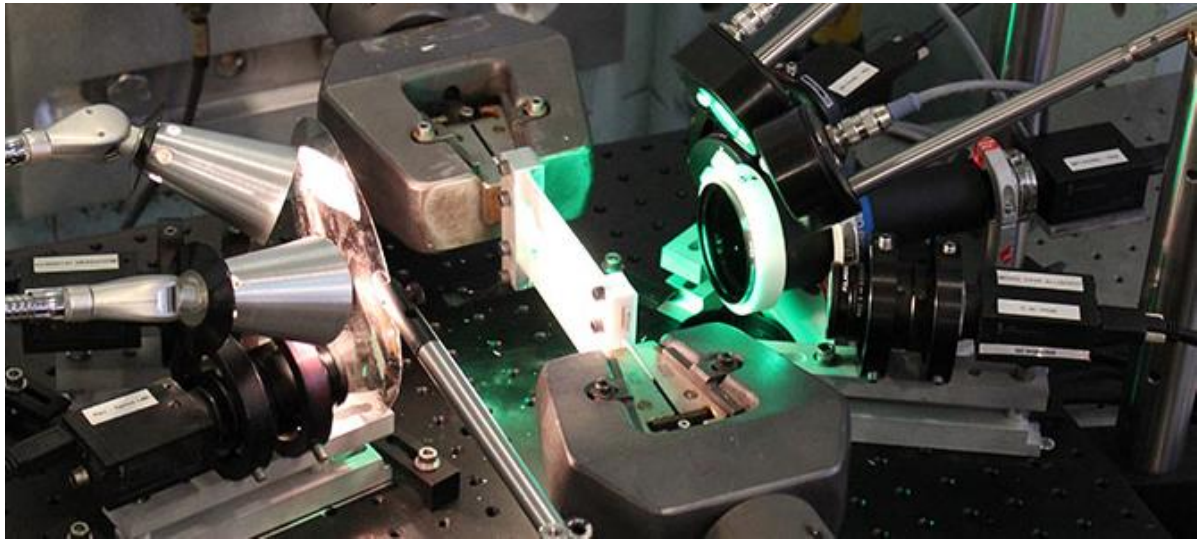
SAND2020-9051 TR (slides)
SAND2020-9046 TR (videos)

DIC 101



Elizabeth Jones and Amanda Jones

Sandia National Laboratories

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Welcome to DIC 101!

Course Instructors

- Special thanks to Dave Johnson for video editing

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Course Description

- Follows the *Good Practices Guide for DIC* (GPG)
- Developed by the International Digital Image Correlation Society (iDICs)
- Focuses on practical applications of DIC rather than theory or algorithms

Target Audience

- New practitioners, to supplement vendor-based or other formal training
- Experienced users, to refresh their fundamental knowledge, assist in troubleshooting, and align practices with larger DIC community

Outline

- Basic, high-level DIC concepts
- Description of the GPG
- Design of DIC measurements
- Preparation for DIC measurements
- Camera calibration
- DIC processing techniques
- Strain calculations
- DIC reporting requirements

Download the GPG!

Before watching these videos, please download the *Good Practices Guide for DIC*, so you can follow along.

https://doi.org/10.32720/IDICS/GPG.ED1

Disclaimers

This class does not address the health or safety concerns regarding applying DIC in a mechanical testing or laboratory environment. It is the responsibility of the laboratory and user to determine the appropriate safety and health requirements.

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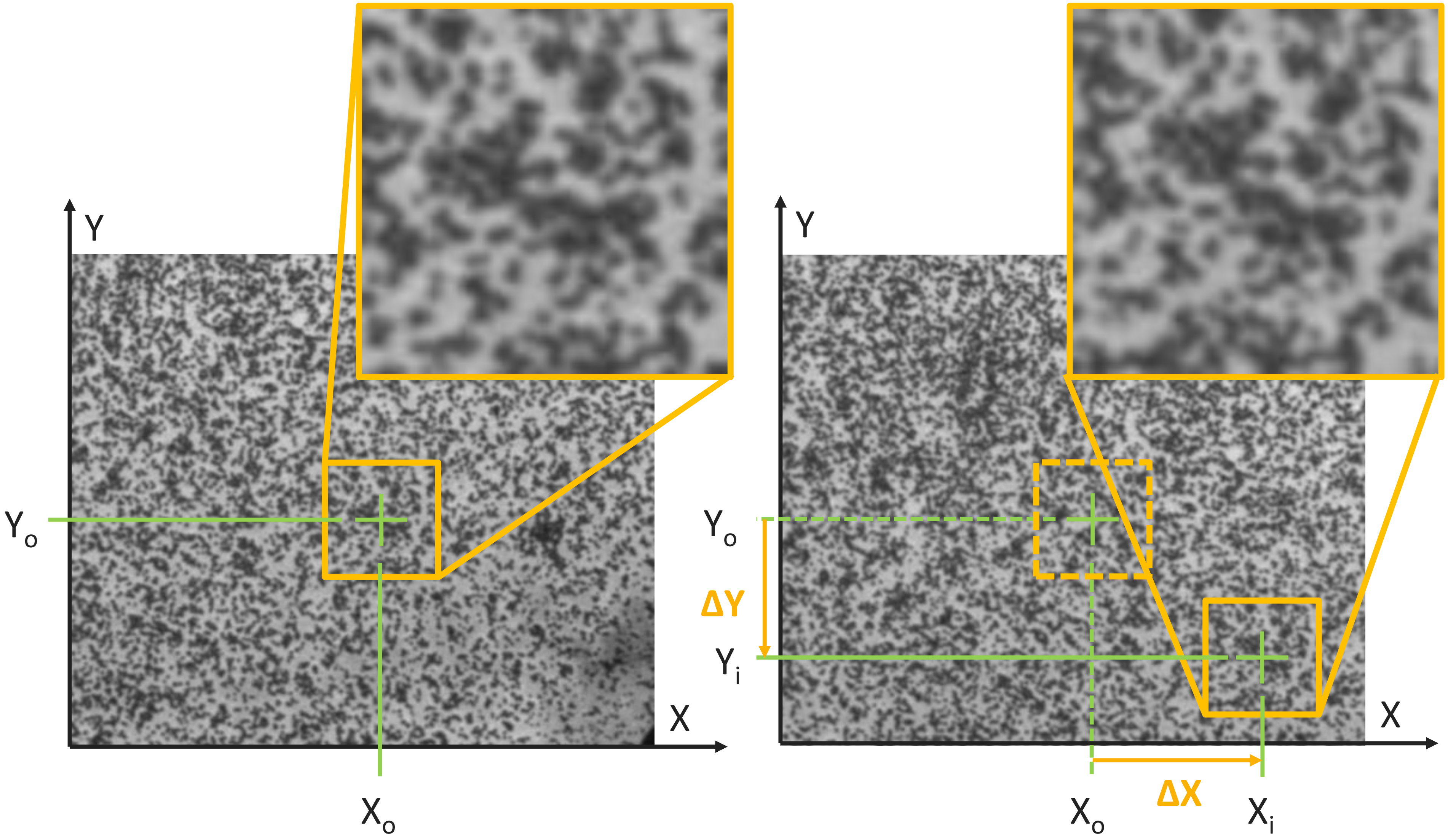
DIGITAL IMAGE CORRELATION (DIC)

INTRODUCTION

"Keep the dots in the box." -- Prof. Samantha Daly

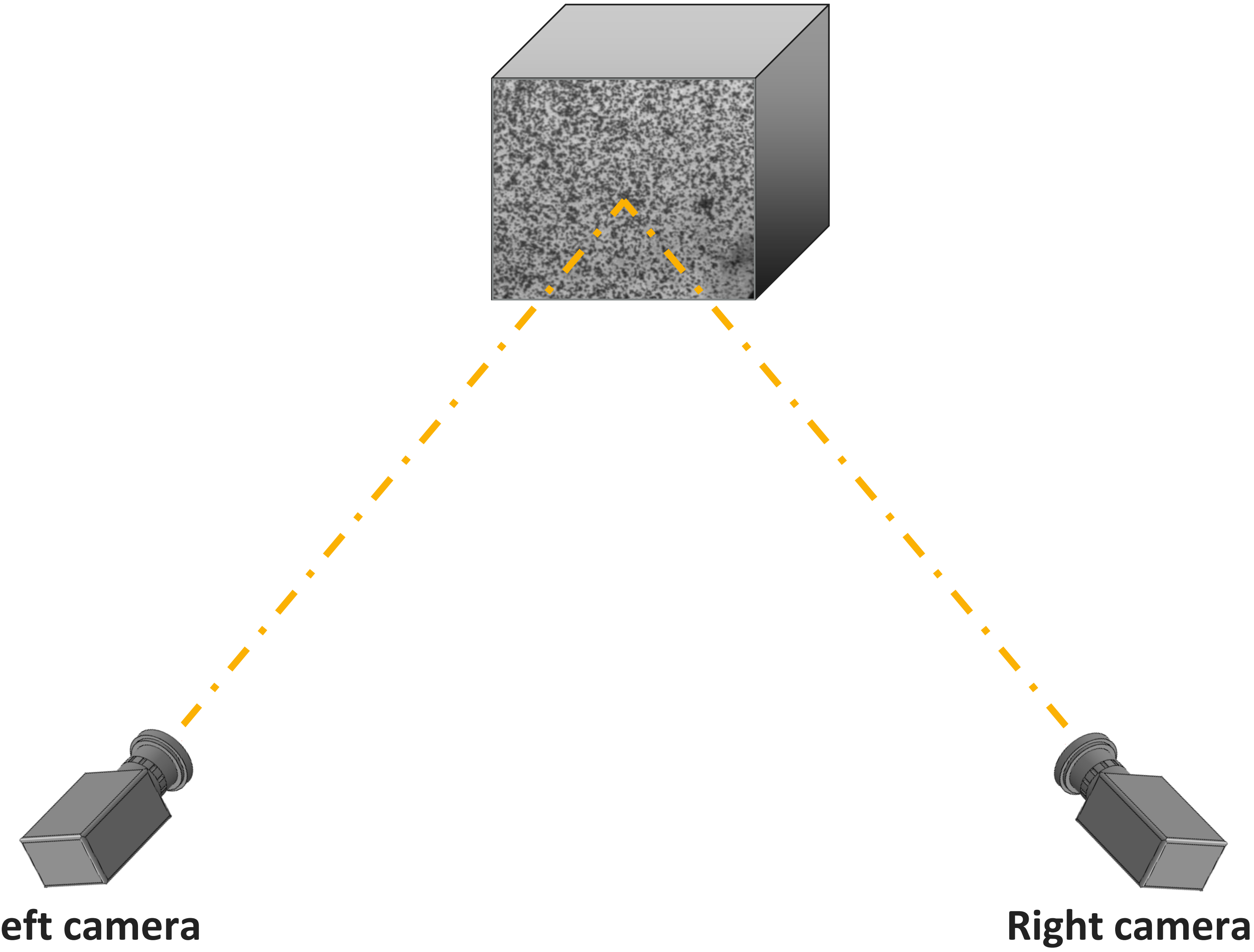
- Digital Image Correlation (DIC) is a diagnostic technique providing full-field shape, displacement and strain measurements on the surface of a solid specimen
- Optical (non-contact)
- Length- and time-scale independent



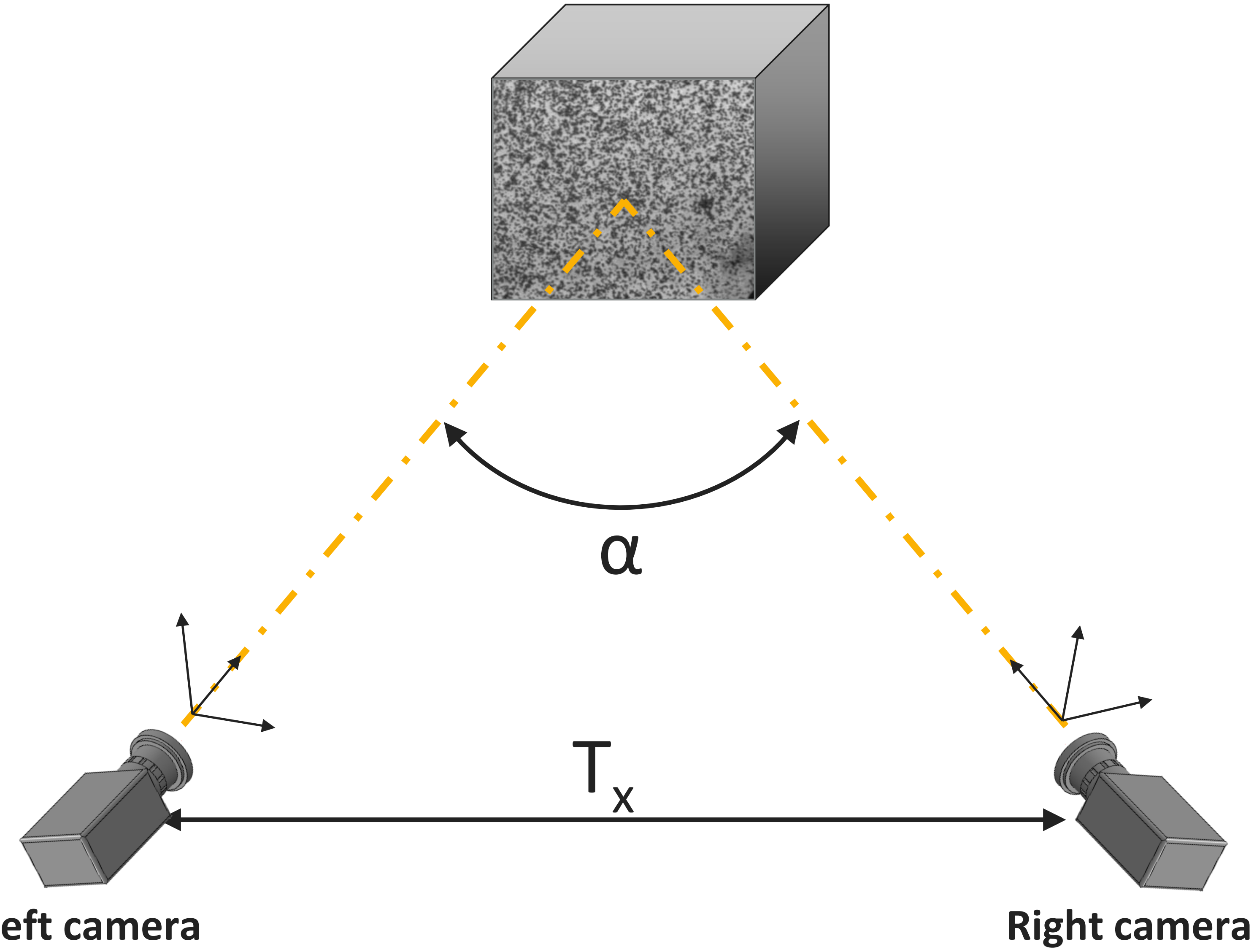
Reference (undeformed) image

Deformed image

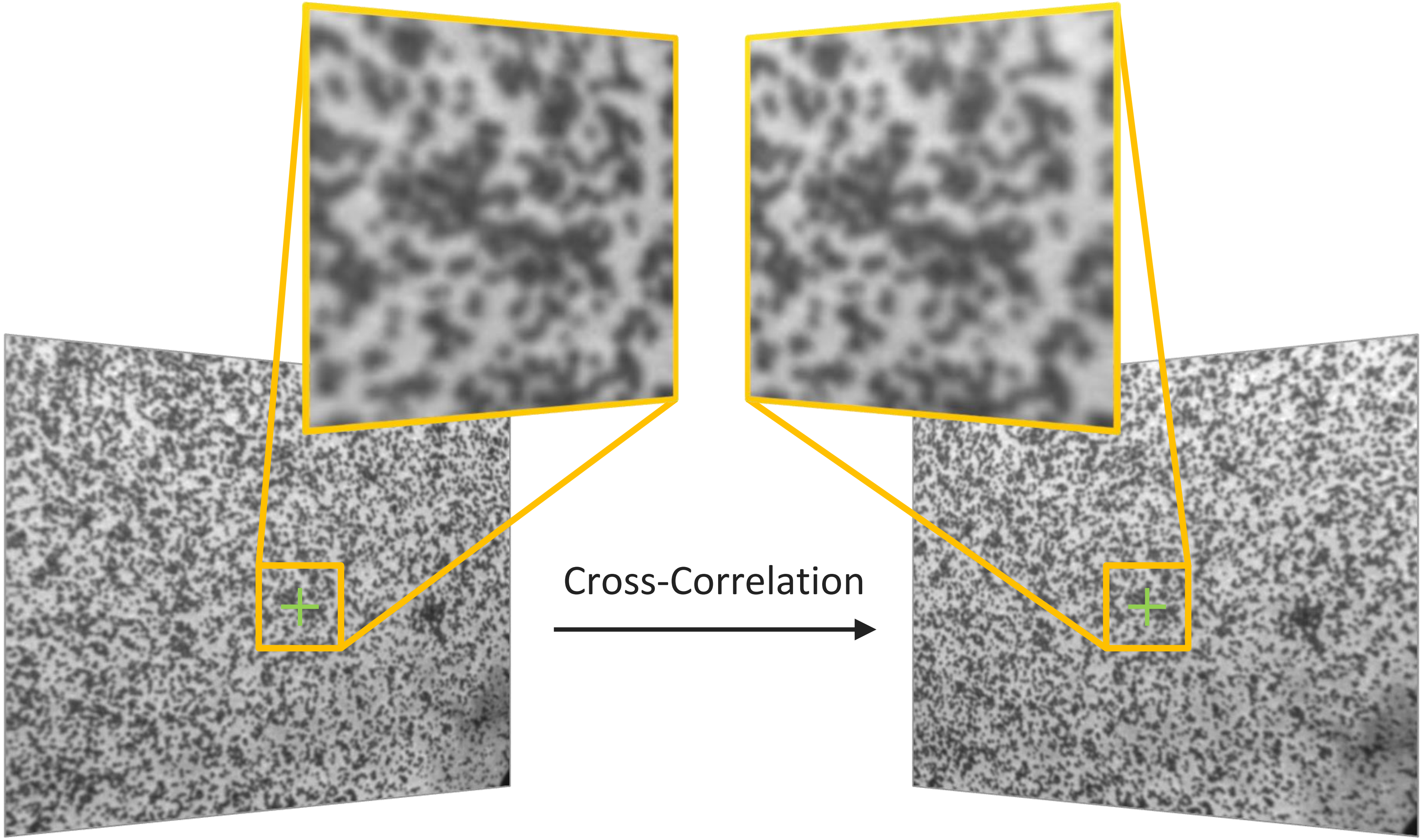
Stereo-DIC utilizes two camera viewing the test piece at an angle to obtain 3D coordinates and displacements.



1. Relative location of one camera with respect to second camera and local camera coordinate systems determined through calibration.



2. Correlation of the left and right cameras identifies the same point in each camera.

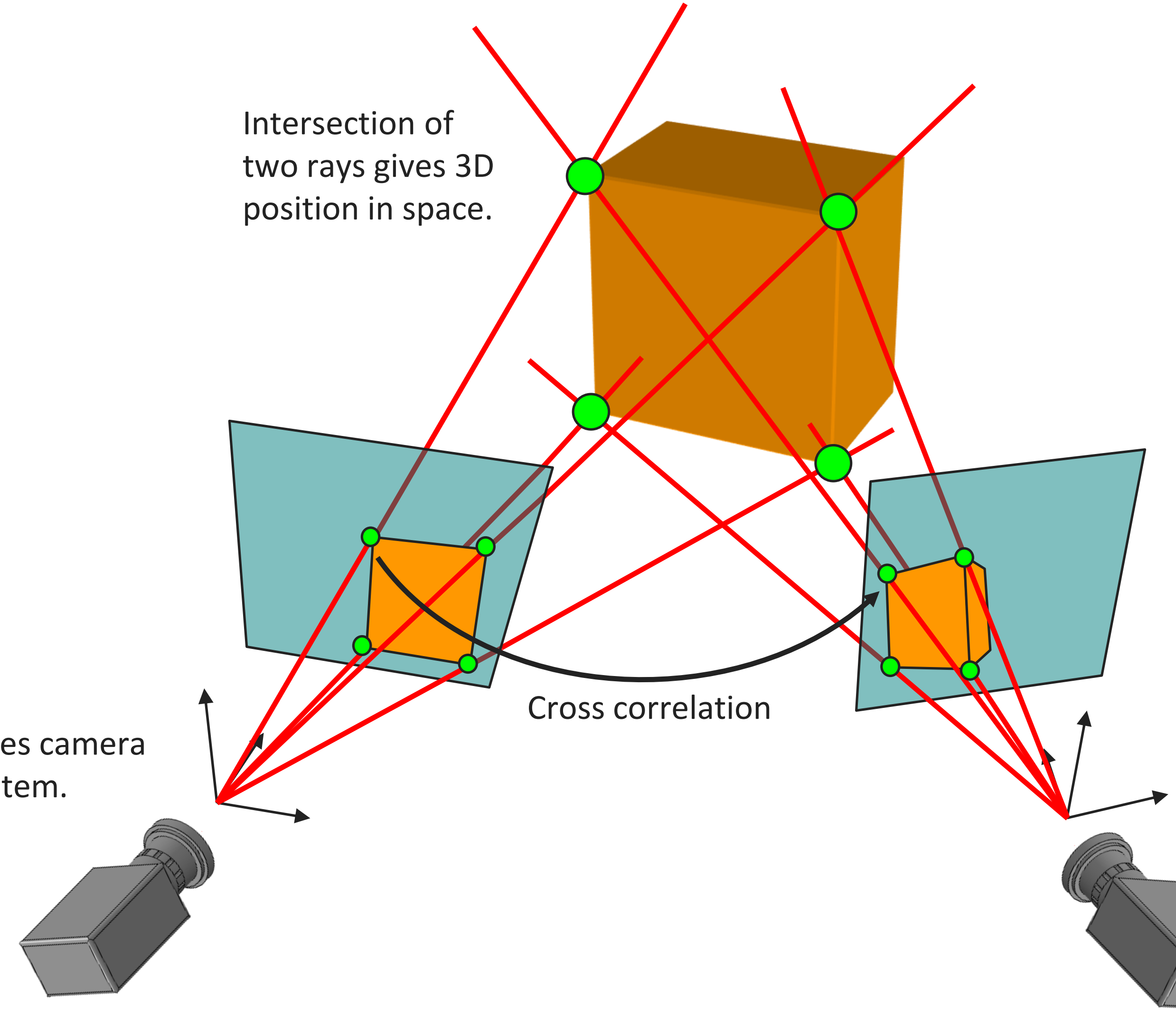


Cross-Correlation

Left camera

Right camera

3. Cross-correlation and triangulation gives coordinates in 3D space.



Intersection of two rays gives 3D position in space.

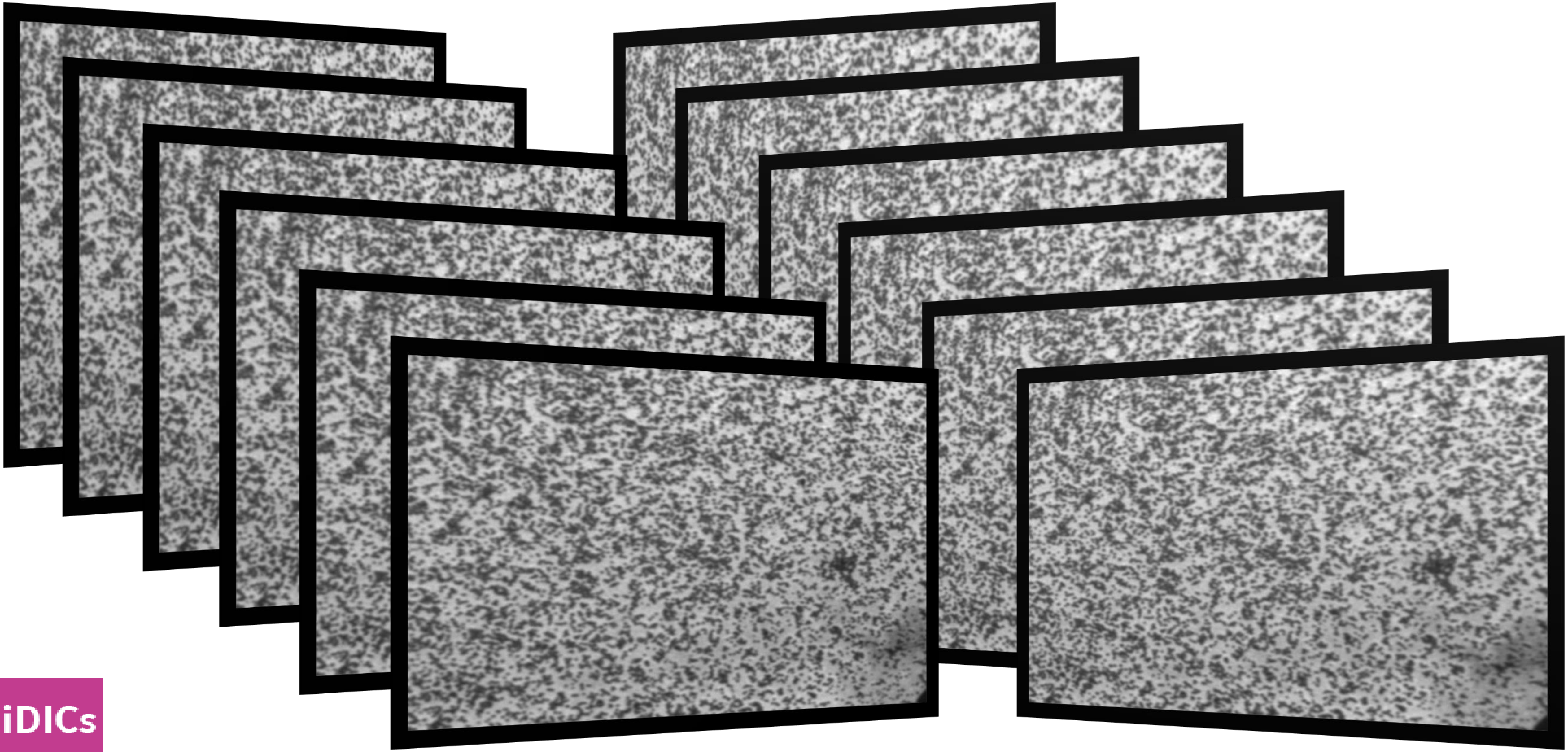
Cross correlation

Calibration gives camera coordinate system.

Left camera

Right camera

Full-field, time-resolved deformation computed from stereo cameras capturing images throughout the mechanical test.



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GOOD PRACTICES GUIDE FOR DIGITAL IMAGE CORRELATION

About the *Good Practices Guide for Digital Image Correlation (GPG)*

Development of the Guide

- Developed by the iDICs Standardization, Good Practices, and Uncertainty Quantification committee

- Approved through an open public comment period Nov 2017-Jan 2018
  - 100 people opted-in to the review process
  - All 500 comments addressed
  - Final review by the iDICs Executive Board

- GPG is freely available!
  - http://idics.org/guide
  - https://doi.org/10.32720/idics/gpg.ed1

- GPG has been translated!
  - 中文 (full version): https://doi.org/10.32720/idics/gpg.ed1.cn
  - Français (glossary): https://doi.org/10.32720/idics/gpg.ed1.fr
  - Deutsch (glossary): https://doi.org/10.32720/idics/gpg.ed1.de

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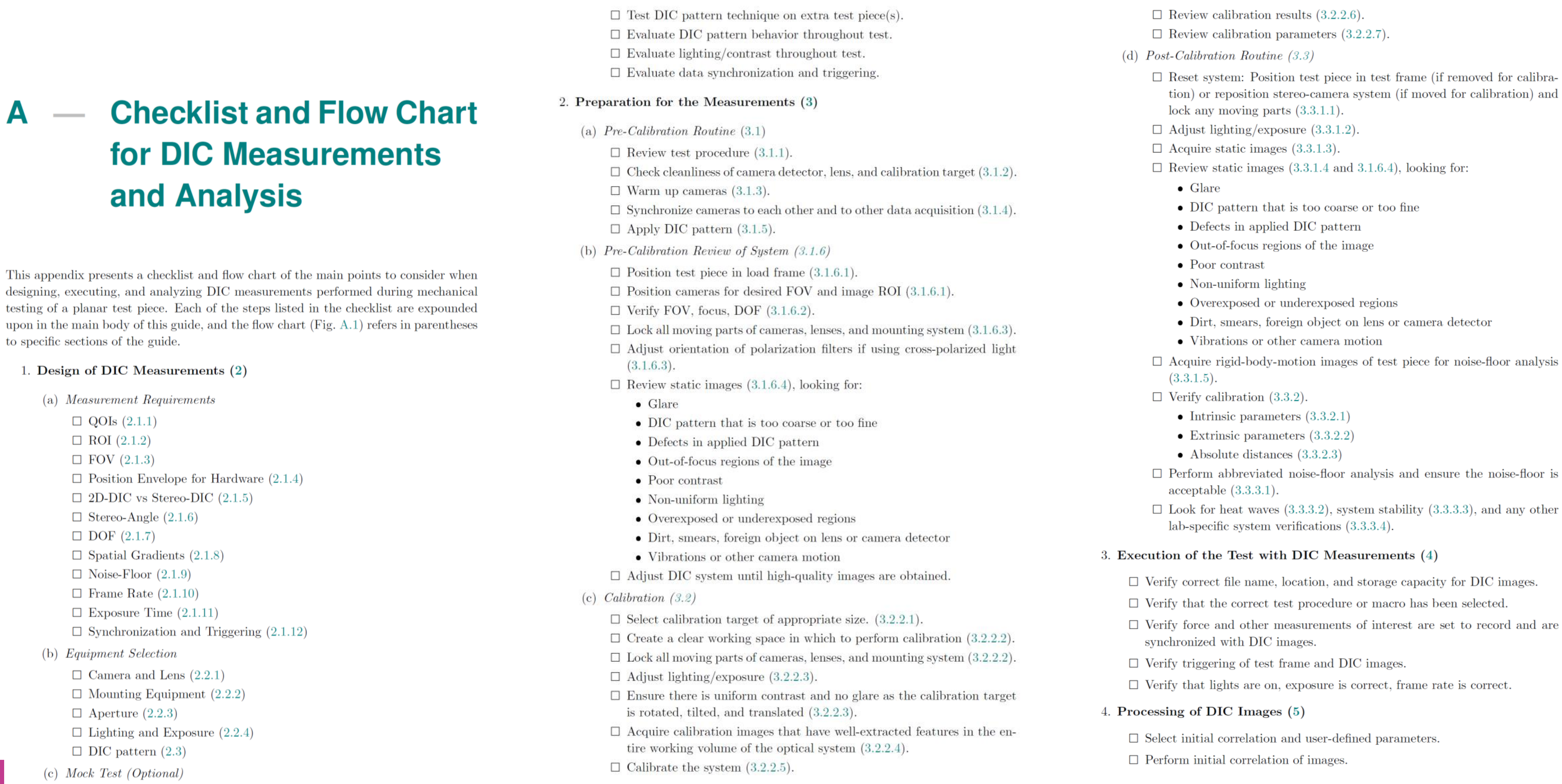
About the *Good Practices Guide for Digital Image Correlation (GPG)*



A — Checklist and Flow Chart for DIC Measurements and Analysis

This appendix presents a checklist and flow chart of the main points to consider when designing, executing, and analyzing DIC measurements performed during mechanical testing of a planar test piece. Each of the steps listed in the checklist are expounded upon in the main body of this guide, and the flow chart (Fig. A.1) refers in parentheses to specific sections of the guide.

1. **Design of DIC Measurements (2)**
   (a) *Measurement Requirements*
      ☐ QOIs (2.1.1)
      ☐ ROI (2.1.2)
      ☐ FOV (2.1.3)
      ☐ Position Envelope for Hardware (2.1.4)
      ☐ 2D-DIC vs Stereo-DIC (2.1.5)
      ☐ Stereo-Angle (2.1.6)
      ☐ DOF (2.1.7)
      ☐ Spatial Gradients (2.1.8)
      ☐ Noise-Floor (2.1.9)
      ☐ Frame Rate (2.1.10)
      ☐ Exposure Time (2.1.11)
      ☐ Synchronization and Triggering (2.1.12)
   (b) *Equipment Selection*
      ☐ Camera and Lens (2.2.1)
      ☐ Mounting Equipment (2.2.2)
      ☐ Aperture (2.2.3)
      ☐ Lighting and Exposure (2.2.4)
      ☐ DIC pattern (2.3)
   (c) *Mock Test (Optional)*
      ☐ Test DIC pattern technique on extra test piece(s).
      ☐ Evaluate DIC pattern behavior throughout test.
      ☐ Evaluate lighting/contrast throughout test.
      ☐ Evaluate data synchronization and triggering.
2. **Preparation for the Measurements (3)**
   (a) *Pre-Calibration Routine* (3.1)
      ☐ Review test procedure (3.1.1).
      ☐ Check cleanliness of camera detector, lens, and calibration target (3.1.2).
      ☐ Warm up cameras (3.1.3).
      ☐ Synchronize cameras to each other and to other data acquisition (3.1.4).
      ☐ Apply DIC pattern (3.1.5).
   (b) *Pre-Calibration Review of System (3.1.6)*
      ☐ Position test piece in load frame (3.1.6.1).
      ☐ Position cameras for desired FOV and image ROI (3.1.6.1).
      ☐ Verify FOV, focus, DOF (3.1.6.2).
      ☐ Lock all moving parts of cameras, lenses, and mounting system (3.1.6.3).
      ☐ Adjust orientation of polarization filters if using cross-polarized light (3.1.6.3).
      ☐ Review static images (3.1.6.4), looking for:
         - Glare
         - DIC pattern that is too coarse or too fine
         - Defects in applied DIC pattern
         - Out-of-focus regions of the image
         - Poor contrast
         - Non-uniform lighting
         - Overexposed or underexposed regions
         - Dirt, smears, foreign object on lens or camera detector
         - Vibrations or other camera motion
      ☐ Adjust DIC system until high-quality images are obtained.
   (c) *Calibration (3.2)*
      ☐ Select calibration target of appropriate size. (3.2.2.1).
      ☐ Create a clear working space in which to perform calibration (3.2.2.2).
      ☐ Lock all moving parts of cameras, lenses, and mounting system (3.2.2.2).
      ☐ Adjust lighting/exposure (3.2.2.3).
      ☐ Ensure there is uniform contrast and no glare as the calibration target is rotated, tilted, and translated (3.2.2.3).
      ☐ Acquire calibration images that have well-extracted features in the entire working volume of the optical system (3.2.2.4).
      ☐ Calibrate the system (3.2.2.5).
      ☐ Review calibration results (3.2.2.6).
      ☐ Review calibration parameters (3.2.2.7).
   (d) *Post-Calibration Routine (3.3)*
      ☐ Reset system: Position test piece in test frame (if removed for calibration) or reposition stereo-camera system (if moved for calibration) and lock any moving parts (3.3.1.1).
      ☐ Adjust lighting/exposure (3.3.1.2).
      ☐ Acquire static images (3.3.1.3).
      ☐ Review static images (3.3.1.4 and 3.1.6.4), looking for:
         - Glare
         - DIC pattern that is too coarse or too fine
         - Defects in applied DIC pattern
         - Out-of-focus regions of the image
         - Poor contrast
         - Non-uniform lighting
         - Overexposed or underexposed regions
         - Dirt, smears, foreign object on lens or camera detector
         - Vibrations or other camera motion
      ☐ Acquire rigid-body-motion images of test piece for noise-floor analysis (3.3.1.5).
      ☐ Verify calibration (3.3.2).
         - Intrinsic parameters (3.3.2.1)
         - Extrinsic parameters (3.3.2.2)
         - Absolute distances (3.3.2.3)
      ☐ Perform abbreviated noise-floor analysis and ensure the noise-floor is acceptable (3.3.3.1).
      ☐ Look for heat waves (3.3.3.2), system stability (3.3.3.3), and any other lab-specific system verifications (3.3.3.4).
3. **Execution of the Test with DIC Measurements (4)**
   ☐ Verify correct file name, location, and storage capacity for DIC images.
   ☐ Verify that the correct test procedure or macro has been selected.
   ☐ Verify force and other measurements of interest are set to record and are synchronized with DIC images.
   ☐ Verify triggering of test frame and DIC images.
   ☐ Verify that lights are on, exposure is correct, frame rate is correct.
4. **Processing of DIC Images (5)**
   ☐ Select initial correlation and user-defined parameters.
   ☐ Perform initial correlation of images.

About the *Good Practices Guide for Digital Image Correlation (GPG)*

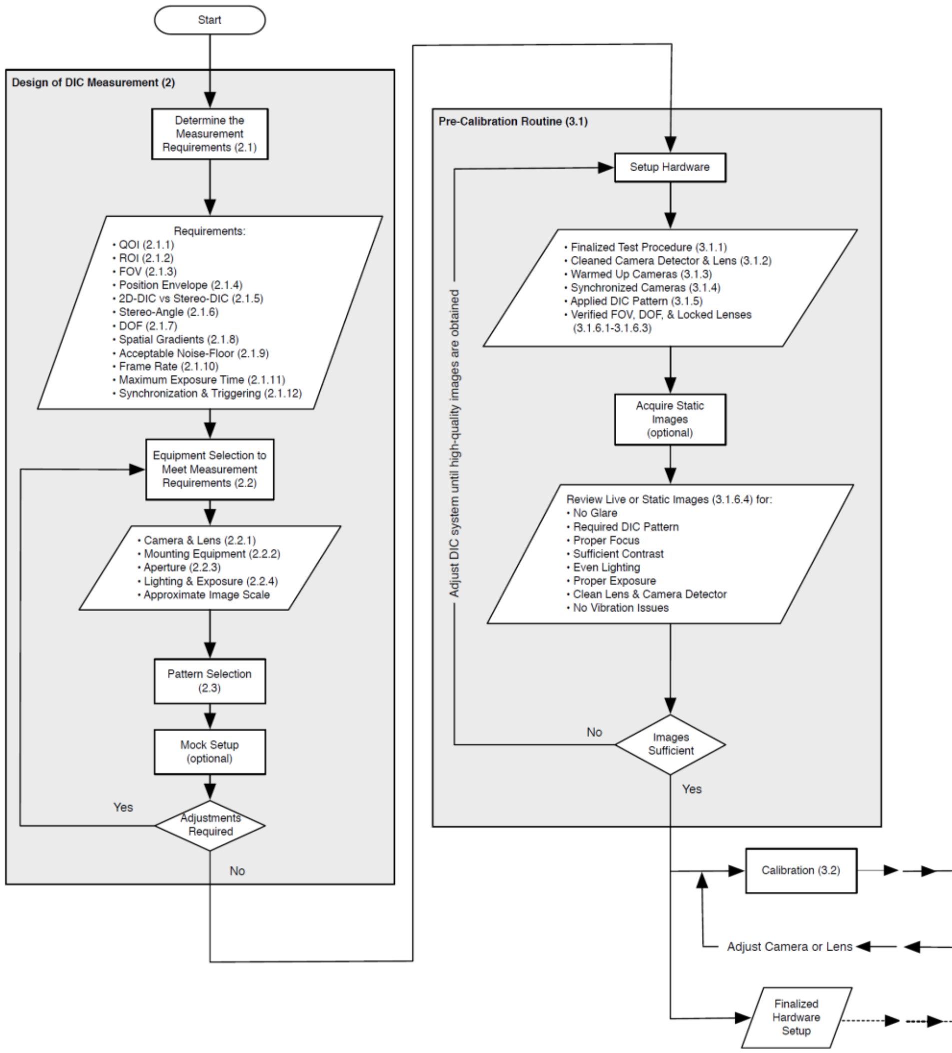


Figure A.1: Flow chart illustrating the main steps involved when conducting DIC measurements in conjunction with mechanical testing of a planar test piece (part 1).

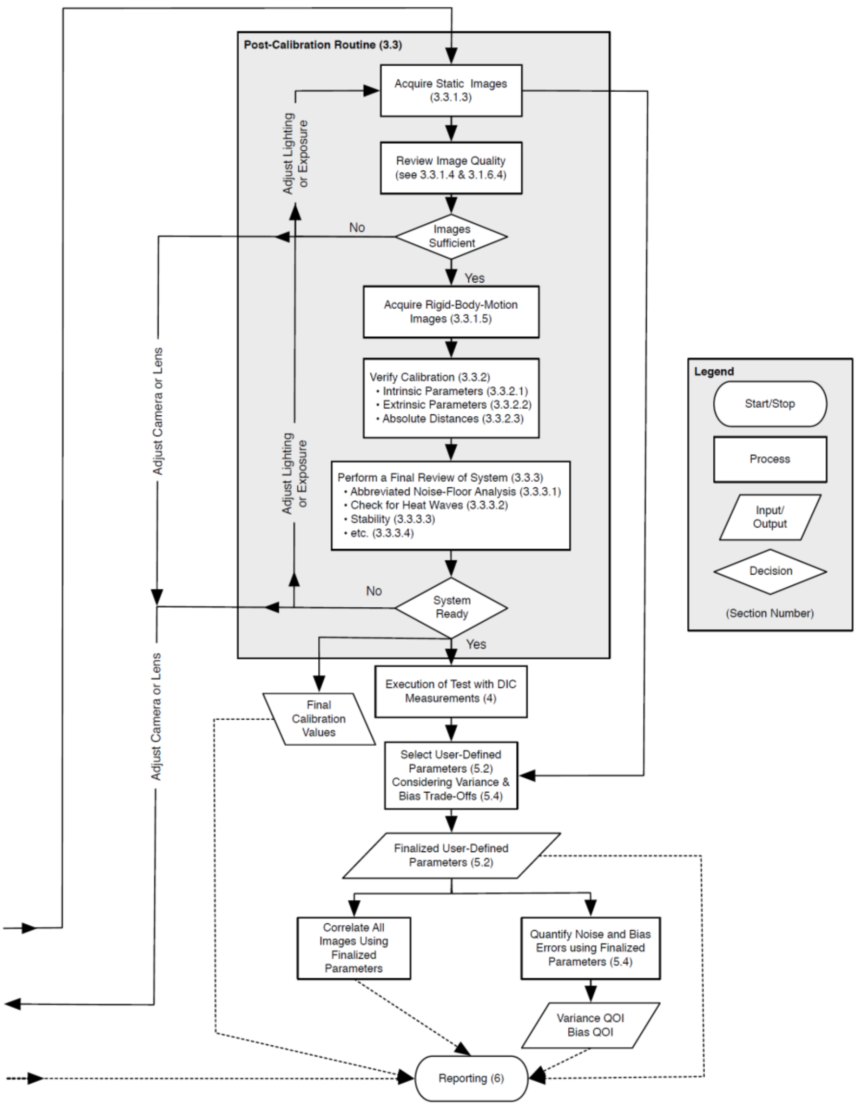


Figure A.2: Flow chart illustrating the main steps involved when conducting DIC measurements in conjunction with mechanical testing of a planar test piece (part 2).

About the *Good Practices Guide for Digital Image Correlation (GPG)*

Current Scope of GPG

- Common mechanical tests with DIC measurements
- Standard lab/ open air environmental conditions
- Planar test piece, moderate sizes, strains, and rates
- 2D-DIC and stereo-DIC using local, subset-based DIC algorithms

Improvement and Expansion of the Guide

- 6 working groups:
  1. Figures, references, and examples
  2. Non-planar test pieces
  3. Global DIC
  4. Library of patterning techniques
  5. Dynamic tests and high-speed DIC
  6. Noise and bias quantification
- Translations to other languages
  - Chinese: Released August 2019
  - German: Released March 2020
  - French: Released March 2020
  - Japanese: In progress
  - Portuguese: In progress

Get Involved!

- All are welcome to participate, regardless of experience level
- Contact guide@idics.org

CHAPTER 2:
DESIGN OF DIC MEASUREMENTS

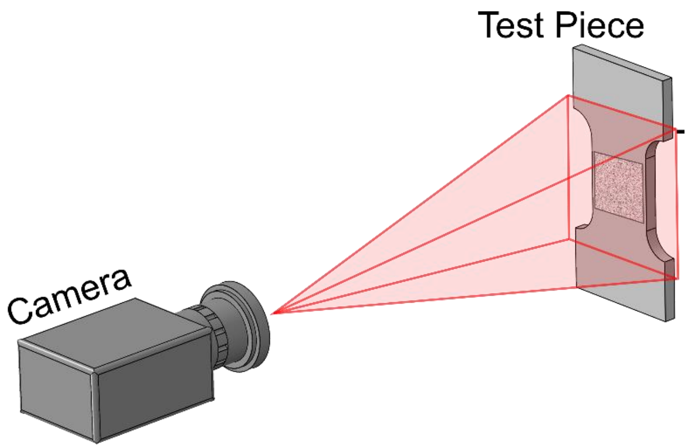
SEC. 2.1:
MEASUREMENT REQUIREMENTS

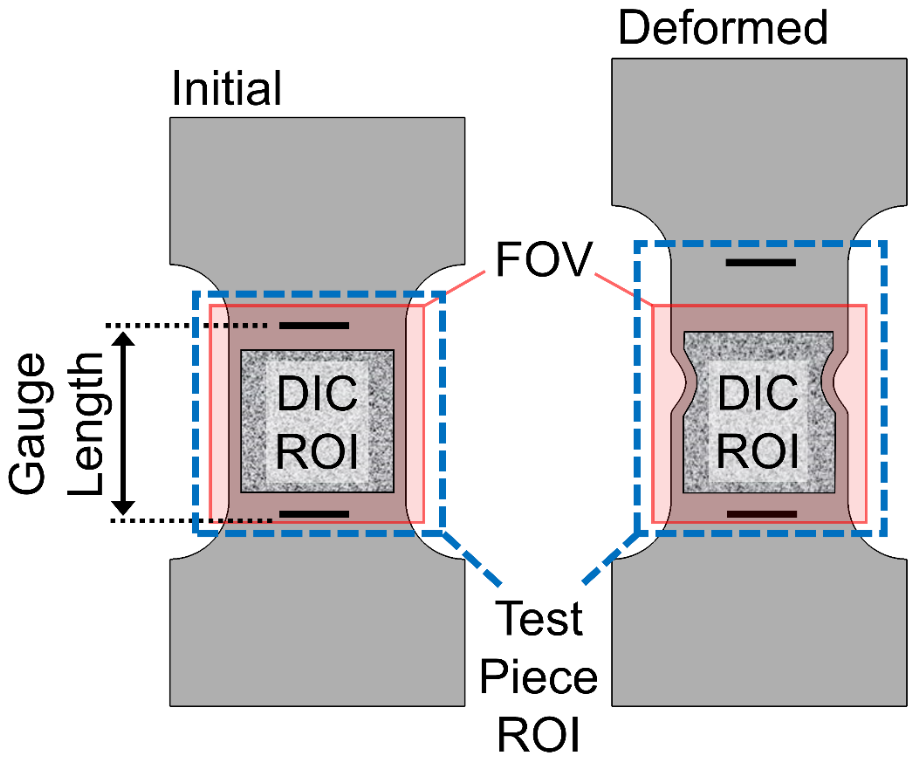
Quantity-of-Interest (QOI), Region-of-Interest (ROI), and Field-of-View (FOV)
Sec. 2.1.1 – Sec. 2.1.3

1. Determine the QOIs
   - Examples include: shape, displacement, velocity, acceleration, strain, strain-rate, etc.
   - Application specific:
     - Strain field near hole or necking region?
     - Displacements at grips?

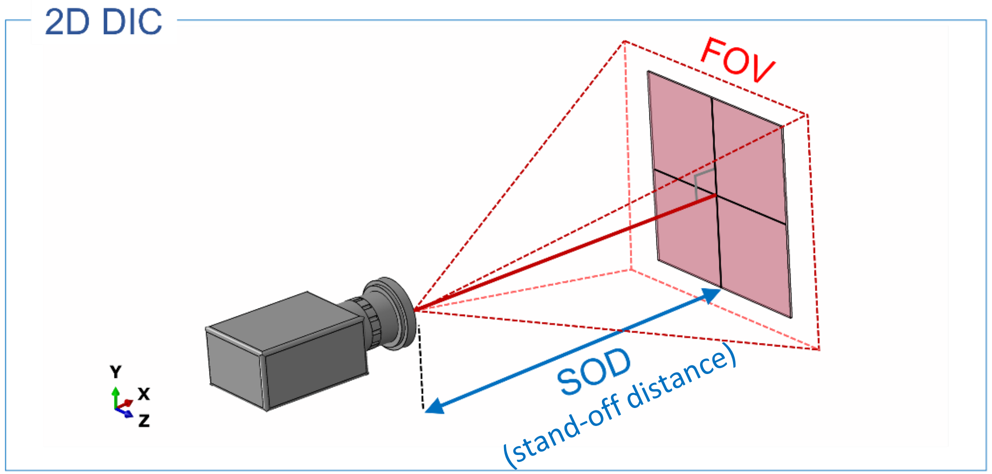
2. Select the ROI of the test piece

3. Determine the required FOV, based on the ROI
   - Recommendation 2.1: ROI should fill FOV, accounting for anticipated motion





2D-DIC vs Stereo-DIC
Sec. 2.1.5



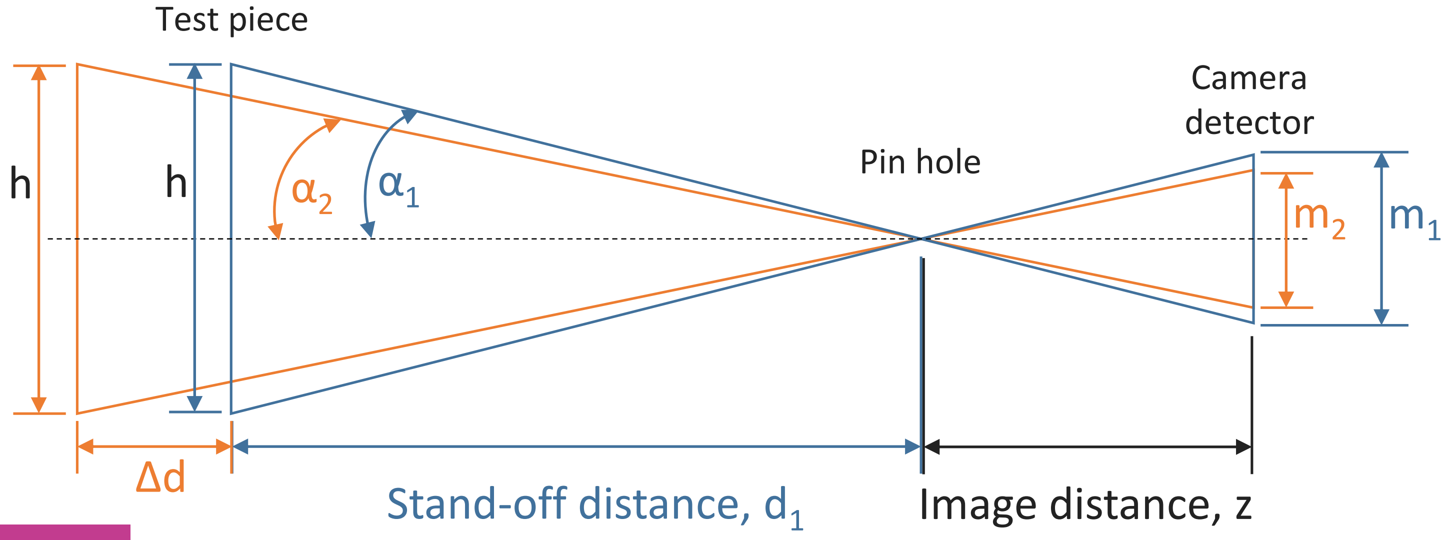
2D-DIC:

- One camera, perpendicular to a planar test piece
- Gives in-plane displacements and strains

- Caution 2.1: Test piece should be planar and perpendicular to camera, and remain so during the test

- Recommendation 2.3: Estimate errors due to out-of-plane motion

Schematic top view of experimental setup



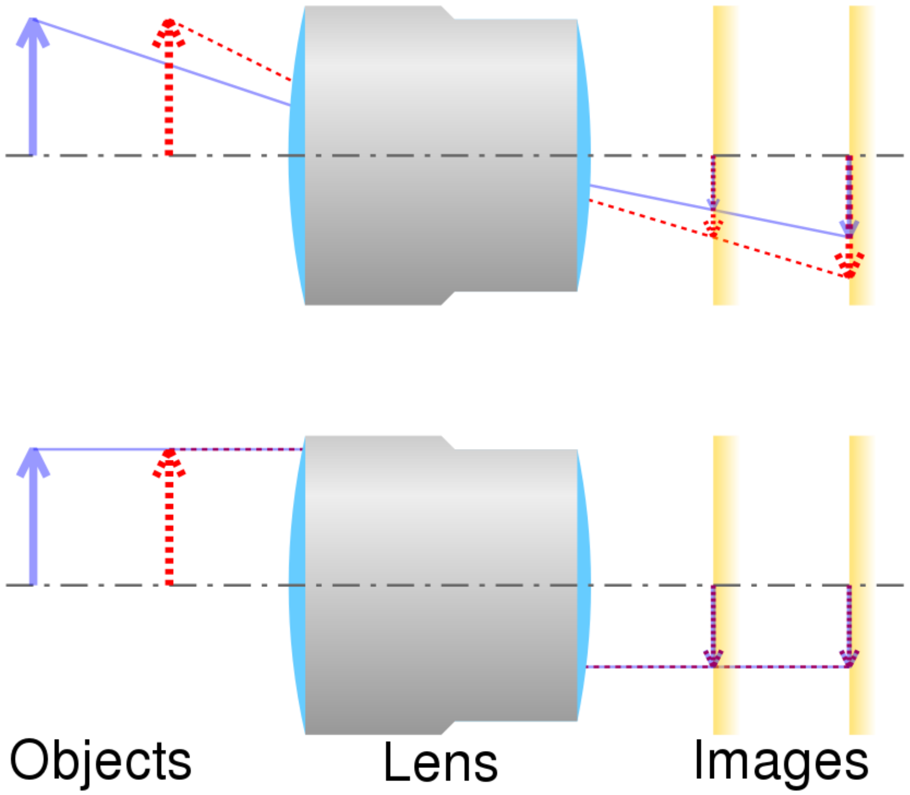
$$① \tan(\alpha_1) = \frac{h}{d_1} = \frac{m_1}{z} \qquad ② \tan(\alpha_2) = \frac{h}{d_1 + \Delta d} = \frac{m_2}{z}$$

$$\text{False Strain} \approx \frac{m_2 - m_1}{m_1} = \frac{d_1}{d_1 + \Delta d} - 1$$

d_1	Δd	False Strain
250 mm	1 mm	0.4 %
500 mm	1 mm	0.2 %
1000 mm	1 mm	0.1 %

2D-DIC: Telecentric lenses
Sec. 2.2.1

- Recommendation 2.6:
  - For 2D-DIC, bi-lateral telecentric lenses are recommended
  - If a telecentric lens isn't available, use a longer focal length lens

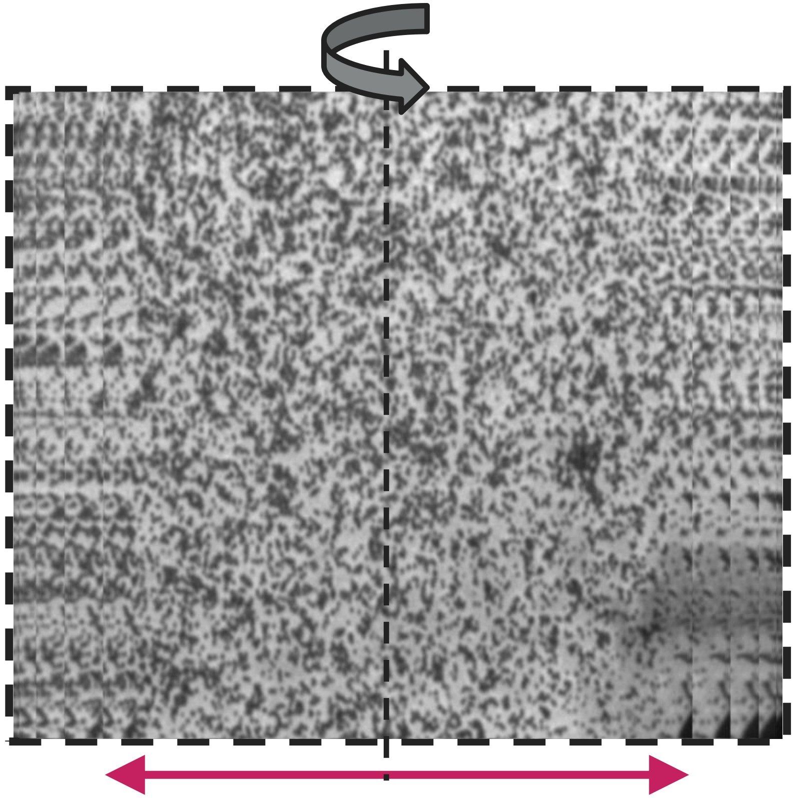


Standard lens:
Image size *depends*
on stand-off distance
and image distance

Bi-telecentric lens:
Image size
independent of
stand-off distance
and image distance

- Caution 2.5
  - Do not use telecentric lenses for stereo-DIC!

- Caution! (not in Guide)
  - False strains may still occur from out-of-plane *rotations*, even with a telecentric lens.



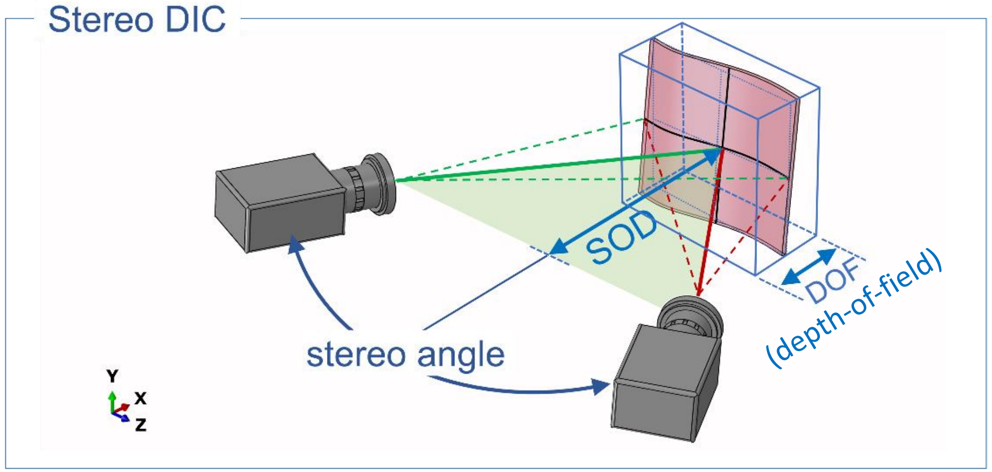
Apparent contraction = false strain

2D-DIC vs Stereo-DIC
Sec. 2.1.5 – 2.1.7

Stereo-DIC:

- Two cameras oriented at a stereo angle (typically 15-35 degrees)
- Gives 3D coordinates, displacements, strains on the surface of the test piece

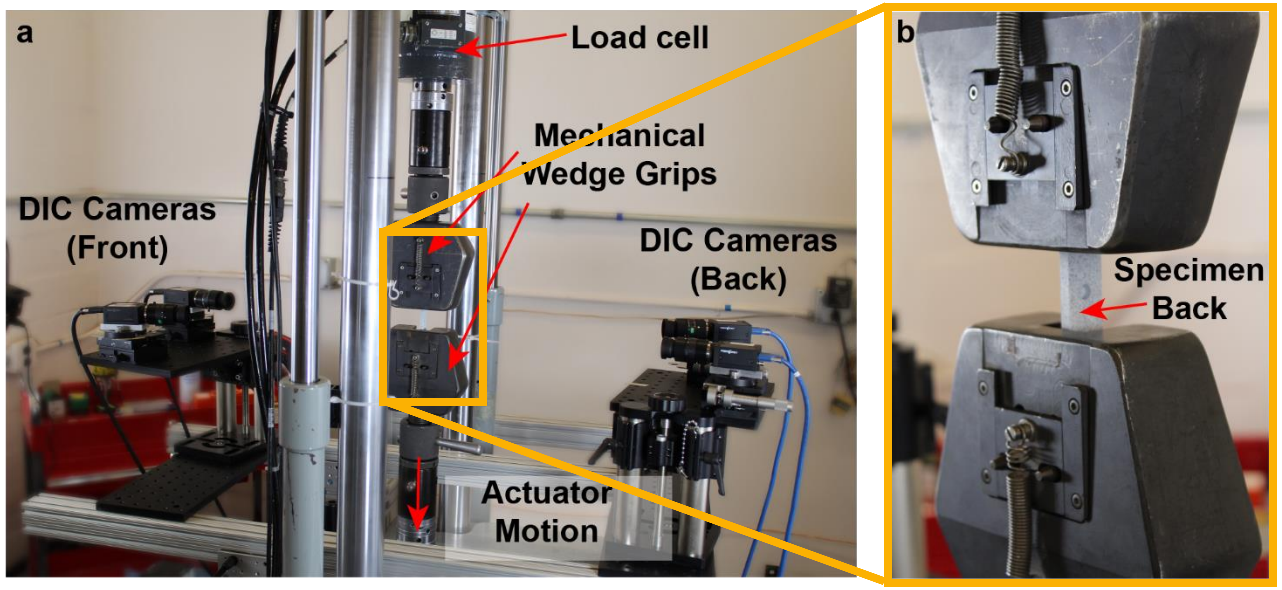
- Tip 2.2
  - Smaller stereo angles
    - better in-plane accuracy
    - ROI in focus for both cameras for larger range of out-of-plane motion
  - Larger stereo angles
    - better out-of-plane accuracy



DEMO 01

Position Envelop for Hardware
Sec. 2.1.4

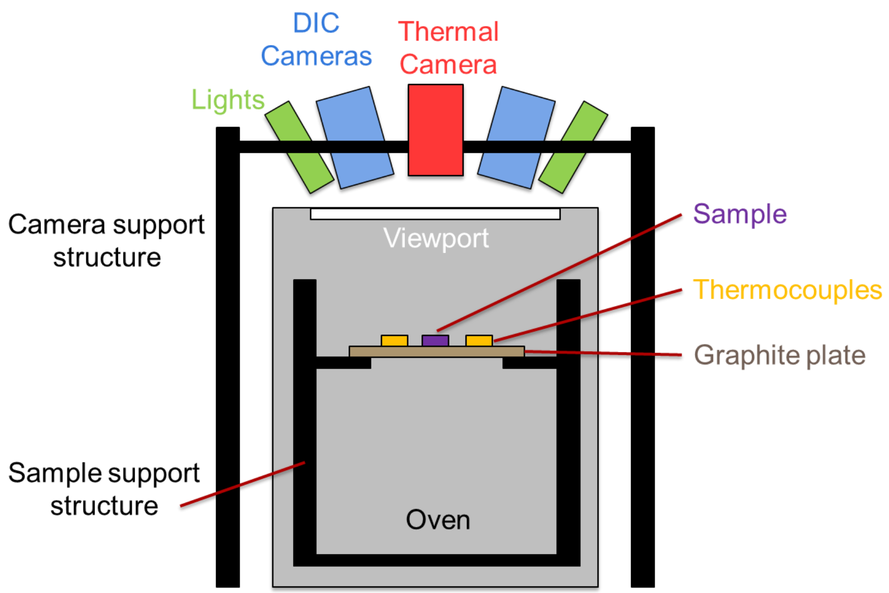
- Considerations include:
  - How big is your load frame?
  - Does any equipment restrict the field of view or causes shadows?
  - How big are your cameras?
  - How will you mount lights? Do you need different lights for the test versus calibration? Can you switch between them without bumping your cameras? (Tip. 2.19)
  - Vibration isolation: physically separate any vibrating equipment (load frame, fans, lights) from cameras
  - Mounting equipment? Need to purchase or fabricate?



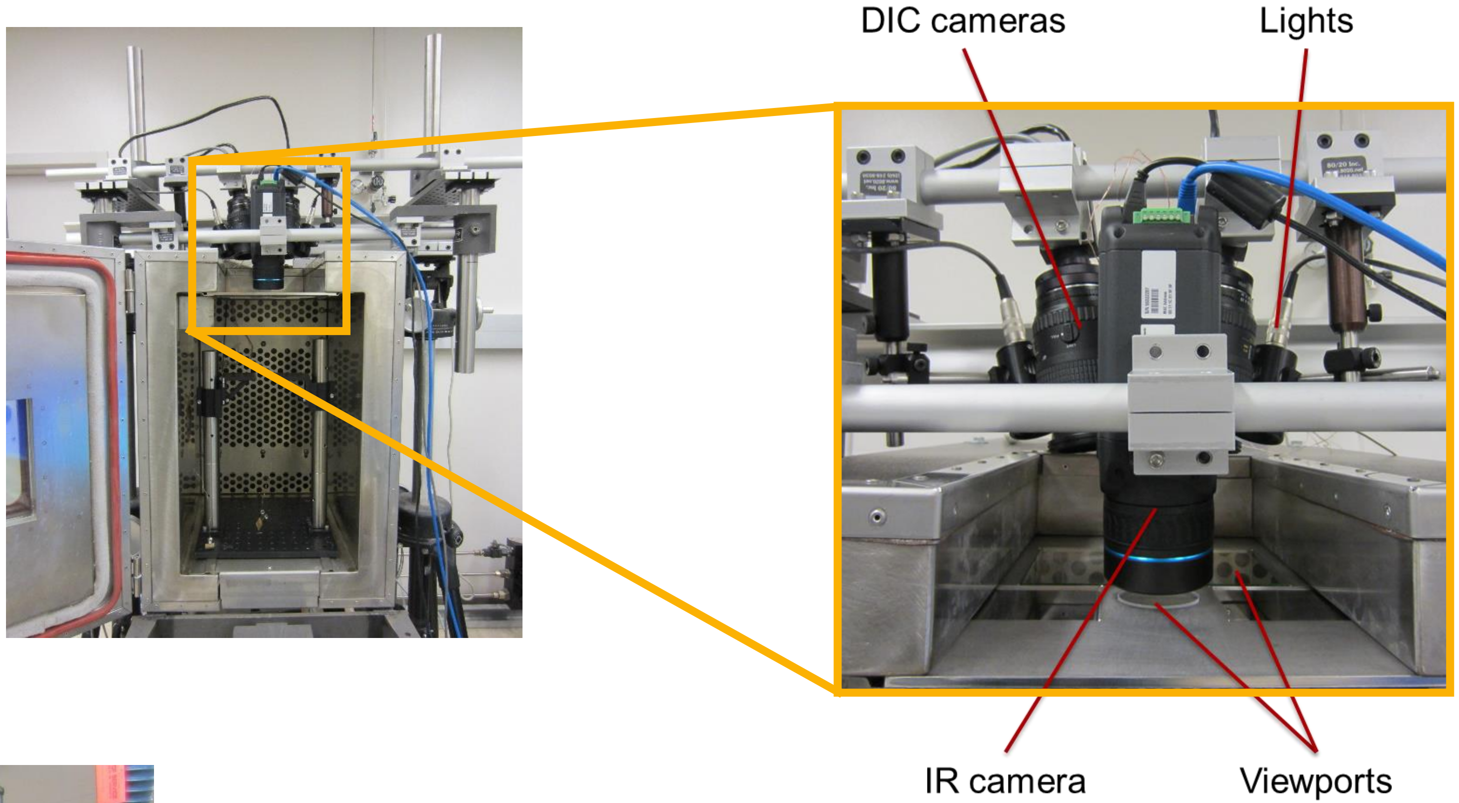
Example 1

- Relatively straightforward setup of a tensile test on a load frame
- Flexibility for hardware position with few major restrictions
- Lights must be placed carefully to avoid shadows from the large grips

Position Envelop for Hardware
Sec. 2.1.4



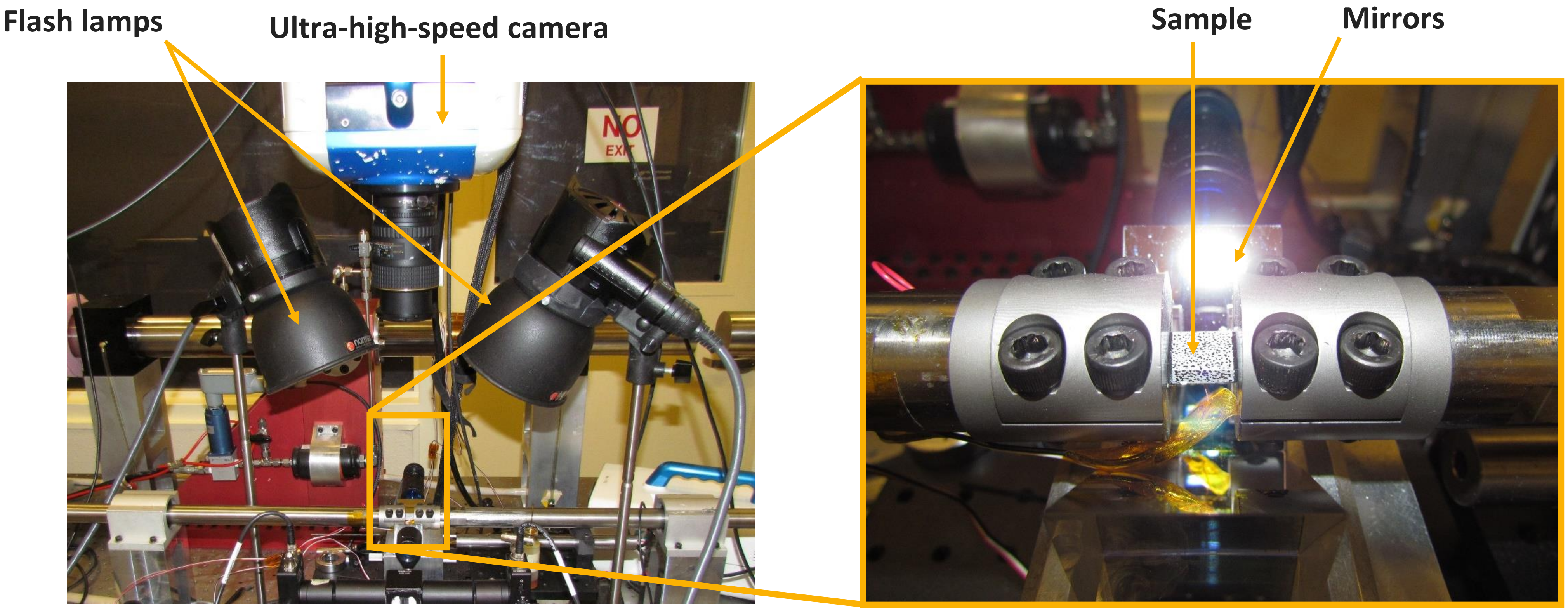
Front View



Example 2

- Test piece was heated in an oven
- Test piece had to be horizontal, forcing cameras to be above the oven
- Limited flexibility and major restrictions on position envelop

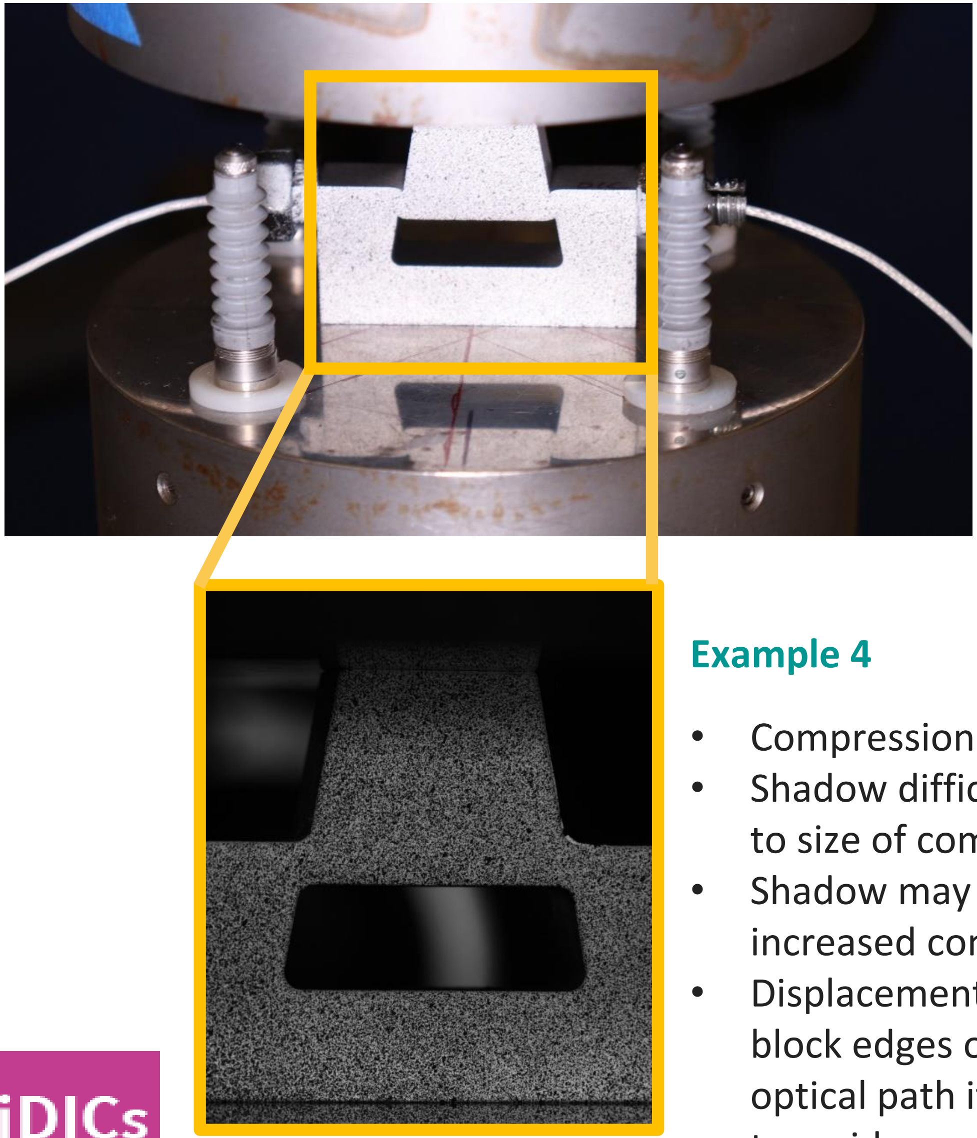
Position Envelop for Hardware
Sec. 2.1.4



Example 3

- Hopkinson bar mechanical test
- Ultra-high-speed cameras usually have a large body
- Hopkinson bar test pieces are usually small
- Mirrors used to view three sides of the test piece with one camera

Position Envelop for Hardware
Sec. 2.1.4

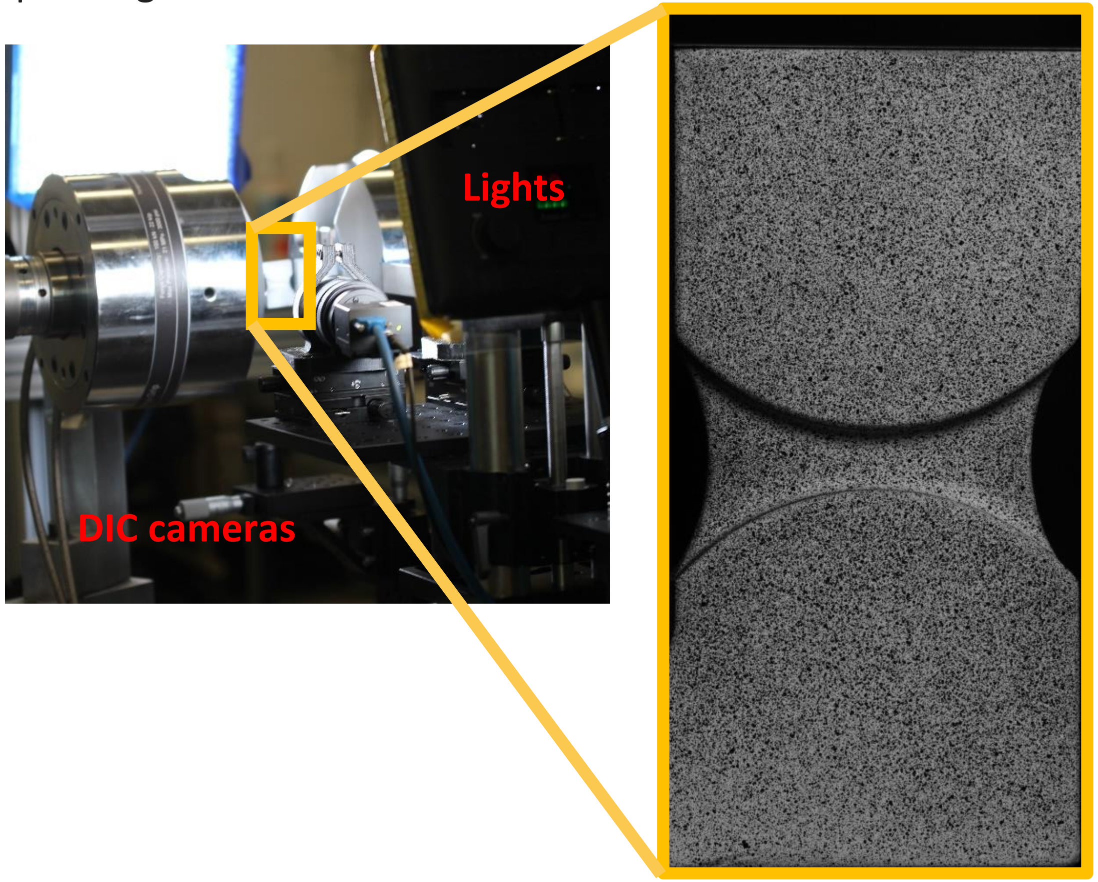


Example 4

- Compression test setup
- Shadow difficult to avoid due to size of compression platens
- Shadow may worsen with increased compression
- Displacement transducers block edges of test piece and optical path if stereo angle is too wide

Example 5

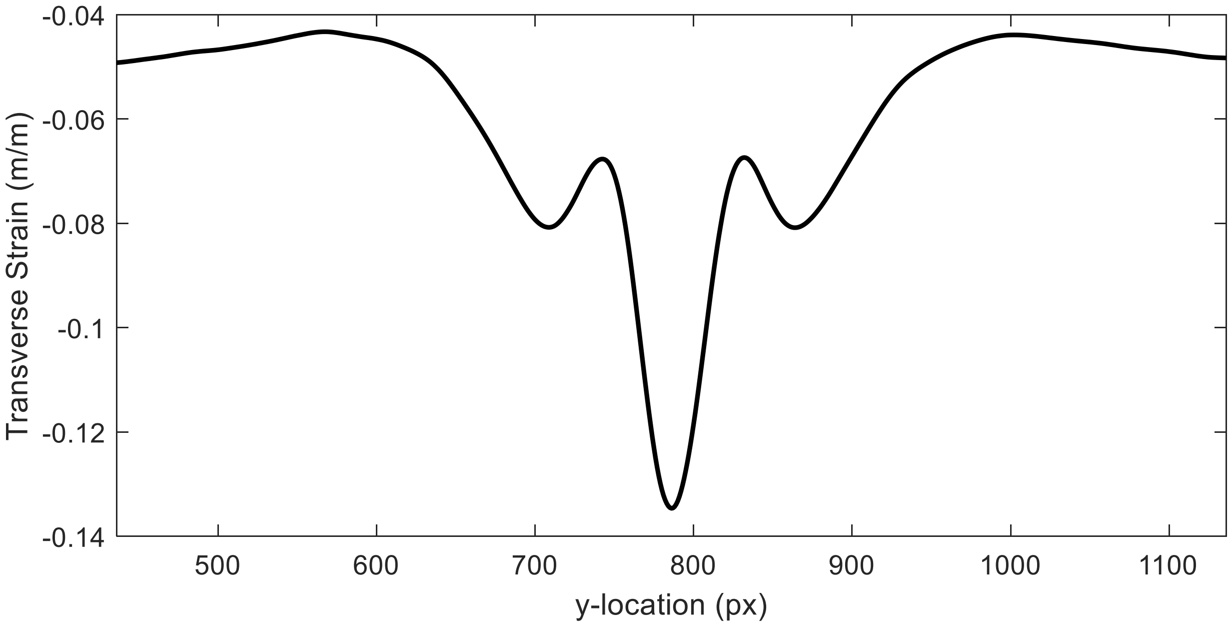
- Tension test of an atypical test piece geometry
- Test piece geometry may cast shadows or block the optical path depending on camera orientation

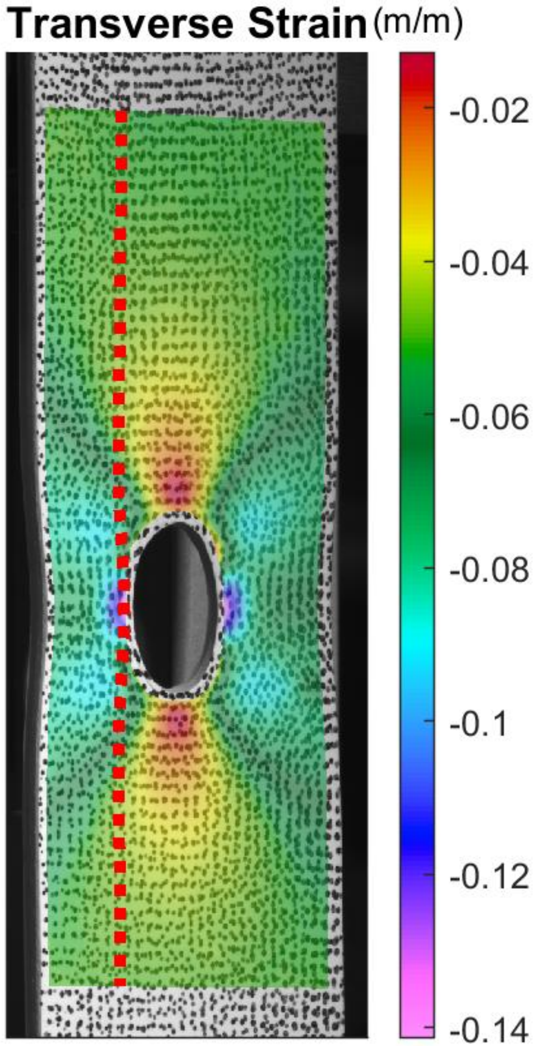


Spatial Gradients
Sec. 2.1.8

- Estimate expected spatial gradients of QOIs
- This determines required spatial resolution
- Estimation typically requires *a priori* information about expected deformation field

- Tip 2.4: If you have high gradients, consider higher magnification
1. Use a camera with a higher resolution and use a pattern with smaller features
2. Reduce the ROI of the test piece and zoom-in on a smaller region





Noise Floor
Sec. 2.1.9

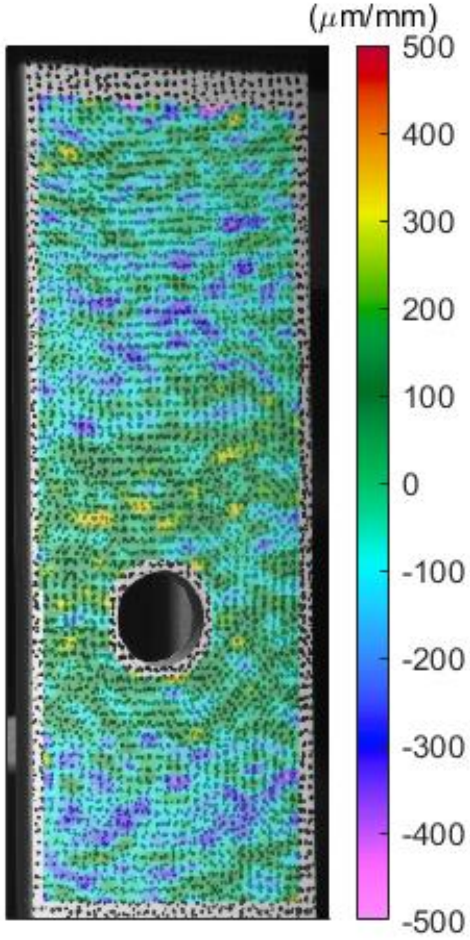
- Smallest resolvable QOI
- Any measurement smaller than your noise floor cannot be distinguished from noise
- Any measurement larger than your noise floor is significant/meaningful

- Typical Values
  - 0.01 px in-plane
  - 3X larger for out-of-plane

- Tip 2.5: Acceptable noise-floor is often determined by subject matter expert

- More information on evaluating the noise-floor in Chapter 5.

Noise of Transverse Strain Field (from correlation of a static image)

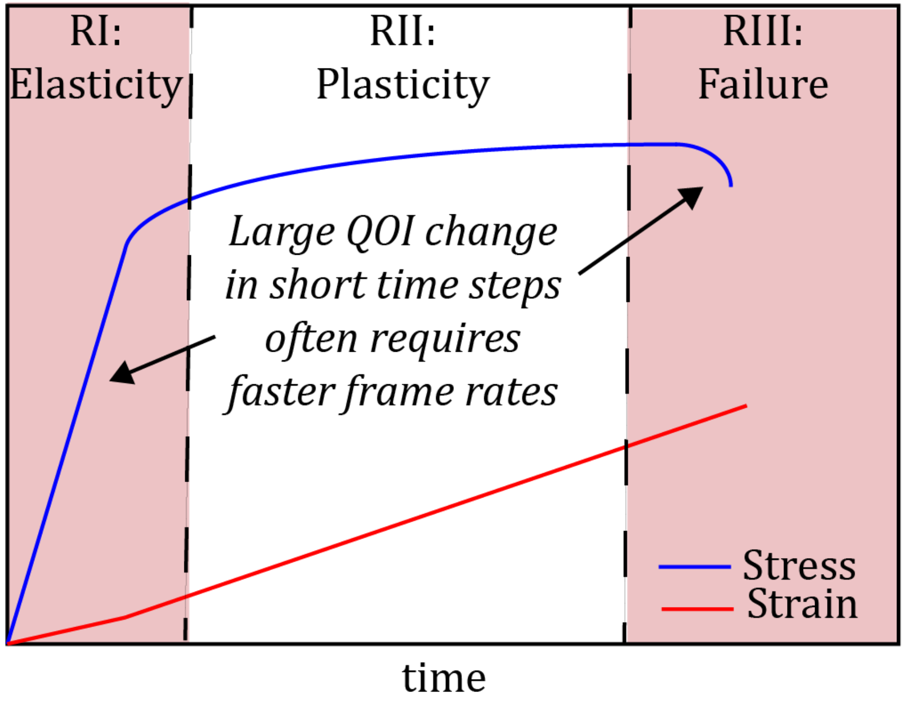


Frame Rate
Sec. 2.1.10

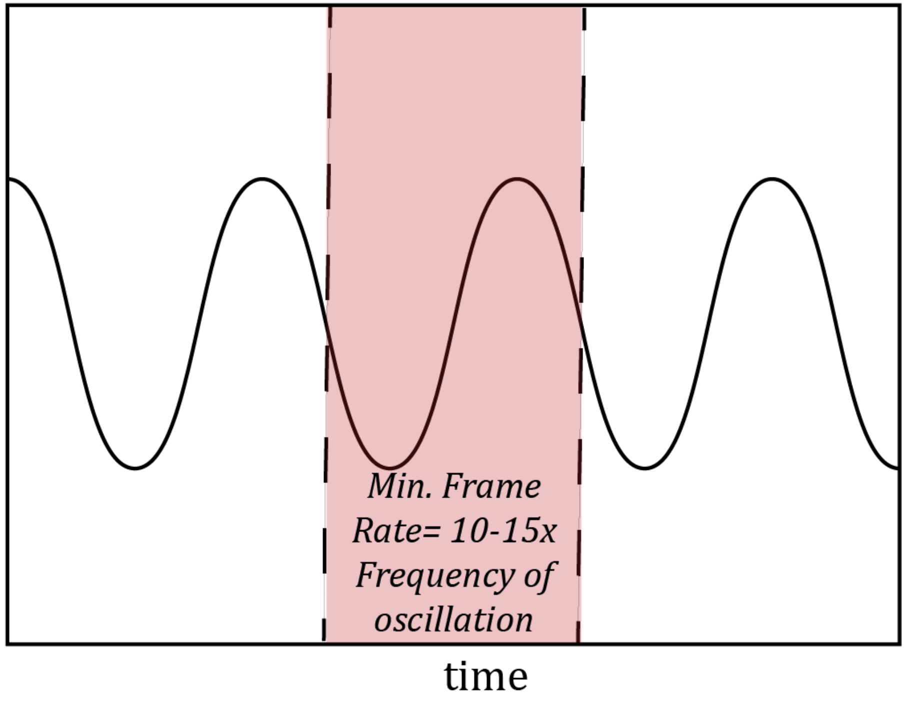
- Optimal frame rate is application specific
- Tip 2.6: Several factors to consider:

1. **Desired temporal resolution**
2. Amount of displacement between frames
3. Amount of data collected during a mechanical test

Example 1: Metal plasticity



Example 2: Cyclic loading



Exposure time, Synchronization and Triggering
Sec. 2.1.11 – 2.1.12

Exposure Time

- Key point: prevent motion blur
- Tip 2.7: Maximum allowable test piece motion over the course of the exposure time is ~0.01 px (conservative) or up to 0.3 px (less conservative)
- $\text{Displacement per exposure (px)} = \left(\text{Velocity } \left(\frac{mm}{s}\right)\right) * \left(\text{Image Scale } \left(\frac{px}{mm}\right)\right) * (\text{Exposure Time } (s))$
- Tip 2.8: Exposure time is independent of frame rate, but cannot be larger than 1/frame rate

Synchronization and Triggering

- How will DIC images be synchronized to other measurements of interest, such as applied force or displacement, strain gauges, thermocouples, etc.?
- How will all data acquisitions be triggered at the start of the test?
  - 3-2-1-GO?
  - TTL pulse?

CHAPTER 2:
DESIGN OF DIC MEASUREMENTS

SEC. 2.2:
EQUIPMENT AND HARDWARE

Lens selection
Sec. 2.2.1

- Field-of-view, stand-off distance, and lens focal length are all intertwined.

Focal Length	Stand-Off Distance	Field-of-View
↑	Constant	↓
↑	↑	Constant
Constant	↑	↑

Constant stand-off distance

28 mm lens

50 mm lens

70 mm lens

210 mm lens

Lens selection
Sec. 2.2.1

- Tip 2.12: Two main types of lenses
  - Fixed focal length lenses: FOV changed only by changing SOD
    - Also called "prime lens"
  - Zoom lenses: FOV changed by either changing SOD or focal length
    - Pro: Adds flexibility to experimental setup
    - Con: More complicated optics can lead to larger lens distortions

DEMO 02

- Recommendation 2.7
  - Lenses with ability to lock moving components (e.g. focus, aperture) are preferred

Fixed focal length or Prime lens

Zoom lens

Camera selection
Sec. 2.2.1

- Tip 2.10: Experience is necessary to determine if a camera or lens is of sufficient quality; vendors evaluate equipment for you.

- Recommendation 2.5: Machine-vision, monochromatic cameras with square pixels and global shutters are recommended

- Caution 2.3: Avoid auto-focus of the lens or apertures that automatically open/close

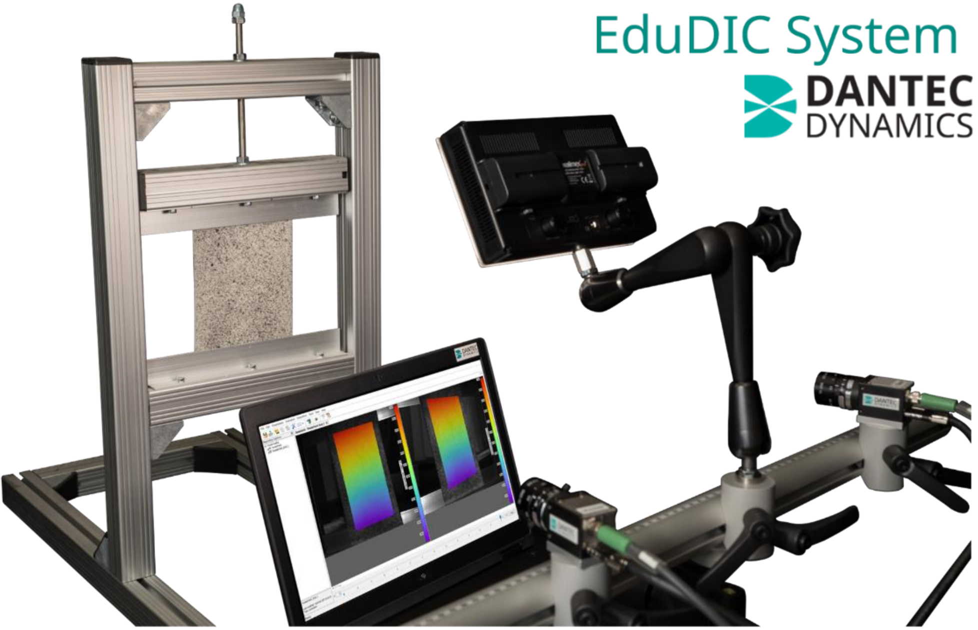
- Tip 2.11: Know if your camera has any built-in low-pass (anti-aliasing) filters in front of the detector

General characteristics of mounting system
Sec. 2.2.2.1

- **Caution 2.7: Any relative motion between cameras will induce errors!**
- Include sufficient degrees of freedom for precise adjustment of the cameras/lenses
- Have a plan for making room for the calibration target
- Mount camera/lens near its combined center of mass
- Stabilize and strain relieve cables
- Ensure camera support structure is stable (can add sandbags)
- Minimize vibrations being transferred to cameras

Types of Mounting Systems
Sec. 2.2.2.2

Examples of vendor-supplied rigs


EduDIC System
DANTEC DYNAMICS


MatchID
Metrology beyond colors


LaVision
FOCUS ON IMAGING


correlated SOLUTIONS

gom
a ZEISS company

Types of Mounting Systems
Sec. 2.2.2.2

Build your own mounting system

- This is not an exhaustive list
- iDICs, SEM, SNL, and NIST do not endorse these companies

Edmund optics | worldwide

THORLABS

Newport
Experience | Solutions

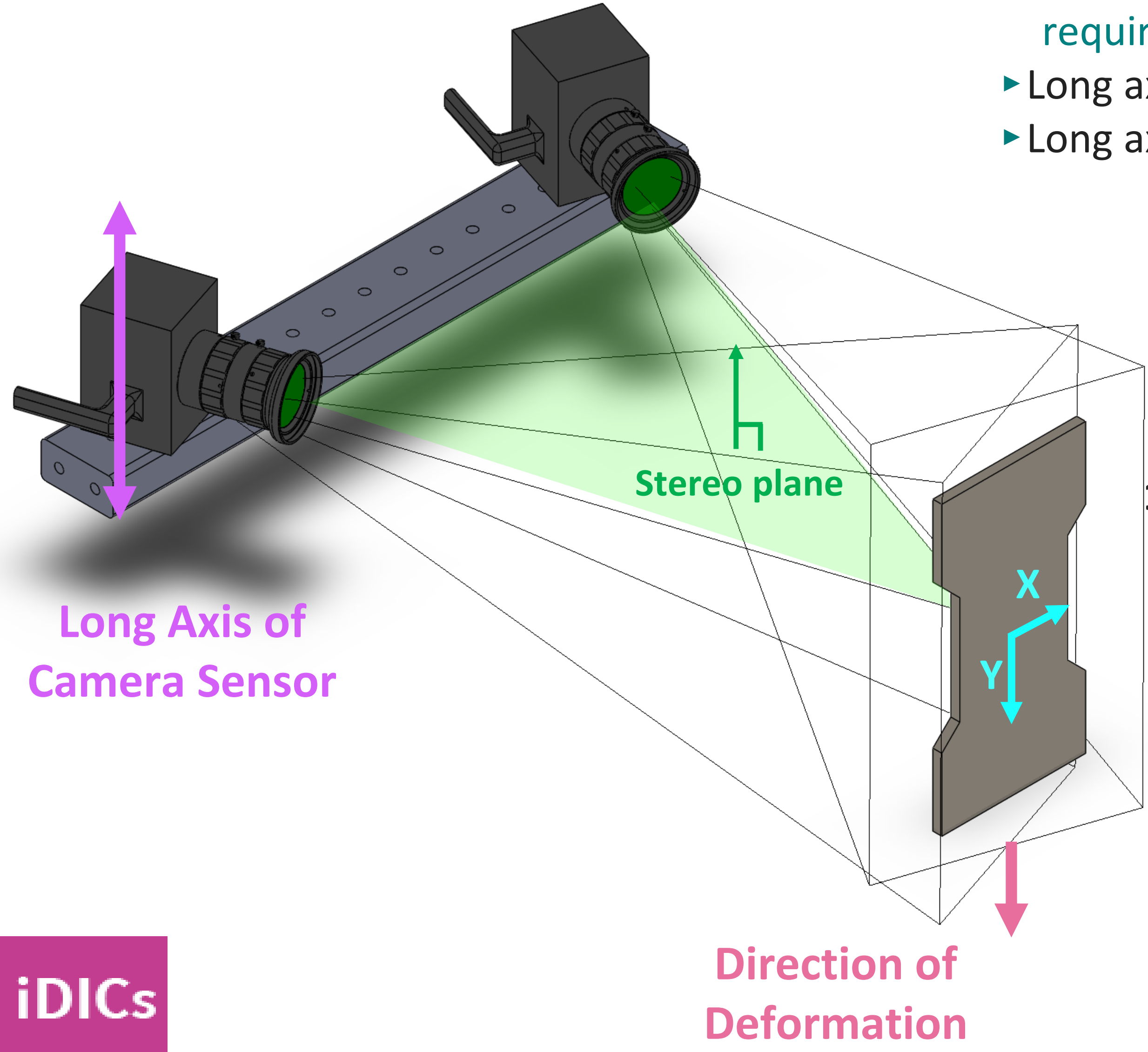
80/20 Inc.
The Industrial Erector Set

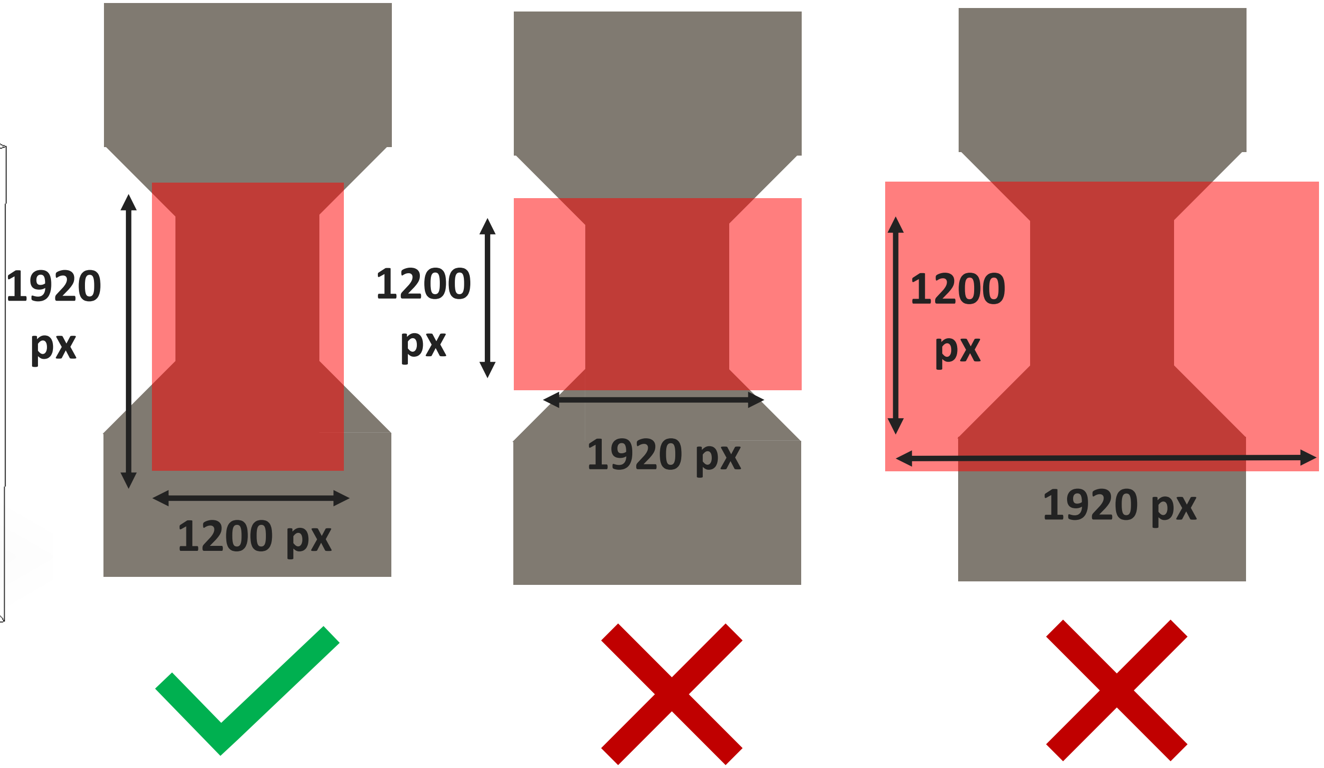
OptoSigma

Recommended Camera Orientations

Recommendation 2.8, Figure 2.1

1. Align the **long axis of your camera sensor** with the direction you require the **highest spatial resolution;** typically this equates to:
   - Long axis of camera sensor aligned with long axis of the test piece
   - Long axis of camera sensor aligned with direction of deformation

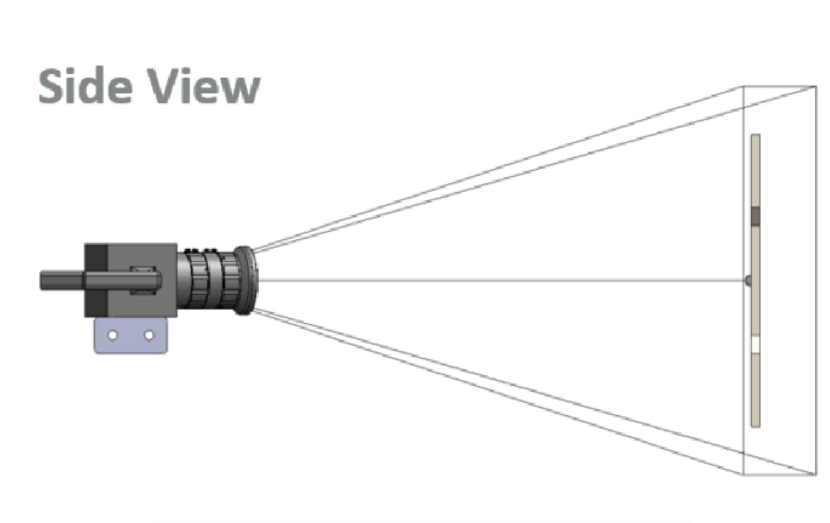


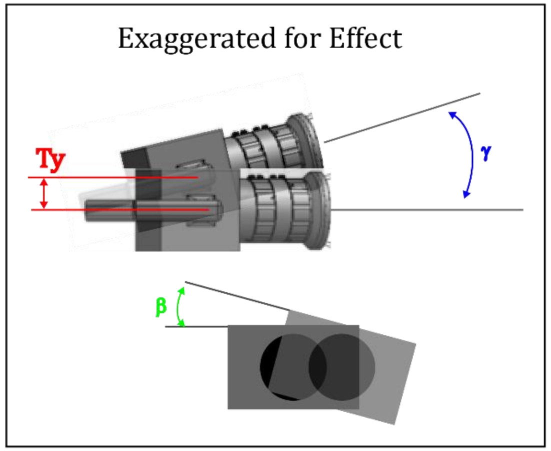


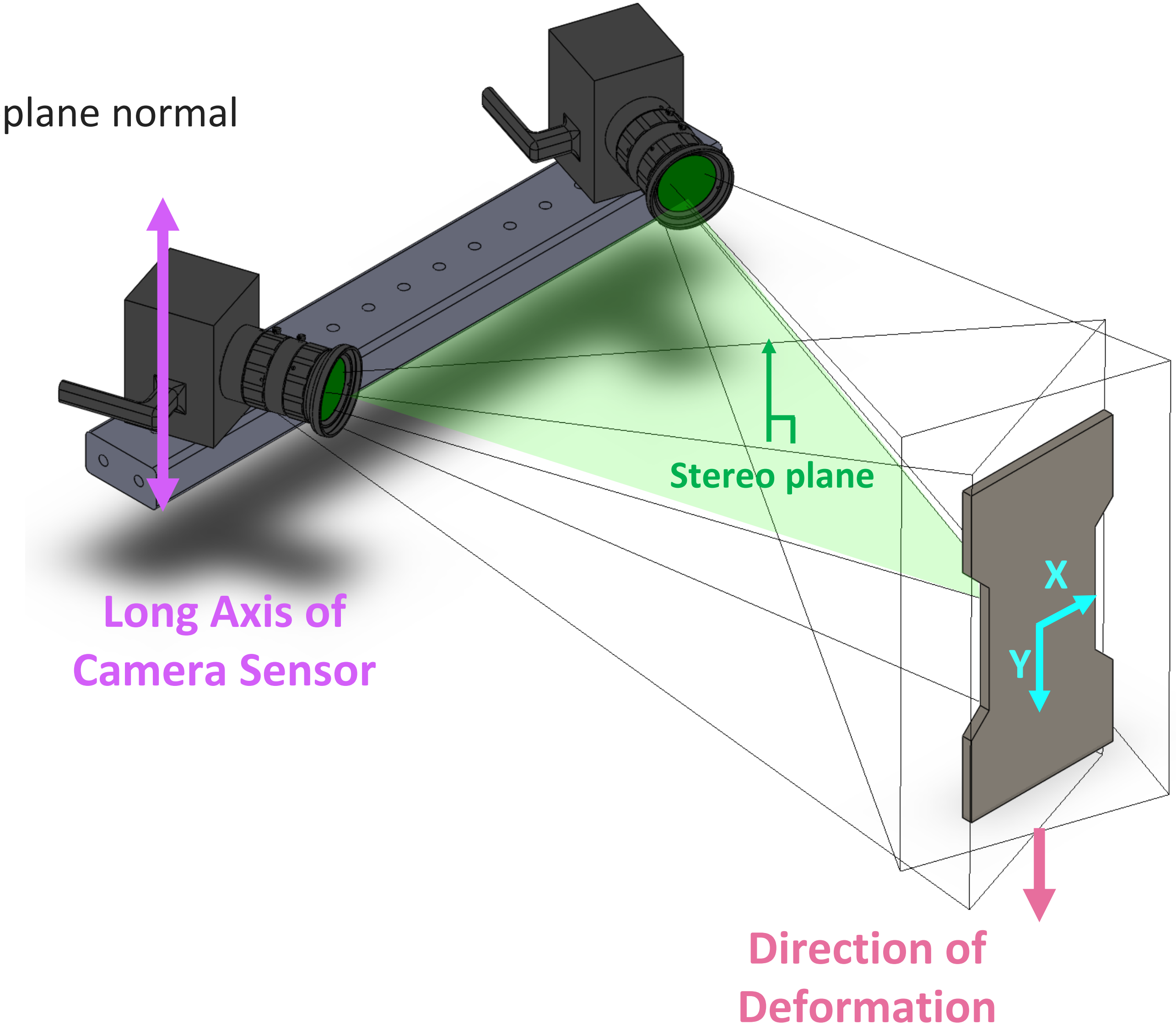
Recommended Camera Orientations

Recommendation 2.8, Figure 2.1

2. Orient your **stereo rig** to minimize **perspective errors**
   - Avoid compound angles
   - Long axis of test piece should be aligned with the stereo-plane normal

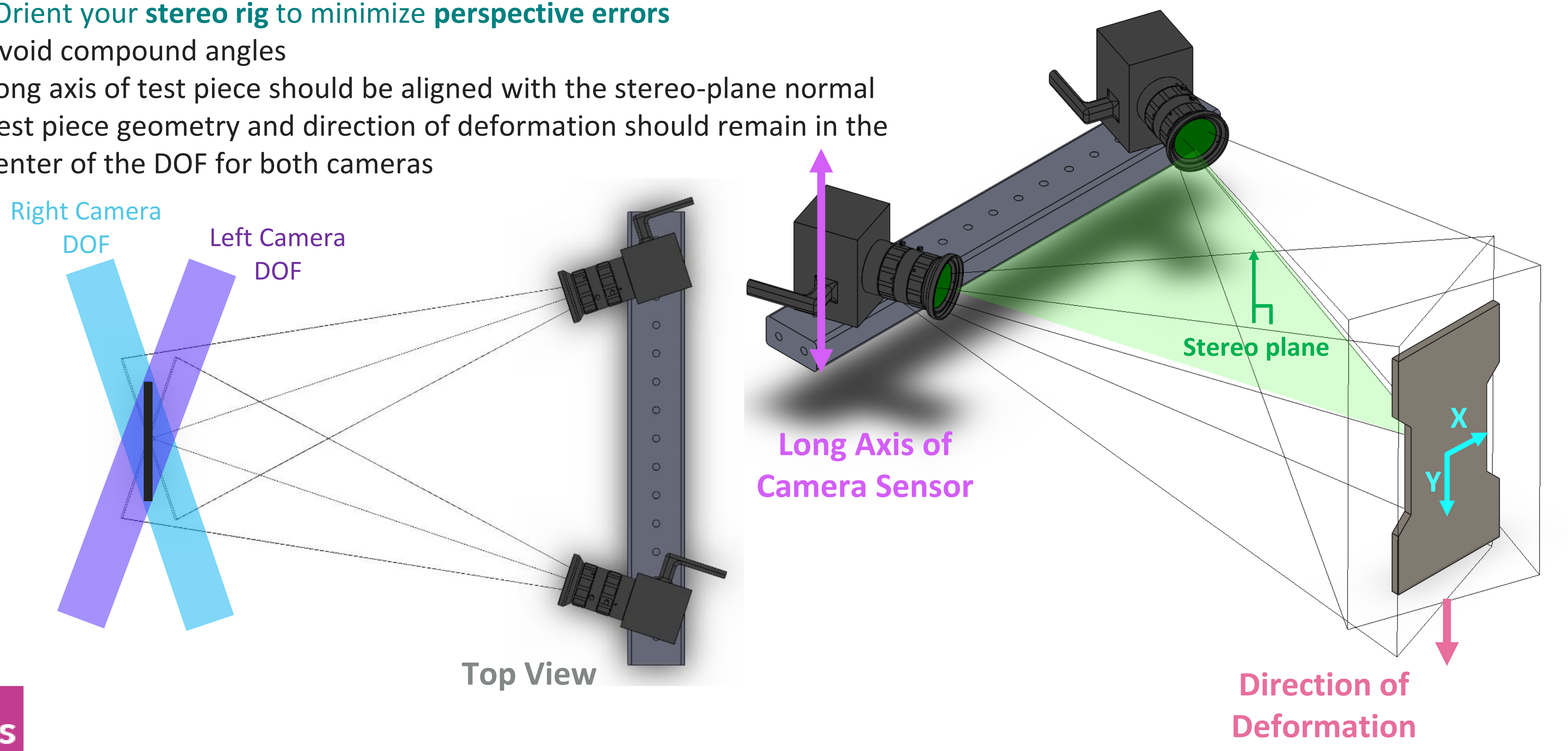






Recommended Camera Orientations
Recommendation 2.8, Figure 2.1

2. Orient your **stereo rig** to minimize **perspective errors**
   - Avoid compound angles
   - Long axis of test piece should be aligned with the stereo-plane normal
   - Test piece geometry and direction of deformation should remain in the center of the DOF for both cameras



Recommended Camera Orientations

Recommendation 2.8, Figure 2.1

2. Orient your **stereo rig** to minimize **perspective errors**
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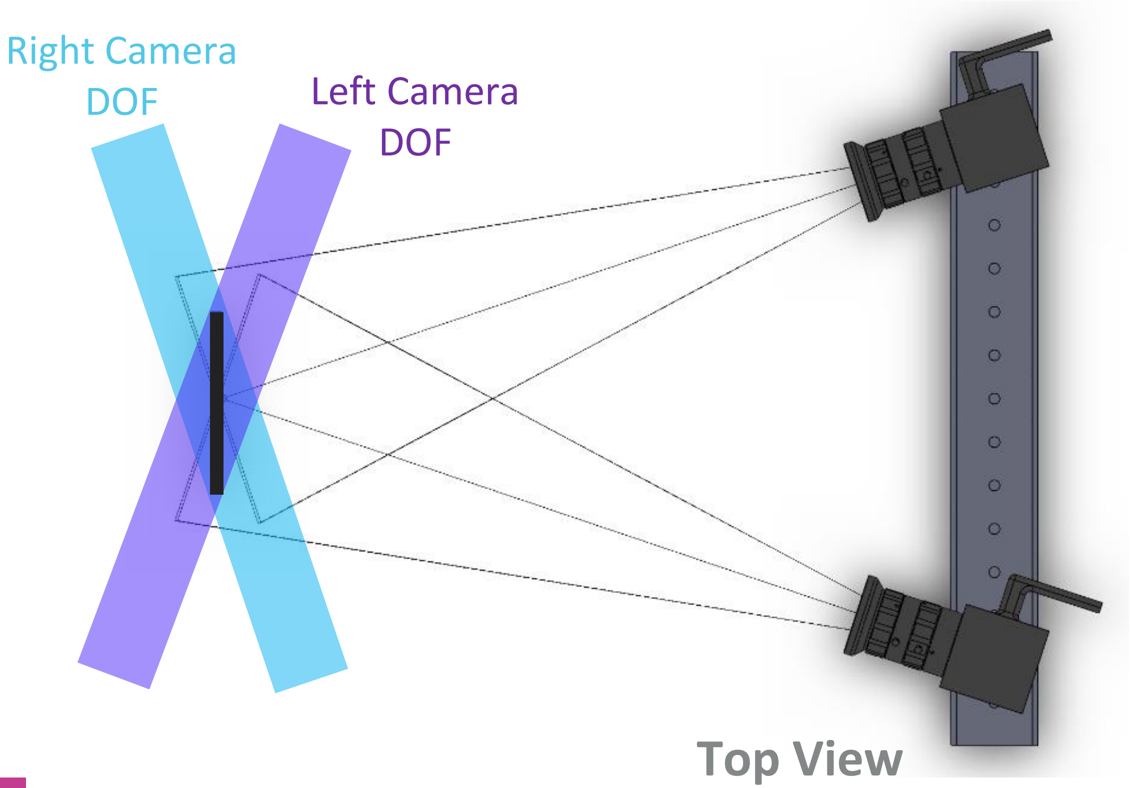

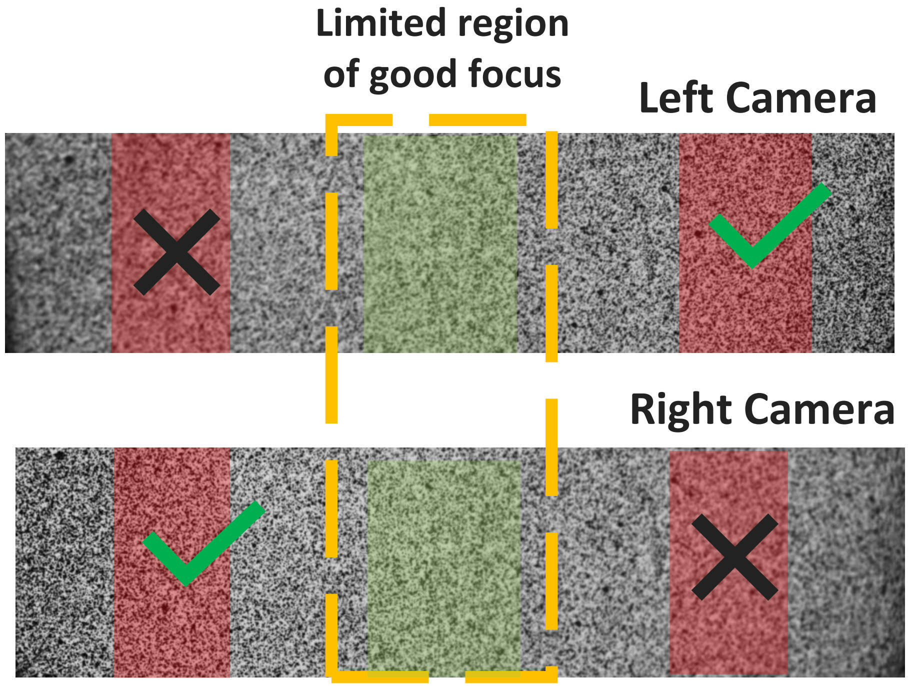

Recommended Camera Orientations
Recommendation 2.8, Figure 2.1

2. Orient your **stereo rig** to minimize **perspective errors**
   - Avoid compound angles
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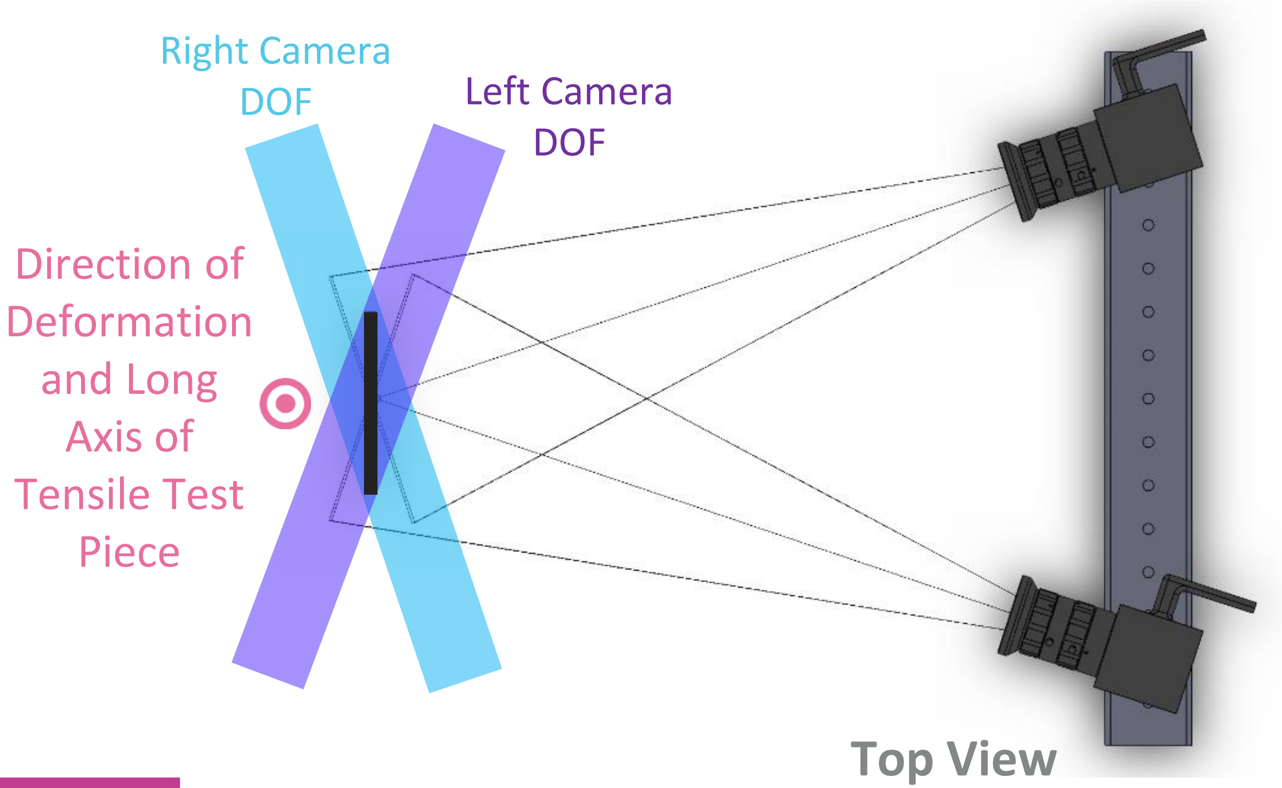
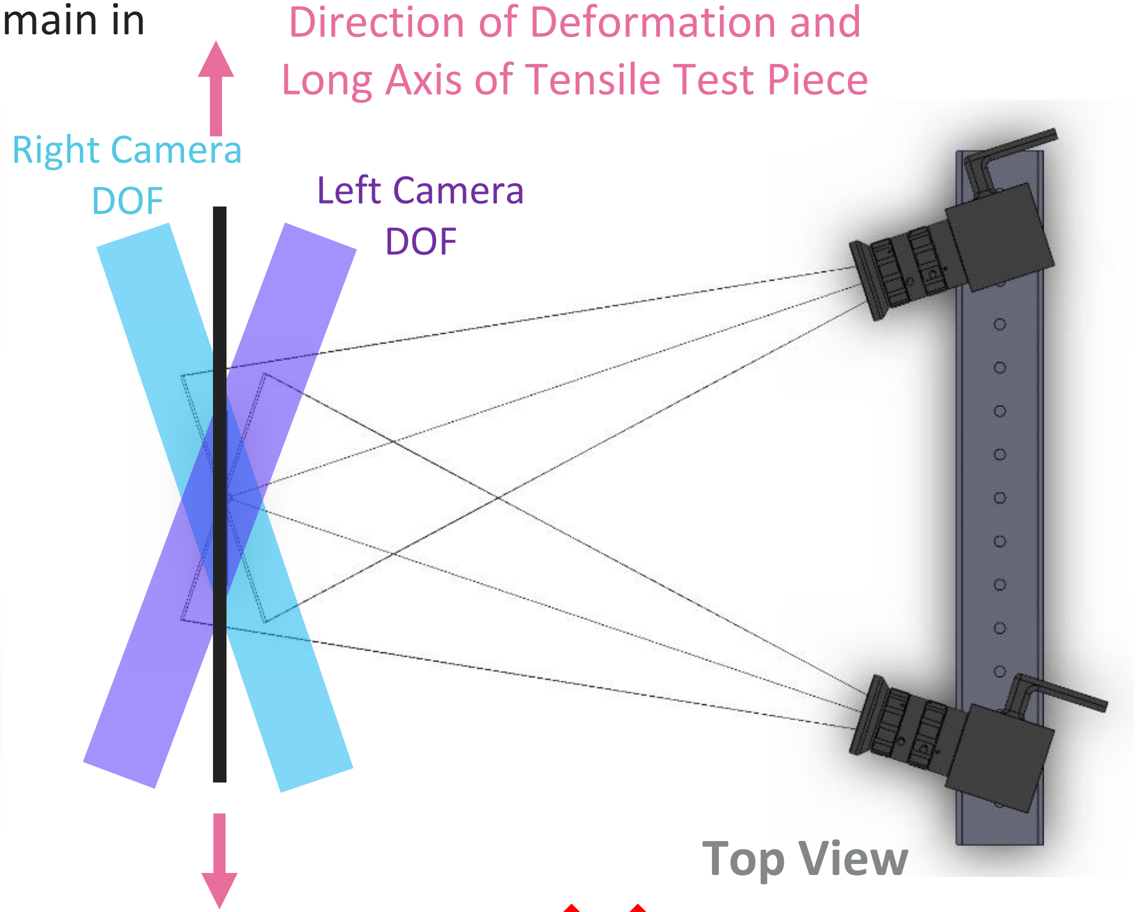


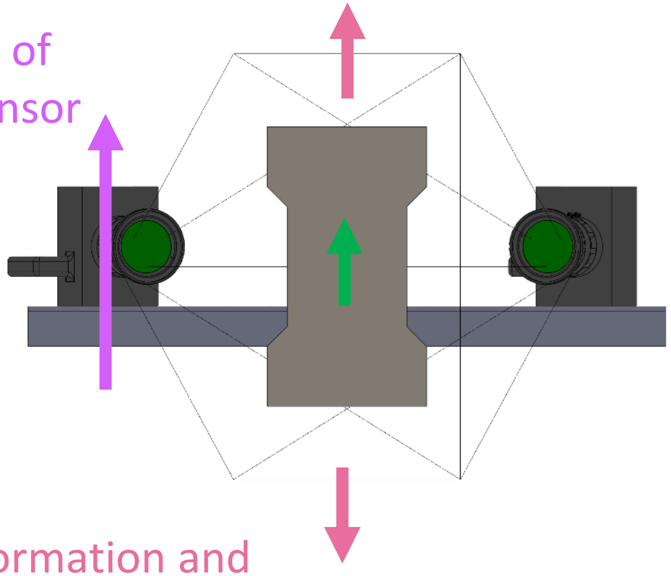
✓



✗

Recommended Camera Orientations
Recommendation 2.8

Recommended Vertical Tensile Test Piece Orientation of Rig and Cameras

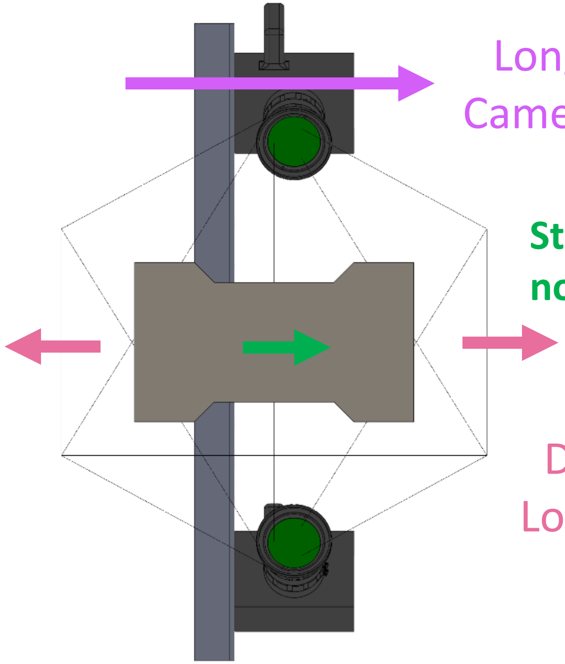


Long Axis of Camera Sensor

Stereo-plane normal

Direction of Deformation and Long Axis of Tensile Test Piece

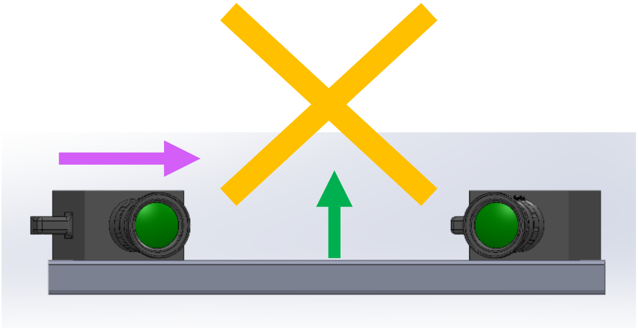
Recommended Horizontal Tensile Test Piece Orientation of Rig and Cameras



Long Axis of Camera Sensor

Stereo-plane normal

Direction of Deformation and Long Axis of Tensile Test Piece



DEMO 03

Note: Some adaptors may be required to optimize the camera mounting scheme for your test design

Aperture
Sec. 2.2.3

- Often measured by the f-number: ratio of focal length to aperture diameter


f/32, long exposure

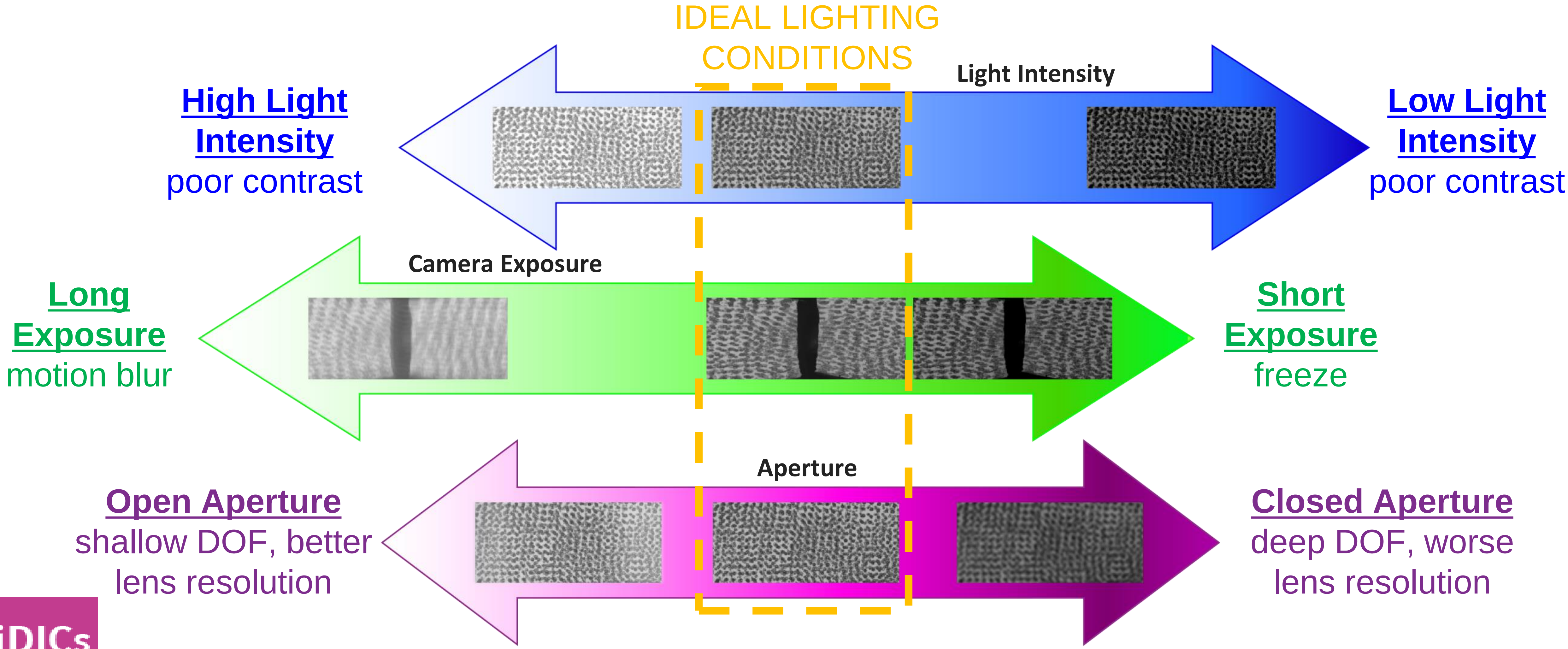

f/5, short exposure

- Tip 2.16 / Tip 2.17:
  - Larger aperture = more light and smaller DOF
  - For DIC, aperture should be used only to control DOF
  - Control image brightness with exposure and lighting

- Caution 2.11:
  - Small apertures may cause diffraction errors
  - Large apertures may accentuate optical aberrations
  - Recommend moderate apertures in the range of f/5.6-f/11

Aperture, Lighting, Exposure, Gain and Contrast
Sec. 2.2.3 – Sec. 2.2.4

- **Recommendation 2.13:** **The better the image contrast is, the less noisy the DIC results are.**
  - For 8-bit cameras, minimum contrast is 50 grey-level counts or 20%.



Aperture, Lighting, Exposure, Gain and Contrast
Sec. 2.2.3 – Sec. 2.2.4

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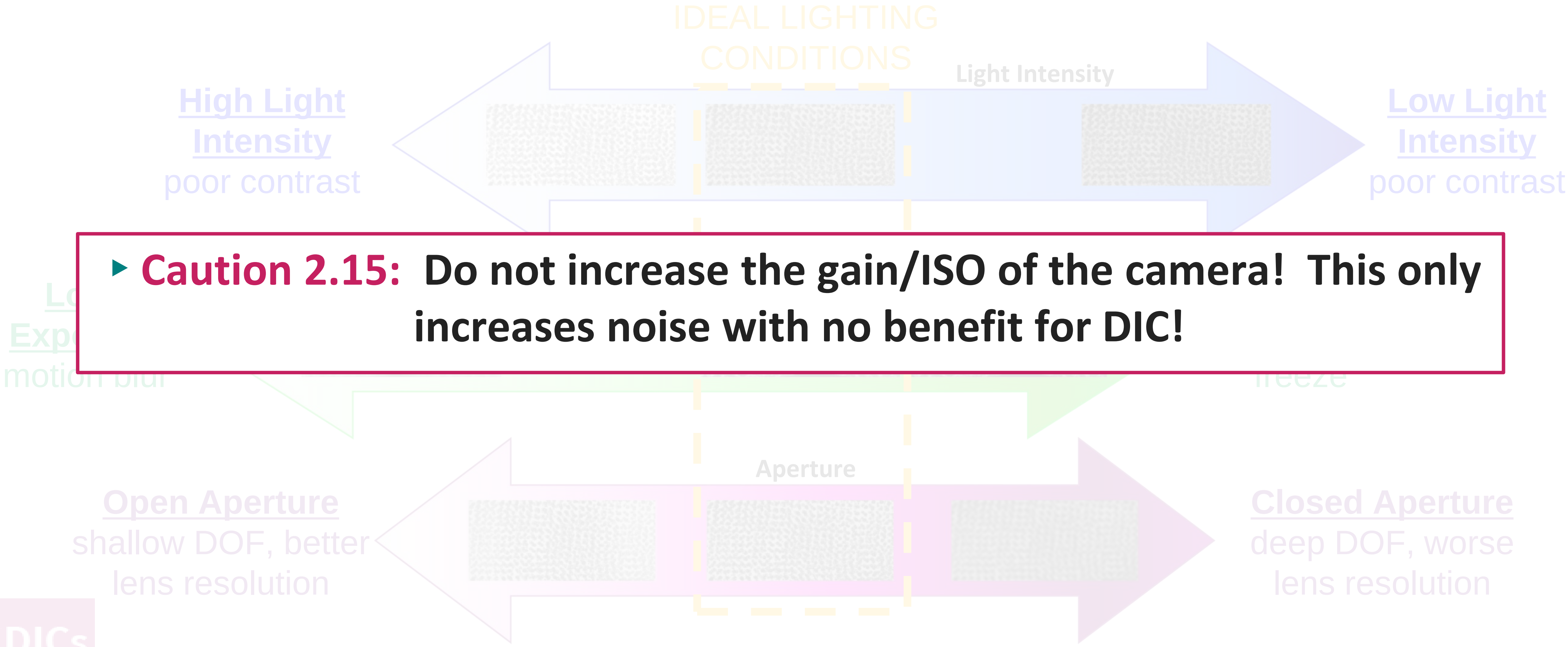
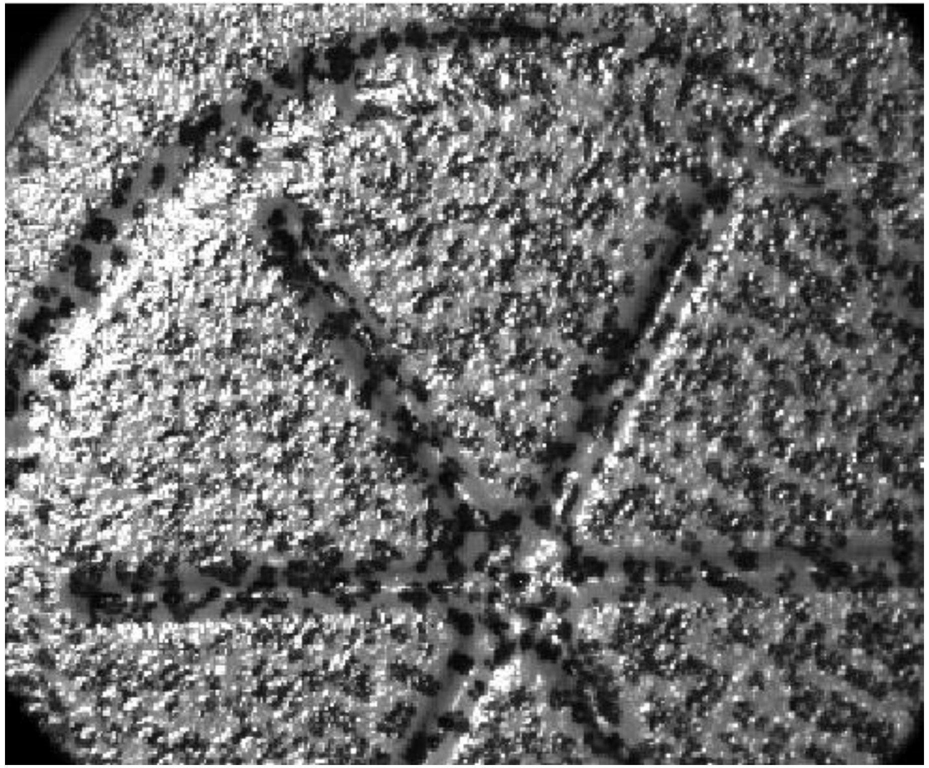


- **Caution 2.15:** **Do not increase the gain/ISO of the camera! This only increases noise with no benefit for DIC!**

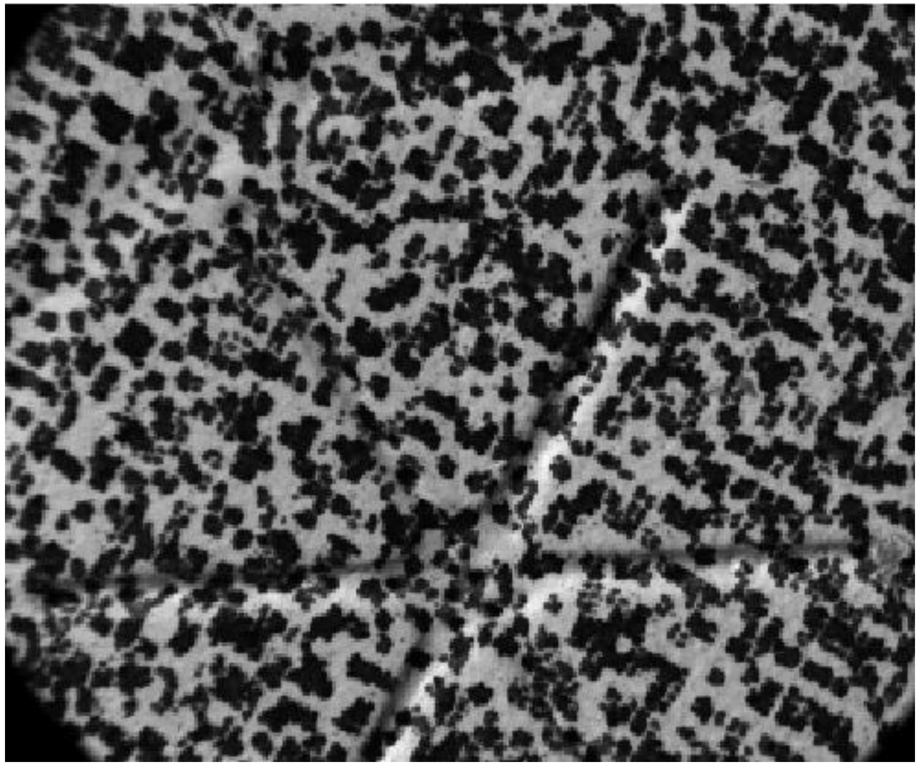
Cross-Polarized and Diffuse Light
Sec. 2.2.4.1

- Image brightness needs to be uniform across the ROI.
- Caution 2.14: Ensure no ROIs are overexposed or underexposed, and that there is no glare.
- Recommendation 2.11: Cross-polarized light or diffuse light reduce or eliminate glare caused by specular reflections.

Randomly polarized light = strong glare



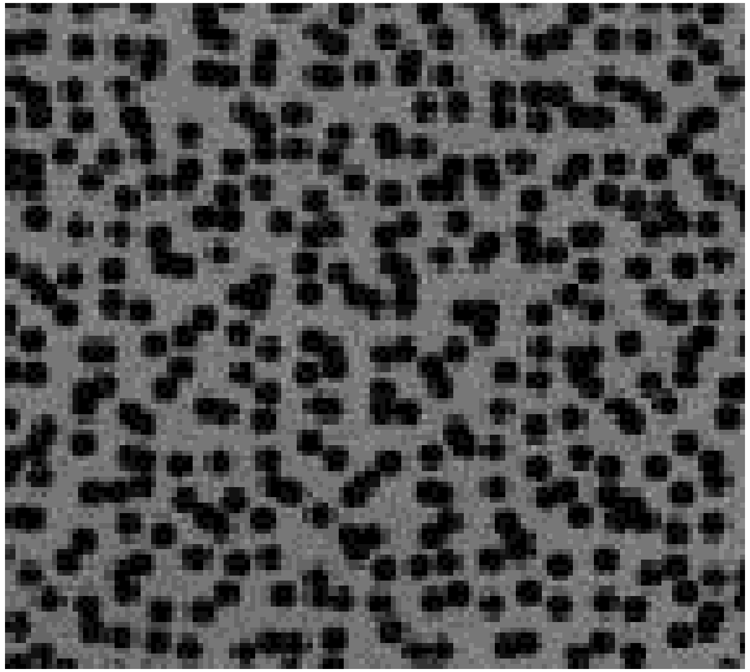
Cross-polarized light eliminates glare

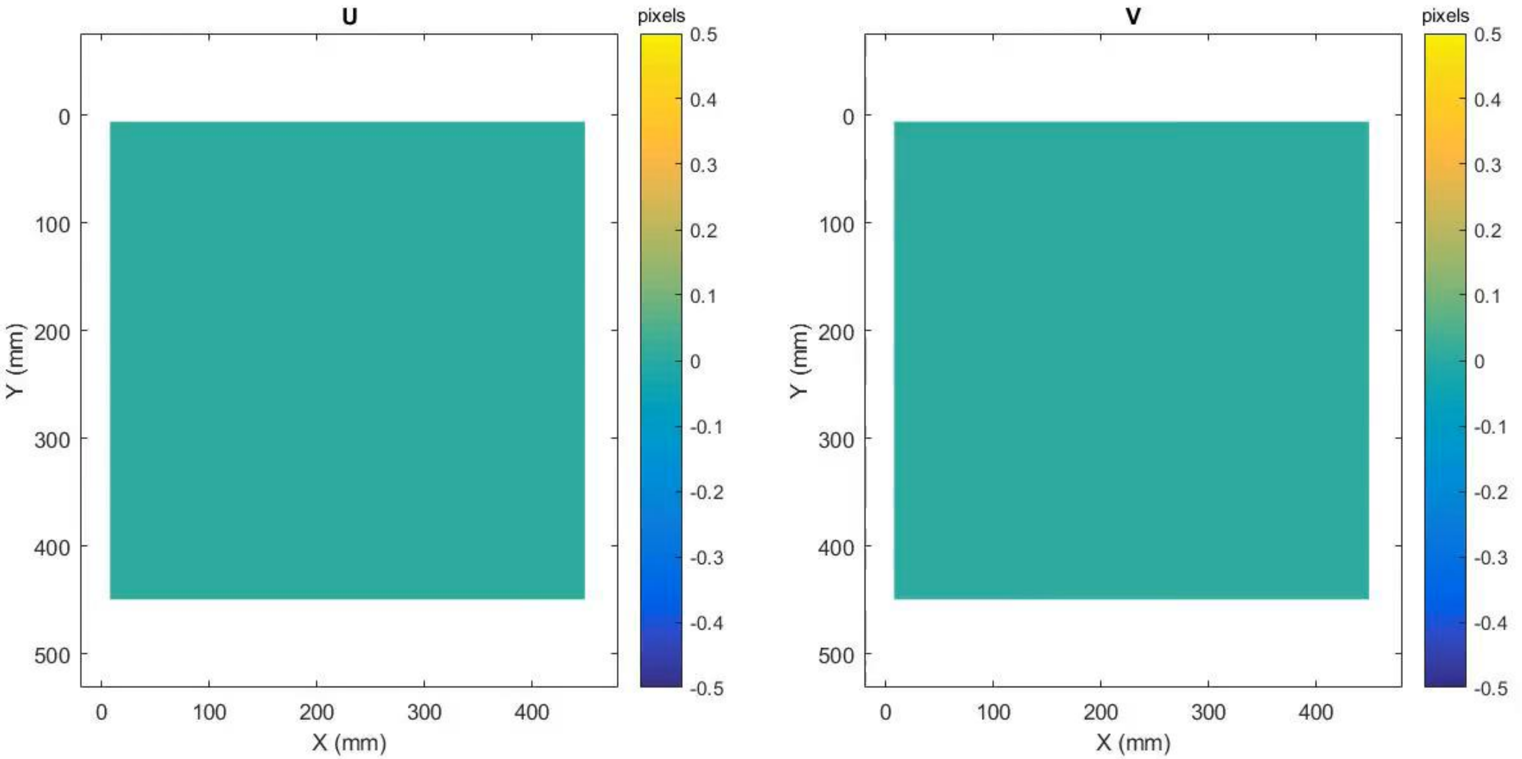


Hardware Heating
Sec. 2.2.5

DEMO 04

- **Caution 2.16: Almost all cameras and lights become hotter than room temperature.**
  - Changes size and positions of camera detector and lenses
  - Heats mounting structure, which can result in relative motion between two cameras
  - Induces convective air currents – “heat wave”, “heat haze”, “mirage effect”
- Tip 2.21, Recommendation 2.15: Avoid introducing hot equipment between cameras and the test piece. Mount lights *above* and *behind* cameras.





EMC Jones (2018) *Exp. Mech.* 58:1133-1156

SAND2020-9051 TR (slides)
SAND2020-9046 TR (videos)

CHAPTER 2:
DESIGN OF DIC MEASUREMENTS

SEC. 2.3:
DIC PATTERN

General Characteristics of DIC Patterns
Sec. 2.3.2 – 2.3.3

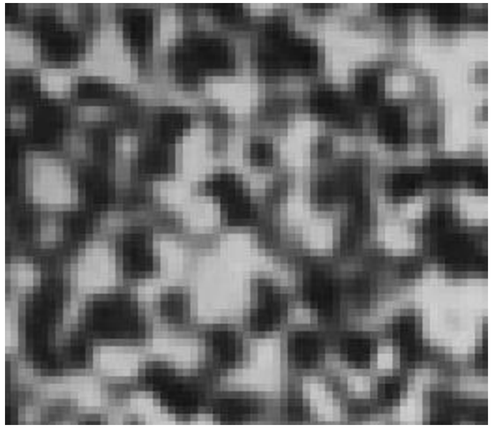
- **One fundamental assumption of DIC is that motion and deformation of the pattern that is imaged exactly replicates the underlying test piece motion and deformation.**

- *Natural patterns:* If the sample surface is heterogeneous, you may be able to image the test piece directly

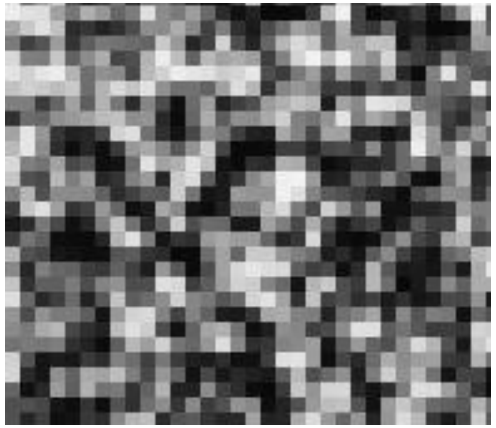
- *Applied patterns:* Much more common

- *Size (Sec. 2.3.2.1):* 3-5 pixels
  - Applies to both white and black features!
  - Caution 2.19:
    - Aliased features add error to DIC results
    - Large features reduce spatial resolution

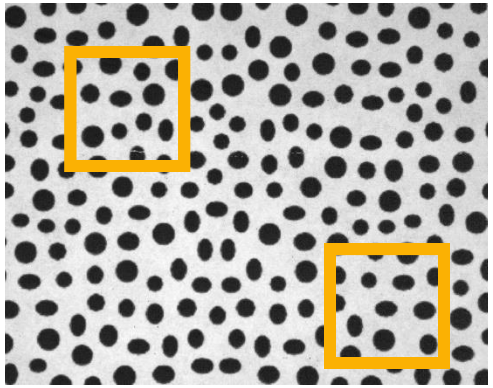
- *Variation (Sec. 2.3.2.2)*: Sufficient variation that subsets can be identified uniquely.



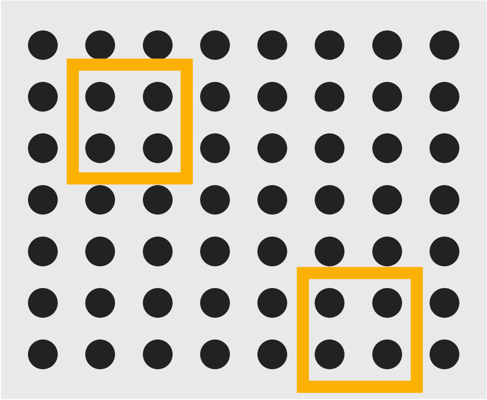
Appropriate size



Too small – aliased



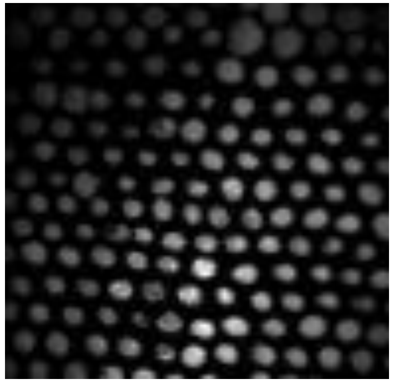
Random



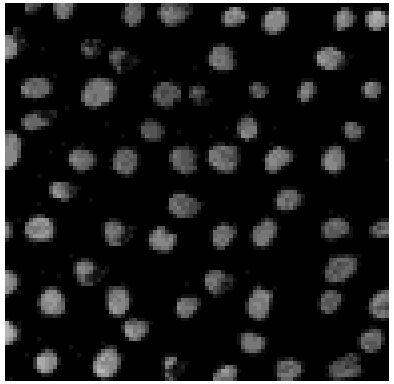
Oriented, regular

General Characteristics of DIC Patterns
Sec. 2.3.2 – 2.3.3

- *Density (Sec. 2.3.2.3)*: ~ 50% black and white
  - With round speckles, density may be closer to 25-40% in order to maintain at least 3 pixels between speckles

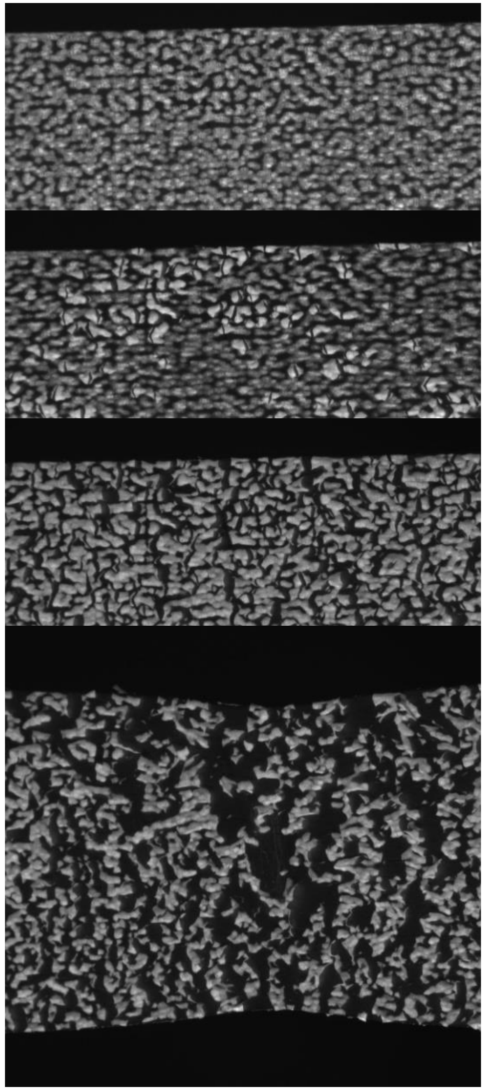


Appropriate density

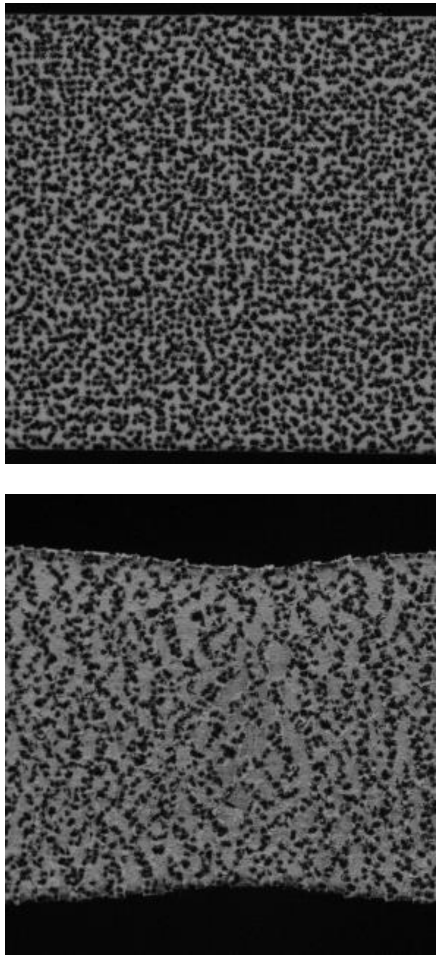


Sparse pattern

- *Quality (Sec. 2.3.2.4)*: Pattern should not degrade during testing
  - Tip 2.26: Types of degradation include:
    - Morphological changes, slip bands (natural patterns)
    - Fading, cracking, debonding (applied patterns)
  - Tip 2.27: Pretest samples to verify suitability of pattern throughout test



Speckle cracking and debonding



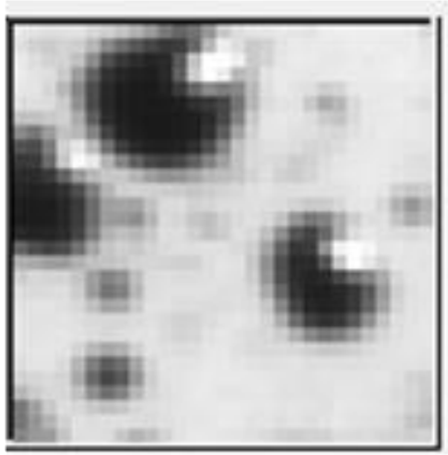
Paint debonding and speckle banding

General Characteristics of DIC Patterns
Sec. 2.3.2 – 2.3.3

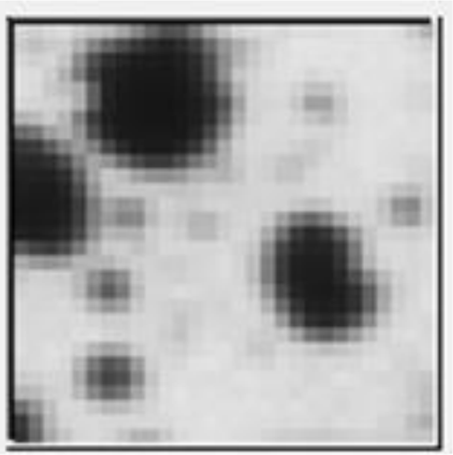
- *Reflections (Sec. 2.3.2.5):* Pattern should be matte, not glossy

- *Compliance (Sec. 2.3.3.1):* Applied patterns should be thin and compliant relative to the test piece
  - Caution 2.22: Thick/stiff patterns could affect deformation of thin/compliant test pieces.

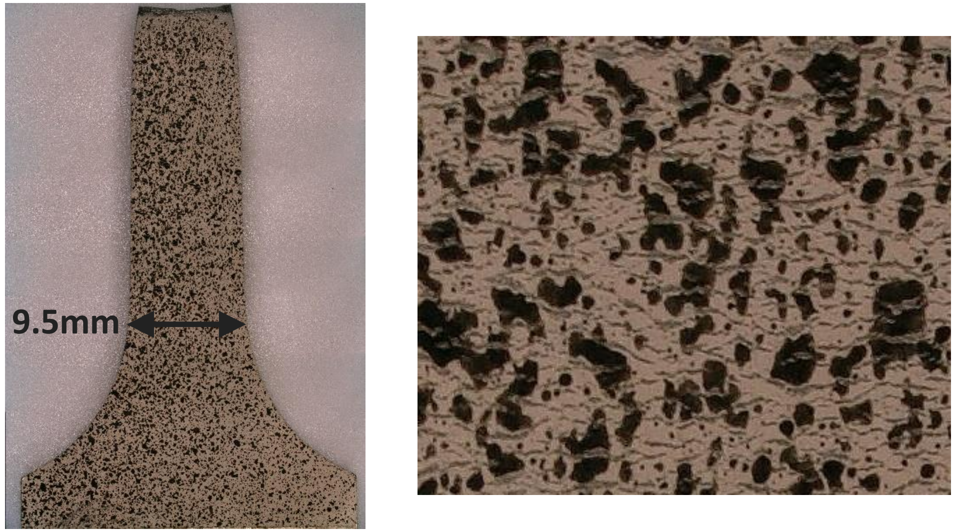
- *Bonding (Sec. 2.3.3.2):* Applied patterns should be well-bonded to the test piece



Specular reflection on each speckle



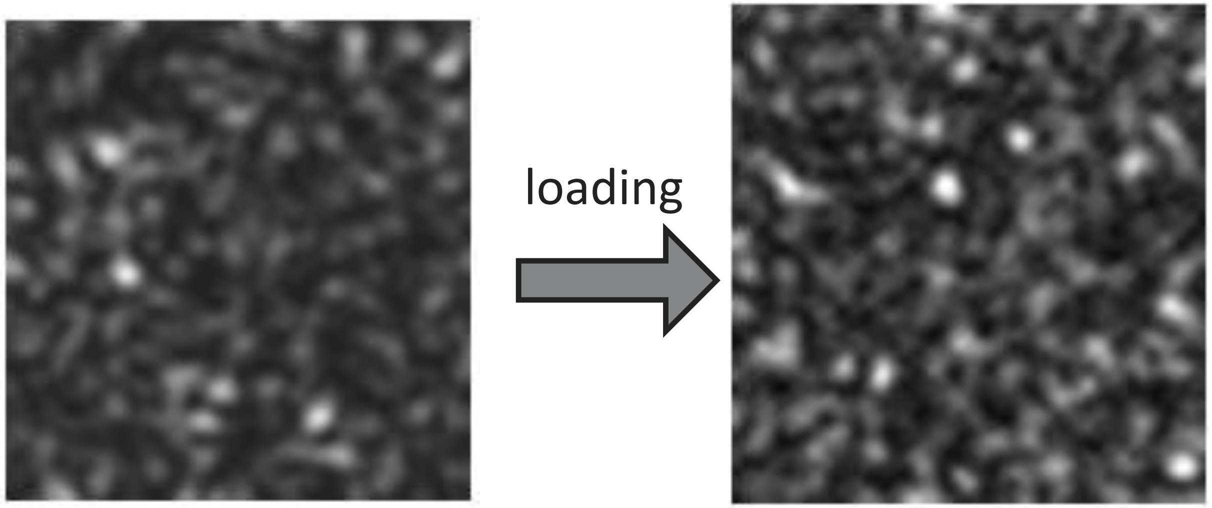
Matte pattern



Paint cracking and debonding at a small scale

General Characteristics of DIC Patterns
Sec. 2.3.2 – 2.3.3

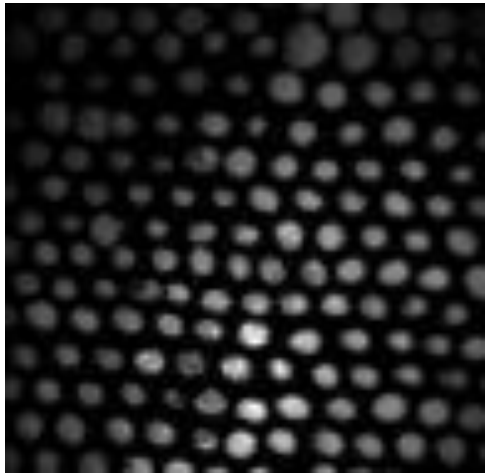
- *Fidelity (Sec. 2.3.3.3):* Applied pattern should deform conformally with the test piece.
  - Tip 2.29:
    - Large deformation → ductile pattern
      - Test immediately after painting, while the paint is still wet/ductile
    - Brittle fracture → brittle pattern
      - Fully cure the paint (consider baking) so paint cracks at same time as the test piece
  - Caution 2.24:
    - Laser speckle patterns are not appropriate for DIC!
- *Thickness (Sec. 2.24):* Applied patterns should be uniform thickness.



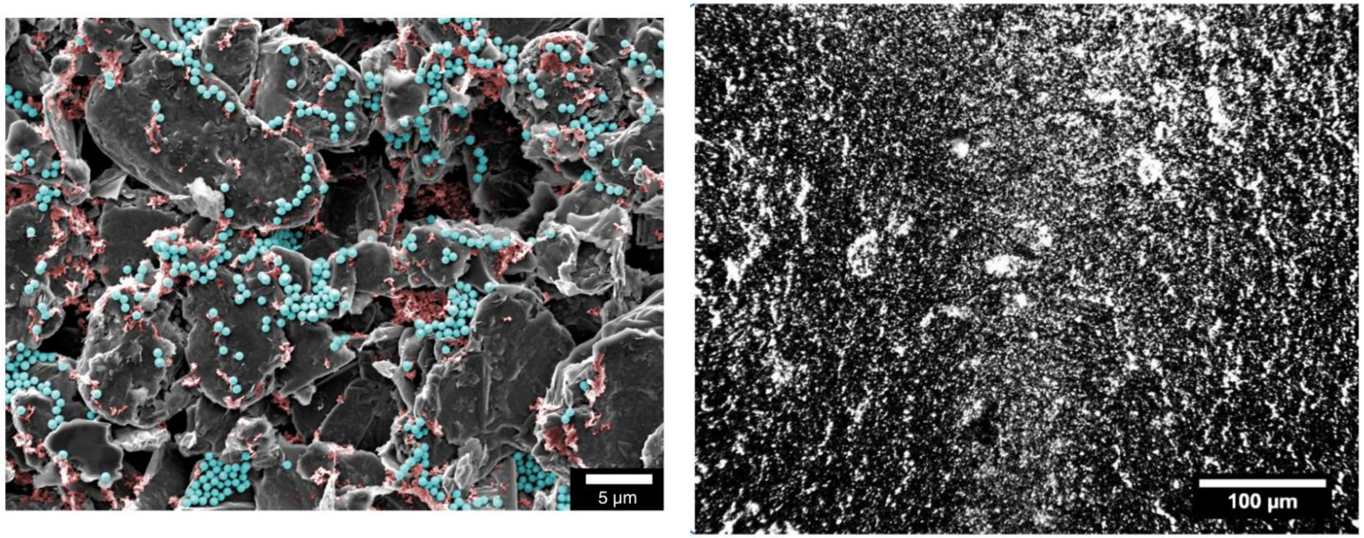
Laser speckle pattern before/after loading

Note: Issues with patterns may appear in results as:
- Higher correlation residual / uncertainty
- Missing data points (holes) / failure to correlate
- Higher epipolar error
- Non-physical data
- **Or no obvious effect! → Carefully examine patterns**

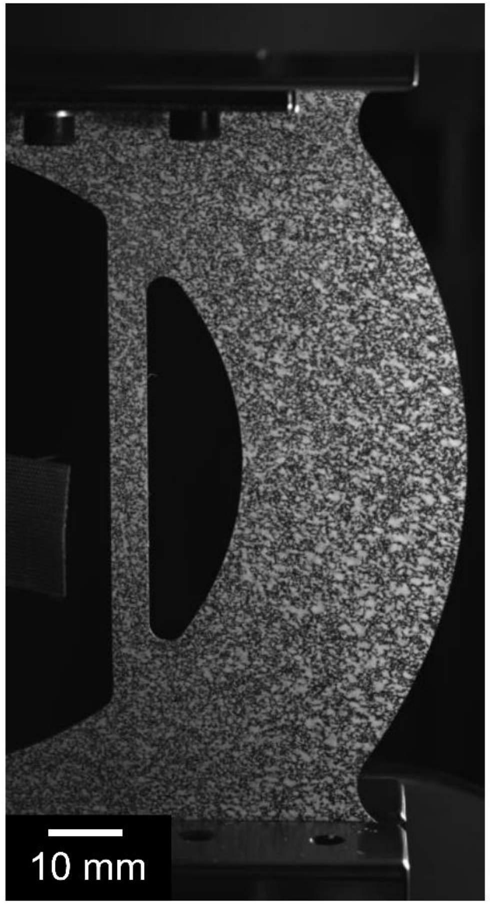
Patterning Techniques: Limited only by the imagination
Sec. 2.3.4



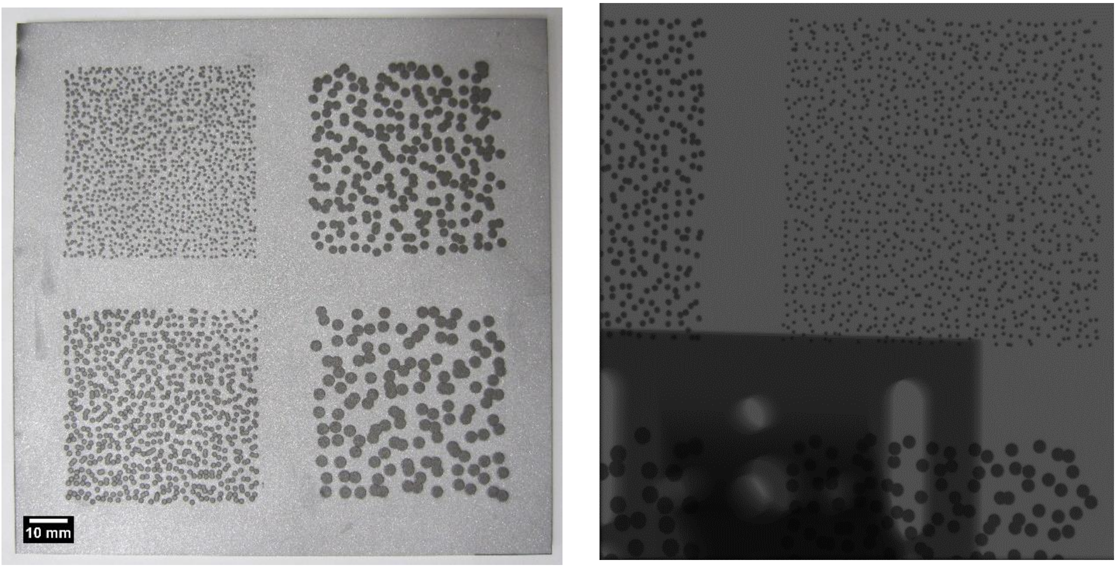
Thermographic phosphor



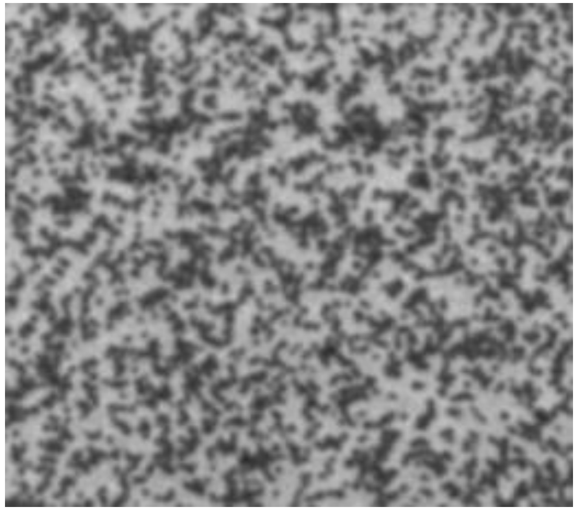
Fluorescent silica nano-particles on a composite battery electrode



White paint on bare metal



Ta on Al – X-ray DIC



Carbon powder on white paint

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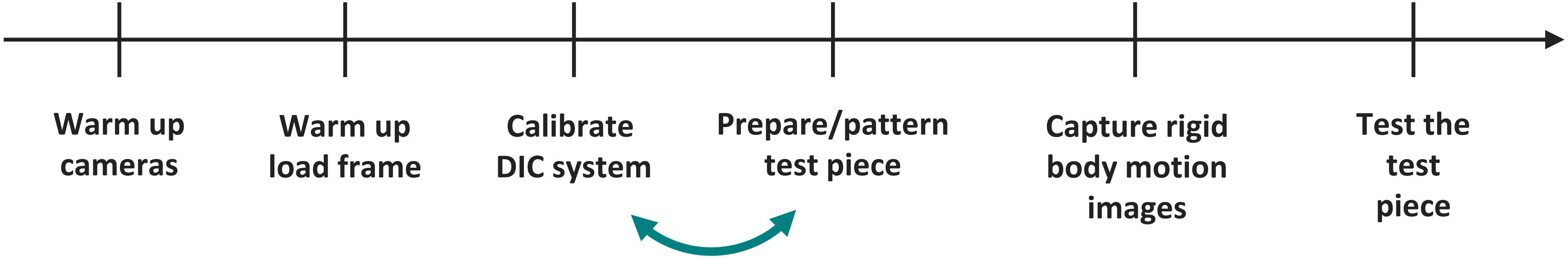
SAND2020-9046 TR (videos)

CHAPTER 3:
PREPARATION FOR THE MEASUREMENTS

SEC. 3.1:
PRE-CALIBRATION ROUTINE

Review the Test Procedure
Sec. 3.1.1



Stable environmental conditions

Ensure pattern will not be damaged

Consider adding a backdrop behind test piece

Warm up cameras

Warm up load frame

Calibrate DIC system

Prepare/pattern test piece

Capture rigid body motion images

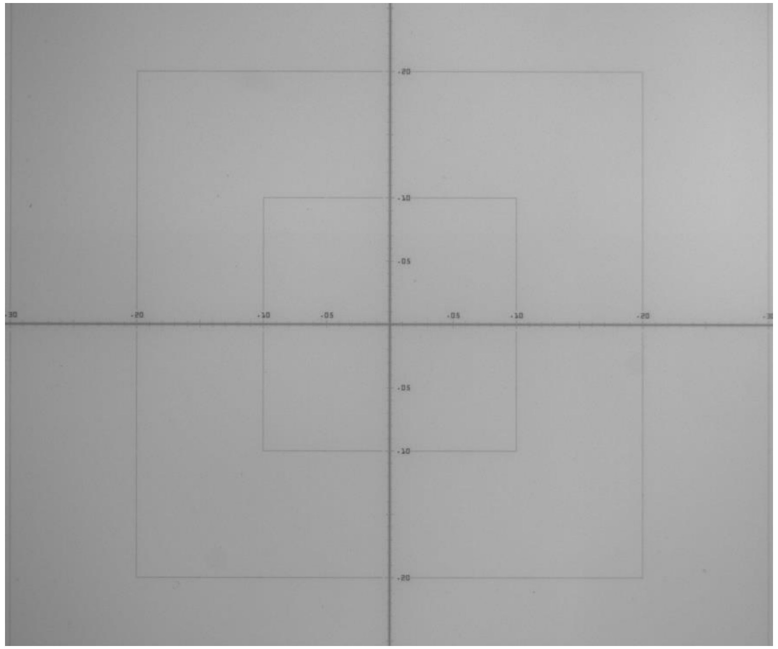
Test the test piece

Load frame is adjusted/tuned/calibrated

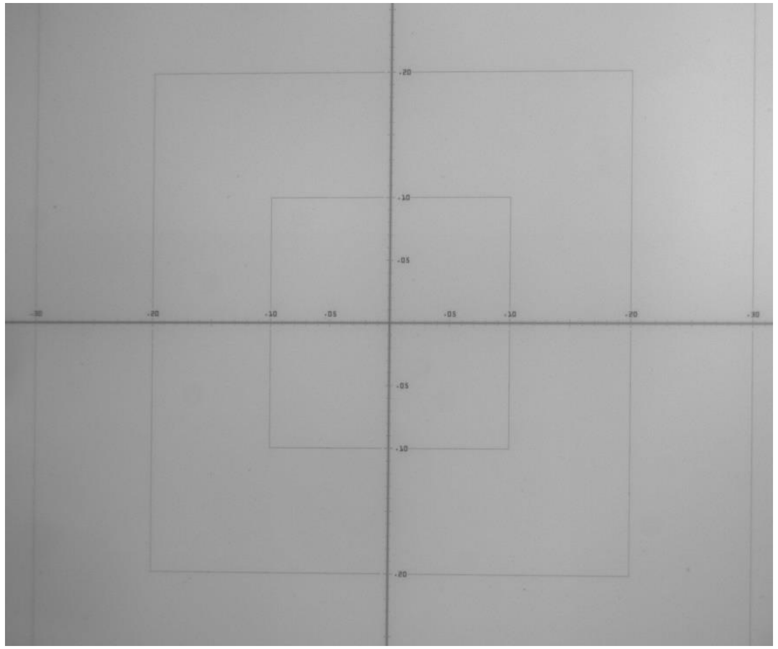
Cleanliness of Equipment
Sec. 3.1.2

- Ensure there is no dust, water marks, oil, smears, fingerprints, etc. on lens, camera detector, or calibration target.
- Recommendation 3.1: Keep a clear lens filter to protect lens
- Recommendation 3.2: Image a white sheet of paper and look for blurred spots or smears
  - *Translate the sheet:*
    - If spots/smears move with the paper, the dirt is on the paper; otherwise, the dirt is on the optical system
  - *Rotate the lens:*
    - If the spots/smears rotate with the lens, they are on the lens; otherwise, they are on the camera detector

UV filter



Left camera



Right camera

Cleanliness of Equipment
Sec. 3.1.2

DEMO 05

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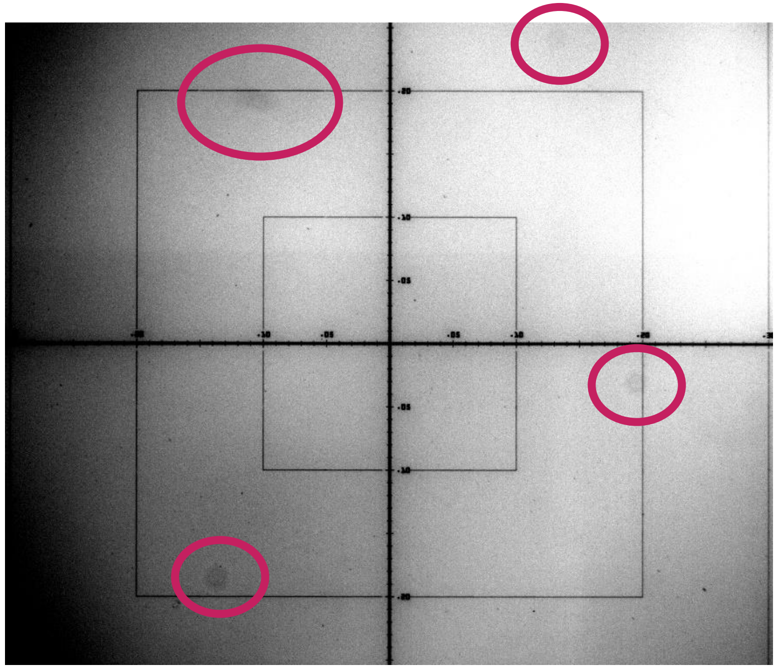
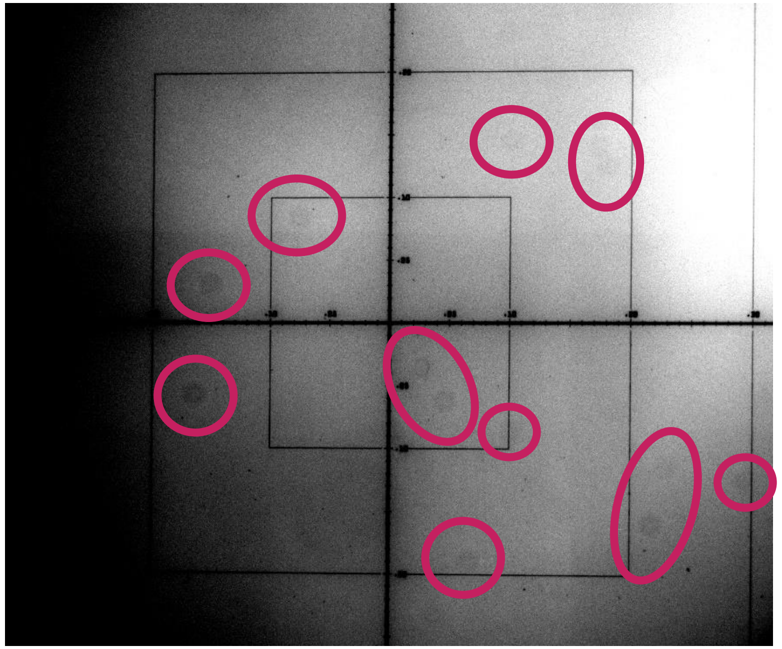
  - *Translate the sheet:*
    - If spots/smears move with the paper, the dirt is on the paper; otherwise, the dirt is on the optical system
  - *Rotate the lens:*
    - If the spots/smears rotate with the lens, they are on the lens; otherwise, they are on the camera detector

UV filter



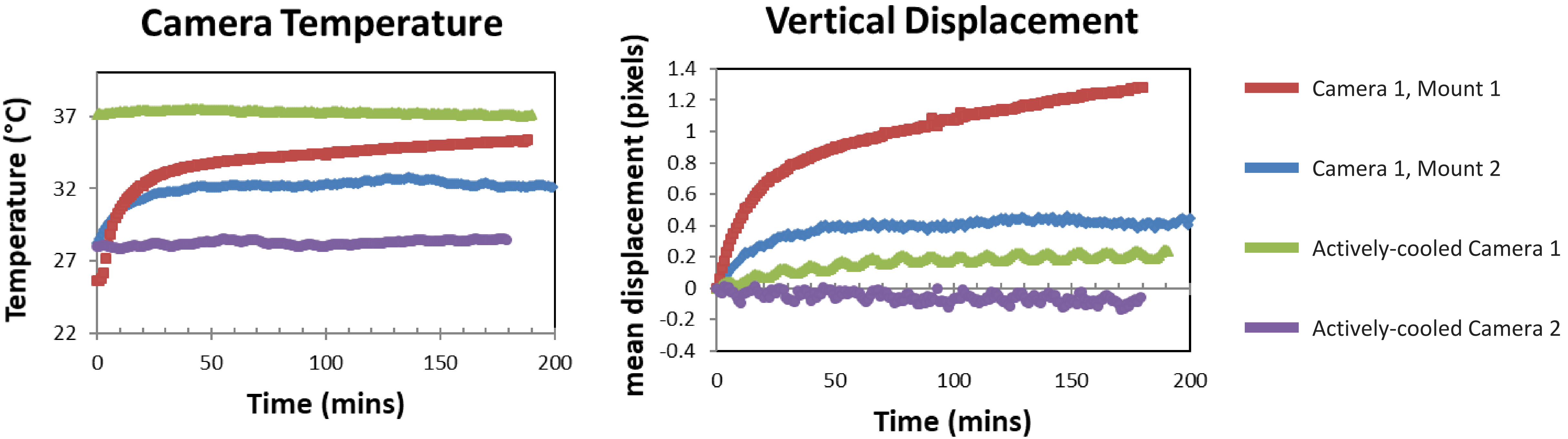
Left camera



Right camera

Camera Warm-Up
Sec. 3.1.3

- Operate cameras at target frame rate until they are at a stable operating temperature
- Tip 3.2: Warm-up times vary from several minutes to several hours, and should be evaluated for each camera and frame rate.



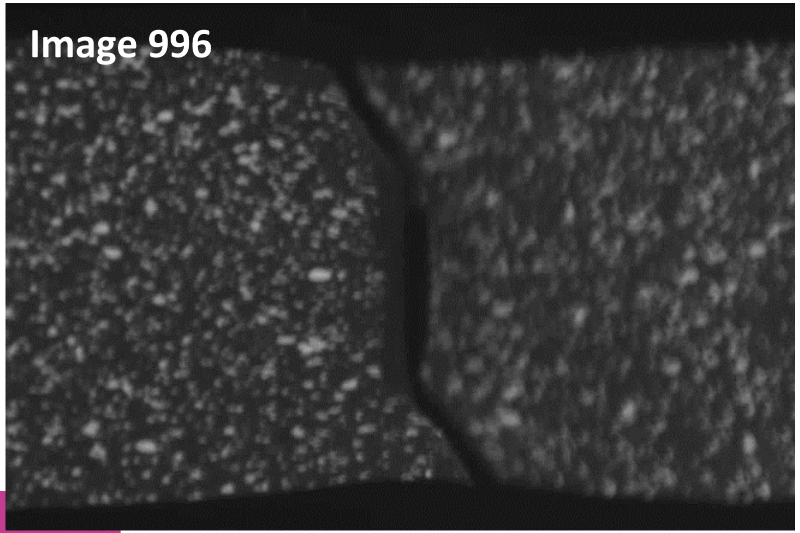
- Increasing temperature → increasing false displacements (red, blue curves)
- Temperature equilibrium depends on camera, frame rate, and mounting structure (red, blue curves)
- Actively cooled cameras more stable than others (green, purple curves)

Synchronization
Sec. 3.1.4

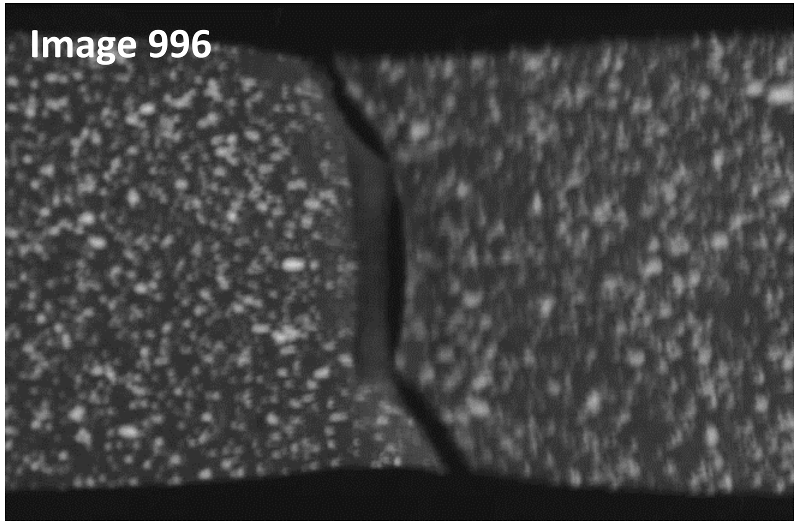
- Caution 3.3: **Synchronization of the cameras in stereo-DIC is critical!** Any delay between the two cameras will result in errors in the DIC measurements.
  - Cameras can be synchronized via software or hardware

- Tip 3.3: Multiple ways to verify synchronization:
  - Image a moving test piece, correlate images, verify that the epipolar error is acceptable
  - Image a strobe light set to the same frequency as the image acquisition frequency
  - Measure strobe or exposure signal from the cameras on an oscilloscope
  - Image a dynamic event

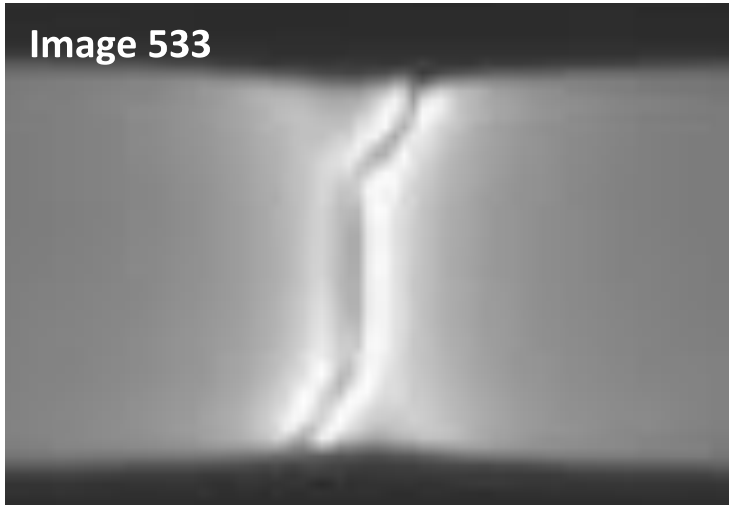
Left camera



Right camera

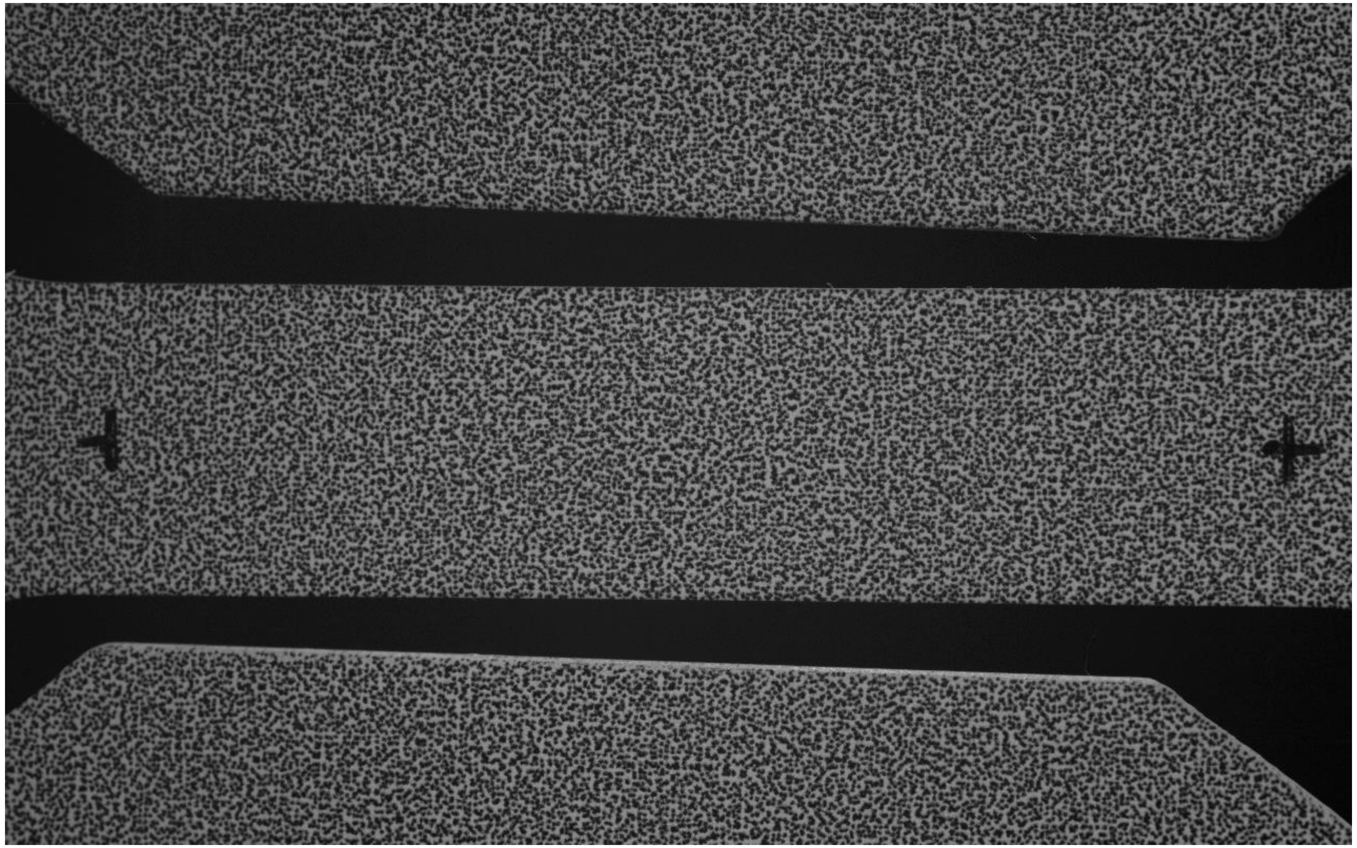


IR camera



Application of DIC Pattern
Sec. 3.1.5

- Recommendation 3.3: Apply two fiducial marks a known distance apart on the test piece
  - Useful for defining coordinate systems
  - Useful for checking absolute distances as part of calibration verification



Pre-Calibration Review of the System
Sec. 3.1.6

- Caution 3.4: This is the time to make adjustments and fix any issues with the DIC measurement setup. Once calibration images are taken, very few aspects of the DIC system can be changed.

- Sec. 3.1.3.1: Position test piece and cameras
- Sec. 3.1.6.2: Verify FOV, focus, DOF, magnification/SOD
- Sec. 3.1.6.3: Adjust polarization filters. Lock adjustable components (e.g. aperture, focus rings, translation/rotation stages). Strain relieve cables.
- Sec. 3.1.6.4: Review images, looking for
  - Glare
  - DIC pattern that is too coarse/fine
  - Defects in applied pattern
  - Out-of-focus regions
  - Poor contrast
  - Non-uniform lighting
  - Dirt or foreign object on lens
  - Vibrations

- Sec. 3.1.6.5: Accept DIC system

DEMO 06

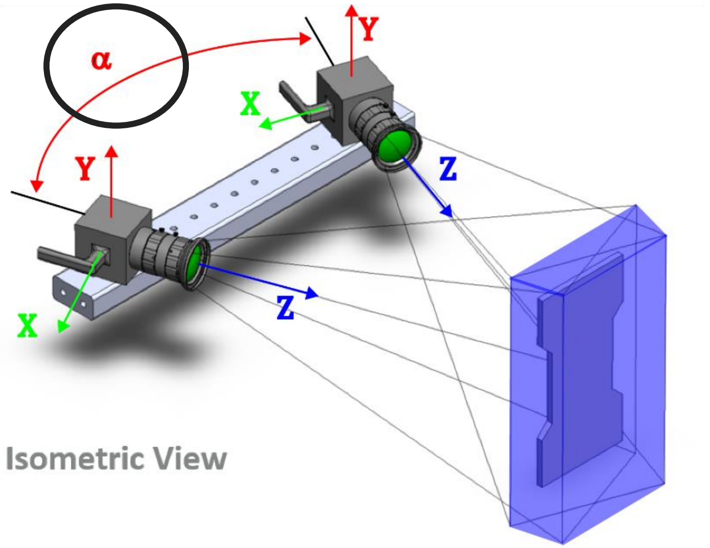
CHAPTER 3:
PREPARATION FOR THE MEASUREMENTS

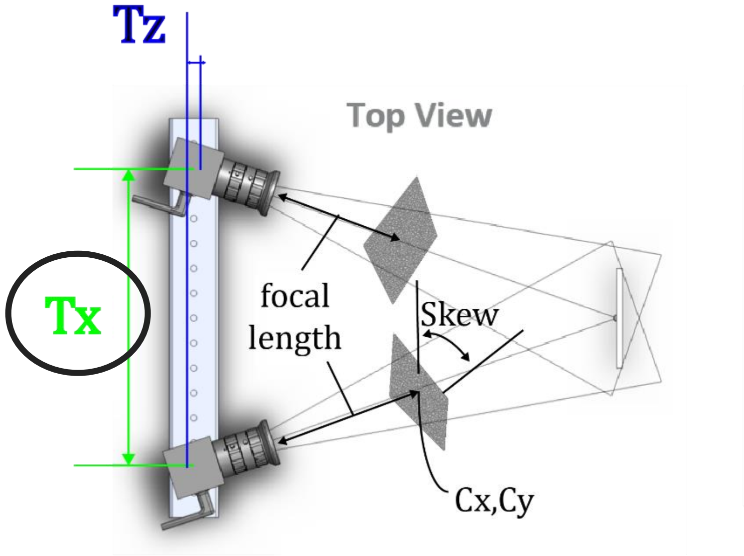
SEC. 3.2-3.3:
CALIBRATION

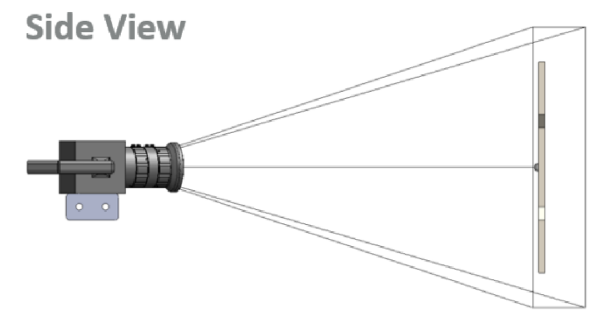
Purpose of Calibration – Stereo-DIC
Sec. 3.2.1

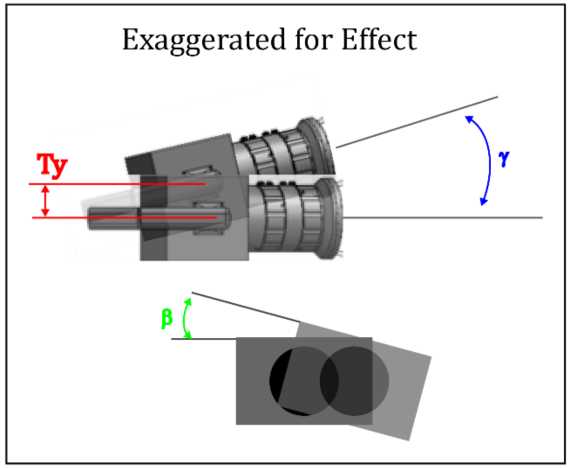
- *Intrinsic Parameters*
  - Focal length
  - Skew
  - Image Center (Cx, Cy)
  - Lens Distortions

- *Extrinsic Parameters*
  - Translations (X,Y,Z)
  - Rotations (α,β,γ)



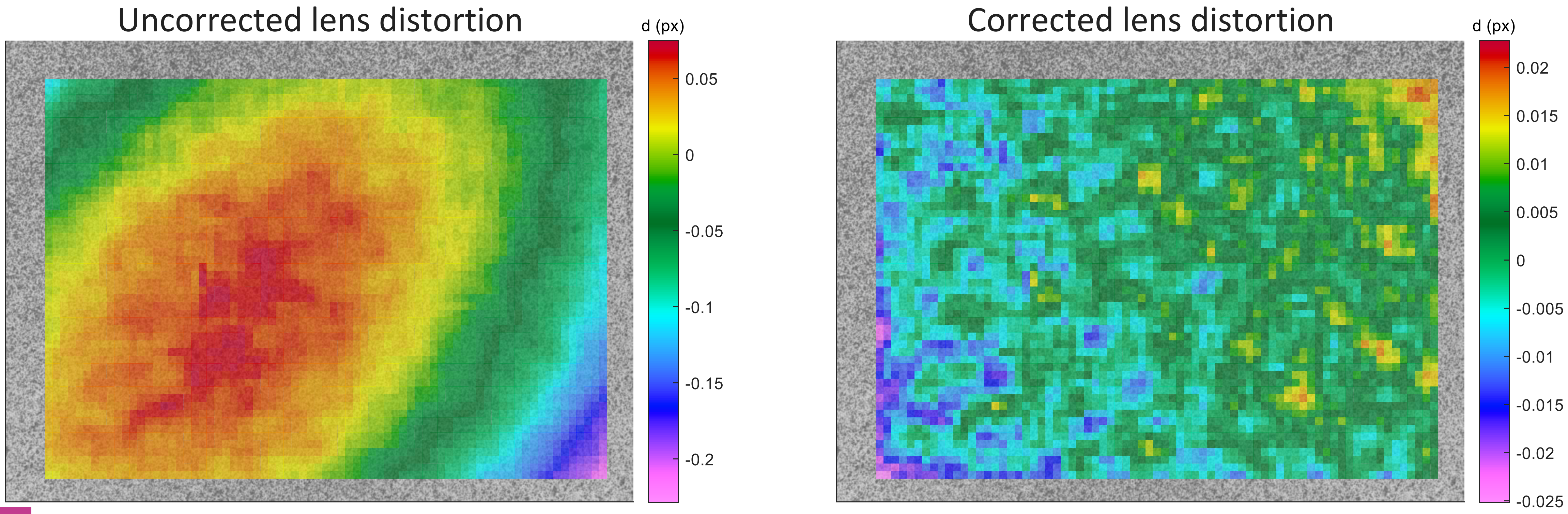






Purpose of Calibration – 2D-DIC
Sec. 3.2.1

- Caution 3.6 / Recommendation 3.5:
  - Calibration is still recommended for 2D-DIC, to correct for lens distortions.
  - If a full calibration is omitted, the magnitude of lens distortions should be evaluated.
    - Translate the sample in-plane and compute strains.
  - Also, the approximate image scale should be established.

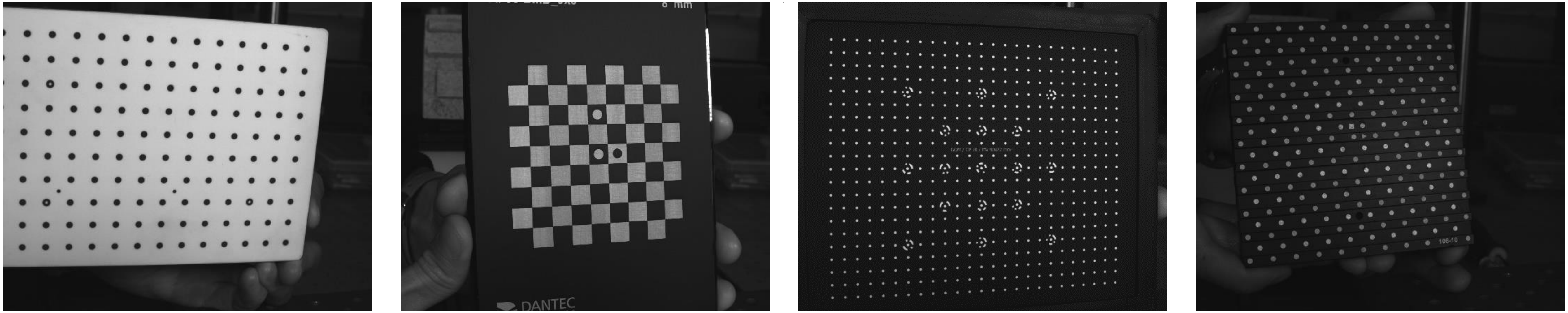


Select Calibration Target
Sec. 3.2.2.1

- Recommendation 3.6:
  - Target should be approximately the same size as the FOV or slightly smaller
  - Target shouldn’t be smaller than ½ the size of the FOV

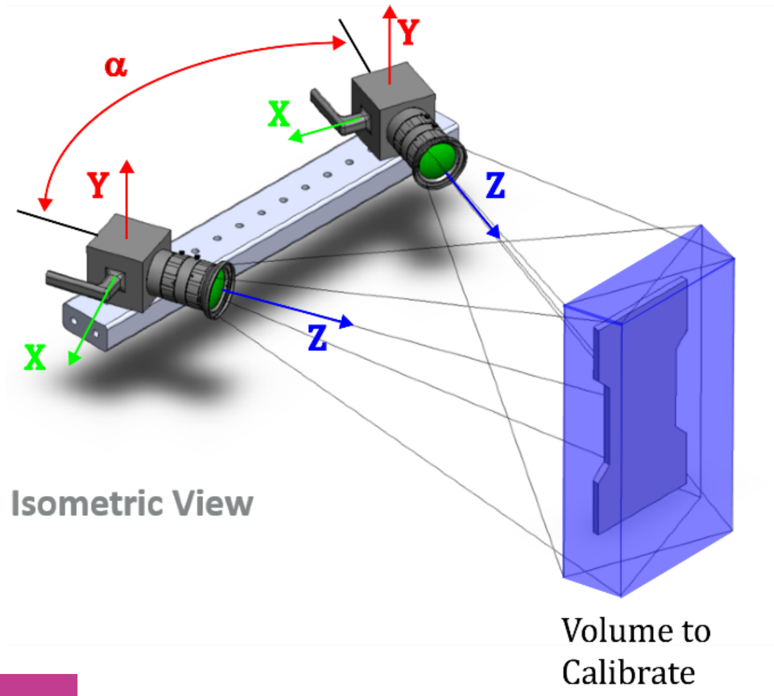
Calibration target examples from the Stereo DIC Challenge

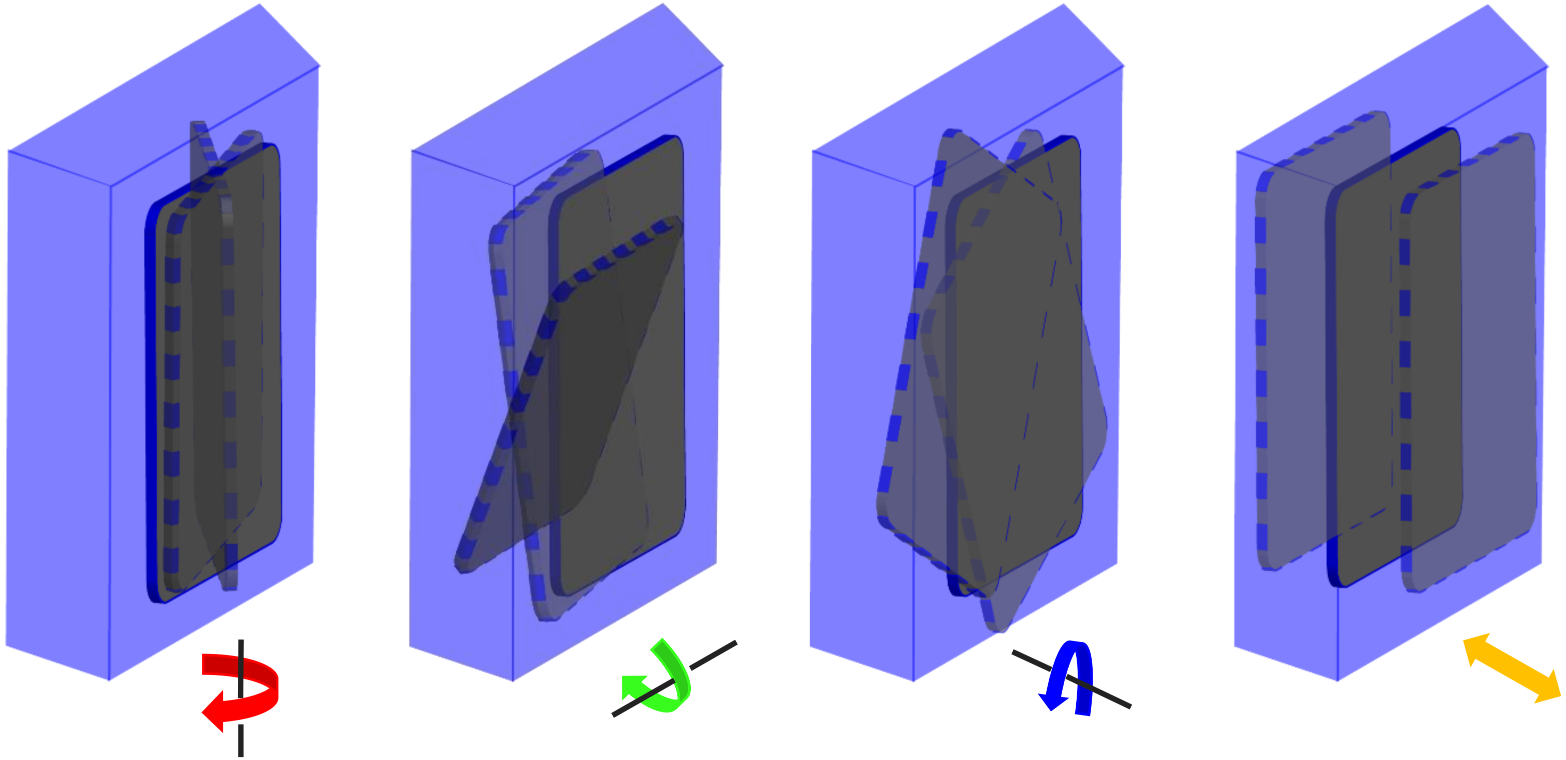
https://sem.org/3ddic



Acquire Calibration Images
Section 3.2.2.2-3.2.2.4

1. Clear working space
   - Recommendation 3.8:
     a) Move the test piece, not the stereo-rig, if possible
     b) Translate the stereo-rig
        - Caution 3.8: It is imperative that the stereo cameras are moved only as a rigid pair!
2. Adjust lighting and exposure
   - Caution 3.10: But not focus and aperture!
3. Acquire images that fill the field-of-view and depth-of-field





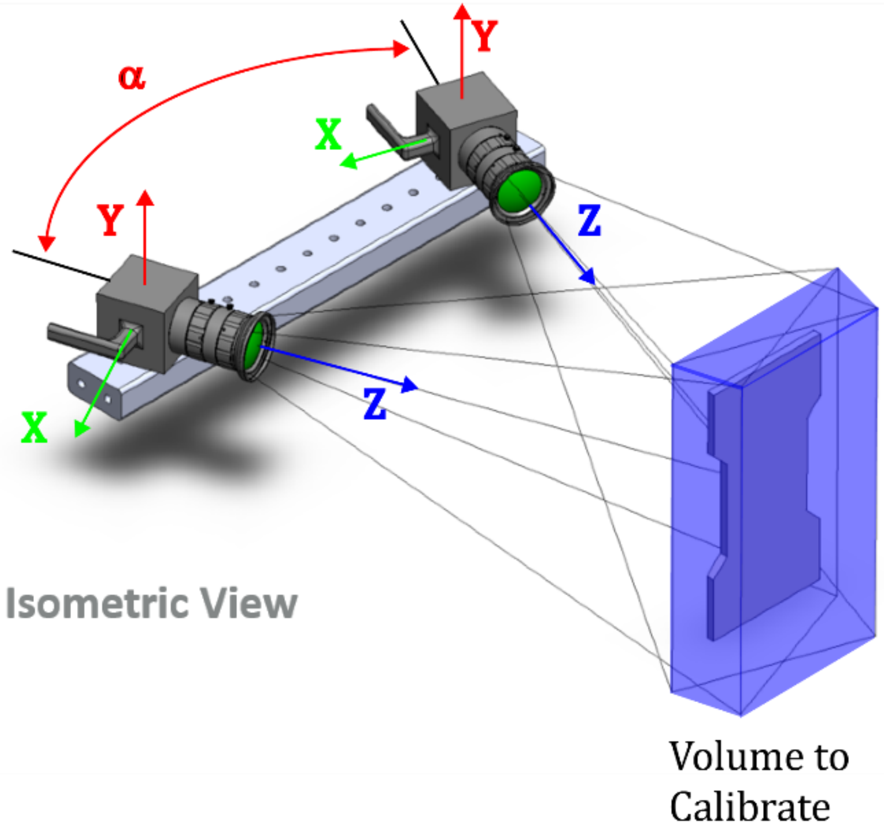
Acquire Calibration Images
Section 3.2.2.4

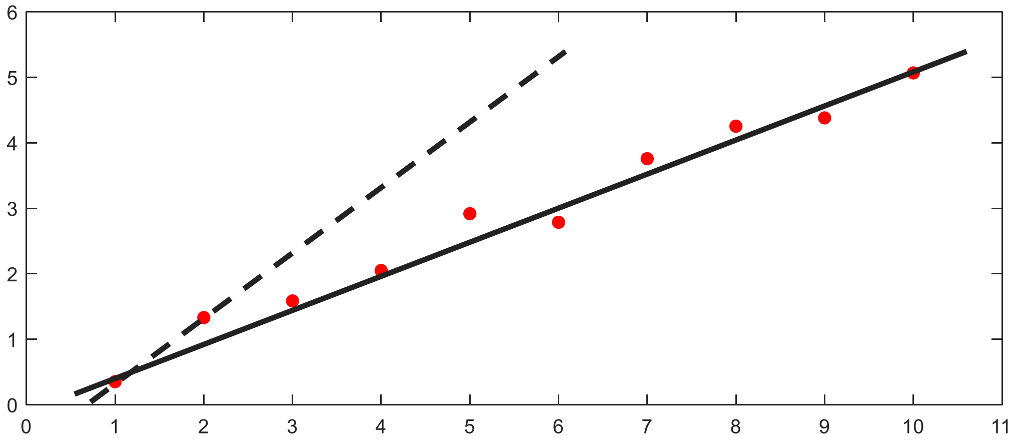
- Tip 3.6: The number of images recommended depends on calibration target and software ranging from *8* to *50-100*

- Caution 3.11: Quality over quantity!
  - Recommendation: Take care to gather images over entire volume

- Recommendation 3.11: Rigid calibration holder recommended, but may not be required, especially when exposure is less than 25 ms

- Caution 3.12: It is possible to achieve a "good score" with insufficient number of images





DEMO 07

Calibrate System and Review Calibration Results/ Parameters
Sec. 3.2.2.5-3.2.2.7

1. Select an appropriate camera or lens-distortion model and calibrate!

2. Review calibration results
    - Verify extracted features are correct (not dirt, glare etc)
    - Understand reason image/feature was rejected
    - Verify working volume was filled (i.e. dropped images were not all taken in the same region/ rotation)
    - Compare calibration score amongst individual images and to final score. Remove images if appropriate.
    - Save a copy of all pertinent information

Tip 3.8: All of the above is software dependent and may be user-defined; explore these effects

Calibrate System and Review Calibration Results/ Parameters Sec. 3.2.2.5-3.2.2.7

3. Review calibration parameters
   - Image center
   - Lens focal length
   - Angles
   - Distance between two cameras

Tip 3.9: This review is broad, and often focuses on range of values, rather than precise measurements

Example: 5MP Basler camera with 29 mm focal lens and 100 mm FOV

Caution 3.13: A good calibration score doesn't always mean success, but a bad calibration score rarely leads to success

Parameter	Theoretical	Good	Unexpected
Camera 1:			
Cx	1224 px	1210 px	-962 px
Cy	1024 px	1030 px	-50 px
Focal Length X	8405.8 px	8761 px	8000 px
Focal Length Y	8405.8 px	8612 px	9000 px
Camera 2:			
Cx	1224 px	1210 px	1225 px
Cy	1024 px	1010 px	1024 px
Focal Length X	8405.8 px	8375 px	4000 px
Focal Length Y	8405.8 px	8457 px	4100 px
Extrinsic:			
Stereo Angle (α)	25	25	50
β	0	0.1	5
γ	0	0.1	-4
Tx	160 mm	150 mm	300 mm
Ty	0 mm	5.1 mm	-1 mm
Tz	375 mm	370 mm	200 mm

Non-physical

Should be same for spherical lenses

Focal lengths don't match between cameras

Angles not optimal for DIC

Non-physical

Calibrate System and Review Calibration Results/ Parameters
Sec. 3.2.2.5-3.2.2.7

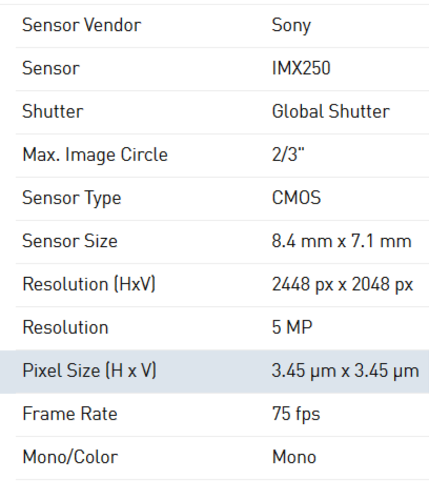
How to convert focal length from pixels to physical units

$$\underbrace{(\text{Focal Length [px]})}_{\text{Focal length from calibration}} \quad * \quad \underbrace{(\text{Pixel size [µm/px]})}_{\text{Physical size of pixels on detector}} \quad = \quad \underbrace{(\text{Focal Length [mm]})}_{\text{Physical focal length of the lens}}$$

$$\sim 8551\ \text{px} \quad * \quad 3.45\ \text{µm/px} \quad \overset{?}{\approx} \quad 29\ \text{mm lens}$$

$f_{x,0}$ = 8761 px
$f_{y,0}$ = 8612 px
$f_{x,1}$ = 8375 px
$f_{y,1}$ = 8457 px

Not the image scale!
Look on camera brand website.

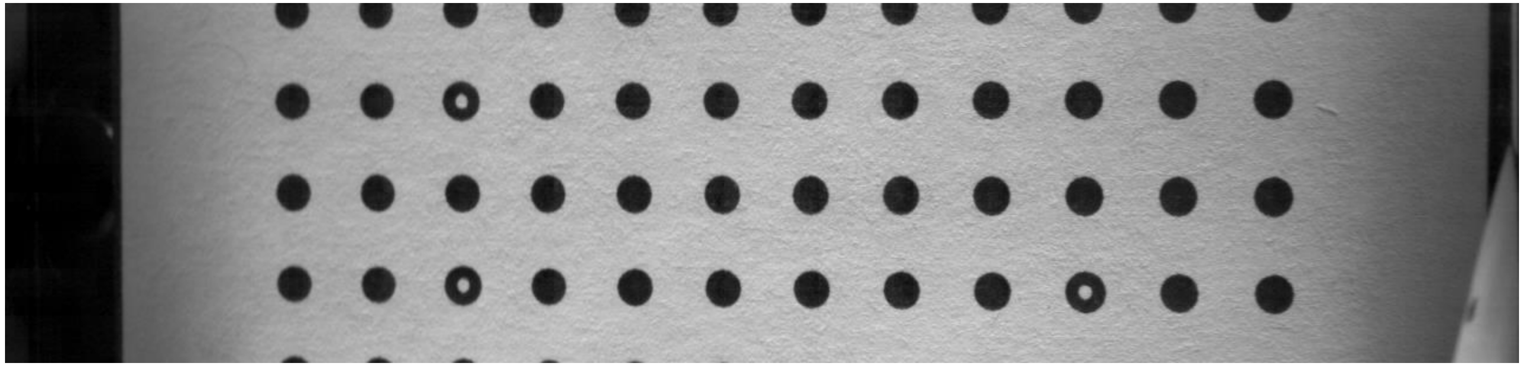


Sensor Vendor	Sony
Sensor	IMX250
Shutter	Global Shutter
Max. Image Circle	2/3"
Sensor Type	CMOS
Sensor Size	8.4 mm x 7.1 mm
Resolution (HxV)	2448 px x 2048 px
Resolution	5 MP
Pixel Size (H x V)	3.45 µm x 3.45 µm
Frame Rate	75 fps
Mono/Color	Mono

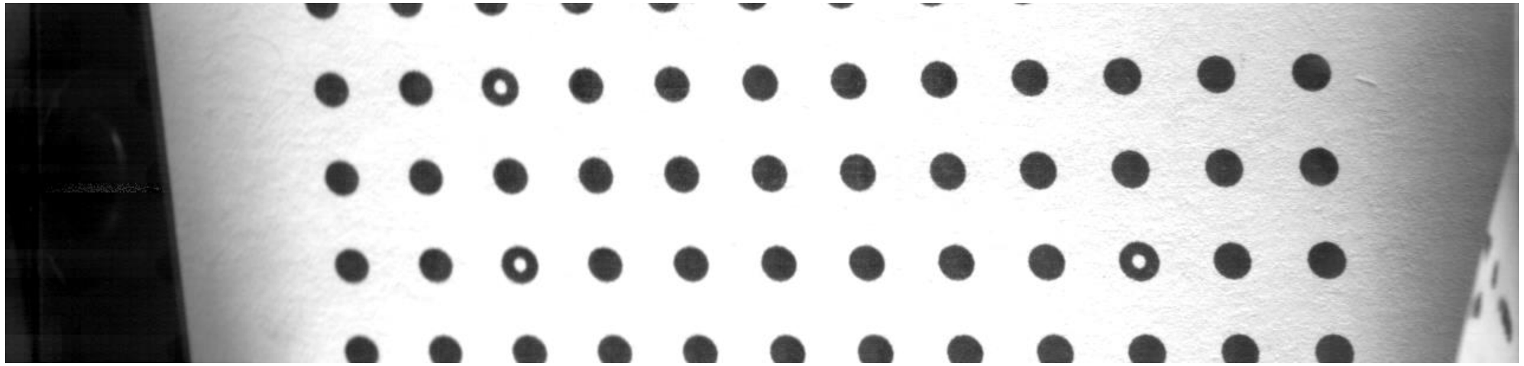
What’s wrong with my calibration?

What’s wrong with my calibration?

Calibration target perpendicular to light source

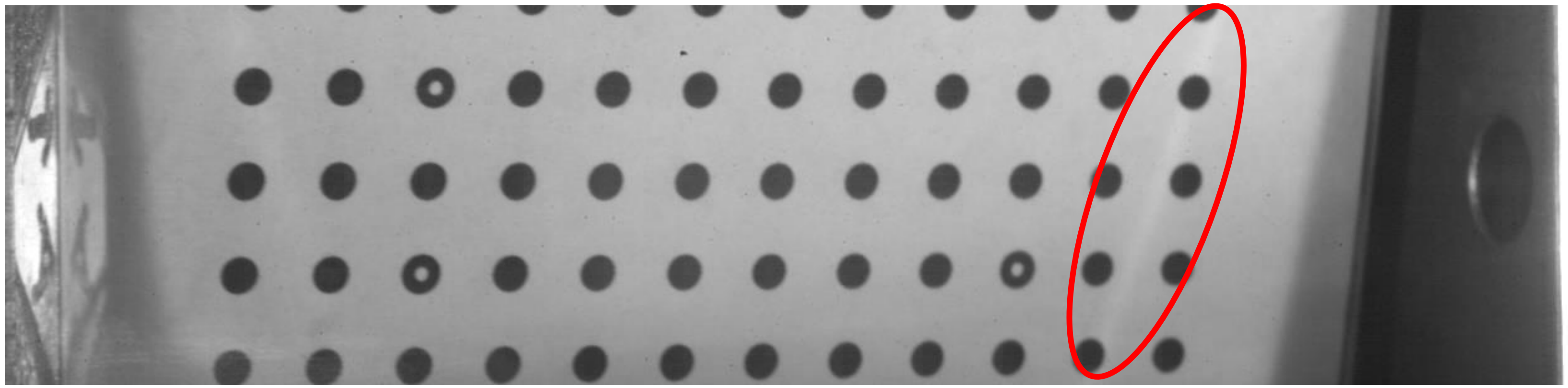


Calibration target titled to light source



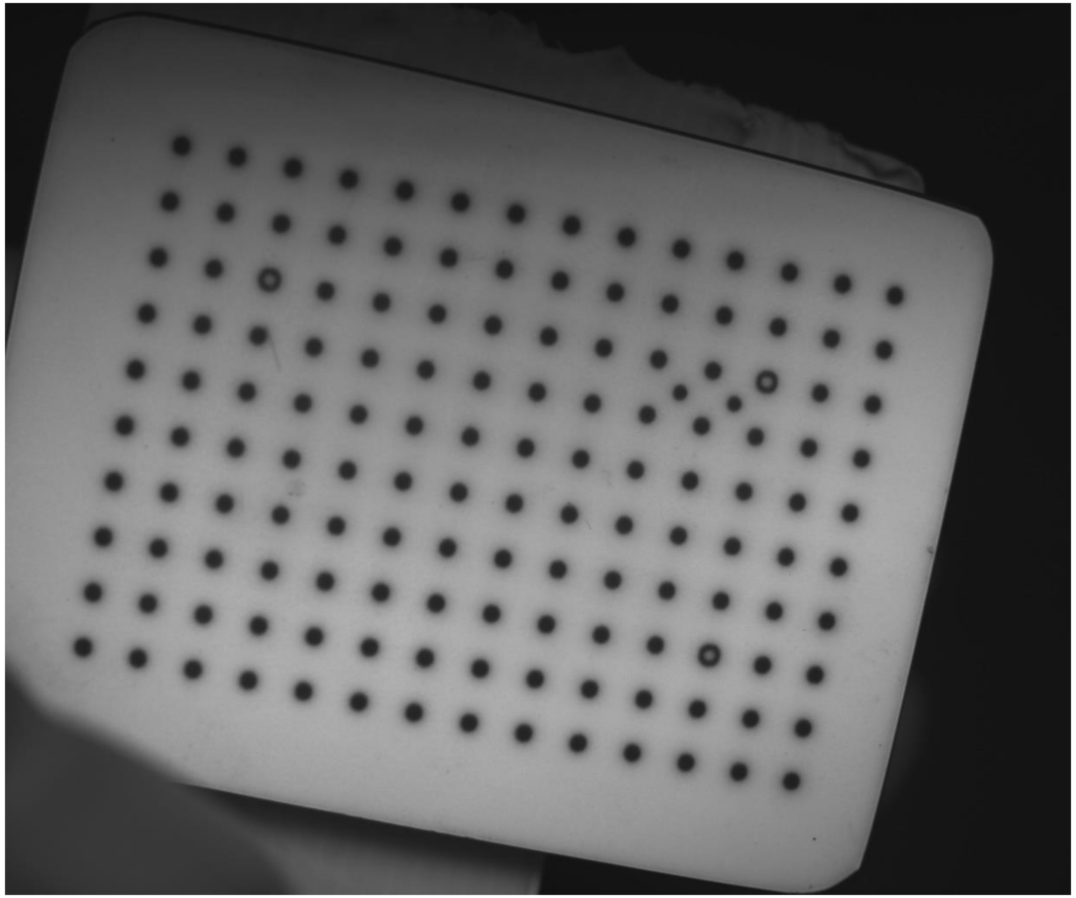
Saturated light due to tilt

What’s wrong with my calibration?



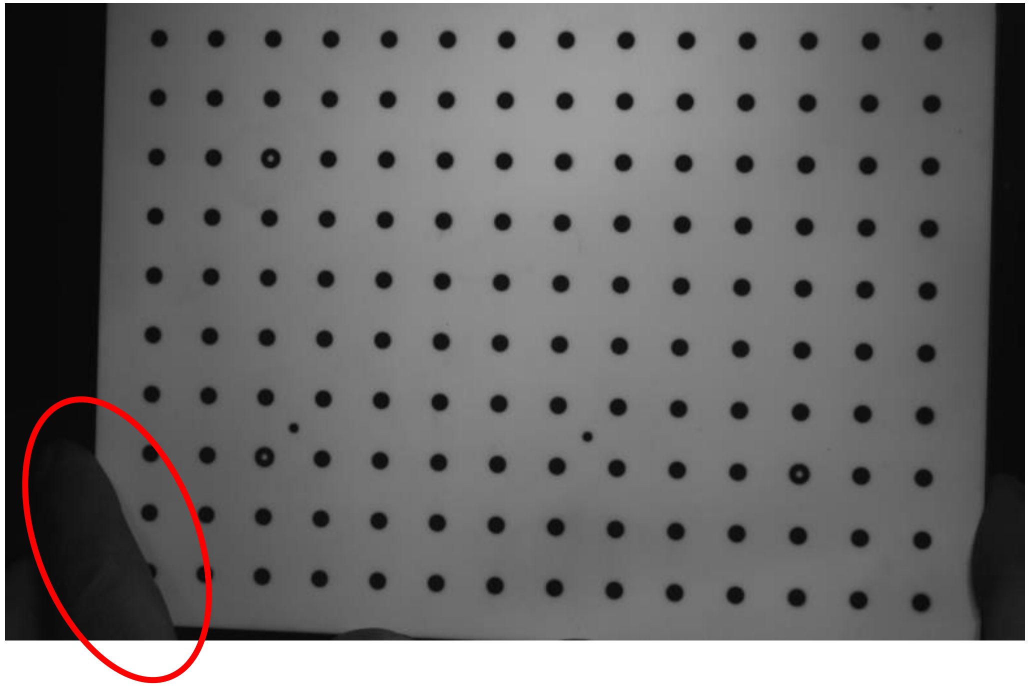
Reflections or glares

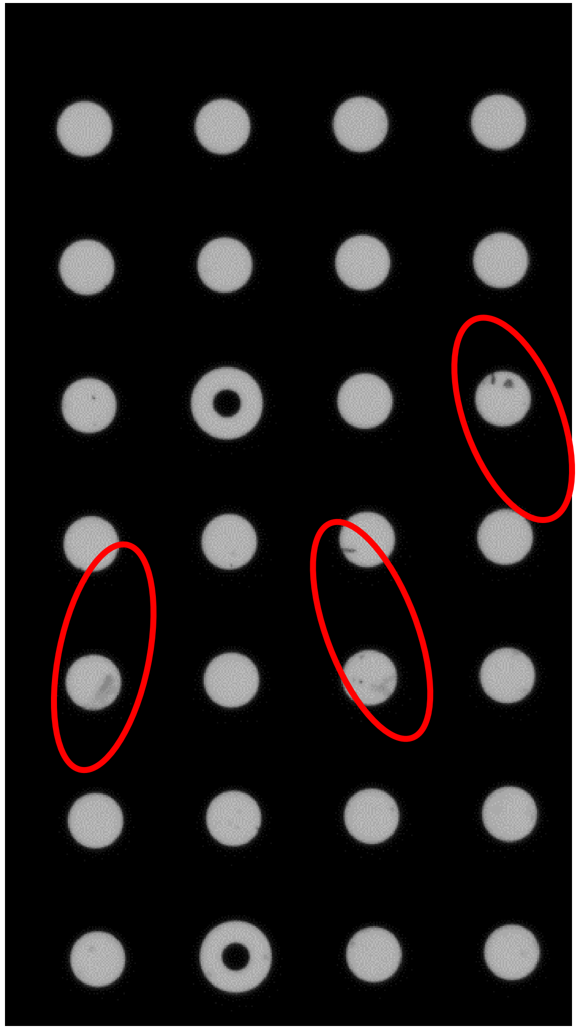
What’s wrong with my calibration?



Shadows

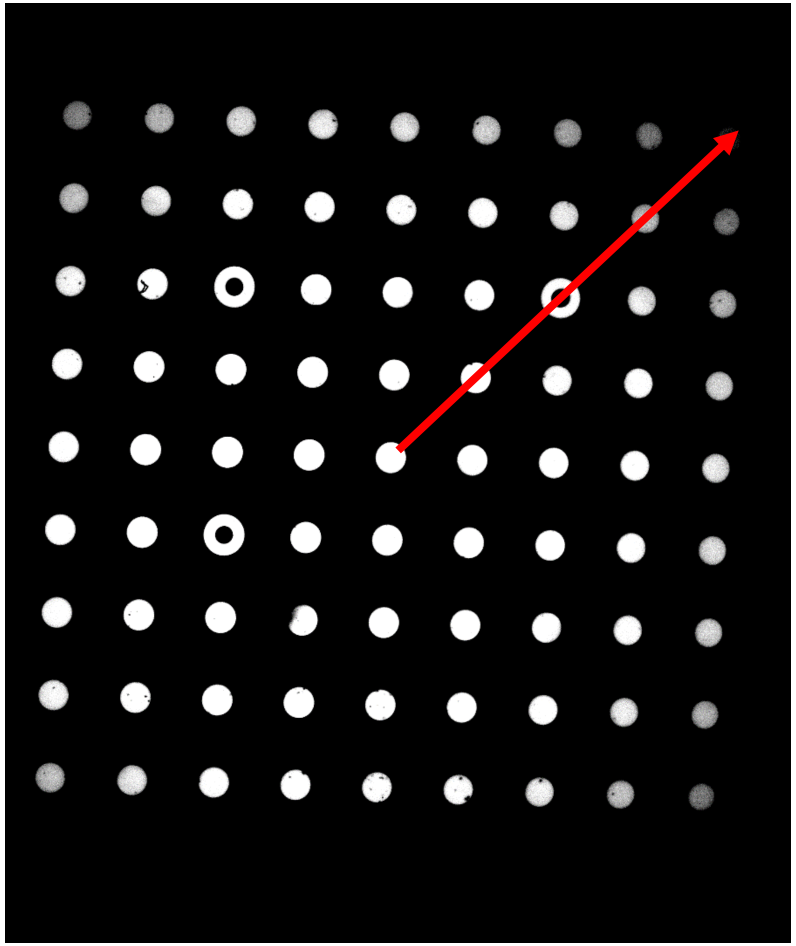
What’s wrong with my calibration?





Dirt or other obstructions

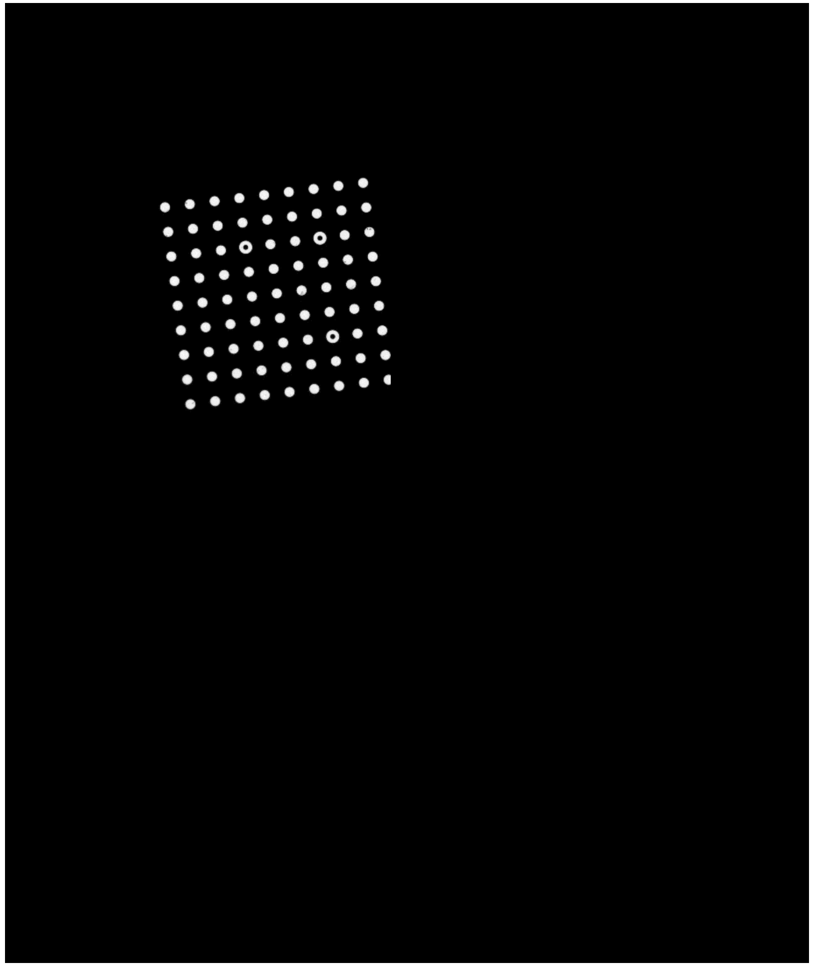
What’s wrong with my calibration?



Decreasing Intensity towards the edges of your calibration target

Vignetting

What’s wrong with my calibration?



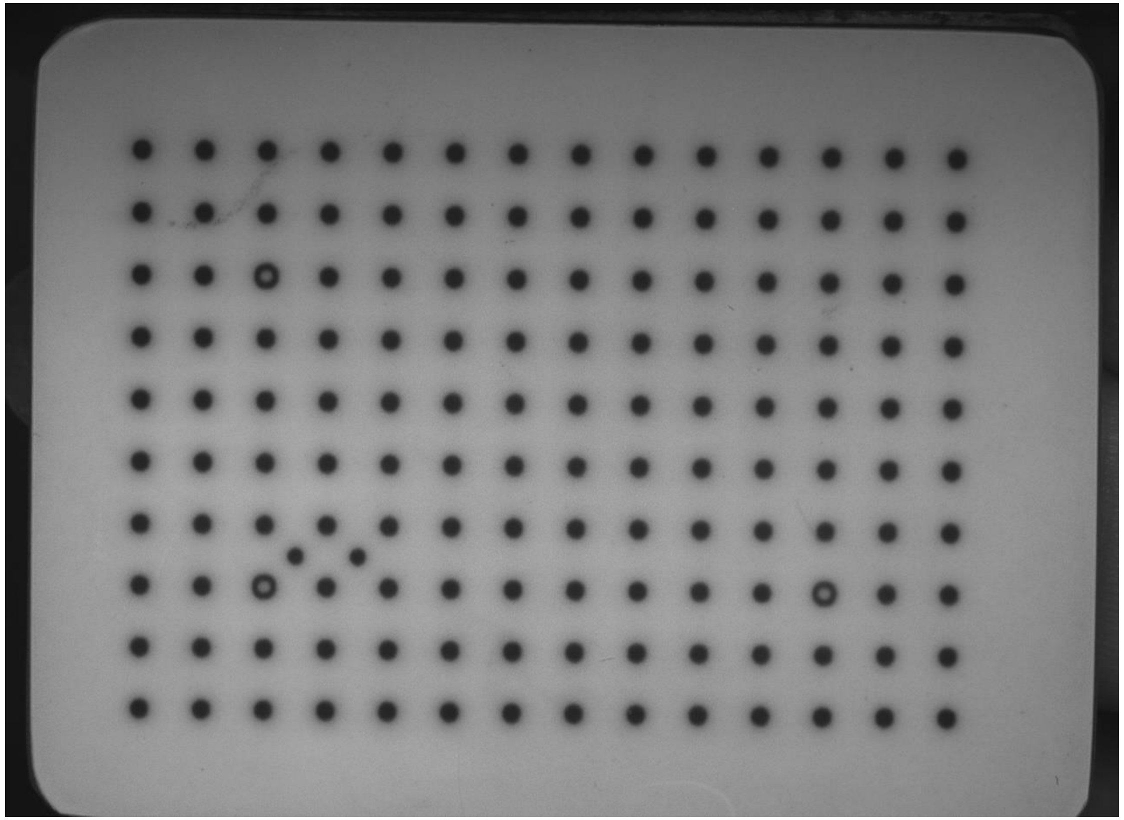
Calibration target should not be smaller than approximately half of the FOV

Smaller targets may produce an acceptable calibration score, but precautions must be taken outside the scope of this course

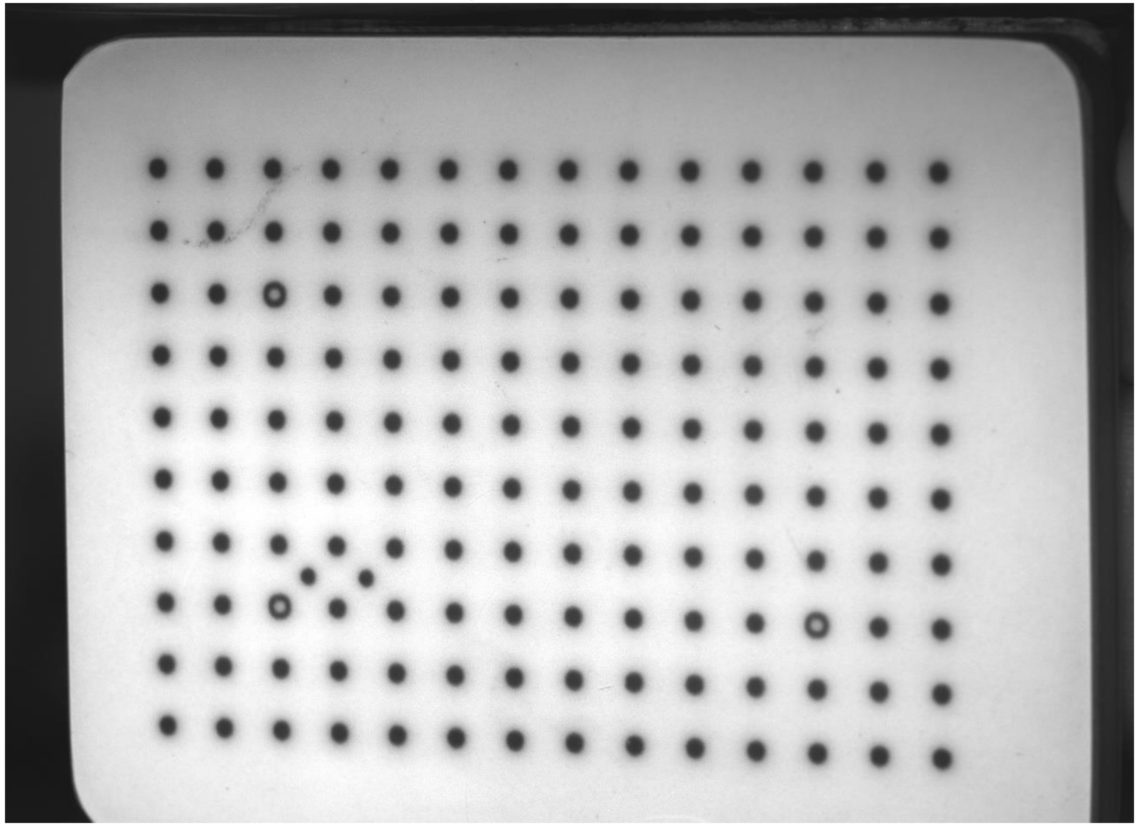
Calibration target is too small for FOV

What’s wrong with my calibration?

Left Camera



Right Camera



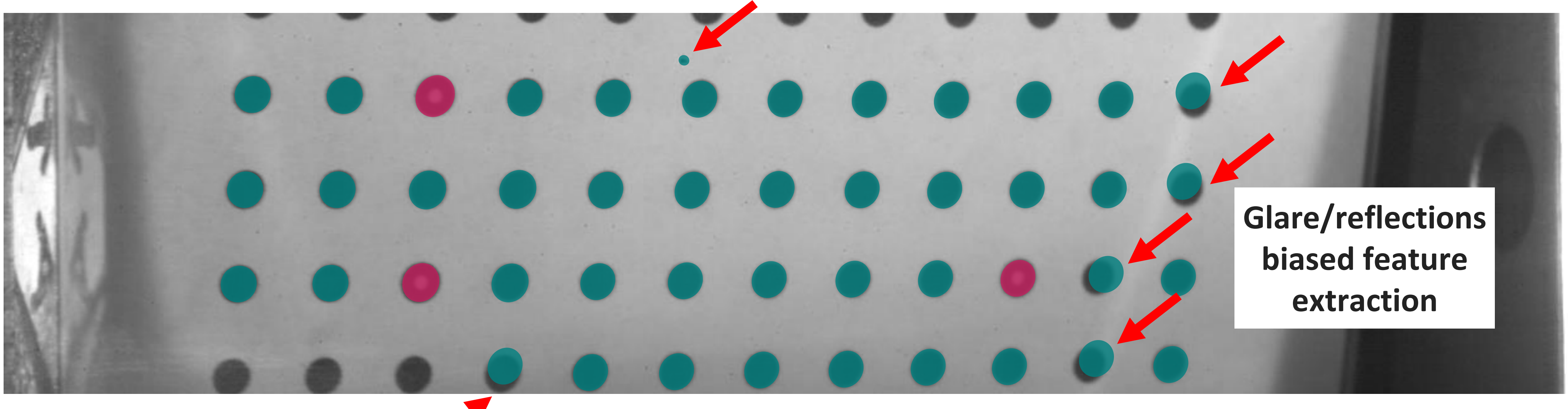
Lighting or apertures are unbalanced

What’s wrong with my calibration?

- Compare calibration score amongst individual images and to final score. Remove images if appropriate.

	I1	I2	I3	I4	I5	I6	I7	I8	I9	**Final**
Cam0	0.0256	0.0274	0.0298	0.0224	0.0238	0.0289	0.0225	0.0271	0.0215	**0.0718**
Cam1	0.0267	0.0231	0.0287	0.0249	0.8567	0.0276	0.0253	0.0242	0.0268	

Dirt extracted as a feature

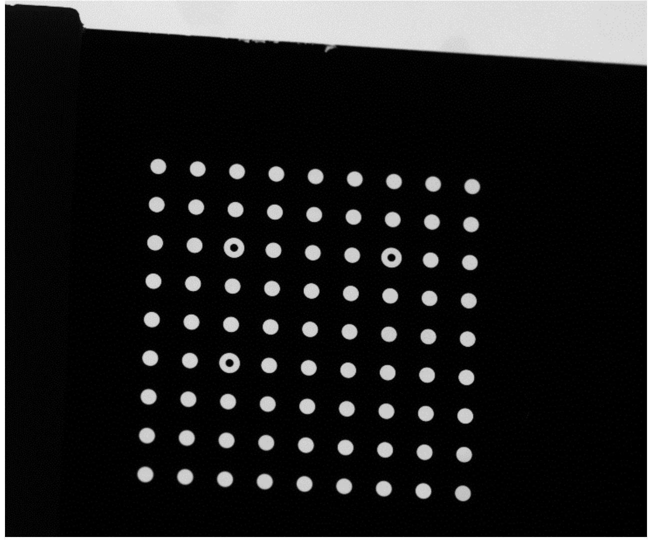


Glare/reflections biased feature extraction

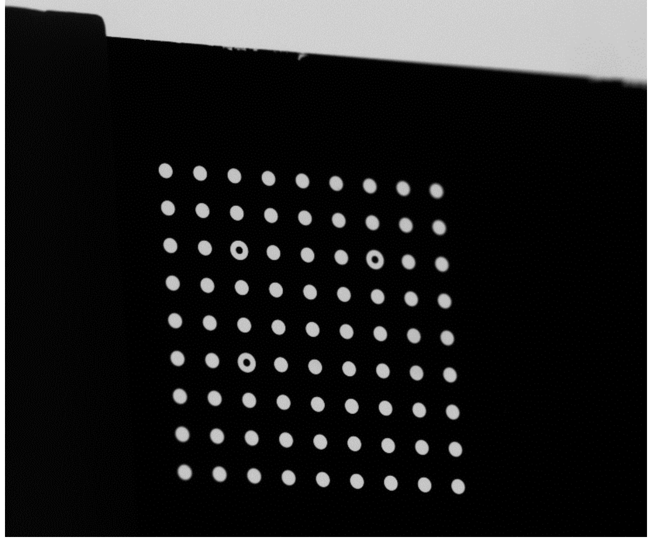
Feature too close to edge of FOV

What’s wrong with my calibration?

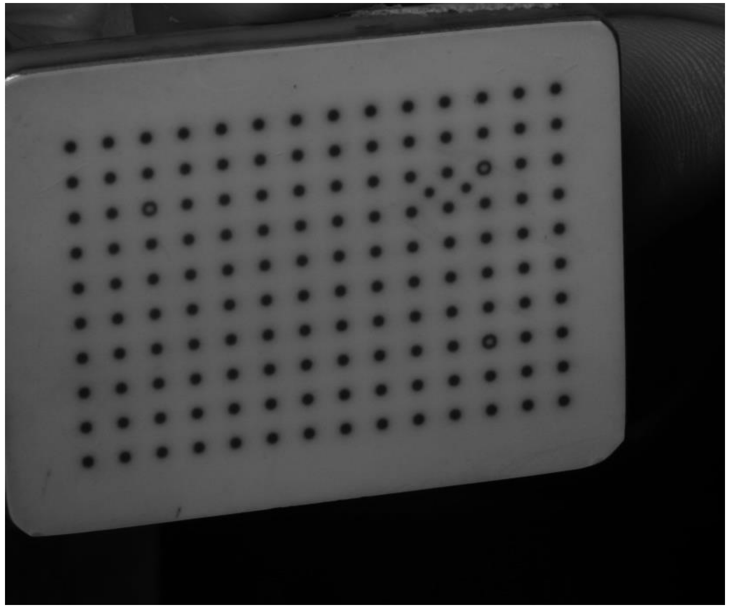
Left Camera



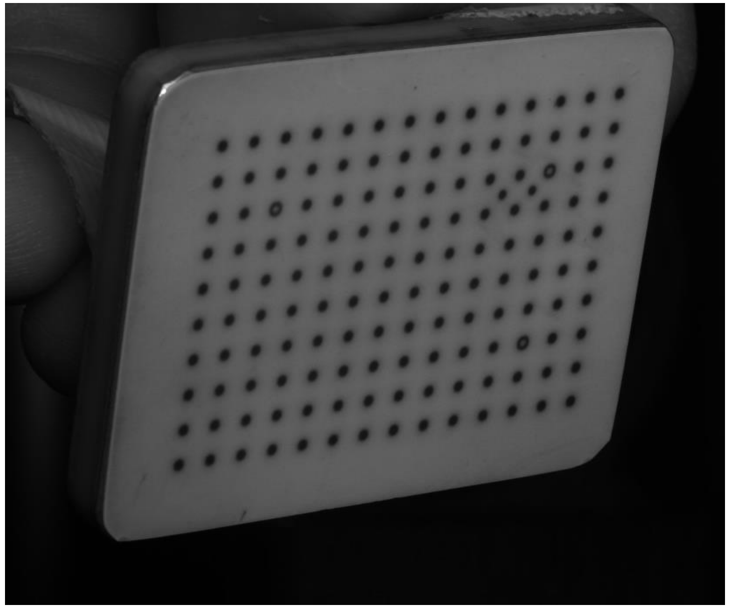
Right Camera



Left Camera

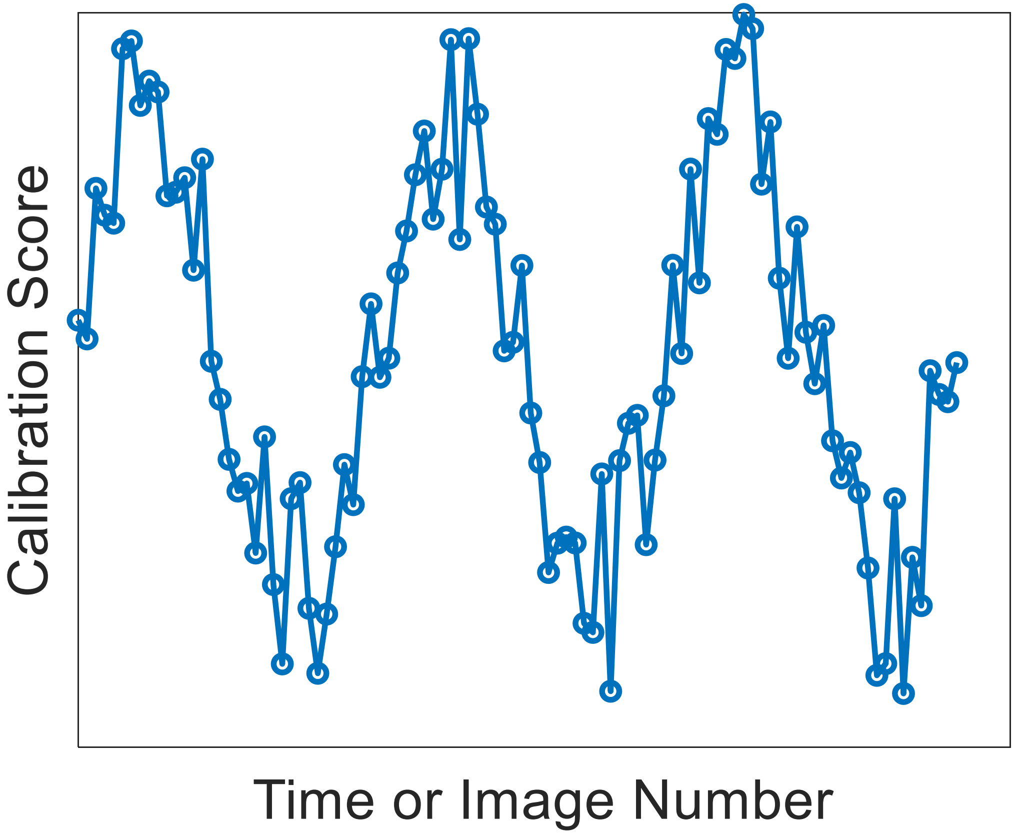


Right Camera



Angle is too extreme for one or both cameras

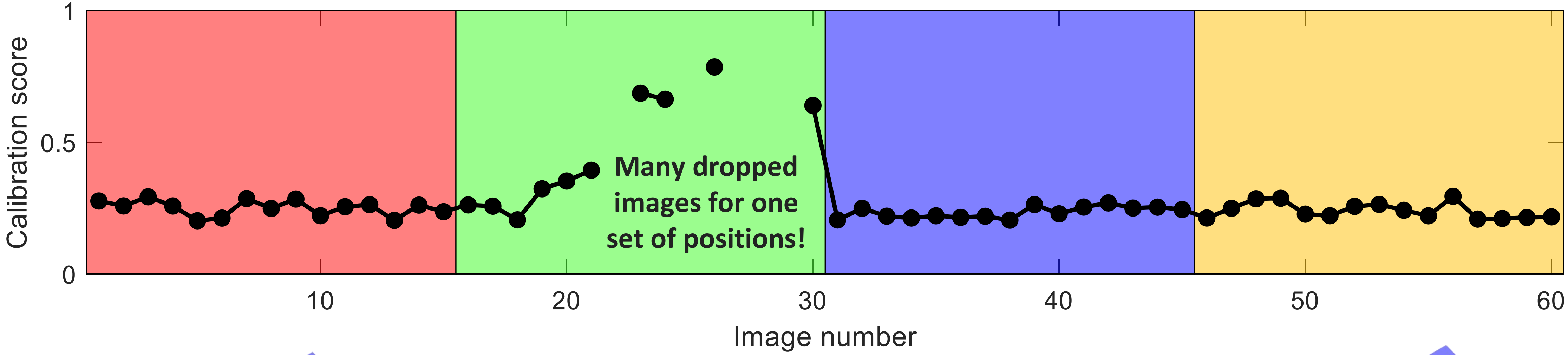
What’s wrong with my calibration?



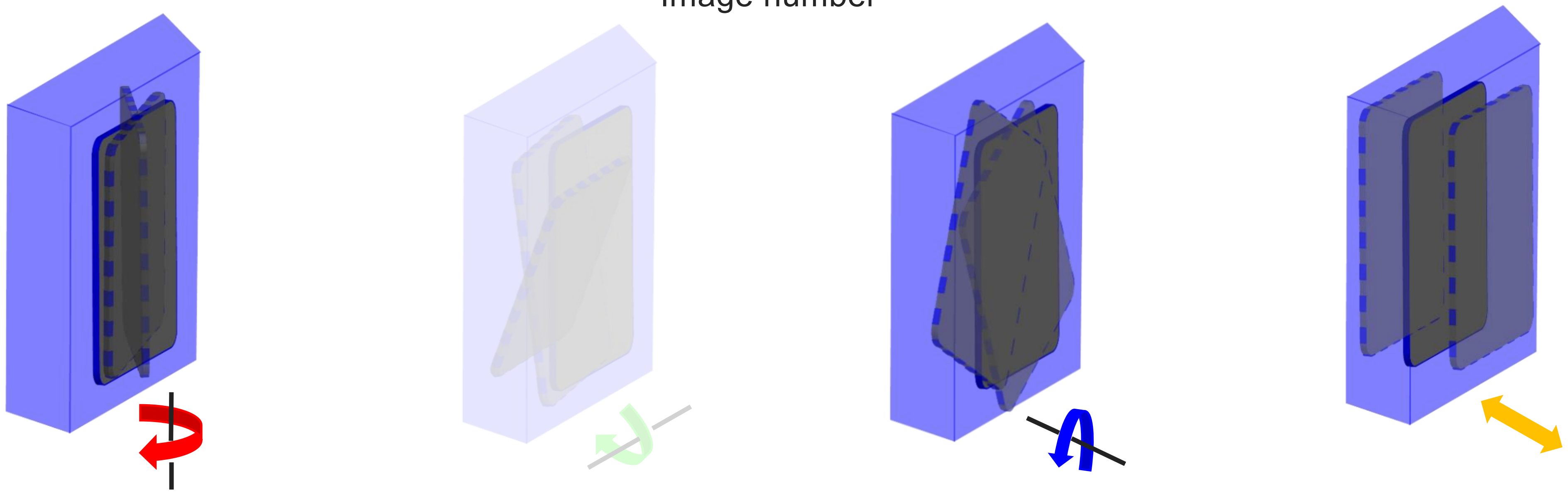
Vibrations potentially due to unstable camera mounting system or fluctuating calibration target

What’s wrong with my calibration?

- Verify working volume was filled (i.e. dropped images were not all taken in the same region/ rotation)



Many dropped images for one set of positions!



What’s wrong with my calibration?

Thanks for playing!!

Images for Calibration Verification and Noise-Floor Analysis
Sec. 3.3.1

1. Reset system to point cameras at test piece

2. Adjust lighting

3. Acquire static images

Recommendation 3.13: Take images at same frame rate and duration as the test

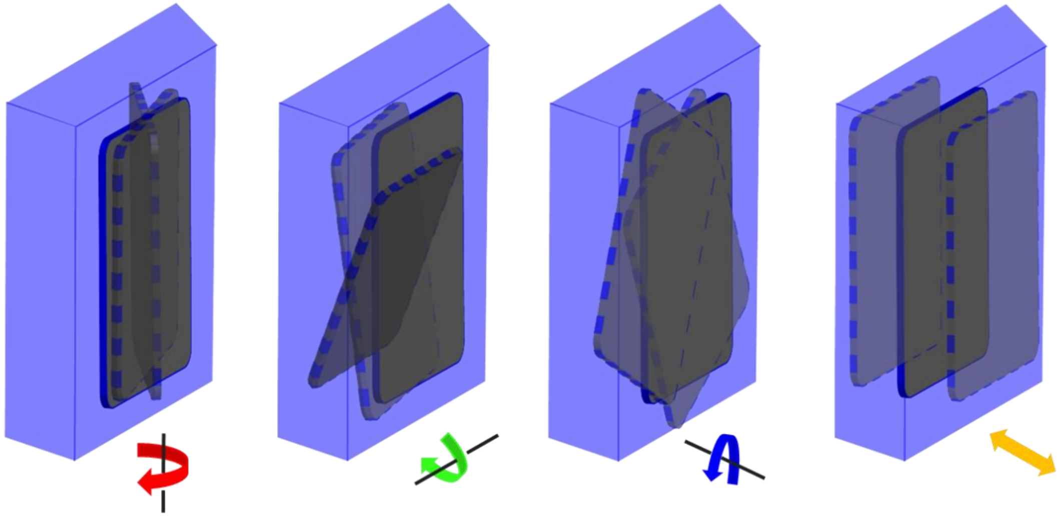
4. Review images
   - Glare
   - DIC pattern that is too coarse/fine
   - Defects in applied pattern
   - Out-of-focus regions
   - Poor contrast
   - Non-uniform lighting
   - Dirt or foreign object on lens
   - Vibrations

Caution 3.14: If you adjust anything, the calibration will have to be repeated!

5. Acquire rigid body motion images

Recommendation 3.14: At minimum, translate the test piece within the volume it is expected to move

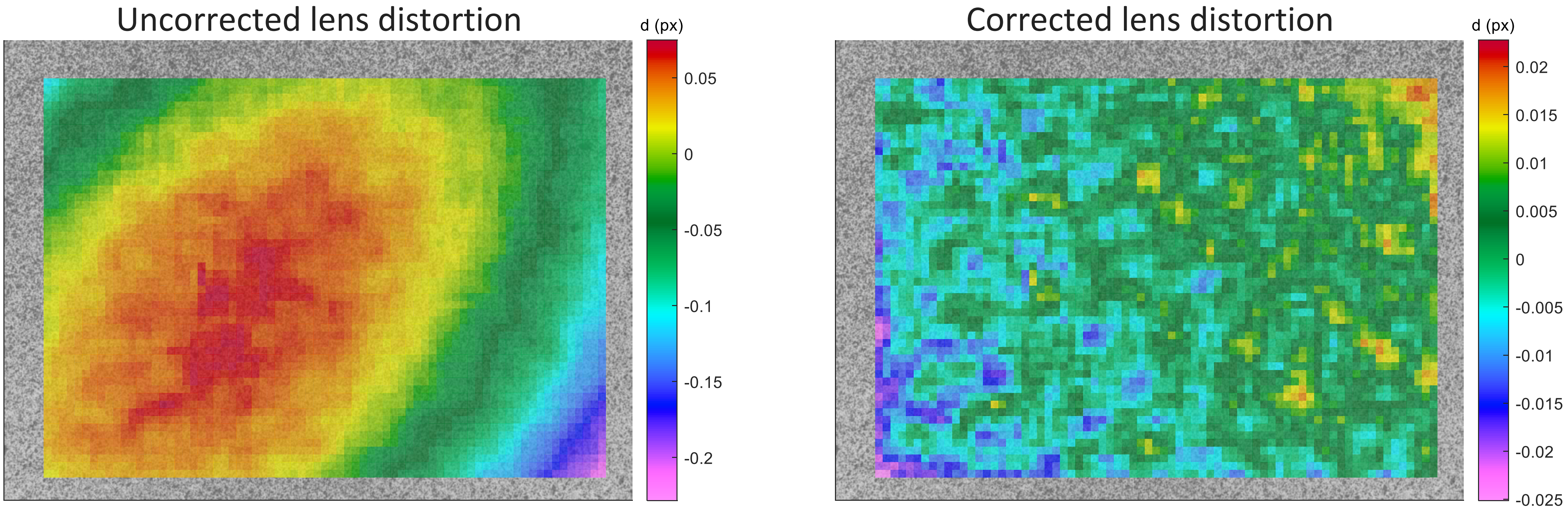
Recommendation 3.15: For 2D-DIC, capture two image sets:
- In-plane translations (used to check for lens distortions and quantify noise floor)
- Out-of-plane translations and rotations (strain error)



Verification of Calibration
Sec. 3.3.2

- Correlate static and rigid body motion images

1. Recommendation 3.16: Evaluate lens distortion

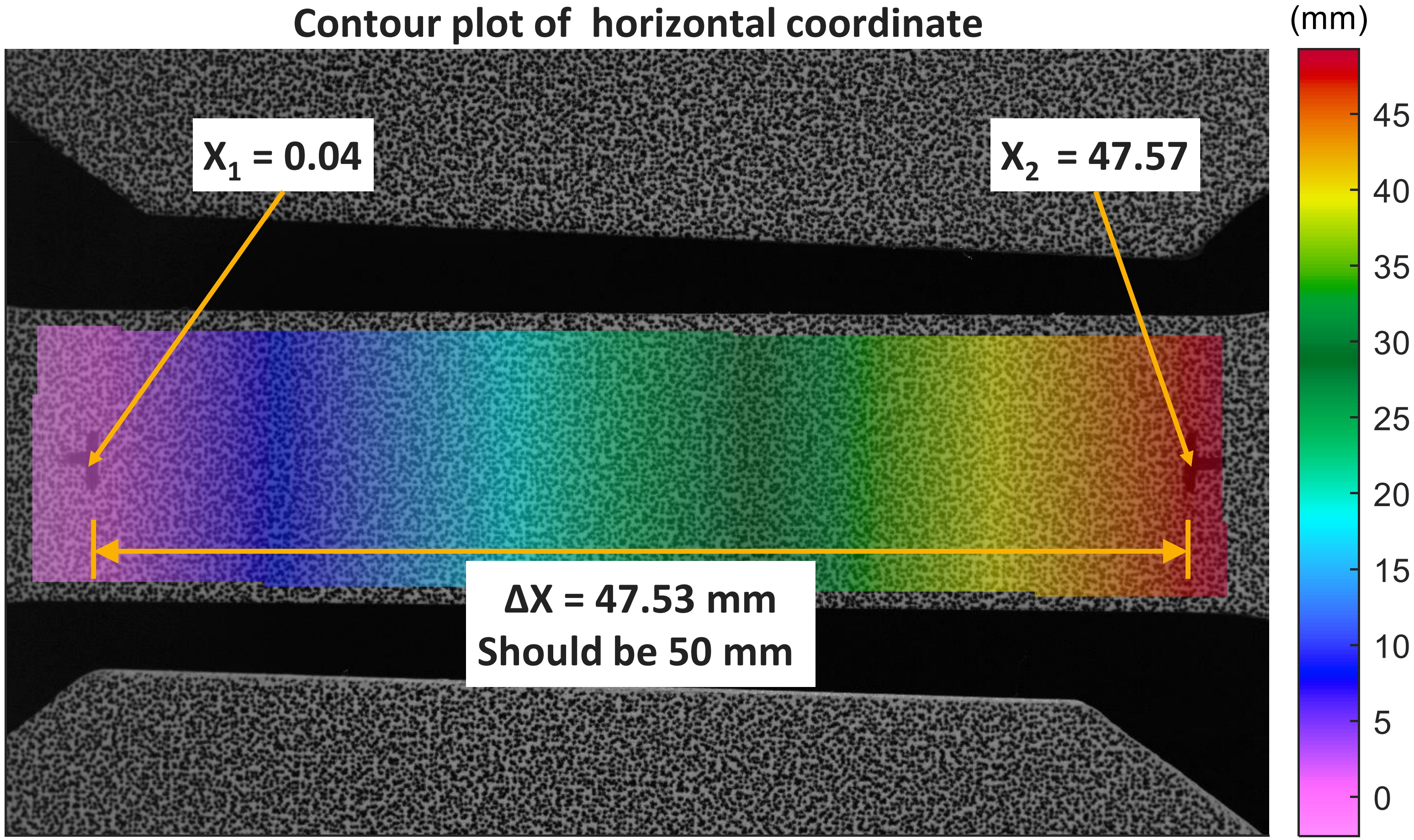


Verification of Calibration
Sec. 3.3.2

- Correlate static and rigid body motion images

1. Recommendation 3.16: Evaluate lens distortion
2. Recommendation 3.17: Evaluate fiducial marks and applied distances

Contour plot of horizontal coordinate



X_1 = 0.04

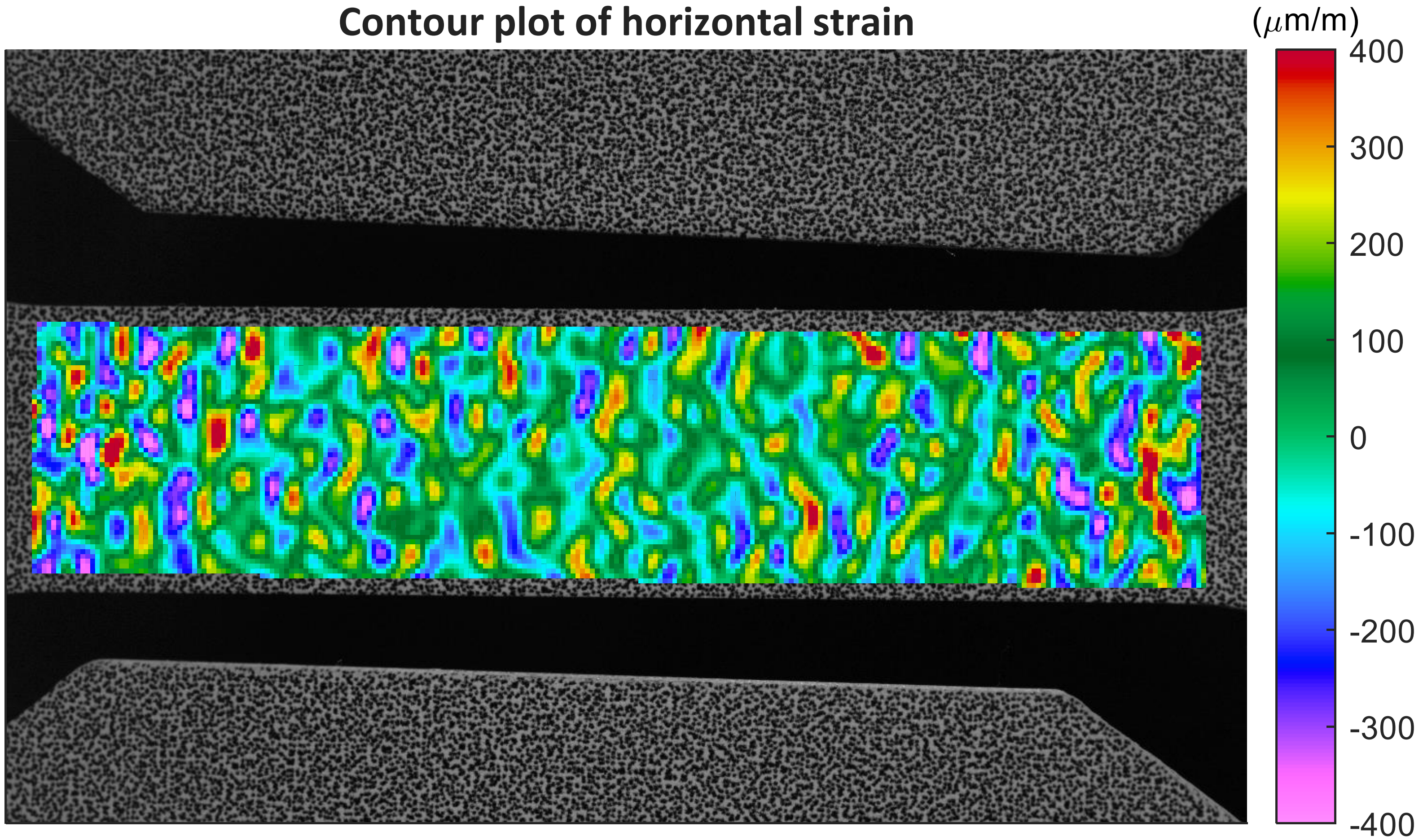
X_2 = 47.57

ΔX = 47.53 mm
Should be 50 mm

Verification of Calibration
Sec. 3.3.2

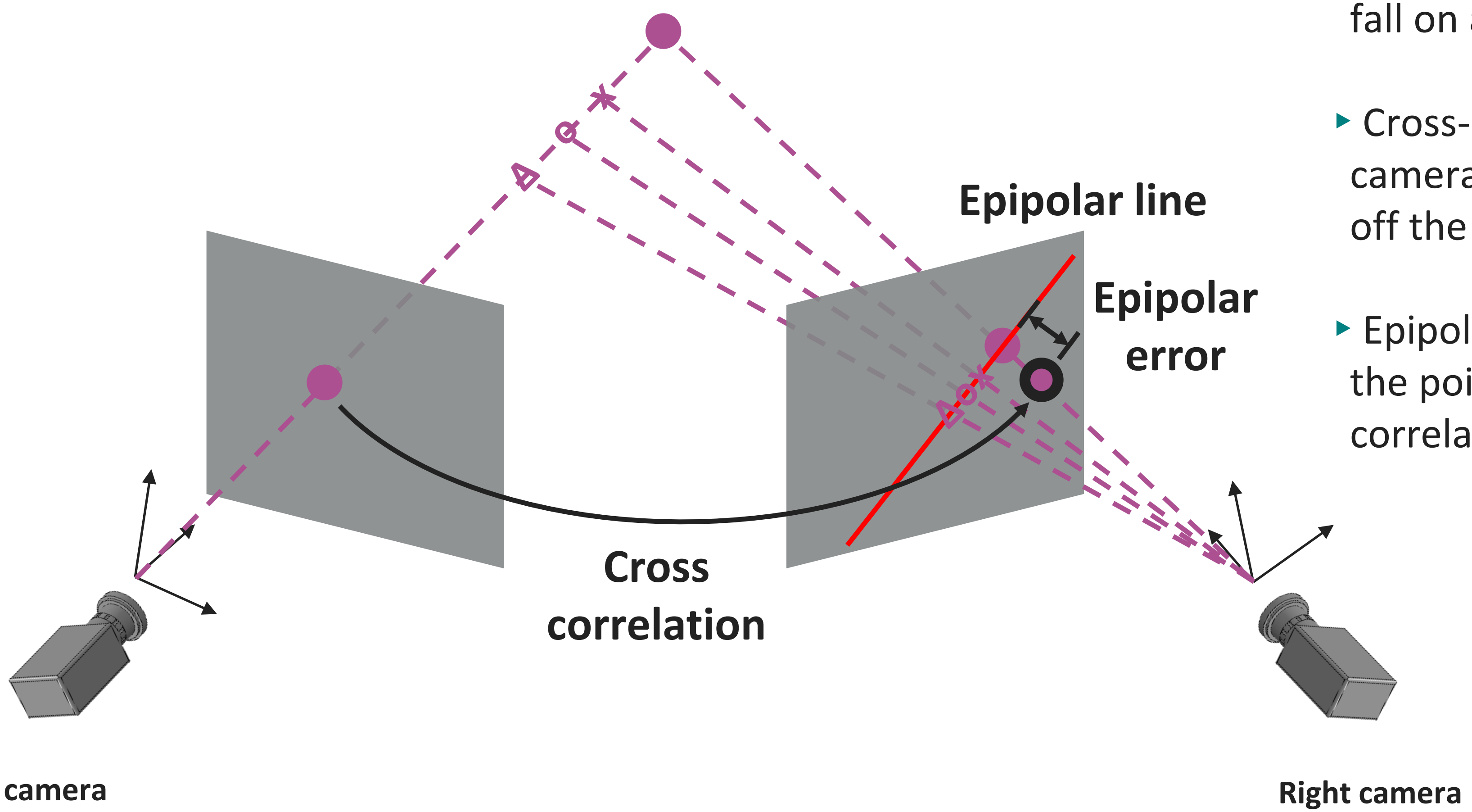
- Correlate static and rigid body motion images

1. Recommendation 3.16: Evaluate lens distortion
2. Recommendation 3.17: Evaluate fiducial marks and applied distances
3. Recommendation 3.18: Perform abbreviated noise floor analysis



Verification of Calibration
Sec. 3.3.2

- Correlate static and rigid body motion images
  1. Recommendation 3.16: Evaluate lens distortion
  2. Recommendation 3.17: Evaluate fiducial marks and applied distances
  3. Recommendation 3.18: Perform abbreviated noise floor analysis
  4. Tip 3.13: Epipolar error is directly related to error in DIC measurements



Epipolar Geometry

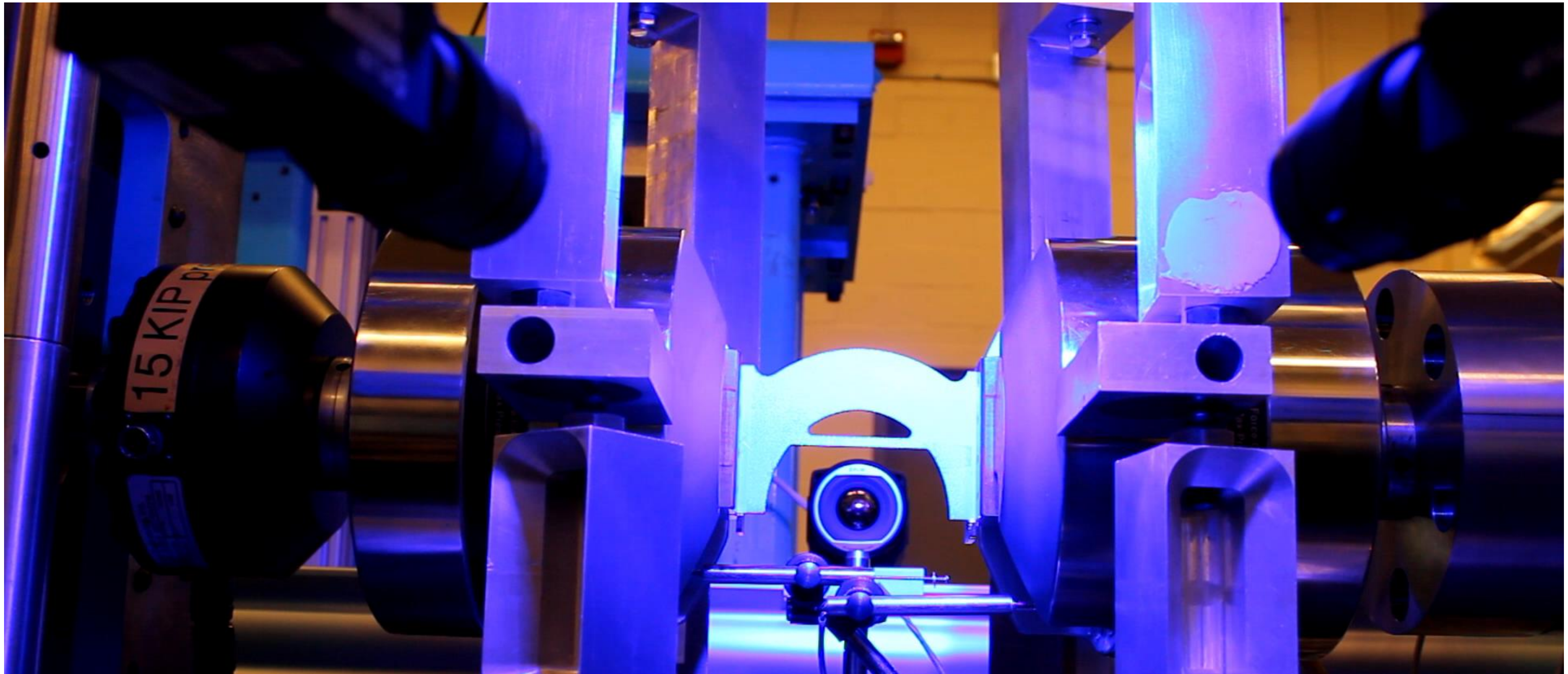
- Stereo-camera calibration defines epipolar geometry
- Every point in one camera should fall on a line in the second camera.
- Cross-correlation from left-to-right camera may identify a point that is off the epipolar line
- Epipolar error is the distance from the point identified by cross-correlation to the epipolar line

- Tip 3.13: Epipolar error should be on the order of your calibration score.

CHAPTER 4:
EXECUTION OF THE TEST

Review all data acquisition systems

- Correct file name, location, storage capacity for DIC images
- Correct test procedure or macro
- Force signals and other measurement signals are set to record and are synchronized with DIC images
- Triggering of the test frame and/or DIC images is ready
  - Caution 4.1: Ensure at least one image is acquired of the test piece prior to any applied force or displacement.
- Lights are turned on, exposure is correct, and frame rate is correct



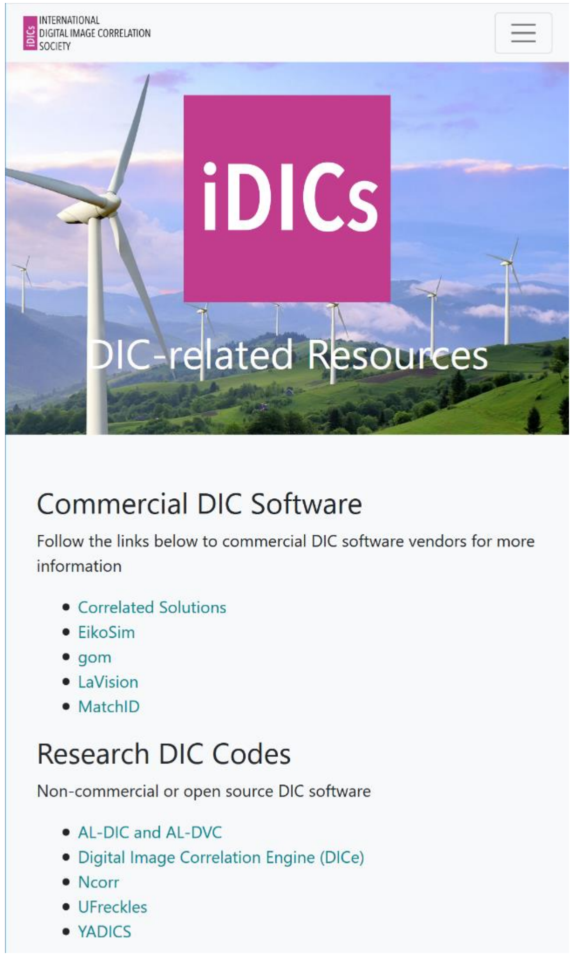
CHAPTER 5: PROCESSING OF DIC IMAGES

SEC. 5.1: DIC SOFTWARE

SEC. 5.2: USER-DEFINED PARAMETERS

DIC Software
Sec. 5.1

- Both commercially and open source codes are available
- https://idics.org/resources/
- Speak with vendors at the conference



Commercial DIC Software

Follow the links below to commercial DIC software vendors for more information

- Correlated Solutions
- EikoSim
- gom
- LaVision
- MatchID

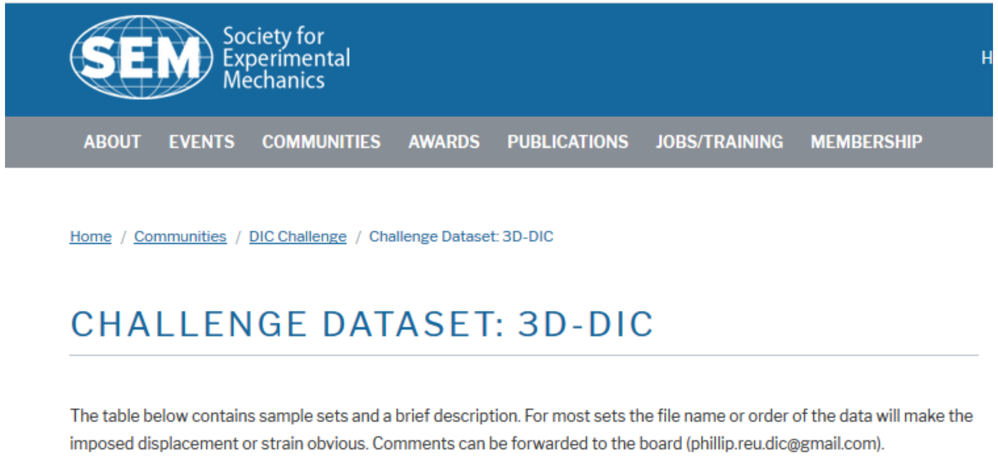
Research DIC Codes

Non-commercial or open source DIC software

- AL-DIC and AL-DVC
- Digital Image Correlation Engine (DICe)
- Ncorr
- UFreckles
- YADICS

- The DIC Challenge provides vetted images
- https://sem.org/dic-challenge/
- PL Reu, et al., *Exp. Mech.* (2018) 58:1067-1099

- Standardized images facilitate:
  - Exploring the “black box” of proprietary/commercial DIC software
  - Verifying custom software implementations

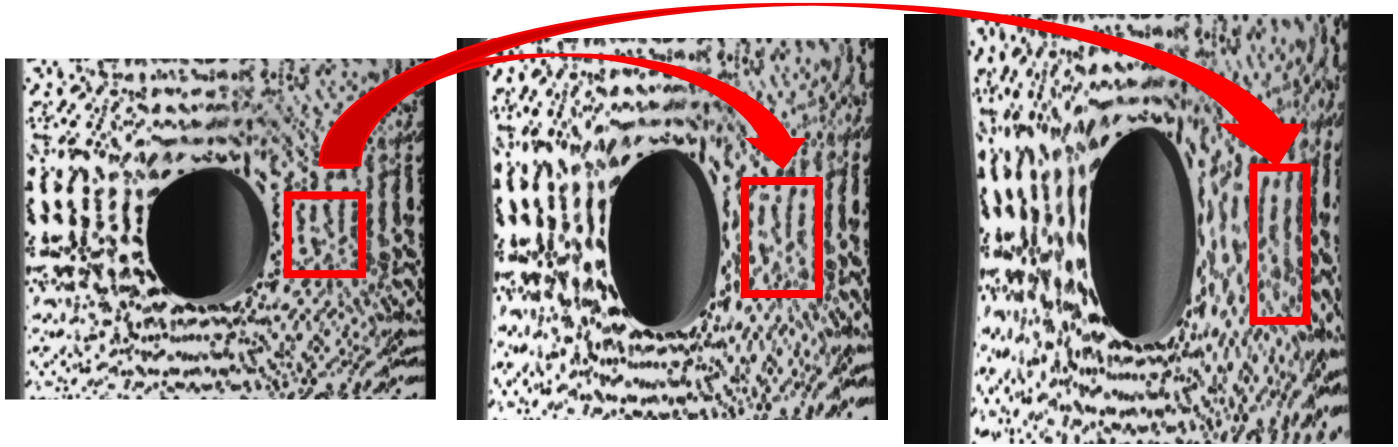


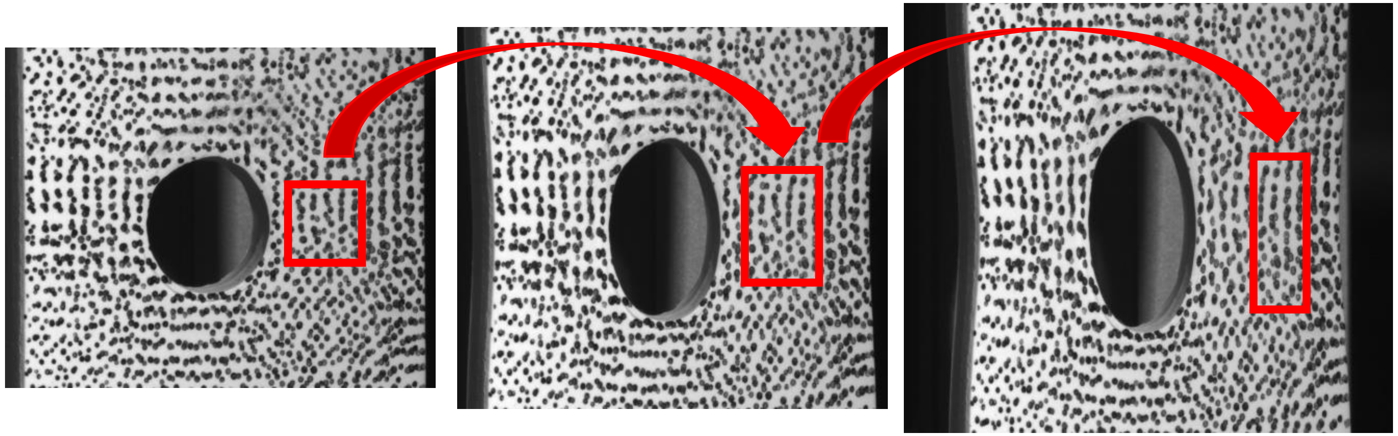
CHALLENGE DATASET: 3D-DIC

The table below contains sample sets and a brief description. For most sets the file name or order of the data will make the imposed displacement or strain obvious. Comments can be forwarded to the board (phillip.reu.dic@gmail.com).

Reference Image
Sec. 5.2.1

- DIC tracks motion, in the Lagrangian sense, of a set of interrogation points, defined on a reference image:
  - **Standard Correlation: A single reference image**
    - Caution 5.1: Collect reference image prior to any displacement or force
    - Tip 5.1: You can collect several (e.g. 10) images of stationary test piece and average, creating an approximately noise-free reference
  - **Incremental Correlation**
    - Each image is correlated to prior image with the drawback of higher error
  - **Partitioned correlation**
    - A test series is broken into sub-series and each batch is correlated back to the first image in that sub-series

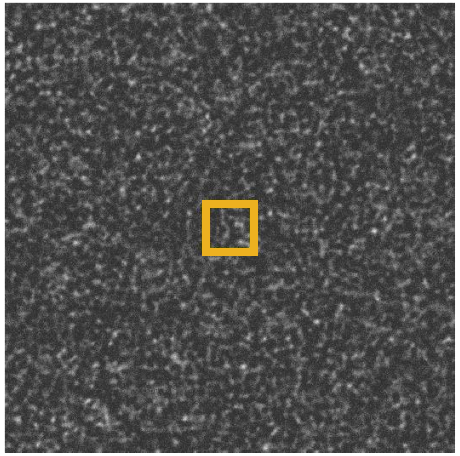




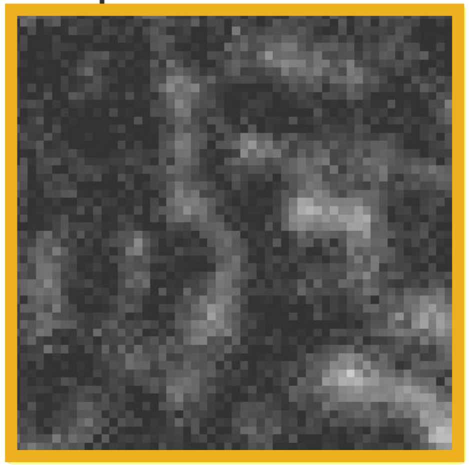
Correlation example: Reference image

- ***DIC Challenge Sample 2***
  - Rigid translation
  - Low signal/noise ratio

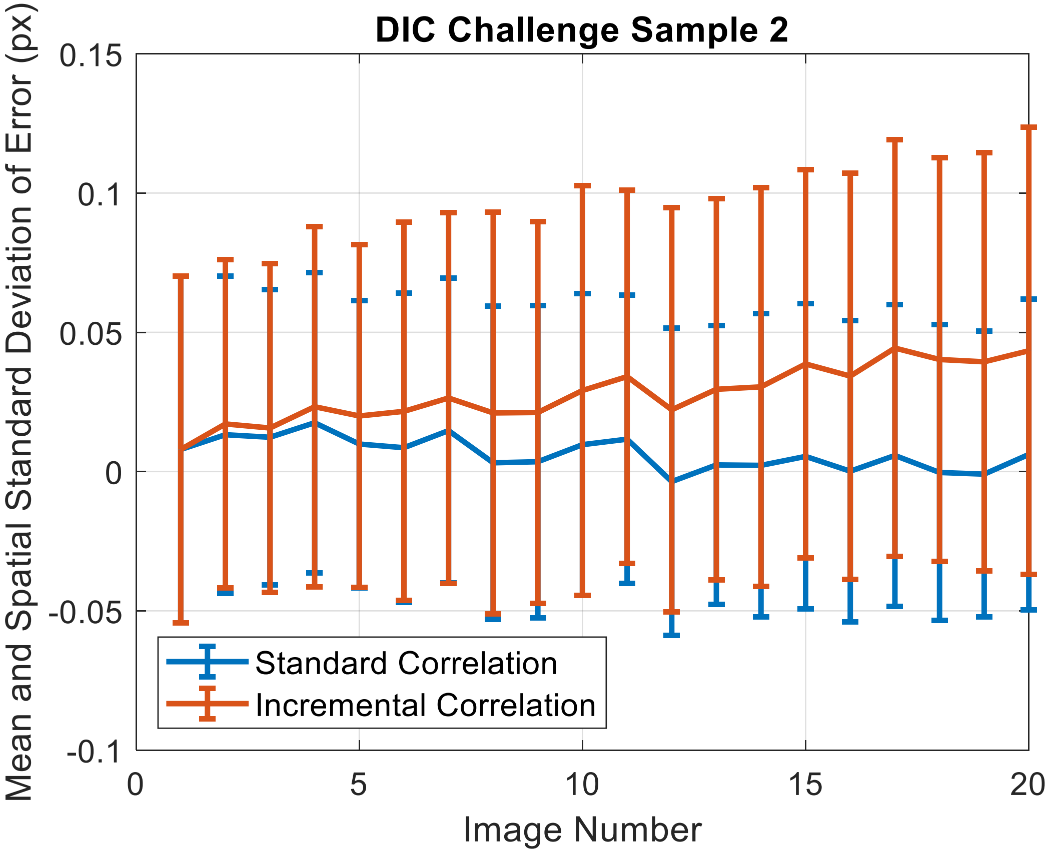
Reference Image



Representative Subset



- *Correlation parameters*
  - Gaussian image prefilter with kernel size 5 px
  - Affine shape function
  - Bicubic spline interpolant
  - ZNSSD matching criterion
  - Subset size 55
  - Step size 20 (529 points total)

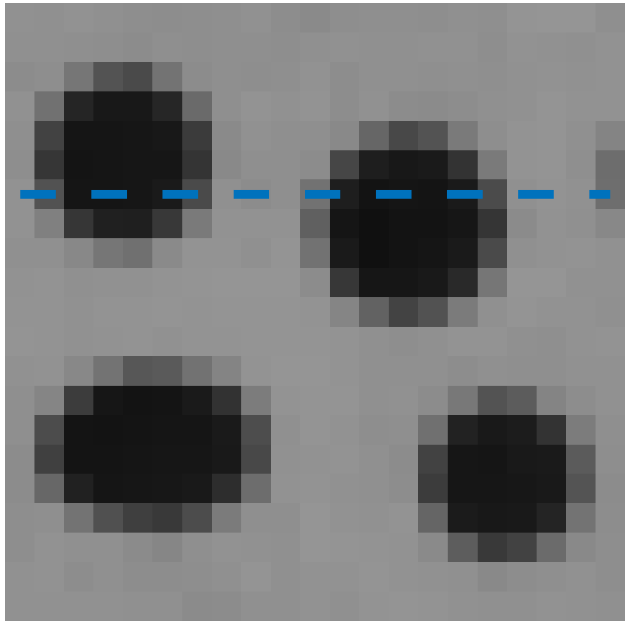


Noise is higher and mean error accumulates over time/image number with incremental correlation.

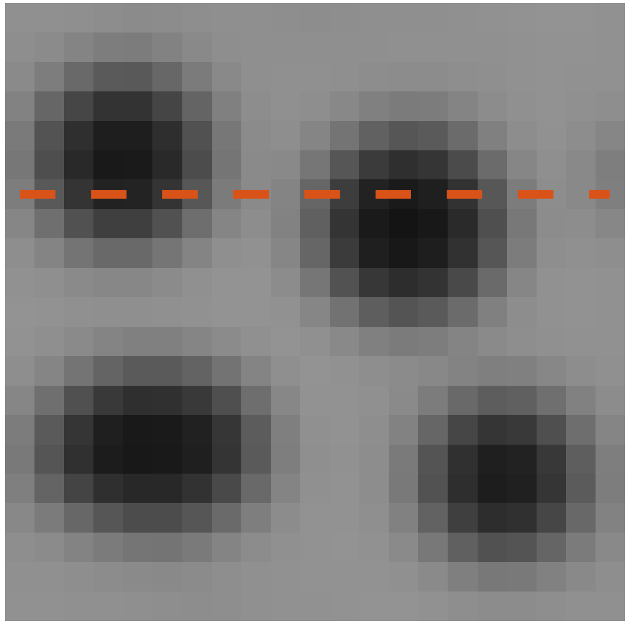
Pre-Filtering of Images
Sec. 5.2.2

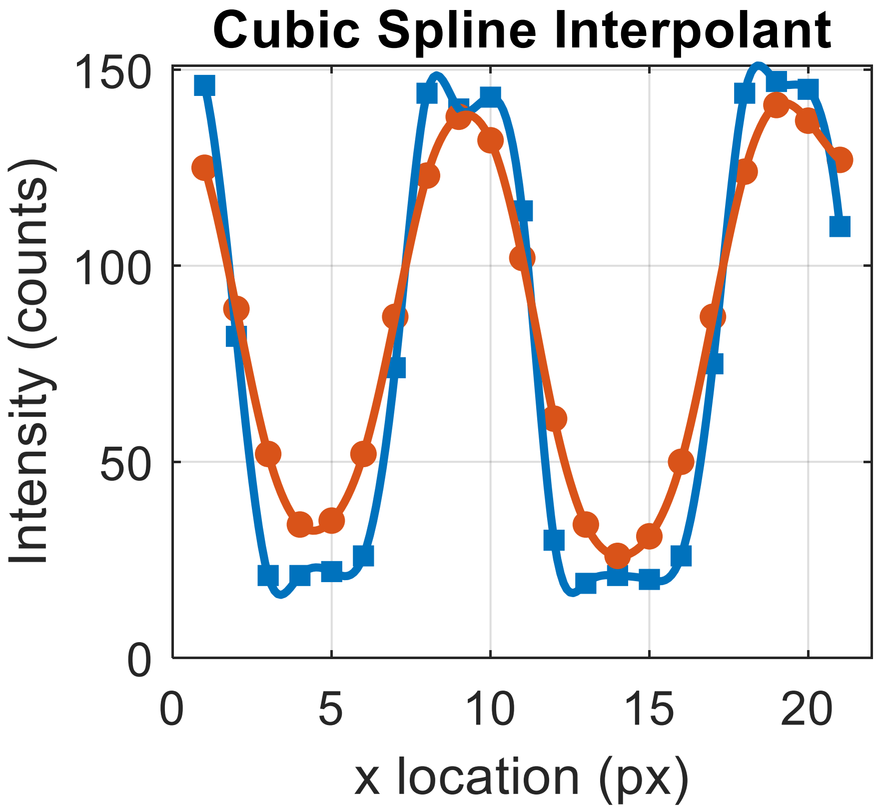
- Subset interpolants often perform better with smooth spatial gradients in image intensity (e.g. Gaussian low pass filter)
- Low pass filter can also reduce image noise and effects of aliased features
- Caution 5.2: Low-pass filters can also bias the results

DIC Challenge Sample 6
Original Image



Gaussian Filter
Kernel 5 px; STD 1 px



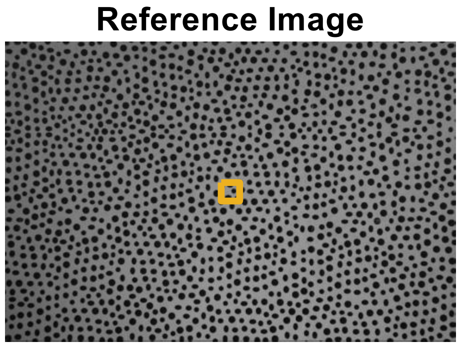


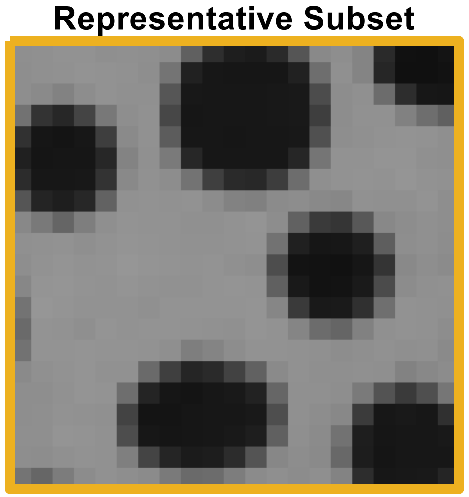
Cubic Spline Interpolant

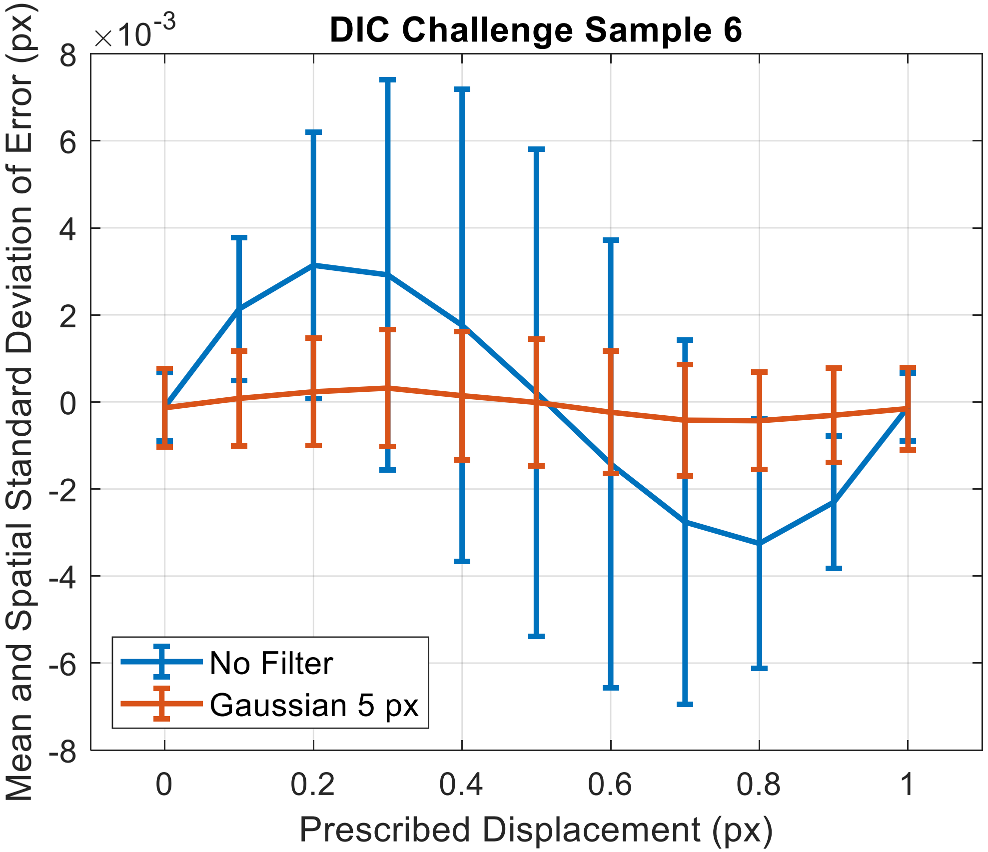
Know if you are pre-filtering your images! This is a reporting requirement.

Correlation example: Pre-filtering

- ***DIC Challenge Sample 6***
  - Rigid translation in sub-pixel increments
  - Sharp-edged speckles



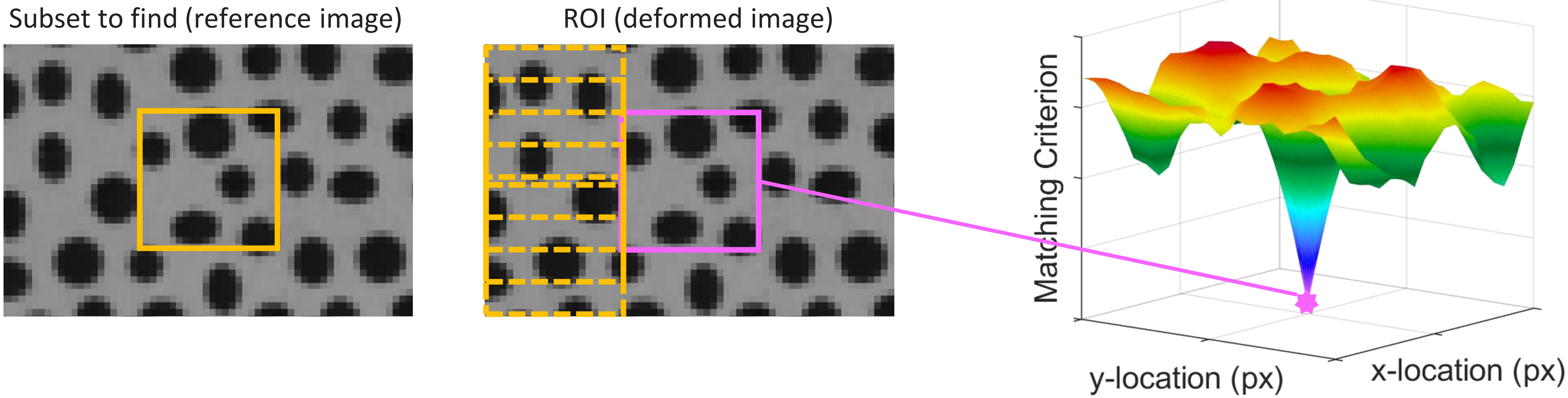




- *Correlation parameters*
  - Affine shape function
  - Bicubic spline interpolant
  - ZNSSD matching criterion
  - Subset size 21
  - Step size 5 (5594 points total)

Image prefiltering reduces both bias and variance errors.

Matching criterion
Not in the guide!



$$\chi^2 = \sum_i (G_i - F_i)^2$$

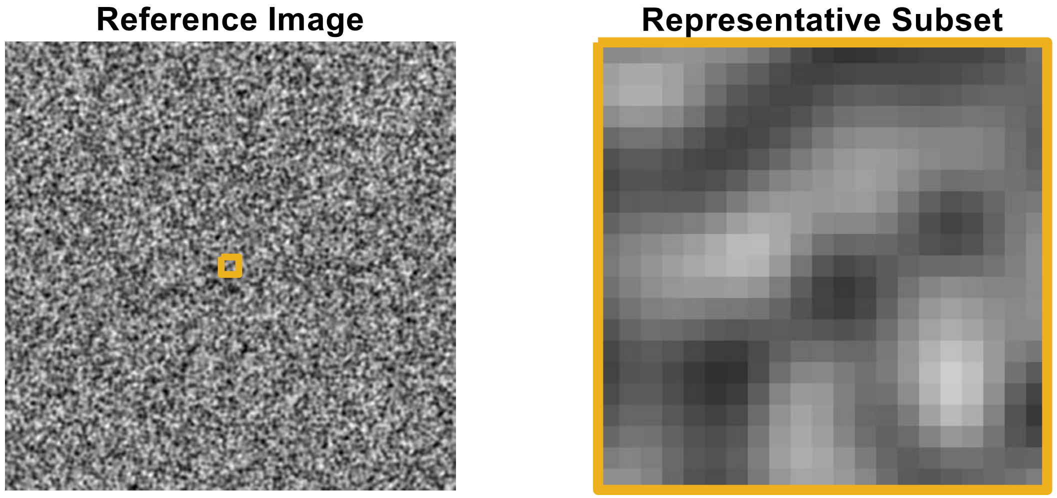
χ – is the value of the matching criterion
F – is the reference image
G – is the deformed image
i – is the pixel in the subset

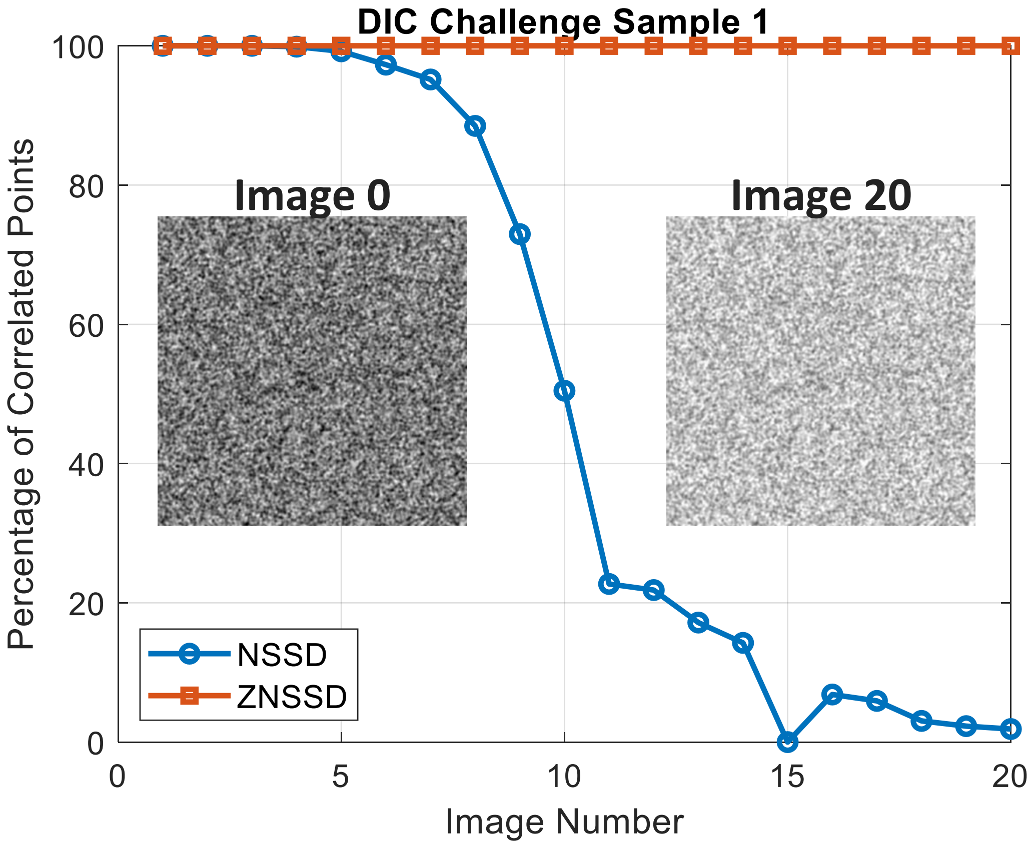
Examples of Matching Criteria

1. Sum Squared Difference (SSD)
2. Normalized Sum Squared Difference (NSSD)
3. Zero Normalized Sum Squared Difference (ZNSSD)

Correlation example: Matching criterion

- ***DIC Challenge Sample 1***
  - Rigid translation
  - Varying intensity and contrast



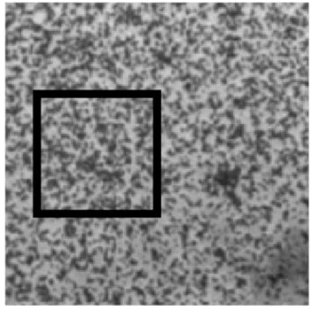


- *Correlation parameters*
  - Gaussian image prefilter with kernel size 5 px
  - Affine shape function
  - Bicubic spline interpolant
  - Single reference image
  - Subset size 21
  - Step size 10 (2402 points total)

Only the ZNSSD matching criterion is able to compensate for the varying intensity and contrast.

Subset Shape Function
Sec. 5.2.3

Reference image, F

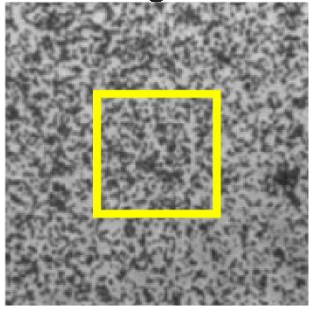


$$\chi^2 = \sum_i \left(G_i(\xi) - F_i\right)^2$$

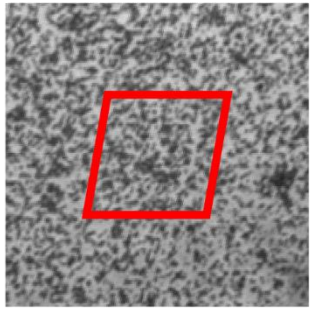
χ – is the value of the matching criterion
F – is the reference image
G – is the deformed image
i – is the pixel in the subset
ξ – is the subset shape function

$$\xi = \underbrace{\underbrace{\underbrace{\underbrace{\begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} u \\ v \end{bmatrix}}_{} + \begin{bmatrix} \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} \\ \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix}}_{} + \begin{bmatrix} \frac{\partial^2 u}{\partial x \partial y} \\ \frac{\partial^2 v}{\partial x \partial y} \end{bmatrix} \Delta x \Delta y}_{} + \begin{bmatrix} \frac{\partial^2 u}{\partial x^2} & \frac{\partial^2 u}{\partial y^2} \\ \frac{\partial^2 v}{\partial x^2} & \frac{\partial^2 v}{\partial y^2} \end{bmatrix} + \begin{bmatrix} (\Delta x)^2 \\ (\Delta y)^2 \end{bmatrix}}_{}$$

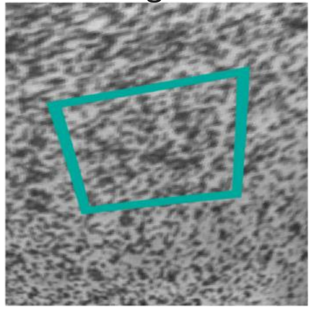
Rigid



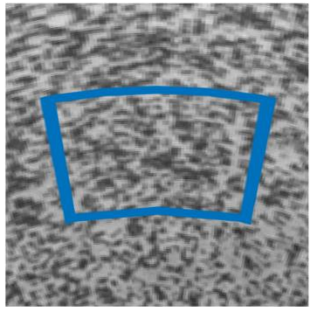
Affine



Irregular

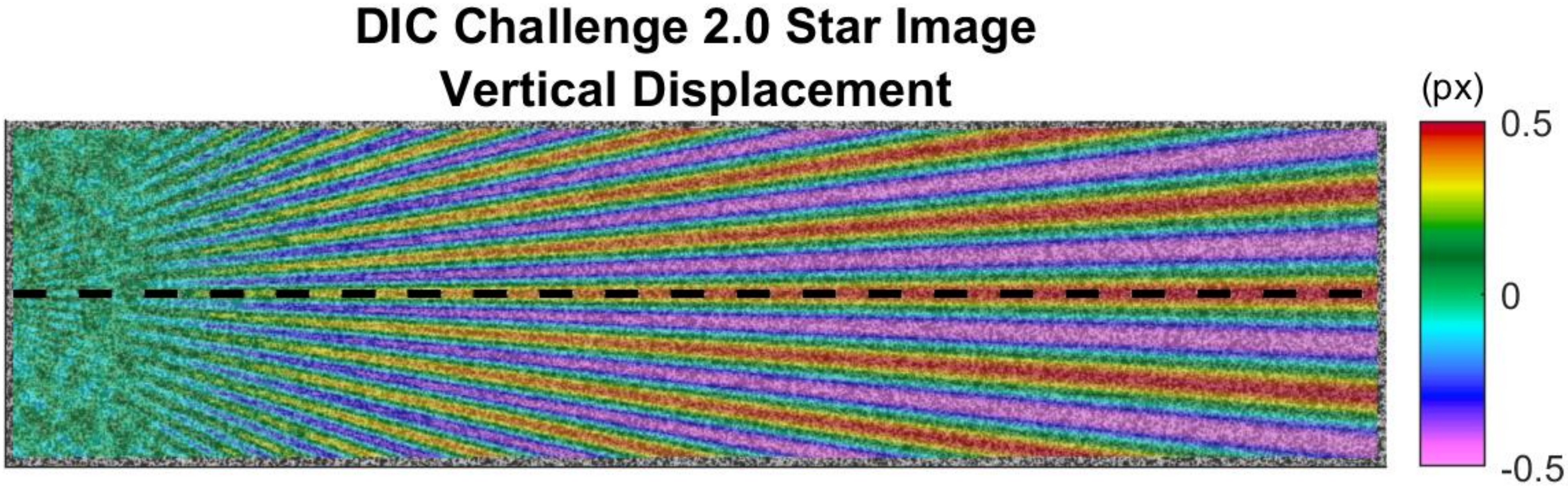


Quadratic



- Lower order shape functions cancel more noise, but have less accuracy
- Higher order shape functions are more accurate, but more noisy
- Some software packages have adaptive shape functions

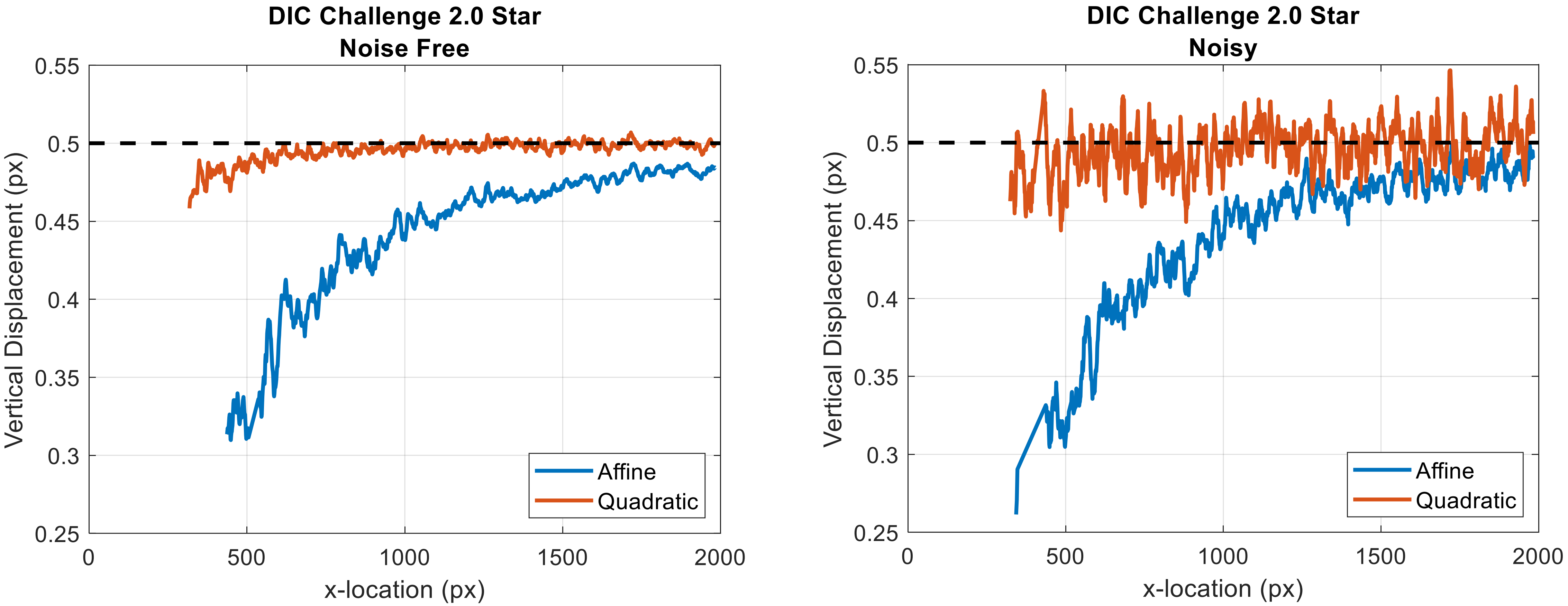
Correlation example: Subset shape function



- Prescribed vertical displacement is sinusoidal
- Large period / low frequency on the right side
- Small period / high frequency on the left side
- Constant amplitude of 0.5 px along the horizontal center line cut
- Amplitude attenuated on left as shape function is inadequate to represent underlying deformation

Correlation Parameters
- No prefiltering
- Bicubic spline interpolant
- Subset size 21
- Step size 1

Correlation example: Subset shape function



Quadratic shape function provides better spatial resolution, but is more susceptible to image noise.

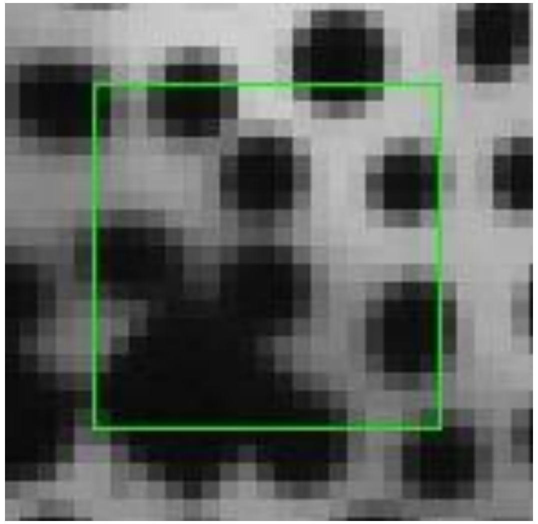
Interpolant
Sec. 5.2.4

Interpolation allows for subpixel precision

Types of interpolants

1. Linear (*bad*)
2. Cubic Polynomial (*bad*)
3. Cubic Spline
4. Fourier Transform
5. Optimized filter (4-Tap, etc.)

Most commercial software packages have optimized interpolants for use!



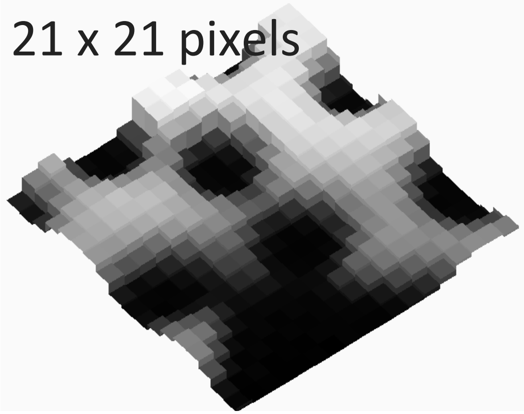
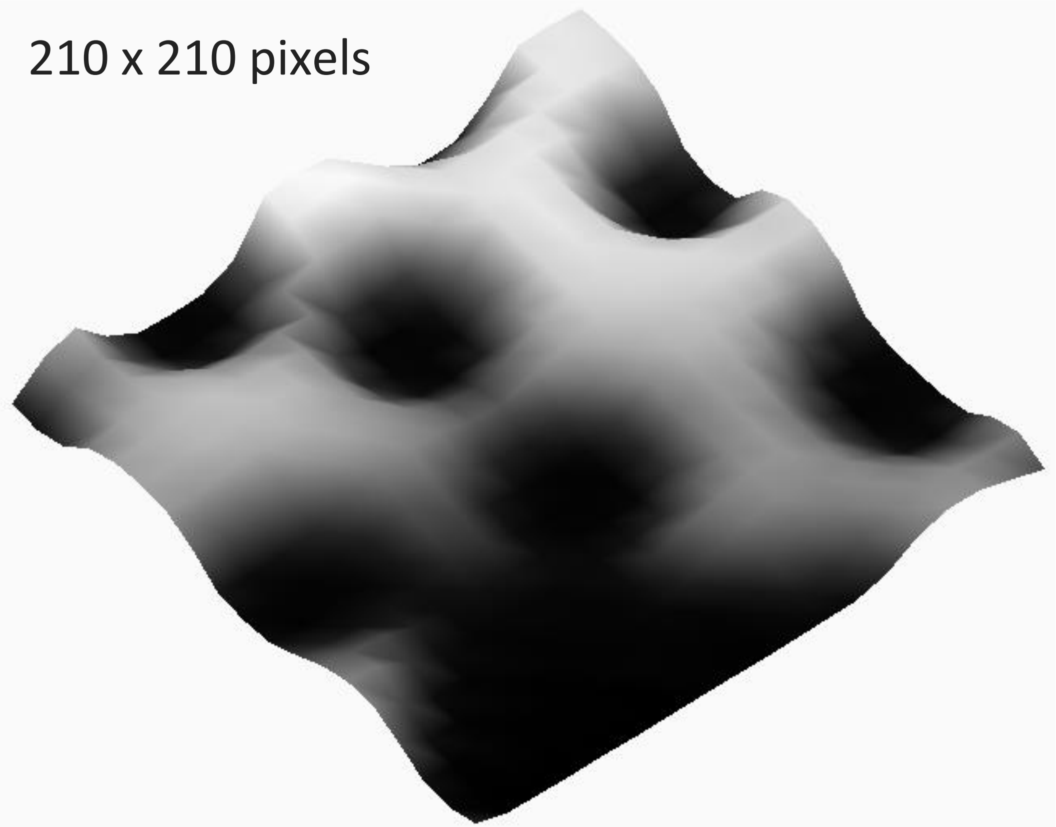

21 x 21 pixels

Image interpolated by a factor of 10x

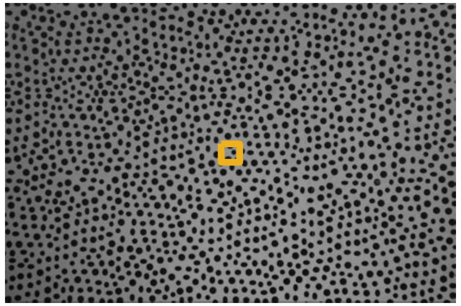

210 x 210 pixels

PL Reu (2012) "The Art and Application of DIC", *Exp Tech*, 36:3-4

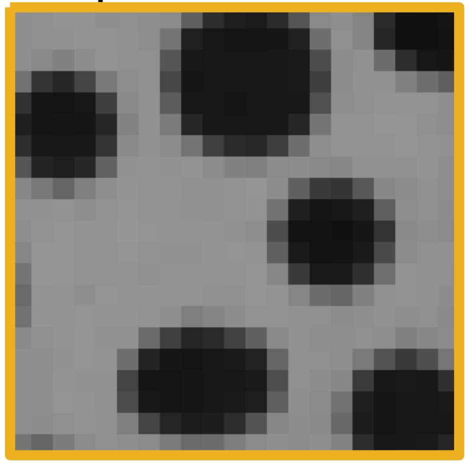
Correlation example: Interpolant

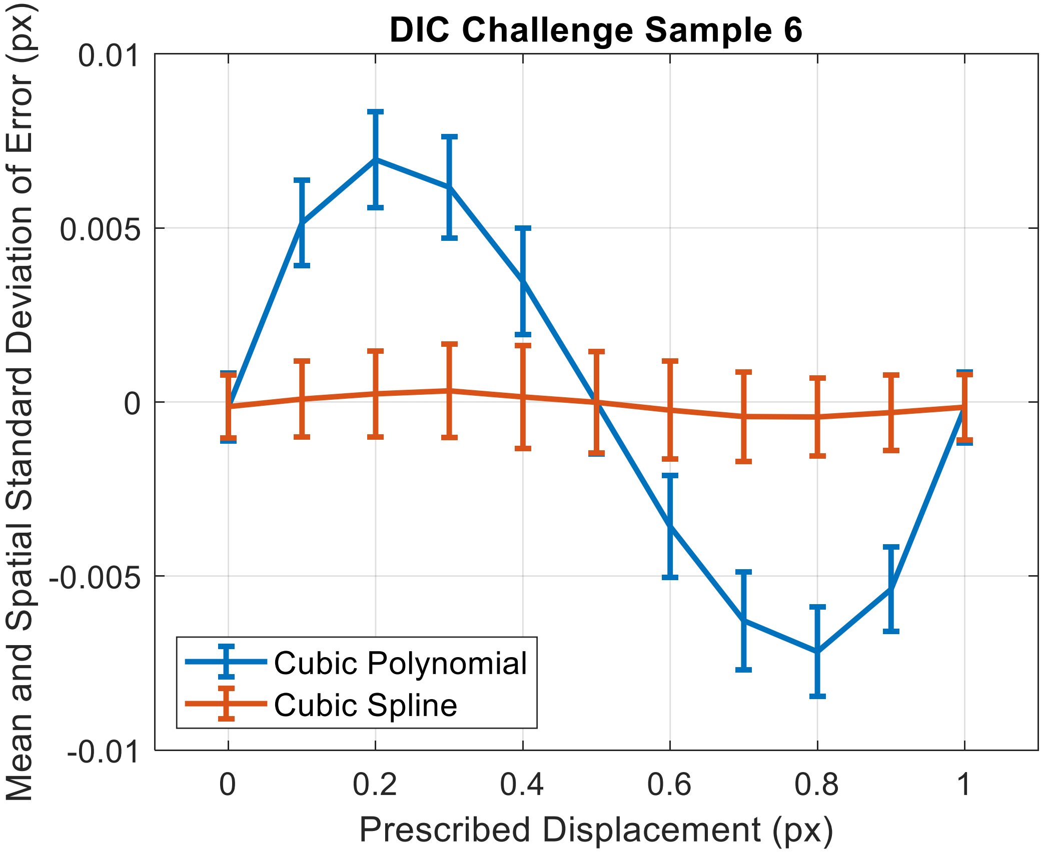
- ***DIC Challenge Sample 6***
  - Subpixel translation in x and y

Reference Image



Representative Subset





- *Correlation parameters*
  - Gaussian image prefilter with kernel size 5 px
  - Affine shape function
  - Single reference image
  - Subset size 21
  - Step size 5 (5590 points total)

The bi-cubic spline has much less bias than the bi-cubic polynomial.

Use these images to evaluate interpolants in your software.

Subset Size and Step Size
Sec. 5.2.5-5.2.6

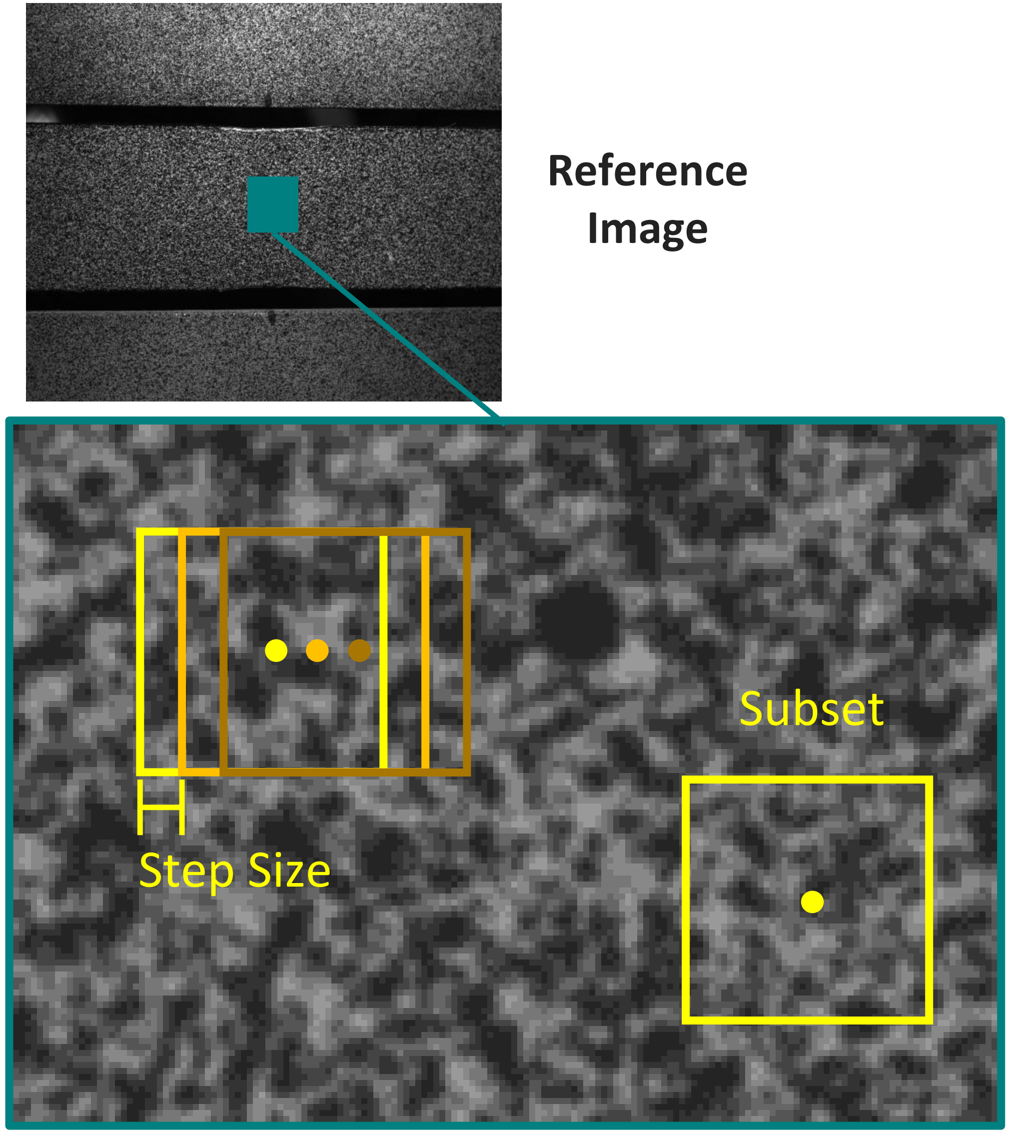
- **Subset**: Portion of image used to calculate one 3D coordinate or displacement value

- **Subset Size**: Length of the subset in the reference image

- **Rules of thumb**:
  1. Subset should contain a minimum of 3 DIC pattern features that are each 3-5 pixels in size
  2. Subset size should be large enough to allow "adequate correlation" for all images in the test series
  3. Subset size should be large enough to minimize correlation error metric

- **Step Size**: Spacing at which subset displacements are calculated

- **Rules of thumb:**
  - 1/3 to 1/2 of the subset size is recommended
  - May need smaller step size to capture peaks

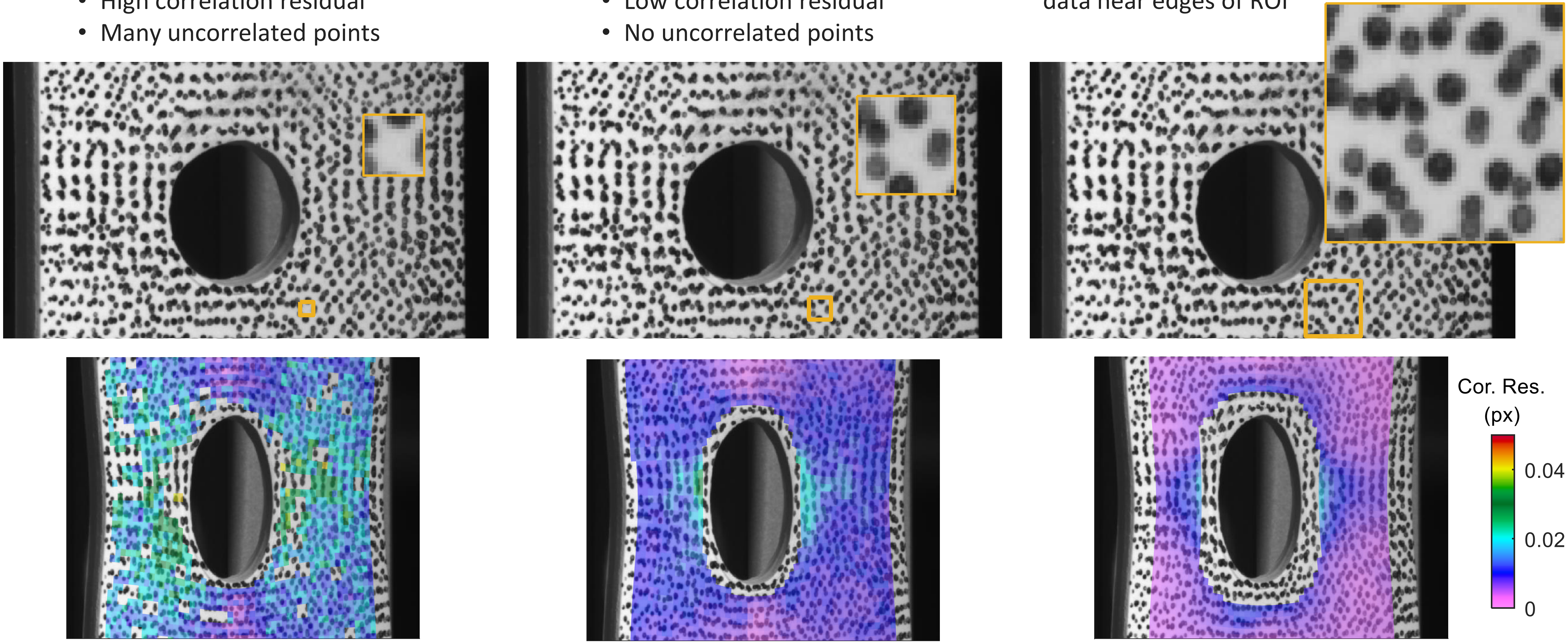


Correlation example: Subset

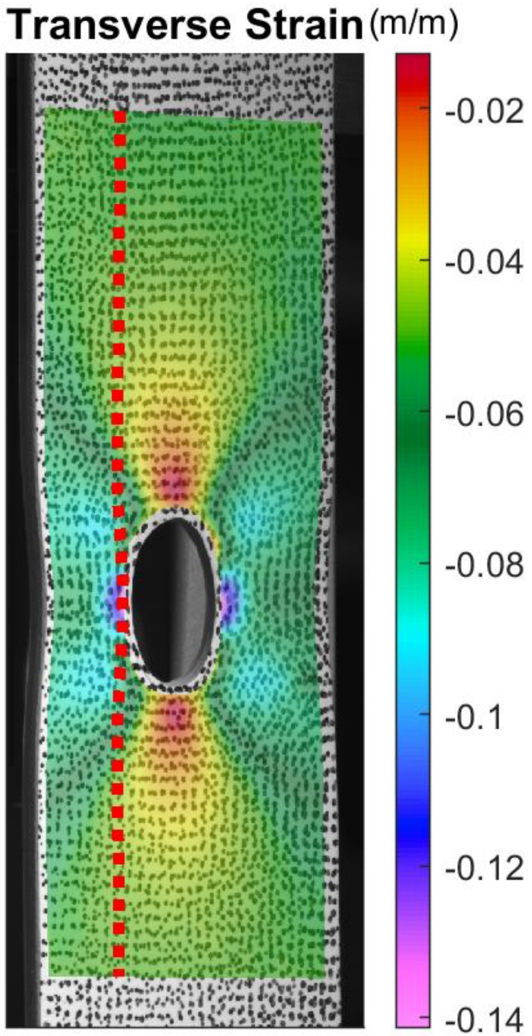
Subset size = 13 px
- Too small
- Insufficient number of features
- High correlation residual
- Many uncorrelated points

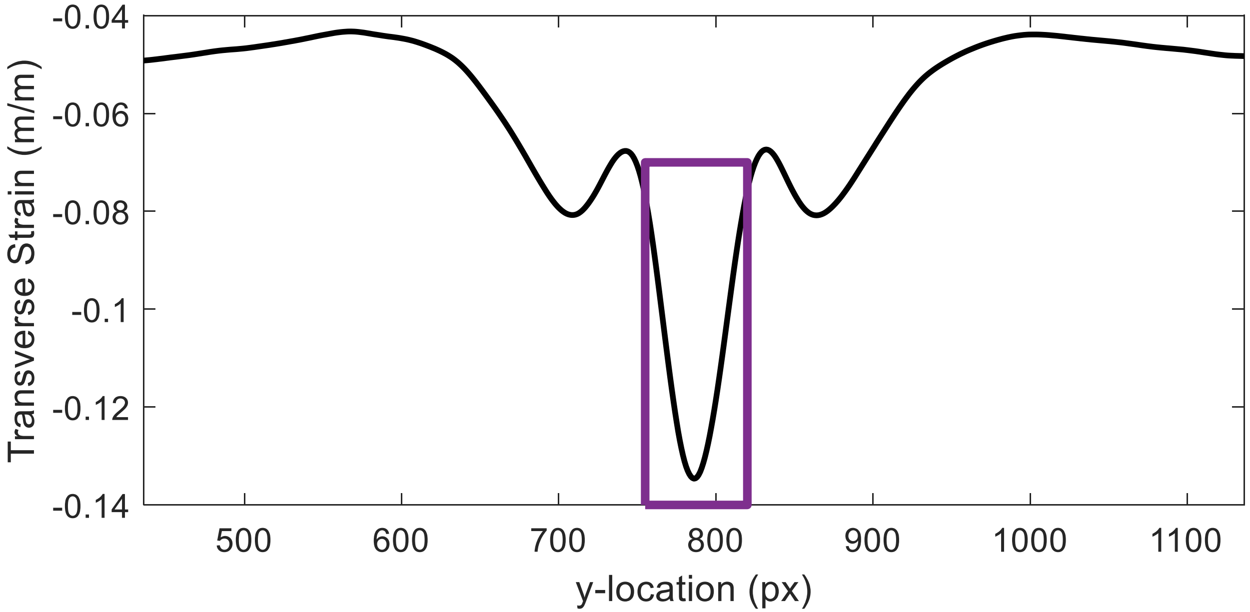
Subset size = 21 px
- Reasonable size
- Sufficient number of features
- Low correlation residual
- No uncorrelated points

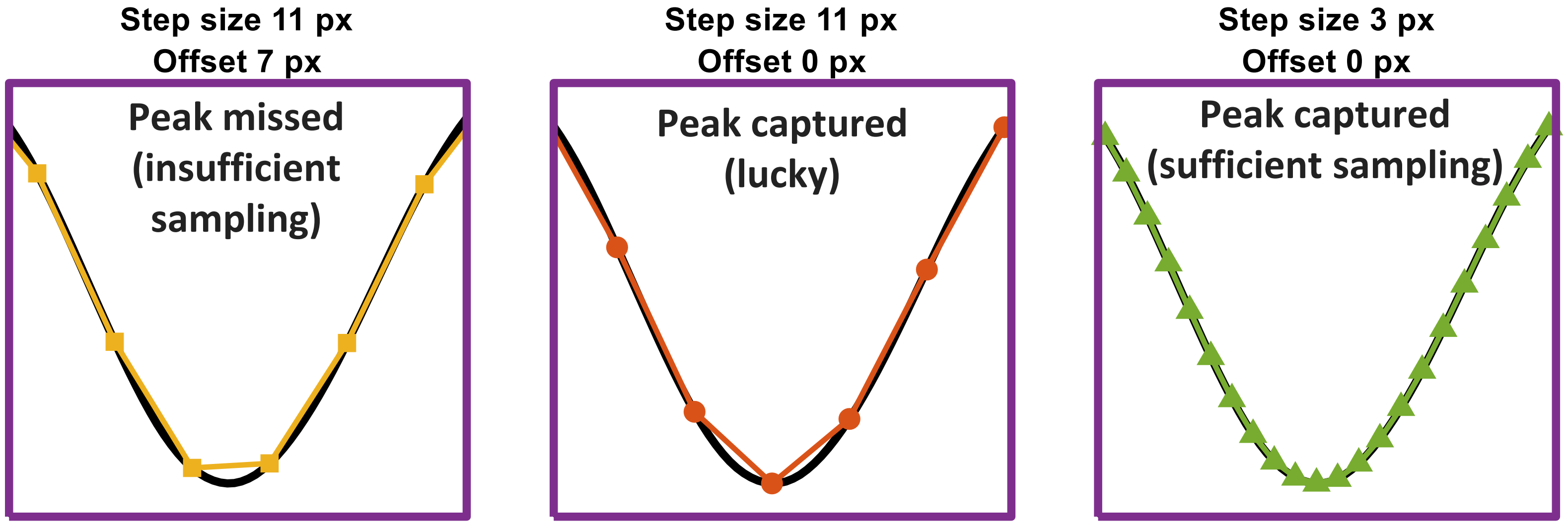
Subset size = 51 px
- Too large
- Large border of missing data near edges of ROI



Correlation example: Step size

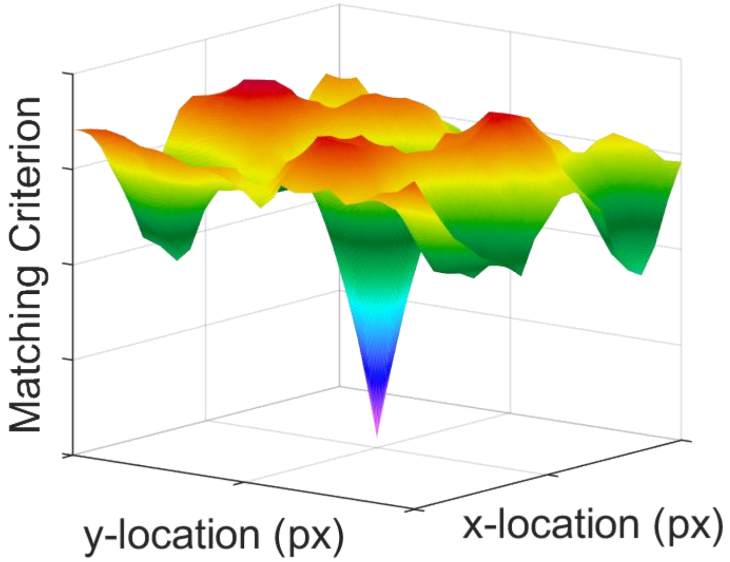


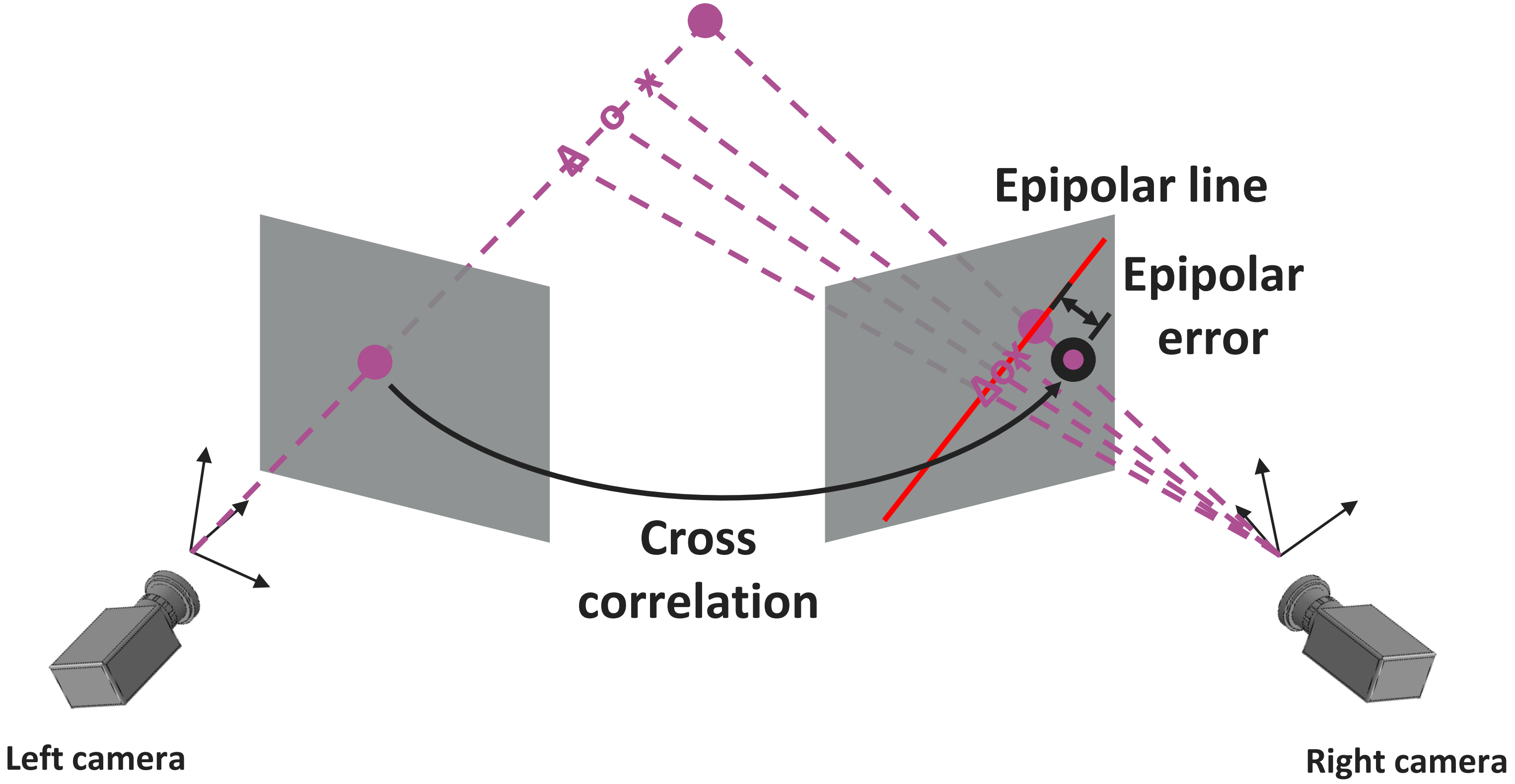




Thresholds
Sec. 5.2.7

- Determine the quality and confidence of the displacement results
- Two main thresholds
  - Value of the matching criterion
  - Value of the epipolar error
- Software dependent





SAND2020-9051 TR (slides)
SAND2020-9046 TR (videos)

CHAPTER 5:
PROCESSING OF DIC IMAGES

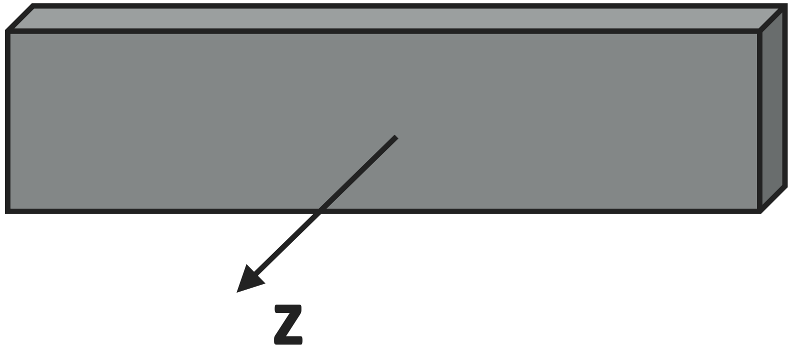
SEC. 5.3: STRAIN CALCULATIONS

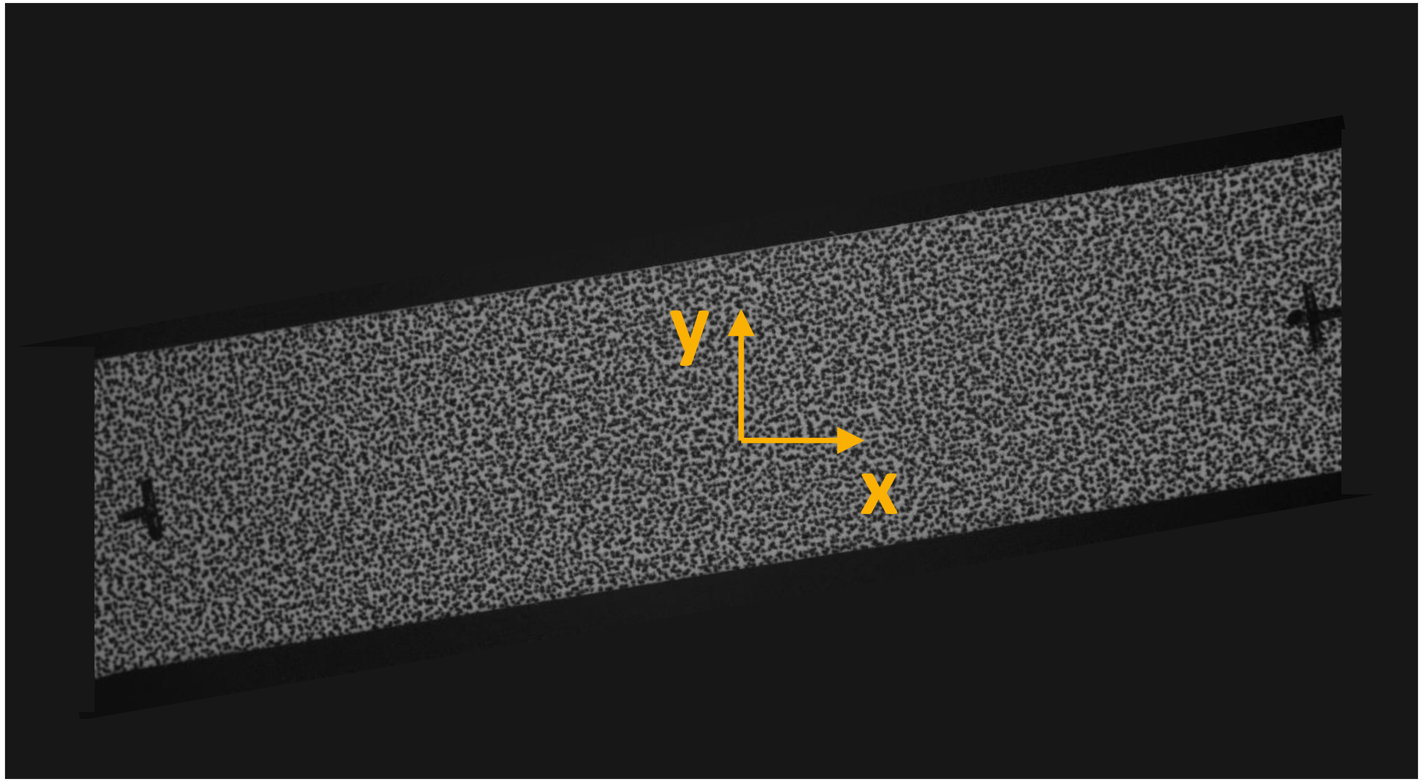
SEC. 5.4: UNCERTAINTY QUANTIFICATION

Coordinate system (Not in the Guide!)

- Default coordinate system depends on software
  - Left camera coordinate system
  - Coordinate system centered between cameras
  - Best plane fit

- Best plane fit
  - Sets z-axis perpendicular to ROI (good for planar specimens)
  - In-plane axes aligned with image

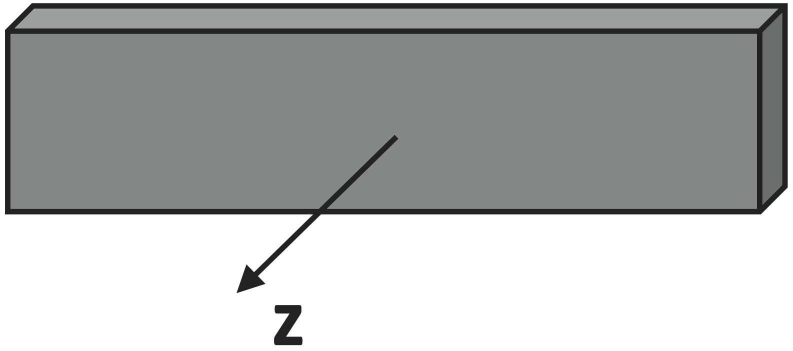


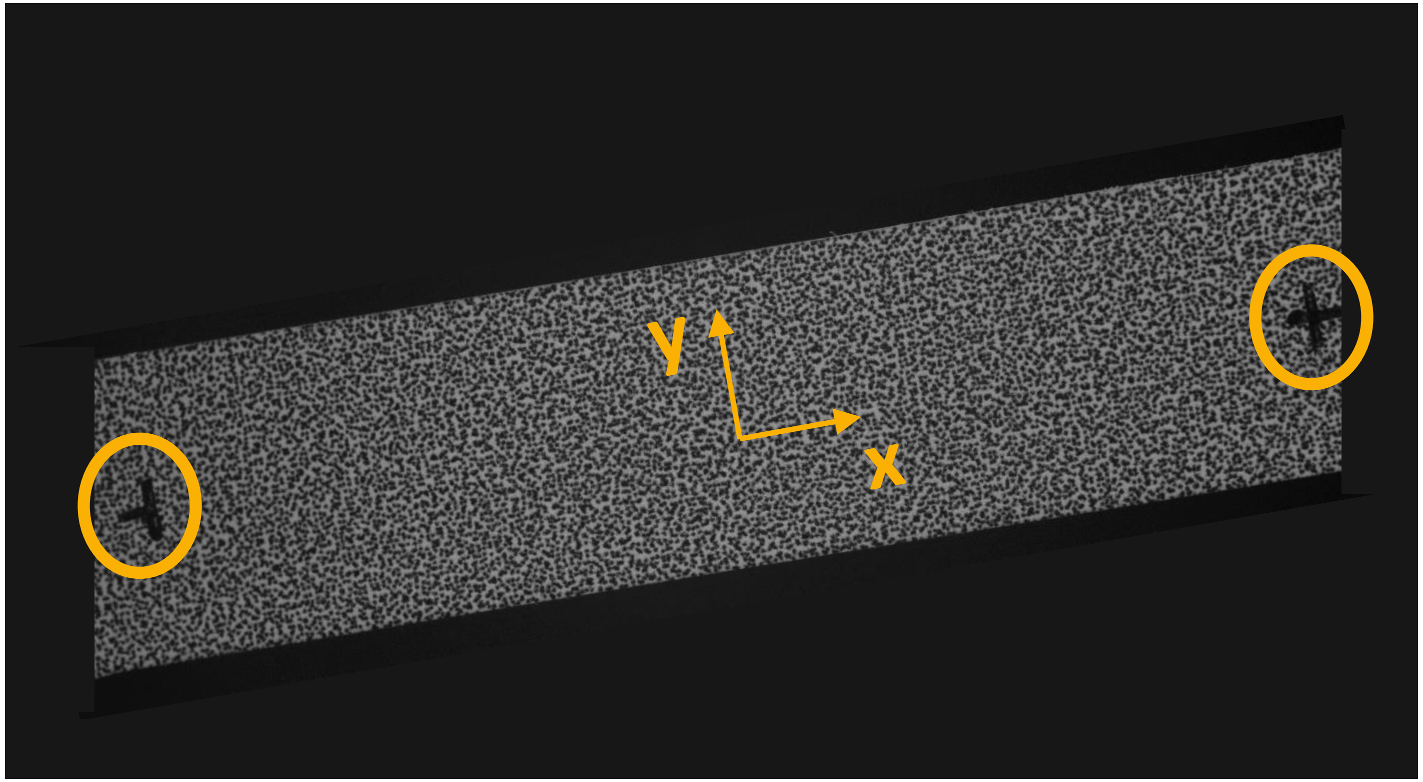


Coordinate system (Not in the Guide!)

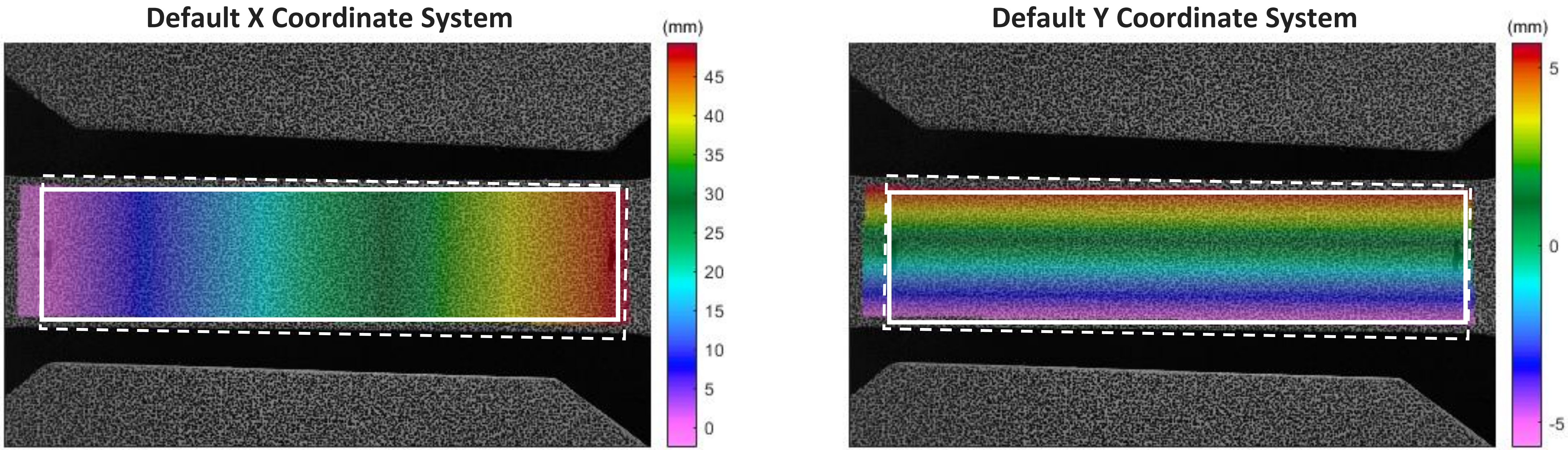
- Best plane fit
  - Sets z-axis perpendicular to ROI (good for planar specimens)
  - In-plane axes aligned with image

- Coordinate transform is often required to align axes with something meaningful, like test piece axis or direction of pull
- Fiducial marks placed on specimen during patterning can help when selecting a coordinate system





Coordinate system
(Not in the Guide!)



Misalignment might be subtle, but aligning system will improve consistency between results

Virtual Strain Gage (VSG) and Examples of Strain Gage Calculation Methods
Sec. 5.3.1 and Sec. 5.3.2

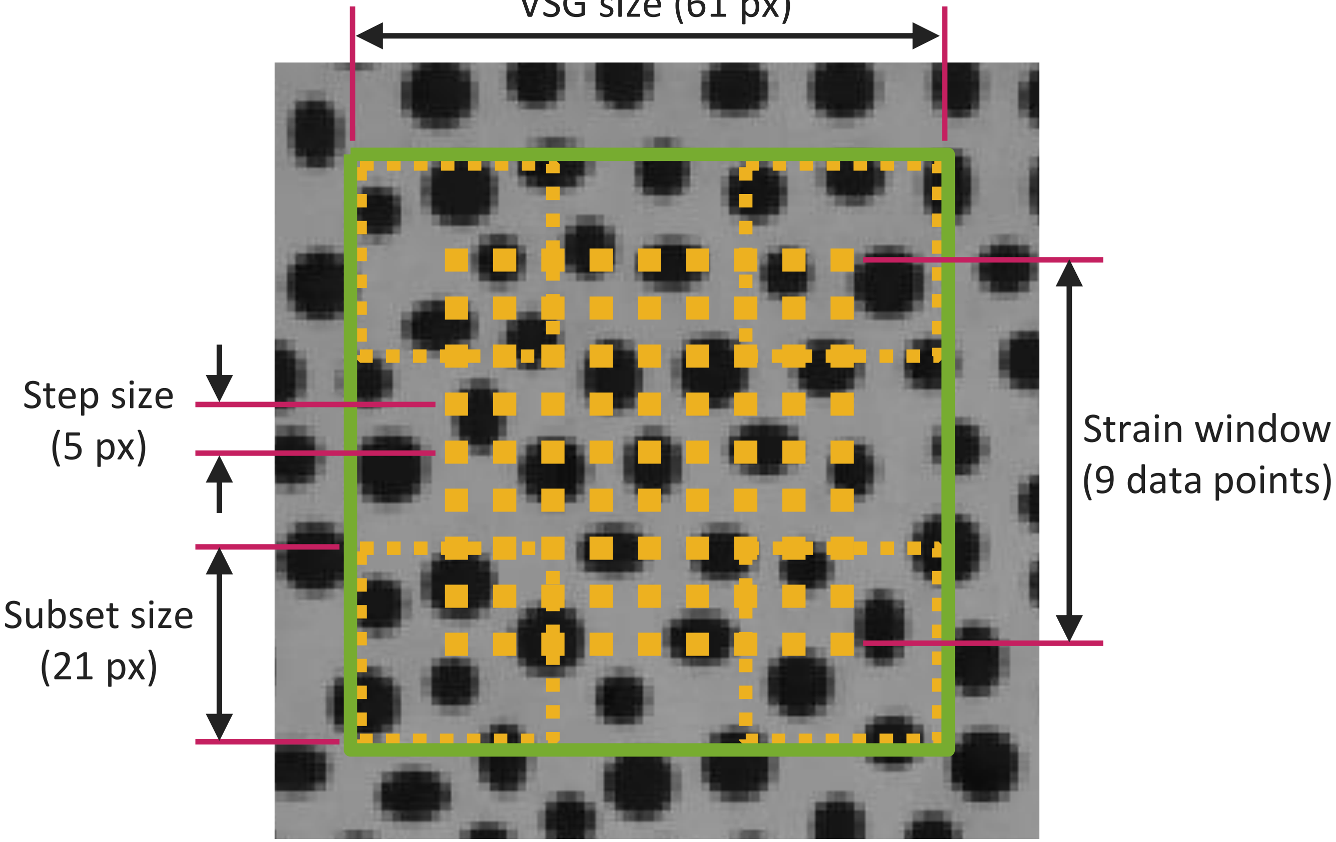
VSG size:

- Local region of the image that is used for strain calculation at a given location
- Analogous to, but not exactly, the size of a physical strain gage

Strain computation methods:

- Many methods, such as:
  - Subset Shape Function
  - Finite Element Shape Function
  - Strain Shape Function
  - Spline Fit
- See software manual for details

$$L_{VSG} = (L_{window} - 1)L_{step} + L_{subset}$$



Uncertainty Quantification (UQ)
Sec. 5.4

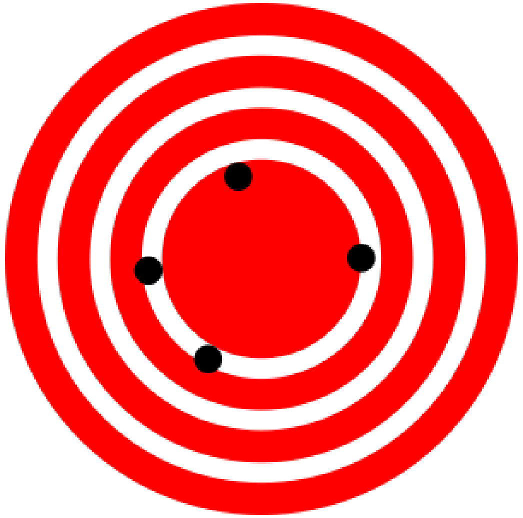
A comprehensive discussion is outside the scope of this course; here, we will only highlight topics in the GPG

- Two types of error:

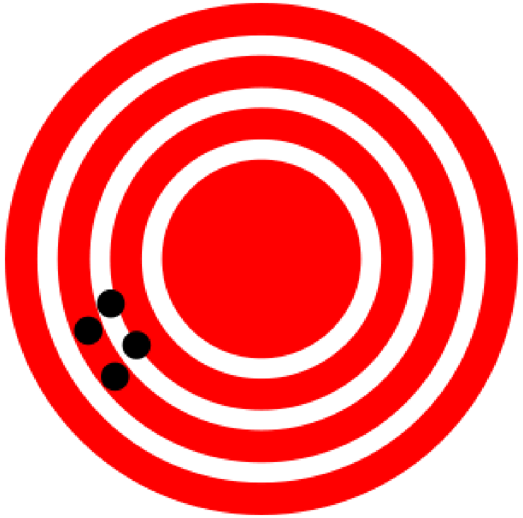
1. Variance (noise): random errors centered about the true value
   - e.g. from camera noise
   - Quantified using a noise-floor analysis

2. Bias: Offset of the mean from the true value
   - e.g. from lens distortions, interpolant choice, out-of-plane motion in 2D-DIC, insufficient spatial resolution
   - Can be interrogated using rigid translation, comparison to a known solution, VSG convergence, and others

- Note! There is often a trade-off between noise and bias due to over-smoothing of the data when choosing user defined parameters



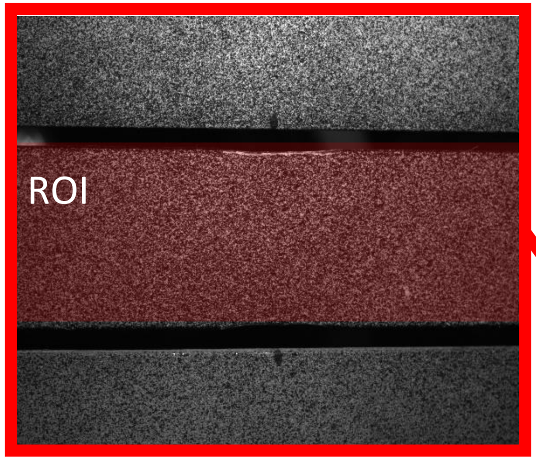
Noisy



Biased

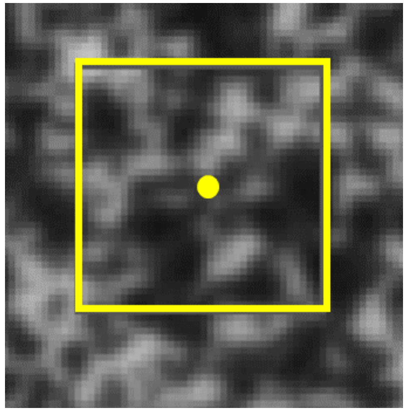
Virtual Strain Gage Study Example using Stereo-DIC Challenge Images: StereoSample5-Tension

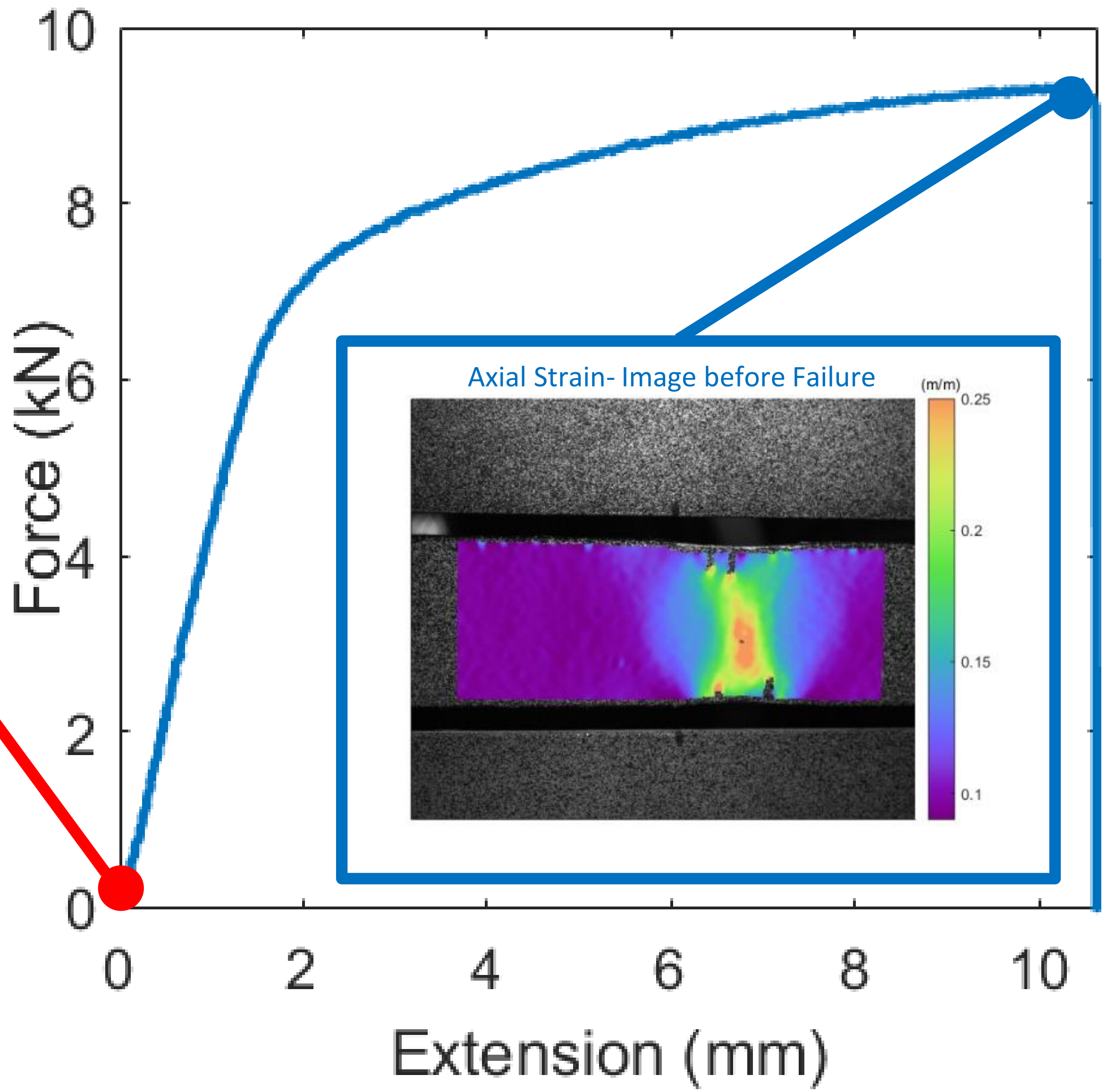
Reference Image: Zero force



1. Select subset size and step size based on previously discussed metrics

Subset: 37 px
Step: 7 px
Pre-filtering: Yes





Virtual Strain Gage Study Example
Sec 5.3.1

2. Select two images to correlate against reference image:
   a) an image after the reference image but zero force,
   b) the image of the highest strain *gradient*.

3. Analyze these images with different DIC settings, varying the VSG size
   - Tip 5.4: The dominant (but not only) variables that affect VSG size are subset size, step size, strain window/filter window, and strain shape function

4. Extract a line cut through the region of highest strain gradient. Plot the strain for each of the image analyzes.
   - Caution 5.3: Ensure that the line cut does not bridge a crack!

Static Image

noise

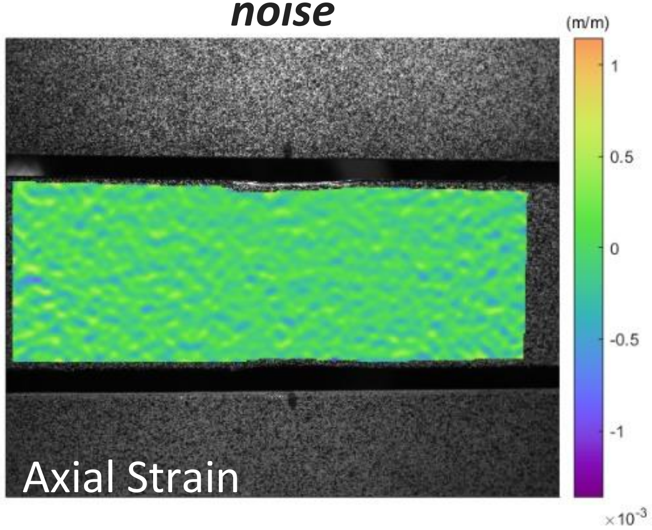
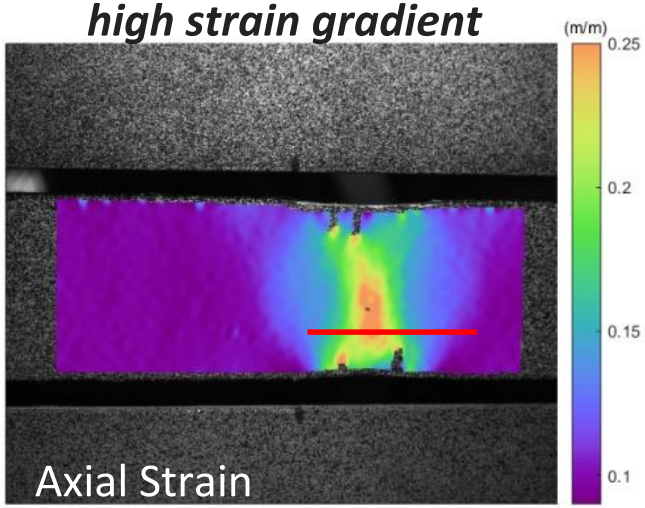
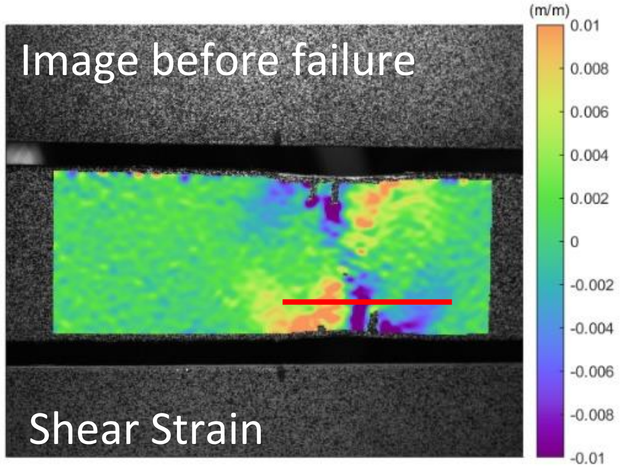
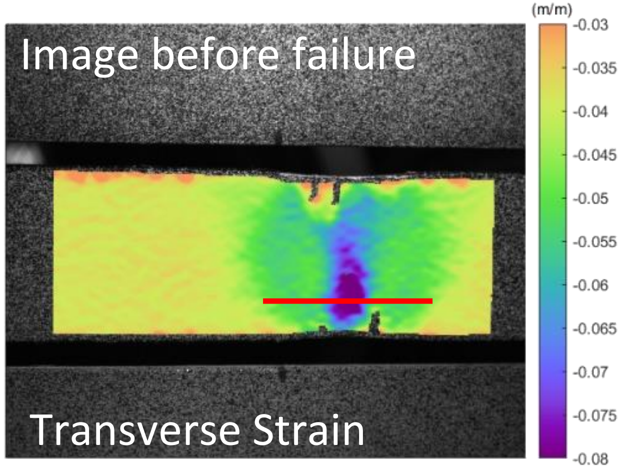


Image before Failure

high strain gradient

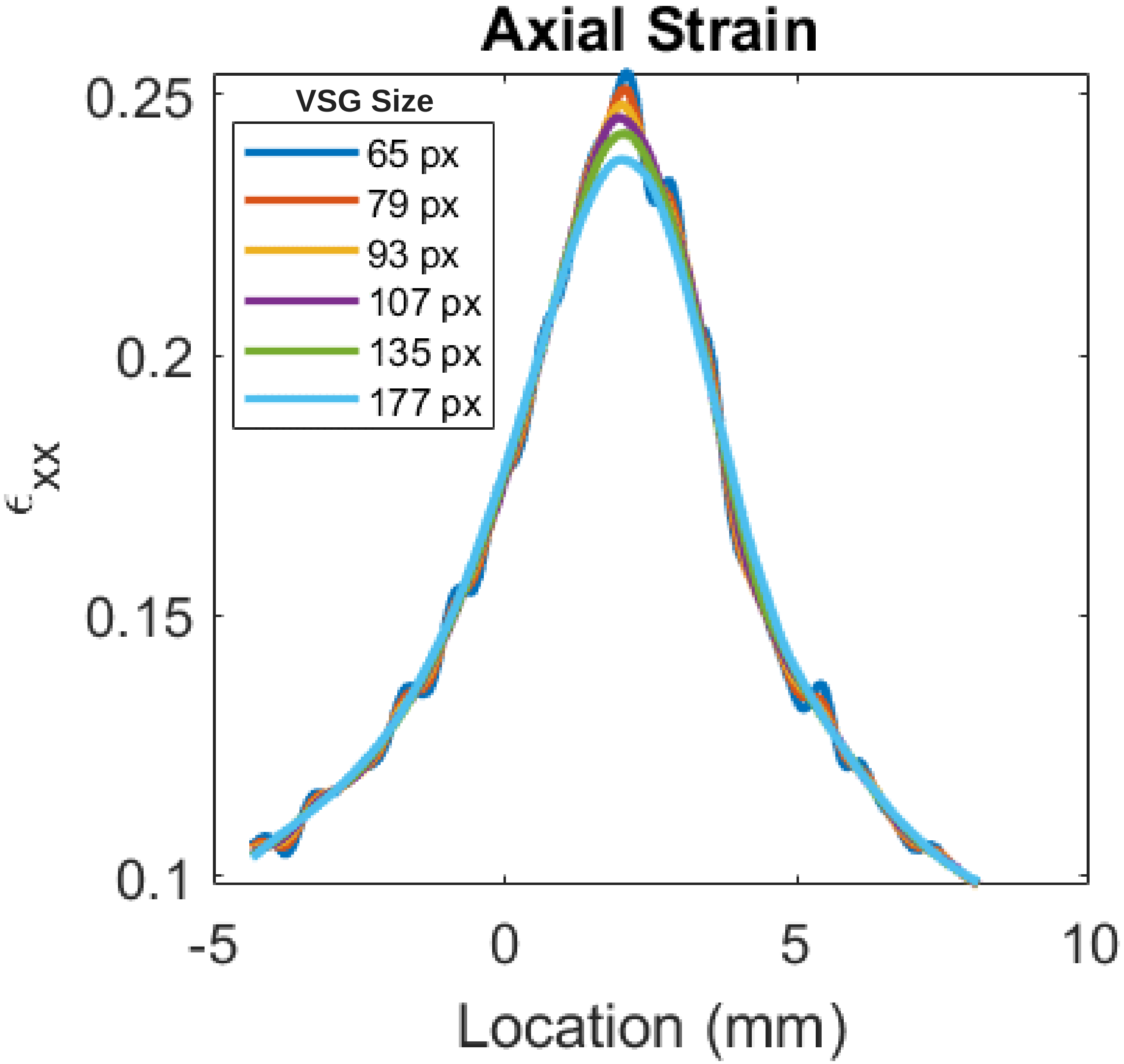


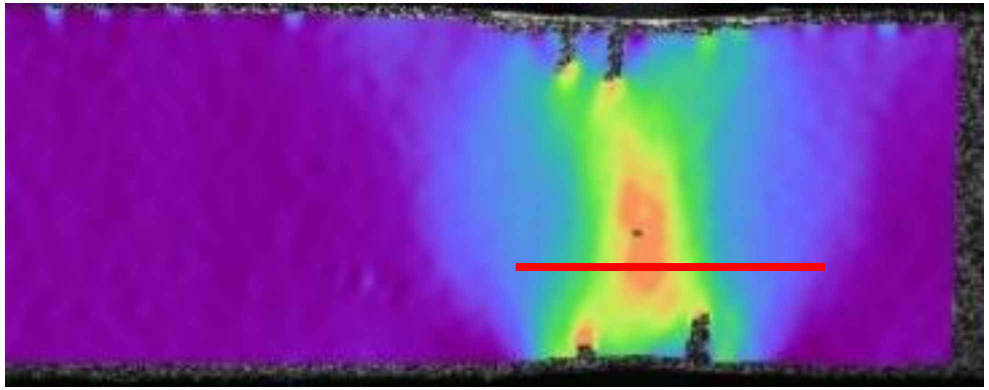




Virtual Strain Gage Study Example
Sec 5.3.1

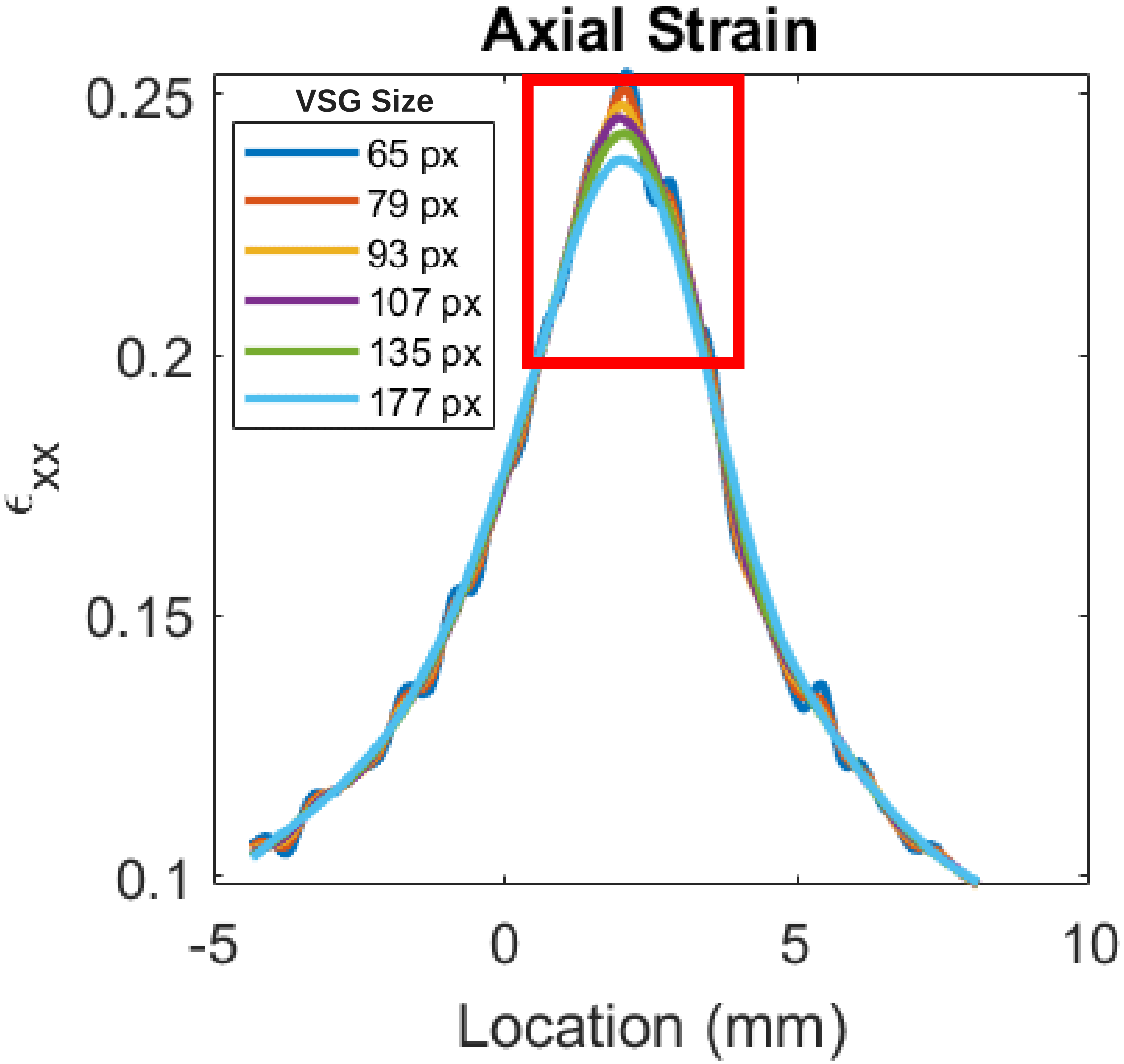
5. Assess convergence.

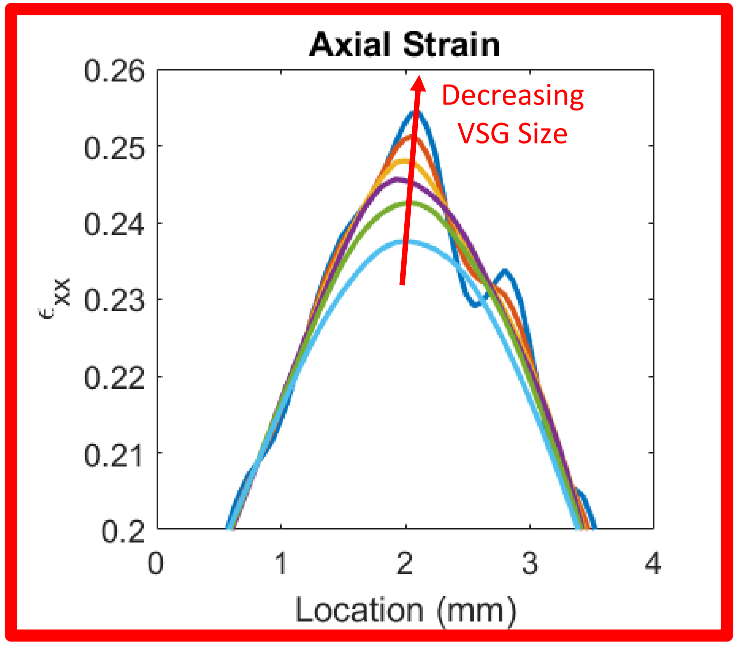




Virtual Strain Gage Study Example
Sec 5.3.1

5. Assess convergence.



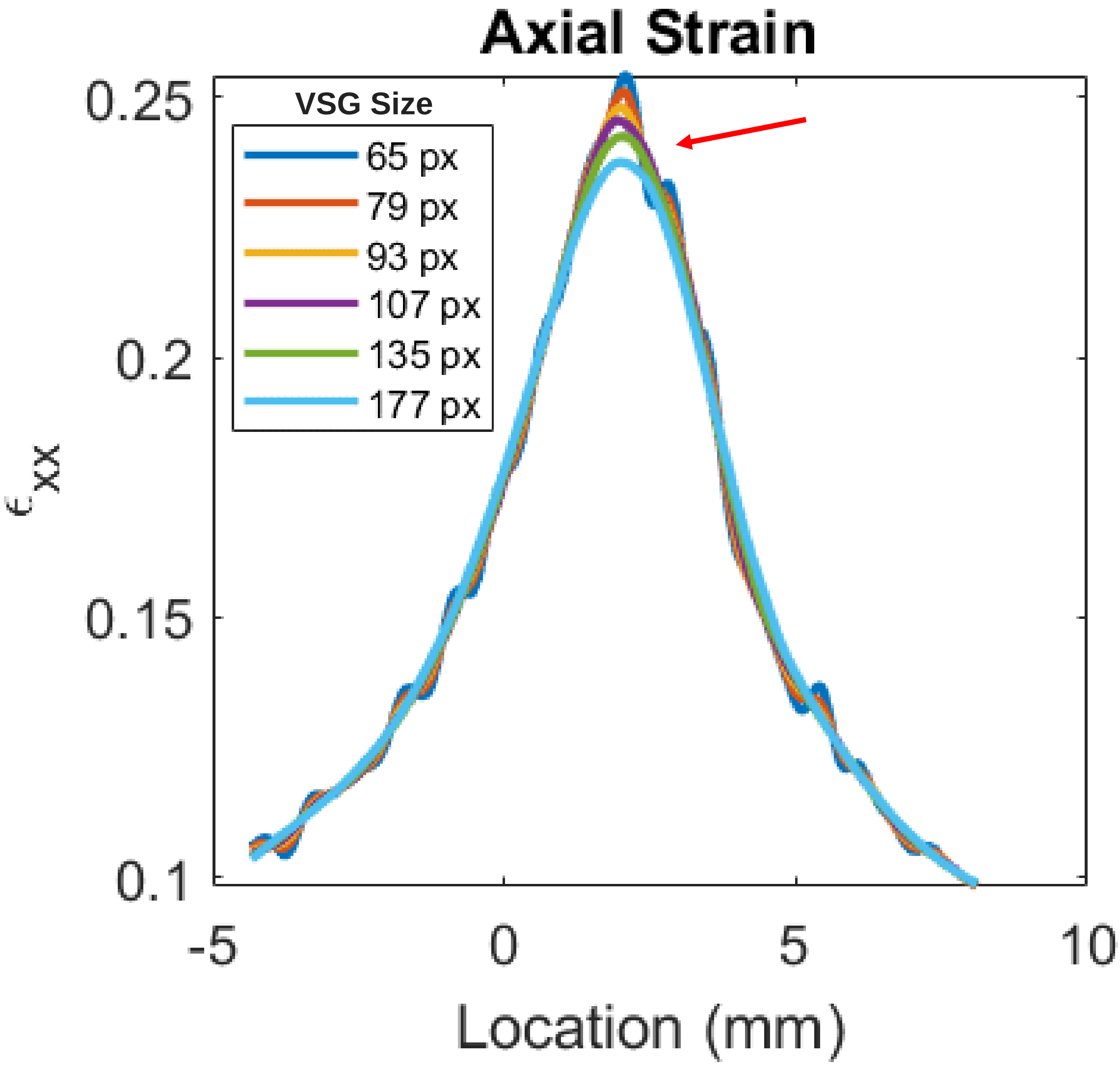


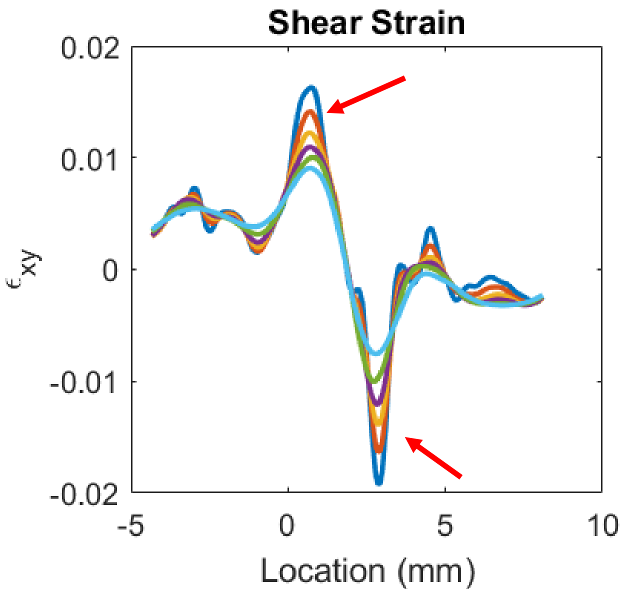
- If the maximum strain amplitude converges with smaller VSG, then the actual maximum strain amplitude has been captured.
- If the maximum strain amplitude never converges, the true value can not be known, but is instead equal to or greater than the reported strain measurements.

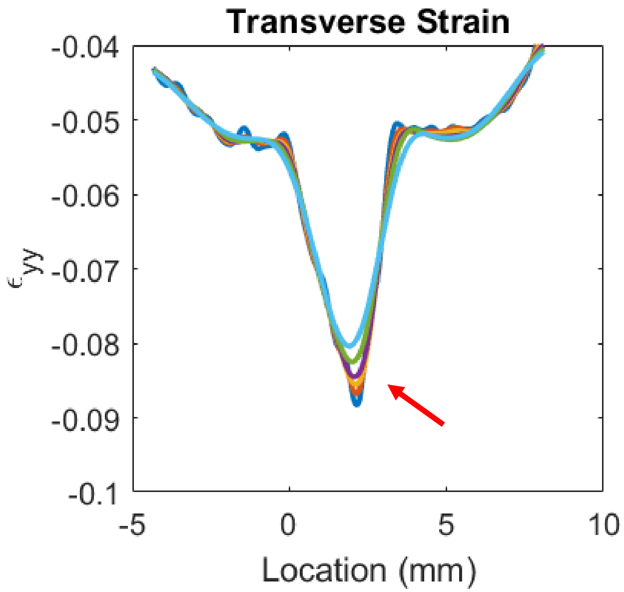
- *Tip 5.5: If strains do not converge, test can be repeated with smaller FOV/ higher magnification*

Virtual Strain Gage Study Example
Sec 5.3.1

5. Assess convergence.



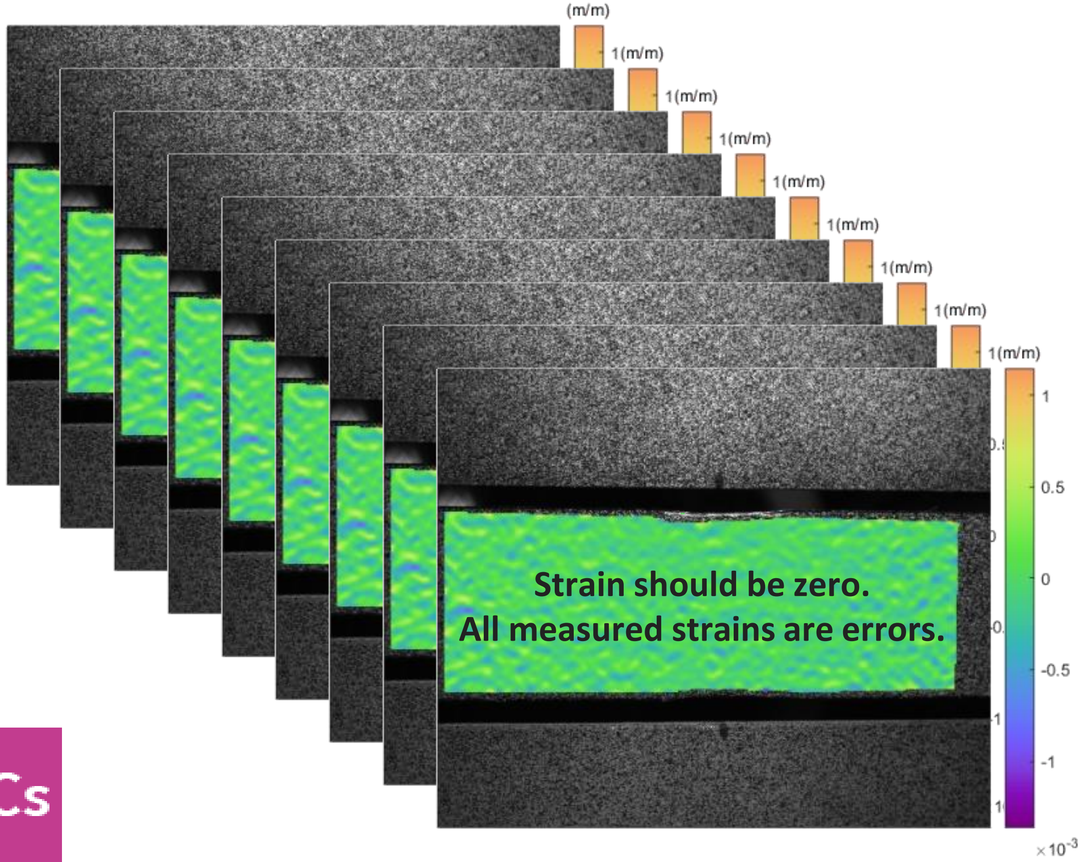




- *Tip 5.5: If strains do not converge, test can be repeated with smaller FOV/ higher magnification*

Virtual Strain Gage Study Example
Sec 5.3.1

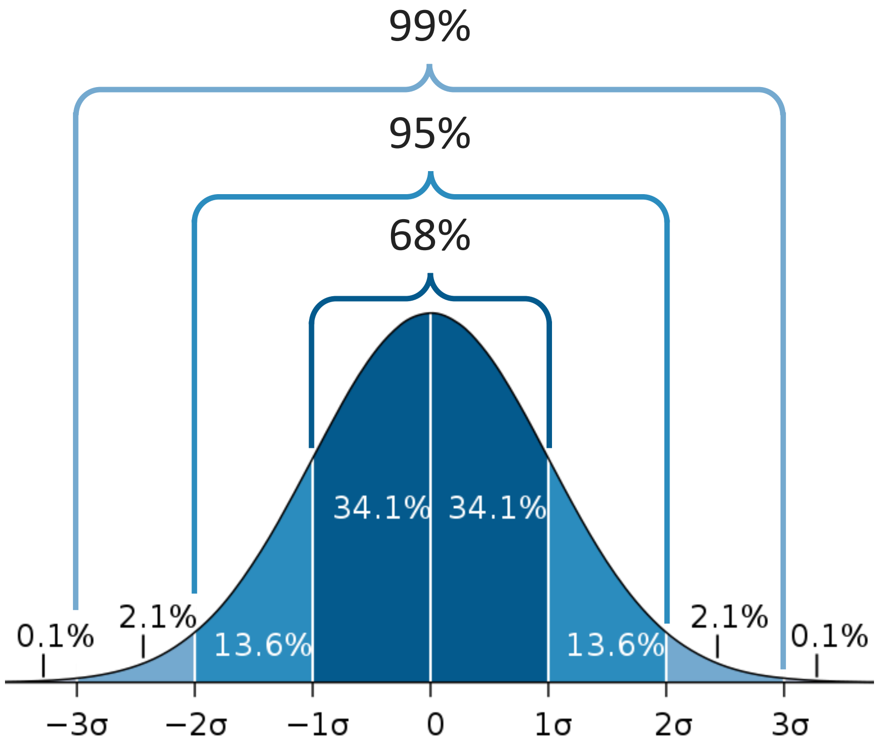
6. Quantify the noise
   a) Series of static images
      - Evaluates camera noise, but not calibration parameters
      - Lower bound of noise floor
   b) Series of rigid-body motion images
      - More thorough evaluation of noise floor



Strain should be zero.
All measured strains are errors.

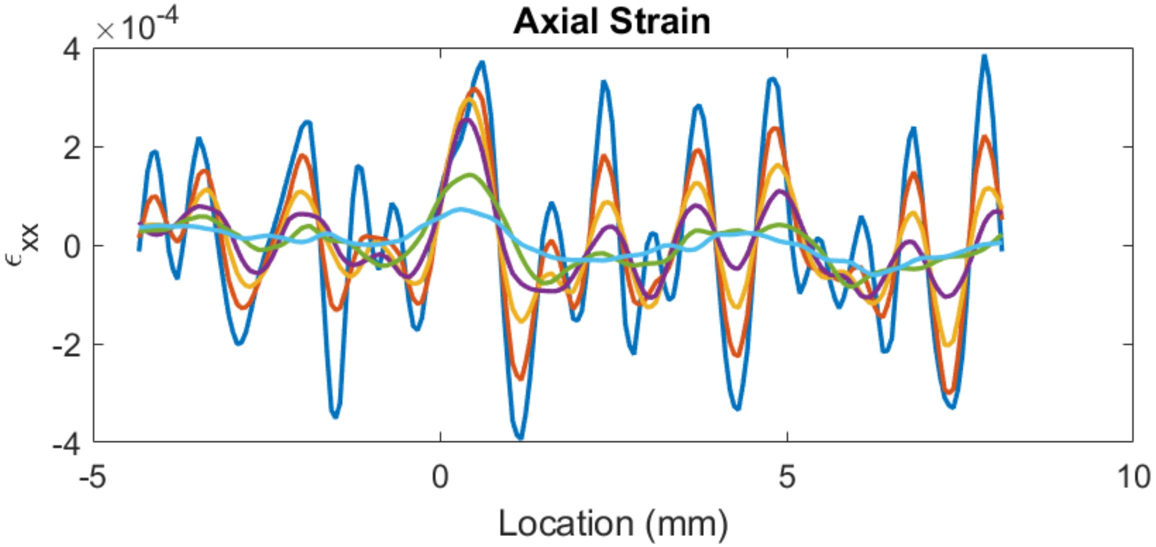
- Noise Floor = α*(standard deviation)
  - Spatial stdev → variance of QoI across ROI
  - Temporal stdev → variance of QoI over time
  - Combine all points in ROI and all images in time

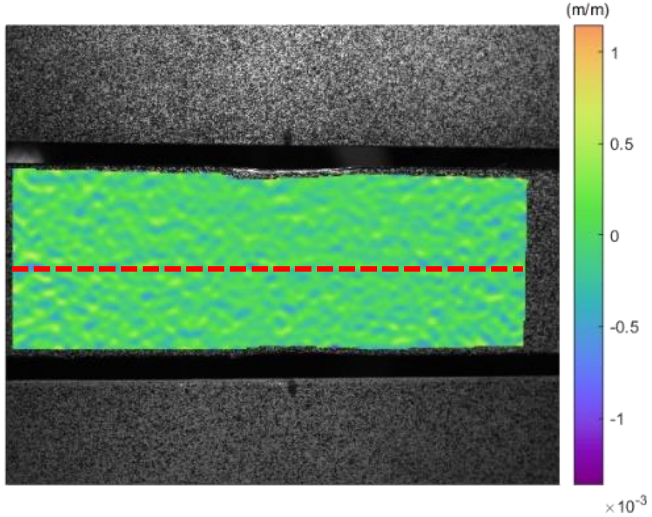
- 3-sigma rule
  - α = 1 → Less conservative
  - α = 3 → More conservative



Virtual Strain Gage Study Example
Sec 5.3.1

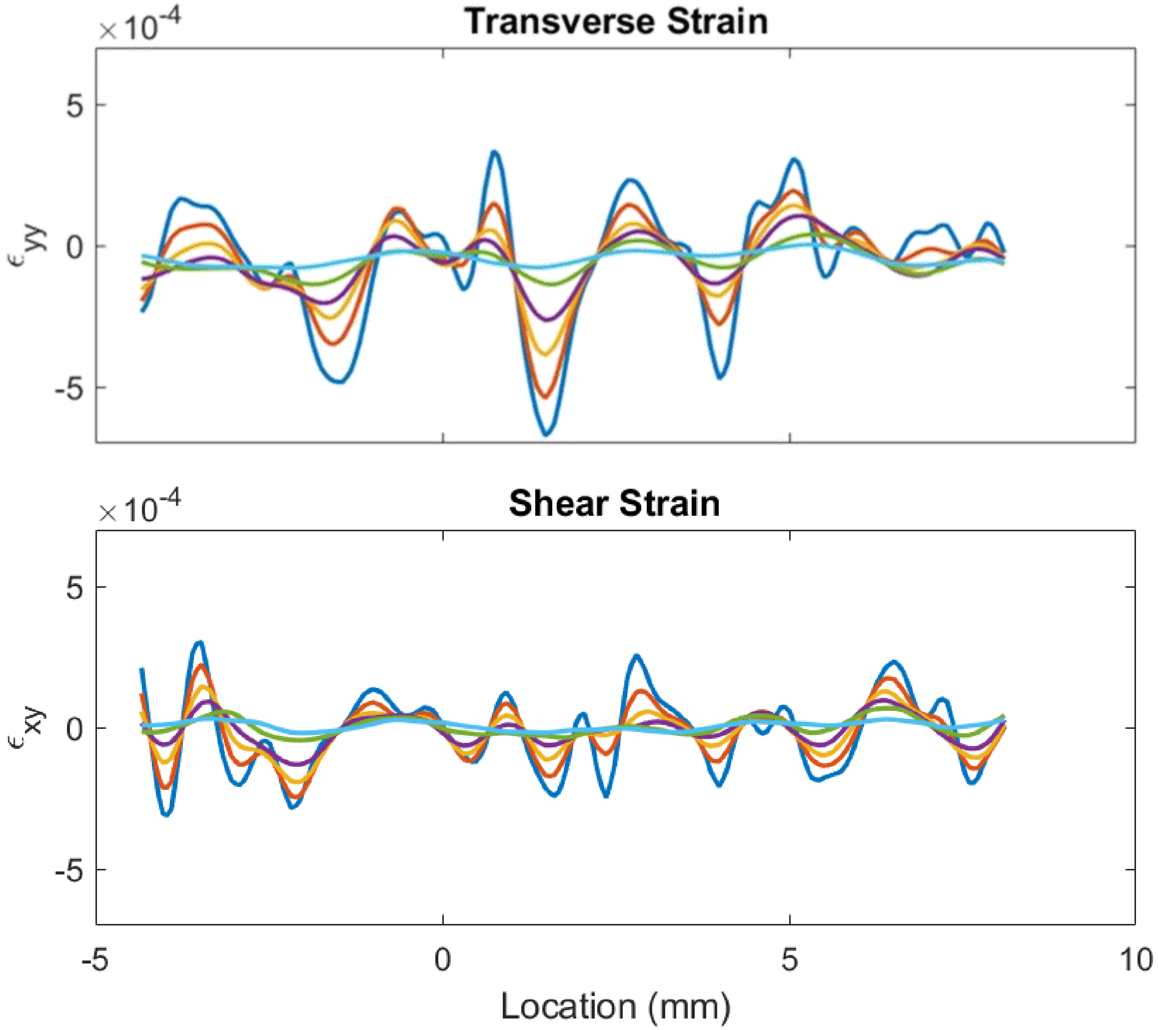
6. Quantify the noise





VSG Size

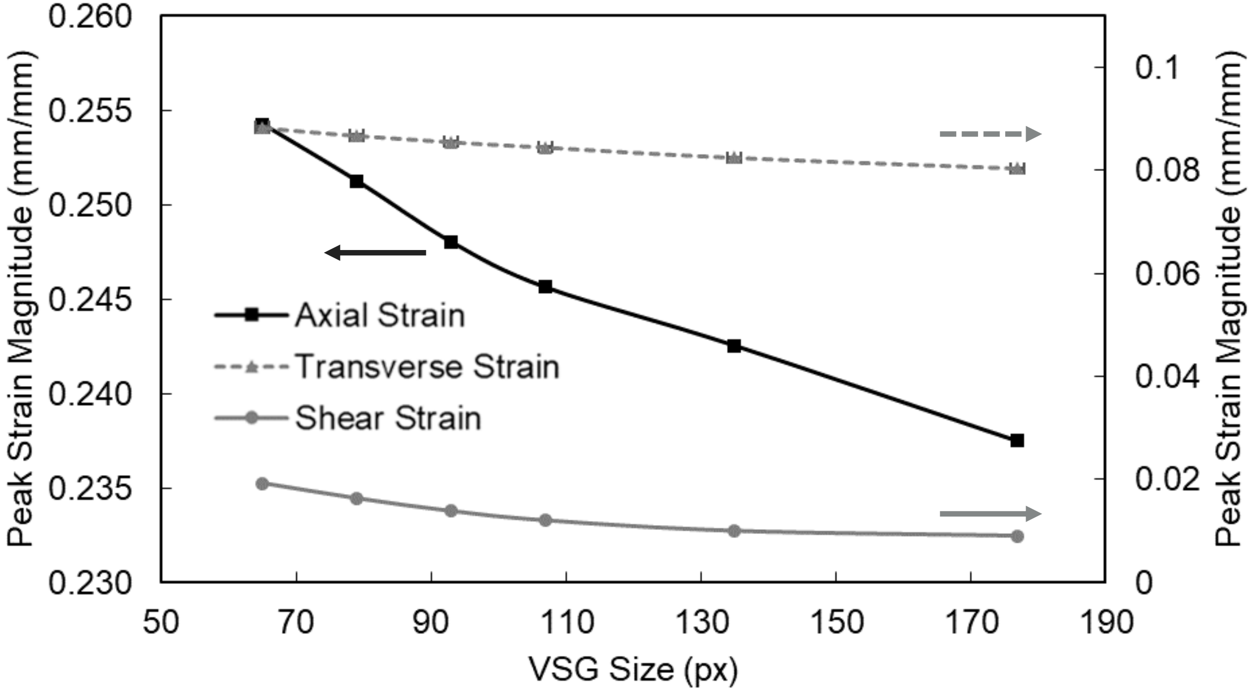
- 🟦 65 px
- 🟧 79 px
- 🟨 93 px
- 🟪 107 px
- 🟩 135 px
- 🟦 177 px



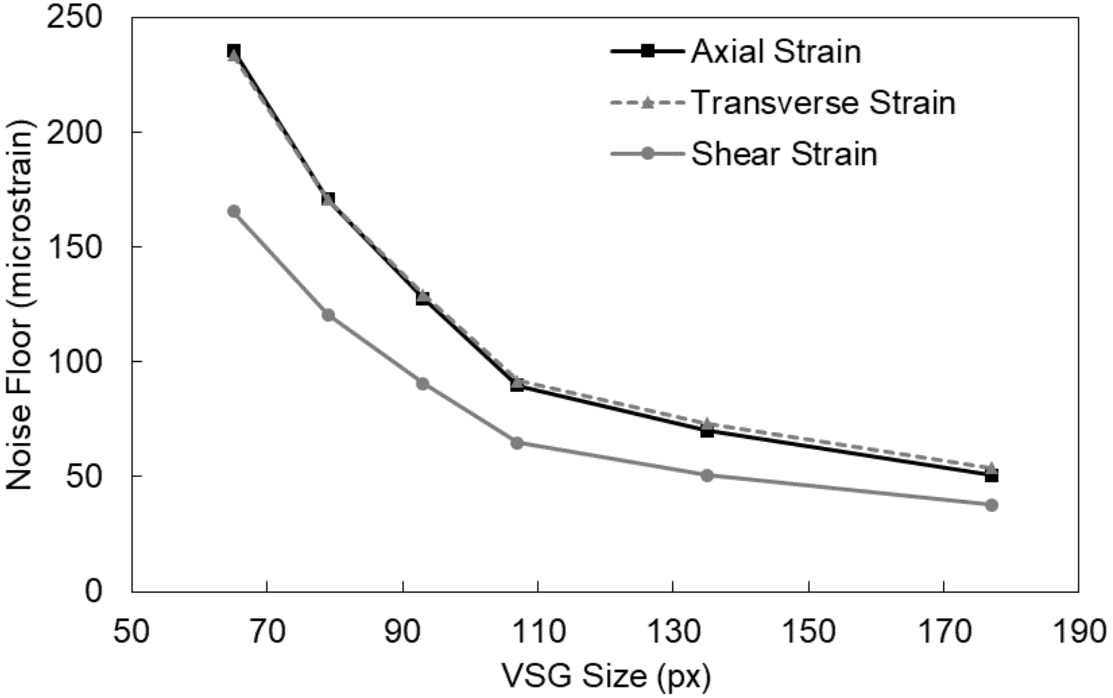
Virtual Strain Gage Study Example
Sec 5.3.1

7. Ultimately, the right parameters are a function of the accuracy to noise ratio for a given QOI and are application dependent and a matter of expert judgement.

Peak Magnitude Convergence (Step 5)



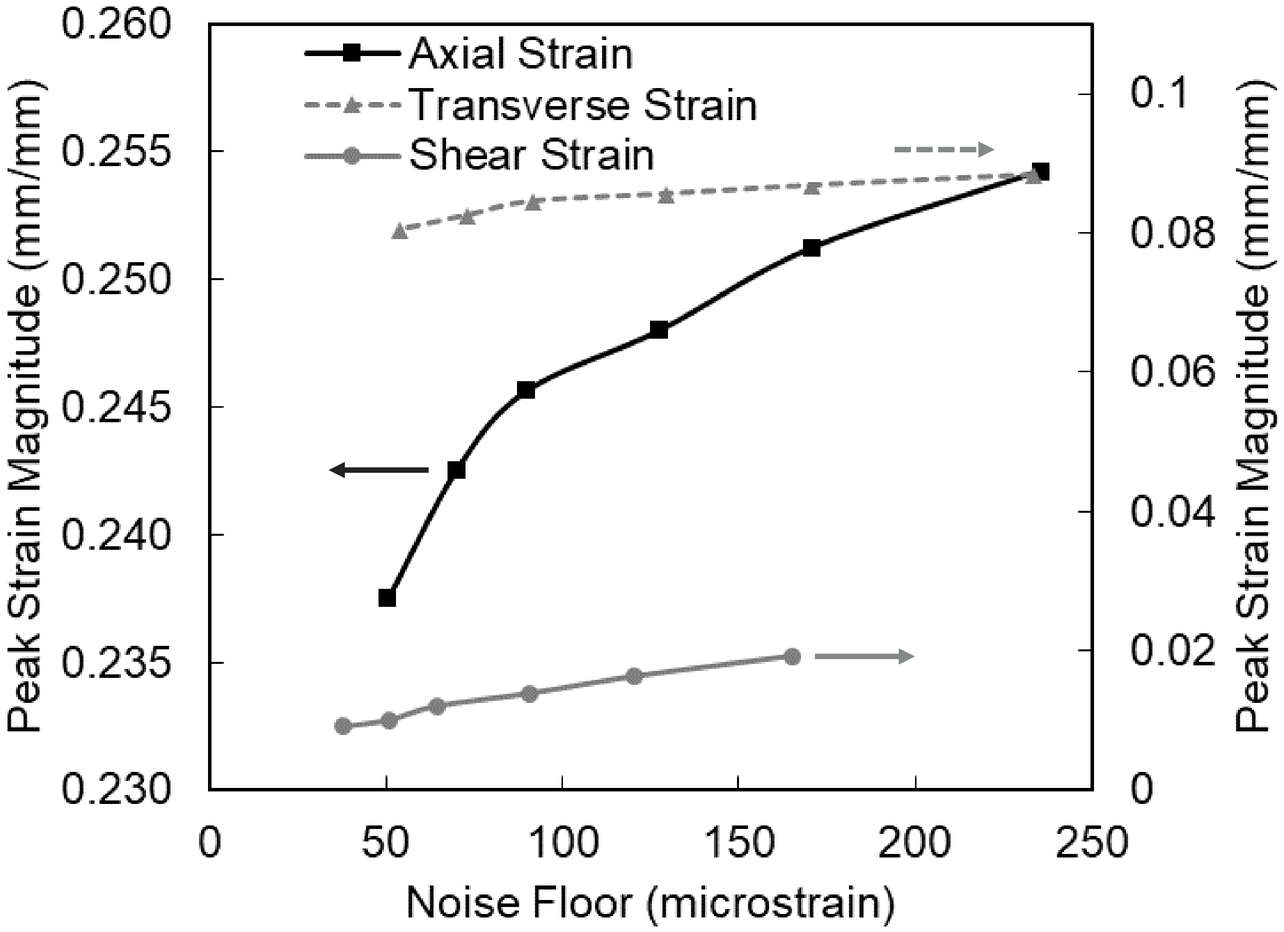
Noise Floor (Step 6)



Virtual Strain Gage Study Example
Sec 5.3.1

7. Ultimately, the right parameters are a function of the accuracy to noise ratio for a given QOI and are application dependent and a matter of expert judgement.

Bias Errors



Variance Errors

CHAPTER 6:
REPORTING REQUIREMENTS

Reporting Requirements

- Necessary for others to understand your measurements and repeat your measurements
- Build credibility for your experimental procedures and analysis

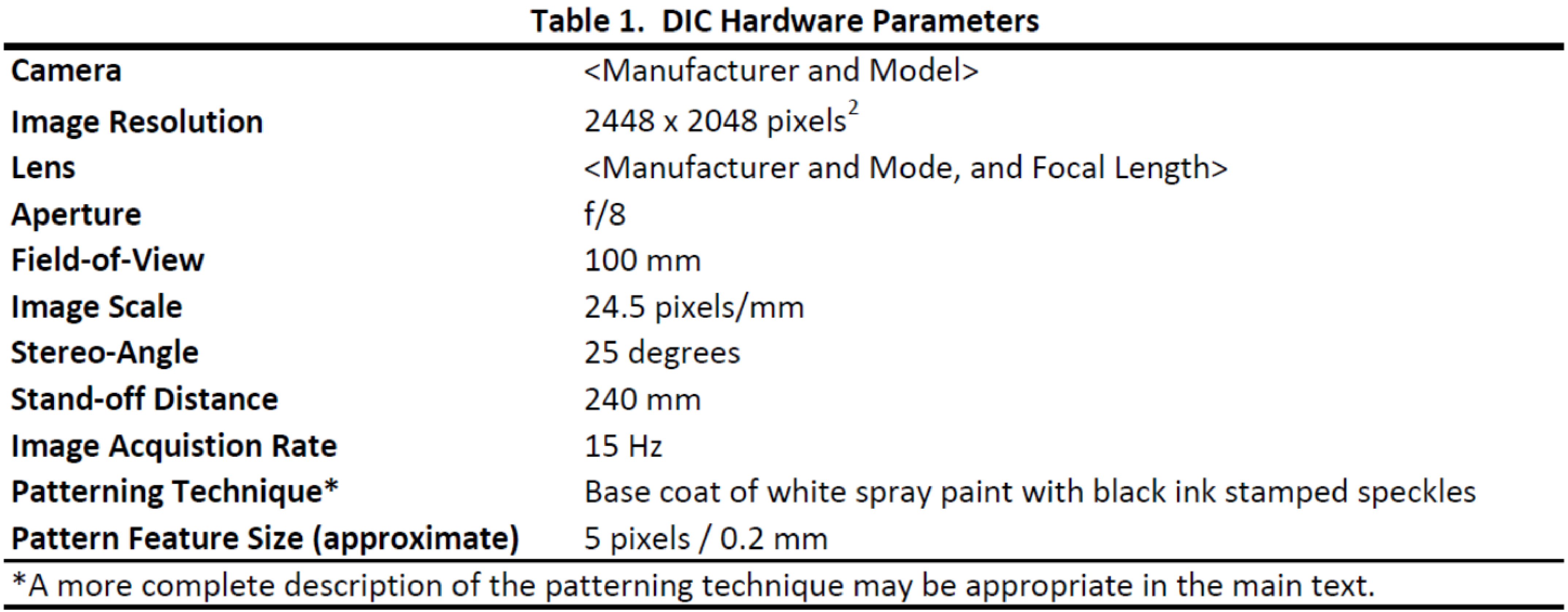


Table 1. DIC Hardware Parameters

Camera	<Manufacturer and Model>
Image Resolution	2448 x 2048 pixels^2
Lens	<Manufacturer and Mode, and Focal Length>
Aperture	f/8
Field-of-View	100 mm
Image Scale	24.5 pixels/mm
Stereo-Angle	25 degrees
Stand-off Distance	240 mm
Image Acquistion Rate	15 Hz
Patterning Technique*	Base coat of white spray paint with black ink stamped speckles
Pattern Feature Size (approximate)	5 pixels / 0.2 mm

*A more complete description of the patterning technique may be appropriate in the main text.

Reporting Requirements

Table 2. DIC Analysis Parameters

DIC Software	<Manufacturer, Version number>
Image Filtering	Gaussian filter with a 3x3 pixel kernel
Subset Size	21 pixels / 0.86 mm
Step Size	7 pixels / 0.29 mm
Subset Shape Function	Affine
Matching Criterion	Zero-normalized sum of square differences (ZNSSD)
Interpolant	Bi-cubic spline
Strain Window	15 data points
Virtual Strain Gauge Size*	119 pixels / 4.9 mm
Strain Formulation	Green-Lagrange
Post-Filtering of Strains**	Median temporal filter, span of 5 data points / 0.33 seconds
Displacement Noise-Floor***	0.01 pixels / 0.4 µm (in-plane); 0.03 pixels / 1.2 µm (out-of-plane)
Strain Noise-Floor***	250 µm/m

*The VSG size is computed from Eqn. 7.2 in the DIC Good Practices Guide [1]. Other estimations of the VSG size may be more appropriate, depending on the strain calculation method used in the DIC software.

**A more complete description of any pre- or post-filtering may be appropriate in the main text.

***A brief description of how the noise-floor was computed should be included in the main text.

Summary

- DIC is an extremely powerful tool that can be used to capture shapes, displacements, strains, and others
- The guidelines presented in this course are for a well-controlled environment; more complicated setups/ tests may require compromises
- Garbage in – garbage out! DIC requires careful attention to setup, test operation, and data processing
- Reporting of DIC parameters gives us credibility as a community
- Join a working group to help us improve DIC practices and guidelines. All experience levels welcome!

guide@idics.org

END MATTER

Image credit

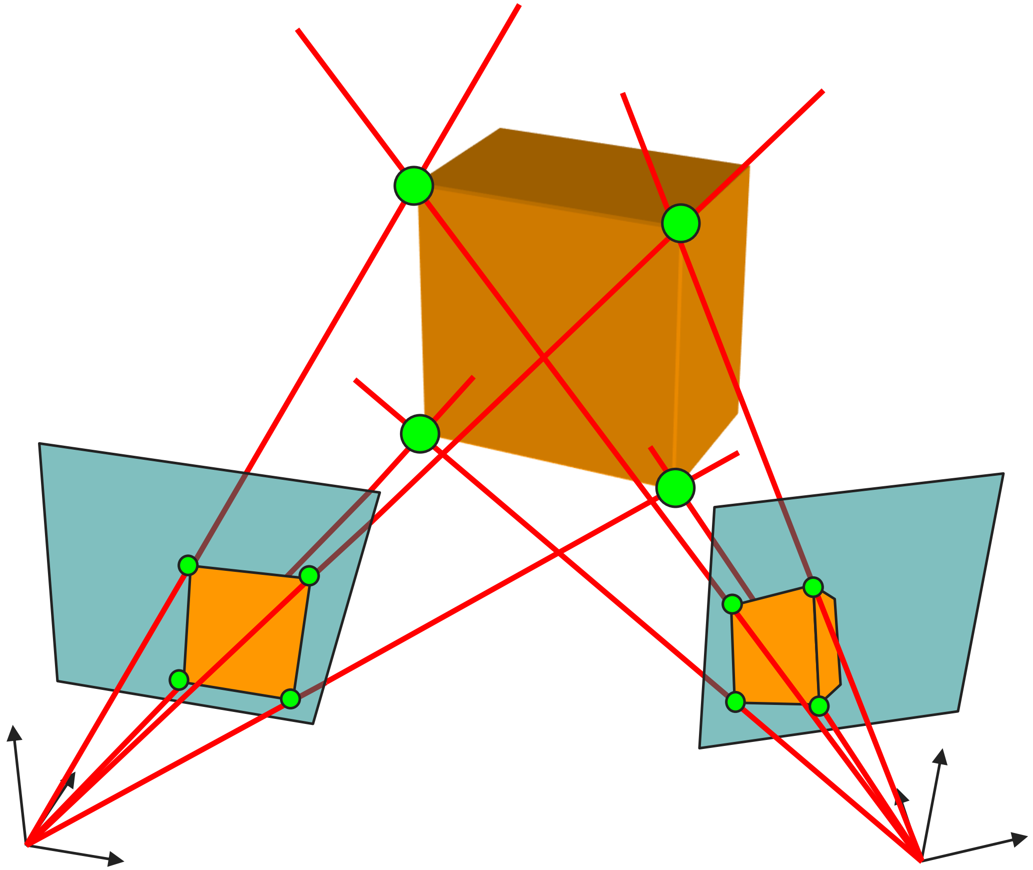


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Image credit: Pleriche. Image available at:
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Image credit

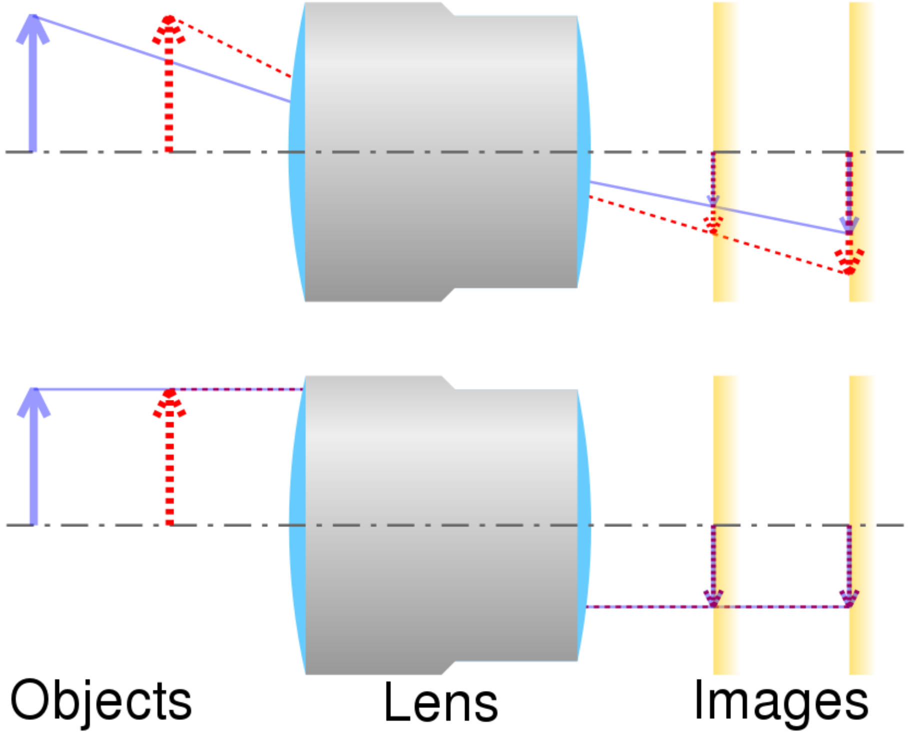

Image credit Cmglee.
Original image available at
https://commons.wikimedia.org/wiki/File:Comparison_of_telecentric_lenses.svg
(Current version shows 2/4 subfigures found in the original.)

Image credit Koyaanis Qatsi.
Images available at https://en.wikipedia.org/wiki/Focal_length

Image credit

Image credit alf sigaro. Image available at: https://commons.wikimedia.org/wiki/File:Pentacon_electric_f2,8_29mm_MC_lens.jpg

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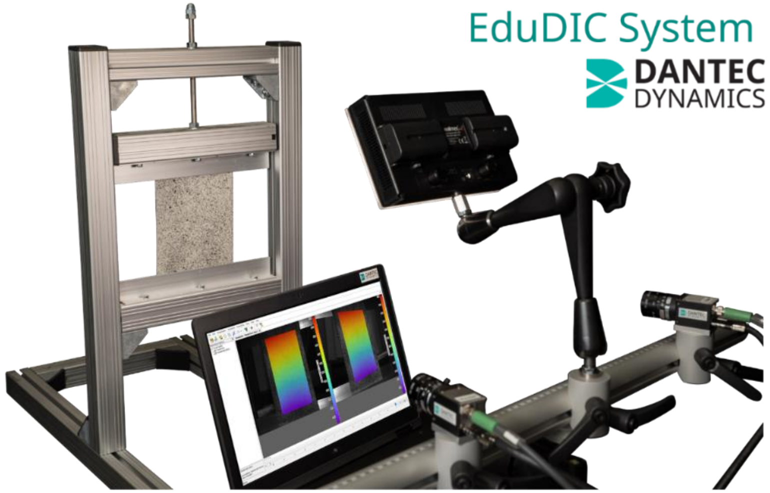
Image credit



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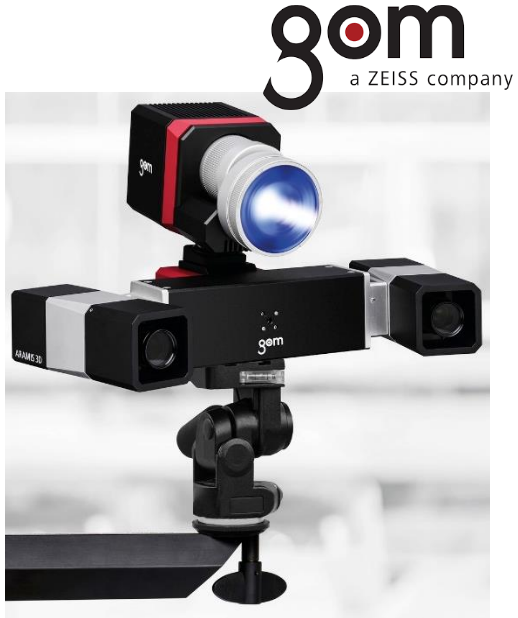

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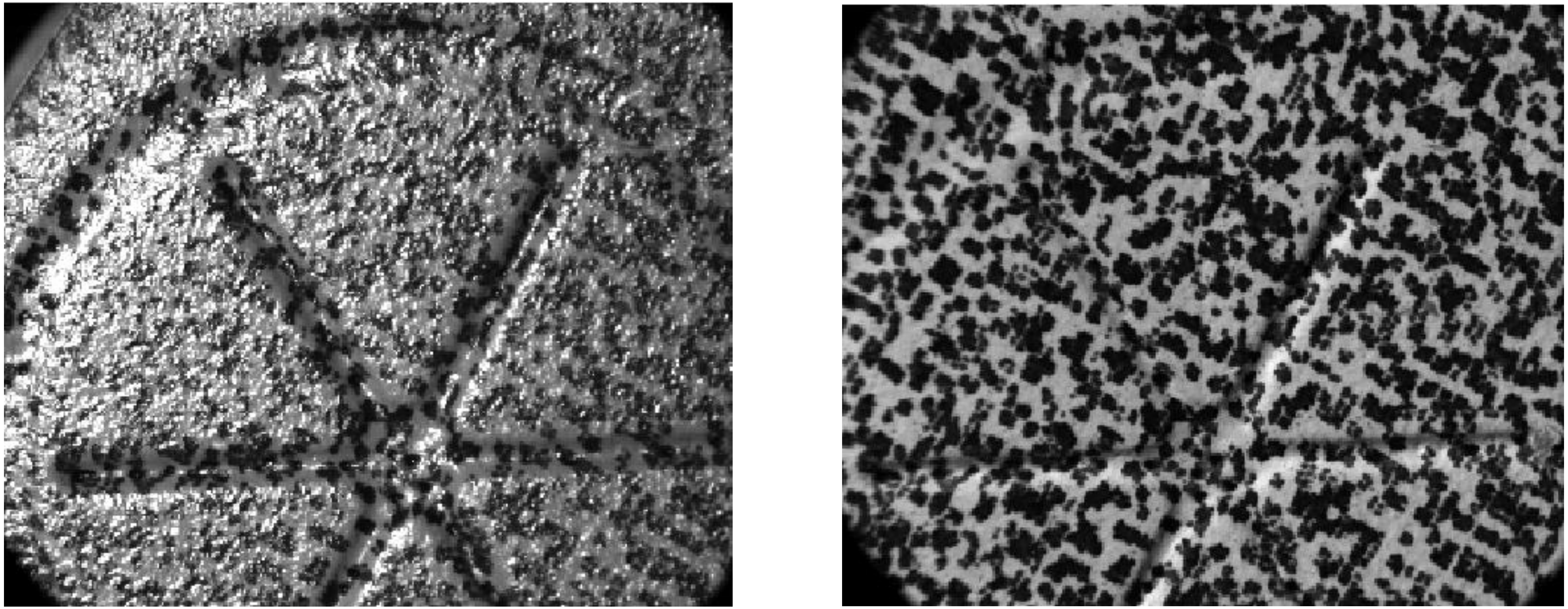
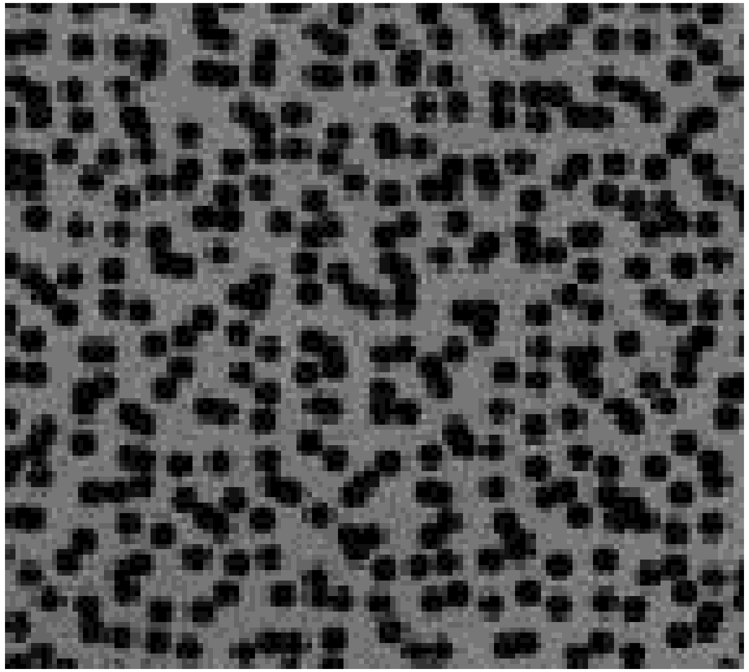
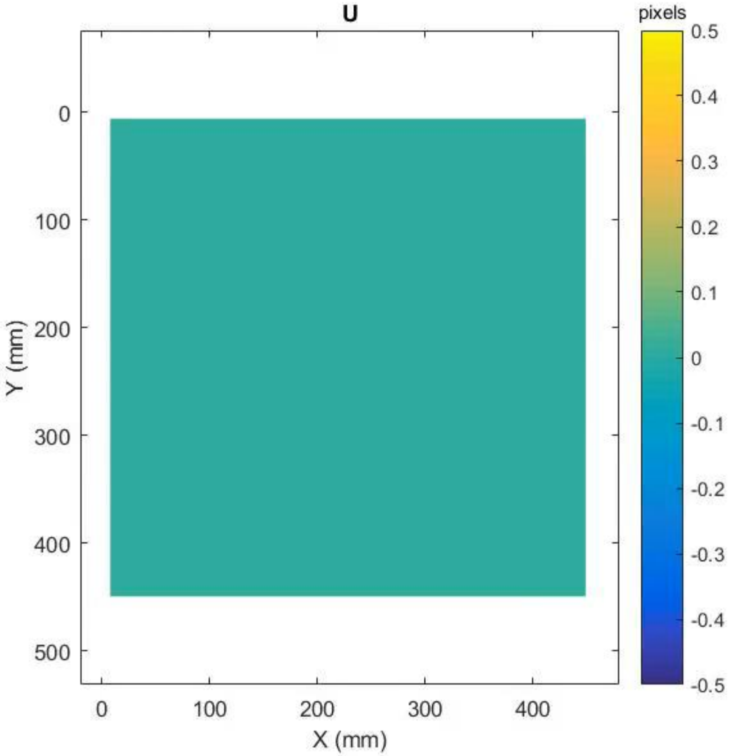
Image credit

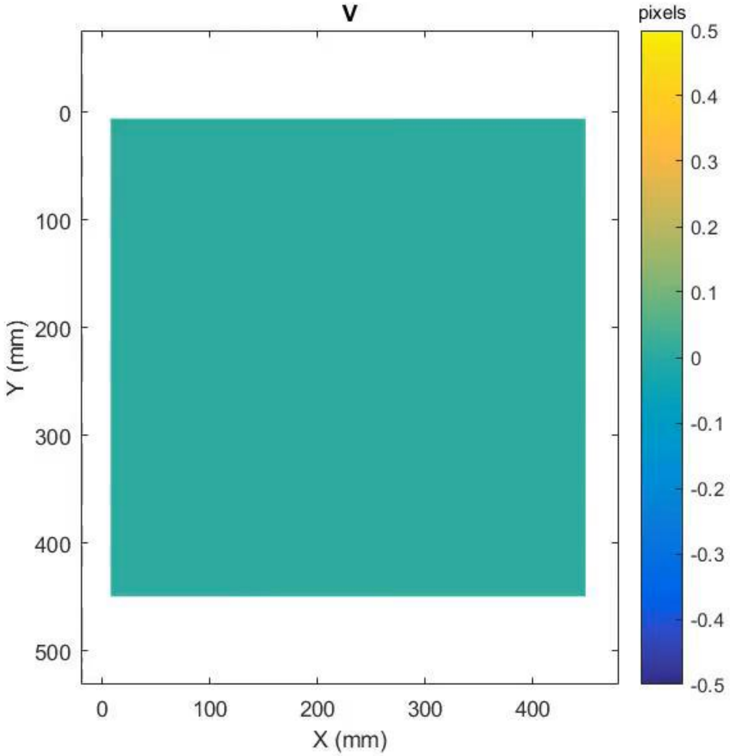


Cooper, M. A., et al. (2016). Advancement of Optical Methods in Experimental Mechanics, Volume 3, Springer**:** 19-26.

Image credit

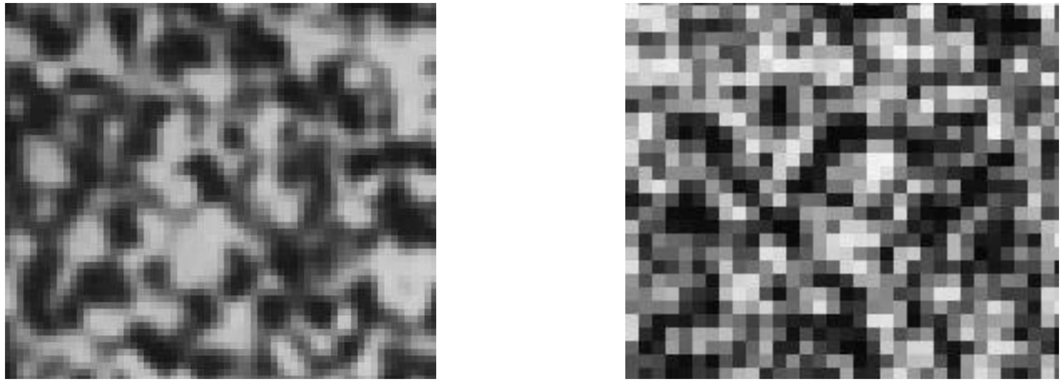






EMC Jones (2018) *Exp. Mech.* 58:1133-1156

Image credit



DIC Challenge Sample 6, www.sem.org/dicchallenge
P. Reu (2011) *Exp. Mech.* 51(4):443-452

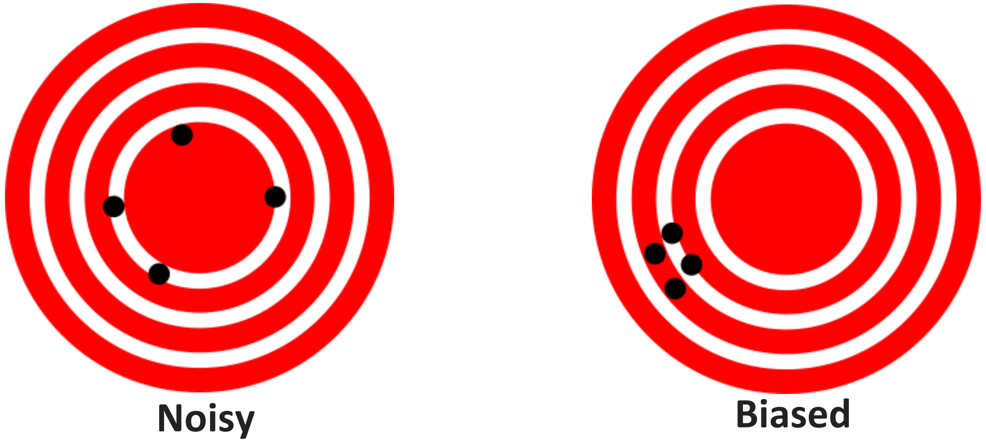
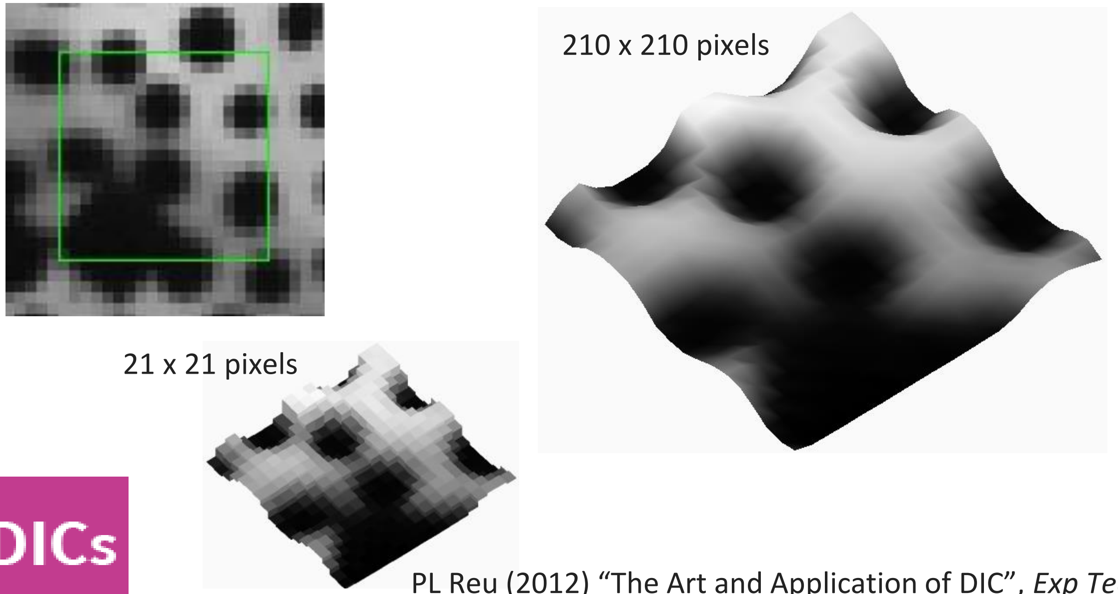
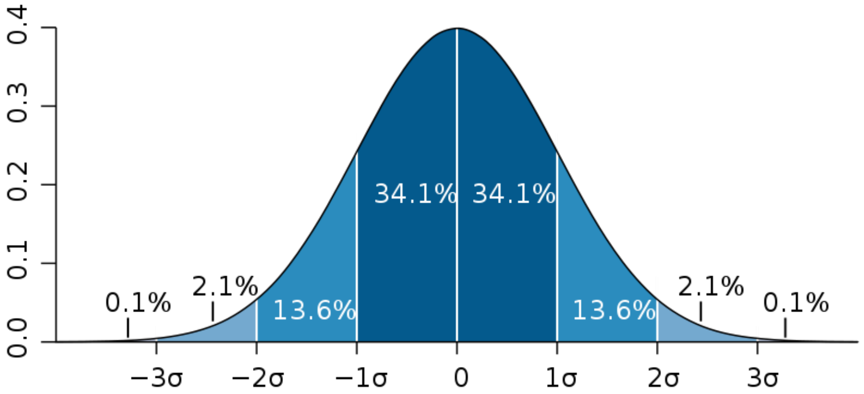


Image credit: DarkEvil. Images available at:
https://en.wikipedia.org/wiki/Accuracy_and_precision



PL Reu (2012) “The Art and Application of DIC”, *Exp Tech*, 36:3-4



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https://en.wikipedia.org/wiki/File:Standard_deviation_diagram.svg