Recent Progress and Development of Self-Aligned Focusing Schlieren

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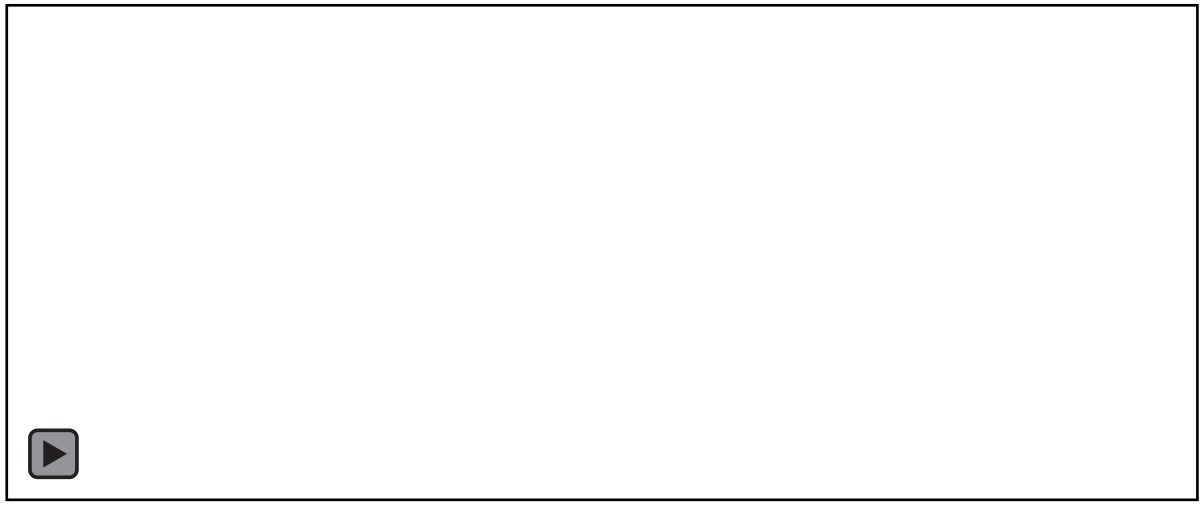
Presentation Overview

- What is Self-Aligned Focusing Schlieren (SAFS)?
  - SAFS System Configurations
- Recent Developments
  - Digital SAFS
  - Scheimpflug SAFS imaging
  - Plenoptic SAFS imaging
  - Event-based SAFS imaging
  - Spectral-spatial Ronchi ruling
- Recent Applications
  - Large-scale imaging
  - Imaging through curved windows
- Component Evaluation and Trade Study

~~Self-Aligned~~ Focusing Schlieren Overview

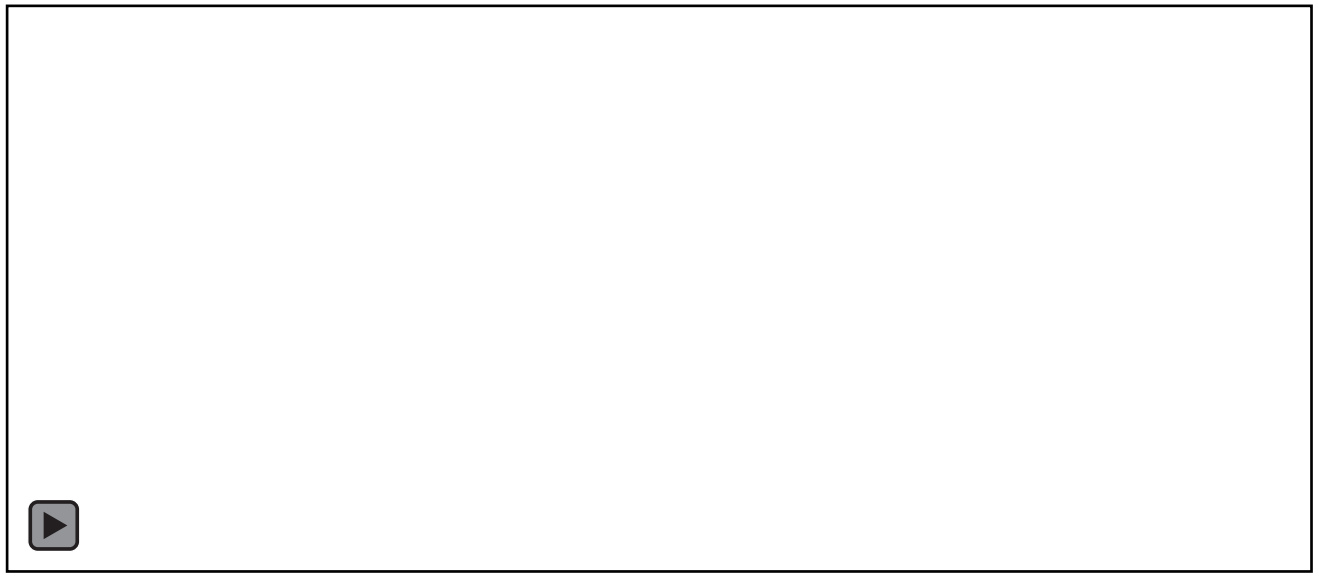
Conventional Focusing Schlieren

- Sensitive to 1st derivative of density
- Provides narrow depth-of-focus
- Setup is time-consuming and restricting
  - Source and cutoff grid MUST be well aligned
  - Requires two-sided optical access
  - Sensitive to vibration



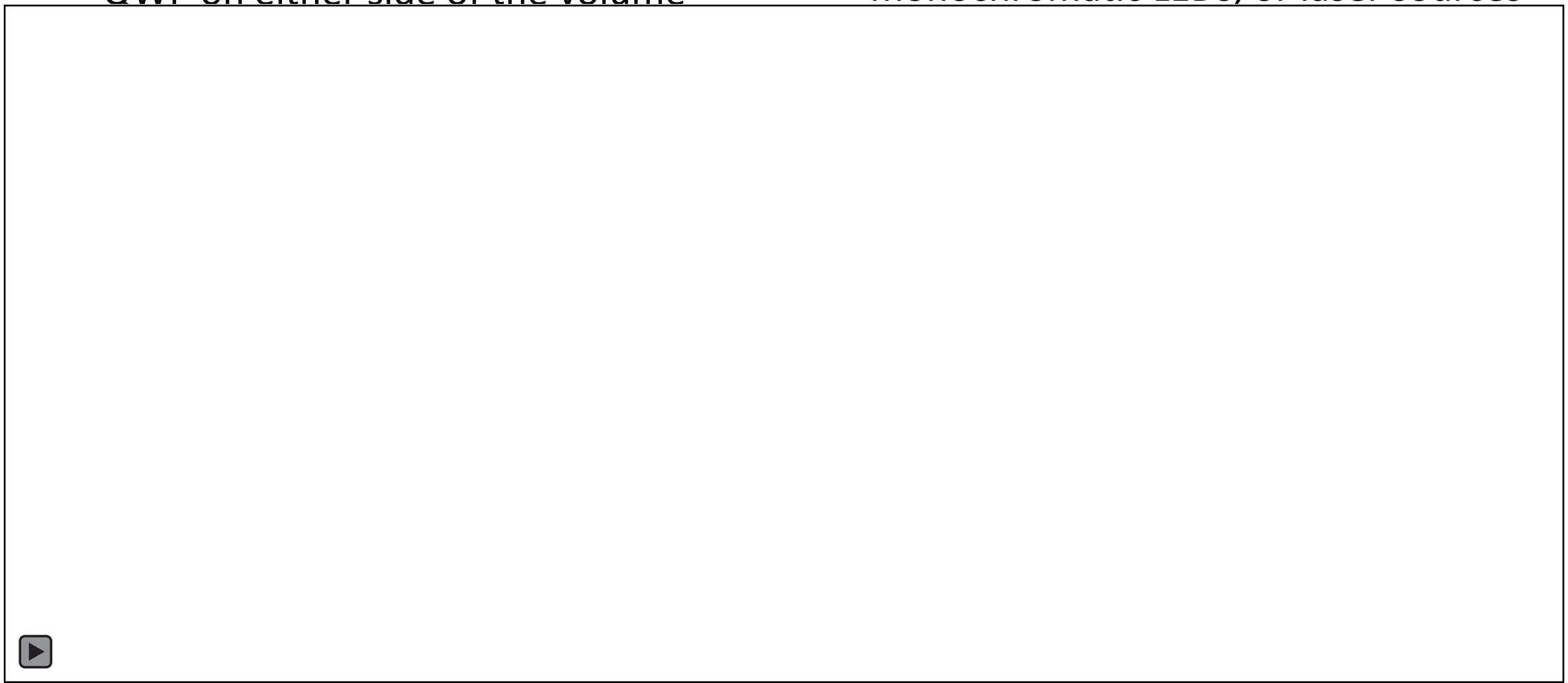
Self-Aligned Focusing Schlieren

- Sensitive to 1st derivative of density
- Provides narrow depth-of-focus
- Relatively easy and compact setup
  - RBG can be placed within the test section
- Inherently self-aligned
  - Provides insensitivity to vibration



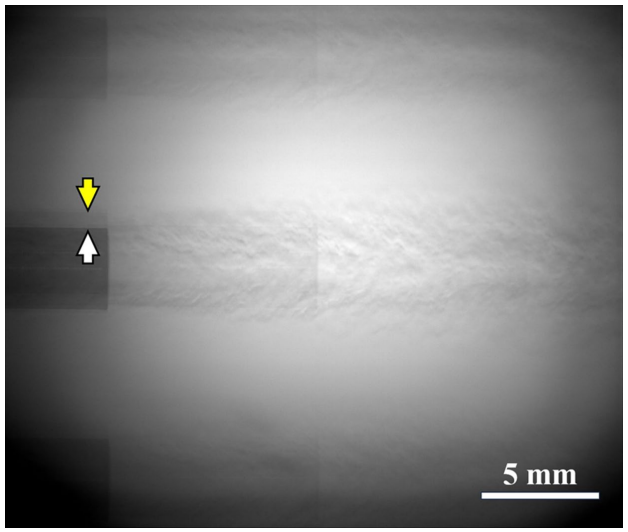
SAFS Systems Configurations

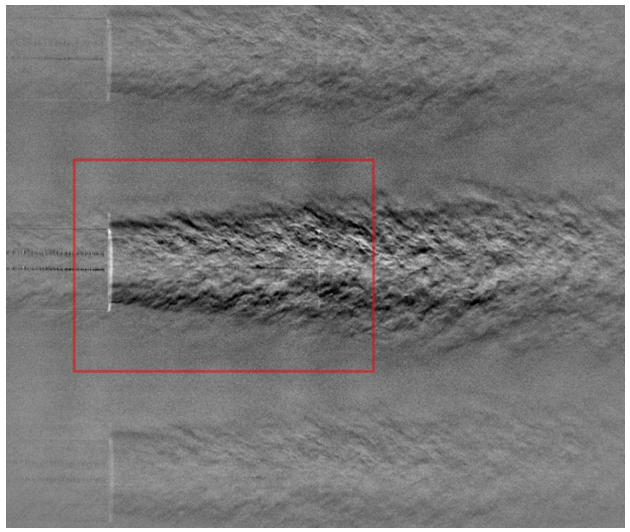
- RP and QWP on either side of FL
- QWP on either side of the volume
- Light sources can be white LEDs, monochromatic LEDs, or laser sources



Digital SAFS (D-SAFS)

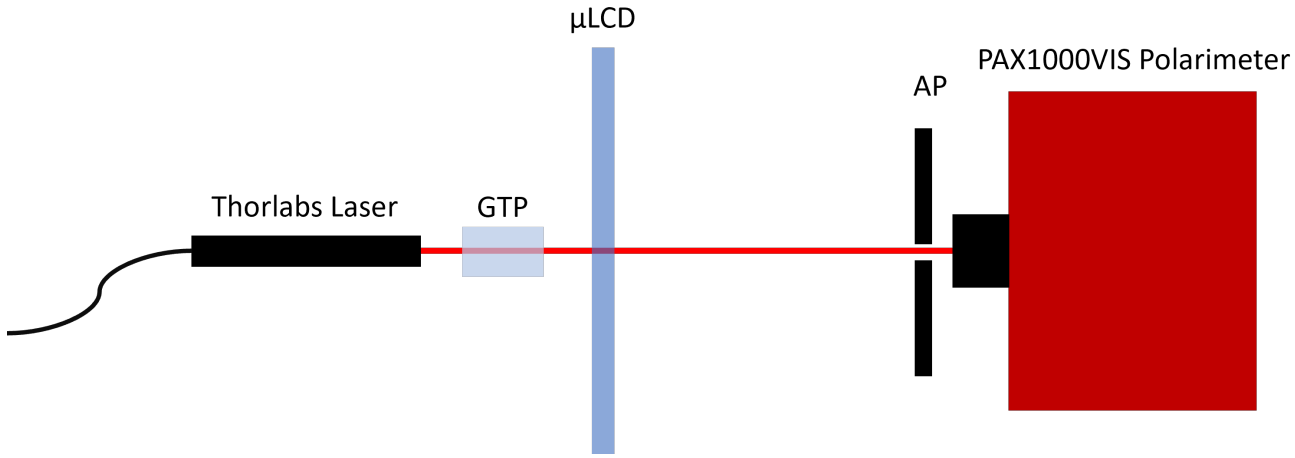
- SAFS requires physical access to make RR adjustments
- SAFS requires procurement of any needed RR prior to use (i.e., lp/mm requirements may vary)
- Replace Ronchi ruling with µLCD
  - Modulates polarization on a pixel
- Alternating lines produced by displaying patterns of varying gray scale
- Termination of light arrays occurs at the linear polarizers

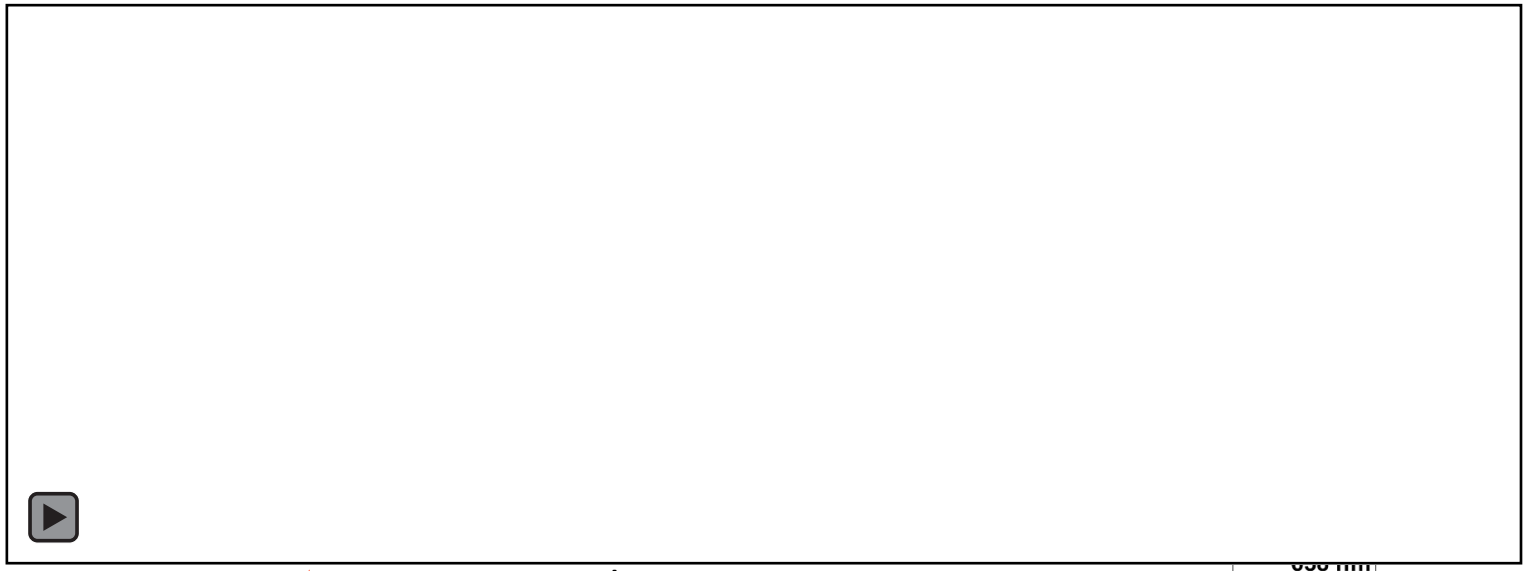




Digital SAFS (D-SAFS)

- Commercial µLCDs used
  - Unknown control of polarization state (Azimuth and ellipticity)
- Can alter both azimuth and ellipticity
- Polarization control is wavelength and gray level dependent
- Previous results likely obtained at sub-optimal values
- Future work looks to use ~450 nm light



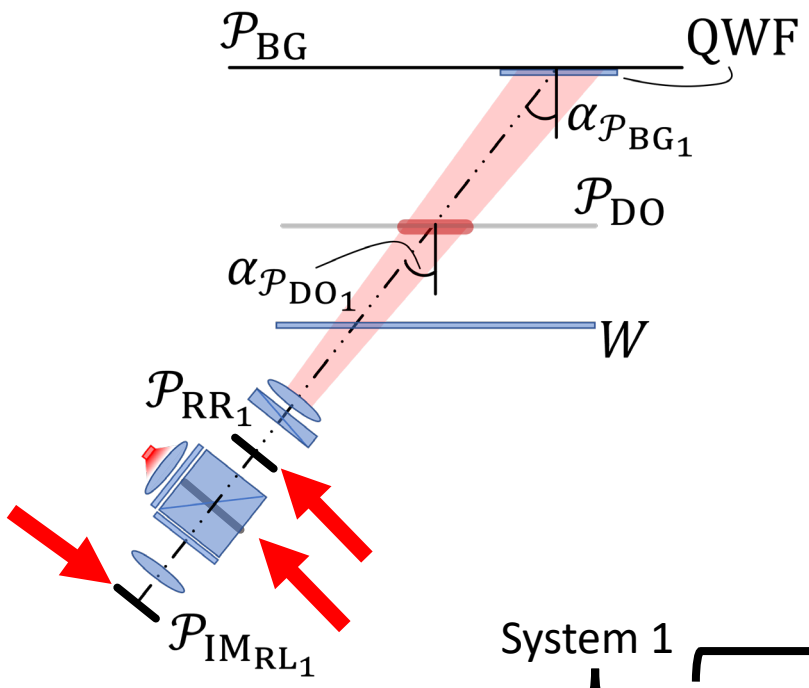


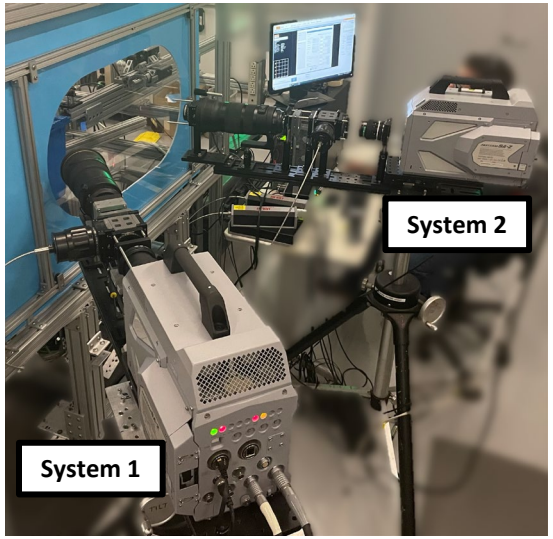
★ Previous results
★ Future Attempt

675 nm
Ideal

Scheimpflug SAFS Imaging

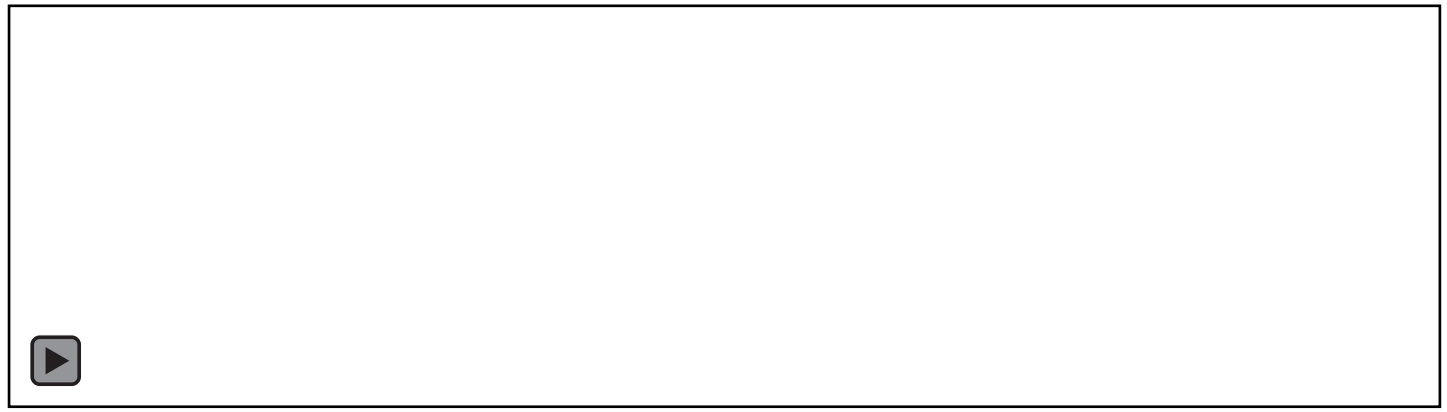
- Off-axis viewing can be difficult with conventional SAFS
- Scheimpflug condition allows for off-axis viewing
  - Must be applied to both the image plane and the RR plane
- Enables imaging in facilities with non-ideal optical access, simultaneous measurements with other techniques, or extended field-of-view imaging





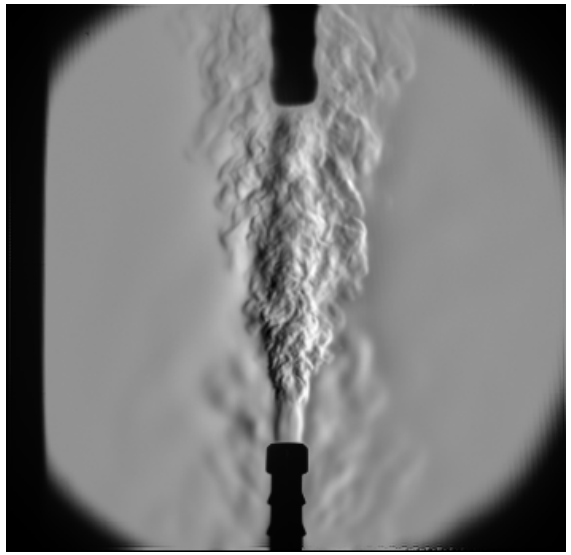
System 2

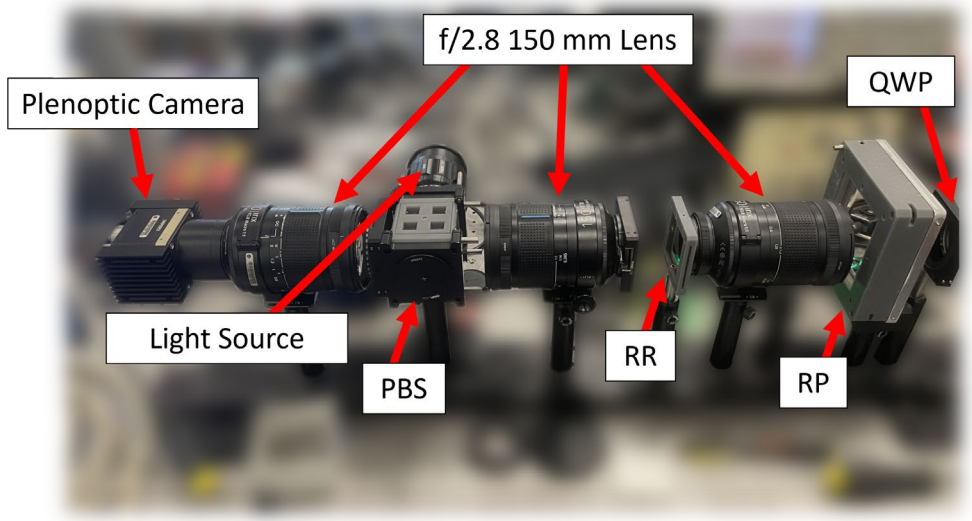
System 1

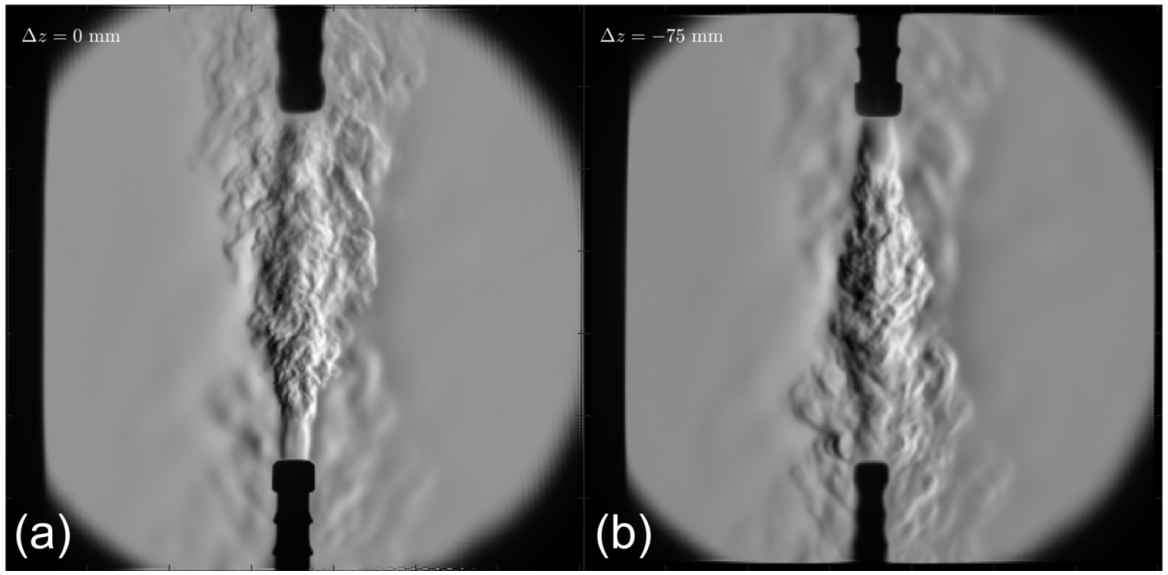


Plenoptic SAFS Imaging

- Conventional SAFS is limited to imaging a single plane
  - Manual adjustments needed to get separate planes
- Simultaneous, multi-plane images can be acquired with the use of a plenoptic camera

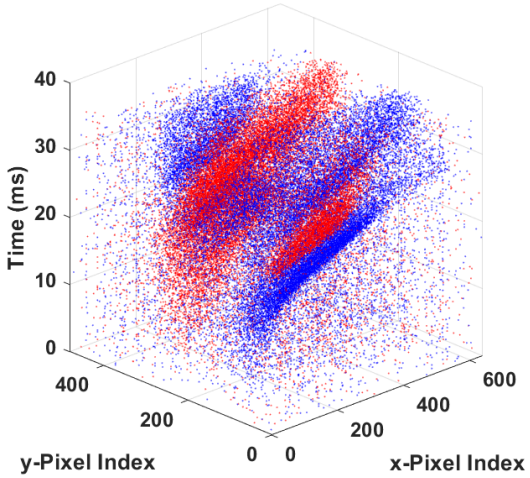


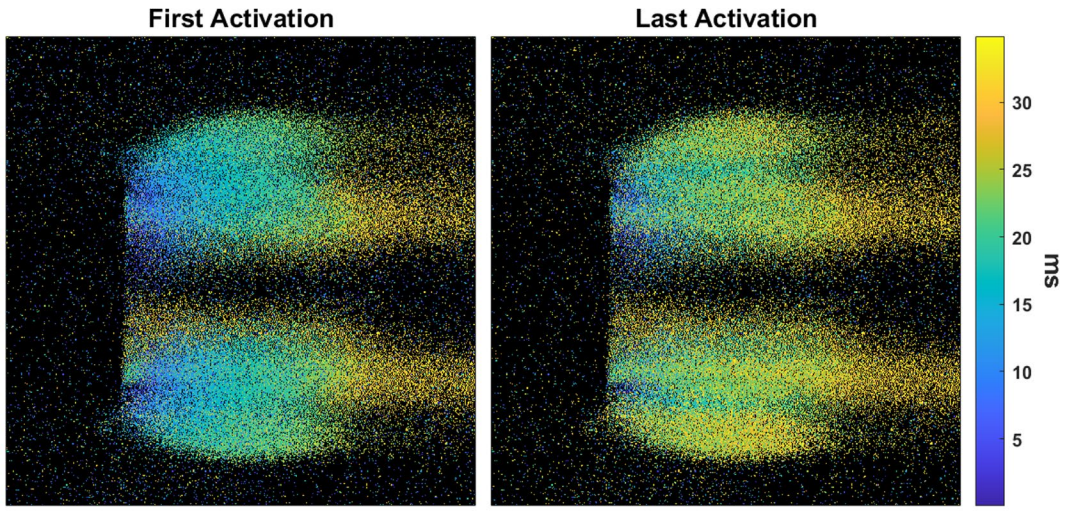


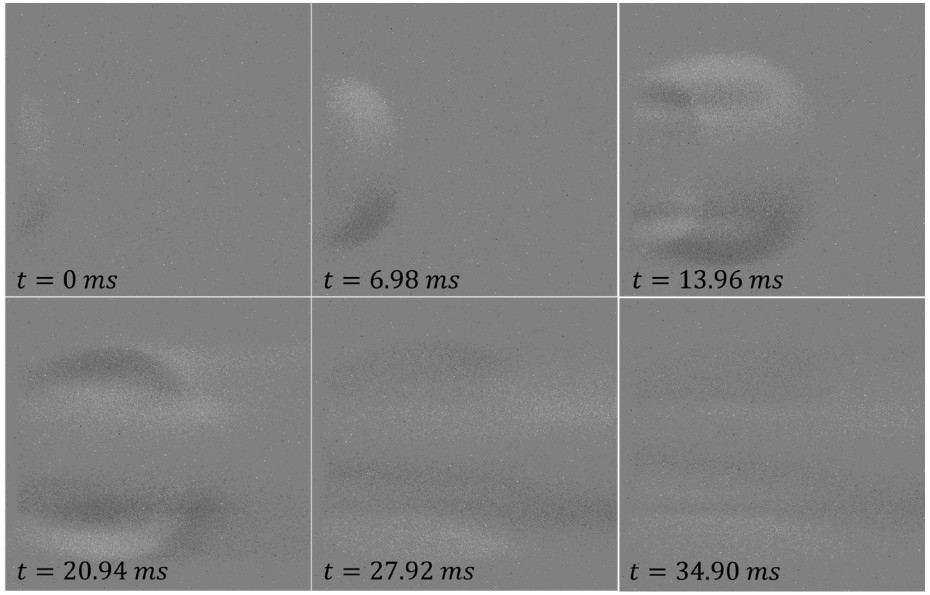


Event-Based SAFS Imaging

- Event-Based cameras provide an asynchronous data stream of events (spatio-temporal data)
  - Events correspond to local changes in brightness on a per-pixel basis
- Effective frame rates in the 10 kHz range
- Can be difficult to provide an intuitive interpretation of data

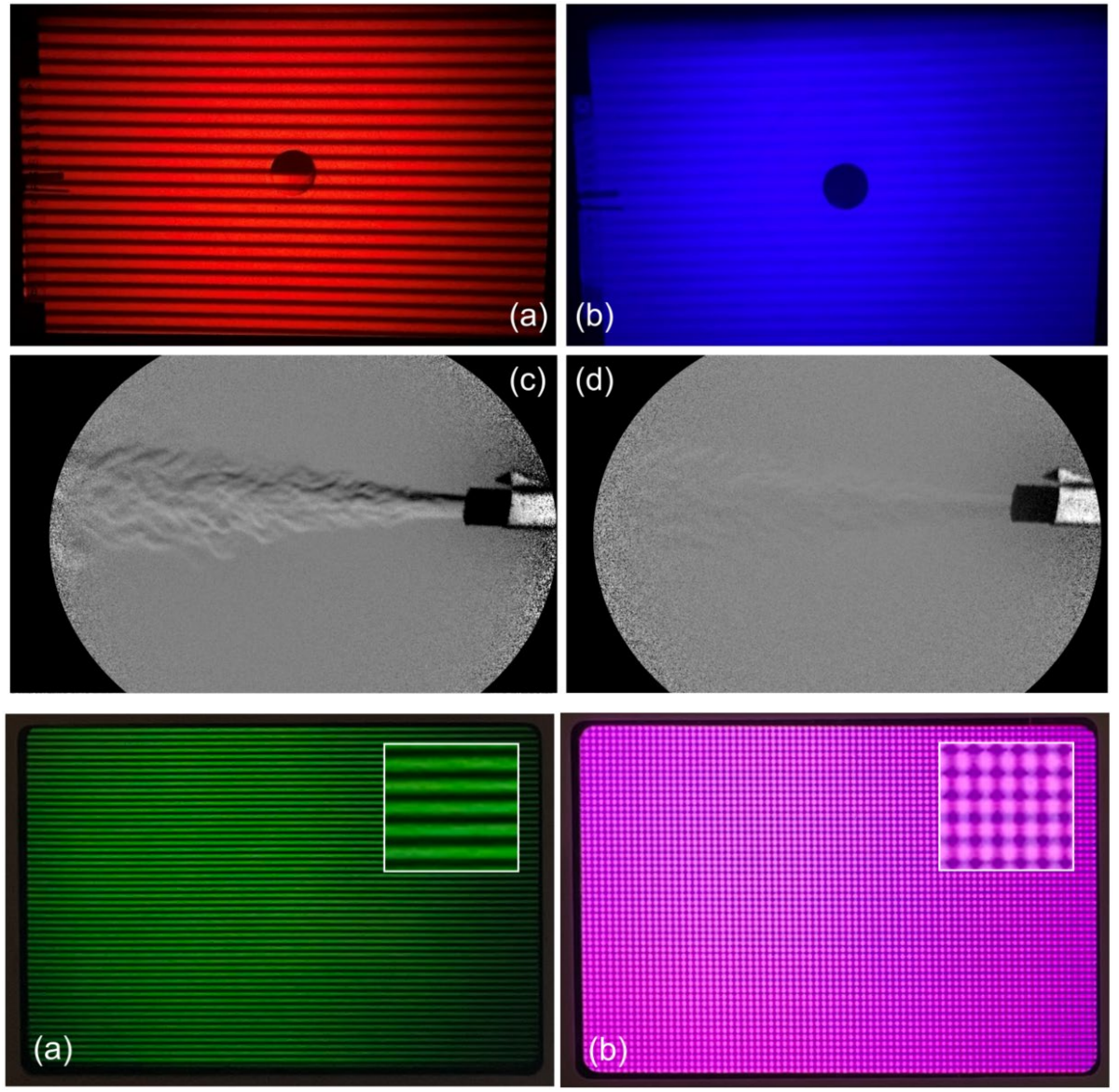






Spectral-Spatial Ronchi Rulings

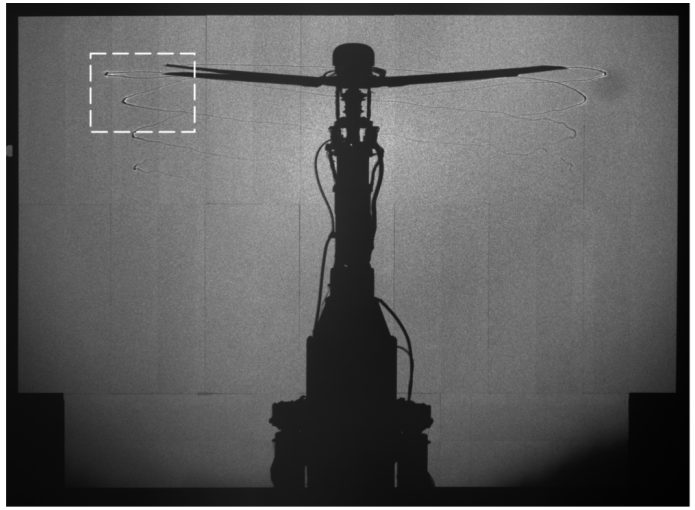
- Spectral (or spatial) filters cannot be stacked for SAFS
  - Stacked filters and their focus would be spatially offset
- Spectral-spatial filters have to manufactured as one filter
  - Traditional methods are expensive and time-consuming
- Can be accomplished with film camera and color film
  - Relatively inexpensive (i.e., < $1/filter)
- Provides simultaneous and compact imaging solution for a variety of measurements

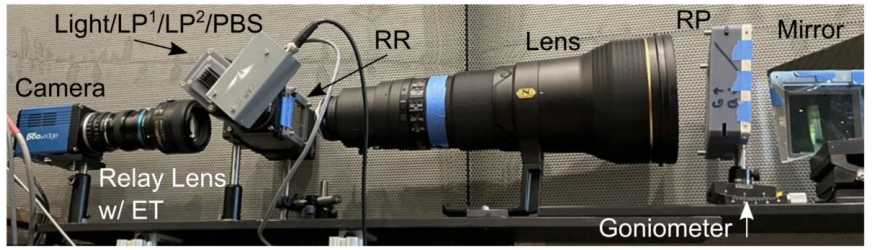


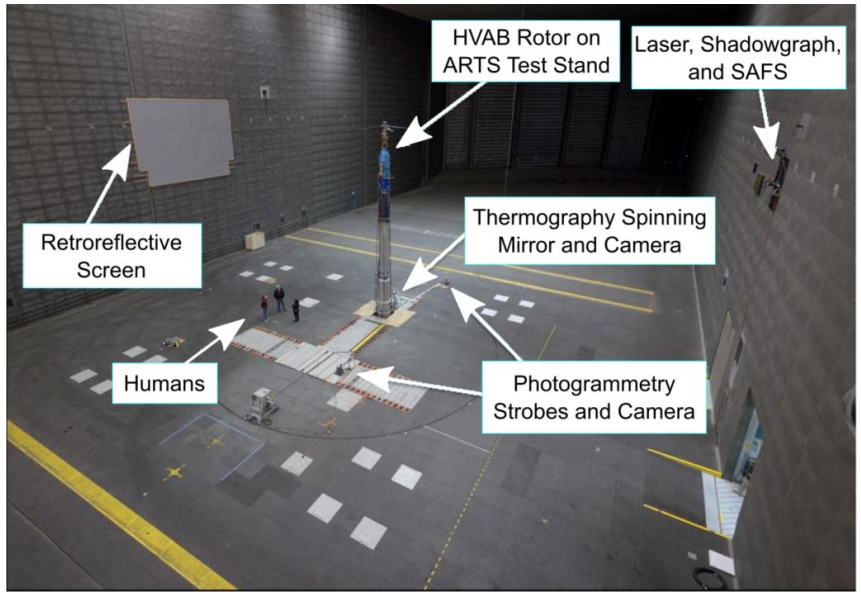
Large-Scale Imaging

POC: Heineck, Bathel, & Weisberger

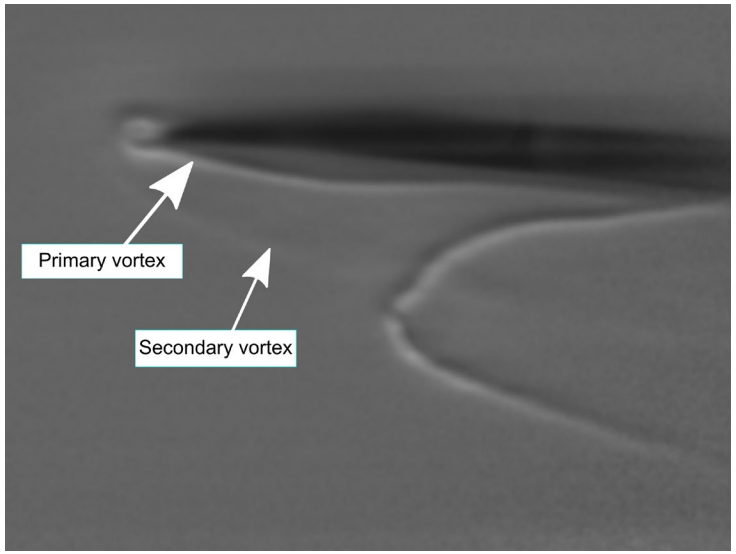
- SAFS demonstrated in National Full-Scale Aerodynamics Complex (NFAC) 80- by 120-ft Wind Tunnel at NASA Ames Research Center
- Test article was the hover validation and acoustic baseline (HVAB) rotor



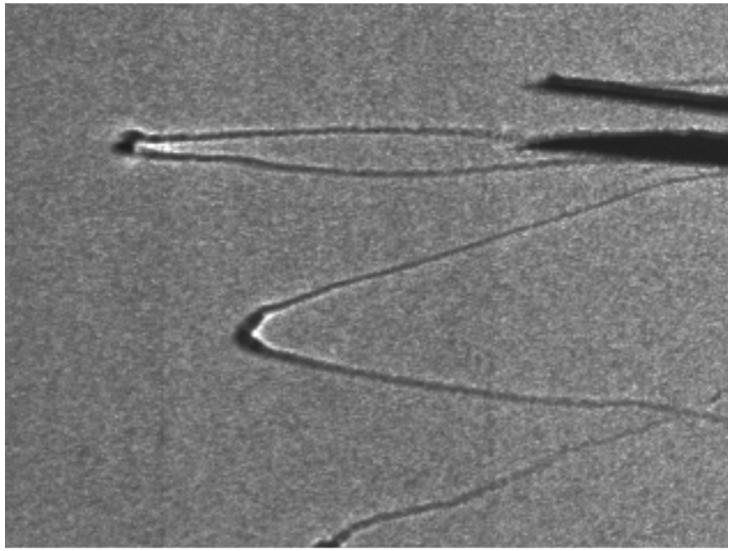




SAFS



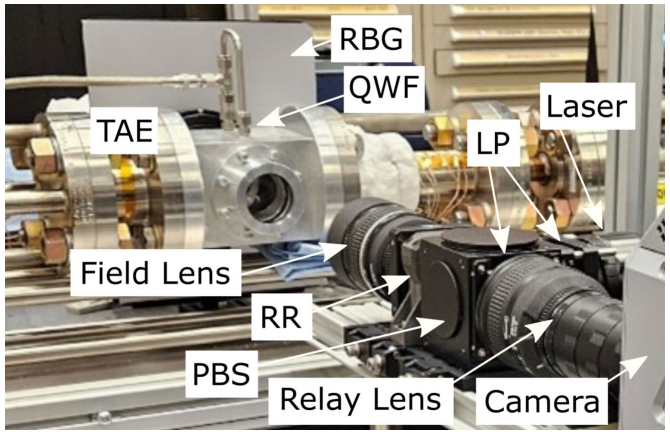
Shadowgraph

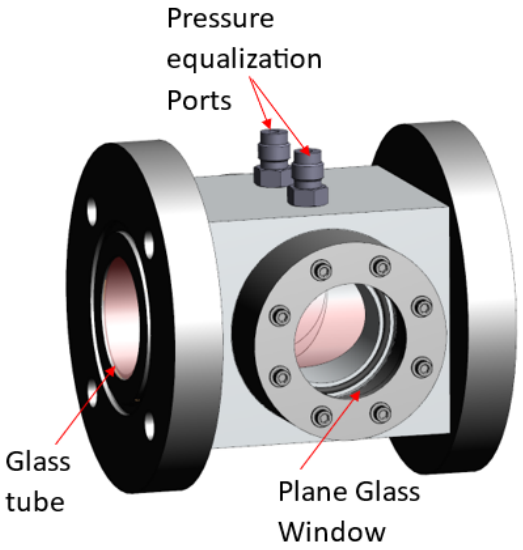


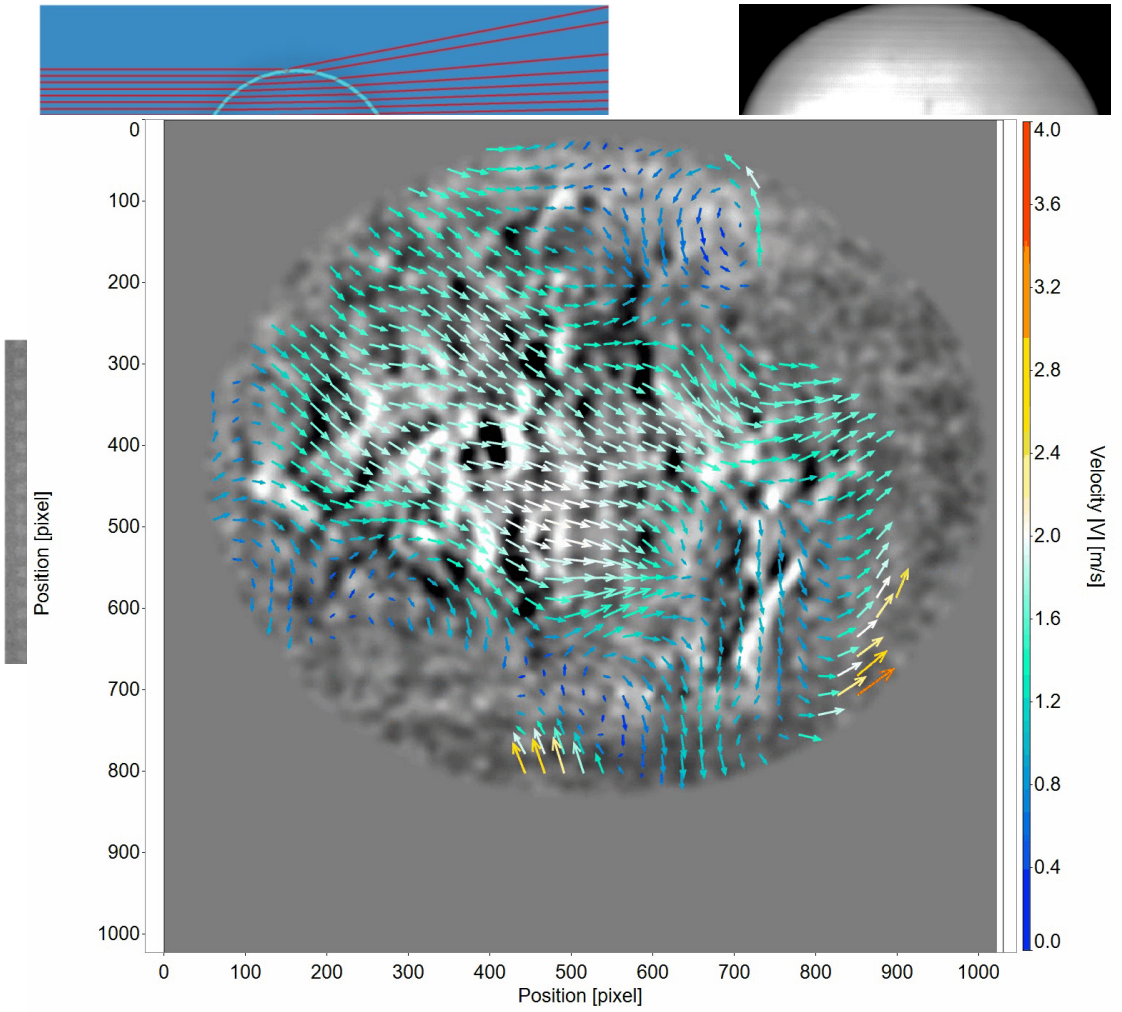
Imaging through Curved Windows

POC: Wernet

- SAFS imaging performed in Thermal Acoustic Engine (TAE) at NASA Glenn Research Center
  - 50-mm ID
  - Operated at 450 psig with helium
- Optical Spool Piece:
  - 50-mm ID, 1-mm thick fused quartz tube and 32-mm thick plane window

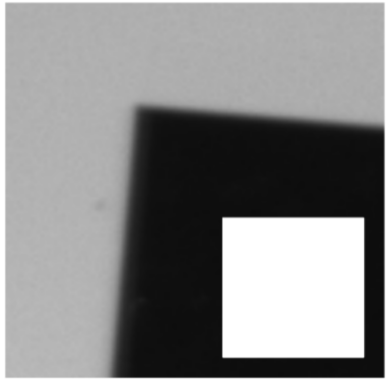


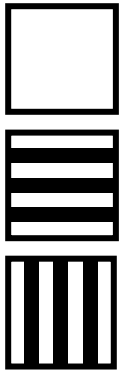




Component Trade Study: Ronchi Ruling

- RR choice is important for SAFS design
  - Large effect on both sensitivity and spatial resolution
- RR can cause significant diffraction

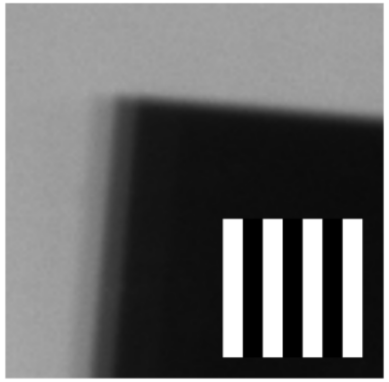


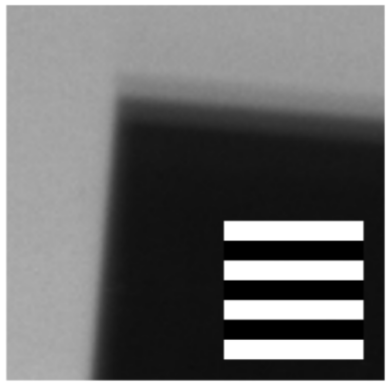


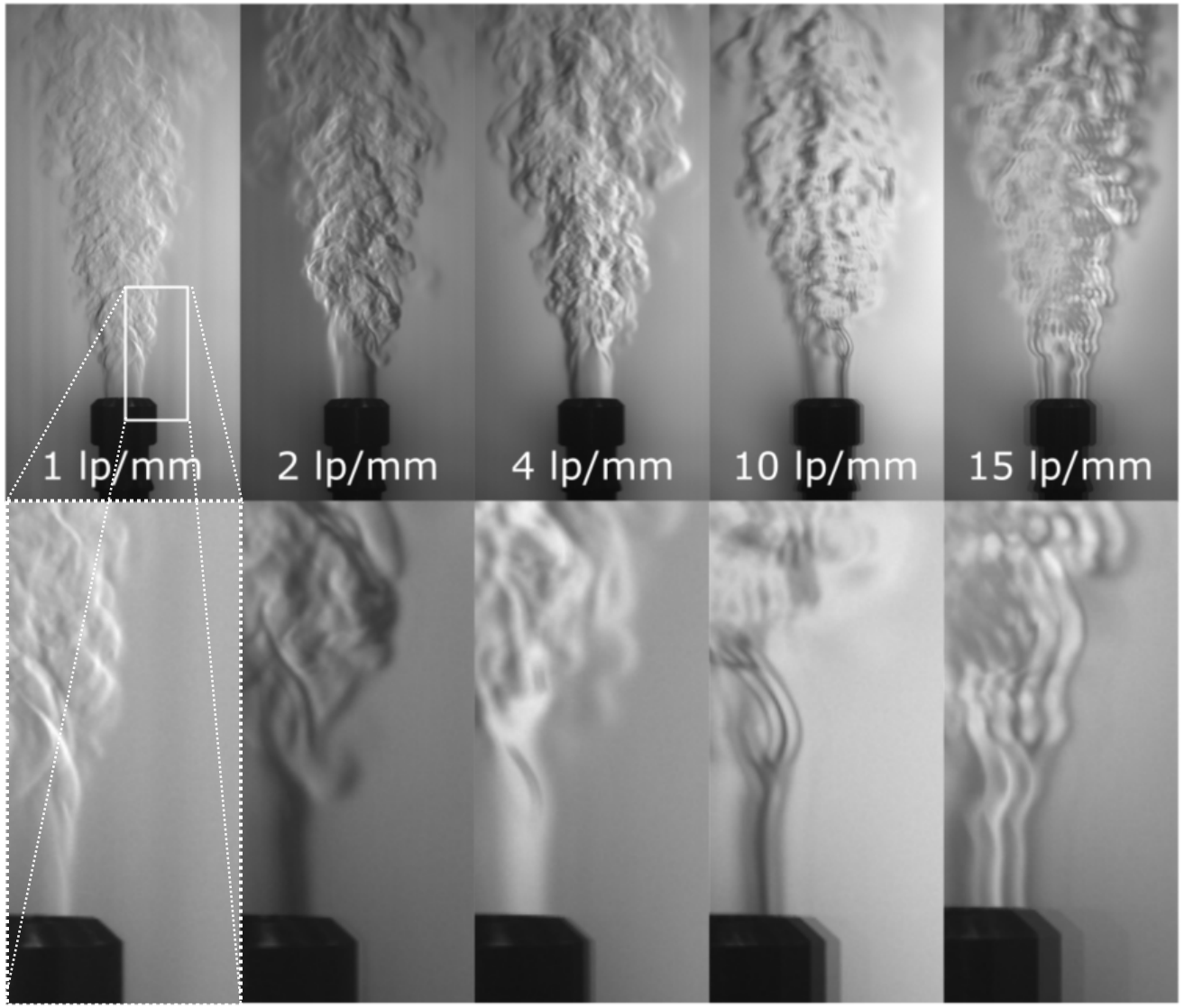
No RR

Horizontal RR

Vertical RR

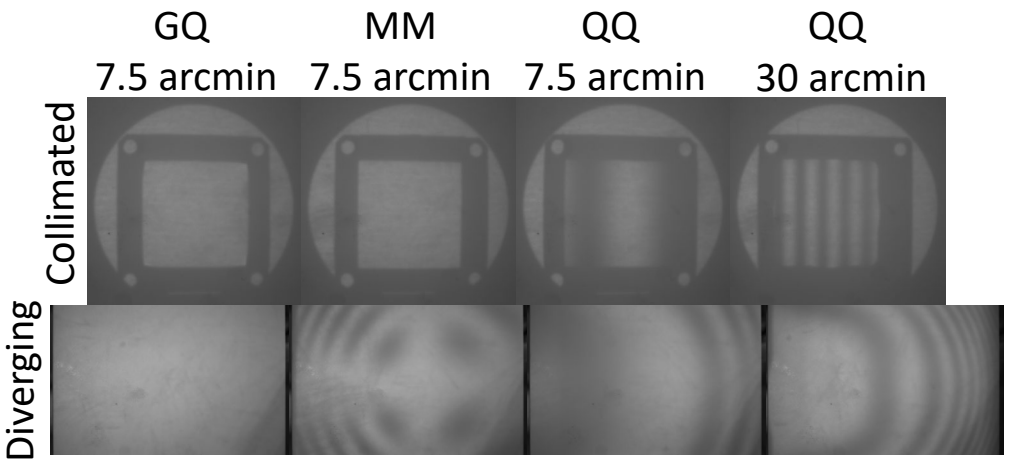


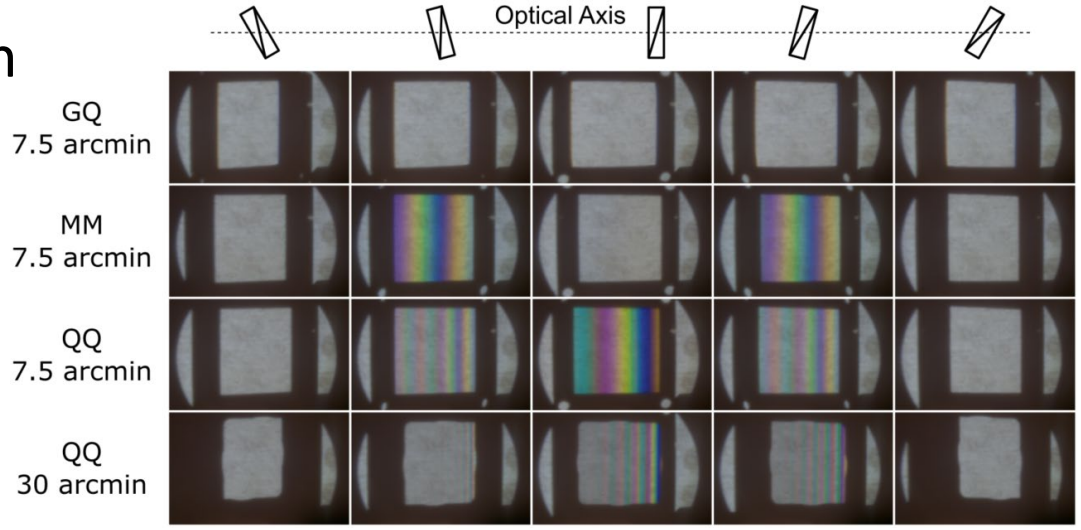




Component Trade Study: Rochon Prism

- RPs can be designed with a variety of materials and splitting angles
- Material choice can exhibit non-ideal polarization effects
  - Can differ between collimated and diverging light
  - Can vary between monochromatic and white light
- Polarization variation in RP can be useful
- Sensitivity can be varied with translation and rotation of RP





Translation



Rotation

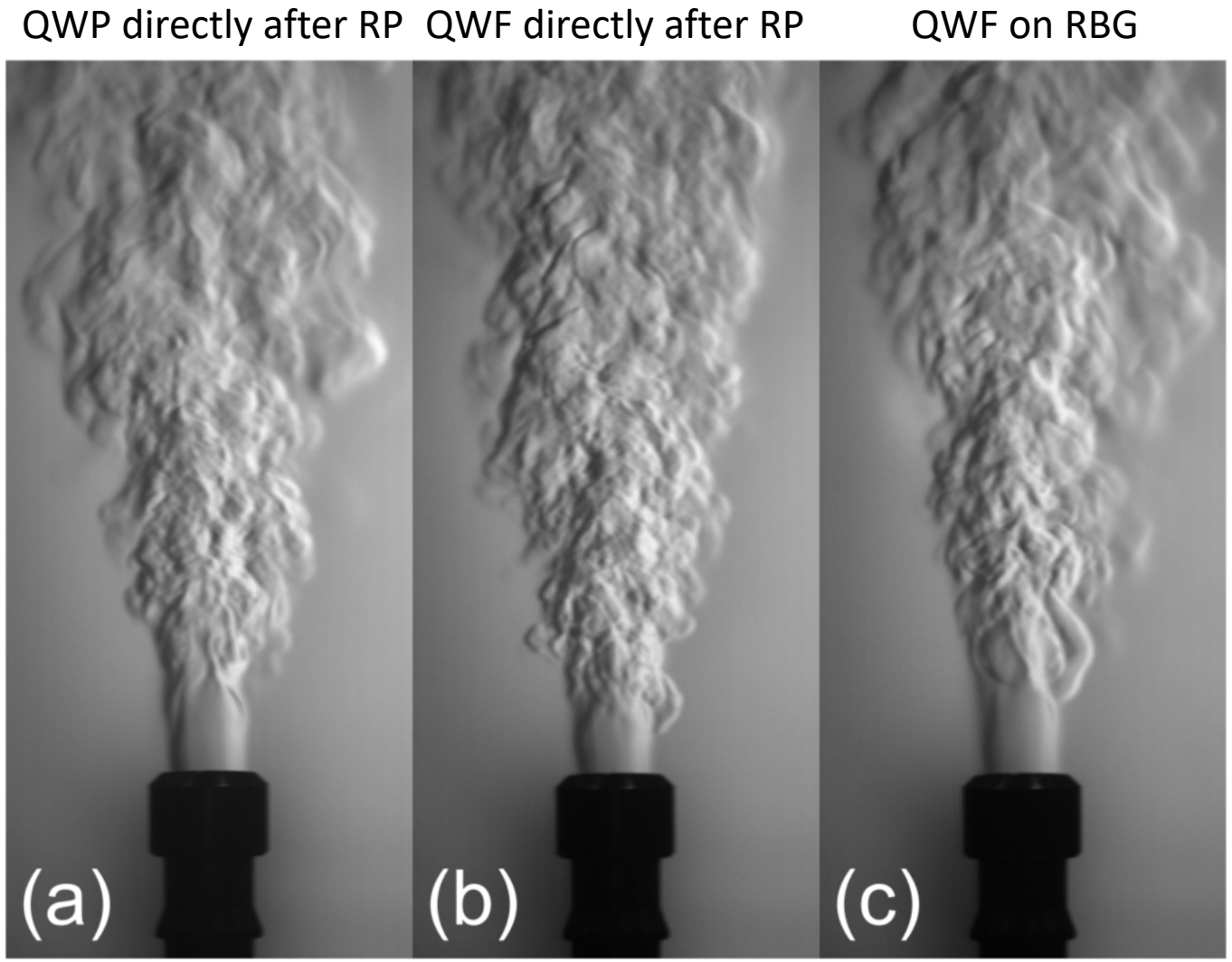


Non-ideal



Component Trade Study: λ/4-plate or -film

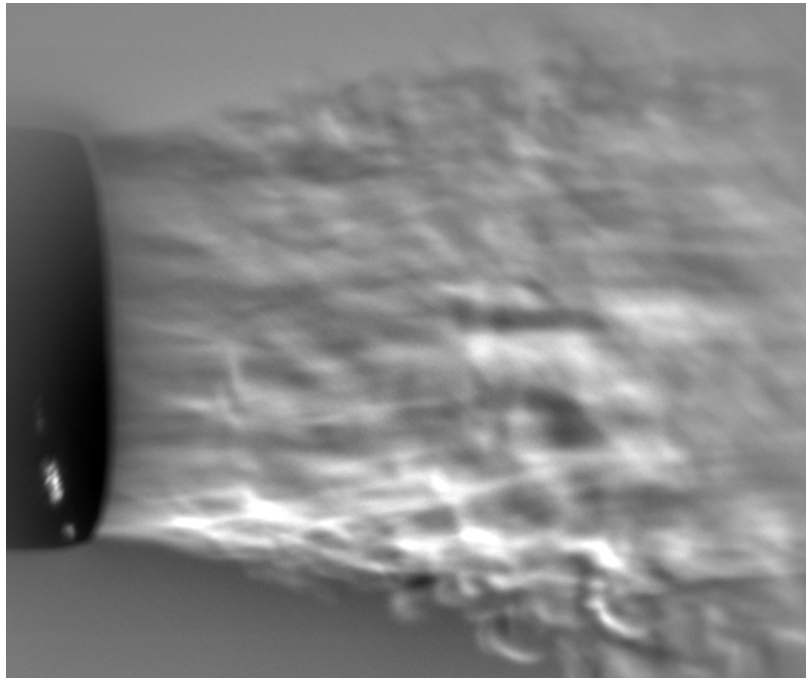
- Double-pass through QWP provides effective 90º rotation of polarization
- QWP can be moved close to RBG to minimize window reflections
- QWP can be replaced with QWF
  - QWP usually more expensive
  - QWP restricted to smaller apertures
  - QWF can be easily damaged
  - QWP can be precisely rotated
- QWP vs. QWF is highly application dependent



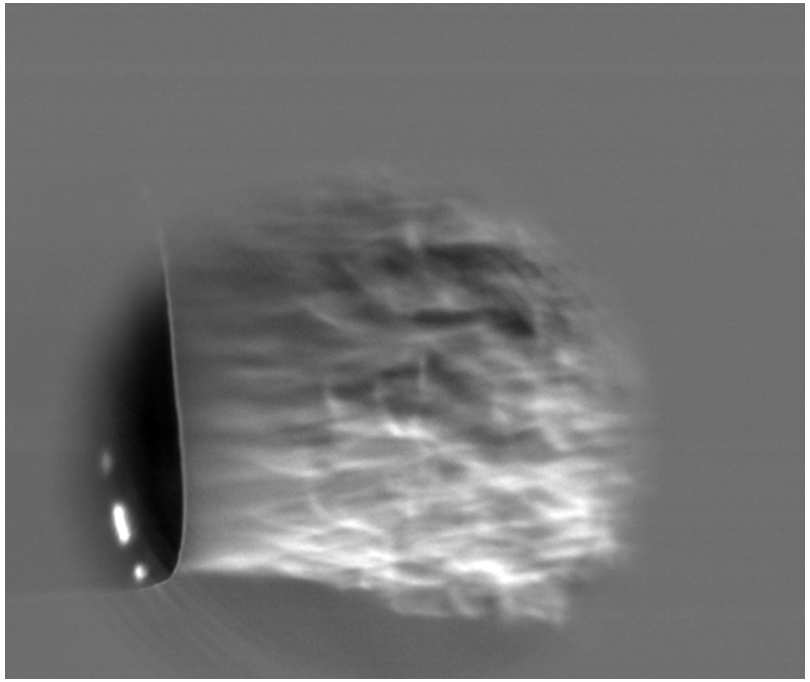
Component Trade Study: Background Material

- Conventional SAFS uses RBG
  - Not required to achieve SAFS sensitivity
- Sensitivity can be achieved with flat mirror or polished metal

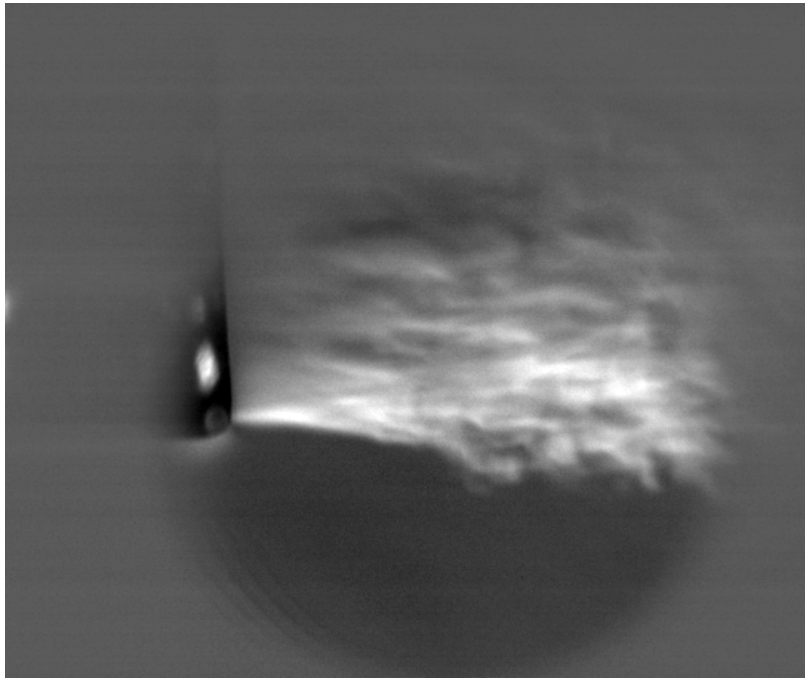
RBG



Flat mirror

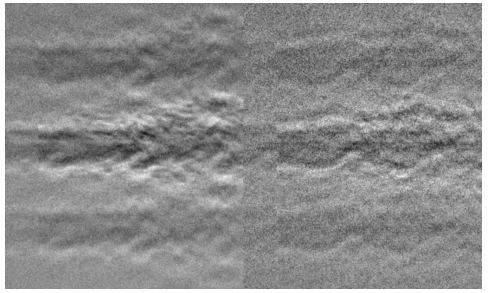


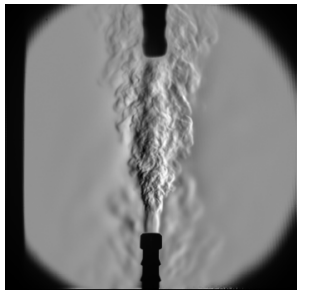
Polished Metal

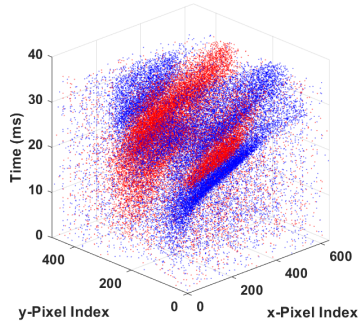


Summary

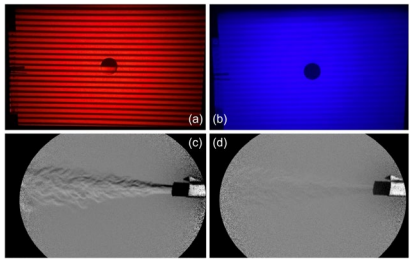
- Numerous adaptations of SAFS presented
  - D-SAFS enables remote variation of RR (direction and frequency)
  - Scheimpflug SAFS enables off-axis imaging
  - Plenoptic SAFS enables simultaneous multi-plane imaging with one camera
  - Event-Based SAFS provides spatio-temporal data
  - Use and manufacturing of spectral-spatial filters in SAFS enabling a variety of simultaneous techniques
- Demonstration of SAFS in NFAC and a TAE
  - Velocimetry performed on TAE images
- Important considerations with various SAFS components
  - Ronchi ruling
  - Rochon prism
  - Quarter-wave plate vs quarter-wave film
  - Background material

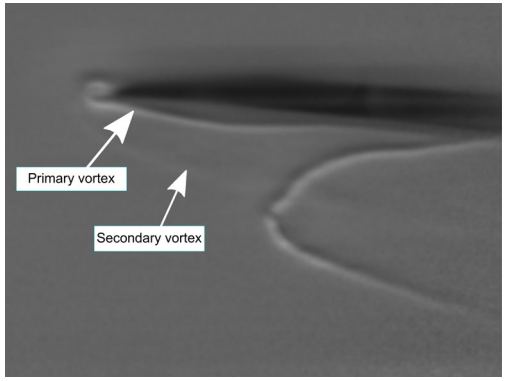


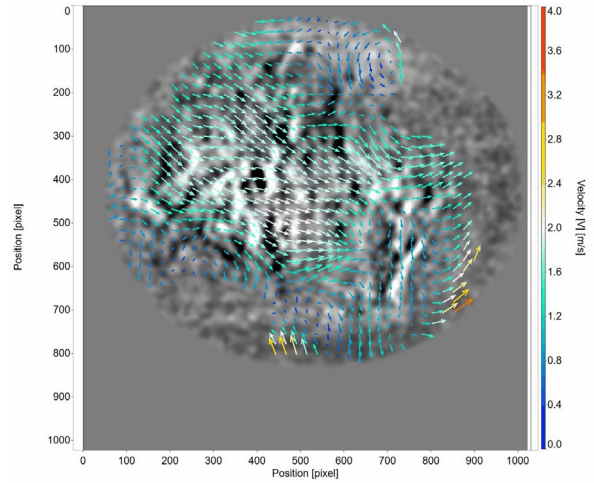












Acknowledgements and References

Acknowledgements:

Transformational Tools and Technologies (T^3) Project
Hypersonic Technologies Project (HTP)
Aerosciences Evaluation and Test Capabilities (AETC) Portfolio

References:

Bathel, B.F. and Weisberger, J.M., "Compact, self-aligned focusing schlieren system," Optics Letters, 46(14), pp. 3328-3331, 2021.

Weisberger, J.M. and Bathel, B.F., "Single source/cutoff grid, self-aligned focusing schlieren system," Exp. Fluids, 63, 2022.

Patents:

Bathel, B.F. and Weisberger, J.M., "Compact, self-aligned projection focusing schlieren method and system," US Patent #11,650,151, 2023.

Bathel, B.F. and Weisberger, J.M., "Methods and apparatus for a self-aligned digital projection and reflected glare reduction imaging system," US Patent #12,072,286, 2024.

Technology Transfer Statement:

Aspects of the SAFS technology discussed in this presentation are protected under US patents #11,650,151, #12,072,286, and others. For more information on licensing these technologies, please visit https://technology.nasa.gov.