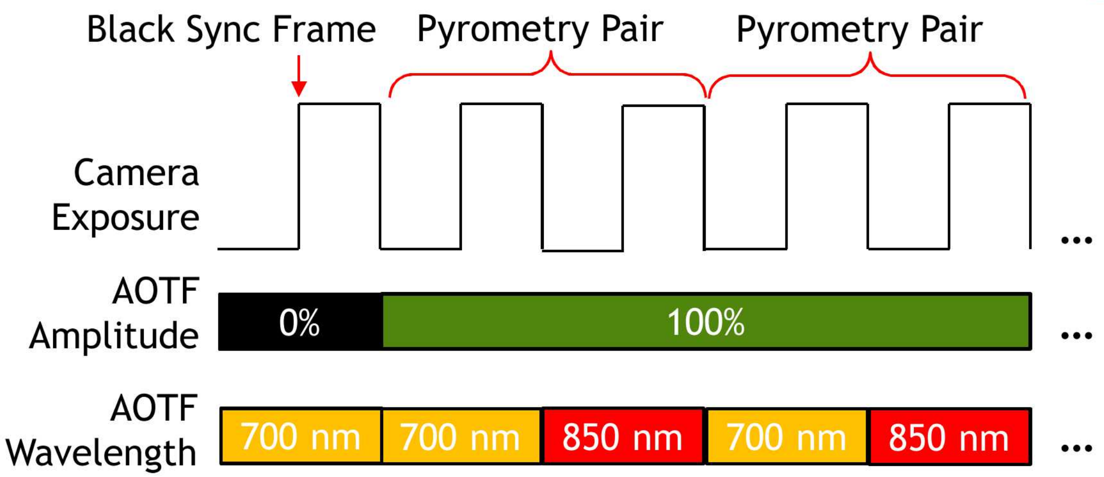
Experimental Setup



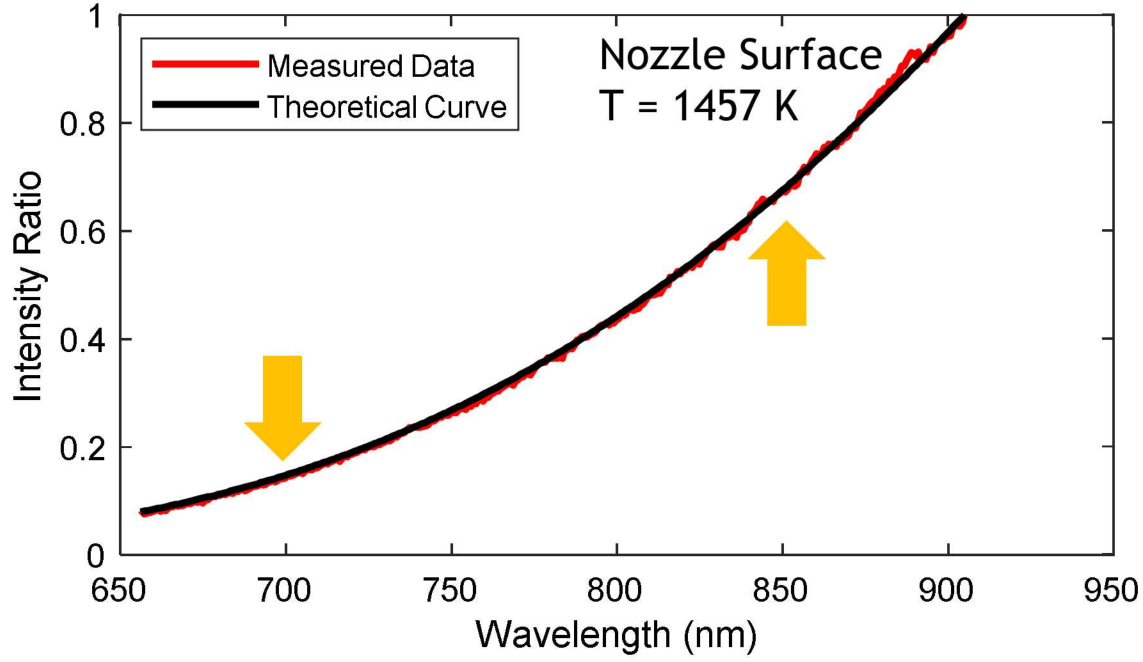
- Emission above ~800 K can be measured in the visible & near IR range
- Brimrose Acousto-Optic Tunable Filter (VA310-.55-1.0, 550 to 1000 nm, 1.5 to 7 nm, f/8 max lens aperture)
- Near IR Camera (Manta G-145 NIR, 12-bit, 1388 × 1038 pixels, 6.45 μm pixel size, 33 dB gain max)
- Synchronized at 9 Hz (LabVIEW, Brimrose, and camera communications)
- AOTF pyrometer placed inside vacuum-proof box
- Line-scan infrared spectrometer (Spectralline model ES200, 1.2 to 4.6 μm range)
- Visible spectrometer (Ocean Optics USB2000+) and power cables placed in instrumentation chamber

Imaging Considerations

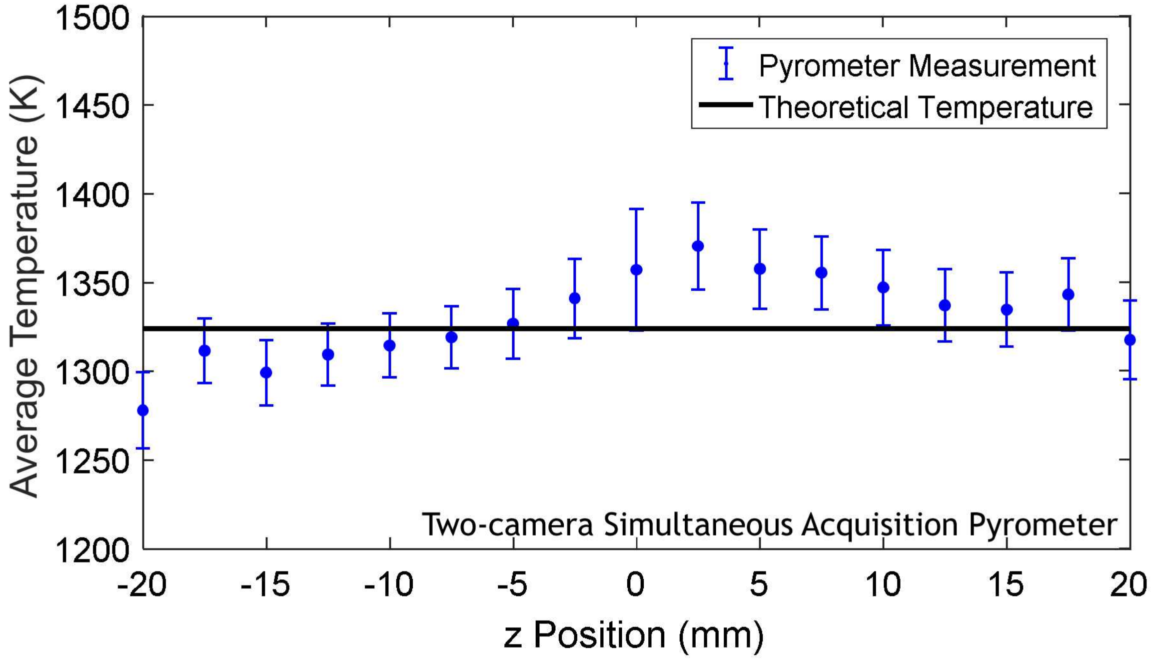
- Choose wavelengths to avoid any non-gray emission peaks
- Several wavelengths were initially collected but the best temporal resolution was obtained using two sequential images + black frame
- Images do not need to be in focus to estimate temperature as long as focal properties are similar



Visible Spectrometer Measurement



Pyrometer Temperature Estimate vs. Focus



Imaging Pyrometer Calculations

- Minimum of 2 colors and the relationship between the emissivities is needed.
- Planck's equation gives:

$$I_p = \frac{2hc^2\epsilon}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda kT}} - 1}$$

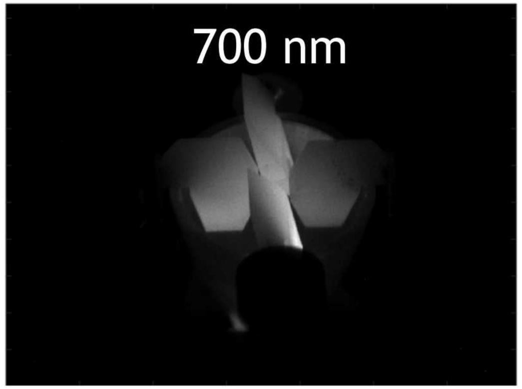
- Wein's approximation is accurate if $hc/\lambda \gg kT$:

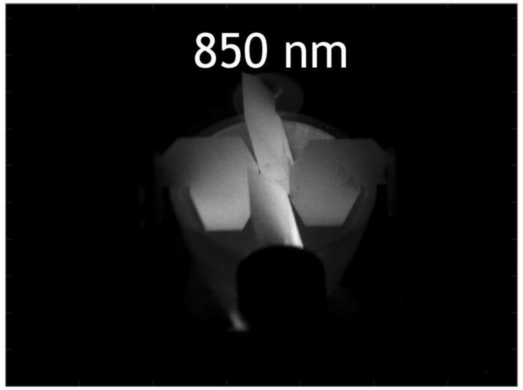
$$I_w = \frac{2hc^2\epsilon}{\lambda^5}e^{-\frac{hc}{\lambda kT}}$$

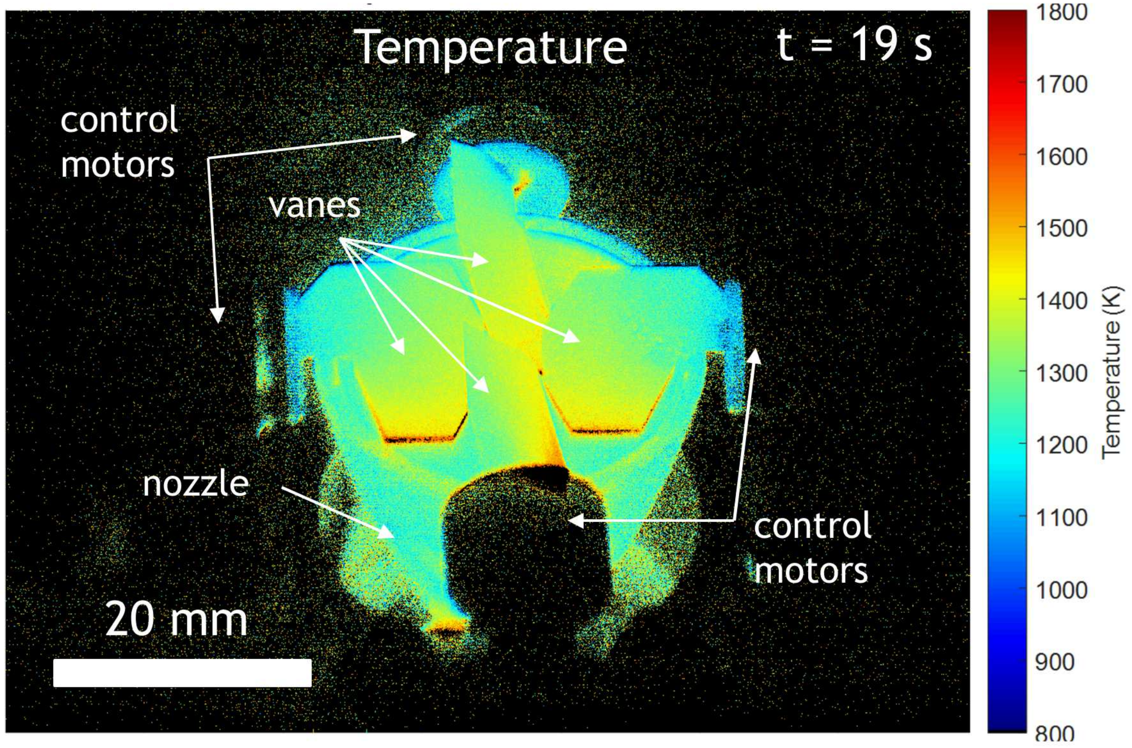
- Dividing intensities and solving for temperature at each pixel:

$$T = \left[\frac{k}{hc}\frac{\lambda_1\lambda_2}{\lambda_2 - \lambda_1}\left(\ln\left(\frac{I_2}{I_1}\frac{\eta_1}{\eta_2}\right) - \ln\left(\frac{\epsilon_2}{\epsilon_1}\right) - 5\ln\left(\frac{\lambda_1}{\lambda_2}\right)\right)\right]^{-1}$$

- Black-body calibration constant $C = \frac{\eta_1}{\eta_2}$
- Assume $\frac{\epsilon_2}{\epsilon_1} = 1$ (gray body approx.) for initial estimates

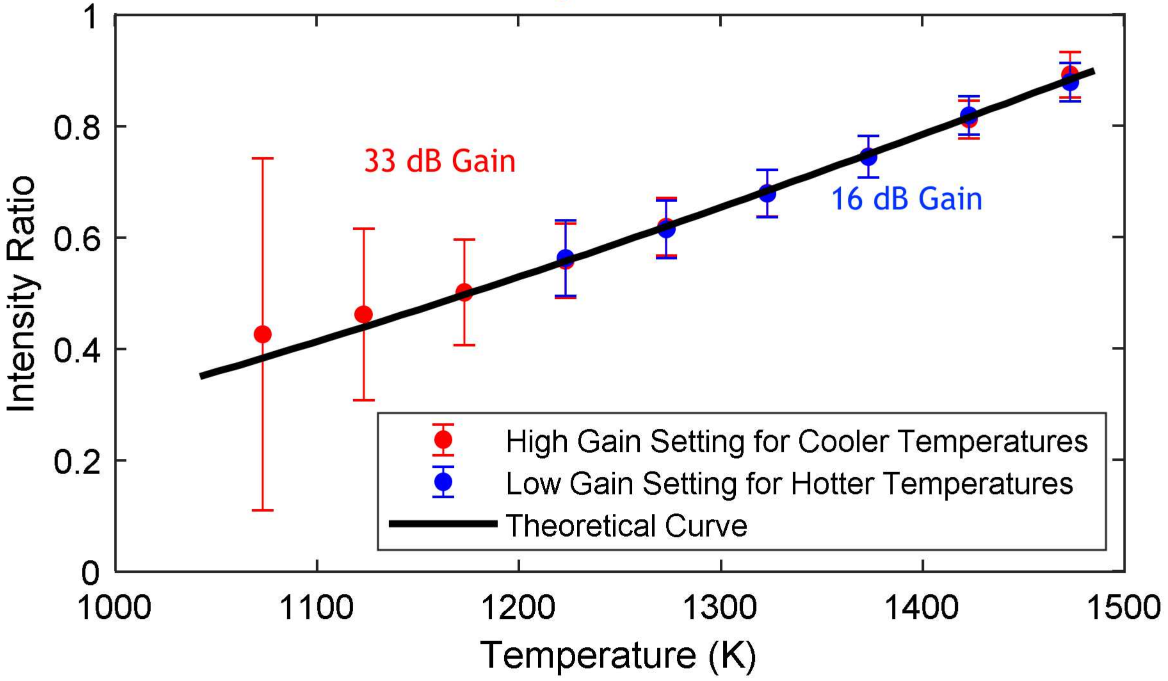




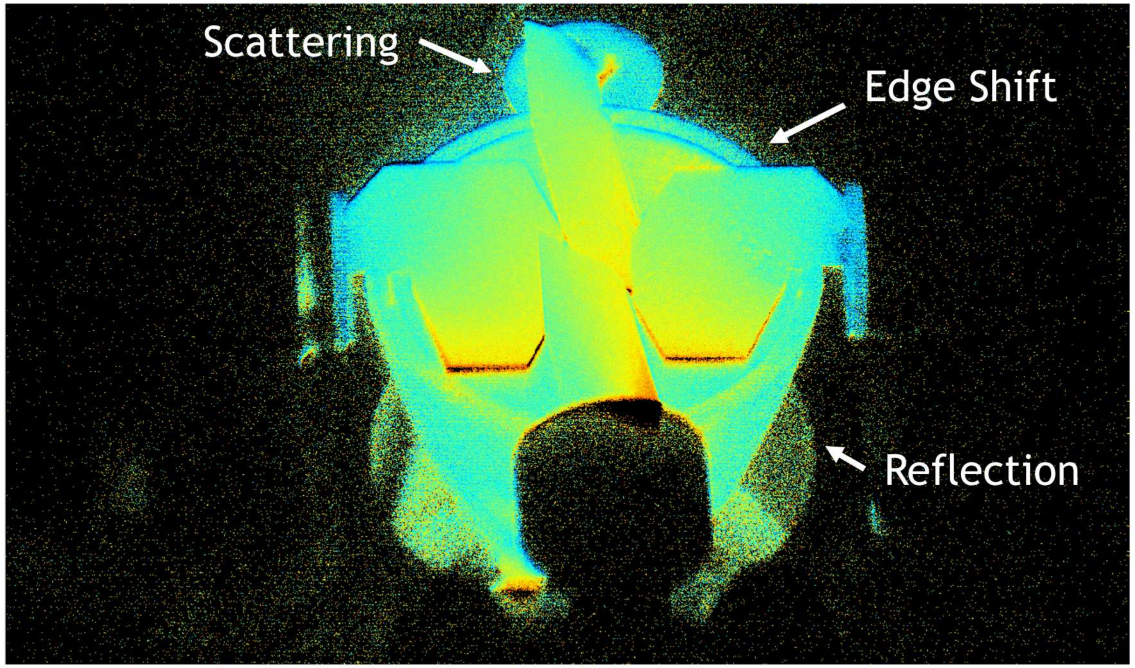


Calibration and Sources of Error

Black Body Calibrations



Temperature Interpretation



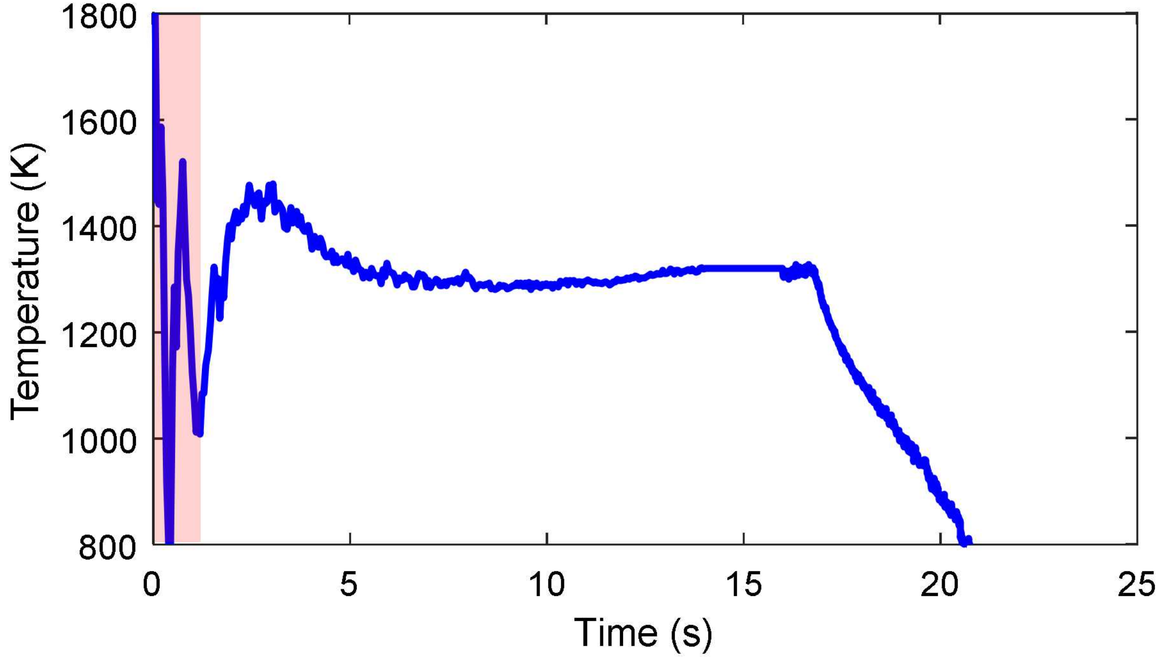
Calibration

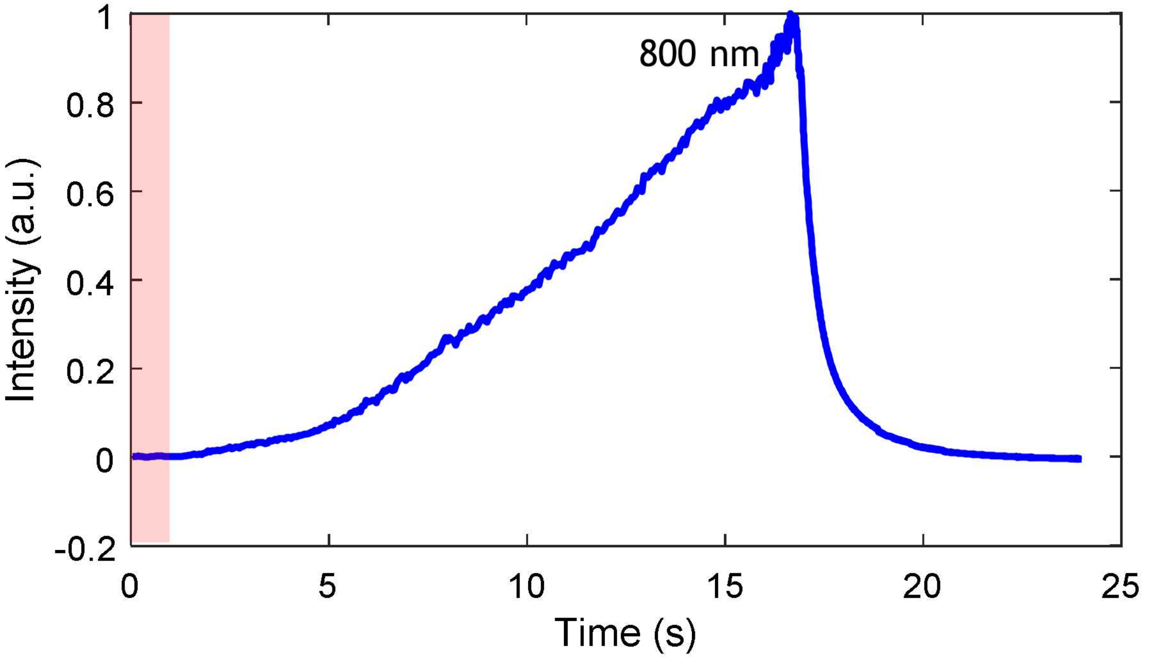
- Black body calibration up to 1500K (Infrared Systems Development Corp. IR-564/301).
- Changing camera gain produces noisier estimates of lower temperatures

Sources of Error

- Low intensities (low emissivity or low temperature)
- Reflections and diffuse scattering
- Lens + AOTF diffracts wavelengths differently (~1 pixel vertical shift). Estimates at edges of objects are affected.

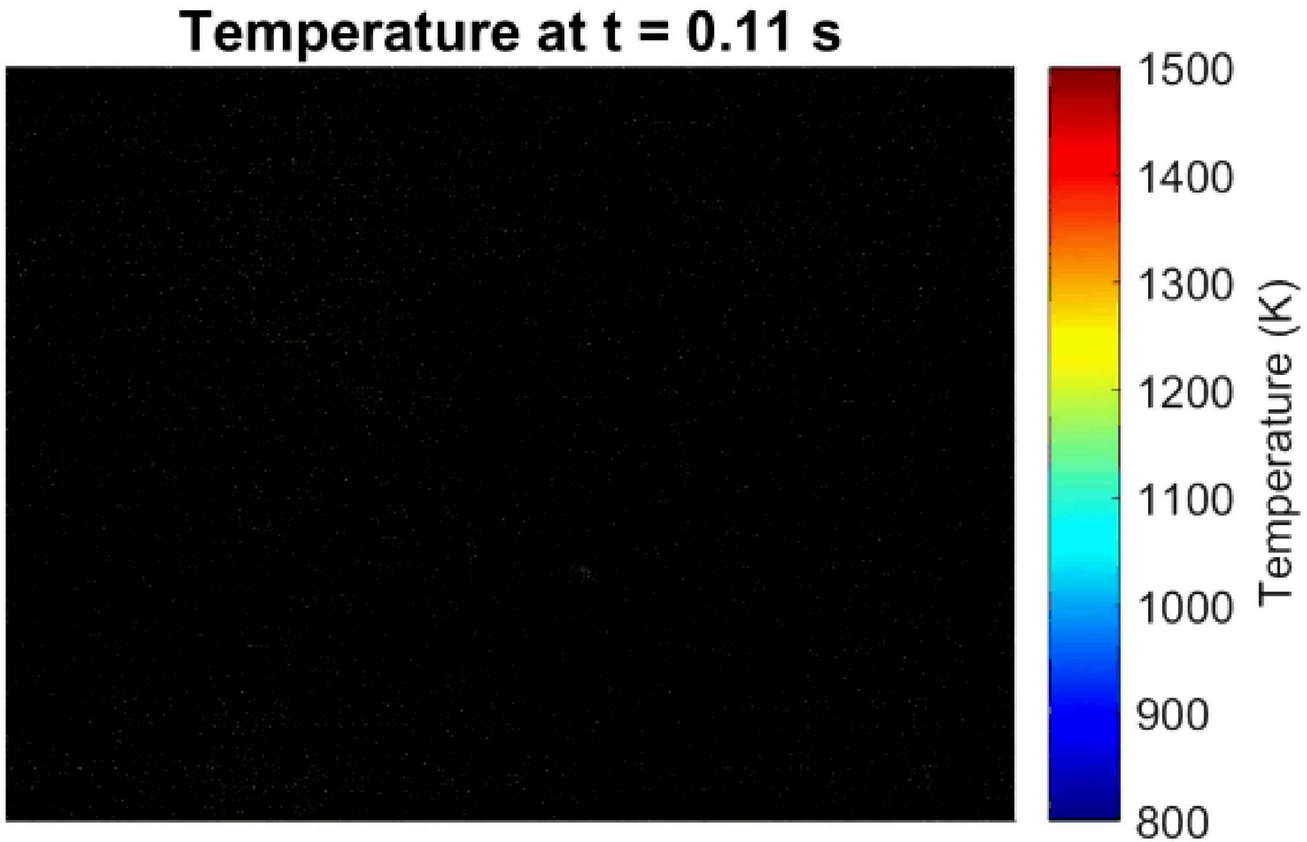
Time-resolved Visible Spectrometer Measurements



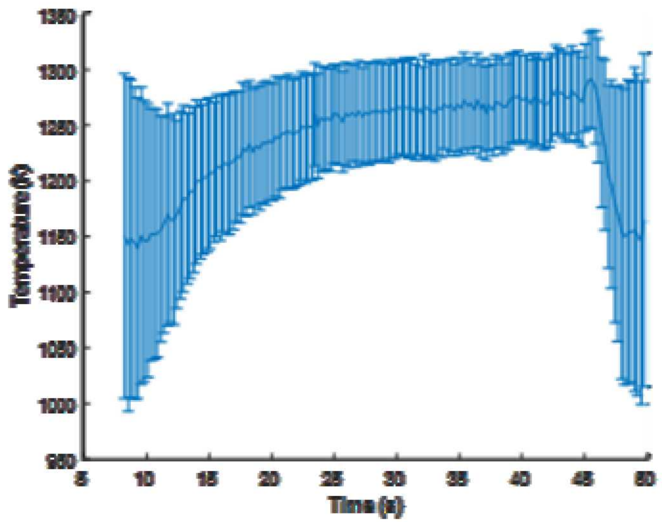


- To verify temperature ranges, a visible point spectrometer aimed at the nozzle throat.
- The spectrometer was calibrated with a black body and temperature was estimated from a fit.
- Initial intensities were low leading to inaccurate temperature estimates (pink region).
- As the intensity increased, the temperature estimates became more consistent. The average temperature at the nozzle for this run was between 1280 and 1460 K.
- Although the temperature was relatively constant, the intensity increased steadily over time. This may be due to soot buildup over time, scattering from other areas as they get hot, etc.
- Lower temperatures (800 K) can be measured after propellant burnout.

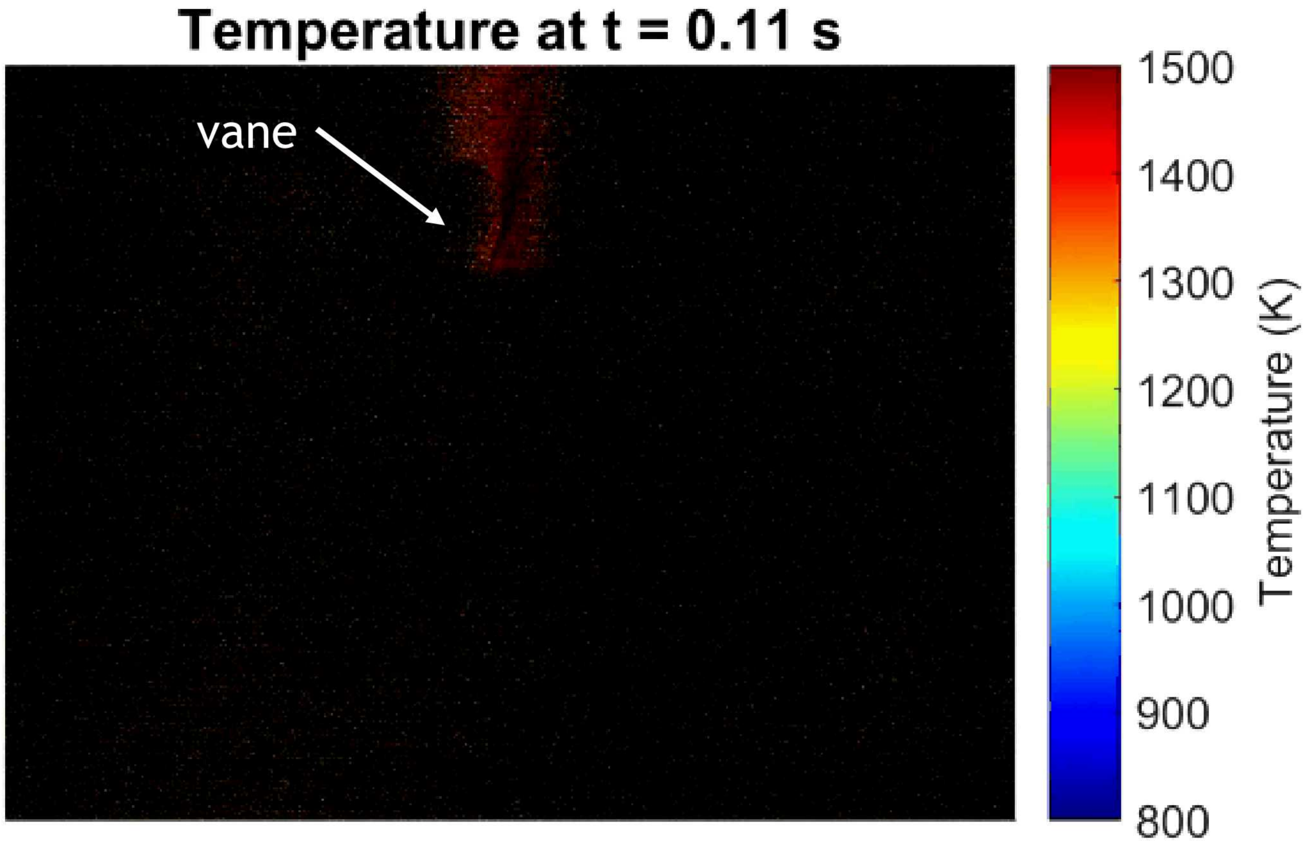
Nozzle Temperature Profile



- Nozzle is hottest just below the throat.
- Temperature spreads from the center and approaches an equilibrium.
- When propellent burns out, the temperature of the nozzle equilibrates across the nozzle before cooling.
- View factor effects from curvature visible near nozzle throat.
- Heating comes from inside the nozzle and temperature is measured from the outside, causing an initial heating delay.

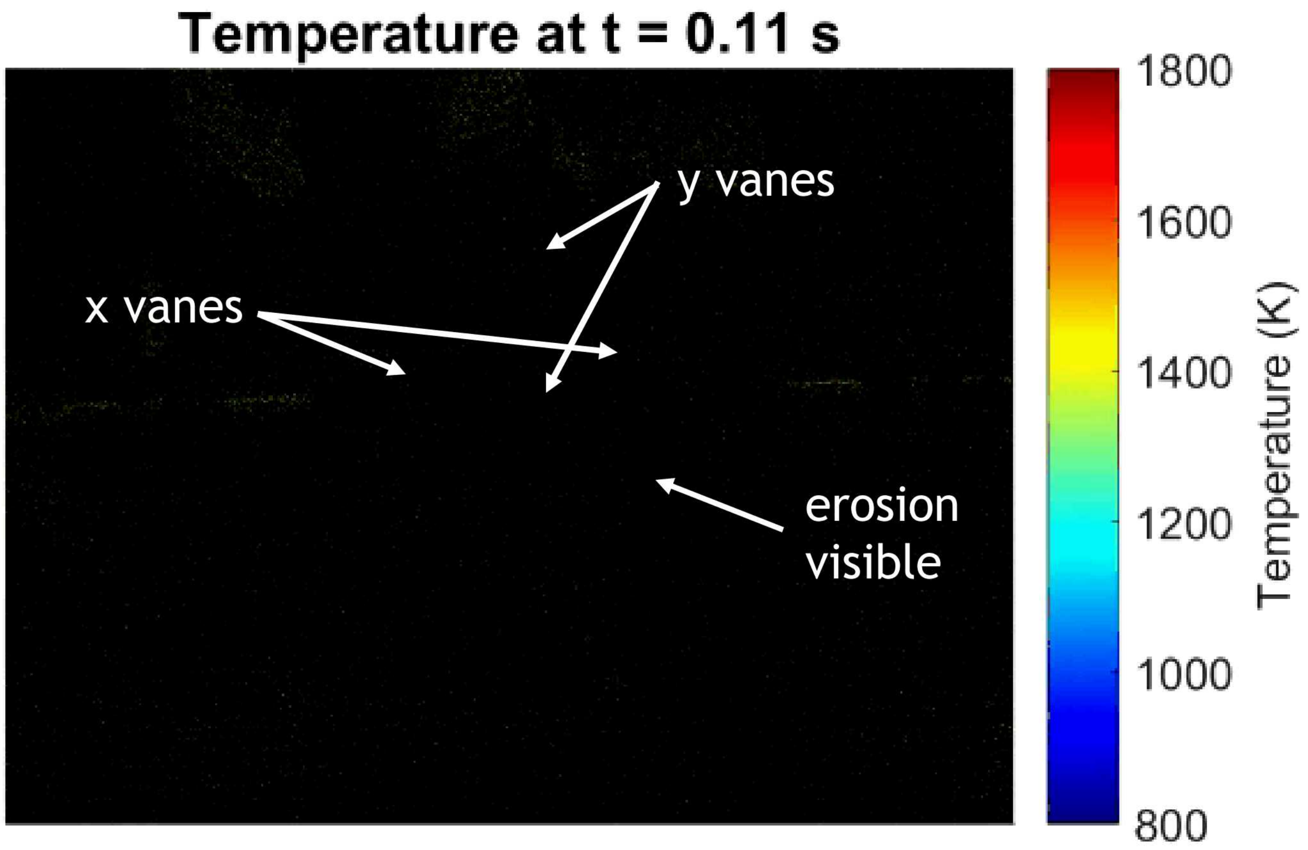


Nozzle with Single Vane



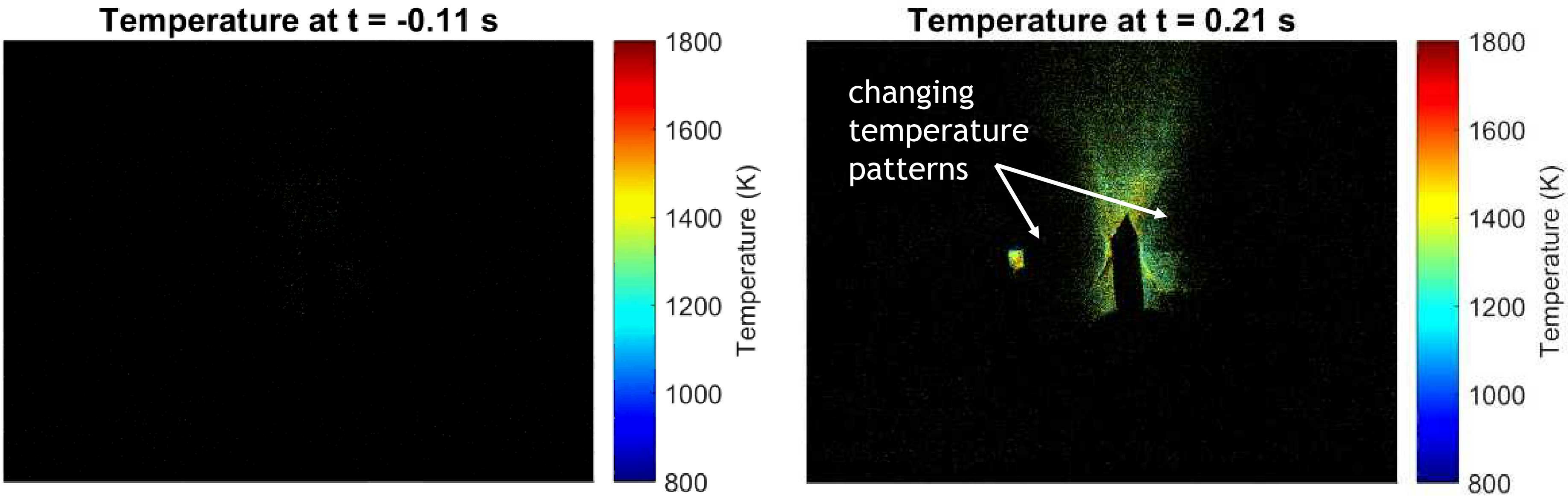
- Higher temperature propellant grain used to test nozzle and vane
- Initial grain ignition can be seen at the beginning.
- Nozzle throat and bottom of vane get hot at the same time, nozzle eventually gets hot as well.
- Leakage at the bottom seam between the nozzle and the case.
- Shock-wave distortions and optically thick flames are possible sources of error at the bottom of the vane (intensity of images are not high, but estimated temperatures are large).
- Intensity saturation due to hotter propellant grain. Experiments were later set to higher maximum temperatures and saturated pixels set to black.

Vane Temperature Profiles



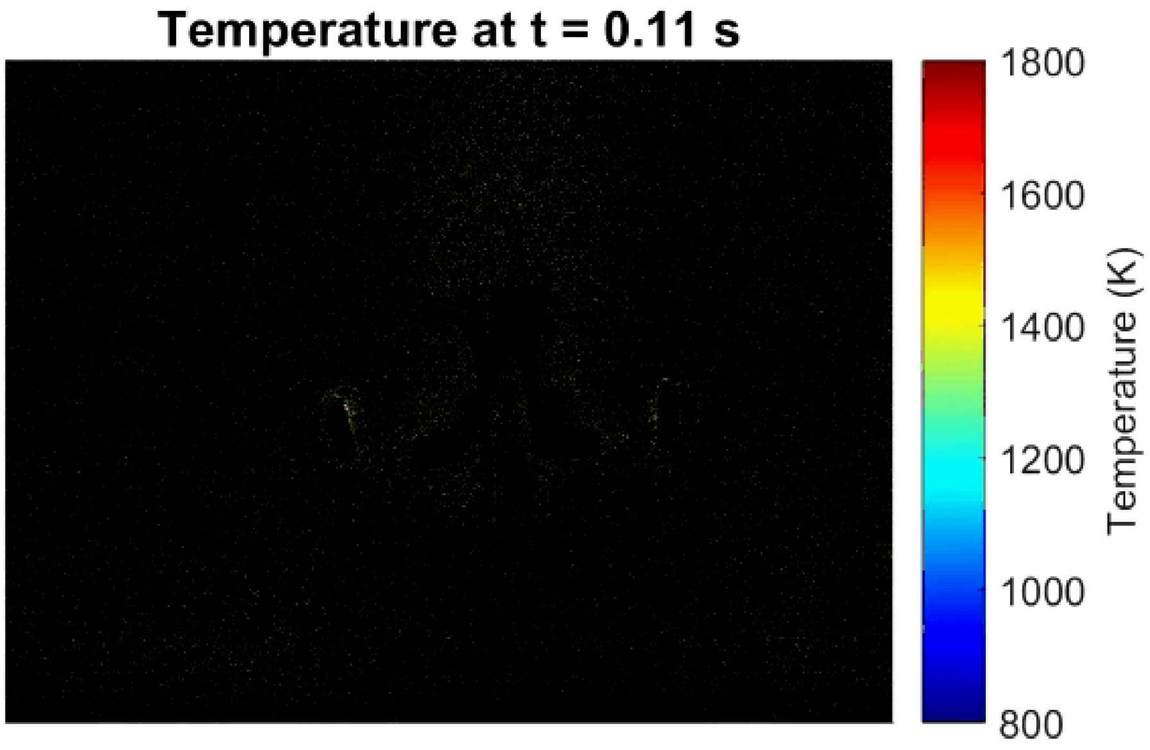
- Experiment with multiple vanes were conducted.
- Different vane materials and small differences in geometry were tested.
- In order to see the vane surfaces, the imaging system had to be tilted facing downwards into the nozzle. Changes in tilt on the fly would have been difficult to do with a larger, more complex imaging pyrometer system.
- Erosion is visible on one of the vanes. This experiment has no moving vanes.

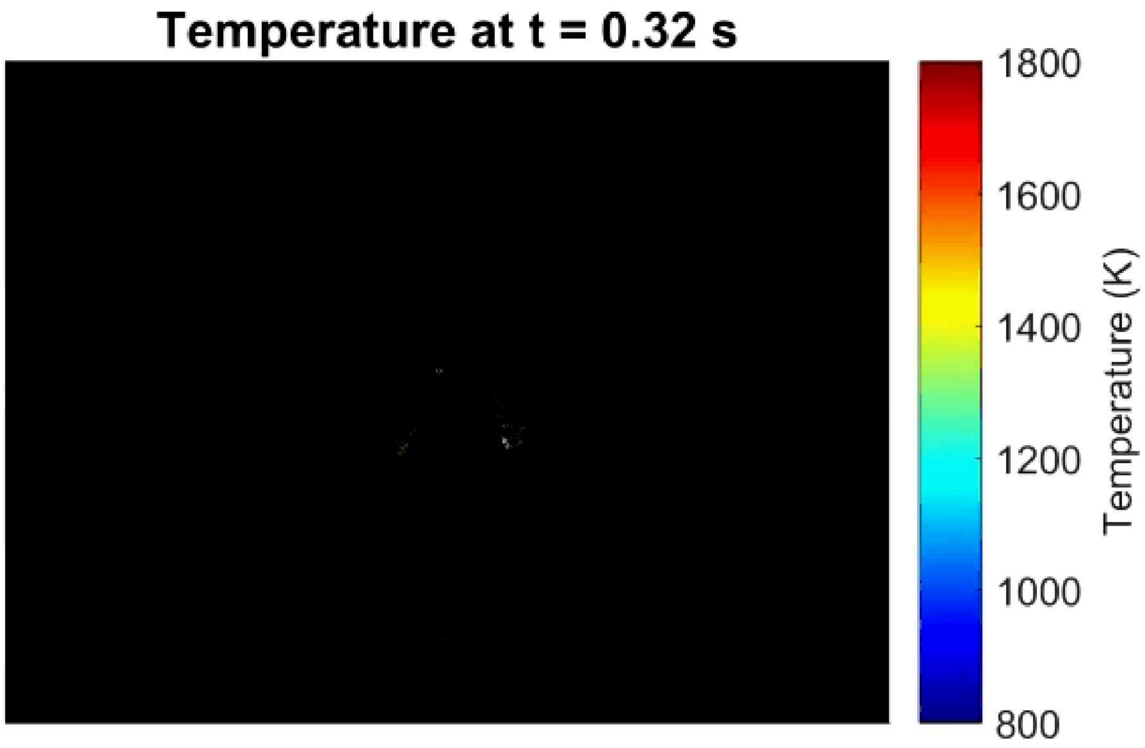
2 Moving Vanes



- Experiments with two moving vanes were conducted to test thrust vectoring.
- In some experiments, different temperature patterns can be seen on the stationary vanes, likely corresponding to changes in flow and changes in shockwave shapes.

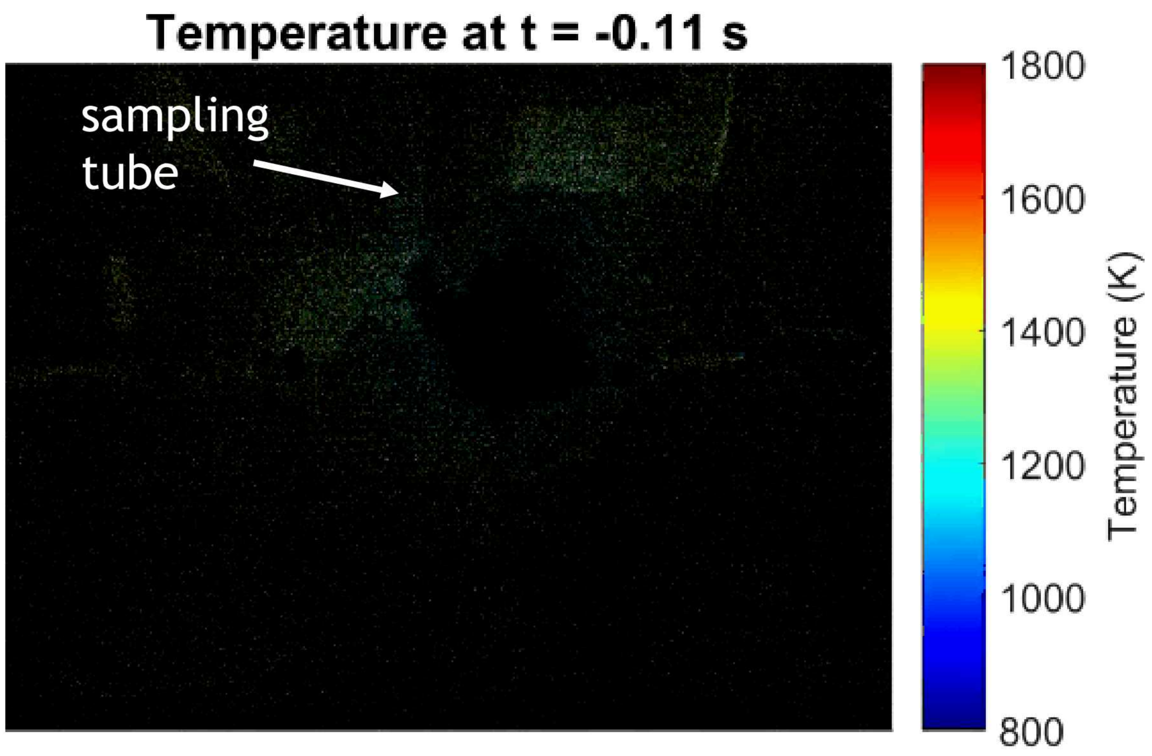
4 Moving Vanes

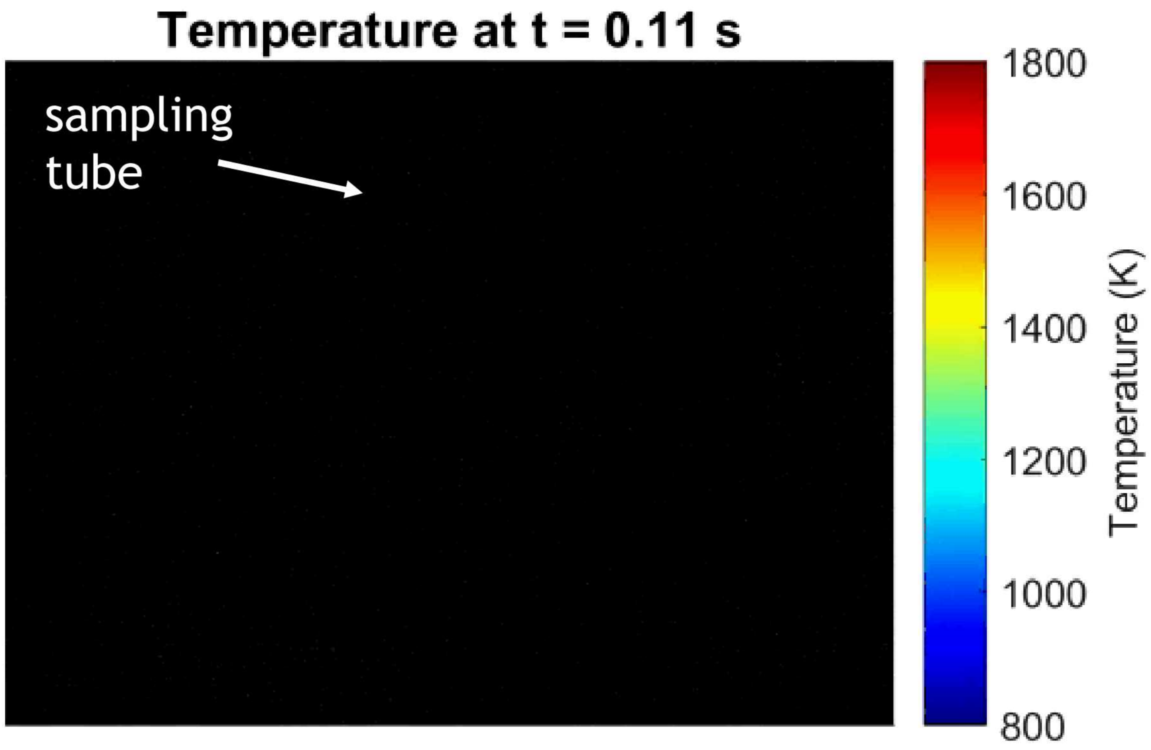




- Additional experiments were conducting with 4 moving vanes.
- X and Y rotation motions were tested in addition to twisting (rotation).

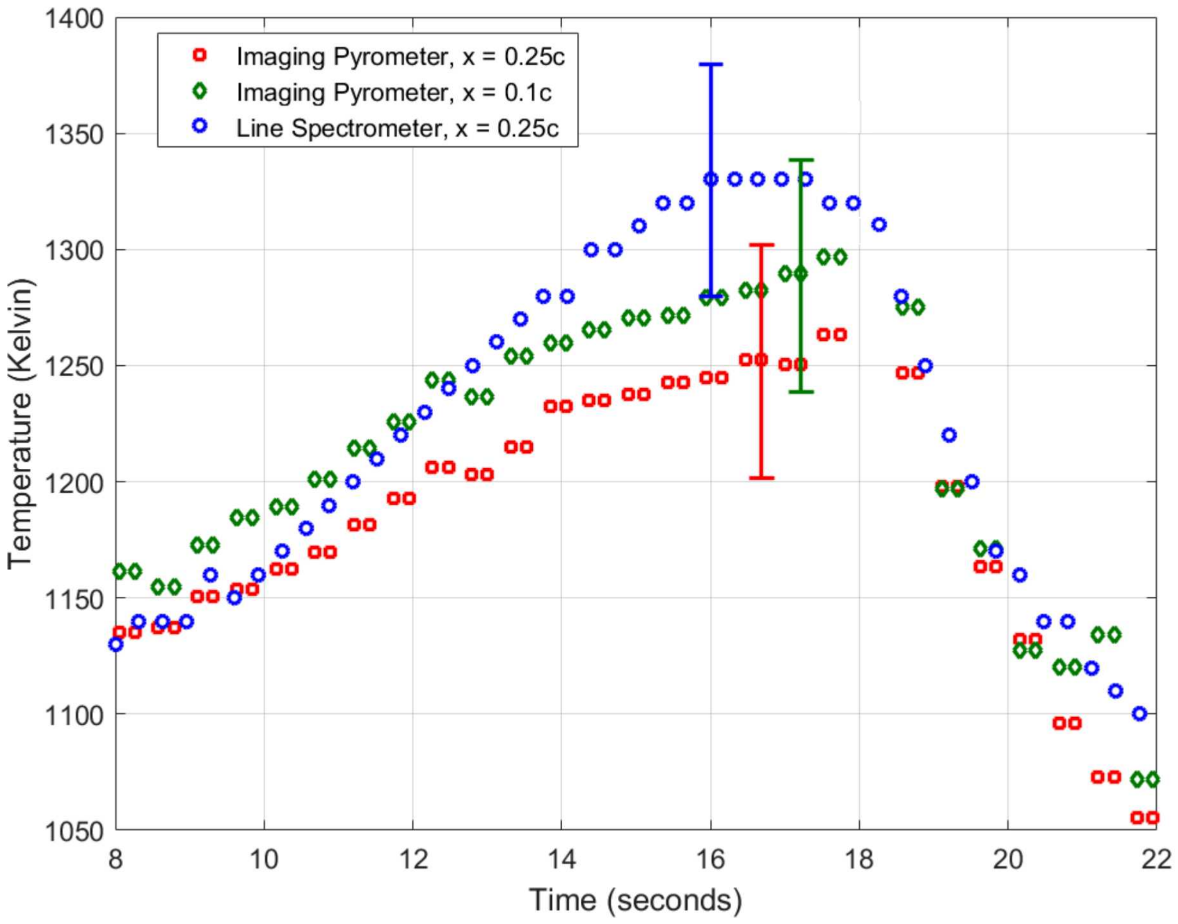
Additional Artifacts





- Experiment with sampling tube to estimate flow properties.
- Right: camera and rocket motor not bolted with respect to one another.
- Shaking of the camera between frames causes misalignment of the images and poor temperature estimates near edges. Large temperature swings between frames are also a source of error.
- Flow pushes sampling tube out of the way.
- Melting features visible at the top of one of the vanes.

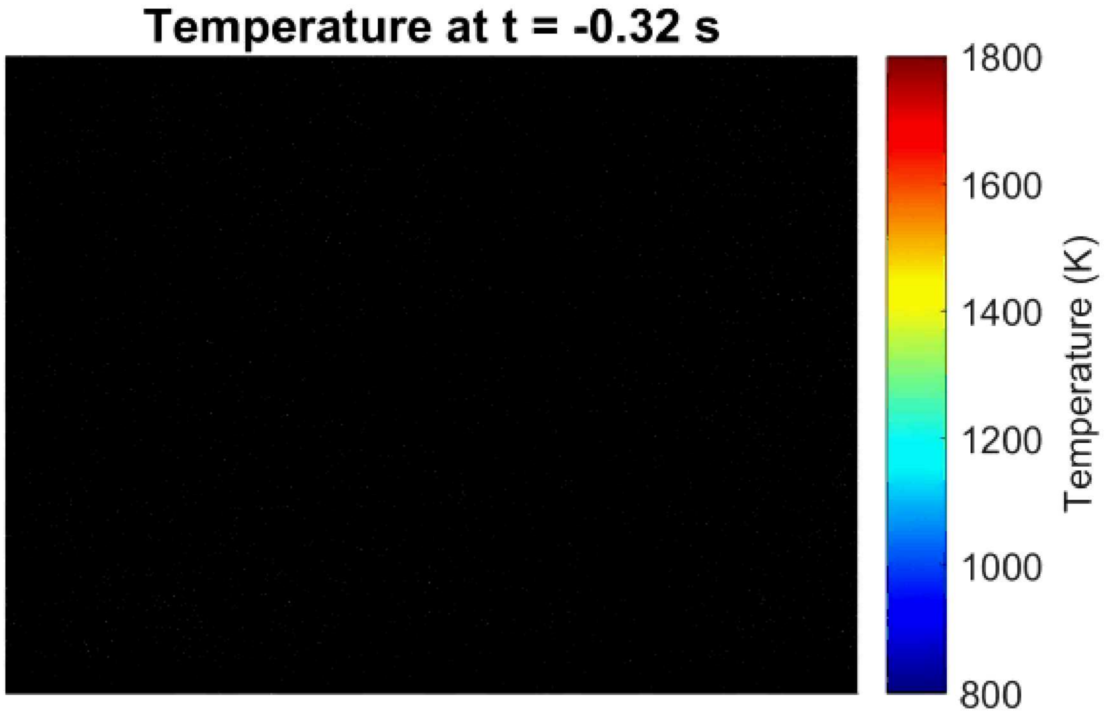
Comparison with IR Line Spectrometer

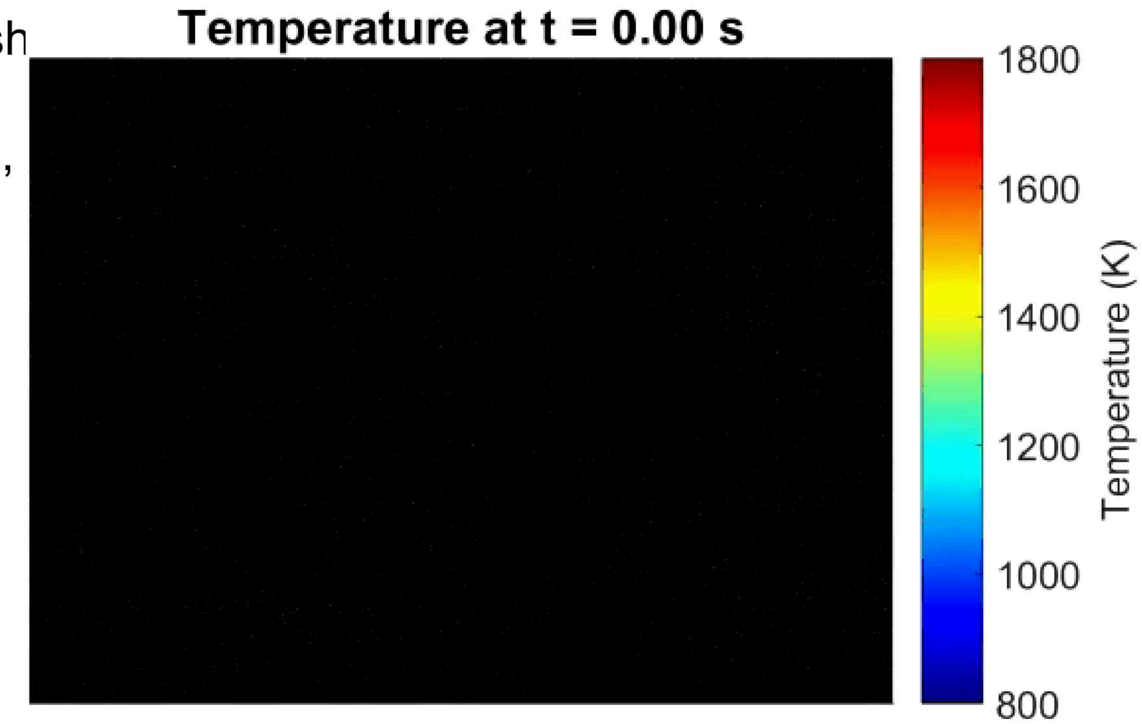


- Comparison of AOTF pyrometry at different locations with maximum temperature from IR line spectrometer show similar temperature ranges.
- Line spectrometer data is fit with a single emissivity and a single temperature estimate.
- Both datasets initially assume gray-body emission (emissivity is constant across all wavelengths).
- Therefore, both datasets are biased.
- Using literature emissivity values, the AOTF pyrometer data can be corrected.
- Note that this correction does not take into account sooting effects from the propellant burn.

Conclusions

- **<u>Compact imaging pyrometry</u>** system using an **<u>AOTF</u>** was created for use in **<u>high-altitude vacuum chambers</u>**.
- The topology works well for experiments that need to be easy to realign and reposition.
- The fine linewidths of the AOTF require longer integration times → best suited where temperatures change slowly.
- Measured surface temperatures of rocket motor nozzles and vanes. Compared pyrometry data with visible and IR spectrometer temperature estimates.
- Interpreting the data requires an understanding of AOTF image shifting, view factors, vibrations, and emissivity





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Questions?

Additional Backup Slides

Backup Slides