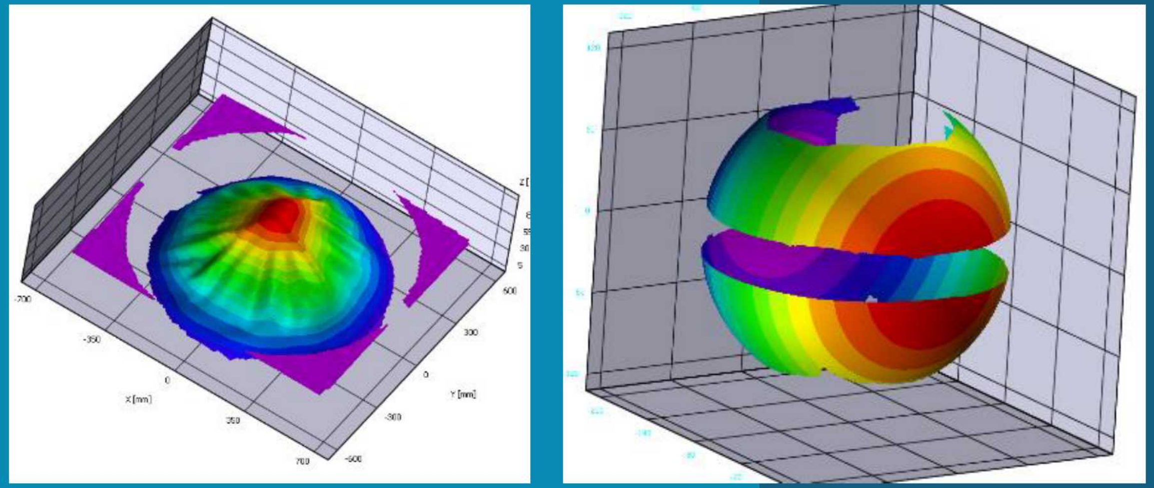
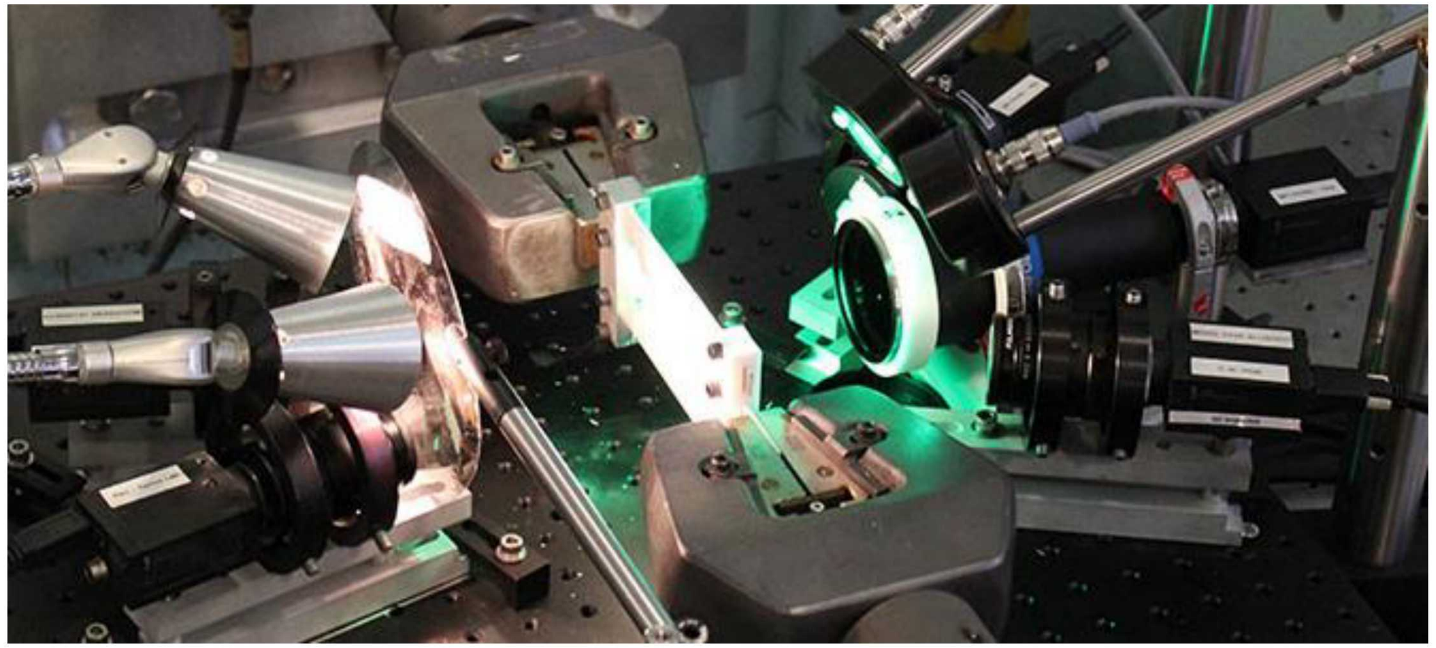
INTERNATIONAL
DIGITAL IMAGE CORRELATION
SOCIETY

SAND2019-12395PE

DIC 201 – Beyond the Good Practices Guide





PRESENTED BY

Phillip Reu & Mark Iadicola

Beyond the good practices guide (GPG)

DIC 201 – Beyond the Good Practices Guide (GPG)

Goals

- Go beyond and below the GPG
- Understand where the GPG recommendations come from.
- Understand how to design and setup a DIC experiment.
- How do you choose the best lens or camera for your DIC experiment
- Principles for DIC hardware setup
- What makes a good DIC pattern.
- Understanding the calibration process
- Smart DIC analysis: VSG, parameter studies, *spatial resolution*
- Applicable to all DIC software implementations.

Non Goals

- Learn to write DIC software.

Minimizing measurement uncertainty is the guiding principle!

Look inside ↓

iDICs INTERNATIONAL DIGITAL IMAGE CORRELATION SOCIETY

A Good Practices Guide for Digital Image Correlation

Standardization, Best Practices, and Uncertainty Quantification Committee

September 2017

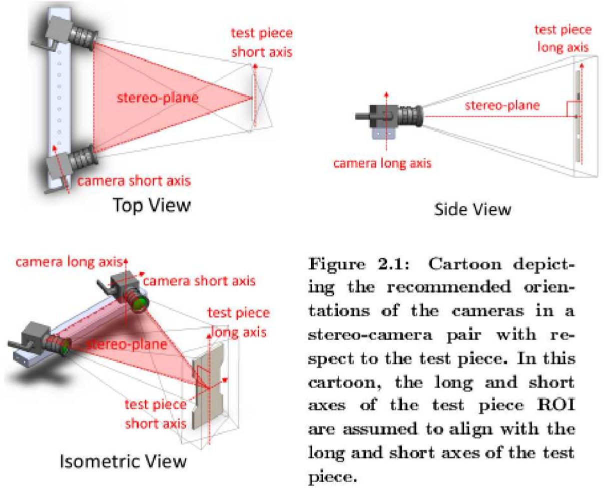


Figure 2.1: Cartoon depicting the recommended orientations of the cameras in a stereo-camera pair with respect to the test piece. In this cartoon, the long and short axes of the test piece ROI are assumed to align with the long and short axes of the test piece.

- For stereo-DIC, mount both cameras rigidly together to avoid relative camera motion.[3] See Sec. 2.2.2.2 for more information on common types of mounting systems.

Caution!

Any relative motion of one camera with respect to the second camera will induce errors in DIC measurements.[a] While these errors can be compensated for to some degree with post-processing calibration corrections,[b] avoiding relative camera motion is much more strongly preferred. Therefore, rigid mounting is critical!

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[a] If both cameras move together rigidly with respect to the test piece, only rigid-body DIC displacements are affected. For most applications where rigid-body motion is not important (e.g. strains are the quantity-of-interest), this rigid-body displacement error is inconsequential.

[b] Rigid-body motion of the stereo-camera *pair* can be corrected for in post-processing if there is a fixed reference point somewhere in the field-of-view. However, correcting for relative motion of one camera with respect to the second camera requires adjusting the extrinsic parameters of the calibration (Sec. 3.2), but this type of correction is outside the scope of this edition of the guide.

These notes refer to a pertinent location in the GPG.

iDICs

Section x.x.x – Guide Chapter

Caution x.x – Guide Warnings

Tip x.x – Guide tips

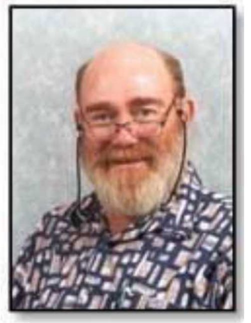
Recommendation x.x – Guide Recommendations

History of DIC

1980 – Ranson & Peters
- 2D
- Through-thickness averaged
- Ultra-sound based
- Scanned images to estimate surface displacements

1996 – Helm & McNeill et al
- Robust stereo-vision system
- Aero-structures and lab scale

2006 – Hild, Roux & Sun, et al
- FE-DIC
- Full-field Material ID

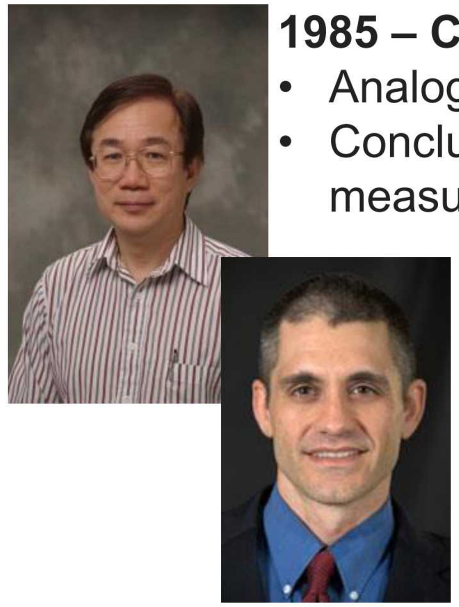


1980 – Cheng, Sutton, & Wolters
- Non-linear least squares using gradients
- Matched local displacements

2000 – Bay et al
- Digital volume correlation (DVC)
- Used computed tomography

2012 – Reu
- Art and Application of DIC Articles
- DIC Course with Lava – Pierron
- DIC Challenge

1980 1985 1990 1995 2000 2005 2010 2015

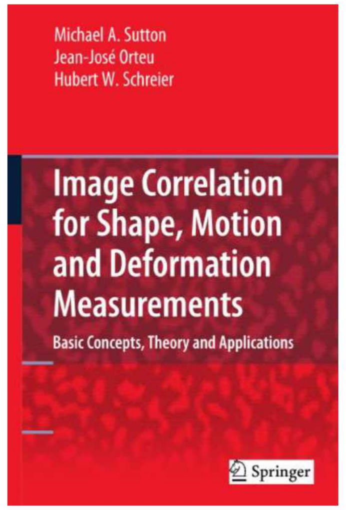


1985 – Chu et al
- Analog camera to record speckle pattern
- Conclusively demonstrated that DIC can measure displacements

1989 – Bruck et al
- Increased speed using Hessian-based method
- Linear shape function on subset matching

1993 – Luo & Chao et al
- Robust stereo-vision system
- Demonstrated on full-scale aero-structures

2009 – Sutton, Orteu & Schreier
- The Book



Michael A. Sutton
Jean-José Orteu
Hubert W. Schreier

Image Correlation for Shape, Motion and Deformation Measurements

Basic Concepts, Theory and Applications

Springer

2016 – 1st iDICs

iDICs INTERNATIONAL DIGITAL IMAGE CORRELATION SOCIETY

SEM Sandia National Laboratories

iDICs 2016 Conference and Workshop
SEM Fall Conference
November 7 – 10, 2016 in Philadelphia, PA

Mission: Extend – Improve – Train
Extending the Frontiers — Training the next Generation
Standardizing for Industry — Improving our Practice
Website: www.idics.org

2018 – 1st GPG from iDICs

iDICs INTERNATIONAL DIGITAL IMAGE CORRELATION SOCIETY

A Good Practices Guide for Digital Image Correlation

Standardization, Good Practices, and Uncertainty Quantification Committee

October, 2018

History References: M. Sutton – Murray lecture at SEM 2013. Supplemented by Reu

There are a large number of commercial vendors and professional societies supporting DIC

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DIGITAL IMAGE CORRELATION
SOCIETY

Sister Societies

SEM
BSSM BRITISH SOCIETY FOR STRAIN MEASUREMENT
ASEM
ICEM 2018
PM 2018 Photo Mechanics

Committee Meetings

- Standards & Best Practices – Mark Iadicola
- Training & Certification – Tim Schmidt
- Applications – Dave Dawicke
- Education – Mark Pankow
- DIC Challenge – Phillip Reu

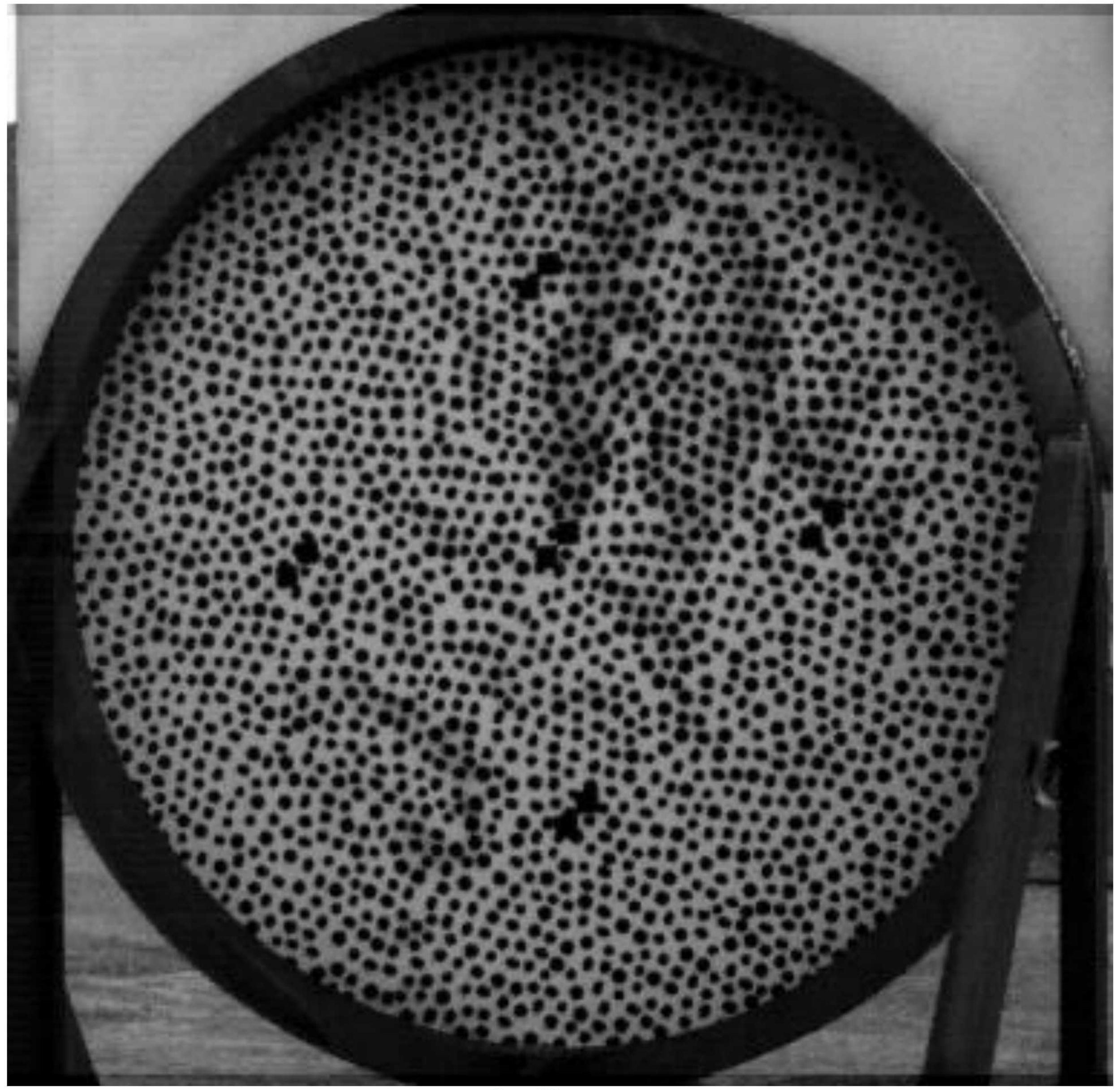
Mission: Extend – Improve – Train

Extending the Frontiers: Training the next Generation:
Standardizing for Industry: Improving our Practice

IDICs Corporate Members and Commercial DIC Vendors

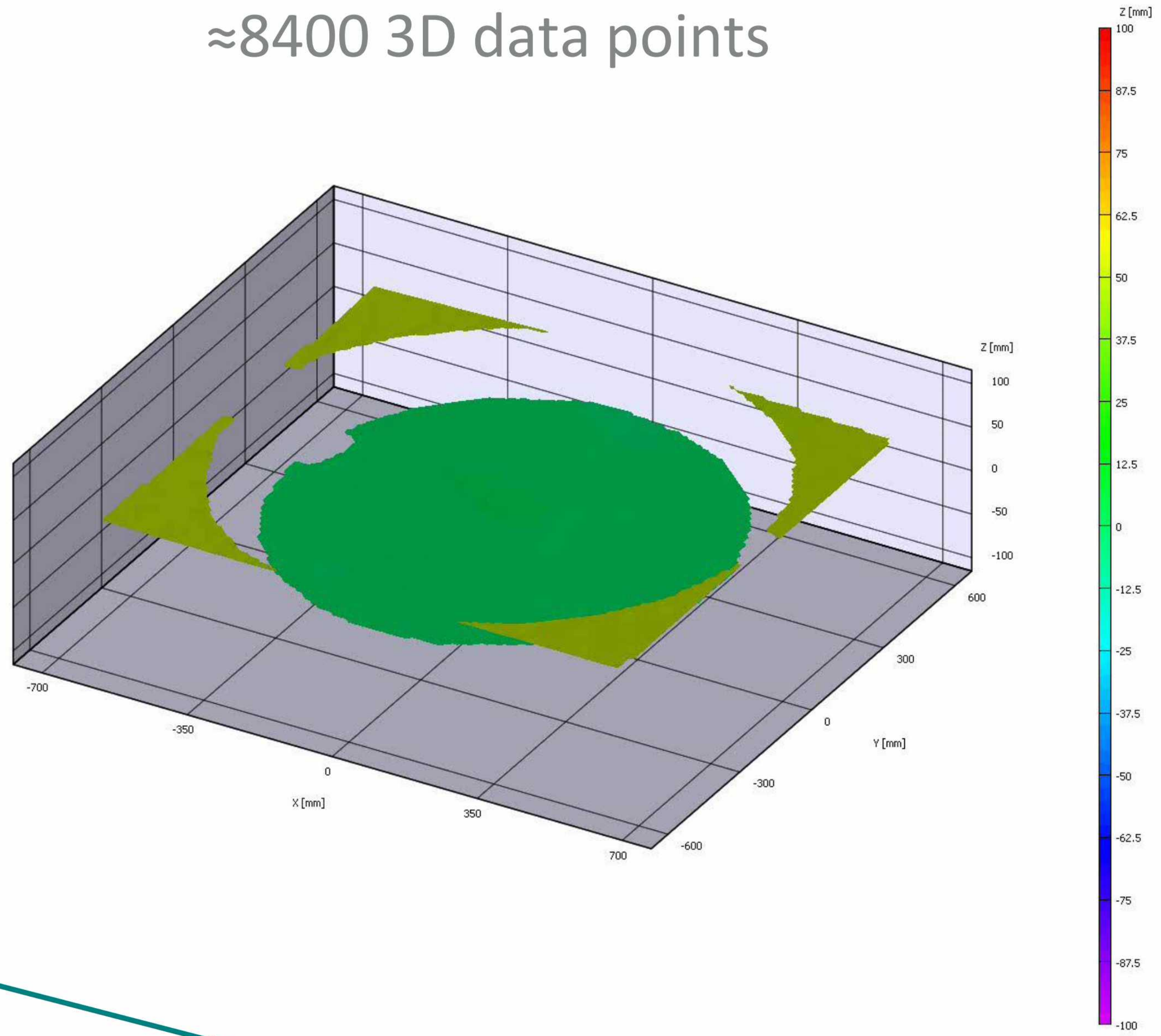
Sandia National Laboratories
NIST National Institute of Standards and Technology U.S. Department of Commerce
correlated SOLUTIONS
gom
Specialised Imaging
LaVision FOCUS ON IMAGING
DANTEC DYNAMICS Turn Measurements into Knowledge
MatchID Metrology beyond colors
HADLAND IMAGING
nac IMAGE TECHNOLOGY
Photron
Trilion
RuituoTech
image SYSTEMS
dom13
Correli STC Link between Experiment and Simulation

What is Digital Image Correlation (DIC)? It is a full-field image based shape, deformation and strain measurement technique.



≈1.2 m

≈8400 3D data points



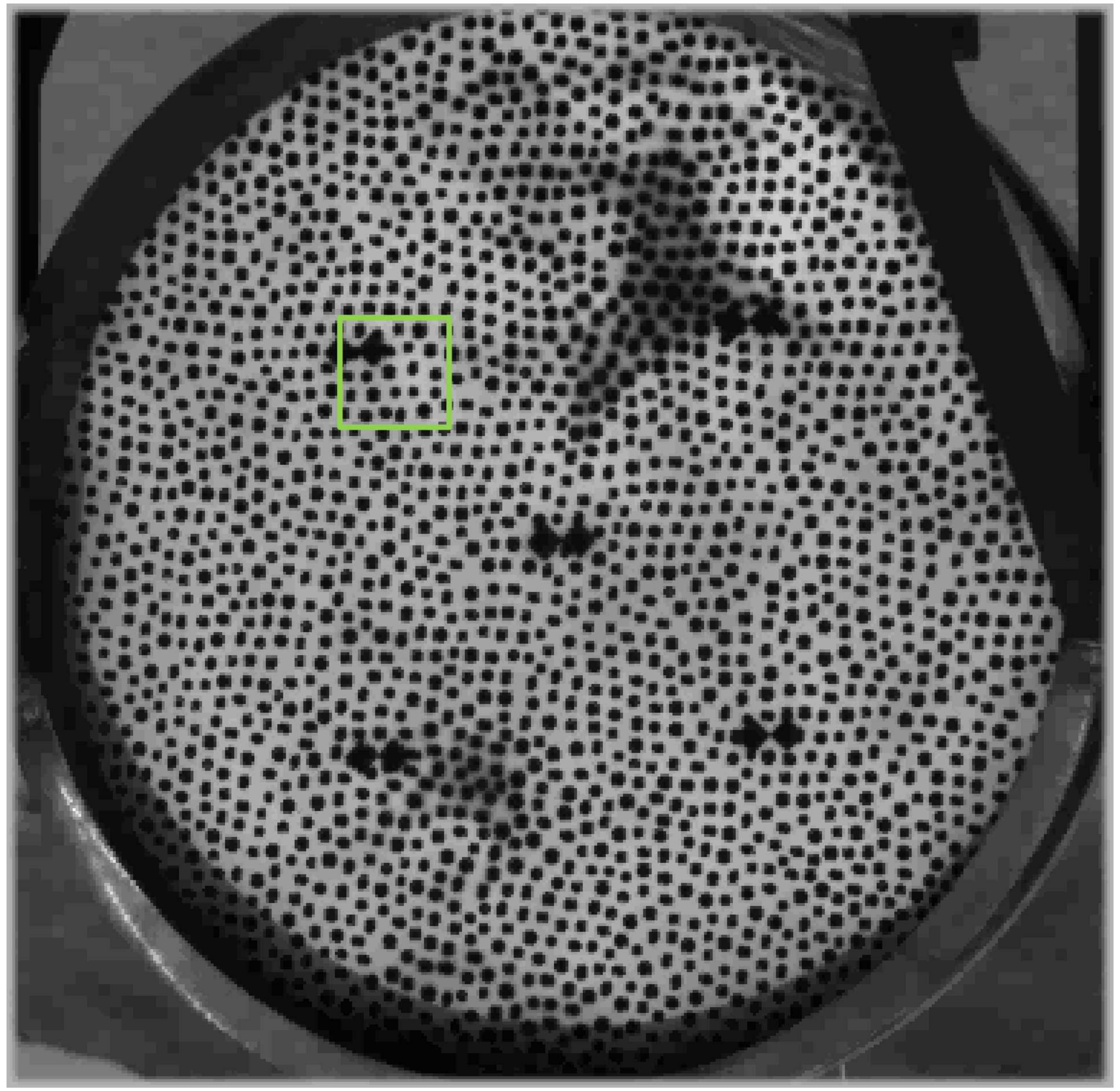
≈7.6 m

What is DIC?

1. Photogrammetry technique used in engineering.
2. Full-field shape, displacement, strain, velocity, etc.
3. What support do we have for DIC training, standards, and certification.

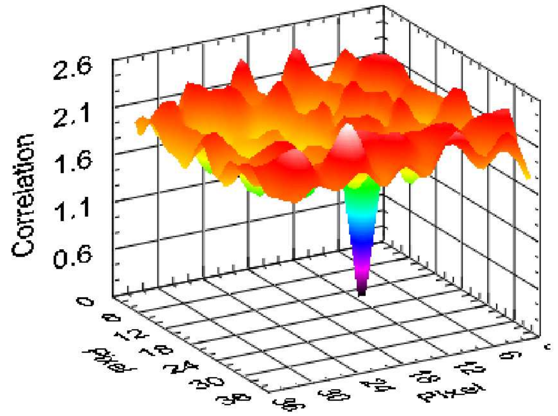
iDICs

2D-DIC: Keep the dots in the box[†]

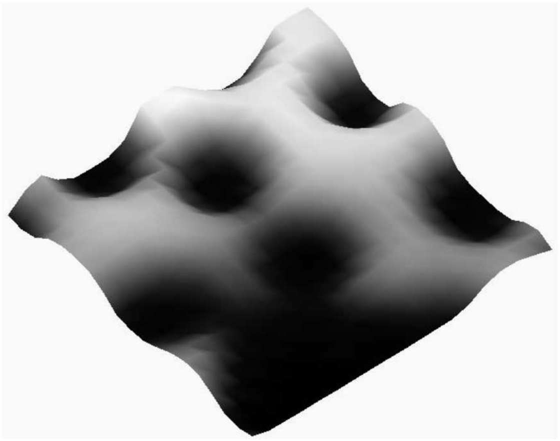


3 Hidden components of DIC[‡]

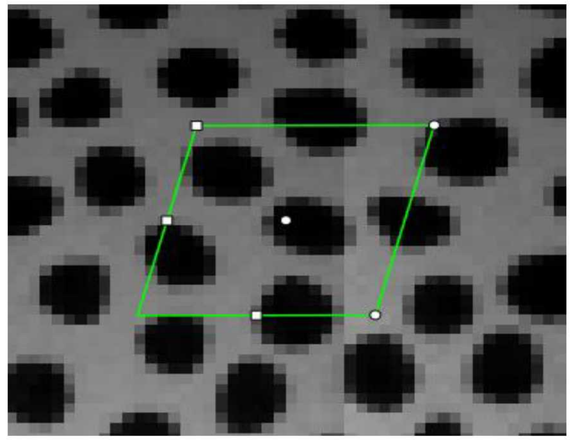
Matching



Interpolation



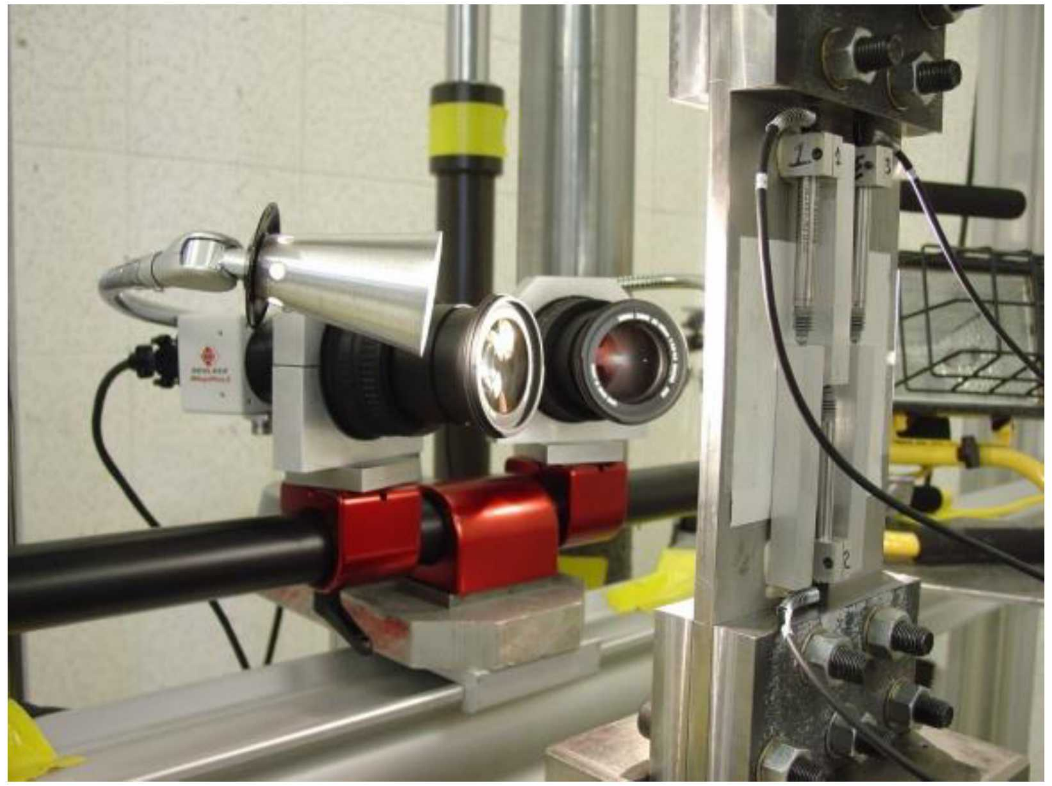
Shape Function

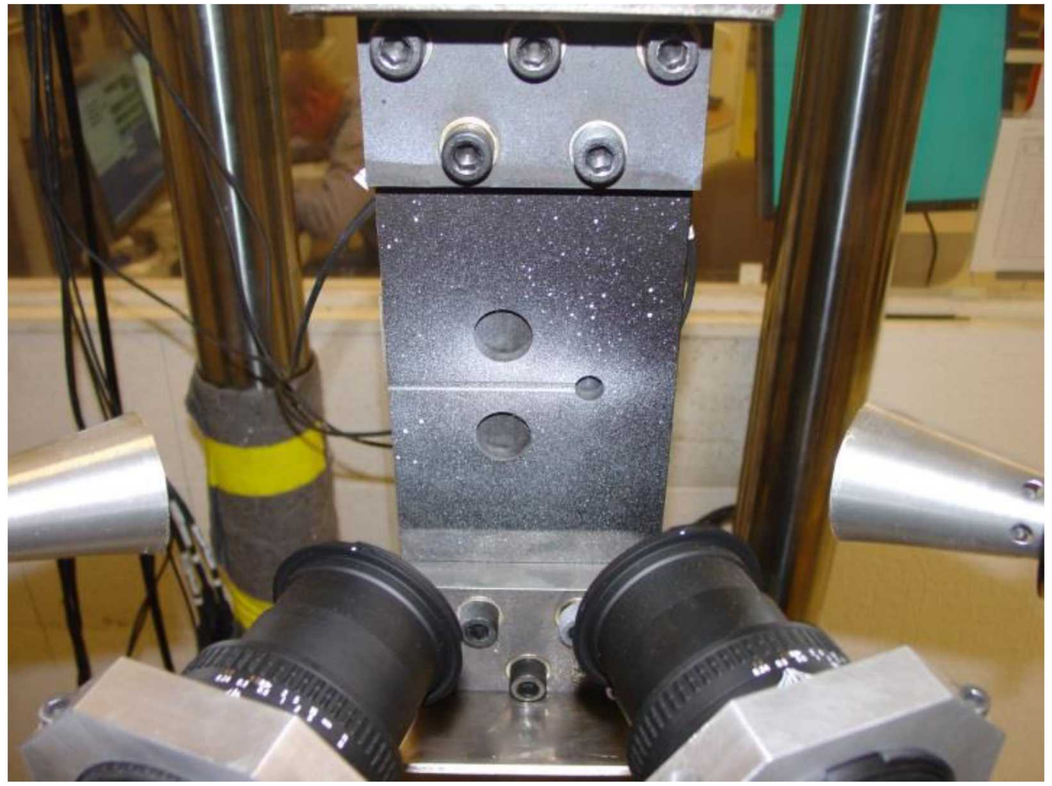


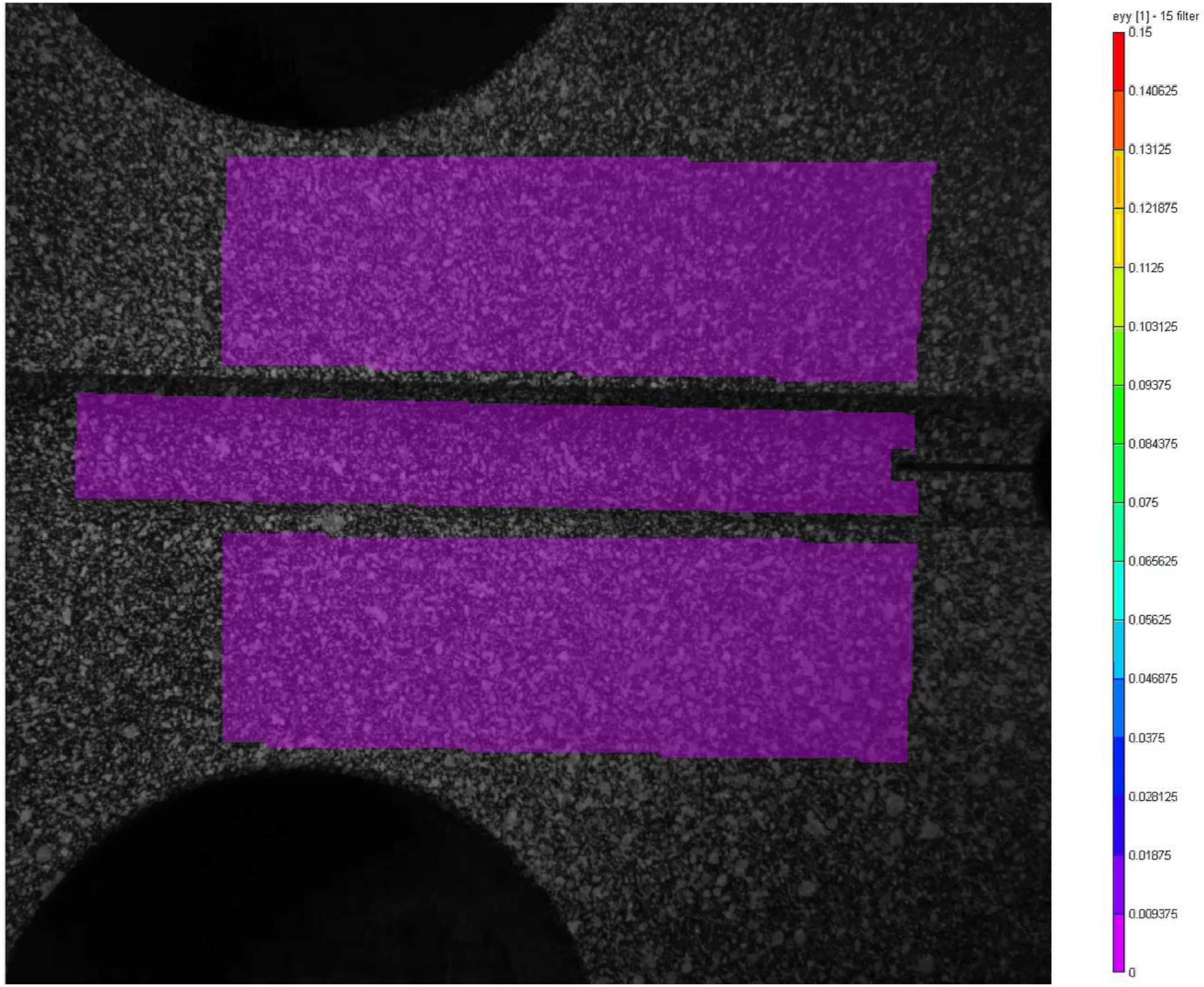
[†] Samantha Daly

[‡] Phillip Reu – Experimental Techniques "Art and Application of DIC"

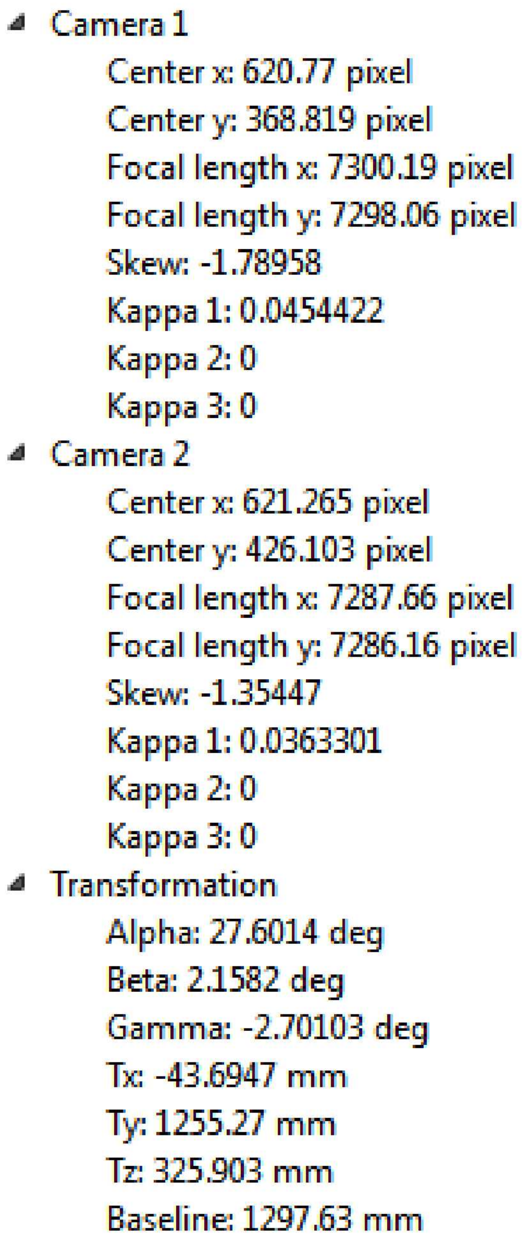
Stereo-DIC uses two cameras at an angle to measure the shape and deformation.





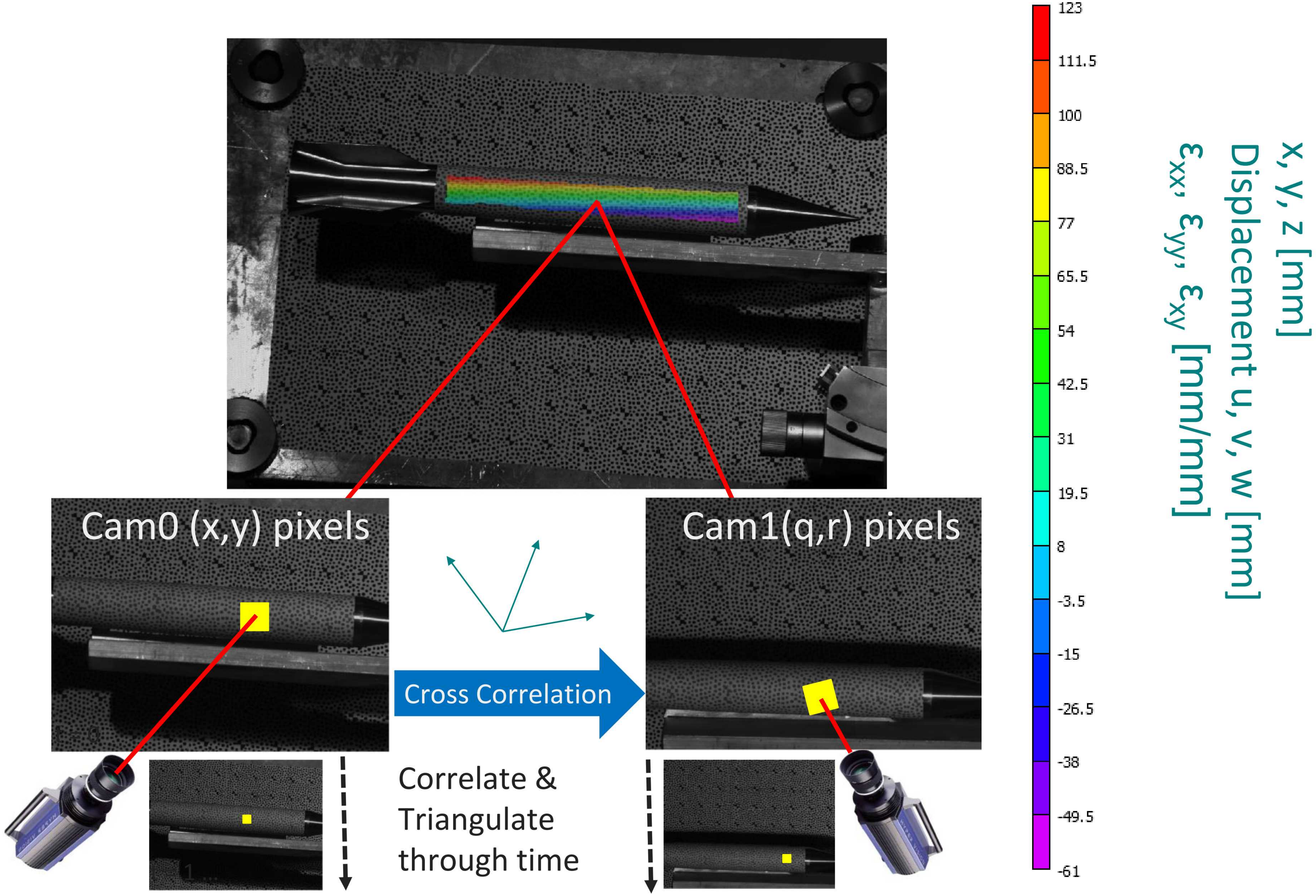


Triangulation uses the calibration and the matched pixel locations in two images to find the 3D point in space



- Camera 1
  - Center x: 620.77 pixel
  - Center y: 368.819 pixel
  - Focal length x: 7300.19 pixel
  - Focal length y: 7298.06 pixel
  - Skew: -1.78958
  - Kappa 1: 0.0454422
  - Kappa 2: 0
  - Kappa 3: 0
- Camera 2
  - Center x: 621.265 pixel
  - Center y: 426.103 pixel
  - Focal length x: 7287.66 pixel
  - Focal length y: 7286.16 pixel
  - Skew: -1.35447
  - Kappa 1: 0.0363301
  - Kappa 2: 0
  - Kappa 3: 0
- Transformation
  - Alpha: 27.6014 deg
  - Beta: 2.1582 deg
  - Gamma: -2.70103 deg
  - Tx: -43.6947 mm
  - Ty: 1255.27 mm
  - Tz: 325.903 mm
  - Baseline: 1297.63 mm

Triangulate



Cam0 (x,y) pixels

Cam1(q,r) pixels

Cross Correlation

Correlate & Triangulate through time

x, y, z [mm]

Displacement u, v, w [mm]

ε_{xx}, ε_{yy}, ε_{xy} [mm/mm]

iDICs

INTRODUCING UNCERTAINTY QUANTIFICATION FOR DIC

NICE TO MEET YOU. HOW WELL DO I KNOW YOU?

Literature on UQ is accessible to all.

1. BIPM, *Evaluation of measurement data – Guide to the expression of uncertainty in measurement. JCGM 100:2008, 2008.*
2. Coleman, H.W. and W.G. Steele, *Experimentation, validation, and uncertainty analysis for engineers. 2009: John Wiley & Sons.*
3. Bell, S., *A beginner's guide to uncertainty of measurement, N.P. Laboratory, Editor. 1999: UK.*
4. Taylor, B.N.K., Chris E., *Guidelines for evaluating and expressing the uncertainty of NIST measurement results, NIST, Editor. 1994, NIST.*


BIPM

JCGM 100:2008
GUM 1995 with minor corrections

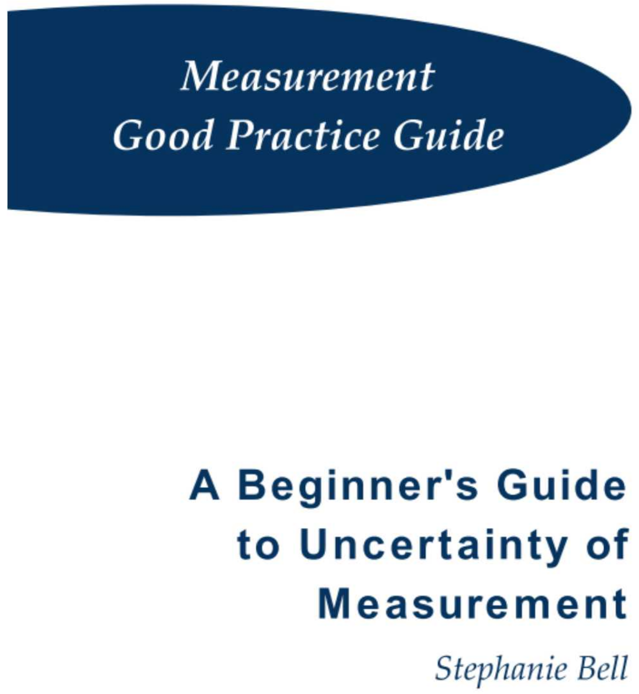
Evaluation of measurement data — Guide to the expression of uncertainty in measurement

Évaluation des données de mesure — Guide pour l'expression de l'incertitude de mesure

METPΩ XPΩ

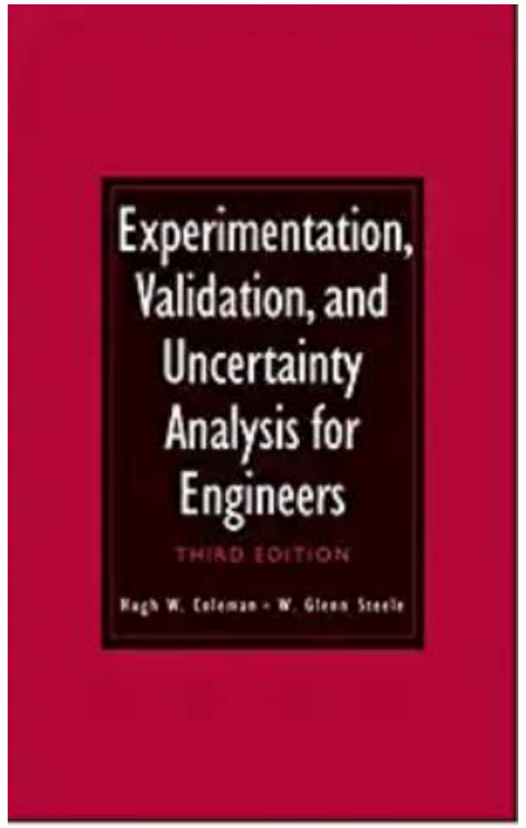
First edition September 2008

© JCGM 2008


Measurement
Good Practice Guide

A Beginner's Guide to Uncertainty of Measurement

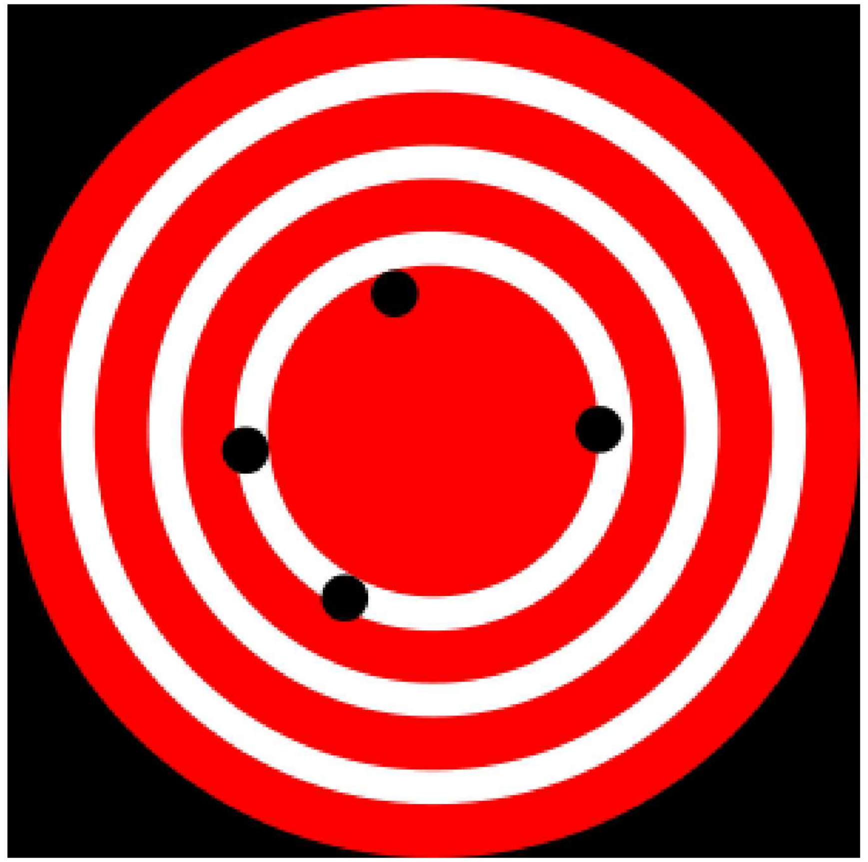
Stephanie Bell


Experimentation, Validation, and Uncertainty Analysis for Engineers

THIRD EDITION

Hugh W. Coleman • W. Glenn Steele

Two types of errors: Random and Systematic



Accurate but not Precise

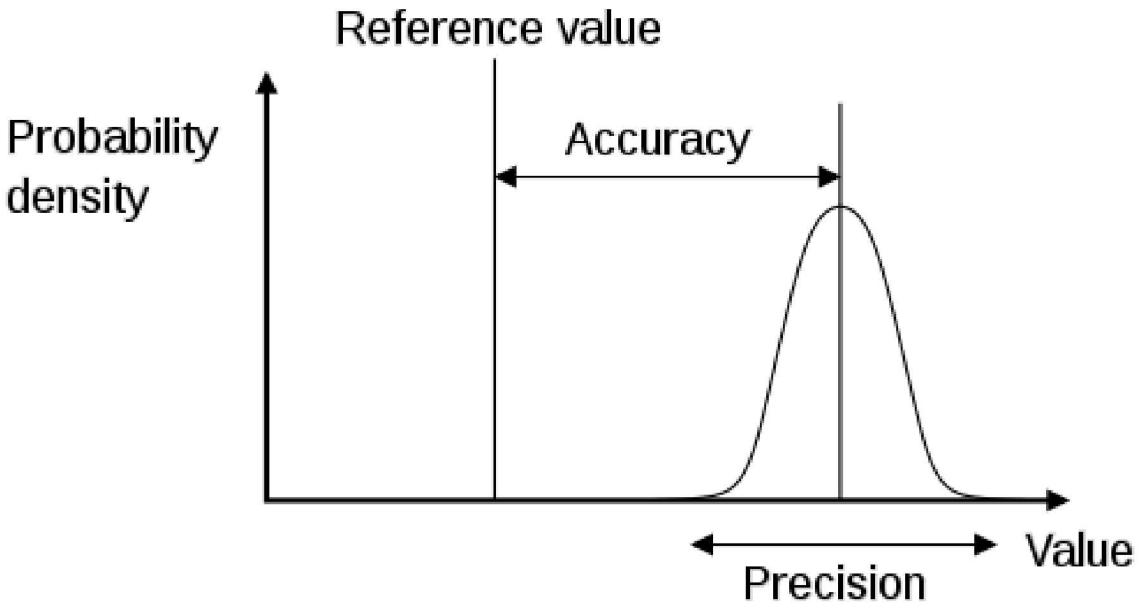
Large *Random* Error

Small *Systematic* Error

Precise but not Accurate

Small *Random* Error

Large *Systematic* Error



Words used interchangeably

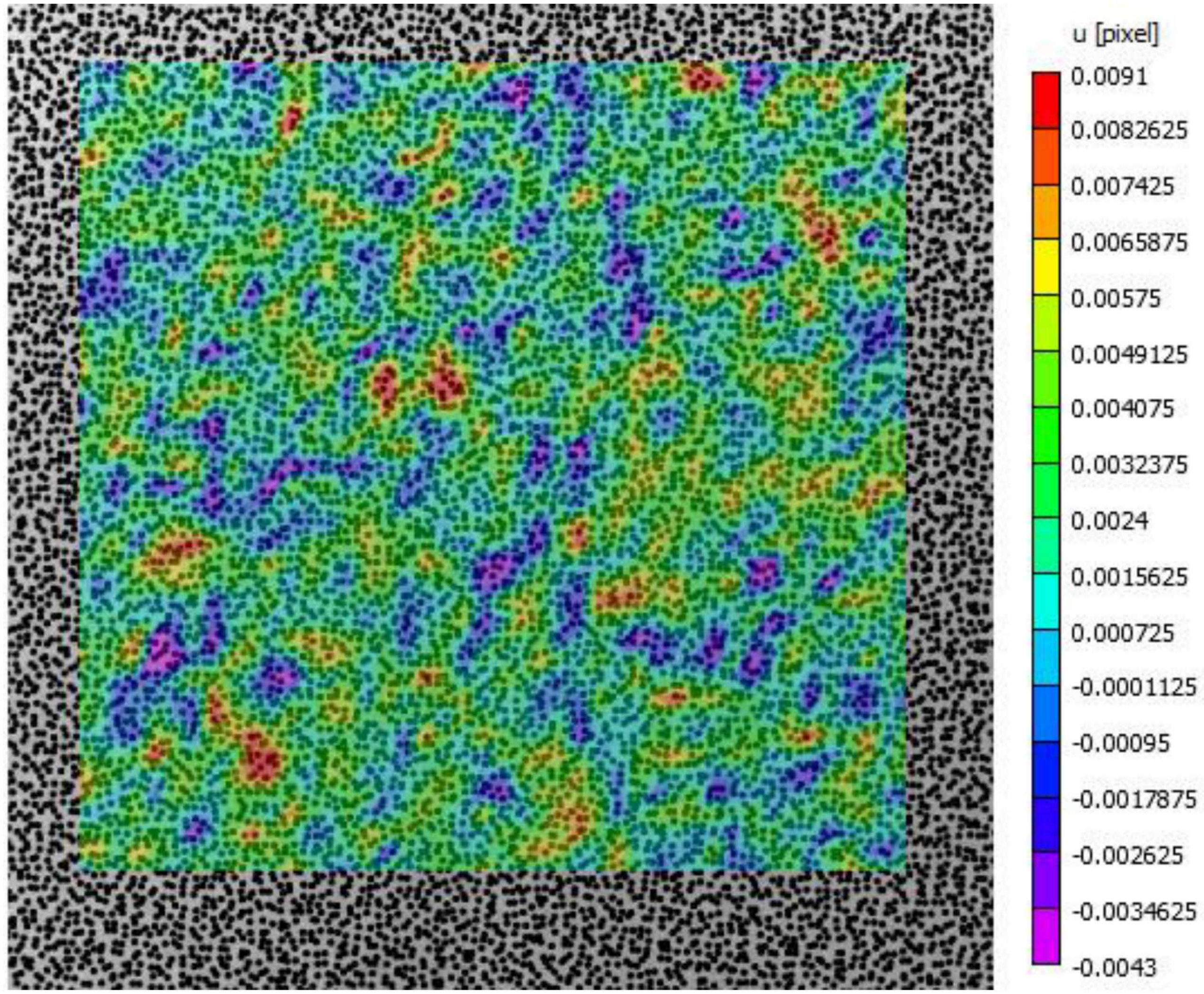
Bias = Systematic Error = Persistent

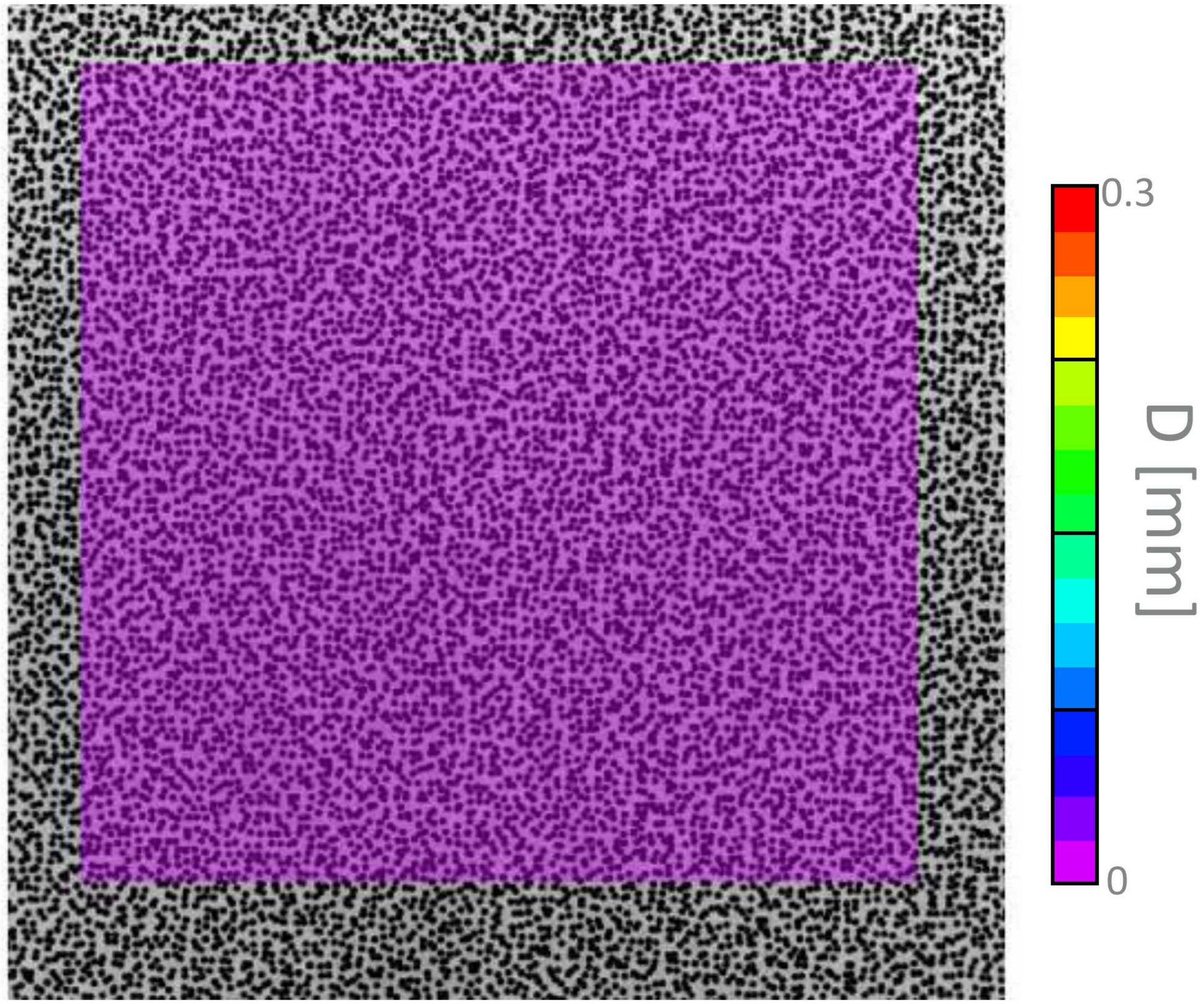
Noise = Variance = Random Error = Volatile

The new view is to categorize as Type A and Type B Error assessments

Image from Wikipedia

Example of random and systematic errors





Random, Noise, Variance error

- Caused by image noise.
- Random pattern by nature.
- Quantified statistically
- “Accurate” not “Precise”
- Type A

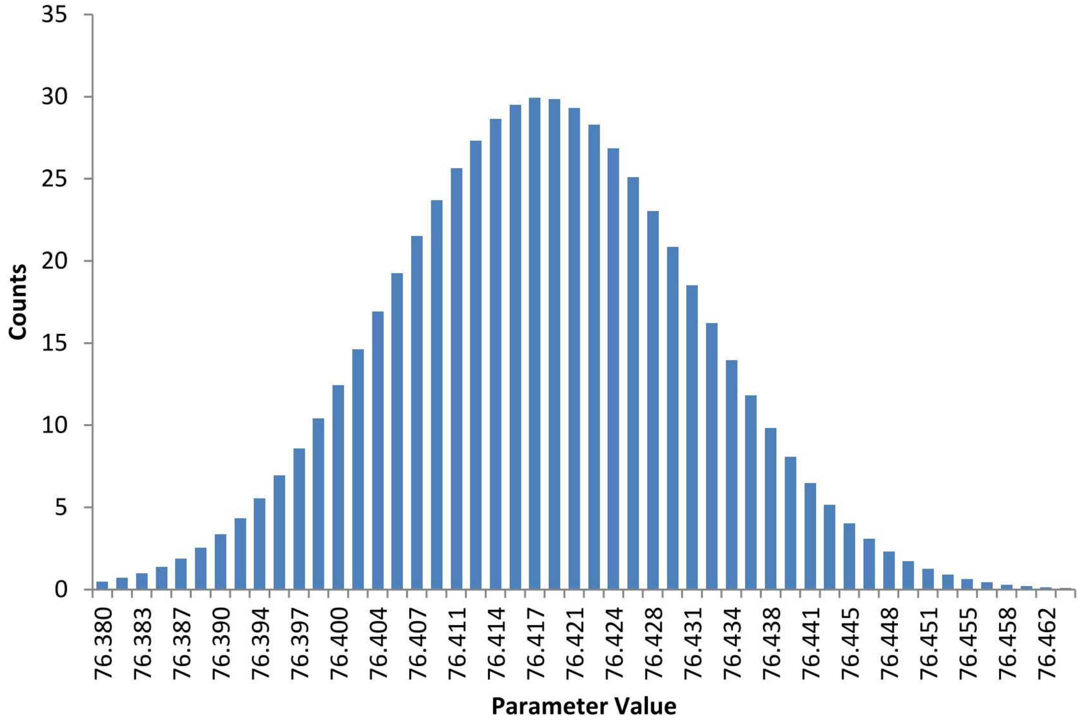
Bias, Systematic, Persistent error

- Caused by air index changes
- Typically causes an “offset”
- Quantified by other means
- Type B

A newer approach assesses errors with two types: Type A and Type B

Type A – Evaluated via statistical methods
- Repeated measurements
- Statistical distributions
  - Normal, Log-normal, etc.

Type B – Evaluated by other means
- Modeling approaches
- Assumed probability distribution
- Experimental expertise



$$Y = f(X_1, X_2, \ldots, X_N)$$

The measurand Y is made up of X other input quantities. The function may be so complicated that it cannot be written down (Section 4.1.2).

Mathematical modeling of the experiment taking into account all error sources is a valid and approved method of estimating uncertainty. (Section 3.4.1)

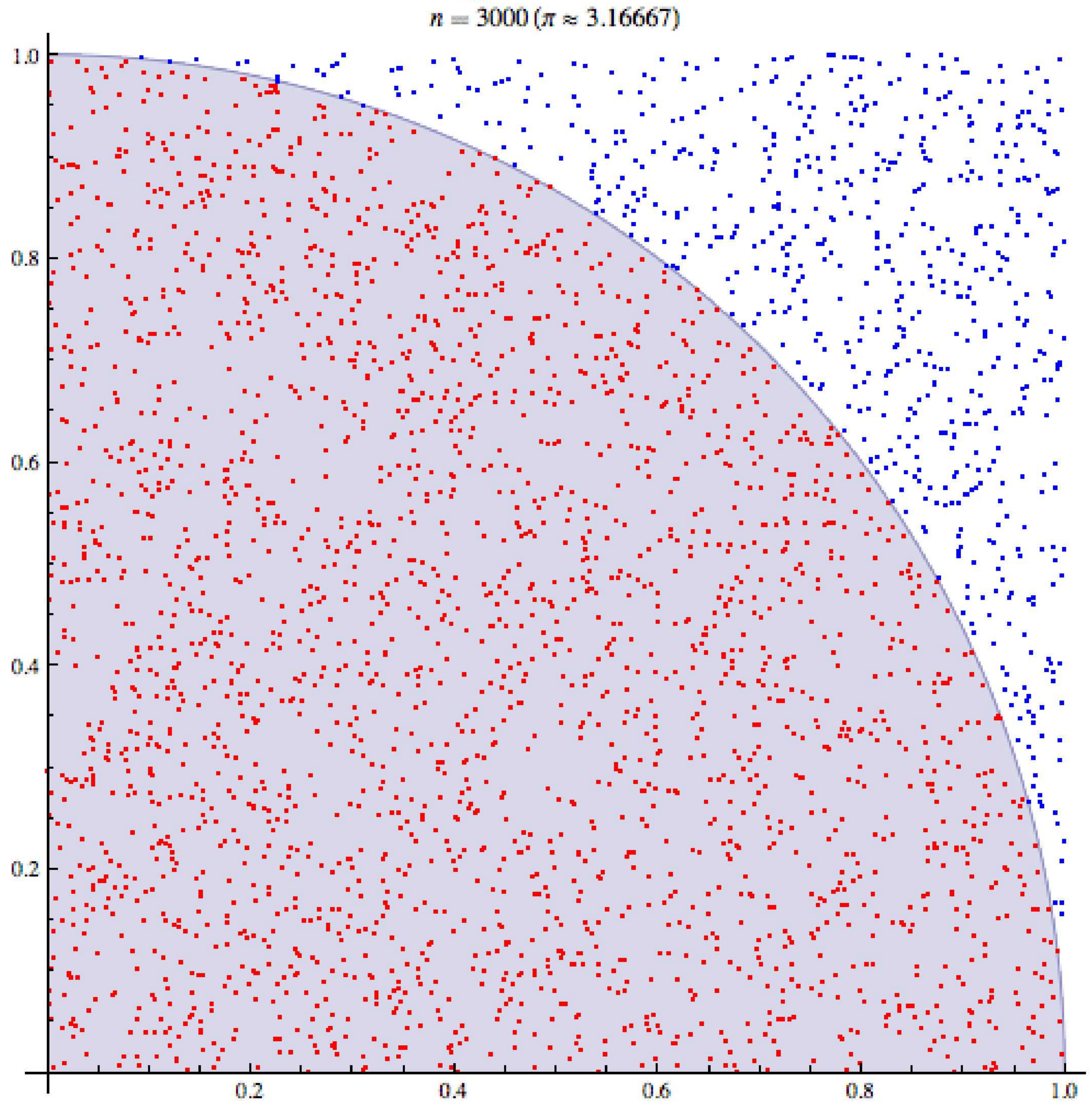
BIPM (2008). "Evaluation of measurement data…" JCGM 100:2008.

Monte Carlo is a good approach for quantifying uncertainty in difficult cases.

Randomly scatter grains in the square. Find the ratio of the grains in the circle, which is π/4. With 30,000 samples, π is known within 0.07%.

Monte Carlo techniques allow you to probe a model by running many "experiments" while varying the inputs. The output quantities can then be statistically analyzed.

Estimating π via Monte Carlo



Wikipedia

There is an important difference between the definition of "error" and "uncertainty".

Error

- Difference between the measured value and the "true" value (often unknown).
- Sometimes described as bias (persistent) and random (volatile).

Uncertainty[†]

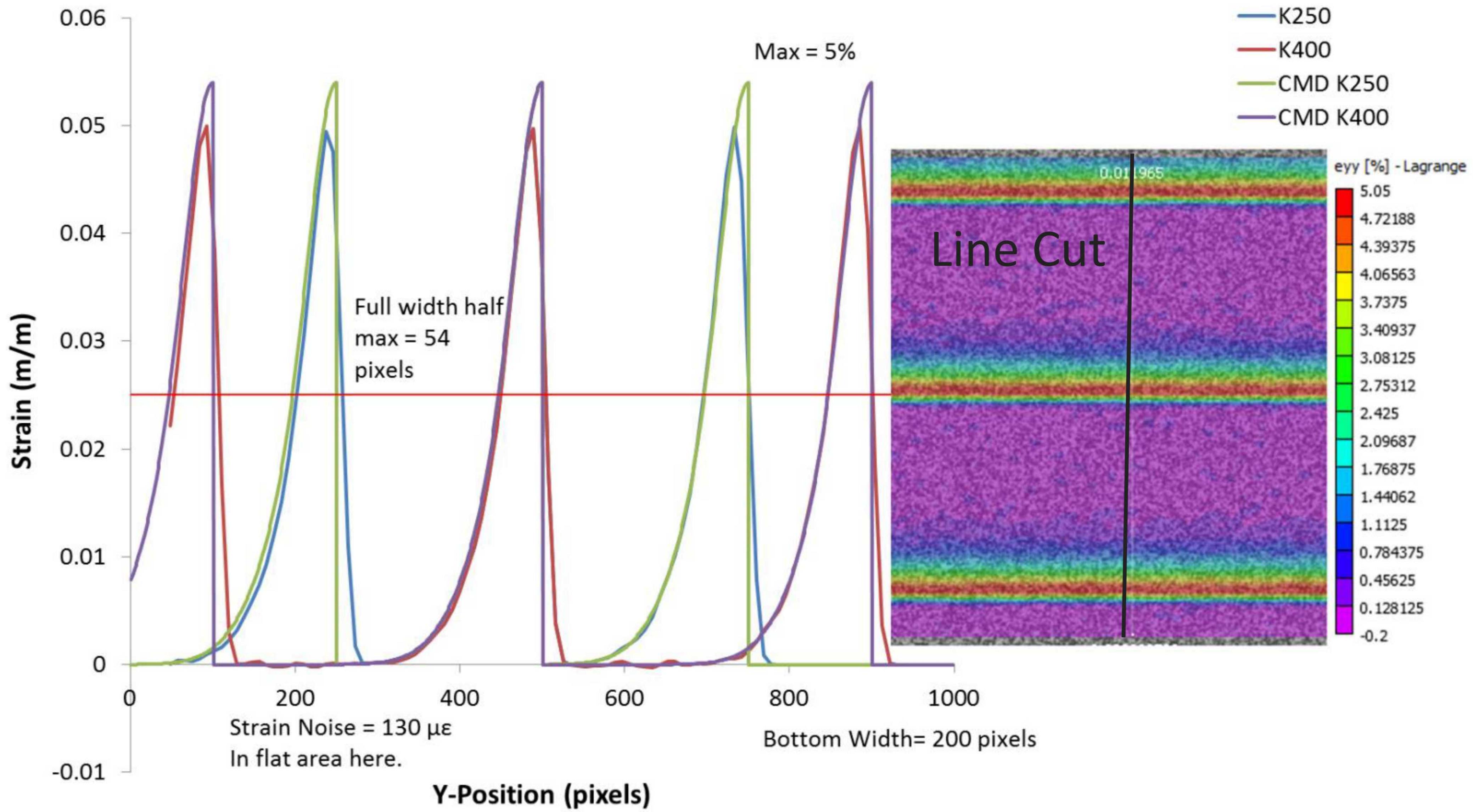
- "Is the doubt that exists about the result of any measurement".
- Determined using standard methods: Type A and Type B.
- Expressed using an interval, standard uncertainty, and a confidence level.
- Standard uncertainty (u) is the standard deviation (s) divided by square root of number of samples (N).

$$u = \frac{s}{\sqrt{N}}$$

[†] **Bell, S.** (1999). A beginner's guide to uncertainty of measurement. N. P. Laboratory. UK.

Error: Difference between a known and measured value.

Simulated or synthetic images provide a “known” displacement field



Max = 5%

Full width half max = 54 pixels

Line Cut

Strain Noise = 130 με
In flat area here.

Bottom Width= 200 pixels

Advantages/Problems with simulated or synthetic images

- You know the answer
- Validates the DIC code
- Investigates numerical issues

- Errors in synthetic image creation.
- **What errors have I missed?**

Bias error, Random error, Type A and Type B: What is the difference?

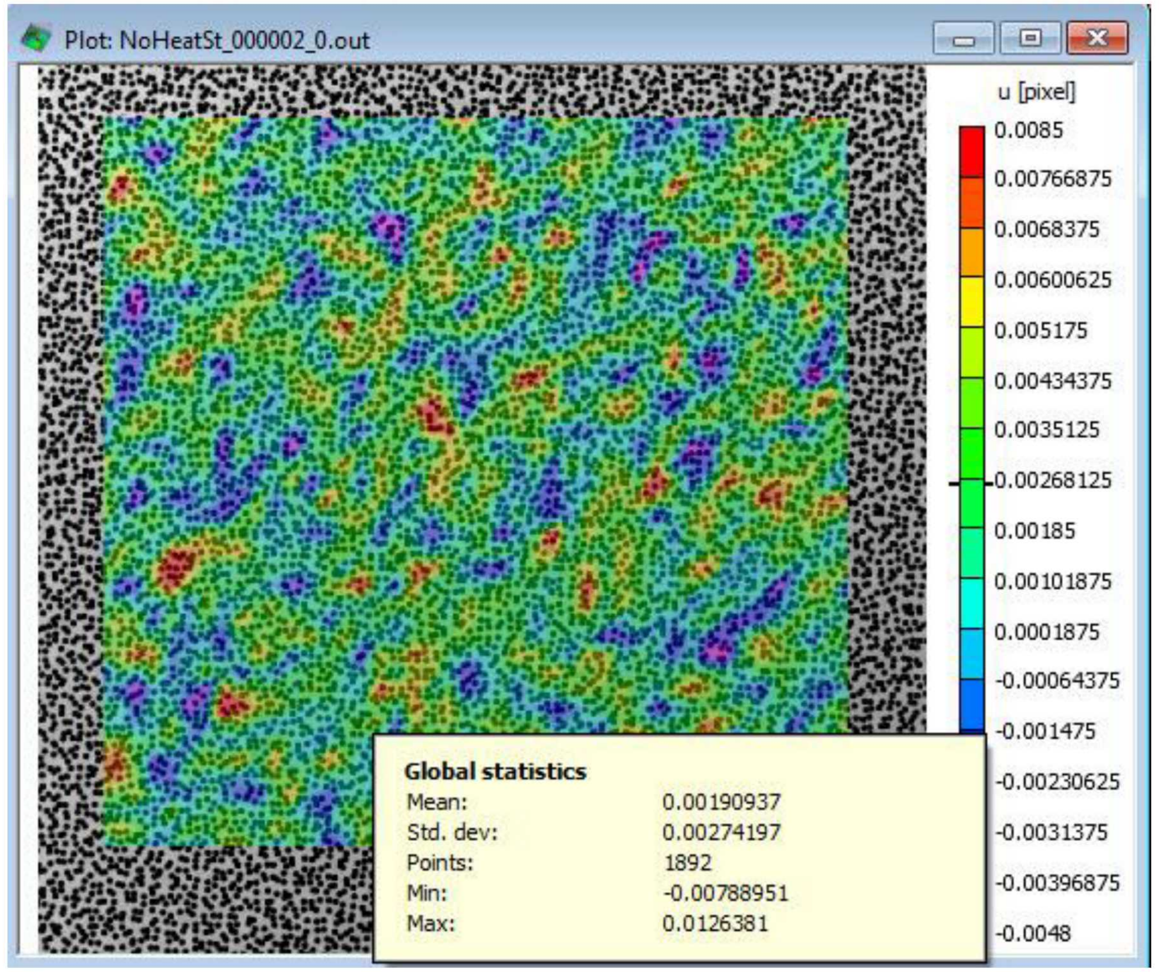
Type A and Type B are methods *of determining error*

- Repeated measurements, uncertainty propagation, etc.
- Both bias and random errors may be assessed with Type A and Type B approaches.

Bias error and random error are descriptions *of the error*

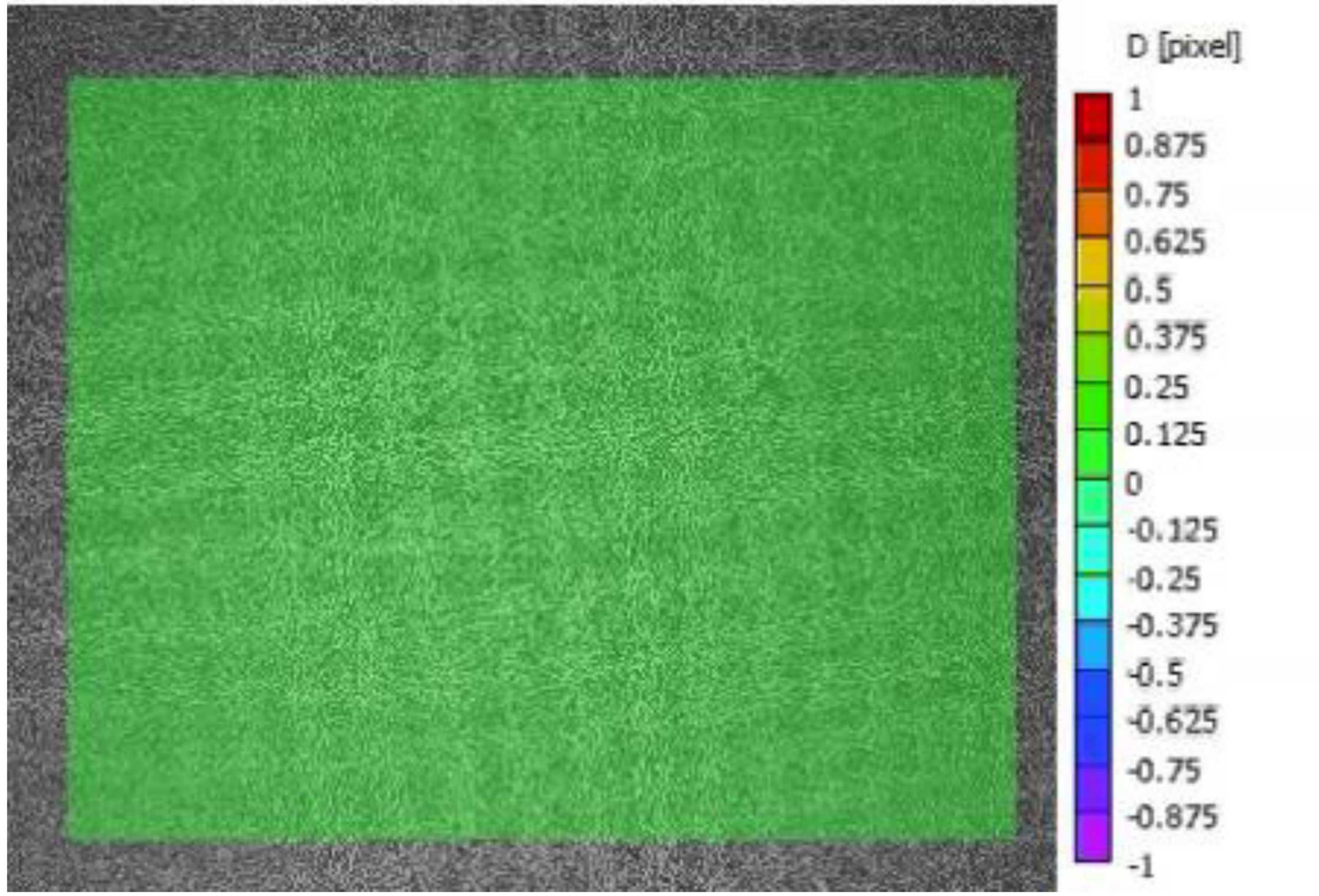
- A bias error is a persistent offset from the true value. Often is corrected reducing it to a variance error.
- In DIC an uncorrectable bias error may occur due to the processing. It may be assessed using a Type B approach: VSG-size study.

DIC noise floor measurements are an example of Type A evaluation.



Global statistics

Mean: 0.00190937
Std. dev: 0.00274197
Points: 1892
Min: -0.00788951
Max: 0.0126381



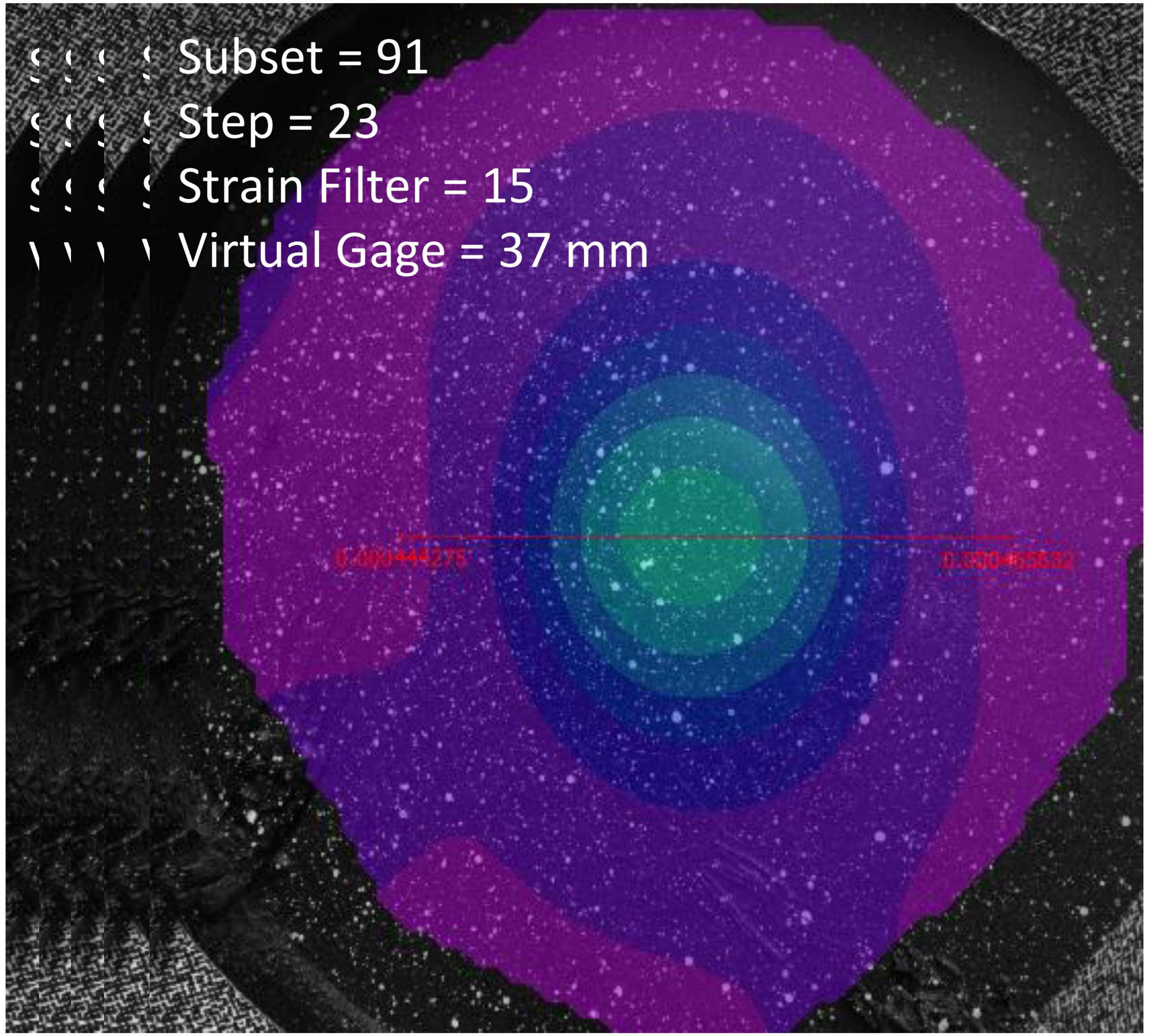
Simple Noise Floor

- 10 Static images
- Analyze the displacement (strain fields) statistically.
- Contains only some of the errors.

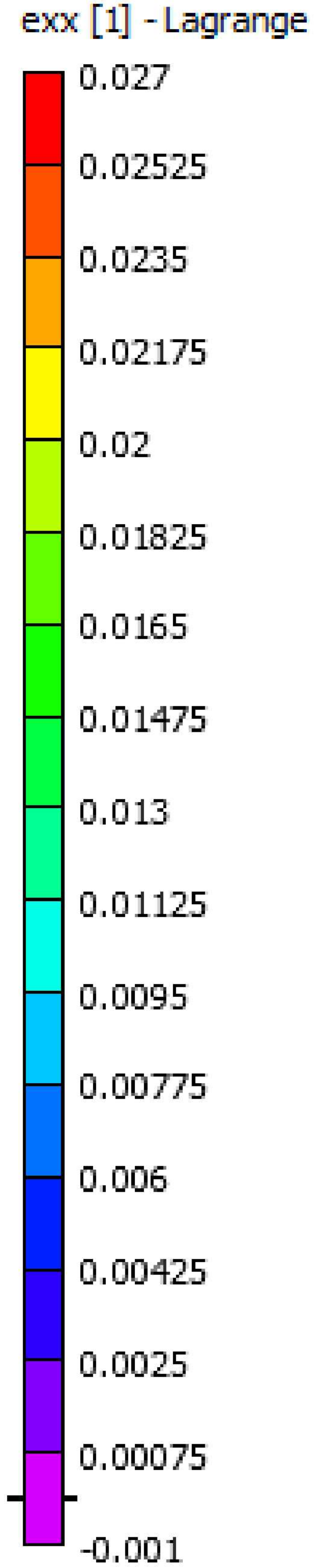
Extended Noise Floor

- Images with rigid-body-motion
- Analyze the displacement (strain fields).
- Contains more of the errors.

Type B example: Virtual strain gage size study



Subset = 91
Step = 23
Strain Filter = 15
Virtual Gage = 37 mm



Type B: Processing Approach

- Varying processing parameters and studying the results!

Top-down versus *bottom-up* uncertainty quantification approach[†].

Top-Down Evaluation

- Does not require study of contributing sources
- Inter-laboratory studies
- Comparisons with a standard
    - Displacement tests
    - Strain gages
    - Shape measurements

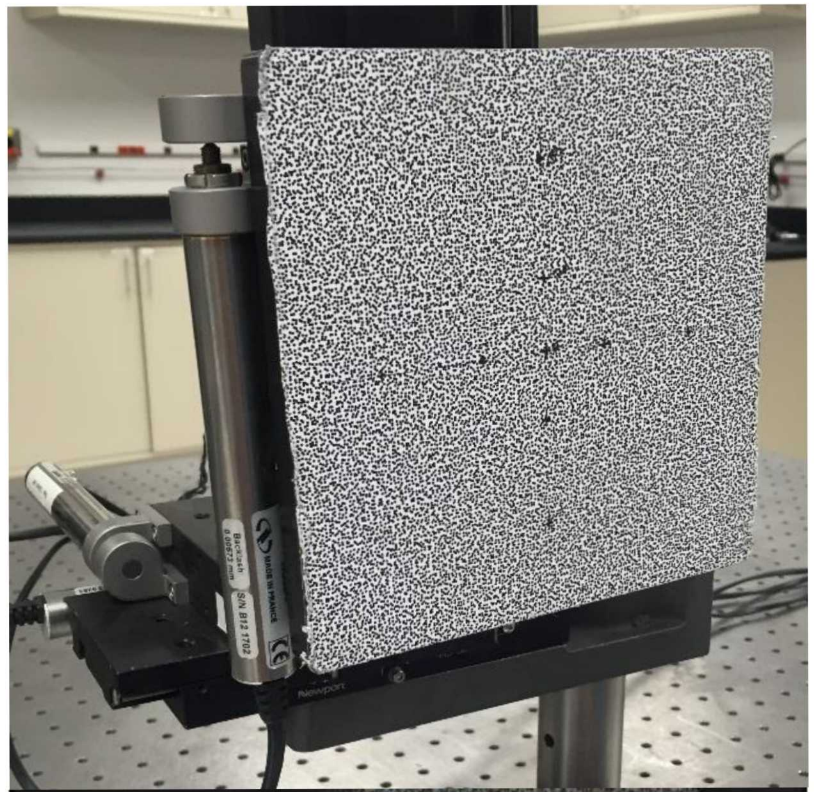
Bottom-Up Evaluation

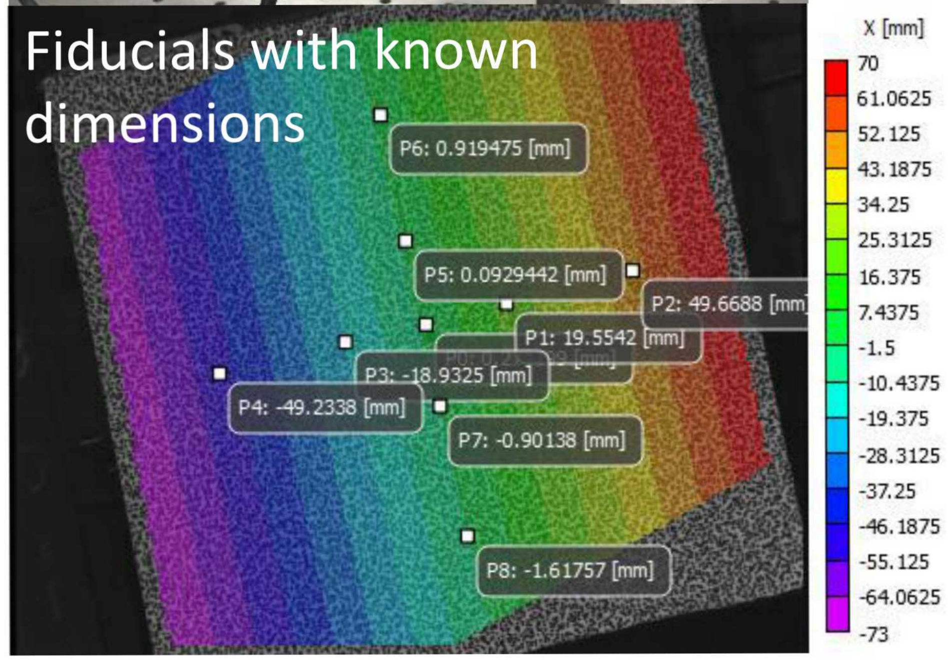
- Complete enumeration of all relevant sources of uncertainty.
- Description of their interplay and UQ influence.
- Characterization of contributions to uncertainty

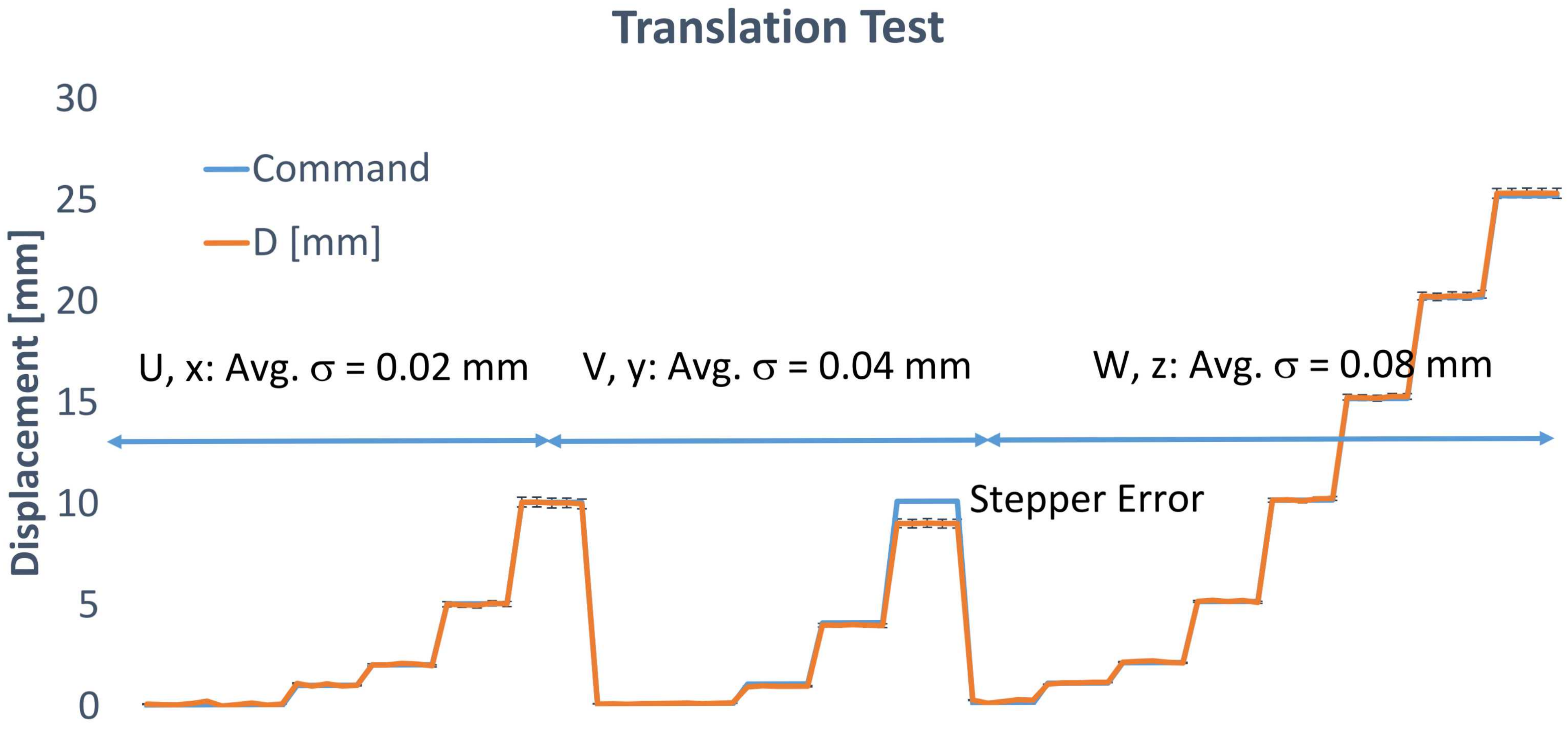
[†] **Possolo, A.** (2015). Simple Guide for Evaluating and Expressing the Uncertainty of NIST Measurement Results Technical Note 1900. NIST.

Top-Down evaluation attempts to quantify all the error sources "experimentally"

X, Y, Z Translation Stage




Fiducials with known dimensions



U, x: Avg. σ = 0.02 mm

V, y: Avg. σ = 0.04 mm

W, z: Avg. σ = 0.08 mm

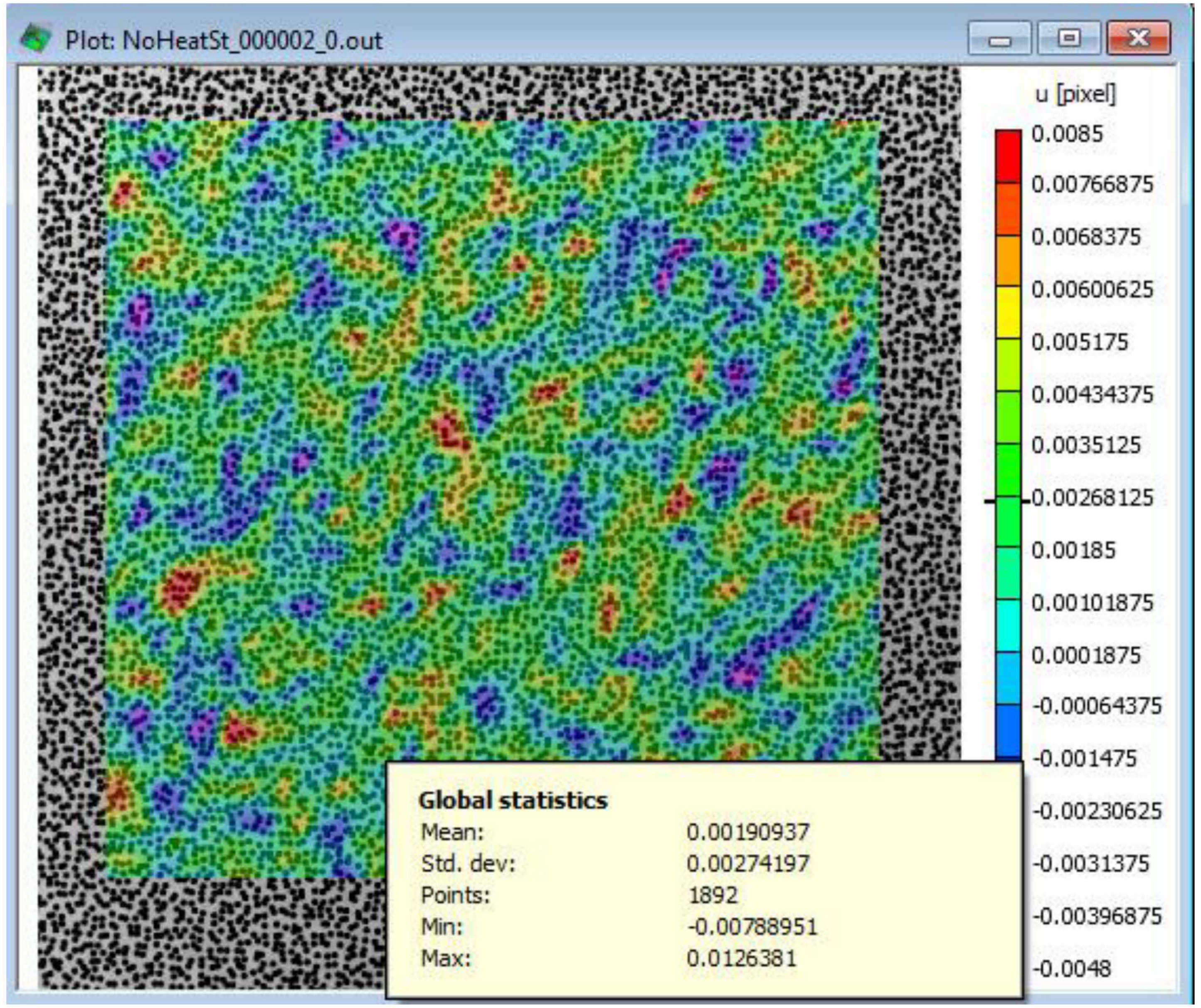
Stepper Error

Bottom-up Methods: Compare DIC results to
- Known shape measurements
- Known fiducial locations
- Known translations

Bottom-up assessment

2D Error Source	Type	Assessment Method/Comments	$\lvert D\rvert$ ≈ mm	$\lvert D\rvert$≈pixels
Lens distortion	B	Previous calibration 100-mm Lens Not motion	<0.001	0.009
Camera motion	A,B	Stationary pattern – See later in slides	<0.02	0.18
Sample motion	B	Fixed target on table	0	0
Turbulence	A,B	This presentation for 50 C heat source	0.01 – 0.07	0.09 – 0.6
Image blur	B	Stationary	0	0
Resolution	B	Adequate pixel size	0	0
Image noise	A	Noise floor (5 frames at start of experiment)	0.001	0.009
Pattern contrast	A	Contrast ≈ 160 counts (Included in noise floor)	Noise floor	
Pattern Induced Bias	A	Extended noise floor	Extended noise	
Pattern size	B	Direct measure of speckle size (μ=6.9; σ=1.2 pixels)	Noise floor	
Aliasing	A,B	Noise floor (not aliased)	Noise floor	
Interpolant	B	Synthetic and experimental image studies for optimum	0.0001	0.0009
Minimization	B	DIC parameter study, synthetic and exp. image studies	0.0001	0.0009
Shape function	B	DIC parameter study, synthetic and exp. image studies	0	
Subset size	B	DIC parameter study, synthetic and exp. image studies	Noise floor	
Filtering	B	DIC parameter study		
Strain calculation	B	DIC parameter study		
Coord. system	B	Other means		

Measurement noise floor is the simplest and minimum check all DIC users should do.



```
Global statistics
Mean:           0.00190937
Std. dev:       0.00274197
Points:         1892
Min:            -0.00788951
Max:            0.0126381
```

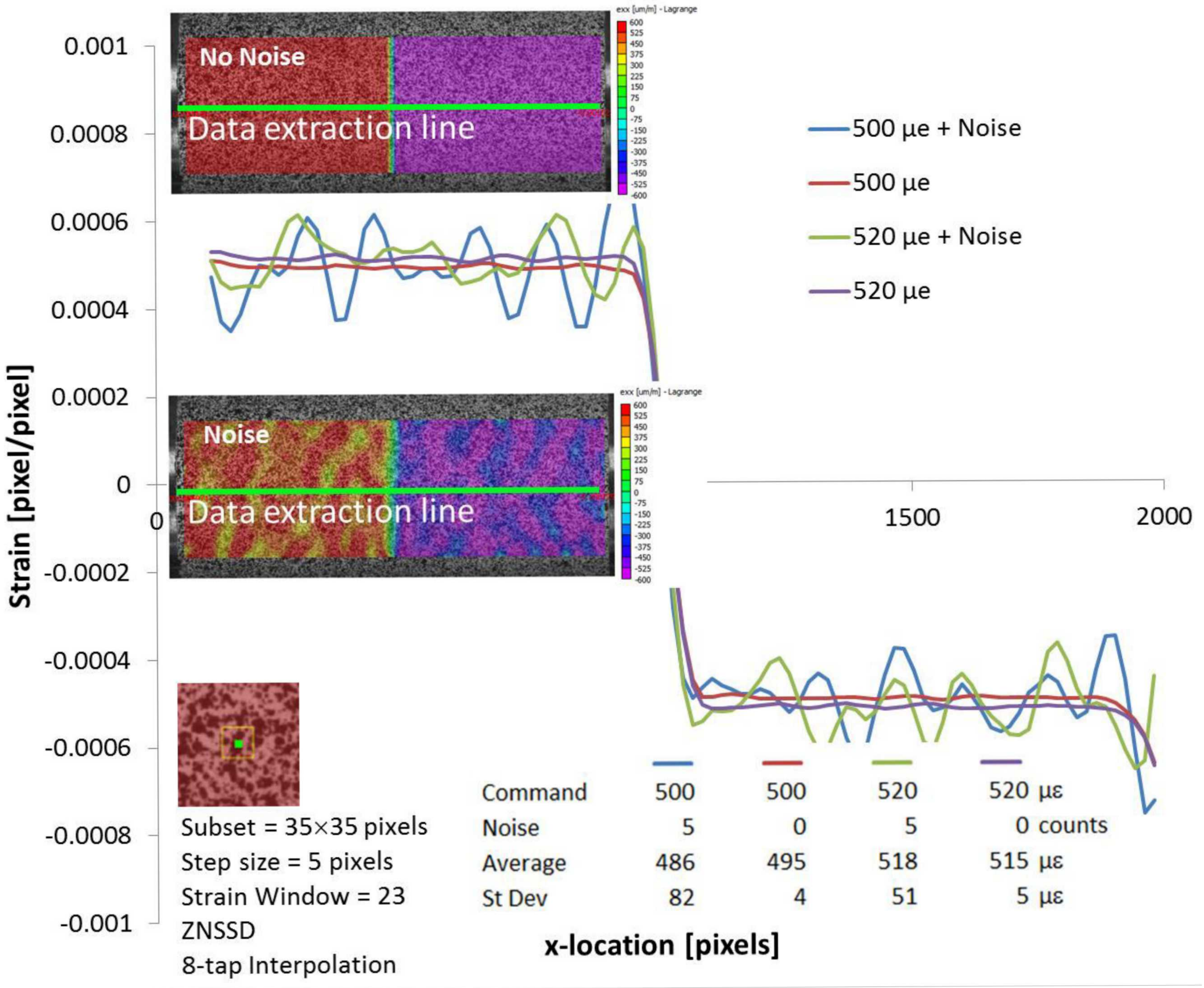
Simple Noise Floor (Resolution)

- 10 Static images
- Analyze the displacement (strain fields) statistically.
- Contains only some of the errors.

Measurement Resolution: Smallest change that can be measured

Resolution of a quantity of interest (QOI)

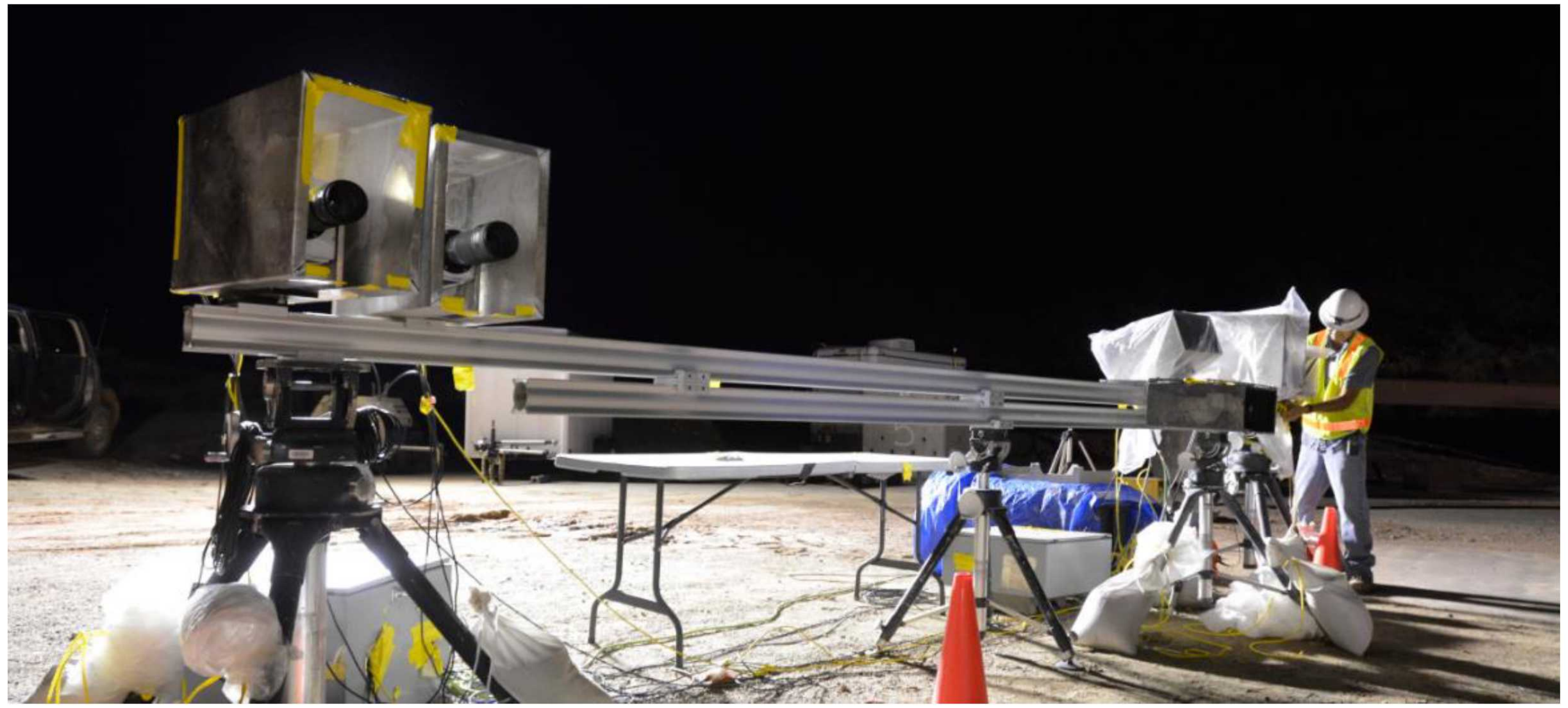
- Standard deviation too large to differentiate between 500 and 520 με.
- Step-response gives some idea of the spatial resolution.

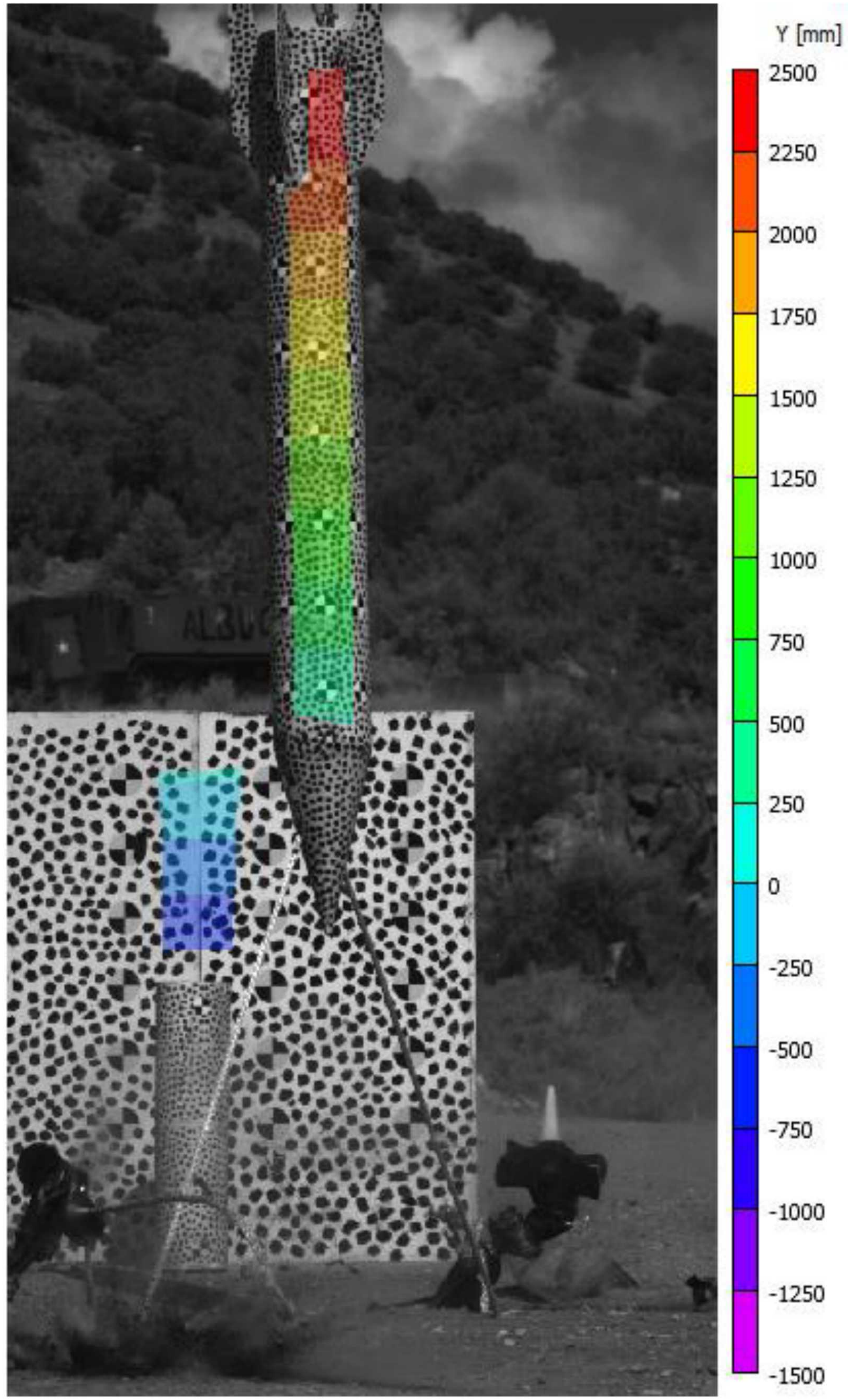


Subset = 35×35 pixels
Step size = 5 pixels
Strain Window = 23
ZNSSD
8-tap Interpolation

Command	500	500	520	520 με
Noise	5	0	5	0 counts
Average	486	495	518	515 με
St Dev	82	4	51	5 με

The measurement range is the field-of-view of the cameras.





Goal: 1-mm resolution in 6 meters

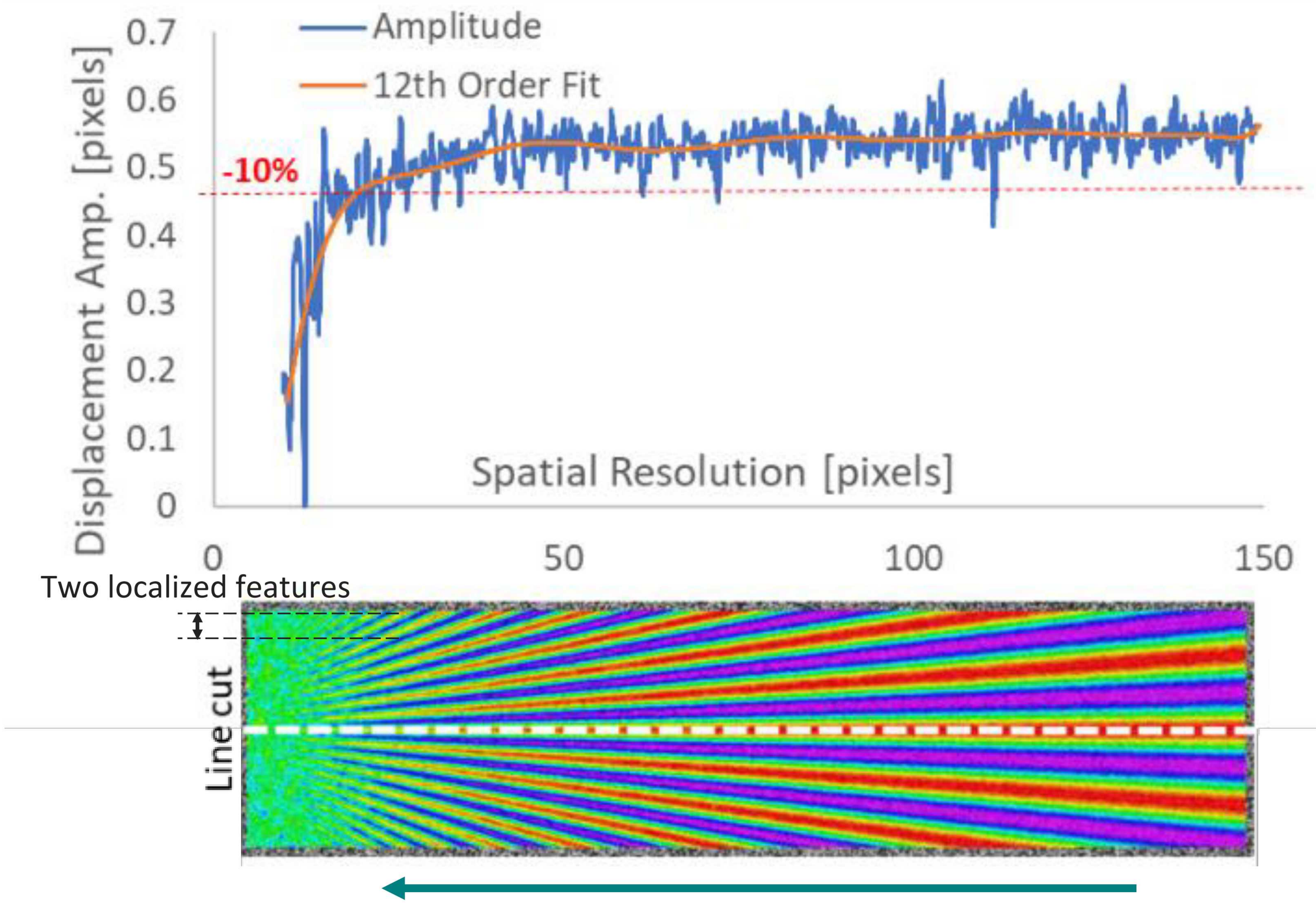
Achieved: 7.5-mm in 6 meters

- 0.125% Field-of-View (or full-range)
- 1.9 pixel error.

Spatial resolution: Ability to reconstruct a varying quantity of interest (QOI)

Spatial Resolution

- Ability to reconstruct a spatially varying displacement or strain field.
- Quantify the roll-off of the reconstruction response.
- Determine some “acceptable” filtering amount.
- “The minimum distance between two localized features that can be independently resolved.”

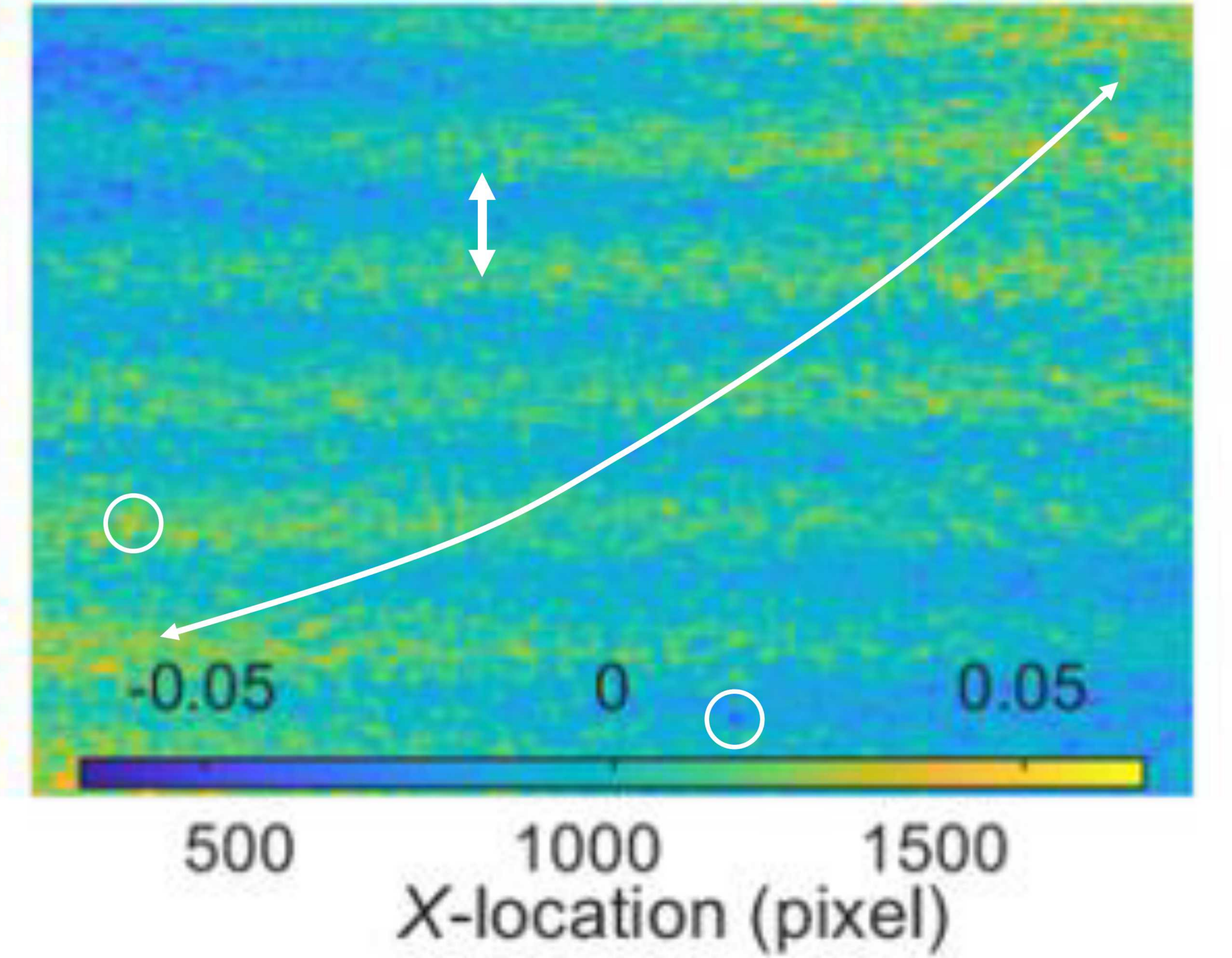


- Higher frequency
- Lower period
- Increased spatial resolution

Spatial Errors: Errors between subsets for a given image.

Common spatial errors

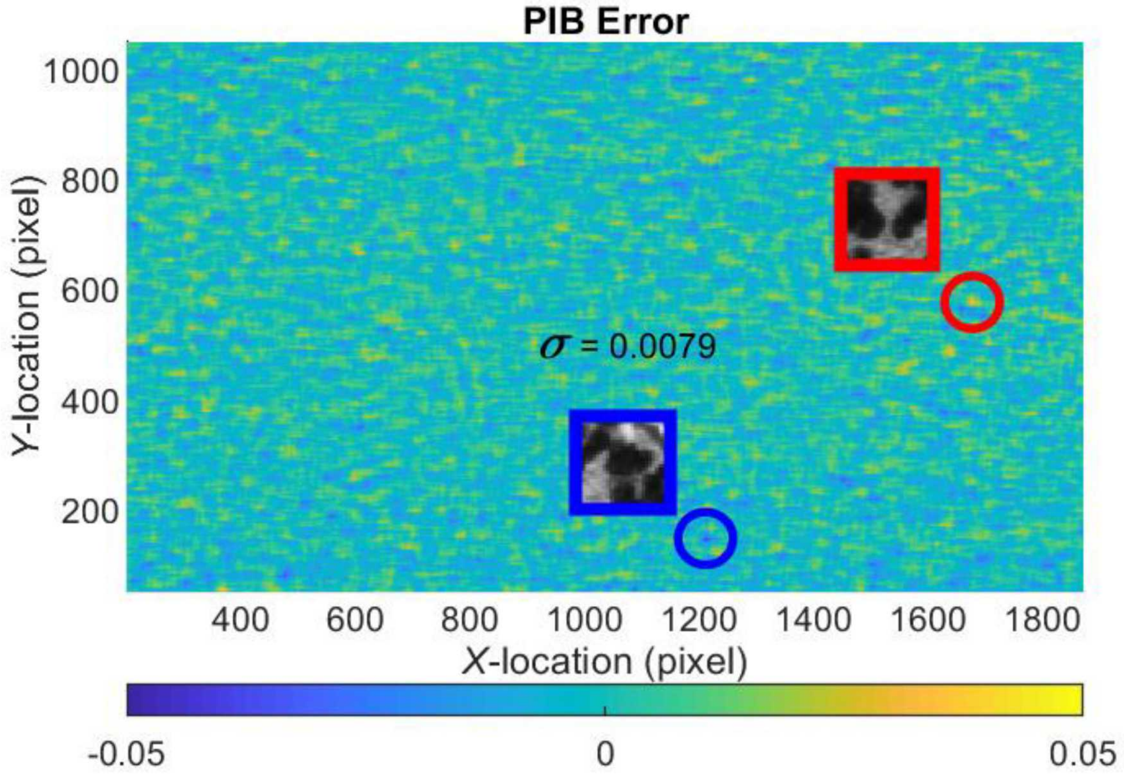
- Interpolation bias error is wave across the image.
- The slight tilt is a lens distortions.
- Pattern Induced Bias (PIB) are the splotches across the image. (Variance error)

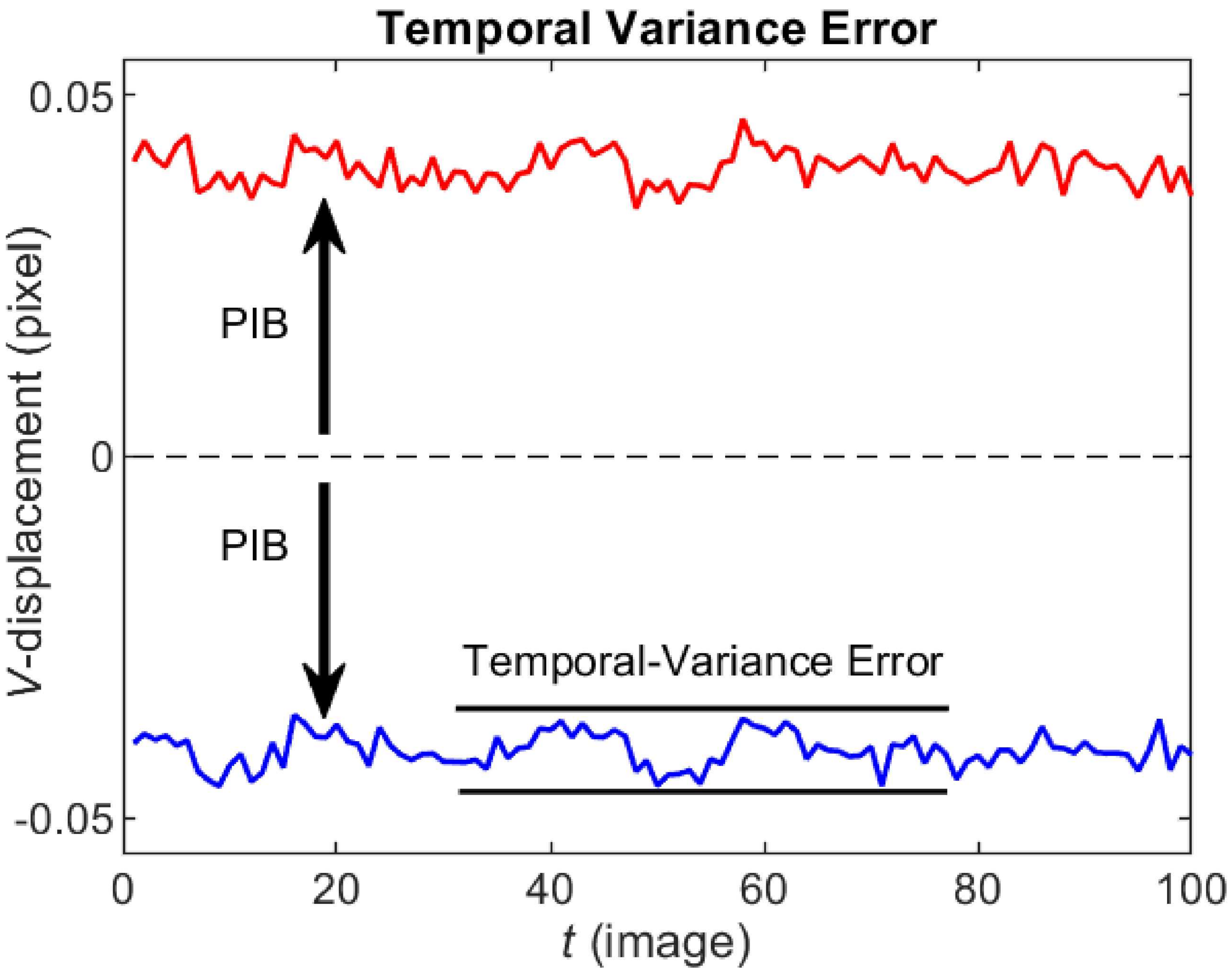


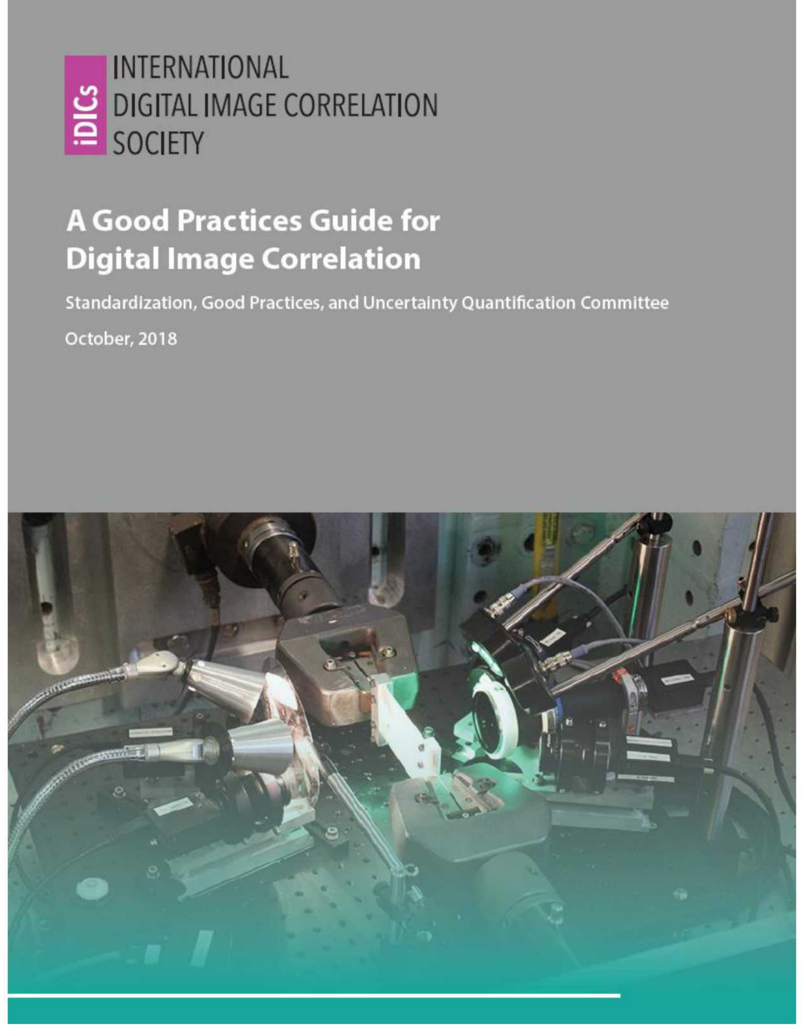
Temporal Errors: Variation of a given subset through time.

Common temporal errors

- Heat waves
- Image noise
- Thermal drift
- Camera vibrations







iDICs INTERNATIONAL
DIGITAL IMAGE CORRELATION
SOCIETY

A Good Practices Guide for Digital Image Correlation

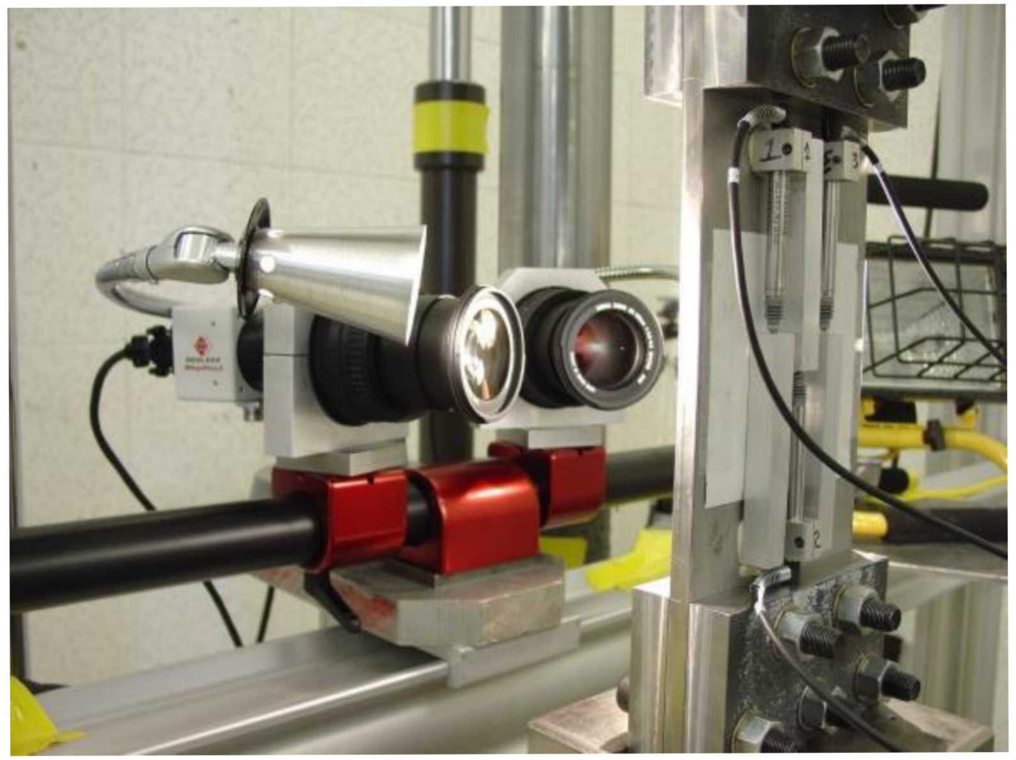
Standardization, Good Practices, and Uncertainty Quantification Committee

October, 2018

DIC MEASUREMENTS DEFINED IN THE GOOD PRACTICES GUIDE

MEASUREMENT REQUIREMENTS
EQUIPMENT AND HARDWARE
DIC PATTERNING

Stereo-DIC setup



Section 2.2 – Equipment and Hardware

- Section 2.2.1 – Camera and Lens Selection
- Section 2.2.2 – Camera and Lens Mounting
- Section 2.2.3 – Aperture
- Section 2.2.4 – Lighting and Exposure

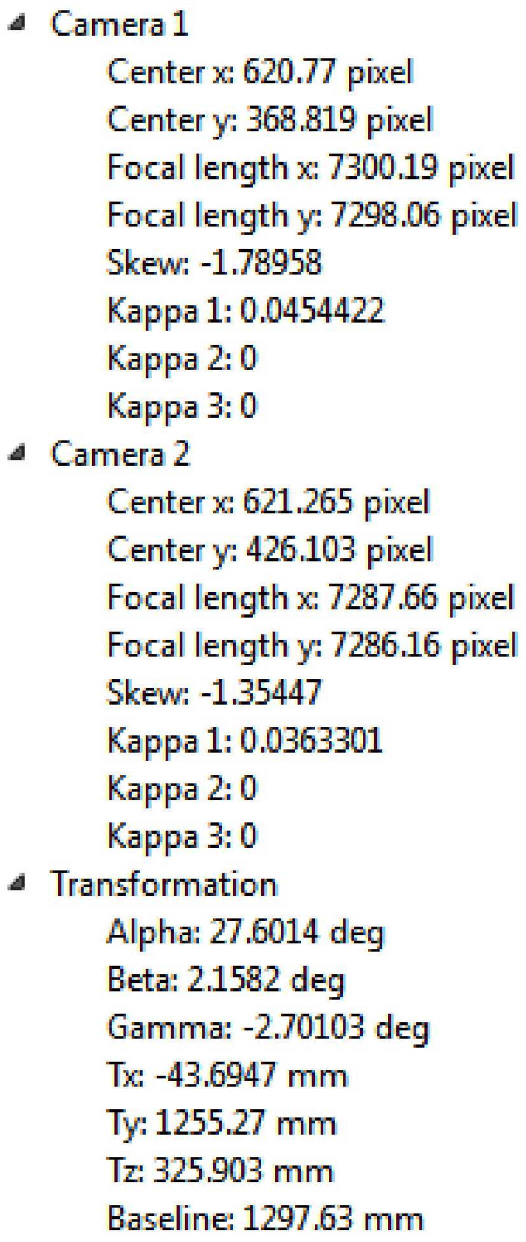
Section 2.1 – Measurement Requirements

- Section 2.1.1 – Quantity of Interest (QOI)
- Section 2.1.2 – Region of Interest (ROI)
- Section 2.1.3 – Field-of-View (FOV)
- Section 2.1.6 – Stereo-Angle
- Section 2.1.7 – Depth-of-Field

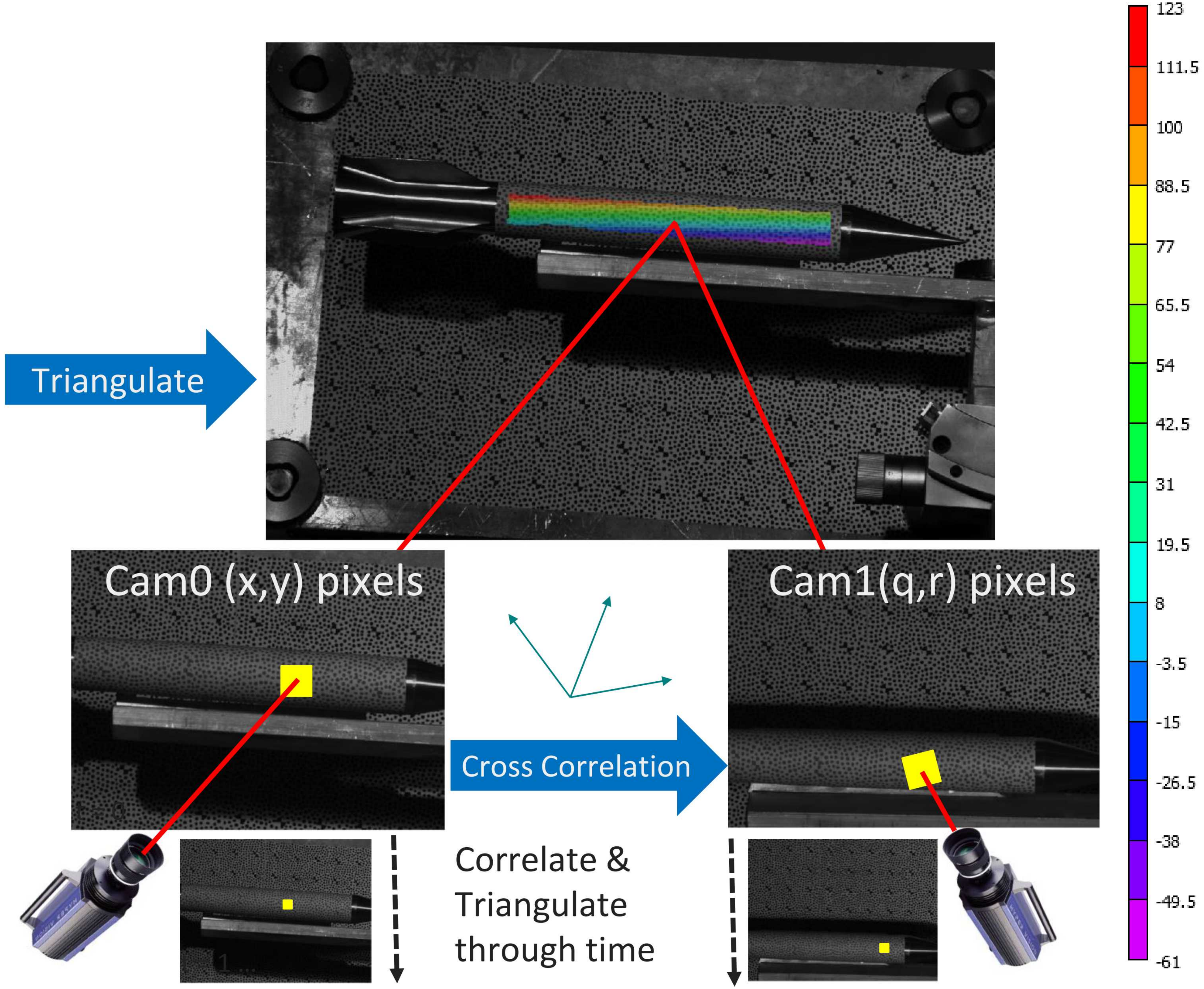
Section 2.3 – DIC Pattern

- Section 2.3.1 – Type of DIC Patterns
- Section 2.3.2 – General Characteristics of DIC Patterns
  - Section 2.3.2.1 – Pattern size (3 – 5 Pixels)
  - Section 2.3.2.2 – Variation, i.e. sufficiently random
  - Section 2.3.2.3 – Density, approximately 50% coverage
  - Section 2.3.2.4 – Quality, i.e. does the pattern hold-up
- Section 2.3.3 – Characteristics of Applied Patterns
  - Section 2.3.3.1 – Compliance, stiffening
  - Section 2.3.3.2 – Bonding
  - Section 2.3.3.3 – Fidelity, i.e. move surface
  - Section 2.3.3.4 – Thickness.
- Section 2.3.4 – Patterning Techniques

Triangulation uses the calibration and the matched pixel locations in two images to find the 3D point in space. This is the primary measurement



- Camera 1
  - Center x: 620.77 pixel
  - Center y: 368.819 pixel
  - Focal length x: 7300.19 pixel
  - Focal length y: 7298.06 pixel
  - Skew: -1.78958
  - Kappa 1: 0.0454422
  - Kappa 2: 0
  - Kappa 3: 0
- Camera 2
  - Center x: 621.265 pixel
  - Center y: 426.103 pixel
  - Focal length x: 7287.66 pixel
  - Focal length y: 7286.16 pixel
  - Skew: -1.35447
  - Kappa 1: 0.0363301
  - Kappa 2: 0
  - Kappa 3: 0
- Transformation
  - Alpha: 27.6014 deg
  - Beta: 2.1582 deg
  - Gamma: -2.70103 deg
  - Tx: -43.6947 mm
  - Ty: 1255.27 mm
  - Tz: 325.903 mm
  - Baseline: 1297.63 mm



Triangulate

Cam0 (x,y) pixels

Cam1(q,r) pixels

Cross Correlation

Correlate & Triangulate through time

Primary Measurement

x, y, z [mm]

Displacement u, v, w [mm]
Subtracted from the reference.

ε_{xx}, ε_{yy}, ε_{xy} [mm/mm]
Spatial derivative of displacement

Velocity [mm/s]
Temporal derivative of displacement

2D Measurement chain – a subset of stereo-DIC.

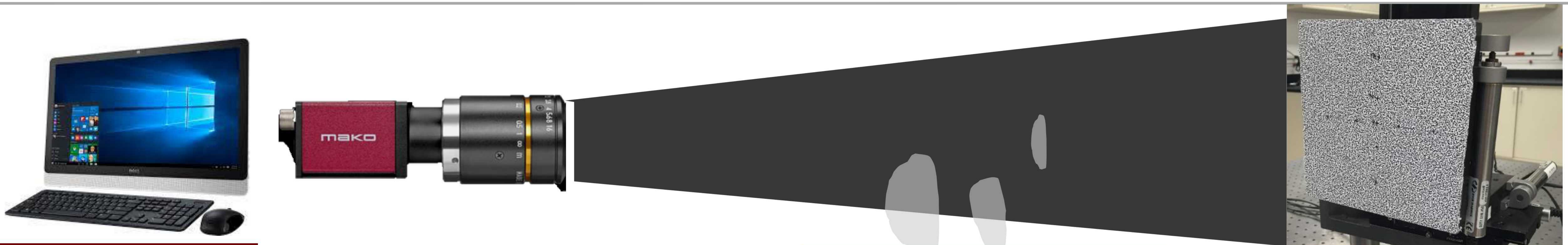


Image Correlation
- Interpolant
- Minimization
- Shape Function
- Subset size
- PIB

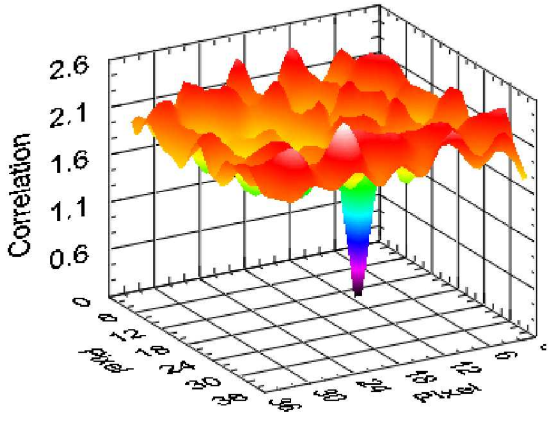
Image Acquisition
- Noise
- Contrast
- Speckle size
- Aliasing

Experimental Setup
- Lens distortion
- Camera motion
- Sample motion
- Air turbulence
- Image blur
- System resolution

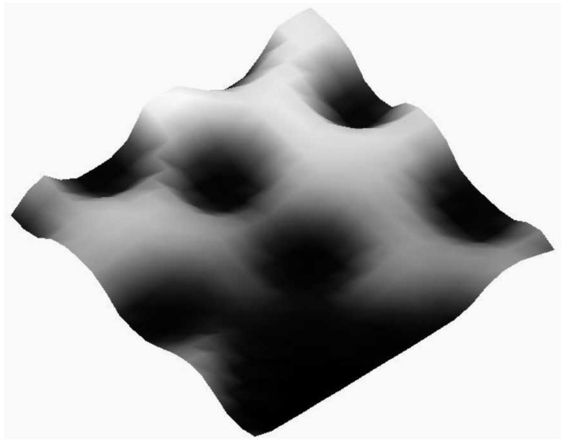
Patterning
- Pattern Induced Bias (PIB)
- Aliasing
- Contrast (lighting)

3 Hidden components of DIC‡

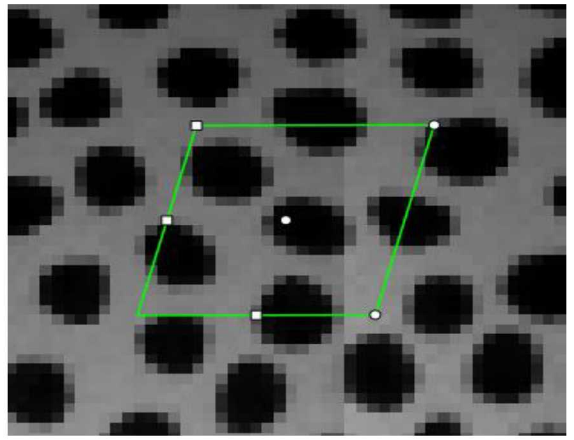
Matching



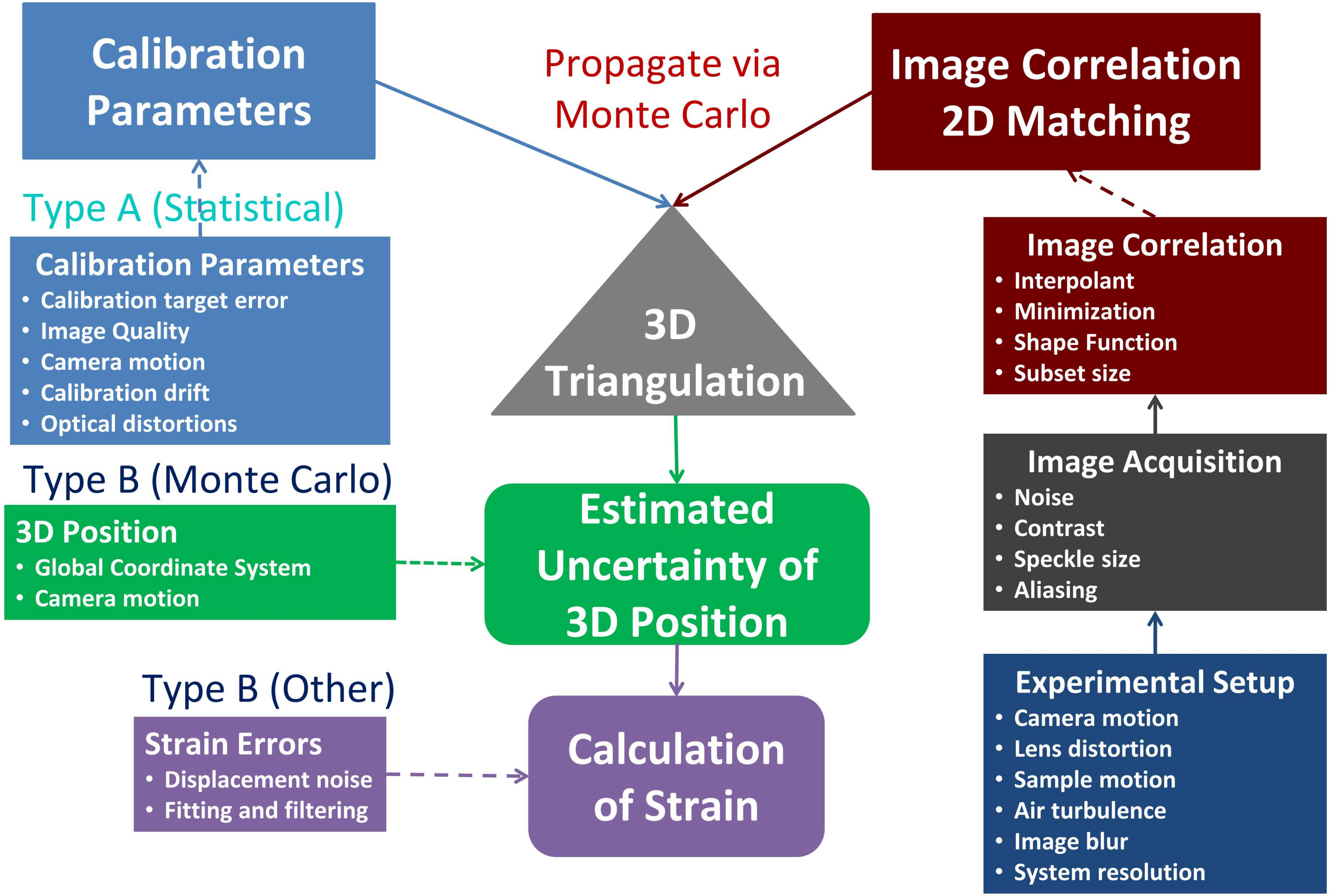
Interpolation



Shape Function



Stereo-vision measurement flow (and uncertainty)



Calibration Parameters

Propagate via Monte Carlo

Image Correlation 2D Matching

Type A (Statistical)

Calibration Parameters
- Calibration target error
- Image Quality
- Camera motion
- Calibration drift
- Optical distortions

3D Triangulation

Image Correlation
- Interpolant
- Minimization
- Shape Function
- Subset size

Image Acquisition
- Noise
- Contrast
- Speckle size
- Aliasing

Type B (Monte Carlo)

3D Position
- Global Coordinate System
- Camera motion

Estimated Uncertainty of 3D Position

Type B (Other)

Strain Errors
- Displacement noise
- Fitting and filtering

Calculation of Strain

Experimental Setup
- Camera motion
- Lens distortion
- Sample motion
- Air turbulence
- Image blur
- System resolution

Calibration Parameters | 2D Correlation | 3D Position, Motion | Strain

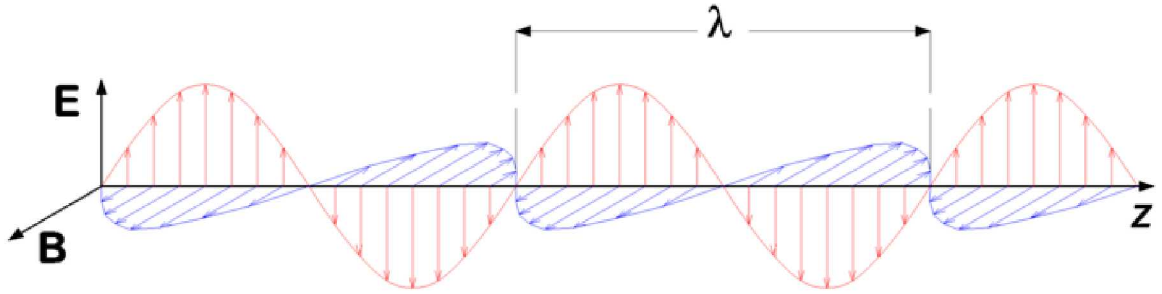
UNDERSTANDING LIGHT AND LENSES

BRINGING THINGS INTO FOCUS

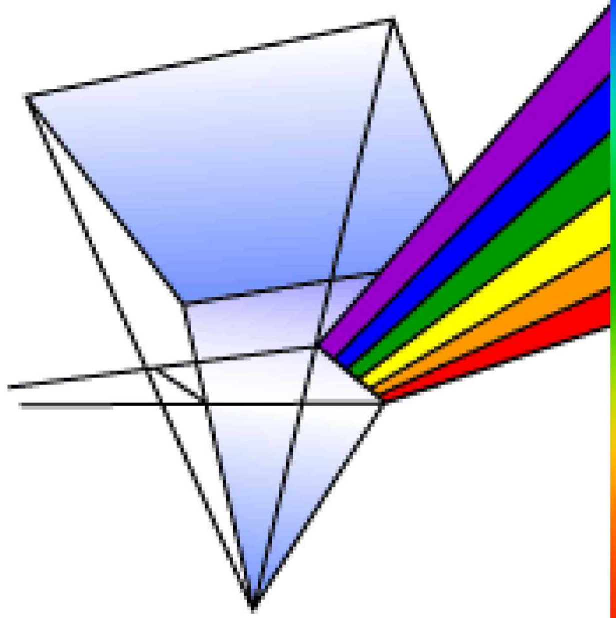
Light is a wave (and a particle).

$\mathbf{E} = E_0 \sin(-\omega t + \mathbf{k} \cdot \mathbf{r})$ Electric Field Vector

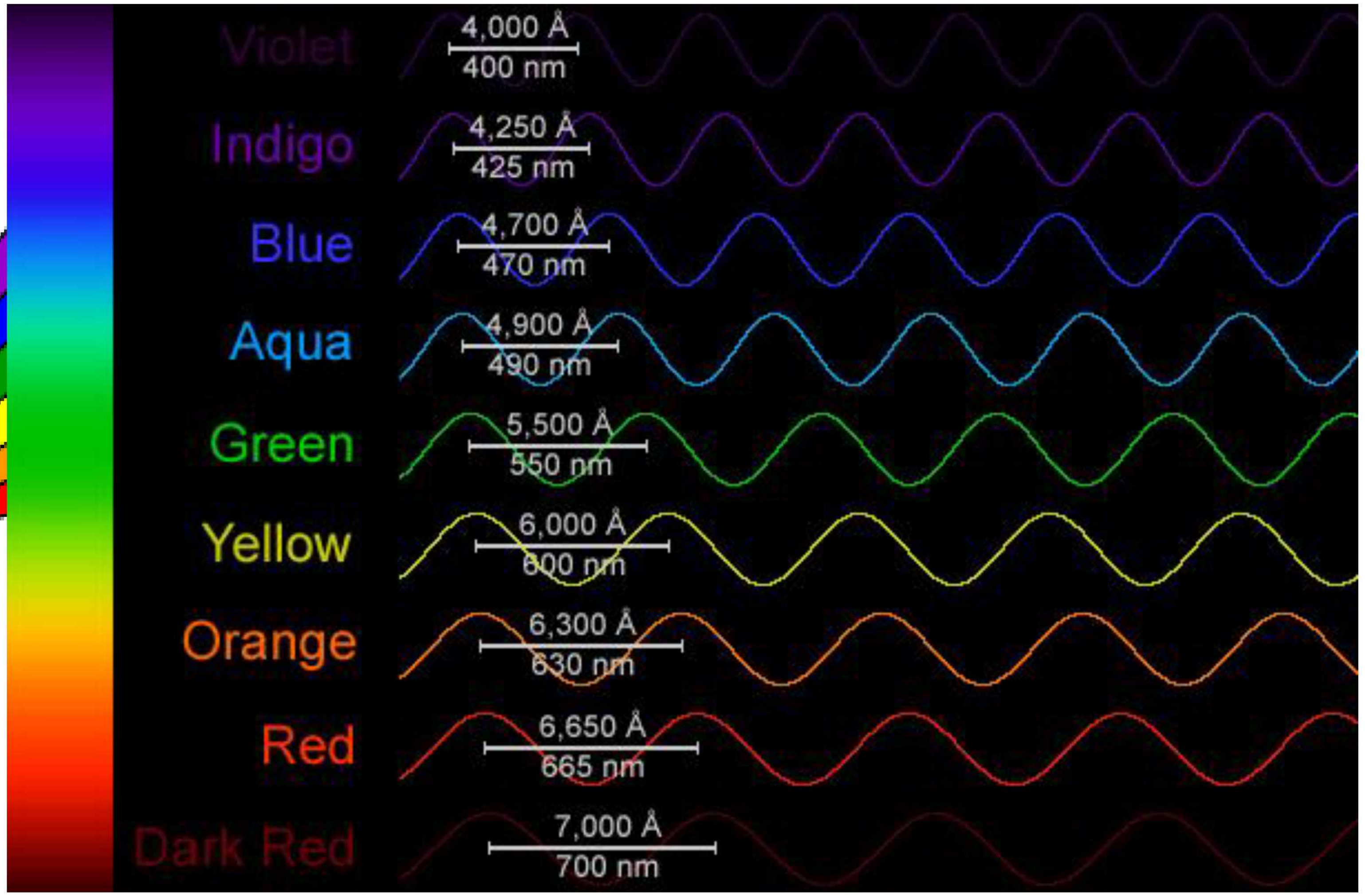
$\mathbf{B} = B_0 \sin(-\omega t + \mathbf{k} \cdot \mathbf{r})$ Magnetic Field Vector



Chromatic Aberration – but a nice case!



http://science.hq.nasa.gov/kids/imagers/ems/visible.html



http://www.windows2universe.org/physical_science/magnetism/images/visible_spectrum_waves_big_jpg_image.html

A form of electromagnetic energy

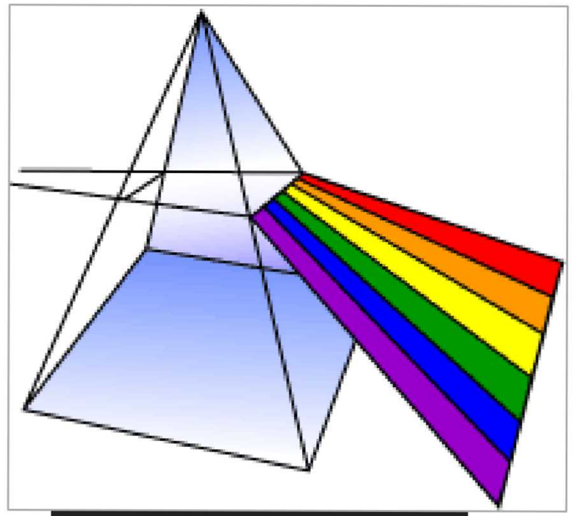
- Can be understood as a wave (i.e. it interferes and diffracts)
- Can be understood as a particle (carries energy)
- The particle is called a “photon”

Monochromatic = one color (wavelength) only

Polychromatic = multiple wavelengths (e.g. “white light”)

Refraction bends the light and allows lenses to focus light

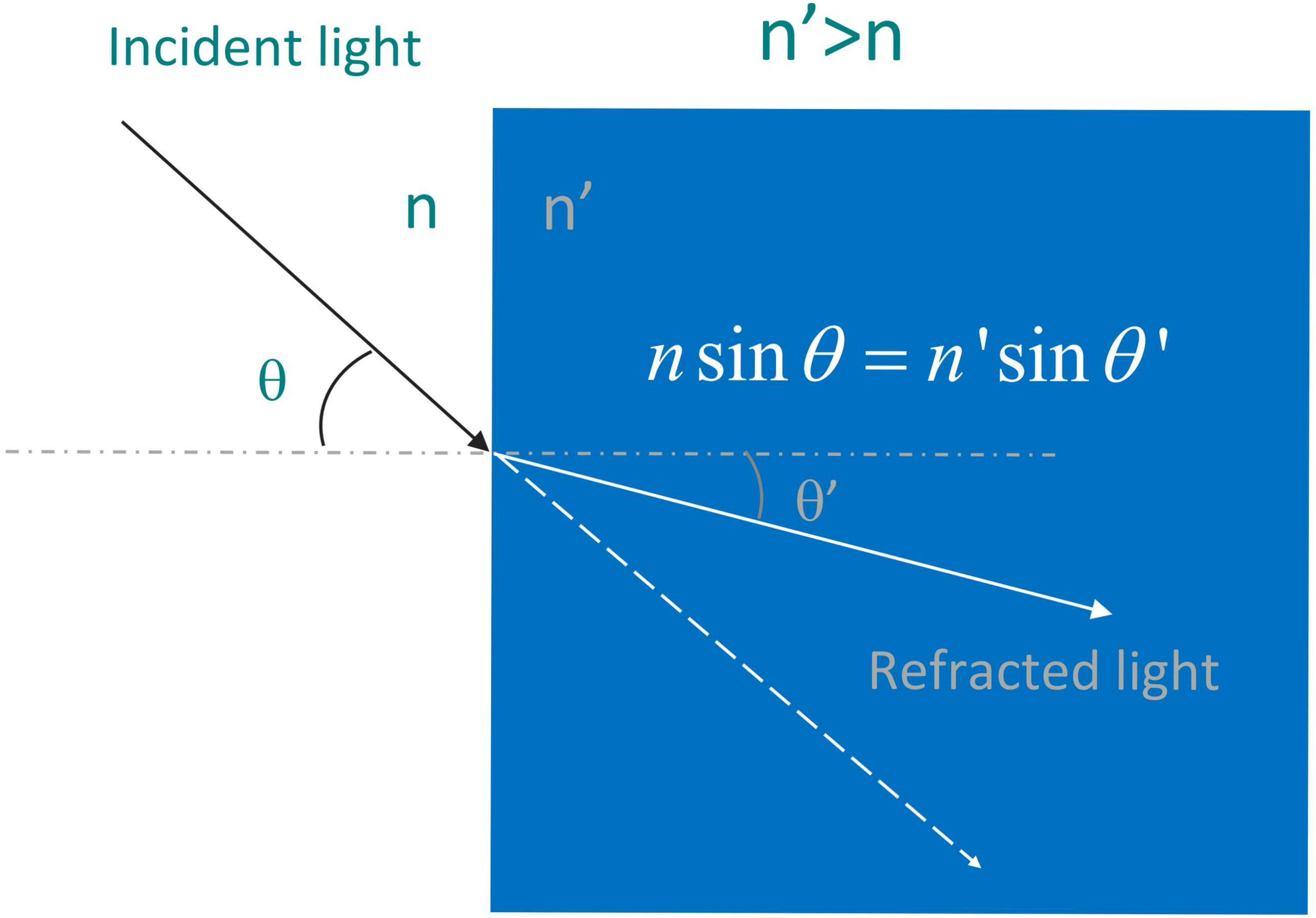
Index varies with wavelength



$$n = \frac{c}{v} \geq 1$$

c: speed of light in vacuum

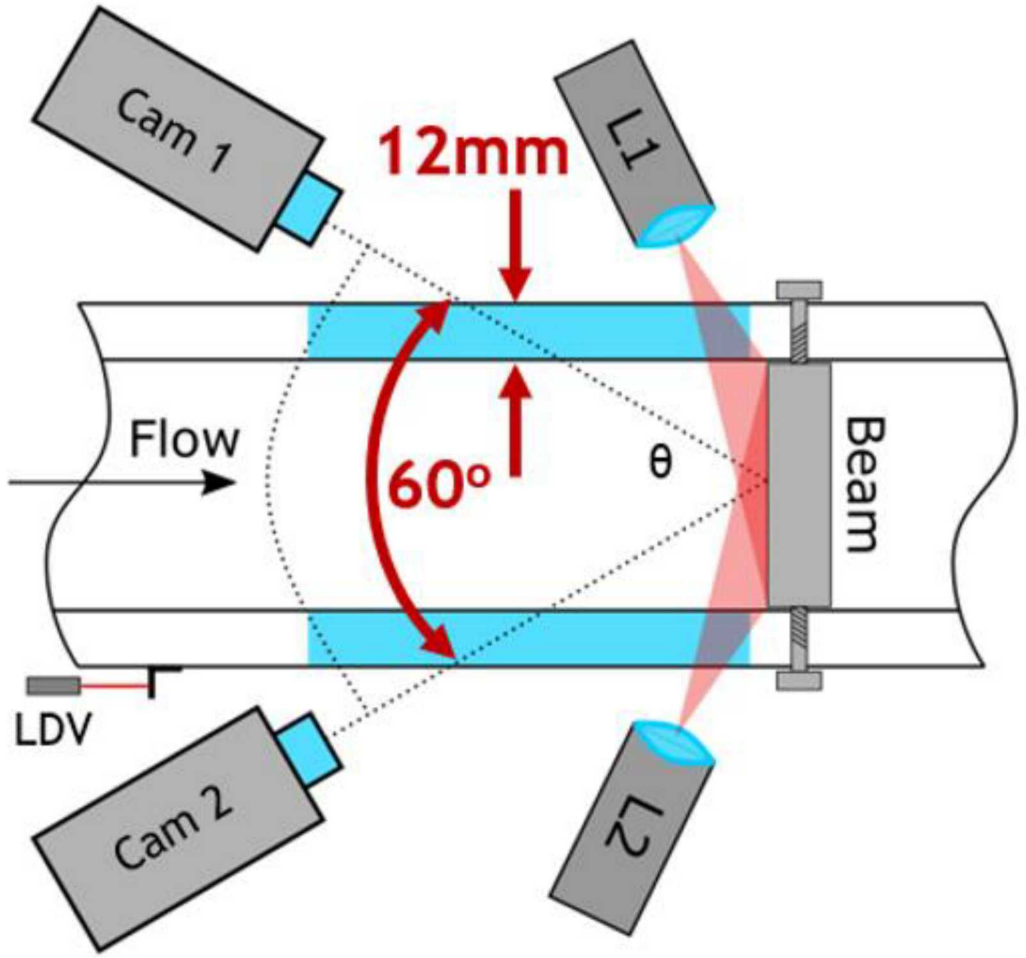
v: speed of light in medium



$$n \sin\theta = n' \sin\theta'$$

Xenon flash lamps may have a problem with chromatic aberration.

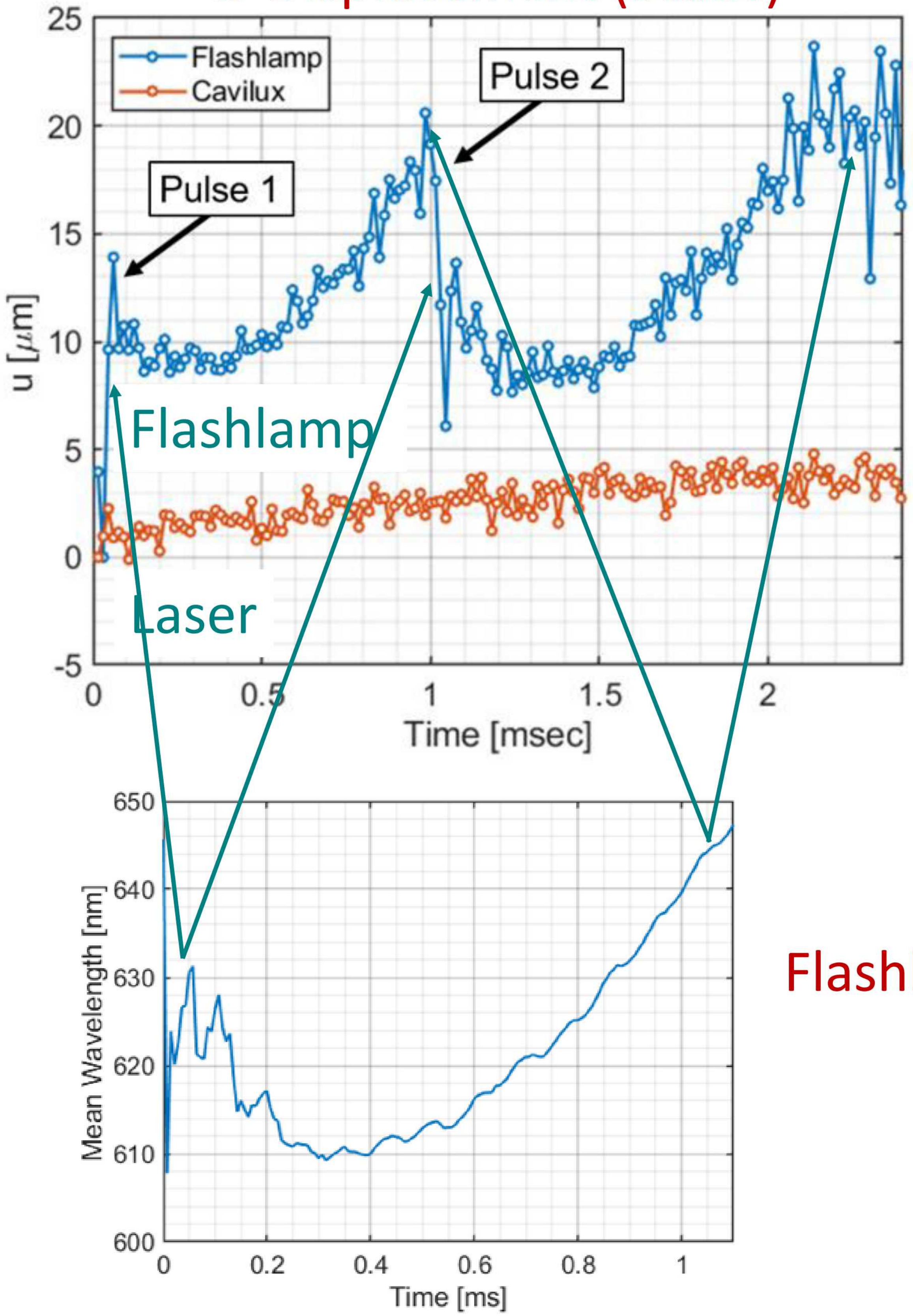
Stereo-DIC Experimental Setup



L1 and L2 are either:

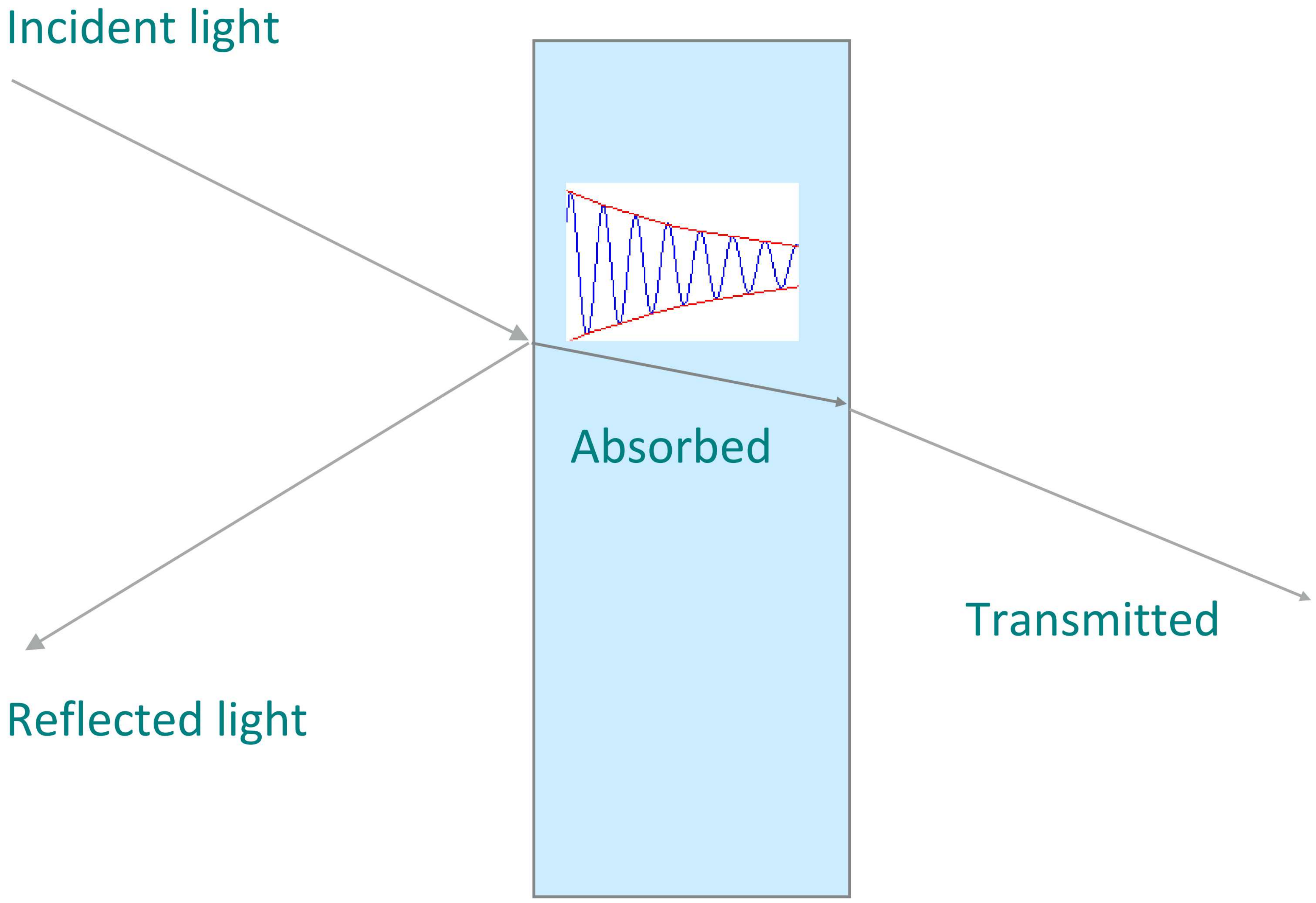
1. Cavilux laser source
2. Xenon flashlamp

U-Displacement (Static)



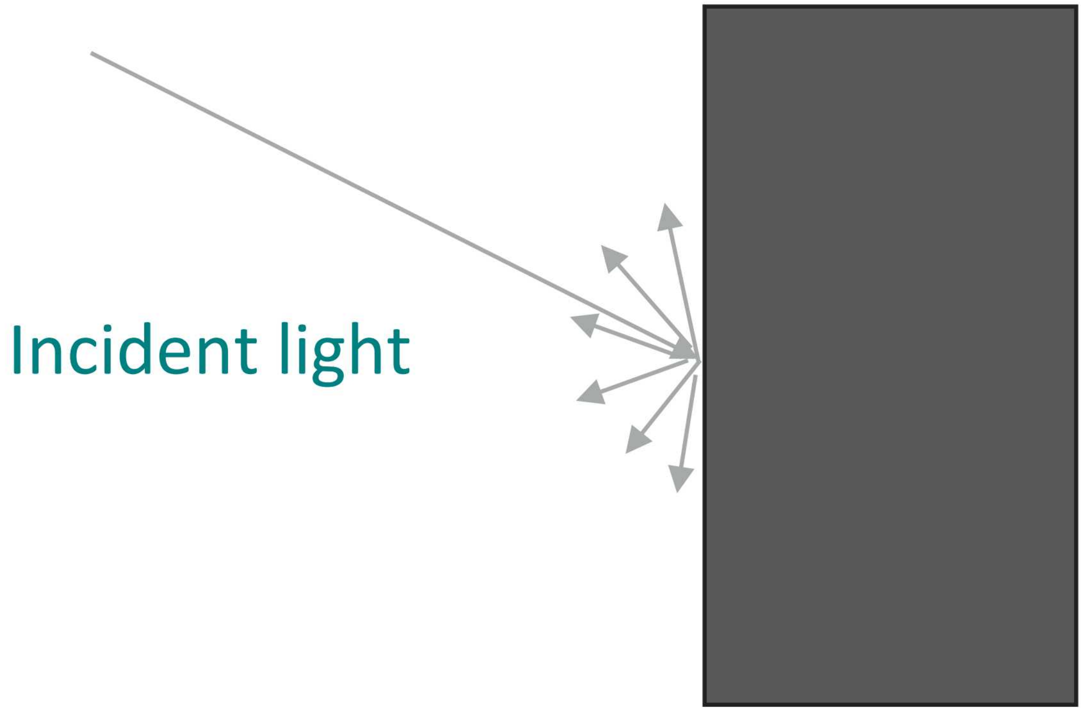
Flashlamp wavelength
(one pulse)

Light interacts with the surroundings in a number of different ways.

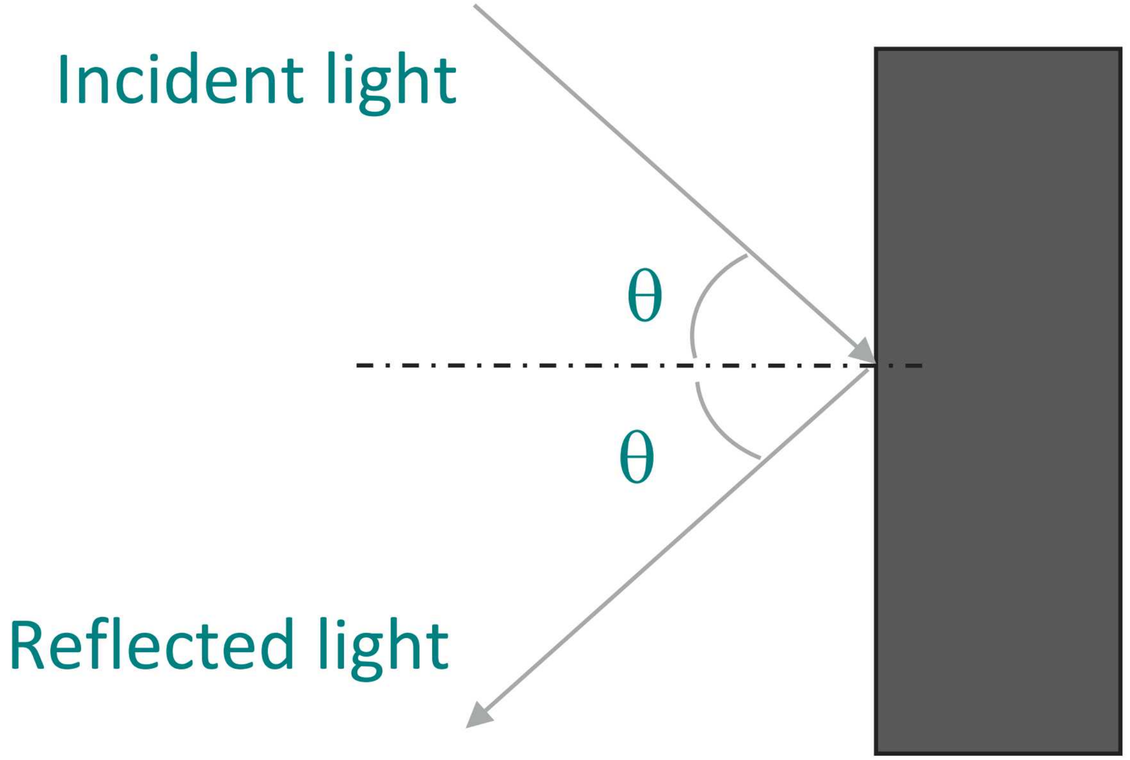


There are two types of reflection: Diffusive and specular

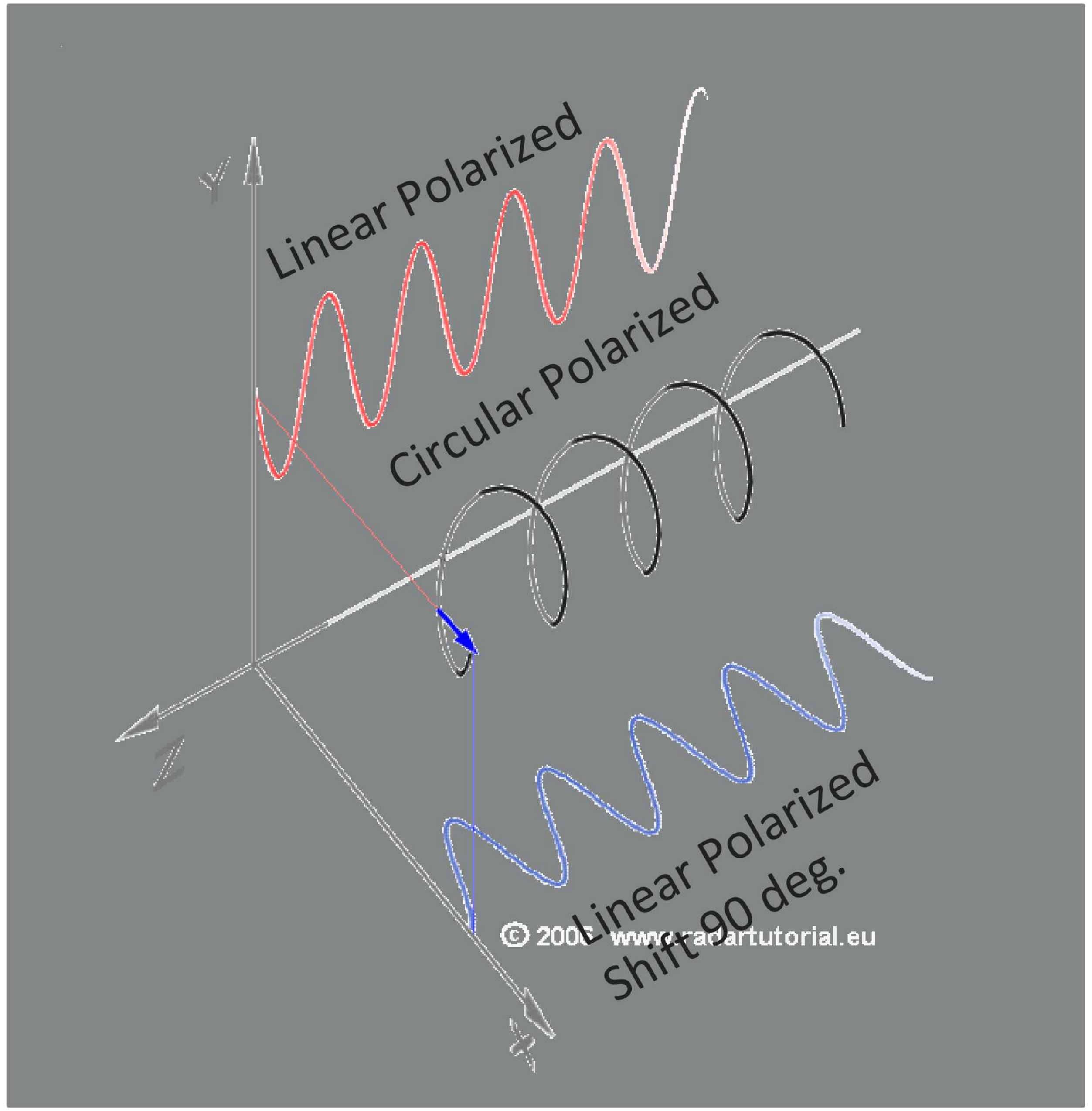
Diffusive

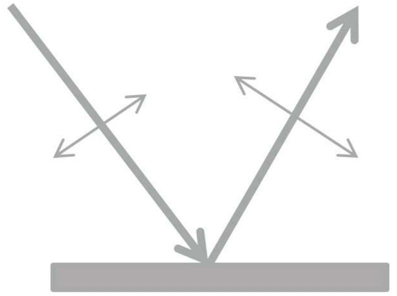


Specular

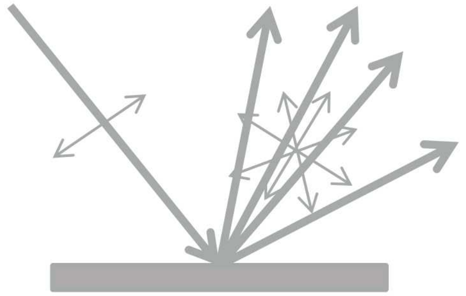


Polarization – or the orientation of the wave in space may play a role in imaging





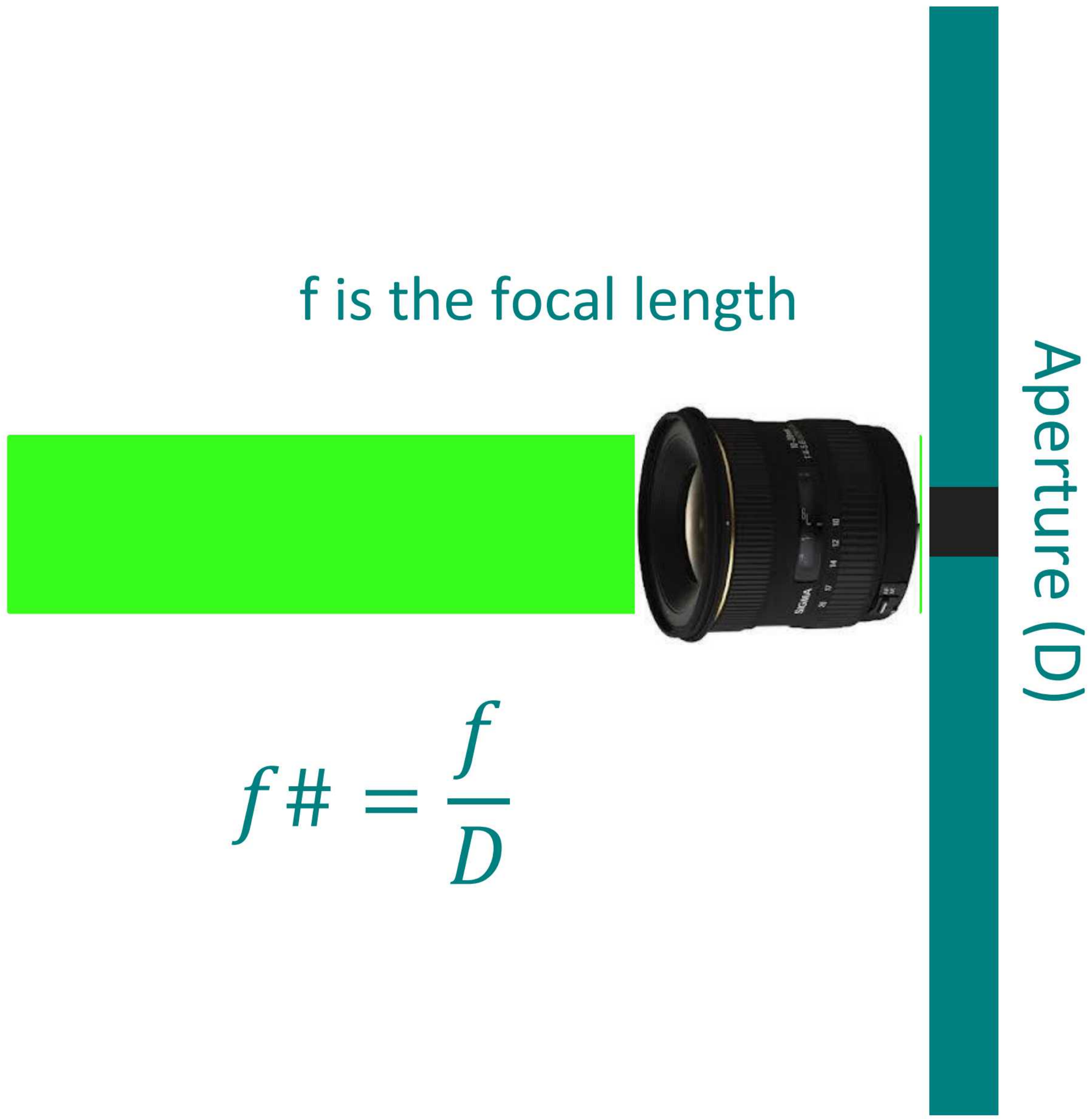
Specular reflection maintains polarization



Diffuse reflection randomizes polarization

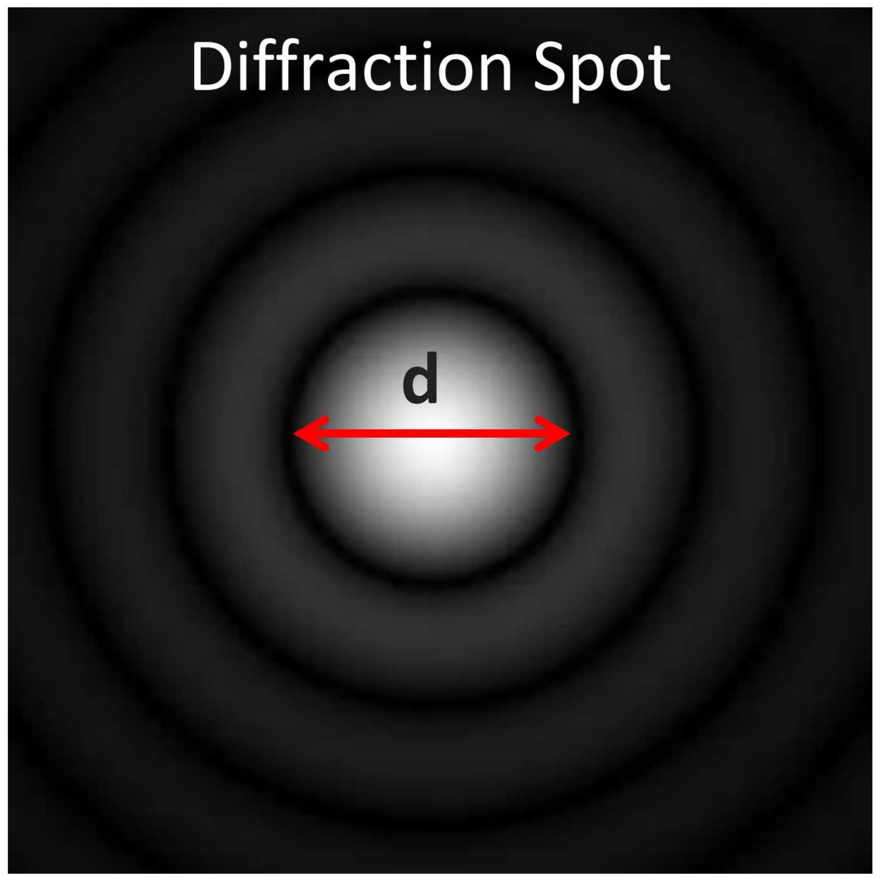
- The polarization is usually random – in white light.
- Filters, reflections, etc. can often select a polarization.
- This can be exploited to improve lighting.

Diffraction is the bending of light at an edge – and will ultimately limit the lens resolution.



f is the focal length

$$f\# = \frac{f}{D}$$

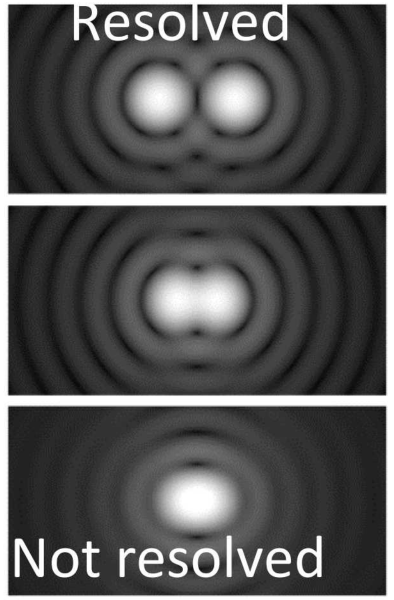


$$d = 1.22 \cdot \lambda \cdot f\#$$

Diffraction limit

Closest resolvable points
(Rayleigh Criterion)

$$x = 1.22 \cdot \frac{\lambda f}{D}$$



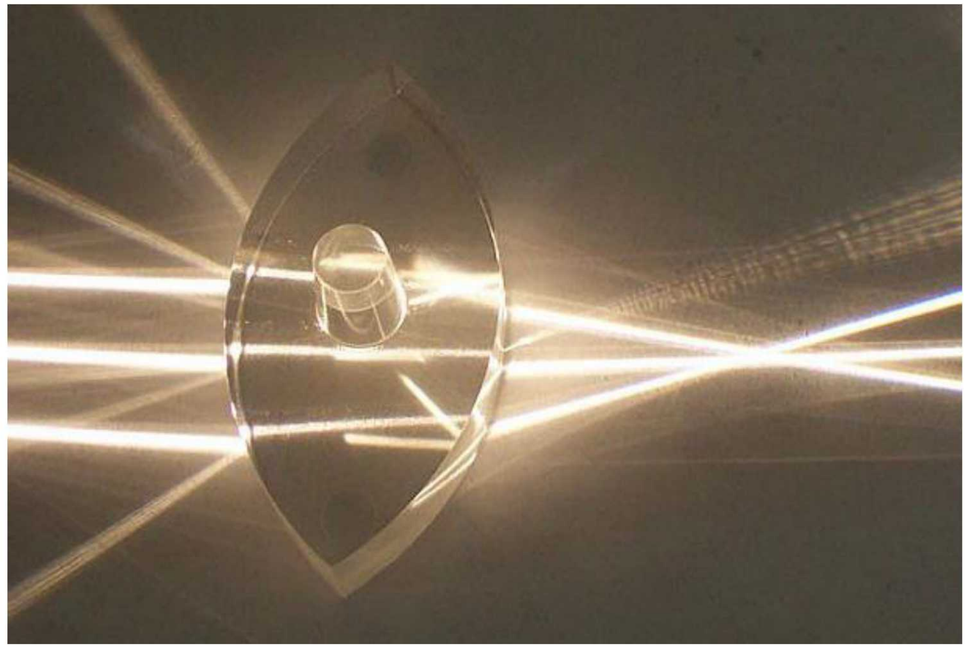
Two speckles imaged

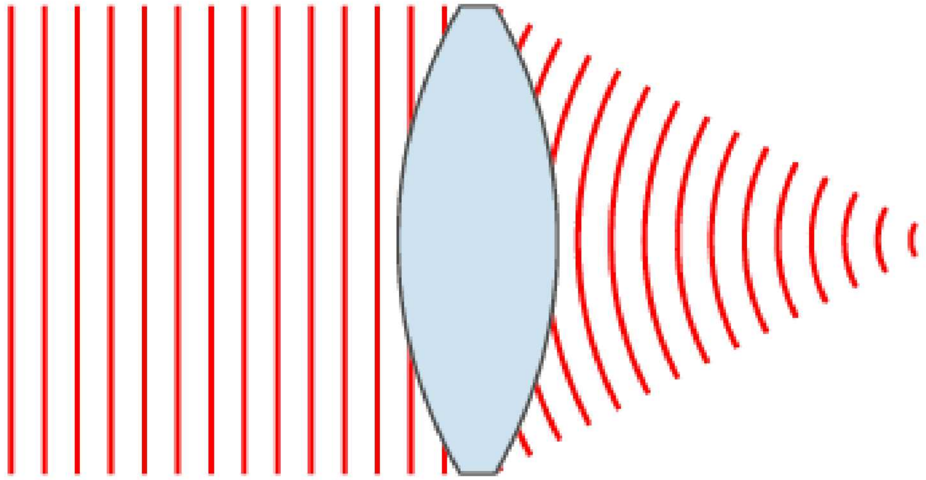
AN INTRODUCTION TO LENSES

BRINGING THINGS INTO FOCUS

Lenses are used to focus the scattered light off of objects.

https://en.wikipedia.org/wiki/Lens_(optics)





https://unsplash.com/photos/VBBs_SWsdwU

And yes, your eye counts as a lens!

Many different types of lenses can be used for DIC. Including zoom, fixed, and telecentric.

Nikon 24-85 mm zoom

Aperture rings are becoming rare.

No-one knows the effect of vibration removal

35 mm fixed focal length

Fixed focal length lenses may limit FOV choices

100 mm Macro

Macro lenses allow high magnification imaging.

Telecentric lenses – fixed magnification

High magnification

iDICs

Caution 2.3 – Beware auto lenses

Tip 2.12 – Fixed focal better

Three common lens mounts: C-mount, Nikon, and Canon

C-Mount Lens

Photos by E. Bystrom

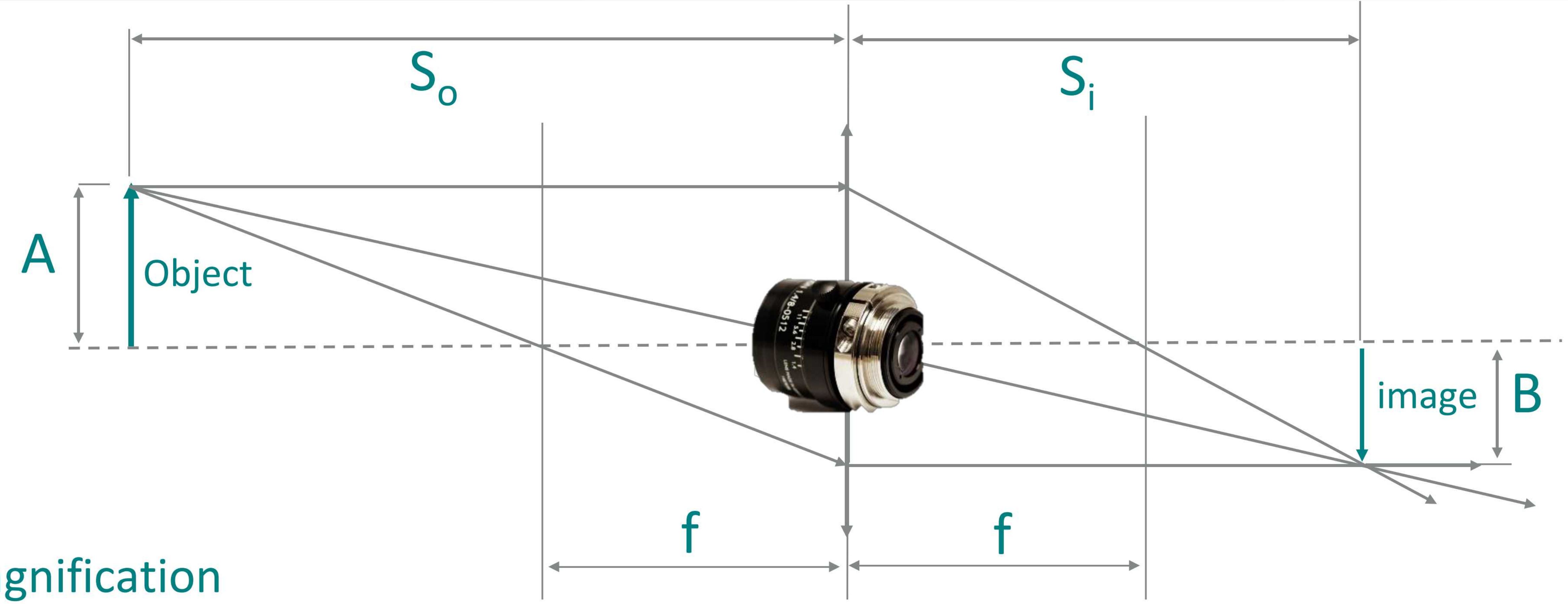
F-Mount Lens (Nikon mount)

EF/RF-Mount Lens (Canon mount)

https://www.the-digital-picture.com/Canon-Lenses/Canon-RF-Lens-Information.aspx

C-Mount is more stable on the camera than bayonet mounts

Magnification is defined as the difference in size between the object and the image.



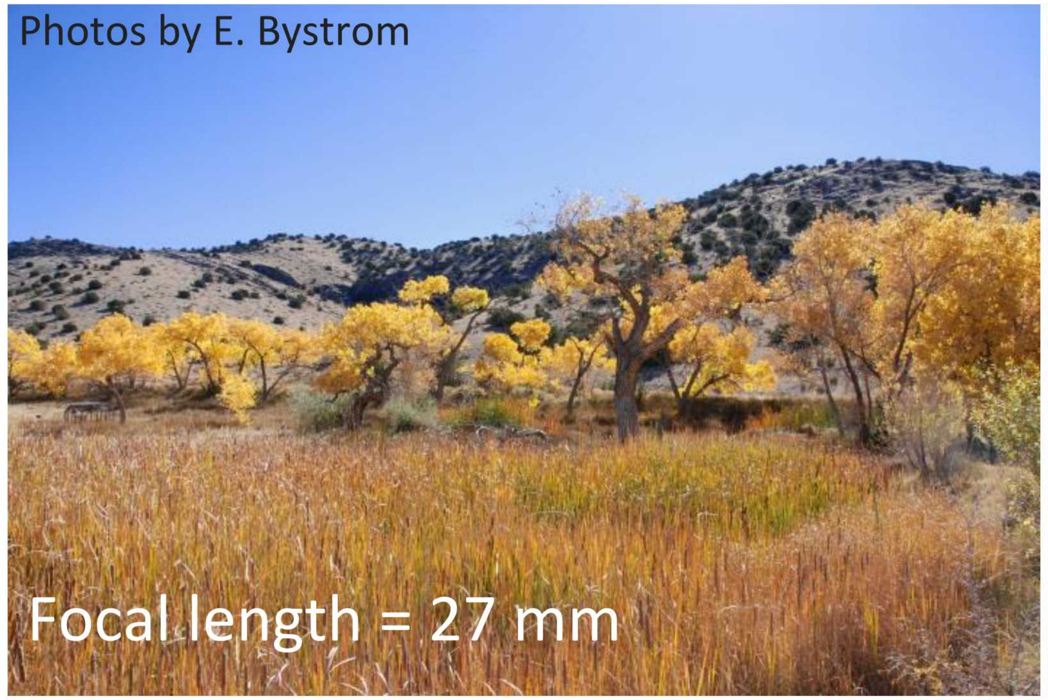
Magnification

$$M = \frac{B}{A} \qquad \frac{A}{S_o - f} = \frac{B}{f} \qquad M = \frac{f}{S_o - f} \qquad M = \frac{S_i - f}{f}$$

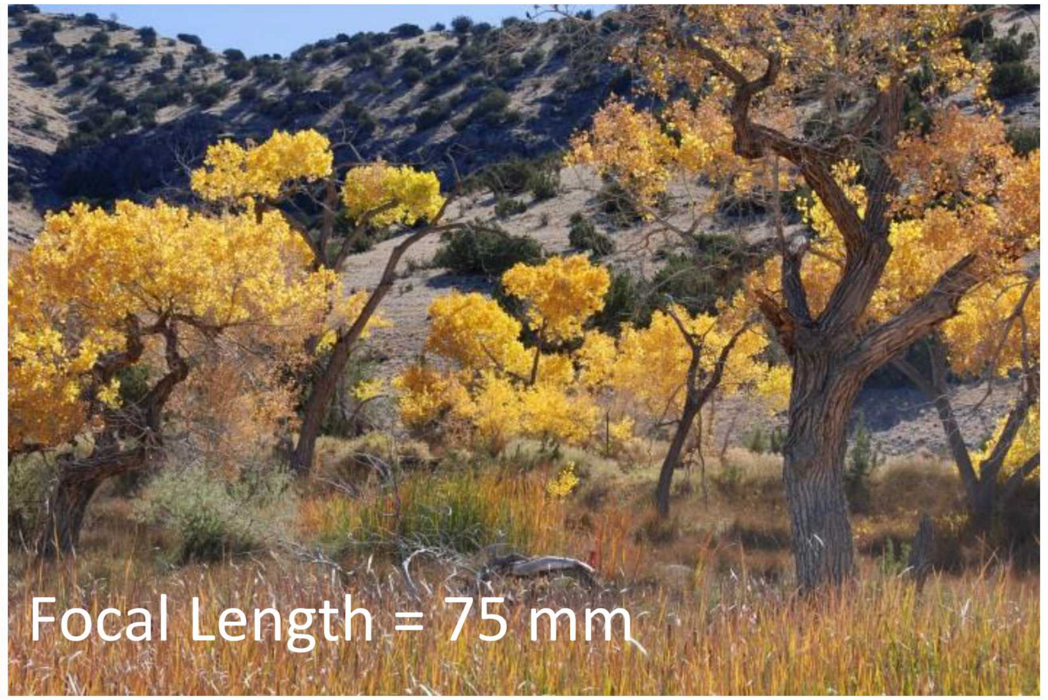
Definitions

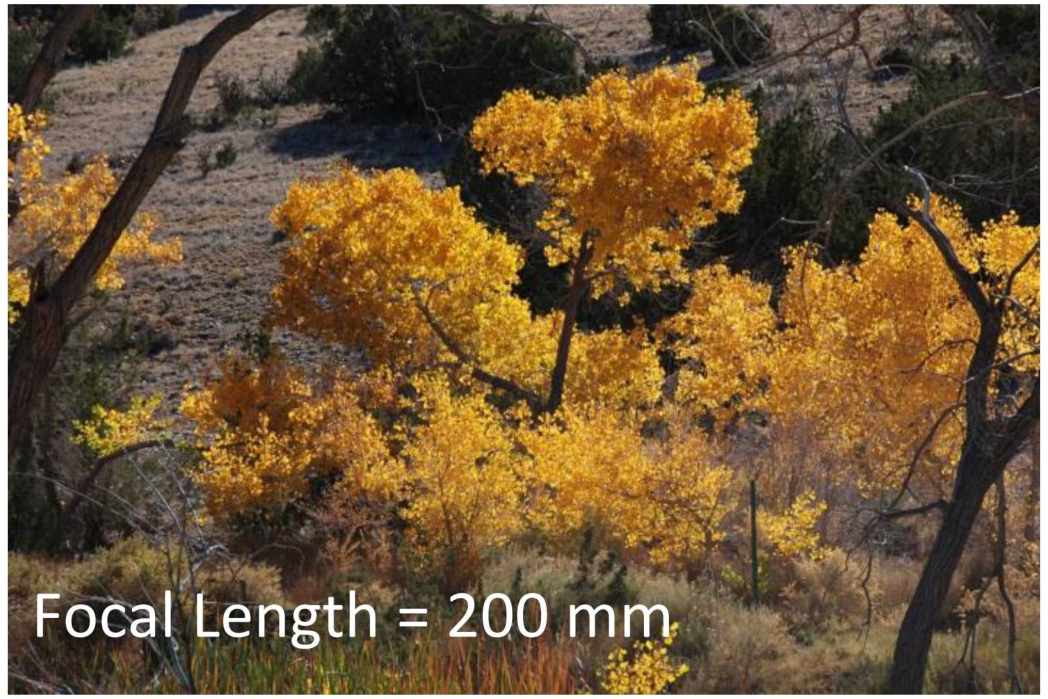
- 1:1 Imaging means object is same size as image. $S_o = 2f$
- Macro lens M = 1:1
- Most lenses M = 0.5

The focal length and distance to the object defines the magnification of the lens.


Photos by E. Bystrom

Focal length = 27 mm


Focal Length = 75 mm


Focal Length = 200 mm

Magnification (M)

$$M = \frac{Sensor\ Size}{Field\ of\ view}$$

Field-of-View (FOV)

$$FOV = \frac{Sensor\ Size}{M}$$

Stand-off Distance (S_o or SOD)

$$FOV = sensor\ size \cdot \frac{S_o - f}{f} \qquad M = \frac{f}{S_o - f}$$

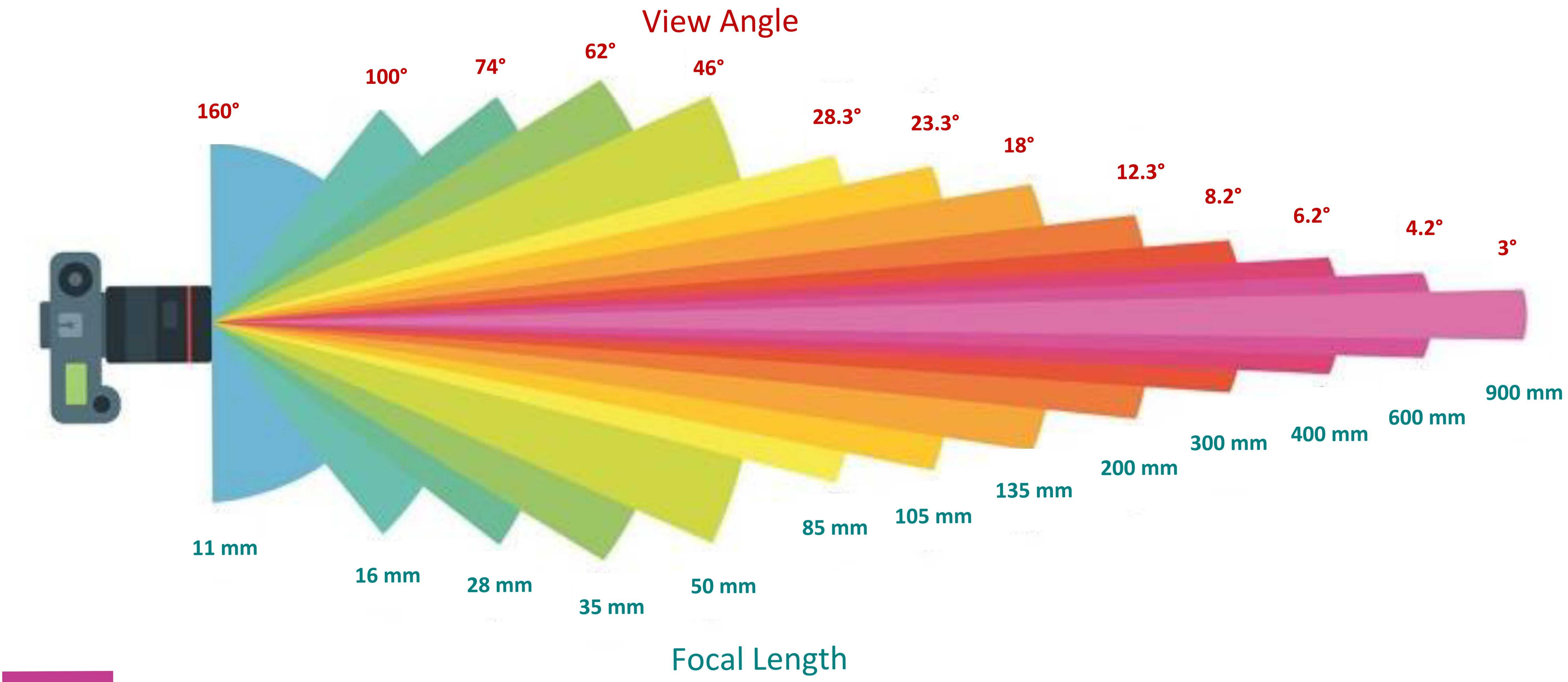
Usually $S_o >> f$

$$FOV \cong \frac{(Sensor\ Size)\cdot(Stand\text{-}off\ distance)}{Focal\ Length}$$

View-angle, stand-off distance and field-of-view are related.

https://learn.zoner.com/what-focal-length-is-best-for-landscape-photography/

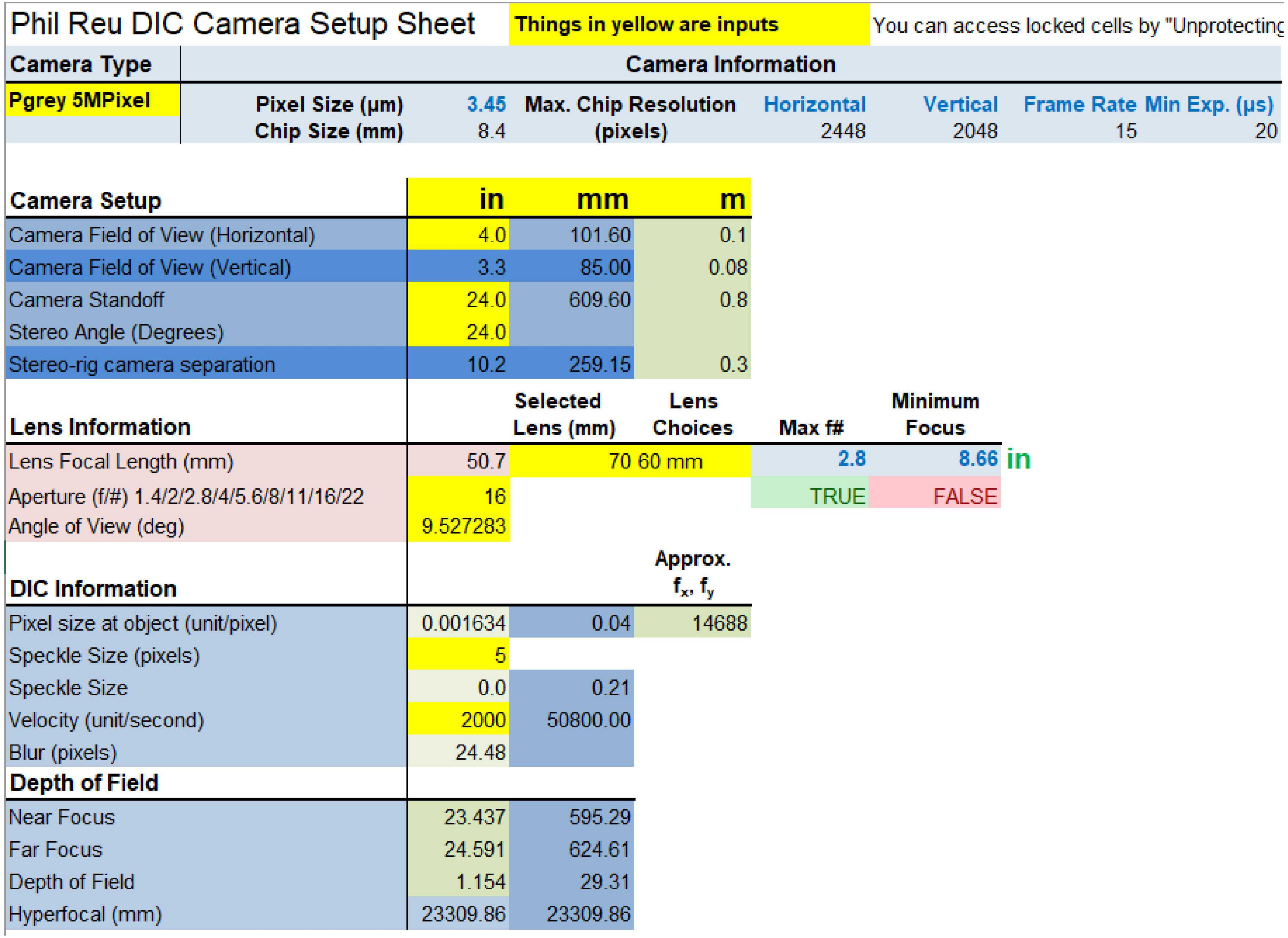
View angle and focal length are related.



iDICs

https://thisactualcamera.com/focal-length-affect-photos/

Spreadsheet lens calculator is available



Phil Reu DIC Camera Setup Sheet | Things in yellow are inputs | You can access locked cells by "Unprotecting

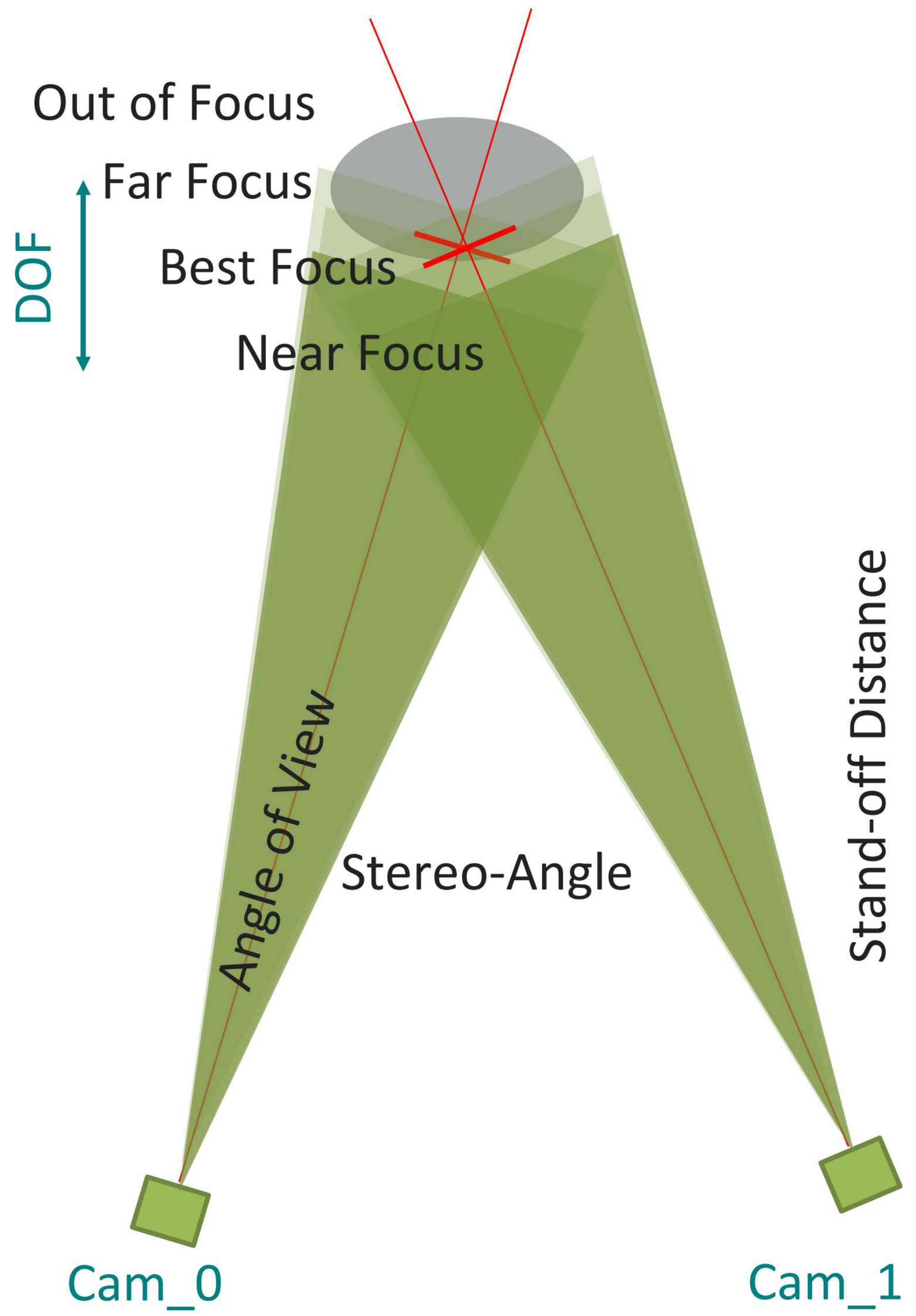
Camera Type	Camera Information						
Pgrey 5MPixel	Pixel Size (µm)	3.45	Max. Chip Resolution (pixels)	Horizontal	Vertical	Frame Rate	Min Exp. (µs)
	Chip Size (mm)	8.4		2448	2048	15	20

Camera Setup	in	mm	m
Camera Field of View (Horizontal)	4.0	101.60	0.1
Camera Field of View (Vertical)	3.3	85.00	0.08
Camera Standoff	24.0	609.60	0.8
Stereo Angle (Degrees)	24.0		
Stereo-rig camera separation	10.2	259.15	0.3

Lens Information		Selected Lens (mm)	Lens Choices	Max f#	Minimum Focus	
Lens Focal Length (mm)	50.7	70	60 mm	2.8	8.66	in
Aperture (f/#) 1.4/2/2.8/4/5.6/8/11/16/22	16			TRUE	FALSE	
Angle of View (deg)	9.527283					

DIC Information			Approx. f_x, f_y
Pixel size at object (unit/pixel)	0.001634	0.04	14688
Speckle Size (pixels)	5		
Speckle Size	0.0	0.21	
Velocity (unit/second)	2000	50800.00	
Blur (pixels)	24.48		

Depth of Field		
Near Focus	23.437	595.29
Far Focus	24.591	624.61
Depth of Field	1.154	29.31
Hyperfocal (mm)	23309.86	23309.86



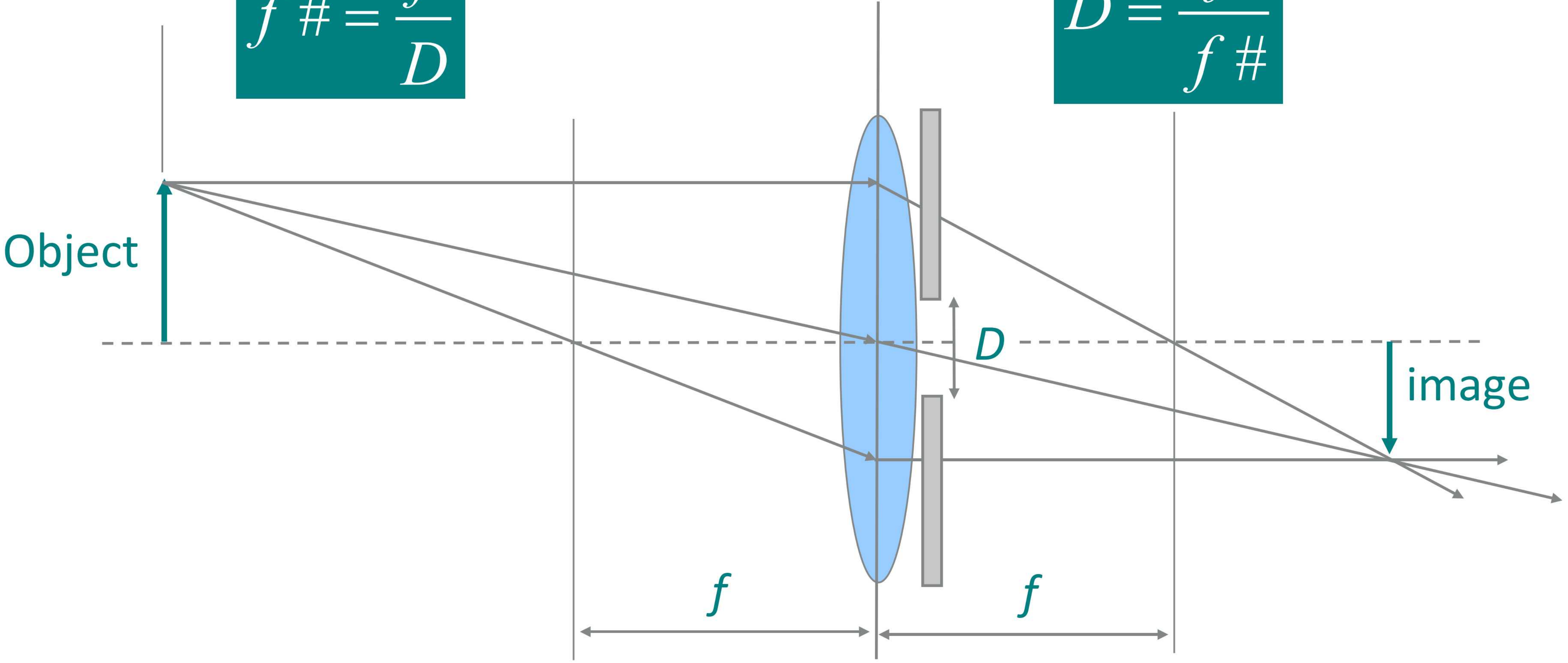
The f-number defines the aperture size and the amount of light getting to the detector

f-number (f# or N)

$$f\# = \frac{f}{D}$$

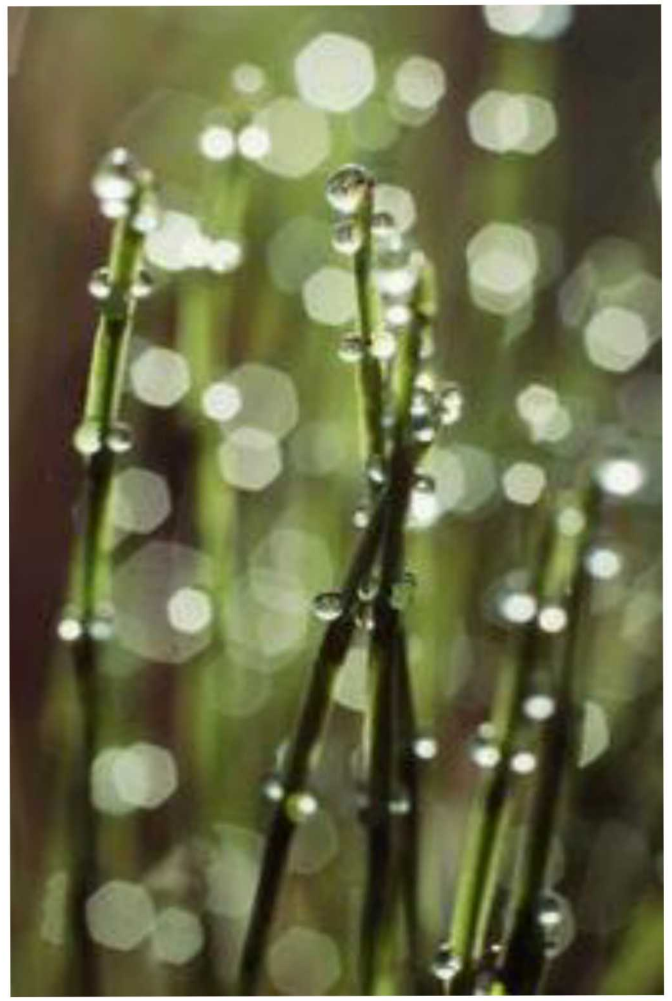
Aperture D

$$D = \frac{f}{f\#}$$

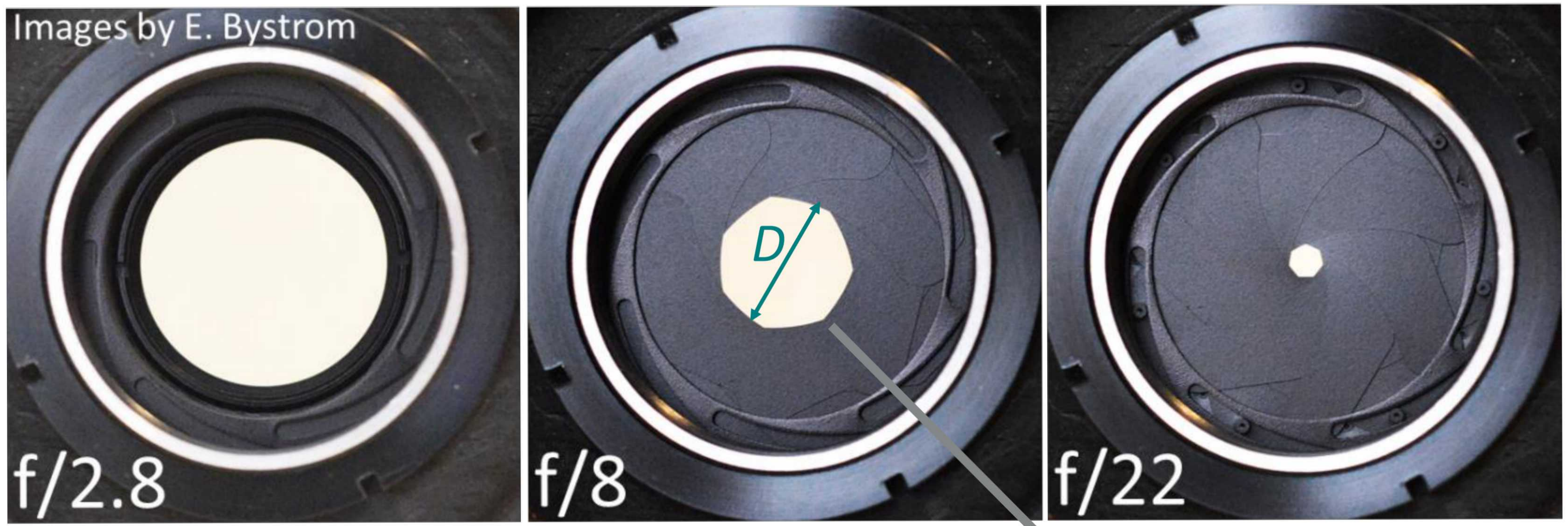


When the aperture diameter is 16 times less than the focal length:
f/# = *f*/16 or “f-16”

The aperture (f#, pupil, D) limits the light passing through the lens.



http://www.ehow.com/how_8629768_repair-lens-flares-aperture-photos.html



Images by E. Bystrom

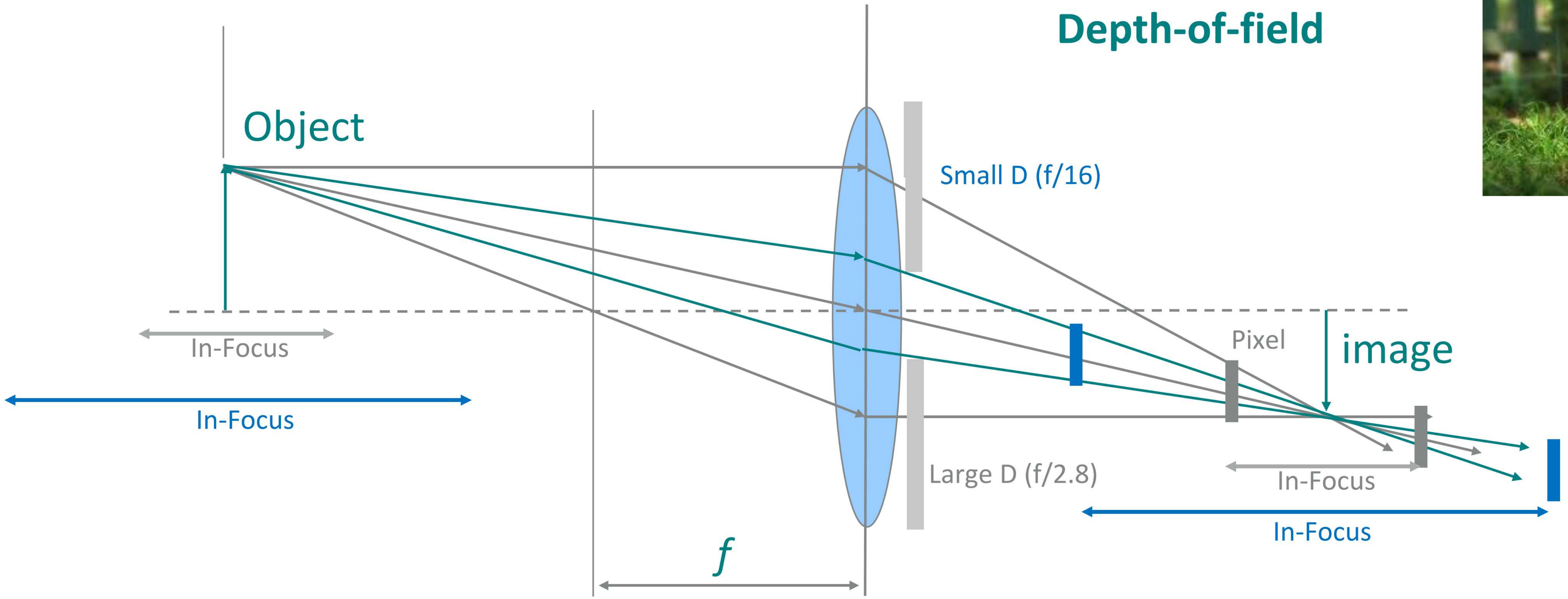
$$D = \frac{focal\ length}{f/\#}$$

F-number series: f/1.4, f/2, f/2.8, f/4, f/5.6, f/8, f/11, f/16, f/22, f/32

- The f/# multiples of ≈ 1.4 = $\sqrt{2}$ are a **doubling** or **halving** of light.
- f/8 to f/16 will require twice the light or twice the exposure.
- A “fast” lens has a large aperture. I.e. lots of light gets through.

Depth-of-field is the range of distances away from the lens where the object will be in focus.

Depth-of-field

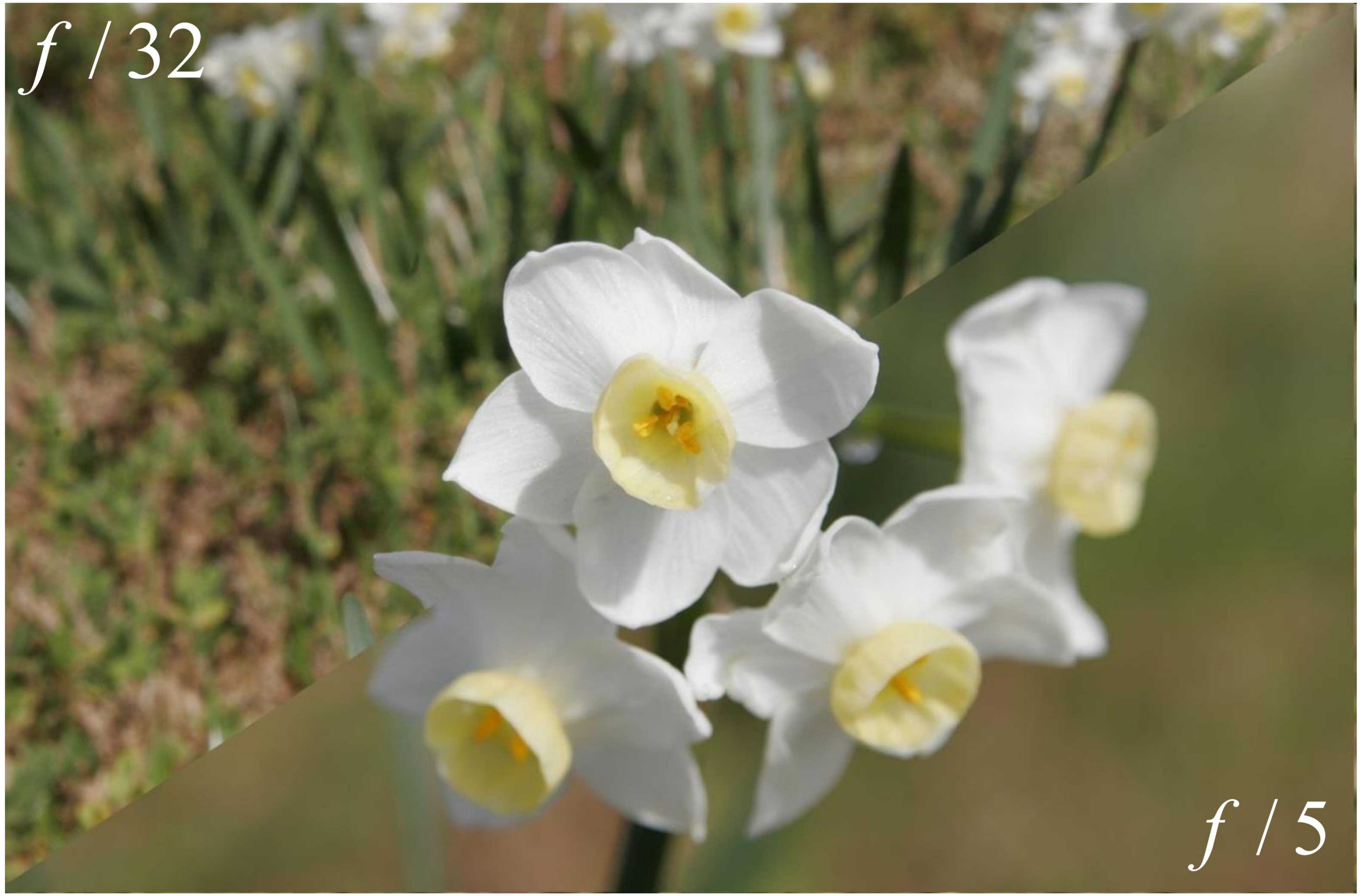


$$f\# = \frac{f}{D}$$

When f# is large (f/16) D is small, objects from a large range of distances will appear focused.

However, less light (increase shutter time or increase lighting), more difficult to focus. Very small pin-holes can generate diffraction…

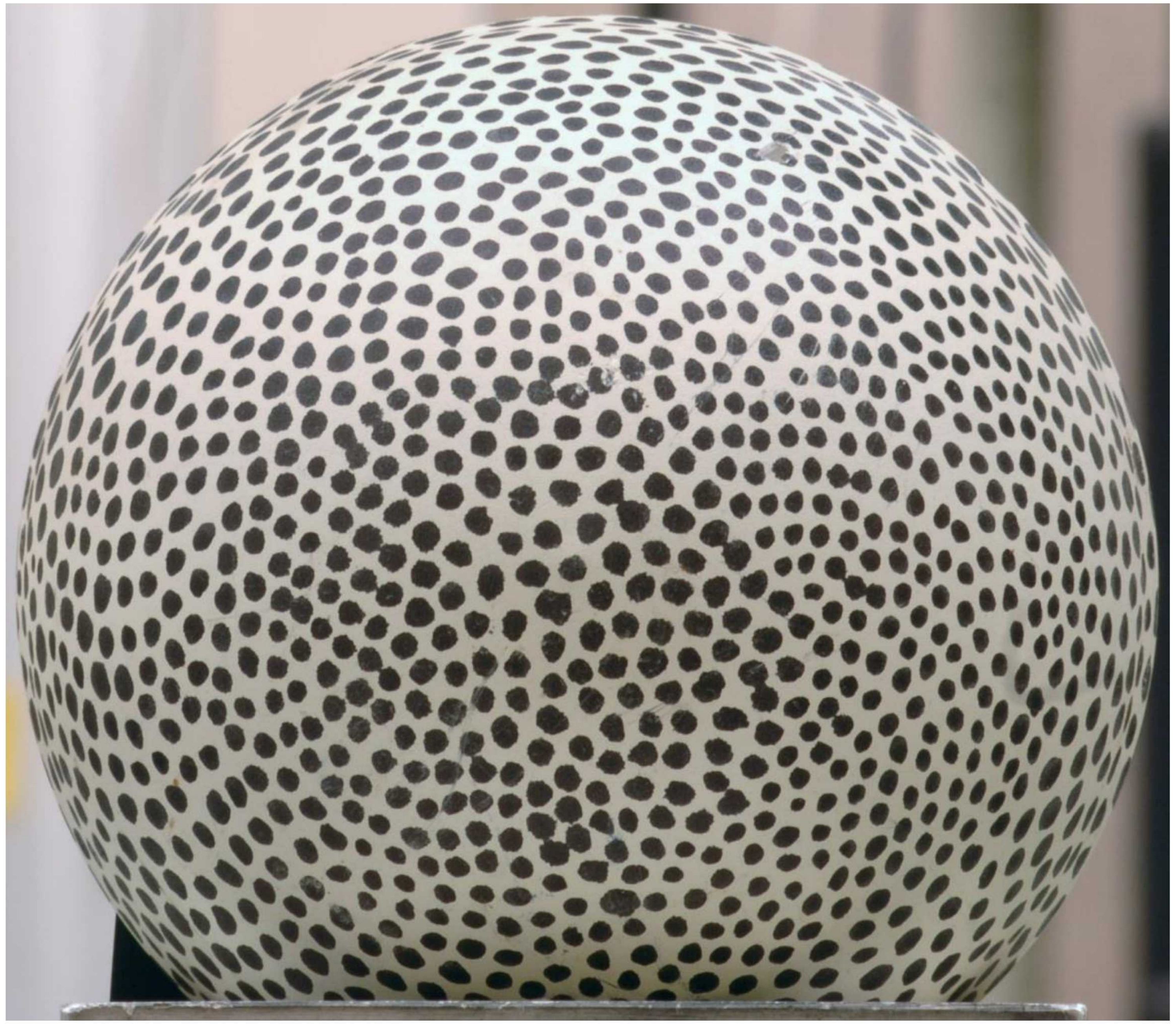
Depth-of-field illustrated at 2 apertures.



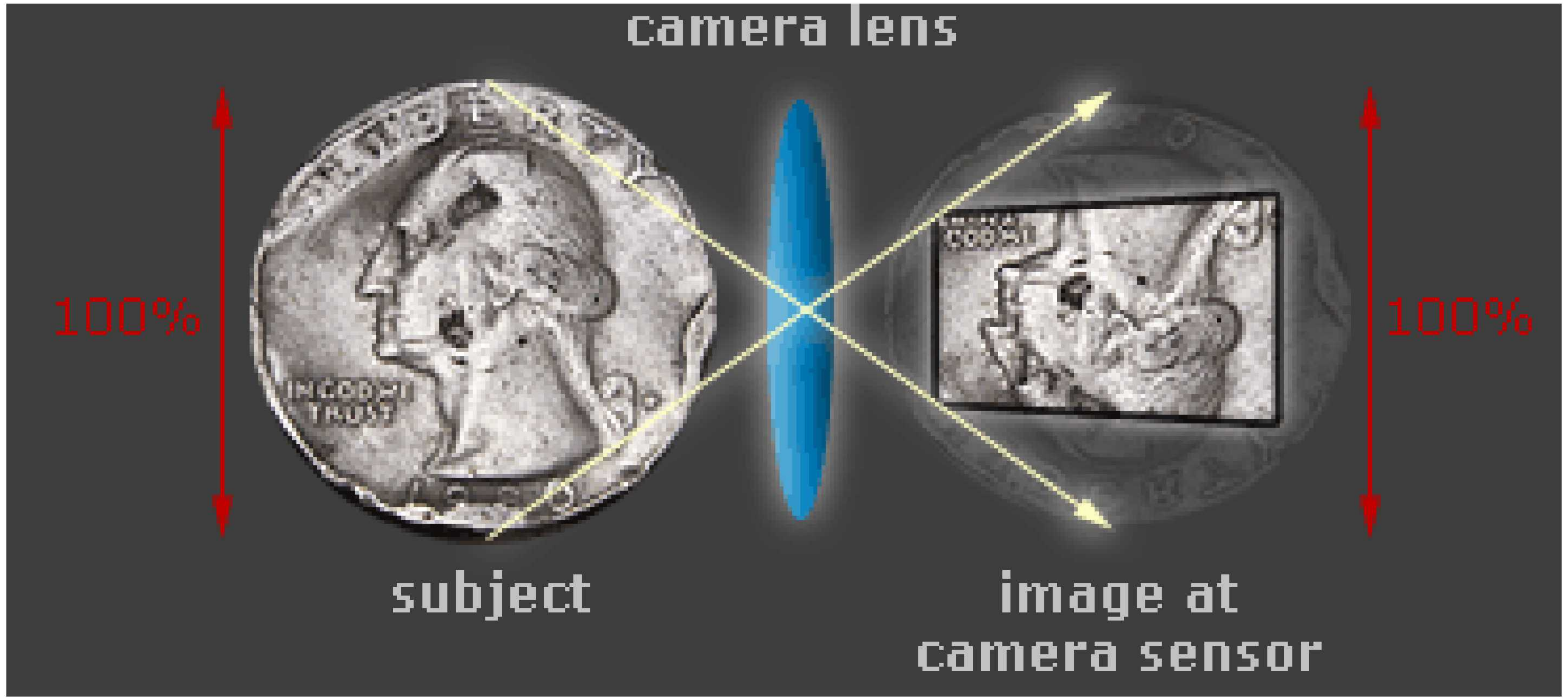
In practice, DOF also depends on sensor size (film format, CCD size) and primary object distance

Tip 2.17 – Large f/# increases DOF

Varying depth-of-field and focus points for a larger aperture (f/2.8)



Macro lenses are used for magnifying the scene.



- Technically macro is 1:1
- Size of the FOV = Size of the image sensor (1:1)
- Limited Depth of field
- Focal length determines the stand-off (higher = further away)

$$M = \frac{Sensor\ Size}{Field\ of\ view}$$

$M = 1 =$ Sensor Size = Field of View

iDICs

https://www.cambridgeincolour.com/tutorials/macro-lenses.htm

Extension tubes are a cheap way to add magnification by changing the back focal length

Placed between lens and camera, tube increases S_i

$$\frac{1}{S_0}+\frac{1}{S_i}=\frac{1}{f}$$

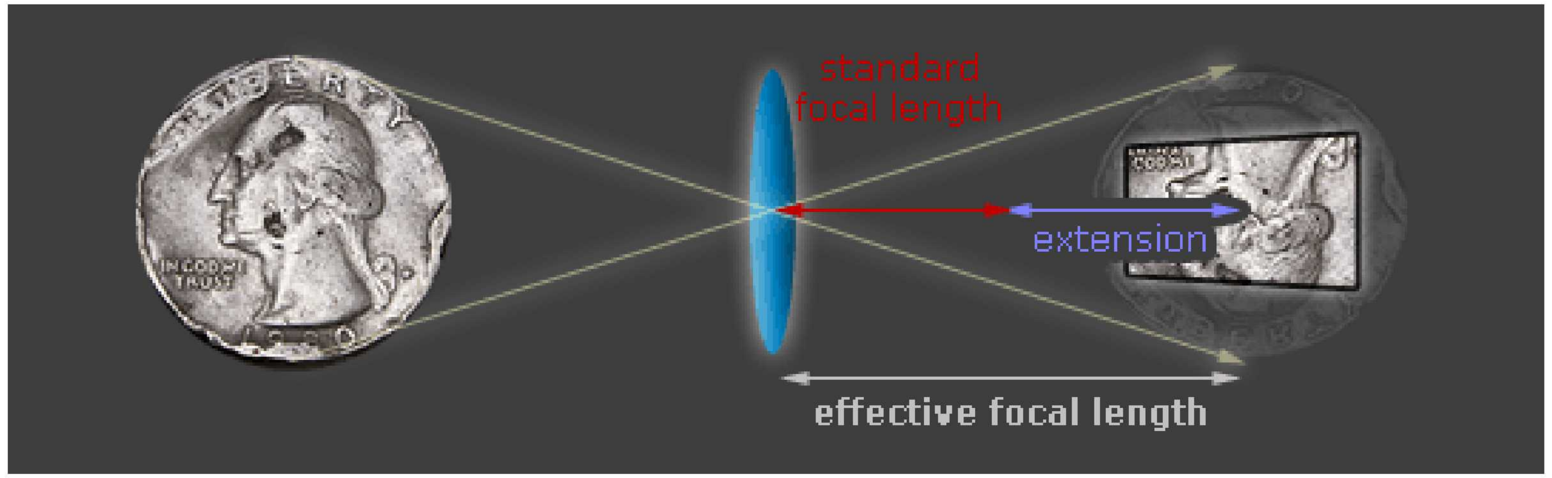
$S_i \uparrow$ then $S_o \downarrow$

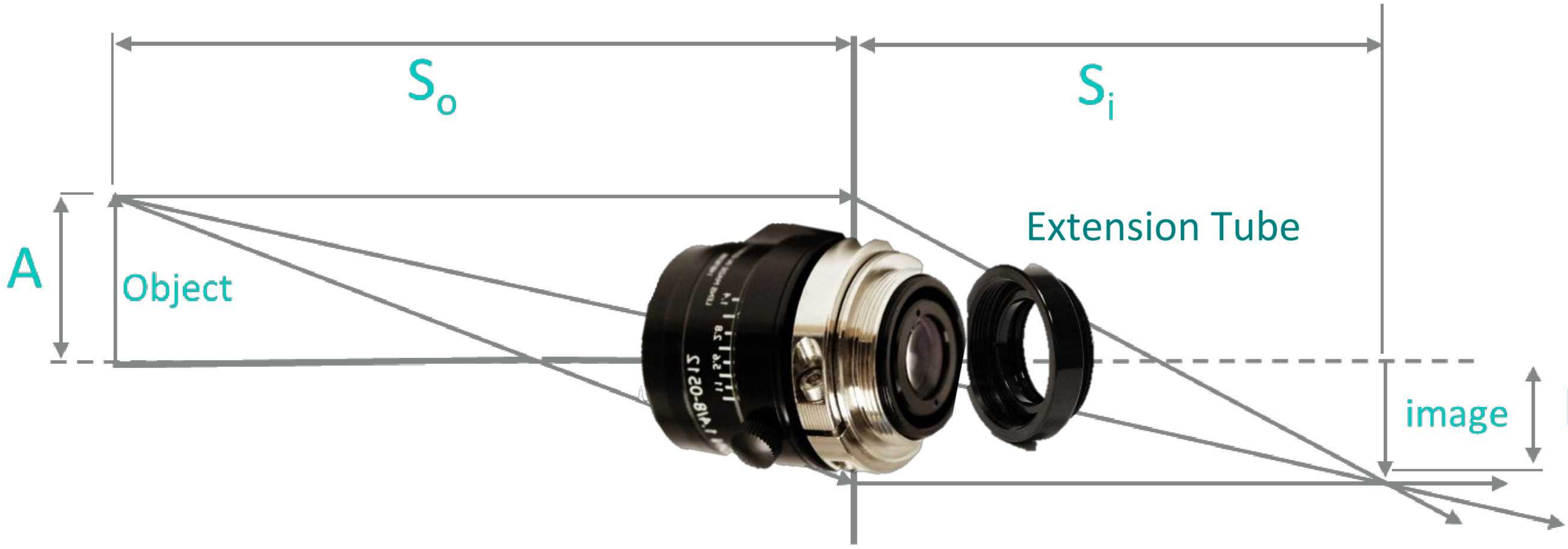
Small S_o moves object closer – making it larger.

Initial Mag. = 0.15, 50 mm lens with 25 mm Tube

Final Mag. = 0.15 + (25/50) = 0.65

$$Tube\ Mag. = \frac{Extension\ Tube}{Focal\ Length}$$





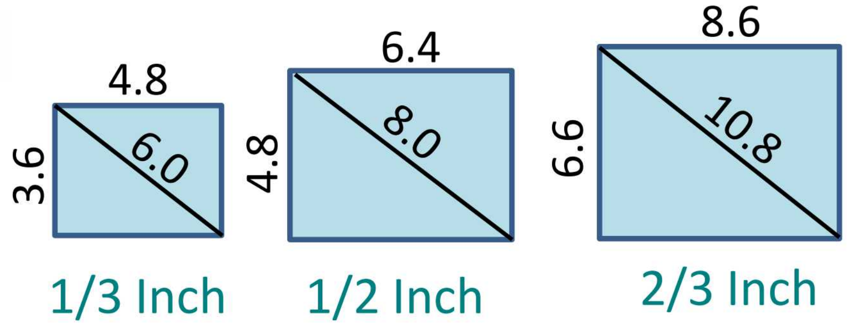
Extension tube goes behind the lens

The lens size matters relative to the detector size: F-mount versus C-mount

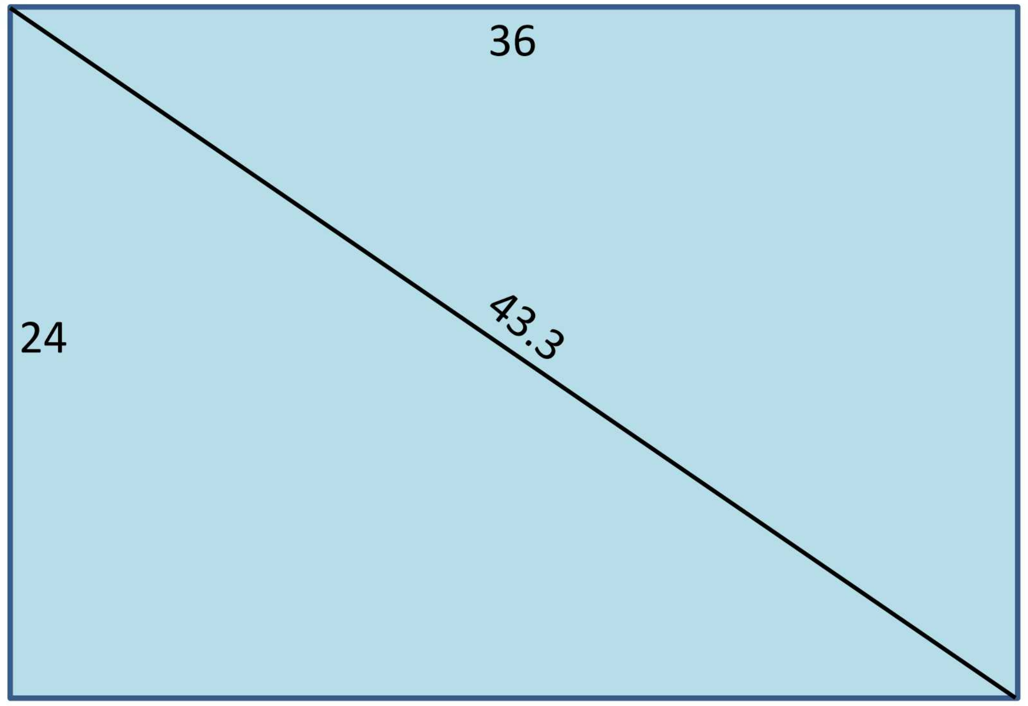
C-mount

Photos by E. Bystrom

Nikon/Canon



Camera Detector Size (mm)



35 mm Format

C-mount causes vignetting at 2/3-inch sensor size and above

Phantom v2512 Detector
35.8 mm × 22.4 mm (1280 × 800 pixels)

Photron SA-Z
20.48 × 20.48 mm (1024 × 1024 pixels)

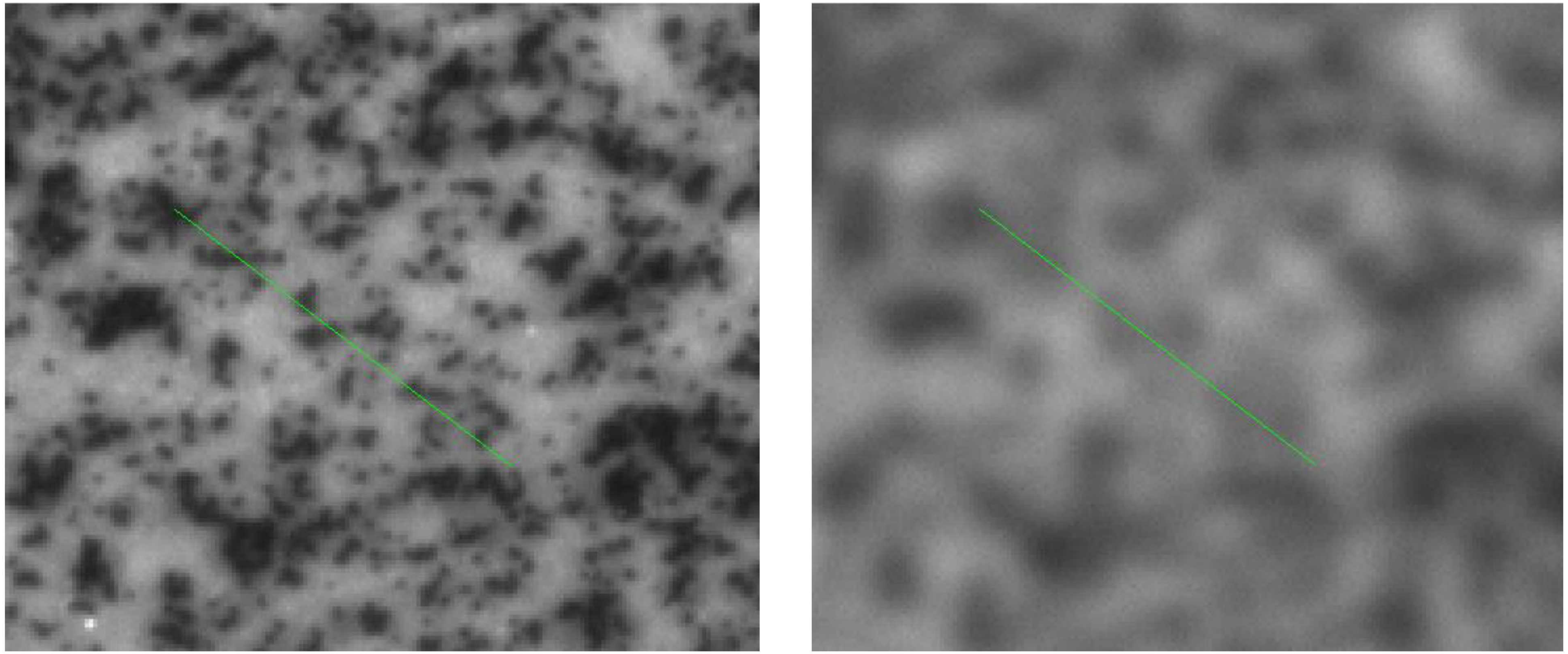
Section 2.1.8

LENS RESOLUTION AND MTF

DON’T PUSH THE LENS TO FAR…

Empty magnification can often be seen by a loss of edge detail in the speckles

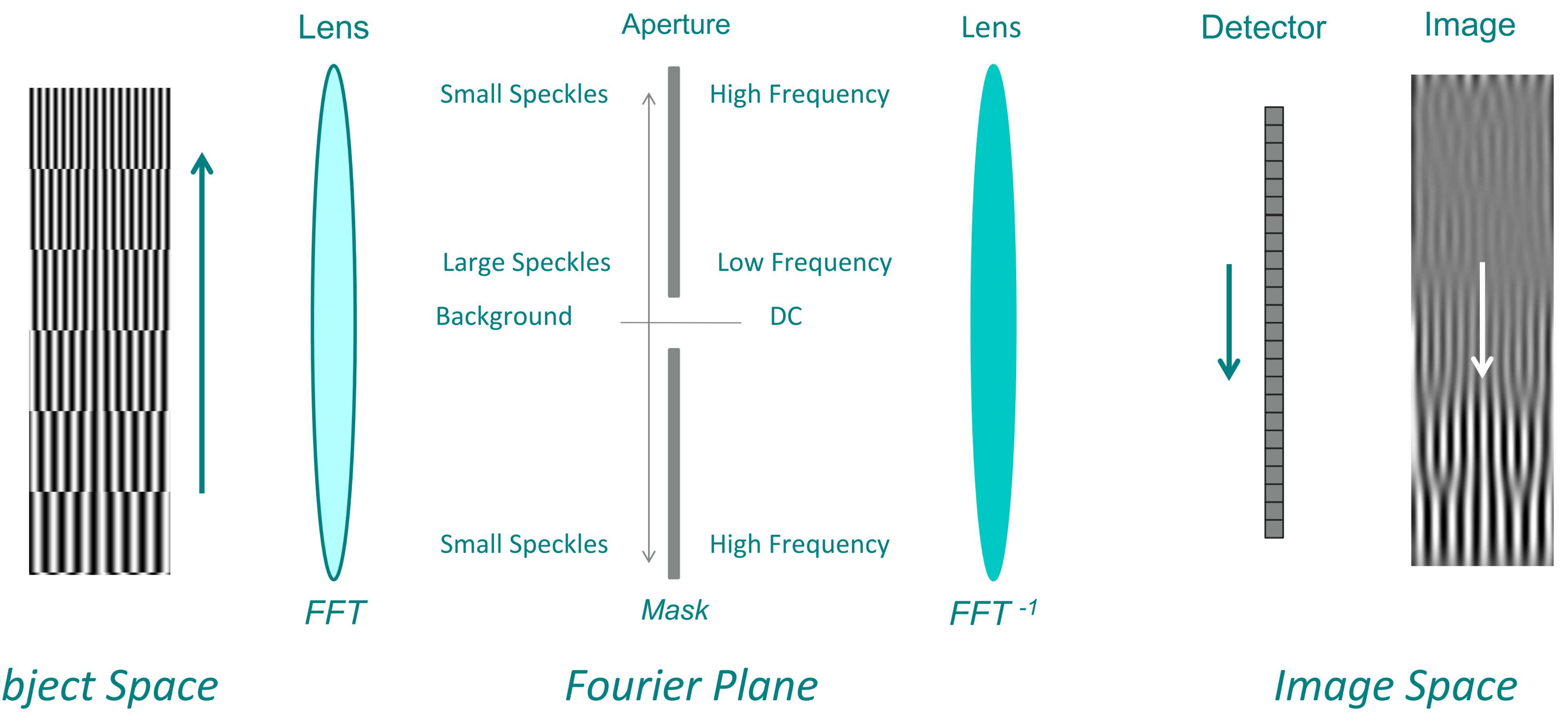
They are both in focus!!



f/1.9 Same speckle pattern f/32

- “Empty magnification” occurs when the image is enlarged (magnification), with no added detail being seen (empty).
- Focal length and distance define lens magnification. Diffraction limits define resolution and contrast.
- This happens when you have extension tubes and/or small apertures.

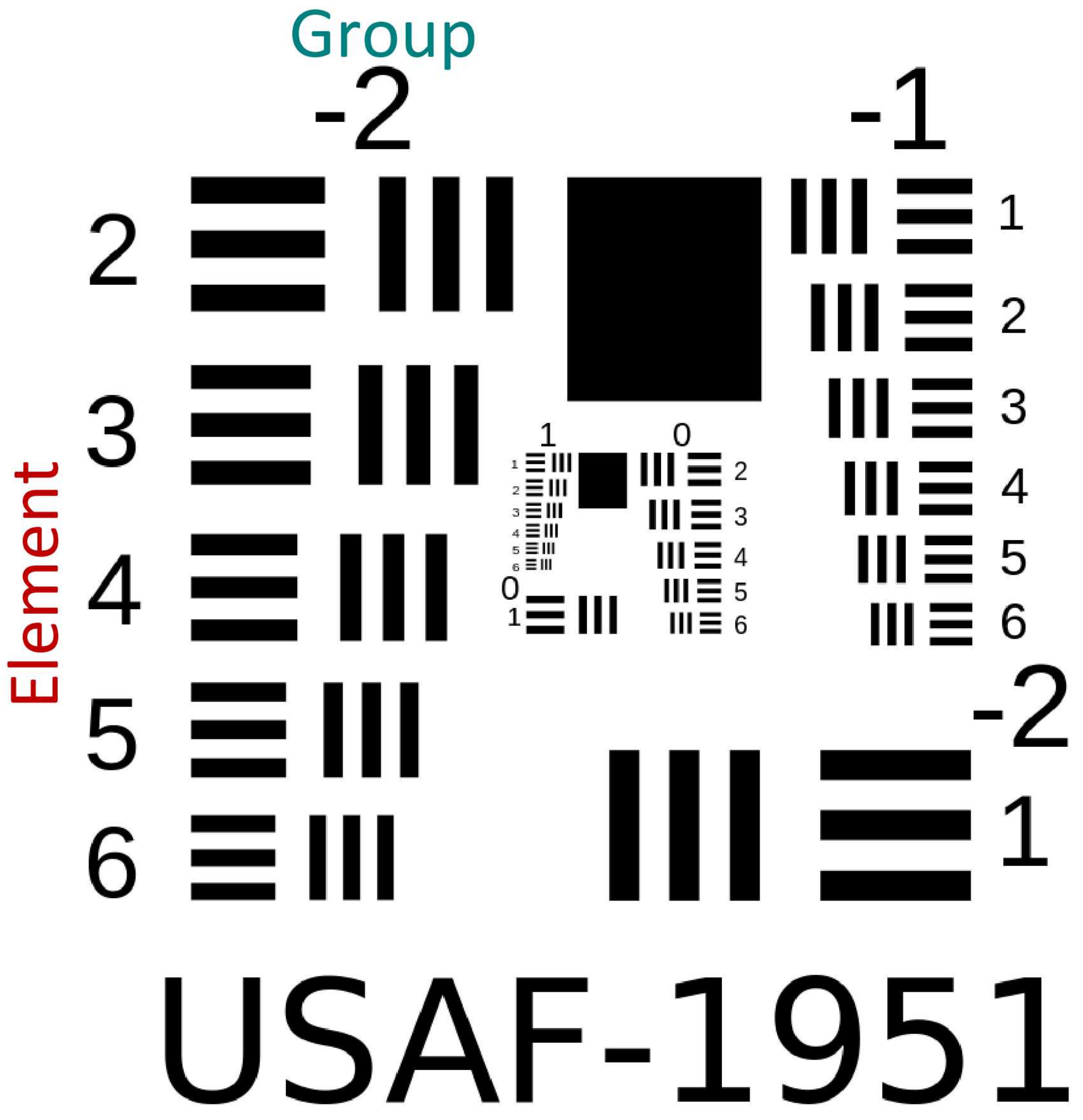
The lens is an analog Fourier transform. We need to think in the frequency domain.

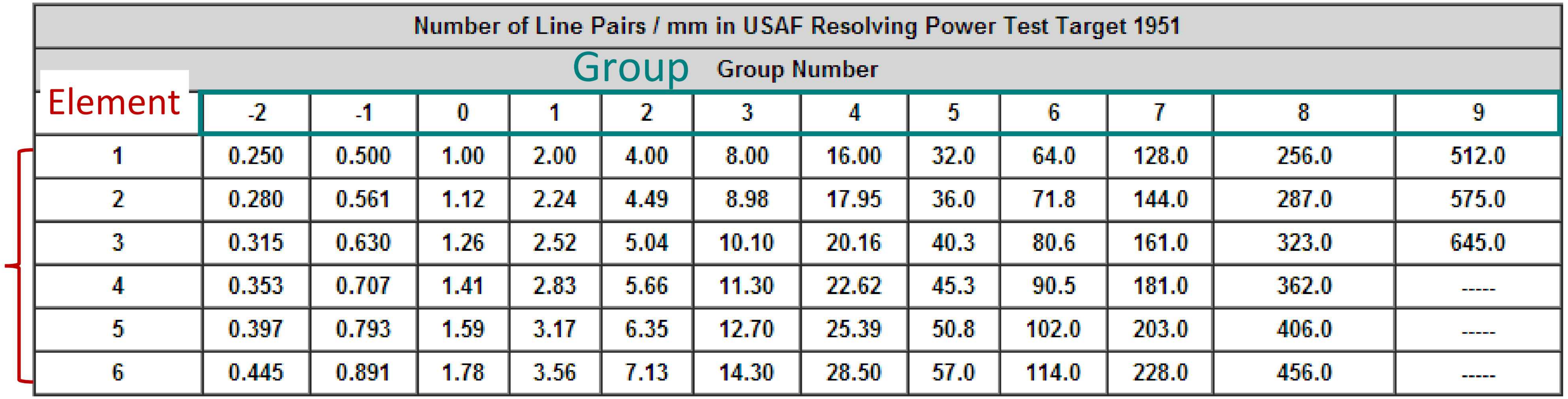


All lenses have an aperture that is imaged through – even if it is just the diameter of the lens.

The aperture controls the lens resolution.

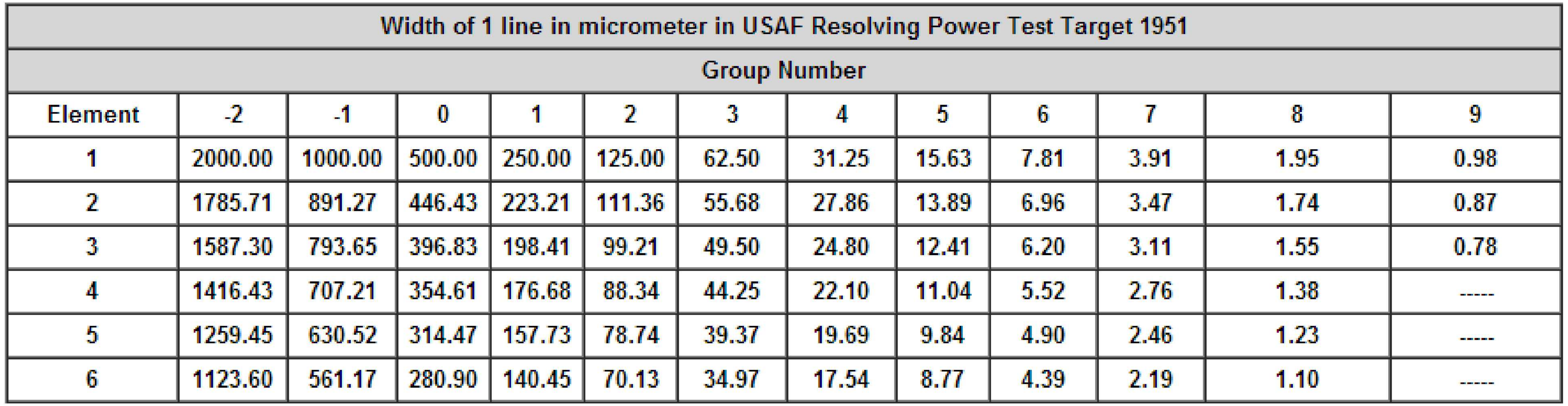
An Airforce target is a great method to ensure you have adequate resolution





Number of Line Pairs / mm in USAF Resolving Power Test Target 1951

Element	Group Number -2	-1	0	1	2	3	4	5	6	7	8	9
1	0.250	0.500	1.00	2.00	4.00	8.00	16.00	32.0	64.0	128.0	256.0	512.0
2	0.280	0.561	1.12	2.24	4.49	8.98	17.95	36.0	71.8	144.0	287.0	575.0
3	0.315	0.630	1.26	2.52	5.04	10.10	20.16	40.3	80.6	161.0	323.0	645.0
4	0.353	0.707	1.41	2.83	5.66	11.30	22.62	45.3	90.5	181.0	362.0	-----
5	0.397	0.793	1.59	3.17	6.35	12.70	25.39	50.8	102.0	203.0	406.0	-----
6	0.445	0.891	1.78	3.56	7.13	14.30	28.50	57.0	114.0	228.0	456.0	-----

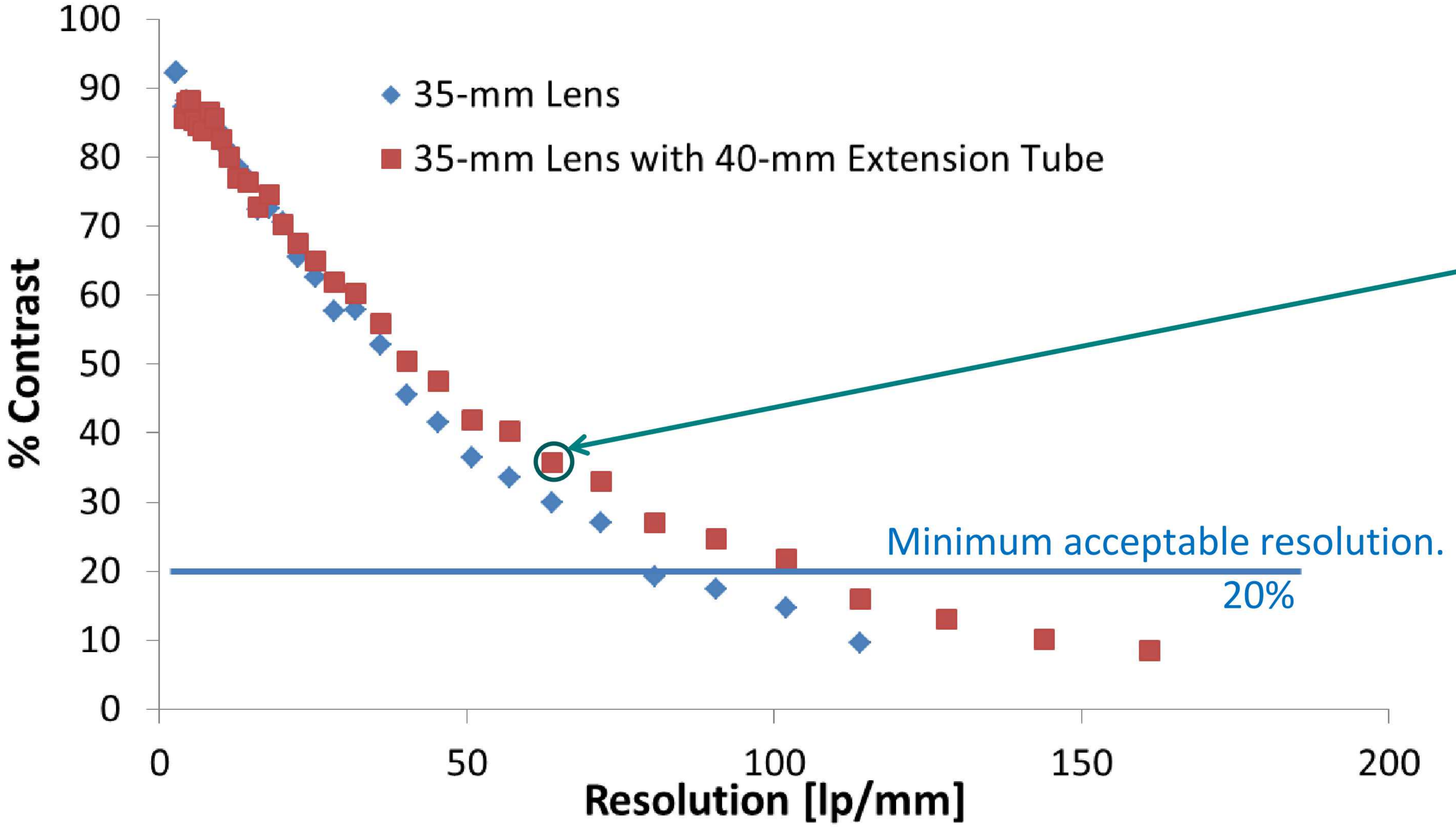


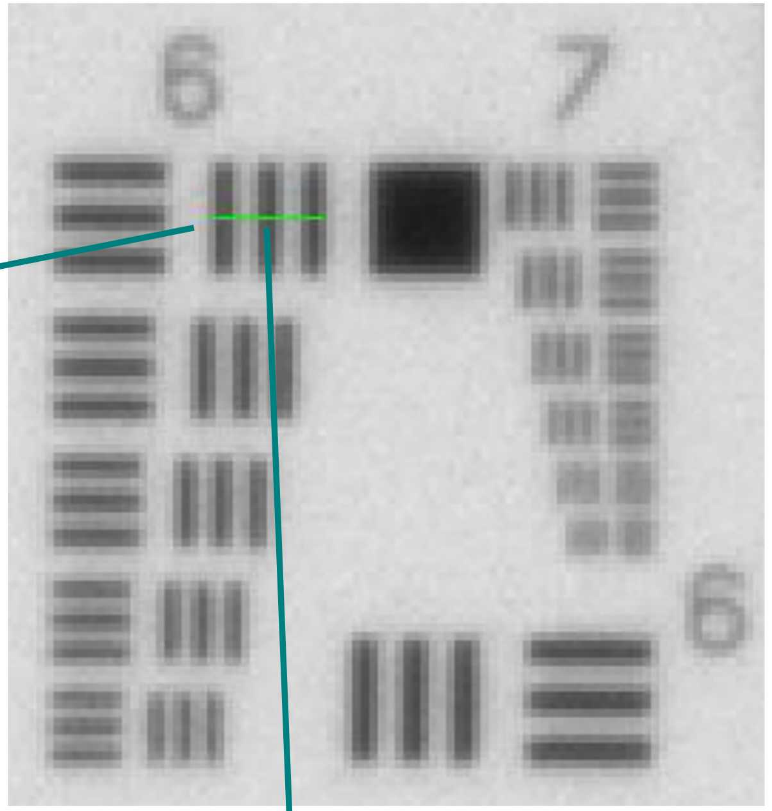
Width of 1 line in micrometer in USAF Resolving Power Test Target 1951

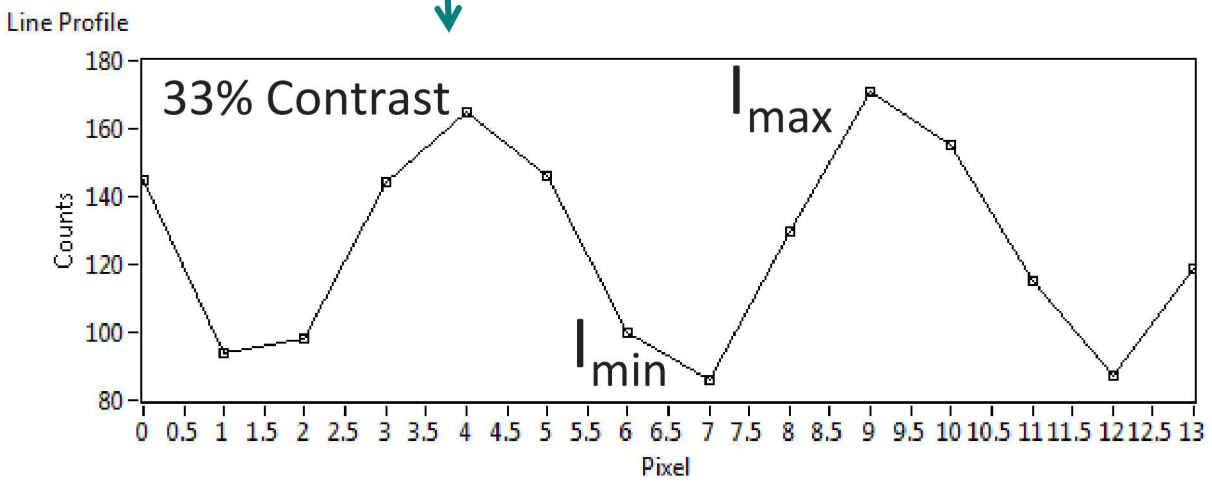
Element	Group Number -2	-1	0	1	2	3	4	5	6	7	8	9
1	2000.00	1000.00	500.00	250.00	125.00	62.50	31.25	15.63	7.81	3.91	1.95	0.98
2	1785.71	891.27	446.43	223.21	111.36	55.68	27.86	13.89	6.96	3.47	1.74	0.87
3	1587.30	793.65	396.83	198.41	99.21	49.50	24.80	12.41	6.20	3.11	1.55	0.78
4	1416.43	707.21	354.61	176.68	88.34	44.25	22.10	11.04	5.52	2.76	1.38	-----
5	1259.45	630.52	314.47	157.73	78.74	39.37	19.69	9.84	4.90	2.46	1.23	-----
6	1123.60	561.17	280.90	140.45	70.13	34.97	17.54	8.77	4.39	2.19	1.10	-----

Lens resolution is measured in line pairs/mm.

An approximate MTF can be obtained from the AF target image.



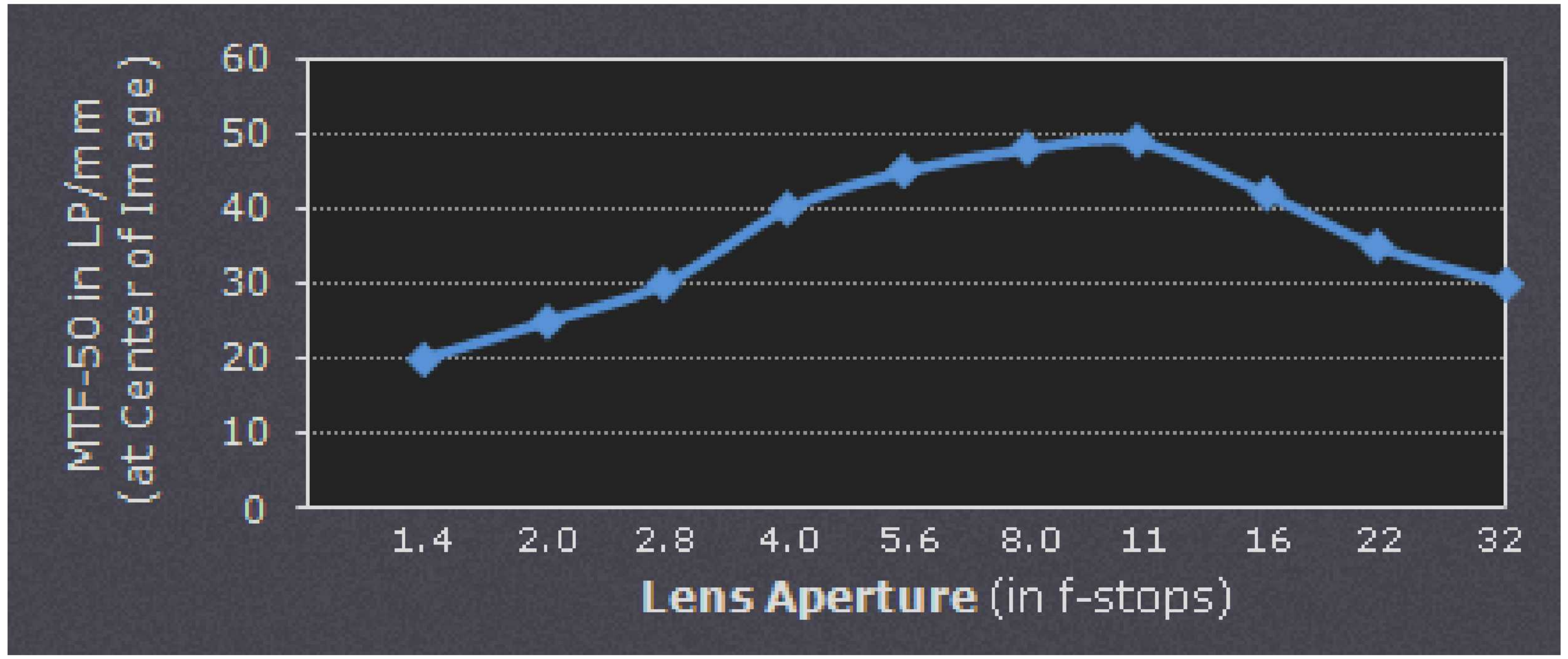


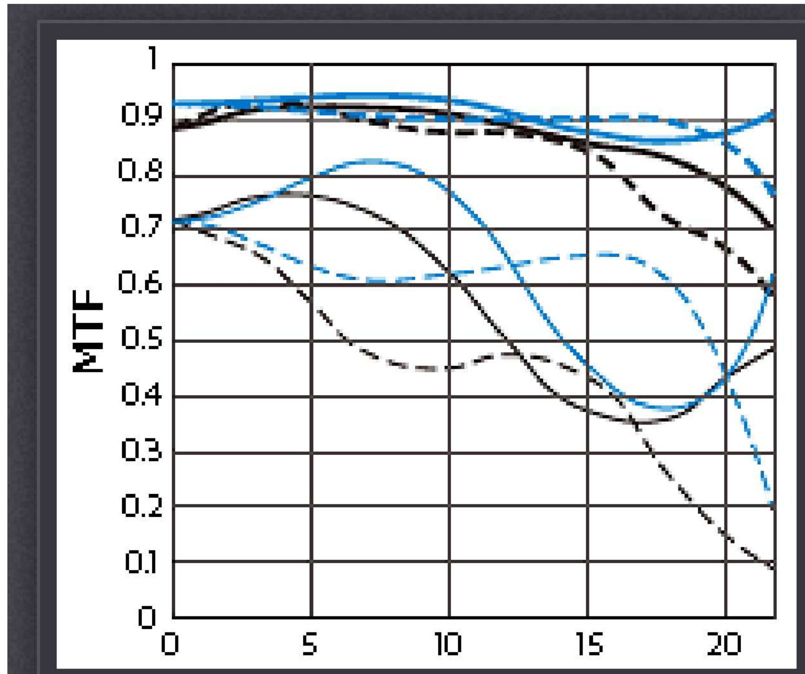


$$Contrast(\%) = 100\,\frac{(I_{max} - I_{min})}{(I_{max} + I_{min})}$$

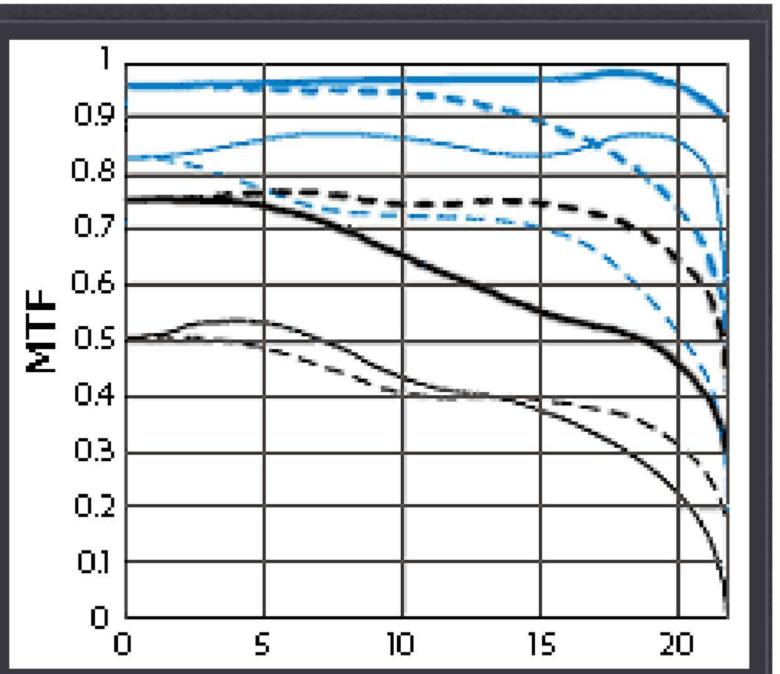
We still don't know if it is "lens" or "camera" limited at this point.

MTF can be much more complicated and varies throughout the FOV.

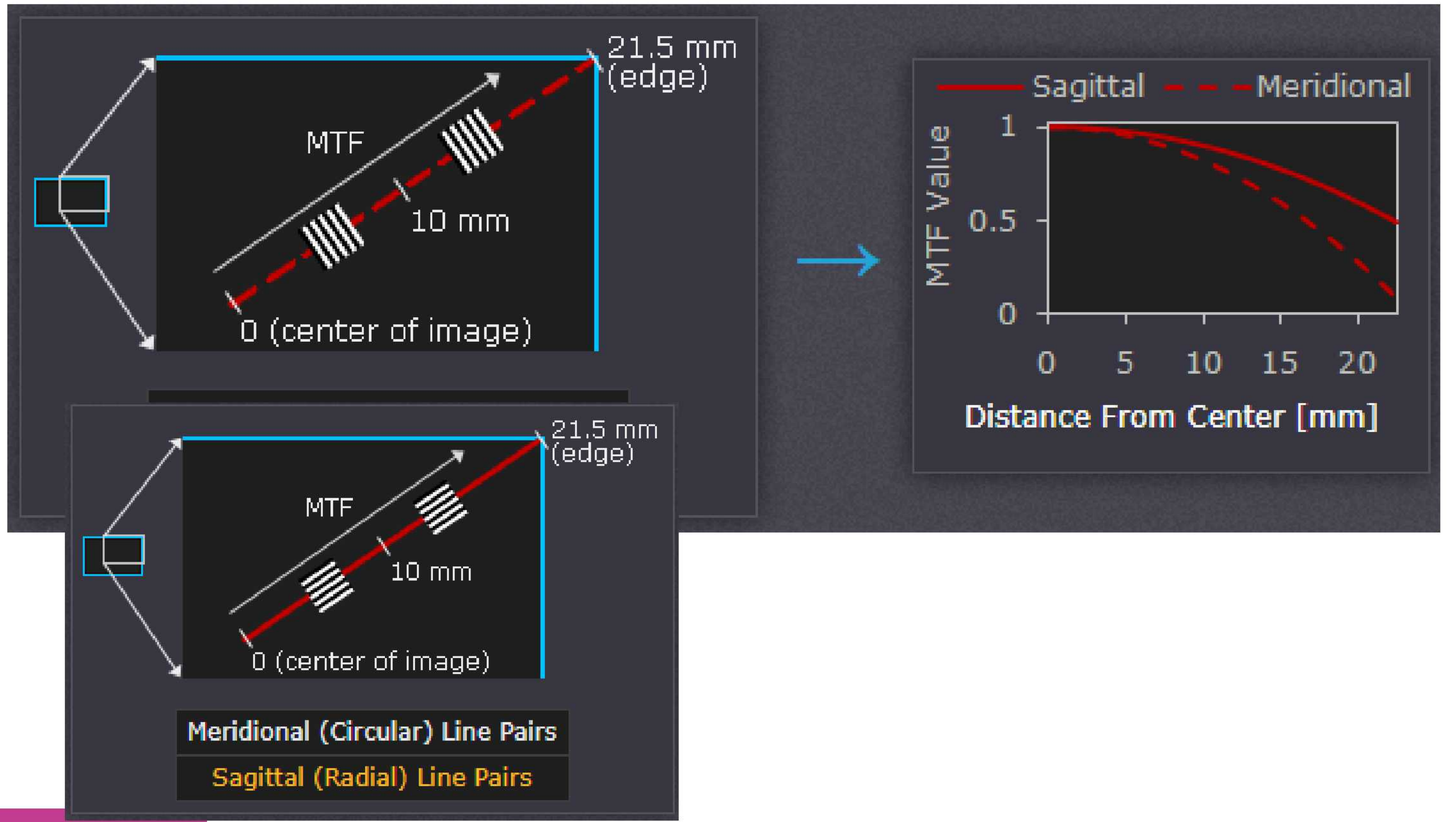


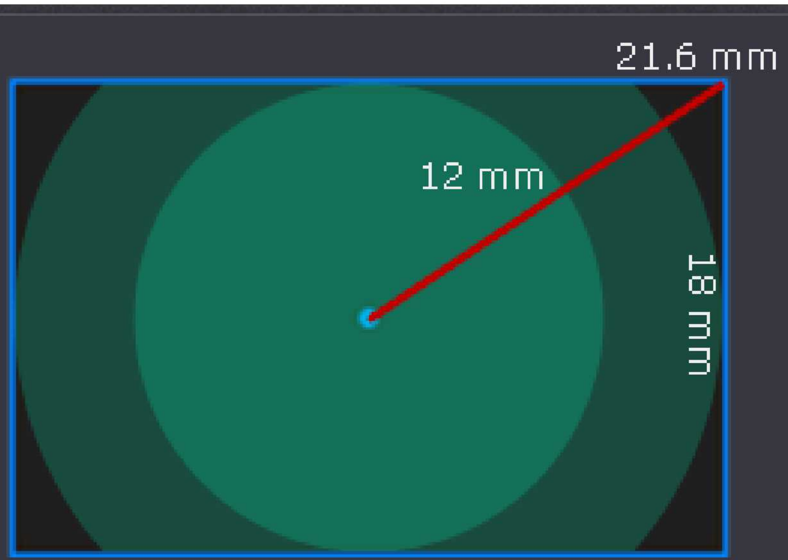


Canon 16-35mm f/2.8L II Lens (zoom set at 35mm)

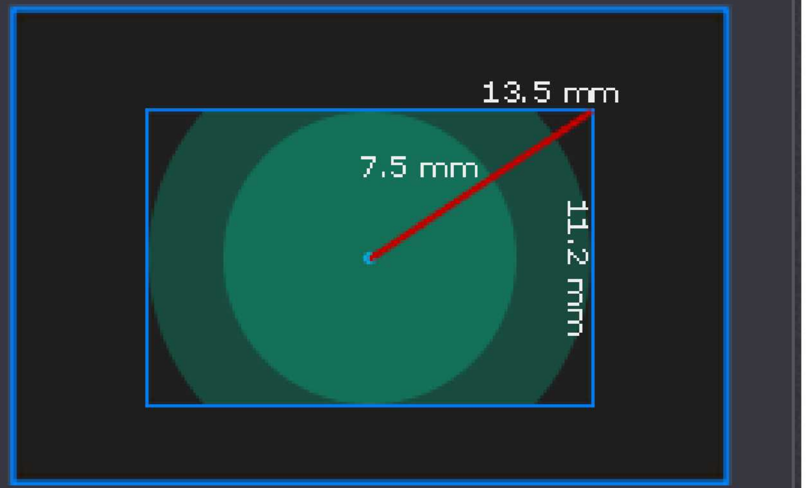


Canon 35mm f/1.4L Prime Lens





Full Frame 35 mm Sensor

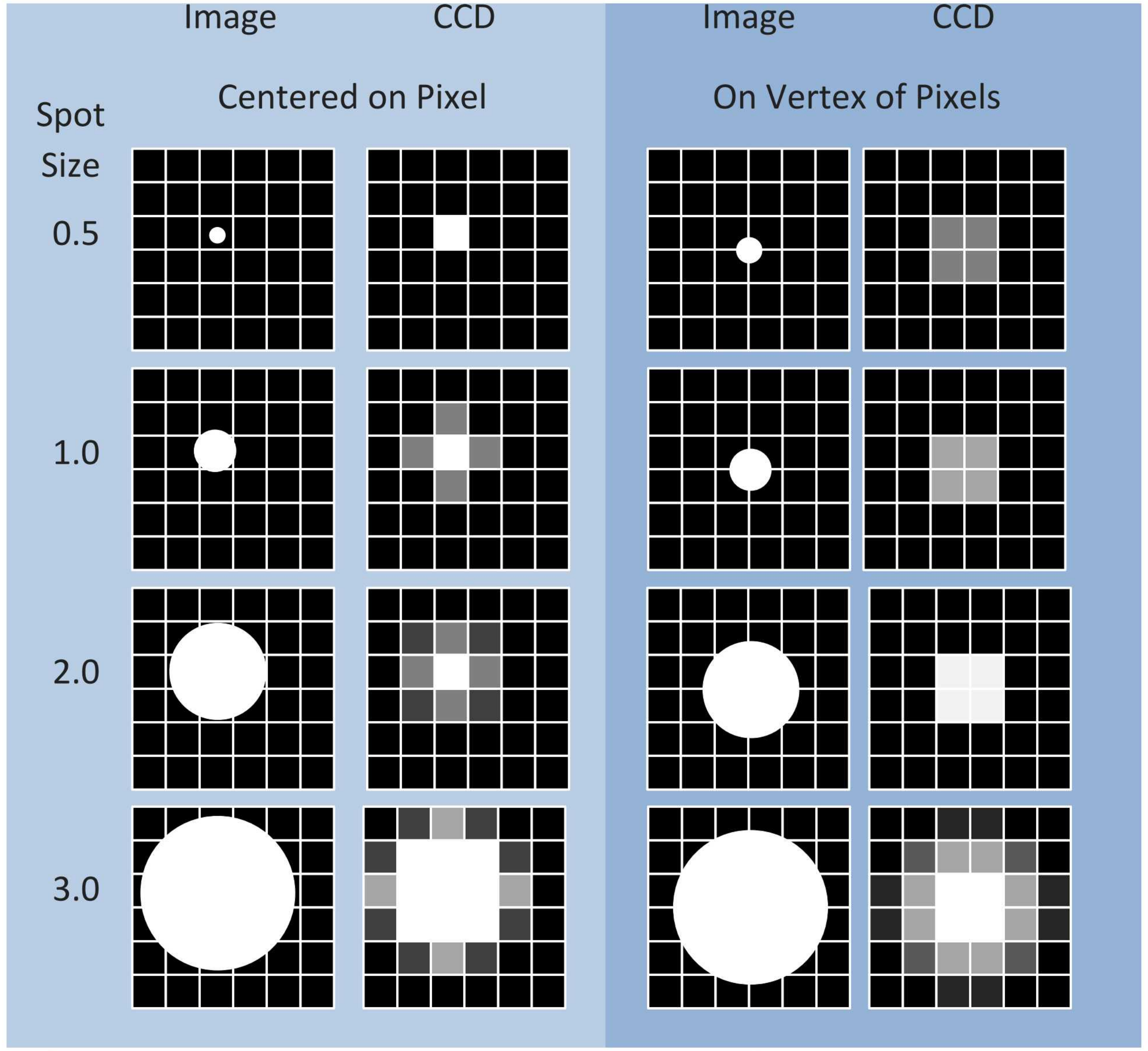


1.6X Cropped Sensor

iDICs

https://www.cambridgeincolour.com/tutorials/lens-quality-mtf-resolution.htm

Pixel size affects the digital cameras MTF – Camera limited

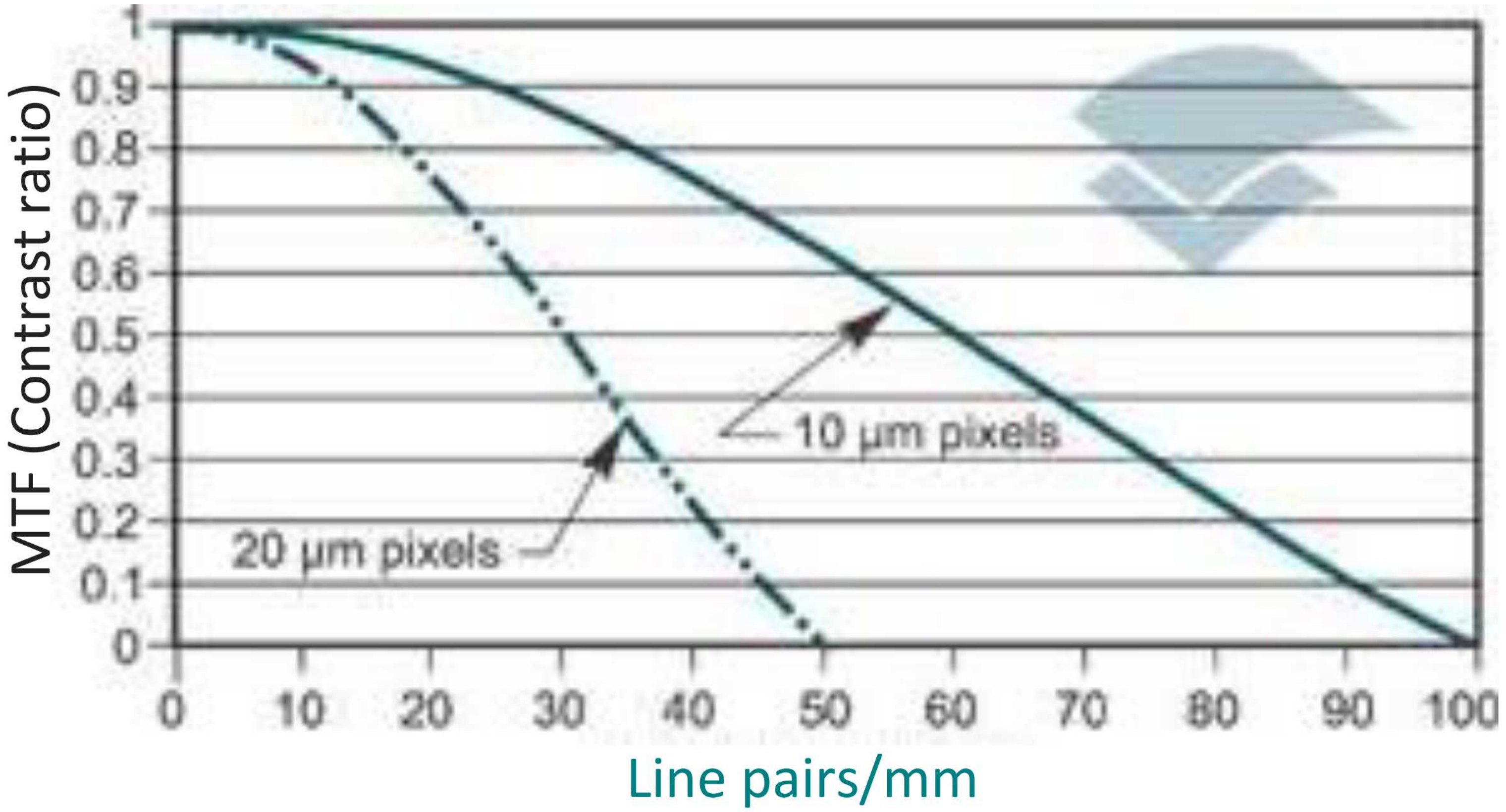


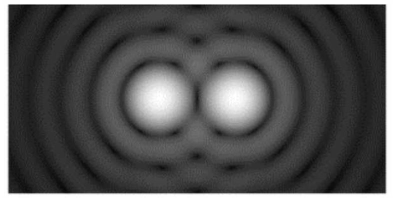
$$MTF_{CCD} = \frac{1}{2p}(lp/mm)$$

p = pixel size in mm

MTF_{CCD} = 1/(2 · 0.005e-3) = 100 lp/mm

- A 100x objective creates a diffraction-limited spot at the CCD of 27 microns.
- A pixel of 13 x 13 micron pixels would just matched the diffraction limit.
- A 9 x 9 micron pixel is preferred (i.e. 3 pixels = 27 µm).

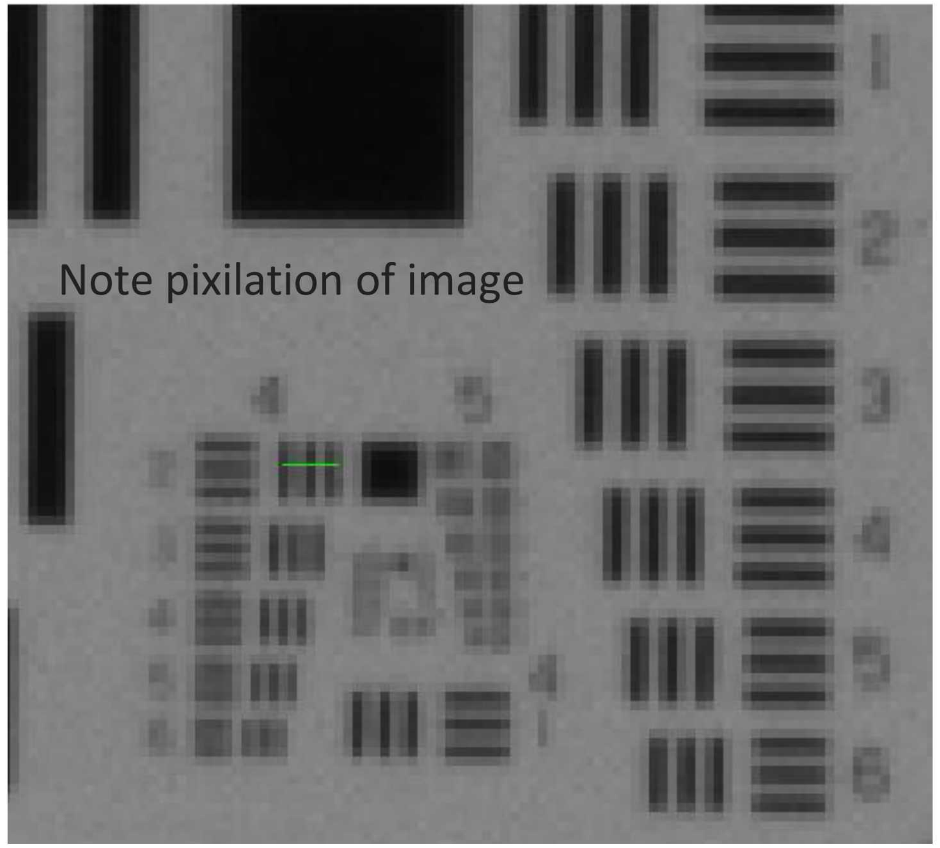




http://www.andor.com/learning/digital_cameras/?docid=319

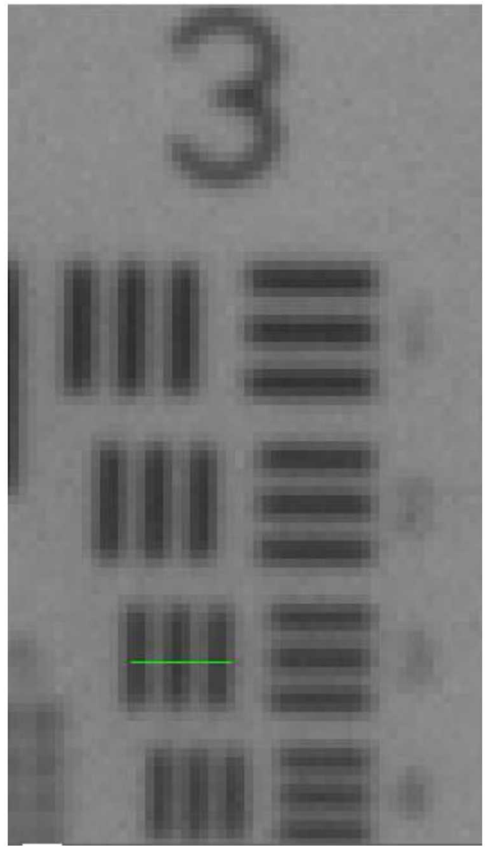
Is the system lens limited or camera limited?

35 mm lens – with lens magnification the pixel size at the object is 22 µm

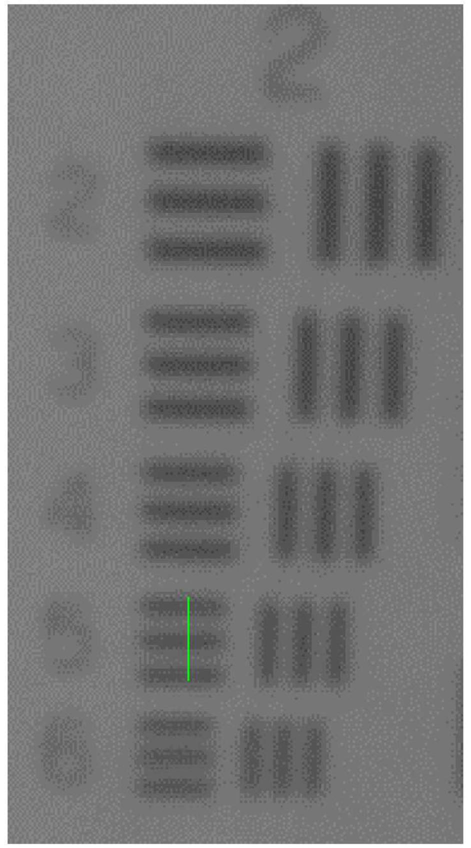


Note pixilation of image

f/1.9 – Group 4/Element 2
27 µm line width
Camera limited (pixel)



f/16 – Group 3/Element 3
50 µm line width
Lens limited

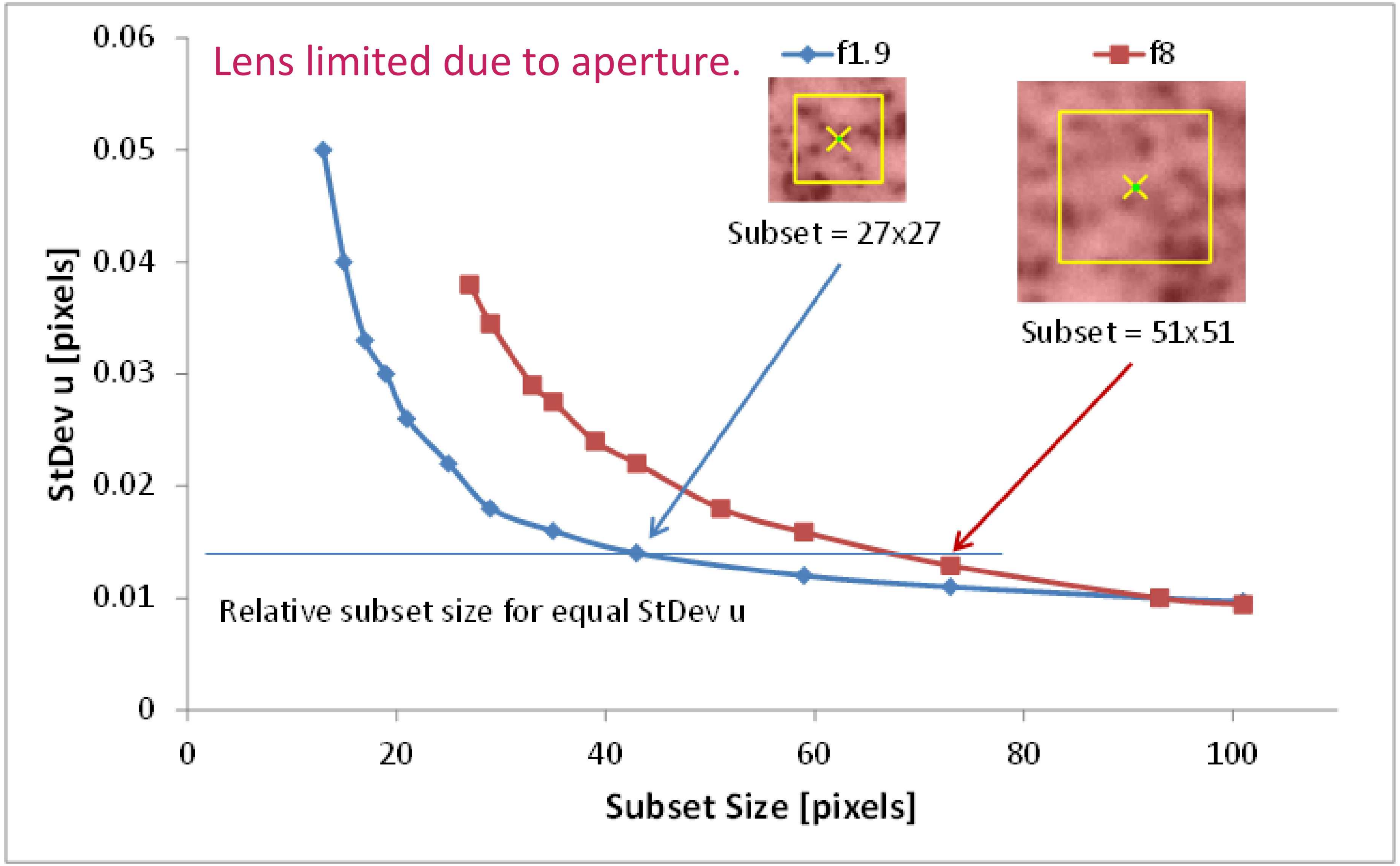


f/32 – Group 2/Element 5
79 µm line width
Lens limited

Remember: The aperture controls the lens resolution.

Remember: The pixel size controls the camera resolution.

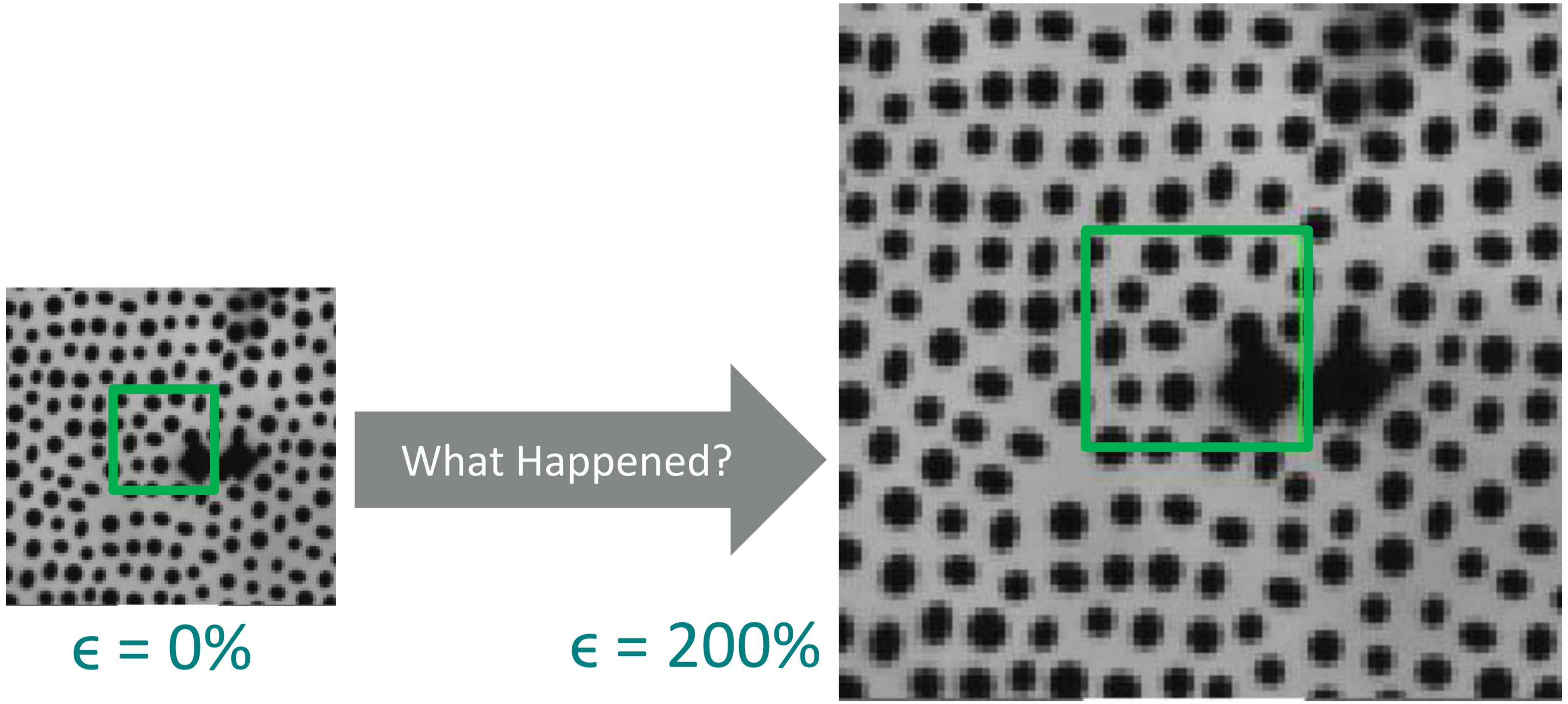
Lens limited systems will decrease the contrast and reduce the matching accuracy.



At f/1.9 a subset of 27×27 pixels is equivalent to 51×51 pixels at f/8

System resolution limits can be caused by either the lens or the detector.

- Lens limited – indicates that the resolution of the lens is the limiting component.
- Detector (camera) limited – indicates that the pixel size is the limiting resolution component.
- Either situation will limit the spatial resolution of the measurement (but not necessarily the accuracy).
- Without investigation, you will not know what the limiting component is.
- As a general rule, without extension tubes, it is the camera.



$\epsilon = 0\%$

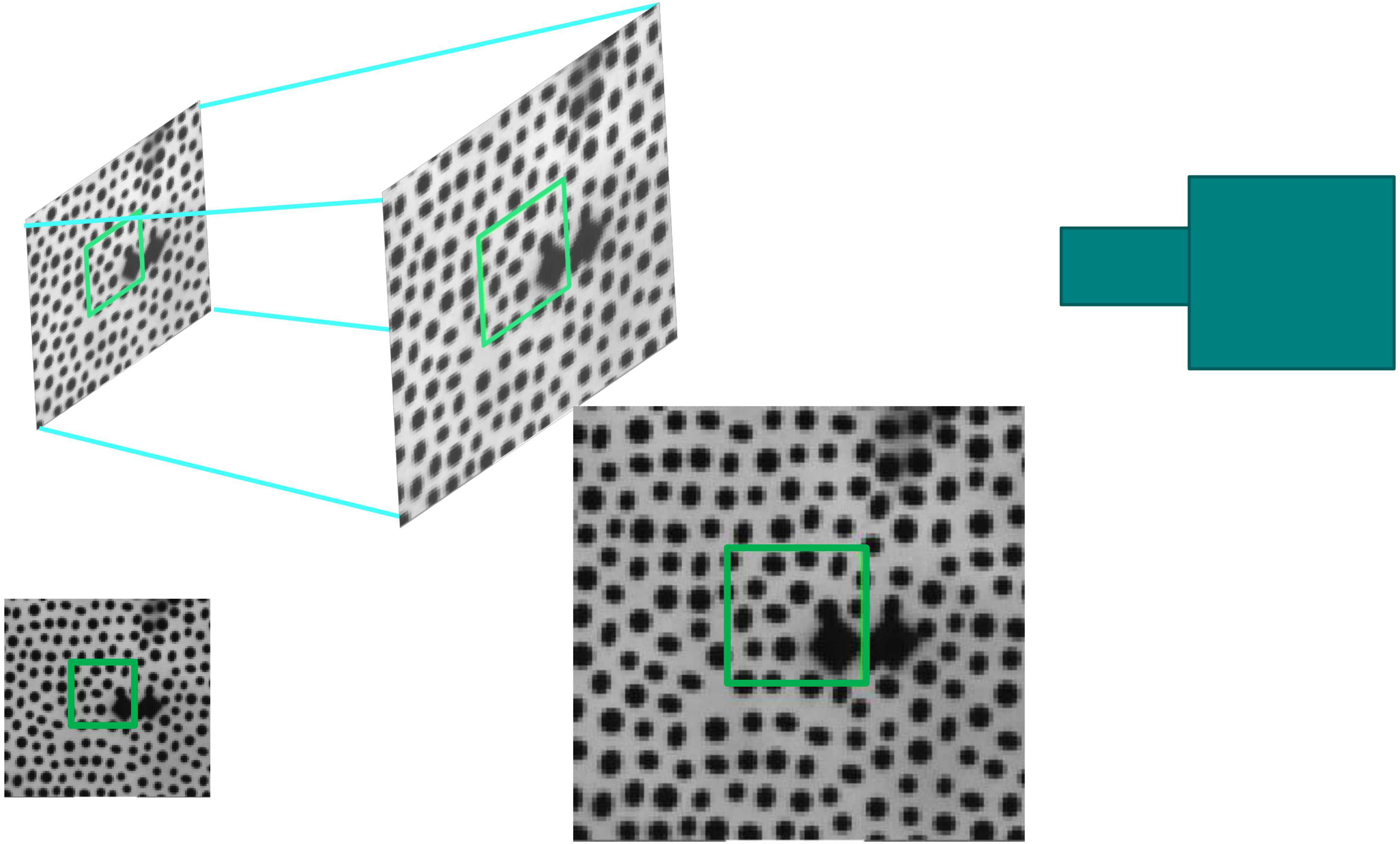
$\epsilon = 200\%$

OUT-OF-PLANE MOTION IN 2D - BEWARE

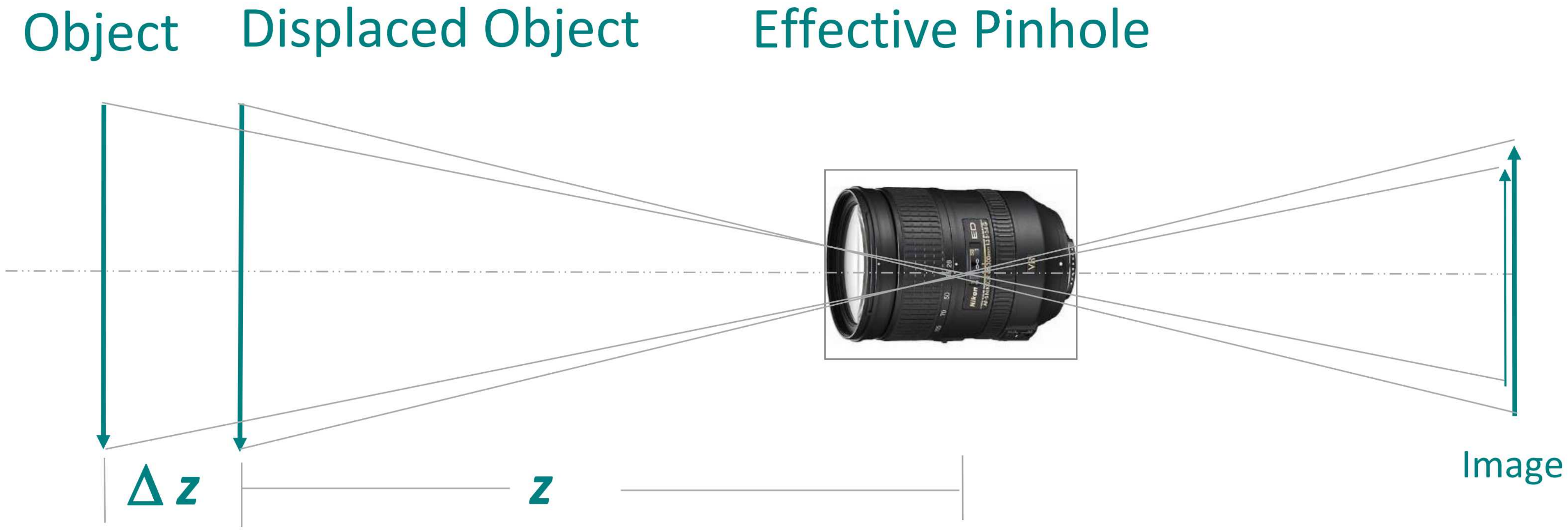
WARNING! WARNING! WARNING!

Caution 2.1 – Out-of-plane motion errors

The image moving towards the camera looks like a uniform strain

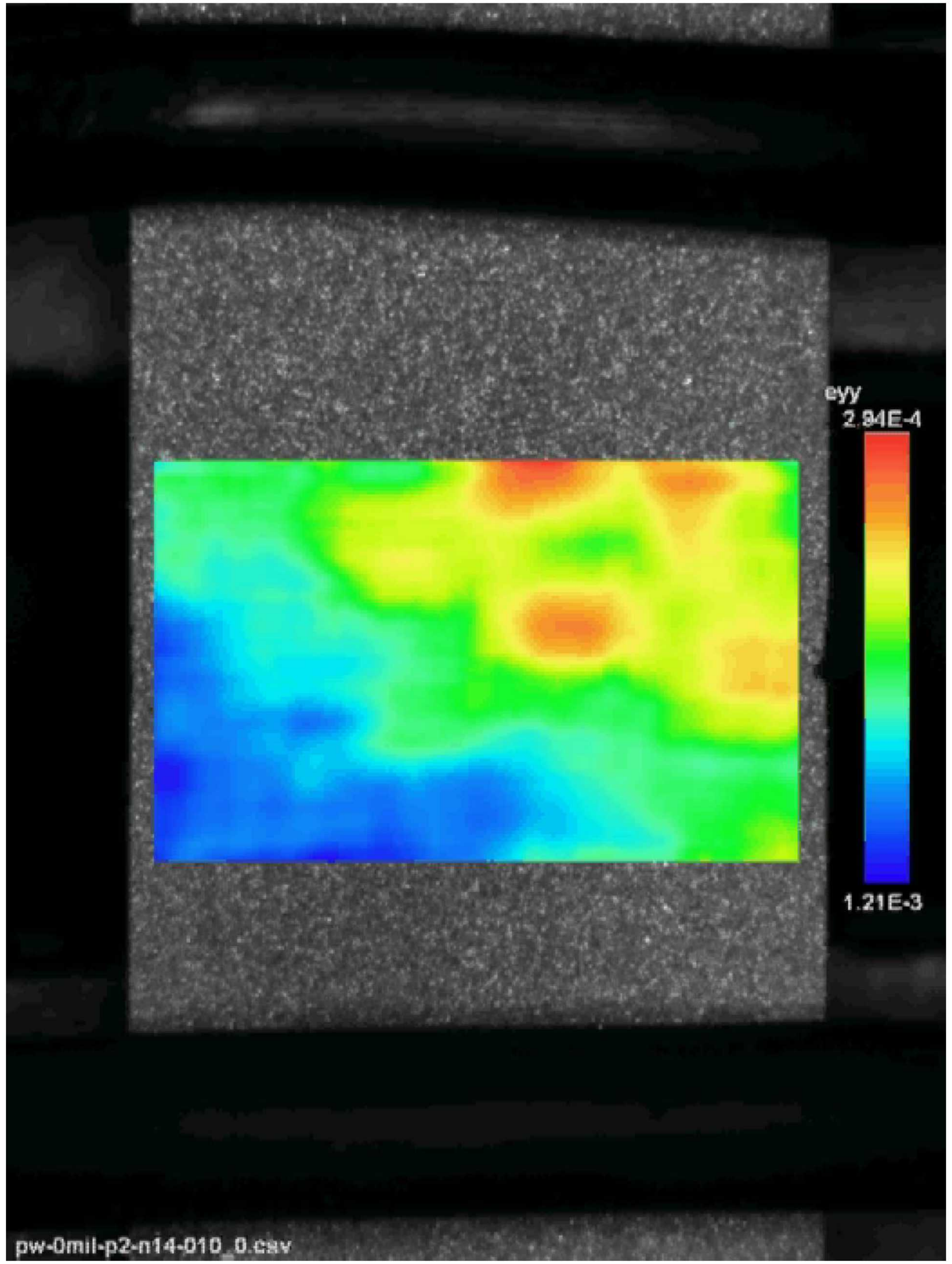


You can estimate your strain error using simple geometric optics



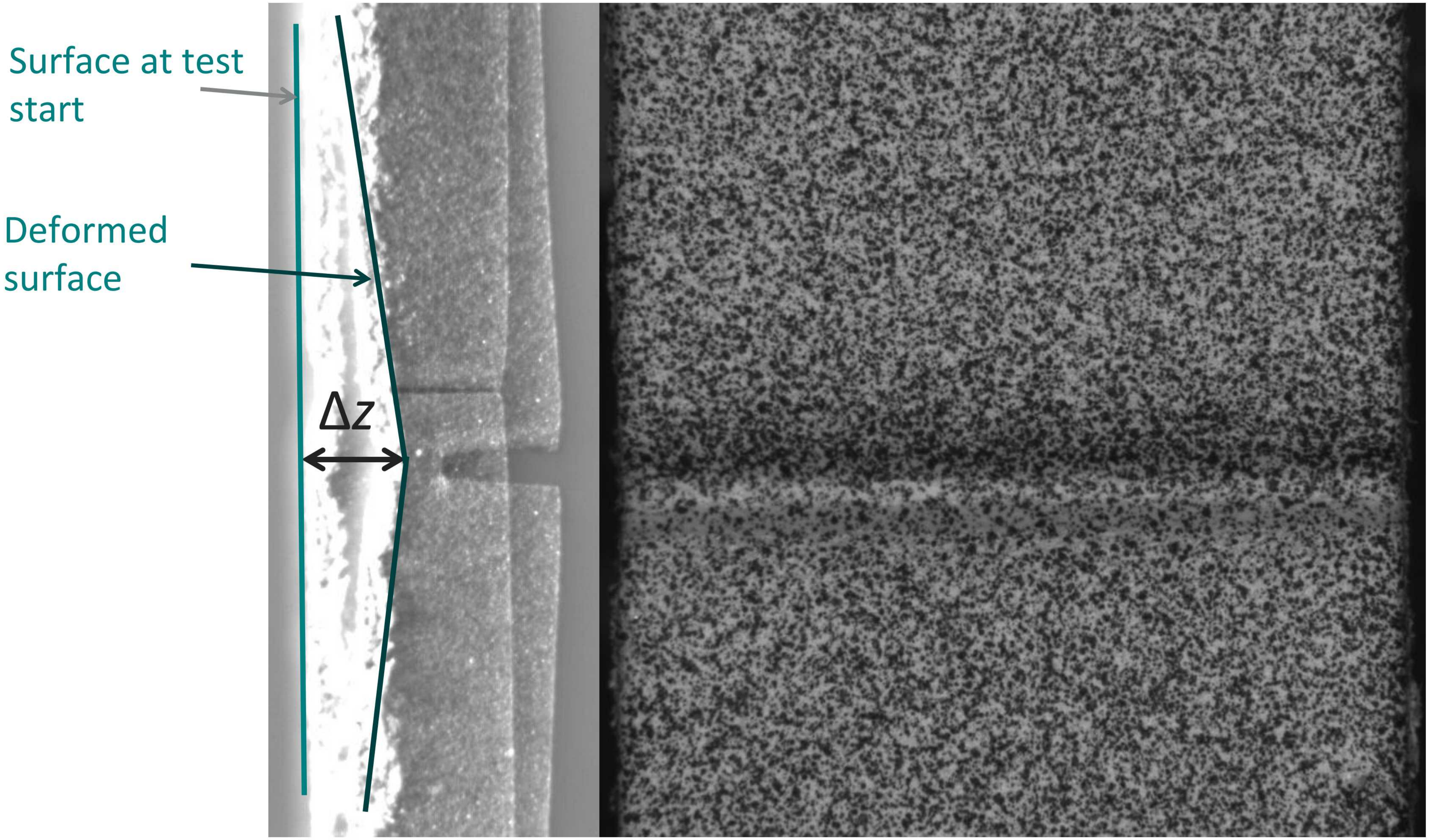
z = 200 mm for the current setup.

$$\varepsilon_{error} = -\frac{\Delta z}{z}$$



Is this the correct strain?

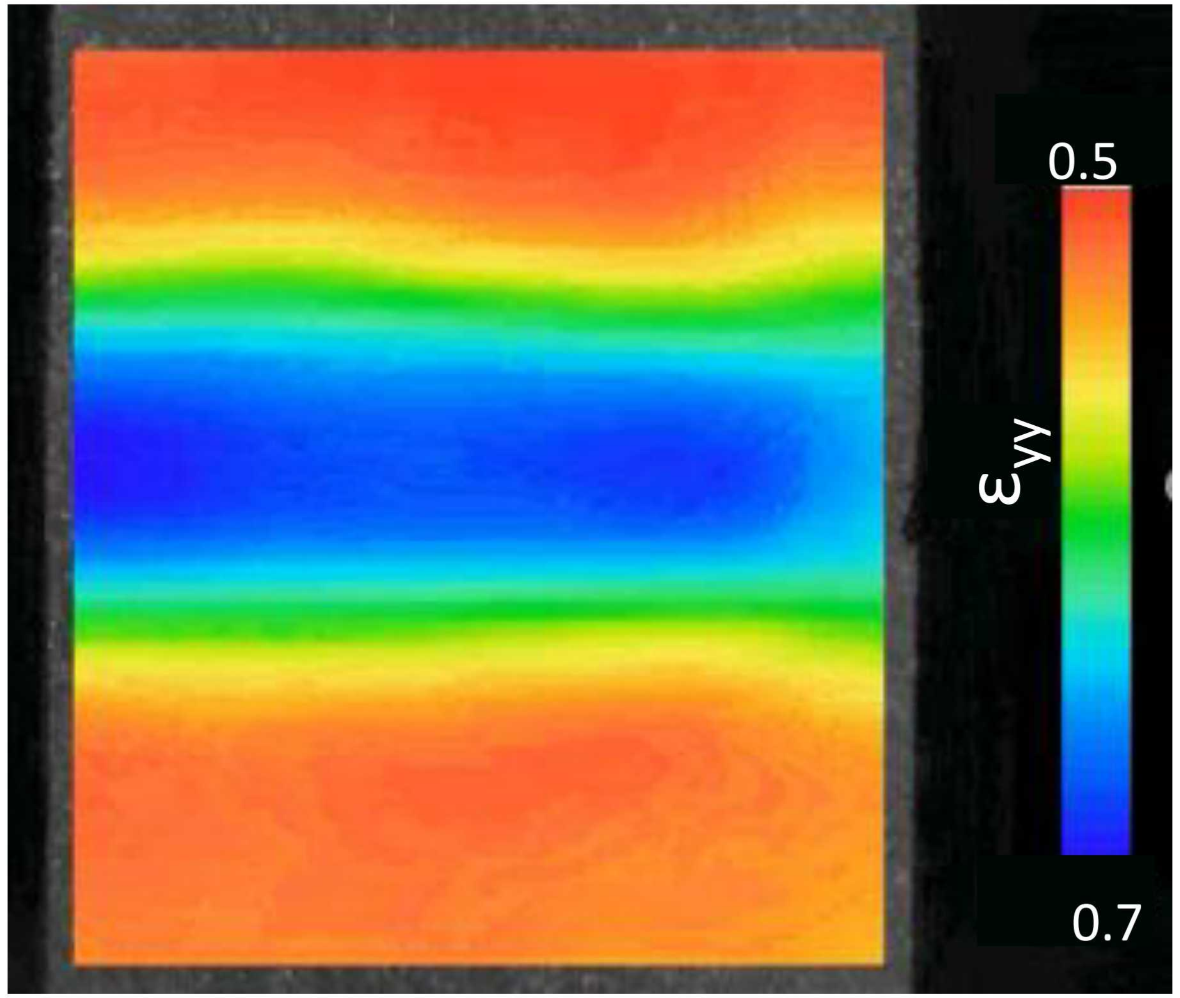
Out-of-plane motion will cause a strain error



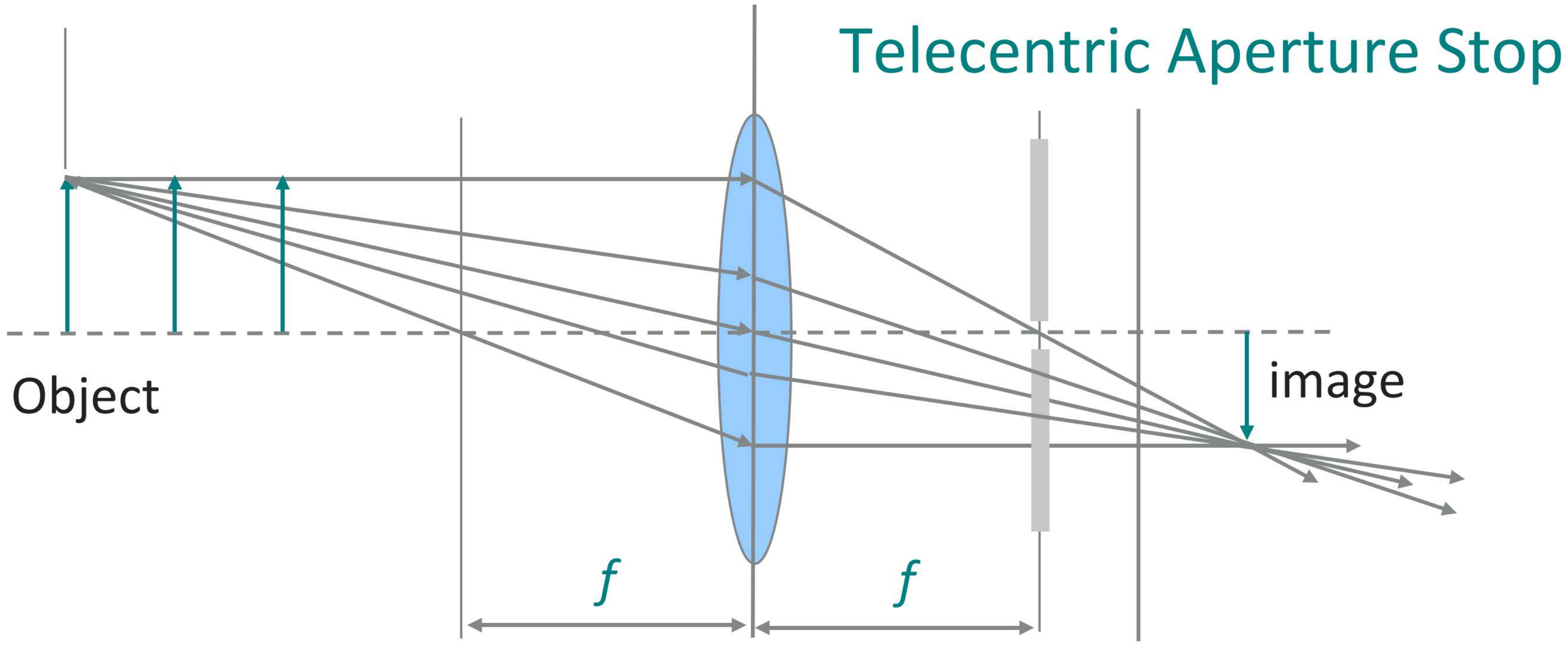
$$\varepsilon_{error} = -\frac{\Delta z}{z}$$

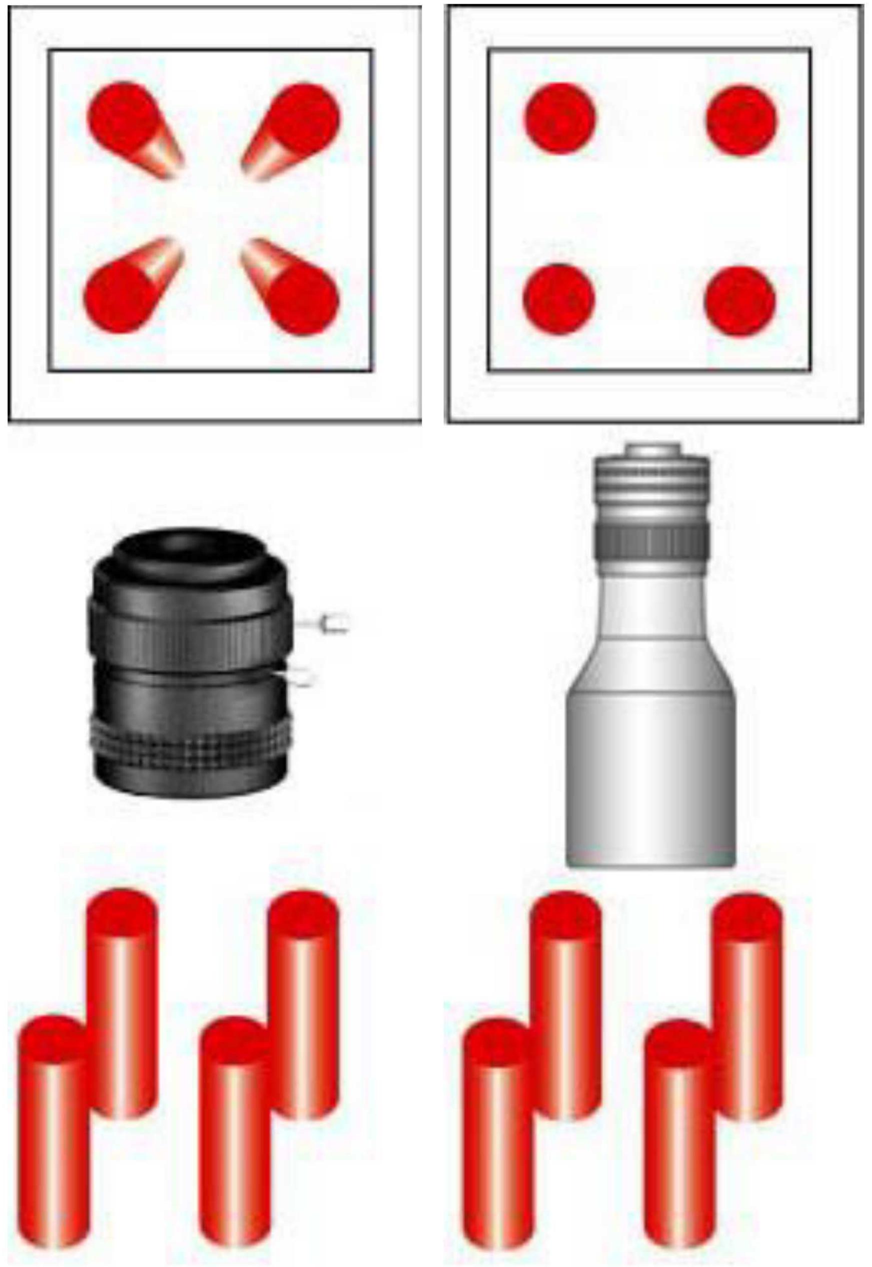
Max out-of-plane, Δz = 0.41 mm

$\Delta\varepsilon \cong 0.41/200$ = -0.0021= -2100 με



A telecentric lens maintains constant magnification over the field-of-view





- Passes the parallel rays only. (Removes all others)
- If rays are parallel – there is no magnification.
- Lighting can be an issue.
- More difficult experimental setup.

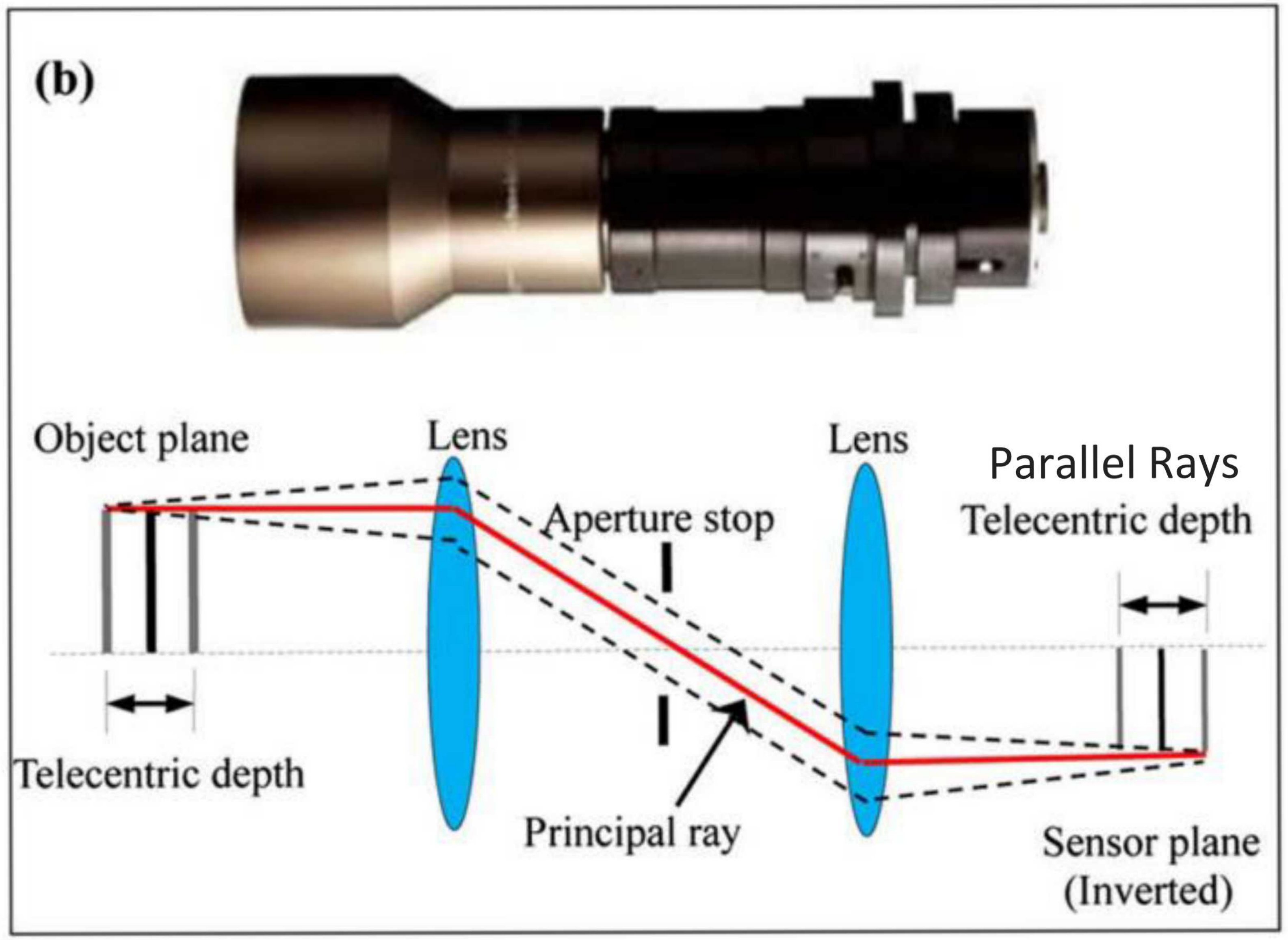
$z^{effective}$ = Becomes much larger.

$$\varepsilon_{error} = -\frac{\Delta z}{z^{effective}}$$

iDICs

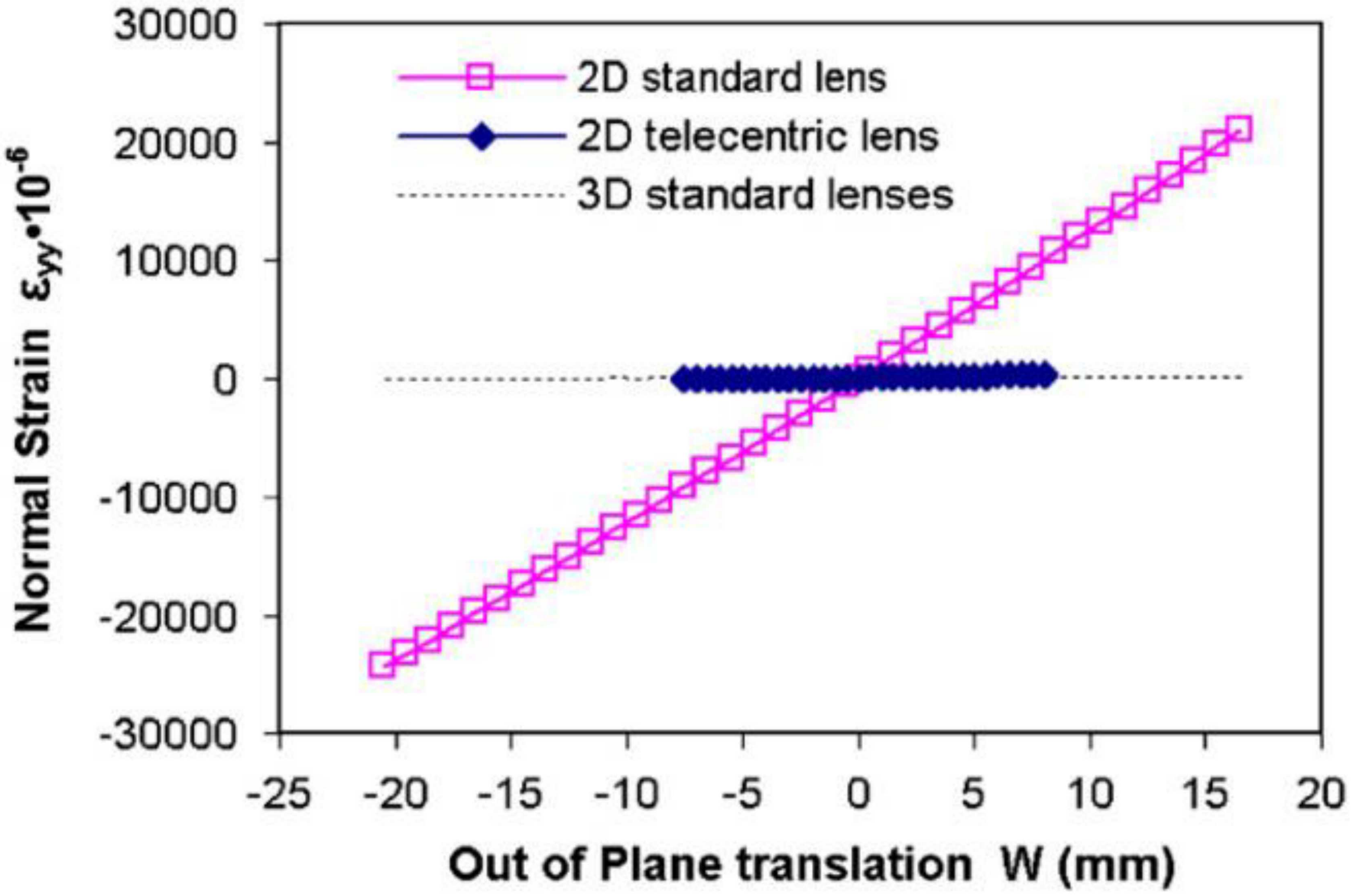
Recommendation 2.6 – Bi-telecentric Lens for 2D

A bi-telecentric lens maintains magnification on both the front and rear of the lens.



Pan, B., et al. (2014). "Accurate ex situ deformation measurement using an ultra-stable two-dimensional digital image correlation system." Applied Optics **53(19): 4216-4227.**

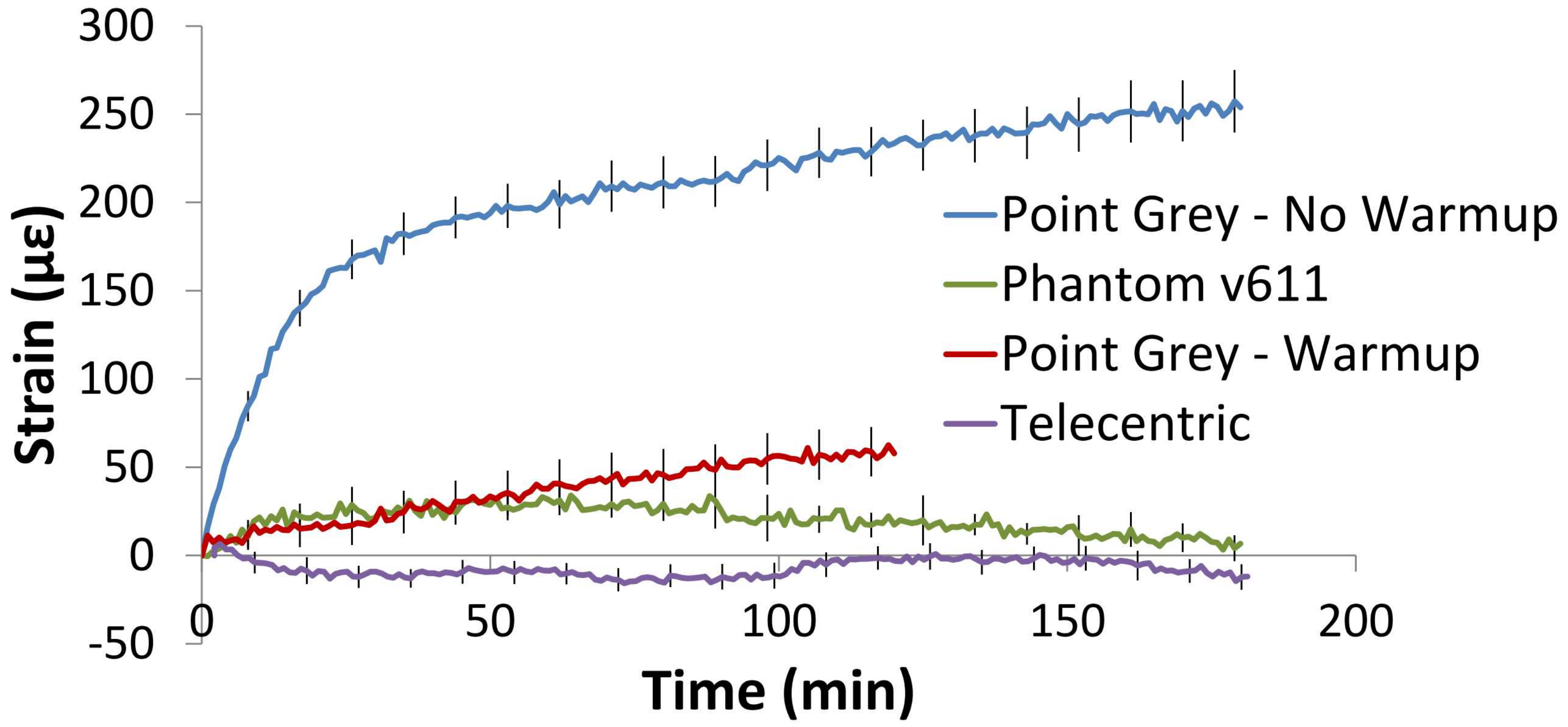
The telecentric lens can help minimize the out-of-plane strain errors.

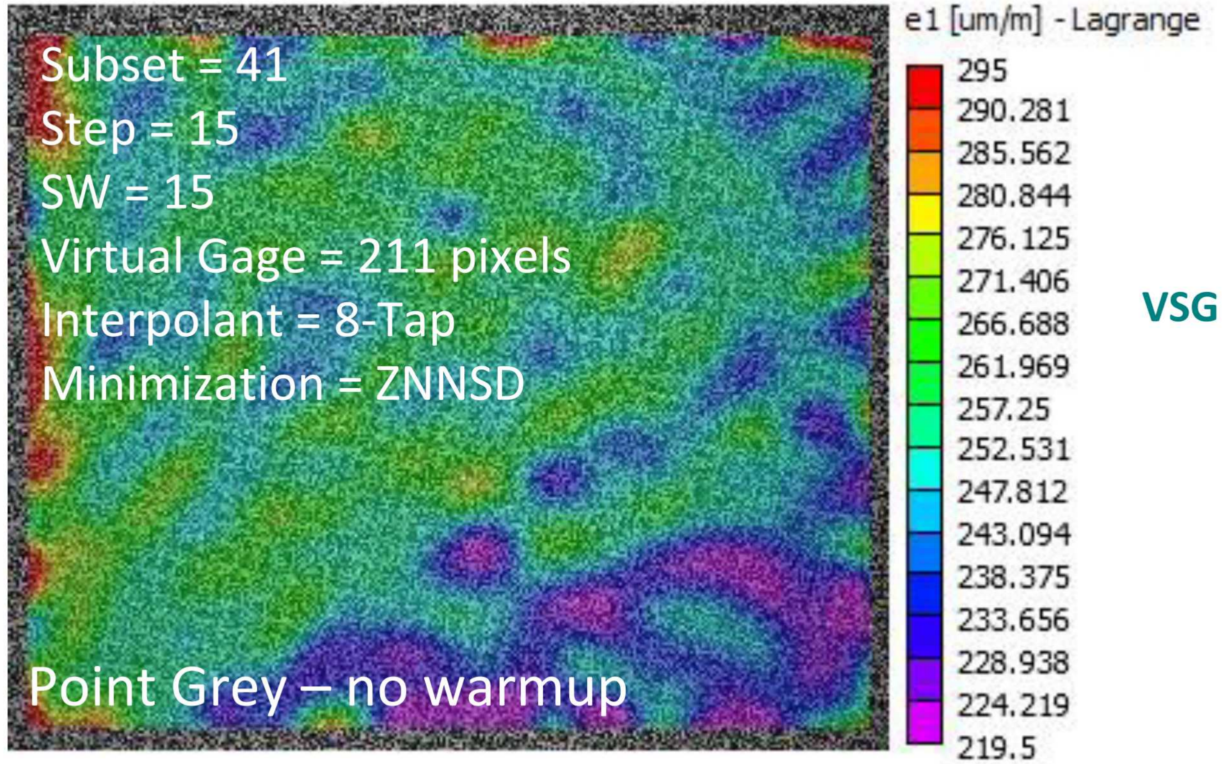


Sutton, M. A., et al. (2008). "The effect of out-of-plane motion on 2D and 3D digital image correlation measurements." Optics and Lasers in Engineering **46(10): 746-757.**

Bi-telecentric will remove the magnification change behind the lens and the resulting apparent strain.

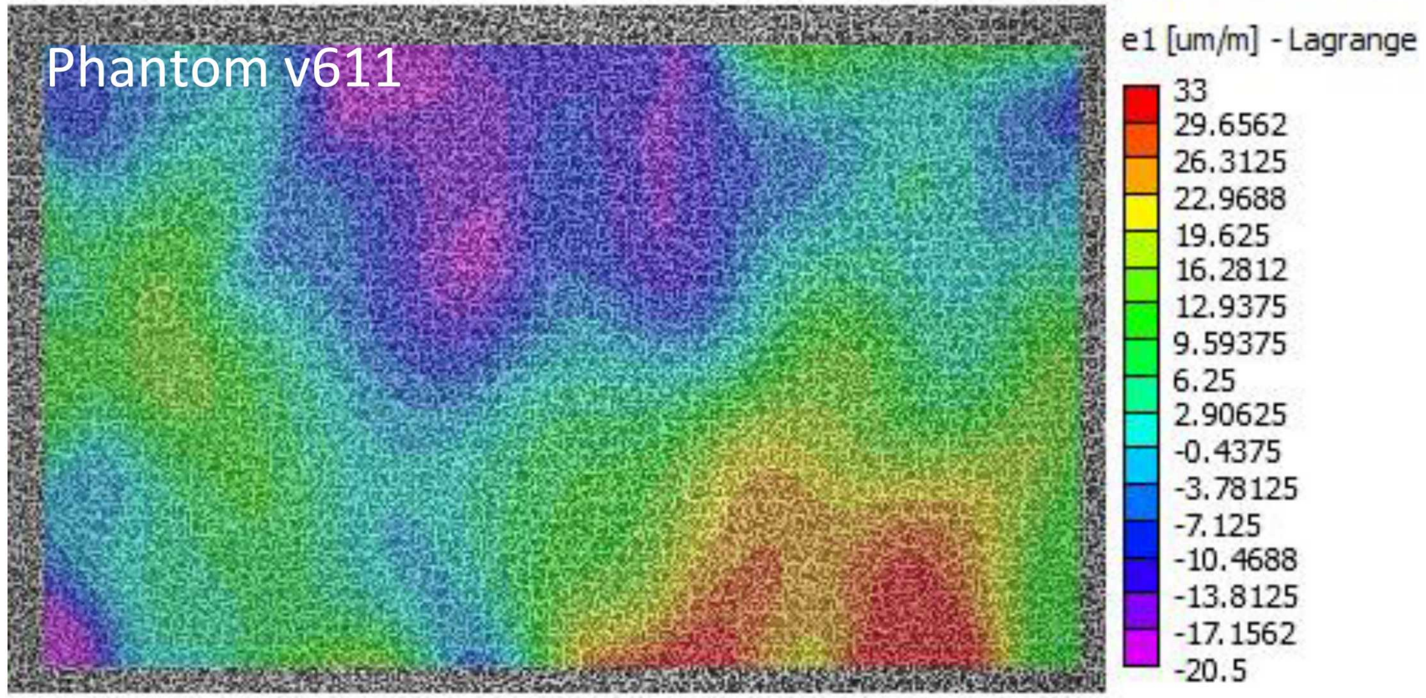
False strain caused by motion of detector behind the lens.

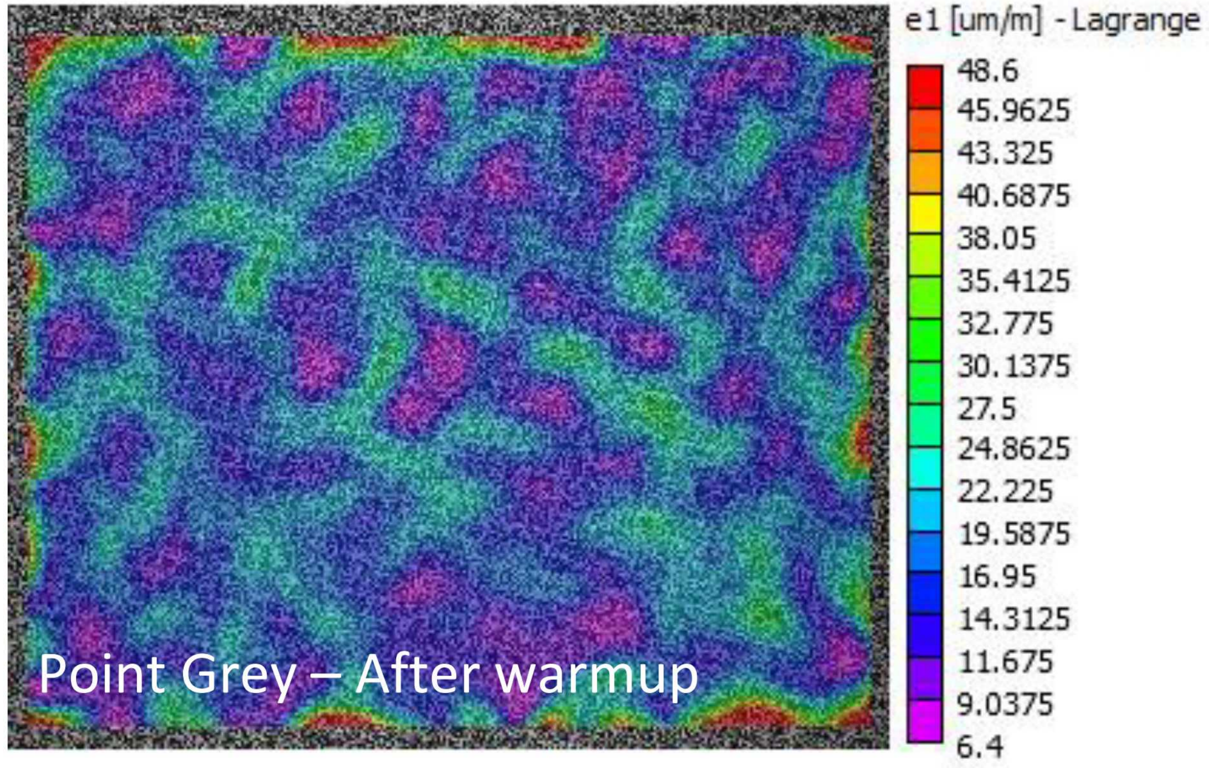




Subset = 41
Step = 15
SW = 15
Virtual Gage = 211 pixels
Interpolant = 8-Tap
Minimization = ZNNSD

VSG = [(SW-1) x ST] + SS





Recommendation 2.14 – Camera warmup

Recommendation 2.6 – BI-Telecentric lenses for 2D

Section 3.2.2.5 – Section 3.3.2.1

LENS DISTORTIONS

HOW GOOD IS YOUR LENS?

All lenses will have some distortions.

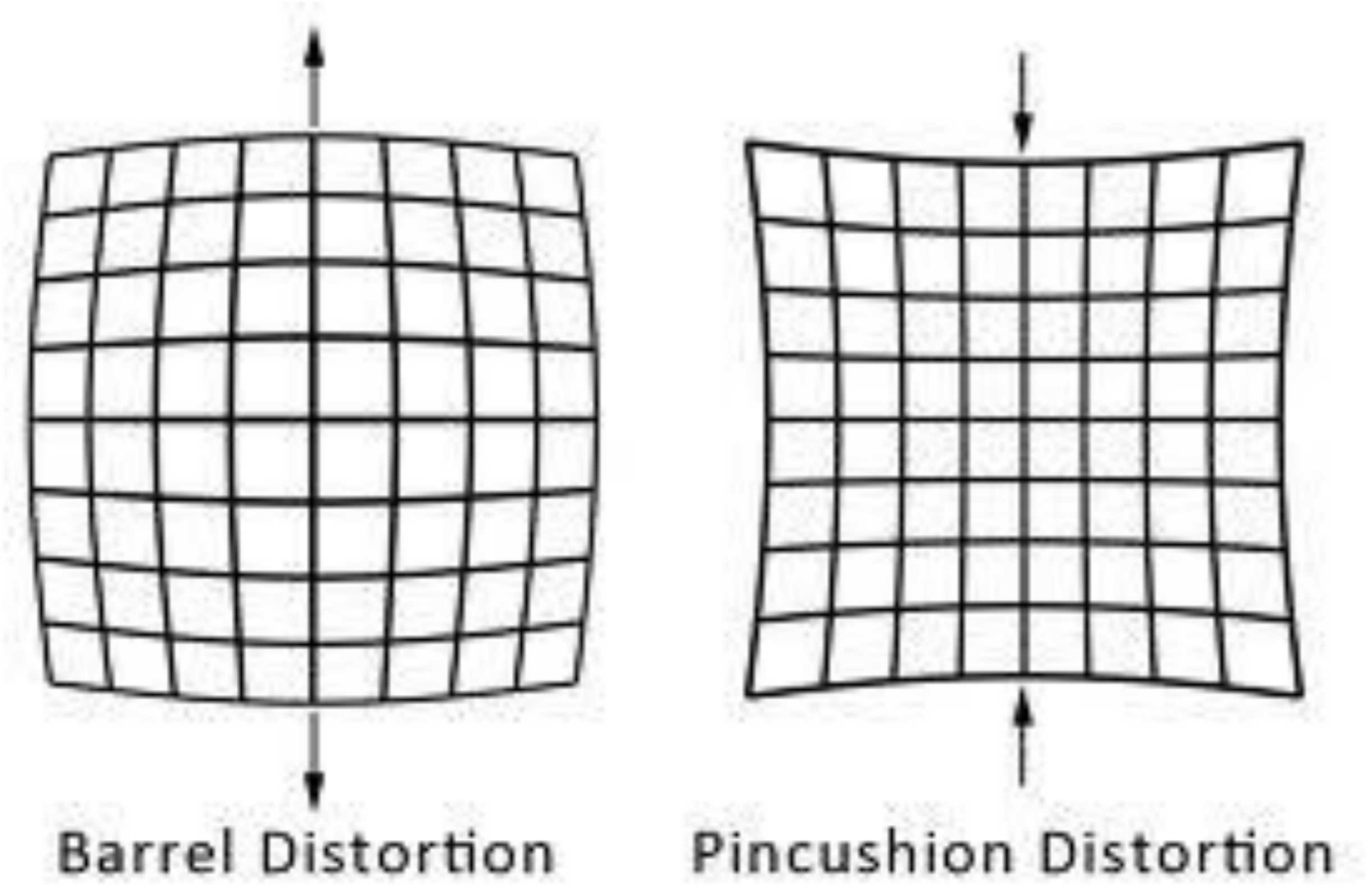
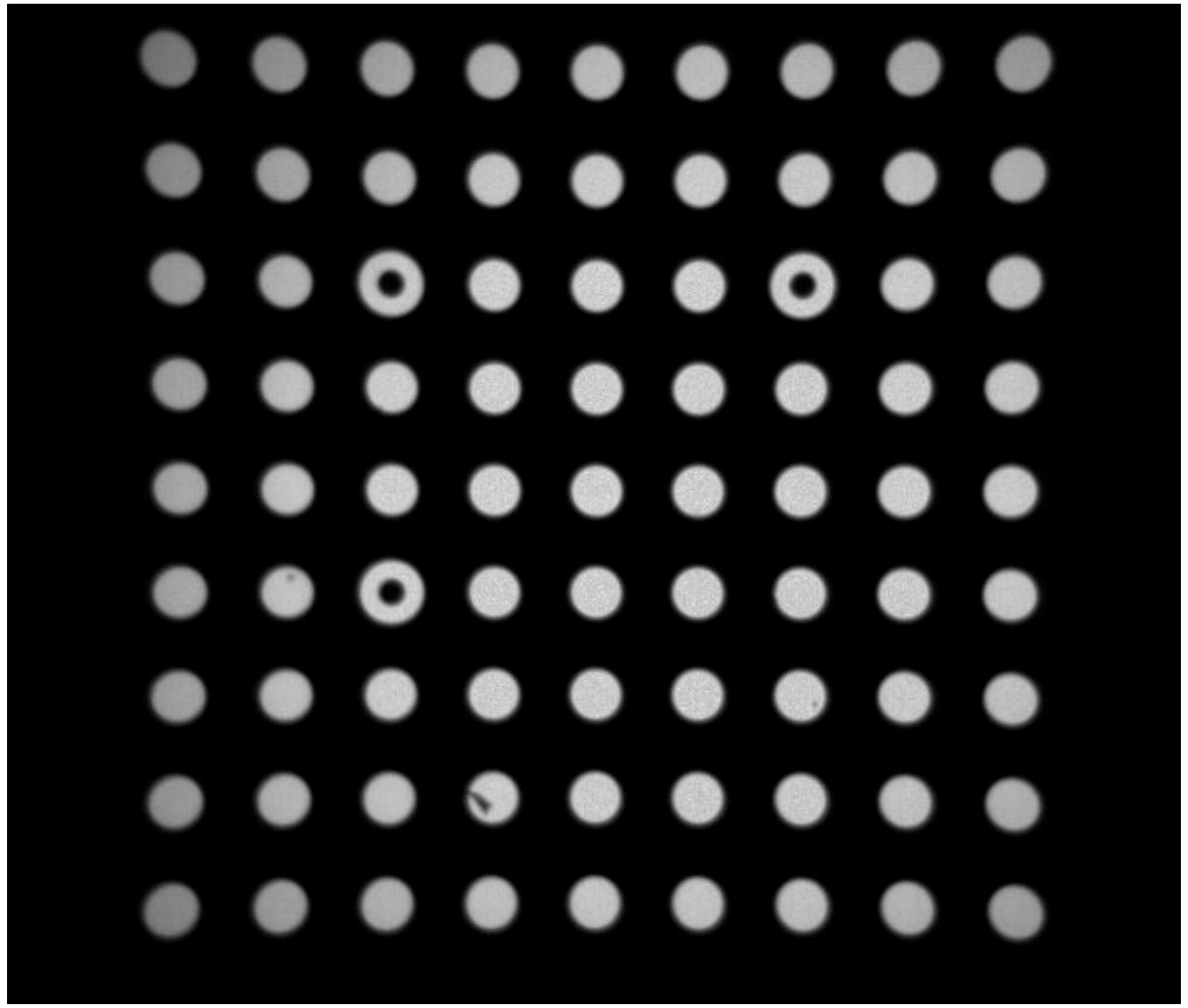


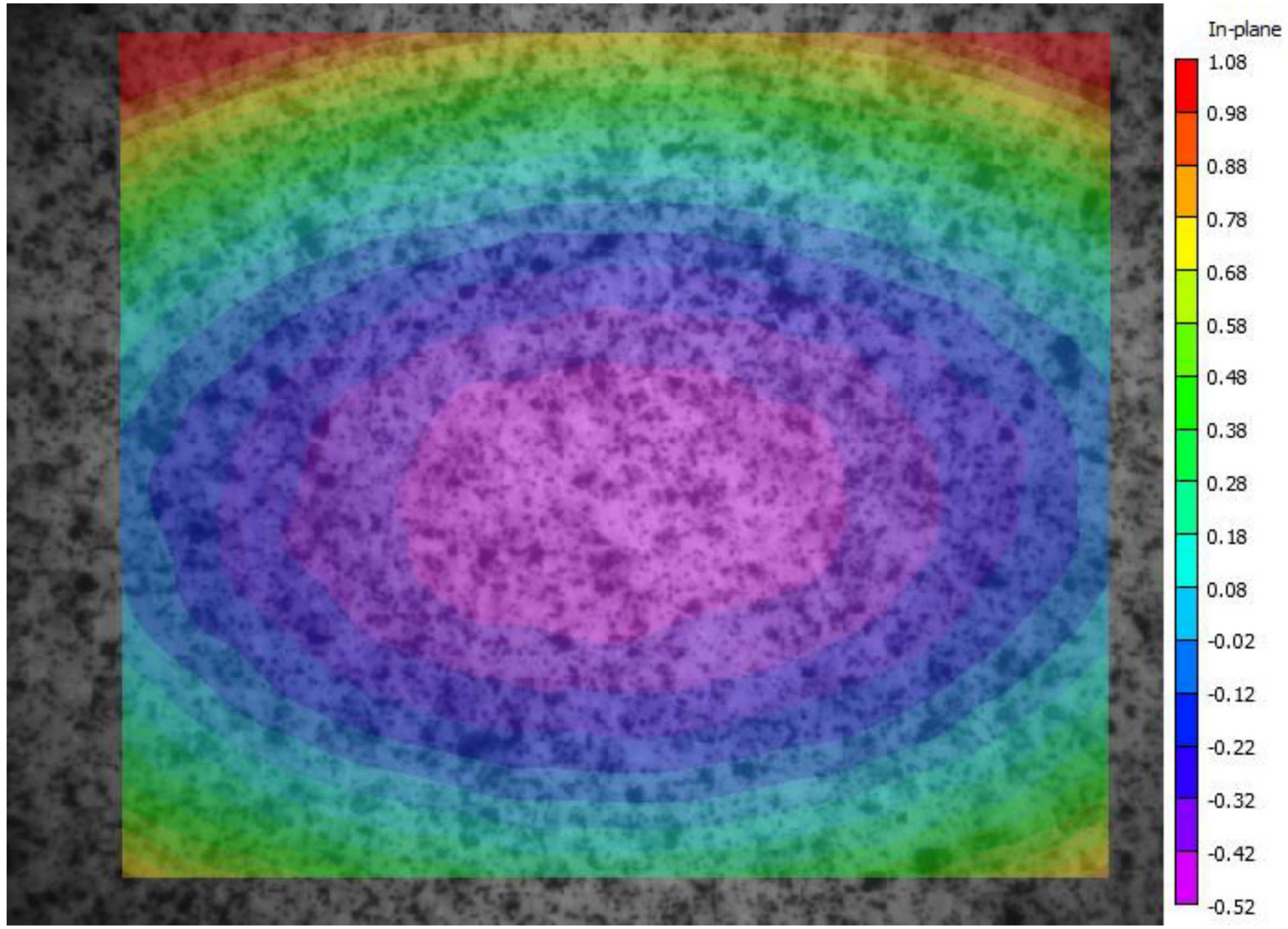

Photo: E. Bystrom

Most lens distortions are radial in nature and can be corrected for in DIC.

You can evaluate the lens distortions with DIC. More on that later.

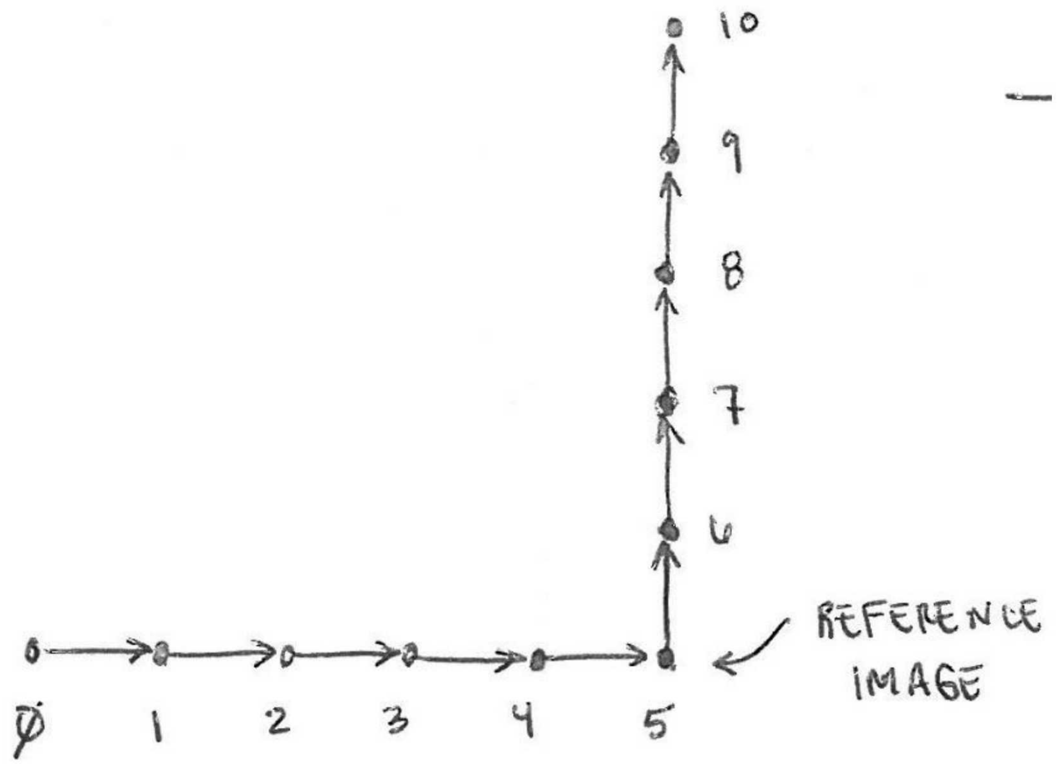


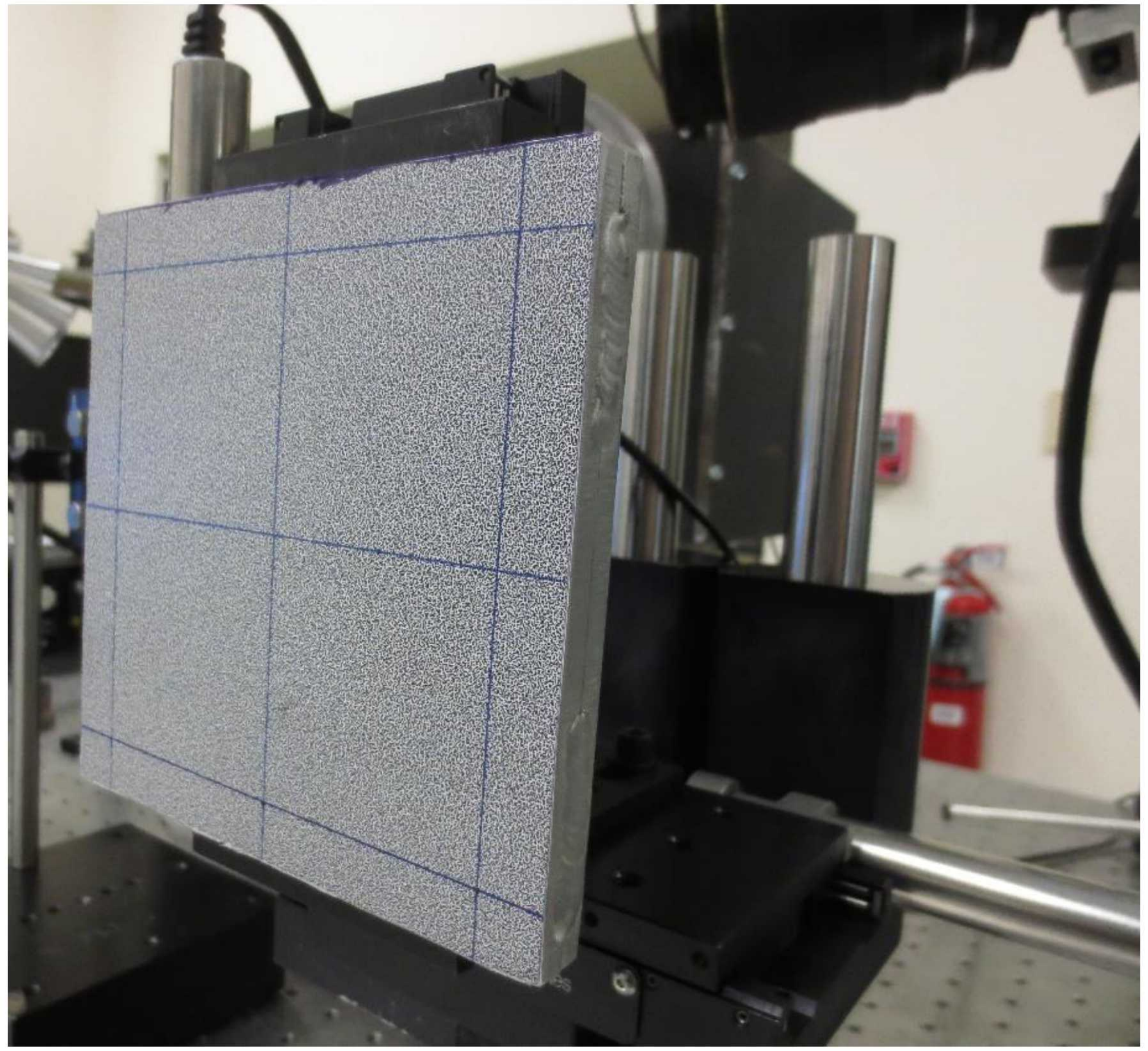
Calculated Lens Distortions (pixels)



Conducting a lens distortion check using in-plane translations.

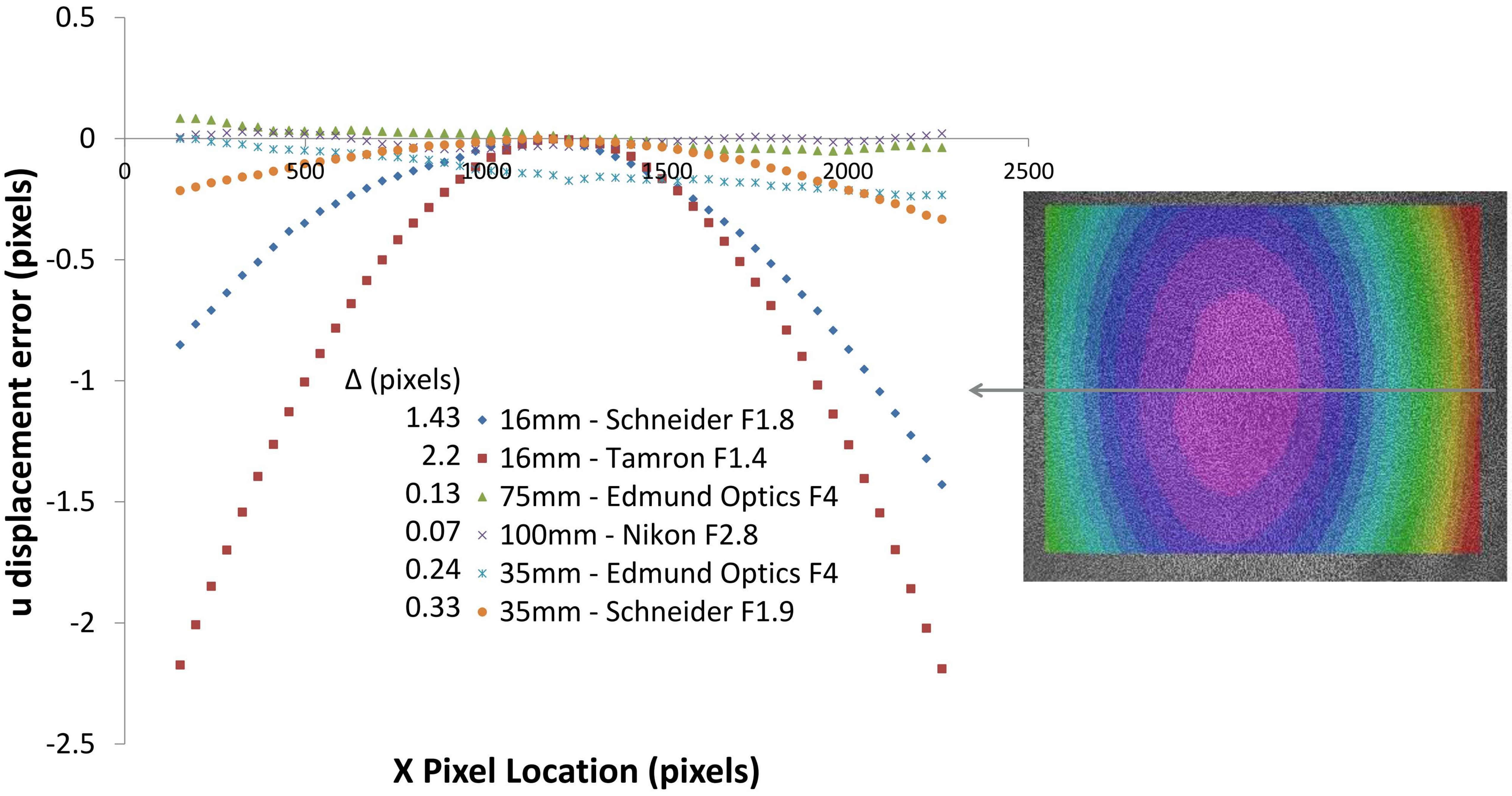
This is one of the lab exercises.



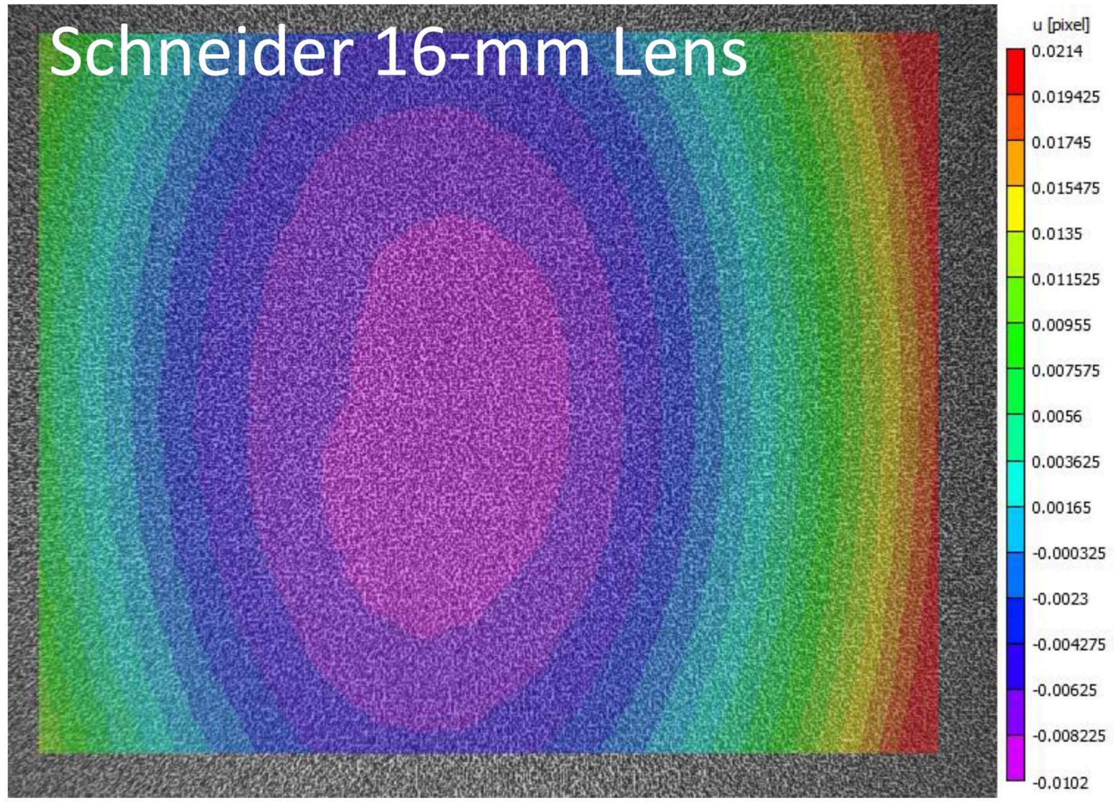


- Translate in-plane in both *x*, and *y*-directions. Move about 15% of the FOV.
- Must remain perpendicular to the camera (or lens and out-of-plane are convolved)
- Correlate with the central image as the reference.
- You can convert to pixels by subtracting the average displacement.
- You can get scaling if you know the stage motion in millimeters.

Understanding lens distortions A 50 pixel shift yields a 2-pixel error!

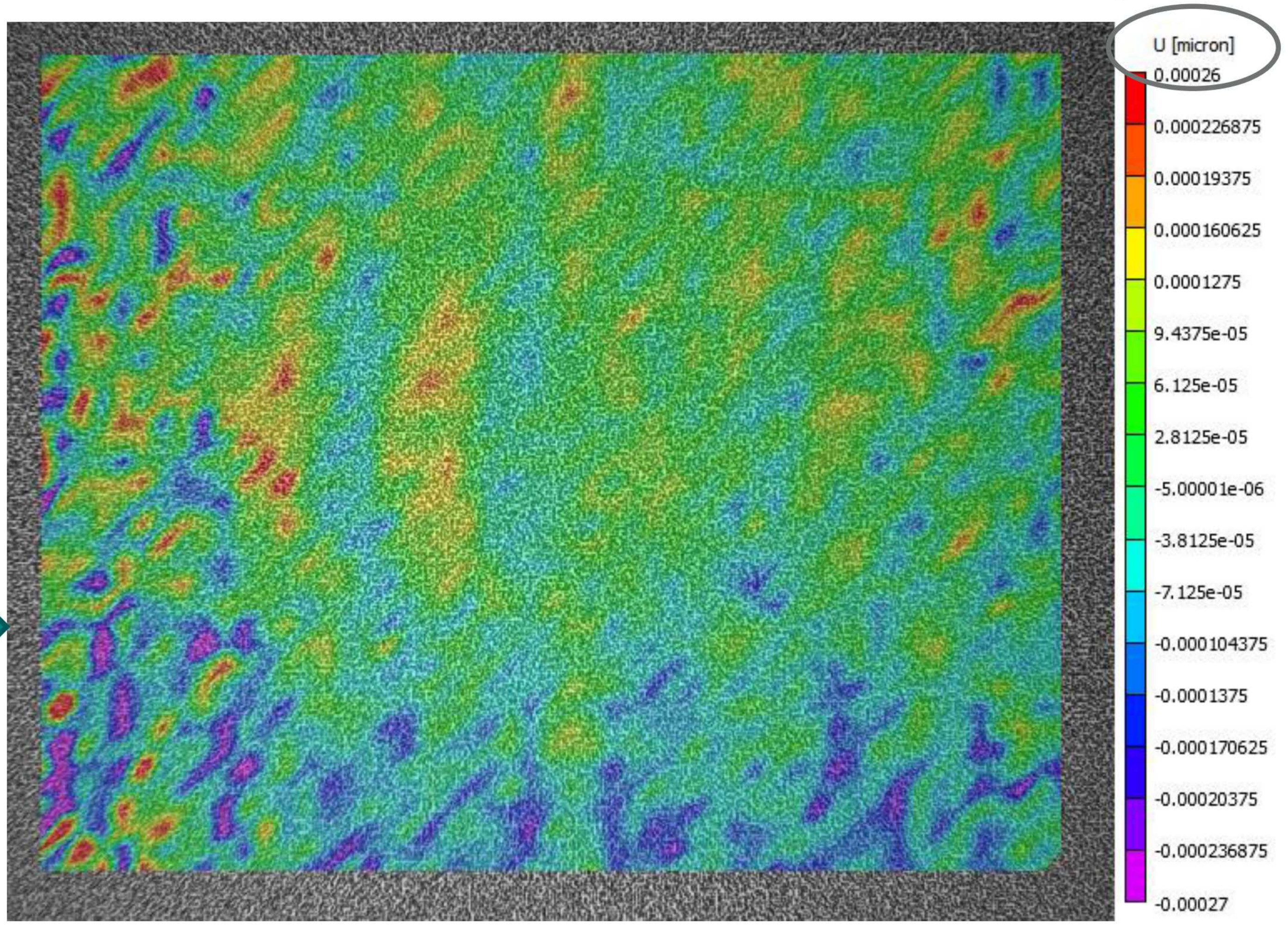


Distortion removal routines are available: Either through calibration or through polynomial fitting.



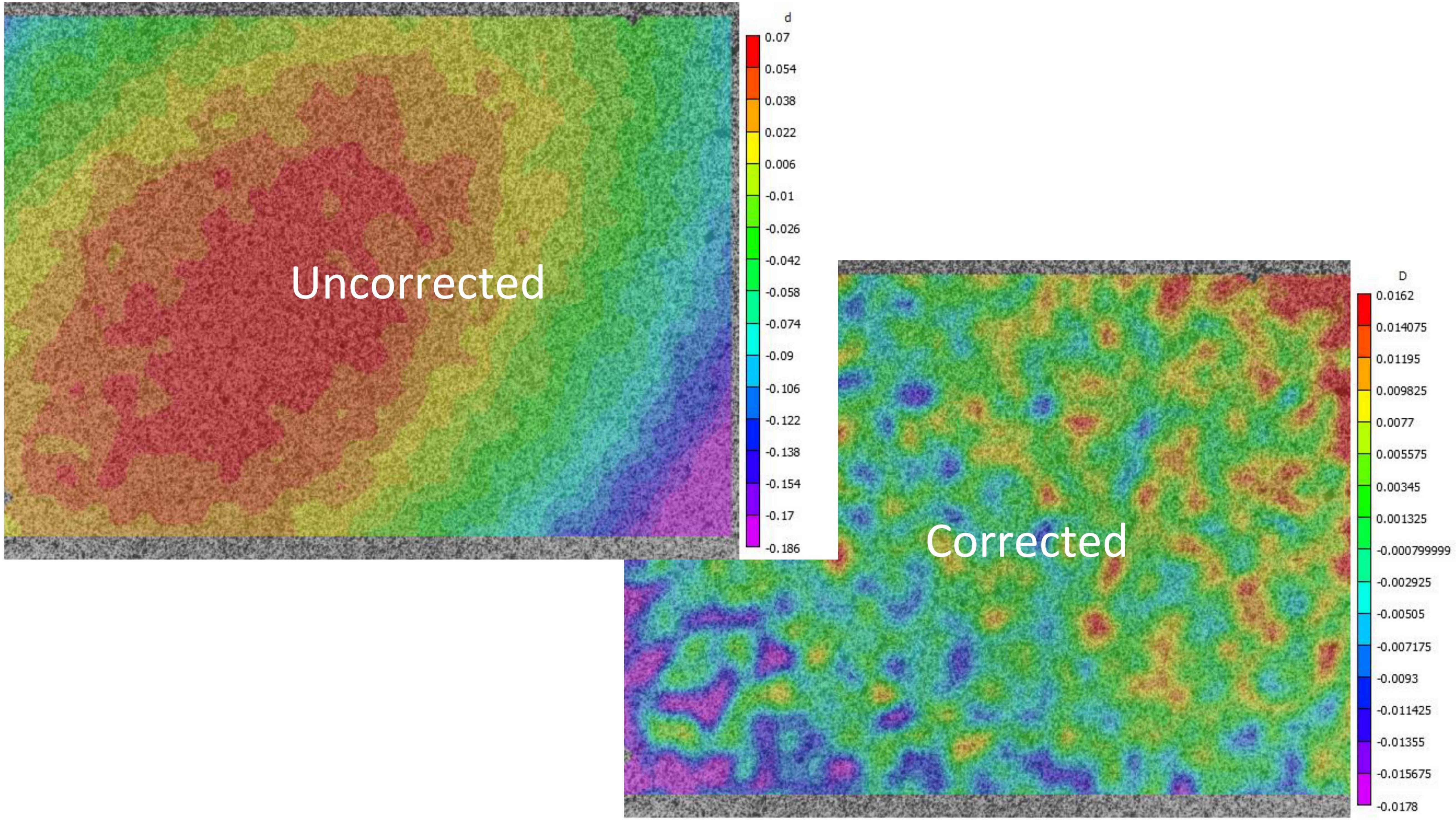
These units are pixels!
(or whatever units you entered in the correction)

Distortion Correction



You should end up with a distortion field that is “noise”.

For a Zeiss 100-mm optic



iDICs

Lenses should be selected to optimize the field-of-view and minimize distortions

- Most modern lenses are adequate for DIC. Including zoom lenses
- The calibration process removes many of the common lens distortions
- The lens distortions can be found using 2D DIC and a flat plate
- C-mount lenses are preferable. They mount more rigidly and have lower distortions due to the smaller optics.
- C-mount lenses can cause vignetting with large CCD chips

Zoom Lens

C-mount lens

Vignetting

Use the correct type of lens for the application: Fixed focal, zoom, or telecentric

- Fixed focal length
  - ✓ Best quality images
  - ✓ Magnification depends on object distance only
- Zoom Lenses
  - ✓ Variable focal length
  - ✓ Heavier
  - ✓ Easiest to setup in the field
- Telecentric Lenses
  - ✓ Fixed magnification regardless of distance

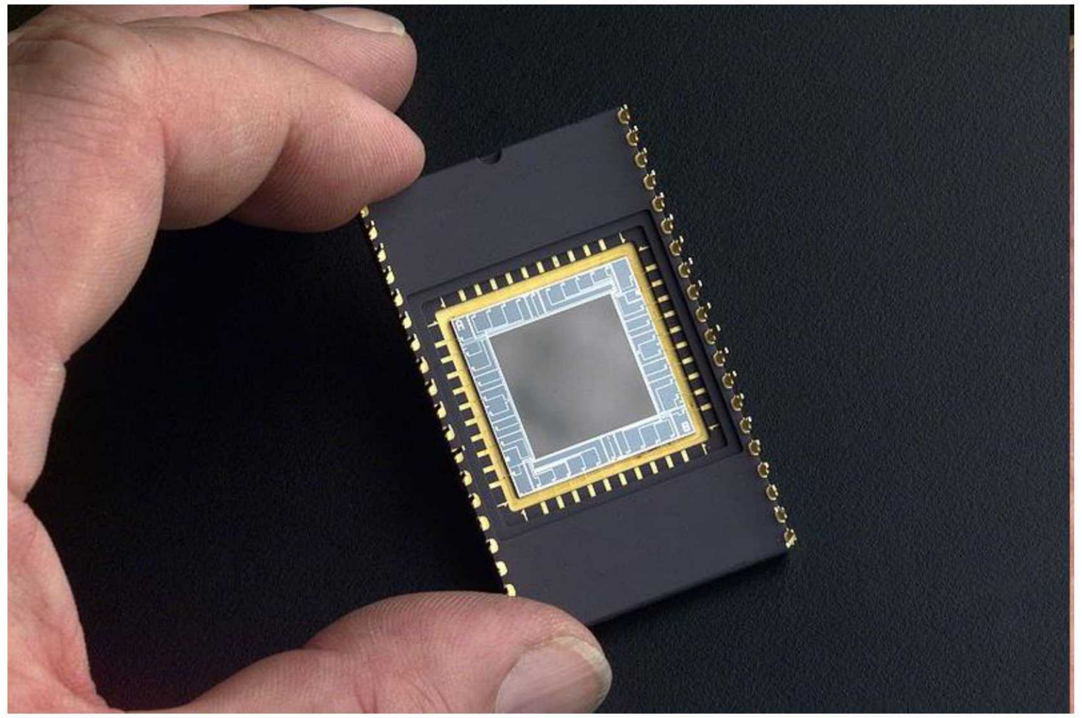
Recommendation 2.6 – Telecentric lenses for 2D

CAMERA SELECTION CAN BE IMPORTANT

SPEND YOUR MONEY WISELY.

The two common digital machine-vision camera types are CCD and CMOS detectors.

- CMOS
  - Complementary metal-oxyde semi-conductor (1969)
  - Much faster than CCDs (fast cameras, reflex cameras)
  - Cheaper
  - Easier to get larger arrays
  - More prone to noise
- CCD
  - Charge-Coupled Device (1969)
  - Principle: Photons hitting the sensor generate electrons by photoelectric effect



A digital detector has a number of important details:

- Detector noise
- Gain

Caution 2.15 – Keep camera gain low!

- Pixel size
- Aspect ratio

Tip 2.10 – Noise, dynamic range, etc.

- Fill factor
- Blind area
- Active area
- Lenslets
- Color/**Monochrome**

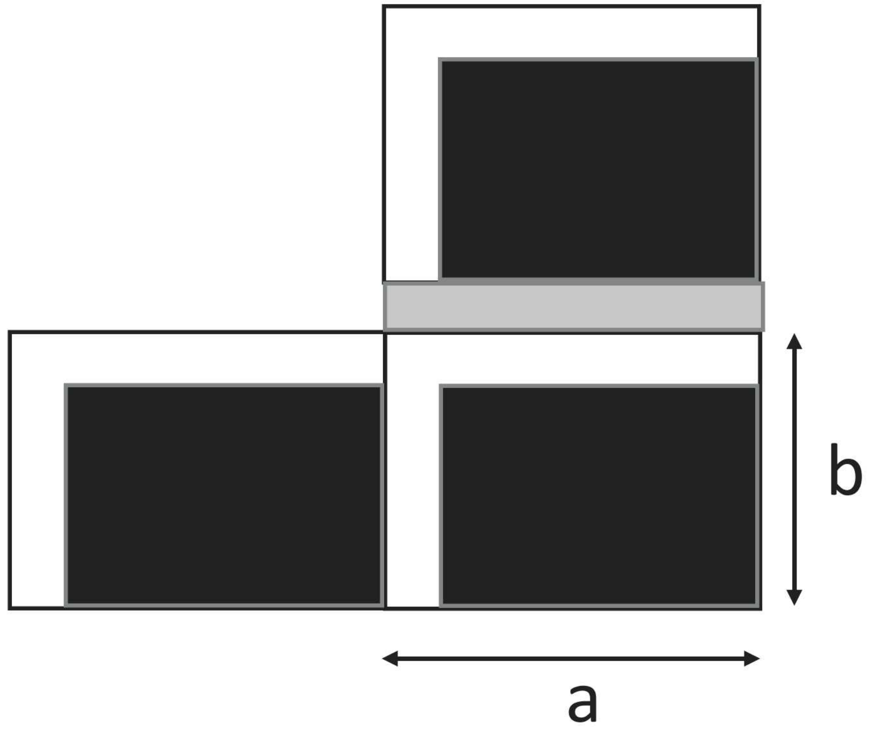
Recommendation 2.5

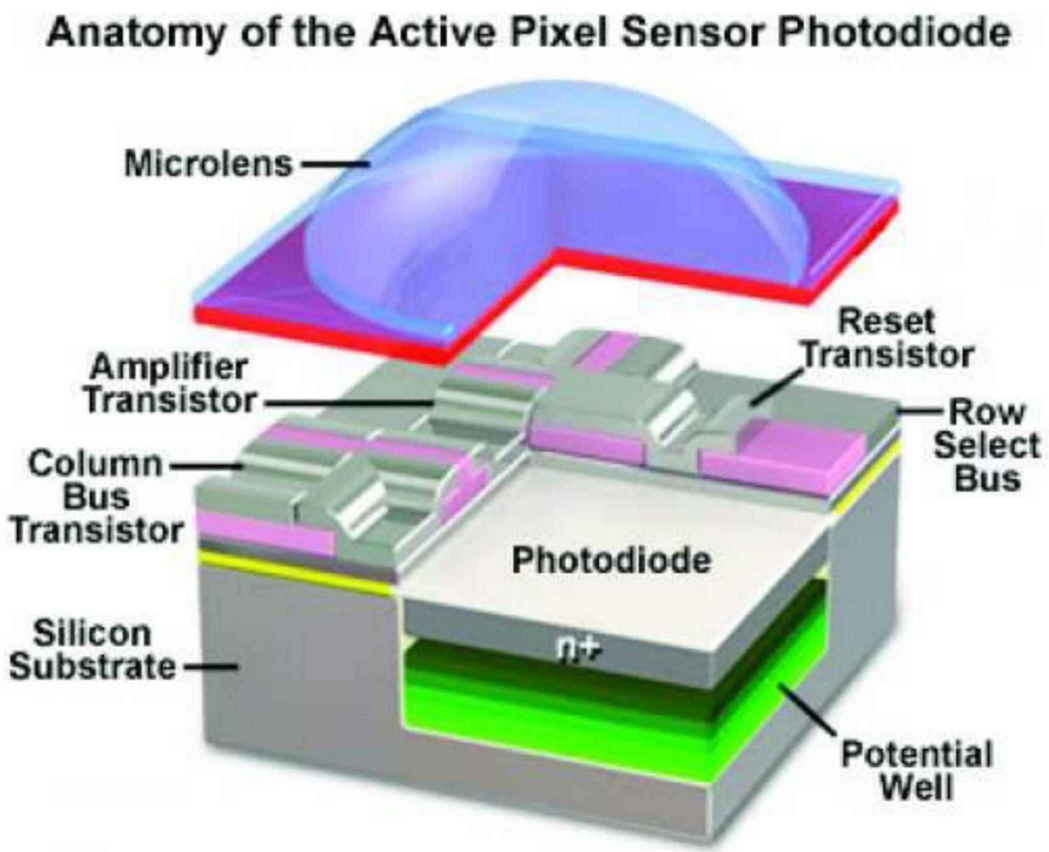
- Color filter type
- Antialiasing filter

Tip 2.11

- Beware older interlaced cameras

Caution 2.4

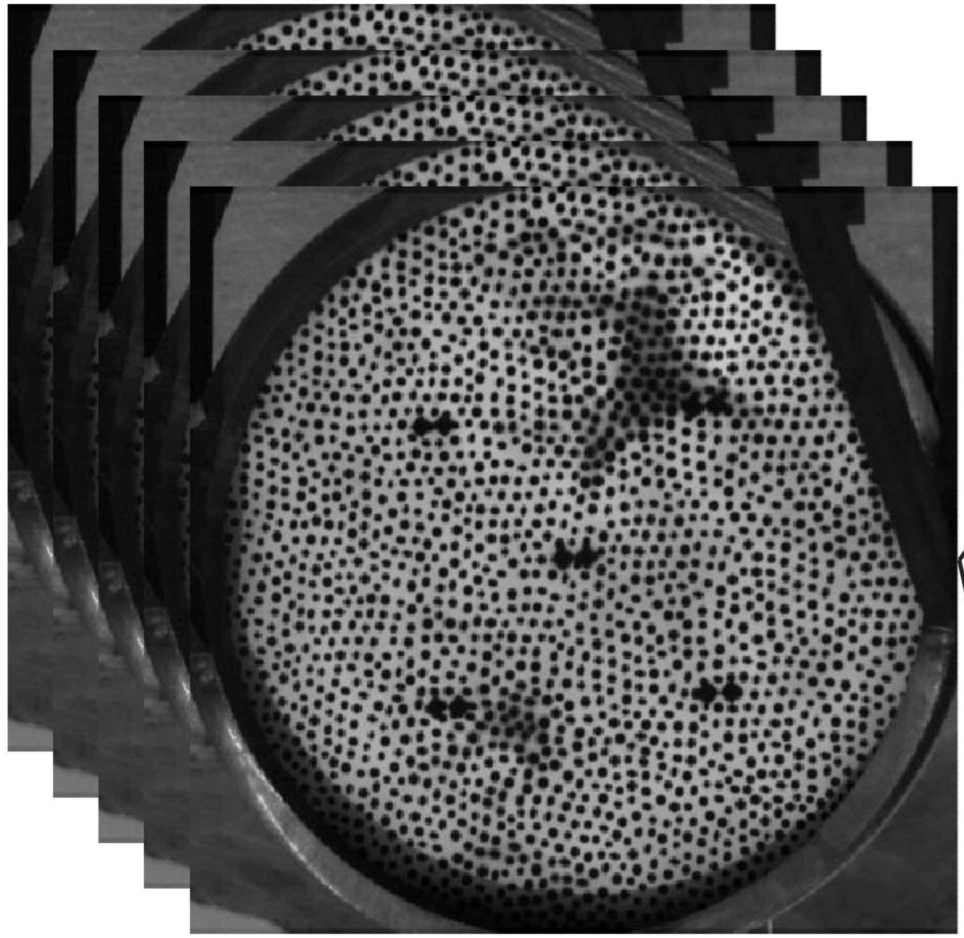




http://www.creativeplanetnetwork.com/dcp/news/cmos-technology-primer/40995

Noise is very important and easy to calculate.

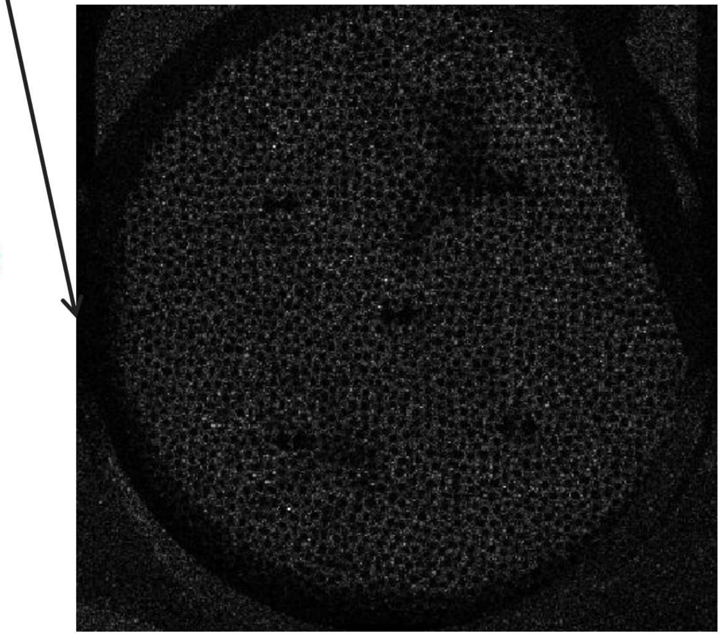
Image 1… *n*

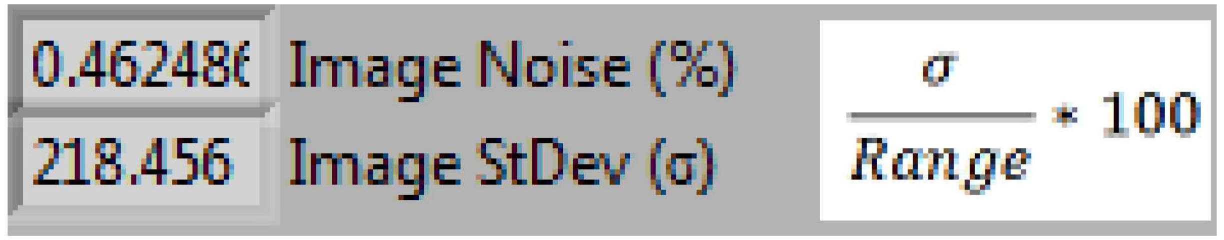


The noise can be found by averaging a number of static images. (Note: they must be truly static.)

Mean image: Pixel-by-pixel Average

Pixel-by-pixel StDev





0.46248(Image Noise (%)

218.456 Image StDev (σ)

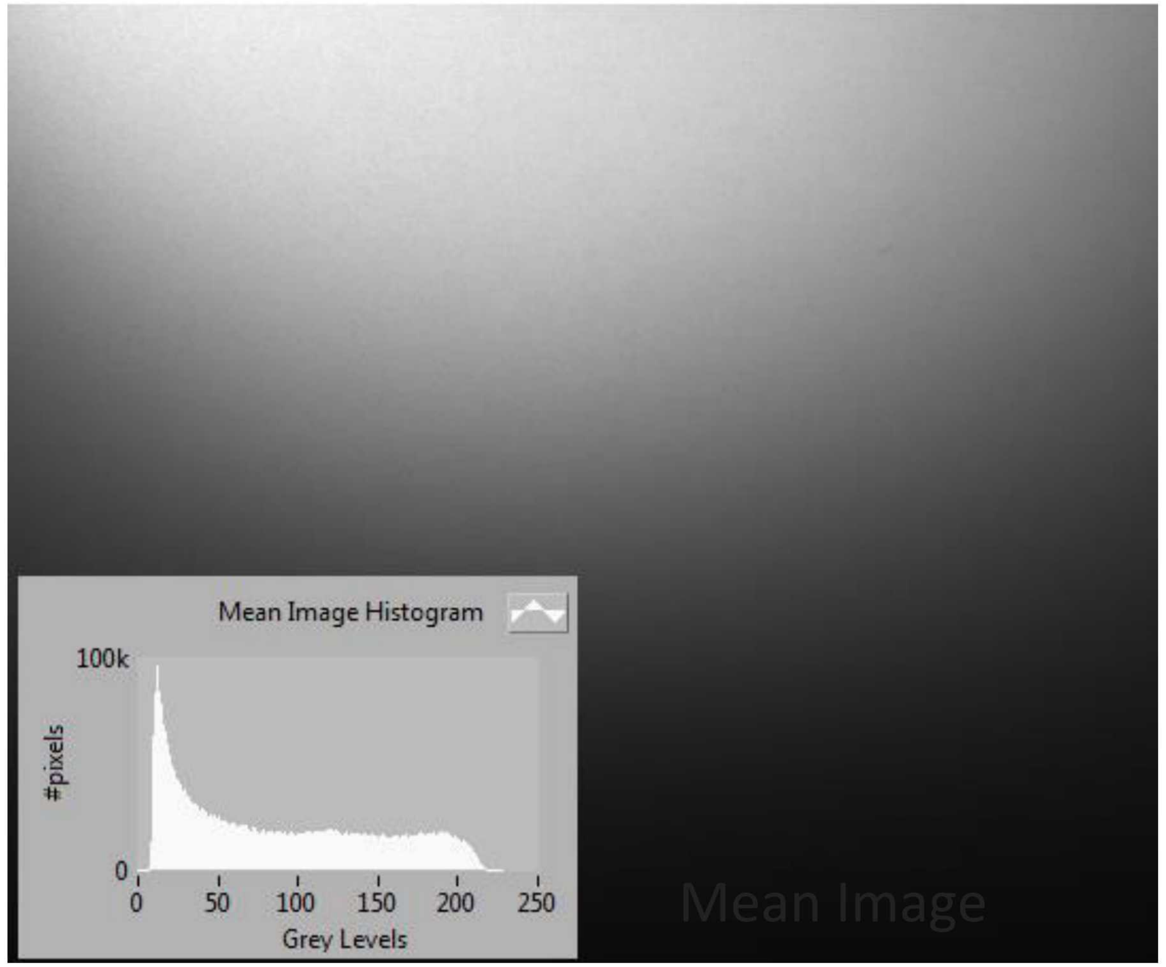
$$\frac{\sigma}{Range} * 100$$

Noise attributes:

- Comes from the sensor and is temperature and digitization level dependent
- High spatial frequency, i.e. varies independently from pixel to pixel.

It is better to use a “grey card” to remove camera motion as an issue.

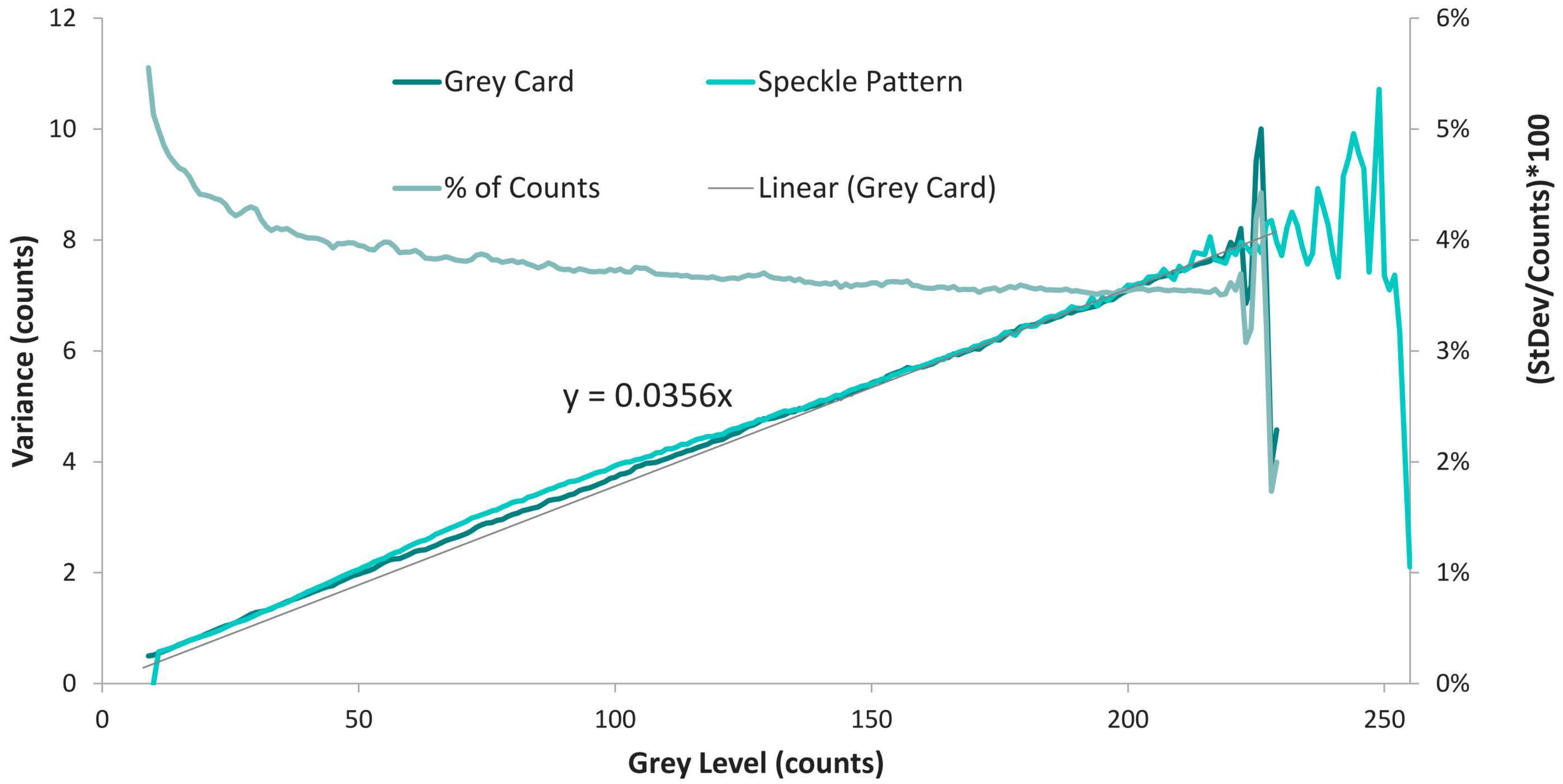
Take many images and calculate out mean and standard deviation



What do you notice about the noise?

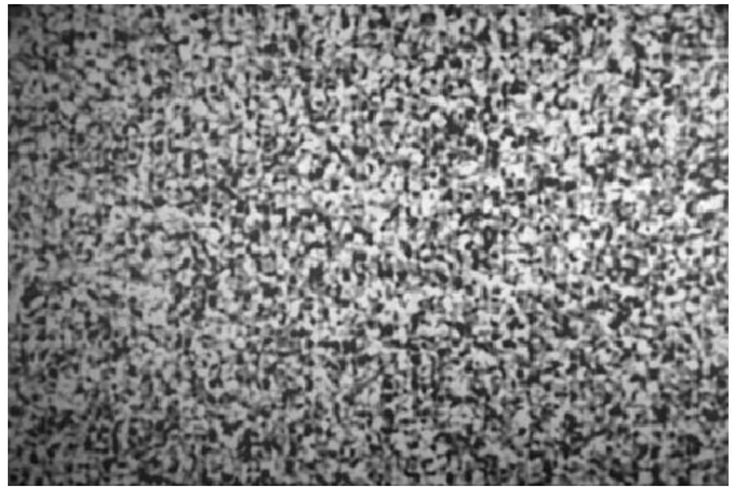
The relationship of noise to intensity still occurs. But the noise is usually lower because camera motion has been removed as an issue.

Noise scales up with grey level, that is, heteroscedastic.

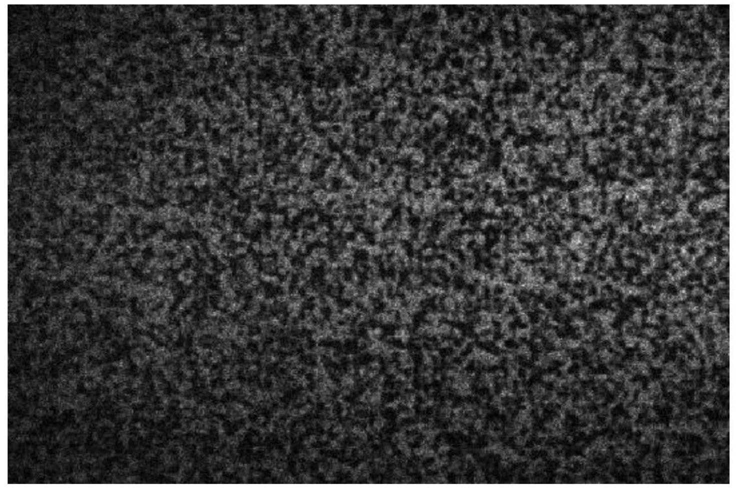


There is a small effect on the intensity because of the moving camera and the speckle pattern. But it is conservative in that it overestimates the noise!

Mean Image

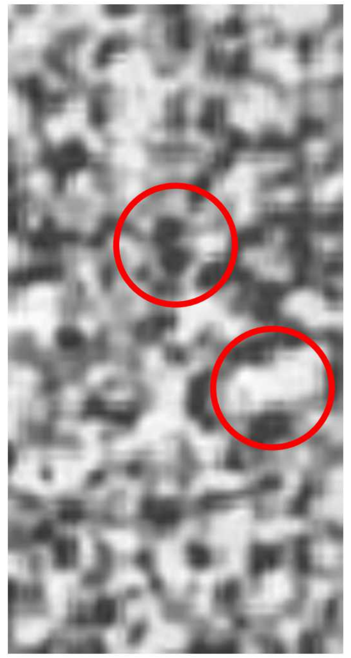


Standard Deviation Image

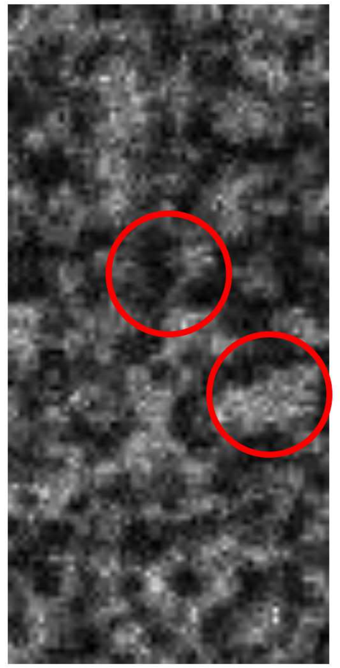


zoom in

Mean



Standard deviation



An example of the influence of image noise on the DIC results.

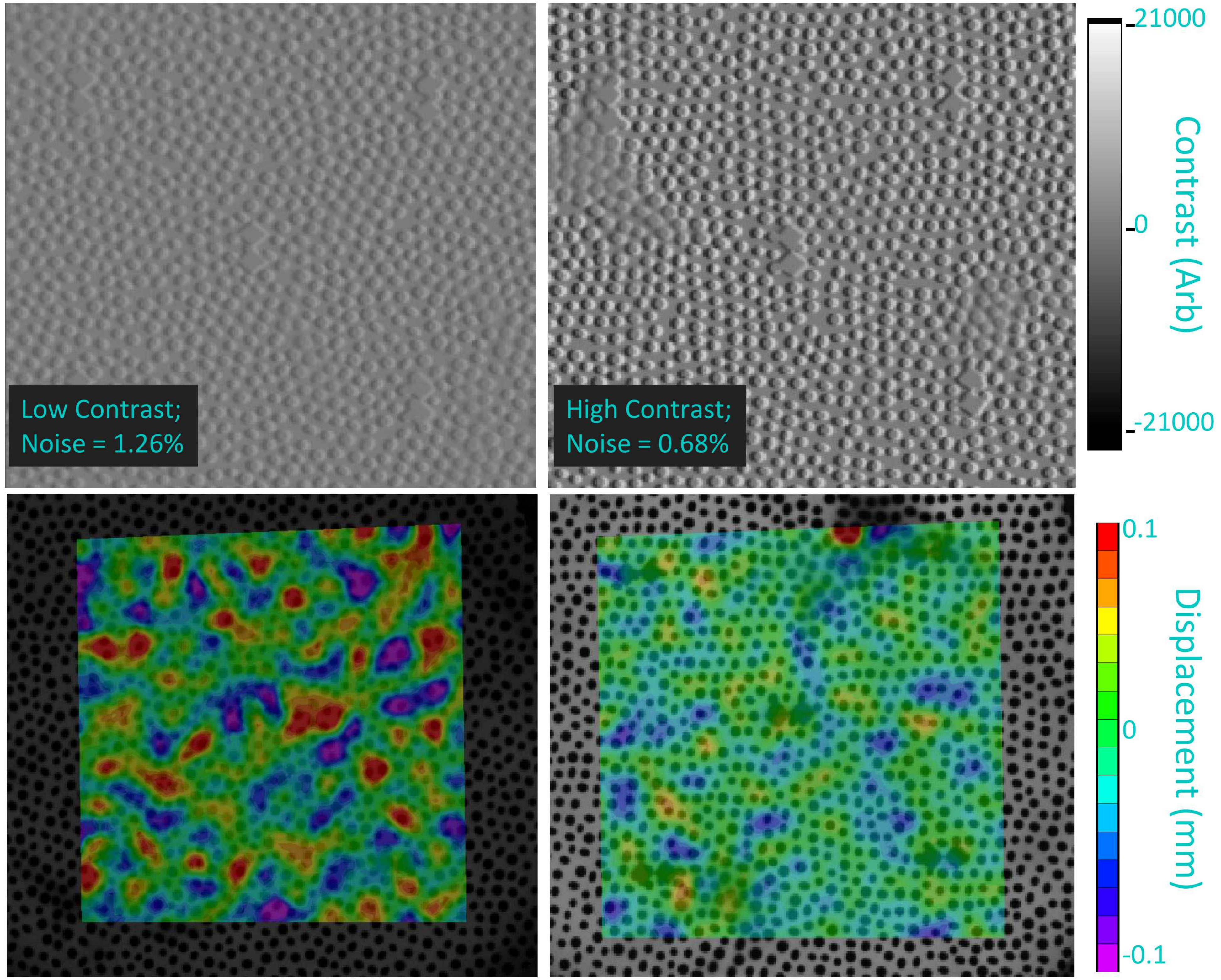


Image Acquisition: Noise

Section 5.4.2 – Noise floor analysis

Caution 2.15 – Keep camera gain low!

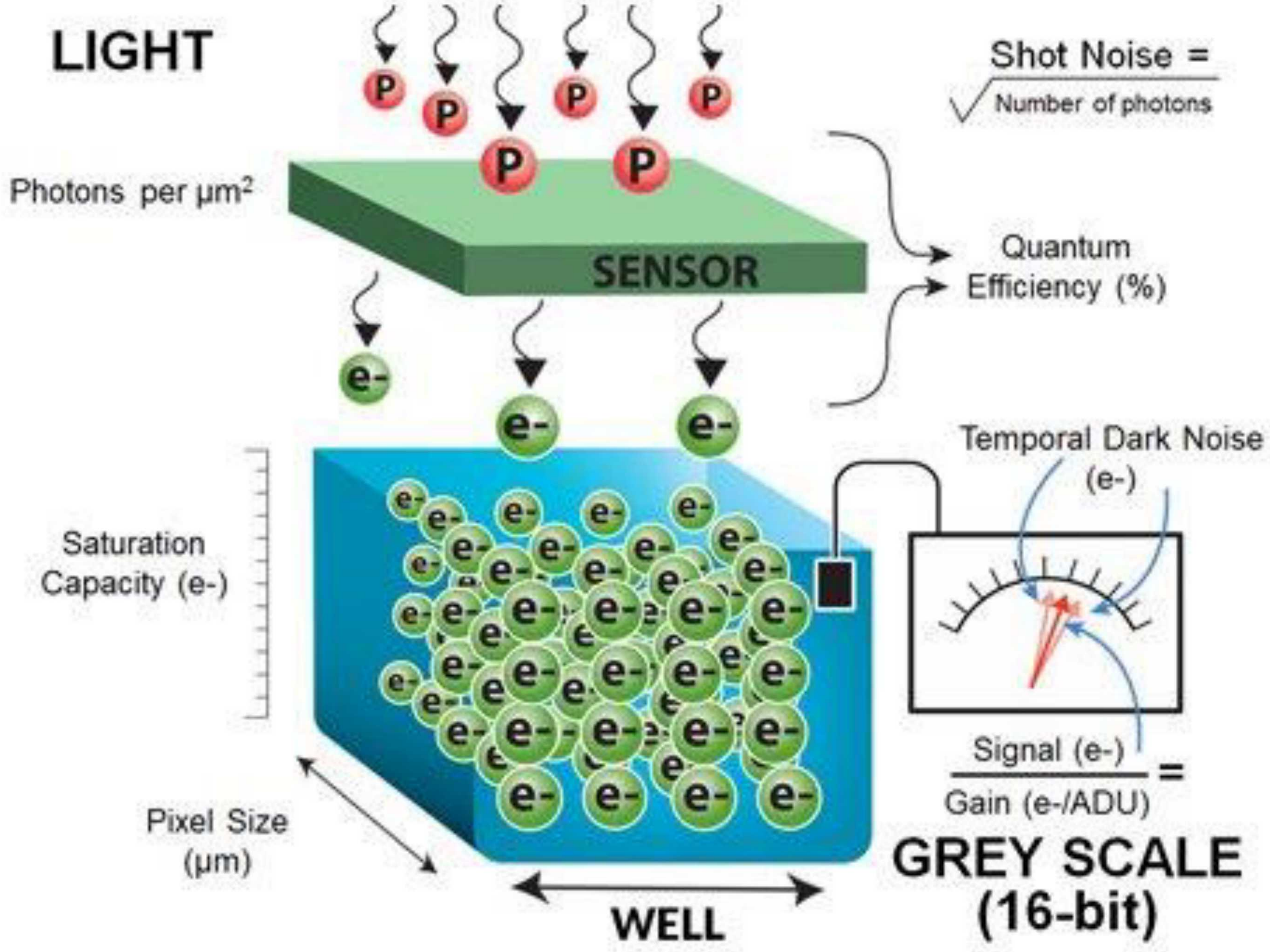
A communication protocol will need to be decided on: This is a moving target…

- USB3.0
  - Very fast and easy to use
  - Cable length may be an issue
- FirewireB Cameras
  - This camera allows automatic synchronization between any number of cameras
  - Cable length 15m – but easily extendable
  - Adequate data rate
- GigE Cameras
  - Superior cable length
  - Adequate data rate
  - Synchronization must be done separately
- Cameralink
  - More expensive hardware
  - Superior data rate

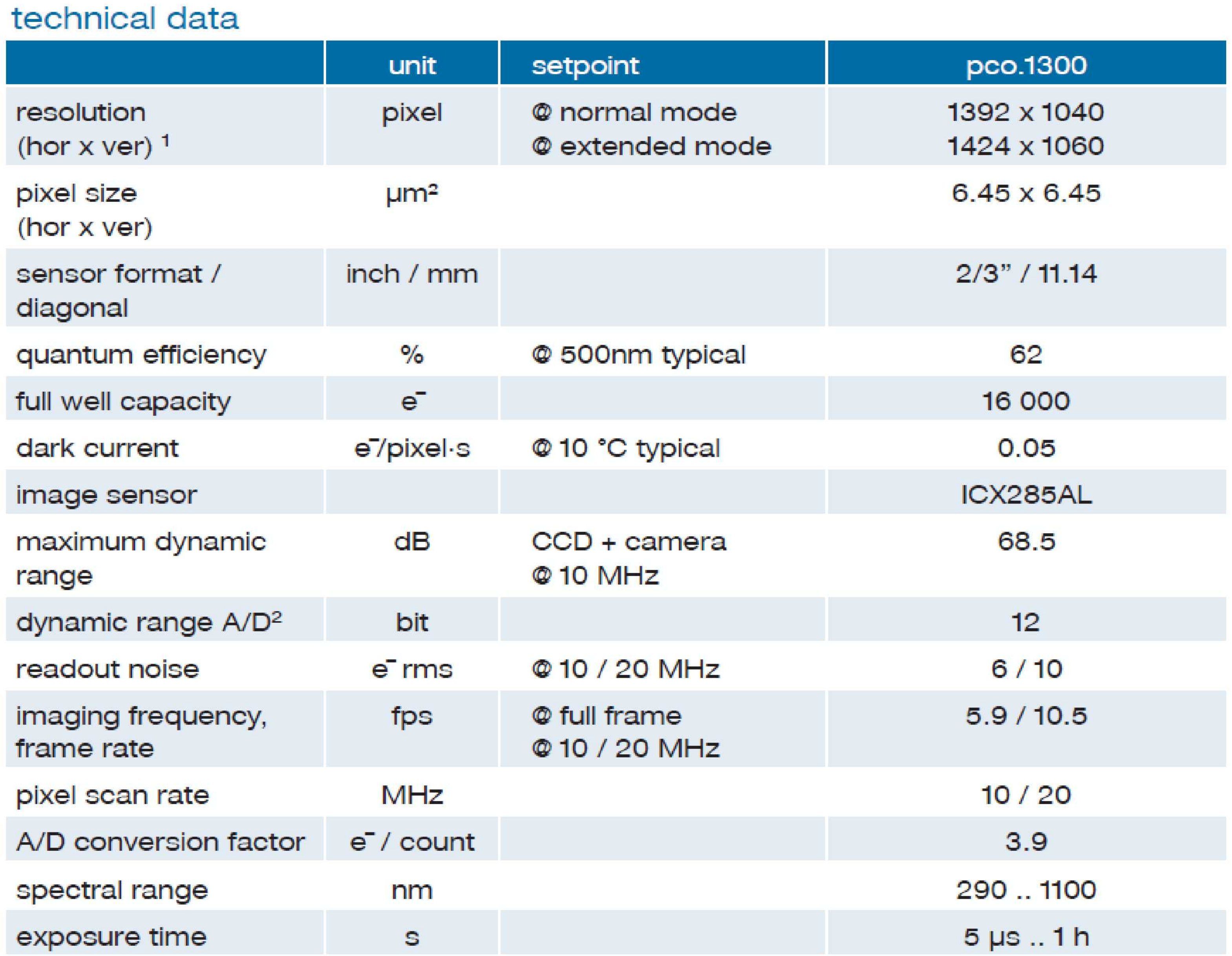
Interface	Speed	Synch.	Cable Length
Firewire	Good	Built In	Short
CoaXPress	6 Gbit	Built In	V. Long
USB 3.0	Good	Built In	Short
GigE	Good	Separate	V. Long
CameraLink	4 Gbit	Built In	Moderate

Usually a given detector (e.g. Sony or Kodak) is available in any number of communication formats.

Camera specifications sheet and definitions



https://www.flir.com/discover/iis/machine-vision/how-to-evaluate-camera-sensitivity/

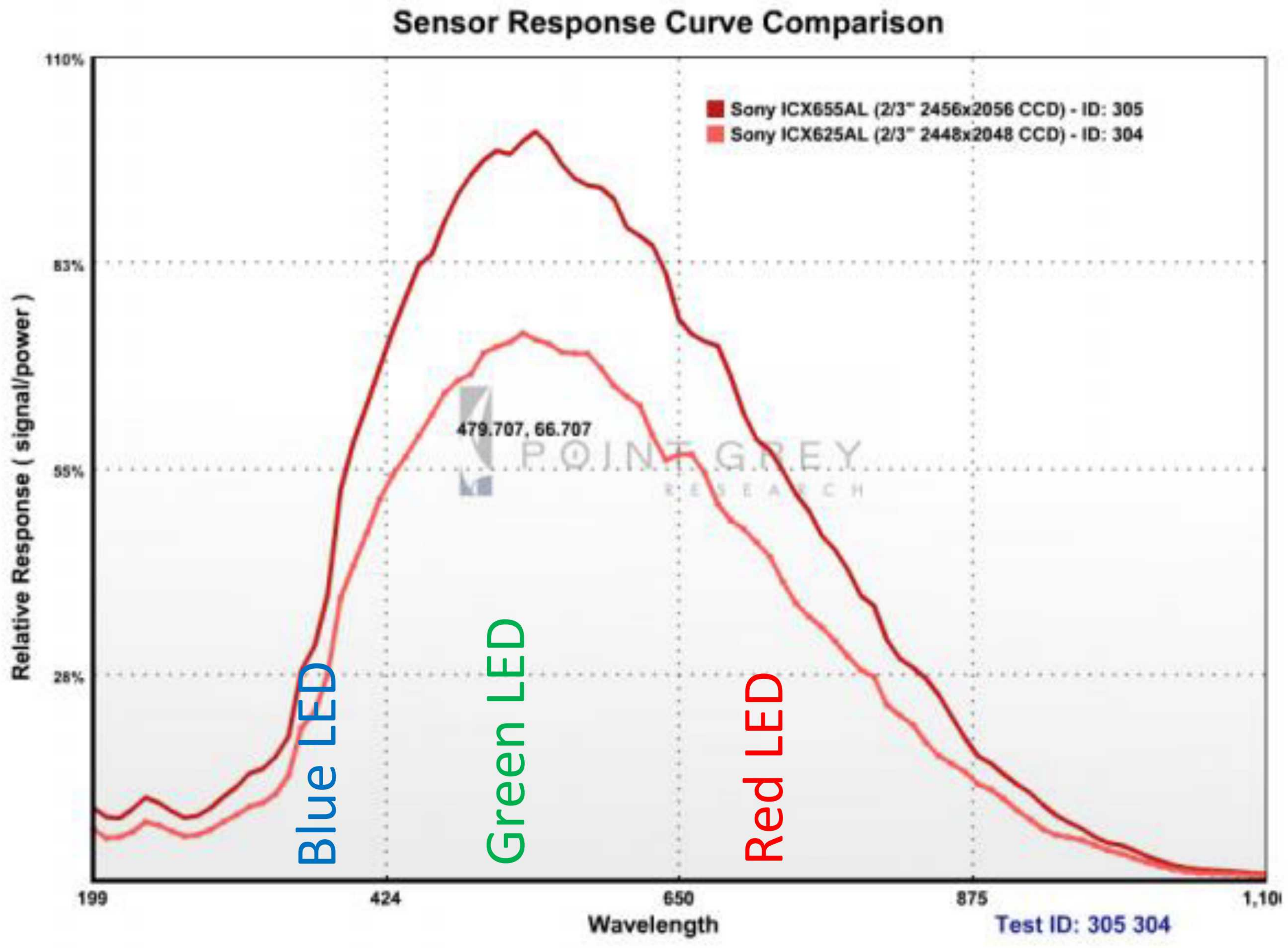


technical data

	unit	setpoint	pco.1300
resolution (hor x ver) ^{1}	pixel	@ normal mode @ extended mode	1392 x 1040 1424 x 1060
pixel size (hor x ver)	µm^2		6.45 x 6.45
sensor format / diagonal	inch / mm		2/3" / 11.14
quantum efficiency	%	@ 500nm typical	62
full well capacity	e^-		16 000
dark current	e^-/pixel·s	@ 10 °C typical	0.05
image sensor			ICX285AL
maximum dynamic range	dB	CCD + camera @ 10 MHz	68.5
dynamic range A/D^2	bit		12
readout noise	e^- rms	@ 10 / 20 MHz	6 / 10
imaging frequency, frame rate	fps	@ full frame @ 10 / 20 MHz	5.9 / 10.5
pixel scan rate	MHz		10 / 20
A/D conversion factor	e^- / count		3.9
spectral range	nm		290 .. 1100
exposure time	s		5 µs .. 1 h

Caution 2.15 – Keep camera gain low!

Grasshopper spectral response

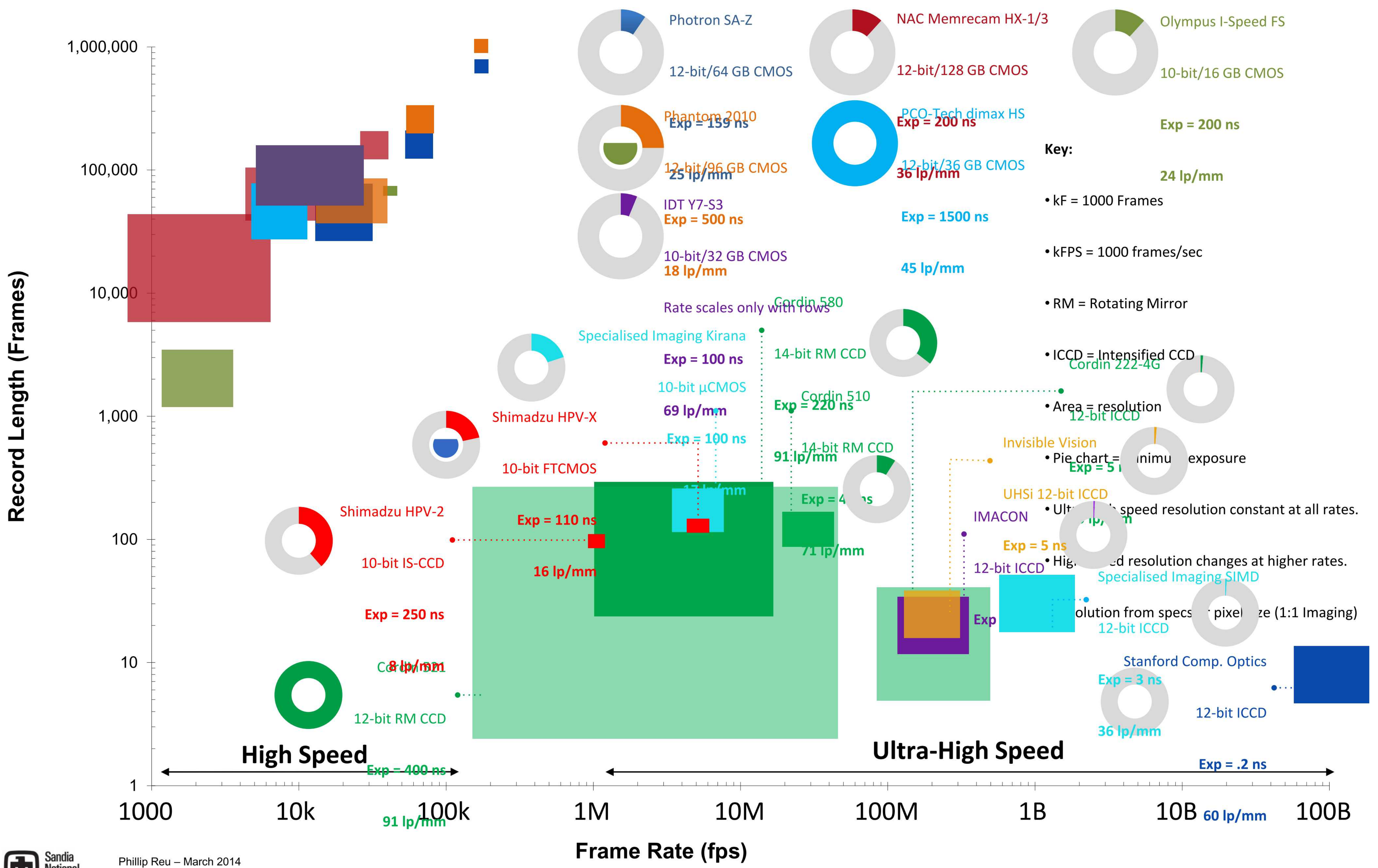


Important: When using monochrome illumination you should check this curve and make sure there is good sensitivity. More light may be needed towards the tails of the curve.

Camera overview

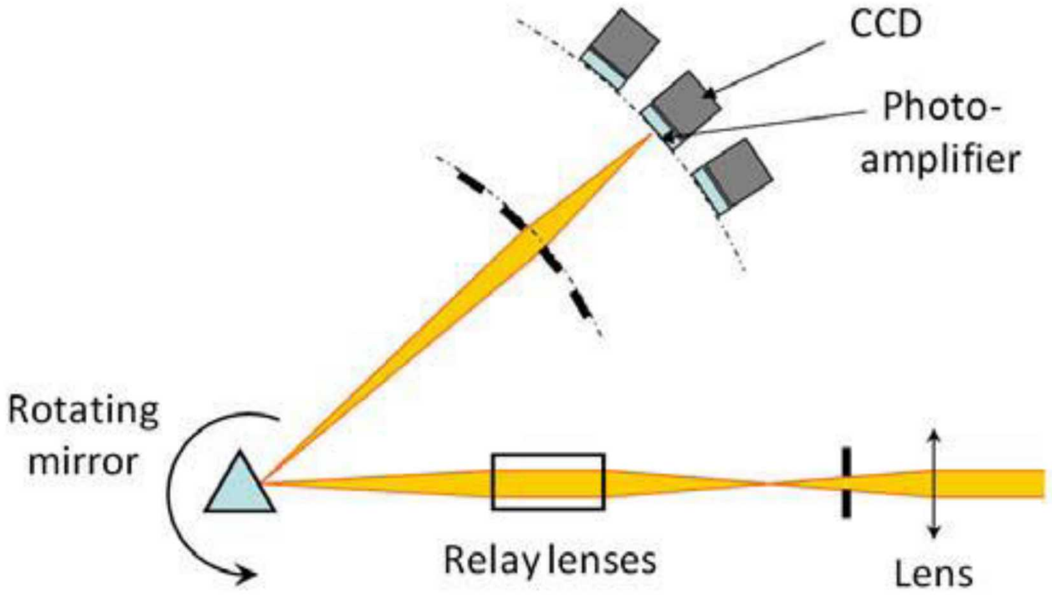
- Do not use color cameras – you loose resolution with no added accuracy
- Commercial point-and-shoots (including SLR) may have image stabilization and processing that needs to be turned off (usually on the lens).
- The noise level is important and determines the strain noise
- Keep the camera gain low
- Bit depth is nice for providing flexibility in lighting.
- Must synchronize cameras.
- Use uncompressed image formats. *.tif, *.bmp, raw formats.

The state of high-speed imaging



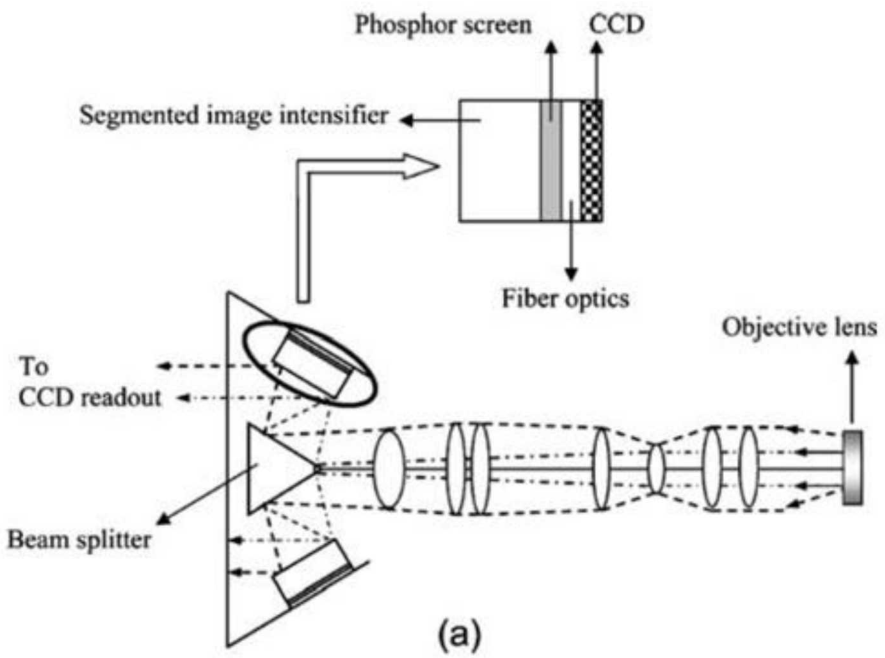
There are 3-Types of Ultra-high speed cameras

- Rotating mirror (CORDIN)



Cordin 521 Rotating Mirror

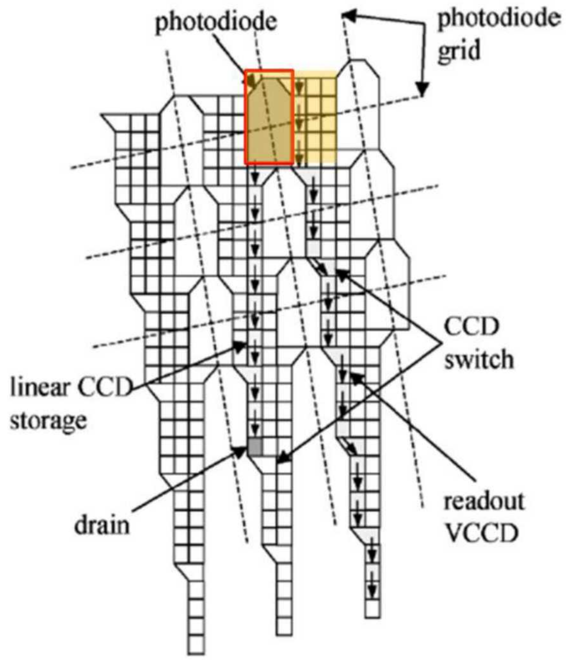
- Beam splitting (IMACON)



Intensifier resolution is 1k x 1k or 70 lp/mm is typical (Wikipedia)

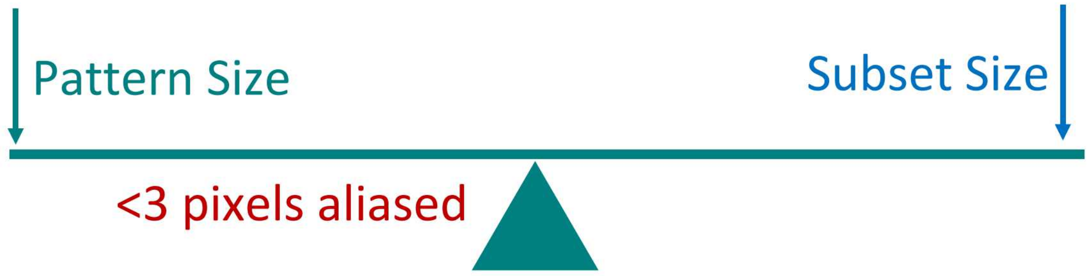
Specialized Imaging SIMD Intensified

- In-situ Storage Image Sensor (Shimadzu/Kirana)



- Ultra high speed cameras allow to acquire images over $1 \cdot 10^6$ fps
- The main limitation to reach high speed acquisition is the storage time
- The available technologies to reach these results are:

Pattern size



Pattern Size

Subset Size

<3 pixels aliased

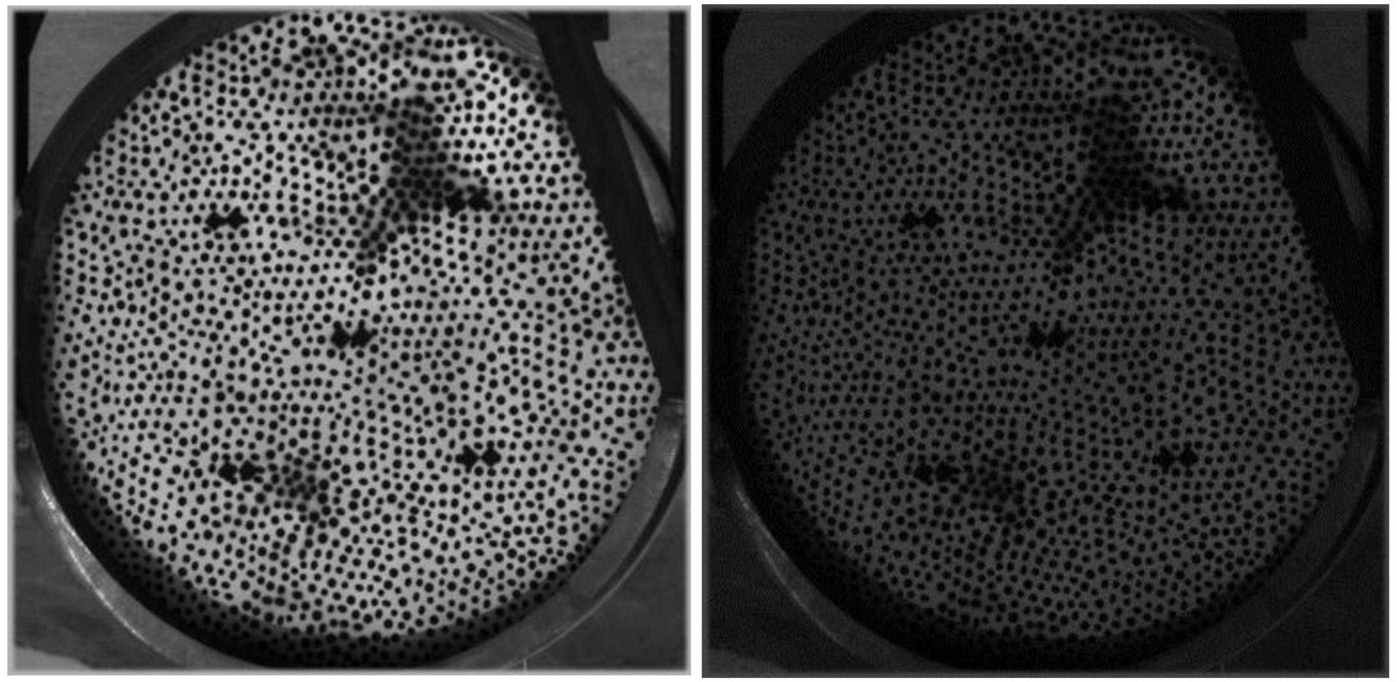
For equivalent displacement noise.

PATTERNING

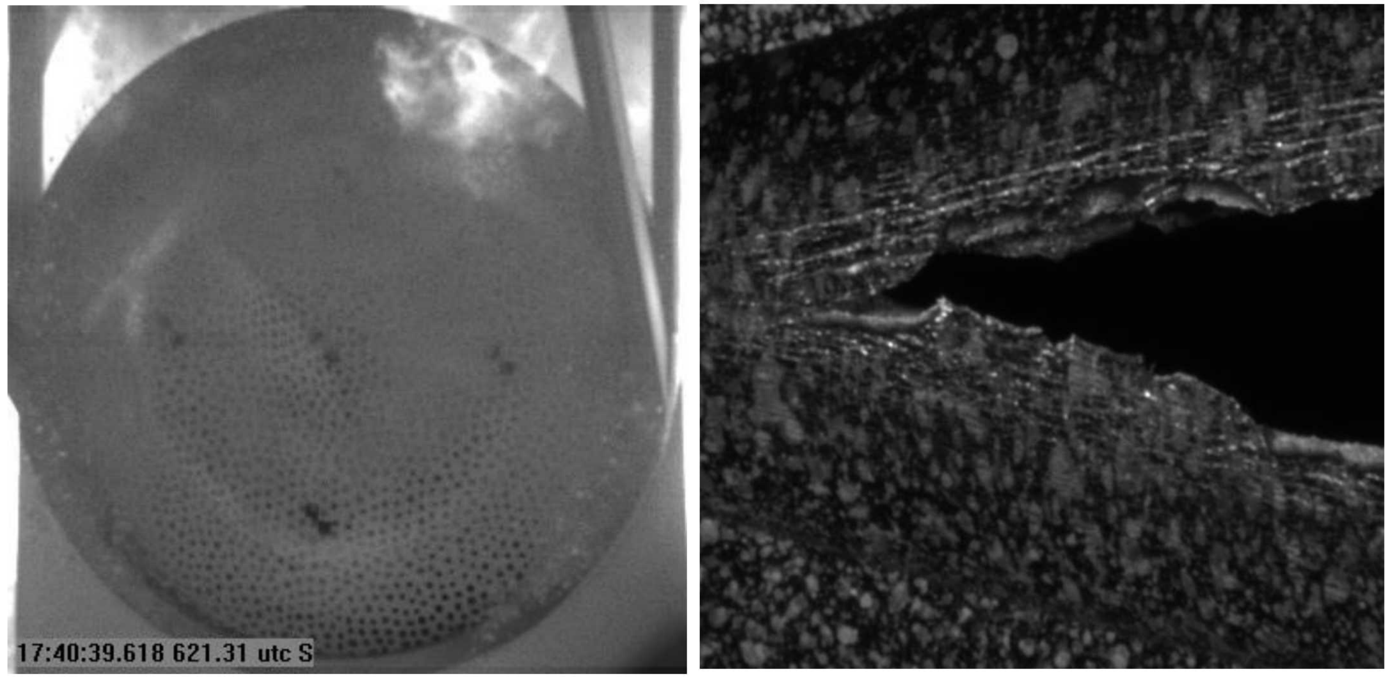
THE PATTERN AND THE LIGHTING WORK TOGETHER AND ARE FUNDAMENTAL TO YOUR ACCURACY

Section 2.3 – DIC Pattern

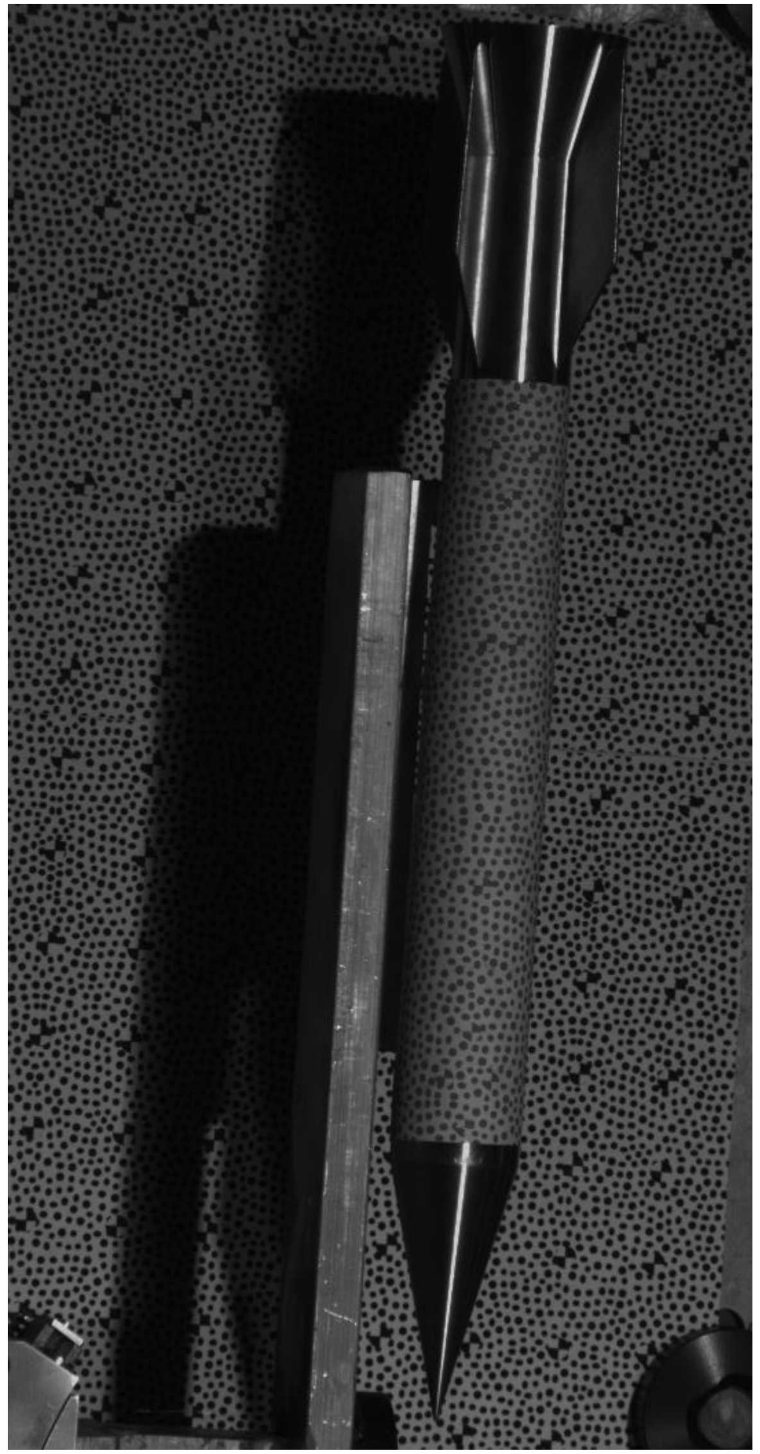
A good pattern is critical to making great DIC measurements



Good contrast (lighting and speckling)



Stays bonded to the surface



Is relatively unique

Section 2.2.4.3 – Contrast, Intensity, and Gain

Section 2.3.2.1 – Size (3 – 5 Pixels)

Section 2.3.2.2 – Variation

Section 2.3.2.3 – Density, approximately 50% coverage

Section 2.3.2.4 – Quality, i.e. does the pattern hold-up under load.

Section 2.3.3.1 – Compliance, i.e. the paint doesn’t stiffen the sample.

Section 2.3.3.2 – Bonding

Section 2.3.3.3 – Fidelity, i.e. the pattern moves with the sample surface.

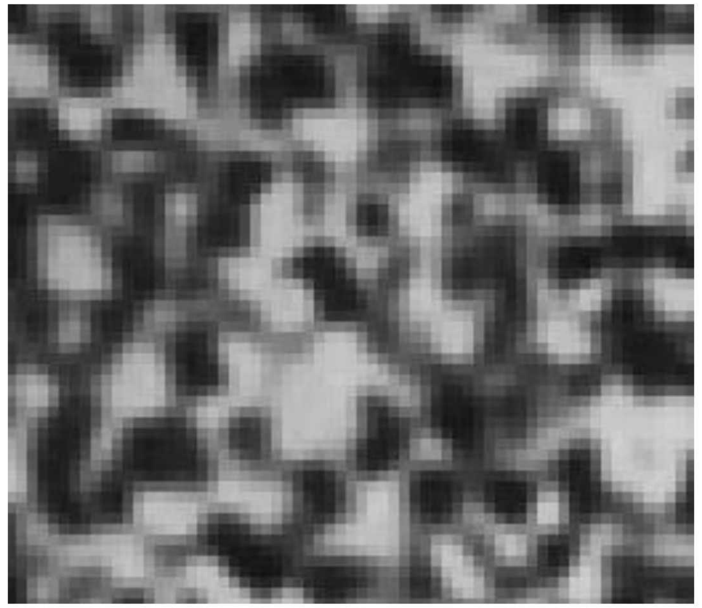
Section 2.3.3.3 – Fidelity, i.e. the pattern moves with the sample surface.

Section 2.3.3.4 – Thickness. Rough patterns will image differently from different angles.

Caution 2.23 – Bonding

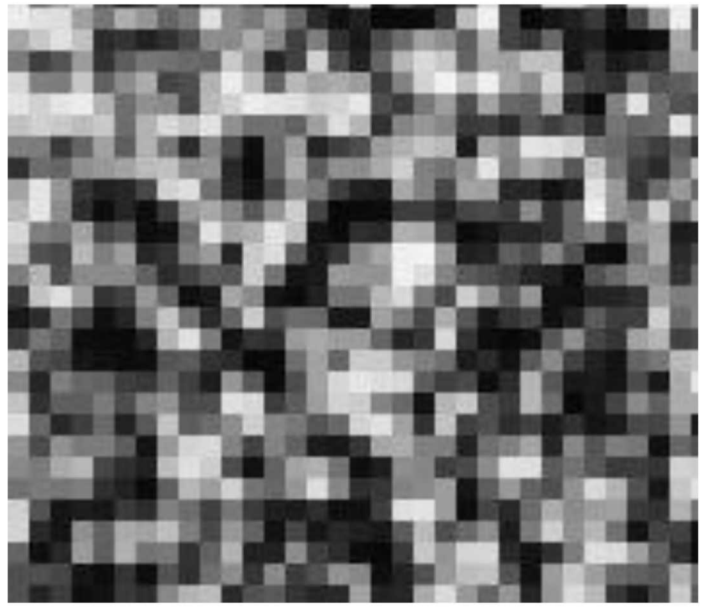
iDICs

It is important to quantify your speckle size and optimize for your experiment.



Good Pattern:
Actual Size = 4-5 pixels
Calculated Size

= 4.8 (autocorrelation)
= 3.6 (auto-threshold)
= 3-5(Eyeball)



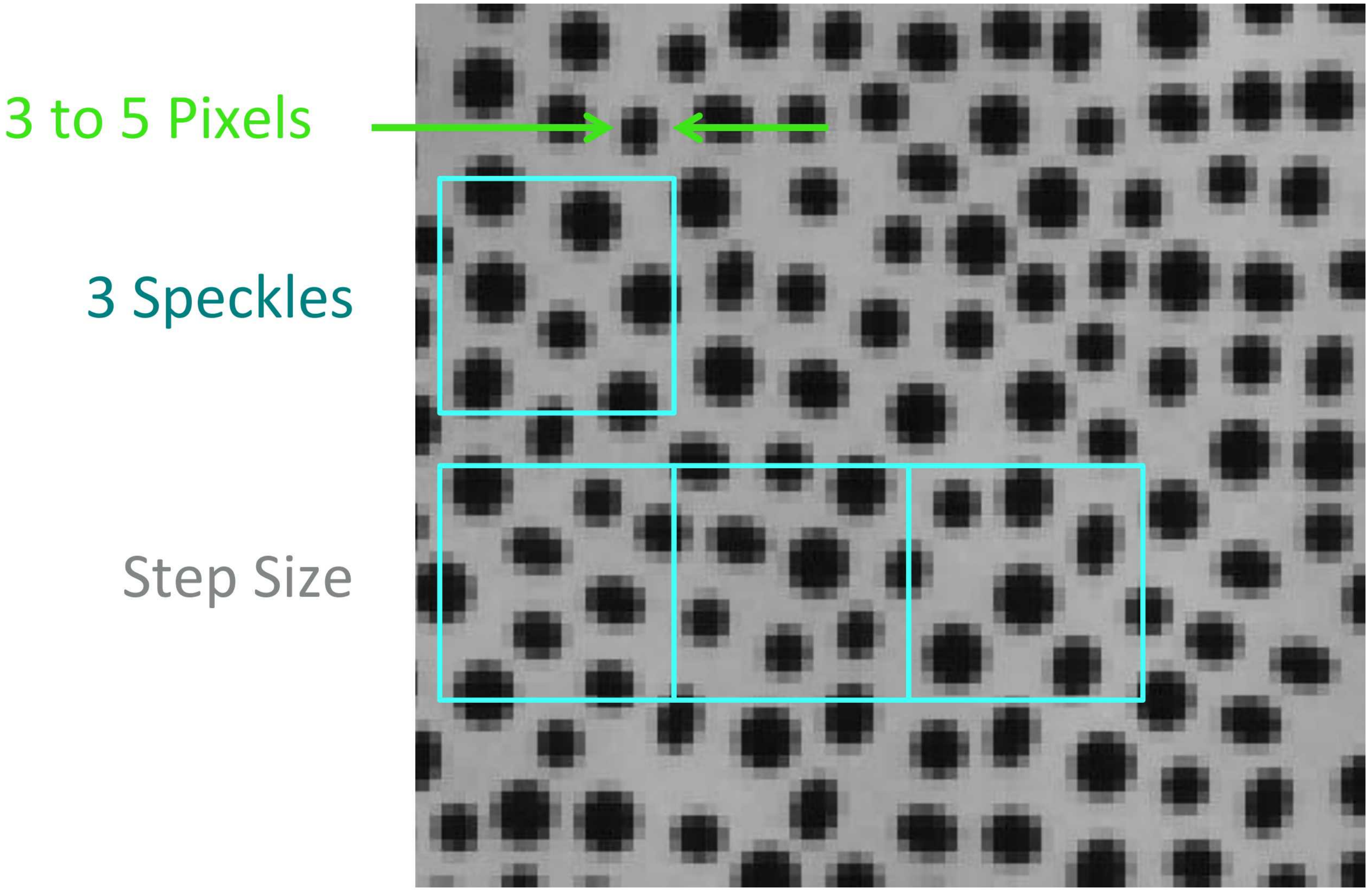
Aliased:
Actual Size = 1.5 pixels
Calculated Size
= 2.1 (autocorrelation)
= 1.6 (auto-threshold)
= 2 to 3 (Eyeball)

Measure and confirm the speckle size

- MatLAB/LabVIEW “blob” analysis (using auto-threshold function)
- Autocorrelation
- By Eye (zoom in)
- Beware of aliasing. No results are correct after an aliased signal is digitized.
- Optimum is 3-5 pixels per speckle.

Tip 2.33 – Feature size by eye.

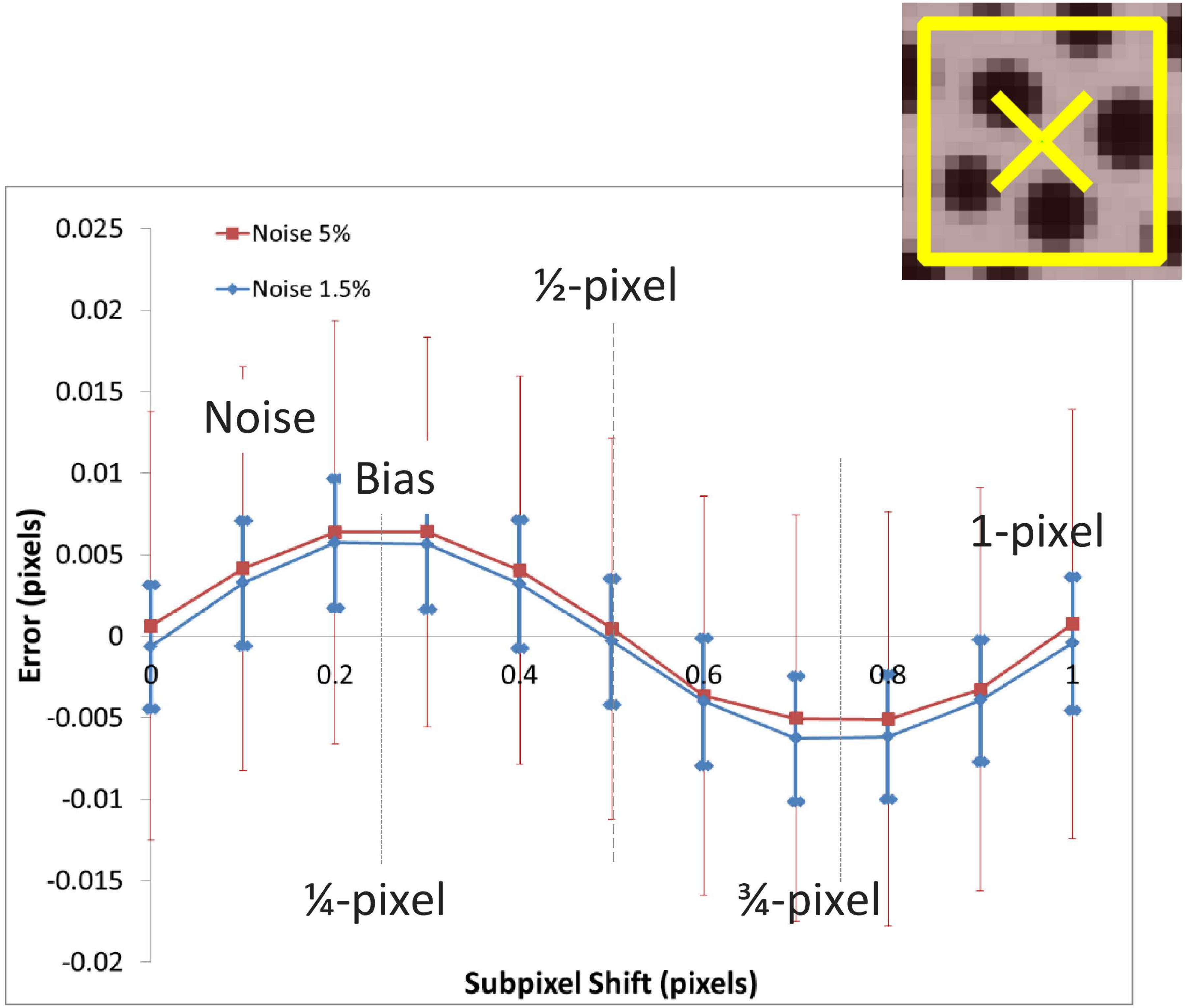
The spatial resolution, subset size, and Pattern size are all inter-related.

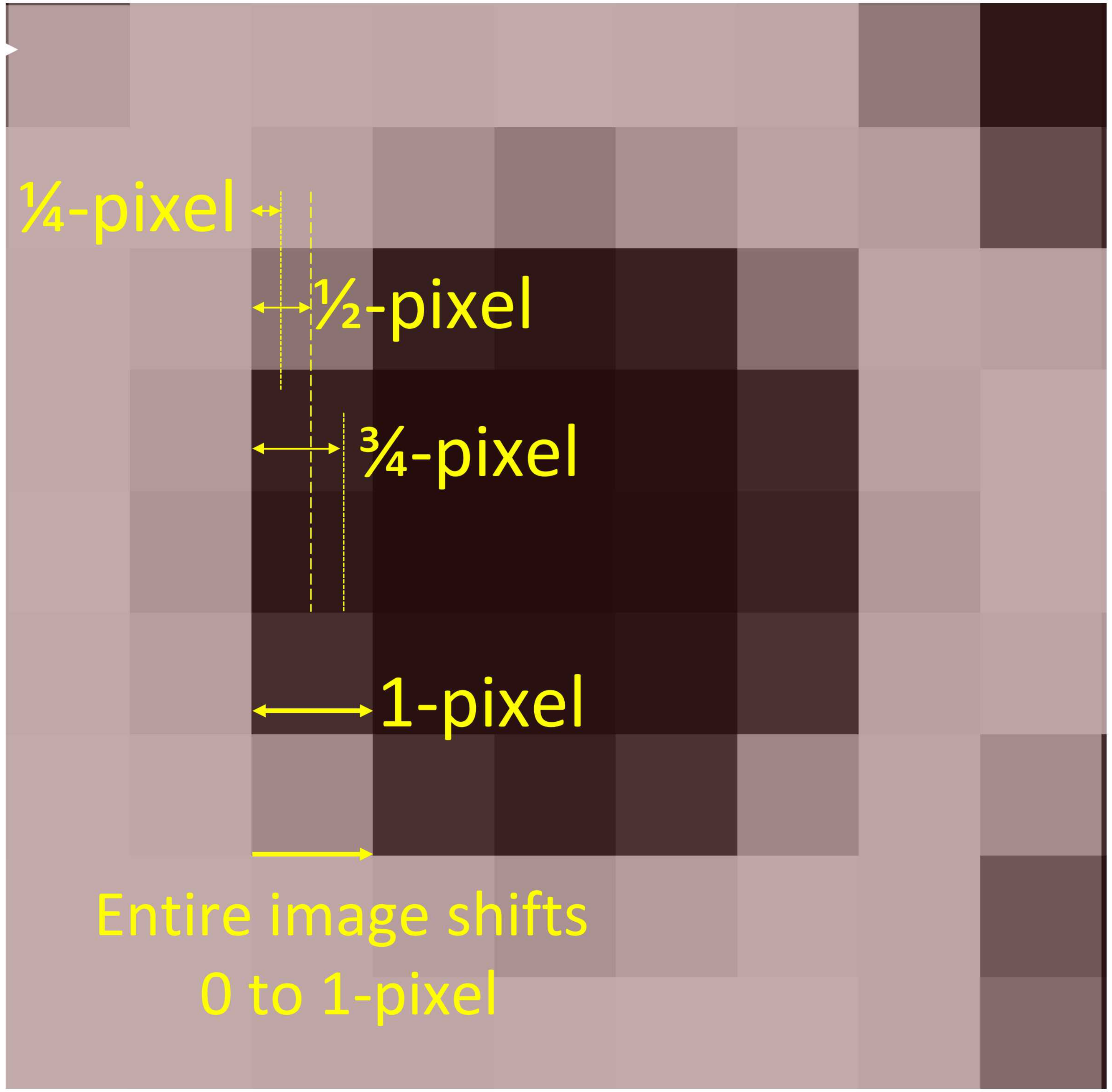


Most common situation: Camera limited

- Pattern edges are clearly delineated.
- You <u>see</u> the pixels in the Patterns!

All DIC errors should be *subpixel*. What does this look like?





Note: All this data has no PIB error! Rigid-body-motion with affine shape function.

The image noise error is defined by the interpolant and the contrast vs noise ratio.

Systematic Bias

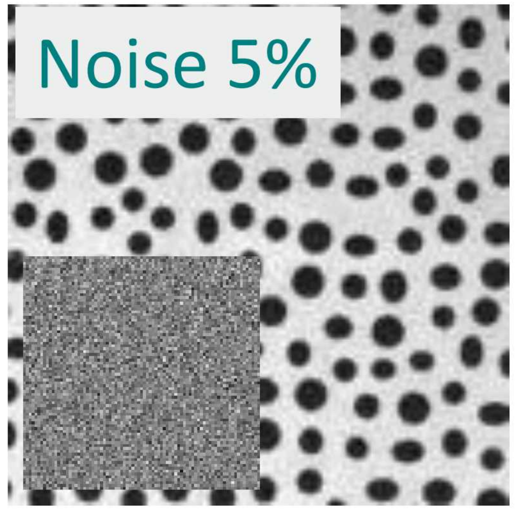
$$\mathrm{E}(t) = \frac{\sum_i \left[h(x_i)\cdot\nabla T(x_i)\right]}{\sum_i \left[\nabla T(x_i)\right]^2} \qquad + A\cdot\frac{n\sigma^2}{\sum_i \left[\nabla T(x_i)\right]^2}$$

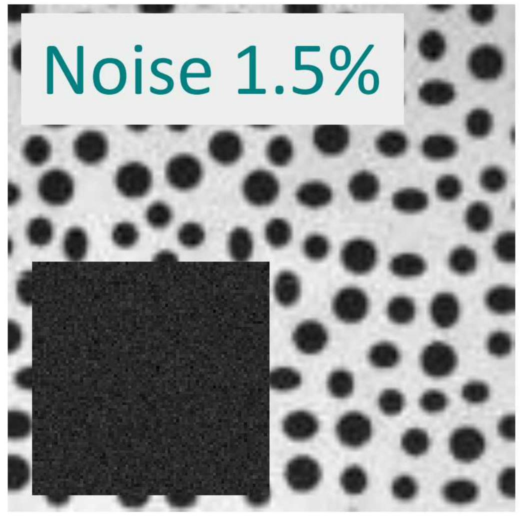
Interpolation Bias **Noise Bias**

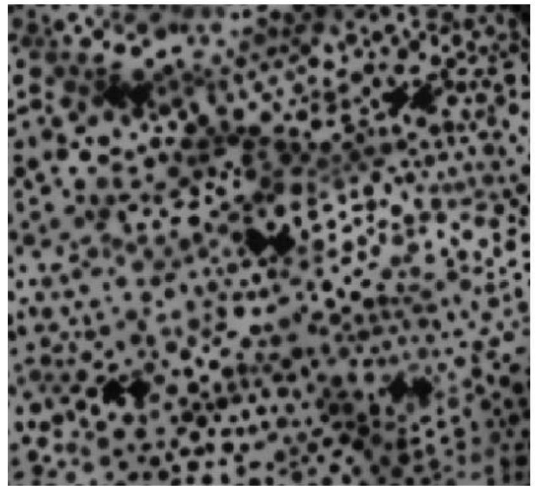
Random Variance

$$\mathrm{Var}(t) \cong \frac{2\sigma^2}{\sum_i \left[\nabla T(x_i)\right]^2}$$

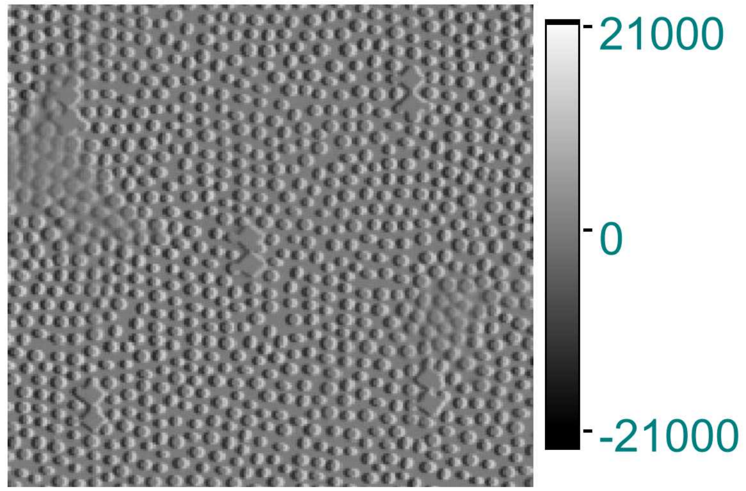
Measurement Variance


Noise 5%

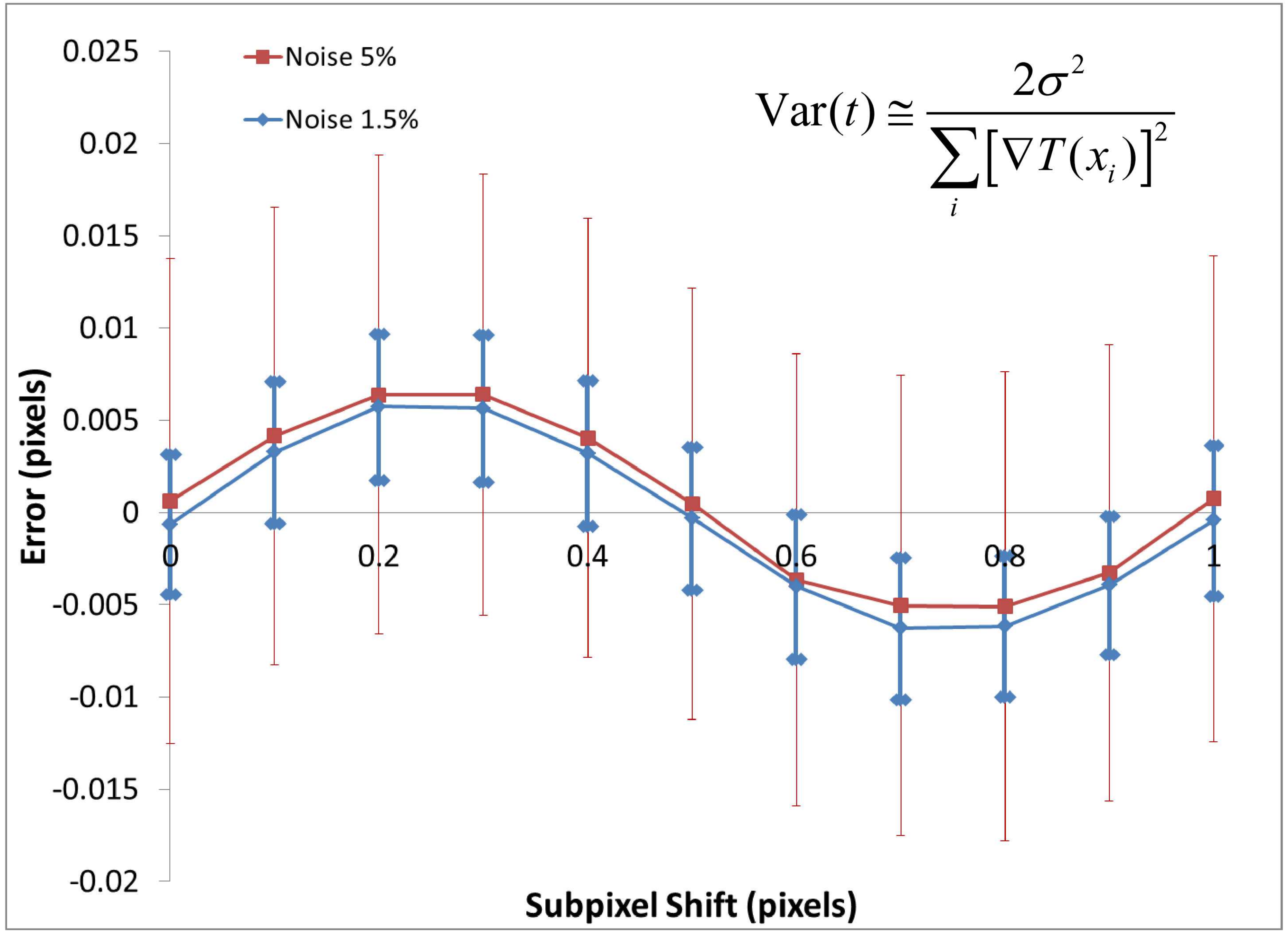

Noise 1.5%



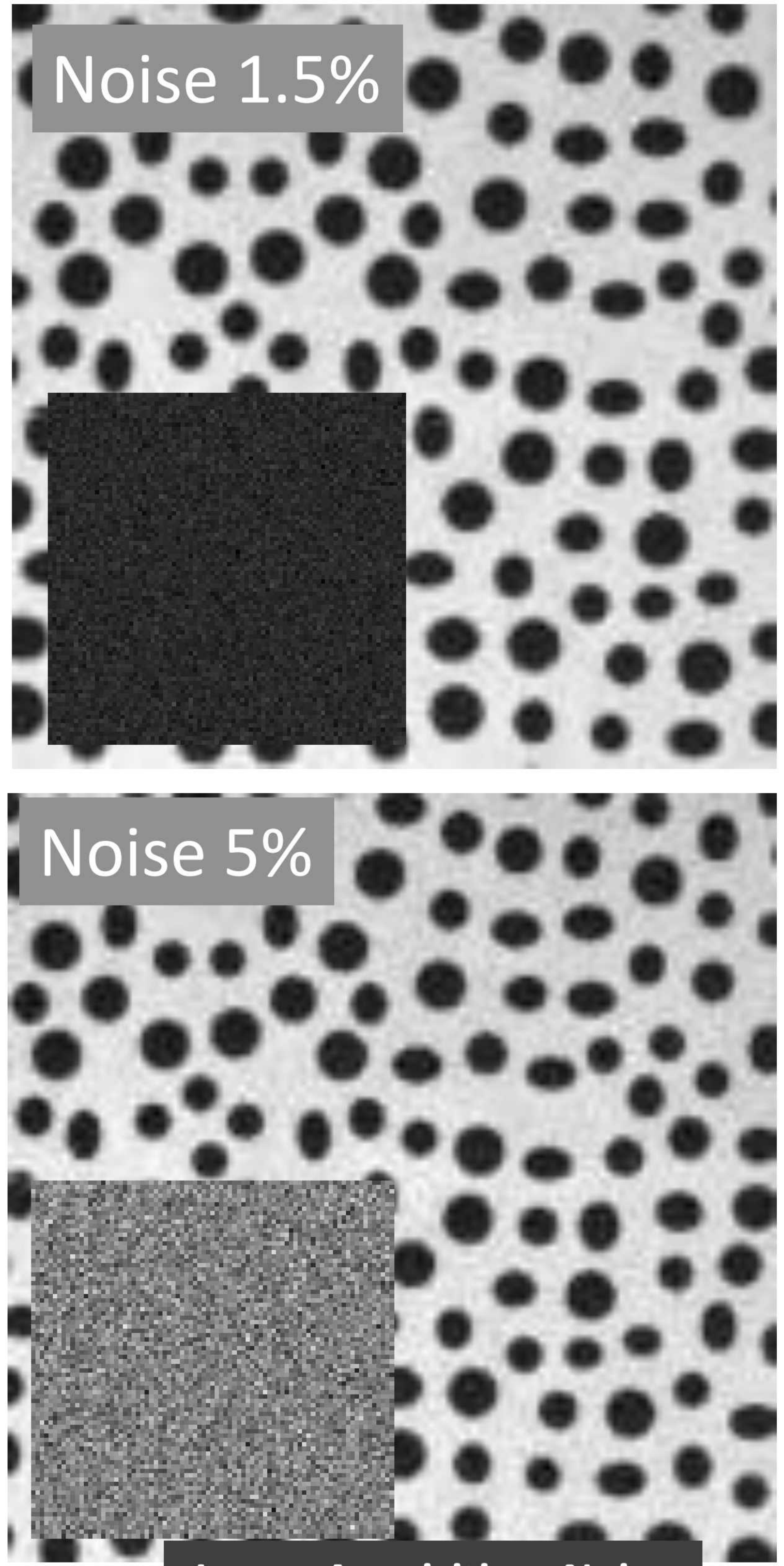
Gradients = $\sum_i \left[\nabla T(x_i)\right]$ =



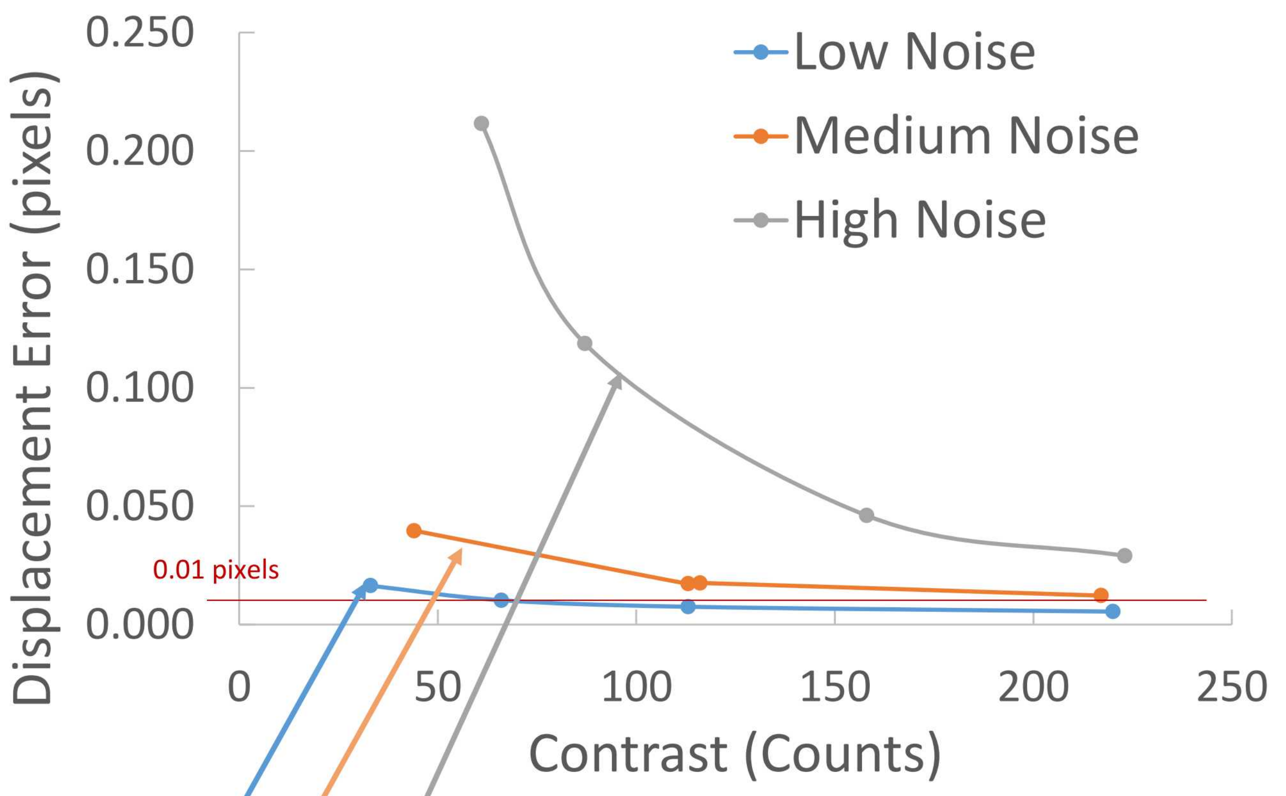
The noise also affects the variance at each measurement point

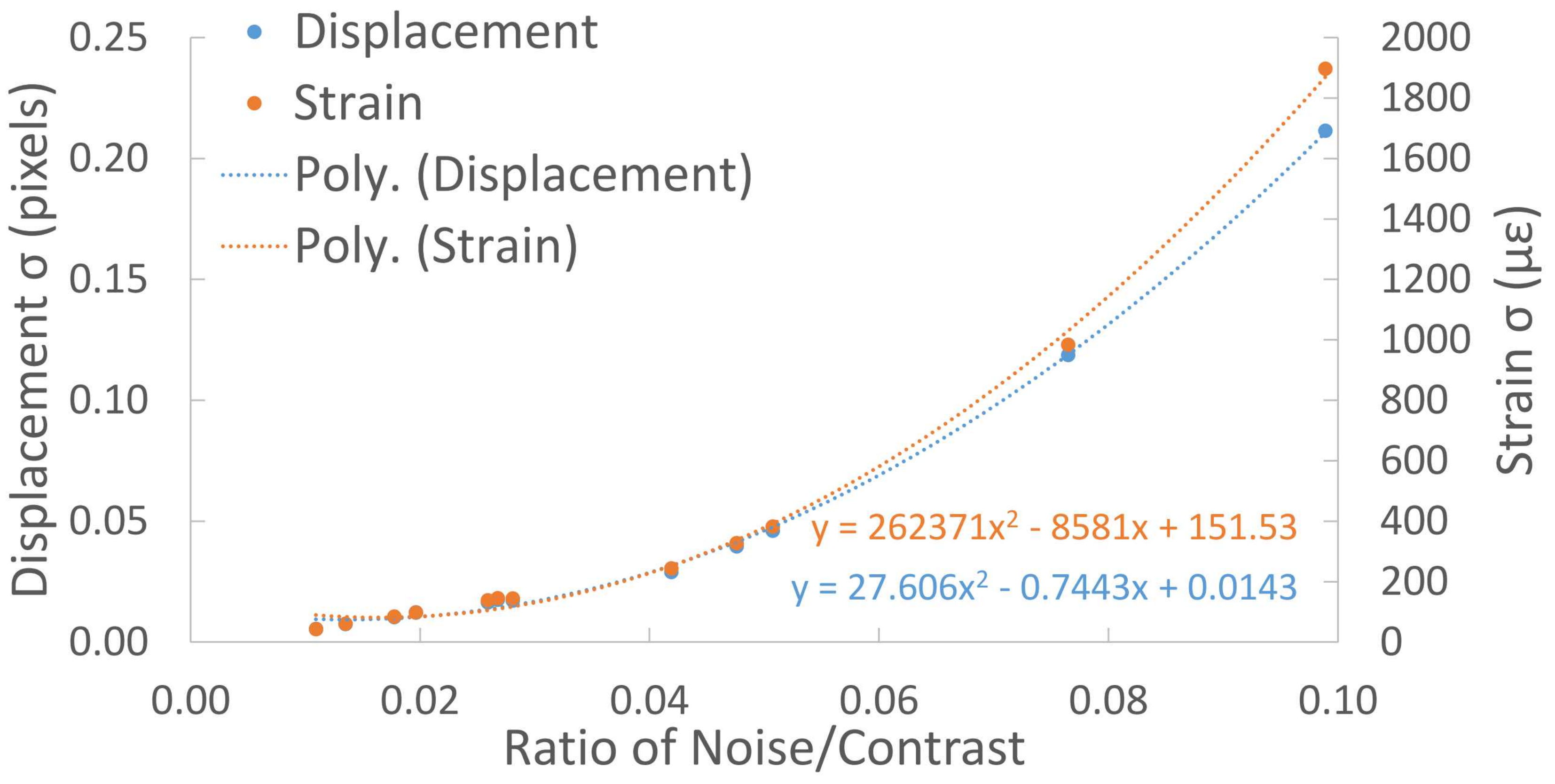


$$\mathrm{Var}(t) \cong \frac{2\sigma^2}{\sum_i \left[\nabla T(x_i)\right]^2}$$

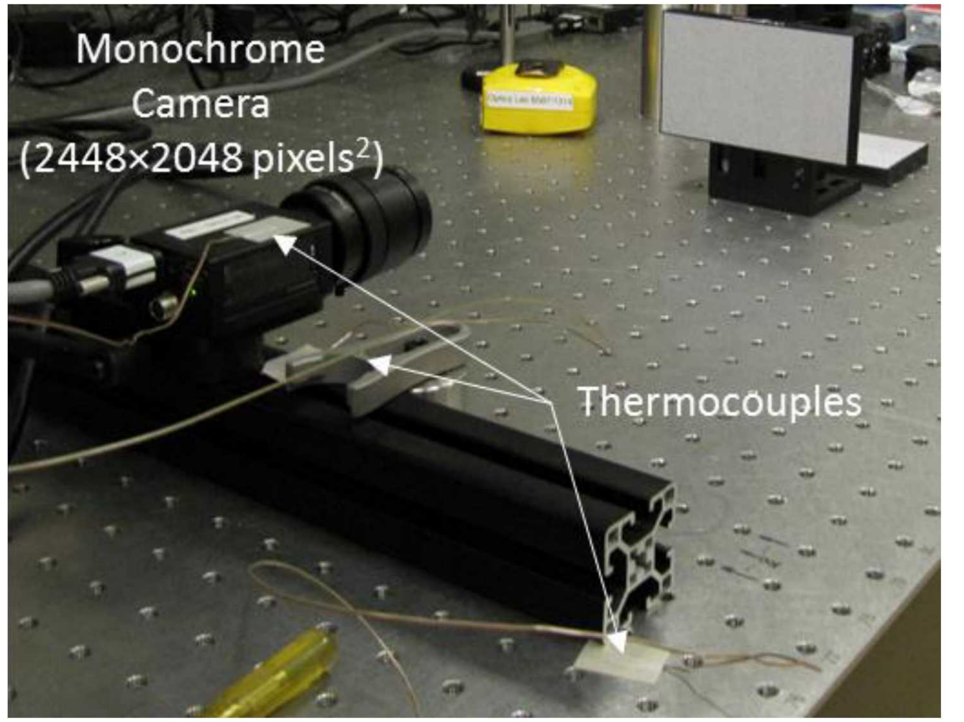


Not just the contrast is important, but also the noise!





Noise	Contrast	Camera Gain (dB)	Noise 1σ (counts)	Contrast (counts)	Ratio (Noise/Cont.)	Gradient (counts)	Noise / Gradient	StDev u (pixels)	St Dev v (pixels)	ε_{xx} (με)	ε_{yy} (με)
Low	High	-4.5	2.4	220	0.011	30.8	0.078	0.006	0.007	44	45
Low	Medium	-4.5	1.5	113	0.014	15.84	0.096	0.008	0.008	61	64
Low	Low	-4.5	1.2	66	0.018	8.93	0.131	0.010	0.010	85	89
Medium	High	12	4.3	217	0.020	28.85	0.148	0.012	0.020	98	97
Low	Terrible	-4.5	0.9	33	0.026	4.2	0.204	0.016	0.017	139	143
Medium	Medium	12	3.1	116	0.027	14.43	0.215	0.018	0.018	146	151
Medium	Low	12	3.2	113	0.028	14.55	0.218	0.017	0.019	145	147
High	High	24	9.3	223	0.042	28.15	0.332	0.029	0.030	245	172



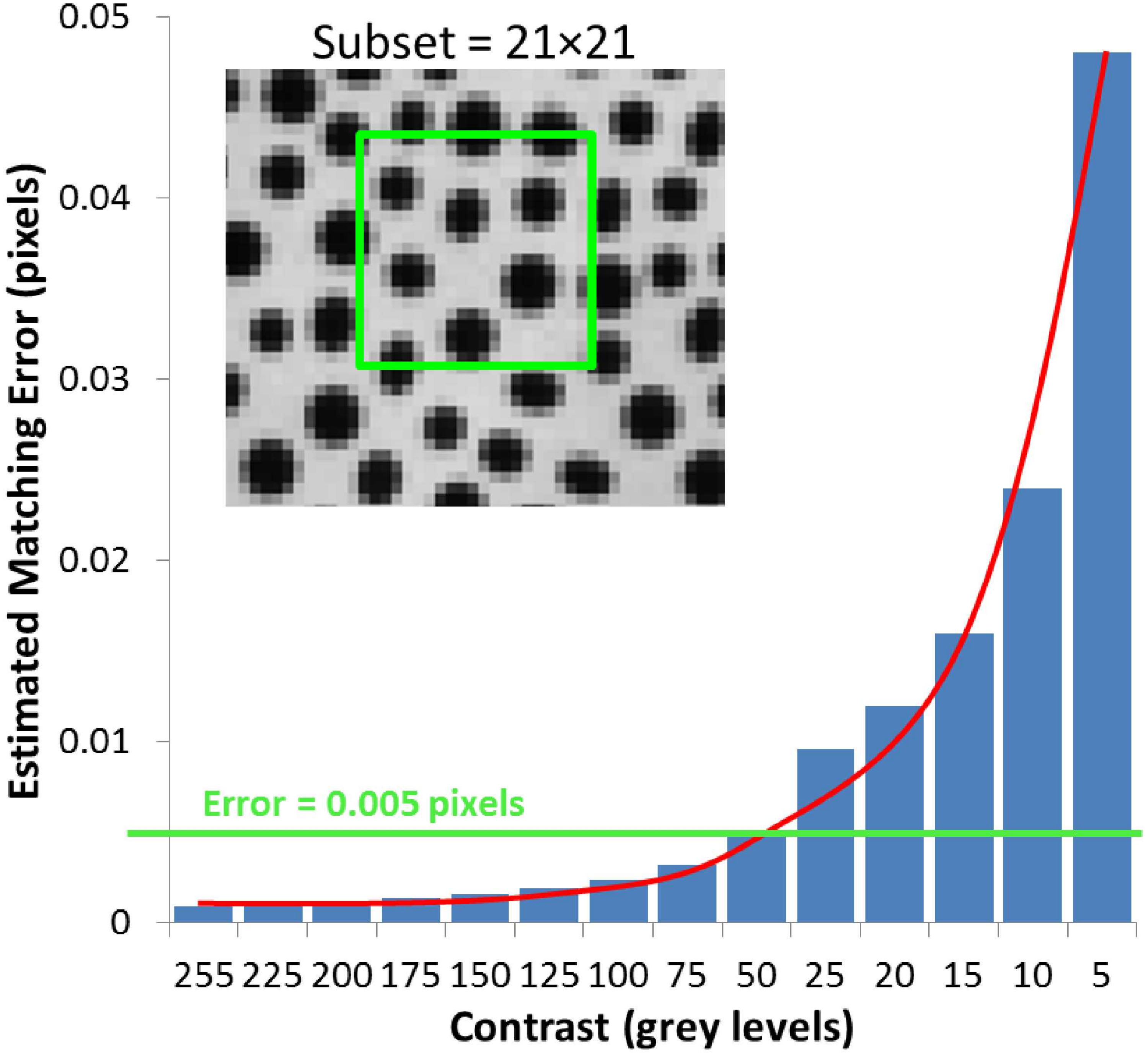
iDICs

Section 2.2.4.3 – Contrast, Intensity, and Gain

Recommendation 2.13

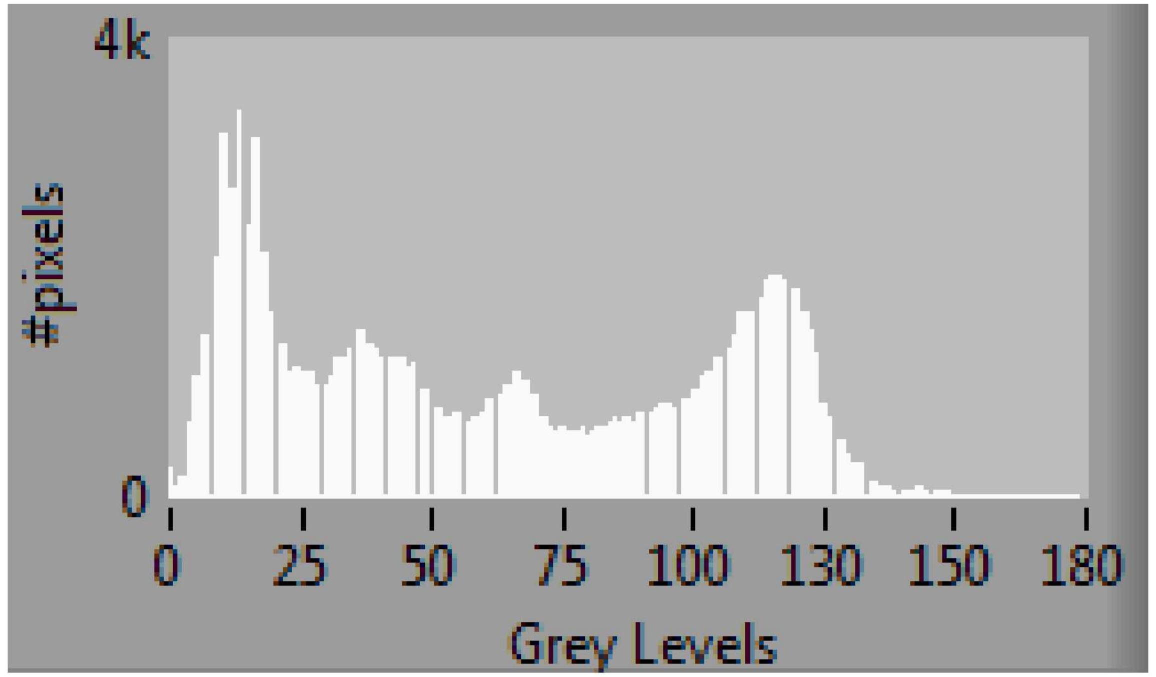
Image Acquisition: Noise

A minimum of 50 counts of contrast are recommended.



Contrast:

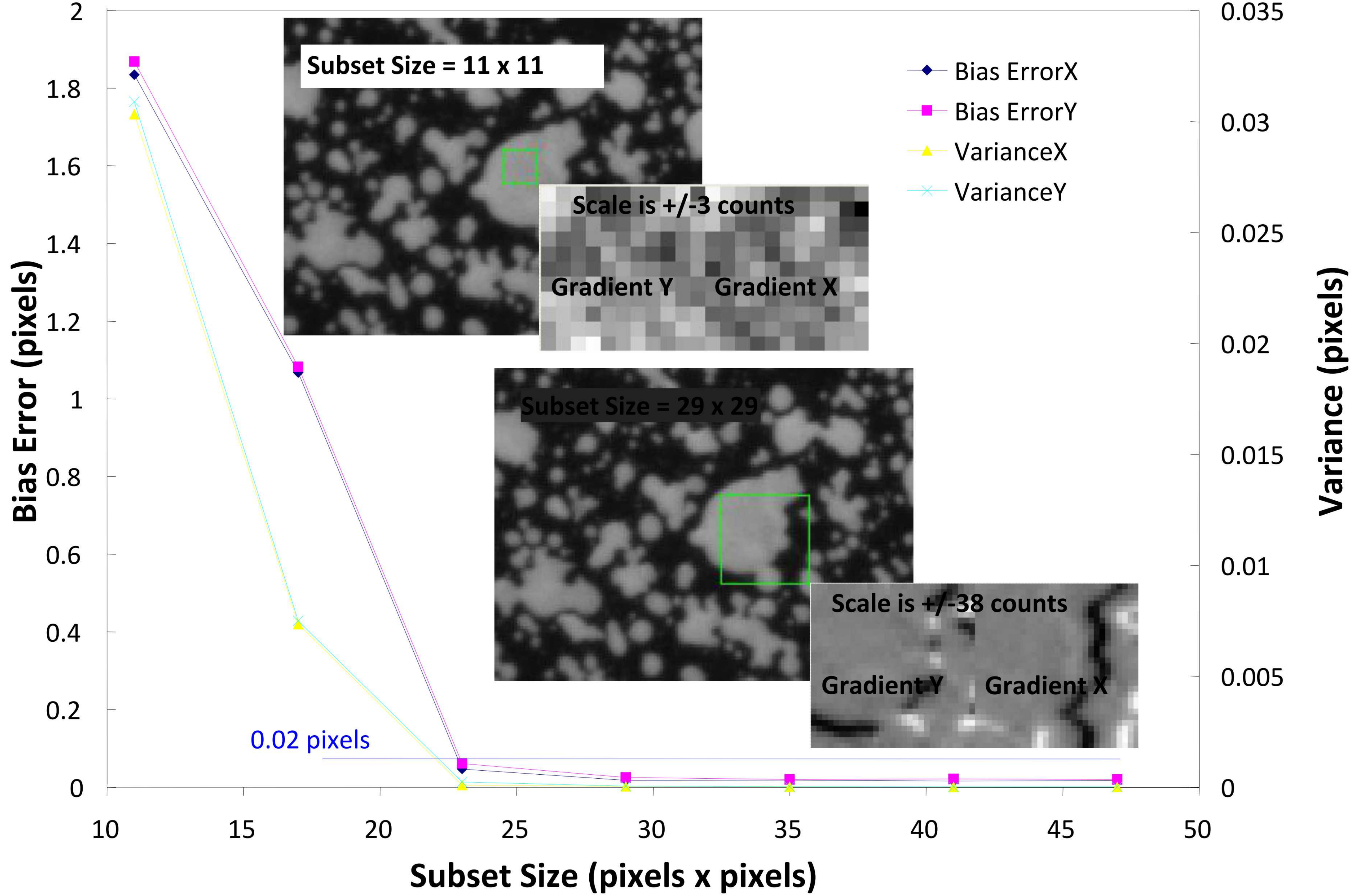
- Minimum 50 counts (8-bit)
- Recommended 130 counts (8-bit)



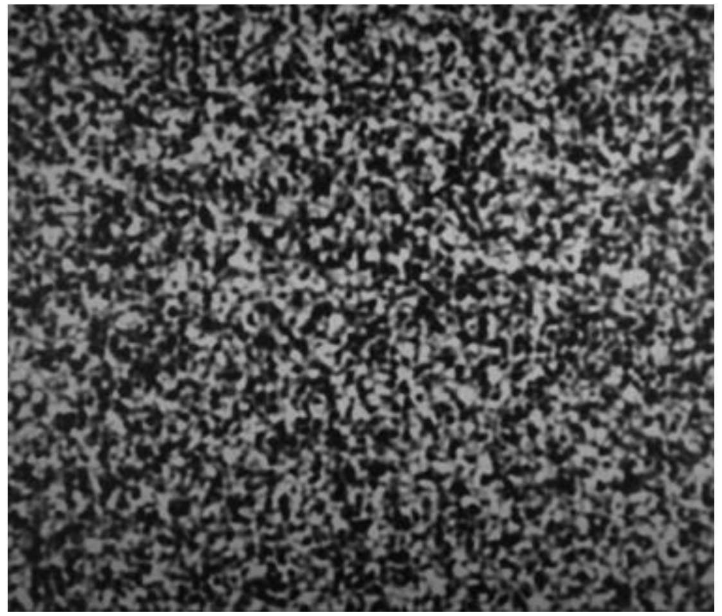
Recommendation 2.13 – Contrast

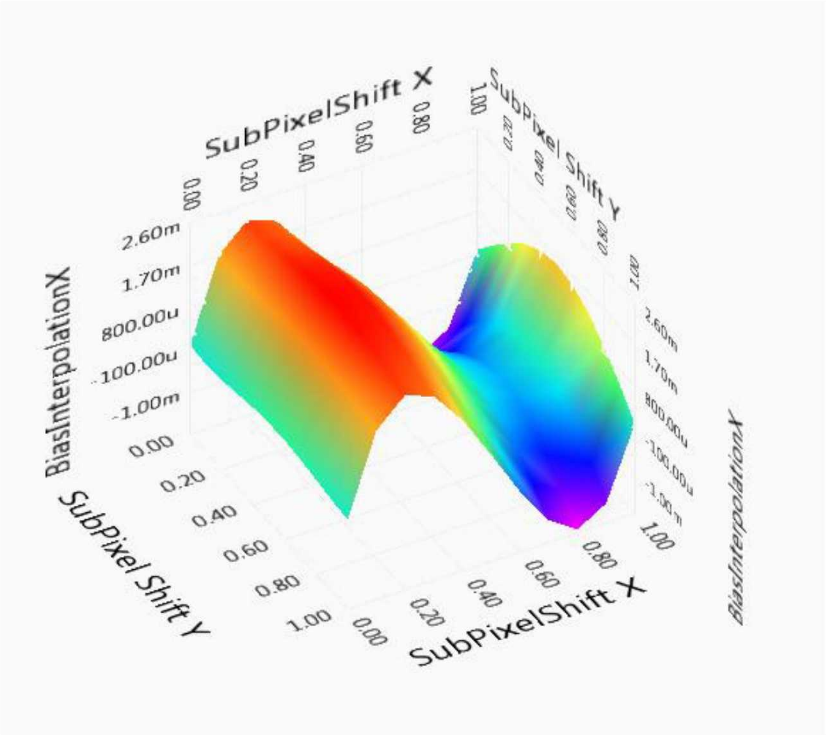
Tip 2.20 – Dark images may be OK.

Bias errors depend on the gradients within the *subsets* being matched

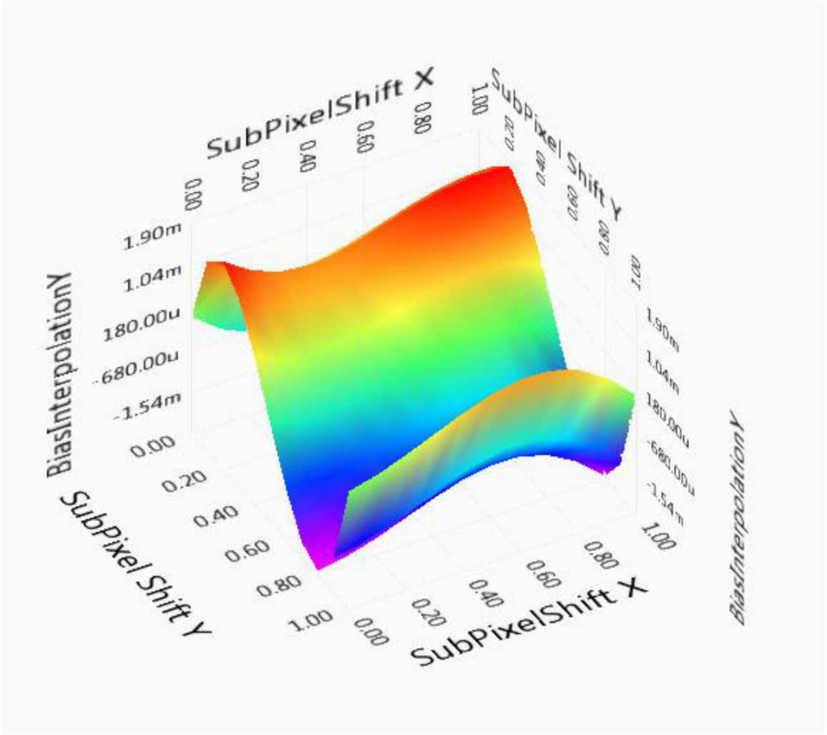


The matching is a 2D process

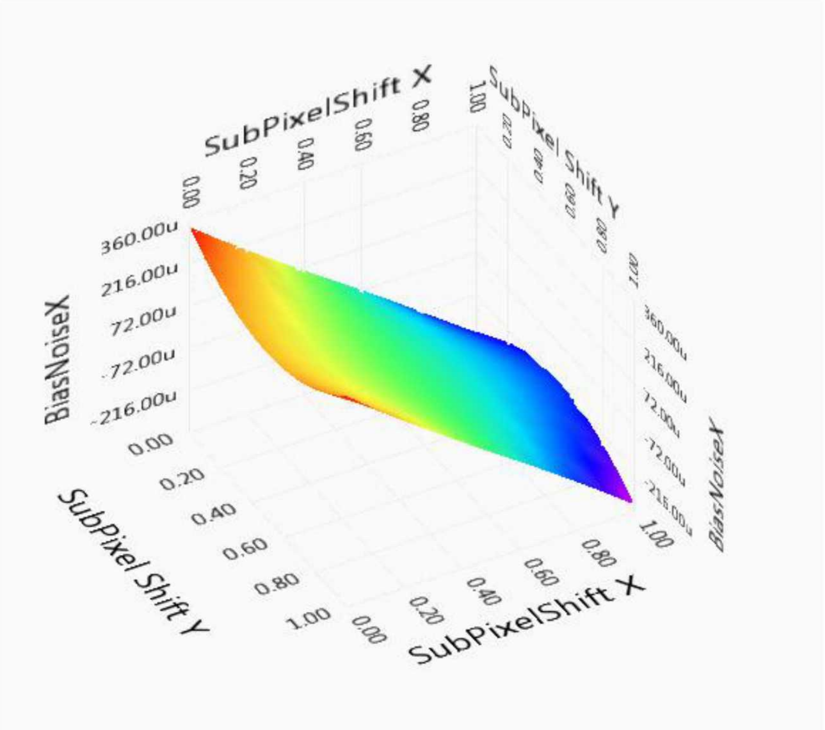




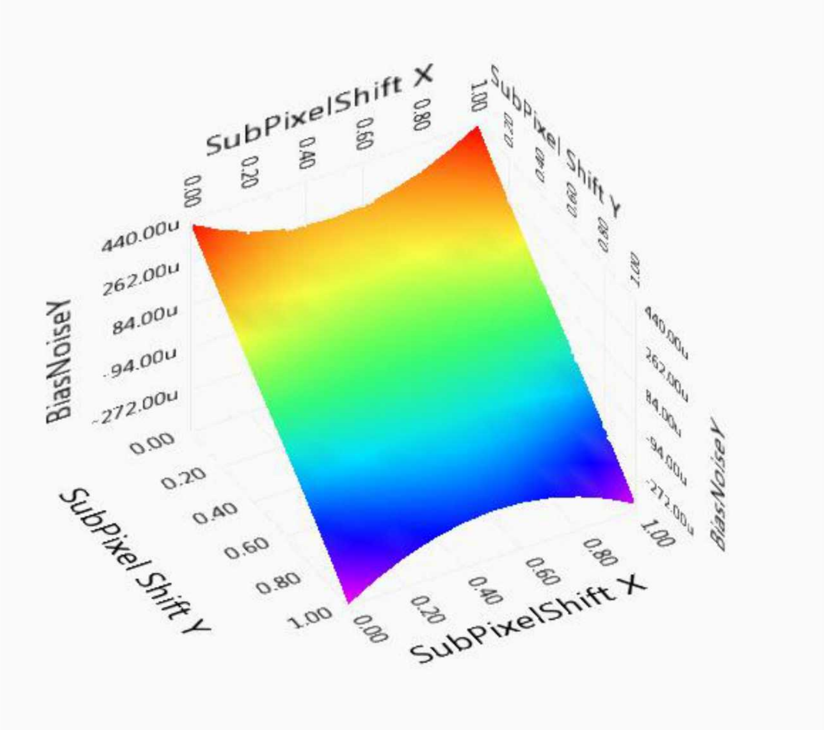
Bias Interpolation X



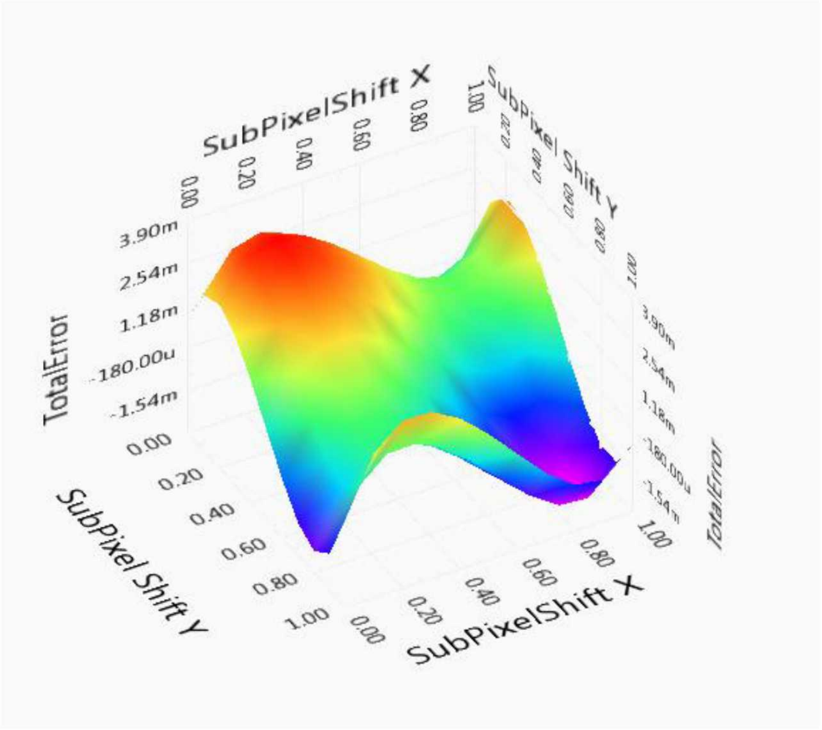
Bias Interpolation Y



Bias Noise X

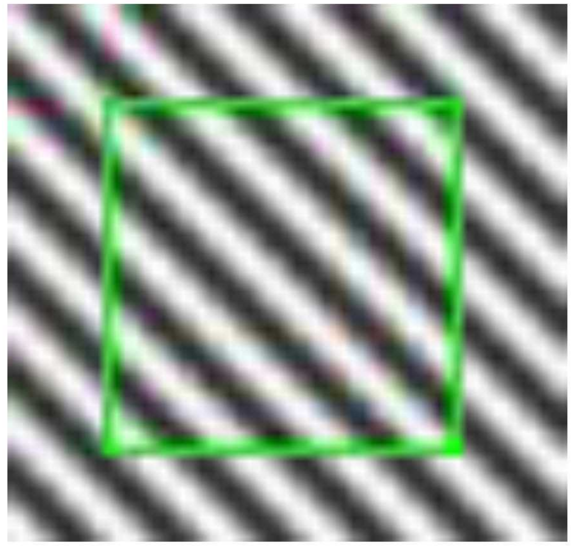


Bias Noise Y

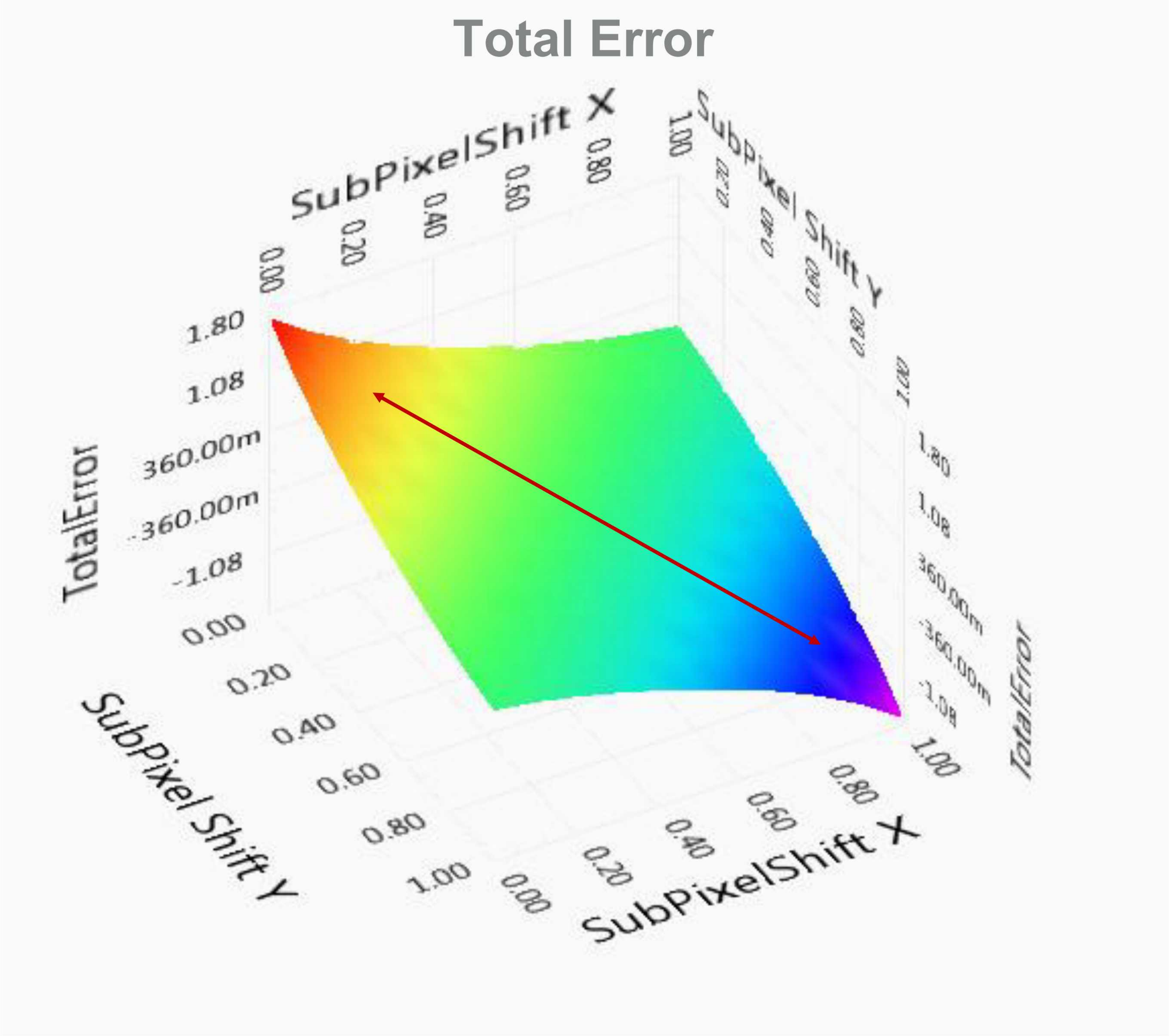


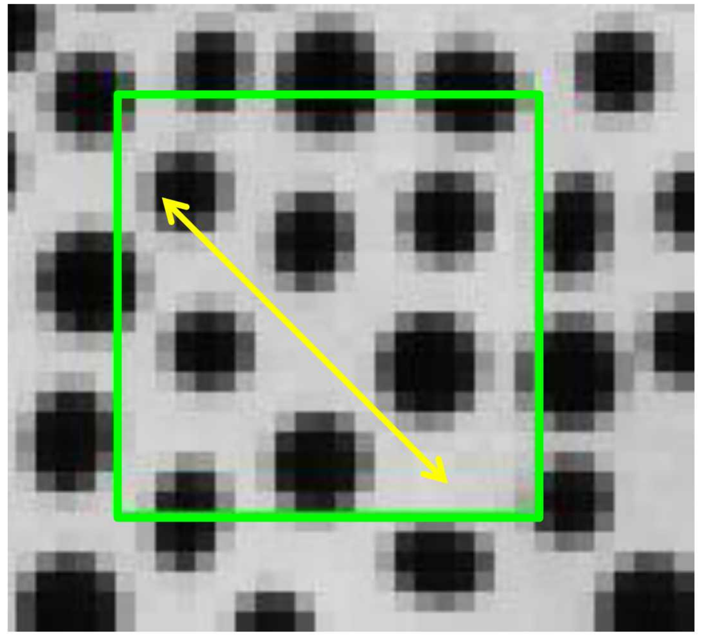
Total Error

Beware of directionality in your speckle patterns



Matching error



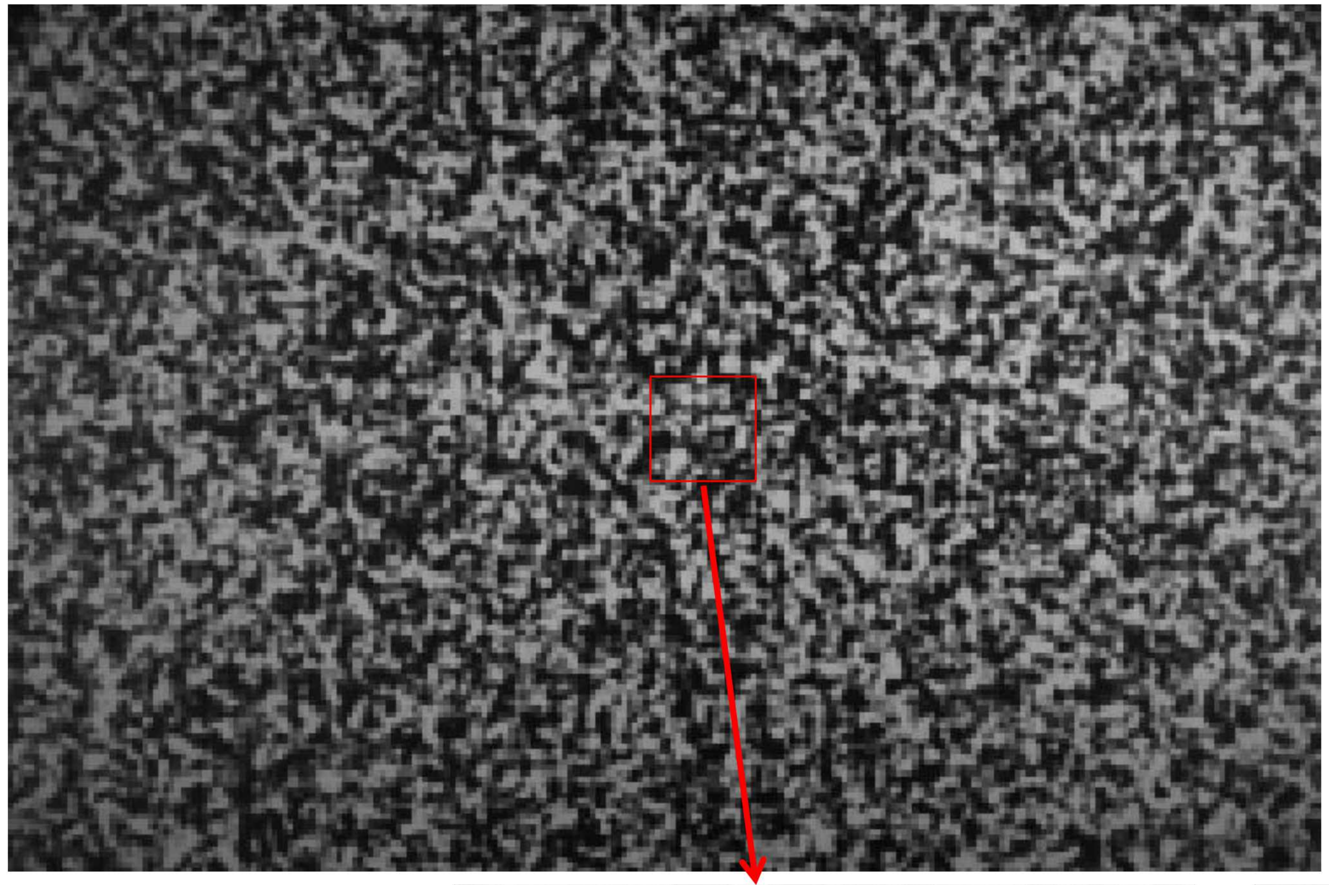


Must have gradients in all directions

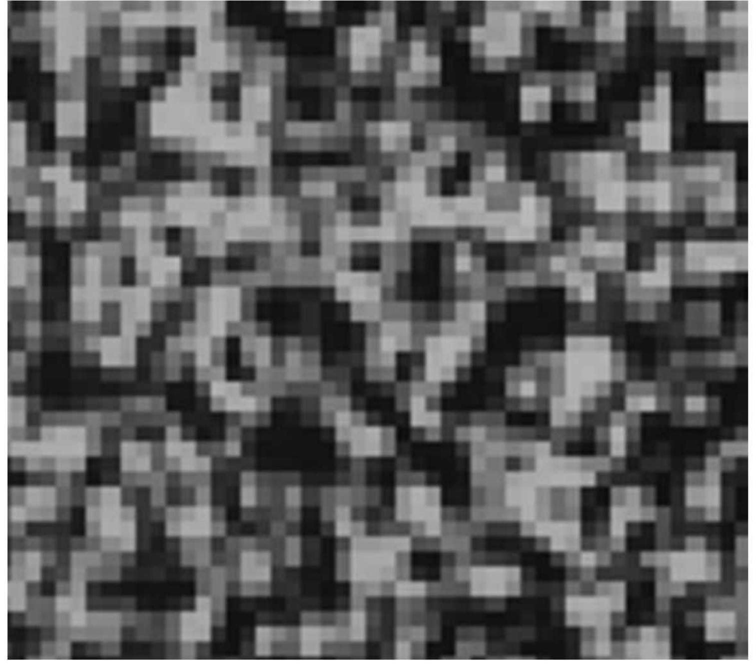
WHEN PATTERNS ARE TOO SMALL.

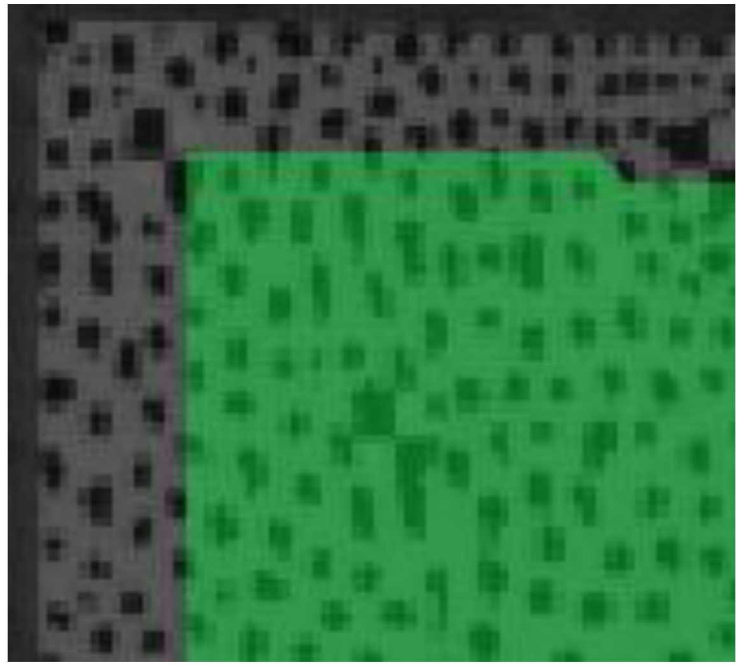
VERY, VERY BAD. ALIASING AND RELATED ISSUES AND THE EFFECT ON THE INTERPOLANT.

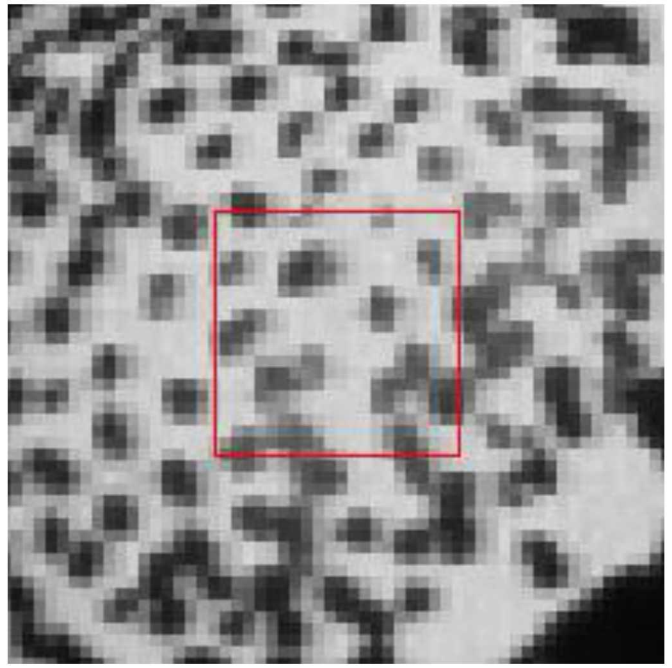
Undersized Patterns (< 3 pixels) lead to aliasing and will compromise the results!

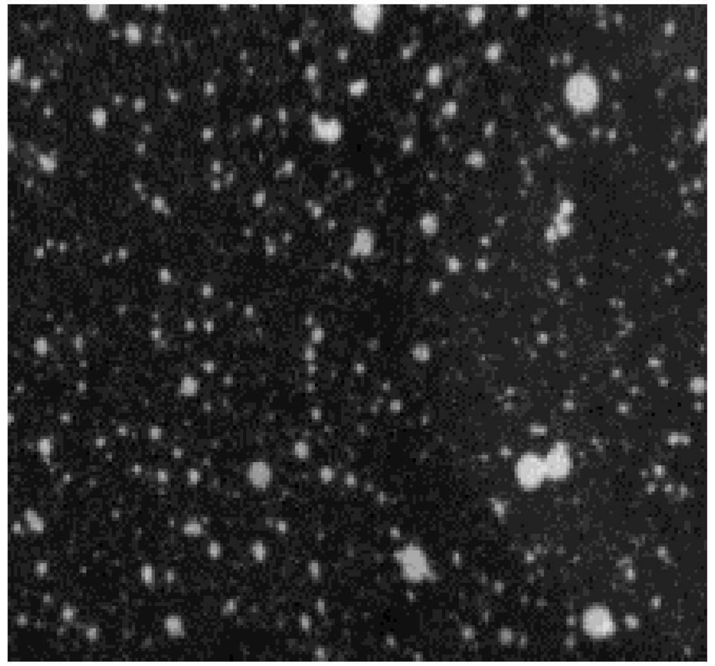


- Aliasing is probably one of the biggest problems in practice, and one of the hardest to detect.
- Your Patterns should be clearly distinguished.
- Patterns must be 3-5 pixels.
- Spray paint often has issues with small dots.

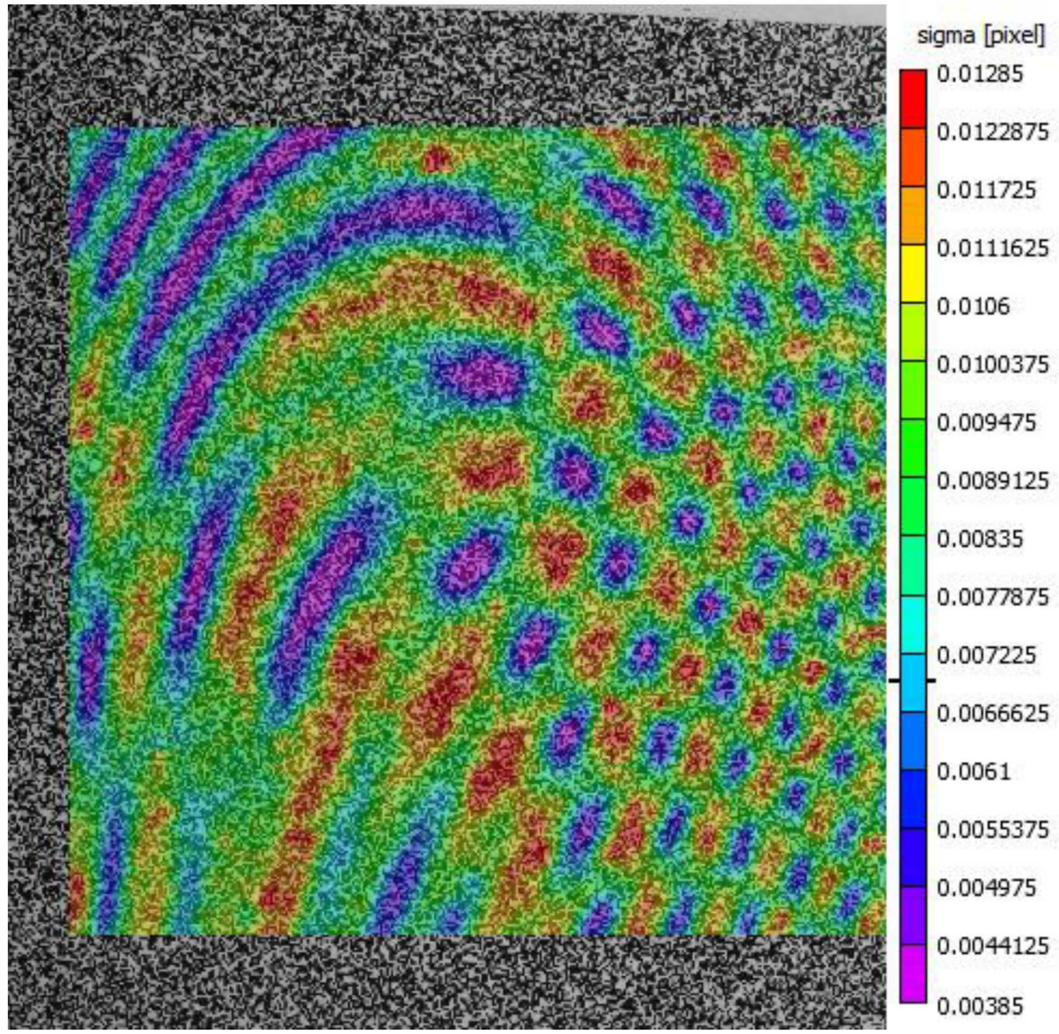




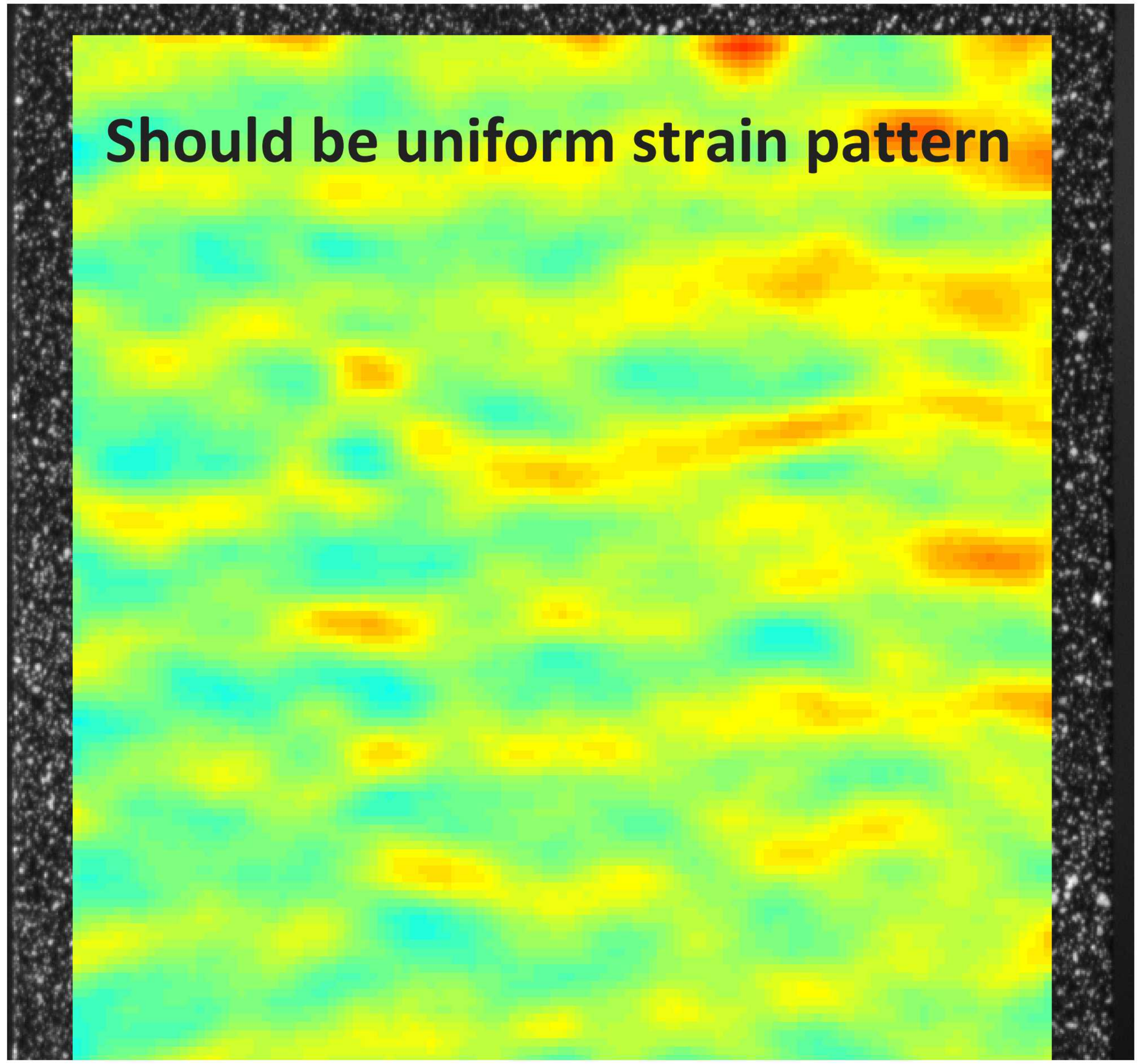




Aliasing is easily seen in the results by looking for “banding”



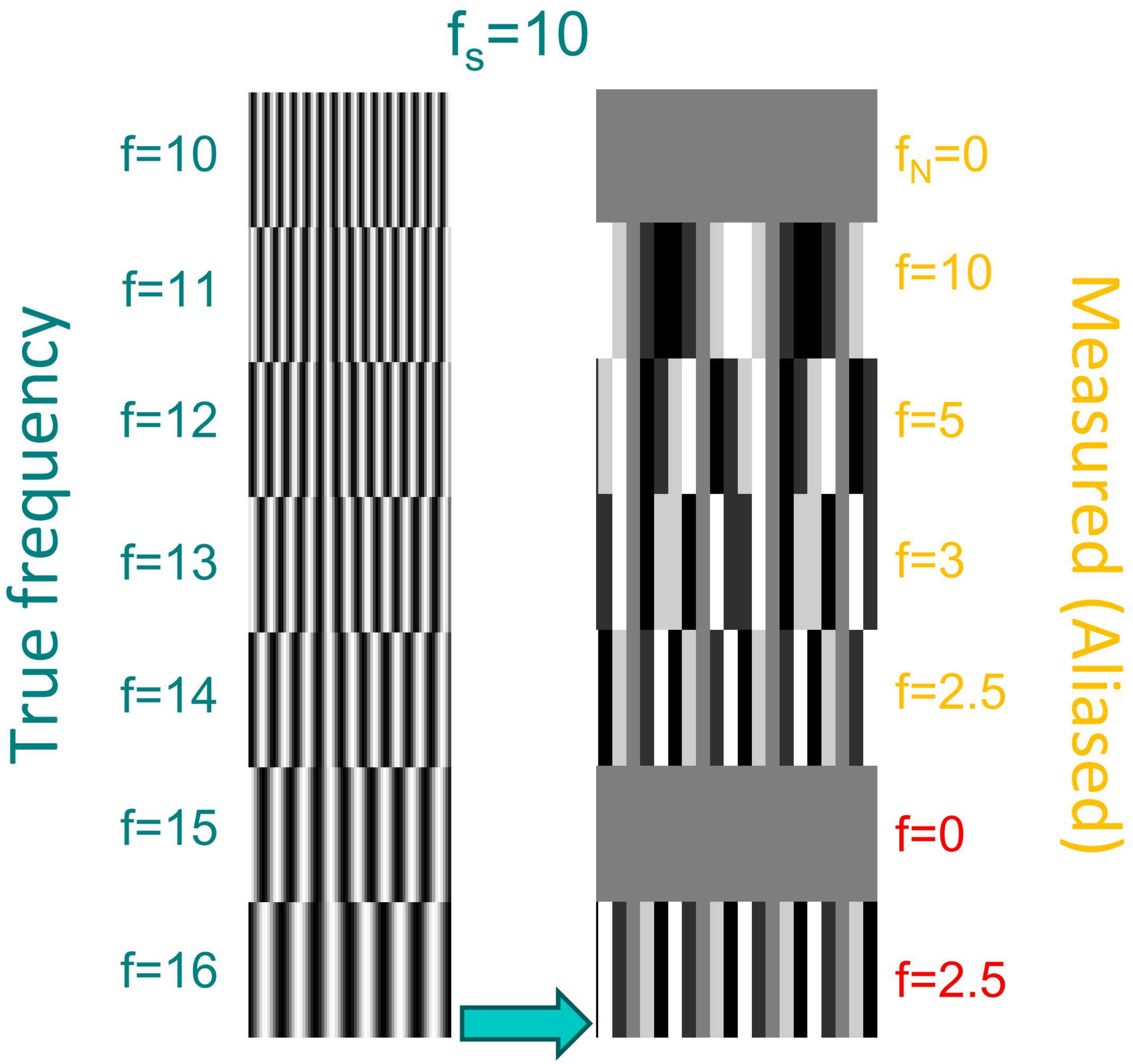
Most easily seen in the matching error sigma

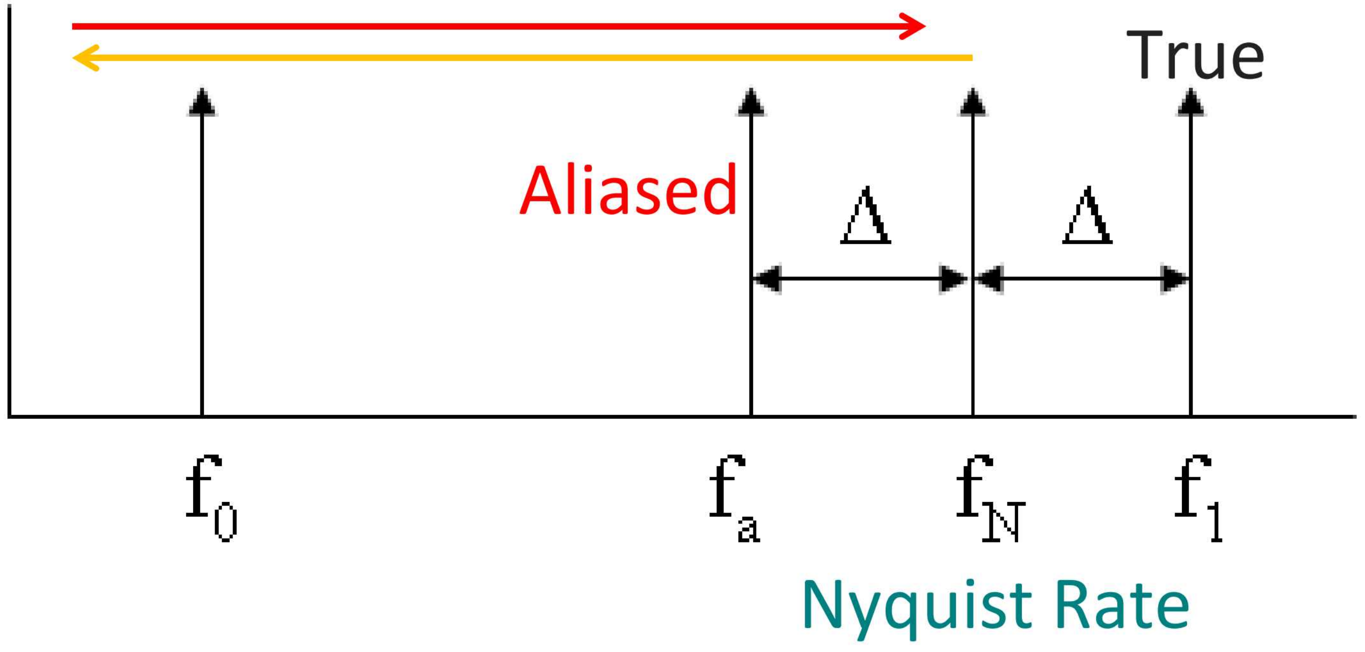


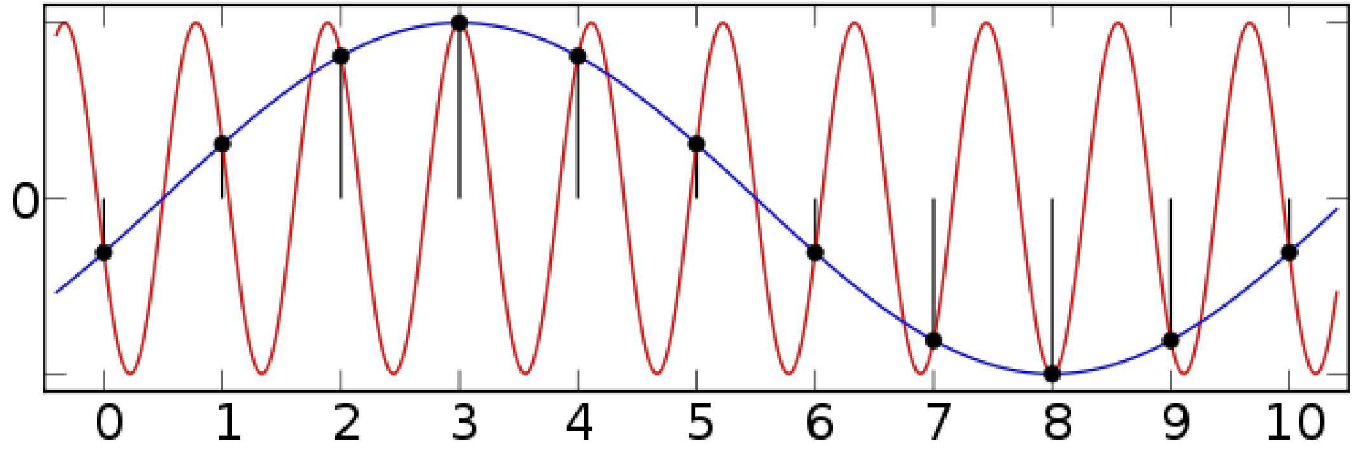
Should be uniform strain pattern

Aliasing will give incorrect frequencies when sampled below the Nyquist rate.

Sampled by CCD with spacing of 10 units.

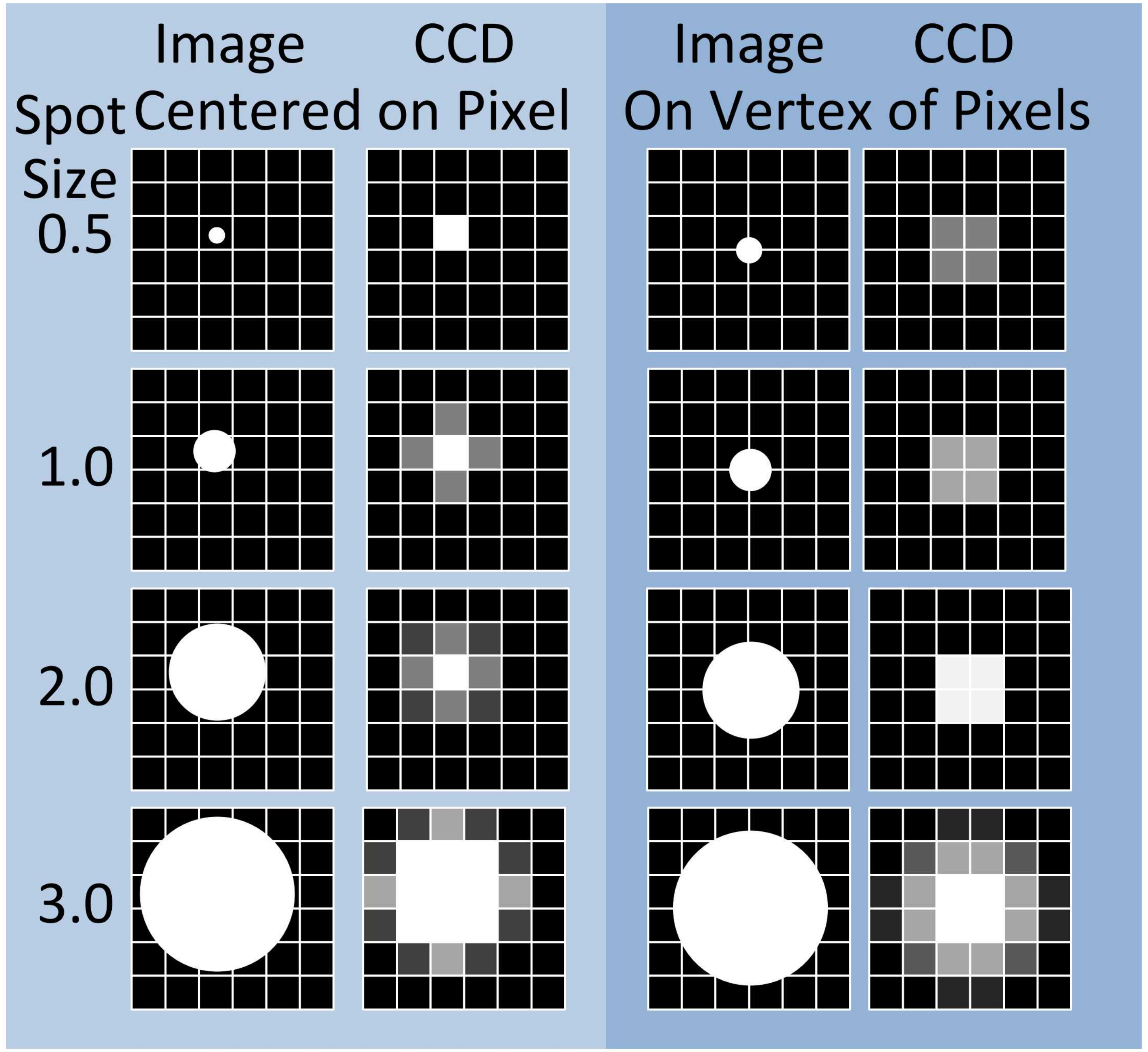






Nyquist: $f_s \geq 2\, f_{max}$

A physical interpretation of aliasing on the grey values of a pixel.



http://www.andor.com/learning/digital_cameras/?docid=319

● Represents a single Pattern

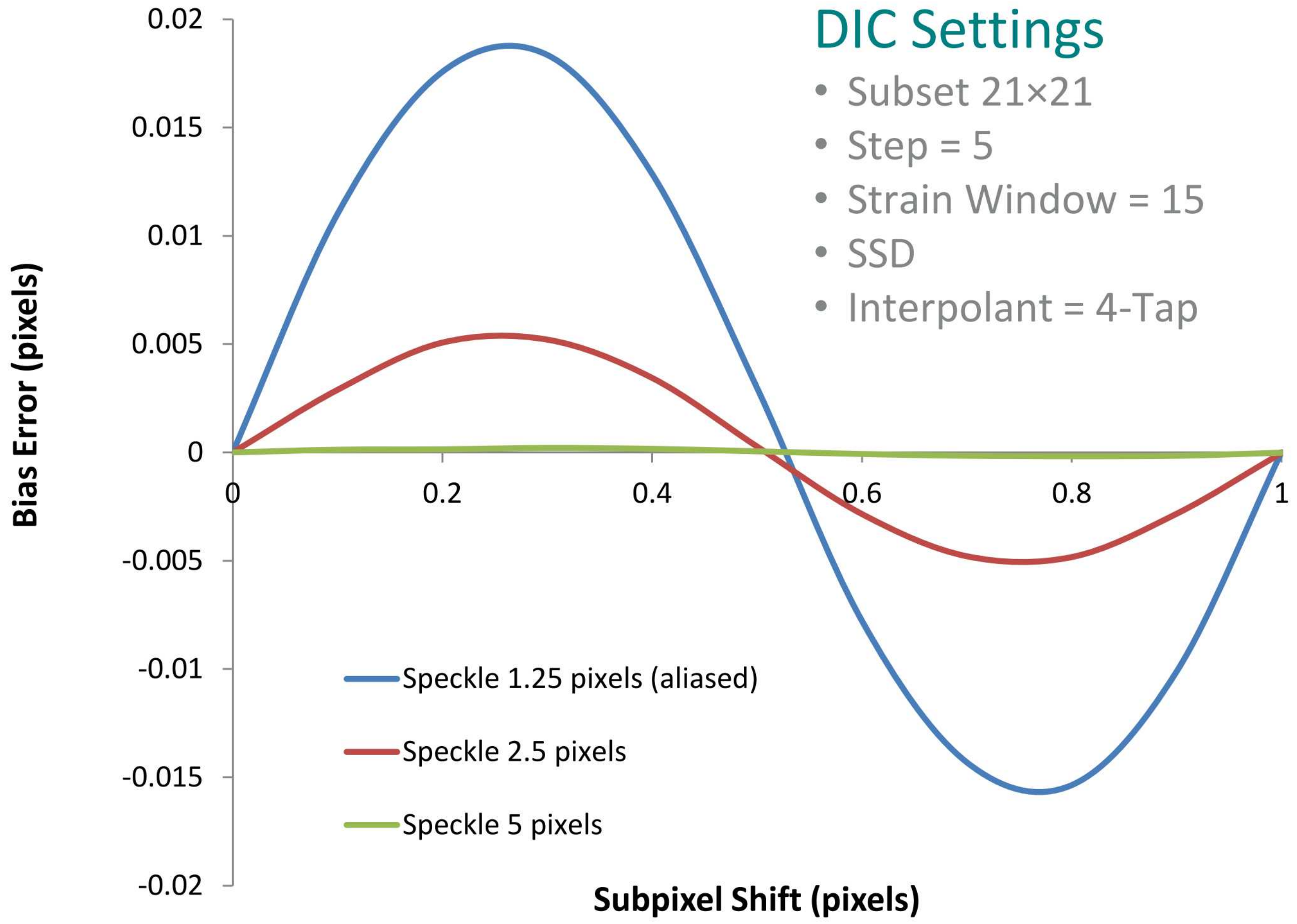
With an aliased Pattern, the pixel no longer "localizes" the pattern!

$$MTF_{CCD} = \frac{1}{2p}(lp/mm)$$

p = pixel size in mm

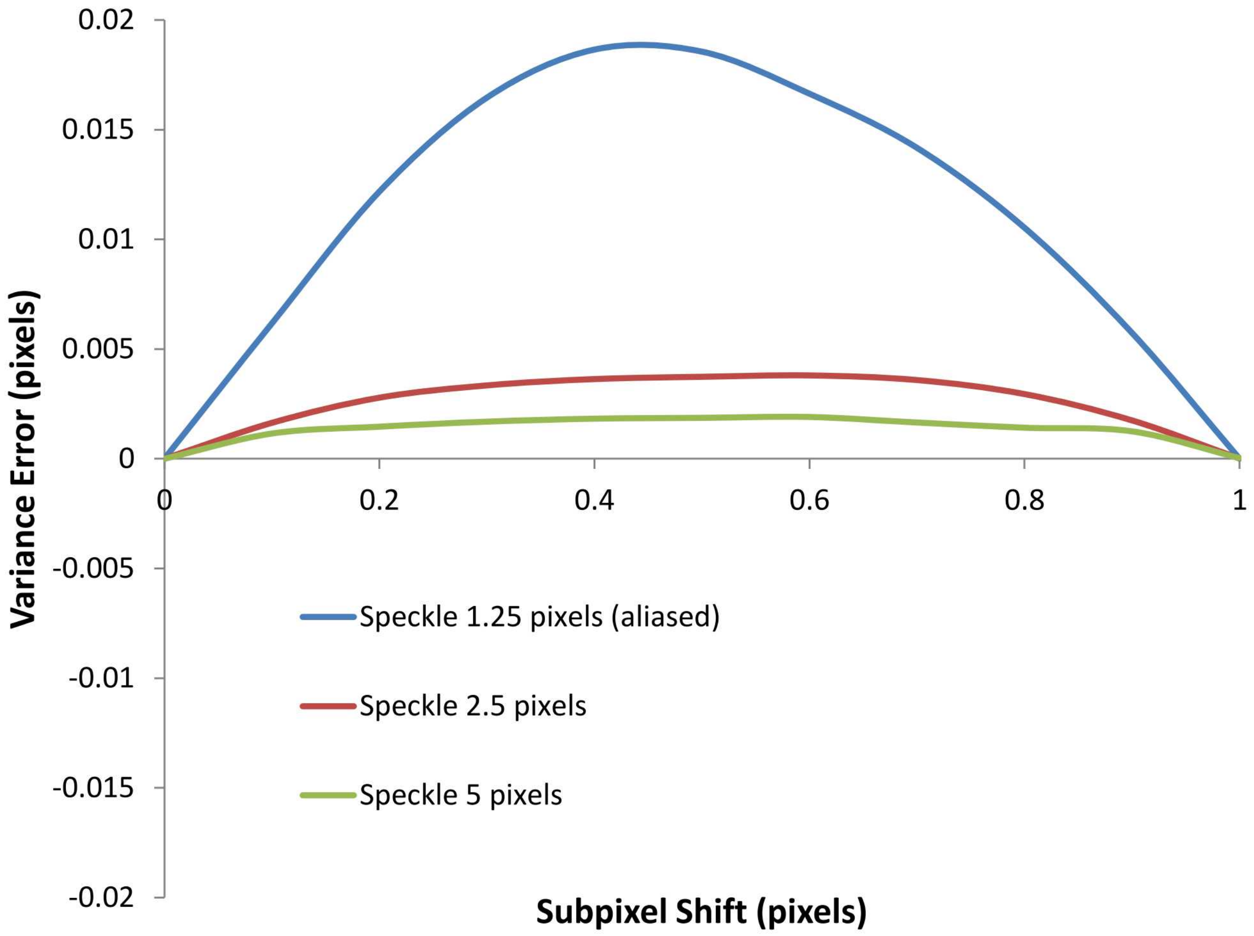
iDICs

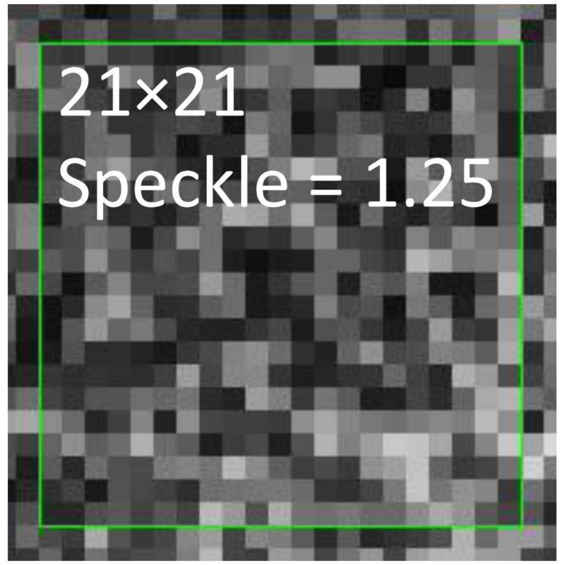
Interpolant bias error will increase with aliased speckles. Some interpolants more than others…

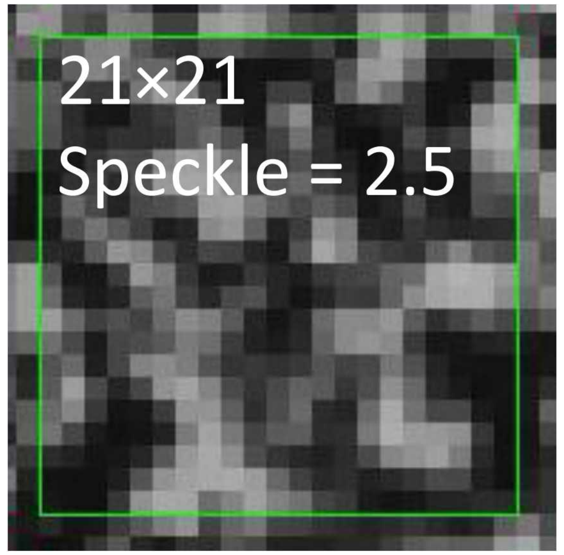


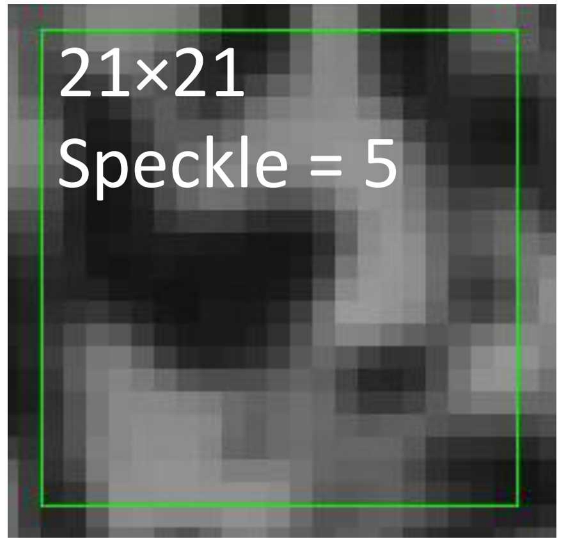
DIC Settings

- Subset 21×21
- Step = 5
- Strain Window = 15
- SSD
- Interpolant = 4-Tap









Maximum strain variance

	ε_{xx} (με)	ε_{yy} (με)
1.25 pixels	434	282
2.5 pixels	78	29
5 pixels	29	25

Spatial anti-aliasing in a camera is an *analog* blur filter.

Antialiasing filters in digital cameras

- Most machine vision cameras *do not* have anti-aliasing
- Uses birefringence to crystals (lithium niobate) to blur the image.
- Must be done in analog. Once digitized anti-aliasing is not possible.
- Lens may also help with filtering of the image.

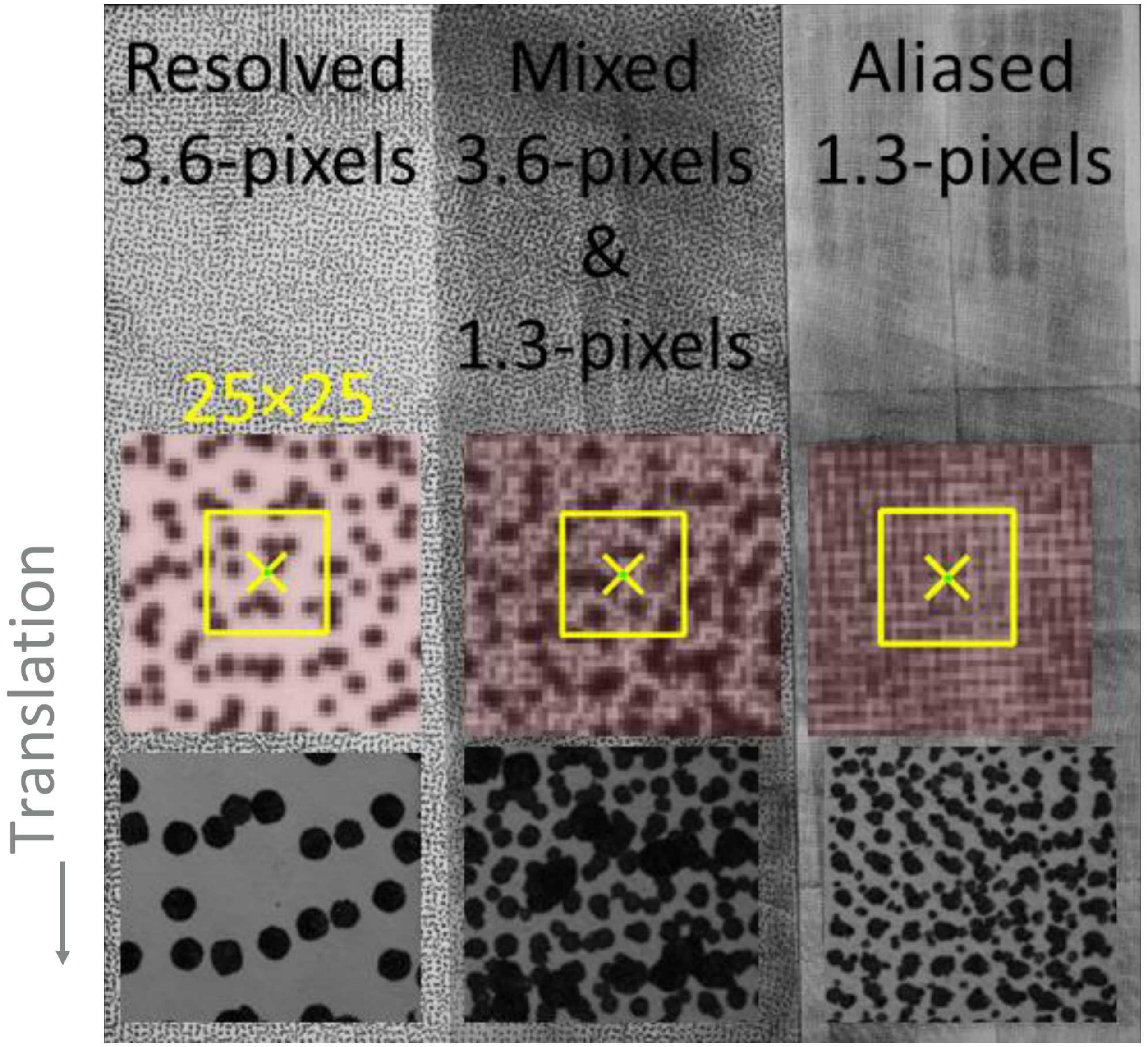
Ma T, Reeves SJ; Adaptive image acquisition by autodefocusing. J. Electron. Imaging. 0001;20(3):033013-033013-10. doi:10.1117/1.3624489.

iDICs

Recommendation 5.1 – With physical filter don’t use digital filtering.

Tip 5.2 – Analog anti-aliasing

Experimental setup combined 3 cameras with an out-of-plane translation to apply a uniform strain.



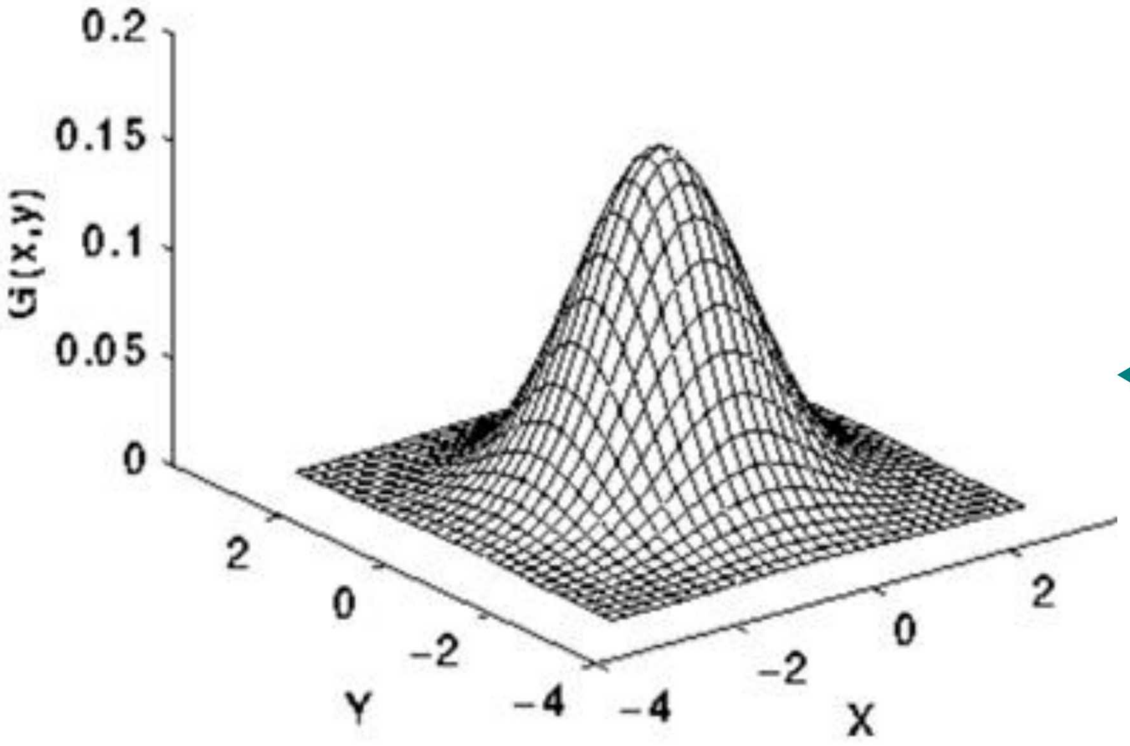
DIC Settings

- Subset 25×25
- Step = 10
- Strain Window = 15
- SSD
- Interpolant (varies)

Image pre-filtering: A growing body of literature suggests this is a good idea.

- Replace central pixel value by weighted average of neighboring pixels
- Removes outliers, low pass filter, tuning parameter: kernel

5 × 5 Gaussian Filter Kernel is convolved with the image.

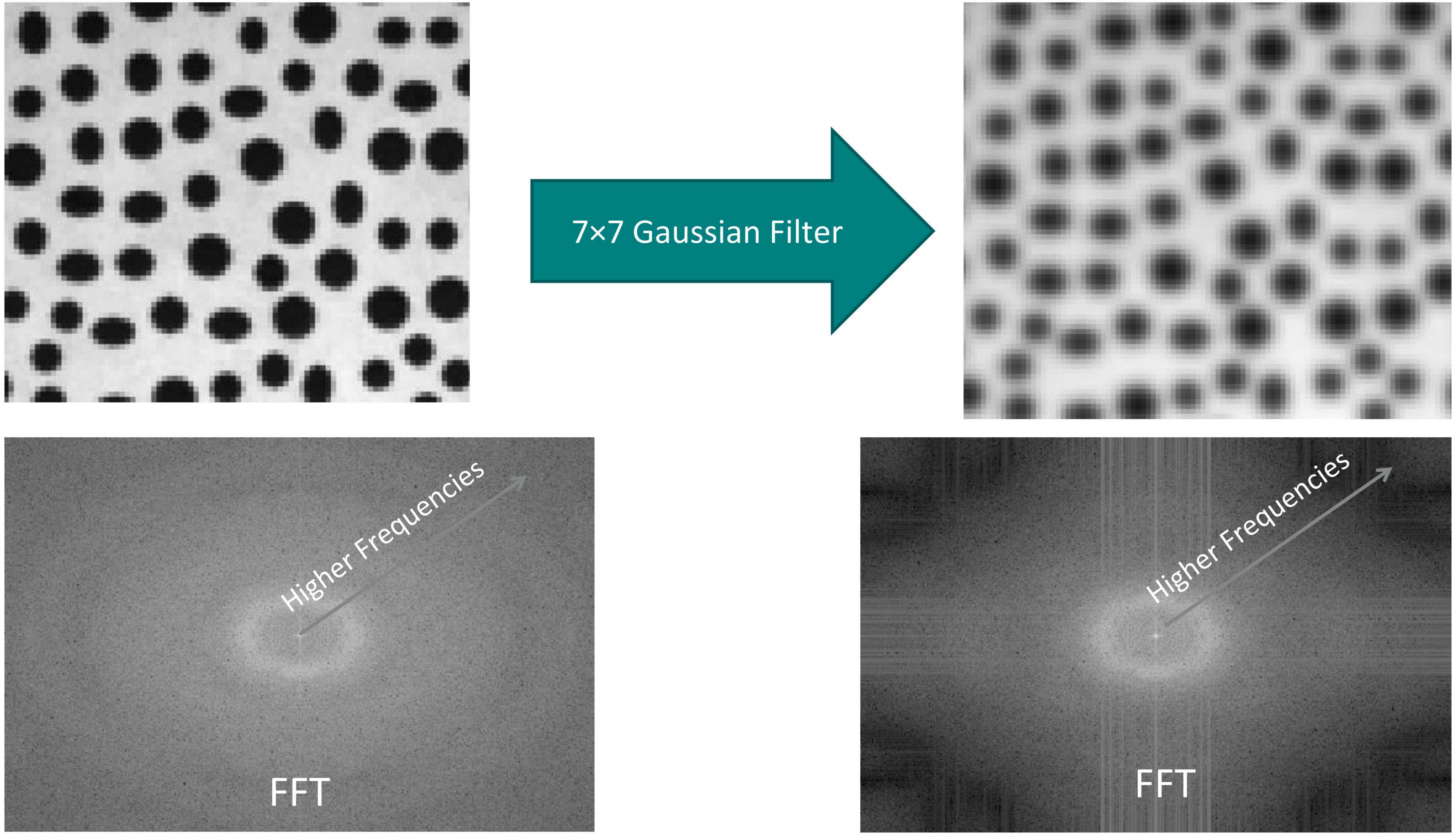


$\frac{1}{273}$

1	4	7	4	1
4	16	26	16	4
7	26	41	26	7
4	16	26	16	4
1	4	7	4	1

Pixel weighting

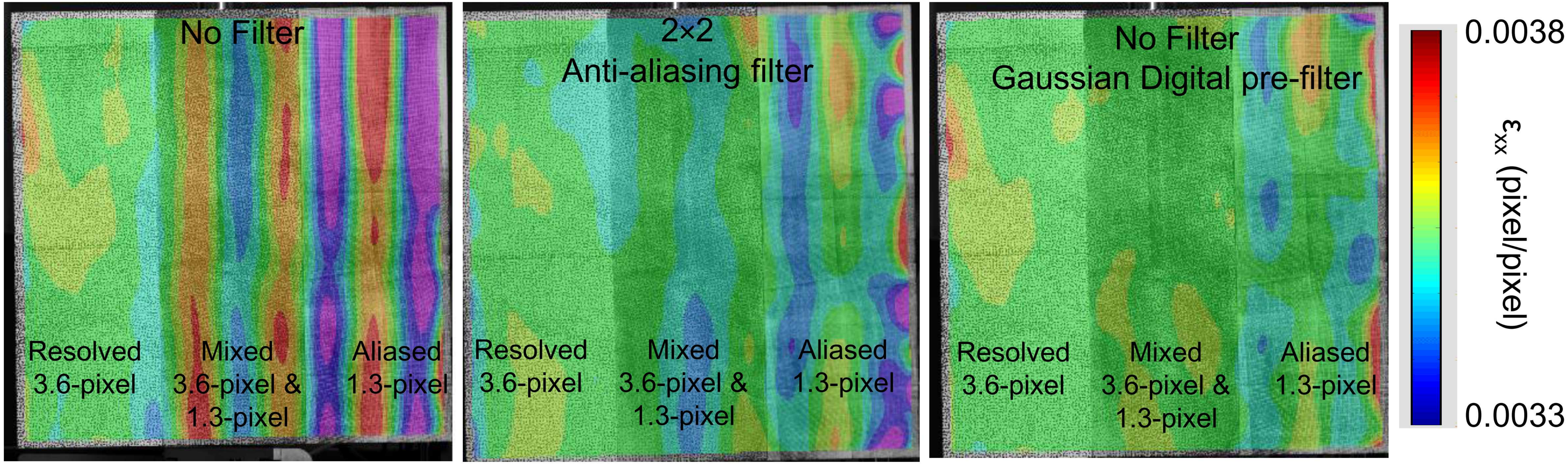
Gaussian filters remove high-frequency content (much of the aliasing).



Air turbulence and speckle aliasing are two largest error sources. (Camera Motion?)

DIC Settings

- Subset 21×21
- Step = 5
- Strain Window = 41
- ZNSSD
- Interpolant: 4-Tap



u-Displacement (1σ)

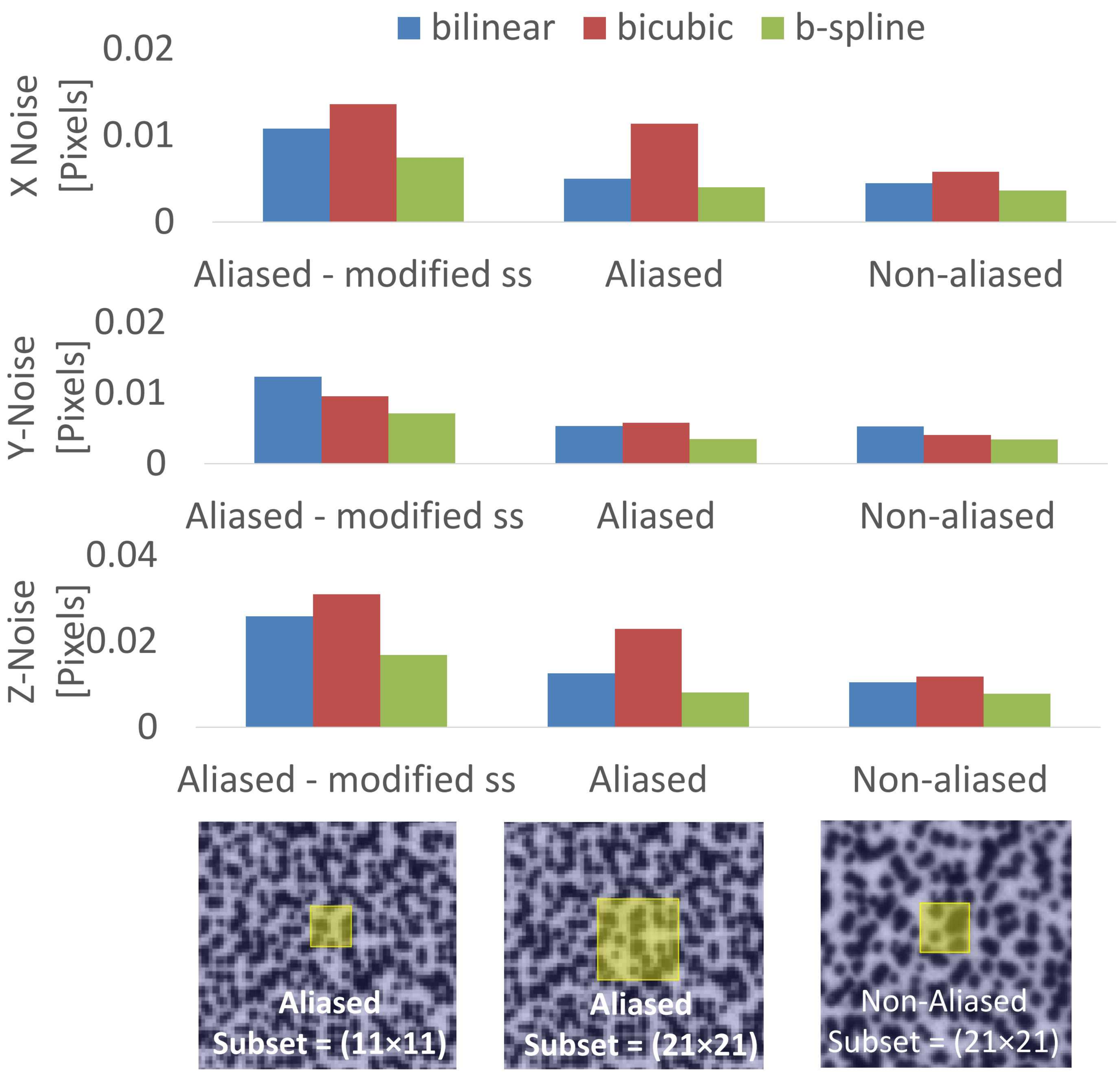
Filter	Good Speckle	Mixed Speckle	Aliased Speckle
None	0.0032	0.0088	0.0156
2×2	0.0036	0.0054	0.0127
Digital	0.0030	0.0038	0.0170

ε_1 (με)- 4-Tap Interpolant (1σ)

Filter	Good Speckle	Mixed Speckle	Aliased Speckle
None	44	94	139
2×2	40	67	117
Digital	41	31	88

Tip 5.2 – Low-pass filters mitigate aliased patterns.

Simulated results prove the same thing: Aliased speckles degrade the results.



Effects of Aliasing

- “Noise” increases
- Smaller subset makes things much worse
- Interpolant choice has a large impact

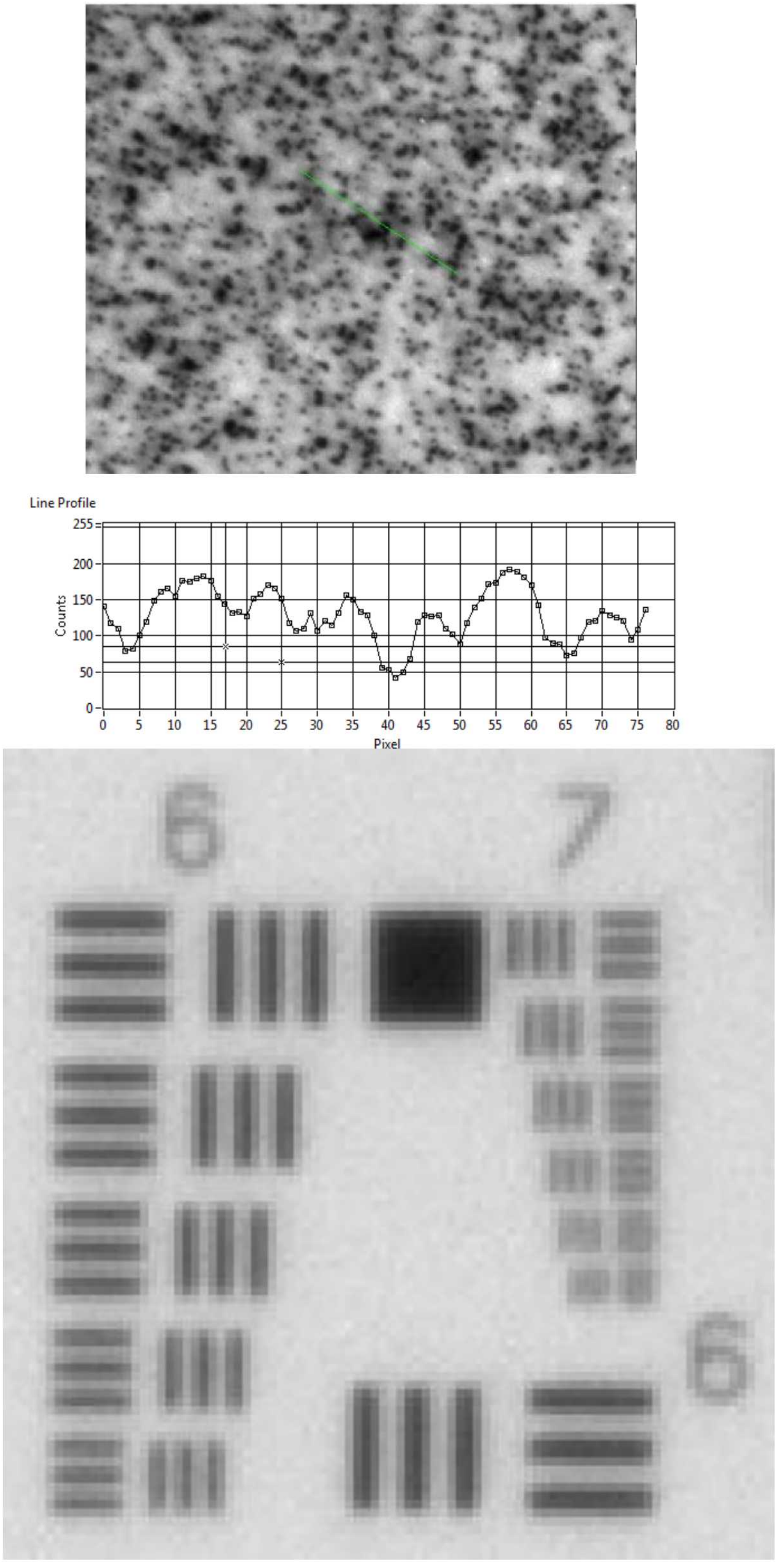
Stereo-simulator synthetic image information

- Dog-bone tensile test
- 1 Count noise (0.39%)
- FOV ± 150 × 200 mm
- 30-mm lens – no lens distortions, perfect calibration
- Optimum is 3-5 pixels per speckle.

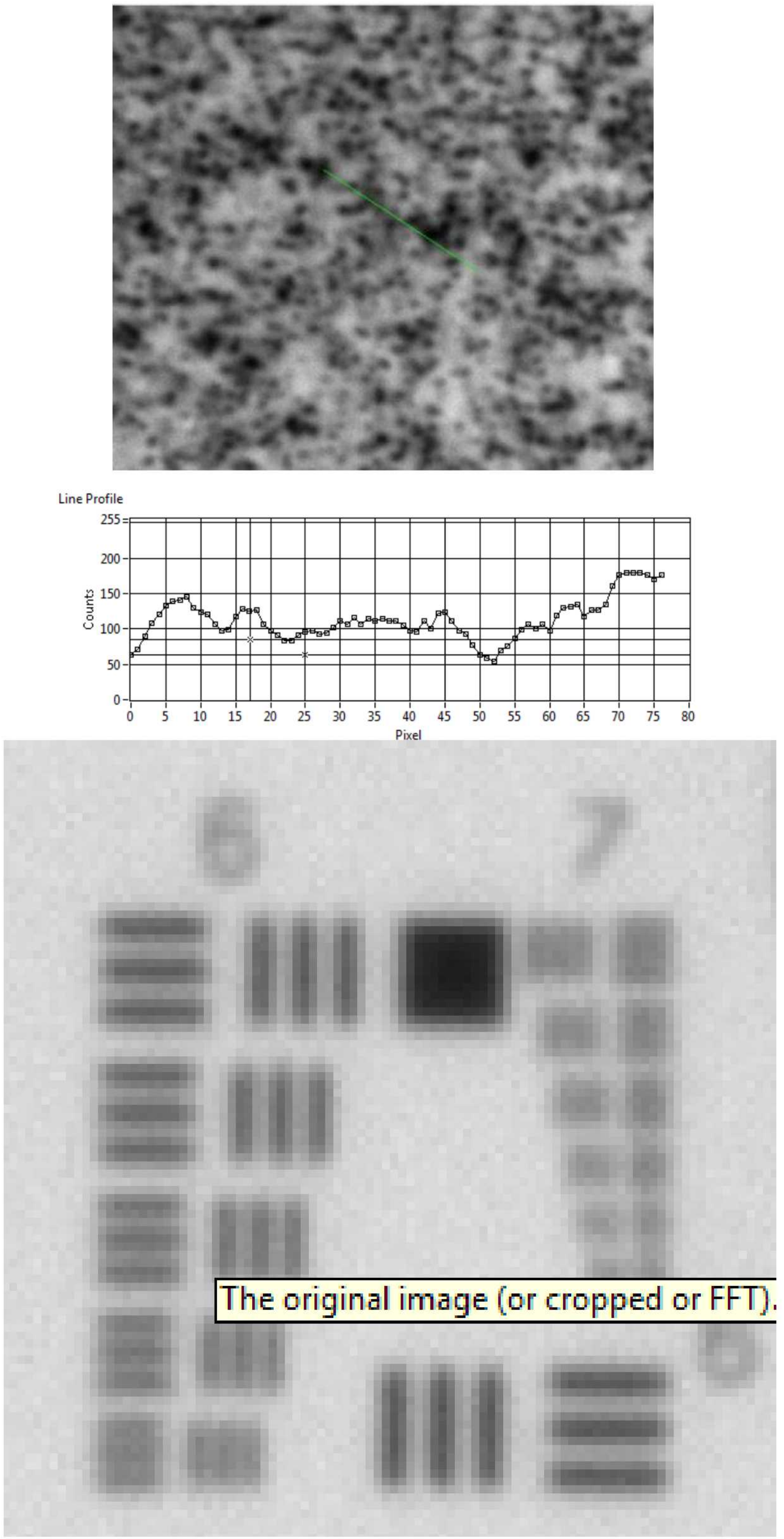
Courtesy Ruben Balcaen – KU Leuven PhD Student

Camera and lens resolution will control the required pattern size.

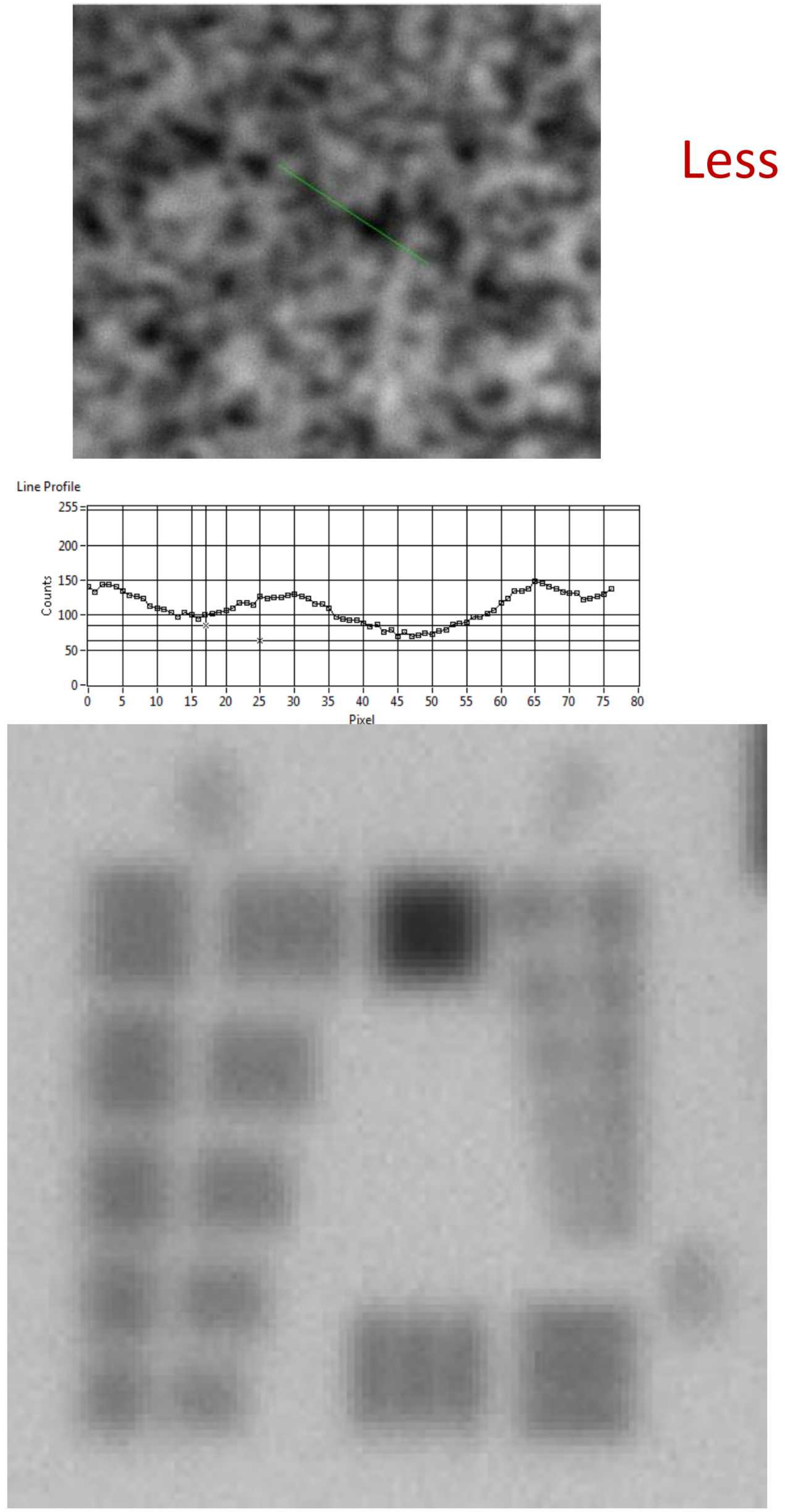
F1.9 - 64.7% Contrast



F8 - 53.8% Contrast



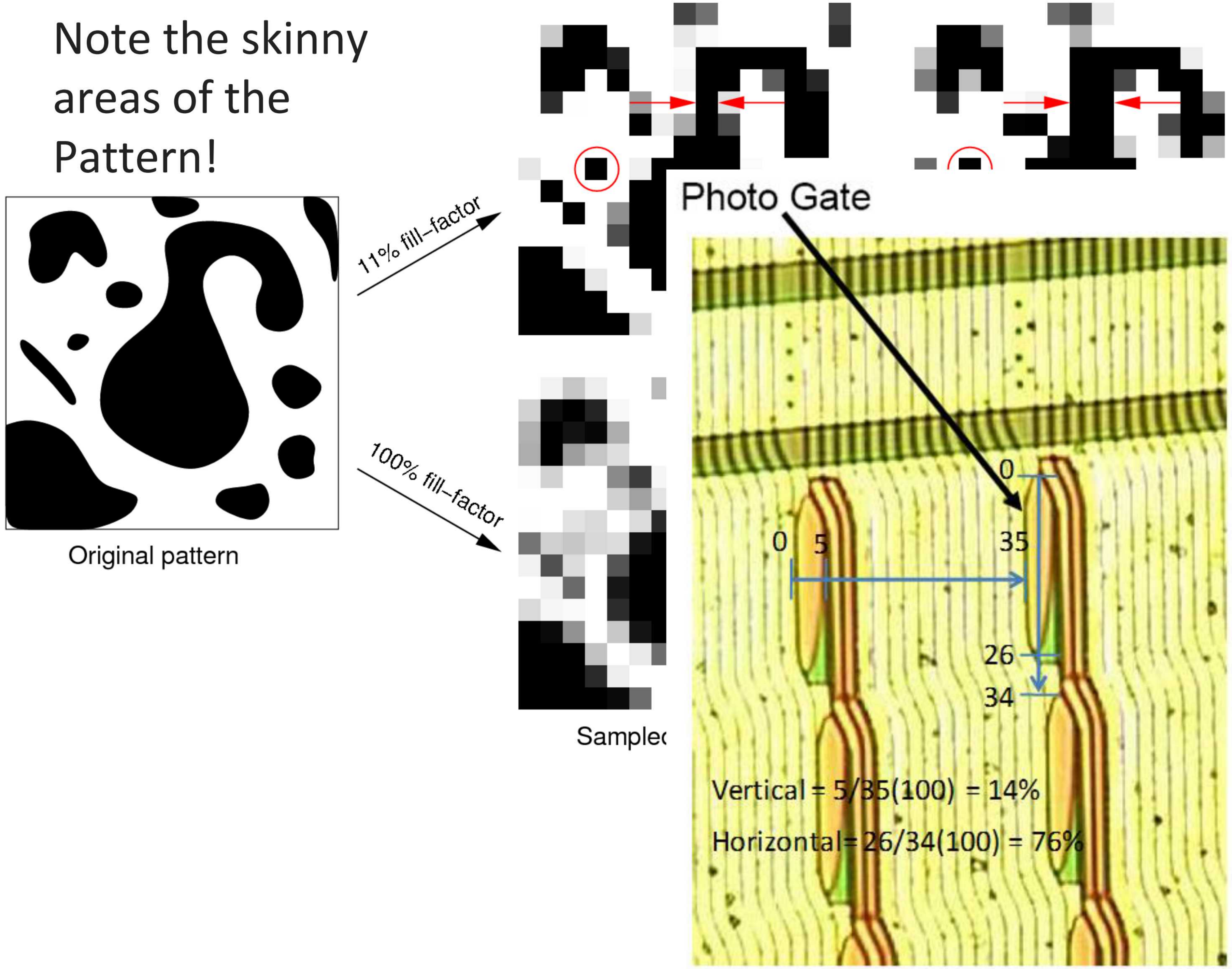
F16 - 36.4% Contrast



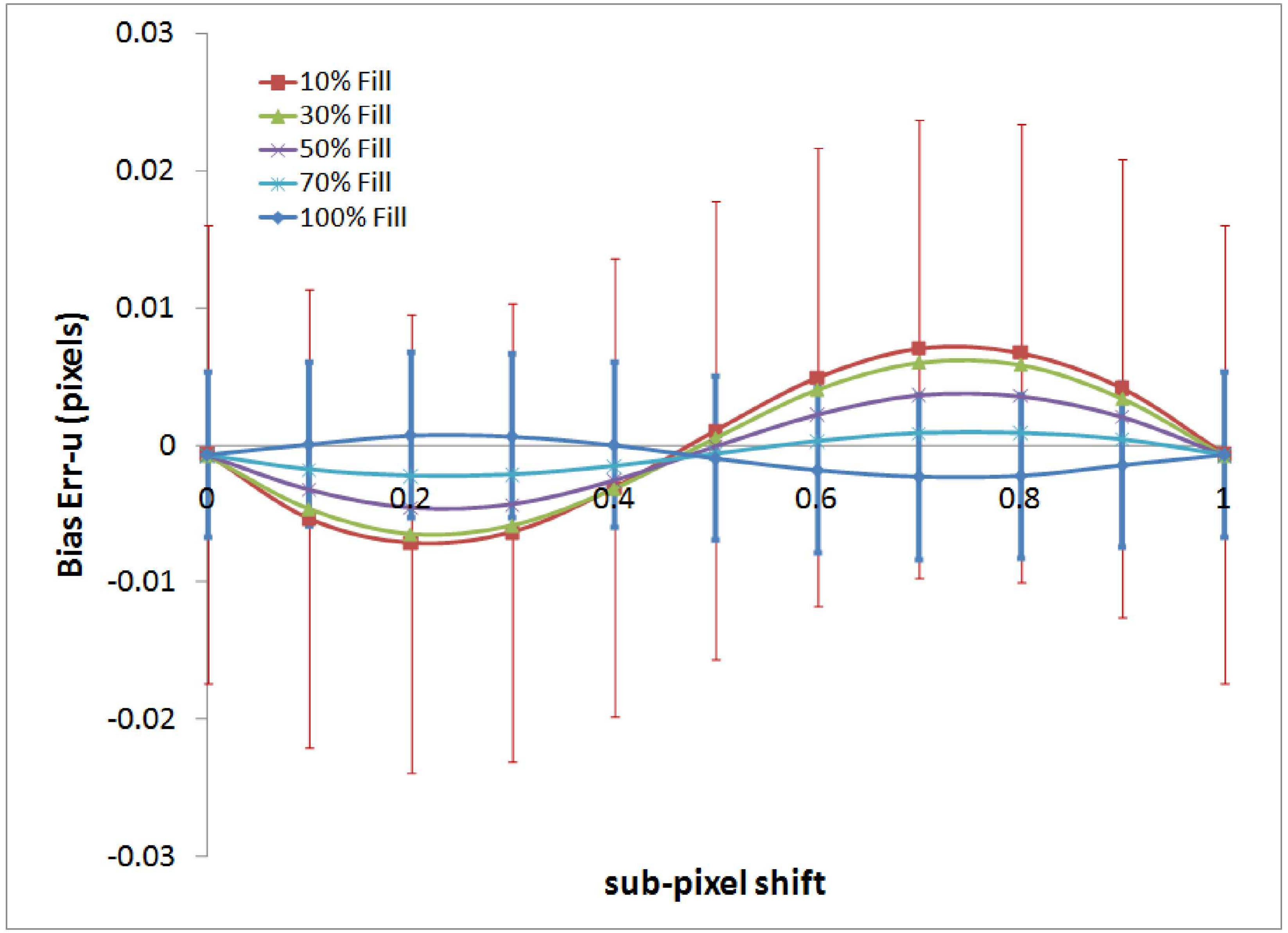
Less common: Lens limited

Pixel low fill-factor will cause aliasing like issues.

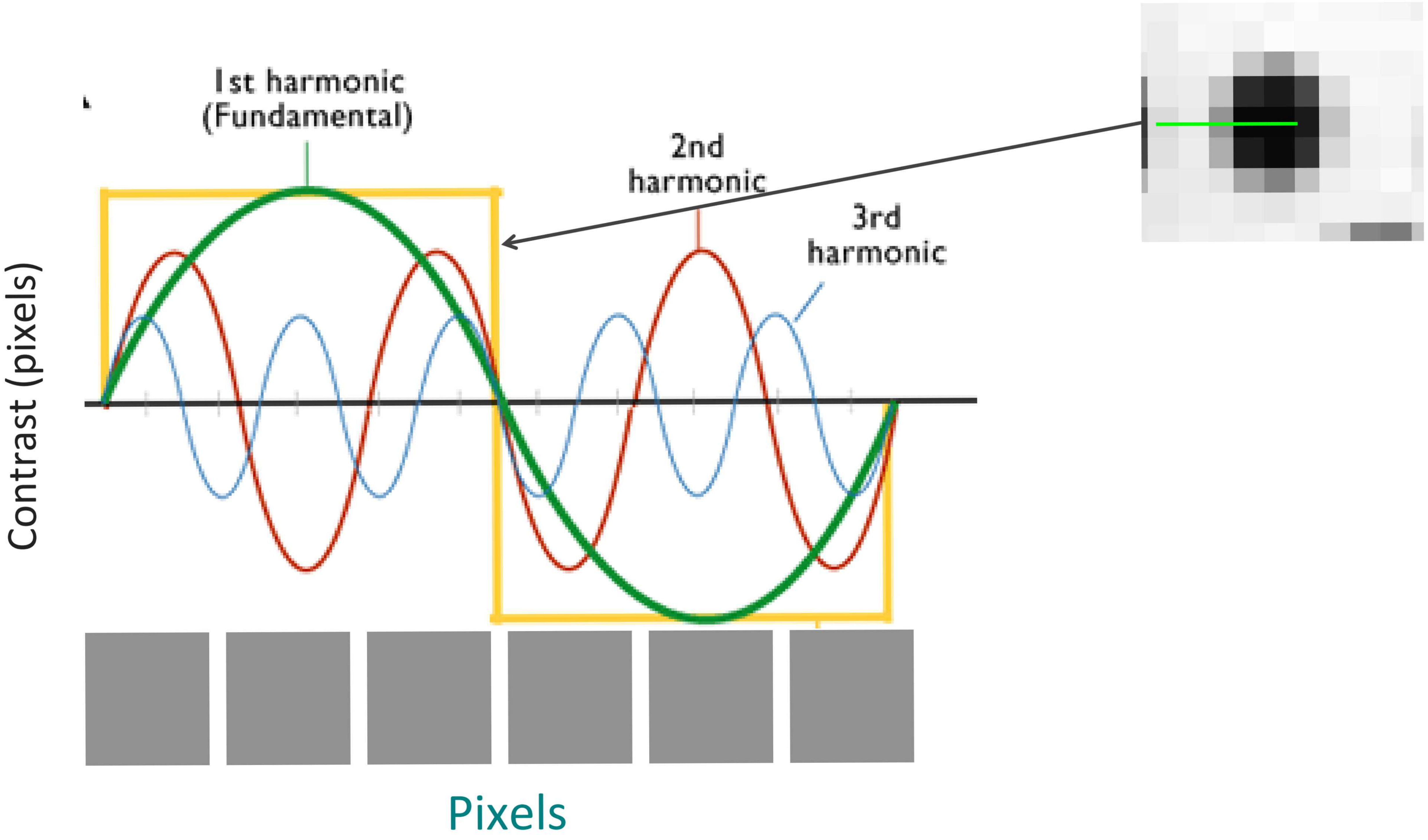
Note the skinny areas of the Pattern!



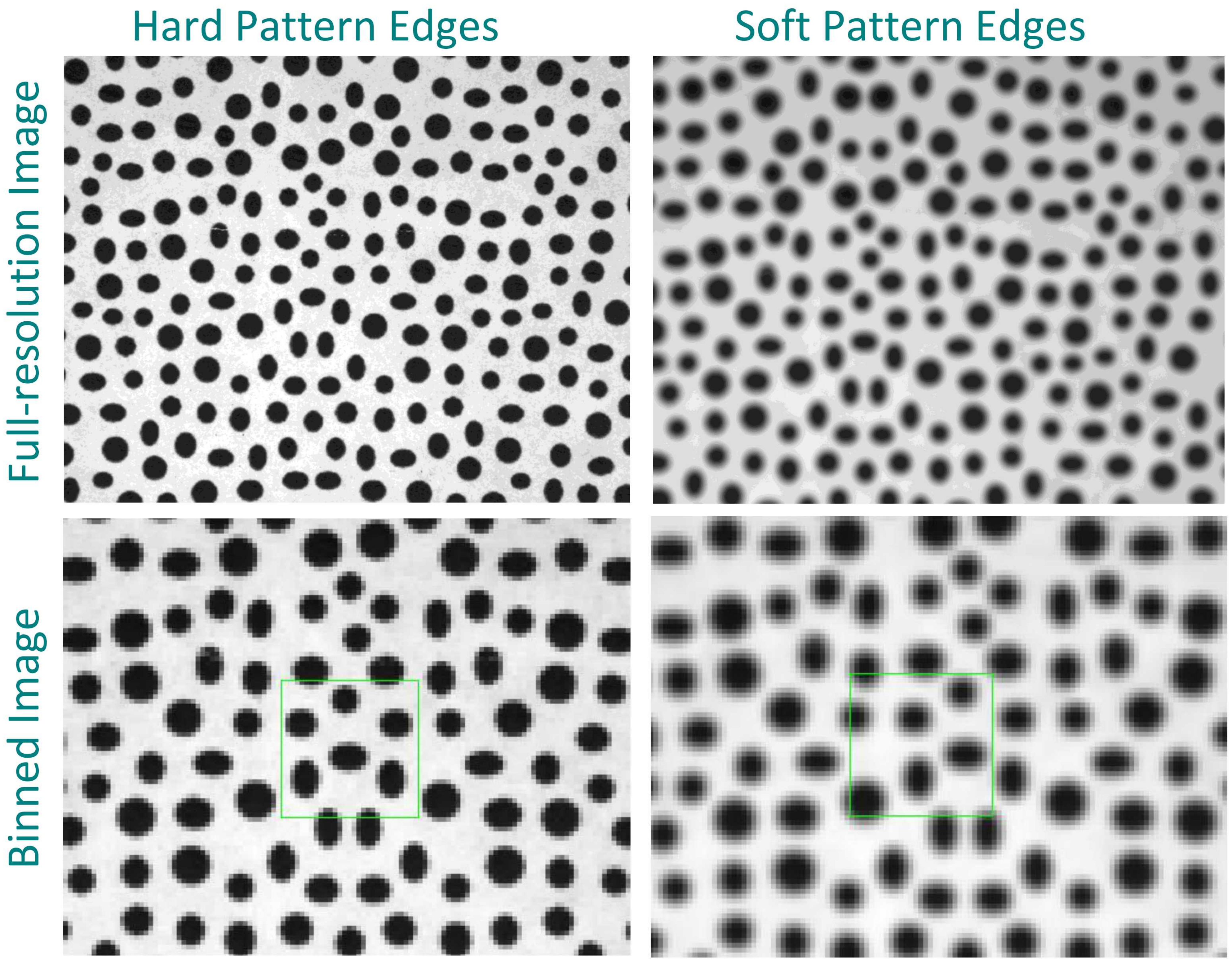
Micrograph of IS-CCD



The real problem with sharp edges is likely the aliasing effect of sampling a square wave.



What should your Patterns look like?



For 2D you can digitally filter the images to create your soft edges (or defocus the lens)

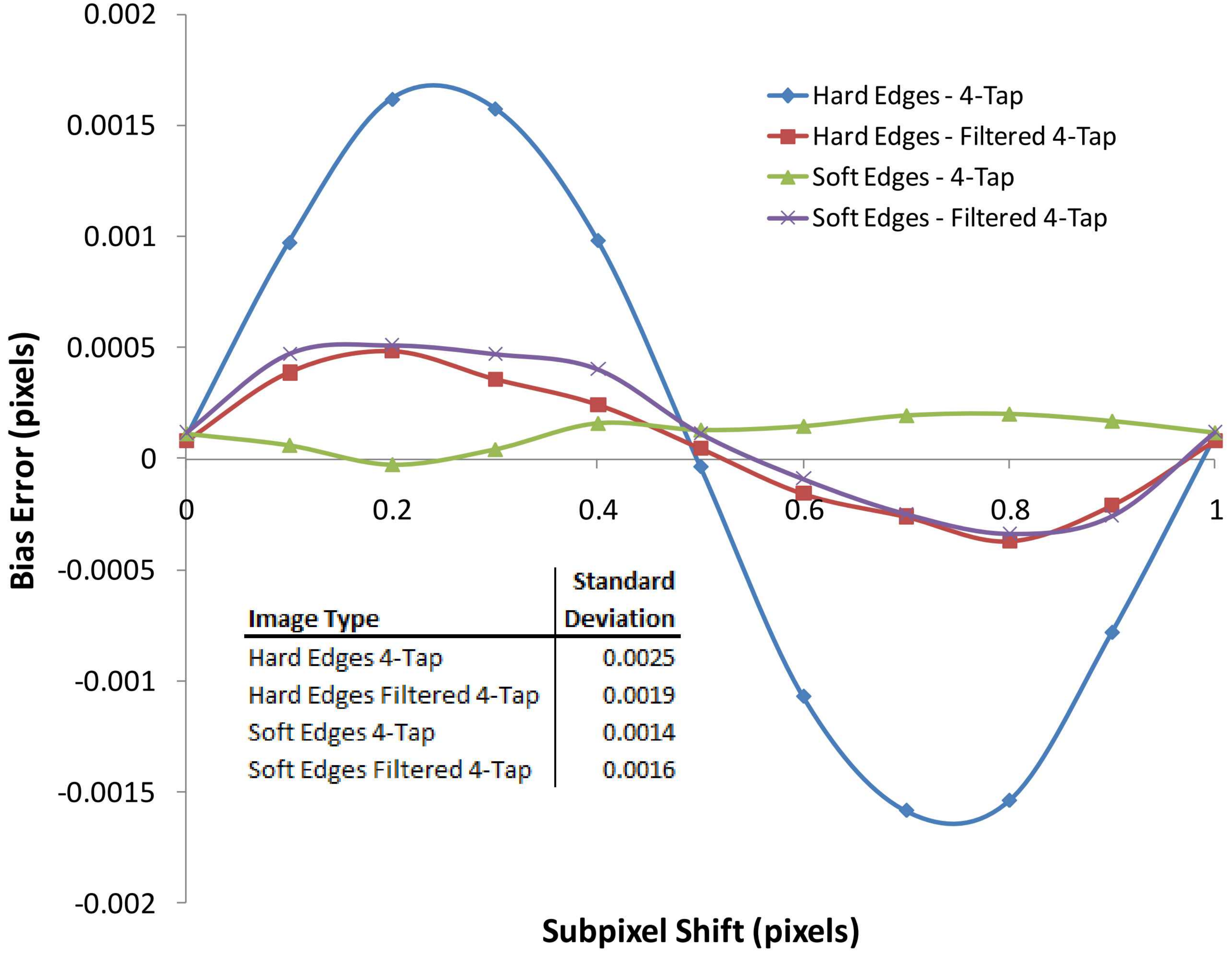


Image Type	Standard Deviation
Hard Edges 4-Tap	0.0025
Hard Edges Filtered 4-Tap	0.0019
Soft Edges 4-Tap	0.0014
Soft Edges Filtered 4-Tap	0.0016

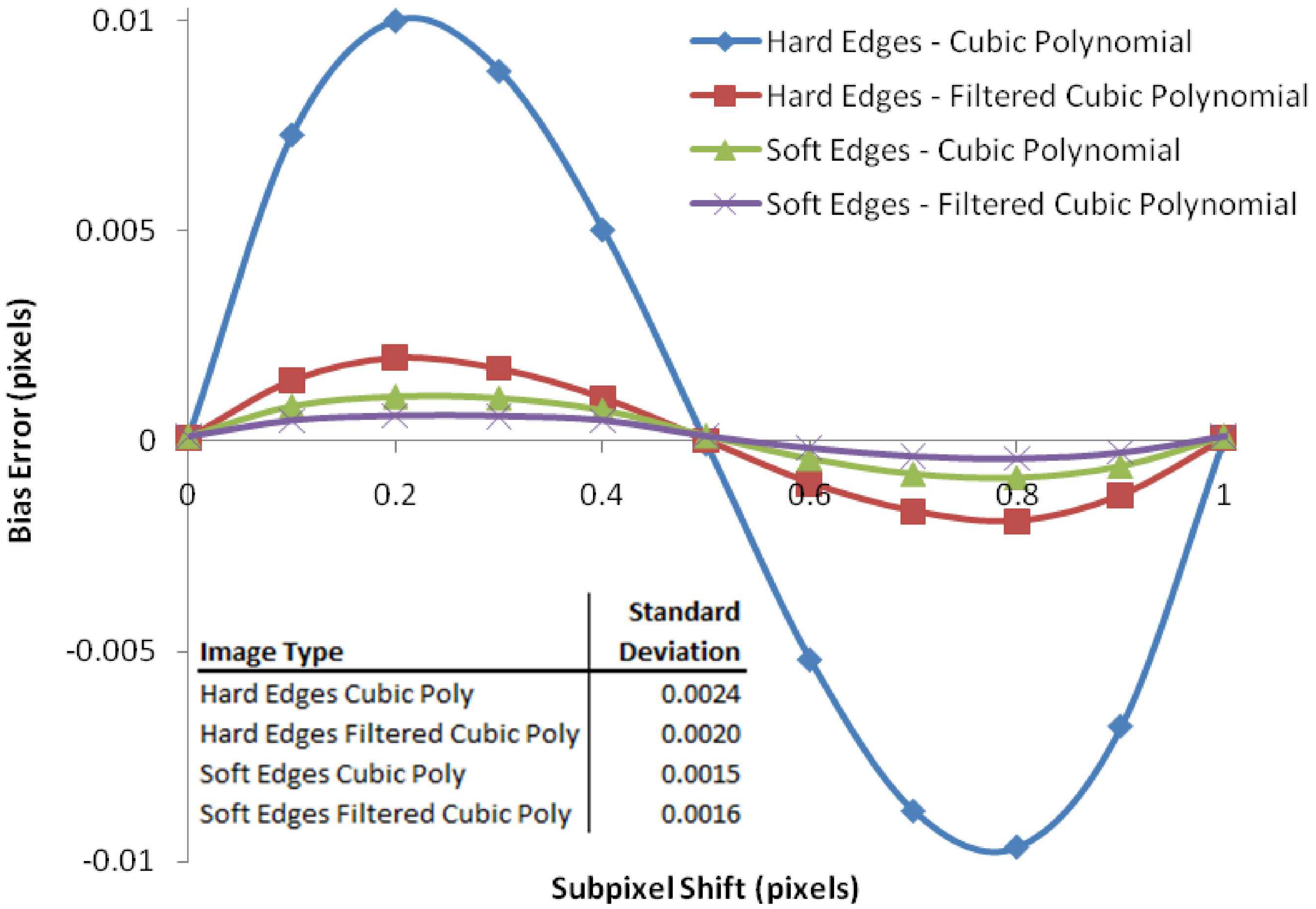


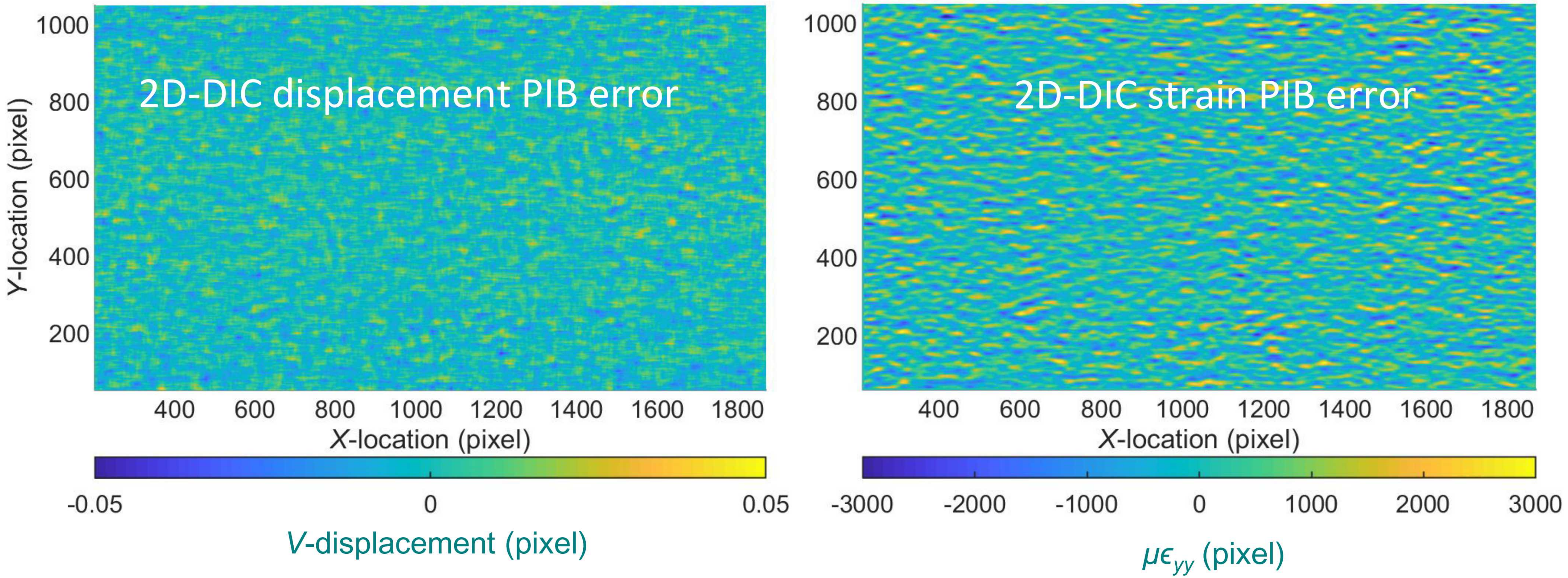
Image Type	Standard Deviation
Hard Edges Cubic Poly	0.0024
Hard Edges Filtered Cubic Poly	0.0020
Soft Edges Cubic Poly	0.0015
Soft Edges Filtered Cubic Poly	0.0016

PATTERN INDUCED BIAS (PIB)

SPATIAL ERROR CREATED BY THE INTERACTION OF THE DISPLACEMENT FIELD, SHAPE FUNCTION AND THE PATTERN.

DIC has a spatial bias error caused by the interaction of the: Pattern, shape function and the deformation field.

Pattern Induced Bias (**PIB**) Error

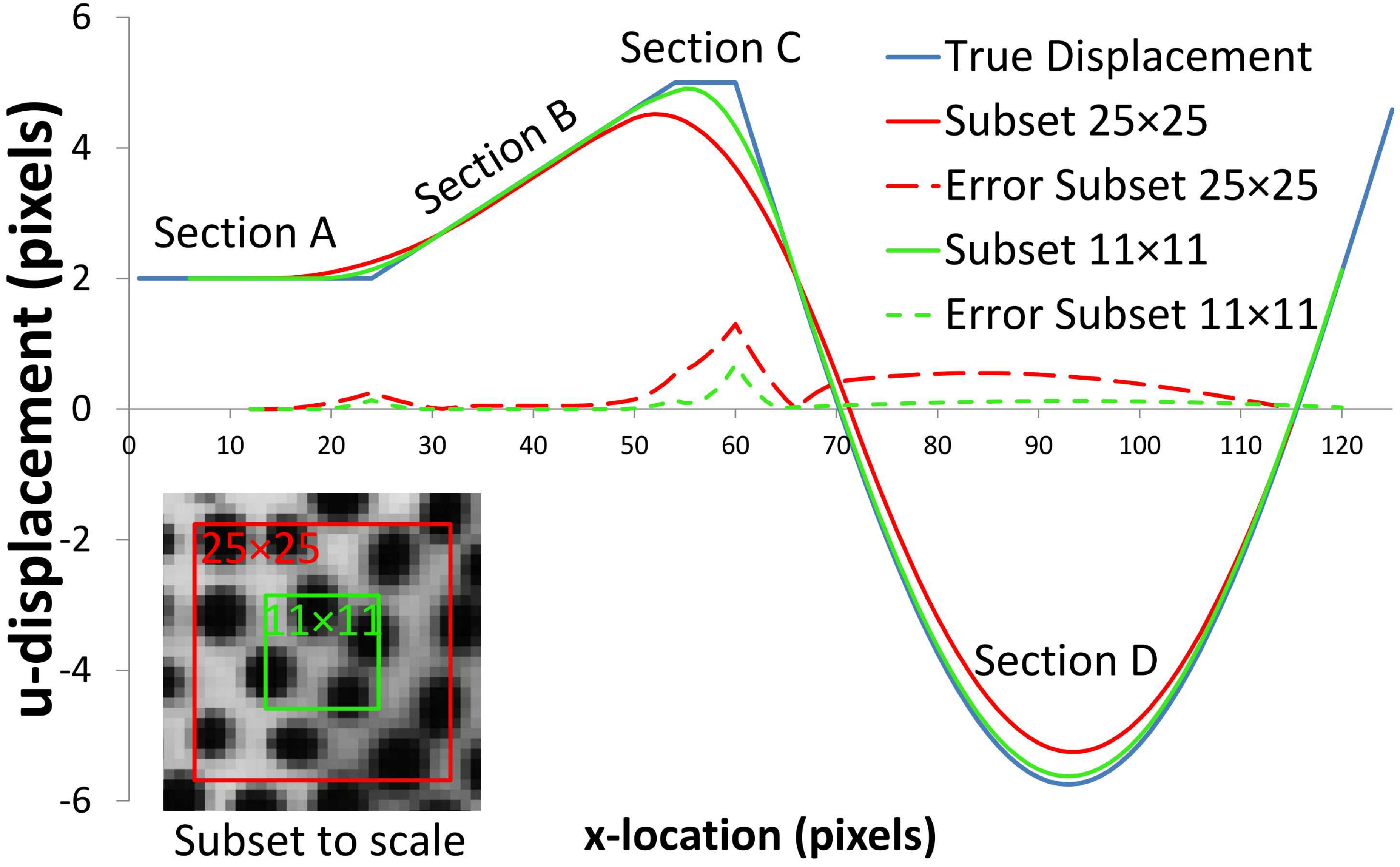


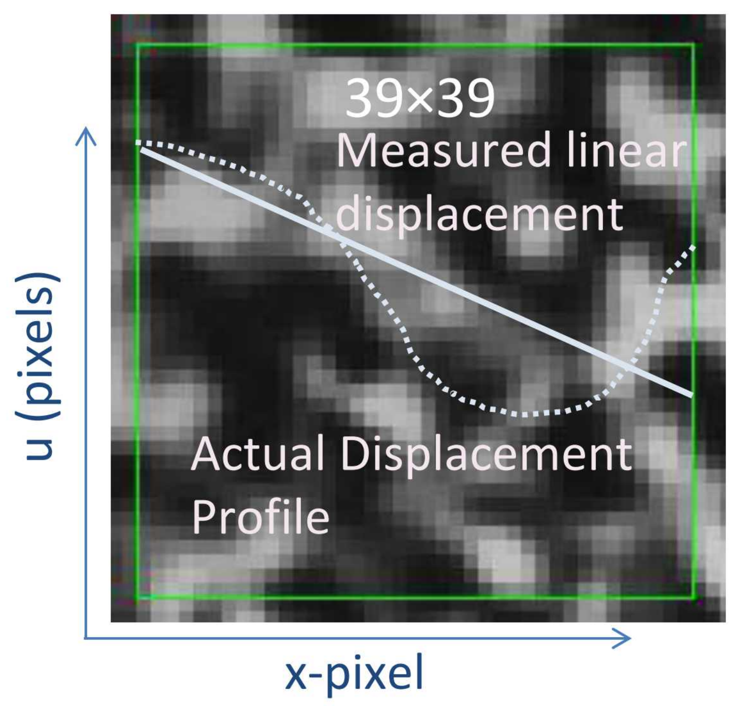
This term was briefly mentioned in literature[ǂ] but has been largely ignored.

PIB can be larger than common terms such as lens distortion, heat haze, and temporal variance errors from vibration or image noise.

[ǂ] Schreier, ExpMech, doi.org/10.1007/BF02410987

Subset shape function acts as a spatial filter

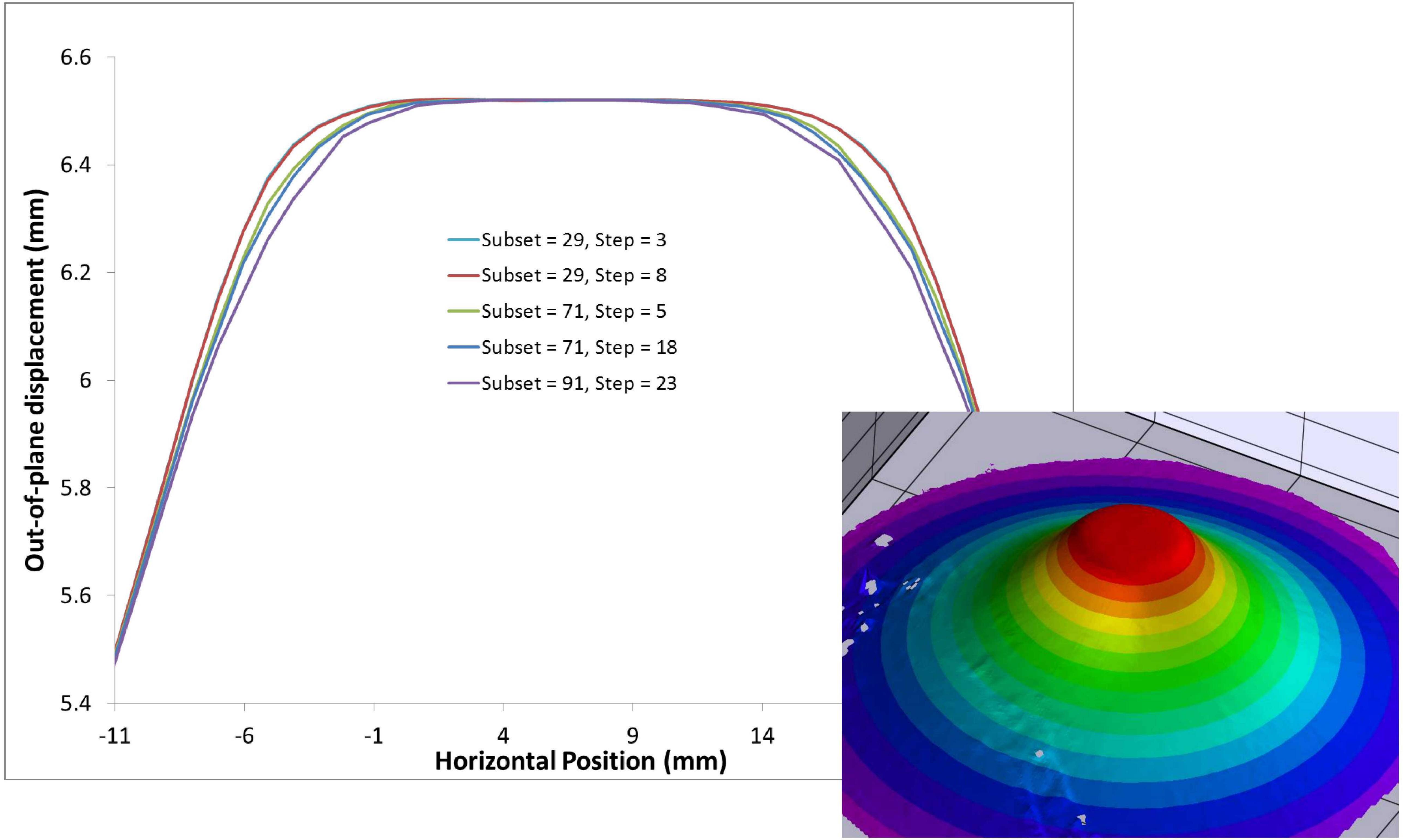




Can the subset size support the underlying displacement field?

- Shape function matters.
- Size of subset matters.

Large subsets will have problems matching a sharp corner – it is “under-matched”

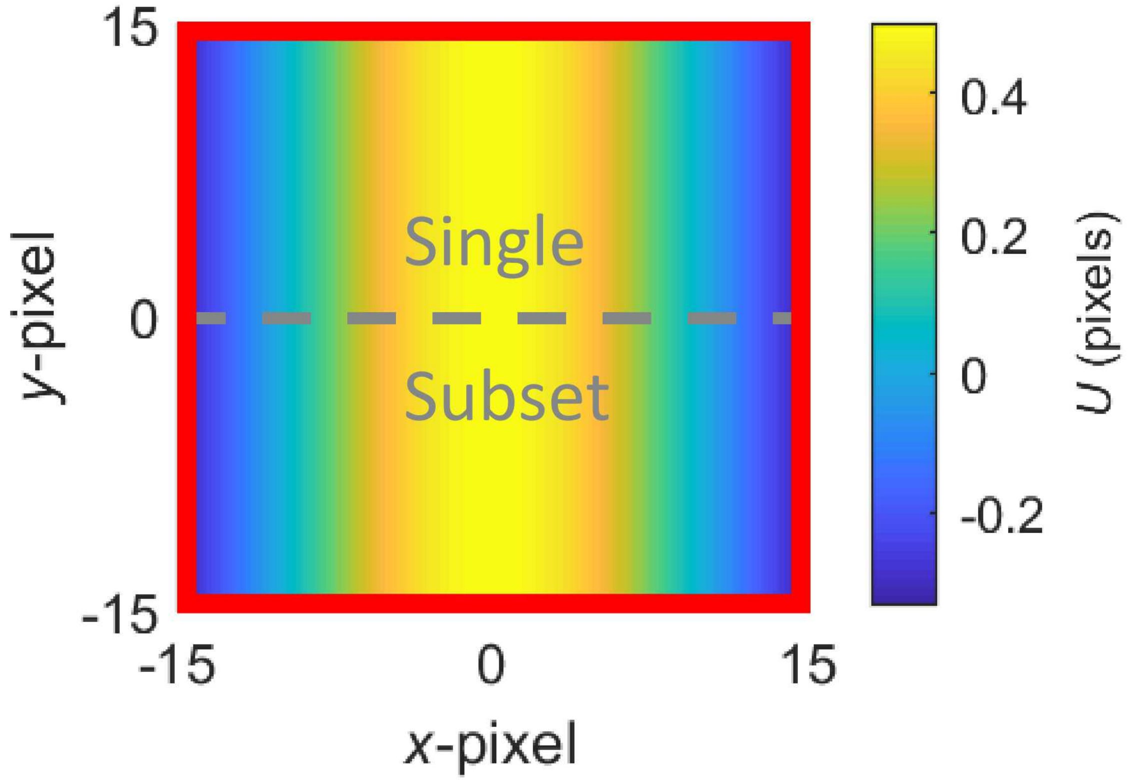


Undermatched shape functions can cause significant bias

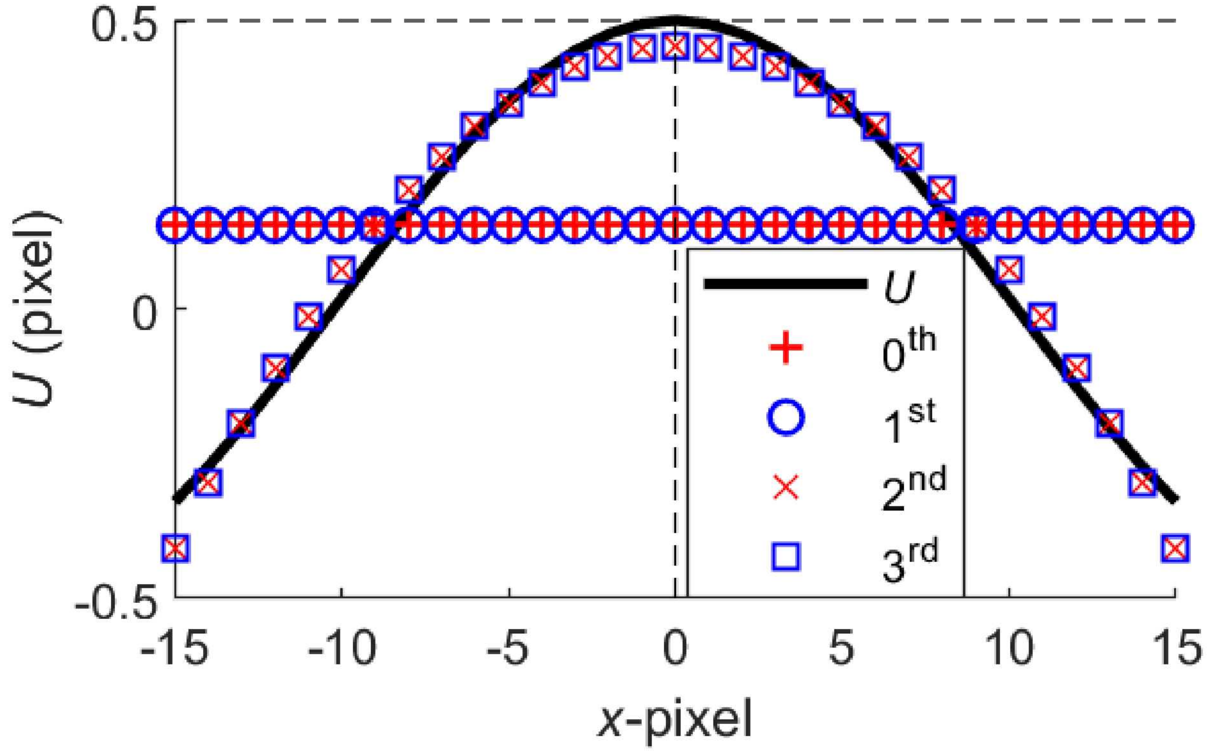
The shape function is undermatched if it can't perfectly match the underlying deformation.

Deviation from true deformation (black line) is shape function attenuation bias

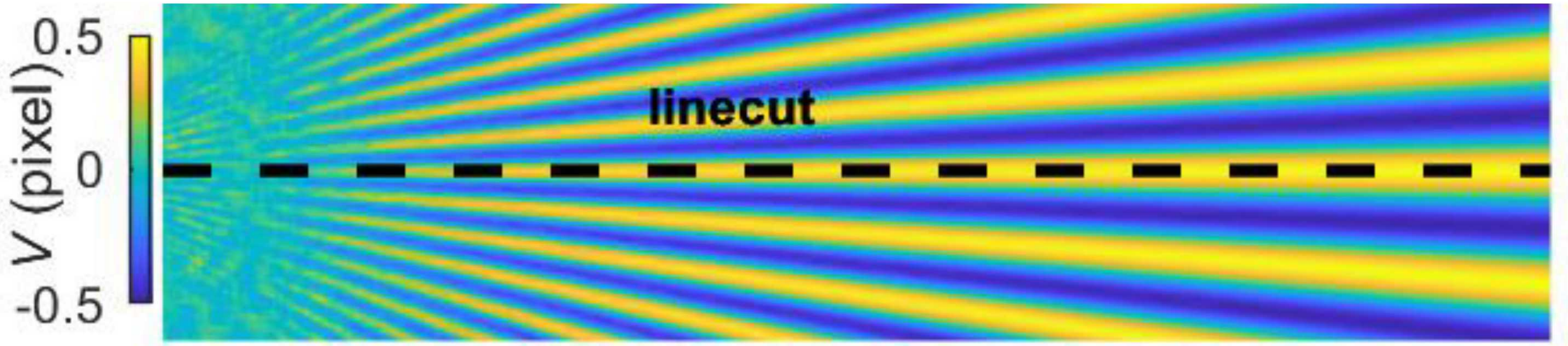
Sinusoidal Deformation



Displacement measured at y=0



An example of PIB with increasingly undermatched shape function and larger errors.



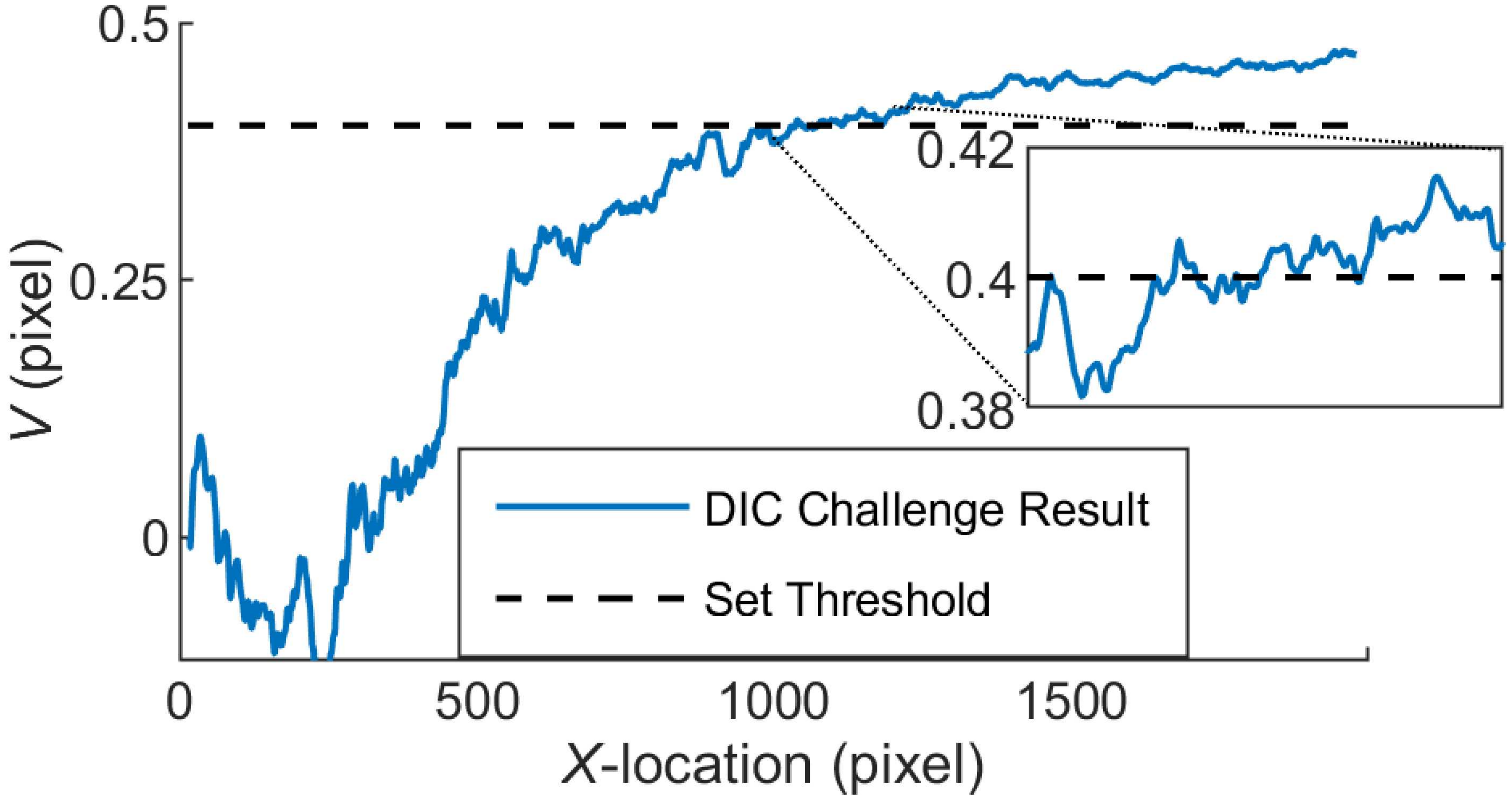


Image Characteristics:

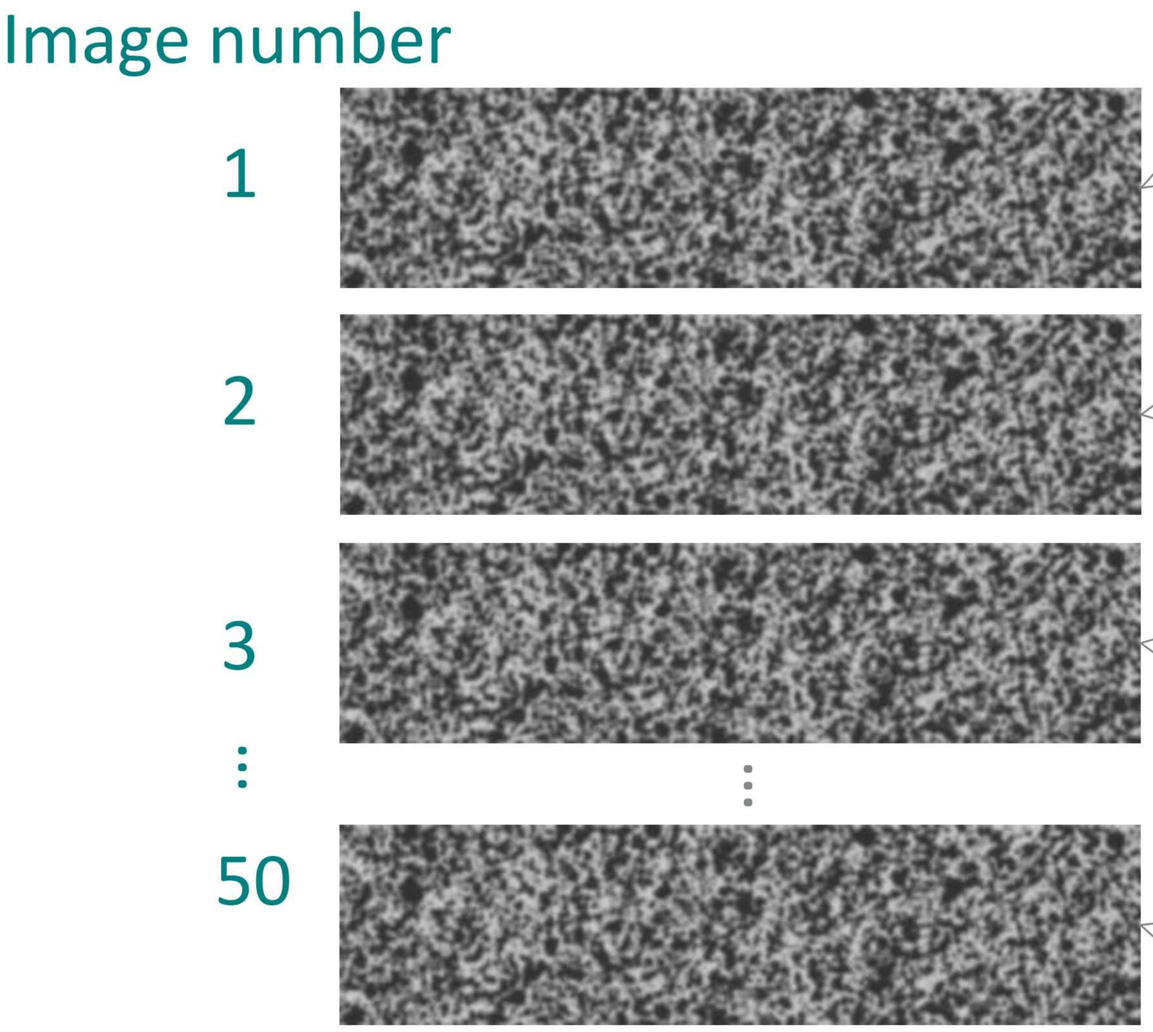
- Constant amplitude along the middle row
- Increasing displacement frequency from right to left

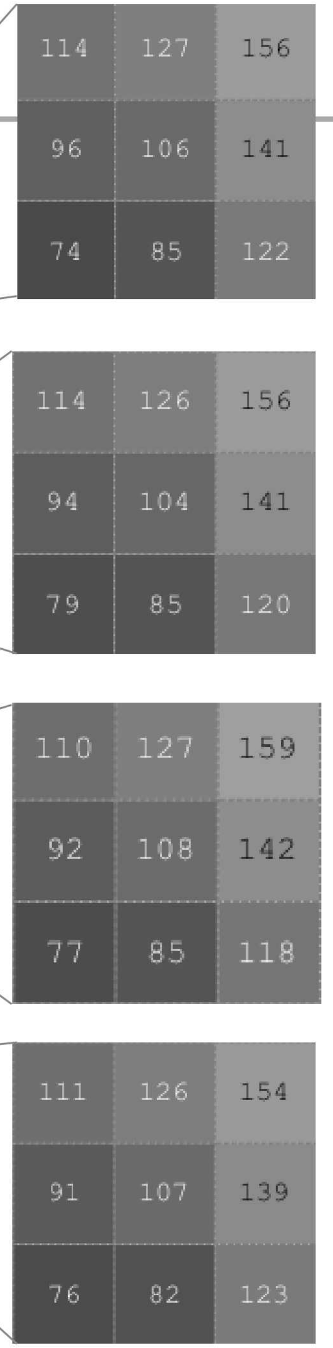
Due to shape function attenuation bias, the displacement is attenuated more at higher frequencies.

The “noise” on the extracted line is due to PIB not image noise.

Introducing image noise did not change the bias

100 pixel x 400 pixel visual samples from the larger image



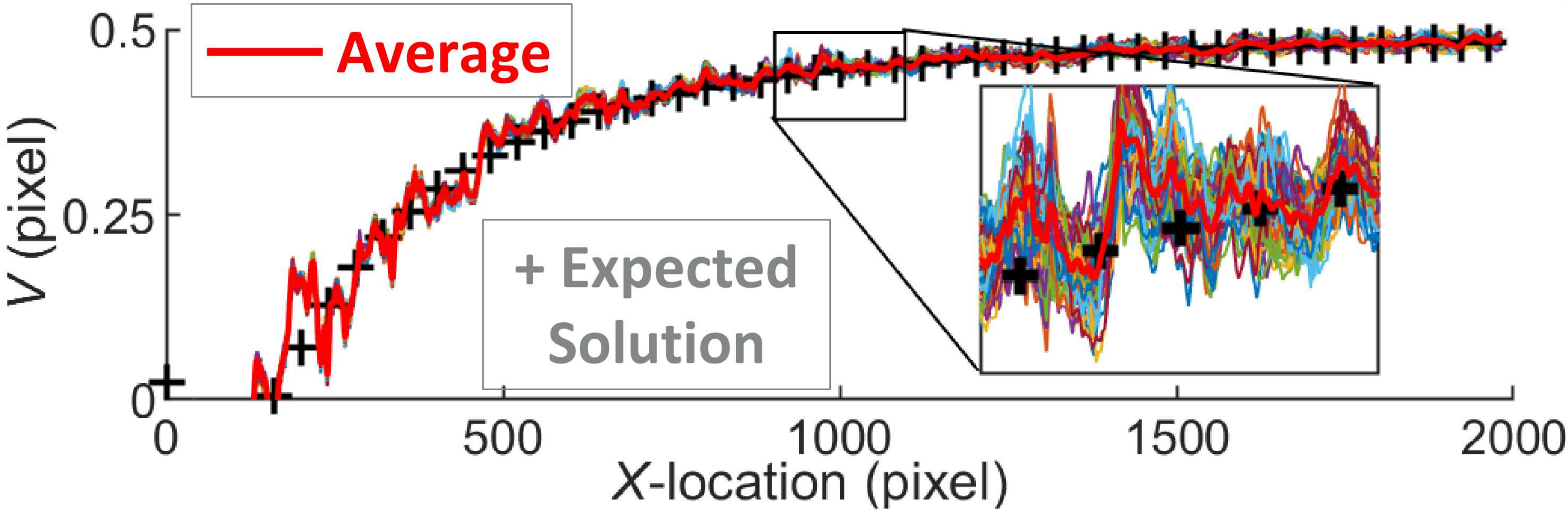


114	127	156
96	106	141
74	85	122

114	126	156
94	104	141
79	85	120

110	127	159
92	108	142
77	85	118

111	126	154
91	107	139
76	82	123



Different instances of unique noise didn't smooth the curve

Averaging unique patterns eliminated this error

100 pixel x 400 pixel samples from the larger image

Image number

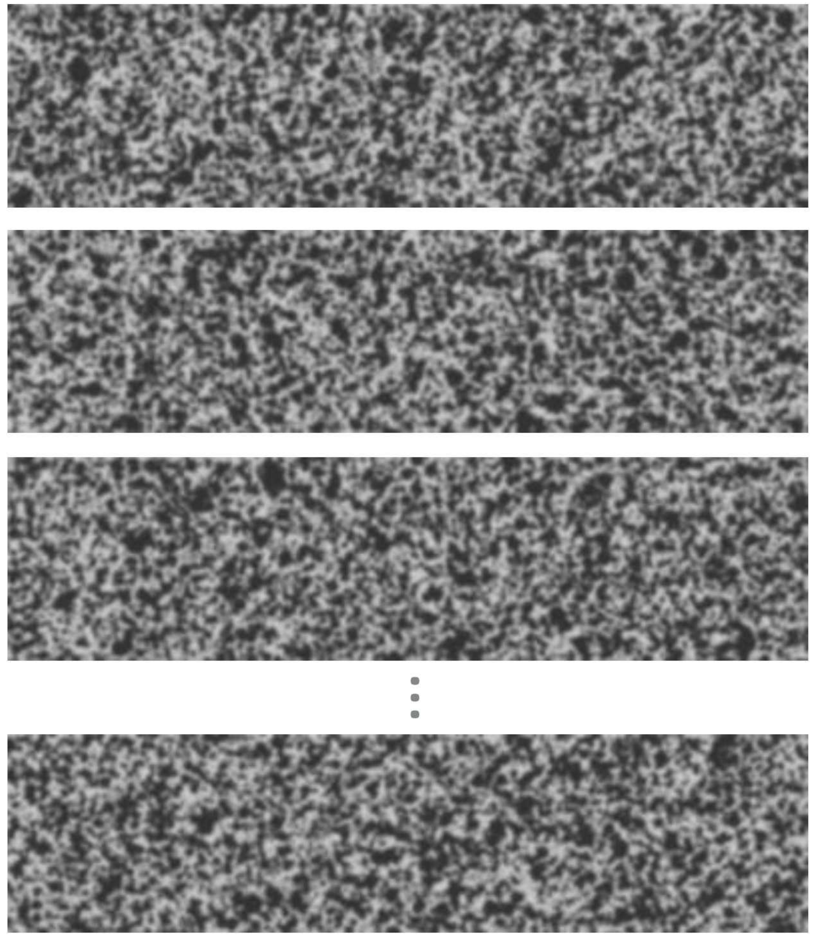
1

2

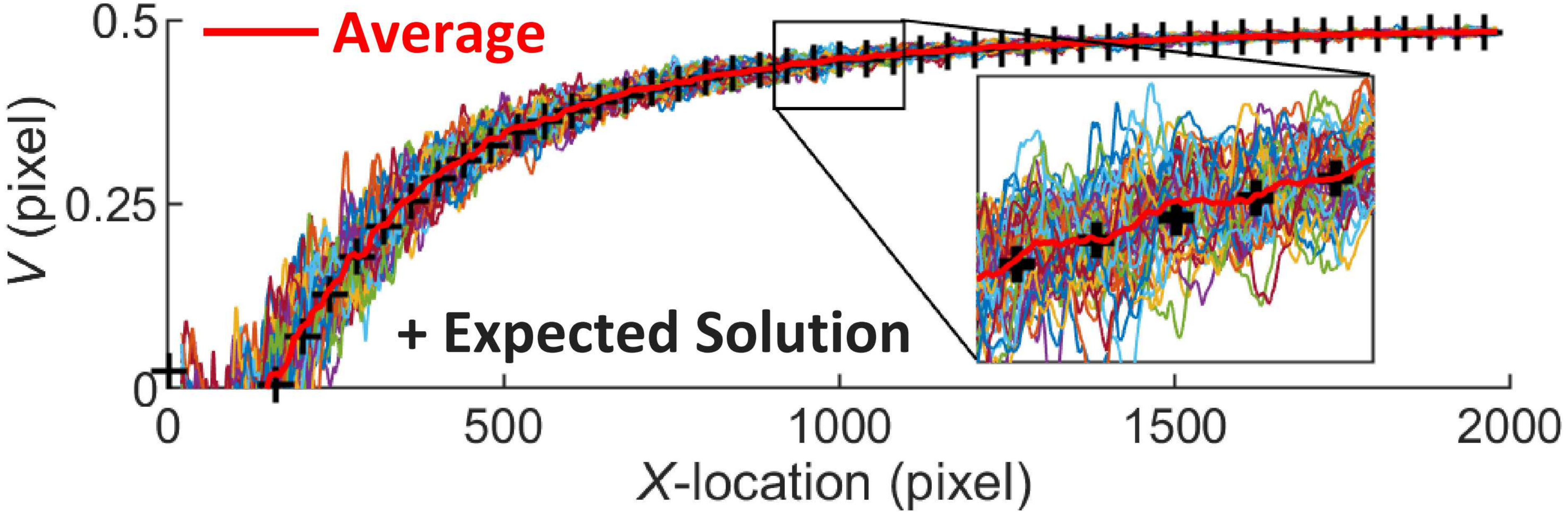
3

⋮

50



Note: Similar results occur for strain

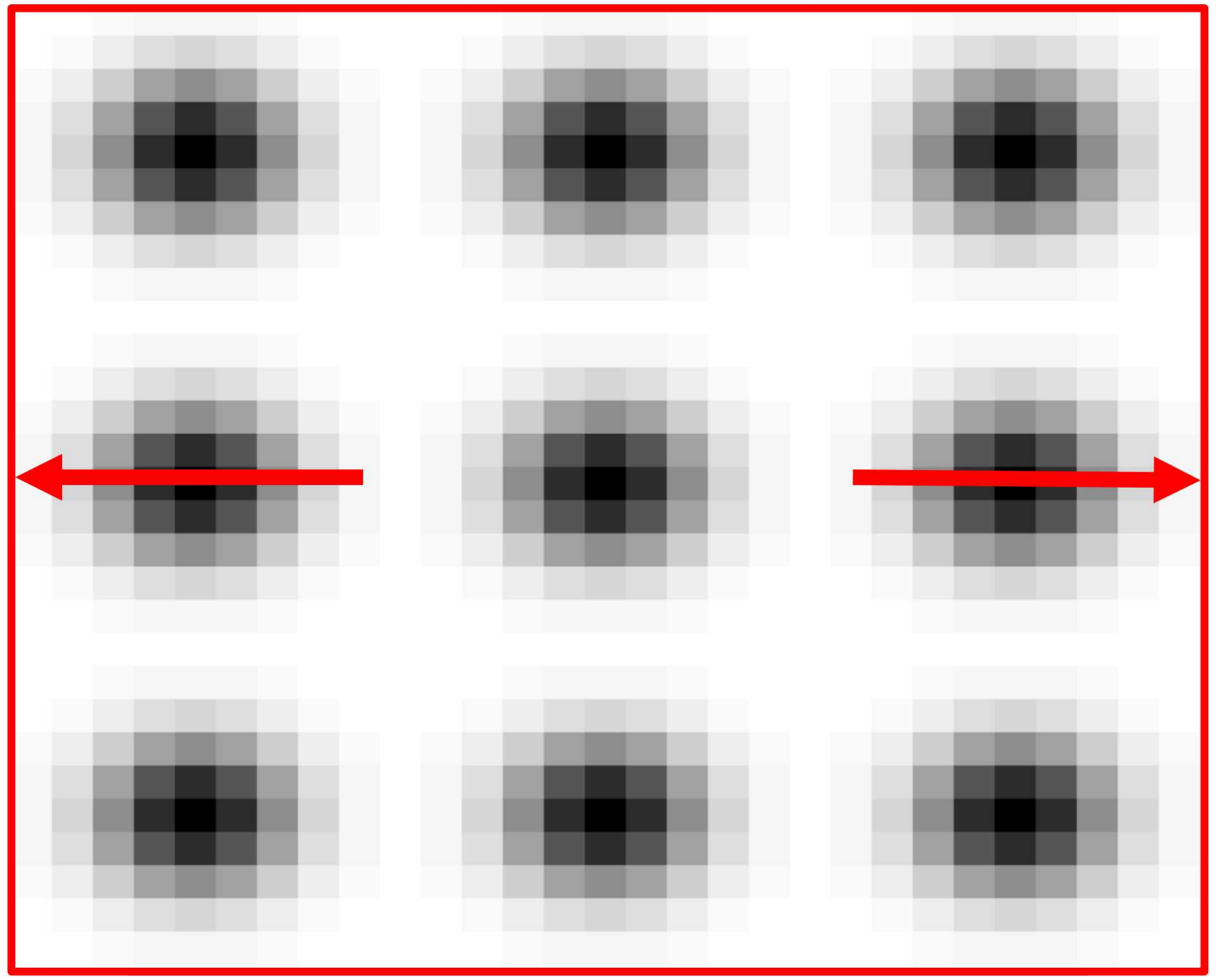


Averaging DIC results from different patterns smoothed the curve

The influence of the pattern was evaluated numerically using a double precision pattern

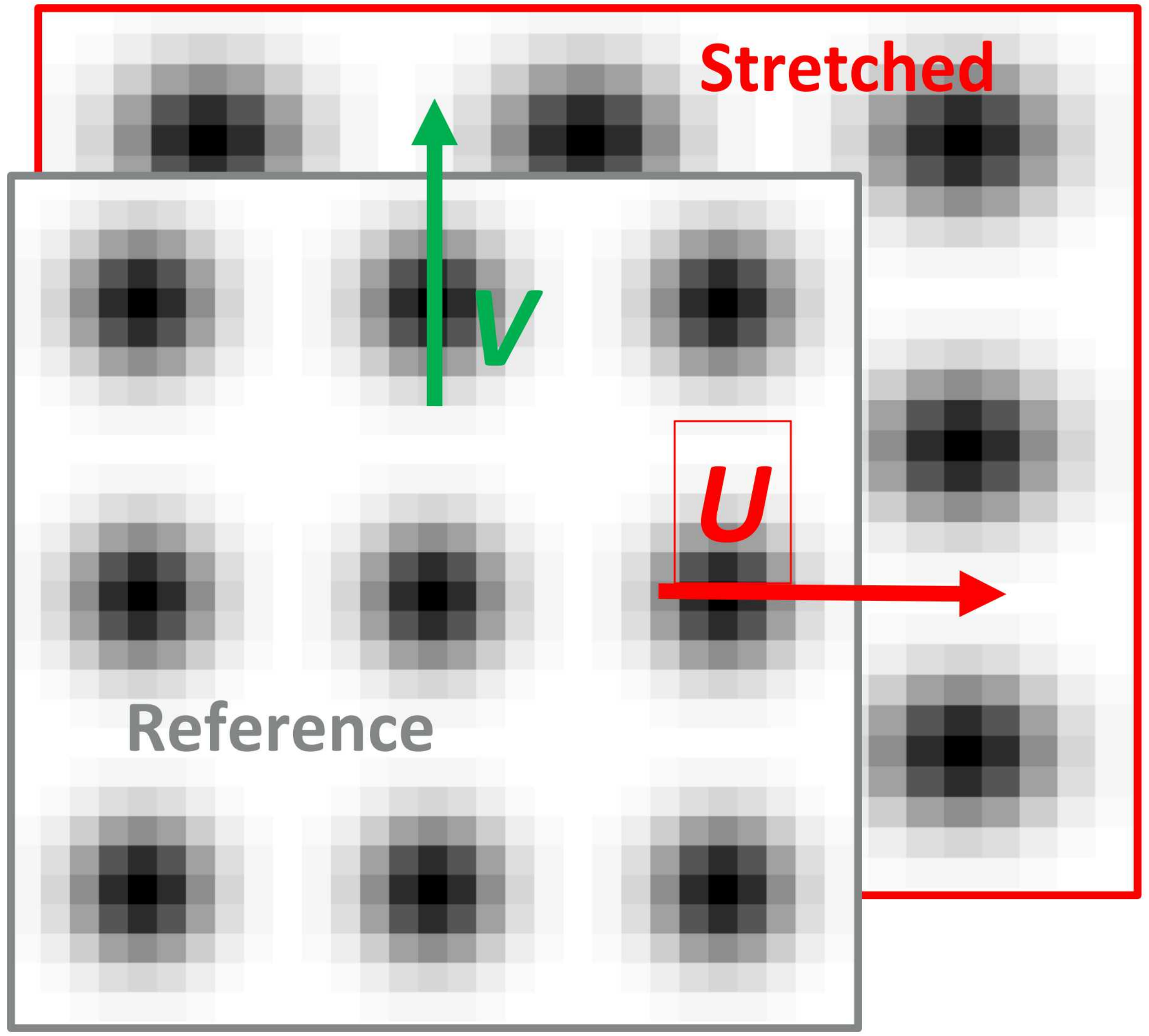
A continuous pattern sampled at 31 “pixels”

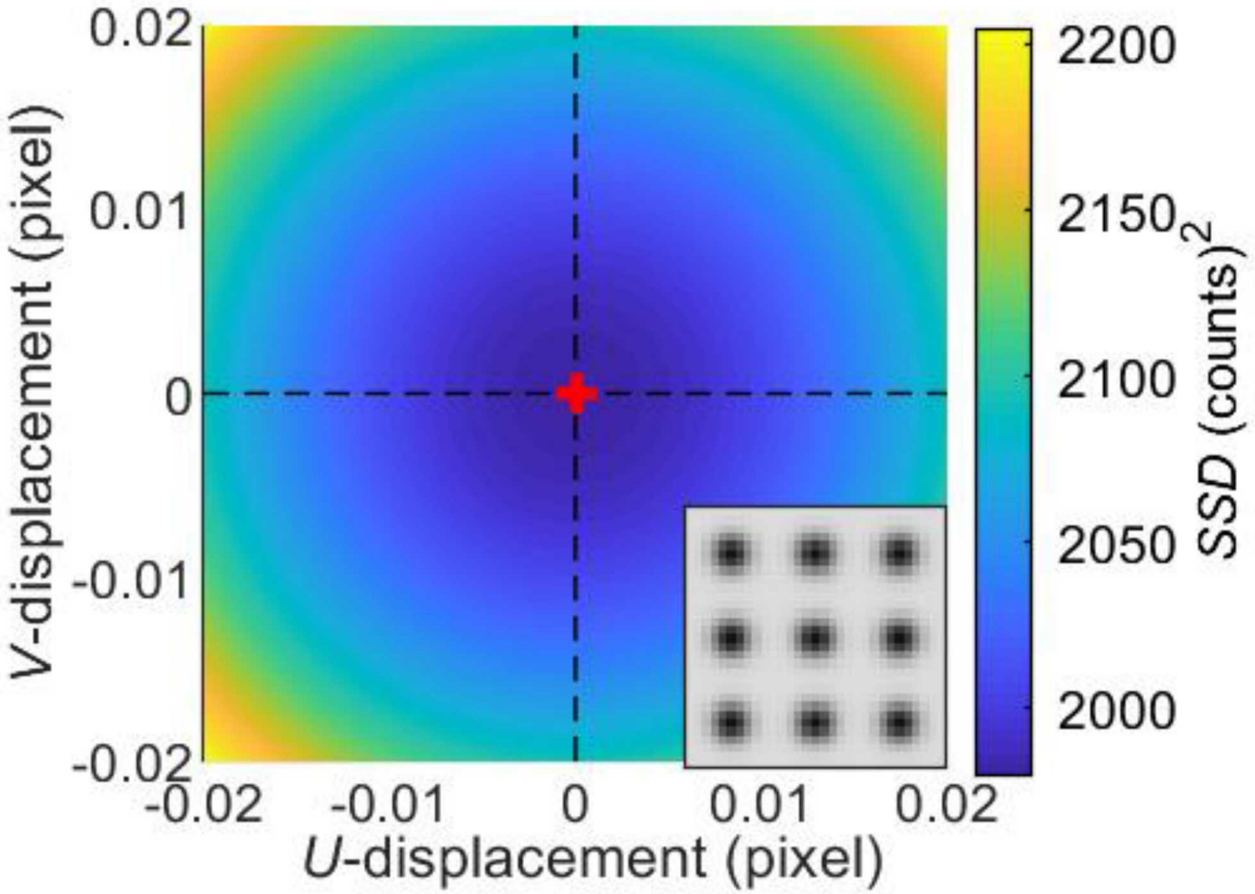
1% uniform horizontal stretch



DIC using a 0th order shape function can be simulated by rigidly shifting the reference pattern over the stretched pattern and evaluating the *SSD.*

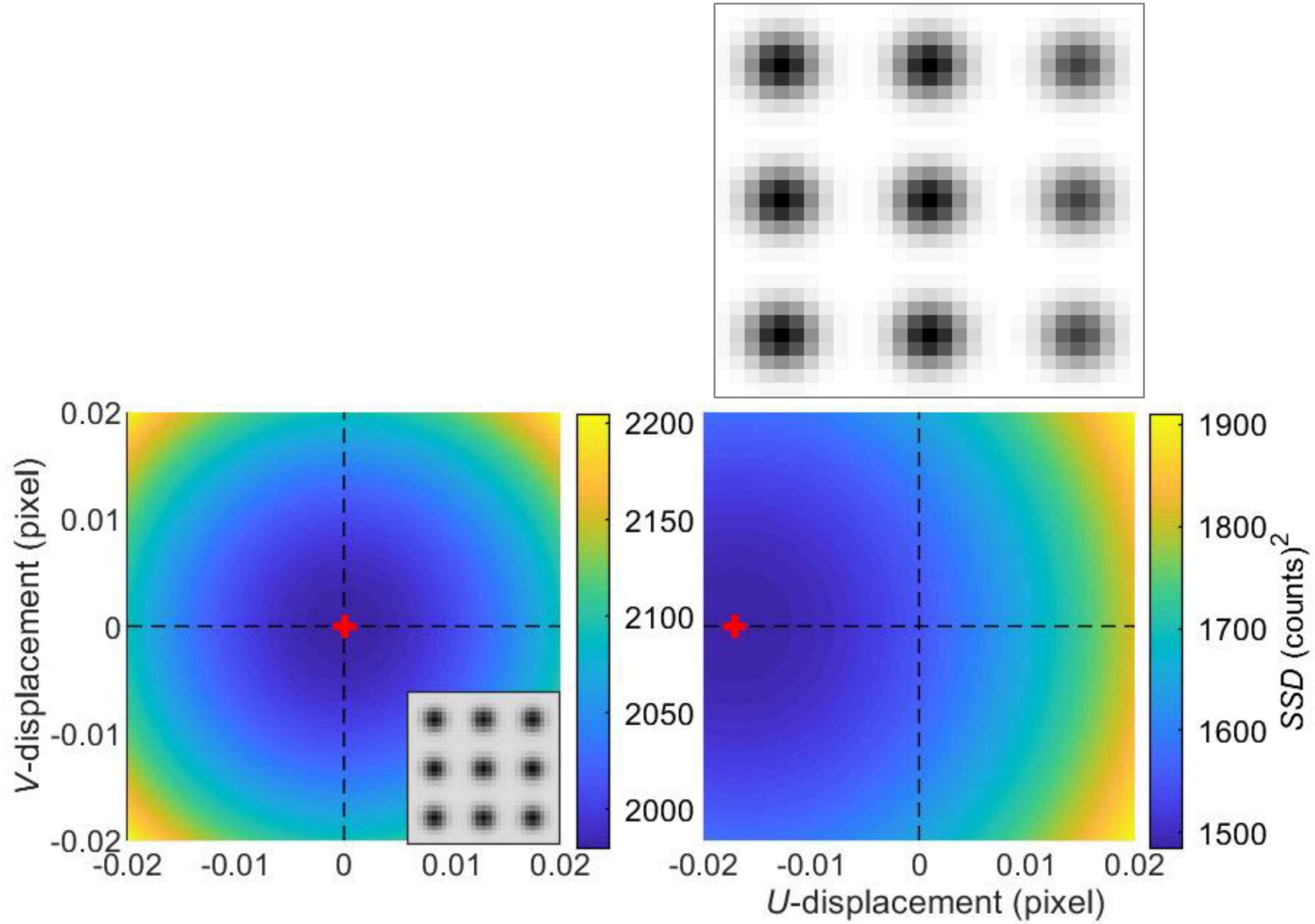
$$SSD \equiv \frac{1}{2}\sum_{x=-M}^{M}\sum_{y=-M}^{M}\boldsymbol{w}(\boldsymbol{x})\left(I(\boldsymbol{x}) - G(\boldsymbol{x}+\boldsymbol{U})\right)^2$$





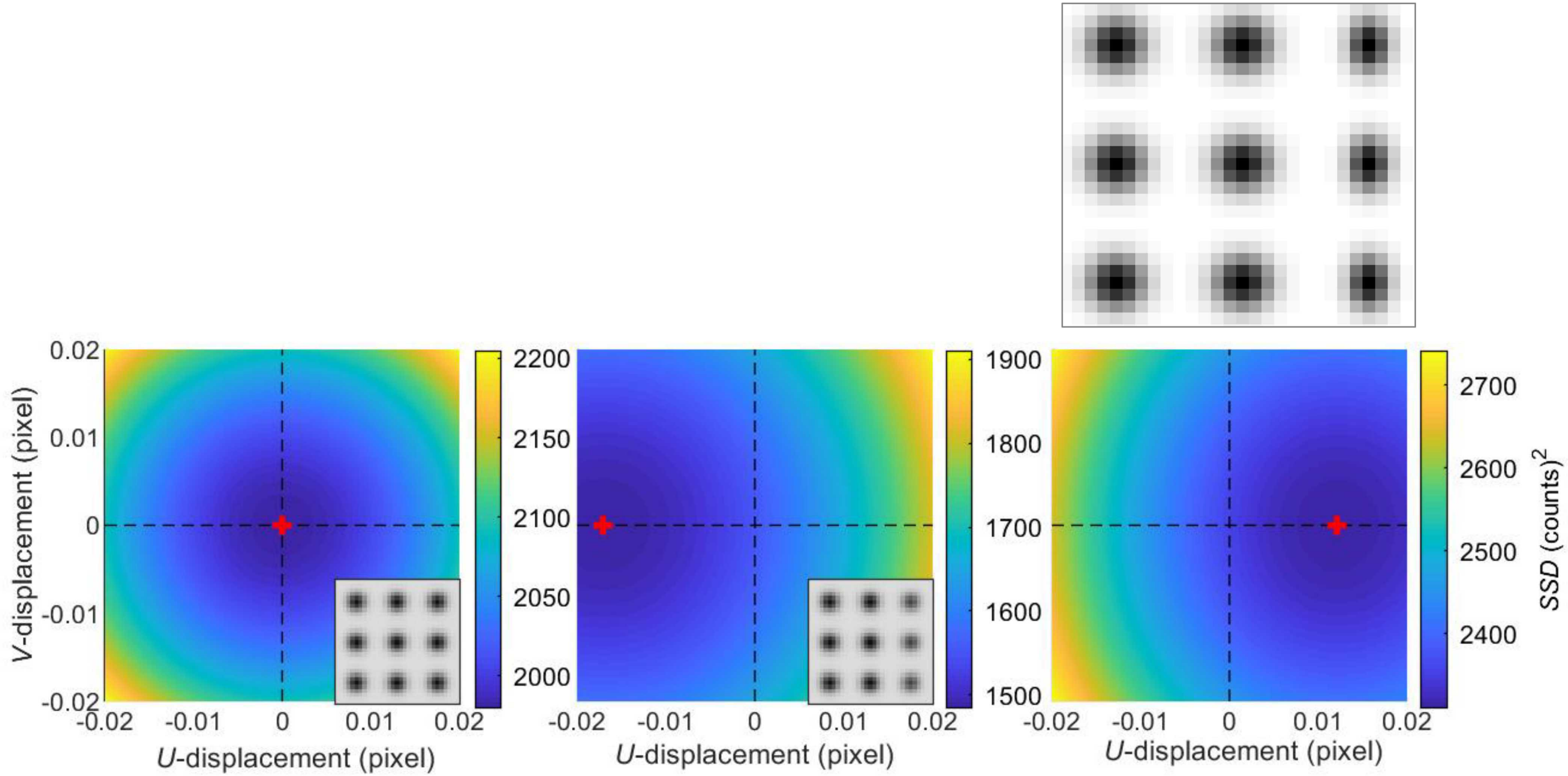
The perfectly symmetric pattern is an unlikely case

PIB is influenced by the characteristics of the features within a pattern such as contrast, gradient, geometry, position,…



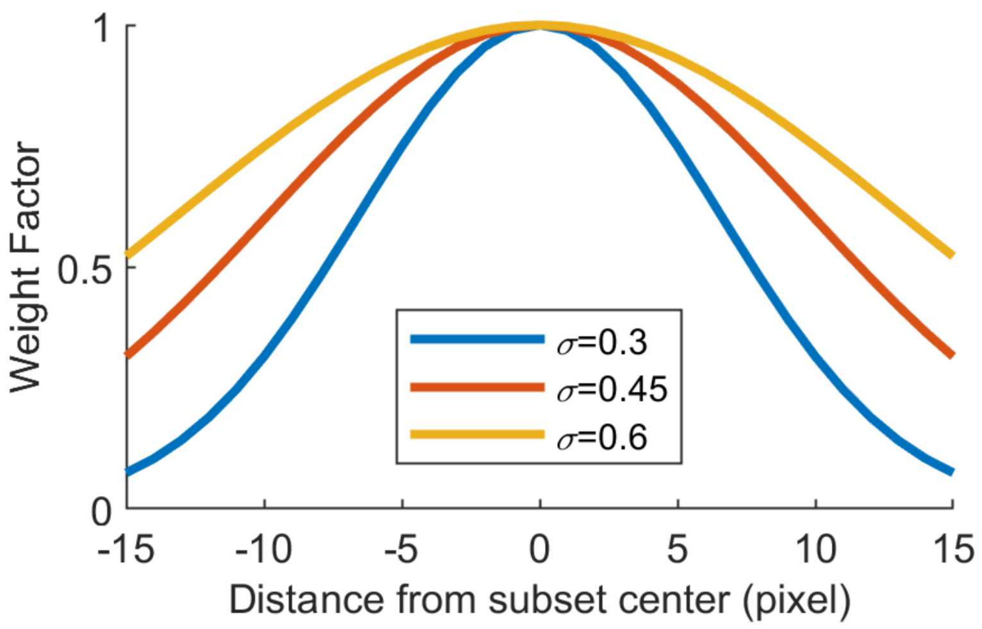
PIB is influenced by the characteristics of the features within a pattern such as contrast, gradient, geometry, position,…

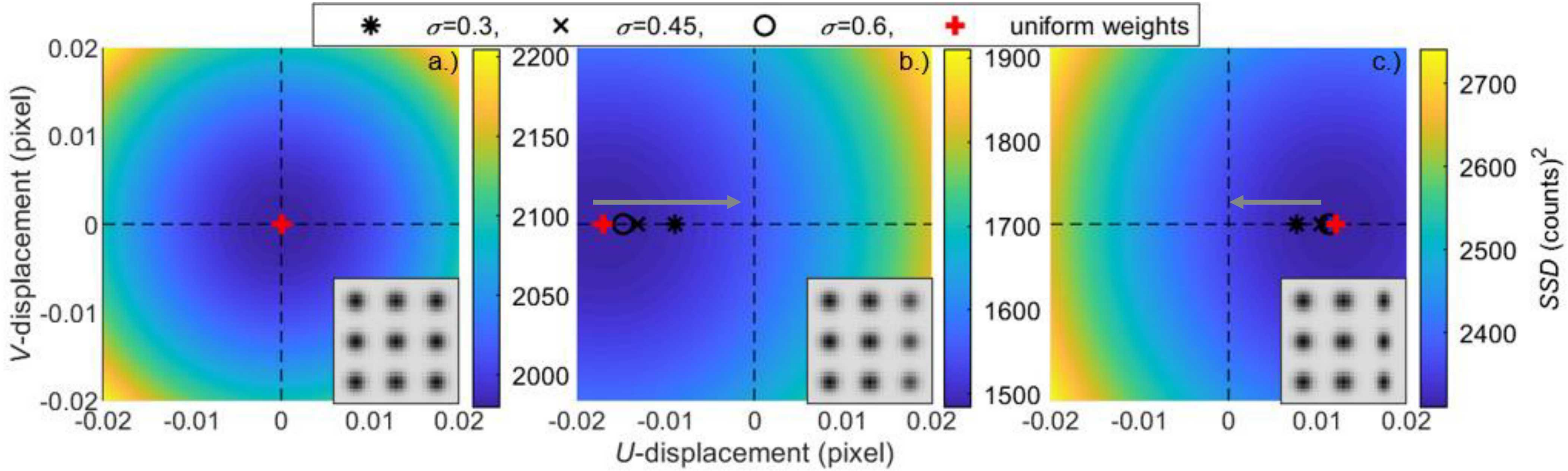
- The DIC solution is biased by higher contrast features.



PIB is influenced by the characteristics of the features within a pattern such as contrast, gradient, geometry, position,…

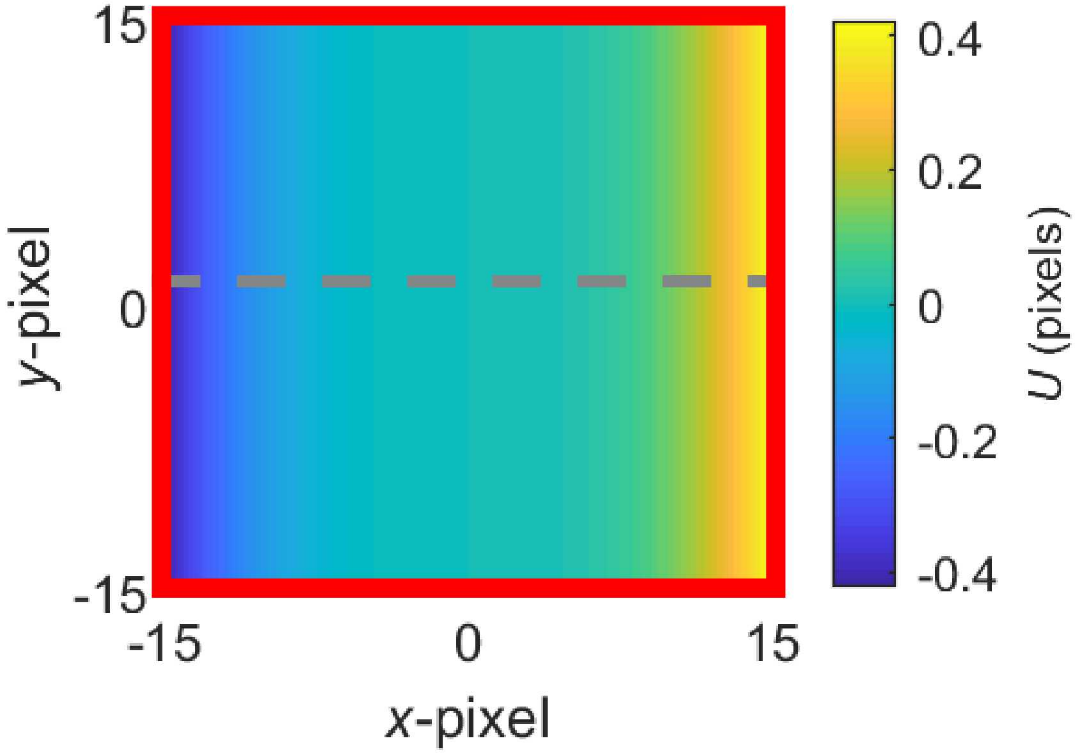
- The DIC solution is biased by higher contrast features.
- The DIC solution is biased by sharper gradients
- Center weighting reduces this error





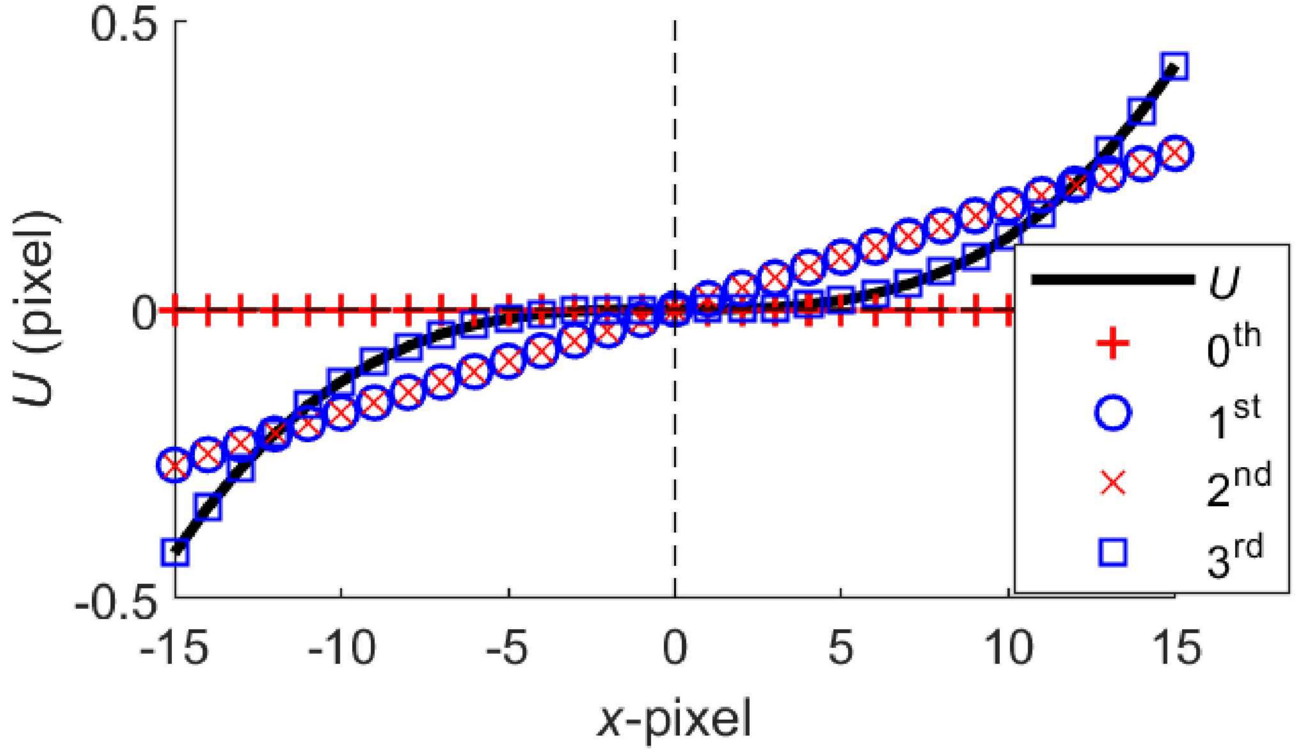
Antisymmetric deformations are undermatched, but don’t produce shape function attenuation bias

Cubically deformed pattern



Lower Contrast

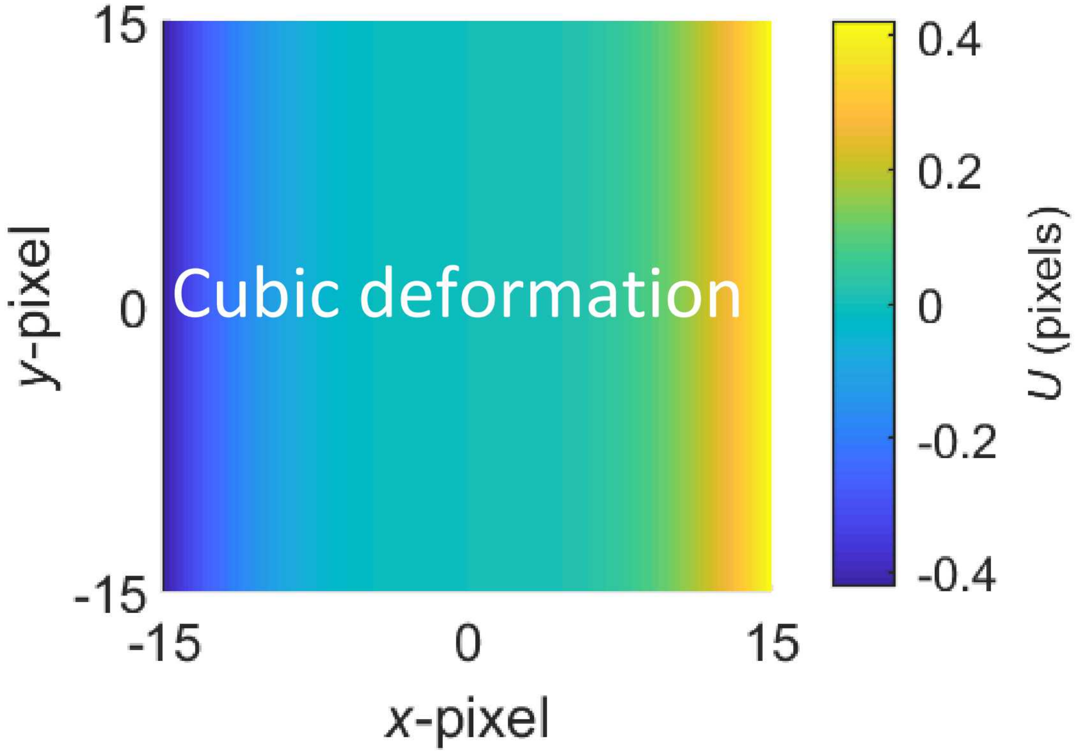
No Bias

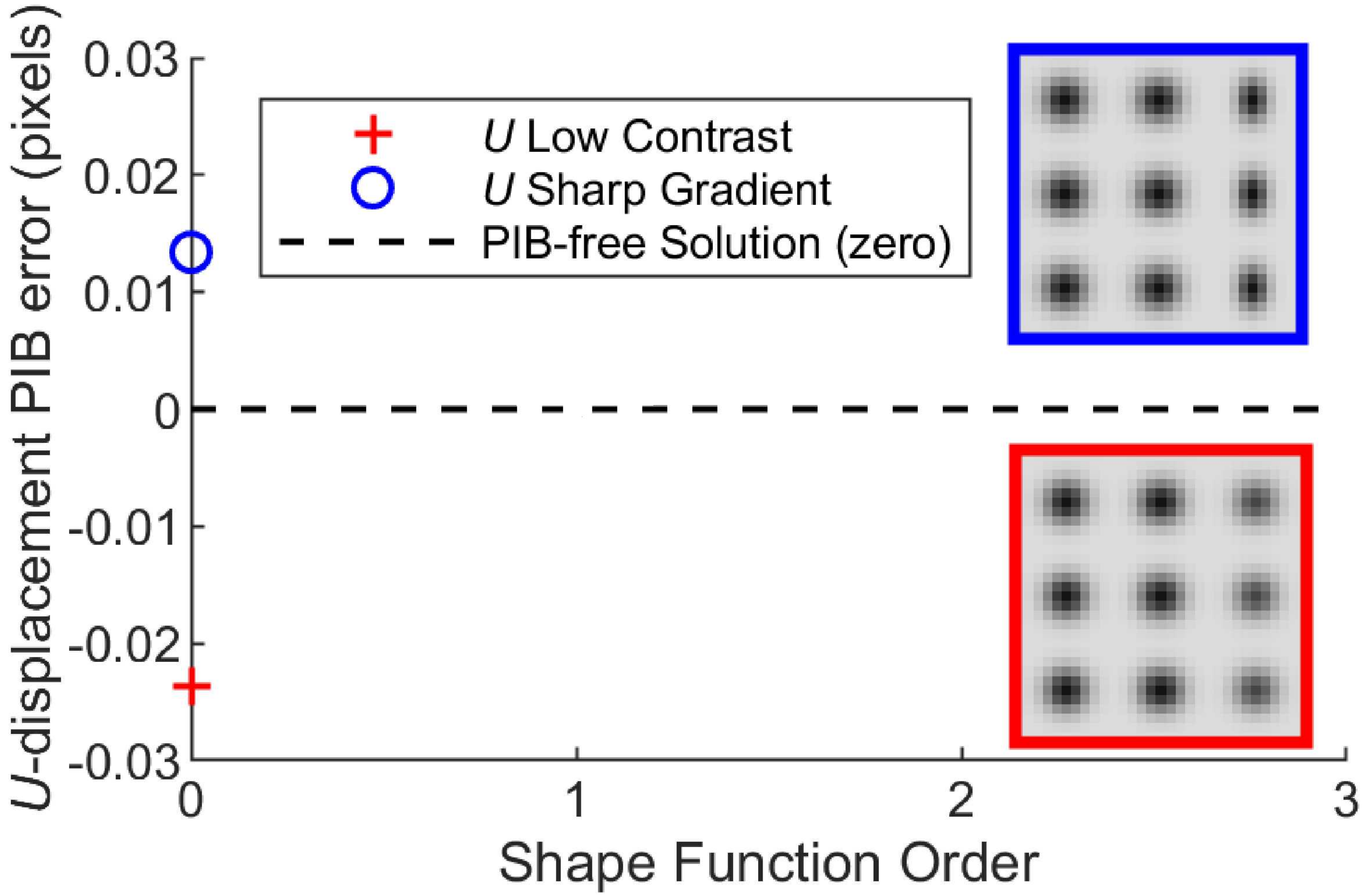


Higher Gradient

Magnitude and direction of PIB evolves with choice in shape function

- The 0th order shape produces large PIB error
- The 1st order shape function better approximates the displacement.
- The quadratic parameter in the 2nd order shape function further biases the results to minimize the SSD.
- The 3rd order shape function is not undermatched, no PIB error





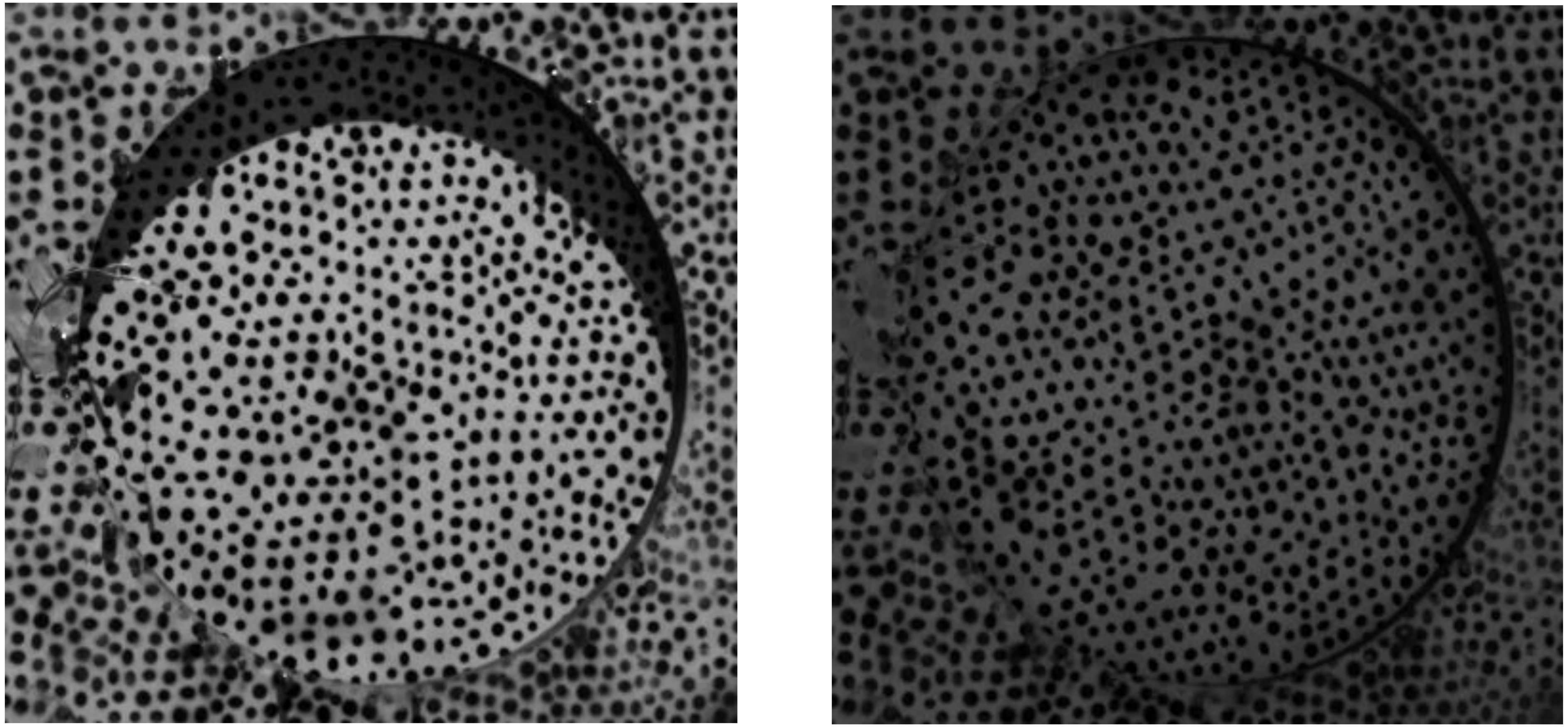
Section 2.2.4 – Lighting and Exposure

THE PAINT AND LIGHTING ARE YOUR MOST IMPORTANT PARTNERS

WORKING TOGETHER TO MAKE DIC POSSIBLE.

Flat light is king! So what is flat light?

Flat = Diffusive (i.e. arrives from many directions).



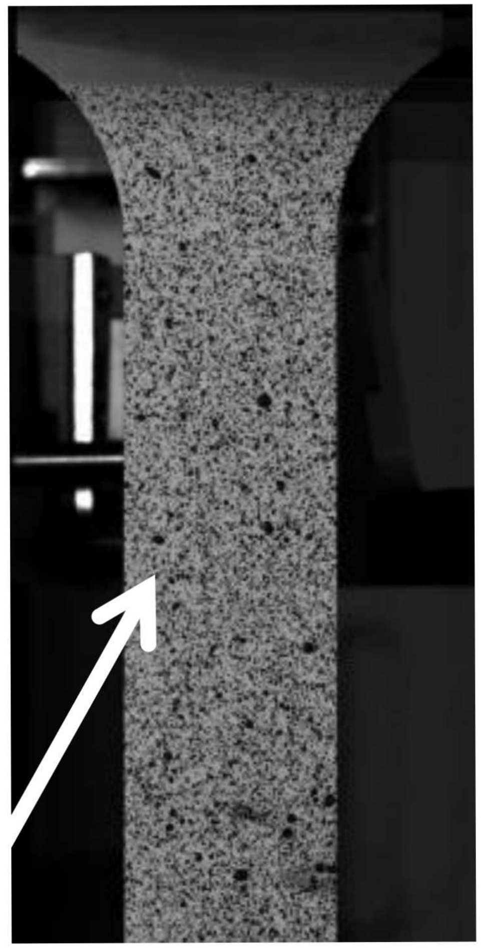
Recommendation 2.11 – Diffuse light

Recommendation 2.18 – Avoid specular reflections

For flat specimens, lighting is easier; avoid a direct path from the light to the camera.

Caution 2.12 – Avoid flickering lights.

LED lights are a good and cheap distributed light source.



The sample will also heat up.

LED lighting can bring higher intensity with lower heat.

Avoid heat waves.

Caution 2.3 – Avoid direct reflections

Recommendation 2.15 – Lights behind camera

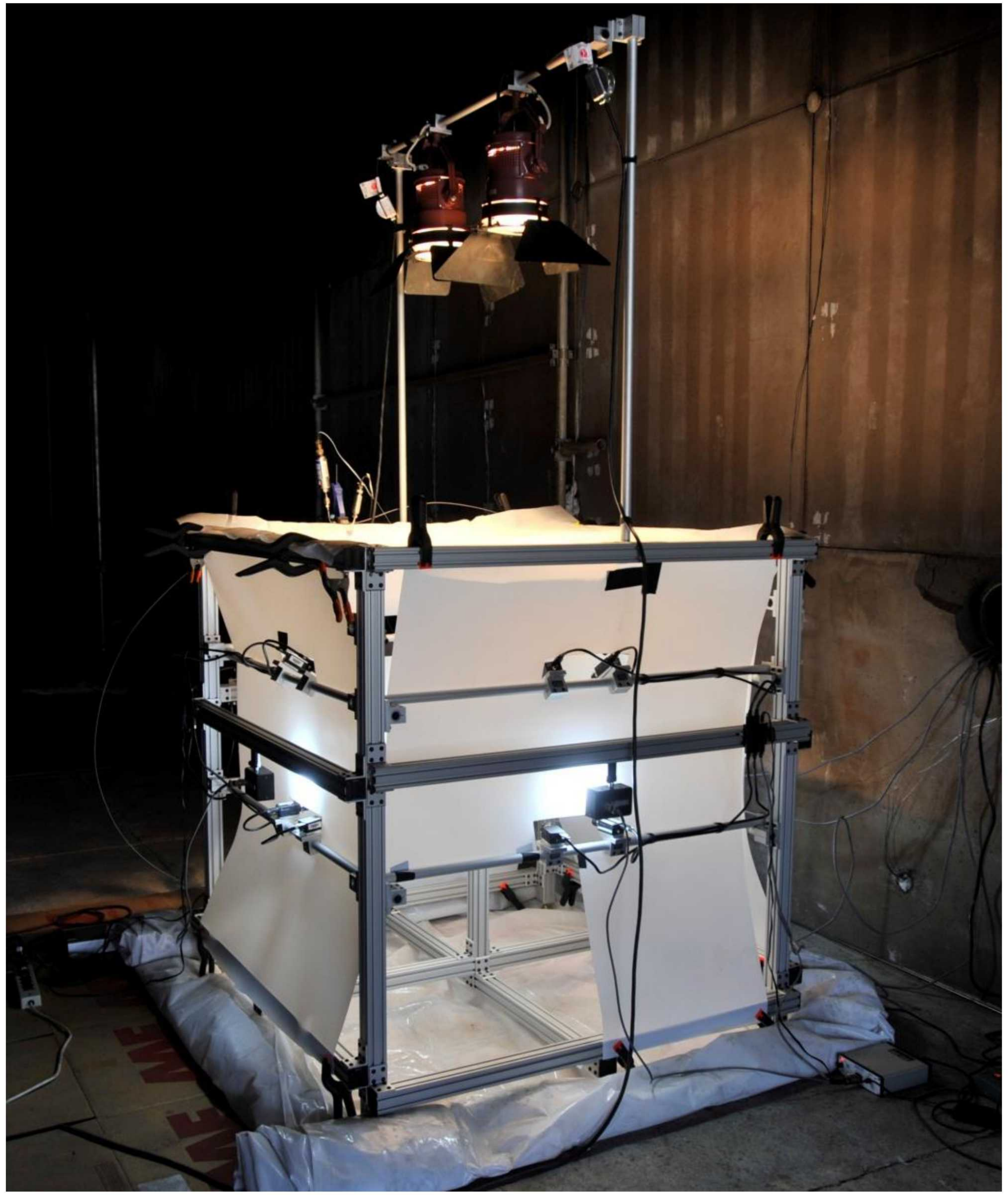
For stereo lighting flat specimens can also be fairly easy.

Unless the object changes shape! Then more work is required.

Caution 2.3 – Avoid direct reflections

Recommendation 2.15 – Lights behind camera

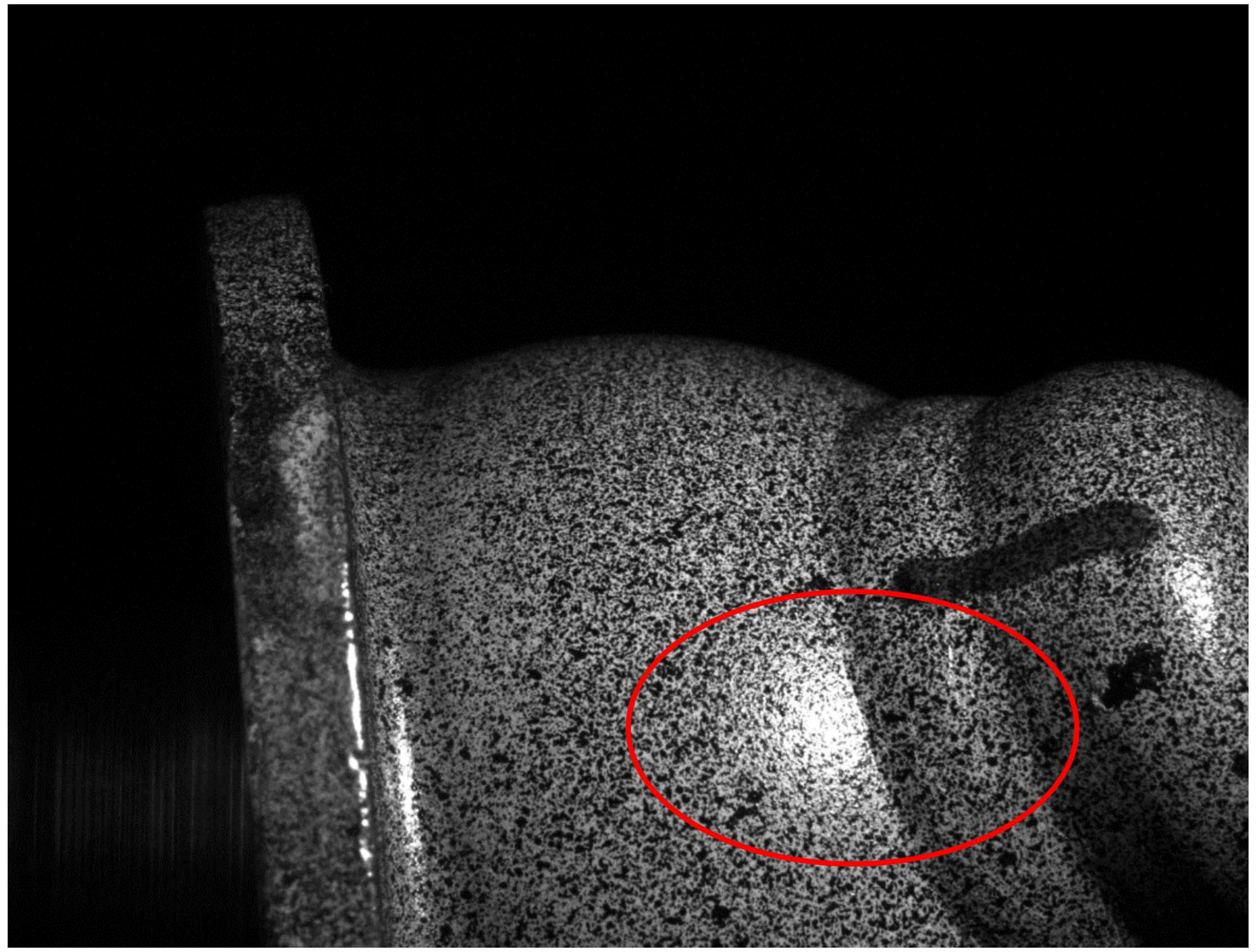
Using diffusers and many light sources will help create flat light.



iDICs

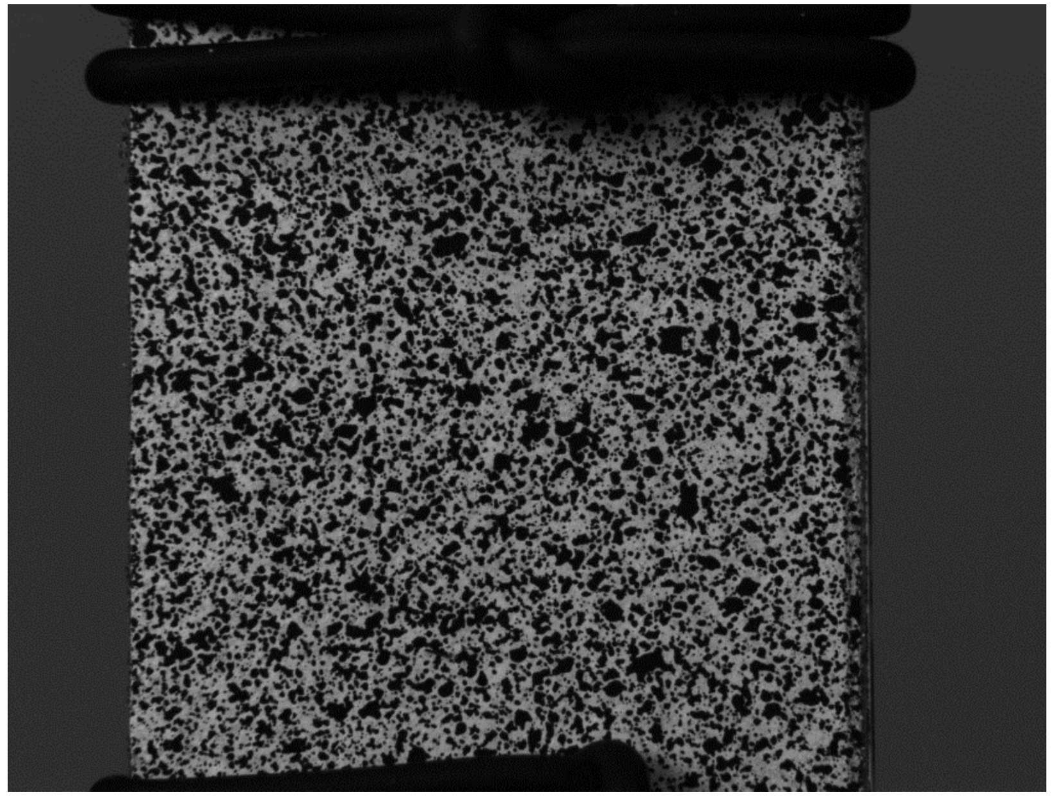
Recommendation 2.11 – Diffuse light

Lighting considerations: Avoid highlights.



Avoid saturation!

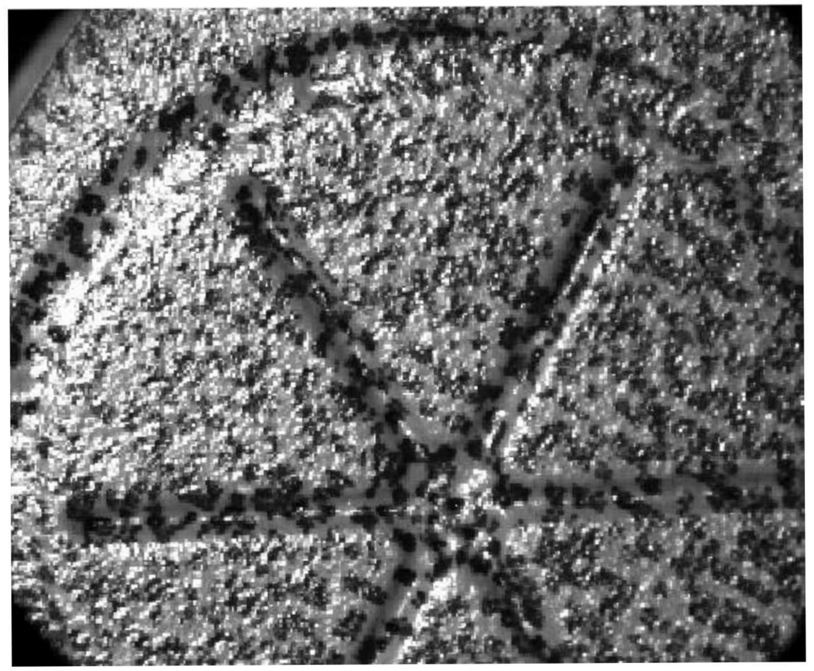
Flat light is best.



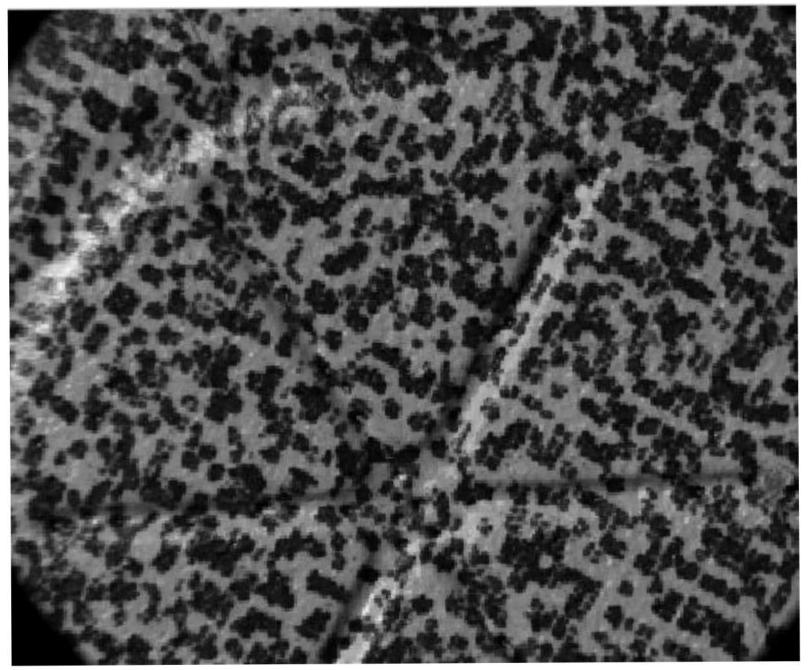
Highlights will occur when objects change shape. Take this into account.

Recommendation 2.11 – Diffuse light

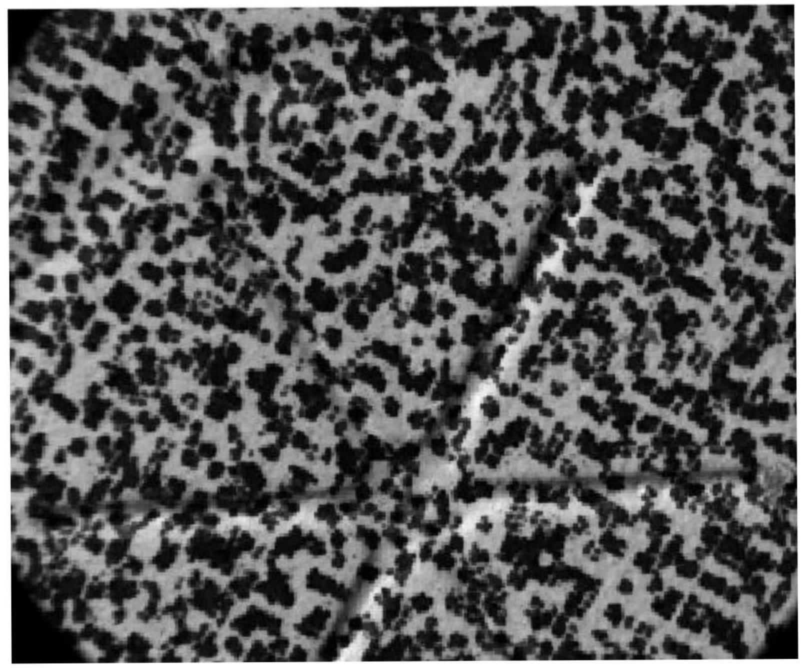
Polarization will remove highlights



Polarization in same direction



Almost correct



Cross-polarized

Linear polarizer
Cross-polarized to light

iDICs

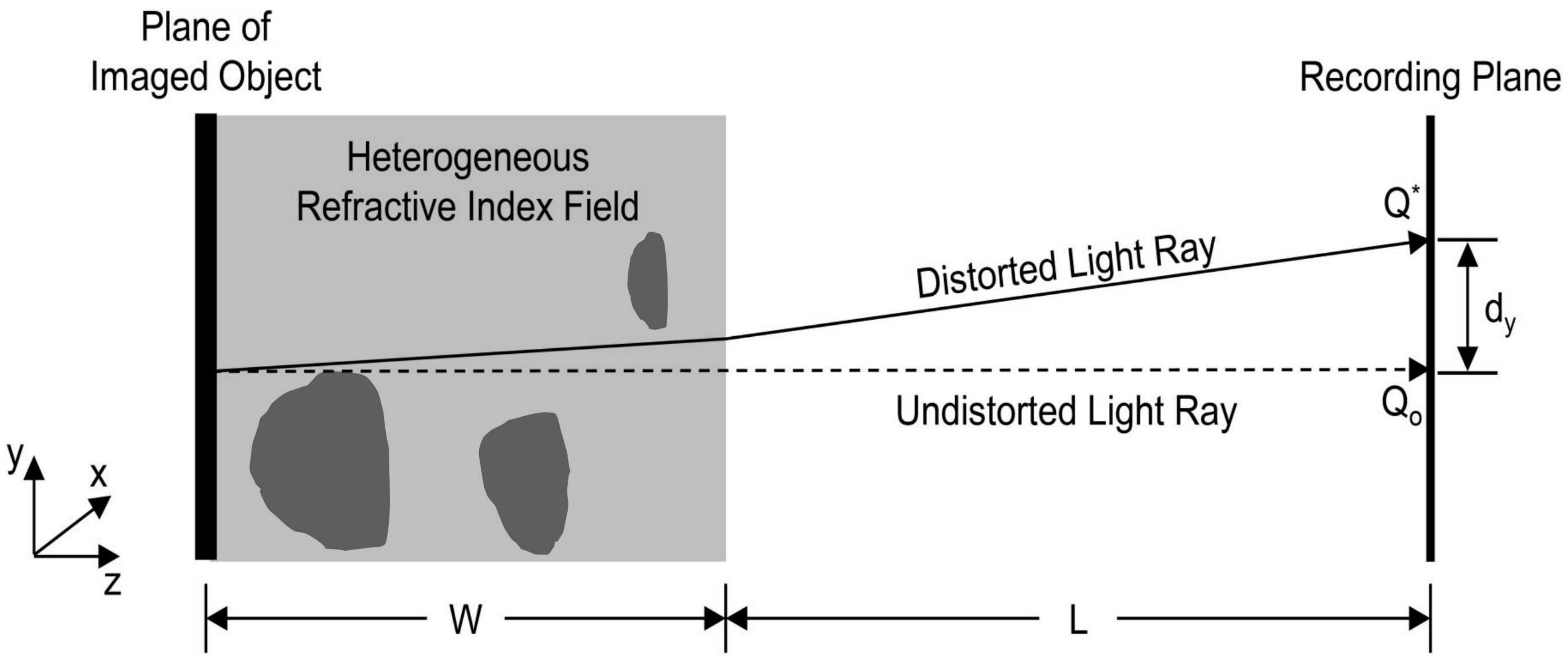
Recommendation 2.11 & 2.18 – Cross-polarized light.

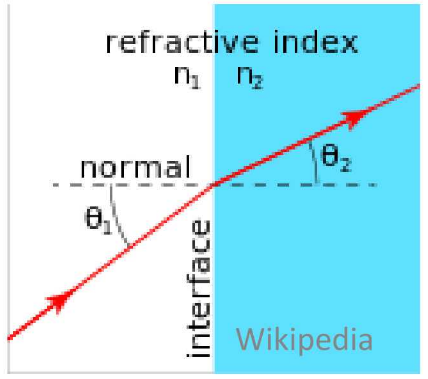
Tip 3.5 – DOF and light

EXPERIMENTAL SETUP: AIR TURBULENCE

THOSE RIPPLES YOU SEE IN YOUR NOISE FLOOR ARE HEAT WAVES.

Index of refraction changes between the sample and camera will distort the image





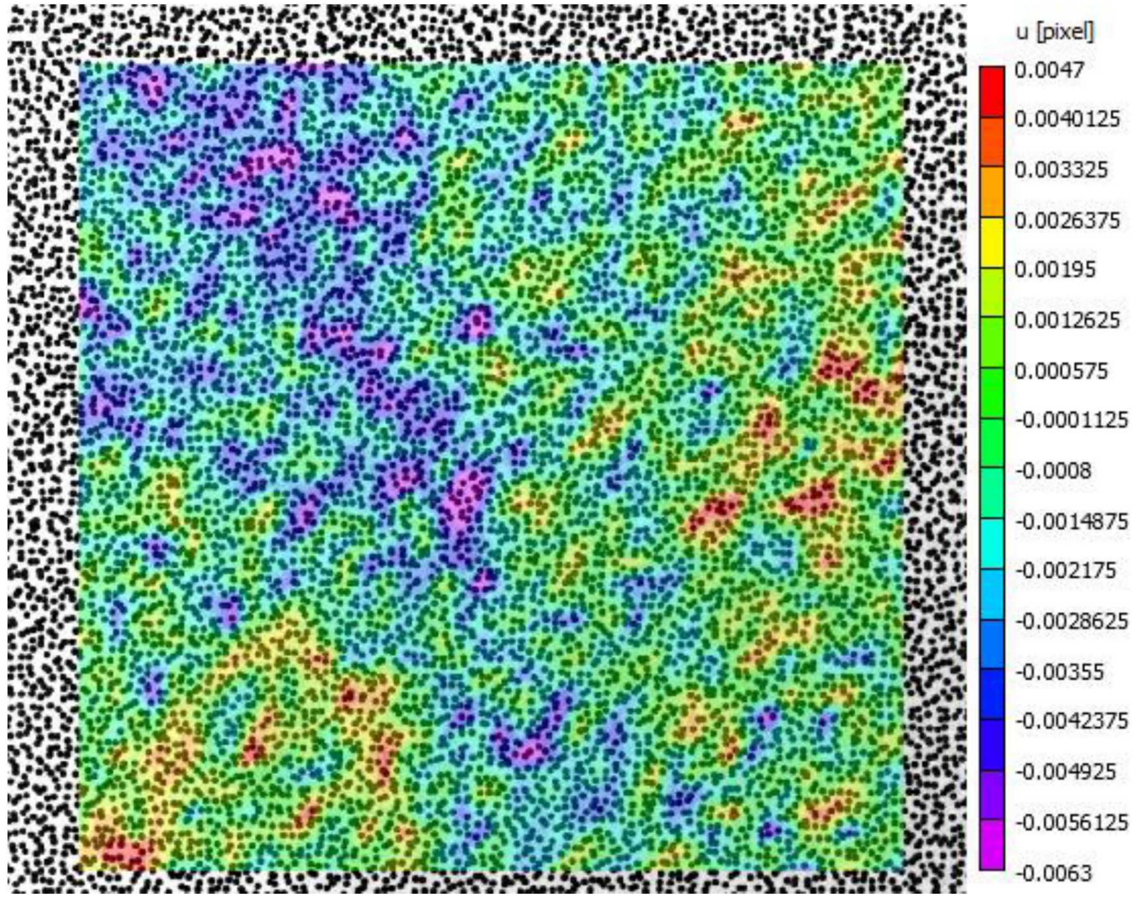
Wikipedia

I am using the phrase “air turbulence” loosely to mean, a volume of air that has both spatial and temporal index of refraction variation.

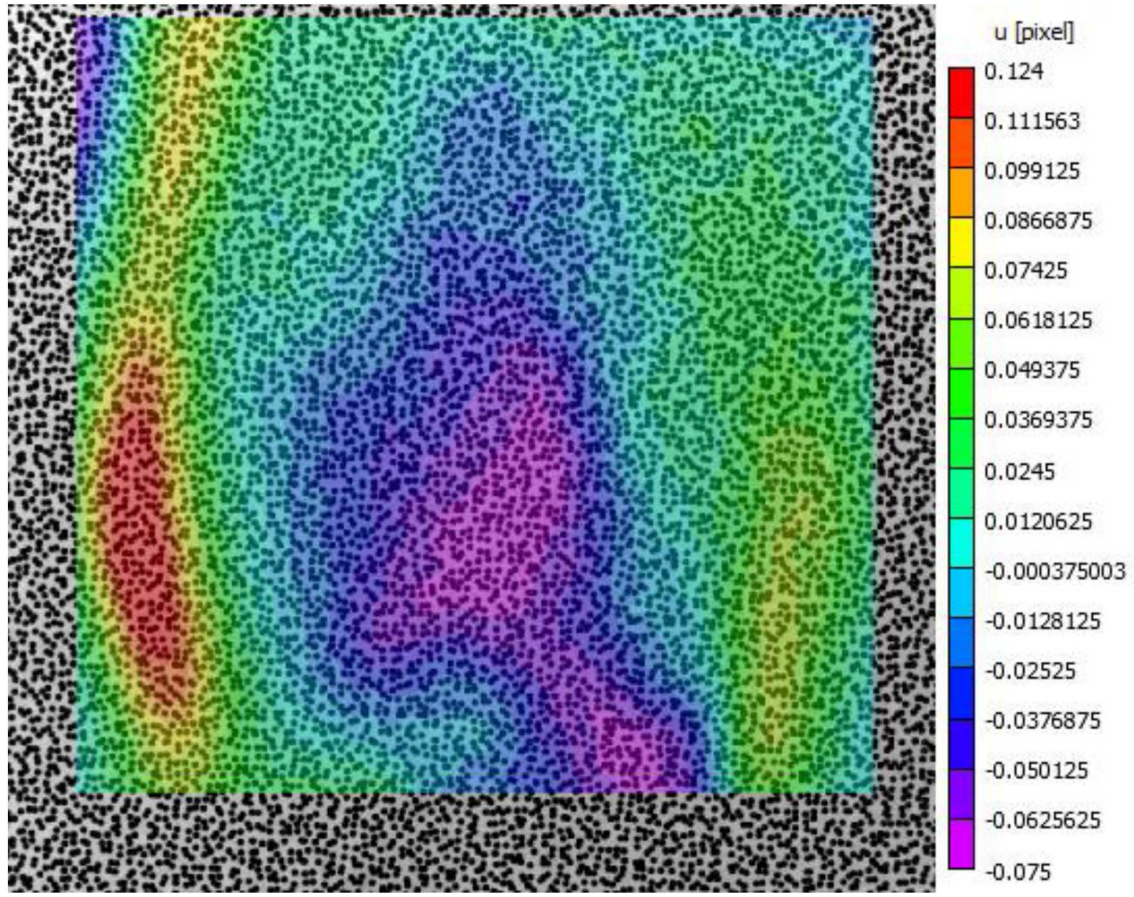
Causes in Air

- Shock waves (explosive or wakes)
- Heated air
- Species of molecule
- Foundation of BOS/Schlieren

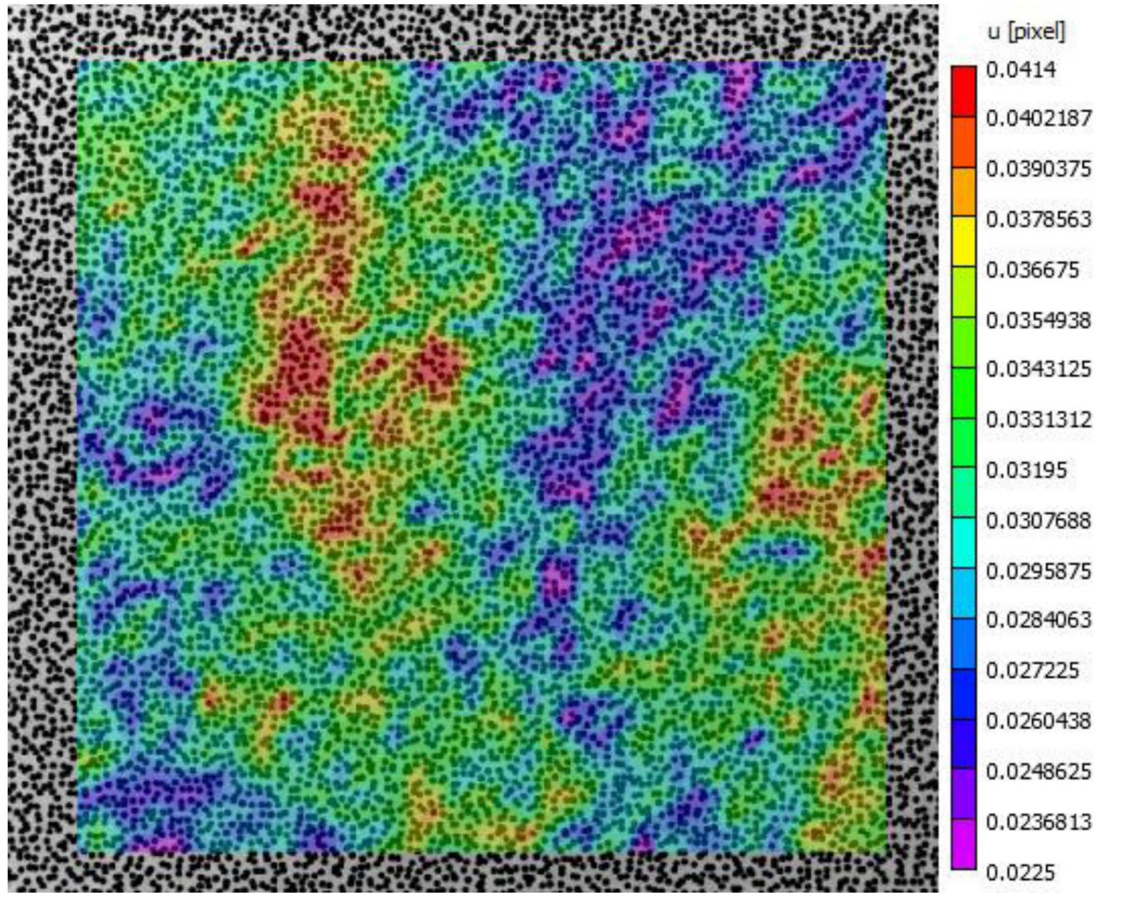
Examples of common heat waves from real experiments.



Cameras just turned on.
σ = 0.0023 (pixel)



Lights on below the sample (50 C)
σ = 0.04 (pixel)



Cameras on for ≈1 hour.
σ = 0.004 (pixel)

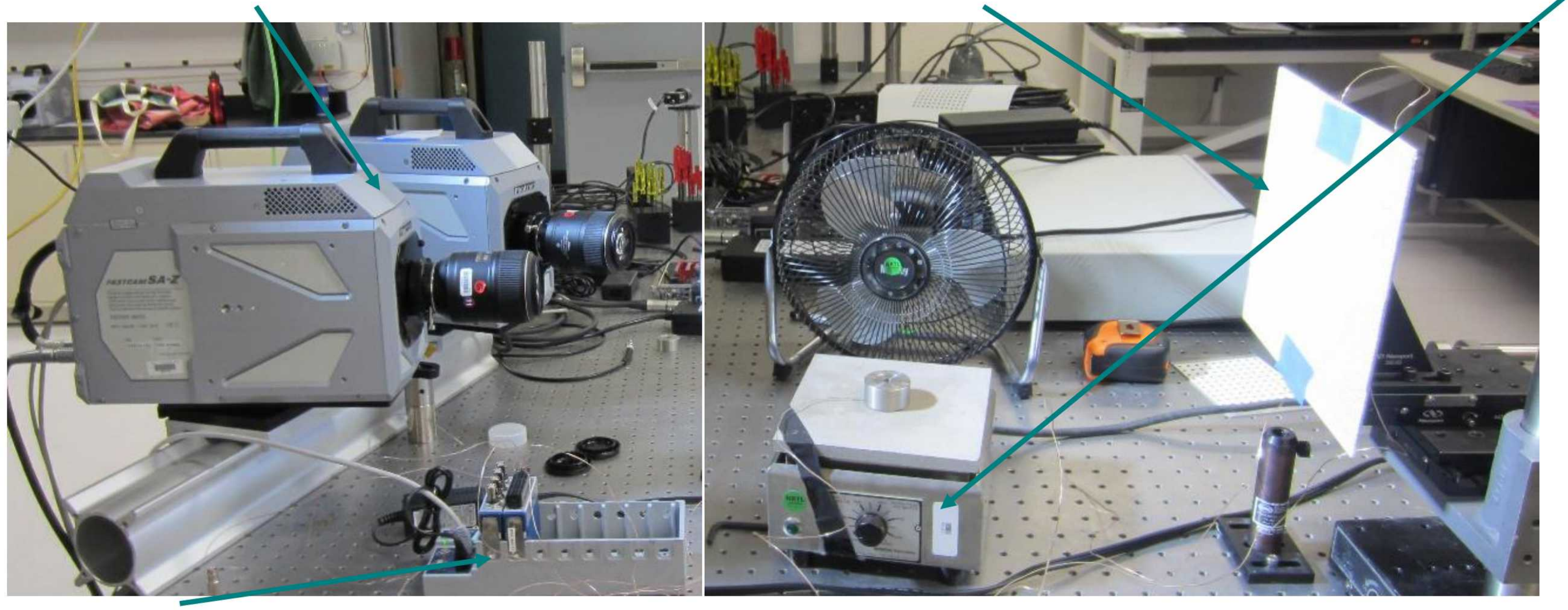
Experimental setup used a hot plate to create index of refraction variations

Photron SA-Z Cameras

Optimal speckle pattern.
FOV = 100 mm × 100 mm

Hot plate in various positions.

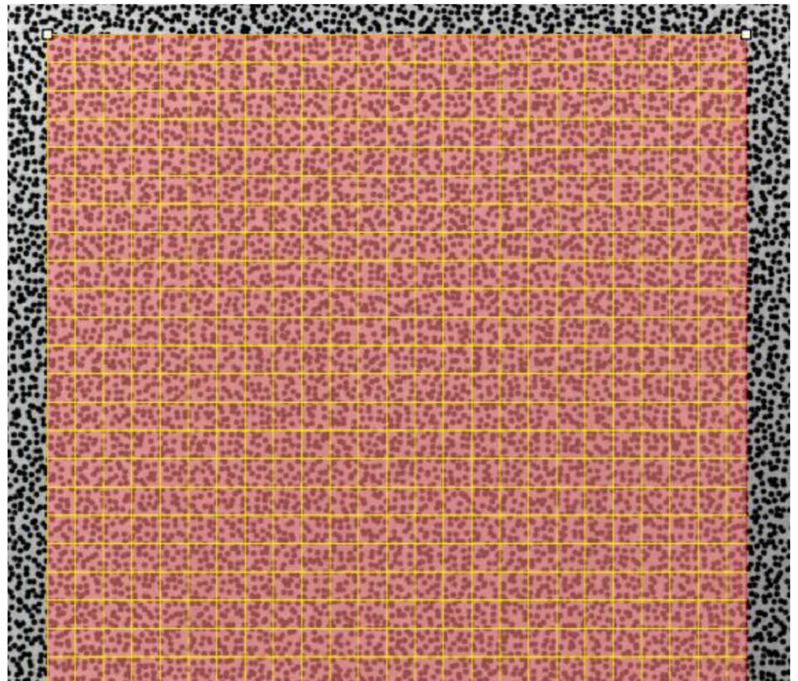
- Near plate
- Centered between
- Above cameras (light position)



NI-DAQ Thermocouple Board

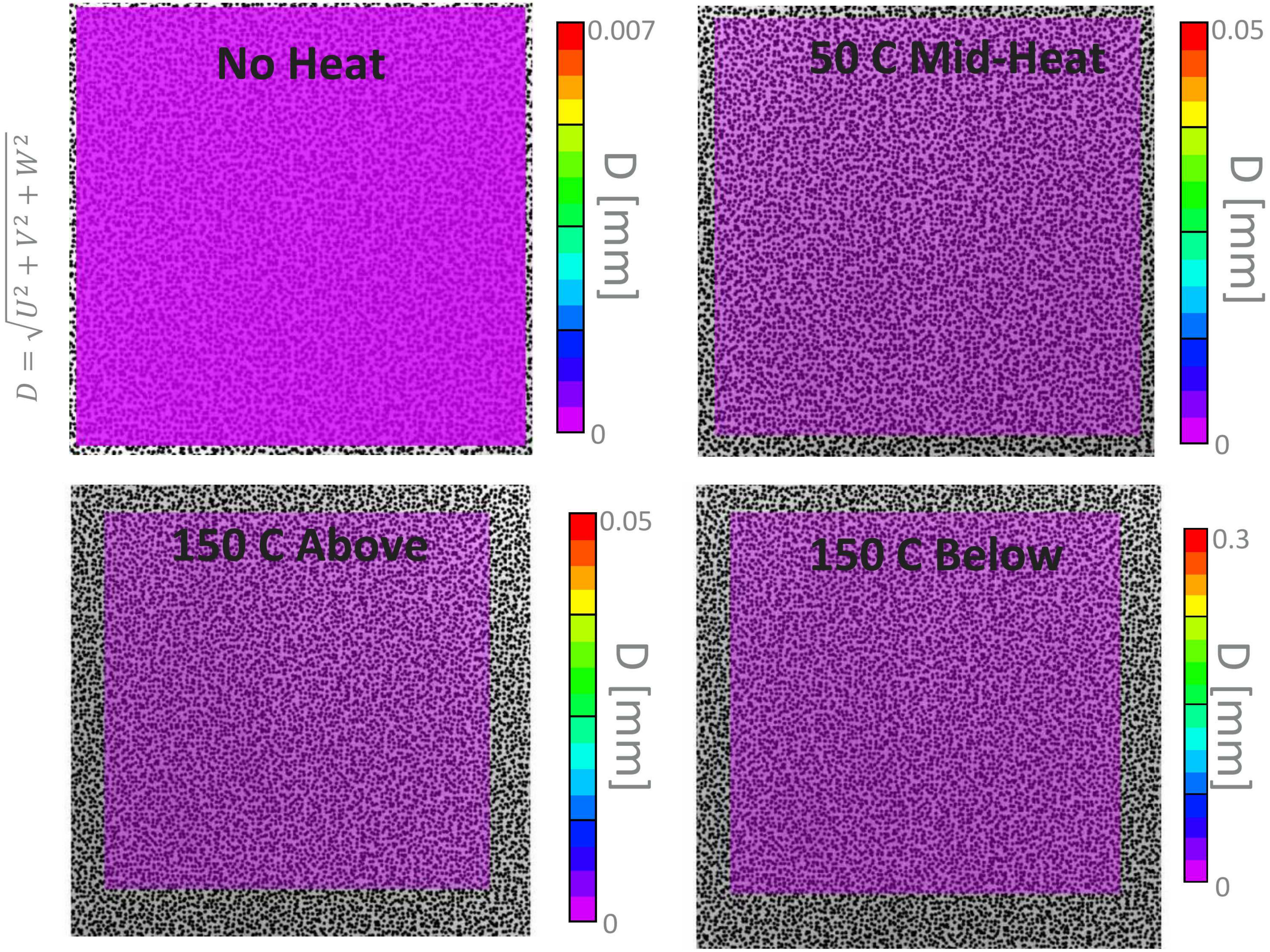
Setup Details

- High-speed cameras needed for adequate bandwidth (250 Hz)
- Temperatures used included LED light temperatures (50 C)
- Fan used to break up turbulence
- DIC settings used to increase solution speed
- Displacement is used as the metric: $D = \sqrt{U^2 + V^2 + W^2}$



Vic3D	Value
Subset	37
Step	20
Interpolation	4-Tap
Minimization	NSSD
Coordinates	Origin X-Axis
Pixel Size	0.115 mm/pixel

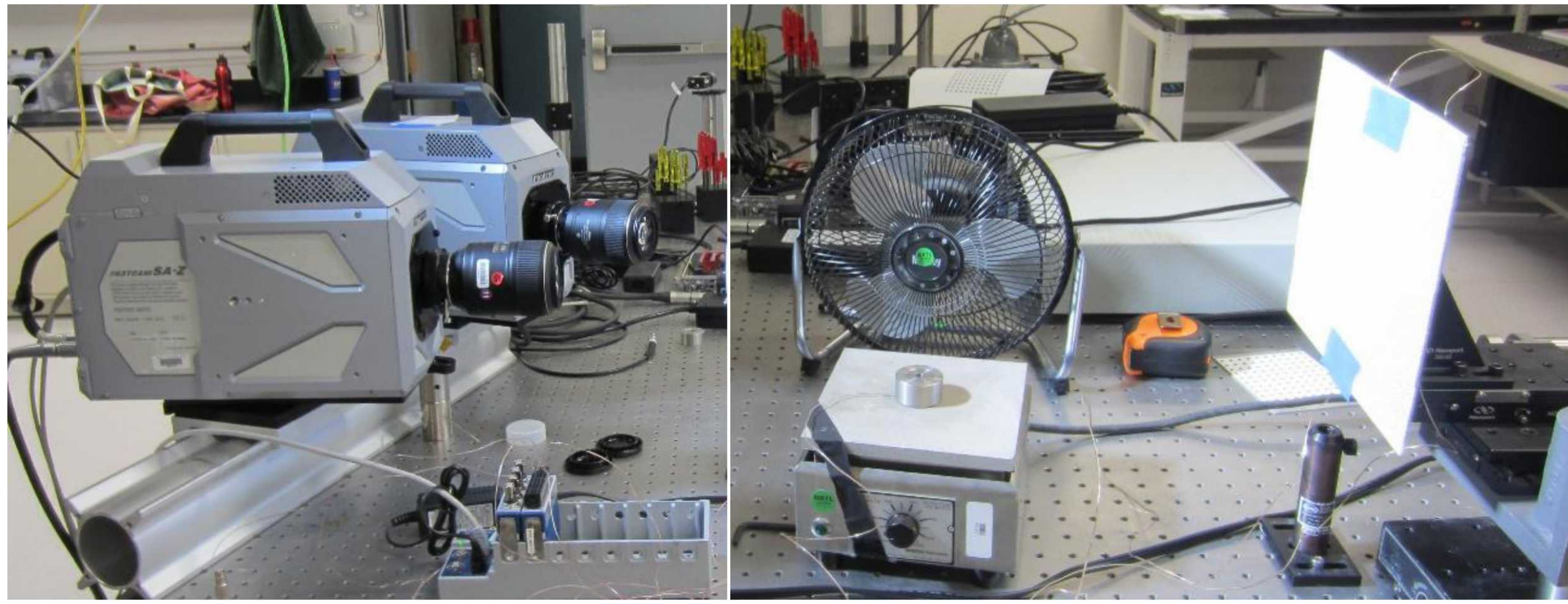
Location of the heat and temperature will strongly influence the results.



$$D=\sqrt{U^2+V^2+W^2}$$

Influence of heat by location

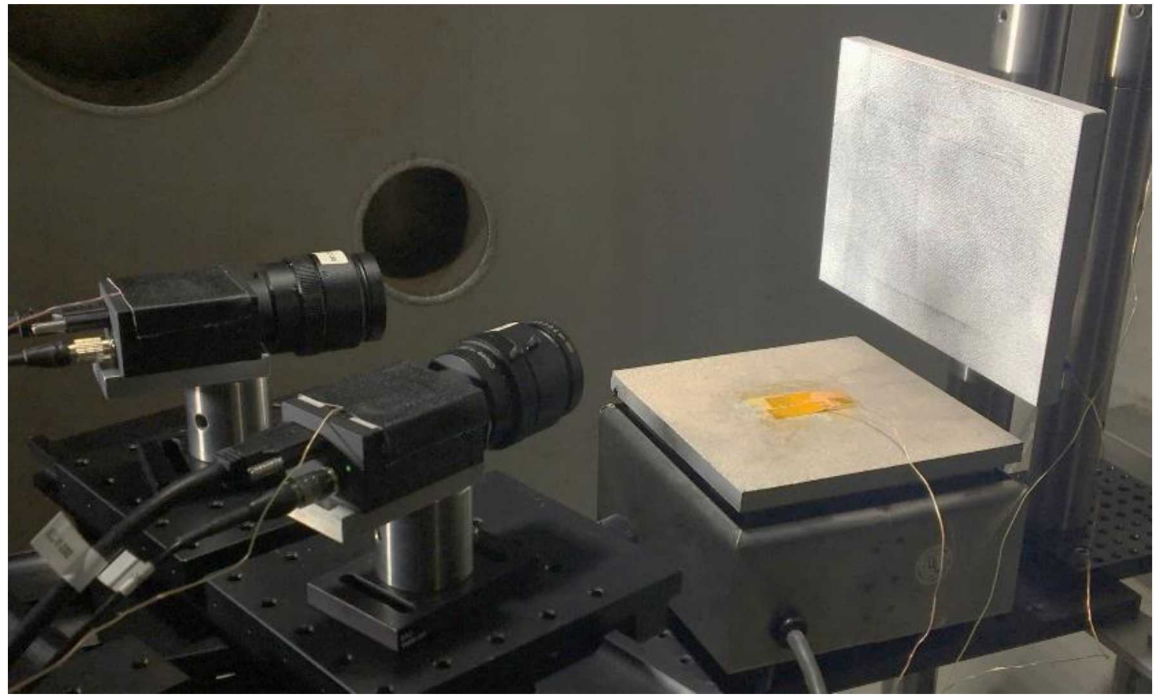
- Closer to sample is better.
- Position lights (heat) above cameras

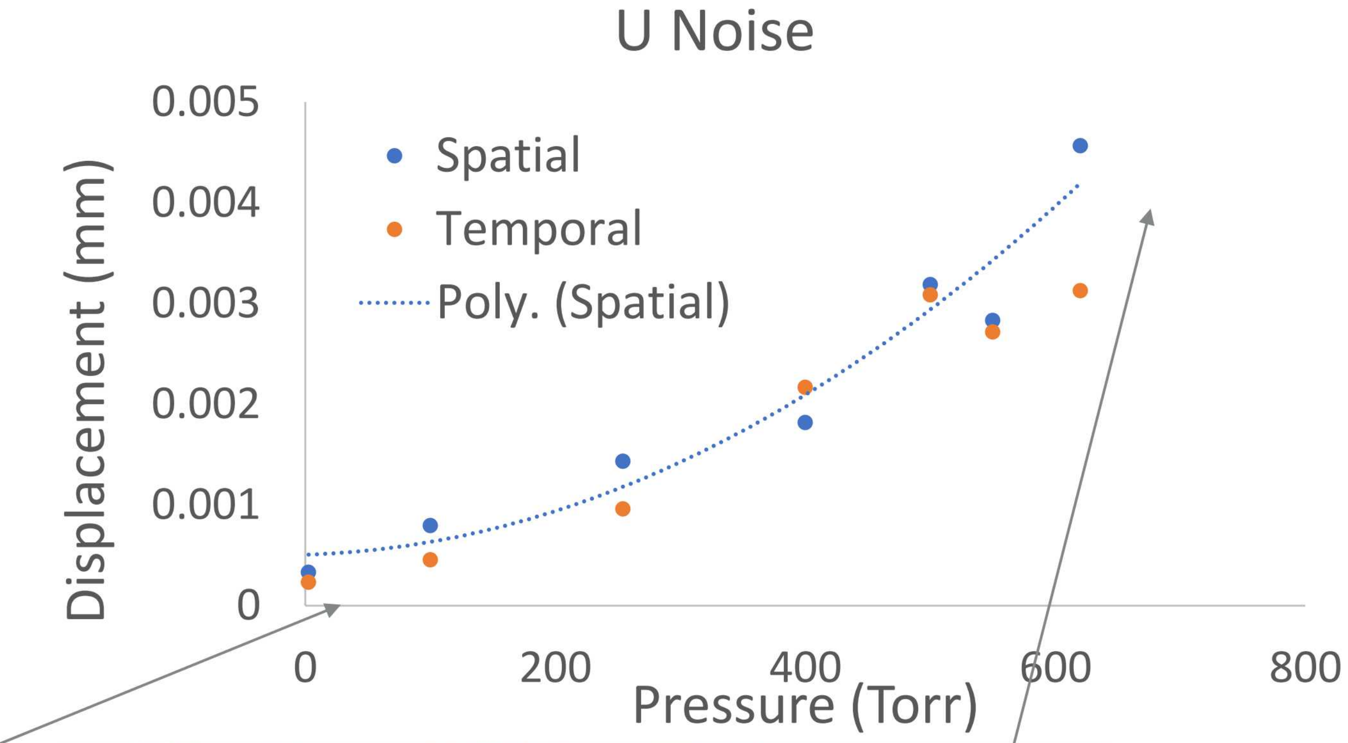


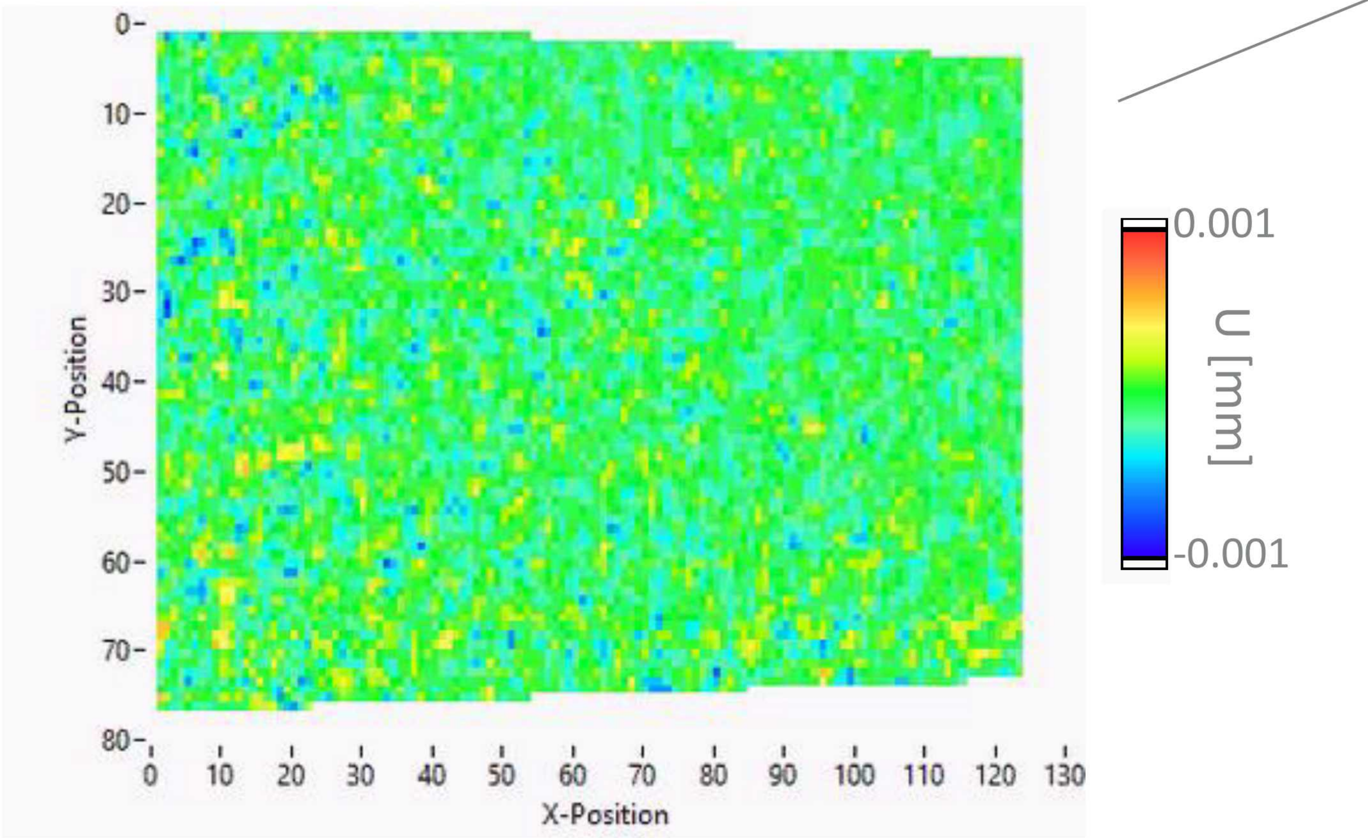
Section 3.3.3.2 – Heat waves

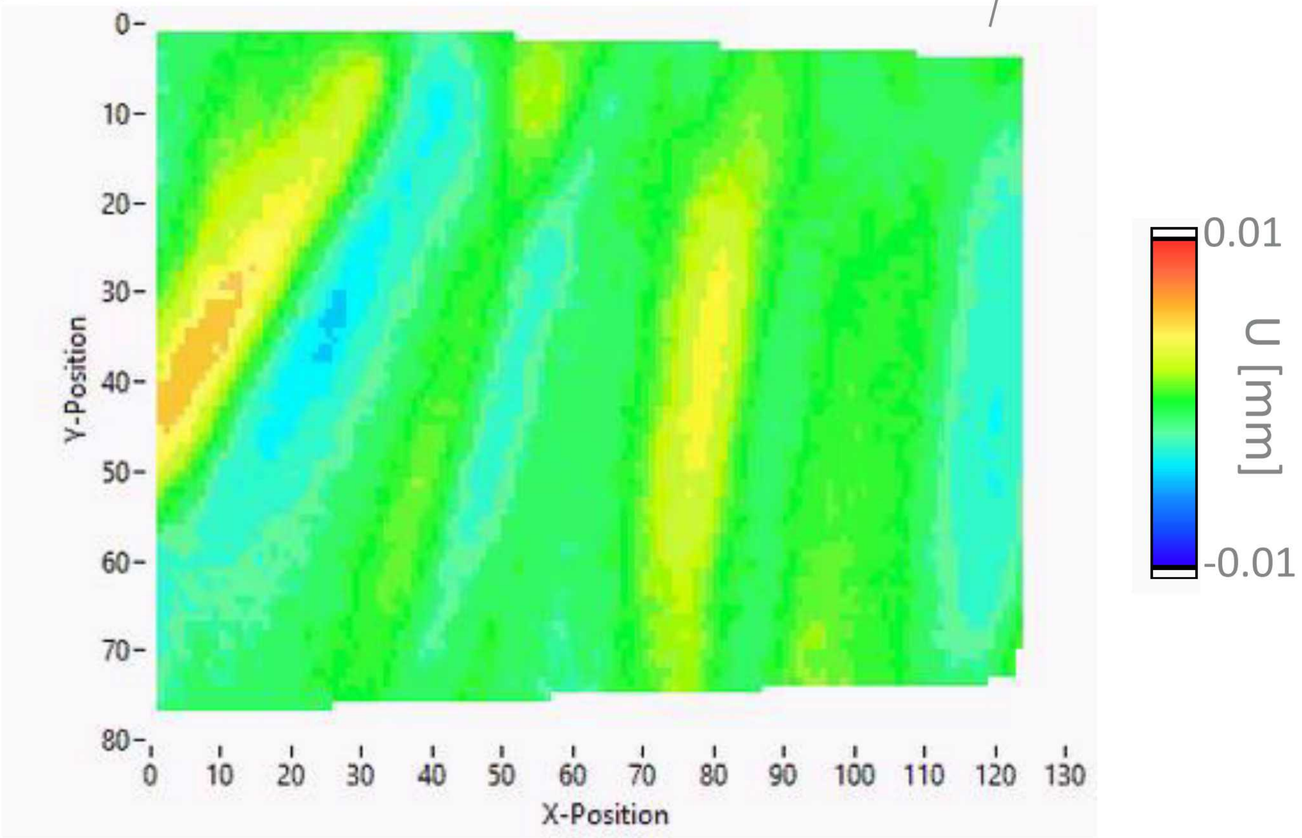
Recommendation 2.15 – Lights behind camera

DIC in vacuum proves heat waves are the culprit!



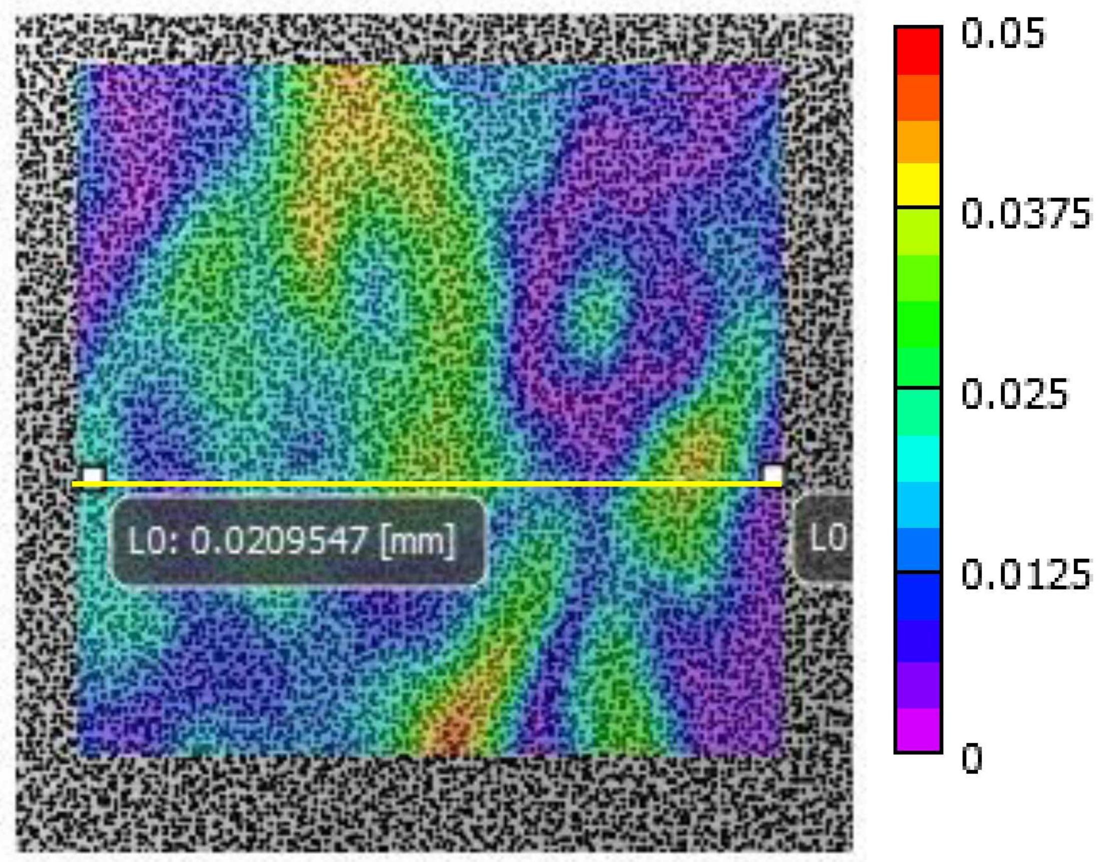






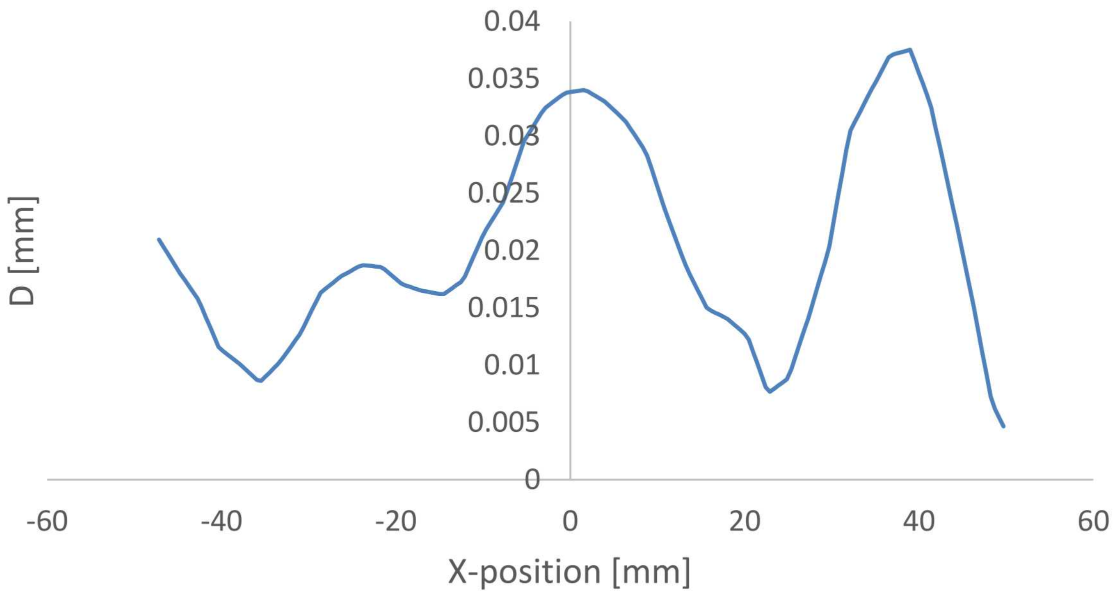
10× improvement under vacuum

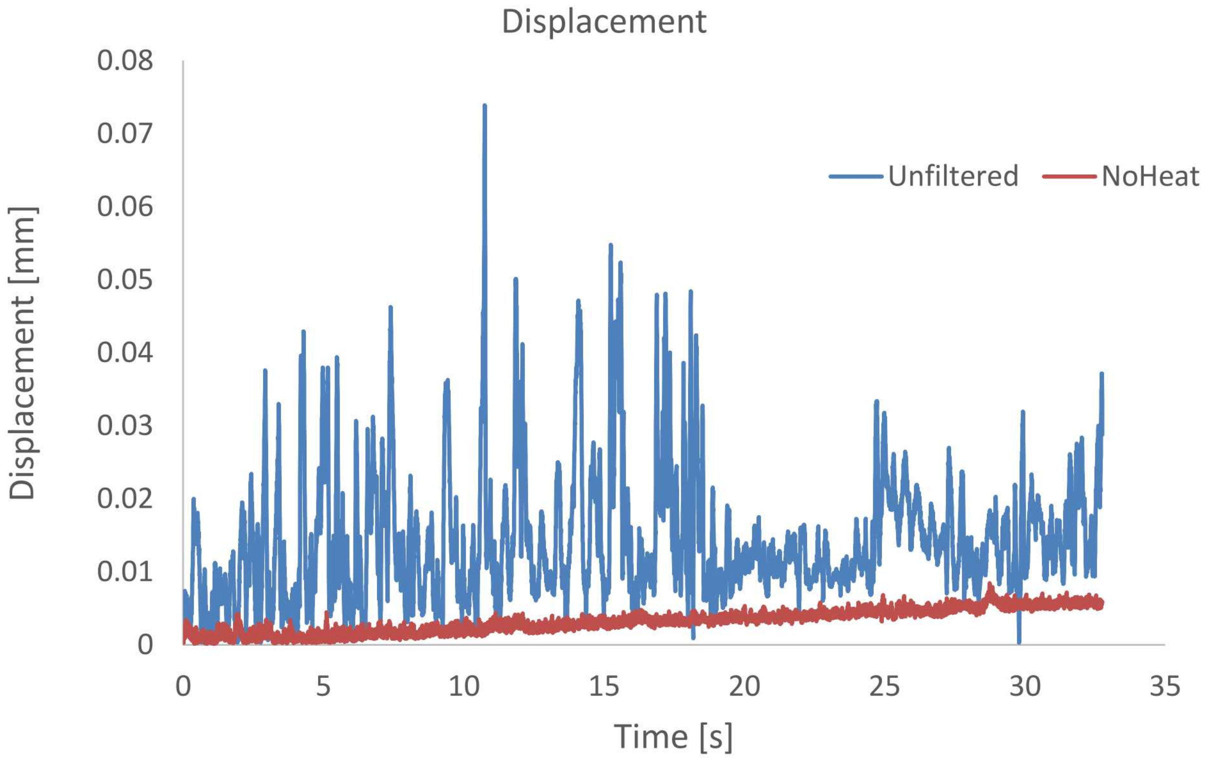
Two types of errors will occur: Spatial and Temporal Errors.



Definitions of errors

- Temporal error varies at a given pixel through time.
- Spatial errors vary across the field-of-view.
- Both displacements and strains are affected.

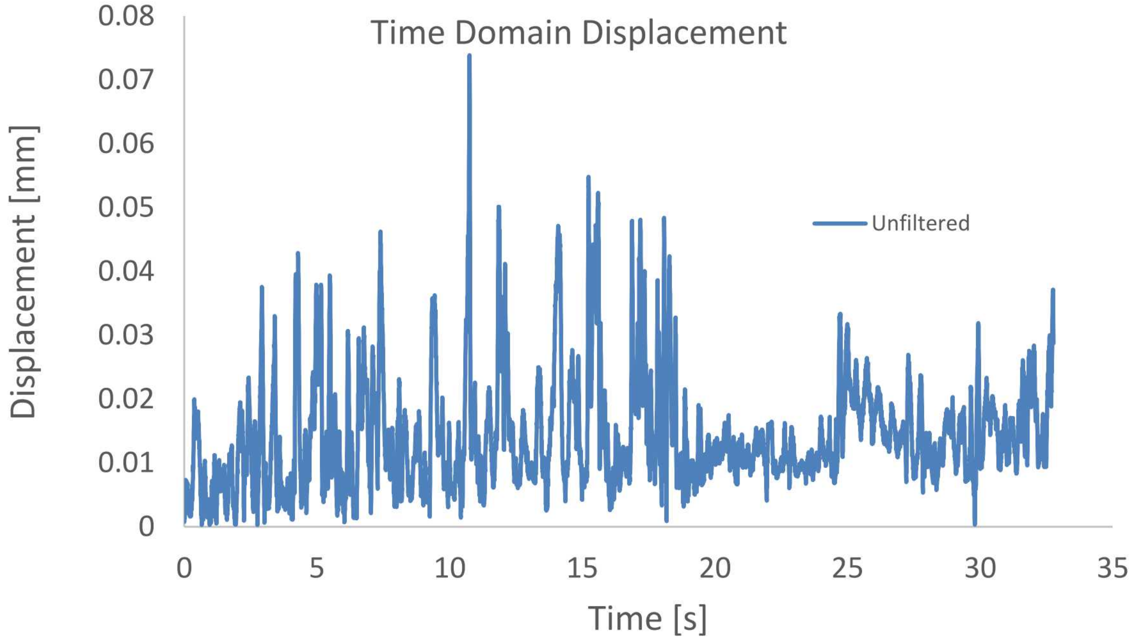


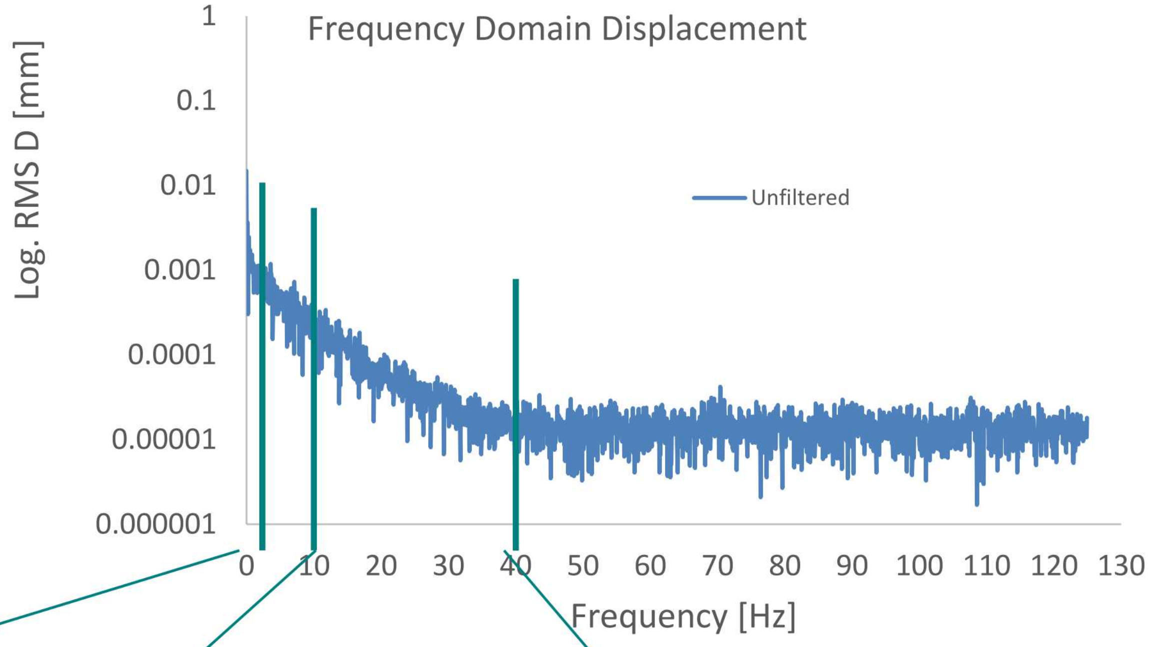


$$D = \sqrt{U^2 + V^2 + W^2}$$

Experimental Setup: Air turbulence

The frequency content of the heat waves is a key to eliminating them.



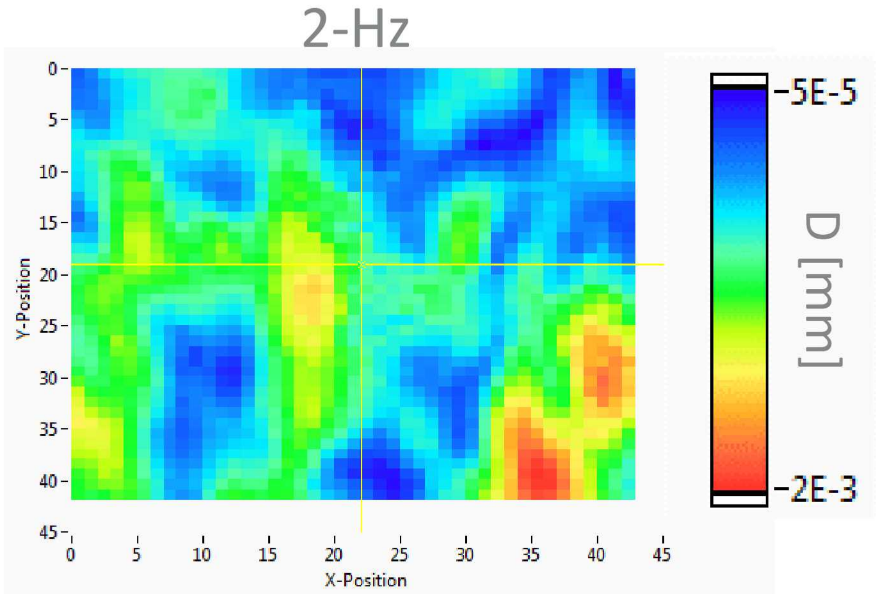


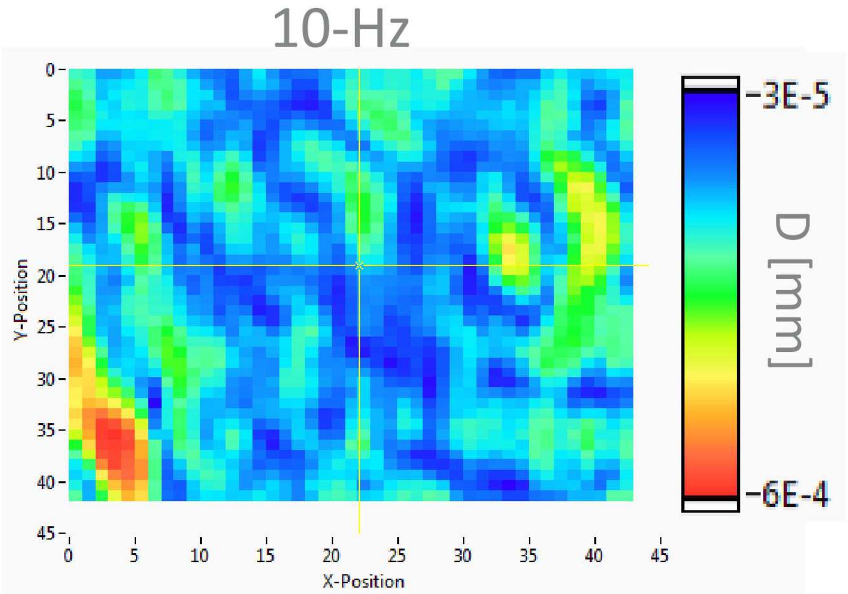
$$D = \sqrt{U^2 + V^2 + W^2}$$

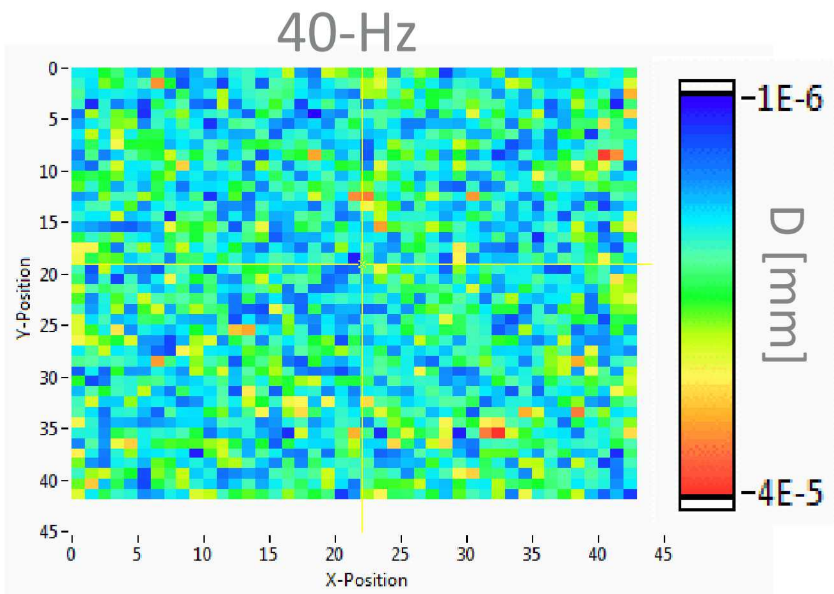
Data point (22,19)

At cross-hair

Shown without speckle pattern

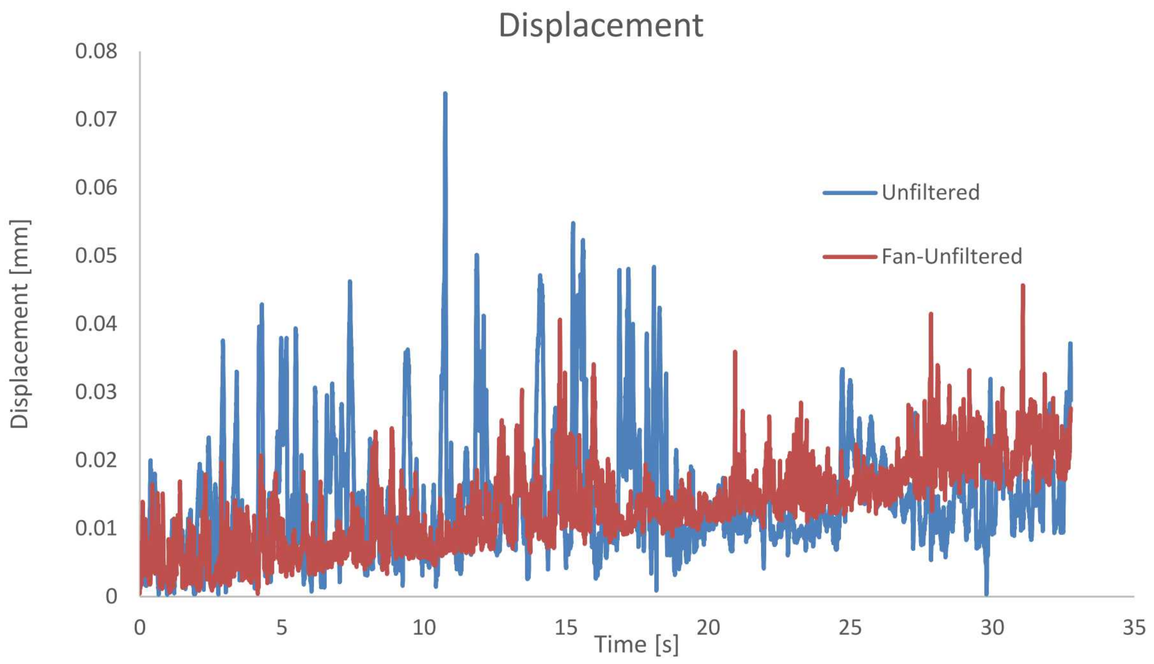


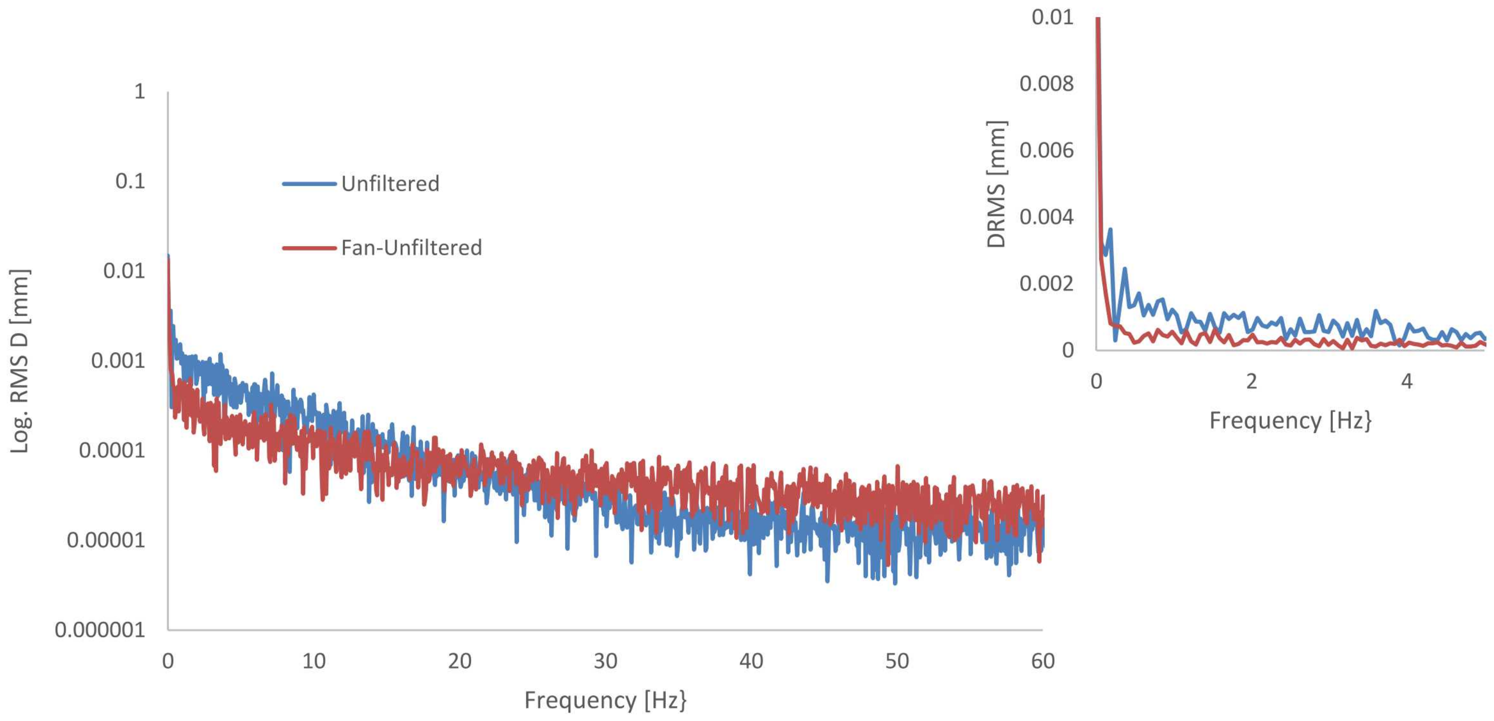


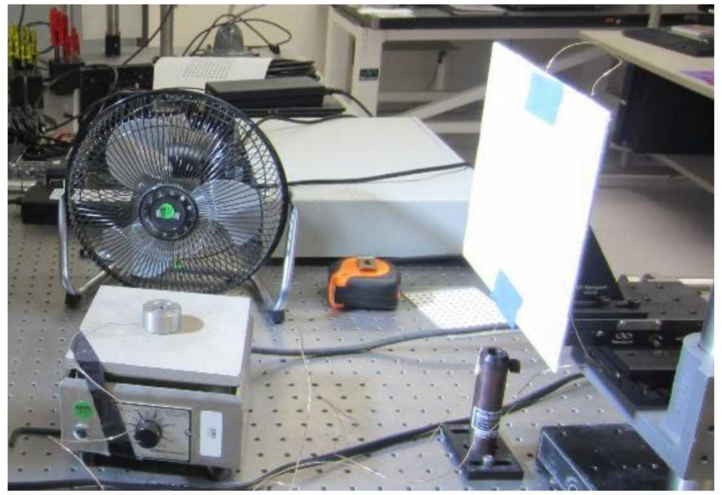


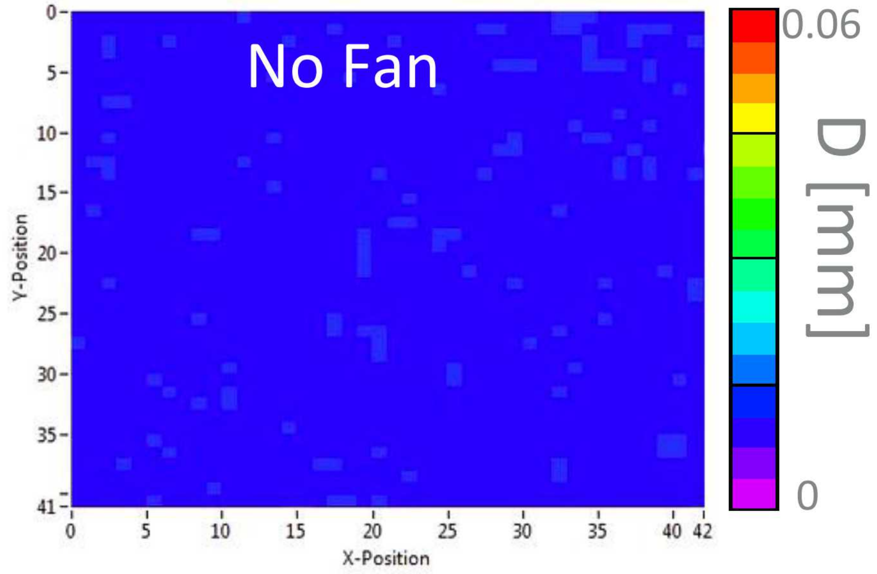
iDICs Recommendation 2.15 – Not easily filtered

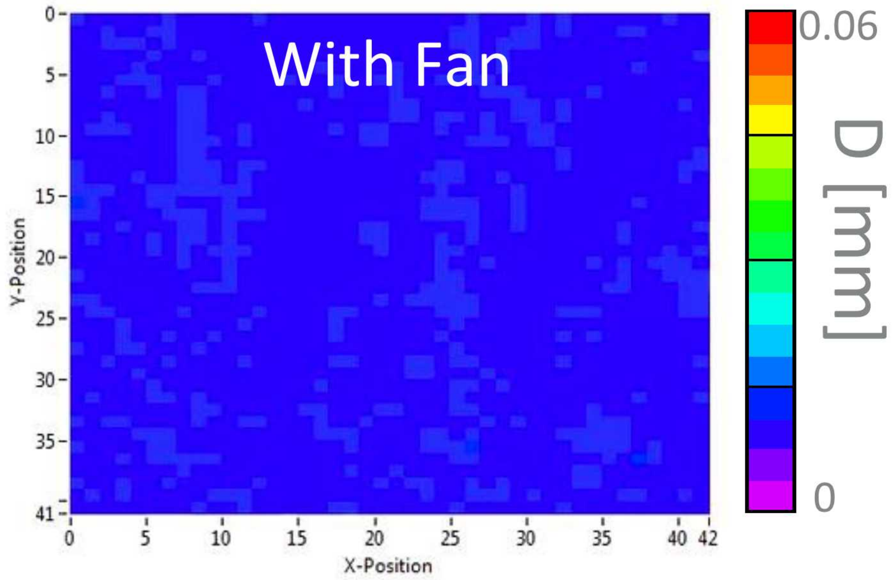
Fans can break up the heated zones minimizing their influence









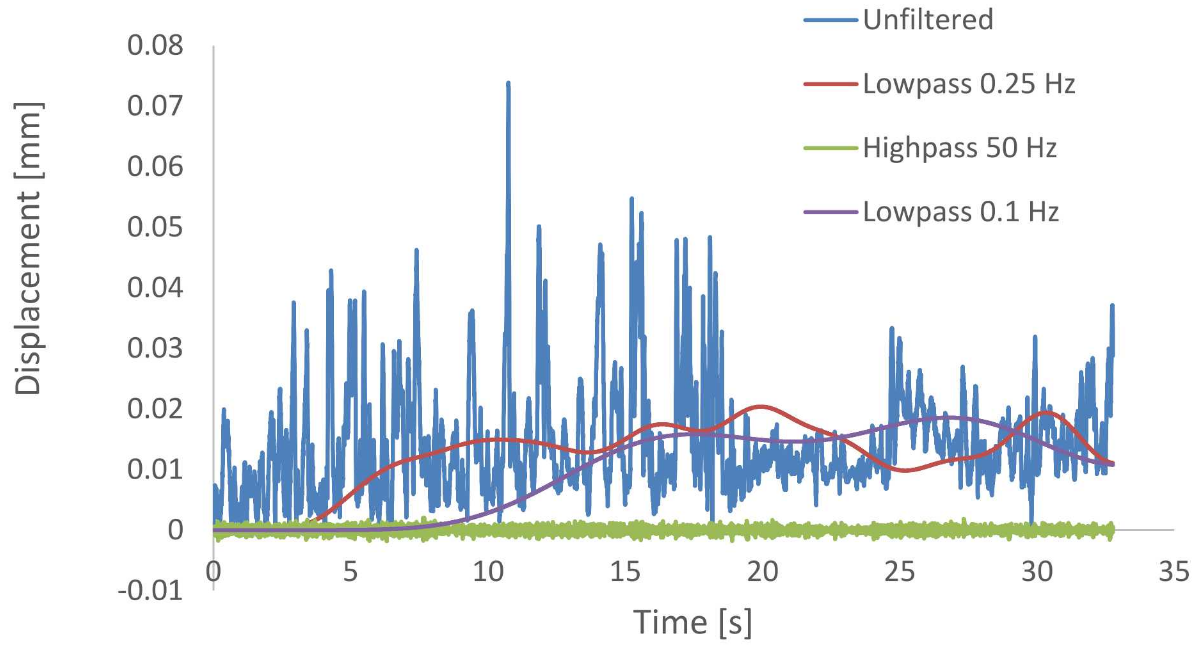


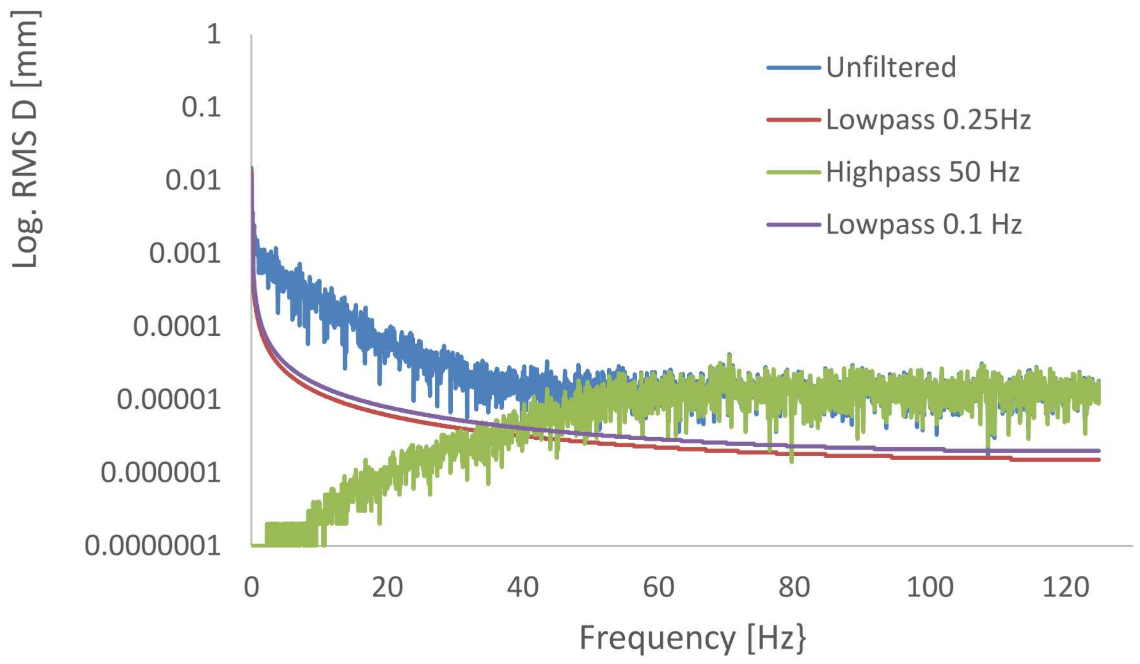
Pros/Cons of Fans

- Breaks up the low frequency turbulence and distributes it to higher frequencies
- Need to consider camera motion and vibrations

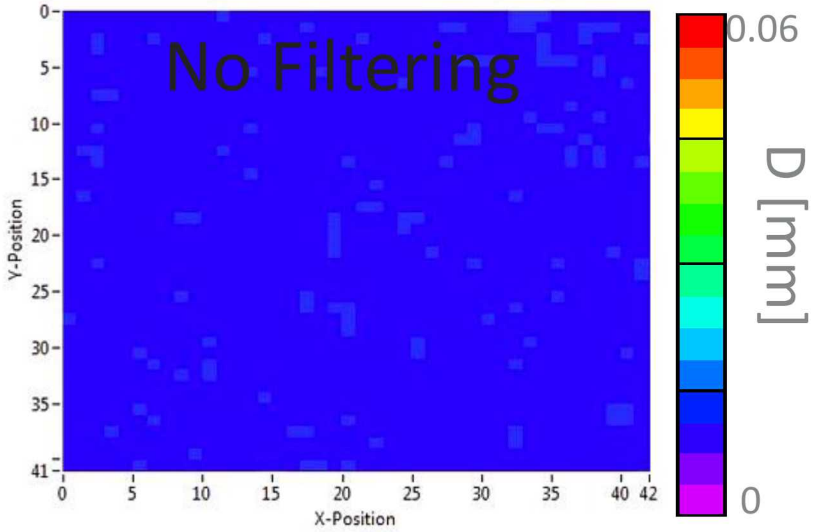
$$D = \sqrt{U^2 + V^2 + W^2}$$

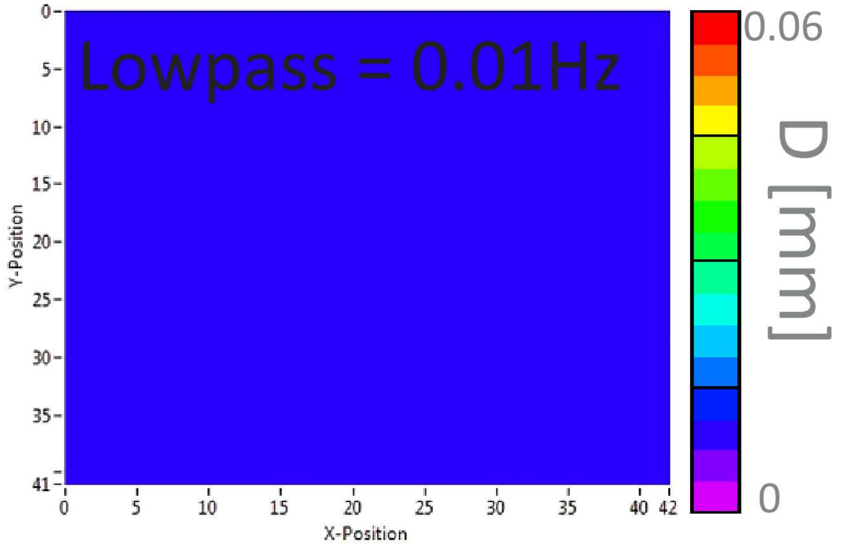
There are optimal filtering strategies to removing the air turbulence.

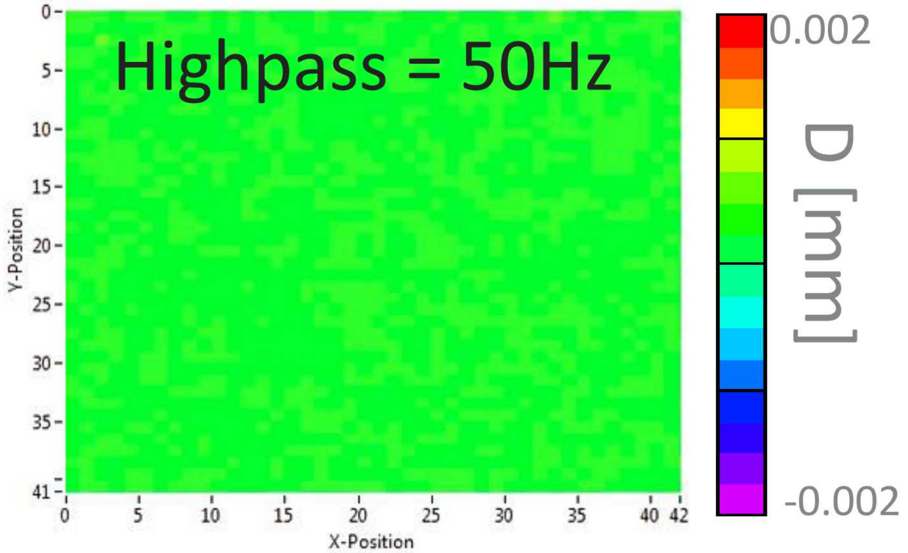




$$D = \sqrt{U^2 + V^2 + W^2}$$







- Lowpass filtering can greatly decrease the magnitude of the heat waves, without changing the spatial frequency.
- Highpass filtering can completely remove the heat waves.

Recommendation 2.15 – Not easily filtered

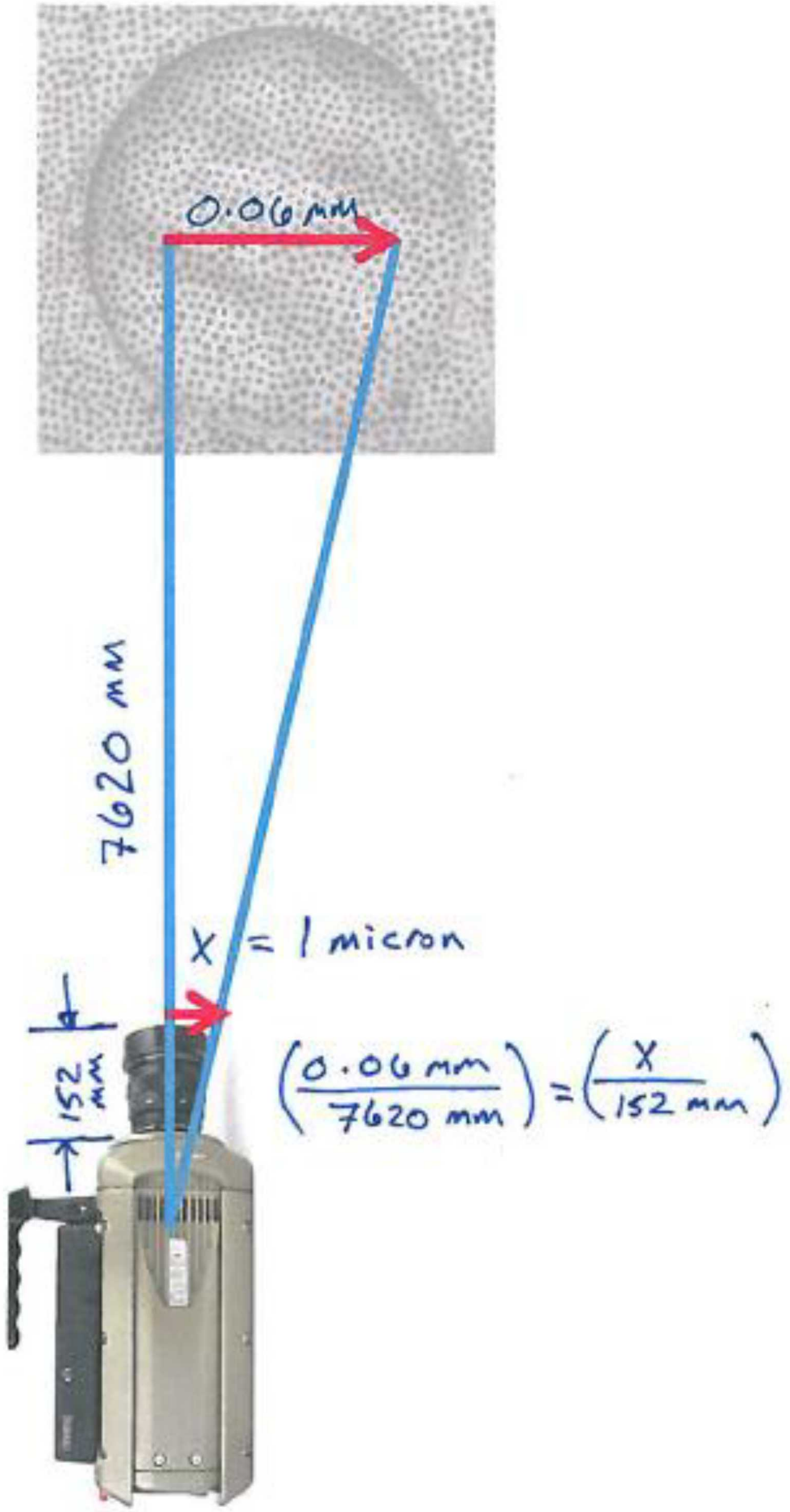
Focal length can cause issues with magnifying camera motion.

A typical outdoor experiment:

a) 7.6 m away
b) Field-of-view 1.2 m
c) Displacement Resolution 60 µm
d) Motion at end of lens < 1 µm

Mounting rules

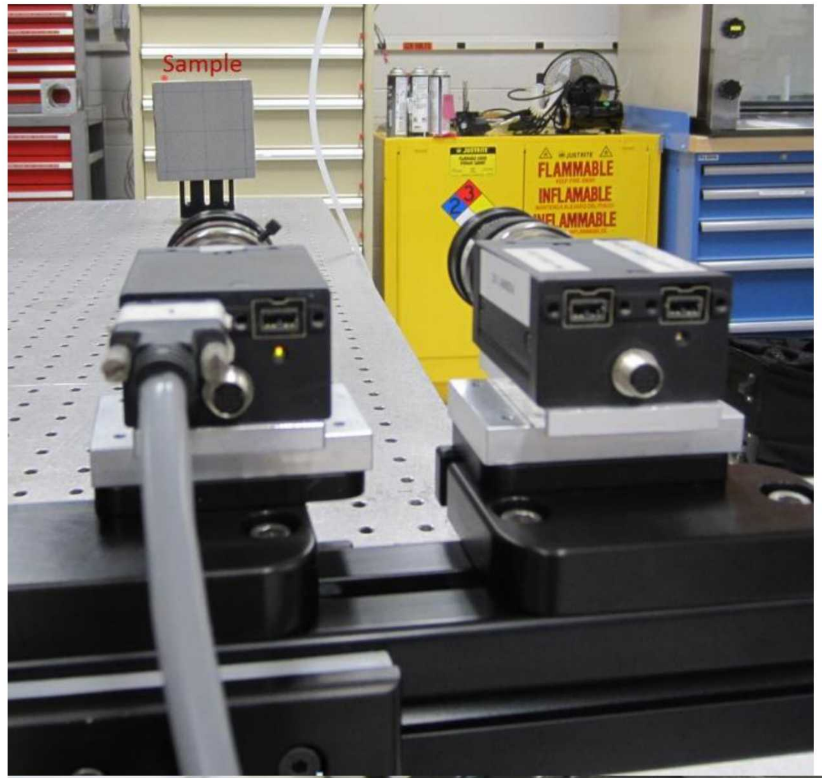
a) RIGID MOUNTING
b) No Tripod heads
c) Be aware of thermal issues
d) Consider shock and vibration from the experiment

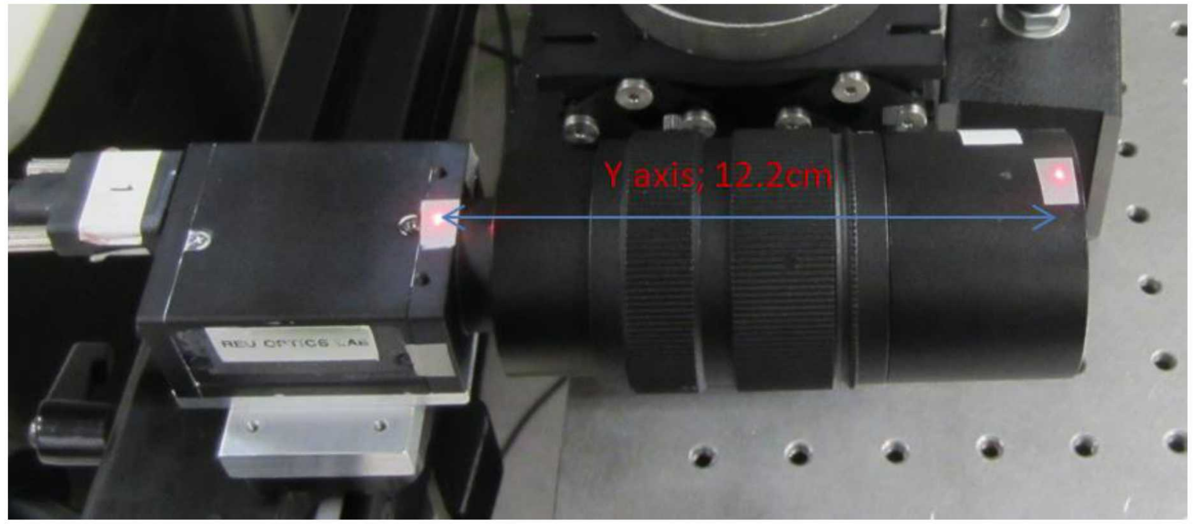


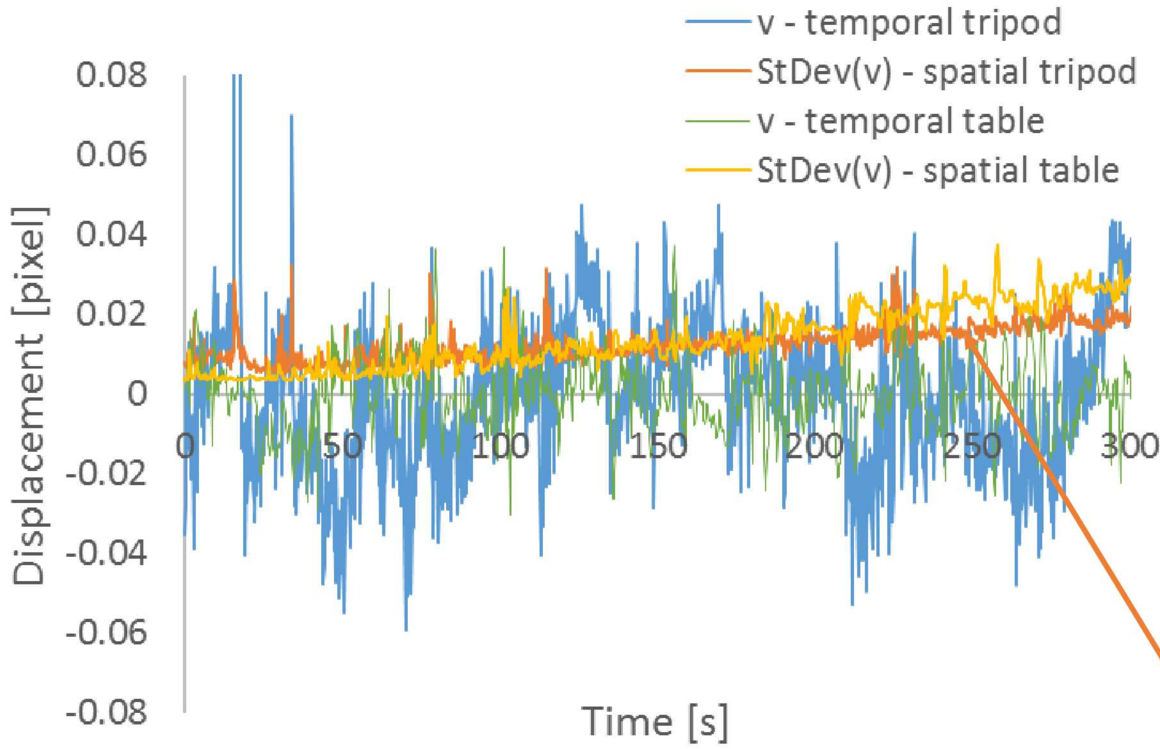
Recommendation 2.9 – Vertical mounting caution

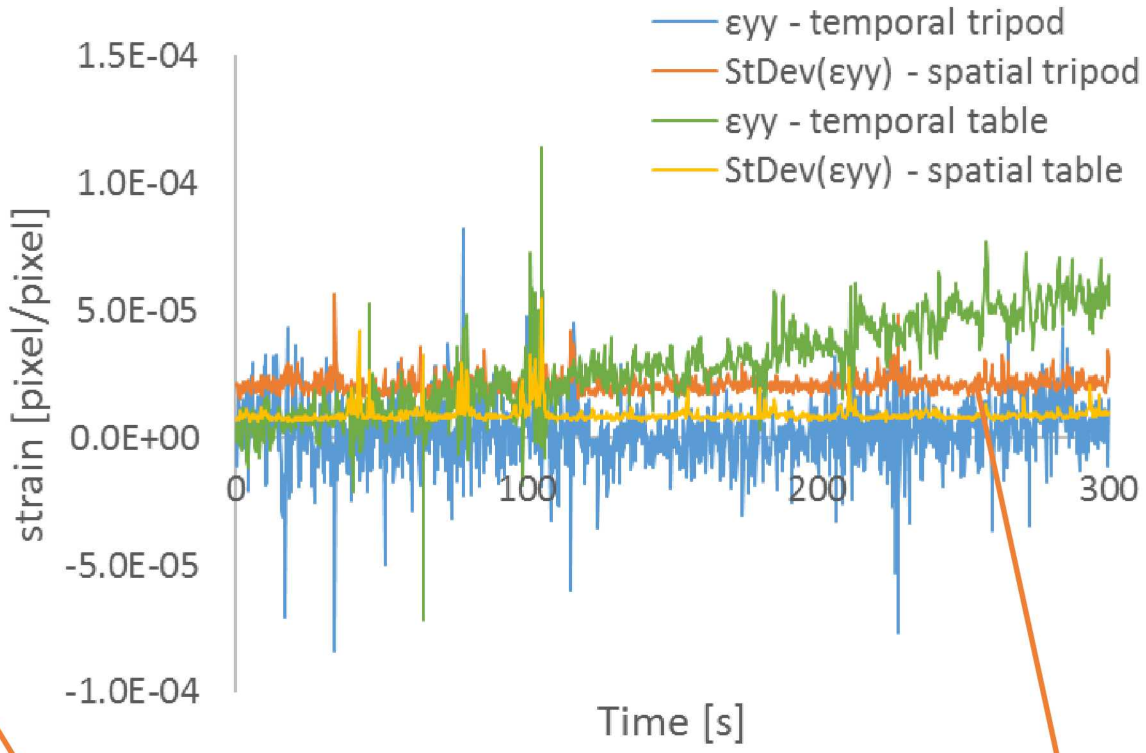
Caution 2.7 – No relative motion

Camera vibrations: The down-side to long focal length lenses.









Temporal error is increased more for 75-mm lens

	Temporal (σ)		Spatial (Avg. σ)		Temporal (σ)		Spatial (Avg. σ)	
	u (pixel)	v (pixel)	u (pixel)	v (pixel)	ε_{xx} (με)	ε_{yy} (με)	ε_{xx} (με)	ε_{yy} (με)
35-mm Tripod	0.019	0.022	0.011	0.013	14	12	22	21
75-mm Tripod	0.045	0.046	0.015	0.018	44	43	47	40
Optical Table	0.011	0.009	0.016	0.014	18	18	11	9
35-mm Difference	0.007	0.013	-0.005	-0.001	-4	-6	10	12
75-mm Difference	0.033	0.037	0.000	0.004	26	25	35	31

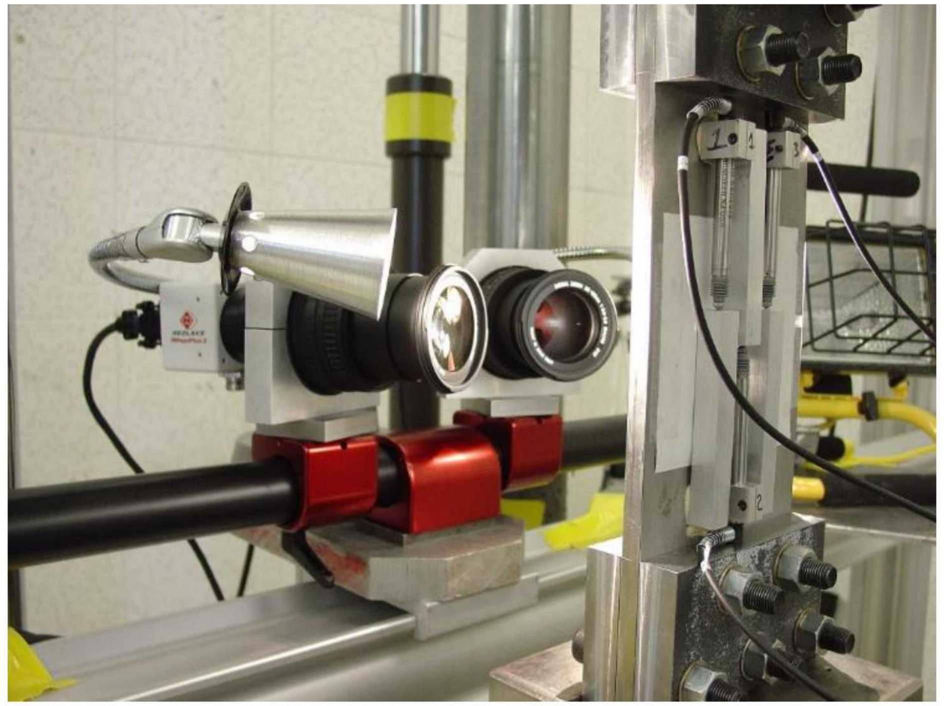
Spatial error is constant. I.e. the same pattern, etc.

75-mm lens with larger standoff has both more vibration & heat waves

Heat waves increases strain errors. More on this later…

Consider what will violate the camera calibration

- Thermal affects on mounting bar
- Vibration of the mounting bar
- Loose lenses, long lenses
- Shock waves/Sound blast
- Balanced with the need to
  - Adjust the camera pointing
  - Change the stereo angle
  - Point the stereo rig



You can move the stereo-Rig

THE BOTTOM-UP ERROR TABLE: TYPE A OR B

WRAPPING IT ALL UP.

BOTTOM-UP: COMPREHENSIVE LIST OF ERRORS

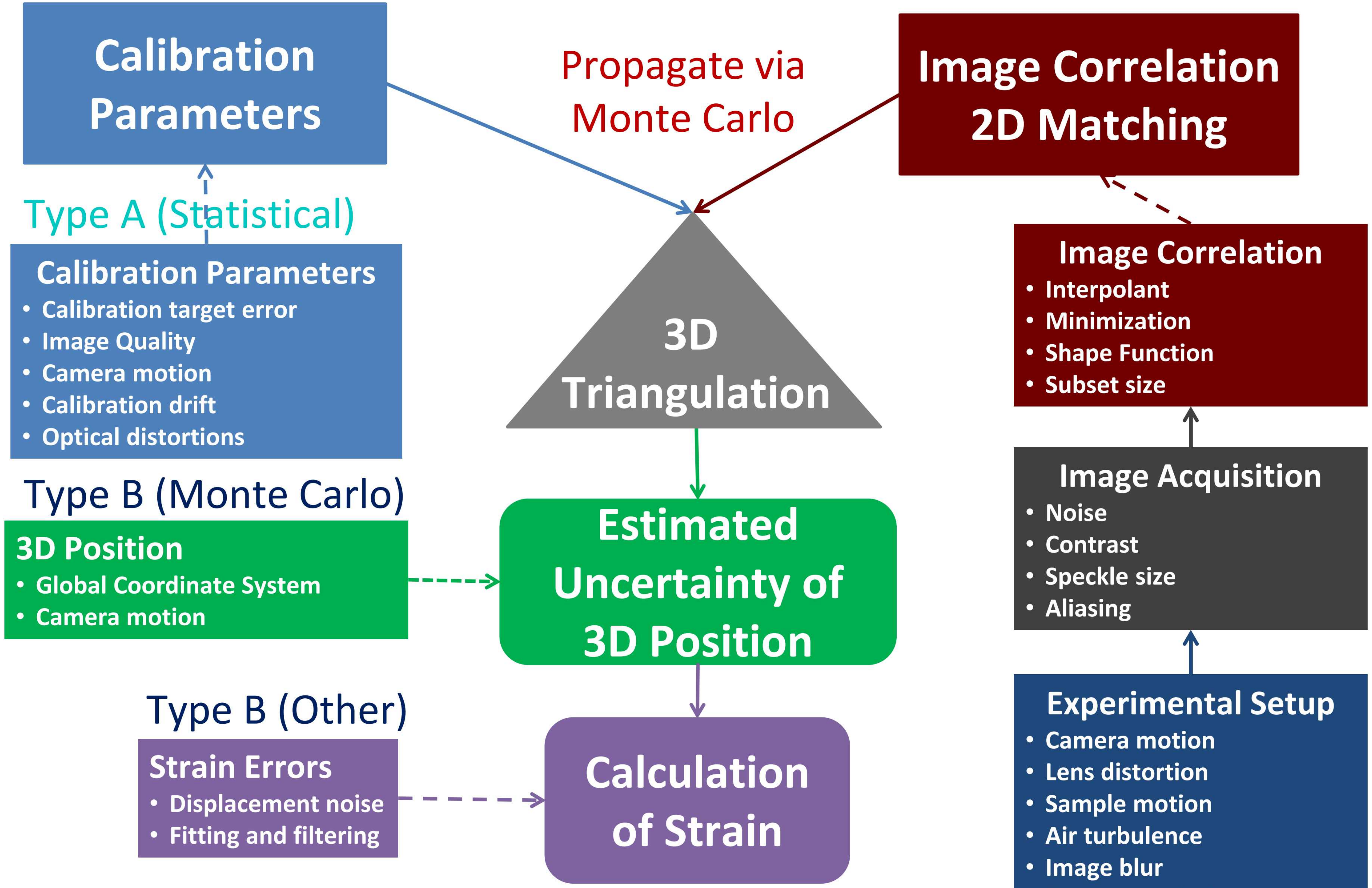
2D Error Source	Type	Assessment Method/Comments	|D| ≈ mm	|D|≈pixels
Lens distortion	B	Previous calibration 100-mm Lens Not motion	<0.001	0.009
Camera motion	A,B	Stationary pattern – See later in slides	<0.02	0.18
Sample motion	B	Fixed target on table	0	0
Turbulence	A,B	This presentation for 50 C heat source	0.01 – 0.07	0.09 – 0.6
Image blur	B	Stationary	0	0
Resolution	B	Adequate pixel size	0	0
Image noise	A	Noise floor (5 frames at start of experiment)	0.001	0.009
Pattern contrast	A	Contrast ≈ 160 counts (Included in noise floor)	Noise floor	
Pattern Induced Bias	A	Extended noise floor	Extended noise	
Pattern size	B	Direct measure of speckle size (μ=6.9; σ=1.2 pixels)	Noise floor	
Aliasing	A,B	Noise floor (not aliased)	Noise floor	
Interpolant	B	Synthetic and experimental image studies for optimum	0.0001	0.0009
Minimization	B	DIC parameter study, synthetic and exp. image studies	0.0001	0.0009
Shape function	B	DIC parameter study, synthetic and exp. image studies	0	
Subset size	B	DIC parameter study, synthetic and exp. image studies	Noise floor	
Filtering	B	DIC parameter study		
Strain calculation	B	DIC parameter study		
Coord. system	B	Other means		

iDICs

STEREO-DIC UQ INTRODUCTION

NOW IT GETS INTERESTING.

Stereo-vision error assessments flow



Calibration Parameters

Propagate via Monte Carlo

Image Correlation 2D Matching

Type A (Statistical)

Calibration Parameters

- Calibration target error
- Image Quality
- Camera motion
- Calibration drift
- Optical distortions

3D Triangulation

Image Correlation

- Interpolant
- Minimization
- Shape Function
- Subset size

Image Acquisition

- Noise
- Contrast
- Speckle size
- Aliasing

Type B (Monte Carlo)

3D Position

- Global Coordinate System
- Camera motion

Estimated Uncertainty of 3D Position

Type B (Other)

Strain Errors

- Displacement noise
- Fitting and filtering

Calculation of Strain

Experimental Setup

- Camera motion
- Lens distortion
- Sample motion
- Air turbulence
- Image blur
- System resolution

iDICs

Calibration Parameters | 2D Correlation | 3D Position, Motion | Strain

Stereo-DIC error table (add 2D errors)

Influences Cal. Parameters

Stereo Setup Decisions

Processing Decisions

3D Error Source	Type	Assessment Method	|D| ≈ mm	|D| ≈ pixels
Calibration	B	Monte Carlo – Übercalibration study		
Cal. Parameters	A	Statistical study from übercalibration.	May cause	bias error
Cal. Target	A,B	Measure target & propagate error	Better than	1/10th pixel
Camera motion	B	Vibration (Magnitude depends on focal length)	0.01	0.0004
Turbulence	A,B	See 2D	0.01 – 0.07	0.09 – 0.06
Stereo Angle	B	Propagate errors		
Location in image	B	Propagate errors	Center is	better
Lens focal length	B	Noise floor, propagate errors, geometry	Cam. motion	vs geometry
Camera standoff	B	Simulate and noise floor	Focal length	vs motion
Shape function	B	Simulate the errors	0.0001	0.003
Subset size	B	VSG size study		
Filtering	B	DIC parameter study		
Strain calculation	B	DIC parameter VSG size-study		
Coord. system	B	Other means to test data alignment.		

- Estimates for a ~100-mm field-of-view (0.04 mm/pixel)
- “Normal” lighting, camera noise, speckle contrast
- Correct subset size, minimization, etc.

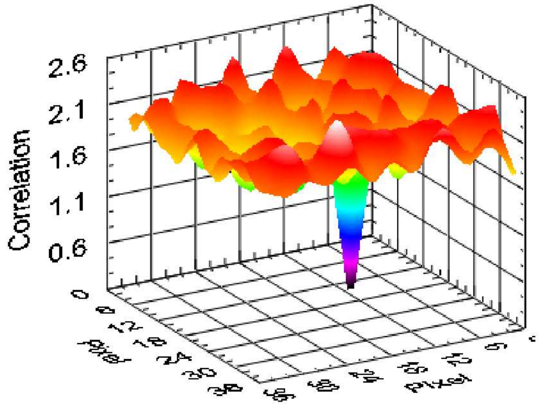
STEREO-DIC UQ: CAMERA CALIBRATION

UNDERSTANDING THE CALIBRATION AND HOW IT EFFECTS THE RESULTS.

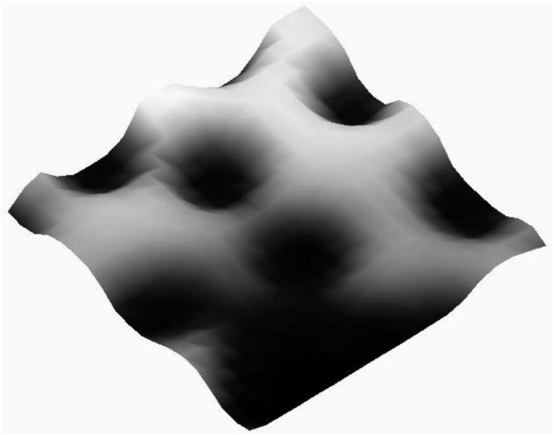
The important components of Stereo-DIC:

Stereo and 2D-DIC

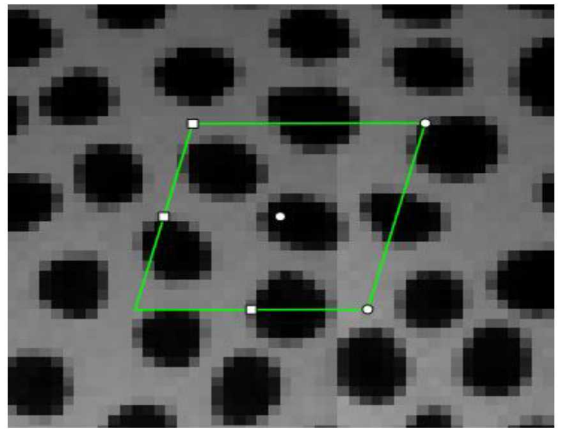
Matching



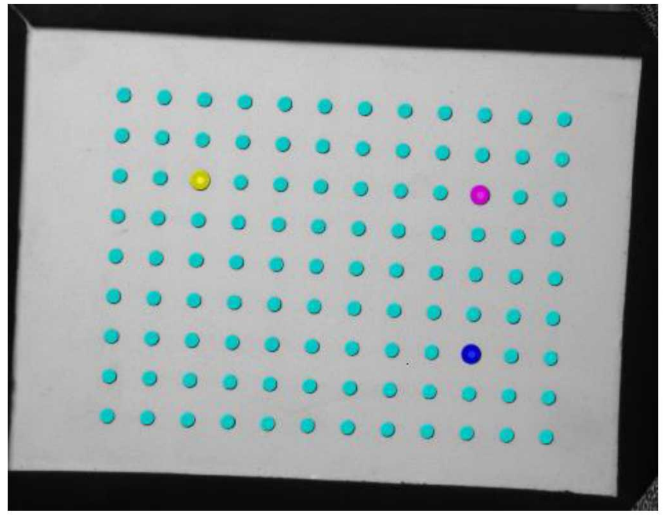
Interpolation



Shape Function

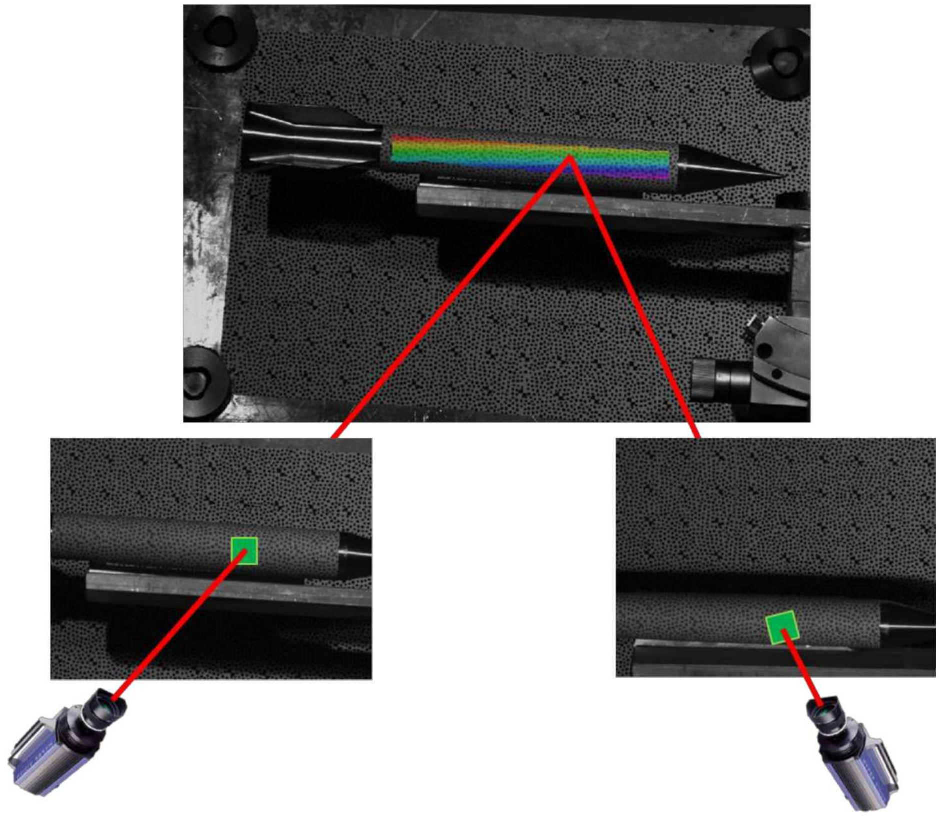


Calibration



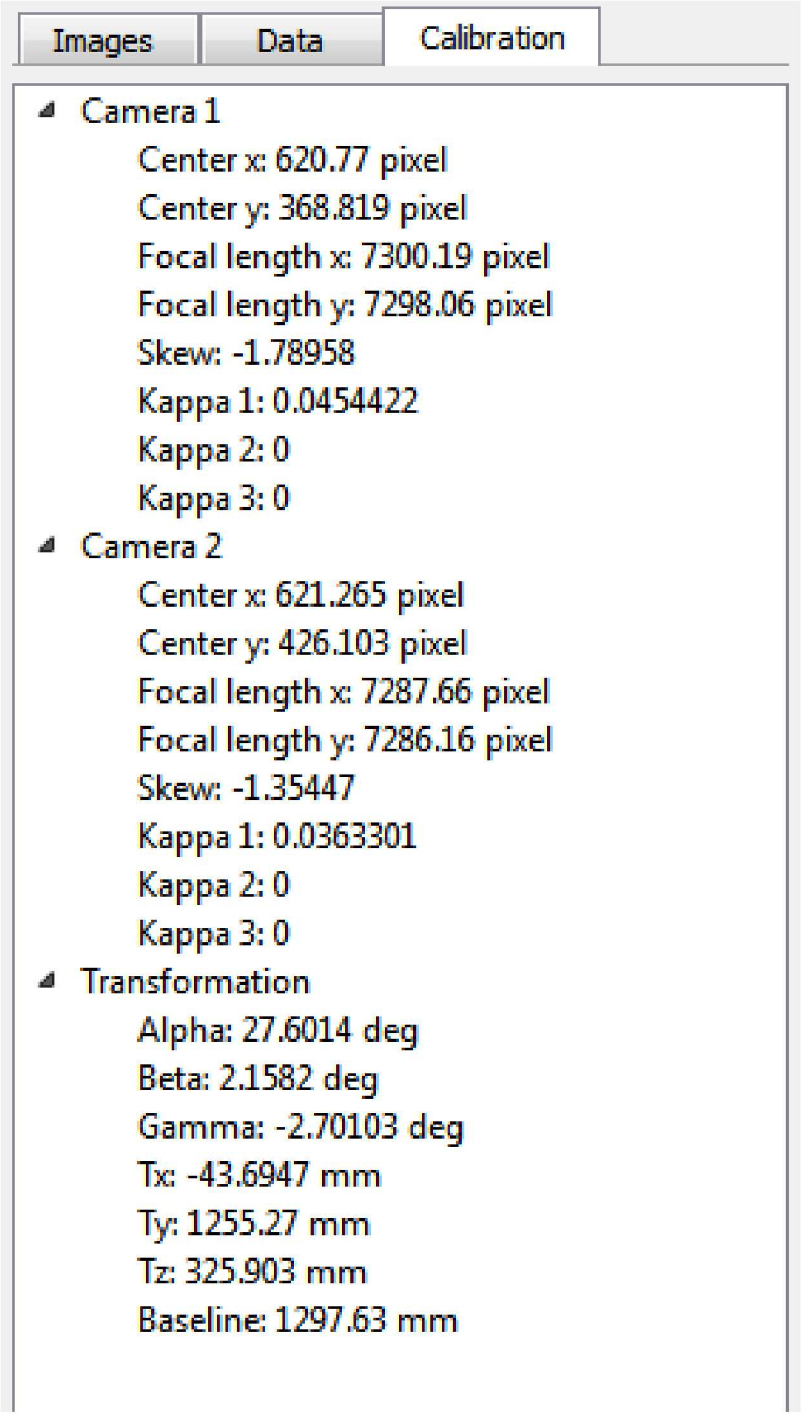
Stereo-DIC

Triangulation



- Position
- Shape
- Displacement
- Strain
- Velocity

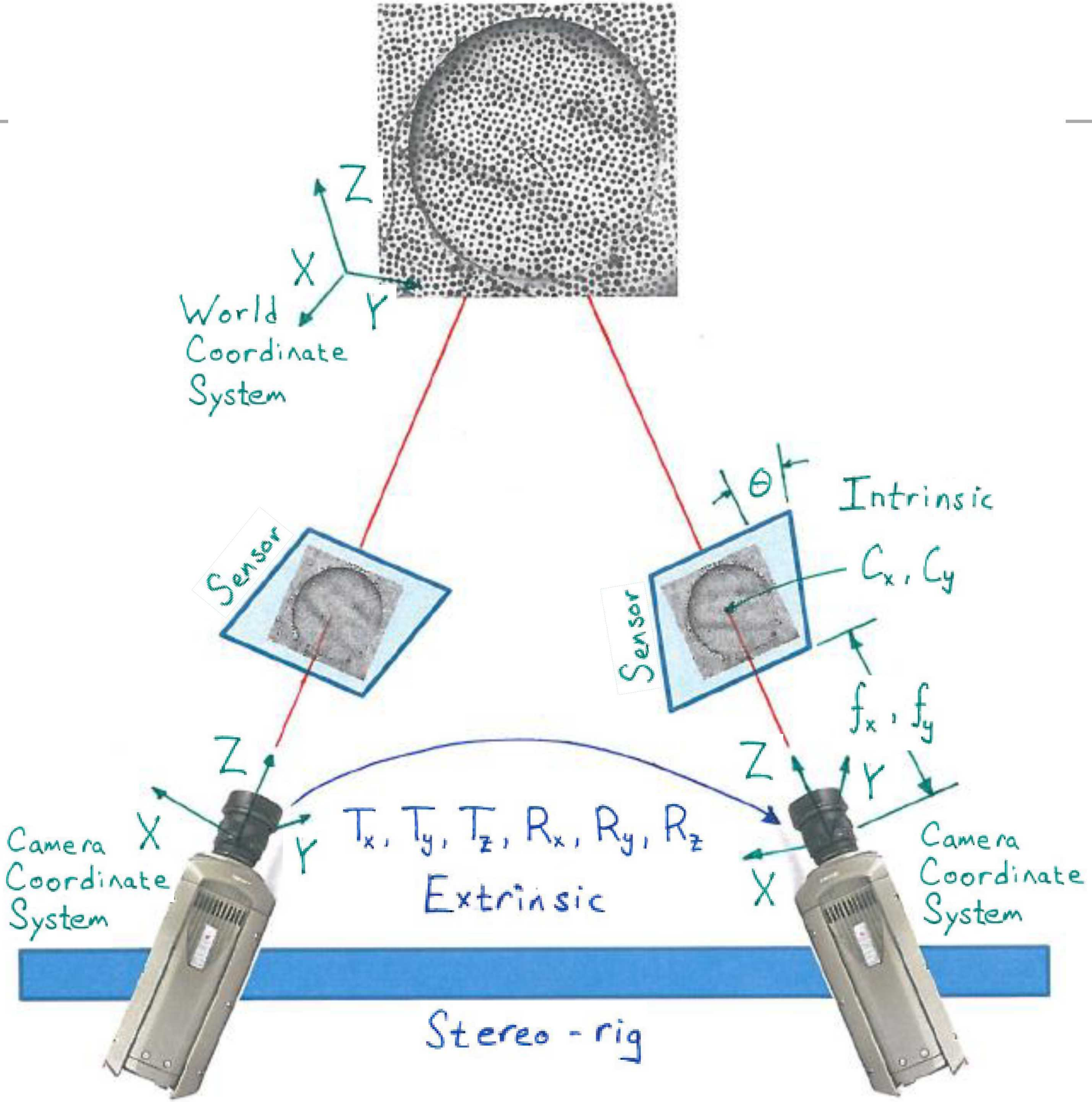
Camera calibration Parameters



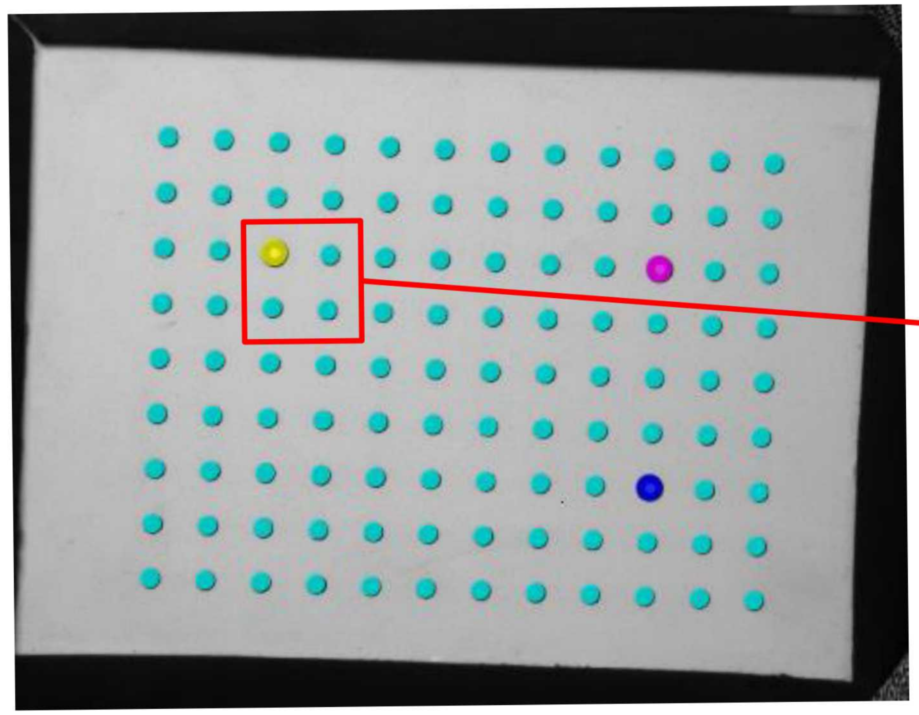
Camera 1
- Center x: 620.77 pixel
- Center y: 368.819 pixel
- Focal length x: 7300.19 pixel
- Focal length y: 7298.06 pixel
- Skew: -1.78958
- Kappa 1: 0.0454422
- Kappa 2: 0
- Kappa 3: 0

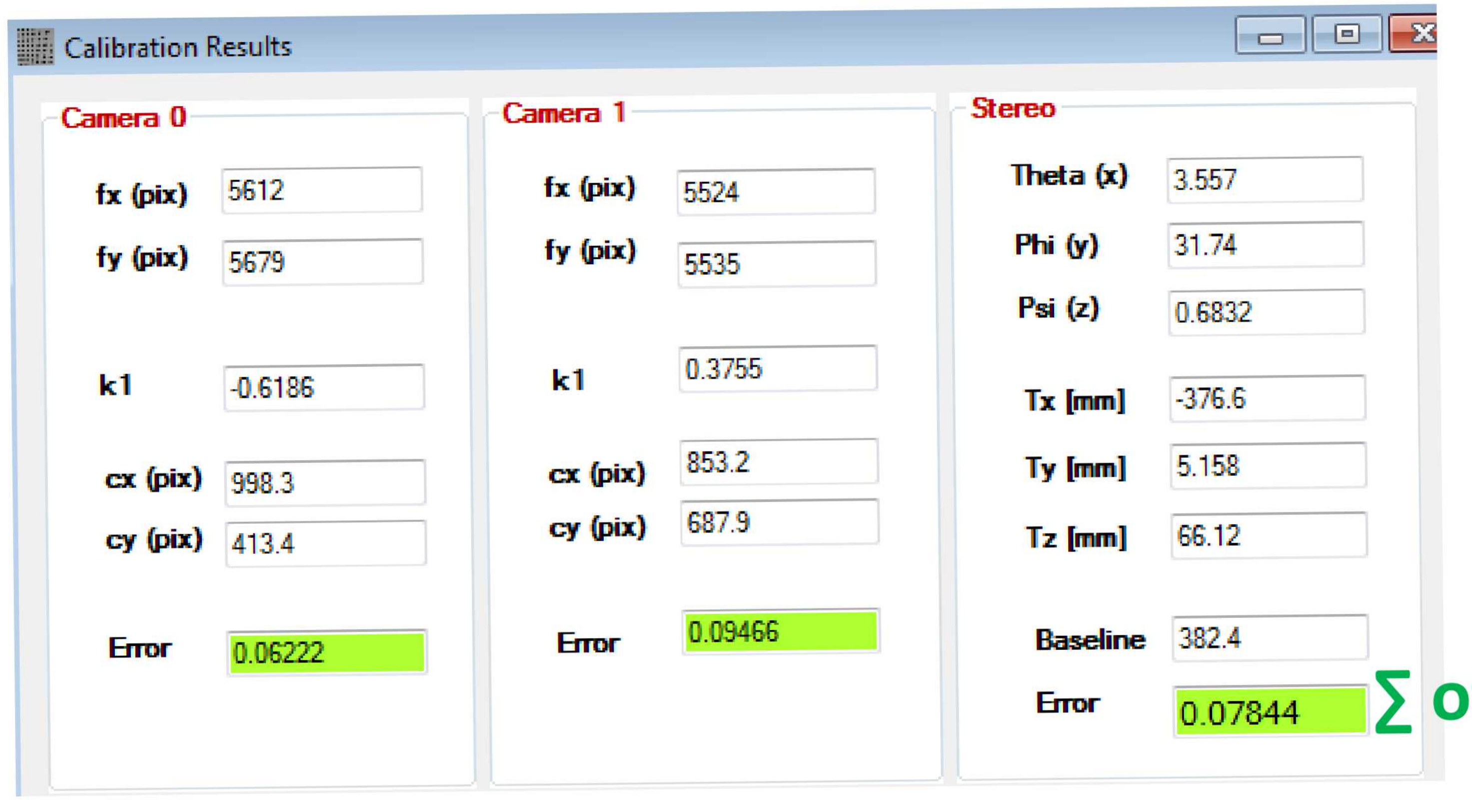
Camera 2
- Center x: 621.265 pixel
- Center y: 426.103 pixel
- Focal length x: 7287.66 pixel
- Focal length y: 7286.16 pixel
- Skew: -1.35447
- Kappa 1: 0.0363301
- Kappa 2: 0
- Kappa 3: 0

Transformation
- Alpha: 27.6014 deg
- Beta: 2.1582 deg
- Gamma: -2.70103 deg
- Tx: -43.6947 mm
- Ty: 1255.27 mm
- Tz: 325.903 mm
- Baseline: 1297.63 mm



The residuals are one means of assessing the calibration quality.





Calibration Results

Camera 0

fx (pix) 5612
fy (pix) 5679
k1 -0.6186
cx (pix) 998.3
cy (pix) 413.4
Error 0.06222

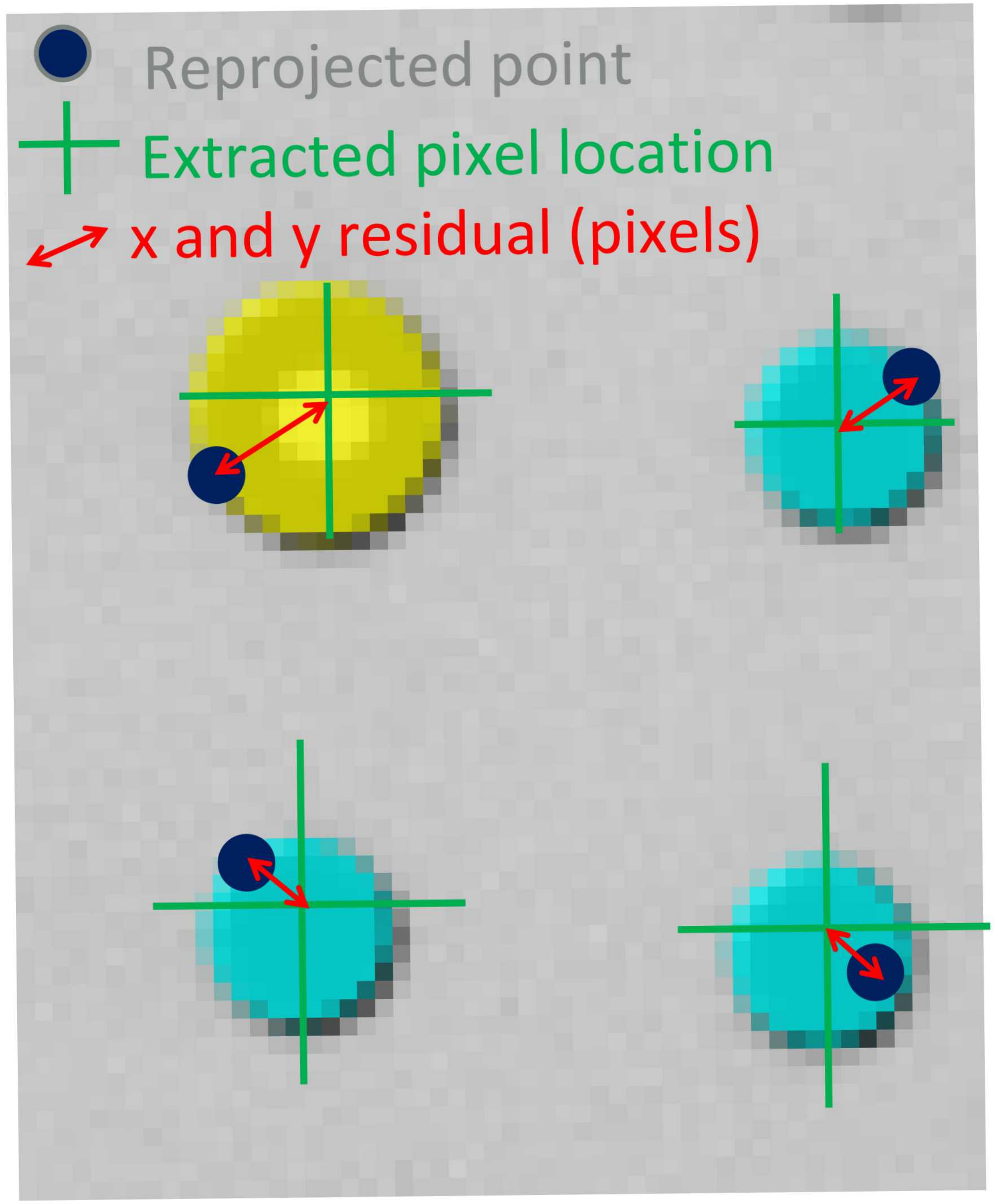
Camera 1

fx (pix) 5524
fy (pix) 5535
k1 0.3755
cx (pix) 853.2
cy (pix) 687.9
Error 0.09466

Stereo

Theta (x) 3.557
Phi (y) 31.74
Psi (z) 0.6832
Tx [mm] -376.6
Ty [mm] 5.158
Tz [mm] 66.12
Baseline 382.4
Error 0.07844

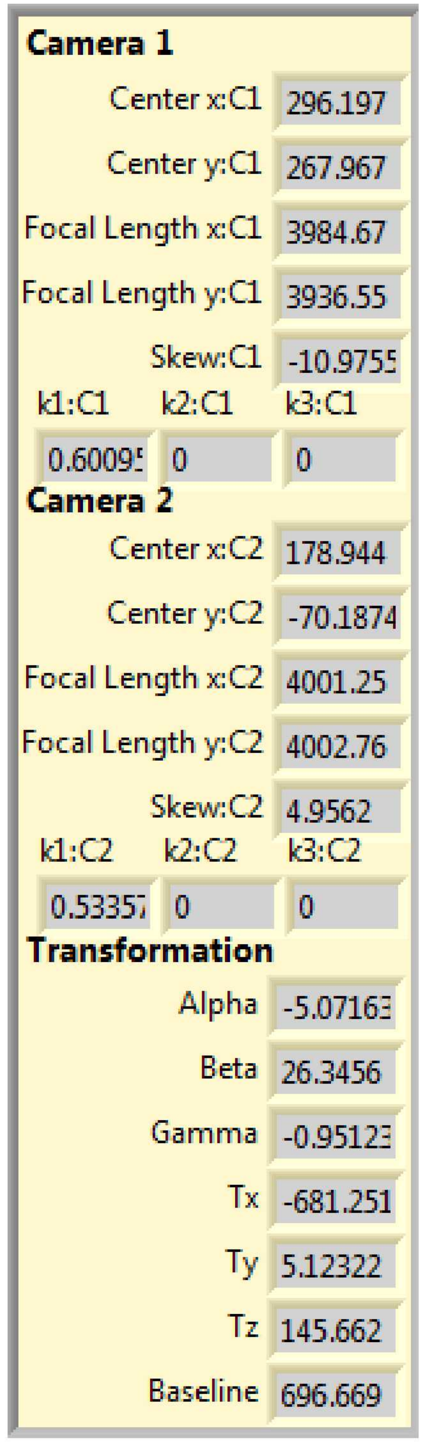
∑ of all residuals (pixels)



Caution 3.12 – The calibration is scored. Not a measure of actual quality.

The epipolar line constrains the location of a match between two calibrated cameras

Camera Calibration



Camera 1

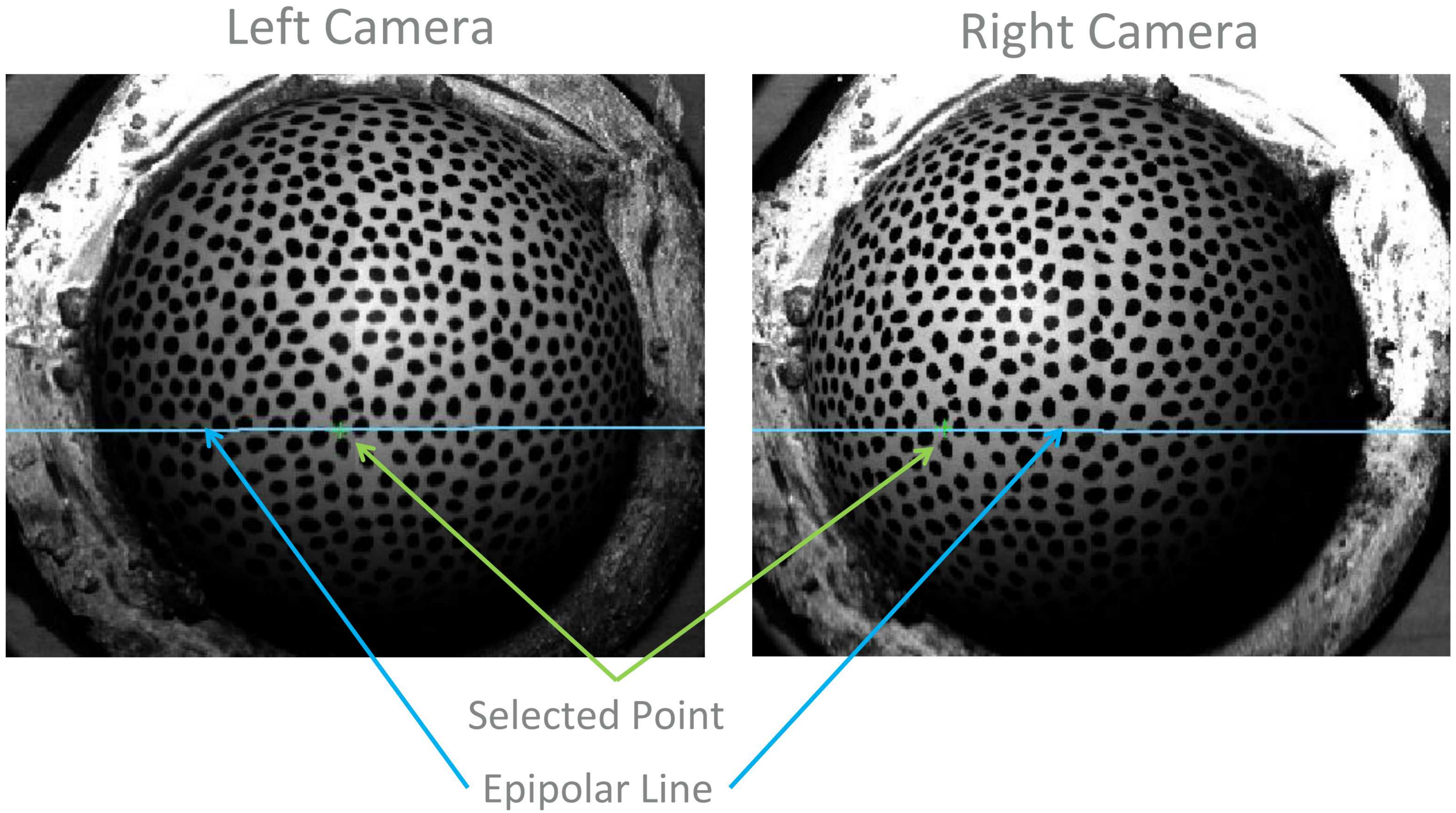
Center x:C1 296.197
Center y:C1 267.967
Focal Length x:C1 3984.67
Focal Length y:C1 3936.55
Skew:C1 -10.9755
k1:C1 0.6009
k2:C1 0
k3:C1 0

Camera 2

Center x:C2 178.944
Center y:C2 -70.1874
Focal Length x:C2 4001.25
Focal Length y:C2 4002.76
Skew:C2 4.9562
k1:C2 0.53357
k2:C2 0
k3:C2 0

Transformation

Alpha -5.07163
Beta 26.3456
Gamma -0.95123
Tx -681.251
Ty 5.12322
Tz 145.662
Baseline 696.669

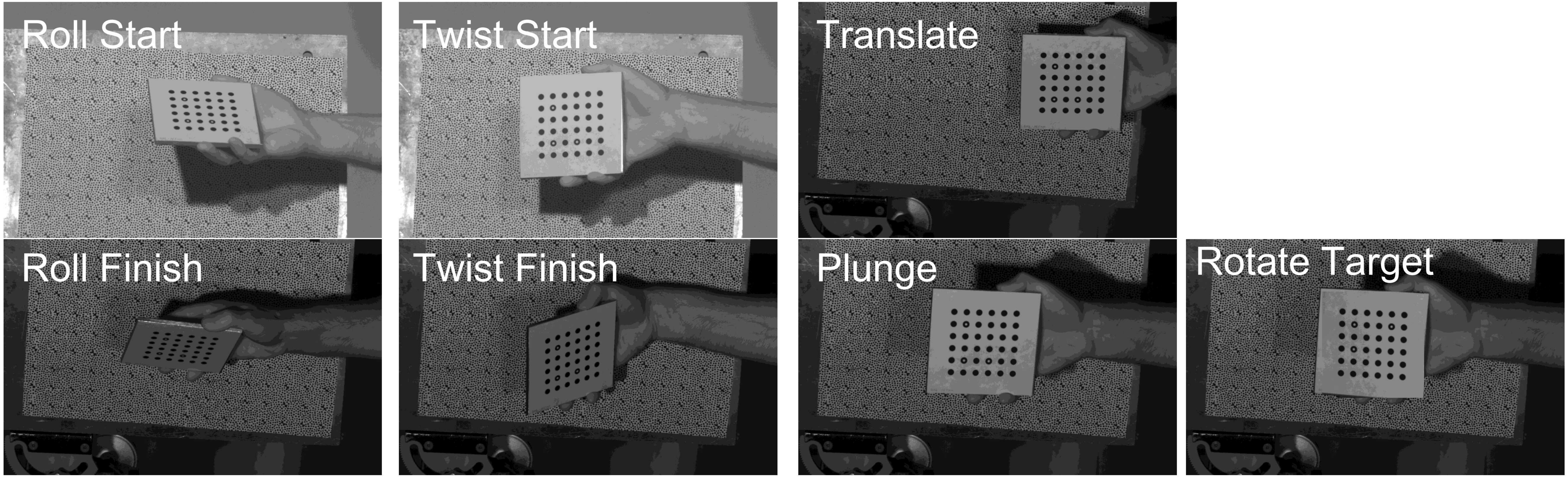


What does the epipolar line tell us?

- Constrained by the calibration parameters.
- Only provides “1” axis of uncertainty.

Übercalibration: Measuring the quality of the calibration via Monte Carlo

Type A – Statistical Measurements **> 1000 Images each motion**

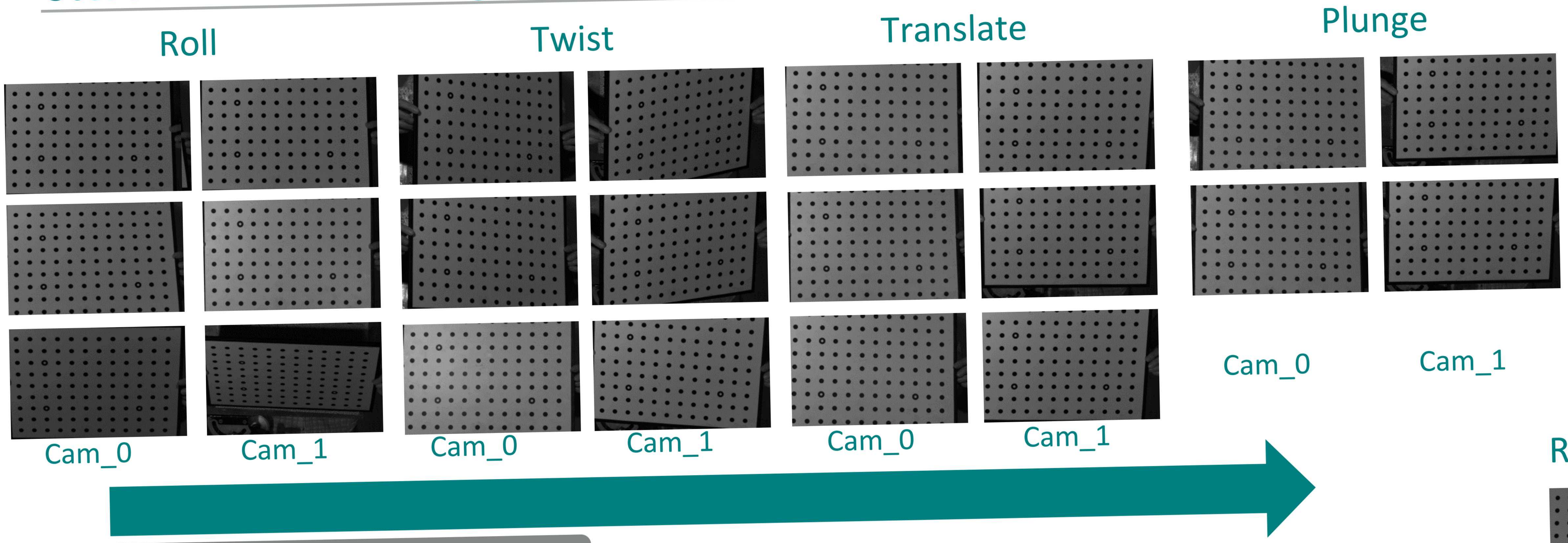


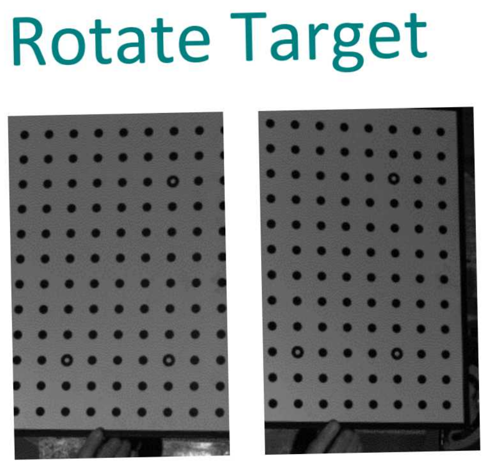
- Images selected at random from the 4 directories
- Independent calibrations run using a different number of images
- Not advocating this approach for all experiments

Recommendation 3.10 – Rotate target

Caution 3.11 – Quality Images

Stereo Calibration Range of Motion





RECOMMENDATION 3.10 – Motions

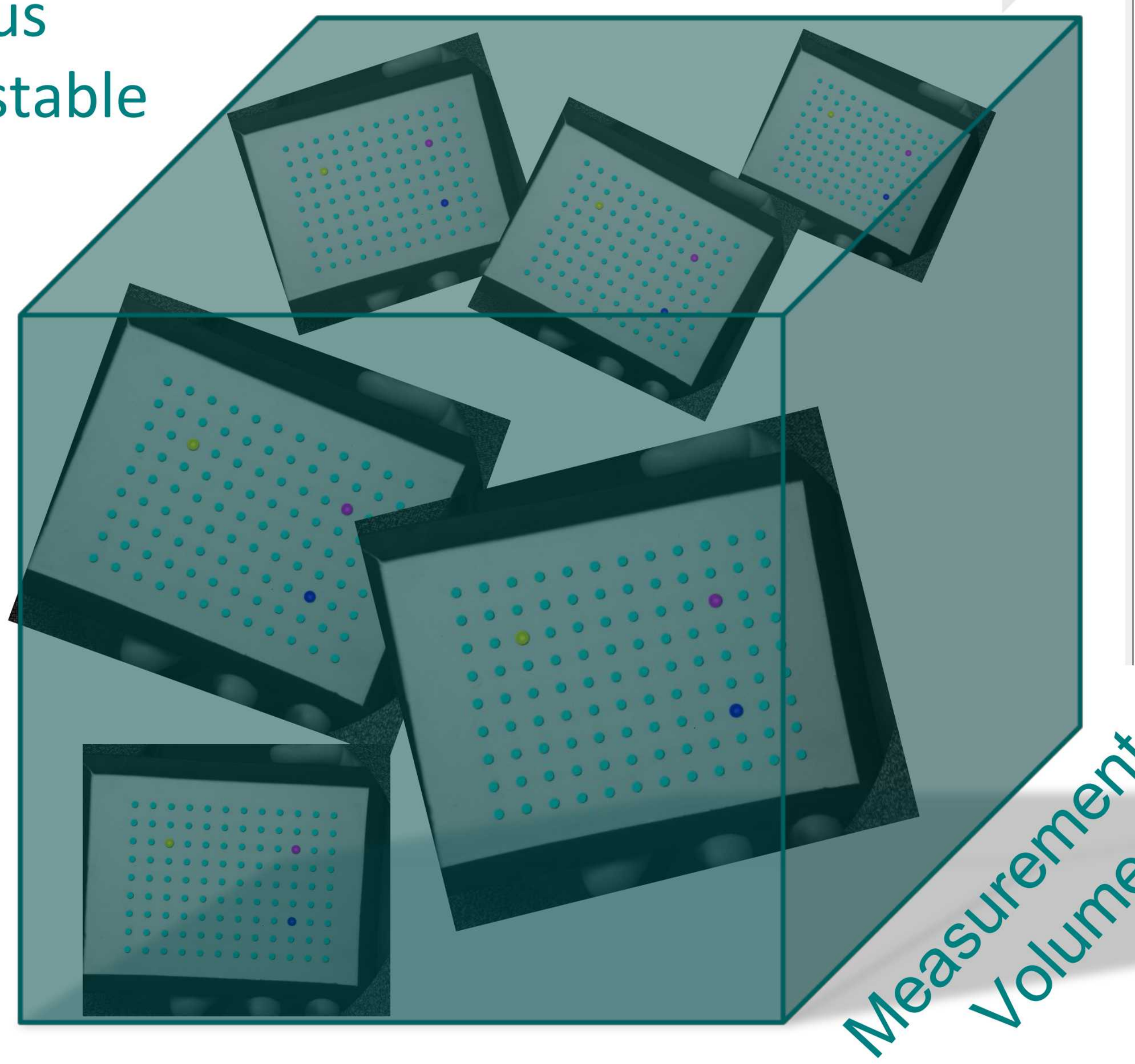
1. Rotate about the horizontal image axis.
2. Rotate about the vertical image axis.
3. Plunge towards and away from each camera, along its optical axis.
4. If the calibration target is smaller than the FOV, translate horizontally and vertically, so that features from the calibration target the entire FOV of each camera.
5. Rotate 90 degrees about the optical axis and repeat the above steps.
6. Perform combinations of the above positions and orientations (i.e. rotate about the horizontal and vertical axes simultaneously while plunging along the optical axis).

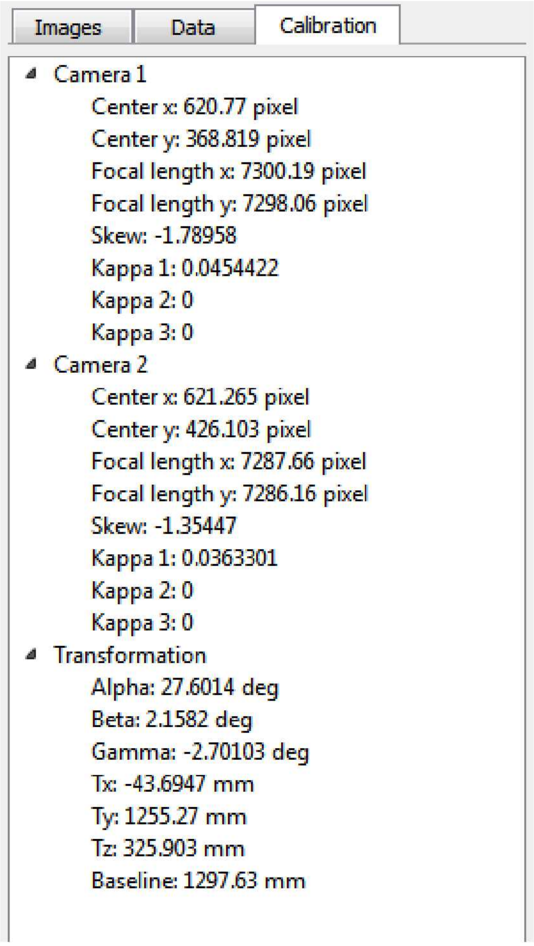
The calibration target should be moved throughout the entire measurement volume.

Caution 3.11

- Must stay in focus
- Hold the target stable
- Avoid highlights
- Fill the volume.

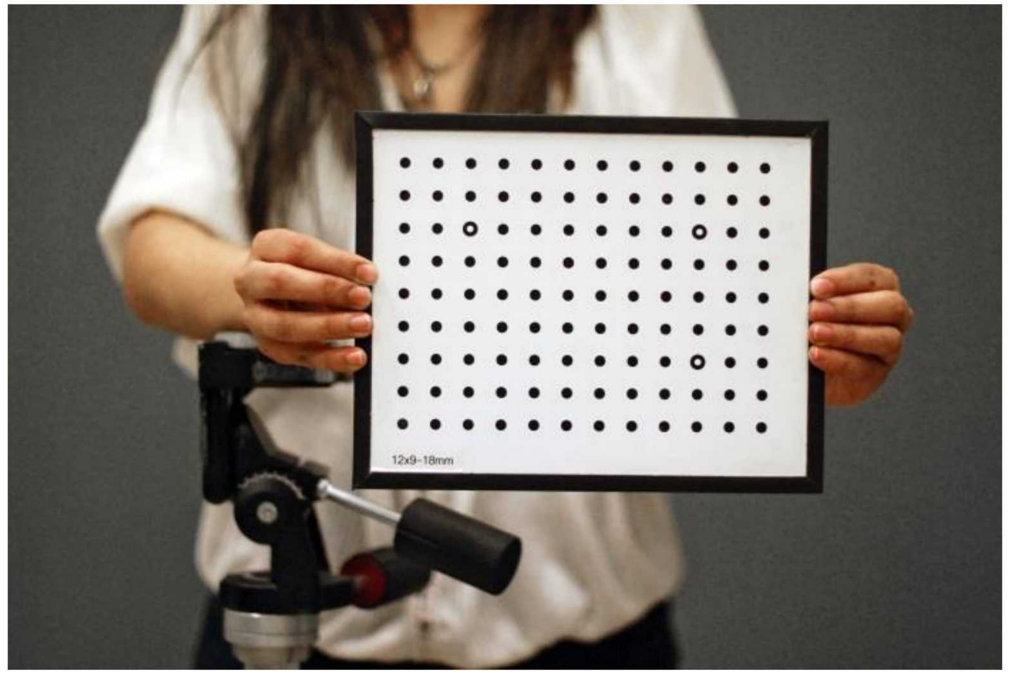
Bundle Adjustment





```
Camera 1
    Center x: 620.77 pixel
    Center y: 368.819 pixel
    Focal length x: 7300.19 pixel
    Focal length y: 7298.06 pixel
    Skew: -1.78958
    Kappa 1: 0.0454422
    Kappa 2: 0
    Kappa 3: 0
Camera 2
    Center x: 621.265 pixel
    Center y: 426.103 pixel
    Focal length x: 7287.66 pixel
    Focal length y: 7286.16 pixel
    Skew: -1.35447
    Kappa 1: 0.0363301
    Kappa 2: 0
    Kappa 3: 0
Transformation
    Alpha: 27.6014 deg
    Beta: 2.1582 deg
    Gamma: -2.70103 deg
    Tx: -43.6947 mm
    Ty: 1255.27 mm
    Tz: 325.903 mm
    Baseline: 1297.63 mm
```

RECOMMENDATION 3.11 – Target holder



Better

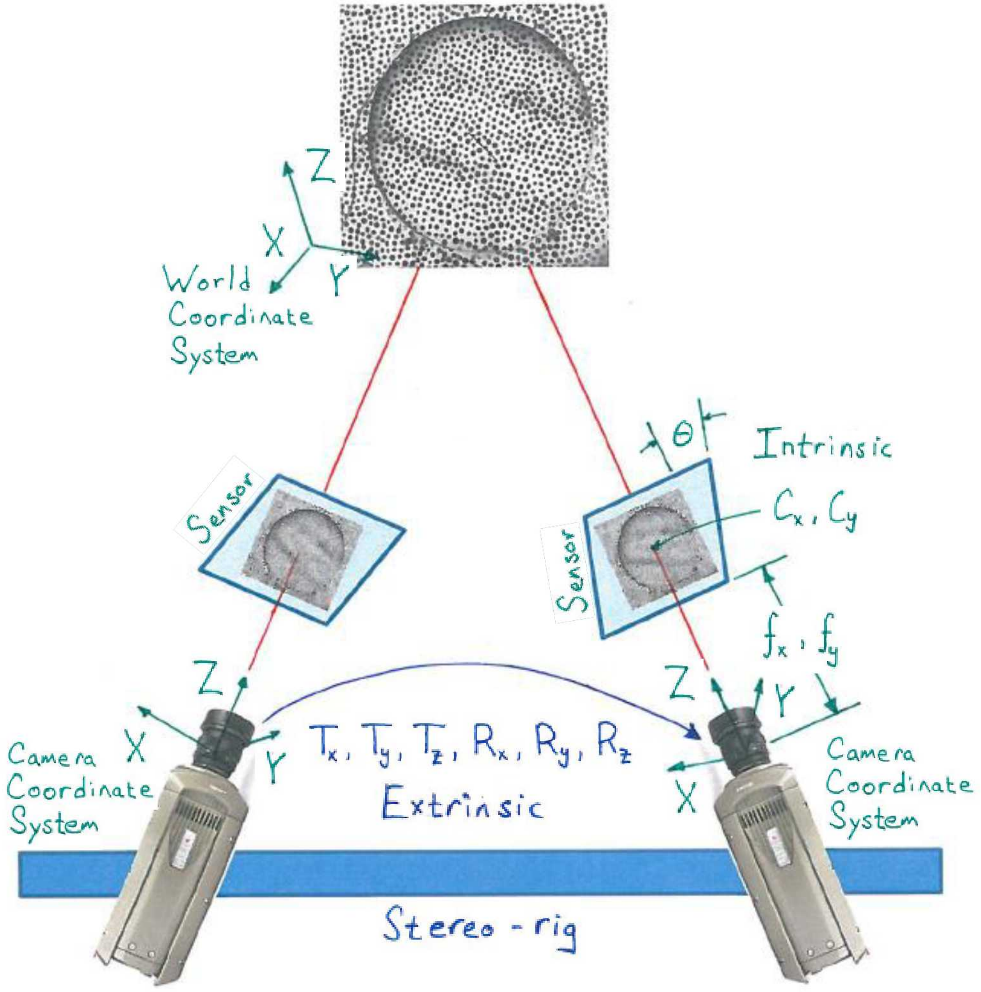
iDICs

Section 3.2.2.4 – Acquire calibration images

Recommendation 3.6 – Fill measurement volume

The calibration residual is not a good estimation of the actual parameter variation

- Calibration covariance matrix or minimization residual is conservative (usually)
- Reprojection error is not very sensitive
- Parameter variation *is not*

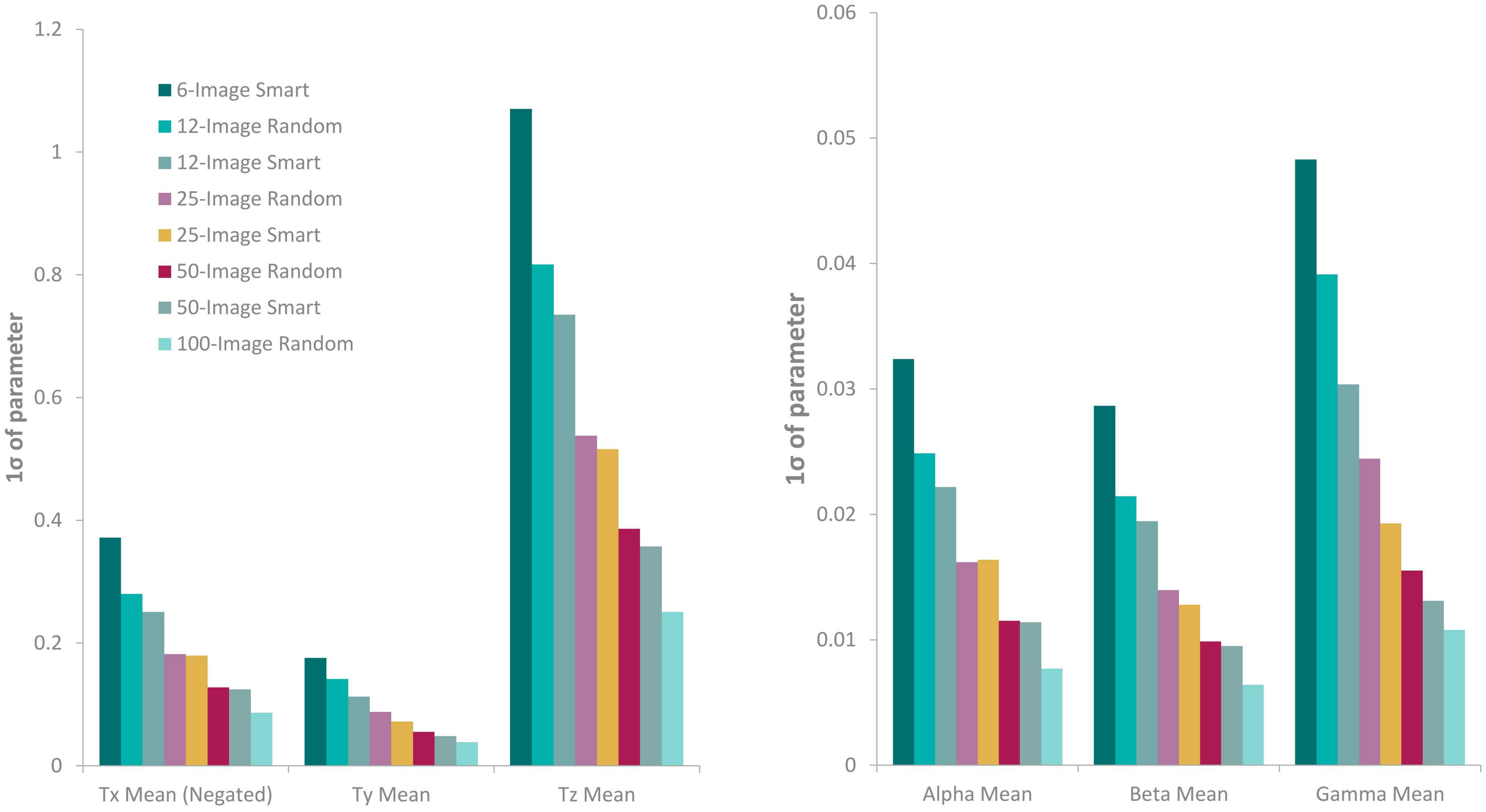


	25 Image StDev		1000 Image StDev	
Parameter	**Actual**	**CoVar**	**Actual**	**CoVar**
Cam_0 Cx Mean	1.15	5.08	0.12	0.08
Cam_0 Cy Mean	1.12	4.89	0.15	0.09
Cam_0 Fx Mean	2.61	27.97	0.20	0.43
Cam_0 Fy Mean	2.52	29.31	0.18	0.45
Cam_0 Skew Mean	0.79	5.25	0.11	0.11
Cam_0 k1 Mean	0.00	0.00	0.00	0.00
Cam_1 Cx Mean	2.00	7.47	0.12	0.10
Cam_1 Cy Mean	0.98	7.69	0.11	0.15
Cam_1 Fx Mean	2.21	35.68	0.24	0.53
Cam_1 Fy Mean	2.28	38.77	0.25	0.58
Cam_1 Skew Mean	0.78	5.25	0.12	0.11
Cam_1 k1 Mean	0.01	0.00	0.00	0.00
Alpha Mean	0.03	0.00	0.00	0.00
Beta Mean	0.04	0.00	0.00	0.00
Gamma Mean	0.01	0.00	0.00	0.00
Tx Mean (Negated)	4.23	69.63	0.32	1.14
Ty Mean	0.60	2.98	0.07	0.05
Tz Mean	9.51	669.30	1.18	10.92

Caution 3.12 – Score isn't the final measure of the calibration.

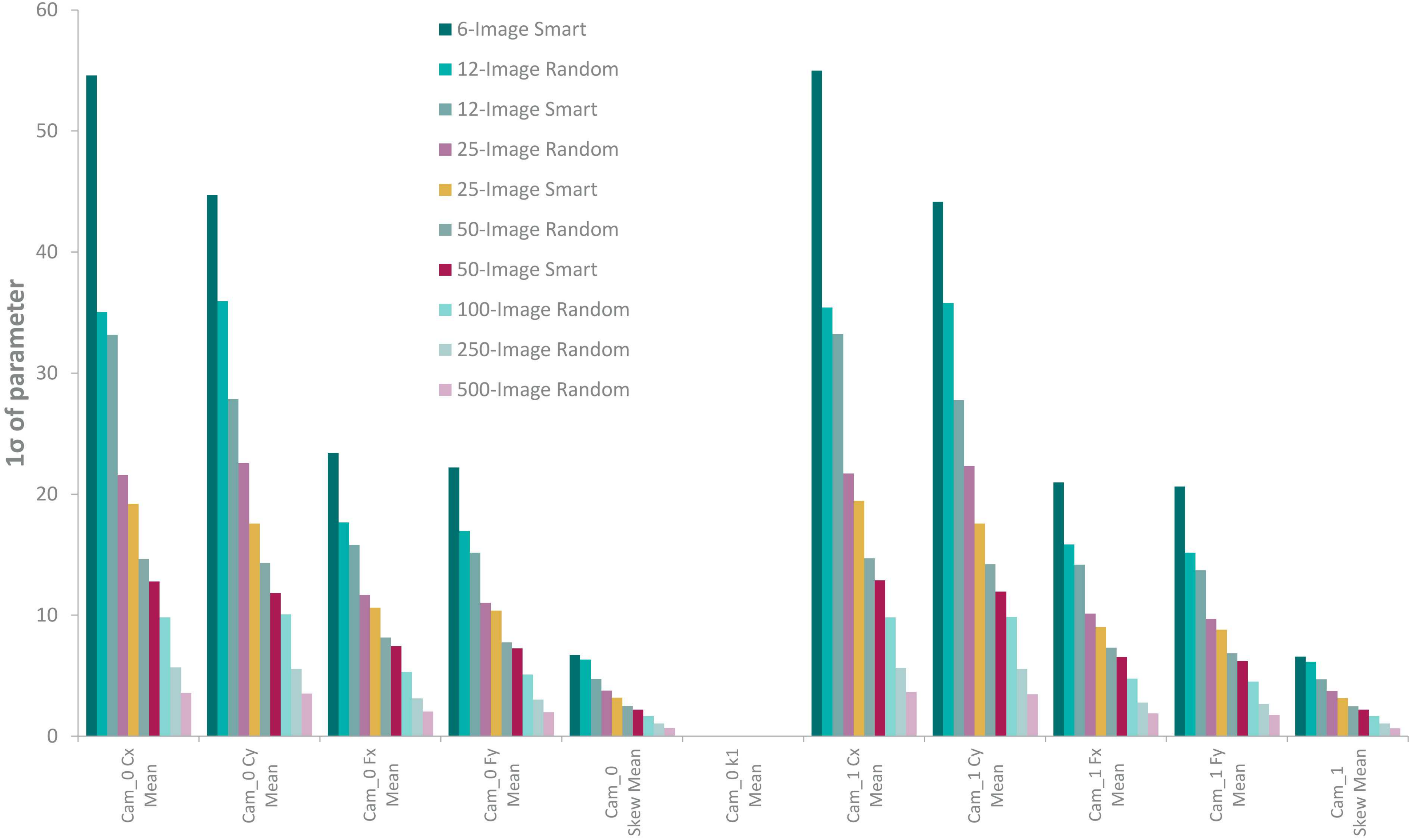
You need a *large* number of images to minimize the calibration variance

Or at least many dots extracted!

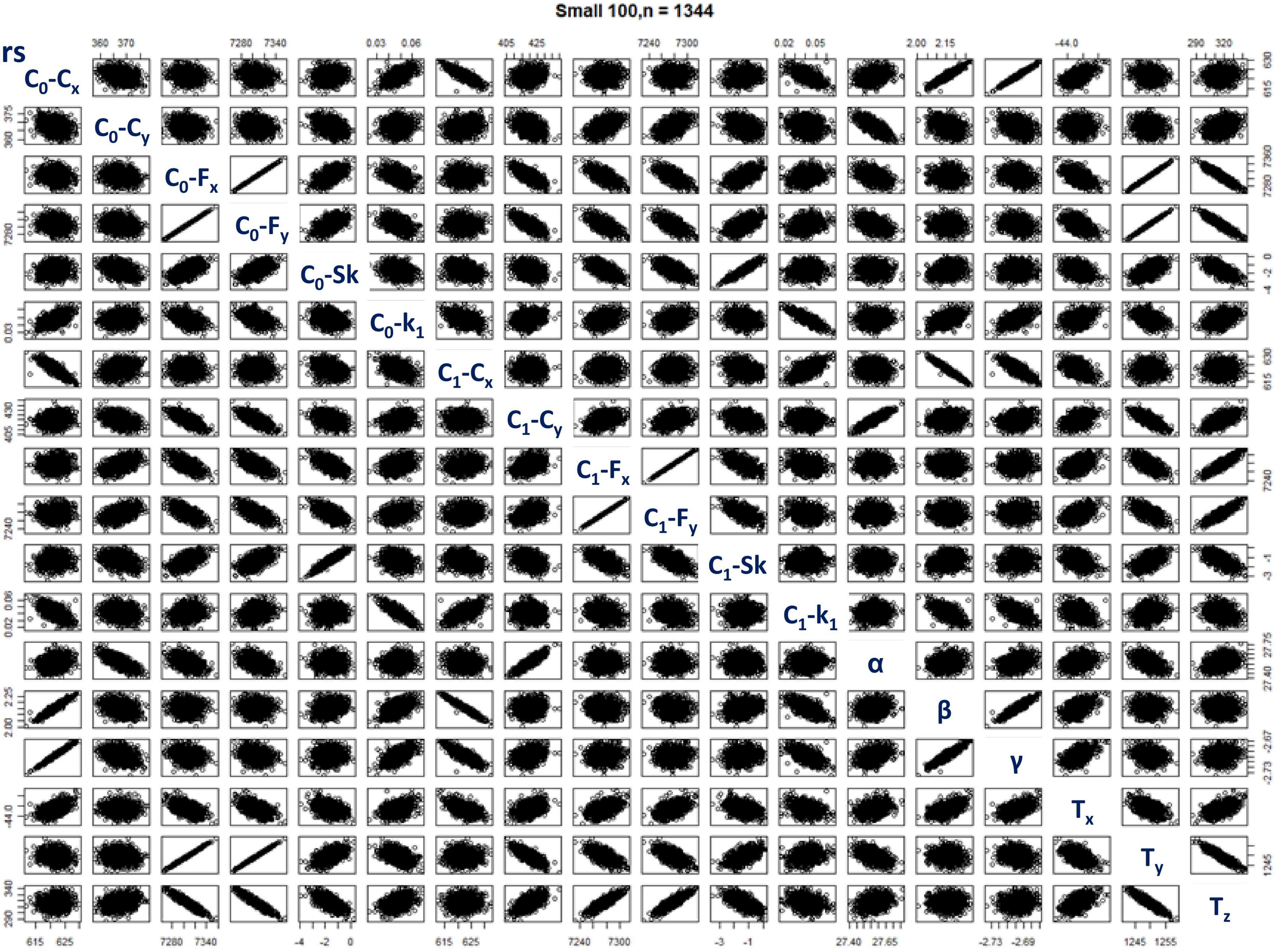


The others behave similarly.

Parameters improve with more calibration images.



Calibration Parameters



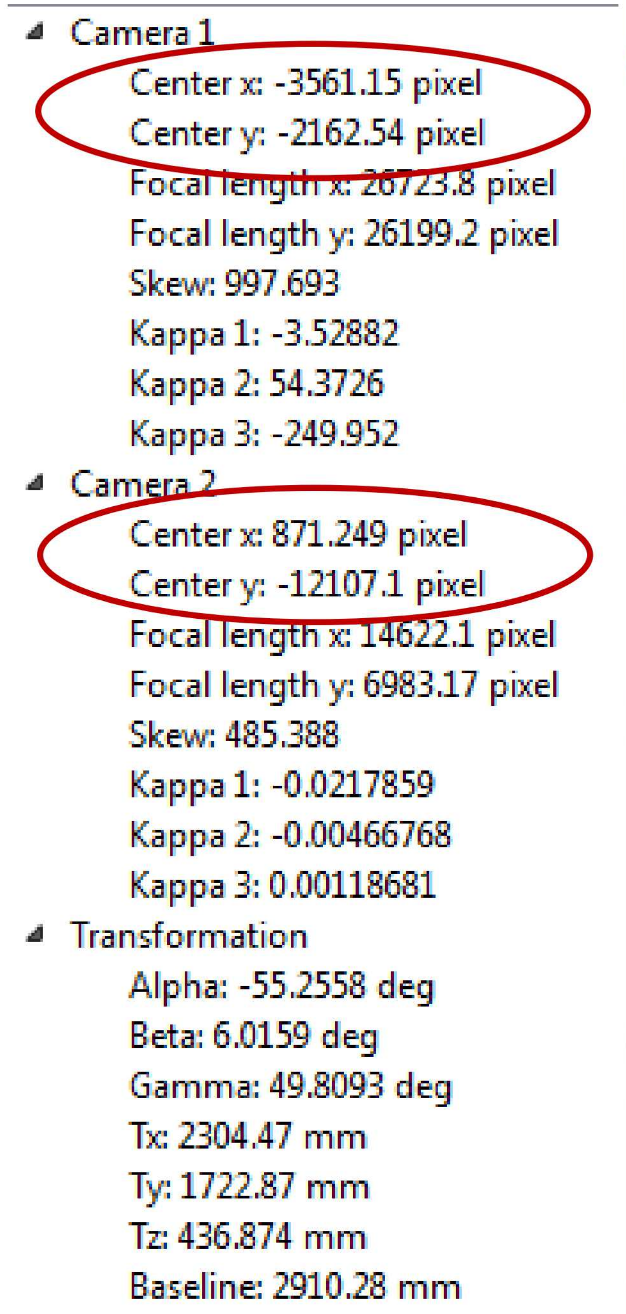
Calibration parameters covary

- Indicated by a line in the dot plots.
- Scatter indicates lack of covariance.
- One parameter will “compensate” for another one.
- May lead to unphysical parameters.

High covariance between Cam_0 C_x and γ

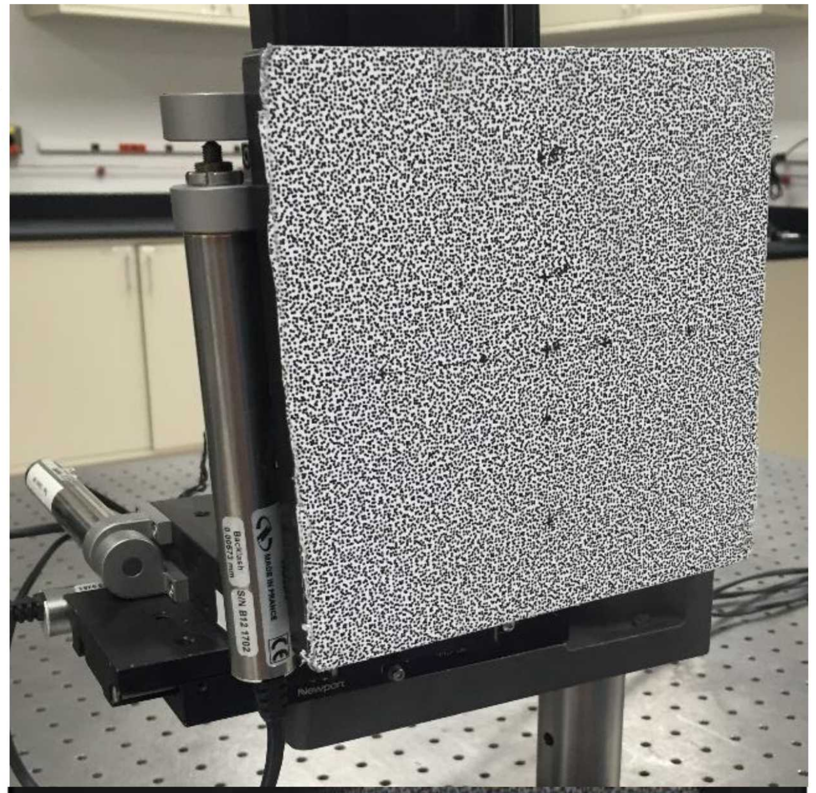
Top-Down evaluation attempts to quantify all the error sources “experimentally”

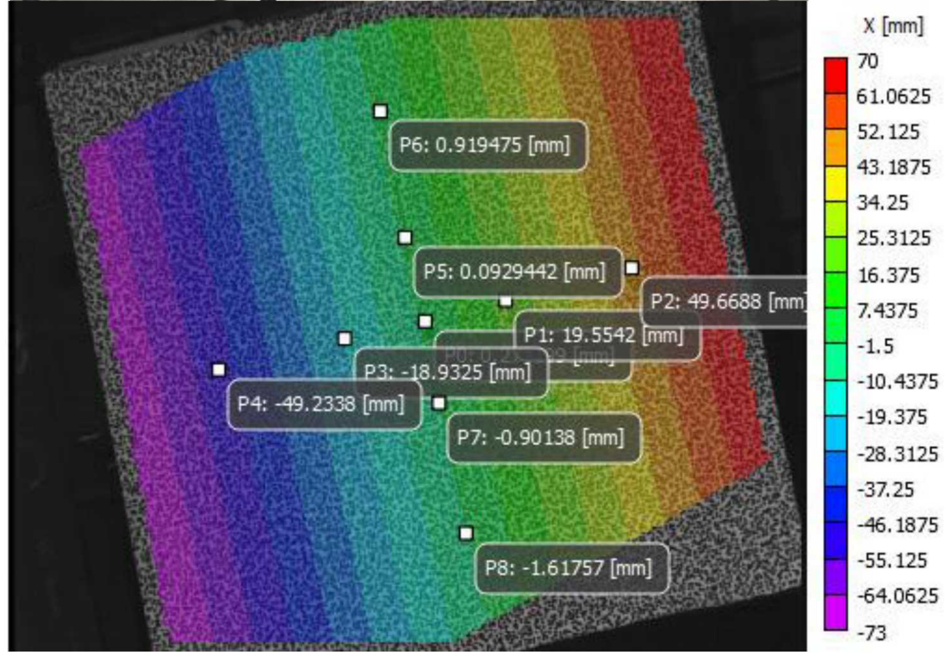
When calibrations go bad.

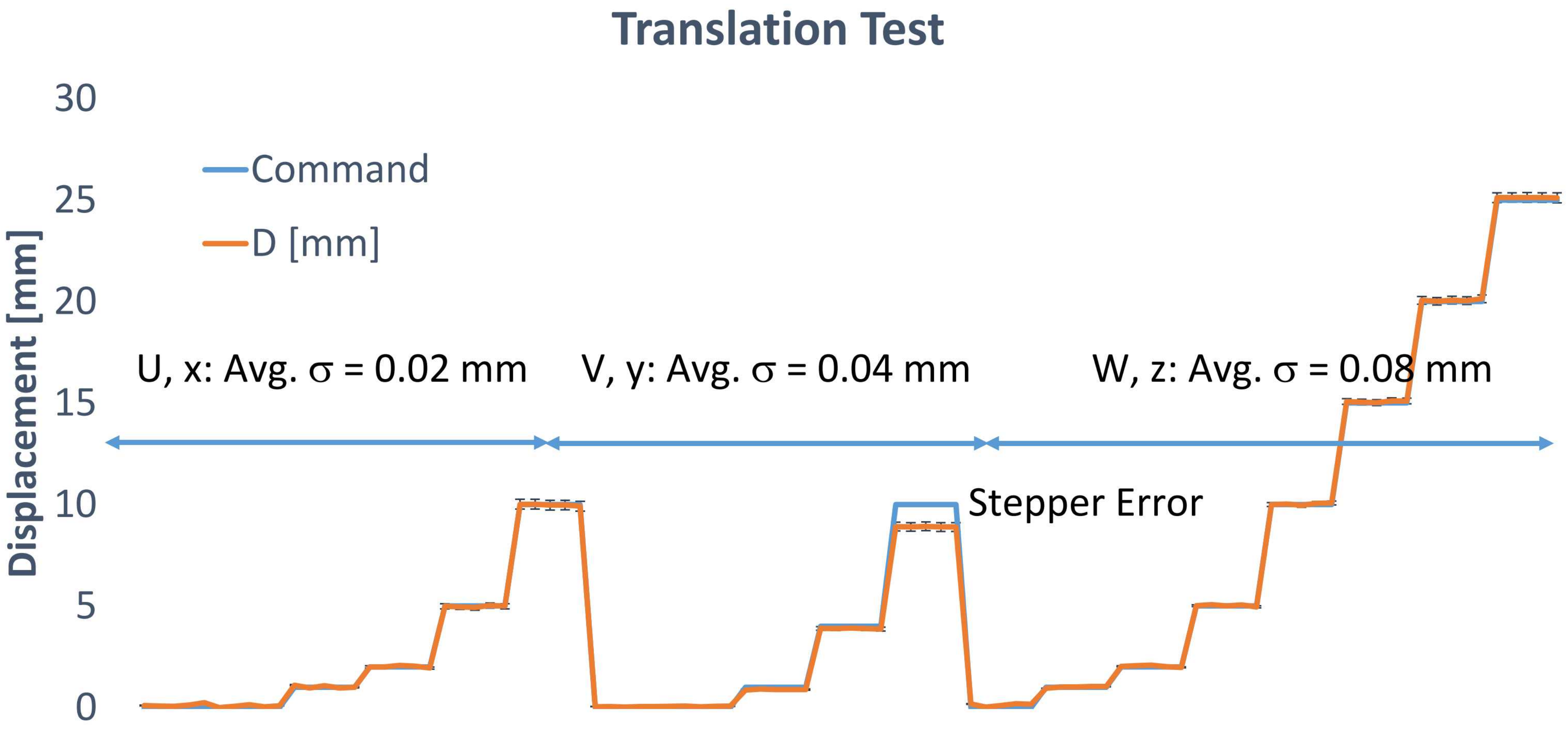


- Camera 1
  - Center x: -3561.15 pixel
  - Center y: -2162.54 pixel
  - Focal length x: 26723.8 pixel
  - Focal length y: 26199.2 pixel
  - Skew: 997.693
  - Kappa 1: -3.52882
  - Kappa 2: 54.3726
  - Kappa 3: -249.952
- Camera 2
  - Center x: 871.249 pixel
  - Center y: -12107.1 pixel
  - Focal length x: 14622.1 pixel
  - Focal length y: 6983.17 pixel
  - Skew: 485.388
  - Kappa 1: -0.0217859
  - Kappa 2: -0.00466768
  - Kappa 3: 0.00118681
- Transformation
  - Alpha: -55.2558 deg
  - Beta: 6.0159 deg
  - Gamma: 49.8093 deg
  - Tx: 2304.47 mm
  - Ty: 1722.87 mm
  - Tz: 436.874 mm
  - Baseline: 2910.28 mm

X, Y, Z Translation Stage



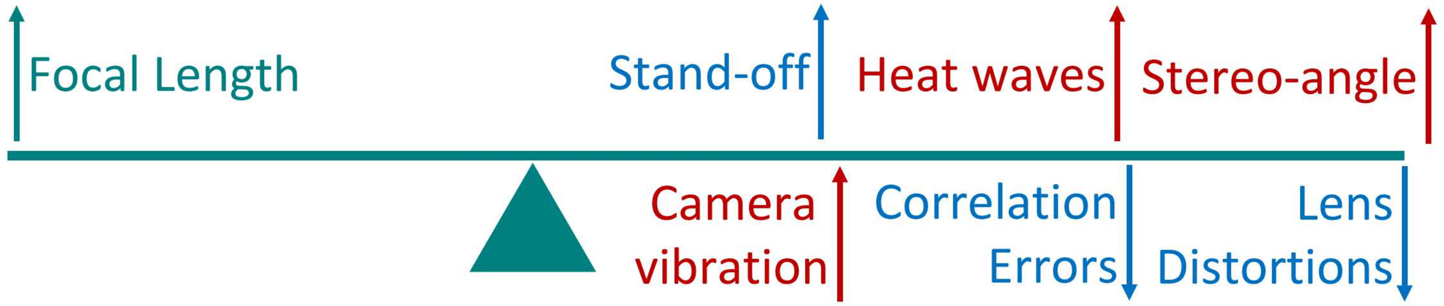




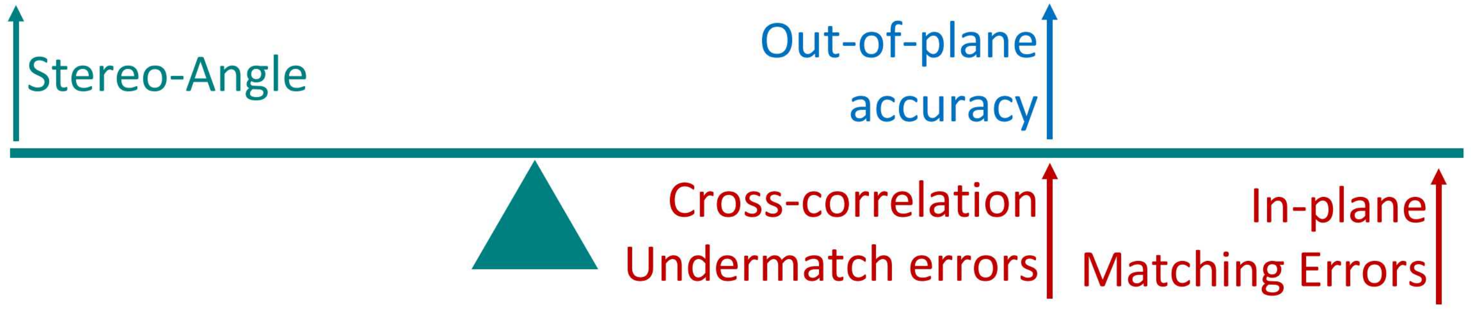
Bottom-up Methods: Compare DIC results to

- Known shape measurements
- Known fiducial locations
- Known translations

Focal Length

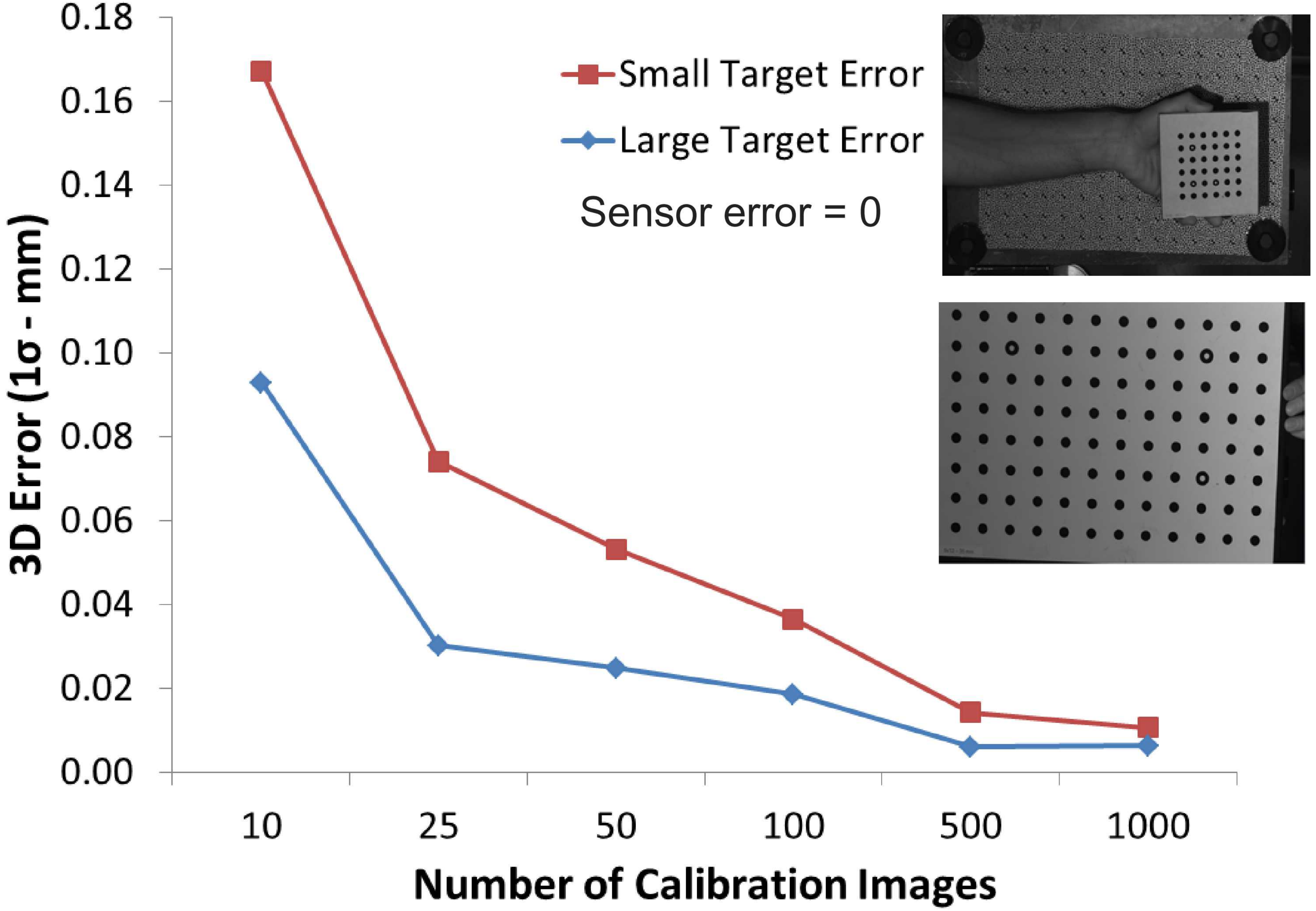


Stereo-Angle

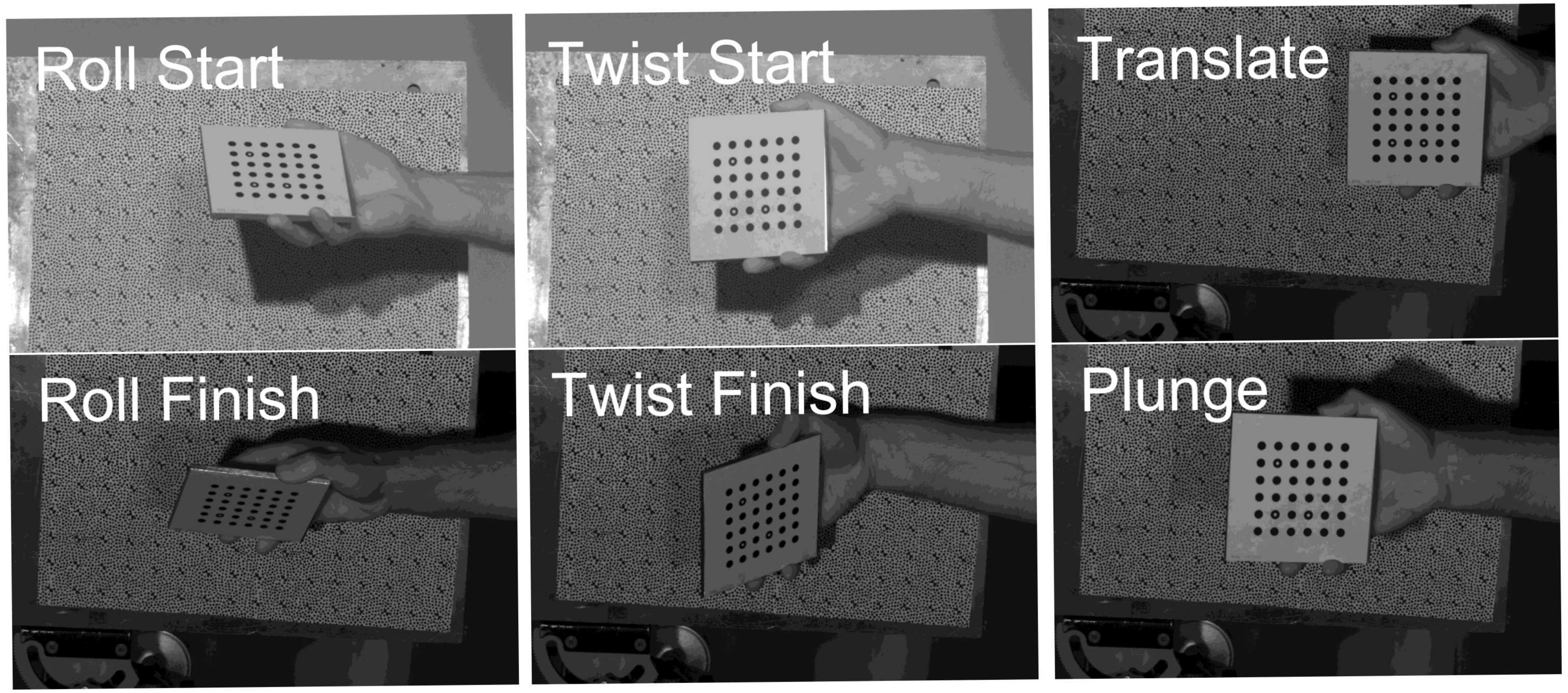


INTERACTION OF THE MATCHING ERROR AND CALIBRATION

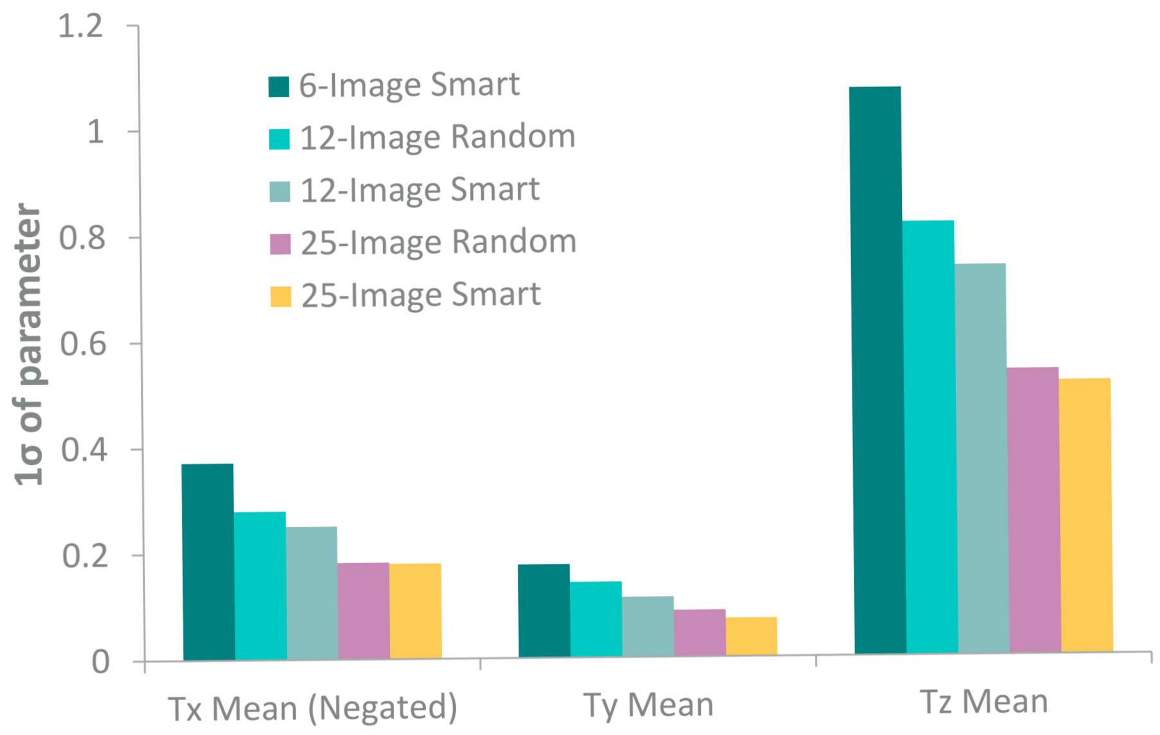
A target that fills the FOV is better and requires less images.

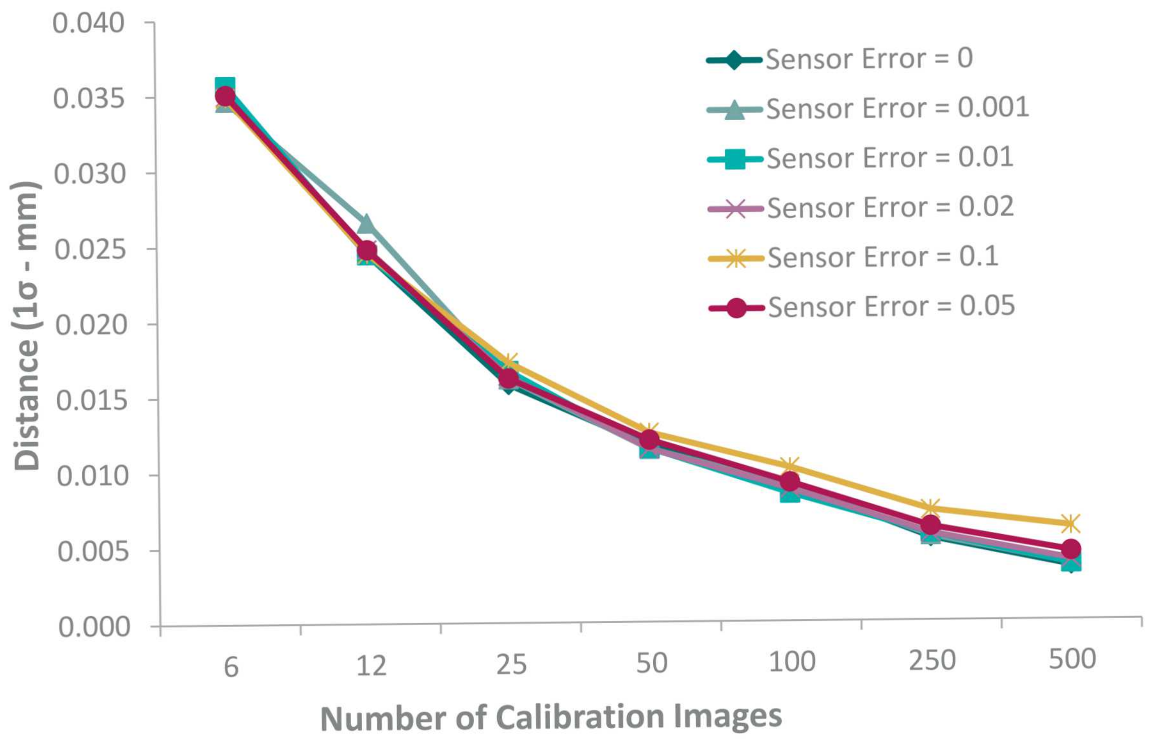


Ill-posed or too few calibration images will cause problems.

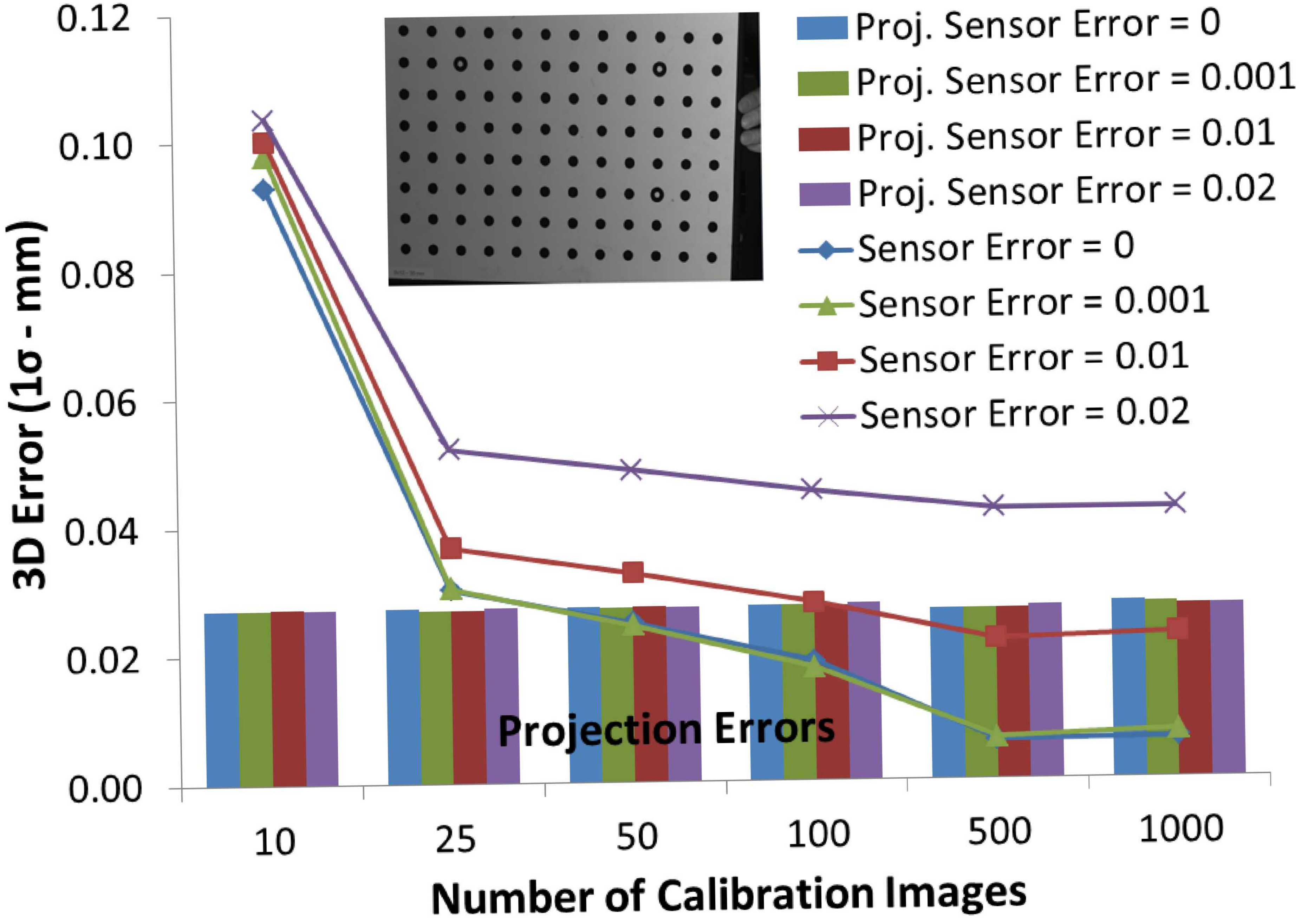


Fill the measurement volume with dots!

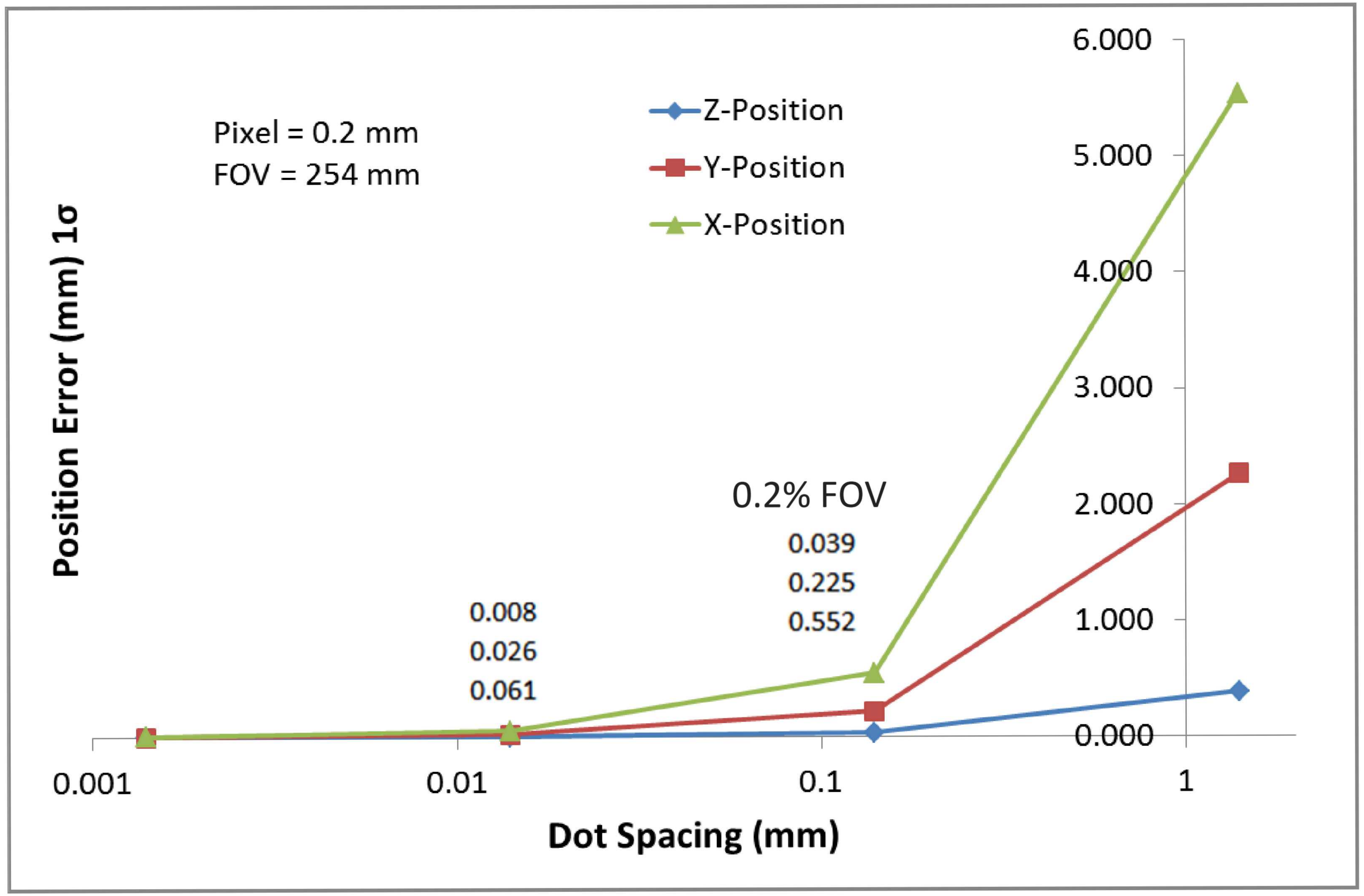




Projection error may not be sensitive enough to calibration issues.



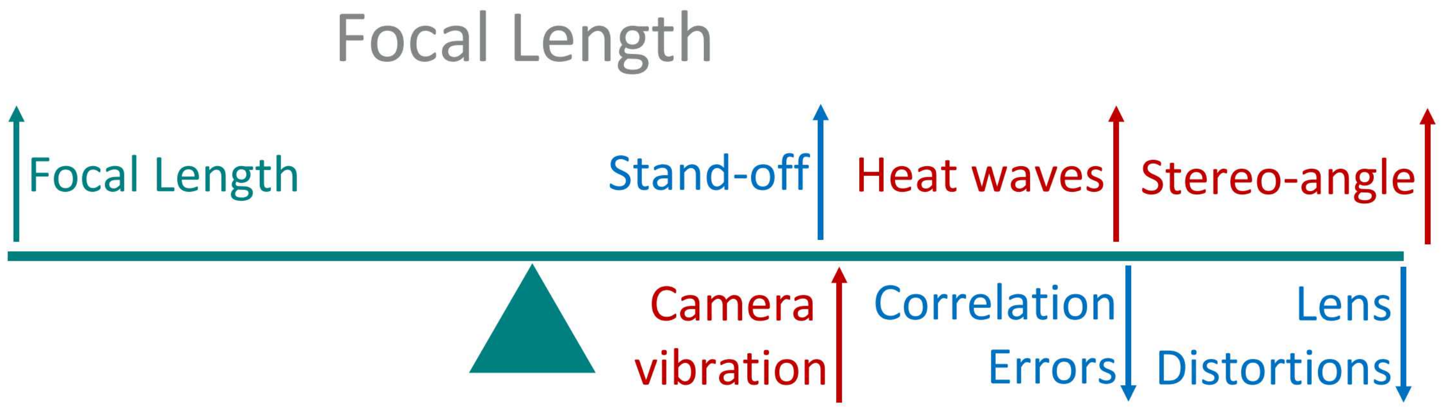
Cal target dot spacing only needs to be known to ~1/10th of a pixel.



iDICs

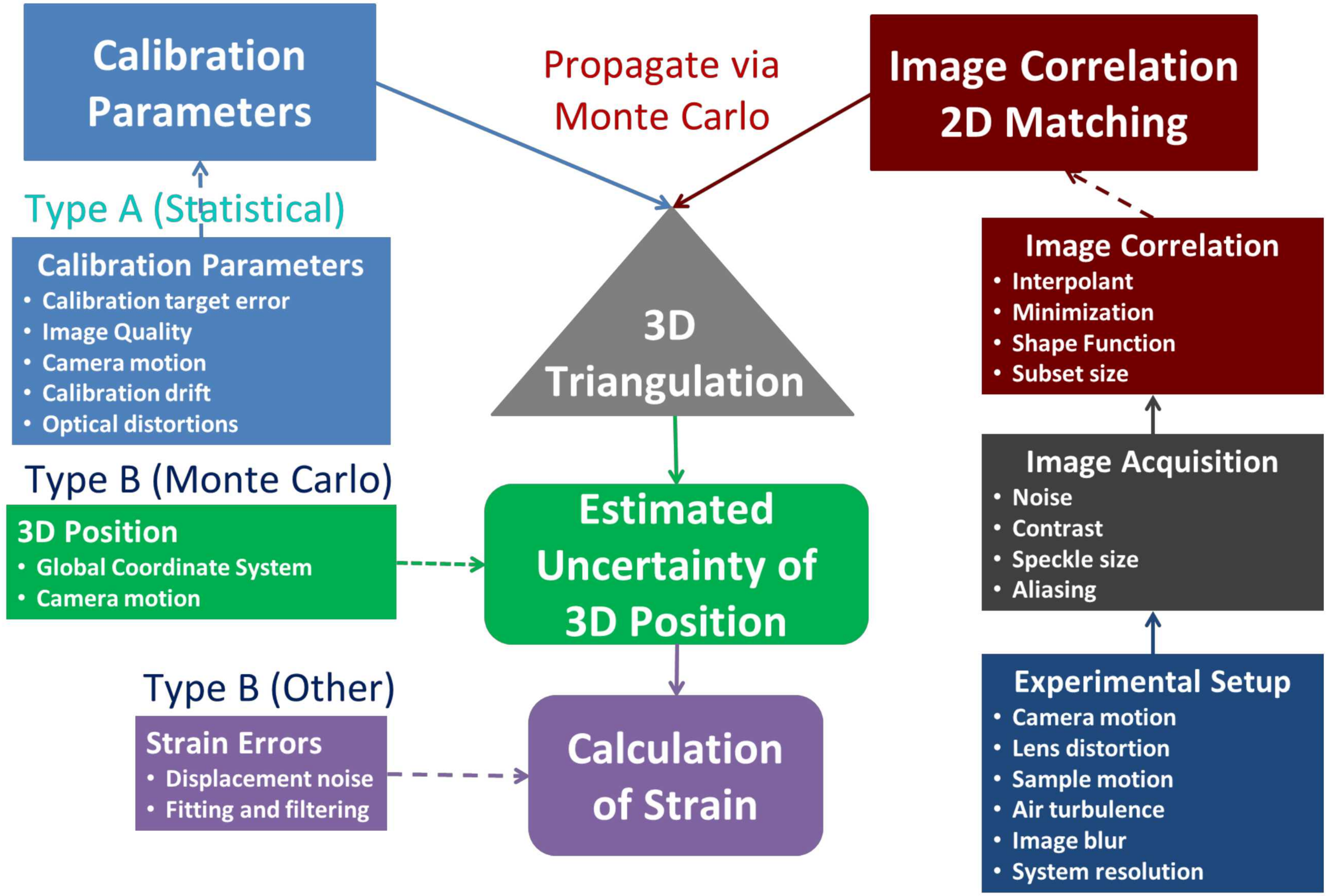
Recommendation 3.6 – Print calibration target better than 0.1 pixels.

Section 2.1.6 – Section 2.2



TRIANGULATED ACCURACY

FOCAL LENGTH
STEREO-ANGLE
CAMERA MOTION
CORRELATION ERRORS



Calibration Parameters

Propagate via Monte Carlo

Image Correlation 2D Matching

Type A (Statistical)

Calibration Parameters
- Calibration target error
- Image Quality
- Camera motion
- Calibration drift
- Optical distortions

3D Triangulation

Image Correlation
- Interpolant
- Minimization
- Shape Function
- Subset size

Type B (Monte Carlo)

3D Position
- Global Coordinate System
- Camera motion

Estimated Uncertainty of 3D Position

Image Acquisition
- Noise
- Contrast
- Speckle size
- Aliasing

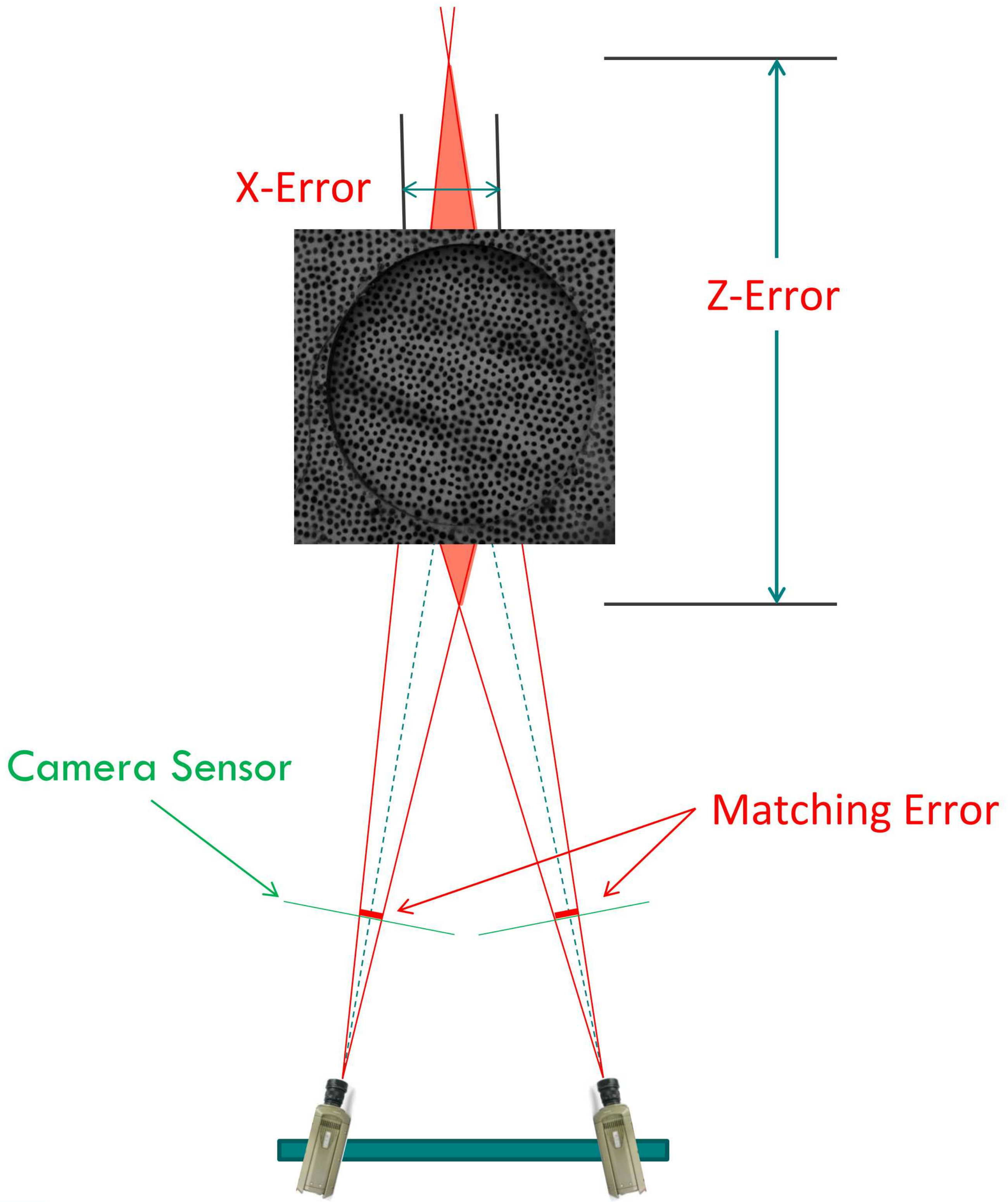
Type B (Other)

Strain Errors
- Displacement noise
- Fitting and filtering

Calculation of Strain

Experimental Setup
- Camera motion
- Lens distortion
- Sample motion
- Air turbulence
- Image blur
- System resolution

Stereo-DIC errors vary depending on lens and stereo-angle.



- Analyze noise in numerical study for simple geometry
- Vary key parameters (focal length, stereo angle, etc)

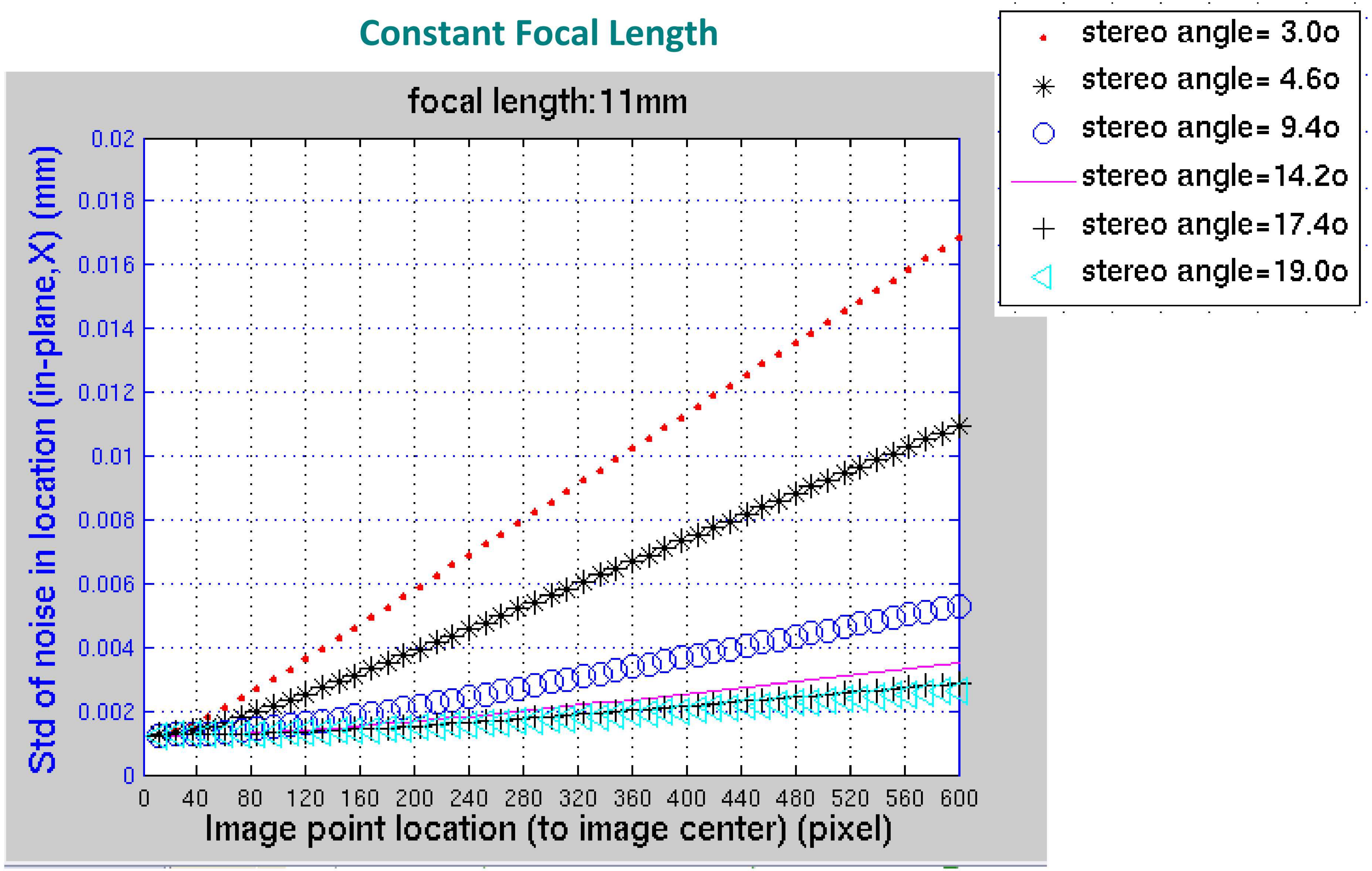
iDICs

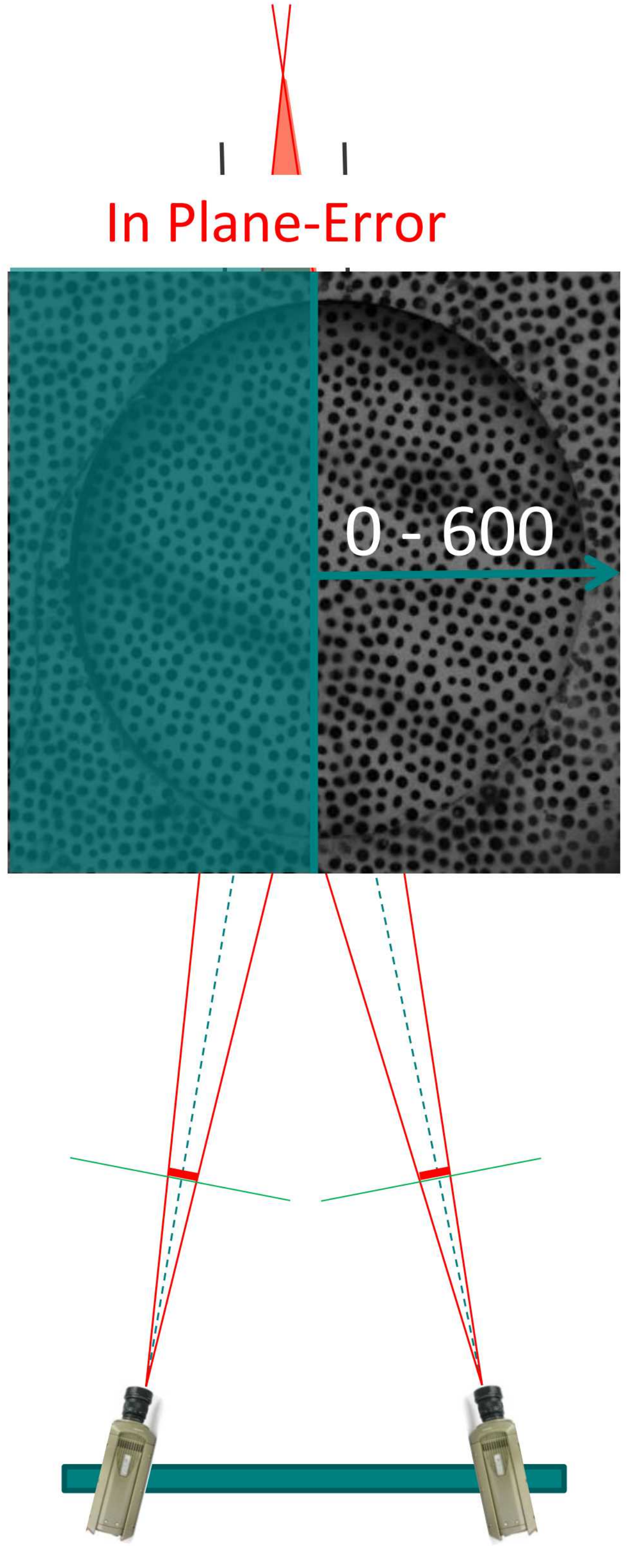
Wang, Y. Q., et al. (2011). Experimental Mechanics **51(4): 405-422.**

Courtesy of Correlated Solutions

Wide angle lenses will have greater in-plane errors

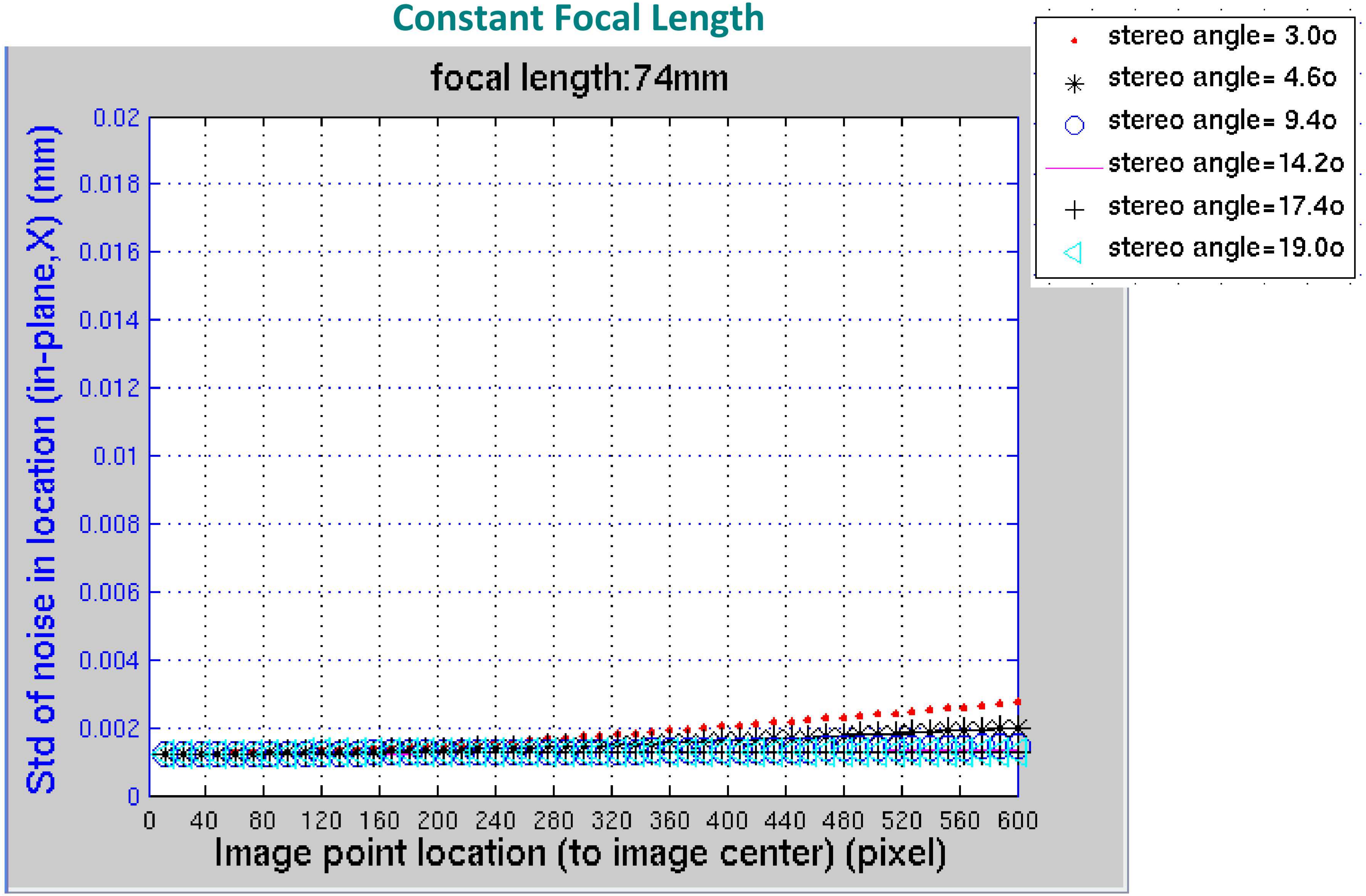
Constant Focal Length

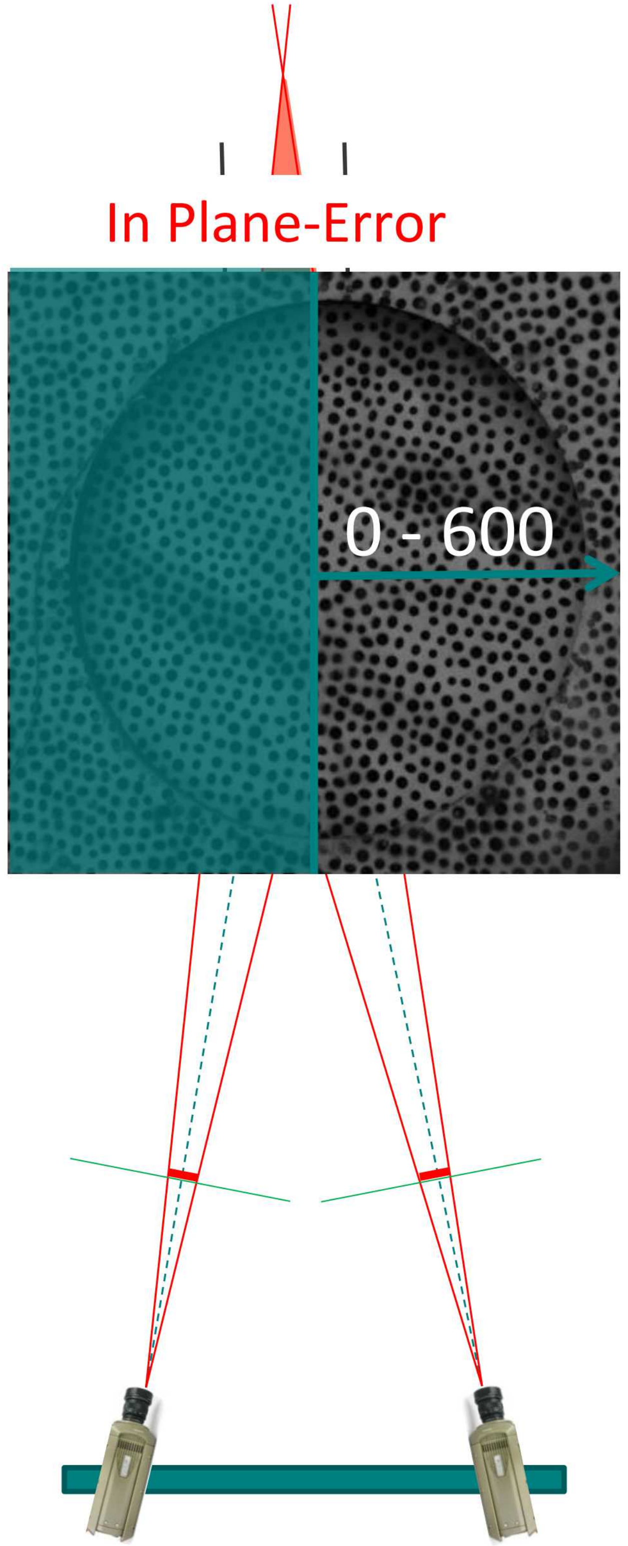




Stereo angle has smaller effect on in-plane uncertainty with longer focal length lens (74mm).

Constant Focal Length



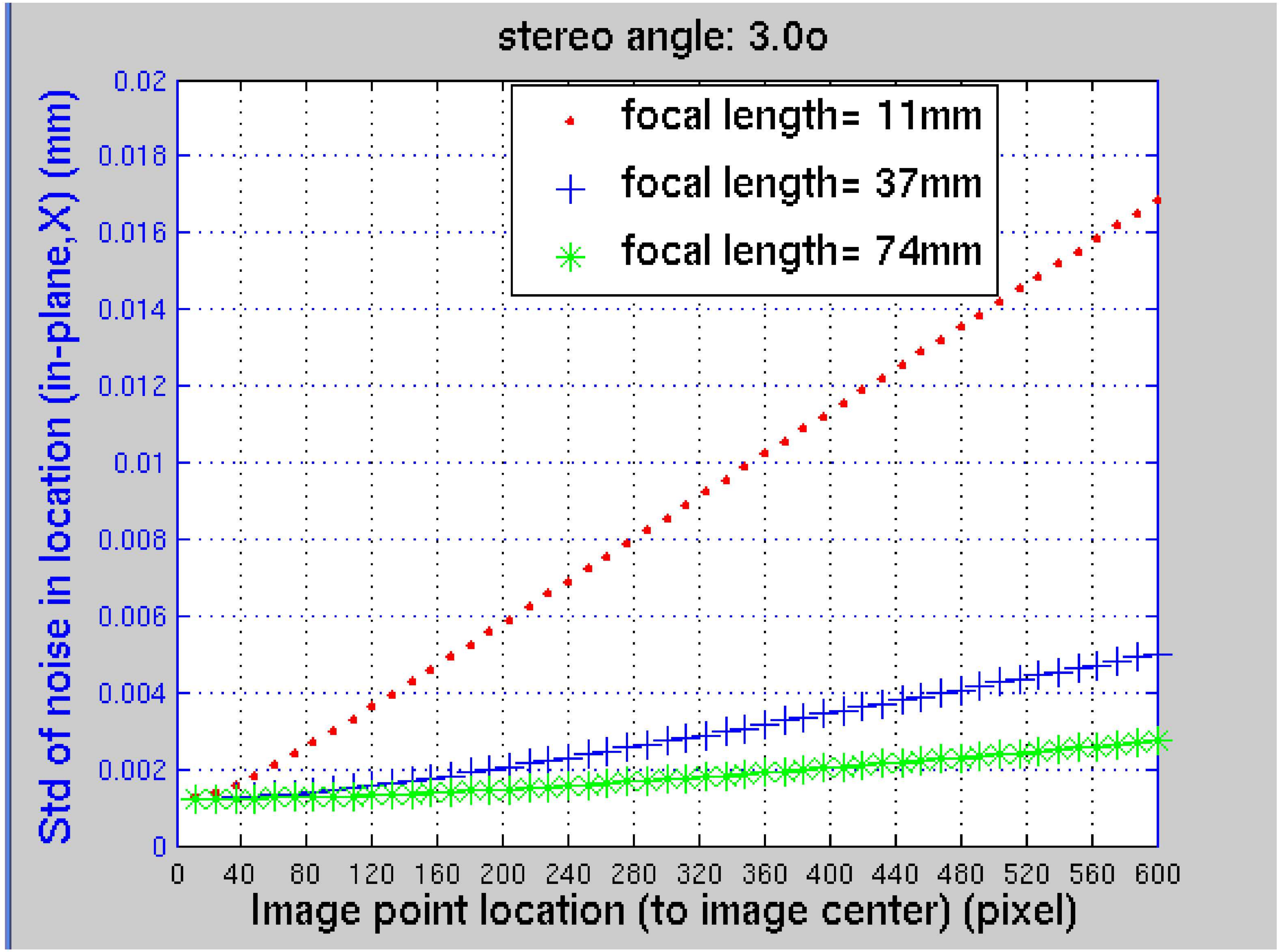


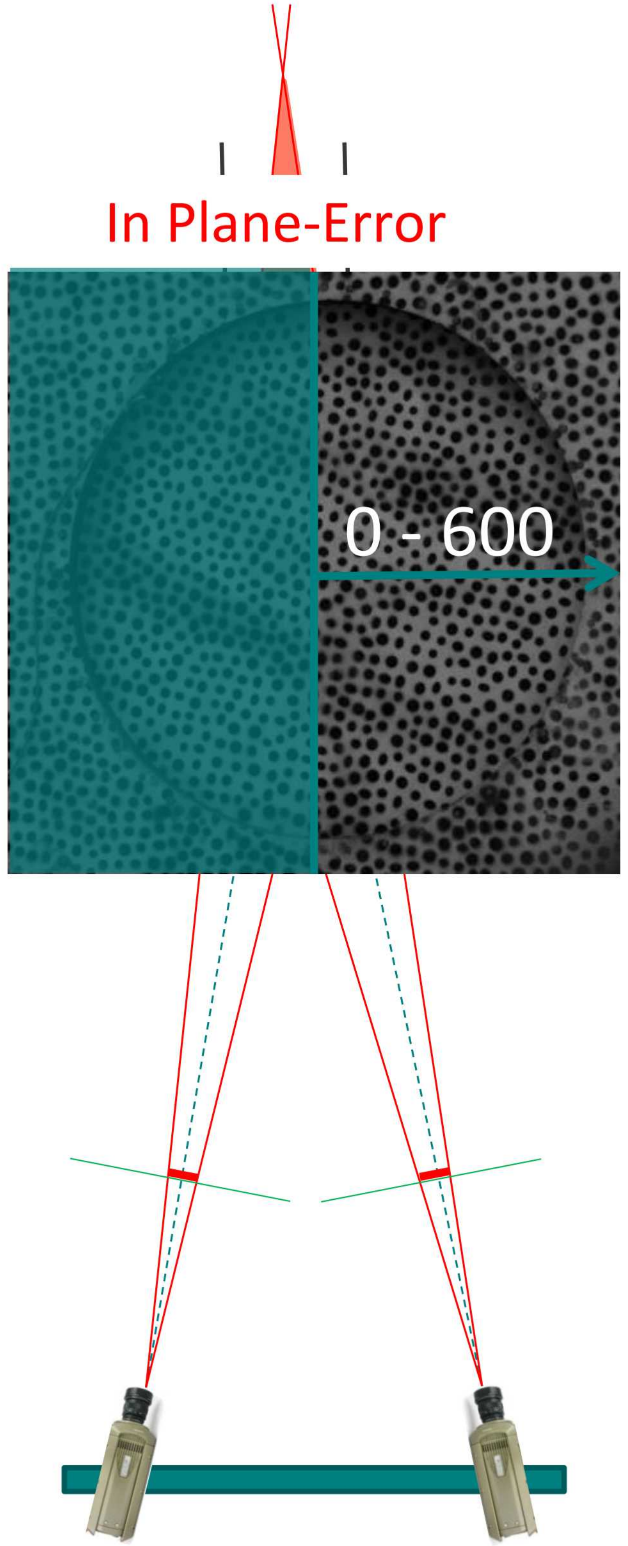
iDICs

Courtesy of Correlated Solutions

Long focal length lenses give lower in-plane uncertainty

Constant Stereo Angle





iDICs

Courtesy of Correlated Solutions

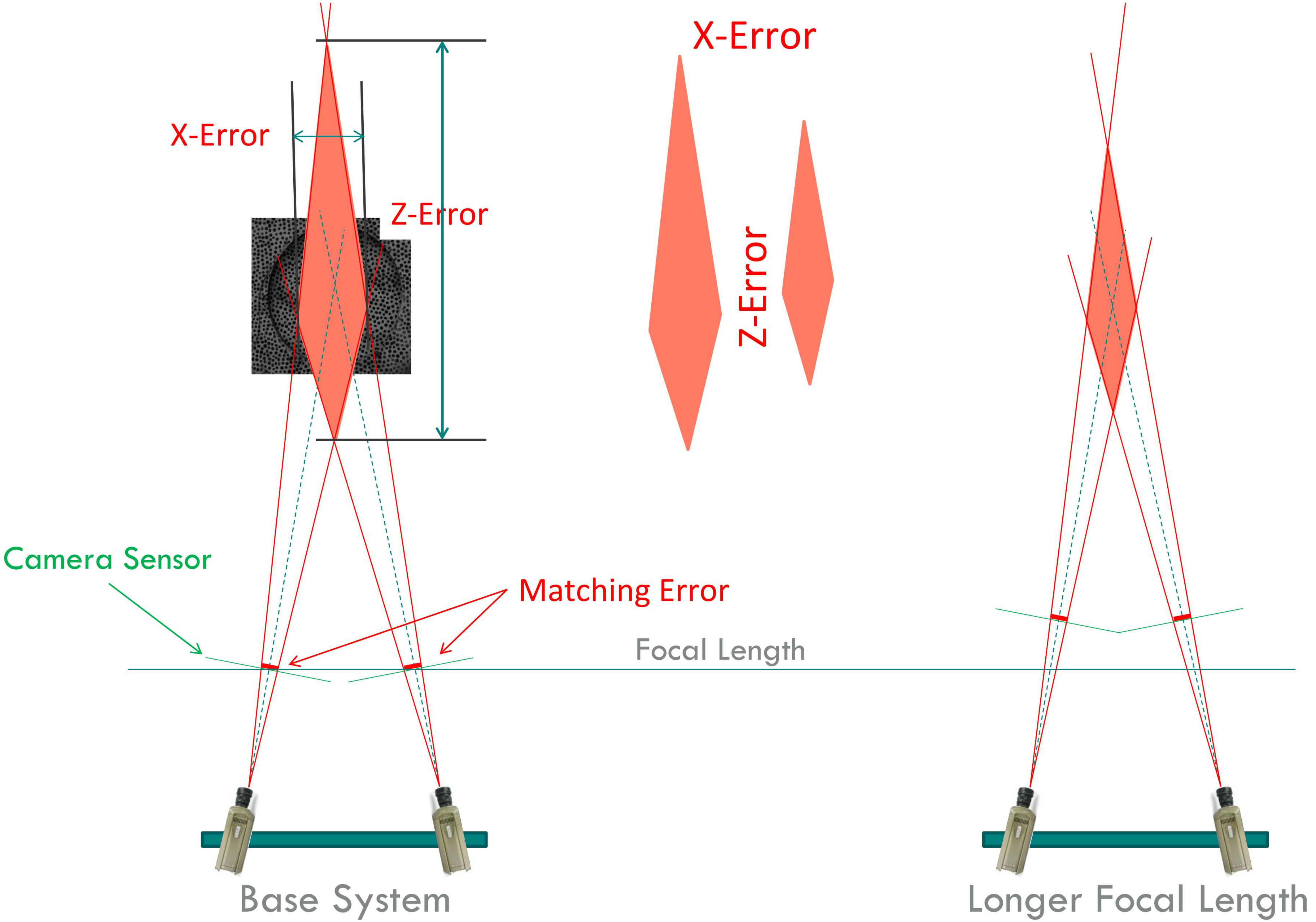
Prediction results: experiments

- Noise increases with distance from optical axis for all configurations
- For small stereo angles, noise increases dramatically
- For longer focal lengths, increase is more gradual
- Why?

A Geometric Explanation

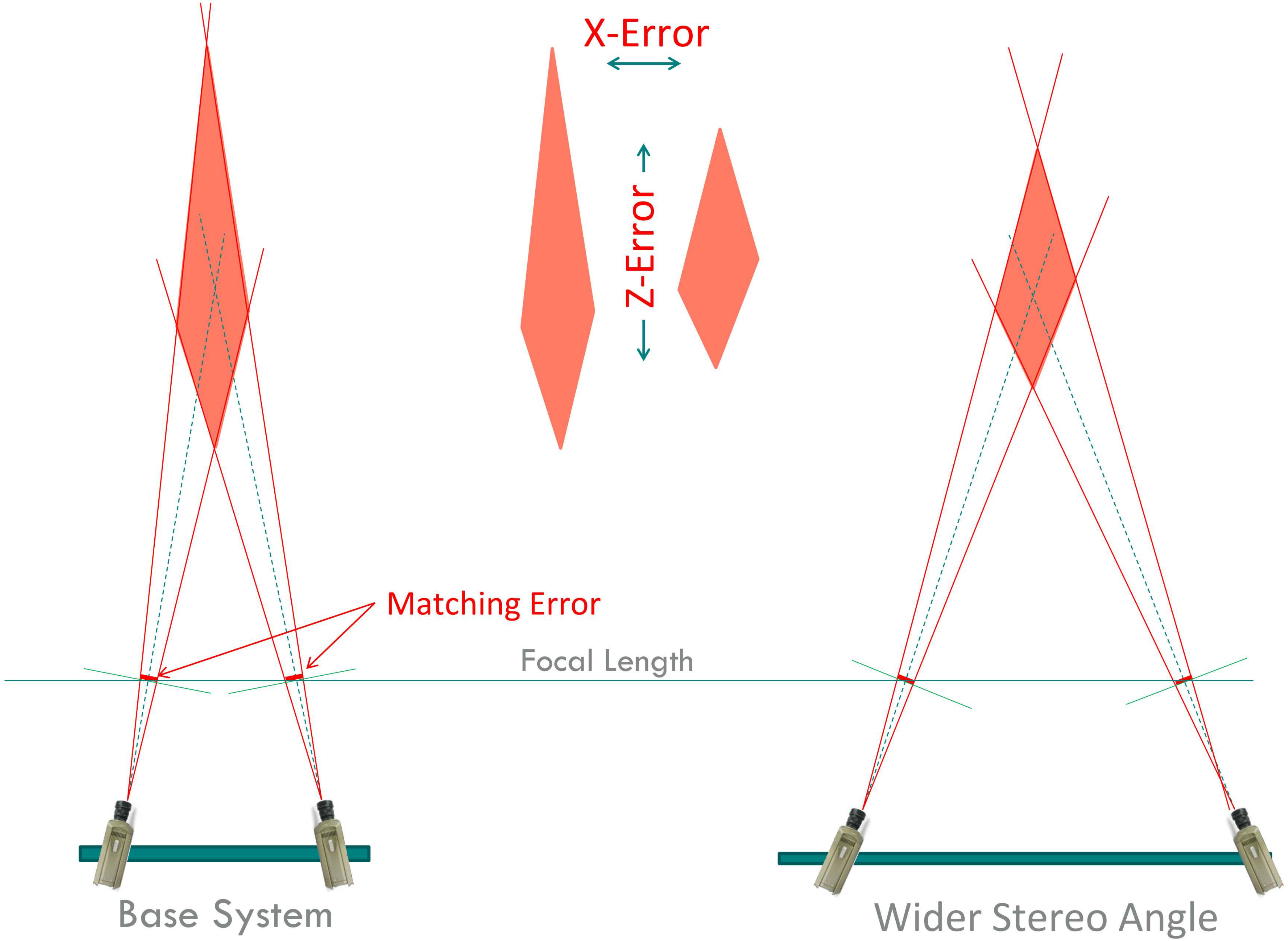
Courtesy of Correlated Solutions

Longer focal length decreases Z-error (depth)



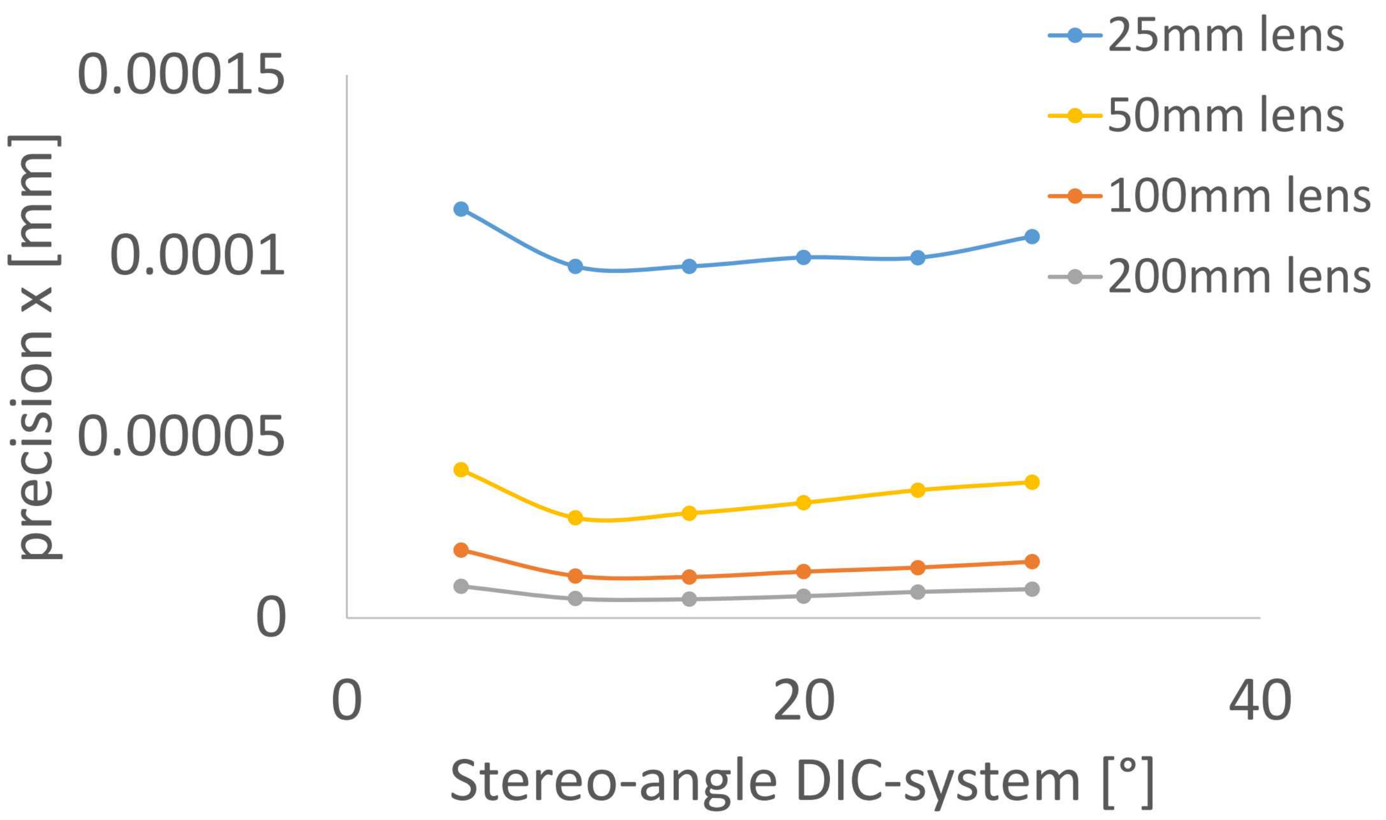
Concepts from Correlated Solutions

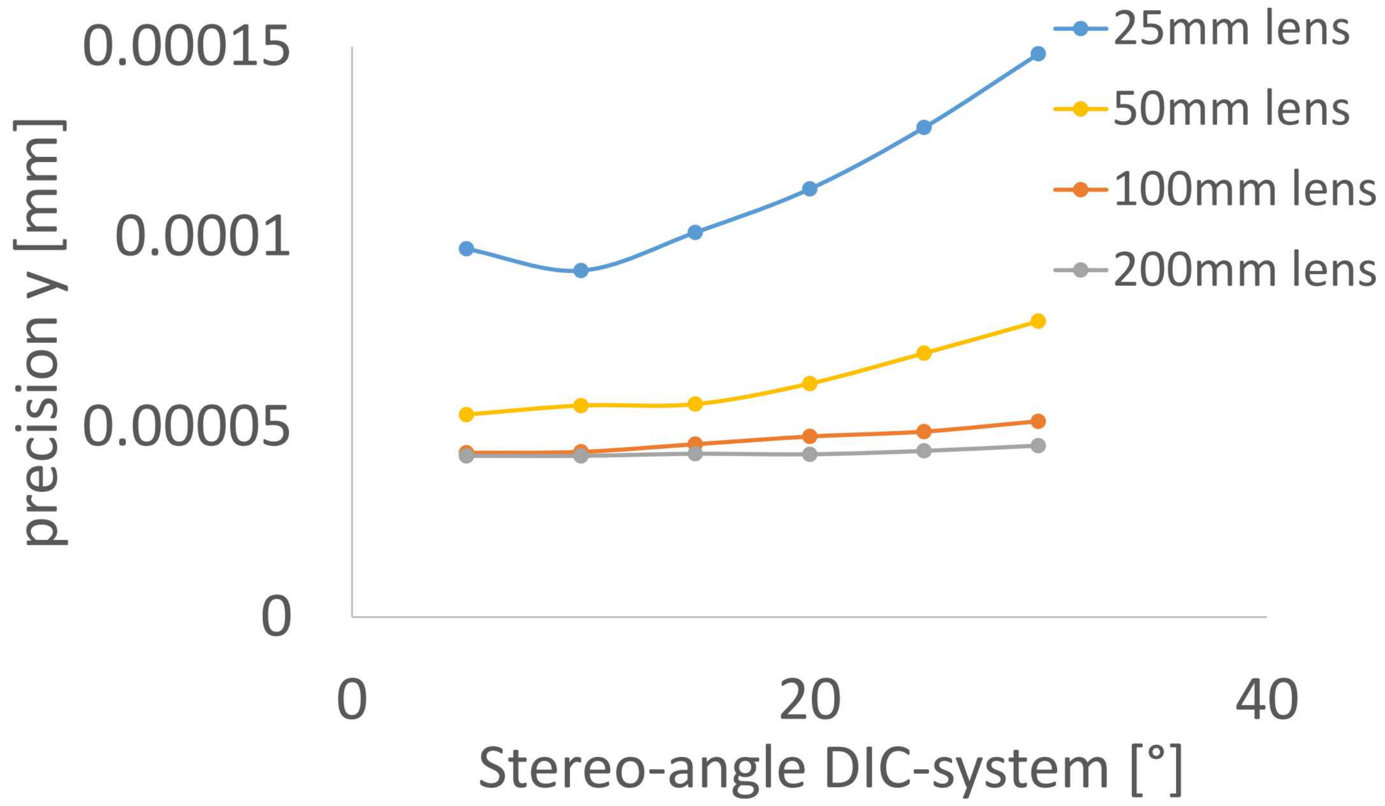
Wider stereo angle decreases Z-error

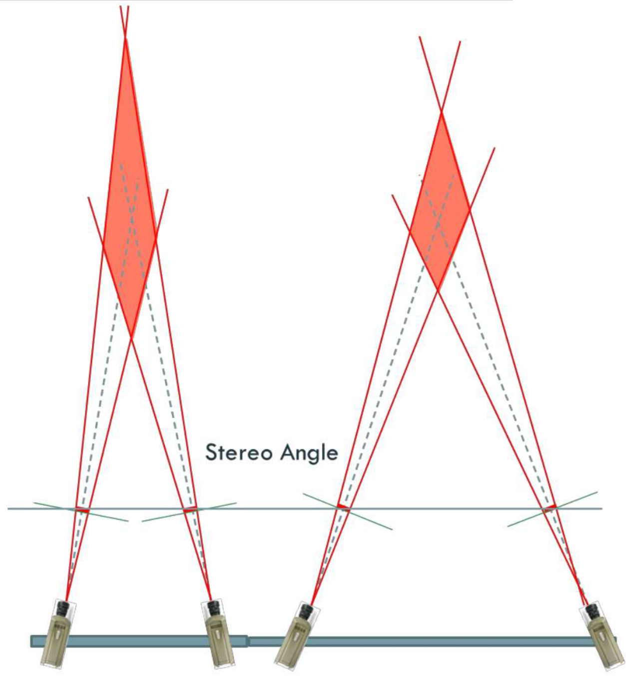


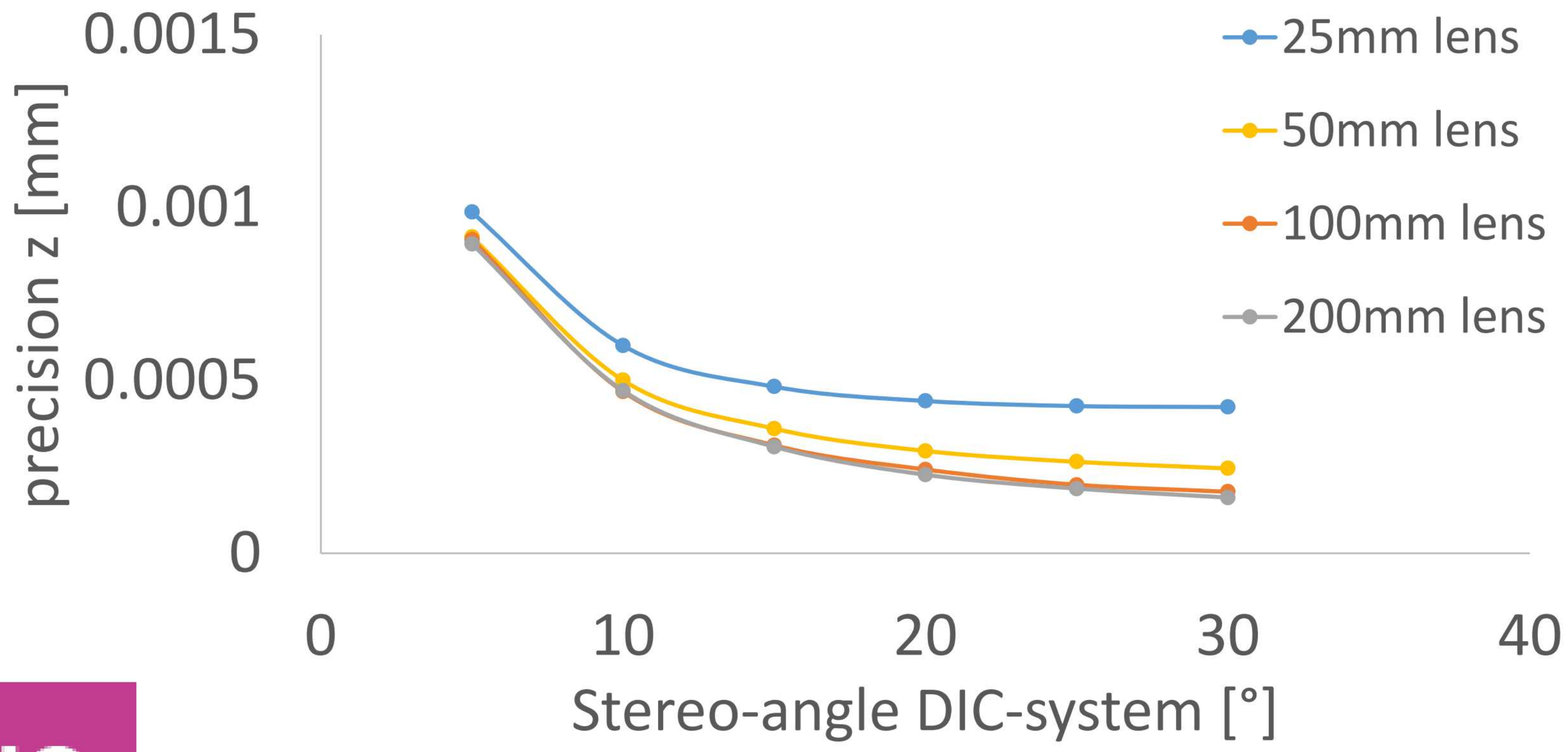
Concepts from Correlated Solutions

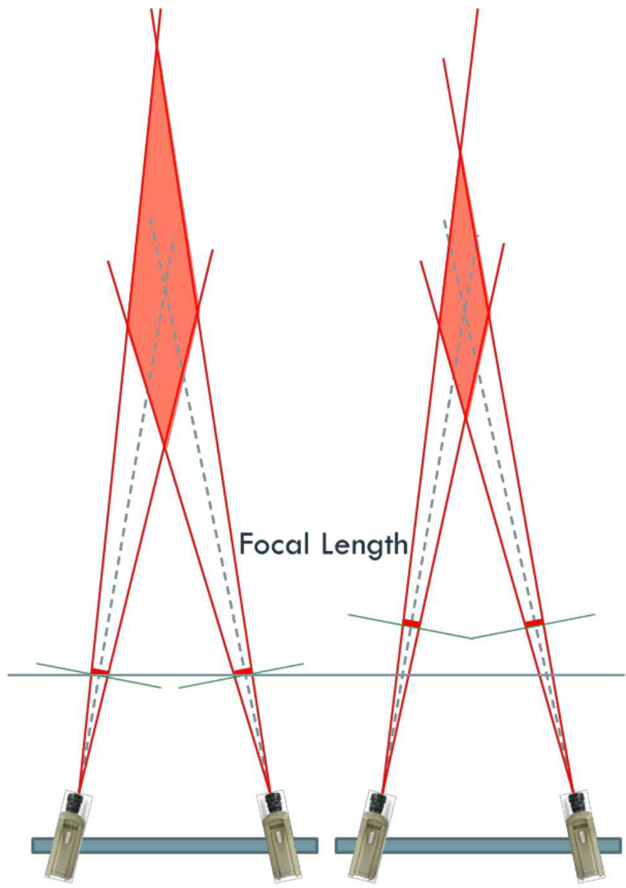
Stereo-DIC Simulation Results: Influence focal length and stereo-angle on accuracy









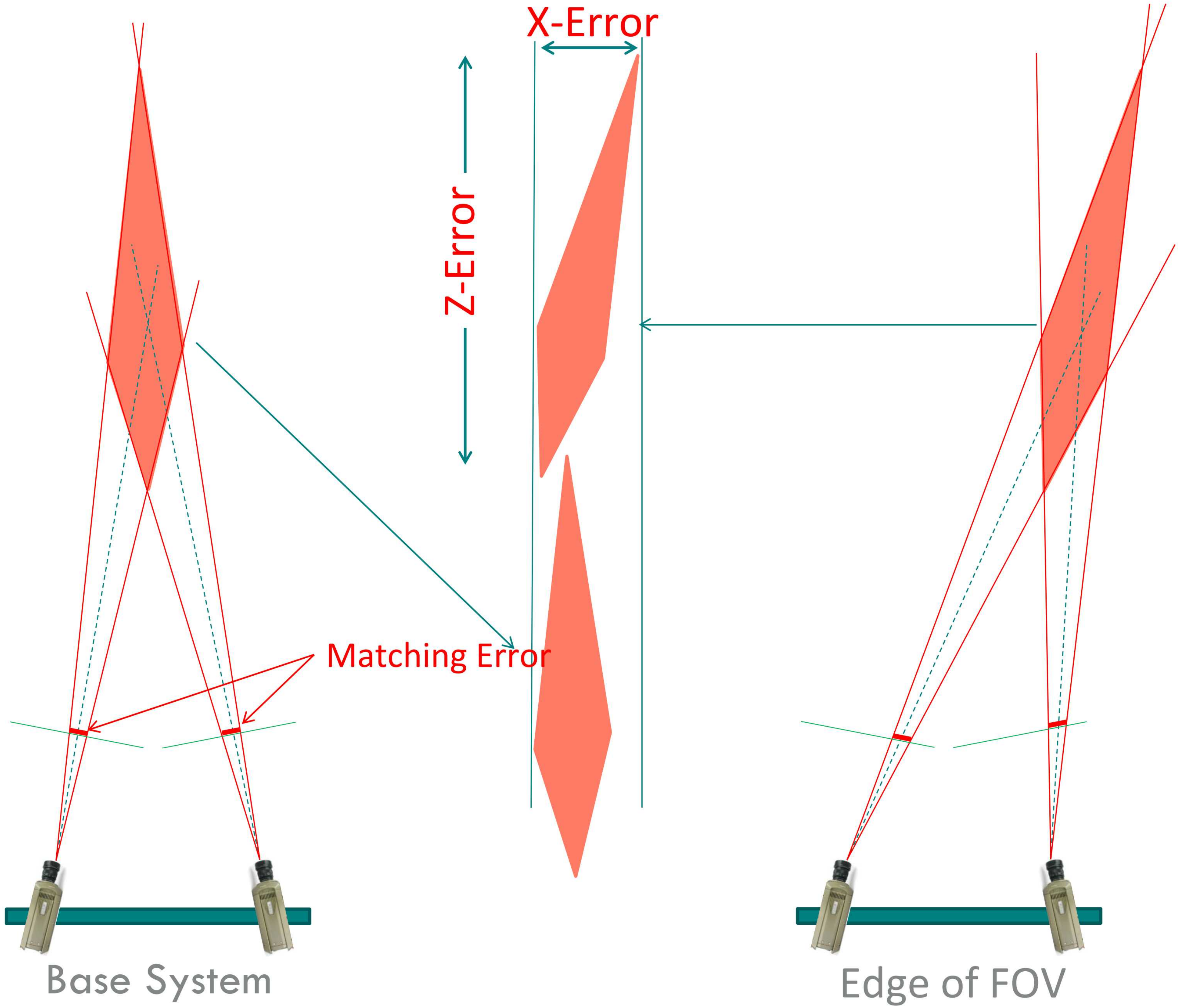


Simulation details

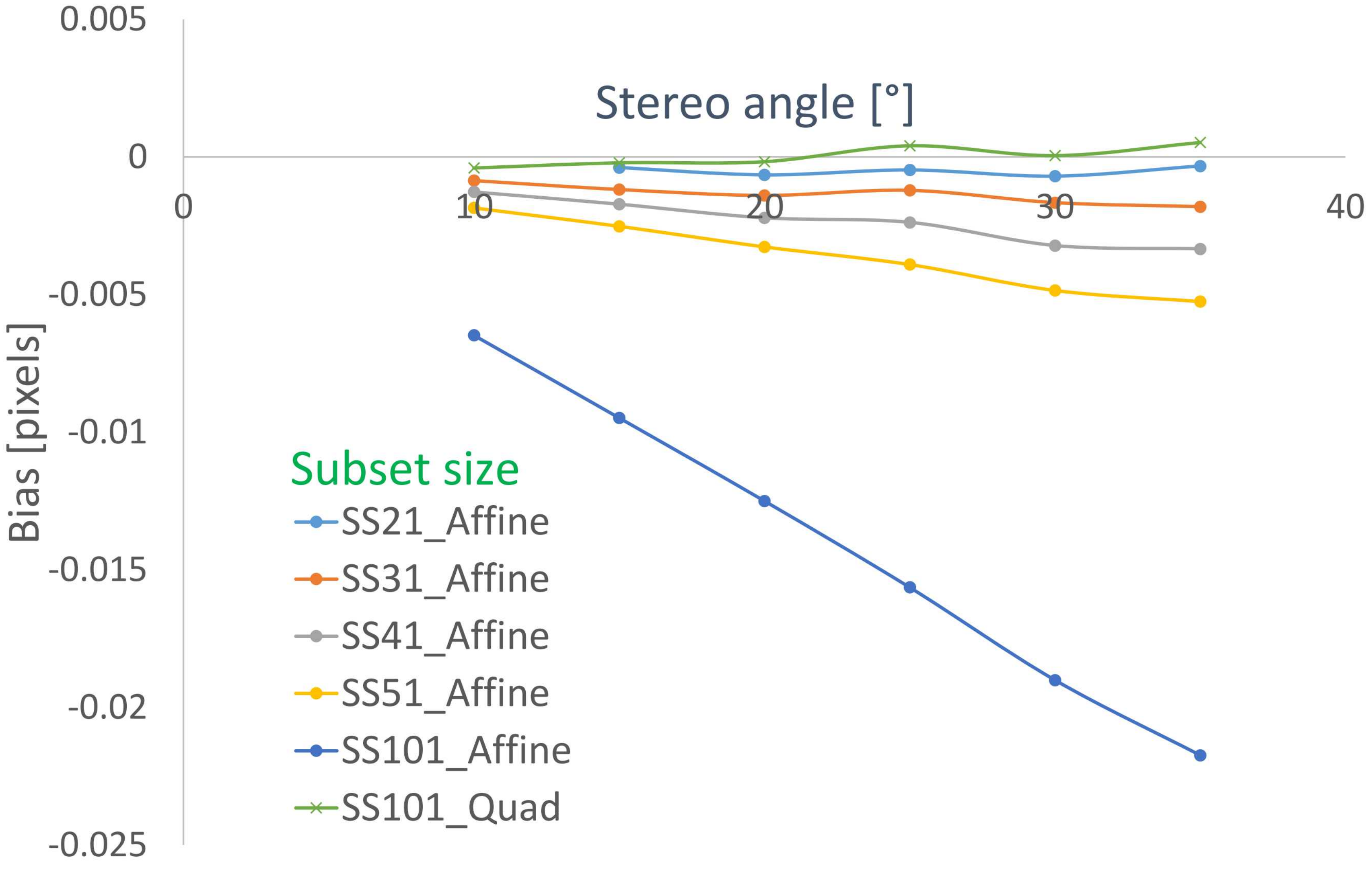
- Flat plate 100×130 mm
- No lens distortion, 0.5% noise
- Focal Lengths: 25-mm, 50-mm, 100-mm, 200-mm
- Stereo angle 5˚ to 30˚

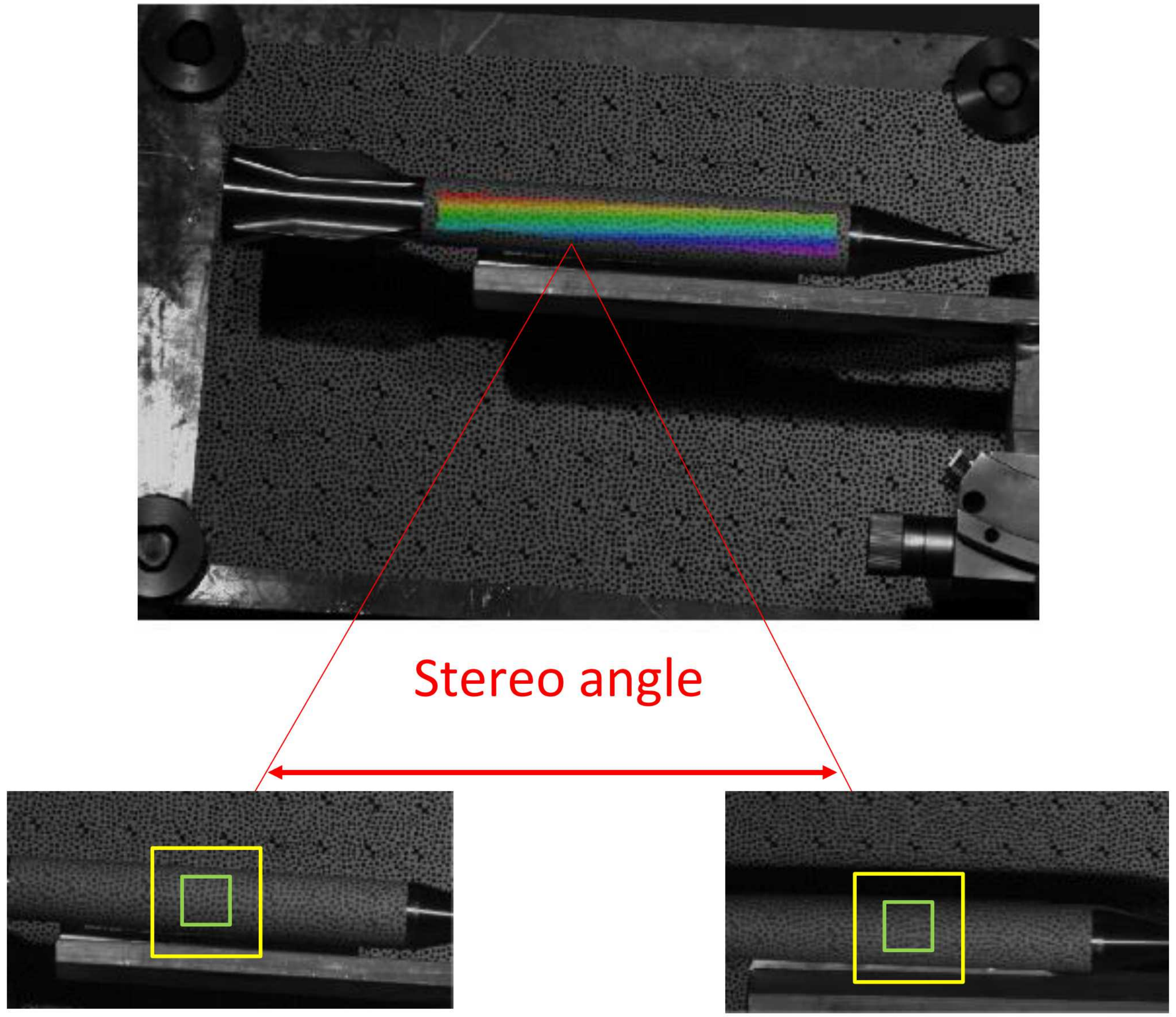
Stereo: Focal Length & Stereo Angle

The edge of the FOV has larger X-error



The shape function can cause bias error in the triangulation.





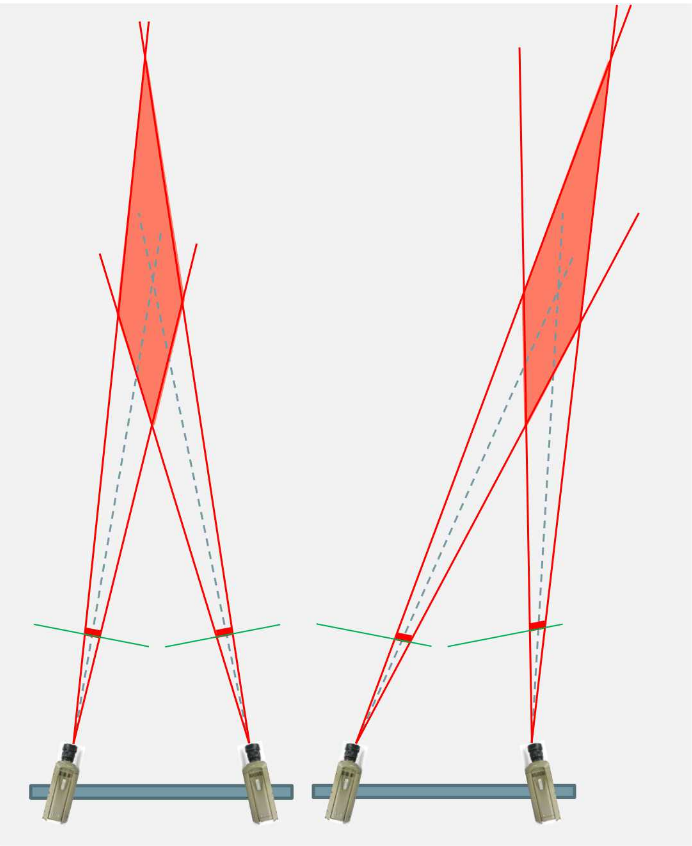
“Under-matched” shape function

- The perspective view is not “perfectly” matched with an affine shape function.
- There are a number of solutions to this problem including, higher-order shape functions, image warping, etc. Some may be better than others…
- Keep subsets small and perspective view lower to minimize.

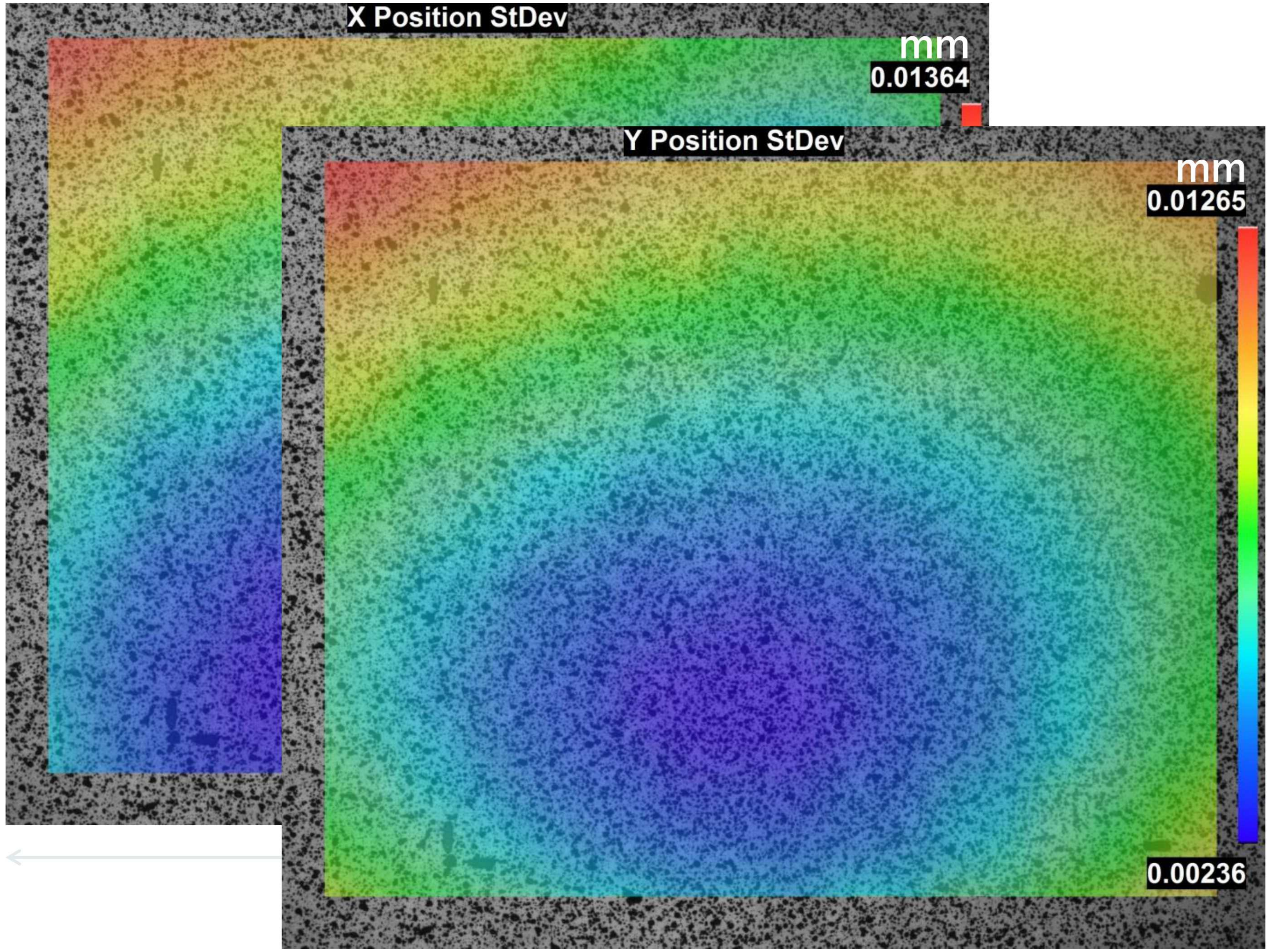
Ruben Balcaen – KU Leuven PhD Student

Full-field UQ results may also be calculated with the same techniques.

75-mm Lens
6 Calibration Images
Sensor = 0 (1σ)



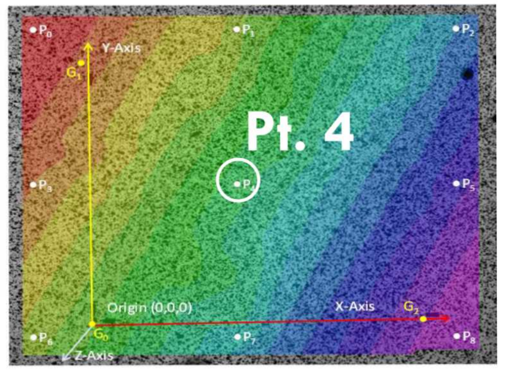
Edges Are Worse.

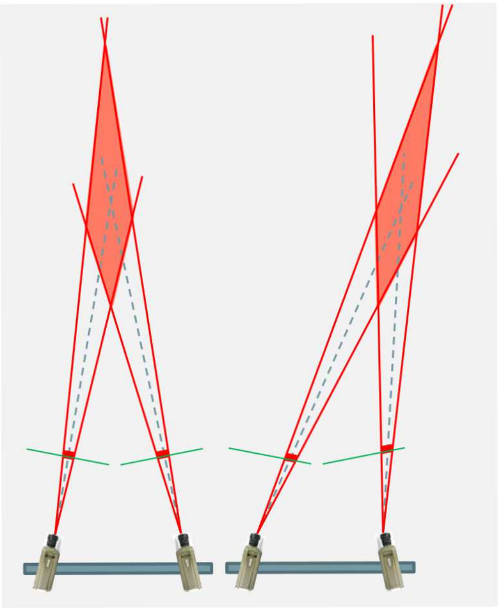


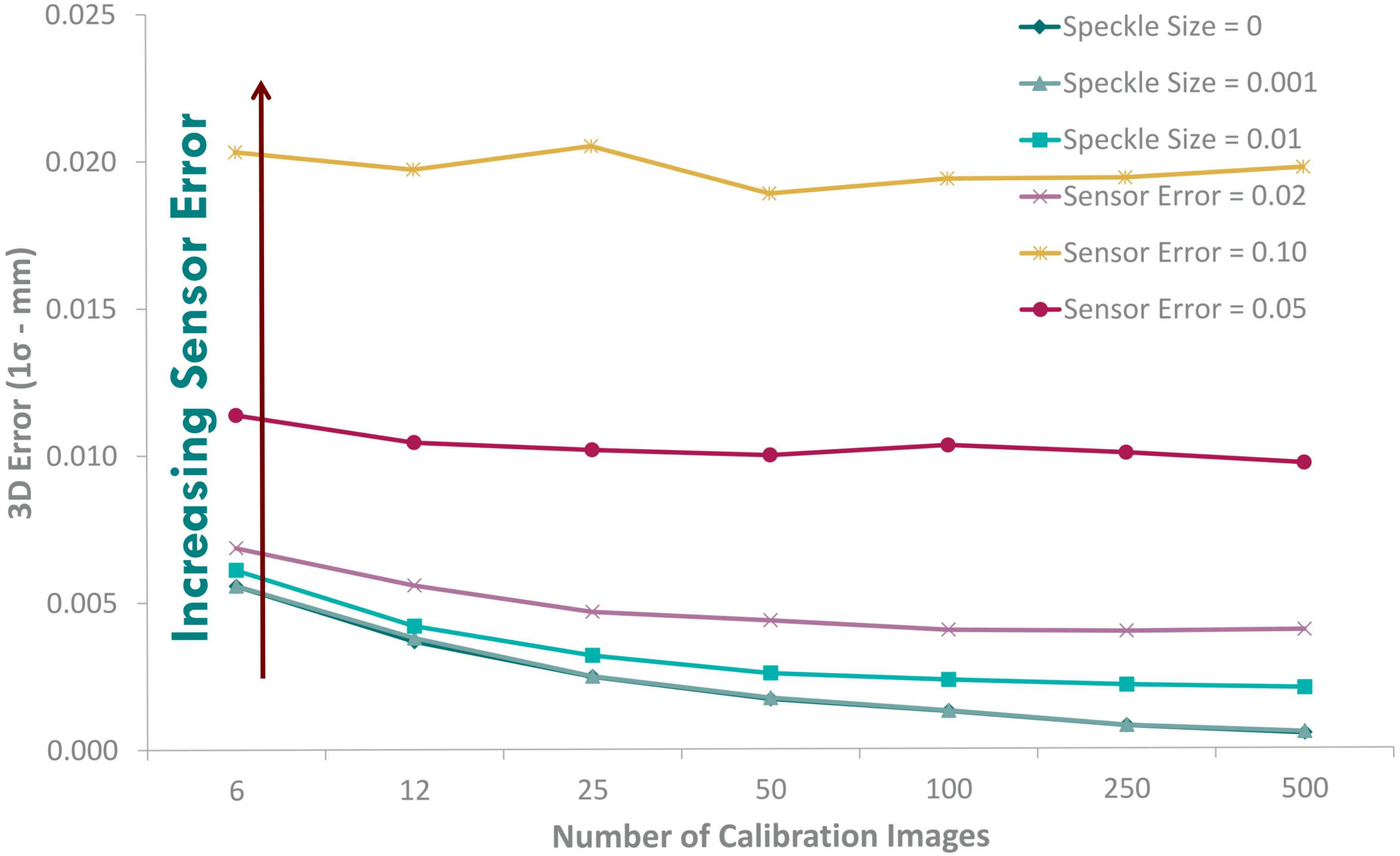
100-mm FOV

Stereo: Image Location

At the center – the matching error dominates the error.

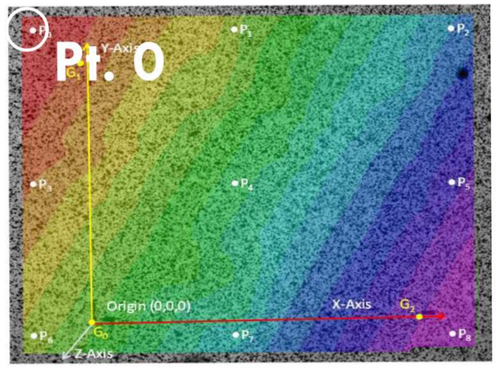


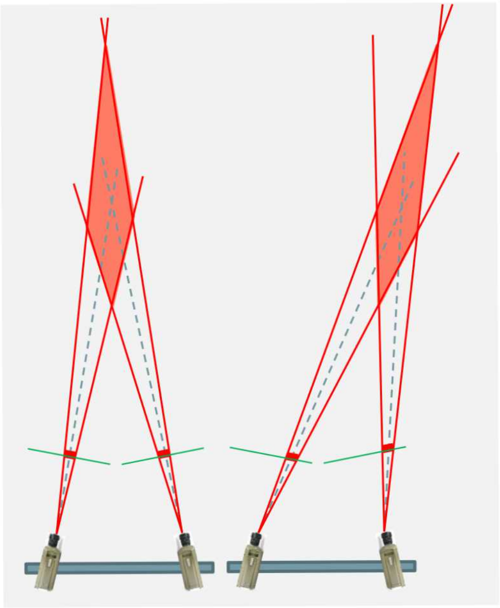


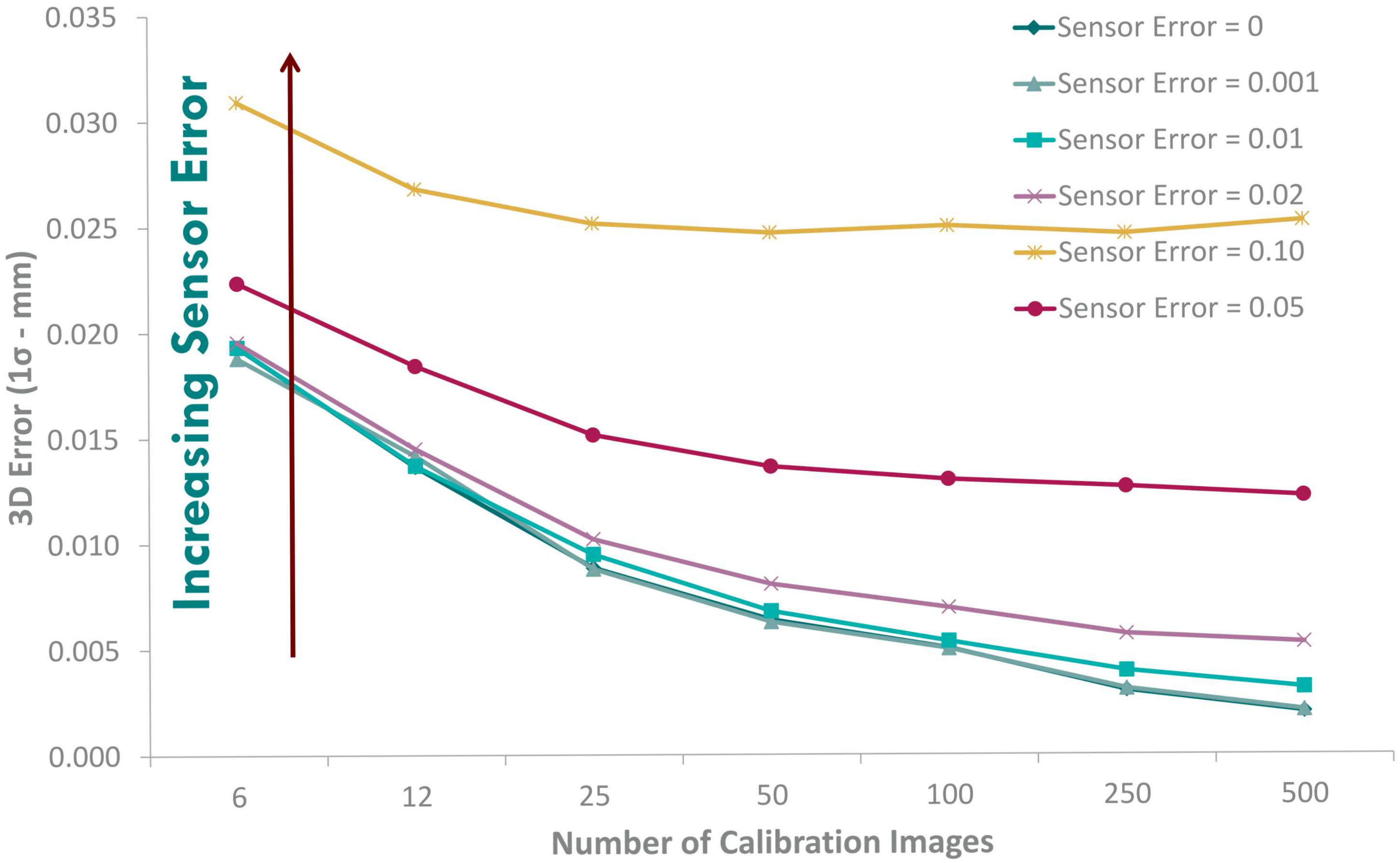


75-mm Lens – 100-mm FOV
Sensor Error = Matching Error (pixels)

At the edge of the FOV, the calibration dominates the uncertainty.



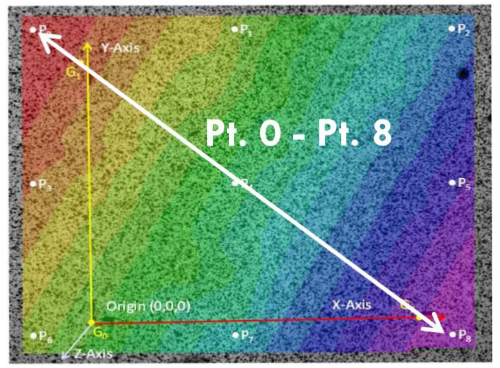


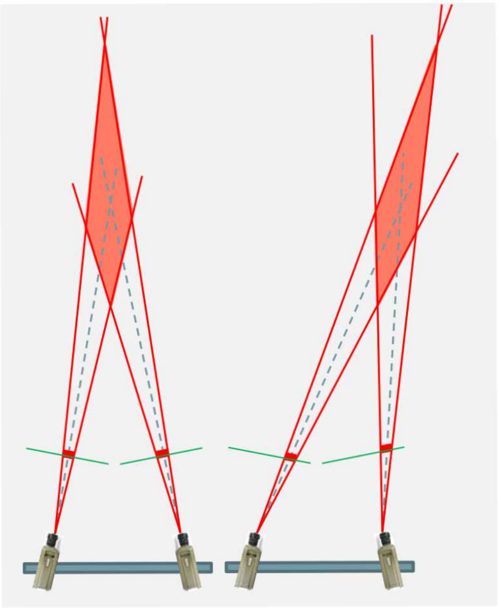


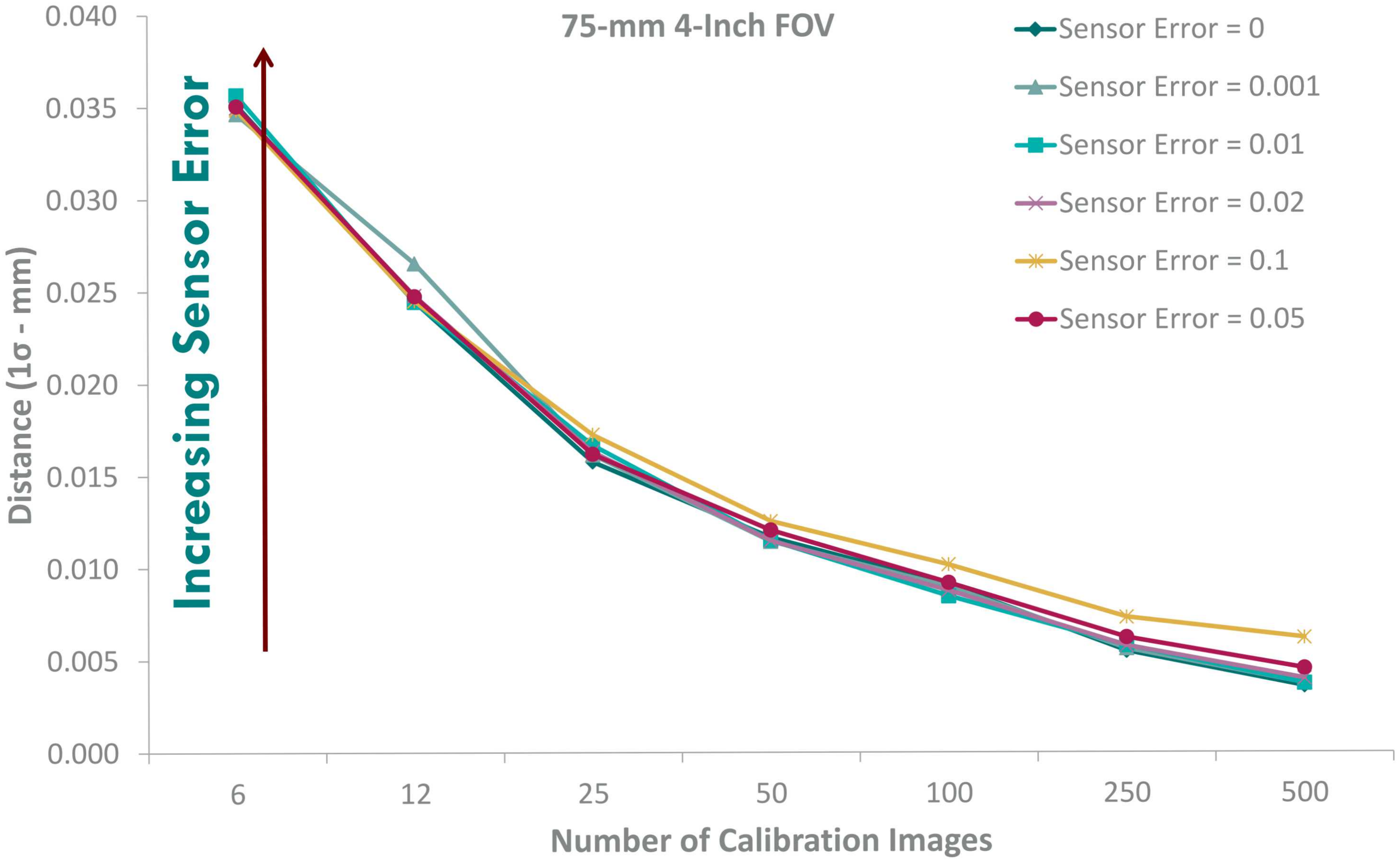
75-mm Lens – 100-mm FOV
Sensor Error = Matching Error (pixels)

Stereo: Image Location, Focal Length, Image Matching, #Cal Images

The edges are dominated by the calibration.







75-mm Lens – 100-mm FOV

Sensor Error = Matching Error (pixels)

VIRTUAL STRAIN GAGE SIZE STUDY

TYPE B ASSESSMENT OF THE BIAS ERRORS.

Strain is a relative displacement over a gauge length.

To improve resolution

1. Increase resolution on Δl
2. Increase the gauge length l_o

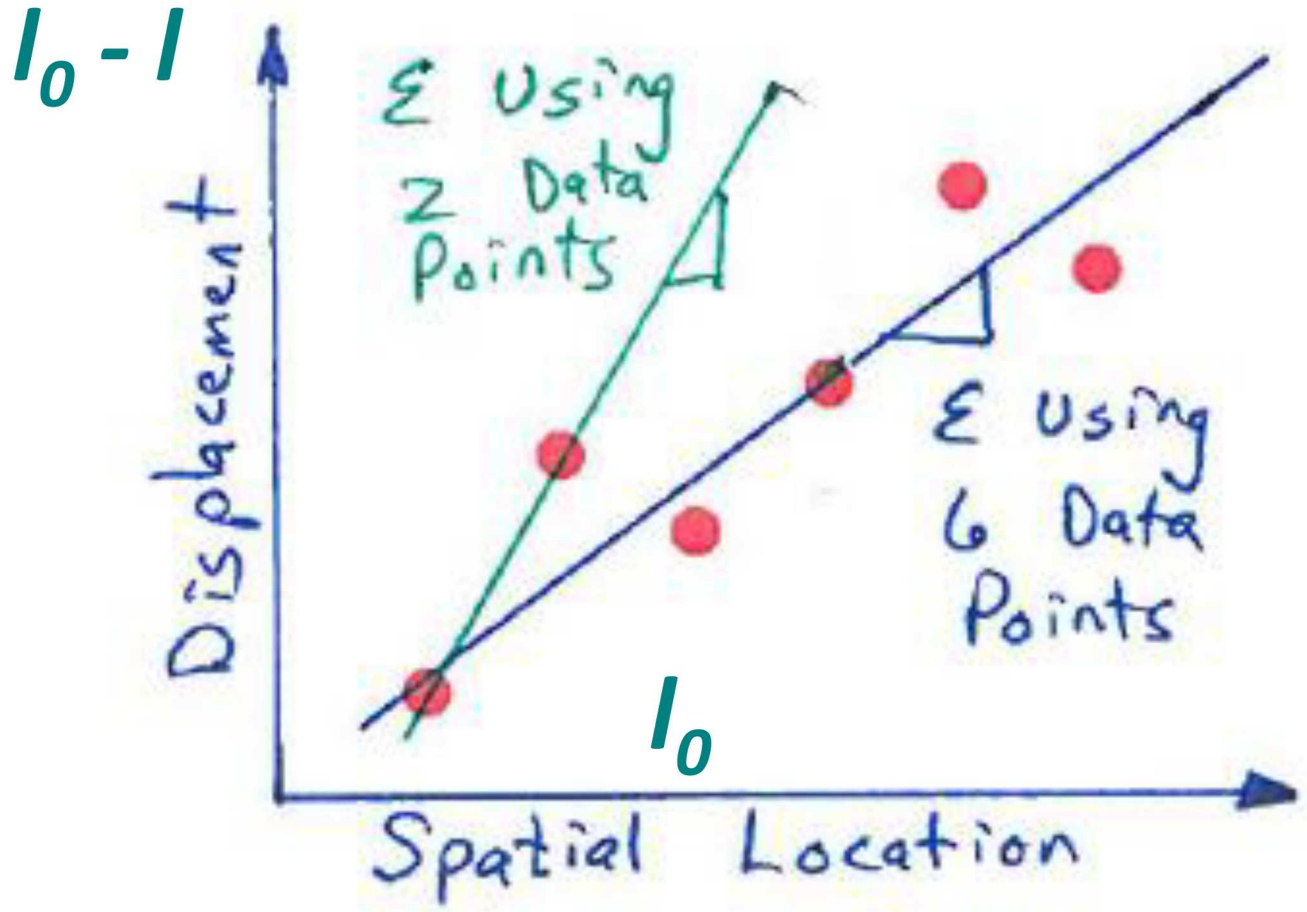
$$\varepsilon = \frac{l_o - l}{l_o} = \frac{\Delta l}{l_o} = \frac{(\text{pixels})}{(\text{pixels})}$$

l_o is the original length
l is the current length, and
ε is the strain

Some basic figures:

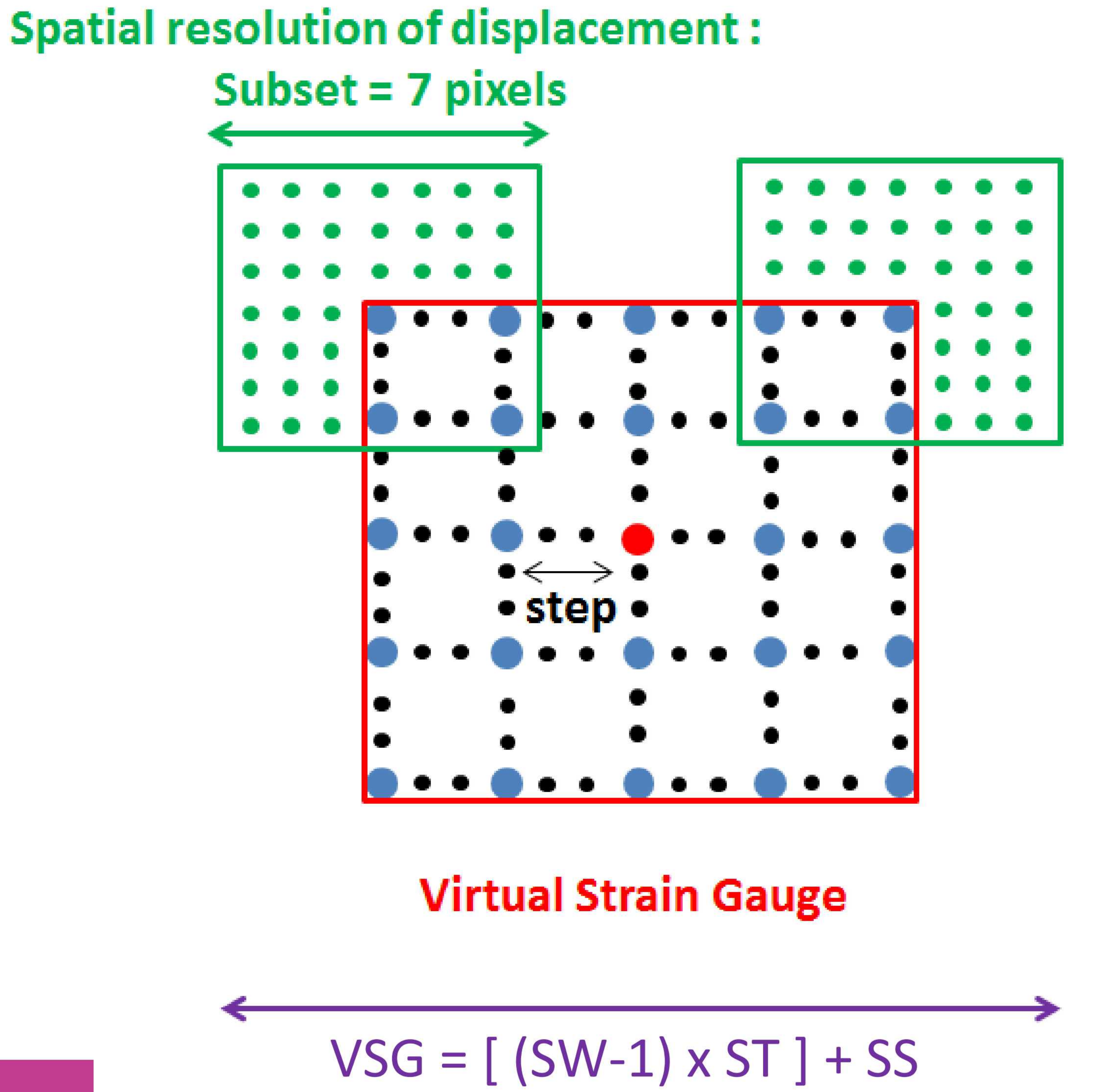
- If displacement resolution is 0.01 pixels, then Δl is 0.02 pixels. If strain is computed between two DIC subsets 20 pixels apart (l_o)
- This yields a strain of 2×10^{-3} ε (2000 $\mu\varepsilon$ or 0.2% strain)

Smoothing will be required to do better!



Strain is extremely sensitive to virtual strain gage size.

Subset (SS)= 7, Step (ST) = 3, Strain window (SW) = 5



VSG = [(SW-1) x ST] + SS

Virtual Strain Gage Size Study

- Investigates the spatial resolution.
- Helps understand bias due to filtering.
- Looks at subset size filtering.
- Is important and easy to do!

SW = Strain window or filter (data points)

ST = Step Size (pixels)

SR = Spatial Resolution (pixels)

The speckle size and spacing dictate your spatial resolution

Virtual strain gauge size

VSG = [(SW-1) x ST] + SS

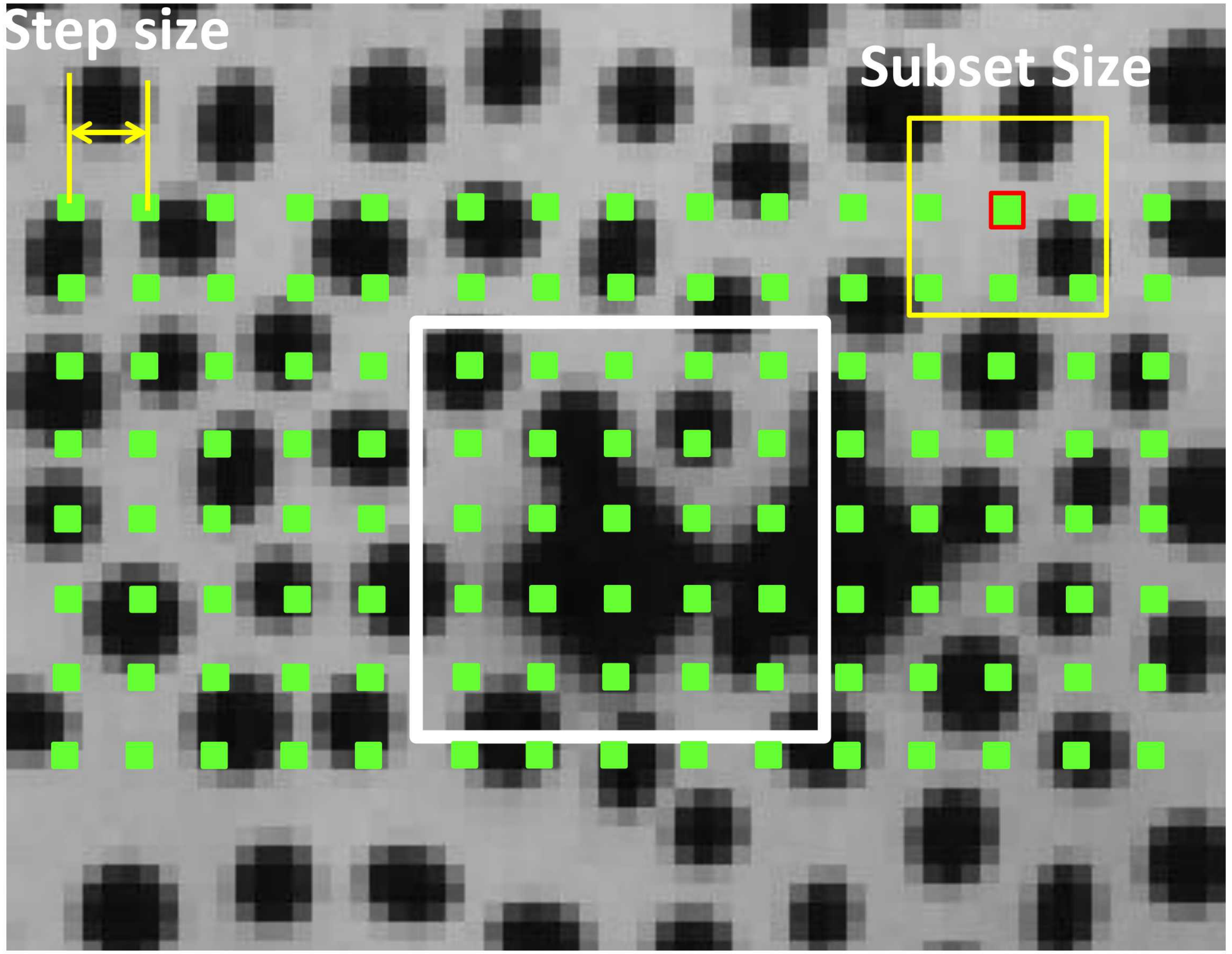
SW = Strain window or filter (data points)

ST = Step Size (pixels)

SR = Spatial Resolution (pixels)

Virtual Strain Gage (VSG)

Each dot represents a measurement point solved for at the center of each subset.



This is an 5x5 virtual strain gage

Section 5.3.2 – Examples of Strain Calculation Methods

Section 5.3.2.1 – Strain from subset shape function

- Highest spatial resolution
- Requires filtering of strain results (Gaussian usually)

Section 5.3.2.2 – Strain from finite-Element Shape Functions

- DIC displacements used as nodes of FE mesh.
- Requires filtering of strain results (Gaussian usually)
- Filter area is the "filter window"
- Larger hexagonal regions may be used, which provides filtering
- This area is the "strain window"

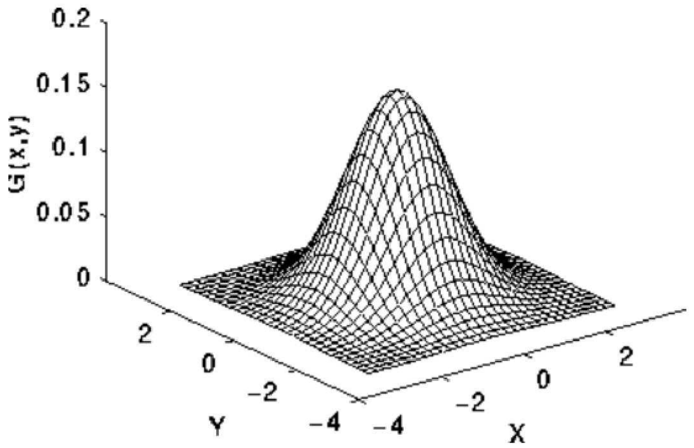
Section 5.3.2.3 – Strain from strain shape function

- Usually a polynomial or spline fit over a region of DIC displacement data.
- The fitting is a filtering process.
- Region used in the fit is called the "strain window"
- The data may also be weighted.

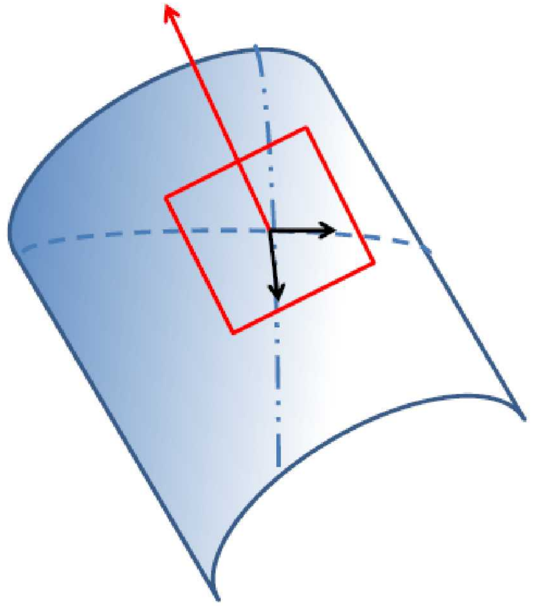
Section 5.3.2.4 – Spline fit over entire ROI

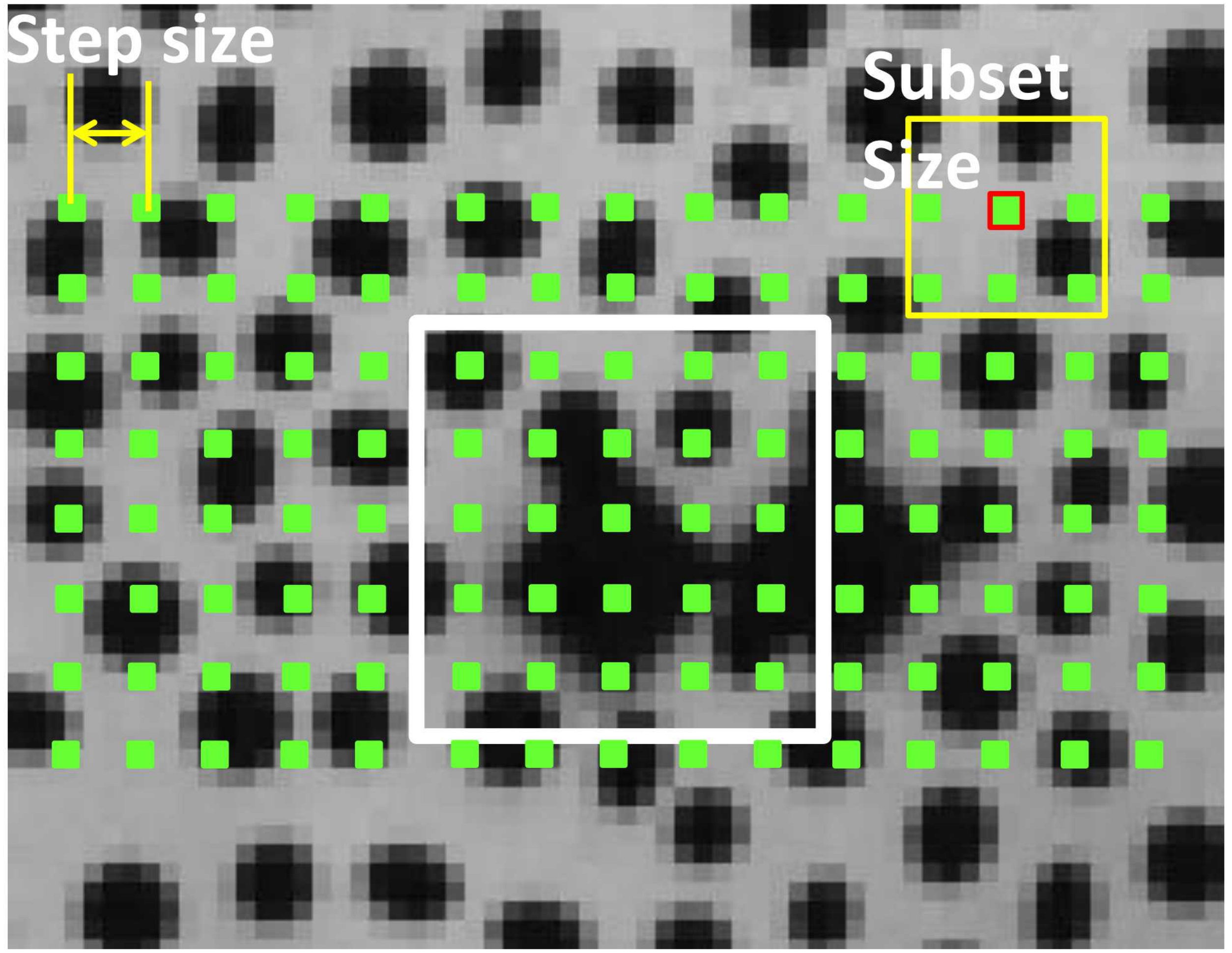
$$\frac{1}{273}\begin{bmatrix} 1 & 4 & 7 & 4 & 1 \\ 4 & 16 & 26 & 16 & 4 \\ 7 & 26 & 41 & 26 & 7 \\ 4 & 16 & 26 & 16 & 4 \\ 1 & 4 & 7 & 4 & 1 \end{bmatrix}$$

Gaussian Smoothing

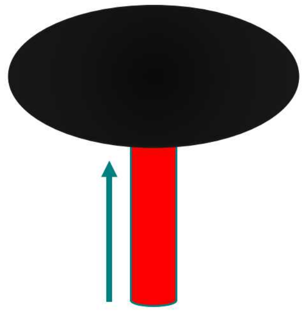


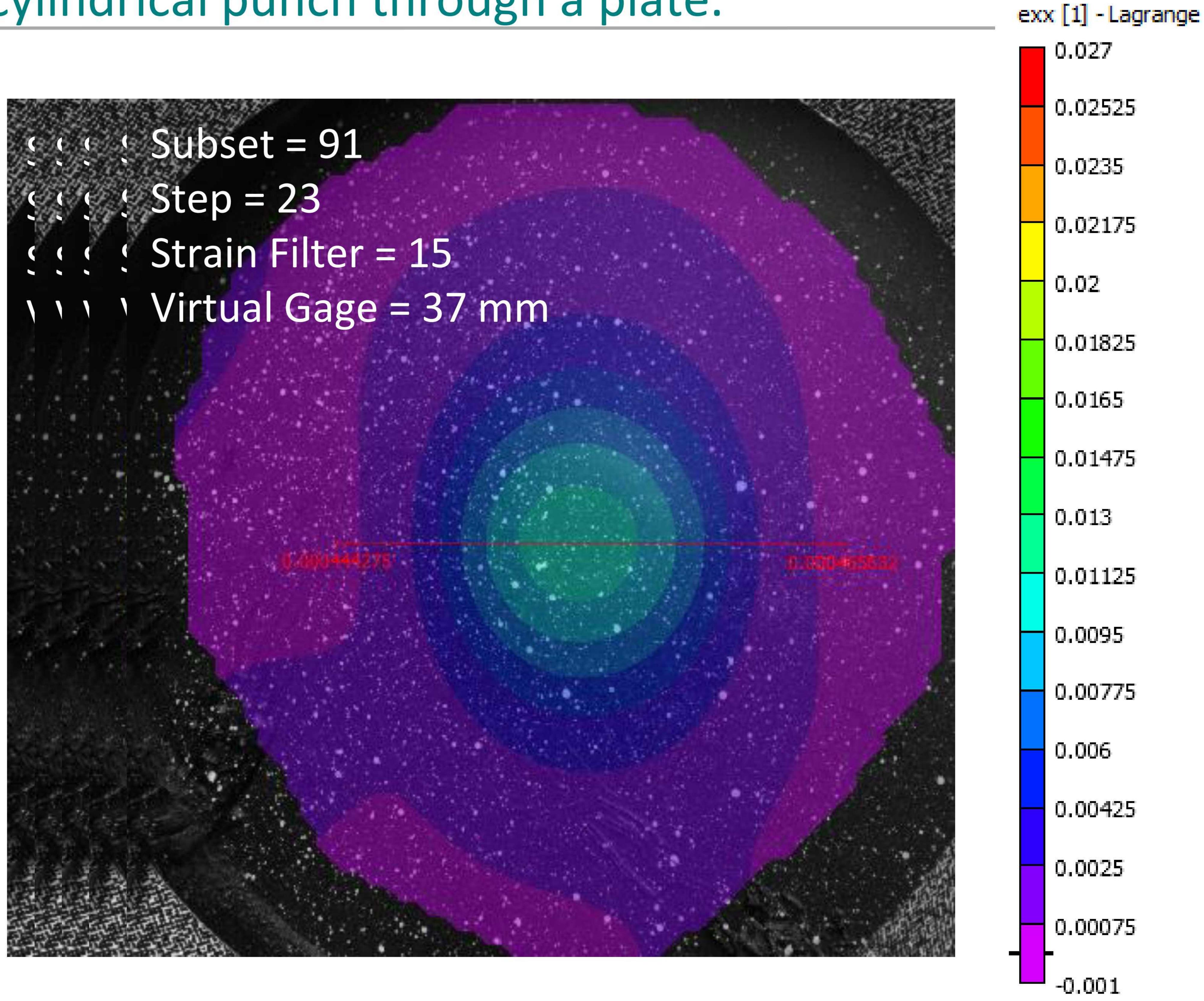
Strain is determined in the local coordinates





VSG Size study on a cylindrical punch through a plate.





Subset = 91

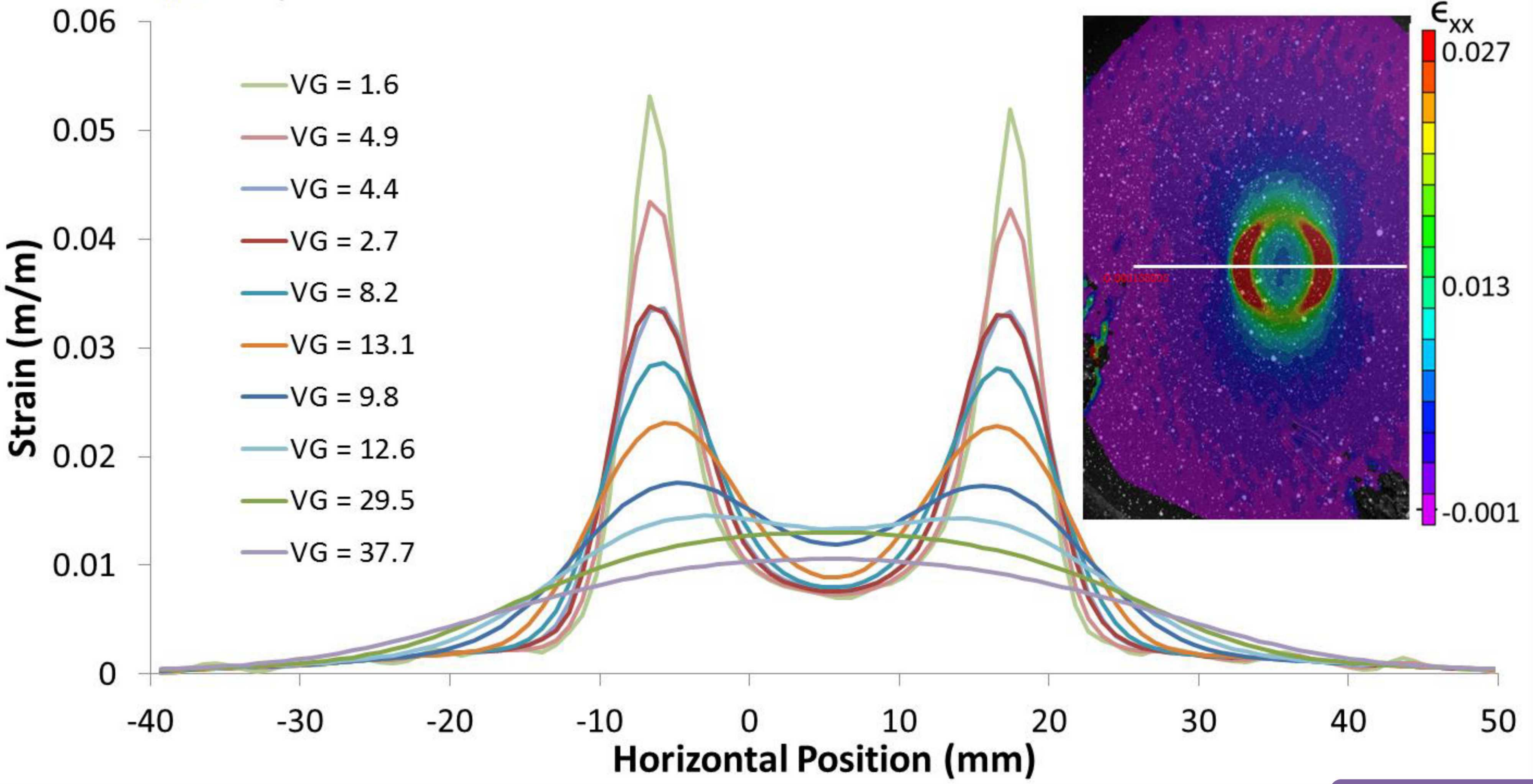
Step = 23

Strain Filter = 15

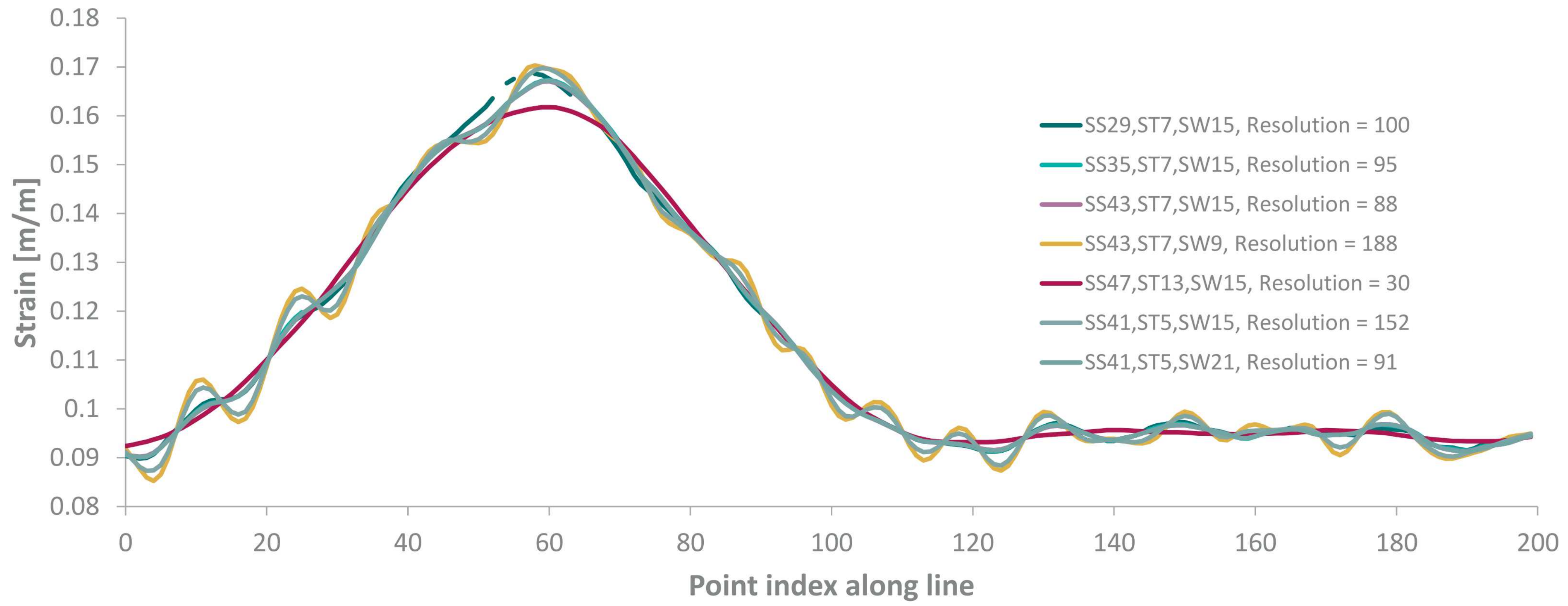
Virtual Gage = 37 mm

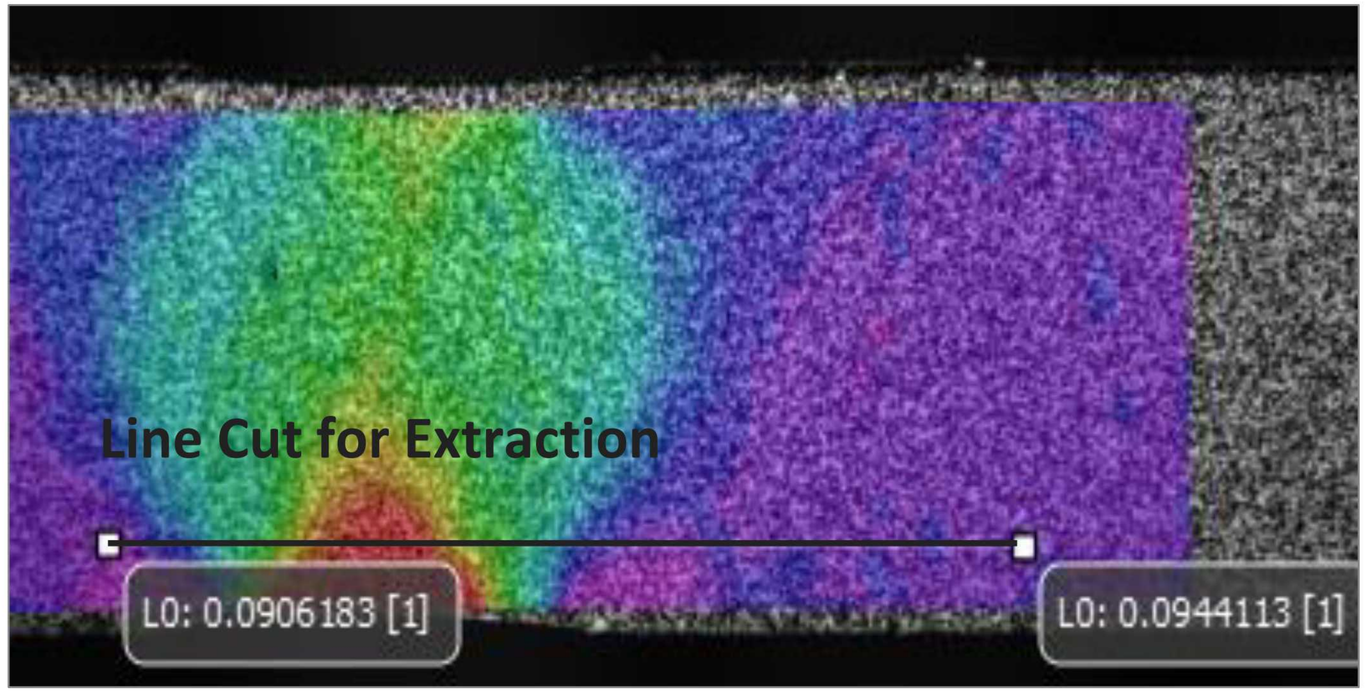
Strain

Subset Size	29	71	29	29	71	71	91	29	71	91
Step Size	3	5	8	3	5	18	23	8	18	23
Strain Window	5	5	5	15	15	5	5	15	15	15
Virtual Gage (pixels)	15	25	40	45	75	90	115	120	270	345
Interpolant	4-Tap	4-Tap	4-Tap	4-Tap	4-Tap	4-Tap	4-Tap	4-Tap	4-Tap	4-Tap
Virtual Gage (mm)	— 1.6	— 2.7	— 4.4	— 4.9	— 8.2	— 9.8	— 12.6	— 13.1	— 29.5	— 37.7
Noise (StDev - με)	174	54	59	93	47	30	22	41	18	15
Max Strain (με)	53109	33811	33589	43392	28645	17607	14555	23094	13039	10586



VSG Study that converges for a tensile sample.





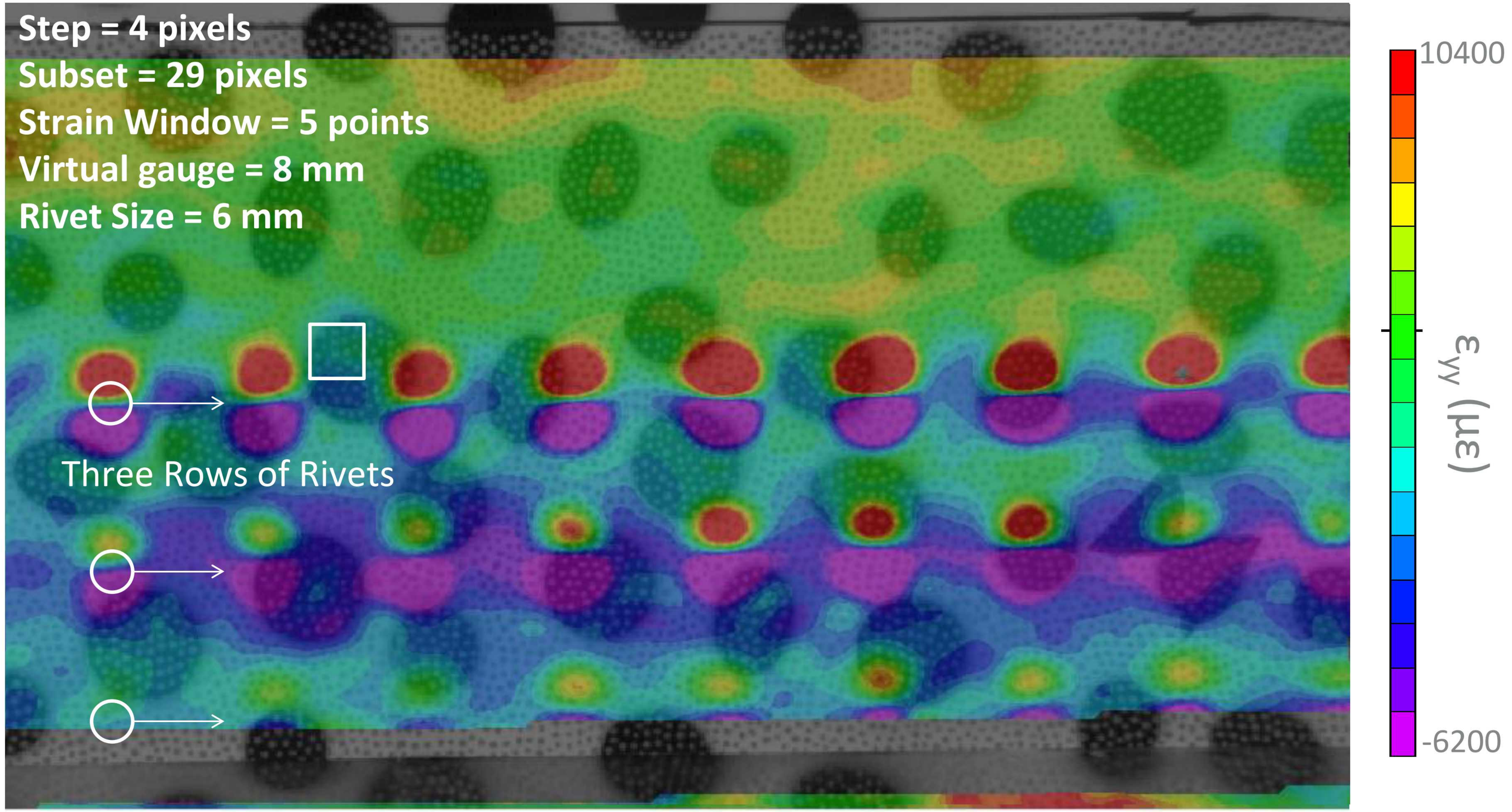
Subset Size (SS)	29	35	43	43	47	41	41
Step Size (ST)	7	7	7	7	13	5	5
Strain Window (SW)	15	15	15	9	15	15	21
VSG = ((SW-1)ST)+1	99	99	99	57	183	71	101
Spatial Resolution (SR) SR=((SW-1)ST)+SS	127	133	141	99	229	111	141
StDev ($\mu\varepsilon_{xx}$)	100	95	88	188	30	152	91

Strain

With proper experimental design small virtual gauge regions can be measured.

Virtual Strain Gauge 8×8 mm

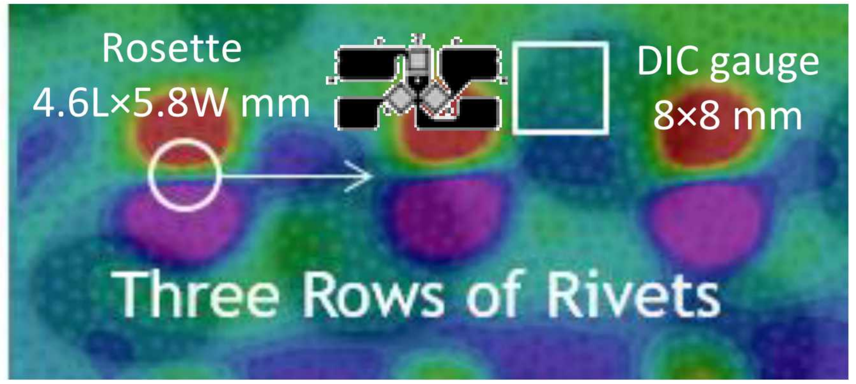
4.6L×5.8W mm



Key: Careful experimental design yields appropriate strain gauge size. With DIC you can explore the effect of gauge size.

Strain gauges versus Digital Image Correlation

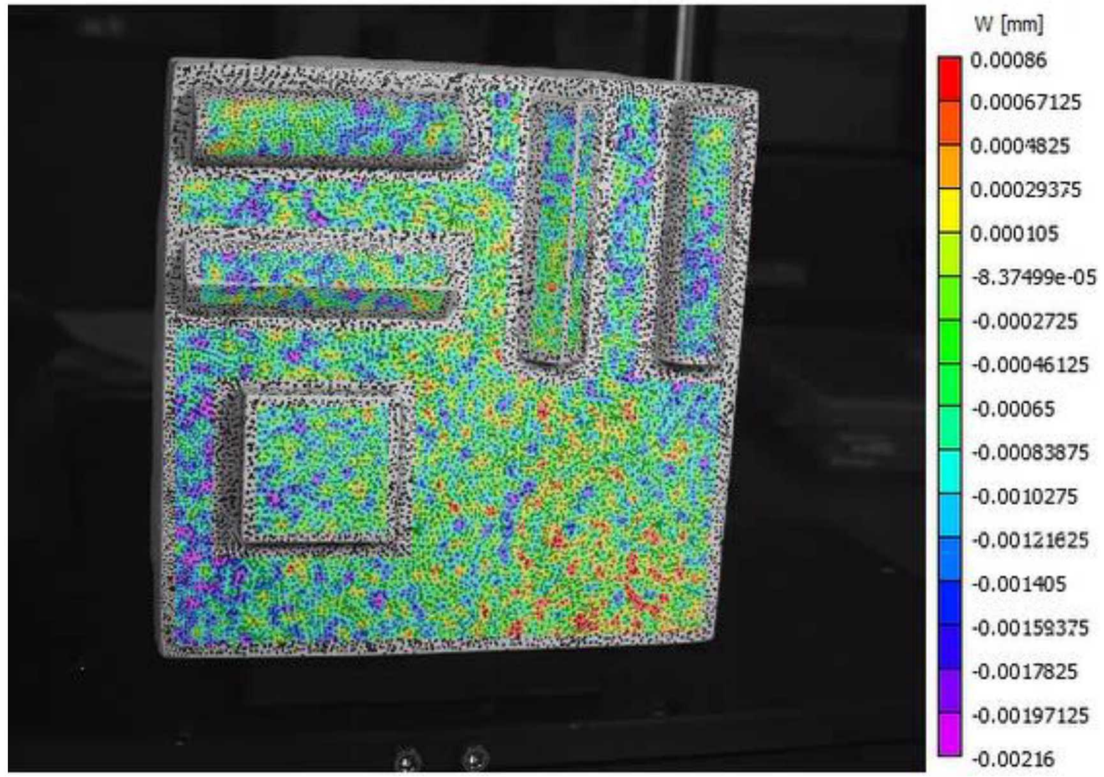
Parameters	DIC	Gauge	Comments
Number of measurement locations	👍		Easily 1000’s
Strain gauge size	👍 ?		Depends on Field-of-view for DIC
Smallest measurable strain		👍	DIC ≈ 100 με : gauge ≈ 5 με (Depends on averaging)
Largest measurable strain	👍		DIC > 30% : gauge < 5%
Wide area measurements			DIC – Tradeoff with Field-of-view
Cost	?		Up front versus per test & analysis time considerations
Traceable Uncertainty	?	👍	Standards are needed for DIC
Acquisition Rate	👍		DIC = MHz : gauge = kHz
Hidden areas		👍	DIC must have visible access (X-ray in development)
Hot spot detection	👍		DIC does not need to know where the maximum is
Strain bias detection	👍		VSG size study possible with DIC



OTHER ANALYSIS DECISIONS AND SETUP VERIFICATION

SORT OF THE REST OF THE IMPORTANT GUIDE POINTS PLUS EXAMPLES

Section 3.3.1 – Images for Calibration Verification and Noise-Floor Analysis



Section 3.3.1.1 – Reset the system to view the sample and lock it down.

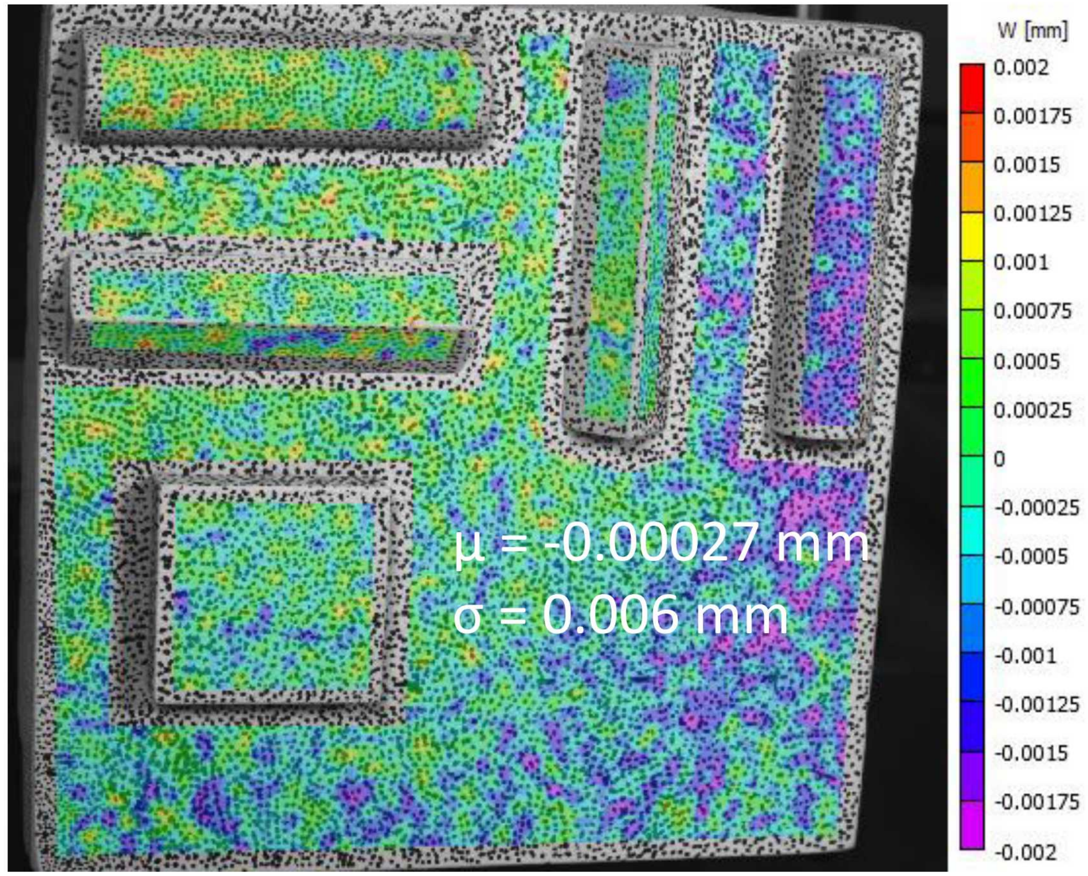
Section 3.3.1.2 – Adjust lighting to be optimal.

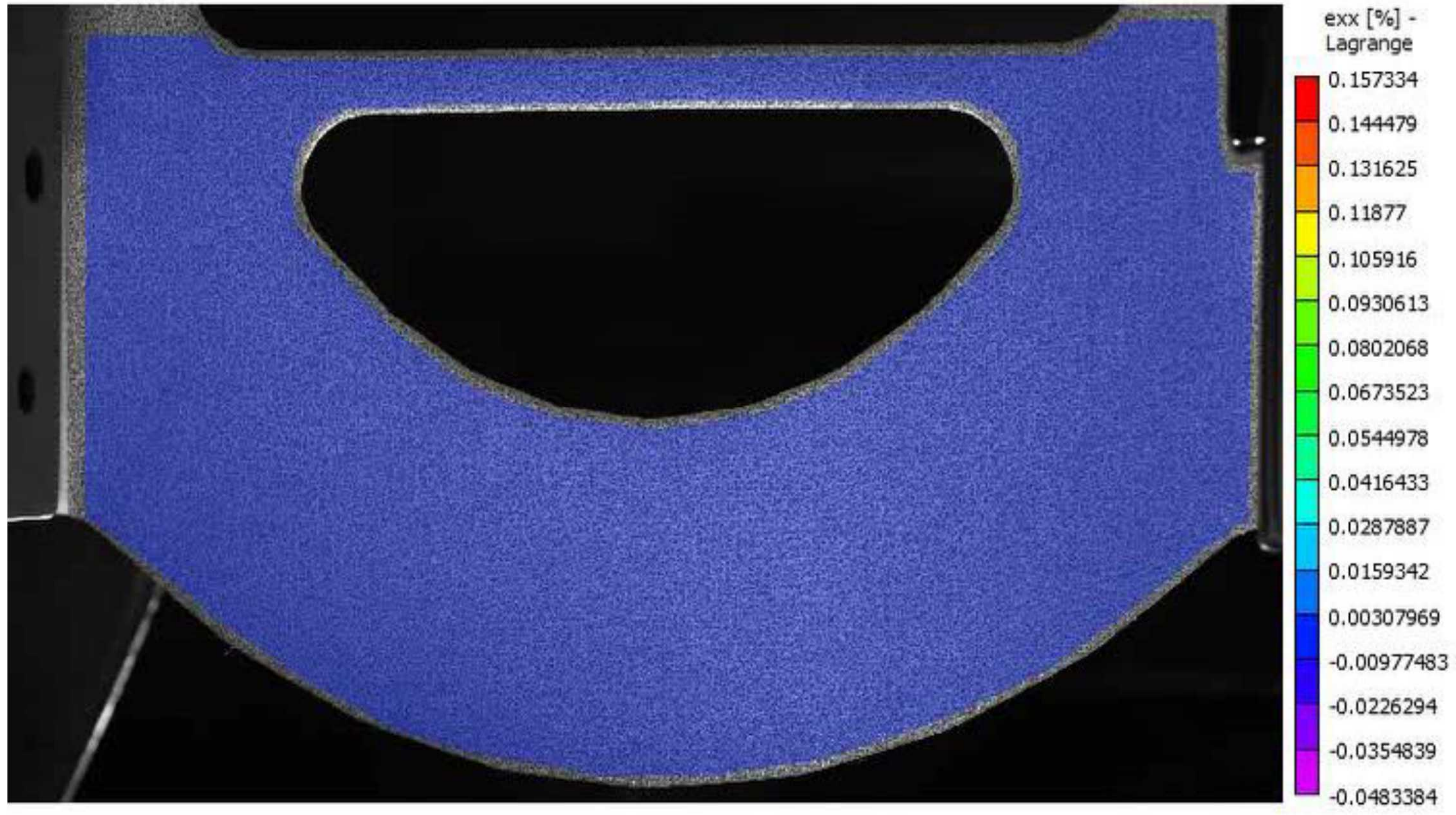
Section 3.3.1.3 – Acquire static images. This is the absolute minimum that should be done!

Recommendation 3.13 – Acquire at same frame rate and exposure as test. Ideally over same time period…

Section 3.3.1.4 – Review images.

Calculate Noise floors of QOI

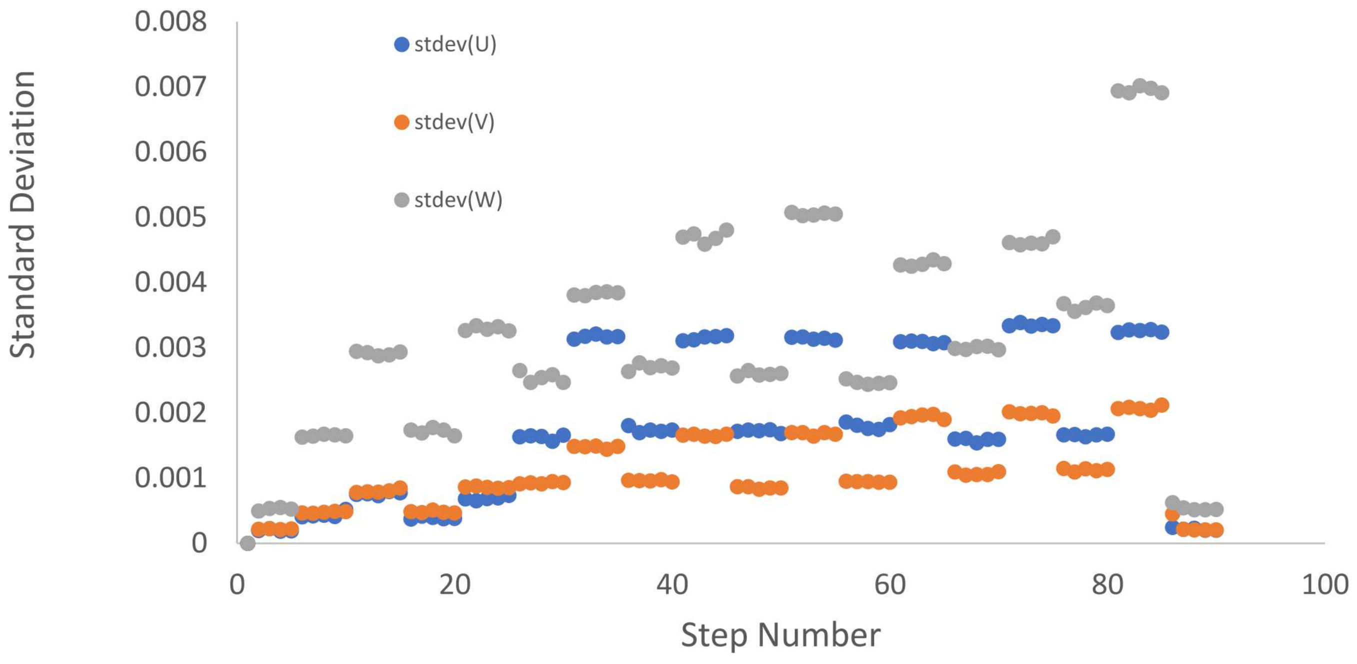

μ = -0.00027 mm
σ = 0.006 mm

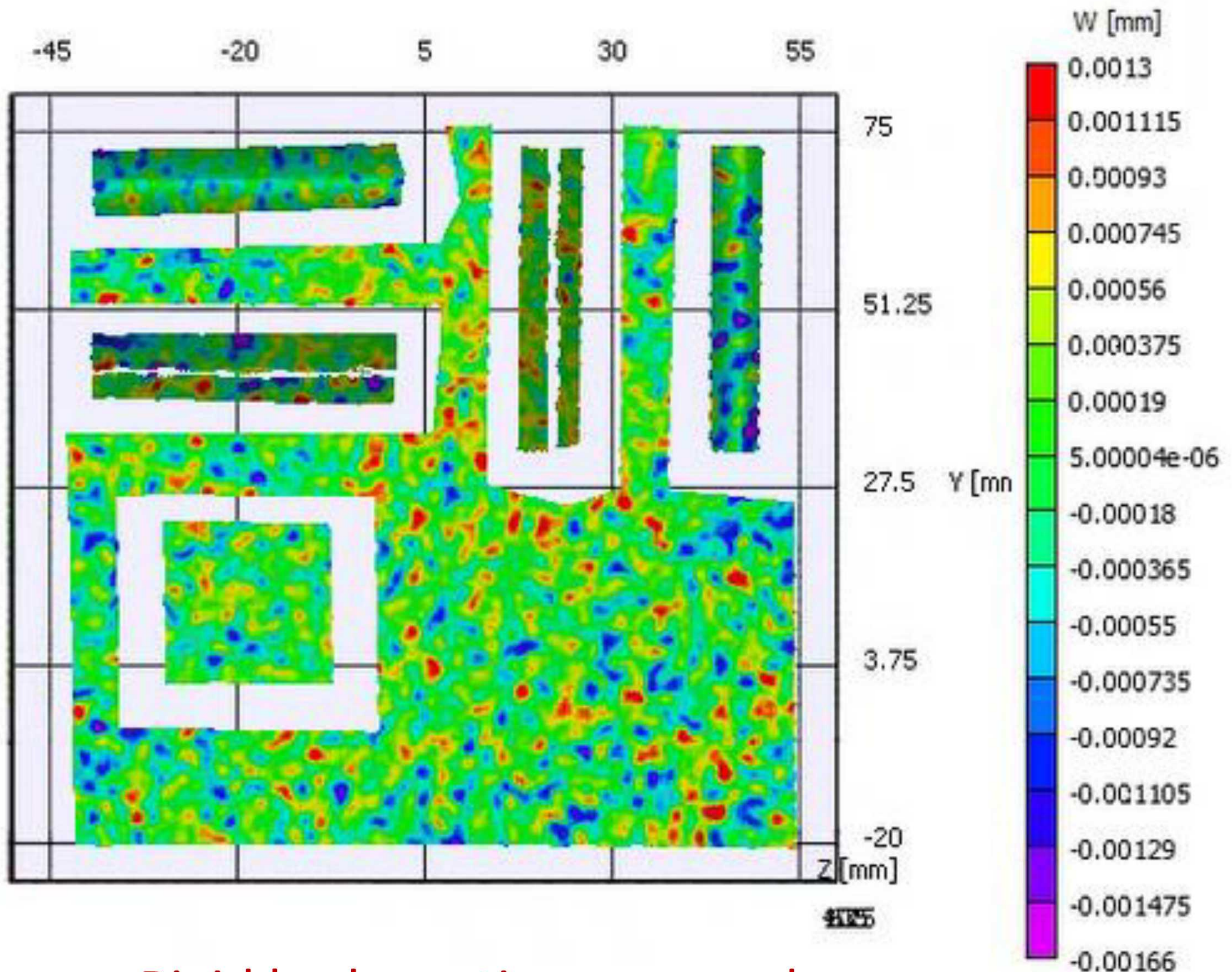


Section 3.3.1.5 – Acquire Rigid-Body-Motion Images

Tip 3.10 – You can either move approximately with your hand or with a stage for better accuracy.

Recommendation 3.14 – Move through the expected range of translation in the experiment.





Rigid body motion removed

Section 3.3.2 – Verification of Calibration

Section 3.3.2.1 – Intrinsic parameters (lens distortions)

Recommendation 3.16 – Compare magnitude of errors from lens distortions to the noise floor.

Tip 3.11 – Add lens distortion parameters and/or more calibration images.

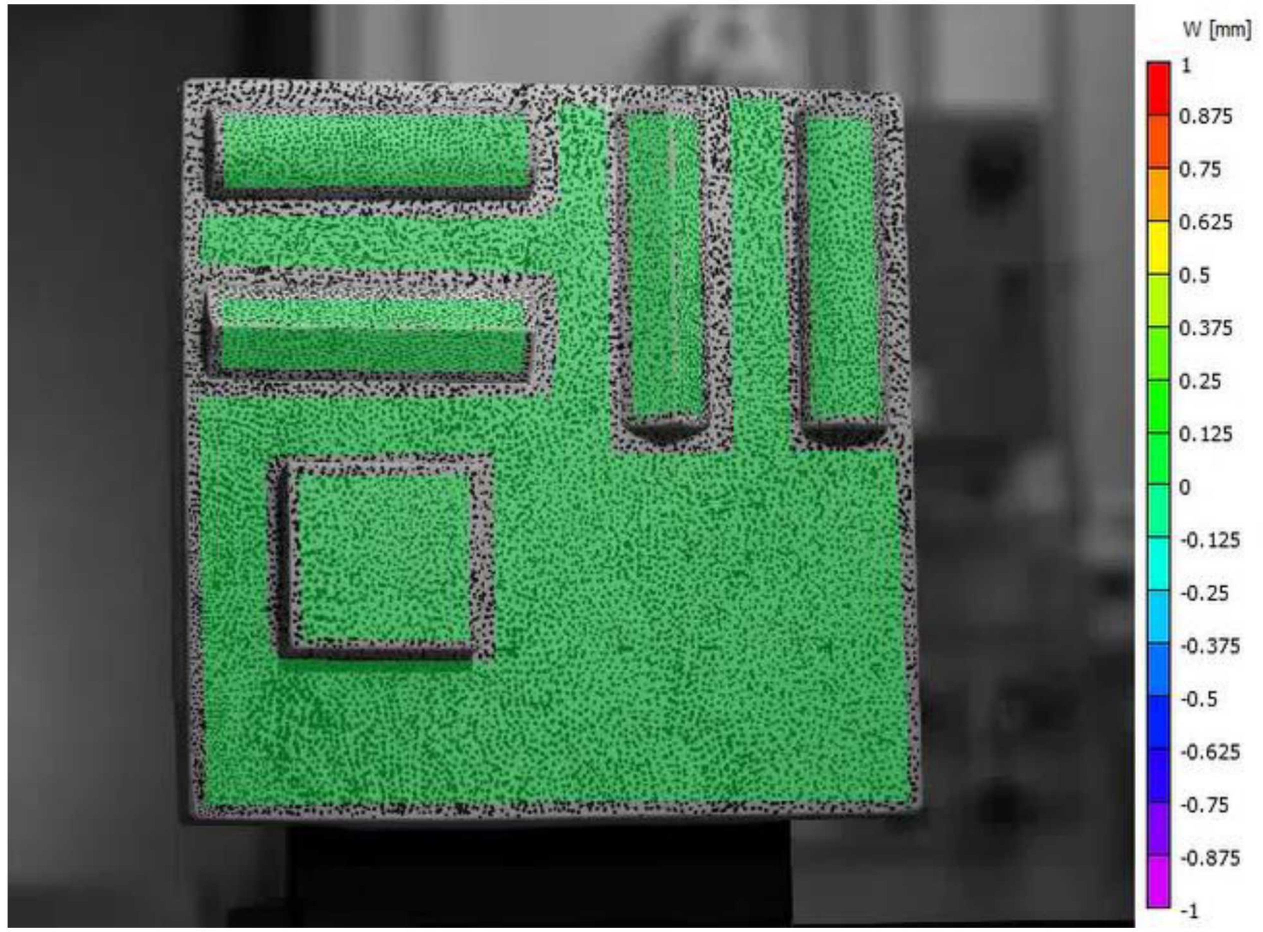
Section 3.3.2.2 – Extrinsic parameters (epipolar error)

Tip 3.13 – There isn't a "good" value.

Tip 3.14 – Spatial distribution of epipolar may be helpful.

Tip 3.15 – Lens distortions may show up in epipolar errors.

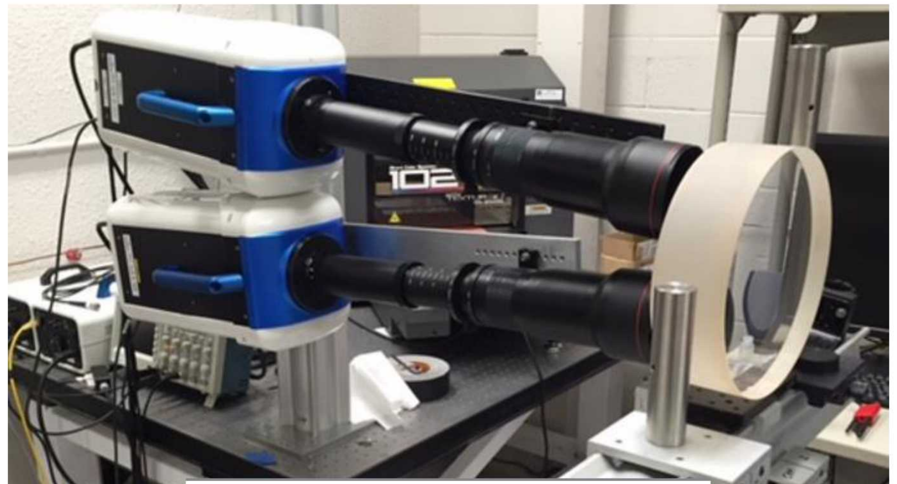
Very Strange distortions

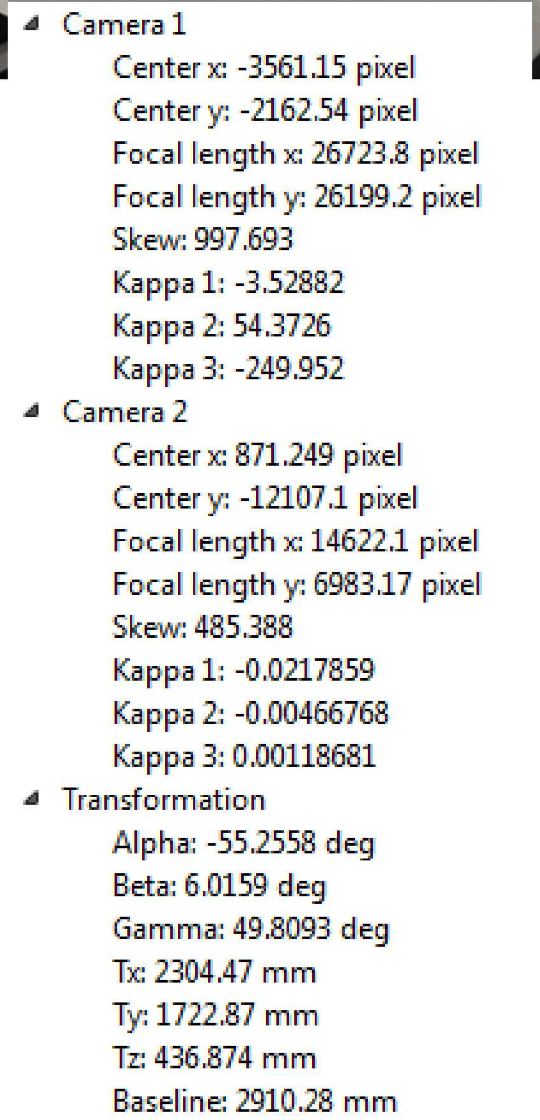


Mirrors will often cause these types of distortions.

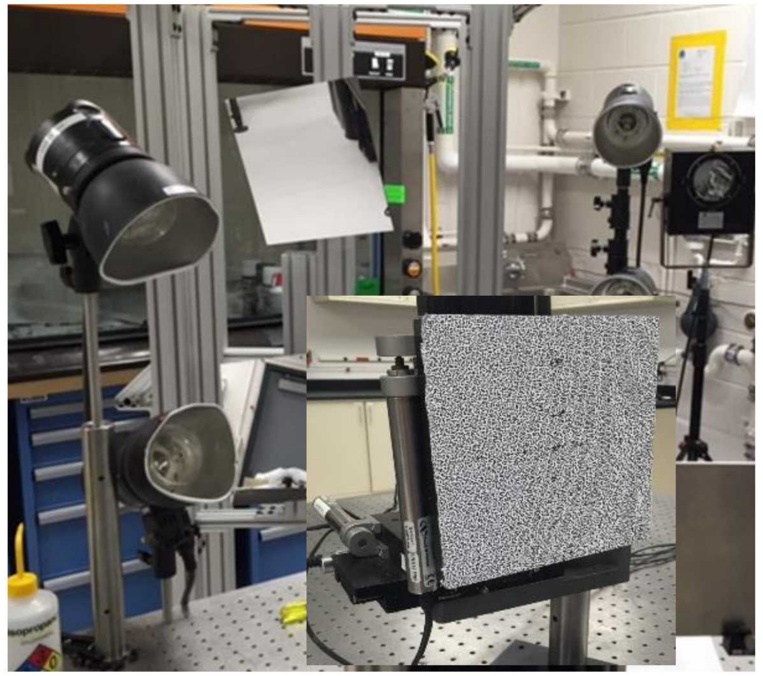
Section 3.3.2.3 – Absolute distances

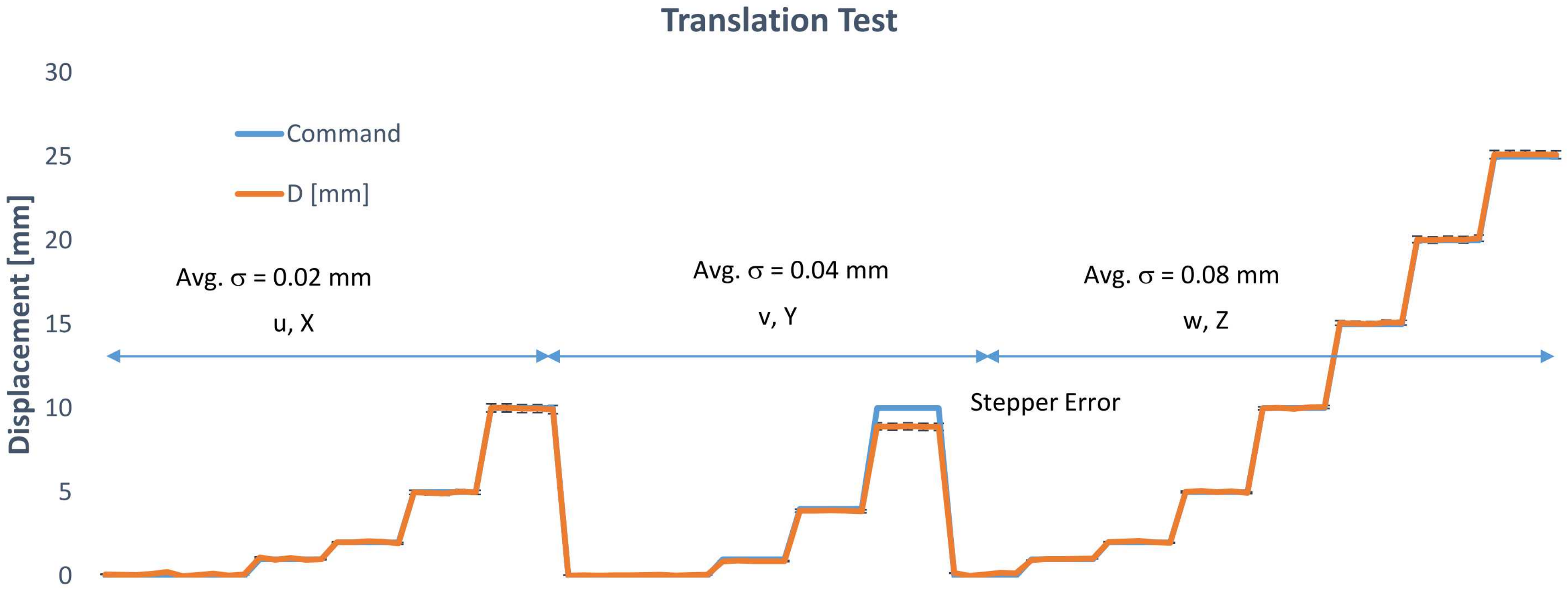
Recommendation 3.17 – Fiducials and applied motions.

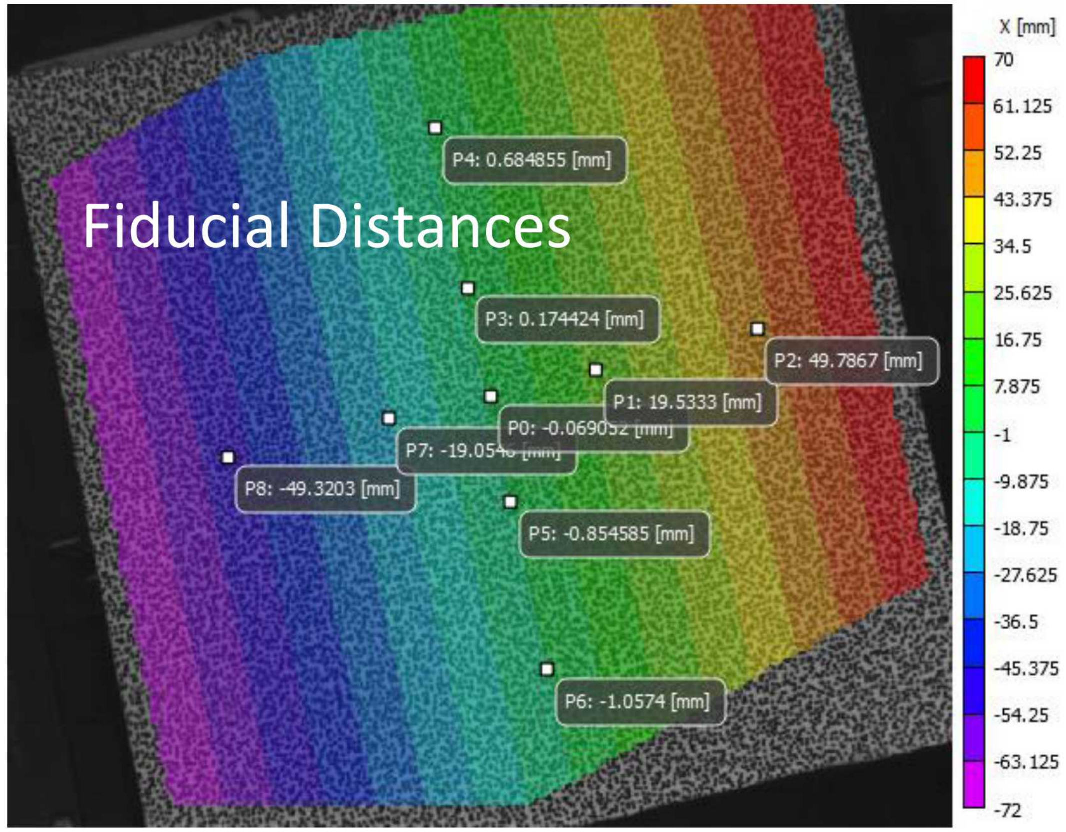


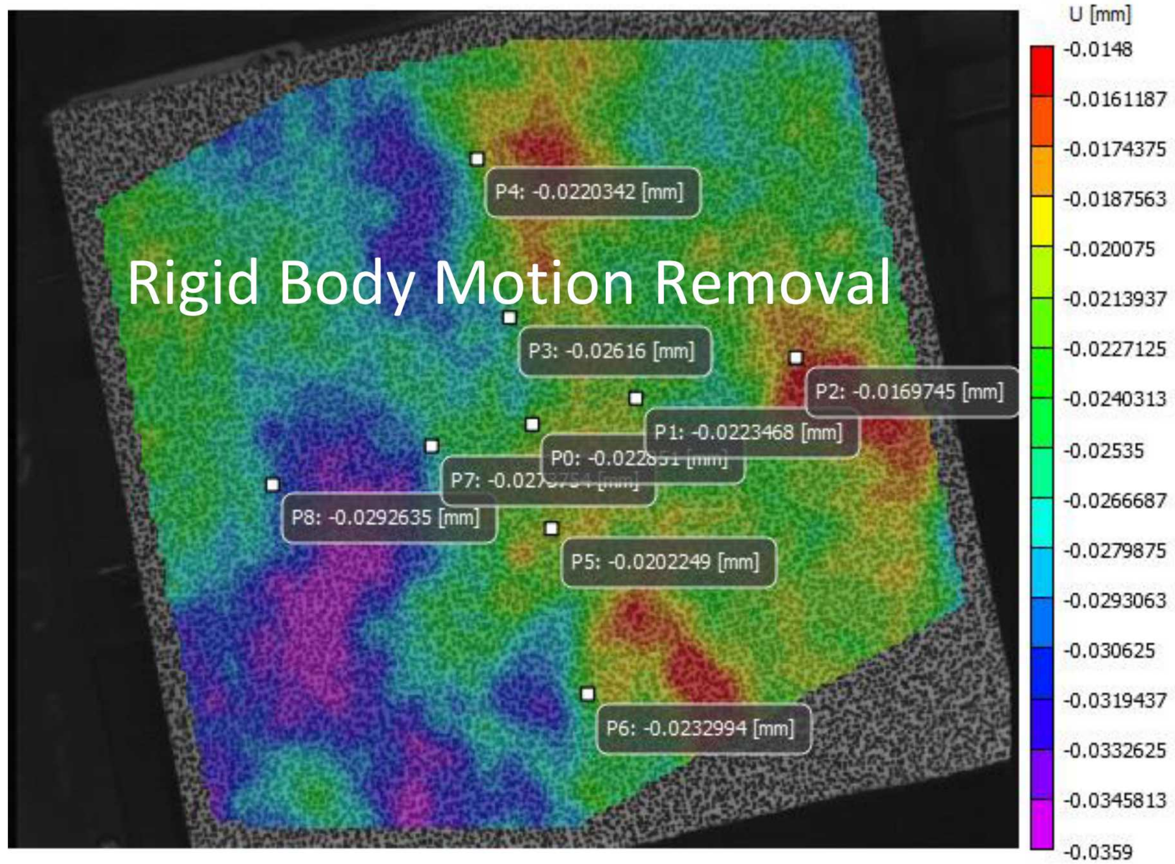


- Camera 1
  - Center x: -3561.15 pixel
  - Center y: -2162.54 pixel
  - Focal length x: 26723.8 pixel
  - Focal length y: 26199.2 pixel
  - Skew: 997.693
  - Kappa 1: -3.52882
  - Kappa 2: 54.3726
  - Kappa 3: -249.952
- Camera 2
  - Center x: 871.249 pixel
  - Center y: -12107.1 pixel
  - Focal length x: 14622.1 pixel
  - Focal length y: 6983.17 pixel
  - Skew: 485.388
  - Kappa 1: -0.0217859
  - Kappa 2: -0.00466768
  - Kappa 3: 0.00118681
- Transformation
  - Alpha: -55.2558 deg
  - Beta: 6.0159 deg
  - Gamma: 49.8093 deg
  - Tx: 2304.47 mm
  - Ty: 1722.87 mm
  - Tz: 436.874 mm
  - Baseline: 2910.28 mm





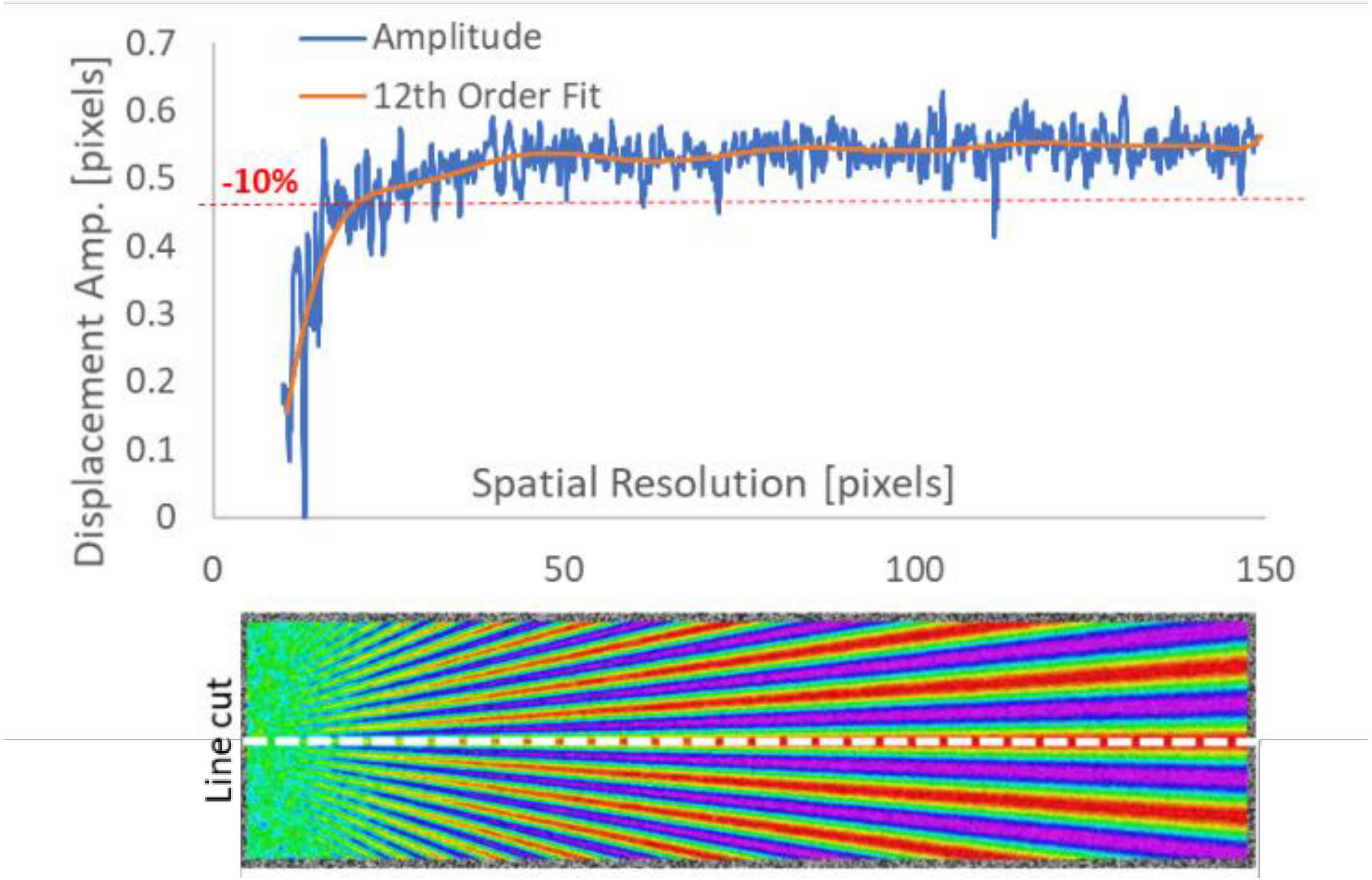




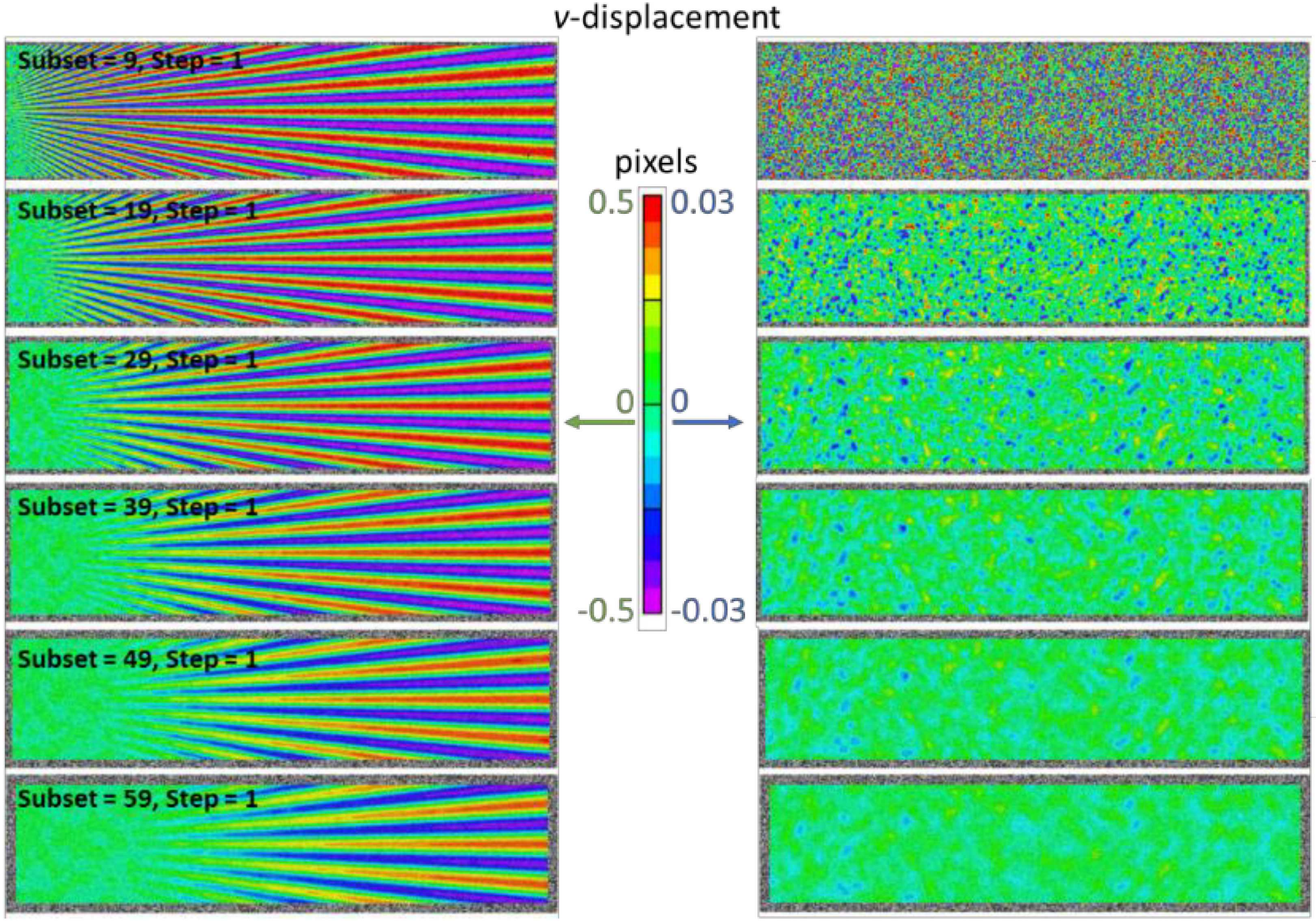
SPATIAL RESOLUTION

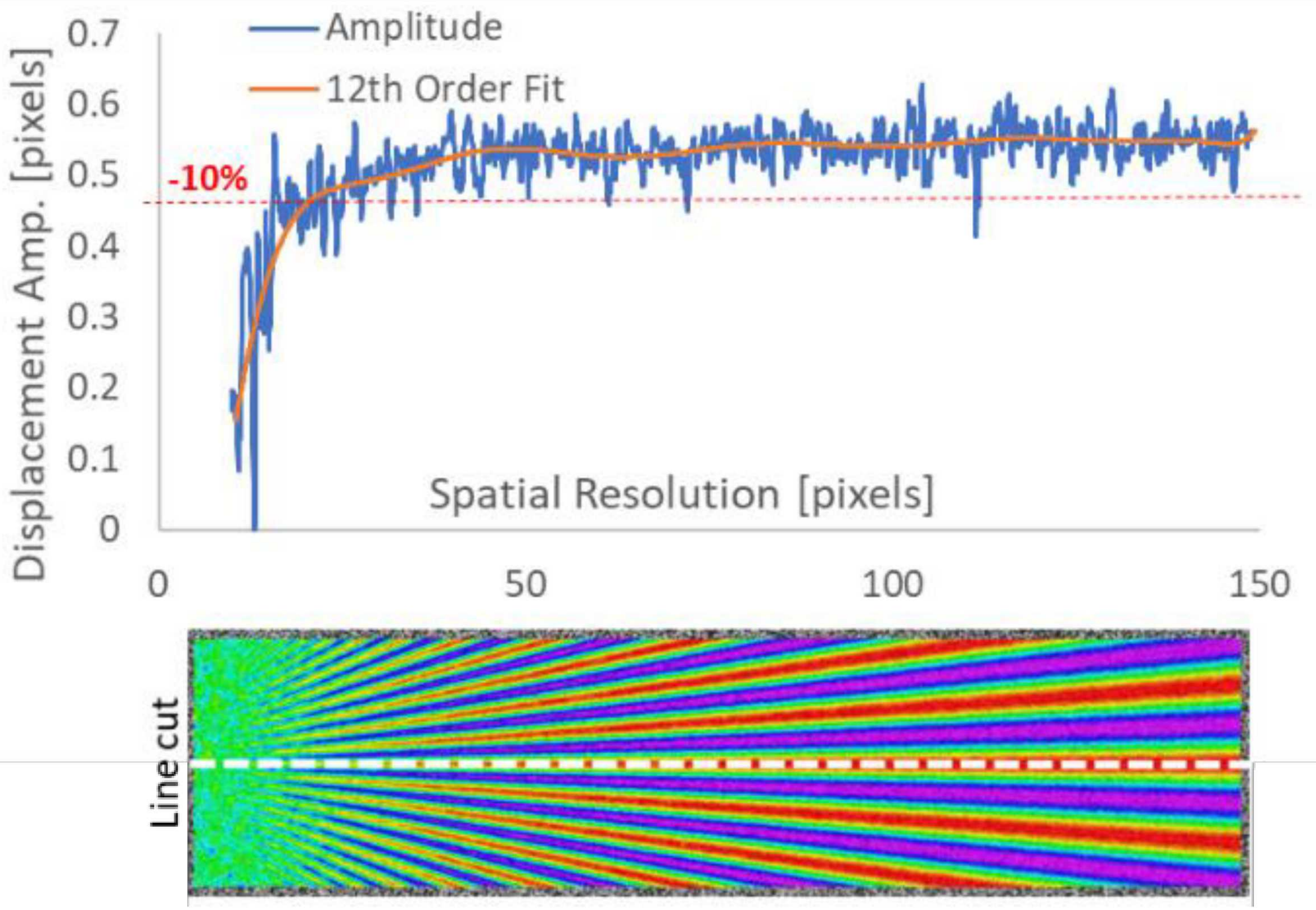
TRADING BETWEEN NOISE AND SPATIAL RESOLUTION

The spatial resolution is calculated using a fit to a 12th order polynomial and finding the 10% attenuation.



Using a spatially varying displacement field a measure of the spatial resolution is possible.





iDICs

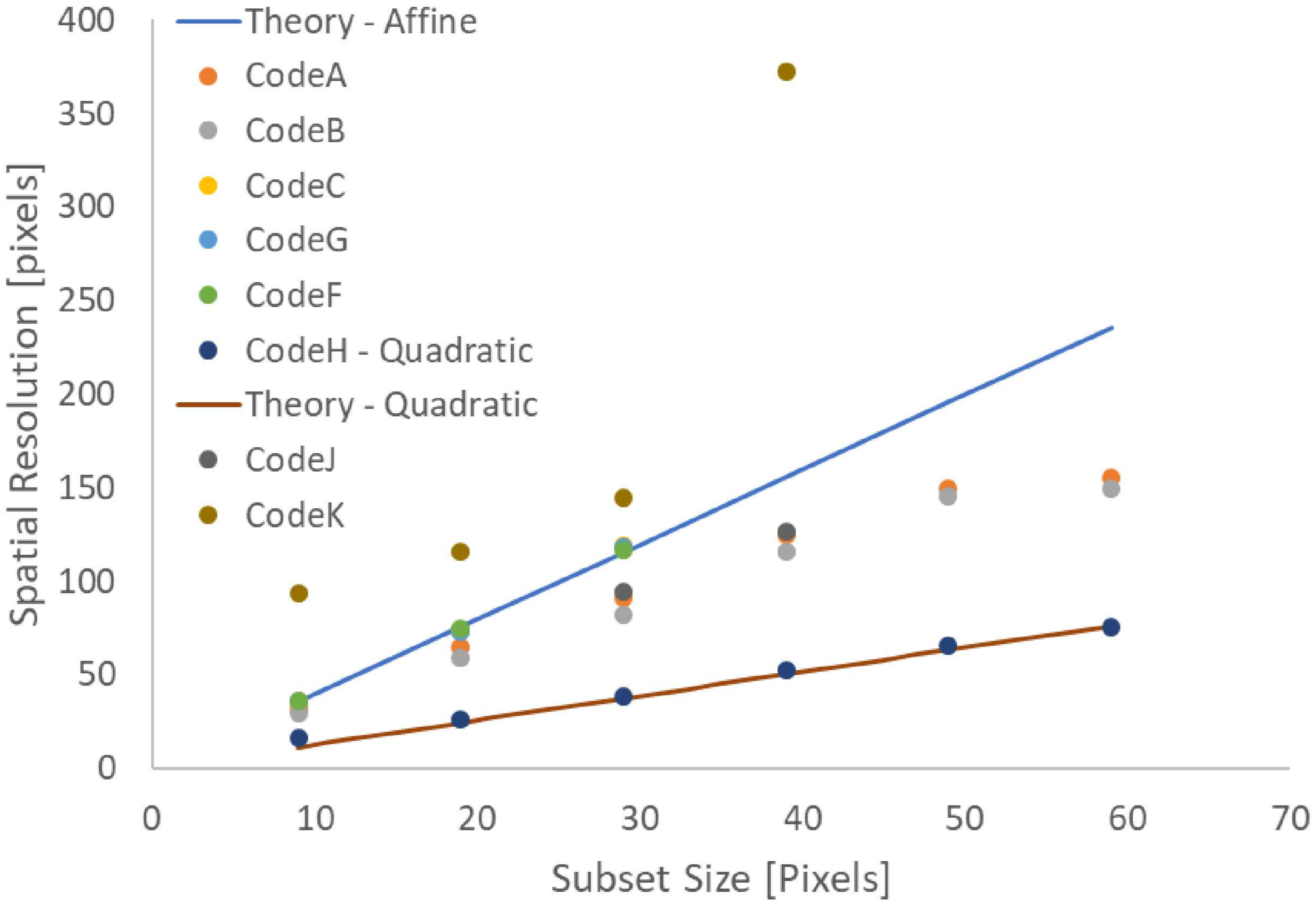
SECTION 5.4.4 & 5.4.5 – VSG Study

TIP 5.3 – Noise vs Smoothing

Displacement results match the theoretical spatial resolution predictions.

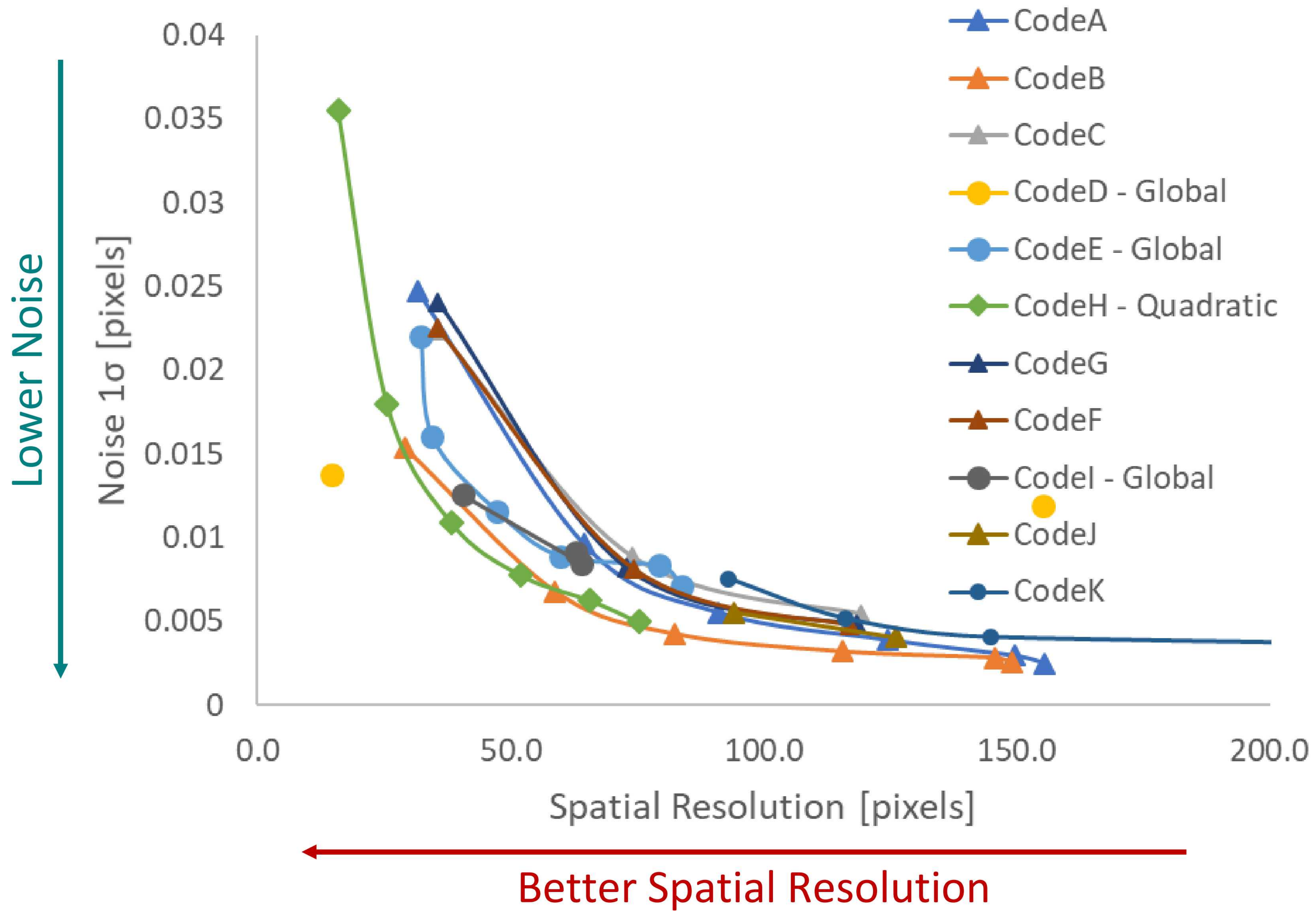
- For a rectangular weighting on the subset.
- Gaussian windowing performs slightly better.
- Some different approaches yield results that are quite different.

All local codes.

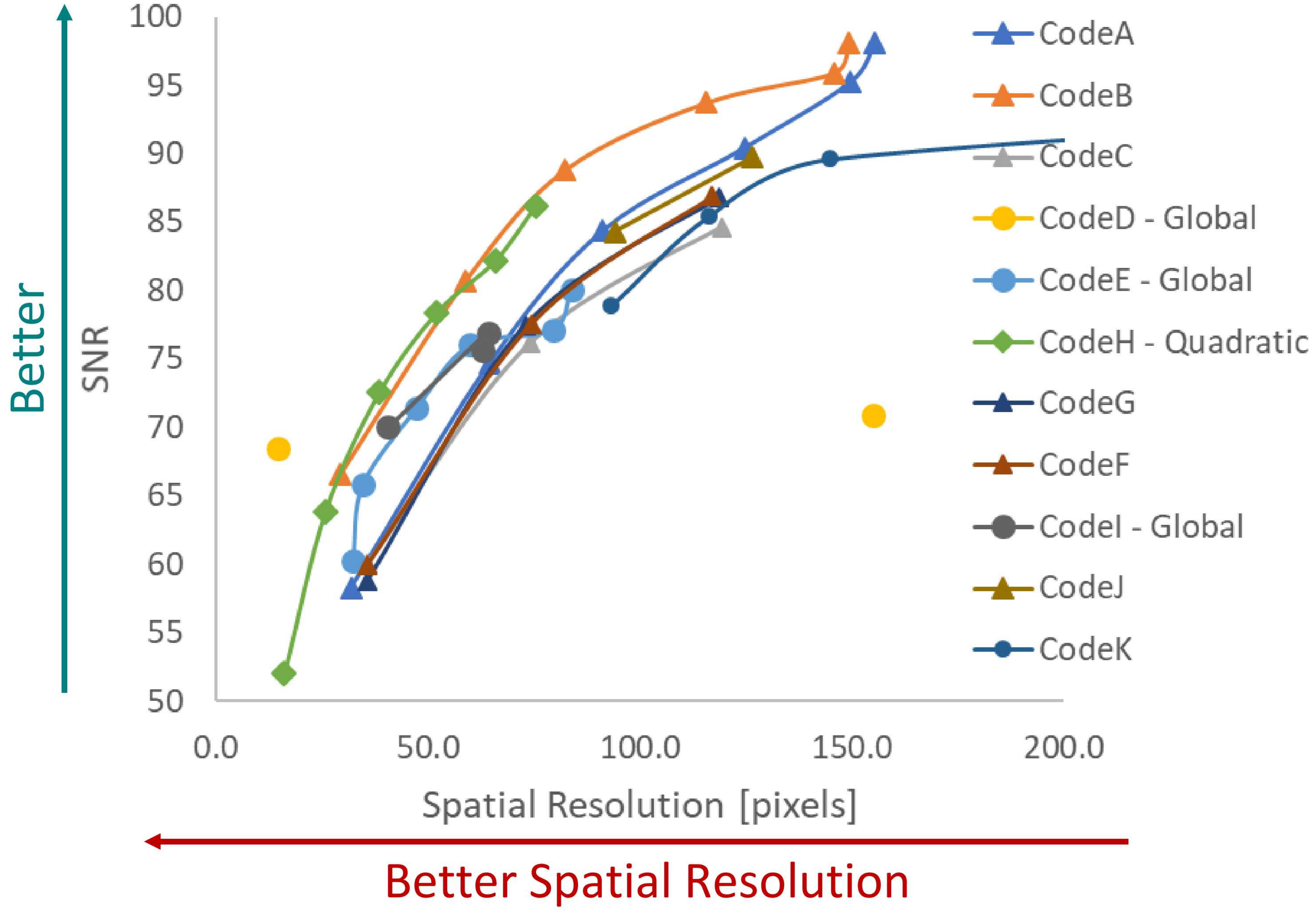


Grediac, M., et al. (2017). "A Critical Comparison of Some Metrological Parameters Characterizing Local Digital Image Correlation and Grid Method." Experimental Mechanics **57(6): 871-903.**

There is a trade-off between spatial resolution and noise for **all** DIC codes – both global and local.



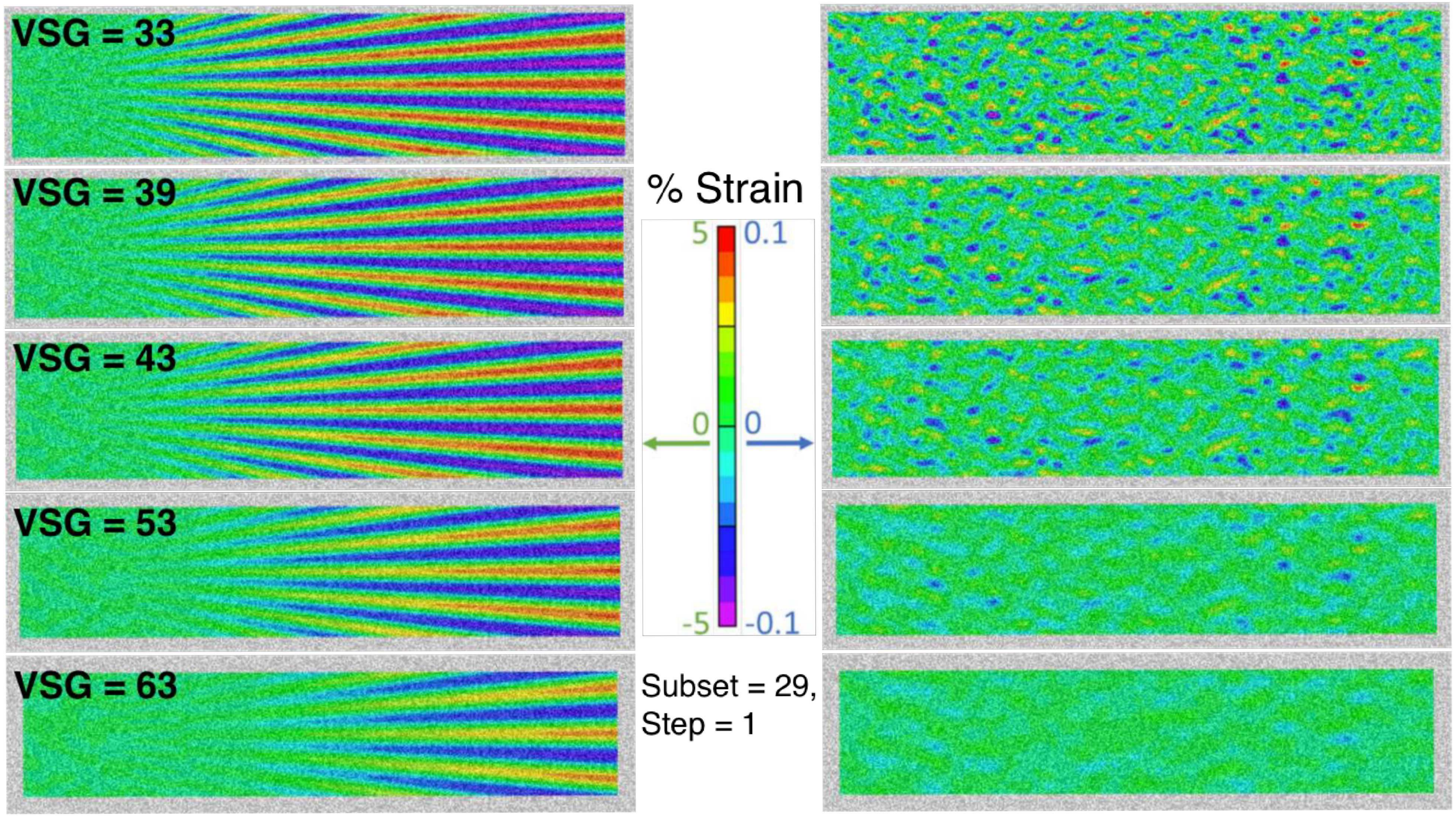
Signal to noise and spatial resolution are similar for all implementations.



SNR = 20Log$_{10}$(A$_{signal}$/A$_{noise}$) where A$_{signal}$ = 0.5 & A$_{noise}$ = σ^2

iDICs

Typical full-field strain results for a single code. Virtual Strain Gauge (VSG) from “small” to “large”.



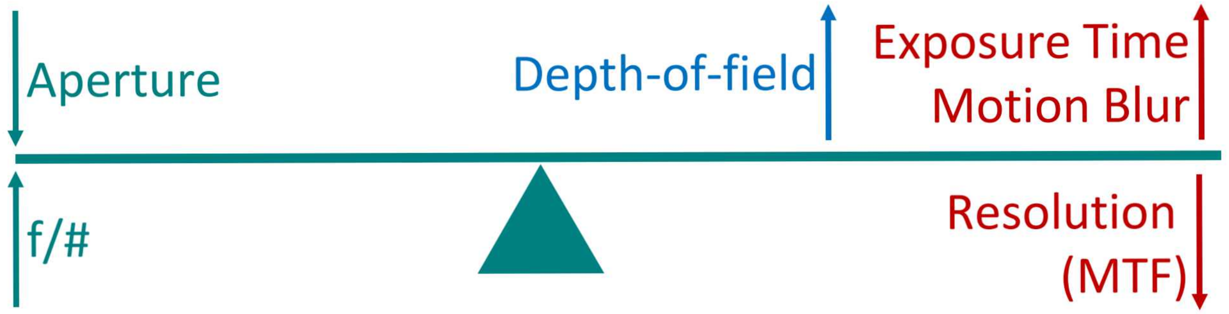
VSG = [(Strain Window - 1)*Step]+Subset

Important Trade-offs

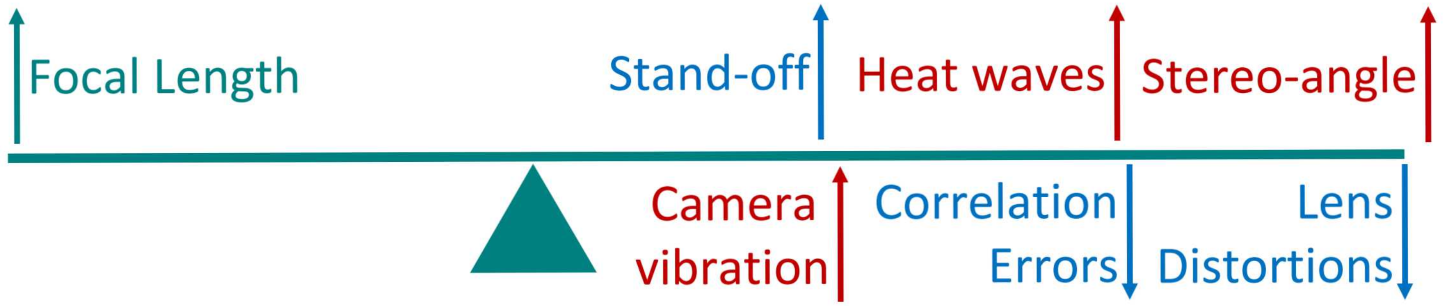
Red is bad

Blue is good

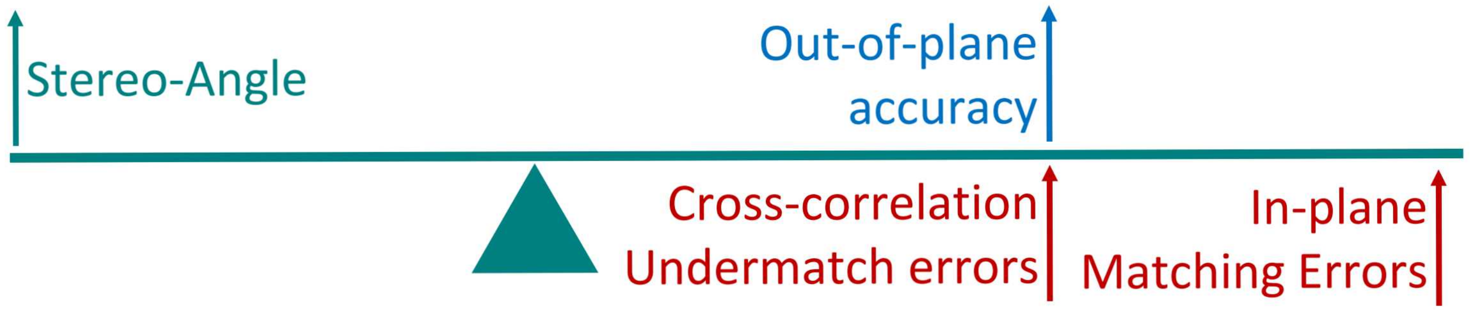
Lens Trade-offs



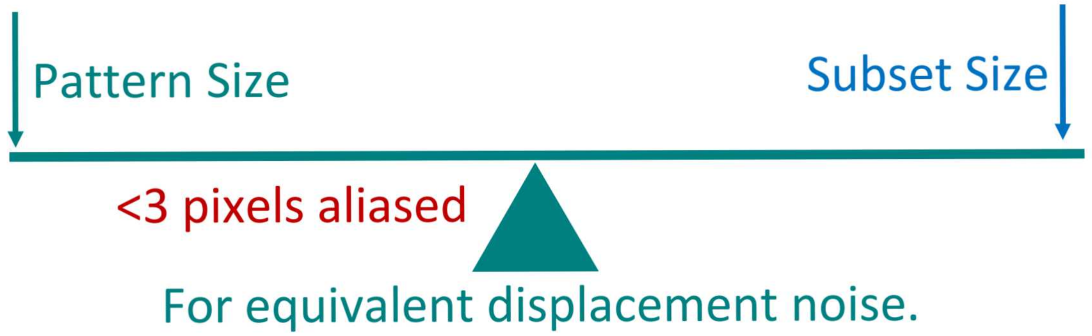
Focal Length



Stereo-Angle



Pattern size



For equivalent displacement noise.

Subset/facet size