Development of a Compact Self-Aligned Focusing Schlieren System for NASA Test Facilities

Brett Bathel and Joshua Weisberger

Advanced Measurements and Data Systems Branch

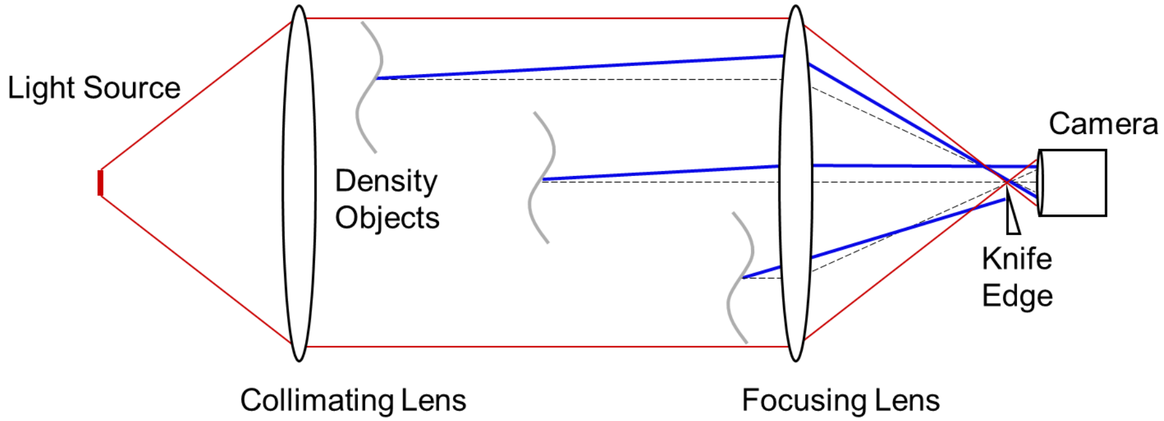
NASA Langley Research Center, Hampton, Virginia, USA

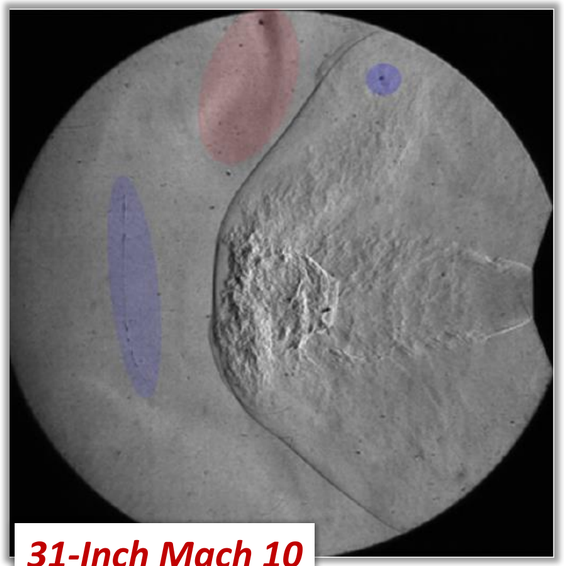
Motivation for the Work

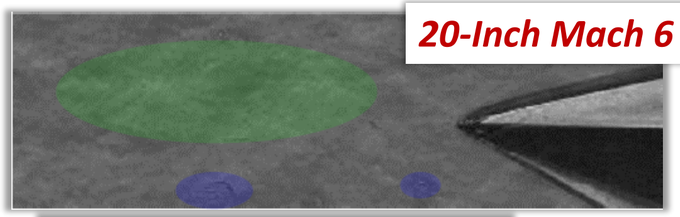
- Schlieren-based visualization of nozzle plume and interaction with lunar/Martian-type surface
  - –Plume/surface interaction
  - –Considered conventional schlieren, background-oriented schlieren (BOS), and shadowgraph

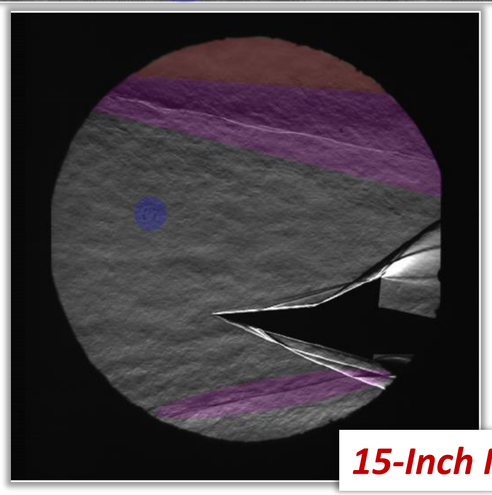
- Development of a focusing schlieren system
  - –Qualities
    - *Filter out flow structures and particles away from object plane*
    - *Good sensitivity at low densities*
    - *Quick to align and will remain aligned*
    - *Compact*
    - *Survivability in low density environments*
    - *Capable of high-speed acquisition*
    - *Insensitive to vibrations*
    - *Change working distance and field-of-view quickly and easily*

- Existing focusing schlieren systems
  - –Most systems difficult to align
  - –Most systems not compact
  - –All sensitive to vibration
  - –Some difficult to adjust working distance and field-of-view







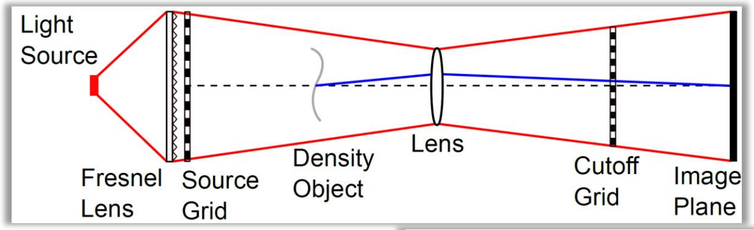


Motivation for the Work

- Schlieren-based visualization of nozzle plume and interaction with lunar/Martian-type surface
  - –Plume/surface interaction
  - –Considered conventional schlieren, background-oriented schlieren (BOS), and shadowgraph

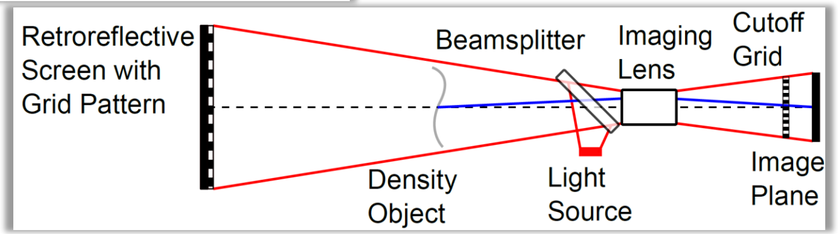
- Development of a focusing schlieren system
  - –Qualities
    - *Filter out flow structures and particles away from object plane*
    - *Good sensitivity at low densities*
    - *Quick to align and will remain aligned*
    - *Compact*
    - *Survivability in low density environments*
    - *Capable of high-speed acquisition*
    - *Insensitive to vibrations*
    - *Change working distance and field-of-view quickly and easily*

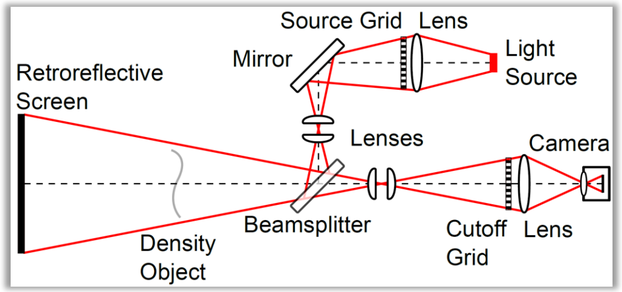
- Existing focusing schlieren systems
  - –Most systems difficult to align
  - –Most systems not compact
  - –All sensitive to vibration
  - –Some difficult to adjust working distance and field-of-view



Refs. 1 & 2

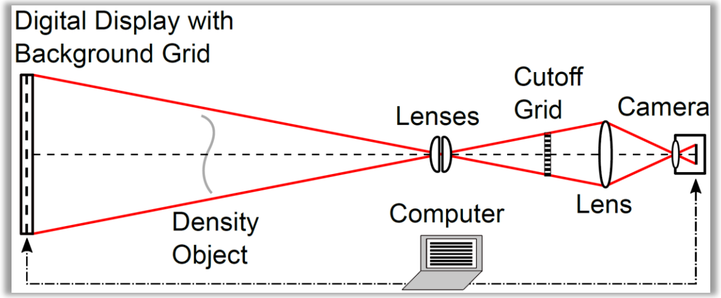
Ref. 3

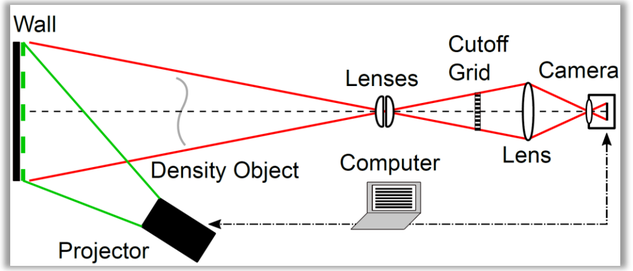




Refs. 4 & 5

Refs. 6-10

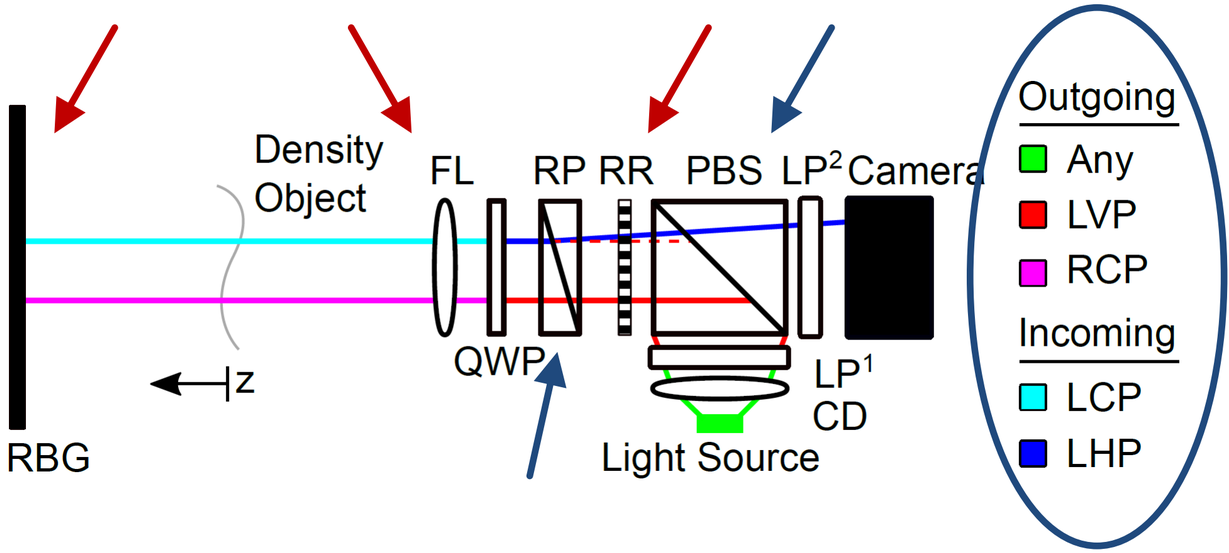




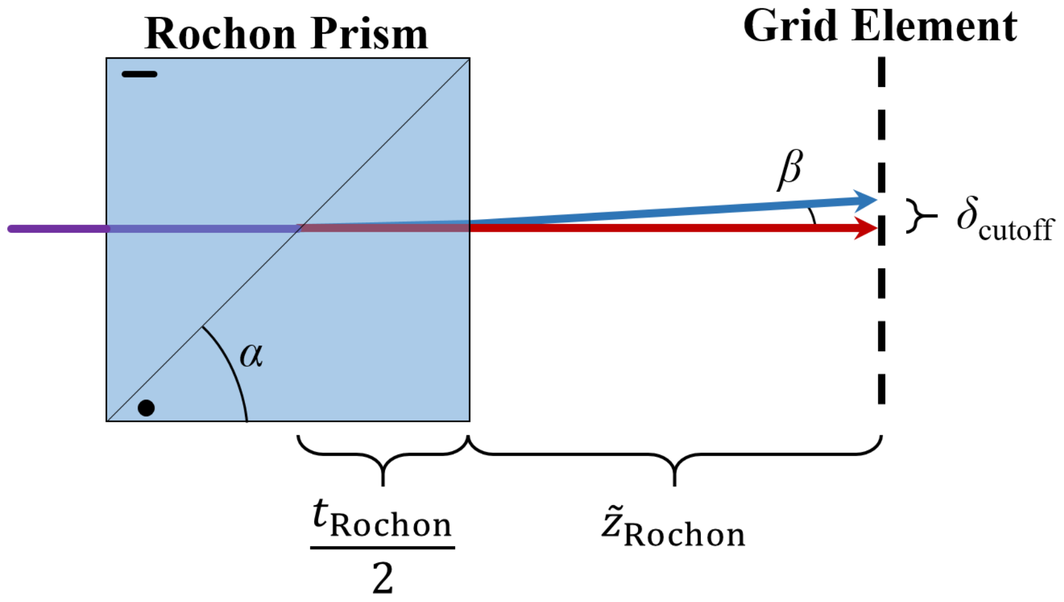
Refs. 6-10

Initial Development of Self-Aligned Compact Focusing Schlieren System

- Self-alignment
  - –Projection of a grid element (*RR*) onto a background
  - –Reimage the projection back onto the original grid element

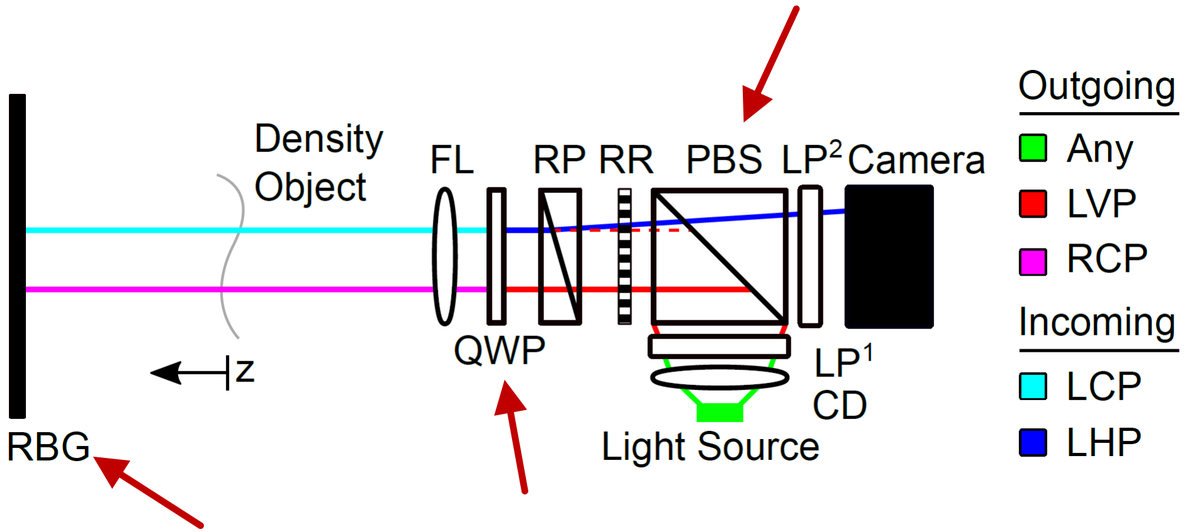


- Sensitivity adjustment
  - –Use of a polarization prism to act on orthogonal components of linear polarized light differently
    - *Rochon prism (RP)*
    - *Outgoing linear vertical polarized (**LVP**) light is unaffected*
    - *Returning linear horizontal polarized (**LHP**) light is refracted by a small angle*
    - *Ideally acts the same in the outgoing and return directions*

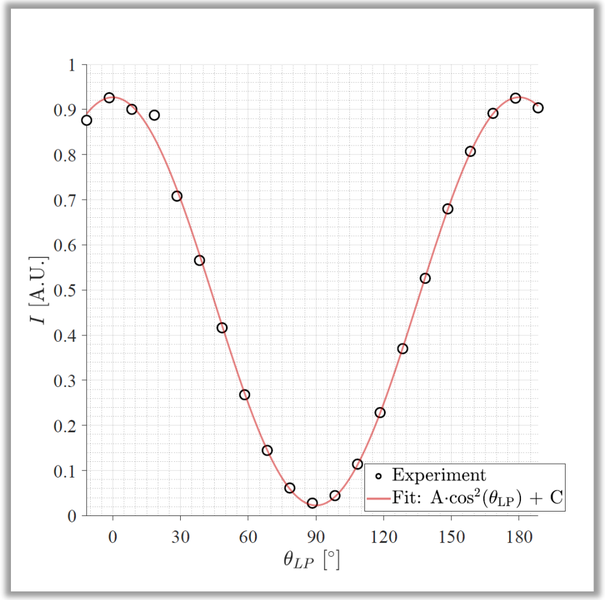


Initial Development of Self-Aligned Compact Focusing Schlieren System

- Retroreflective sheeting to rotate the polarization state
  - Require returning ***LHP*** light to be orthogonal to outgoing ***LVP*** light
  - Construct a simple optical isolator to obtain orthogonal polarizations
    - *Polarizing beamsplitter (PBS)*
    - *Quarter-wave plate (QWP)*
    - *Mirror-like retroreflective background (RBG)*

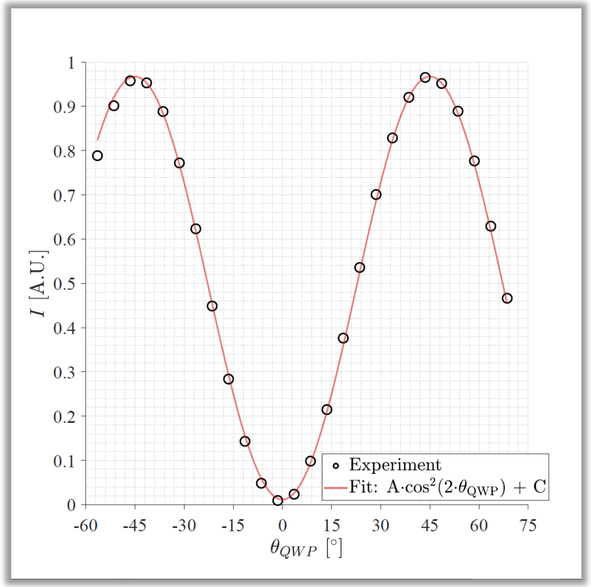


- Polarization performance of retroreflective sheeting
  - Measured ability of *RBG* to preserve linear polarization and reverse handedness of circular polarization
    - *Law of Malus*



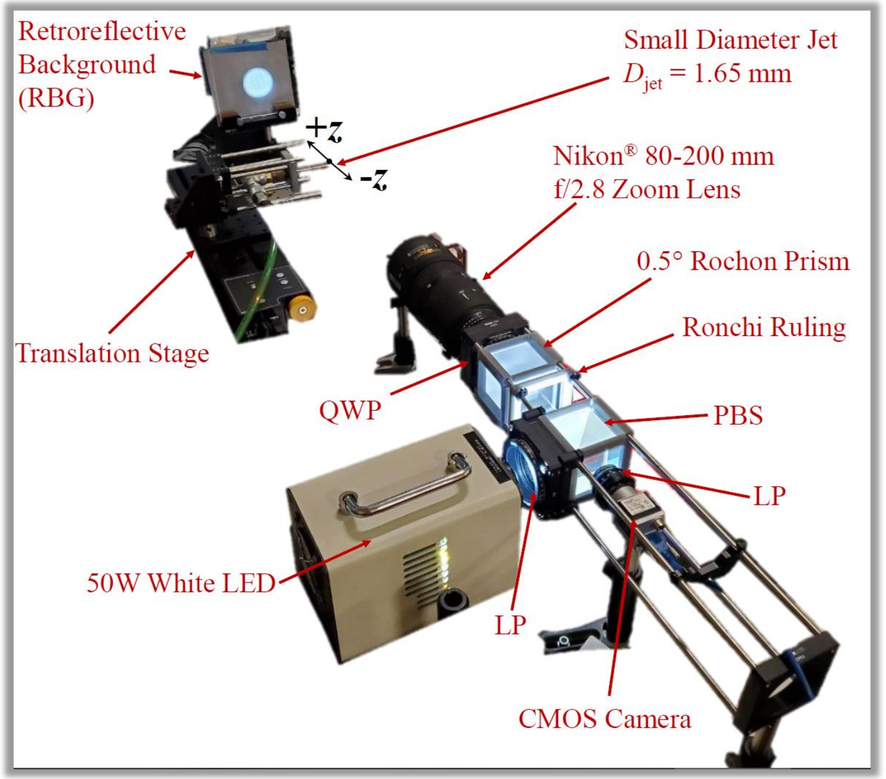
$$I = I_0 \cos^2 \theta_{LP}$$

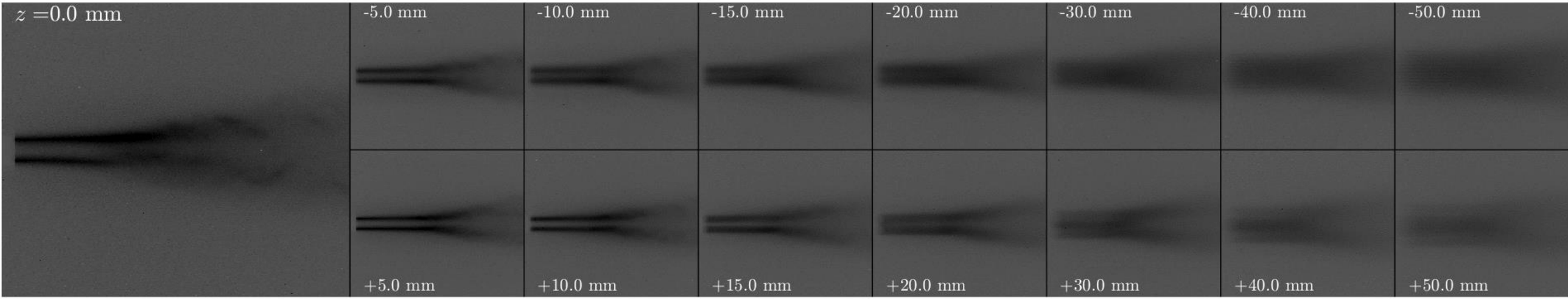
$$I = I_0 \cos^2 2\theta_{QWP}$$



Results: Initial Self-Aligned Compact Focusing Schlieren System

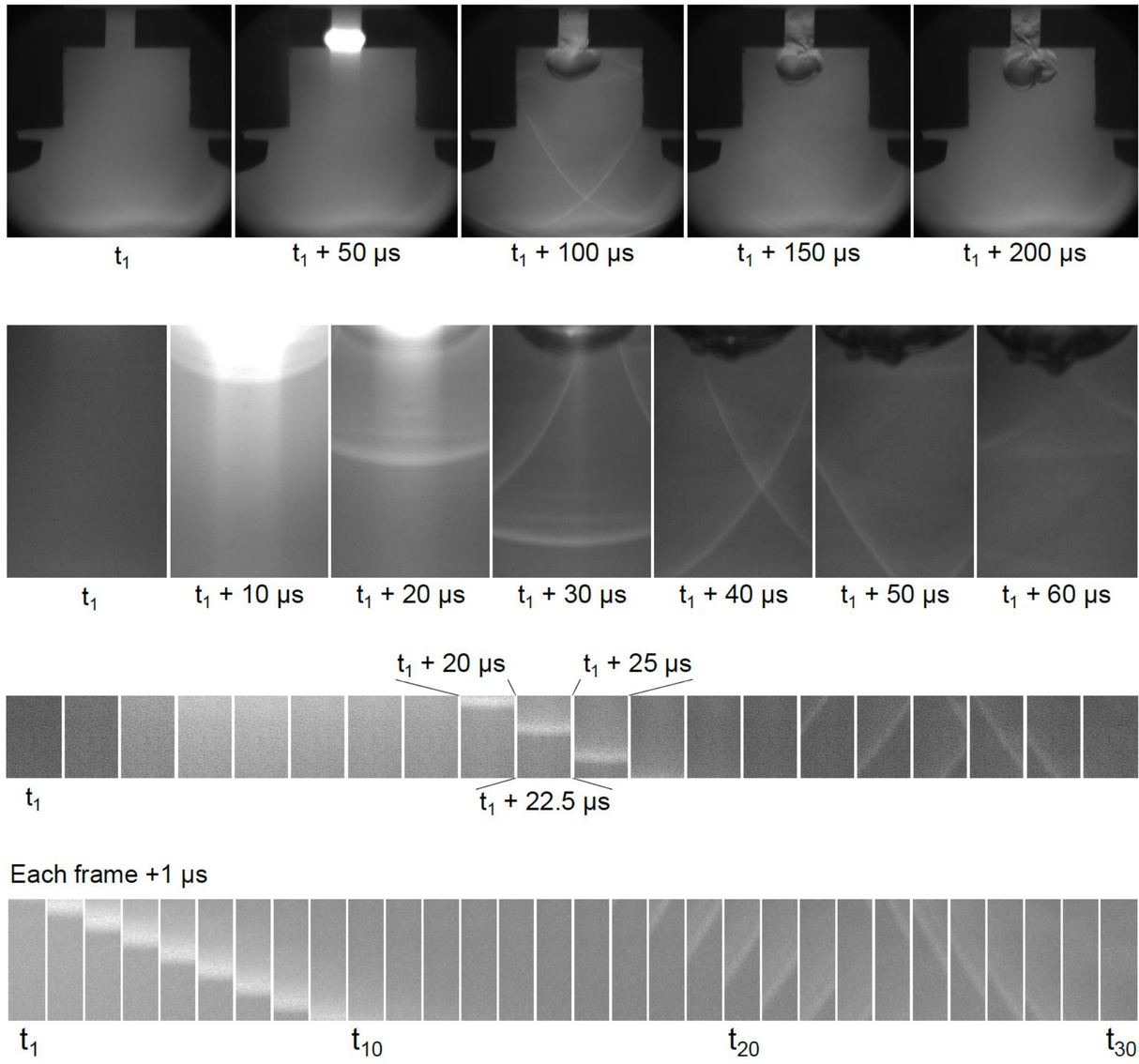
- Constructed basic system to demonstrate concept
  - –Setup
    - *Visualization of D_{jet} = 1.65 mm helium jet*
    - *Jet scanned ±50 mm from focal plane of instrument*
  - –Bright field schlieren images (no Rochon prism)
  - –Focusing schlieren images
  - –Focusing schlieren images with windows
    - *Simulate ground test facility*
    - *Small depth-of-field eliminates window reflections*





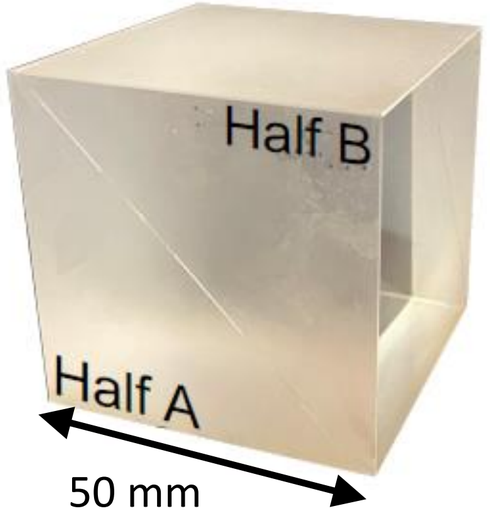
Results: Initial Self-Aligned Compact Focusing Schlieren System

- High-speed focusing schlieren
  - Setup
    - *High-speed Photron SA-Z camera*
    - *Pulsed Cavilux HF laser light source with Ultra High Speed (UHS) module*
    - *Electrode pair generated arc followed by breakdown of air*
    - *Generation of shockwave and thermal plume*
  - Framing rates of 20 kHz, 100 kHz, 400 kHz, and 1 MHz (with UHS module)

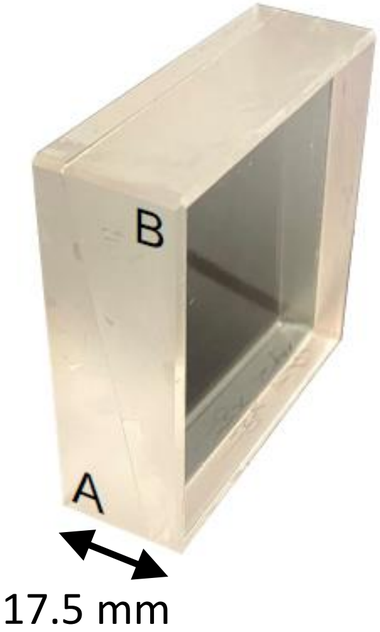


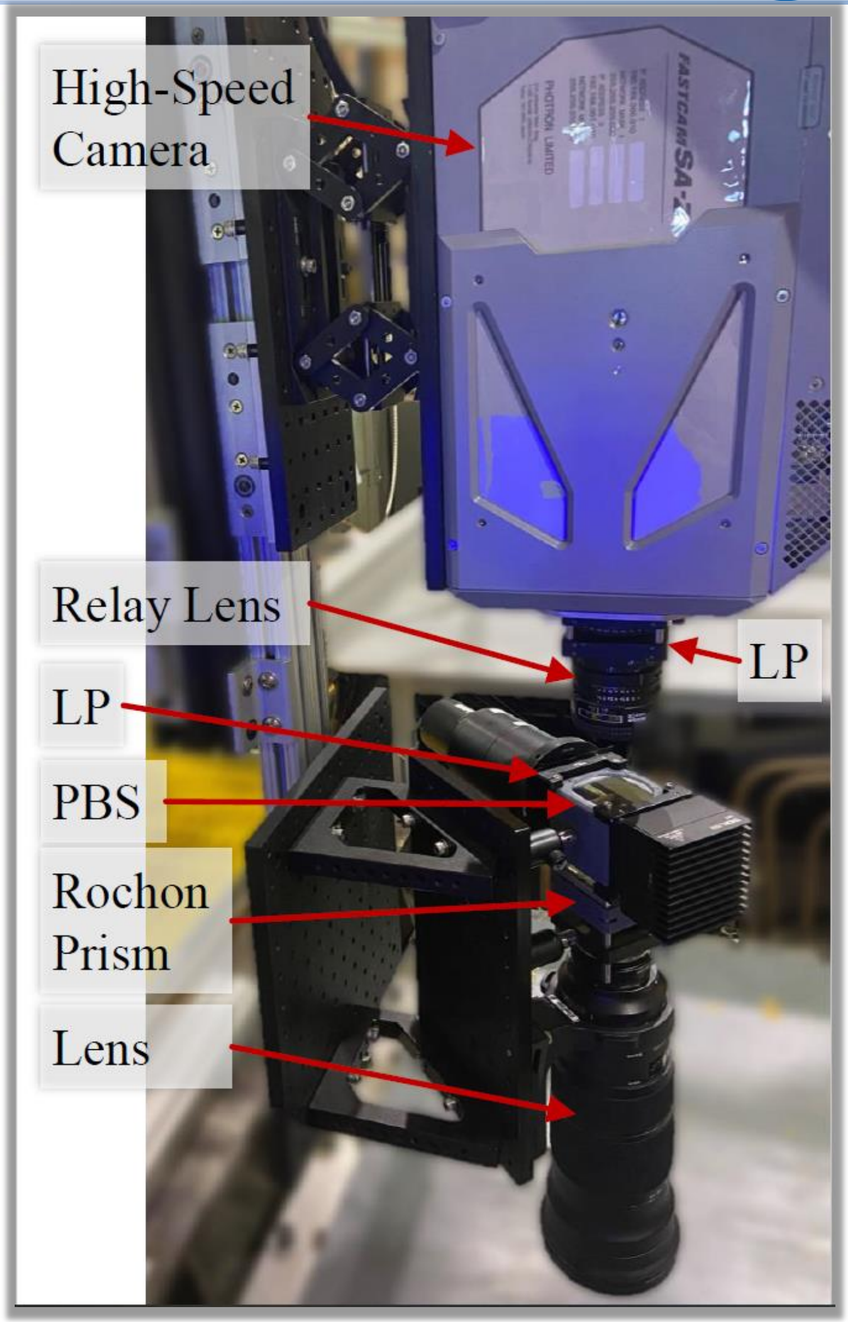
Improvements to Self-Aligned Compact Focusing Schlieren System

- Limitations of initial system
  - Relatively small field-of-view
  - Glare from window reflections
  - Non-ideal behavior of Rochon prism



- Obtaining moderate field-of-view
  - Original use of a relatively thick Rochon prism pushed grid element and image sensor away from lens
  - Switched to thinner Rochon prism to bring grid element and image sensor closer to lens
  - Moved Rochon prism in front of the lens



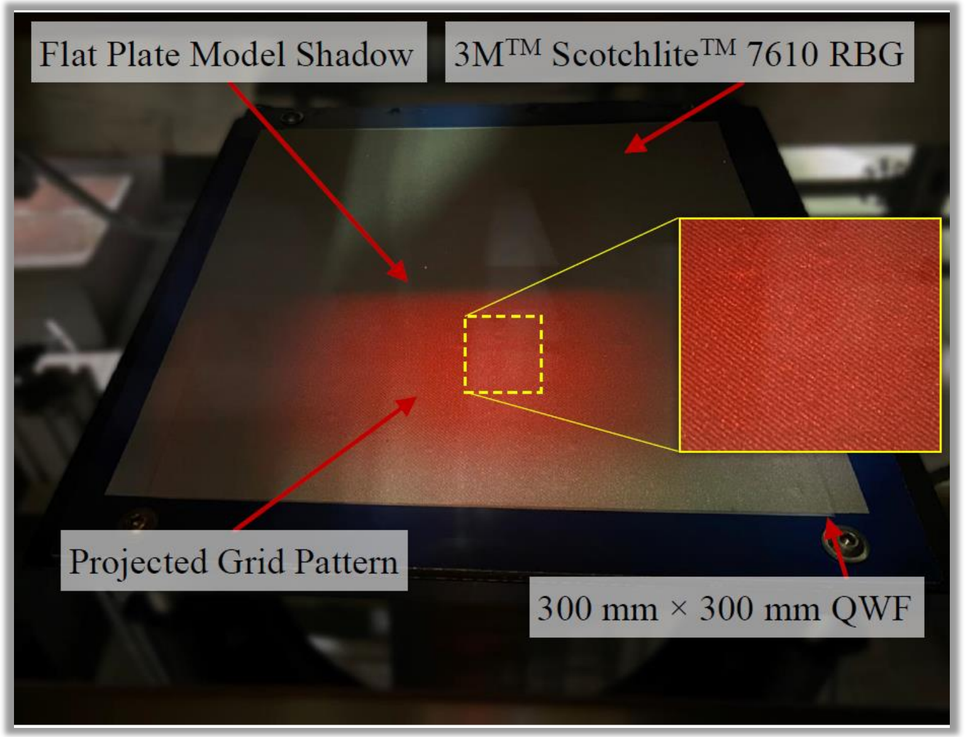


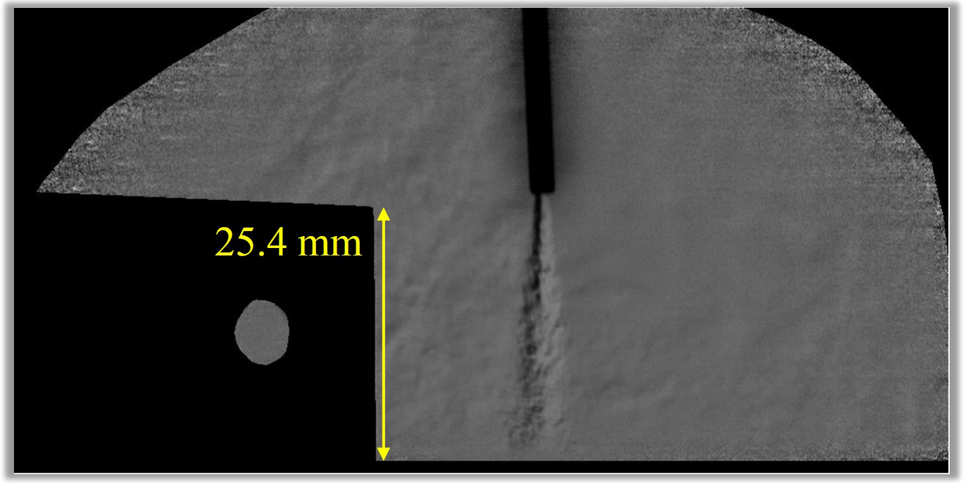
Improvements to Self-Aligned Compact Focusing Schlieren System

- Limitations of initial system
  - –Relatively small field-of-view
  - –Glare from window reflections
  - –Non-ideal behavior of Rochon prism

- Eliminating window reflections
  - –Increased field-of-view results in increased depth-of-field
  - –Use of quarter-wave film (QWF) over RBG
  - –Use of other RBG materials with QWF-like properties

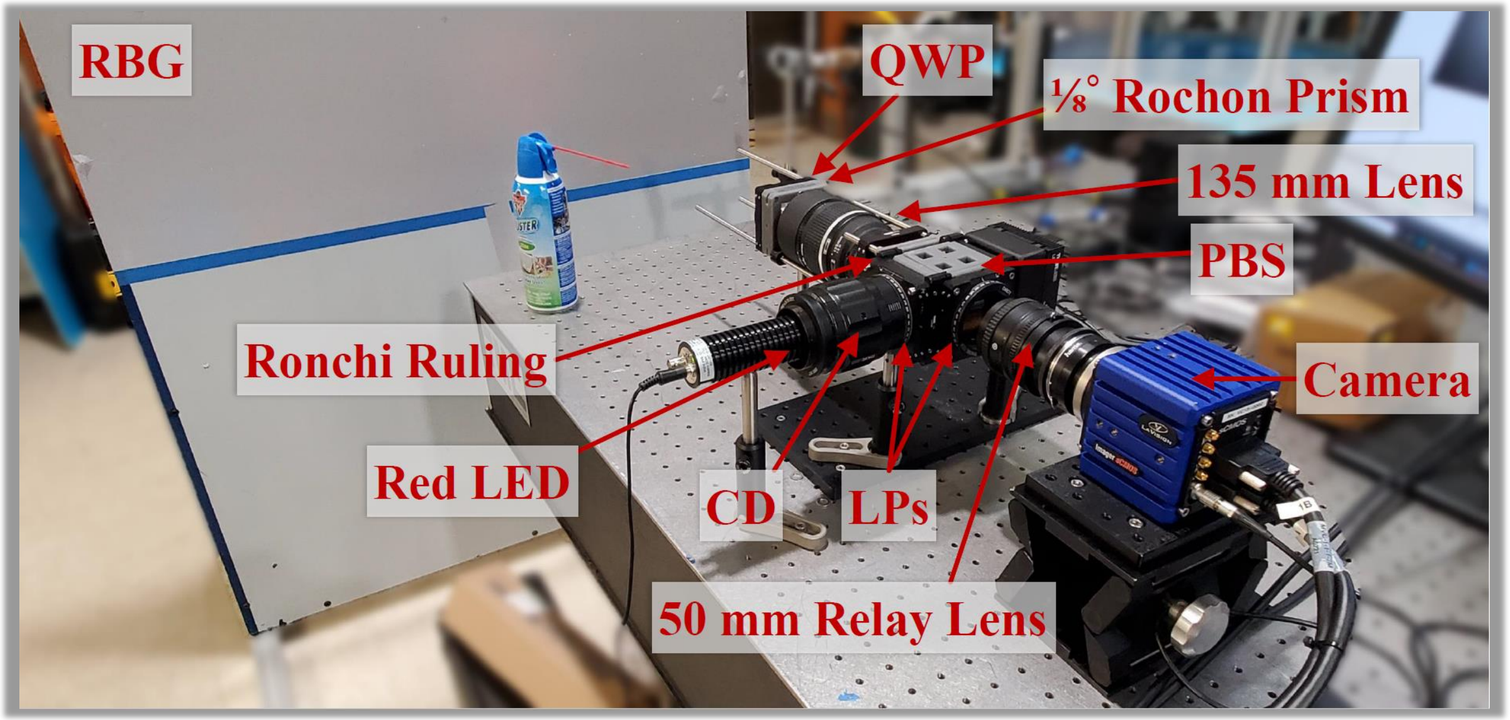
- Finding the ideal Rochon prism
  - –Optical activity in quartz/quartz prisms modifies polarization of light
  - –Considered alternative materials without optical activity
    - *Calcite: Difficult to fabricate large prisms*
    - *MgF_2: Modified polarization when working with diverging light*
  - –Glass/quartz combination (Ref. 11) resulted in ideal Rochon prism performance
    - *Prism acts the same in outgoing and return directions*

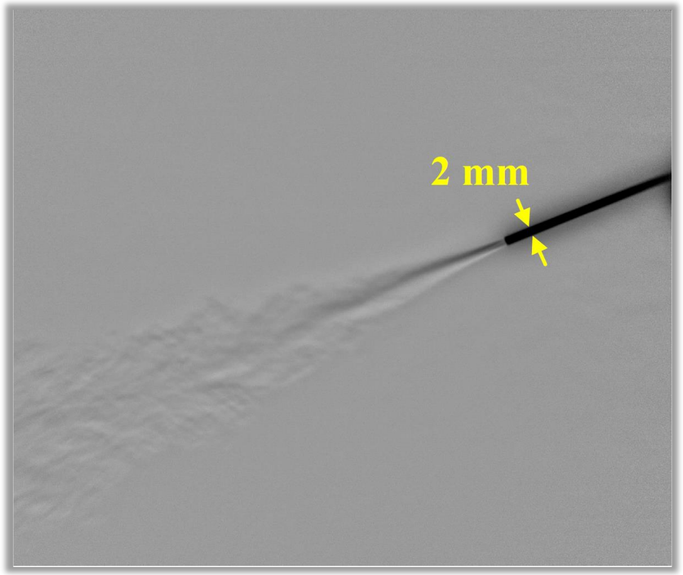


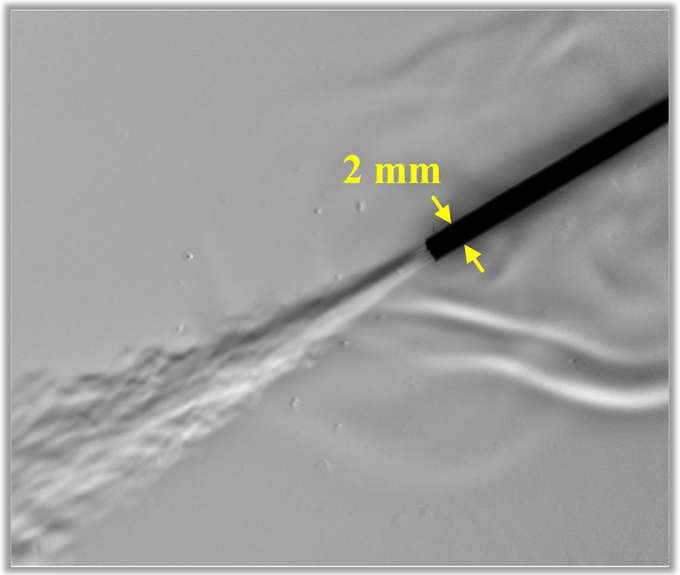


Results: Improved Self-Aligned Compact Focusing Schlieren System

- Demonstration of adjustable working distance
  - –QWP and RP were placed in front of a 135 mm imaging lens
  - –50 mm relay lens mounted to camera
  - –RBG positioned 2360 mm and 1010 mm in front of lens
  - –Ability to quickly refocus system to visualize flow from canned air jet

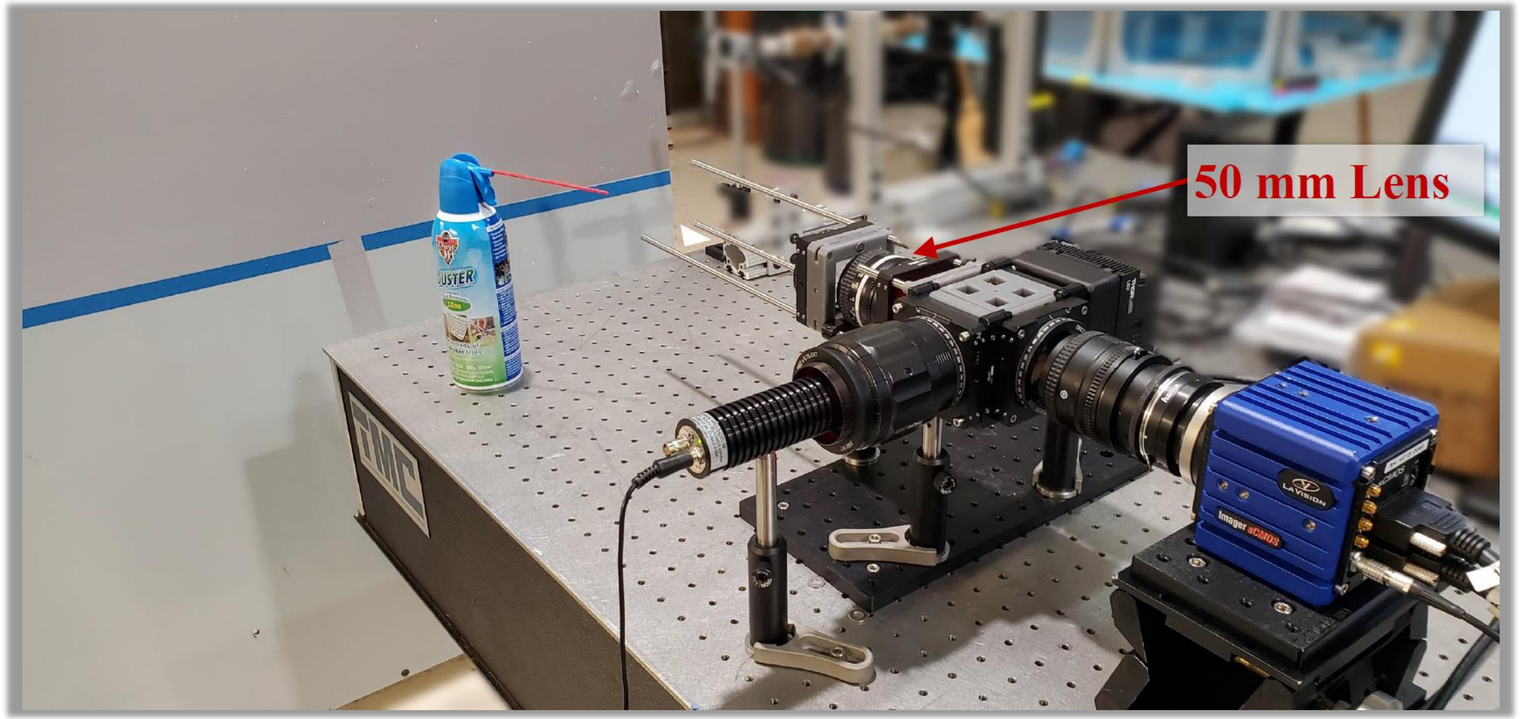


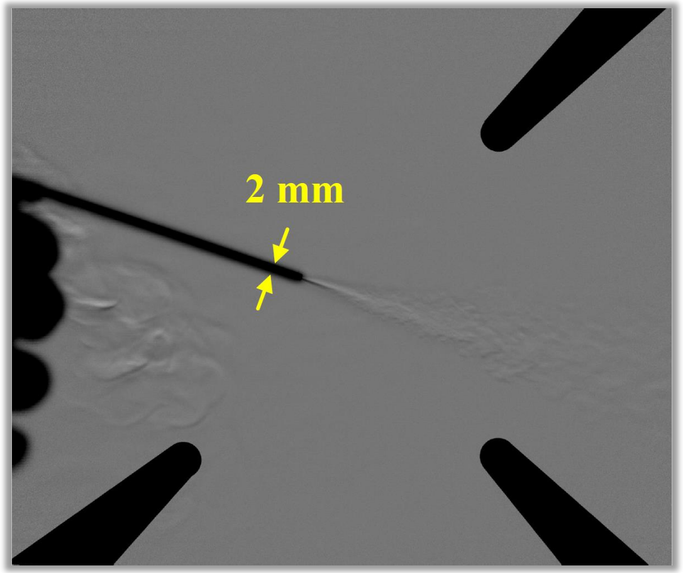




Results: Improved Self-Aligned Compact Focusing Schlieren System

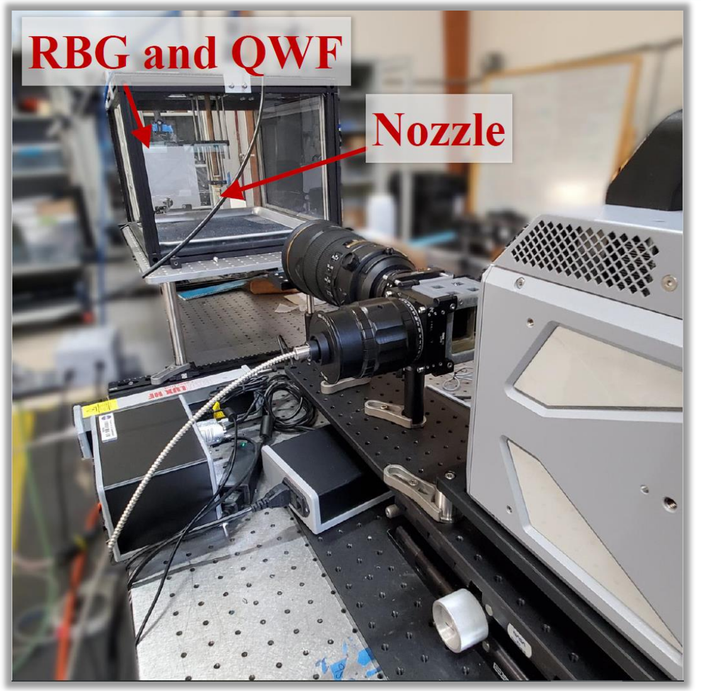
- Demonstration of adjustable field-of-view
  - –Replaced 135 mm lens with a 50 mm lens
  - –RBG at the same position as with the previous test (135 mm lens, 1010 mm separation)
  - –Again, ability to quickly refocus system to visualize flow from canned air jet
  - –Showed that the system can capture relatively large fields-of-view
  - –Could have also incorporated a zoom camera lens to change working distance and field-of-view

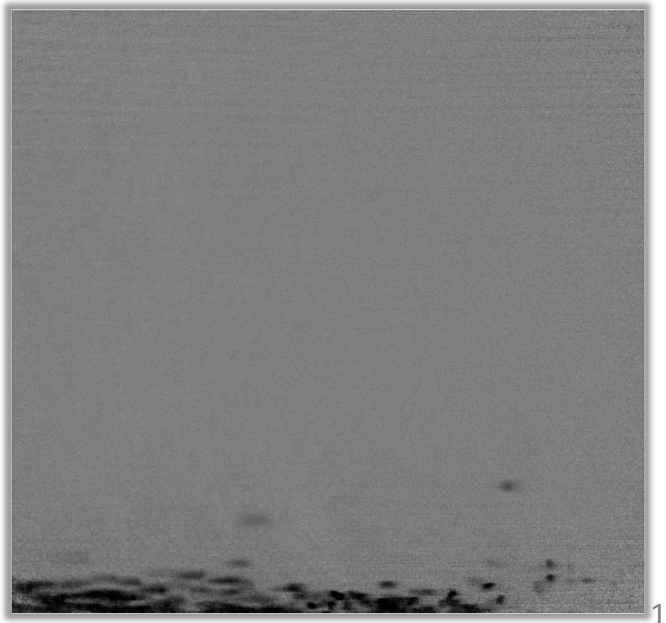




Results: Improved Self-Aligned Compact Focusing Schlieren System

- Demonstrate ability to capture plume/surface interaction event
  - –Setup
    - *High-speed Photron SA-Z camera*
    - *300 mm imaging lens, no relay lens*
    - *Rochon prism placed in front of lens*
    - *RBG and QWF placed behind enclosure with acrylic windows*
  - –Captured images of particles and helium plume in the same image
    - *Particles and plume features away from focal plane were strongly filtered/blurred*
    - *Small clear aperture of the Rochon prism reduced image brightness and potentially increased depth-of-field*





Conclusions and Acknowledgements

- Novel Self-Aligned Compact Focusing Schlieren System
  - Use of a single grid element makes the system inherently self-aligned
  - Polarization of light and use of a Rochon polarizing prism provides sensitivity adjustment
  - Polarization can be used to eliminate reflections from facility windows
  - Narrow depth-of-field
  - Changes to working distance and field-of-view can be adjusted relatively quickly and with little or no modification to the system
  - Acquisition rates up to 1 MHz have been demonstrated
  - Image quality is similar to conventional schlieren system

- Acknowledgements
  - Plume/Surface Interaction (PSI) Project
  - Transformational Tools and Technologies (TTT) Project

References

1. Weinstein, L. M., "*An Improved Large-Field Focusing Schlieren System*," 29th AIAA Aerospace Sciences Meeting, 1991. https://doi.org/10.2514/6.1991-567, AIAA Paper 1991-567.
2. Weinstein, L. M., "*Large-Field High-Brightness Focusing Schlieren System*," AIAA Journal, Vol. 31, No. 7, 1993, pp. 1250–1255. https://doi.org/10.2514/3.11760.
3. Heineck, J. T., "*Retroreflection Focusing Schlieren System*," May 1996. US Patent 5,515,158.
4. Weinstein, L. M., "*Review and update of lens and grid schlieren and motion camera schlieren*," The European Physical Journal Special Topics, Vol. 182, No. 1, 2010, pp. 65–95. https://doi.org/10.1140/epjst/e2010-01226-y.
5. Fagan, A. F., L'Esperance, D., and Zaman, K. B., "*Application of a Novel Projection Focusing Schlieren System in NASA Test Facilities*," AIAA Aviation Forum, 2014. https://doi.org/10.2514/6.2014-2522, AIAA Paper 2014-2522.
6. Buckner, B. D., Trolinger, J. D., and L'Esperance, D., "*Digital focusing schlieren imaging*," SPIE Optical Engineering + Applications, 2015. https://doi.org/10.1117/12.2189533.
7. Schoegl, I., Pisano, A. J., and Sedky, G., "*Development of a Compact Focusing Color Schlieren Technique*," American Institute of Aeronautics and Astronautics, 2016. https://doi.org/10.2514/6.2016-1765, AIAA Paper 2016-1765.
8. L'Esperance, D., and Buckner, B. D., "*Focusing schlieren systems using digitally projected grids*," SPIE Optical Engineering + Applications, 2017. https://doi.org/10.1117/12.2274079, paper 10373-26.
9. Buckner, B. D., and L'Esperance, D., "*Schlieren unwrapped: distortion correction in digital focusing schlieren*," SPIE Optical Engineering + Applications, 2019. https://doi.org/10.1117/12.2528081, paper 11102-26.
10. MetroLaser®, Inc., "*High-Speed Schlieren*," Online, Nov. 2021. Website: http://www.metrolaserinc.com/technologies/highspeed-schlieren/. Accessed Nov 9th, 2021.
11. Ammann, E. O., and Massey, G. A., "Modified Forms for Glan–Thompson and Rochon Prisms," Journal of The Optical Society of America, Vol. 58, No. 11, 1968, pp. 1427–1433. https://doi.org/10.1364/josa.58.001427.