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Simultaneous High-Speed Digital In-Line Holography and Pyrometry Measurements of Aluminized Solid Rocket Propellant Combustion

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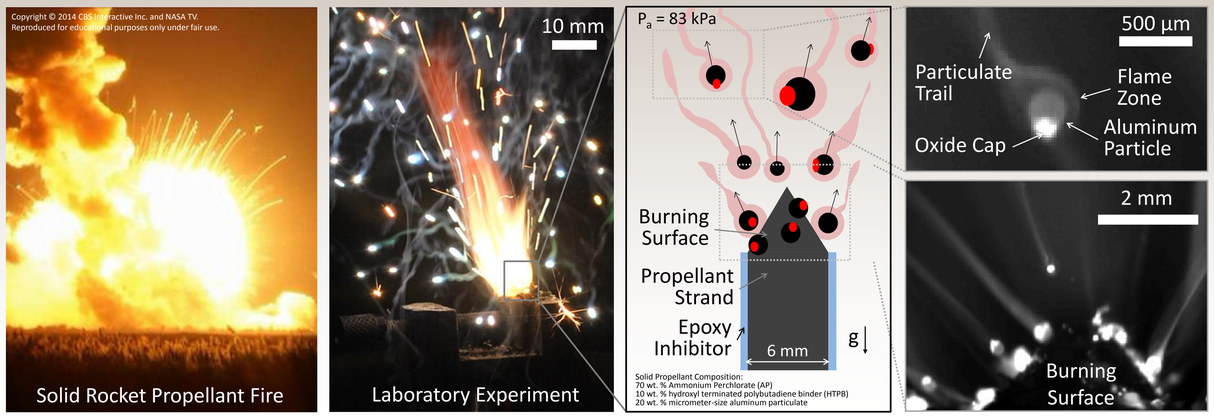
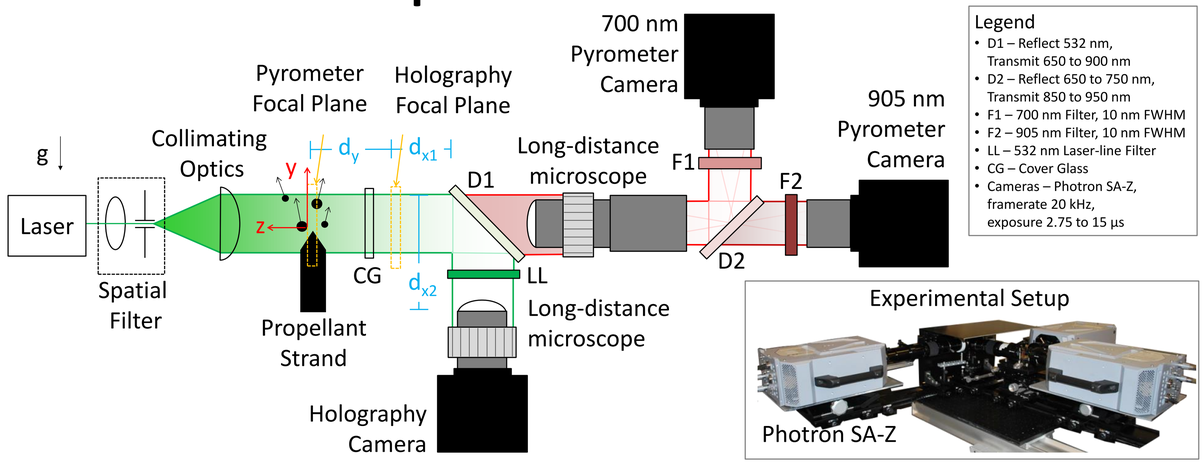
Diagnostic Development Goals

- Obtain joint statistics of position, size, velocity, and temperature for metal combustion
- Solid propellants contain aluminum particles that agglomerate during combustion
- Joint statistics are used for modeling and assessing propellant performance/risks



Experimental Methods



- High-speed (20 kHz) digital-inline holography (DIH) is used to measure size and location
- Two-color imaging pyrometry is a complementary technique for estimating temperature

Particle Temperature

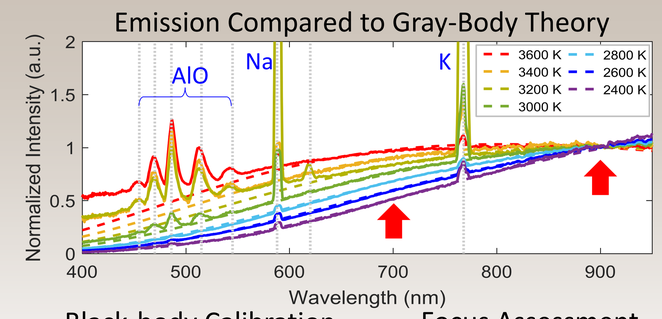
- The emission of aluminum particles is approximated as gray-body
- If $hc/\lambda \gg kT$ then Wien's approximation can be used,

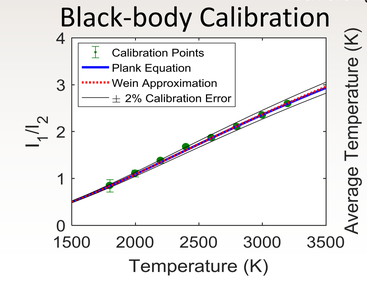
$$I_w = \frac{2hc^2\epsilon}{\lambda^5} e^{-\frac{hc}{\lambda kT}}$$

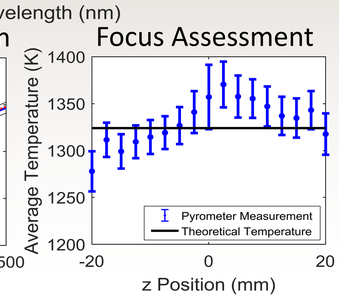
- By comparing two images taken at different wavelengths, the temperature at each pixel is,

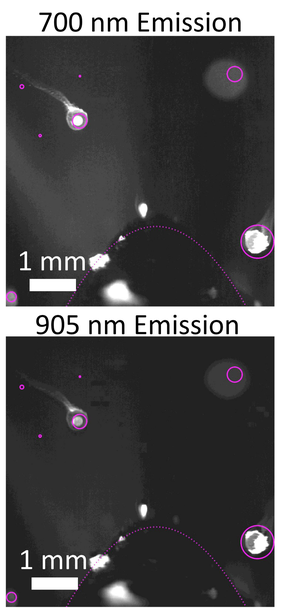
$$T = \left[\frac{k}{hc}\frac{\lambda_1\lambda_2}{\lambda_2-\lambda_1}\left(\ln\left(\frac{I_2}{I_1}\frac{\eta_1}{\eta_2}\right) - 5\ln\left(\frac{\lambda_1}{\lambda_2}\right)\right)\right]^{-1}$$

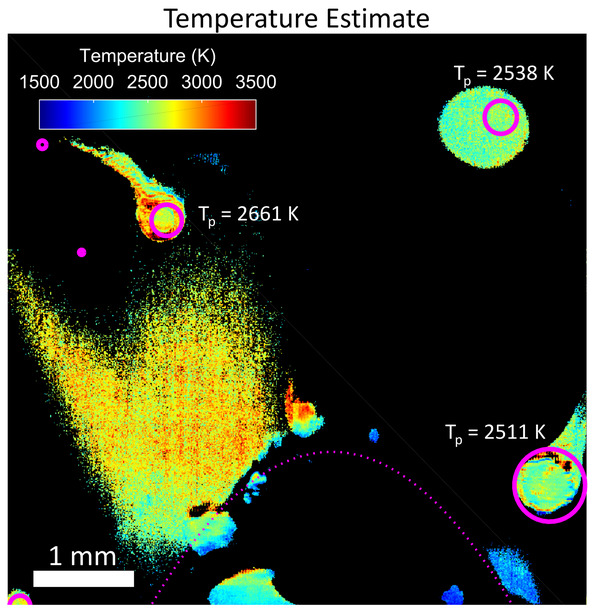
- The constant η_1/η_2 for each pixel is calibrated from a black-body source
- Focus assessment shows <4% temperature variation

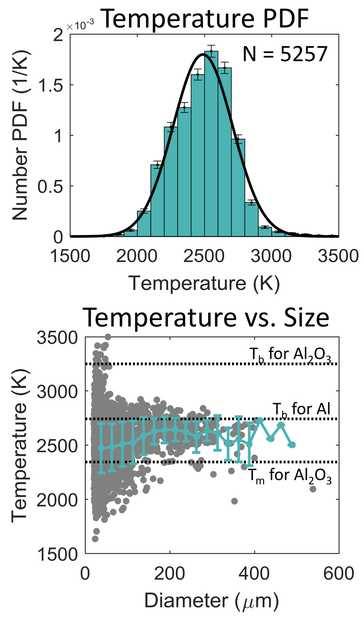




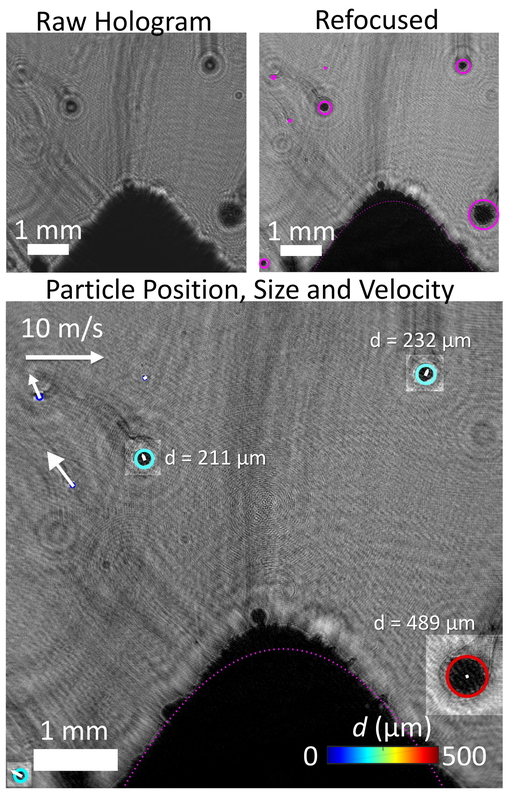








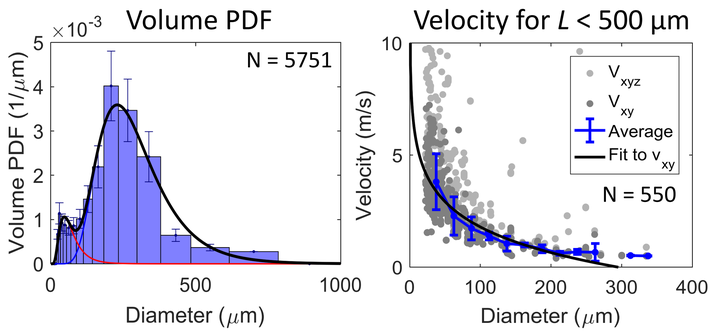
Particle Position, Size and Velocity



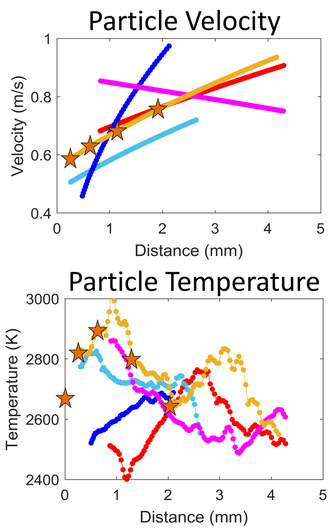
- Raw holograms are collected and numerically refocused by solving diffraction equation for *z*,

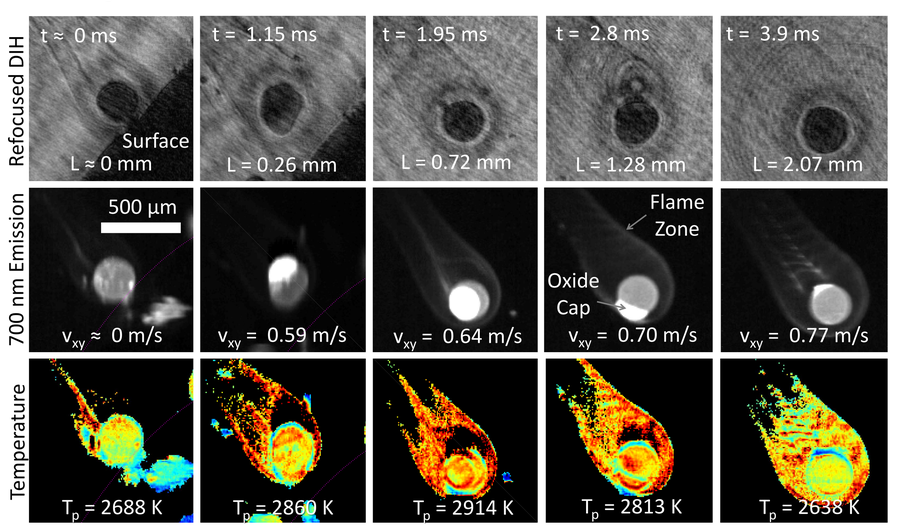
$$E(x,y;z) = [h(x,y)E_r^*(x,y)] \otimes g(x,y;z)$$

- Locations, sizes and distances from the propellant surface (*x, y, z, d, and L*) are automatically processed
- Particle velocities are calculated using tracking across multiple frames; this information can be used to estimate local gas velocities
- Size distributions measure agglomeration effects



Time-Dependent Particle Behaviors





Conclusions and Future Work

- From a single experiment, joint time-dependent position, size, velocity, and temperature statistics are successfully collected and automatically processed using custom algorithms
- Technique is robust and can be applied using high-speed or conventional cameras
- Next step: combine current method with other techniques to assess gas-phase behaviors

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References:
[1] Y. Chen, D. R Guildenbecher, K. N. G. Hoffmeister, M. A. Cooper, H. L. Stauffacher, M. S. Oliver, E. B. Washburn, "Study of Aluminum Particle Combustion in Solid Propellant Plumes using Digital In-line Holography and Imaging Pyrometry," Combustion and Flame, vol. 182C, pp. 225-237, 2017
[2] Y. Chen, D. R. Guildenbecher, K. N. Hoffmeister, P. E. Sojka, "Digital Imaging Holography and Pyrometry of Aluminum Drop Combustion in Solid Propellant Plumes," OSA Imaging and Applied Optics Conference: Laser Applications to Chemical, Security and Environmental Analysis, paper LT4F.2, 2016.
[3] D. R. Guildenbecher, M. A. Cooper, W. Gill, H. L. Stauffacher, M. S. Oliver, T. W. Grasser, "Quantitative, three-dimensional imaging of aluminum drop combustion in solid propellant plumes via digital in-line holography", Optics Letters, vol. 39 (17), pp. 5126-5129, 2014.
[4] D. R. Guildenbecher, M. A. Cooper, P. E. Sojka, "High-speed (20 kHz) digital in-line holography for transient particle tracking and sizing in multiphase flows", Applied Optics, vol. 55 (11), pp. 2892-2903, 2016.