

# Reference-Free, Projection Background-Oriented Schlieren

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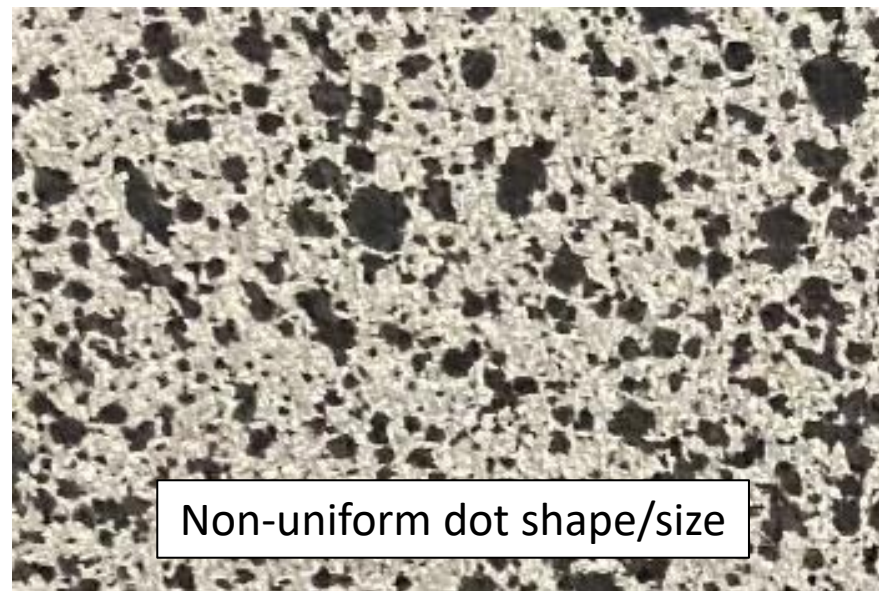
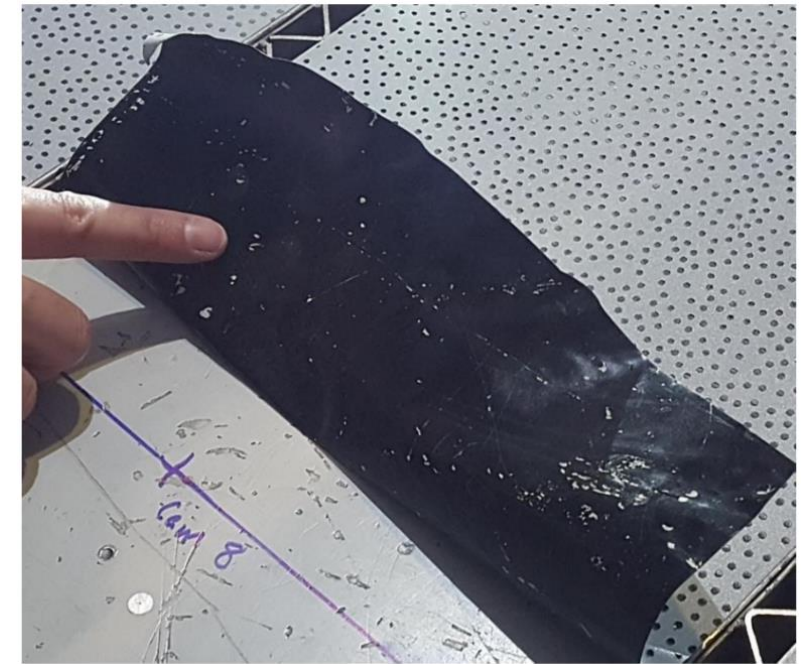
*NASA Langley Research Center*

*Advanced Measurements and Data Systems Branch*

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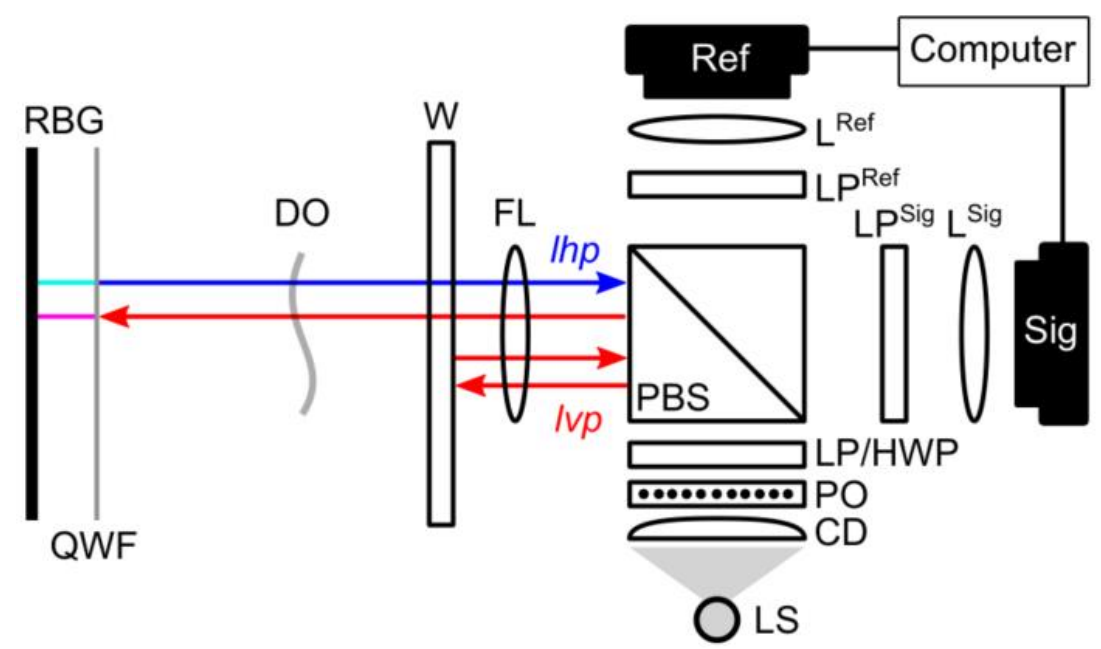
# Motivation for Projection BOS System (P-BOS)

- Background-oriented schlieren (BOS) is a simple optical diagnostic used to image density gradients of flow fields
- Drawbacks of conventional BOS measurements:
  - Speckle pattern permanently printed/painted/sprayed onto retroreflective material
  - Change of speckle size/density requires time-consuming and costly alterations
  - Requires flow-off reference image for BOS calculations
- How P-BOS solves these problems:
  1. Projects speckle pattern onto clean retroreflective material
    - Change speckle pattern without changing retro material
    - Retro material can be used simultaneously for other measurements (shadowgraph, focusing schlieren, etc.)
  2. Two cameras simultaneously take images, one for the flow and one for the reference images
  3. After pre-test transformation, speckle pattern can be changed during a test for BOS optimization, without needing another flow-off reference image



# Polarized P-BOS System – Experimental Setup

- Experimental setup of polarized system used for results in manuscript
- Transparent patterned optic (PO) back-illuminated
- *Ref* camera images undistorted speckle pattern
- PO imaged onto retroreflective background (RBG) by a field lens (FL), passing through density object (DO)
- *Sig* camera images pattern distorted by the DO
- Polarized system eliminates window reflections/glare



- Transparent soda lime glass with opaque chrome pattern, AR-coated
- Left: regular dot pattern calibration target
- Middle: 0.4 mm random dot size/spacing
- Right: 0.2 mm random dot size/spacing



Left



Middle



Right

# P-BOS Operation Flowchart

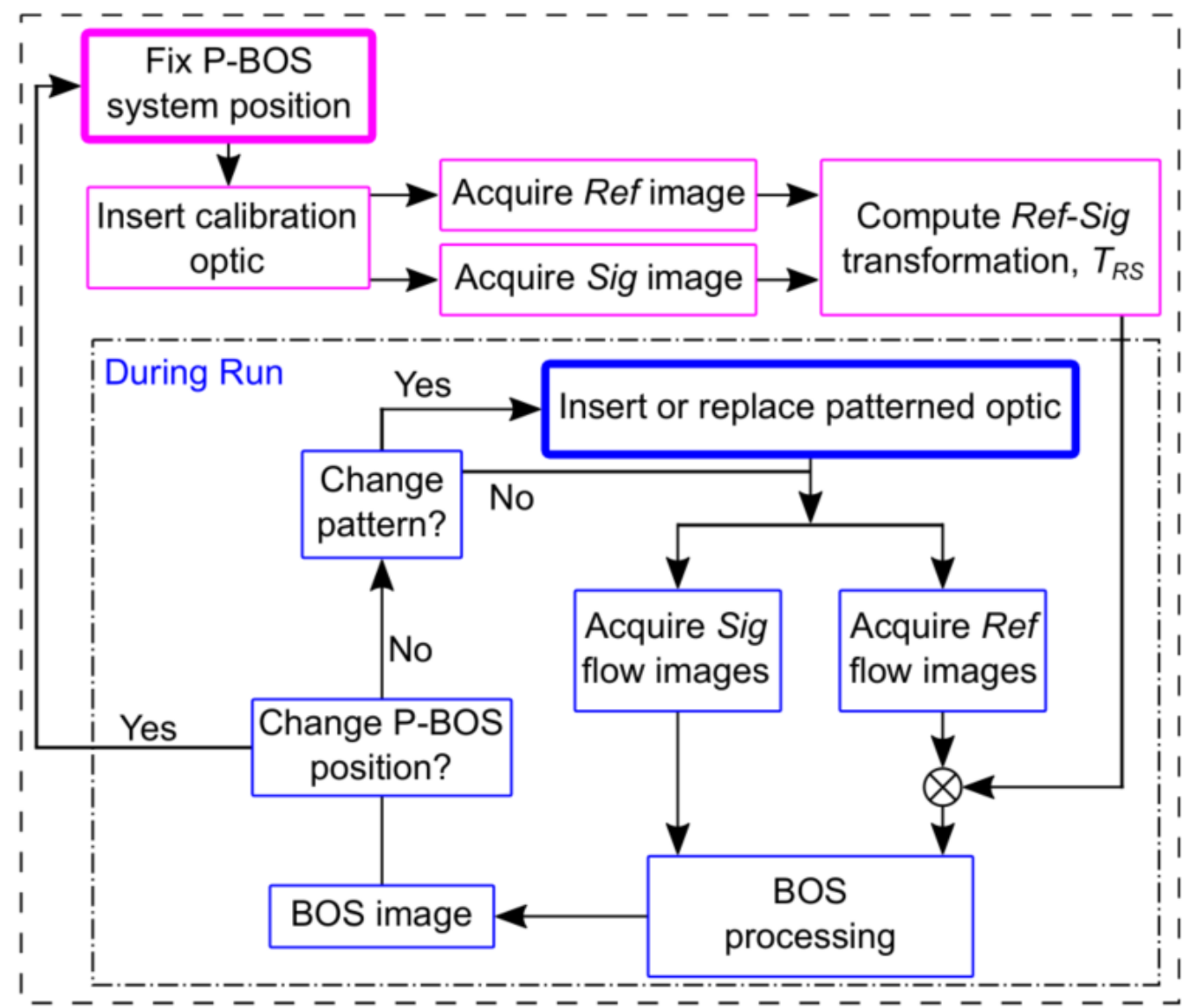
- Flowchart shows steps for running P-BOS system

- Prior to a run:**

- P-BOS system and optics (focal length, focus, etc.) are fixed in place
- Using calibration PO, image is acquired with both *Ref* and *Sig* cameras
- Transformation of coordinate system from *Ref* to *Sig* is computed,  $T_{RS}$

- During a run:**

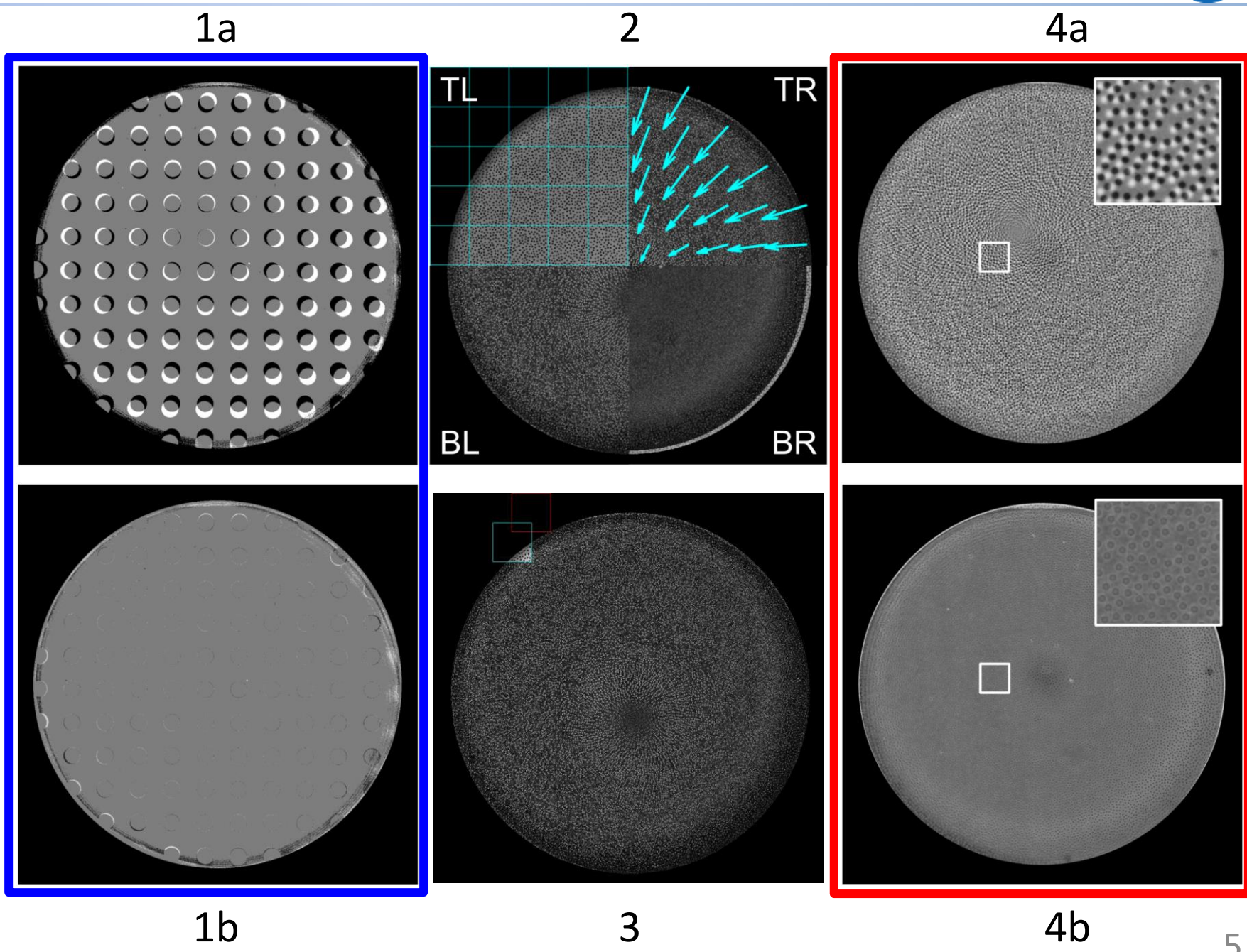
- Desired PO inserted in system
- *Sig* and *Ref* images acquired at every time step
- Transformation  $T_{RS}$  applied to *Ref* image
- BOS signal computed
- If P-BOS system positioning needs to be changed
- **If only PO is changed, continue running without stopping flow**



# Ref-Sig Transformation Calculation

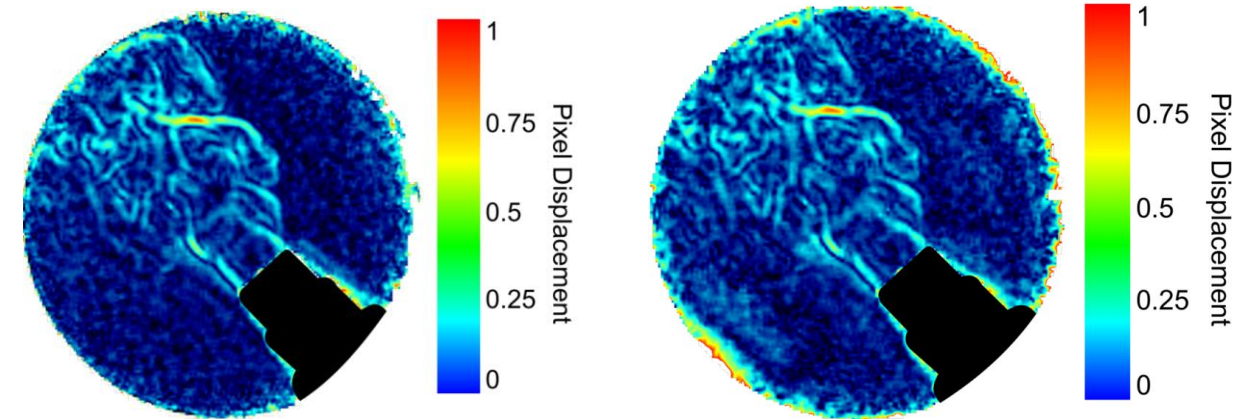
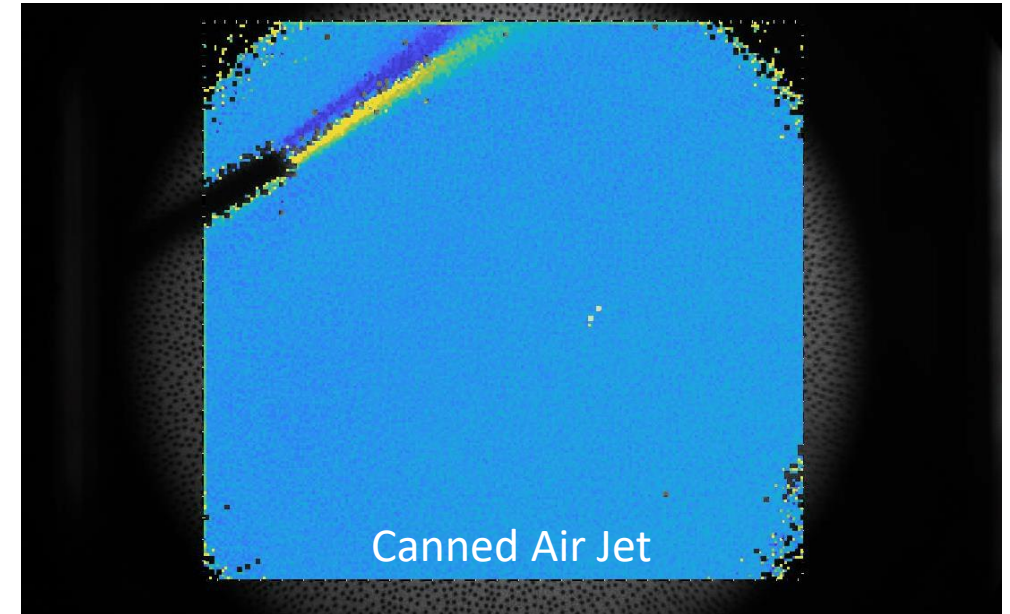
- Pre-test transformation maps coordinate system of *Ref* image to that of *Sig* image,  $T_{RS}$ 
  - Can also map from *Sig* to *Ref*,  $T_{SR}$
- 2D polynomial transformation using discrete anchor points

1. Regular dot pattern Sig-Ref difference images (1a) pre- and (1b) post-transformation
2. Speckle cross-correlation anchor point transformation
3. Image sequence of cross-correlation displacement calculations
4. Speckle pattern Sig-Ref difference images (4a) pre- and (4b) post-transformation



# Initial Testing of P-BOS System

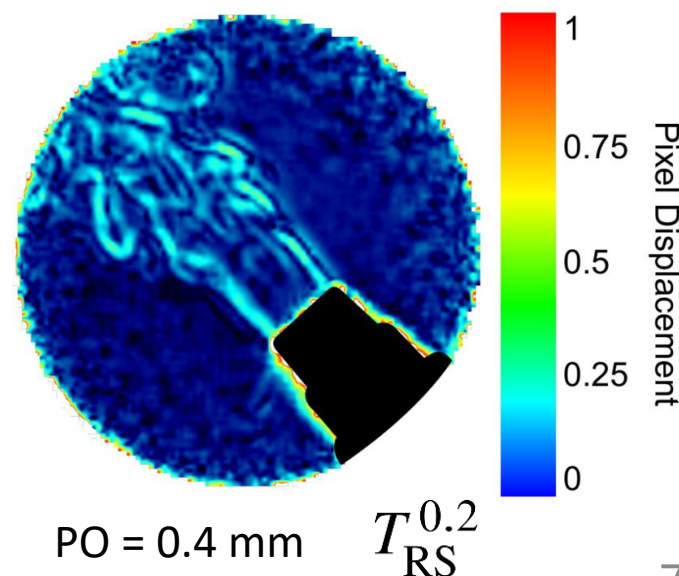
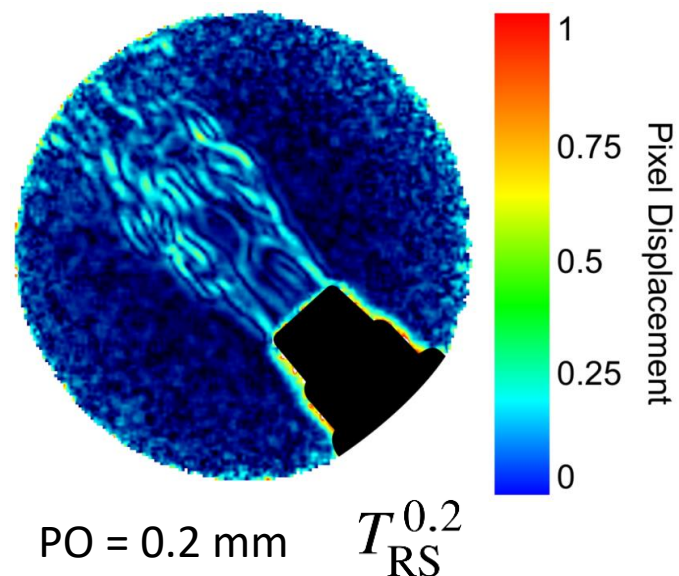
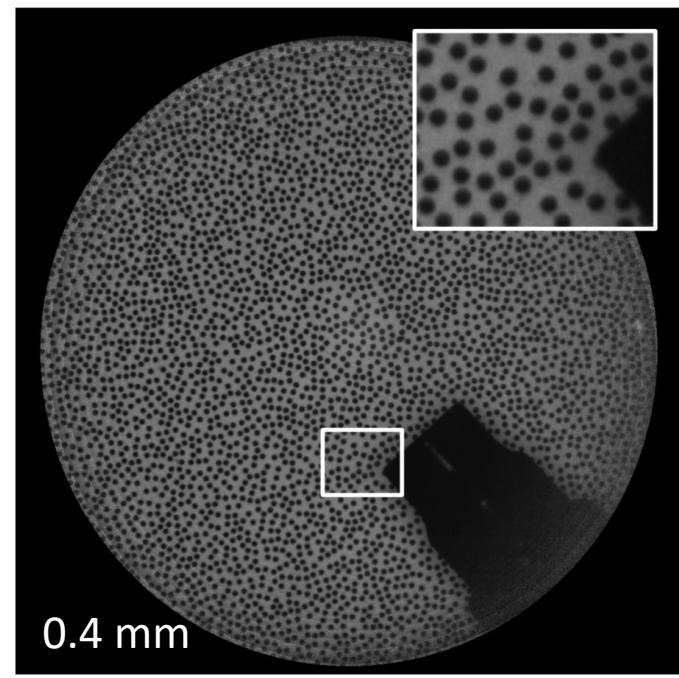
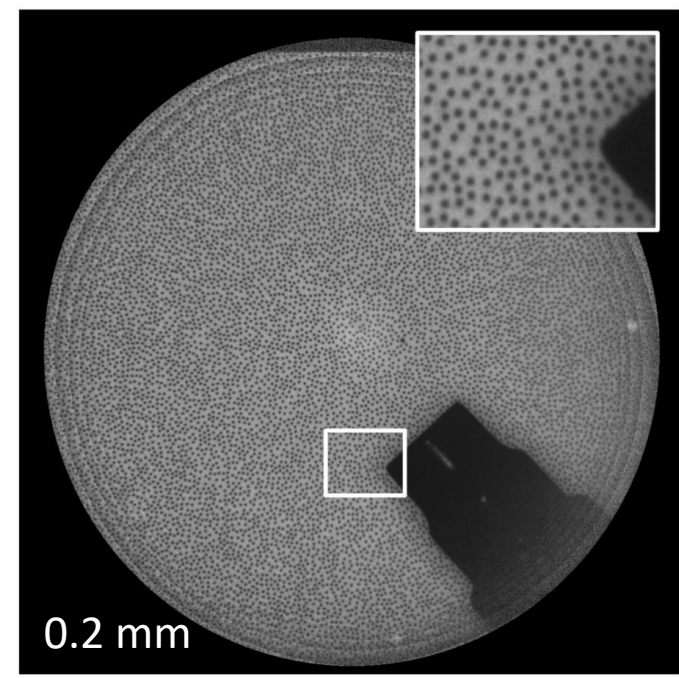
- Canned air jet used to test initial projection concept
  - Referencing flow-*Sig* images to pre-flow-*Sig* images (same as conventional BOS)
  - Room air currents visible, demonstrating sensitivity
  
- Heat gun thermal plume used to test *Sig-Ref* feasibility, using 0.2 mm PO (fine speckled pattern)
  - Bottom-left:
    - Flow-*Sig* referenced to pre-flow-*Sig*
    - Same as canned air jet demo, showing good BOS images
  - Bottom-right:
    - Transformation  $T_{RS}$  computed prior to flow
    - Flow-*Sig* referenced to transformed flow-*Ref*
    - Same thermal plume structure visible, validating technique
    - Higher noise at edges of FOV, likely due to low signal-to-noise at edge of images, and less accurate transformation at the edges



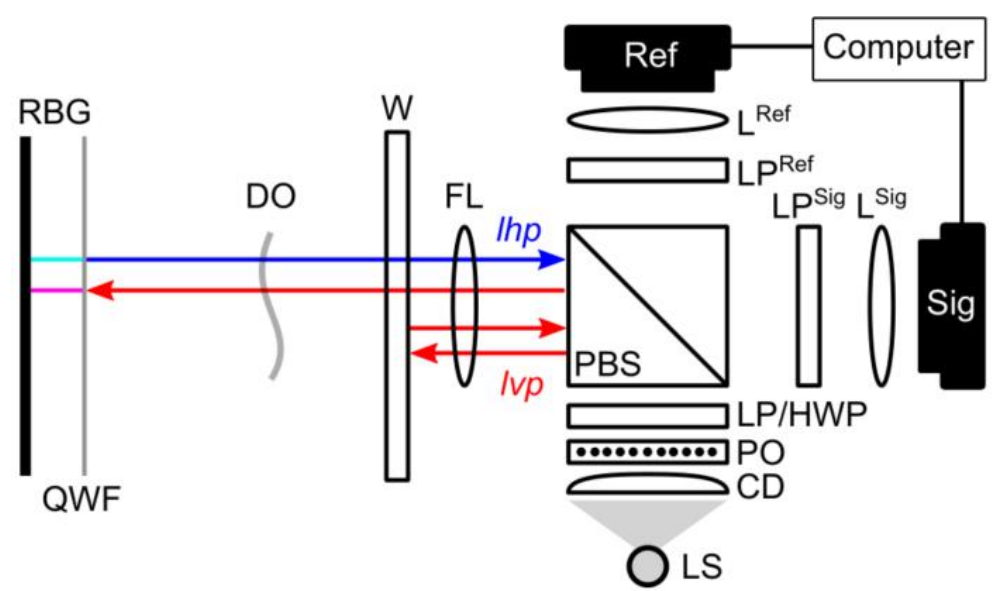
Heat Gun Thermal Plume

# P-BOS Operation Validation

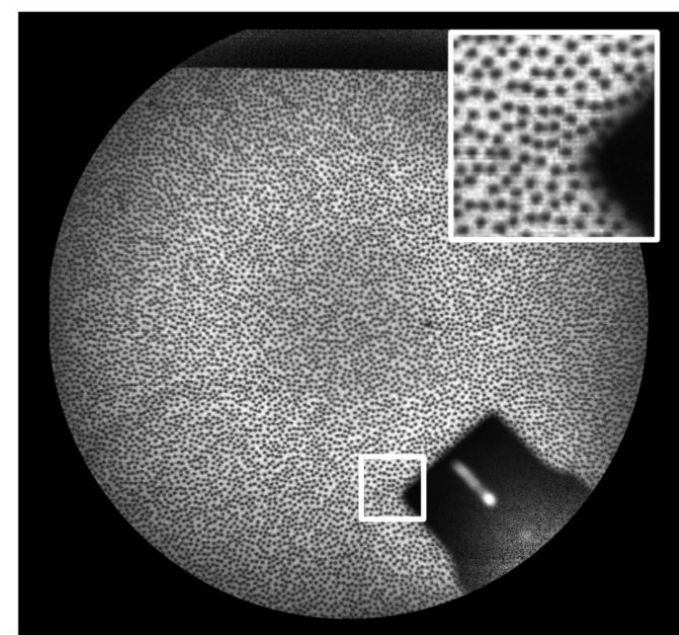
- On previous slide, verified the use of a transformed-*Ref* image for the reference image
  - Now, verify ability to change PO mid-run
1. Pre-flow-*Sig* and pre-flow-*Ref* images captured with 0.2 mm PO, and transformation  $T_{RS}^{0.2}$  computed
  2. Heat gun turned on
  3. BOS image computed using flow-*Sig* and  $T_{RS}^{0.2}$  transformed flow-*Ref*
  4. While heat gun remains on, 0.2 mm PO replaced by 0.4 mm PO
  5. BOS image computed using flow-*Sig* and  $T_{RS}^{0.2}$  transformed flow-*Ref*
- Similarity of BOS images of thermal plume demonstrate the feasibility of this measurement technique



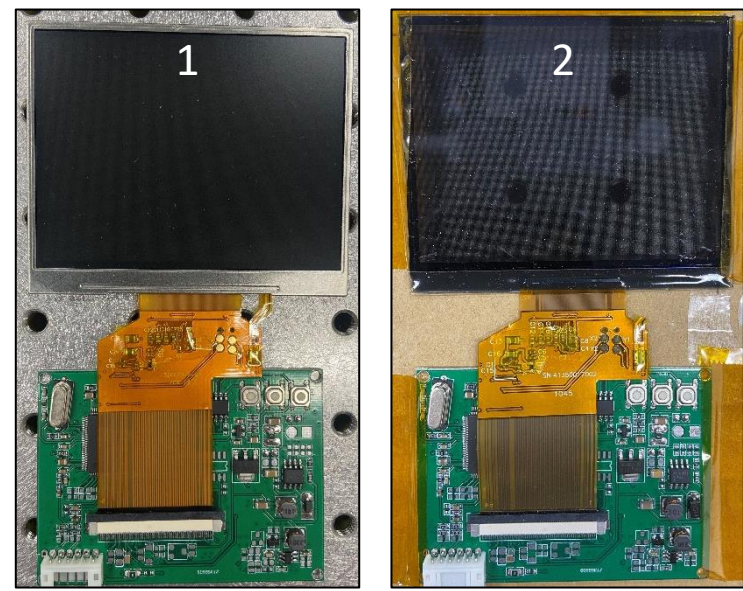
# Digital LCD Display as Patterned Optic



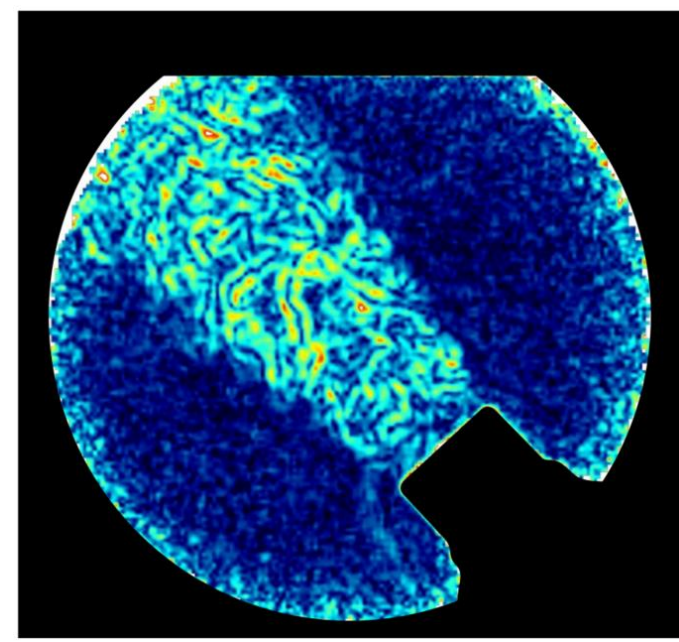
- Results of LCD testing using second method
- Projected speckle pattern nearly equivalent to physical PO
- Defocused very slightly to avoid imaging electrical lines between pixels



- Two ways to implement a digital display:
  1. Remove LS and CD, use built-in back-light of LCD screen for illumination
  2. Keep LS and CD to back-illuminate transparent LCD screen (built-in back-light removed)

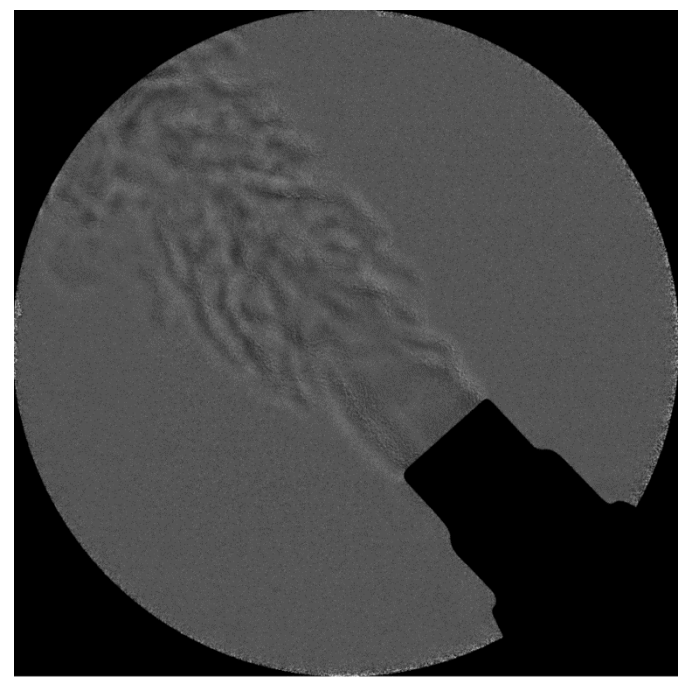
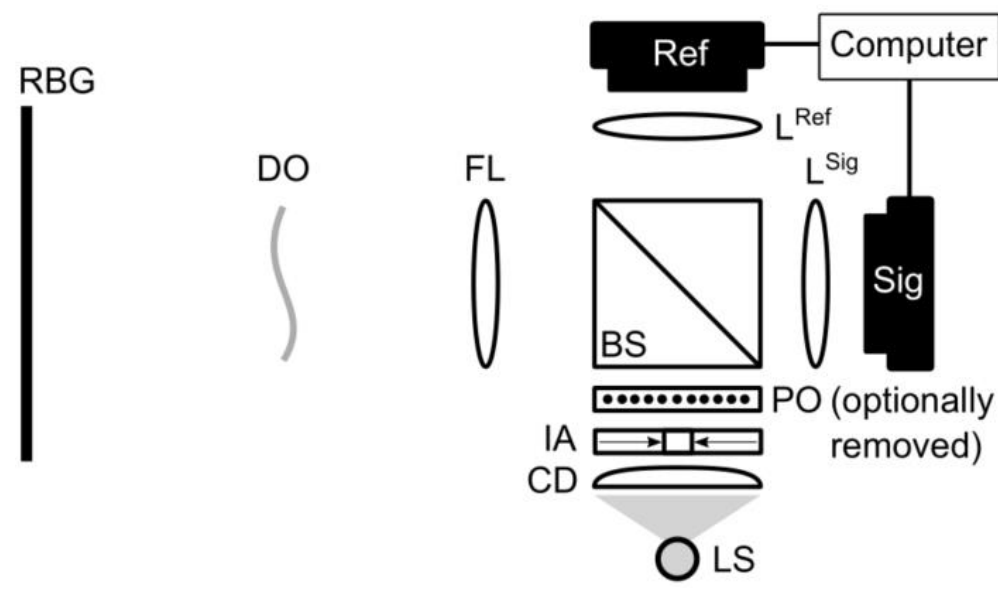


- BOS imaging results comparable to physical PO
- Higher displacements at edge of FOV from transformation

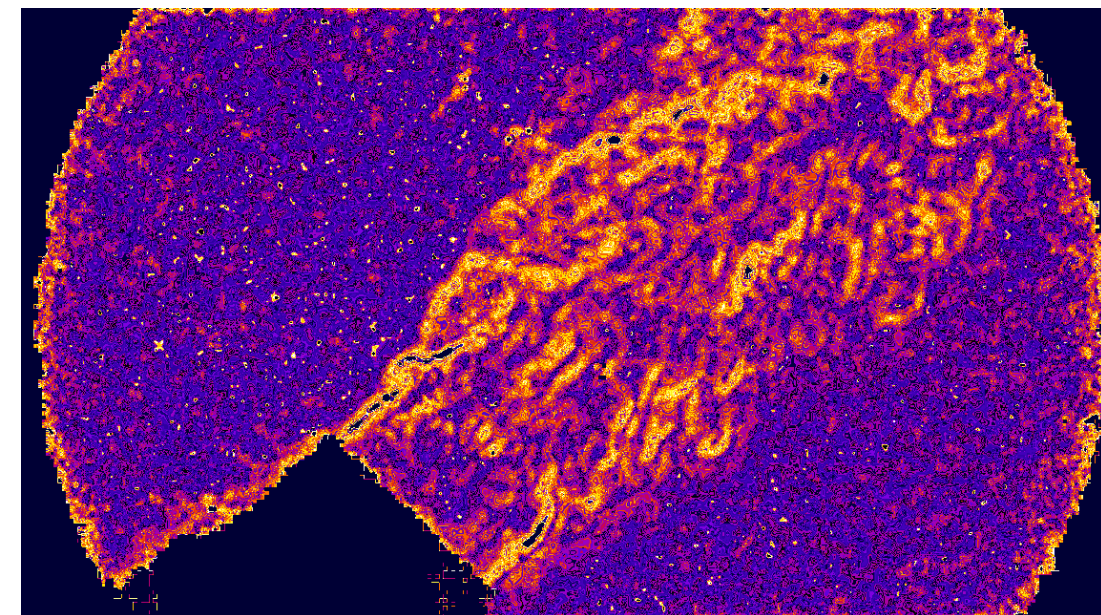
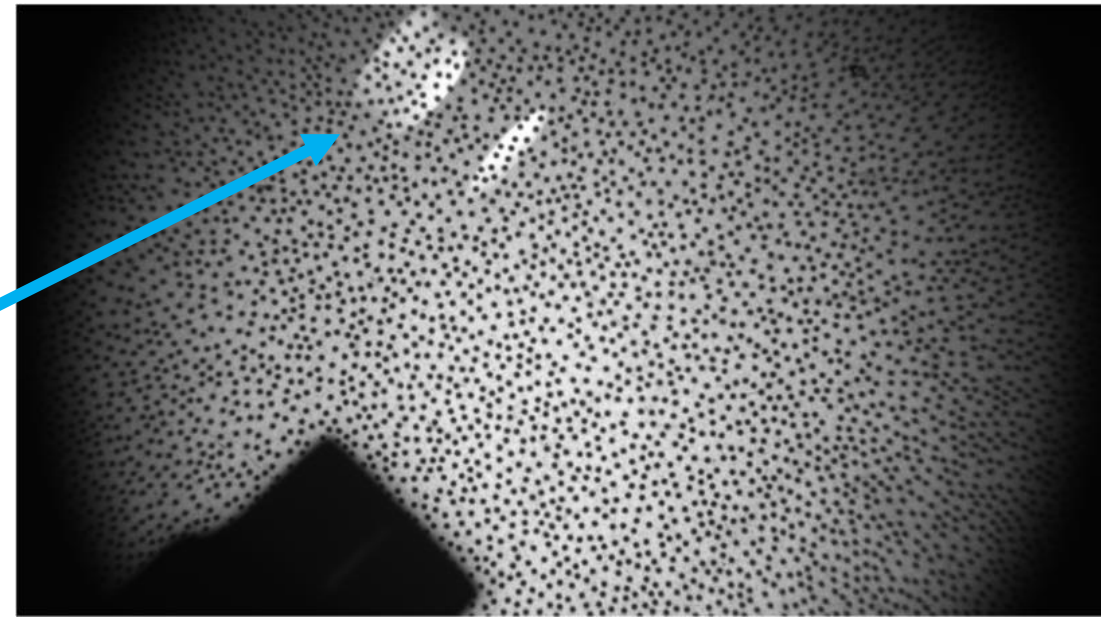


# Shadowgraph Implementation and Results

- Converted system to operate in shadowgraph mode by:
  1. Removing patterned optic, PO
  2. Closing the iris aperture, IA, to its smallest opening
- Reference camera not needed for shadowgraph imaging
- Field-of-view and of shadowgraph and BOS images are similar
- Thermal plume from heat gun qualitatively matches BOS imaging (2<sup>nd</sup> derivative vs. 1<sup>st</sup> derivative)

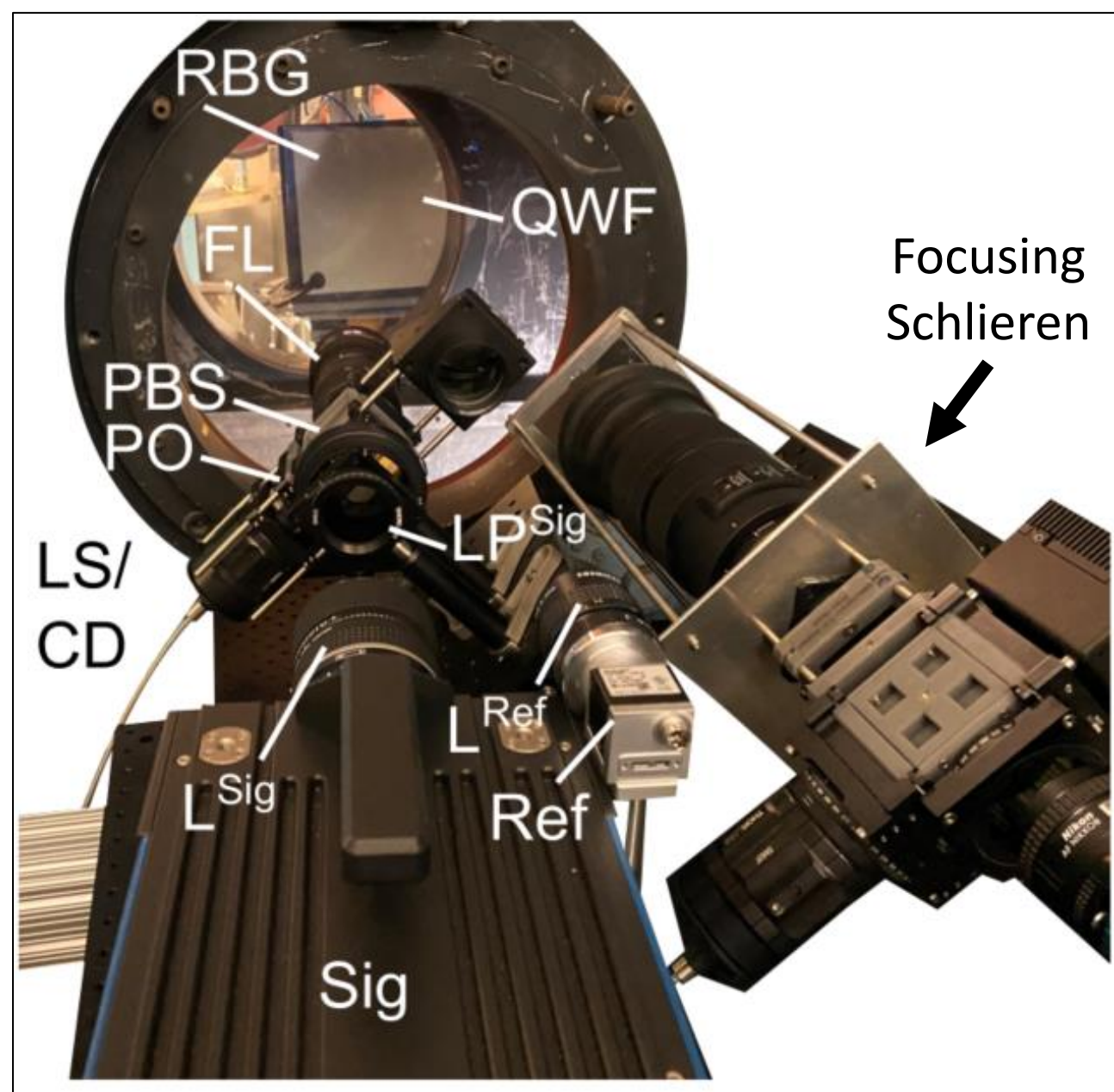


- Used measurements of mounting hardware locations at the wind tunnel to set up lab mock-up
- Bright reflections visible from glare off quarter-wave film (QWF) taped to retroreflective background
  - Fixed this problem during wind tunnel testing by clamping the QWF between the background and a clear acrylic plate
- Using thermal plume of heat gun as density object
  - Good BOS image quality instilled confidence in system being installed at the wind tunnel



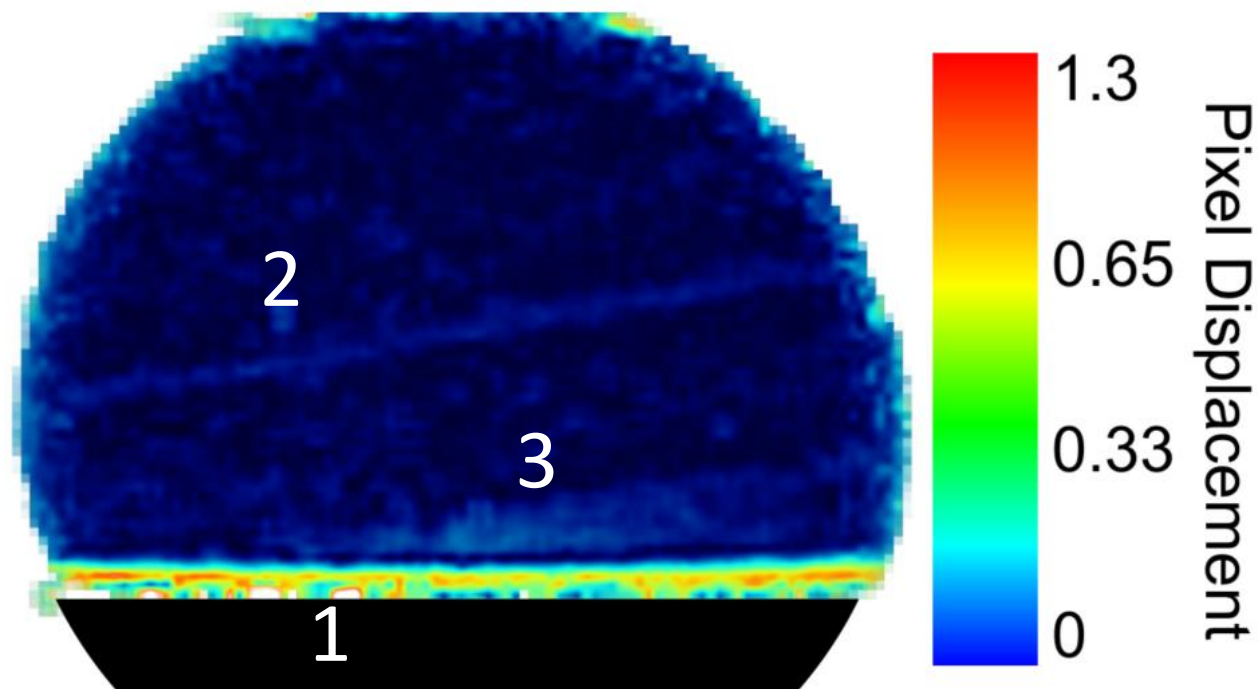
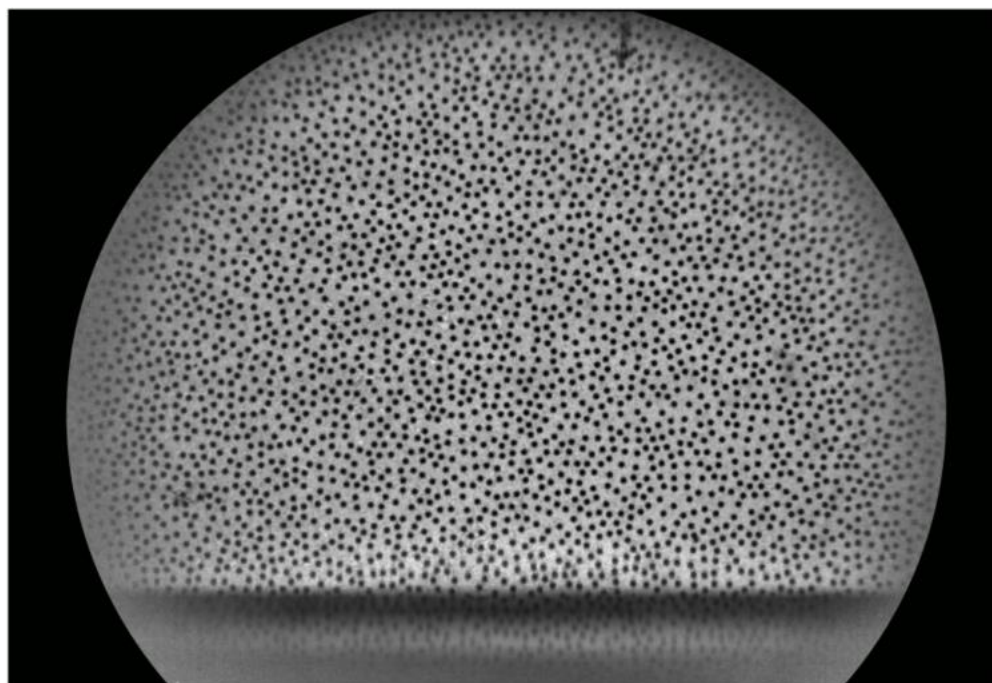
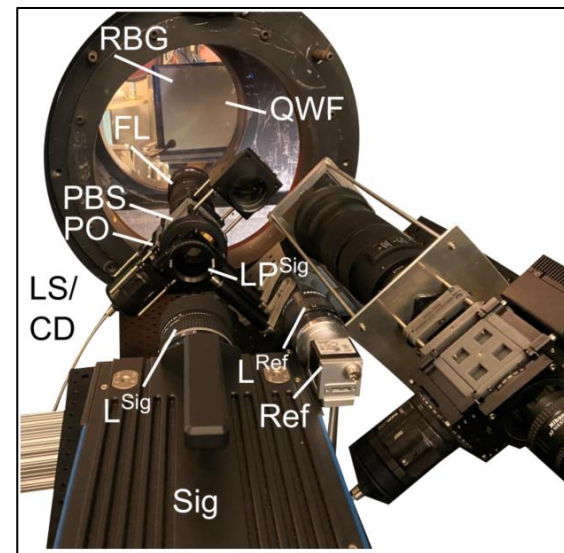
# 20-Inch Mach 6 Setup // Flat Plate Measurements

- P-BOS system installed at tunnel next to the self-aligned focusing schlieren system
- Imaging at a slight downstream angle due to space limitations
  - Not able to view the ramp on the flat plate, viewing upstream of ramp
  - Focusing schlieren system viewing orthogonal to flow, and imaging ramp
- PCO Dimax HD camera used for *Sig* camera, and Basler acA1920-150um used for *Ref* camera
- Because FS system rotated by  $45^\circ$ , the P-BOS system also needed to be rotated by the same amount



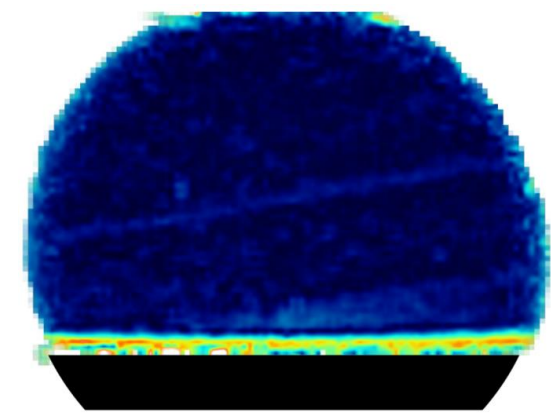
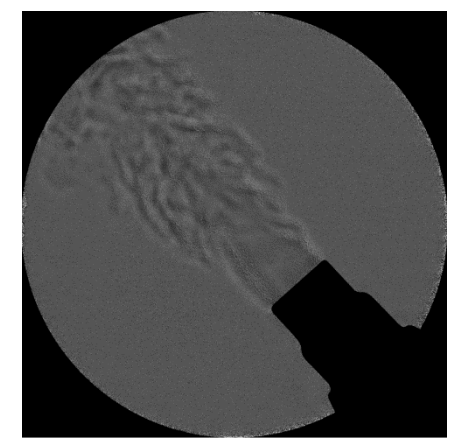
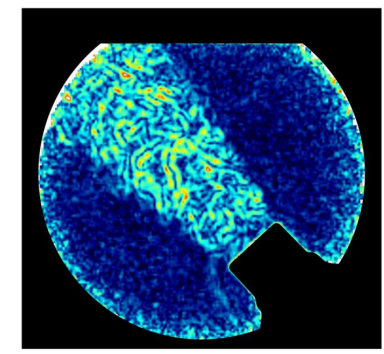
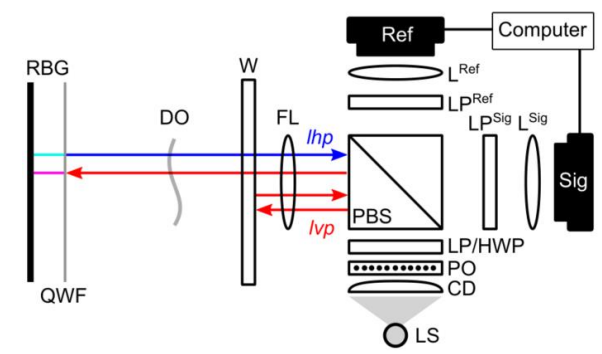
# 20-Inch Mach 6 Testing // Flat Plate Measurements

- Speckle pattern dots too large and coarse to be optimal for this test, but still able to get preliminary data
- Speckle projected and reflected from side edge of flat plate model (bottom-left)
- Three flow features visible in BOS data (bottom-right):
  1. Strong boundary layer on flat plate
  2. Leading edge shock (Mach wave), with  $9.59^\circ$  isentropic angle matching  $9.6^\circ$  angle
  3. Interaction region of ramp and boundary layer (ramp downstream of field-of-view)



# What Was Accomplished

1. Polarized P-BOS system constructed
2. Verified conventional P-BOS imaging
  - Flow-*Sig* referenced to Pre-Flow-*Sig*
3. Verified reference-free P-BOS imaging
  - Flow-*Sig* referenced to transformed *Ref*
4. Demonstrated LCD as patterned optic
5. Demonstrated shadowgraph implementation
6. Testing conducted on flat plate model at 20-Inch Mach 6 wind tunnel at NASA LaRC



Weisberger and Bathel, "Projection Background-Oriented Schlieren," Applied Optics, In Review.

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A provisional patent has been filed for the technology discussed in these slides and associated manuscript