Minimizing Noise and Bias in 3D DIC

Correlated Solutions, Inc.

Overview

- Overview of Noise and Bias
- Digital Image Correlation Background/Tracking Function
- Minimizing Noise
  - Focus
  - Contrast/Lighting
  - Glare
  - F-stop
  - Stereo-Angle/Lens selection
  - **Good speckle pattern**
- Eliminating Bias
  - Eliminating aliasing
  - Eliminating contaminations/dust
  - Using a our Distortion Correction module for instances of non-parametric distortions, such as the stereo-microscope.

Overview of Noise and Bias

- Noise: random, zero-mean deviations from the correct result
- Bias: systematic deviations from the correct result
- Noise and bias are present for location (in-plane, out-of-plane), displacement, and strain
- Noise is unavoidable, but can be minimized with careful setup
- Bias can be reduced or eliminated with proper setup and parameters

Overview of Noise

Minimizing Noise:

- Accuracy can be very variable. Some amount of noise will always be present, but it is possible to minimize noise by paying attention to the following set-up parameters:
  - Focus
  - Contrast/Lighting
  - Glare
  - F-stop
  - Stereo-Angle/Lens selection
- Once we have the proper set-up, **speckle pattern quality** is the **most** important factor for minimizing noise

Overview of Bias

Eliminating Bias:

- Eliminating aliasing
- Eliminating contaminations/dust
- Using a our Distortion Correction module for instances of non-parametric distortions, such as the stereo-microscope.

DIC background

To understand noise and accuracy is presented in DIC, it's essential to understand how we track the specimen

- We track the specimen by assigning subsets throughout the area of interest that contain unique speckle information.
- We track where these subsets move by checking for possible matches at several locations and use a similarity score (correlation function) to grade them. The march is where the error function is minimized.
- **Classic correlation function:** sum of squared differences (SSD) of the pixel values (smaller values = better similarity)

$$C(x, y, u, v) = \sum_{i,j=-n/2}^{n/2} \left(I(x+i, y+j) - I^*(x+u+i, y+v+j) \right)^2$$

Pixel coord., reference image

Pixel value at (*x*+*i*; *y*+*j*)

Pixel value at (*x*+*u*+*i*; *y*+*v*+*j*)

Image before motion

Image after motion

n: subset size (9 in our example)

Displacement (disparity)

Correlation function

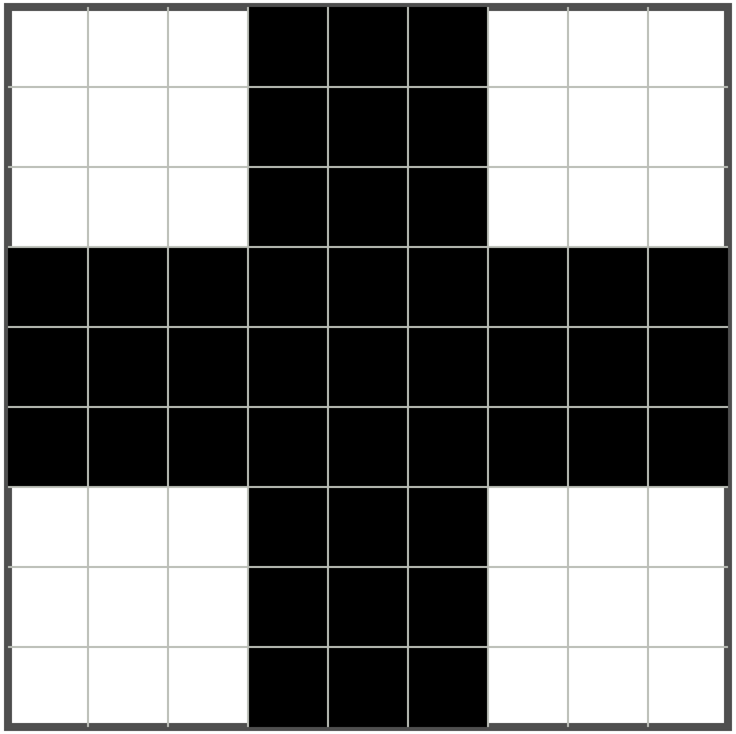
Principle

- **Example**
  - **White pixels** are gray level **100**
  - **Black pixels** are gray level **0**
- An image is a matrix of natural integers

Image, in memory

100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100

Image, on screen



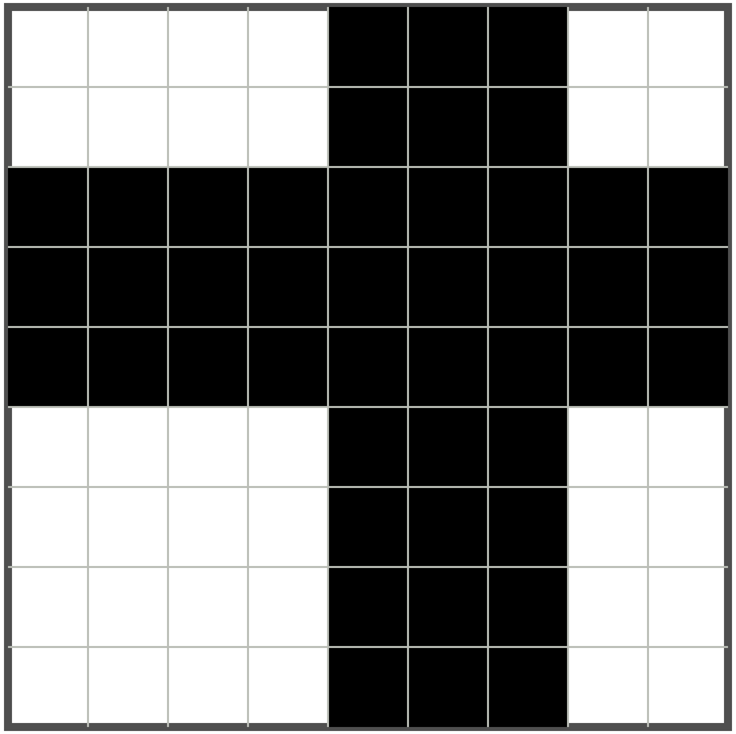
Principle

- Example
  - The **specimen moves** such that **its image moves 1 pixel up and right**

Image after motion, in memory

100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100

Image after motion, on screen



Principle

- Example: subset at **(x;y)=(5;5)**, displacement candidate **(u;v)=(-2;-2)**

$$C(5,5,-2,-2)=\sum_{i,j=-2}^{2}\left(I(5+i,6+j)-I^{*}(5-2+i,5-2+j)\right)^2$$

$$\begin{aligned}&(100-0)^2+(0-0)^2+(0-0)^2+(0-0)^2+(100-0)^2+\\&(0-100)^2+(0-100)^2+(0-100)^2+(0-100)^2+(0-0)^2+\\&(0-100)^2+(0-100)^2+(0-100)^2+(0-100)^2+(0-0)^2+\\&(0-100)^2+(0-100)^2+(0-100)^2+(0-100)^2+(0-0)^2+\\&(100-100)^2+(0-100)^2+(0-100)^2+(0-100)^2+(100-0)^2=18{,}000\end{aligned}$$

Image before motion

(x;y)=(5;5)

100	100	100	0	0	0	100	100	100
100	[illegible]	[illegible]	[illegible]	0	0	100	100	100
100	100	100	0	0	0	100	100	[illegible]
0	0	0	0	0	0	0	0	[illegible]
0	0	0	0	0	0	0	0	[illegible]
0	0	0	0	0	0	0	0	[illegible]
100	100	100	0	0	0	100	100	[illegible]
100	100	100	0	0	0	100	100	100
100	100	100	0	0	0	100	100	100

Image after motion

(u;v)=(-2;-2)

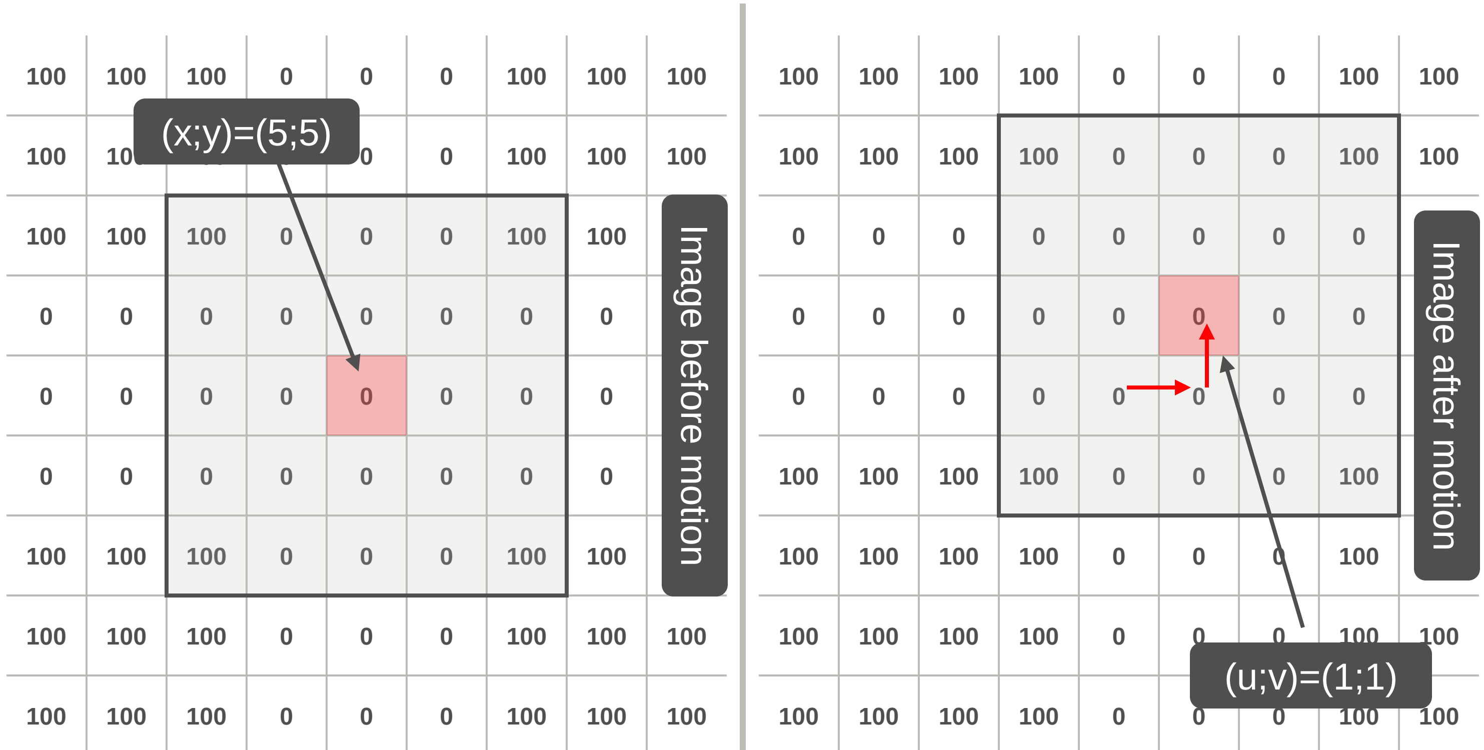
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100
0	0	0	0	0	0	0	0	[illegible]
0	0	0	0	0	0	0	0	[illegible]
0	0	0	0	0	0	0	0	[illegible]
100	100	100	100	0	0	0	100	[illegible]
100	100	100	100	0	0	0	100	[illegible]
100	100	100	100	0	0	0	100	100
100	100	100	100	0	0	0	100	100

Principle

- Example: subset at **(x;y)=(5;5)**, displacement candidate **(u;v)=(1;1)**

$$C(5,5,1,1) = 0$$

- Better correlation score than candidate (u;v)=(-2;-2) [18,000] Indeed it is the smallest score achieveable (perfect match)



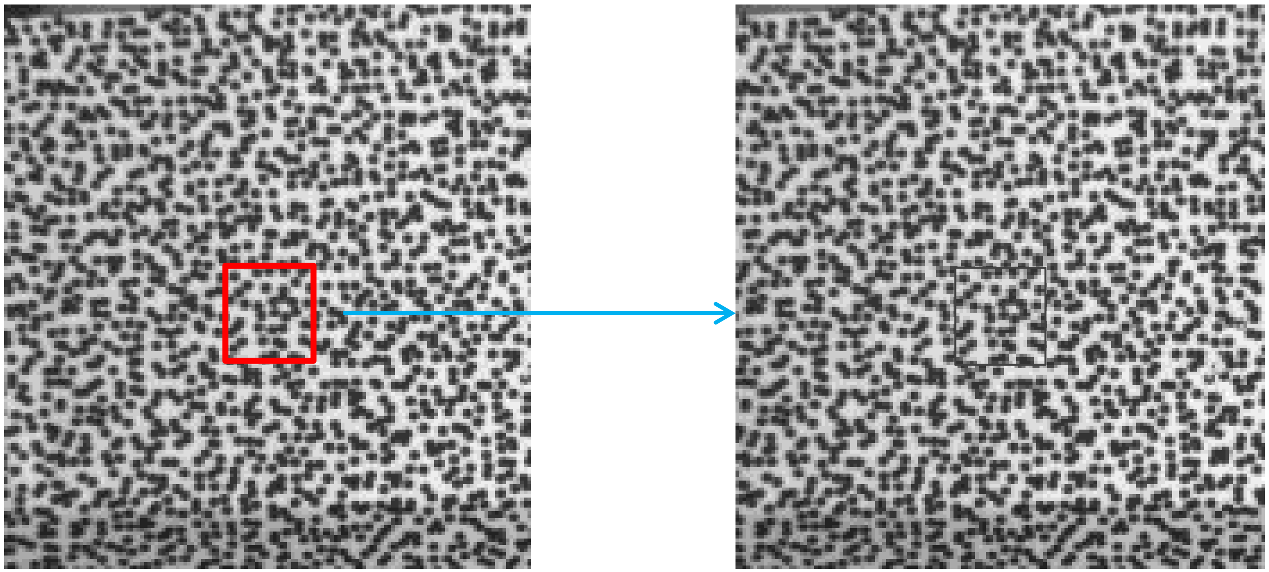
Noise Reduction

- How do we reduce displacement noise?

$$Var = \frac{2\sigma^2}{\sum (\partial G / \partial x)^2}$$

- Reduce camera noise
  - Limited options!
- Increase subset size
  - Loss of spatial resolution
- Optimize speckle pattern and test setup
  - This is our best and most important option

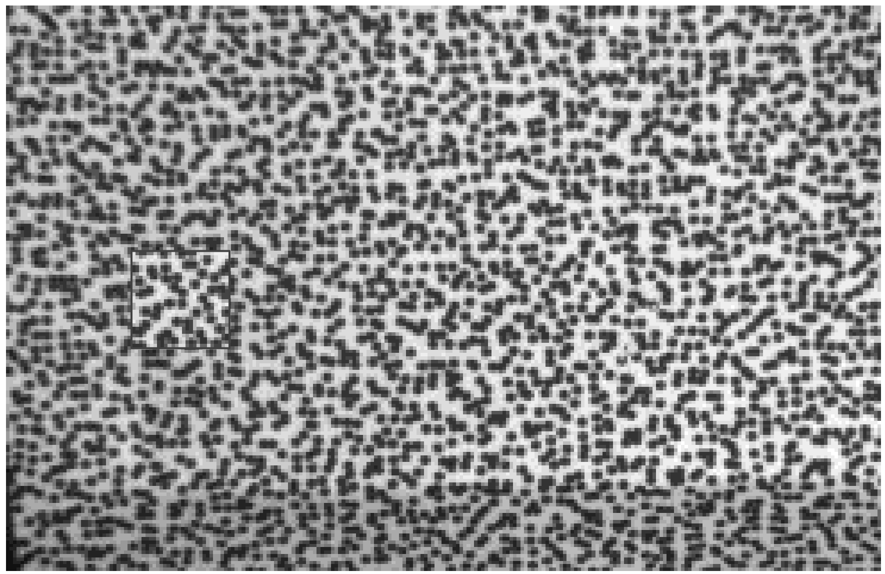
Iteratively finding the match



Reference Deformed

Shape of error curve

- We optimize for U, V, strain, and rotation
- Let us consider the 1D case – U only

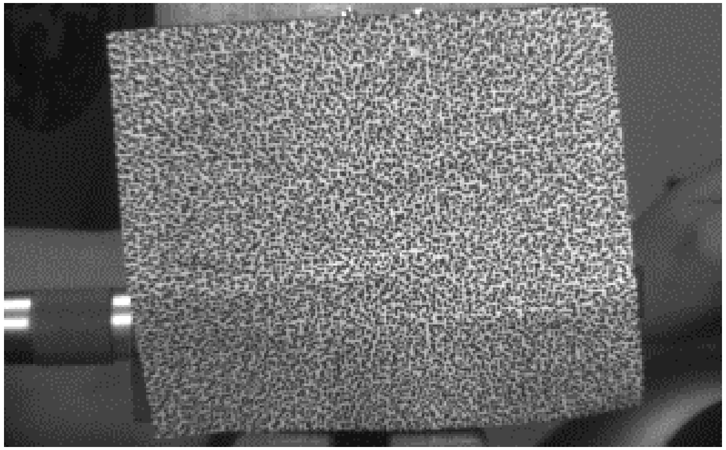


Error

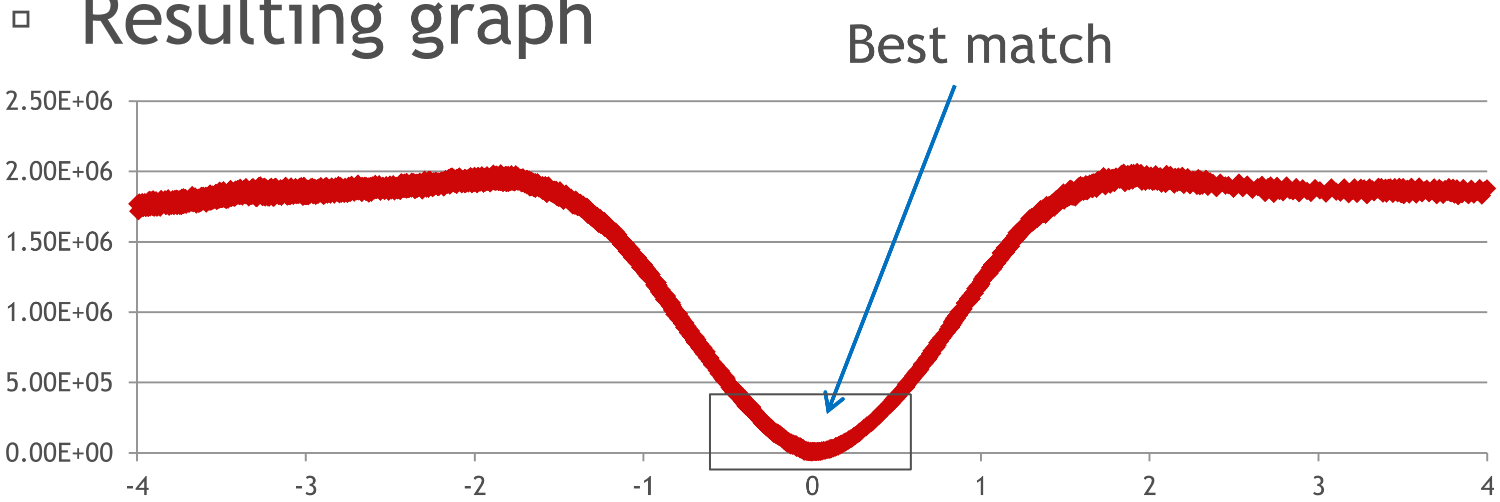
U-position

Shape of error curve

- Typical pattern

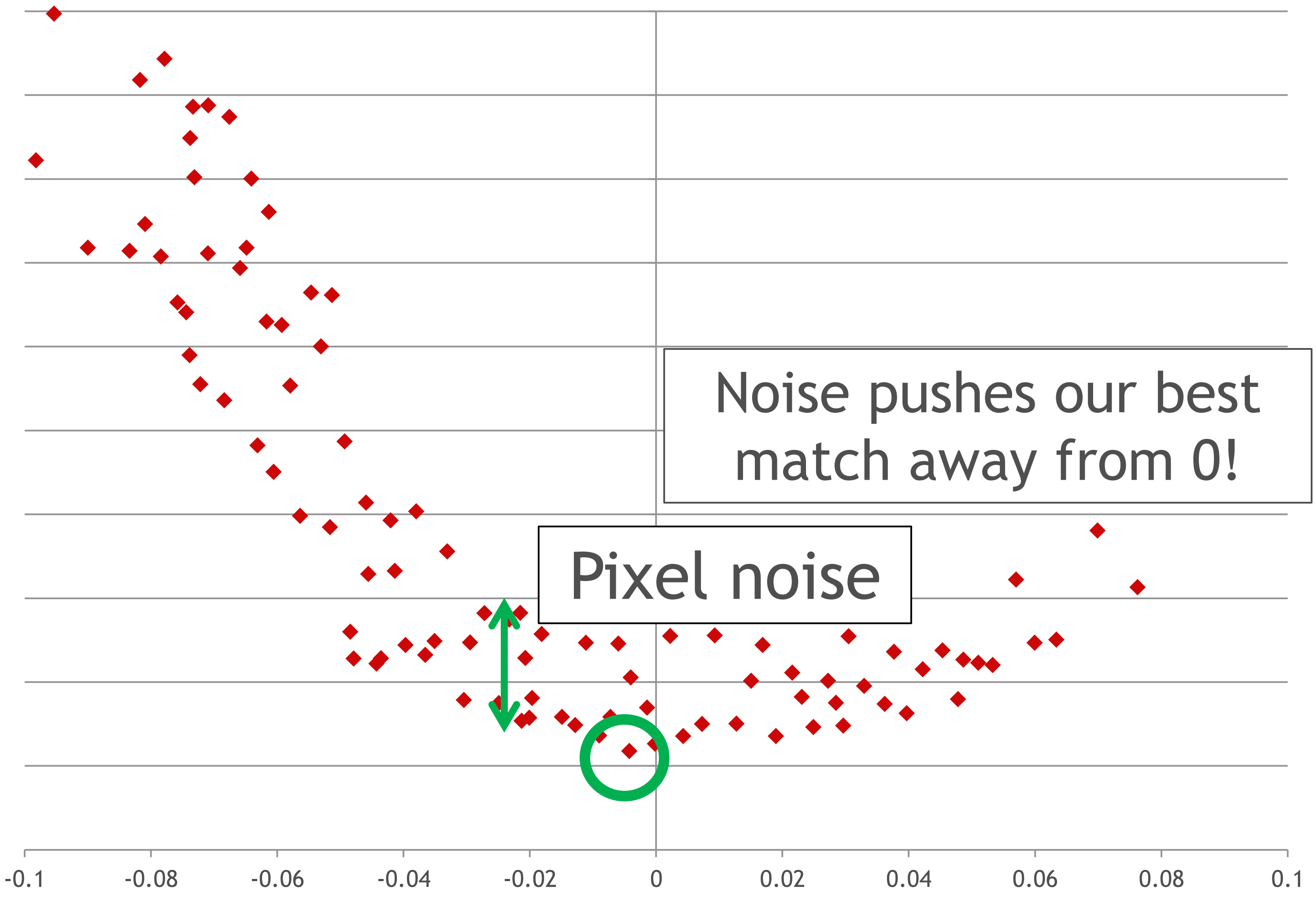


- Resulting graph



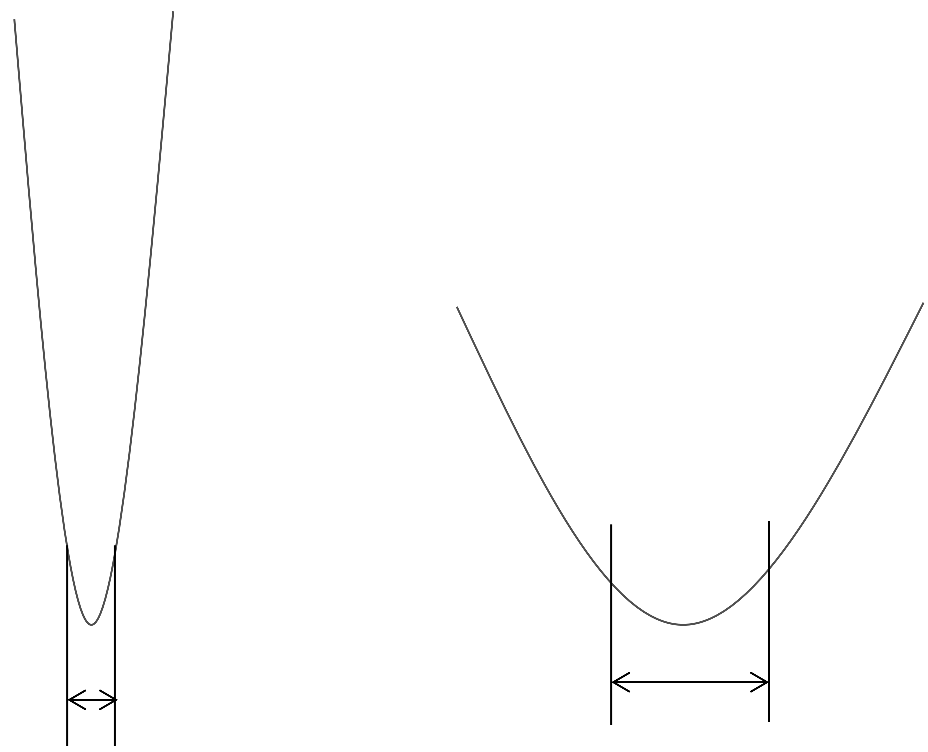
Noise in error curve

- Effect of noise



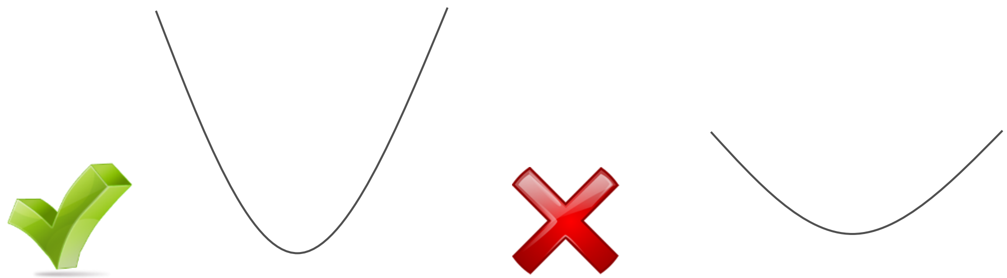
Effects of noise

- Noise normally **cannot** be controlled
- We must increase the **signal**
- Steeper drop = better confidence

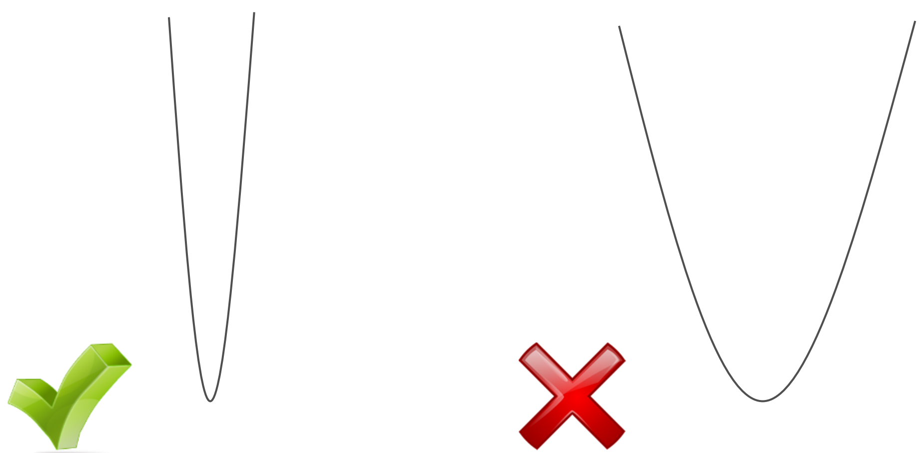


What do we want in a pattern?

- The local minimum should be **deep**

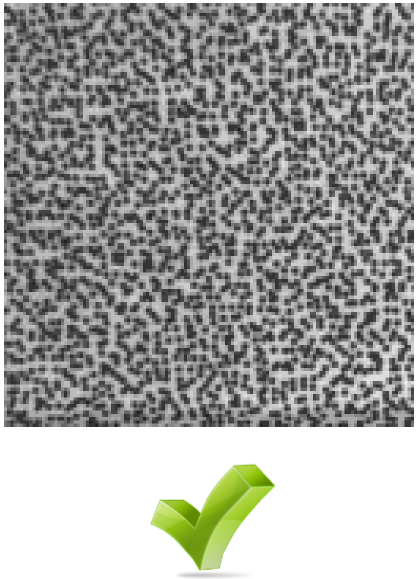


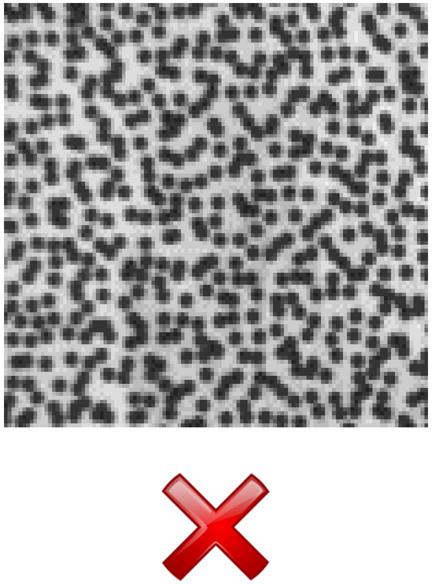
- The minimum should be **narrow**



How do we make the bowl deep?

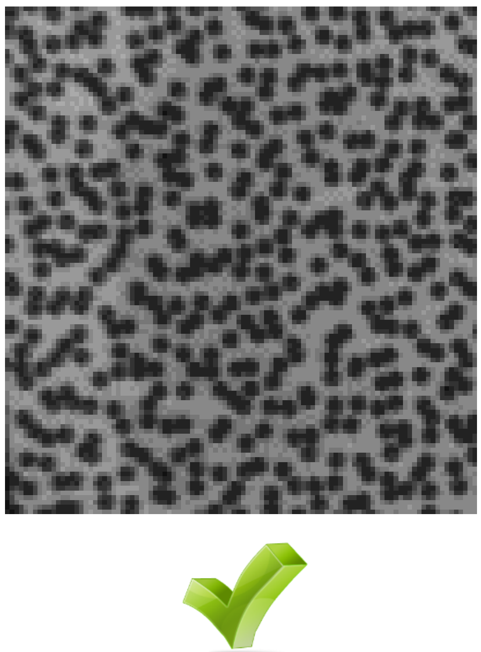
- Good contrast
- Good speckle size

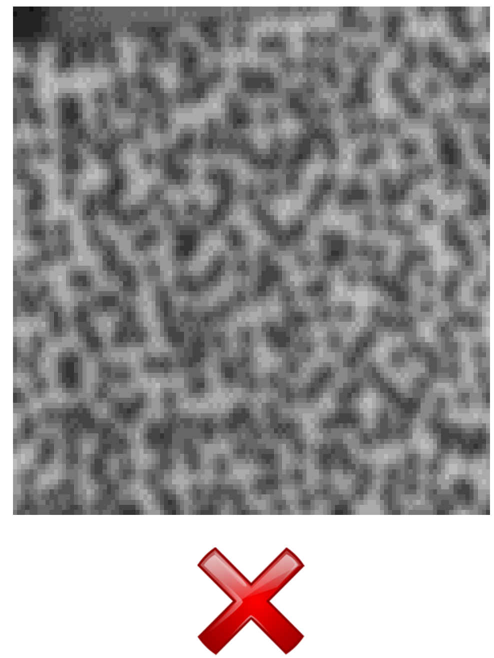




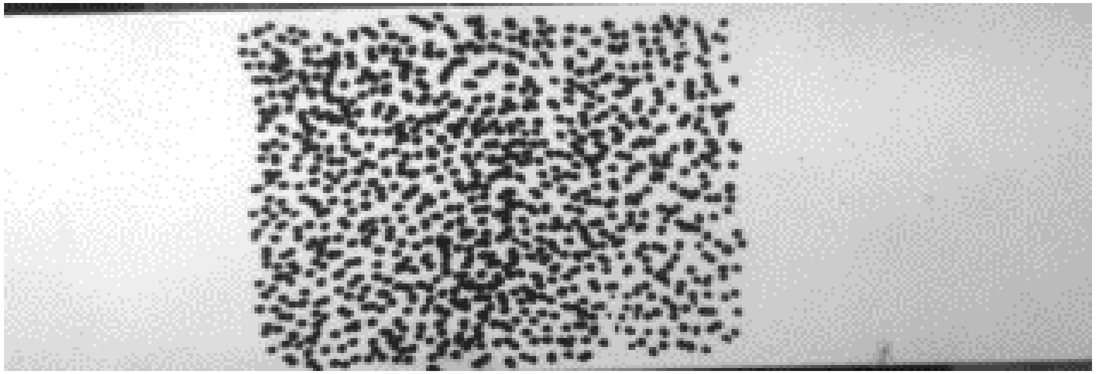
How do we make the bowl narrow?

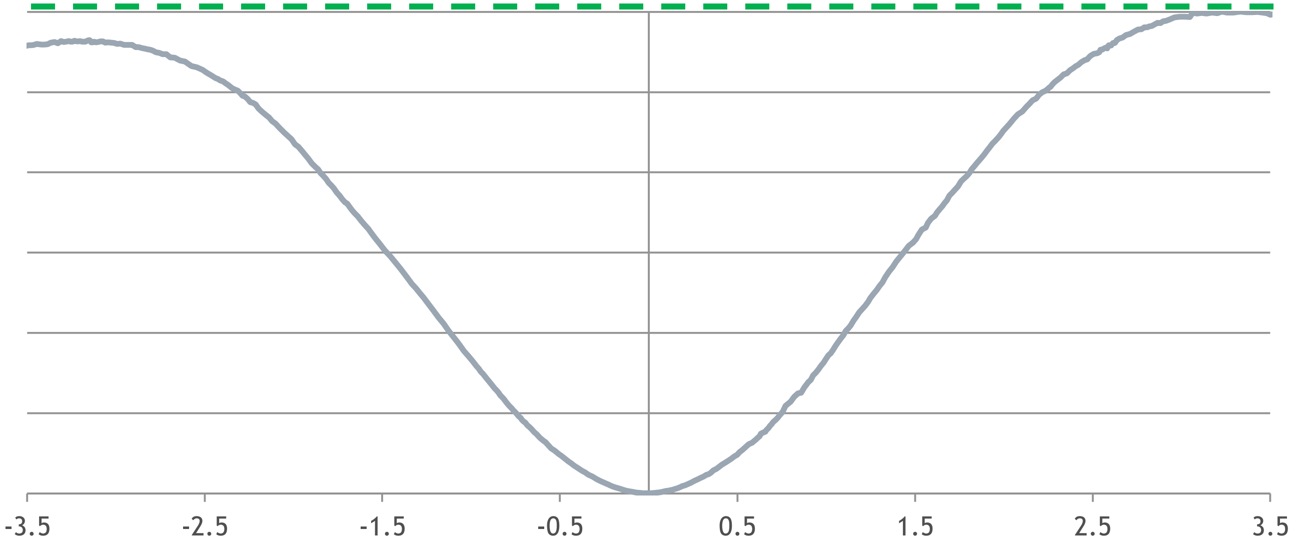
- Sharp edges
- Good focus
- Proper F-stop



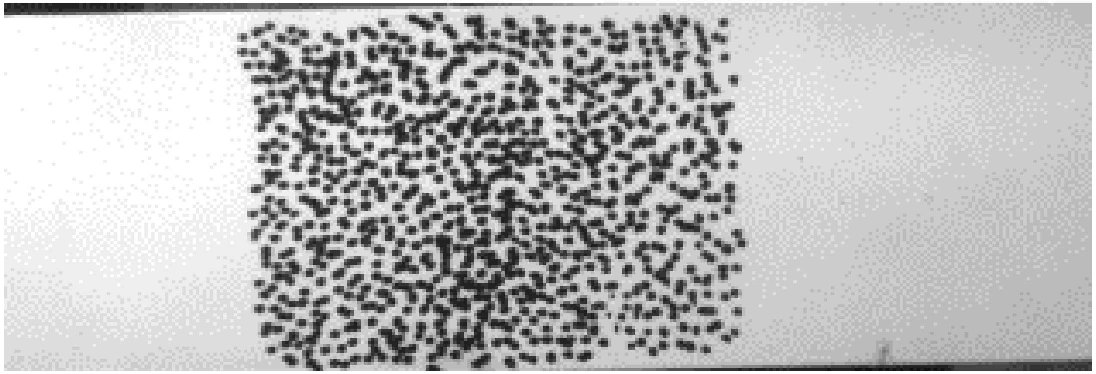


Great pattern example



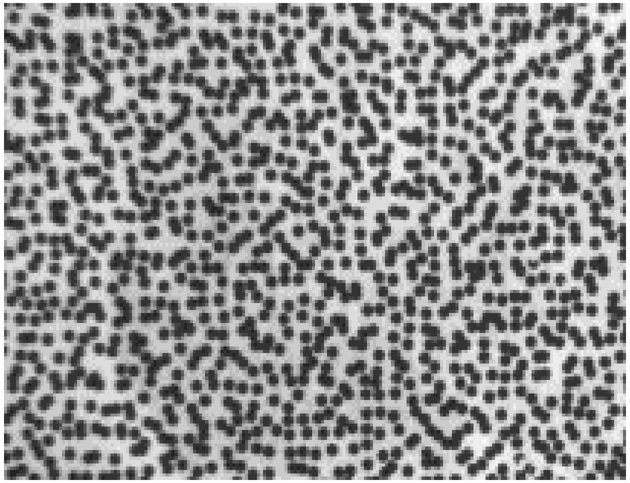


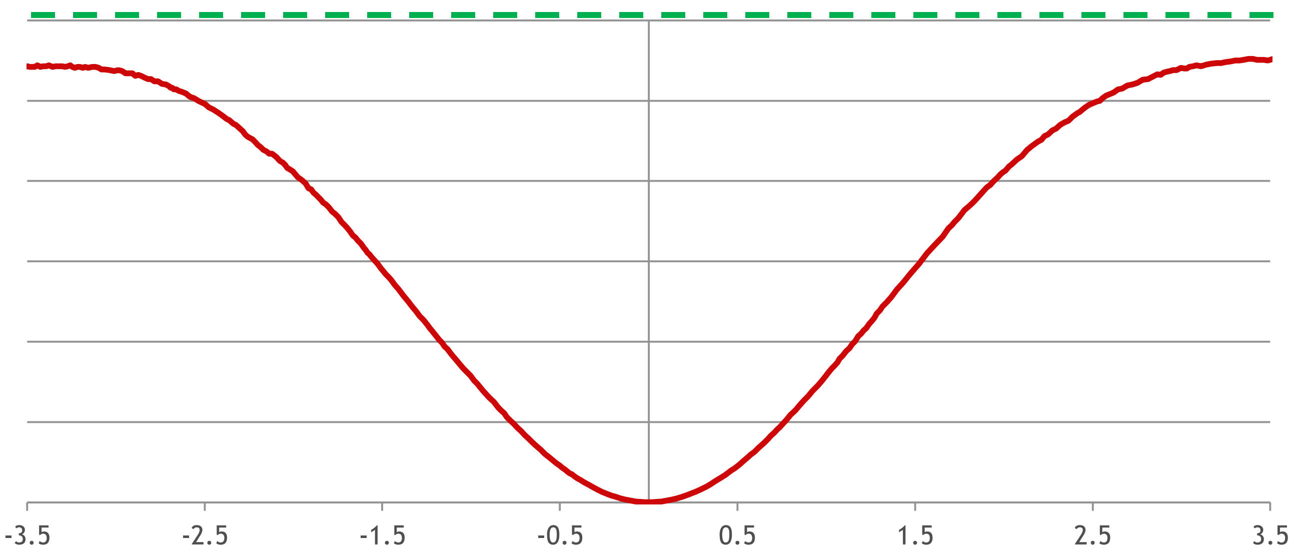
Great pattern example



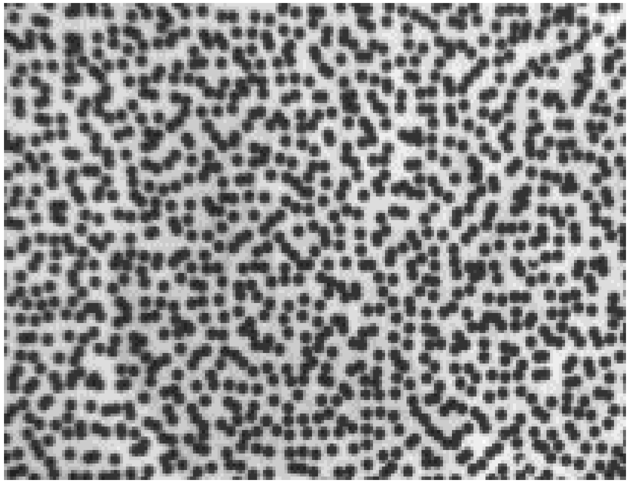
- Sharpie marker on white paint
- Bright whites
- Dark blacks
- Hard edges
- Consistent speckle size

High-contrast printed pattern



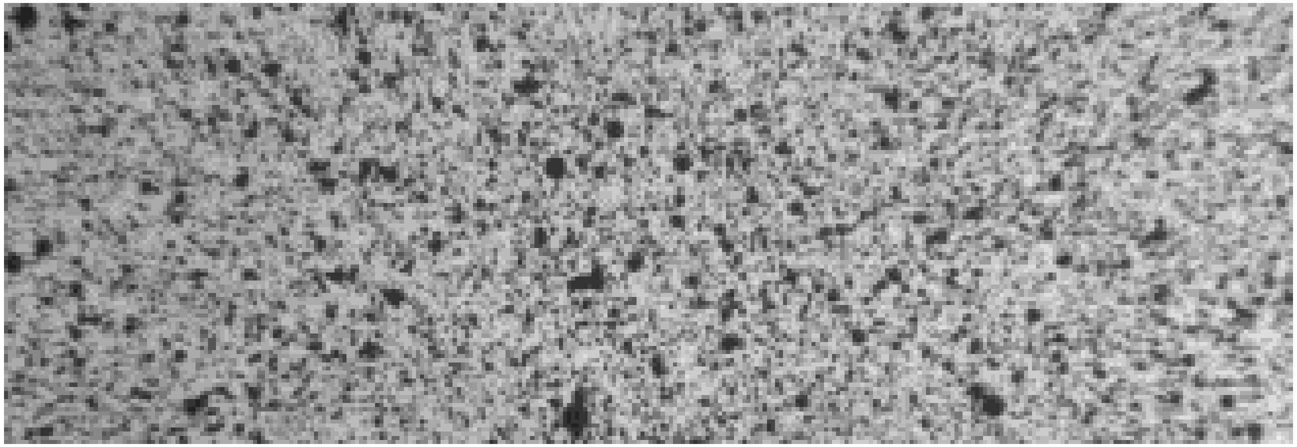


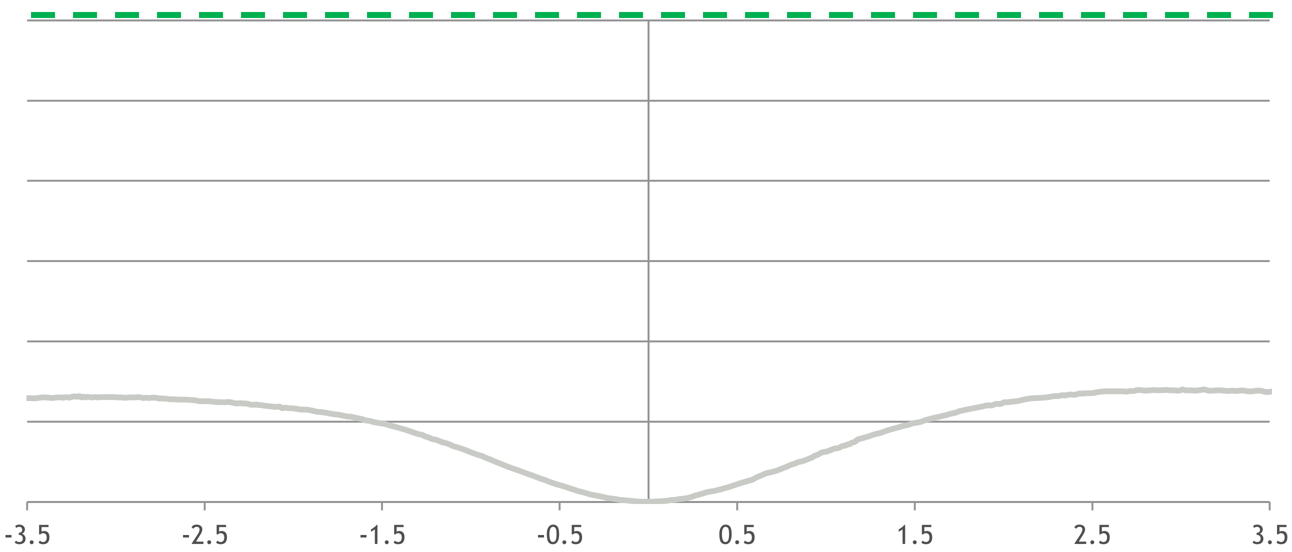
High-contrast printed pattern



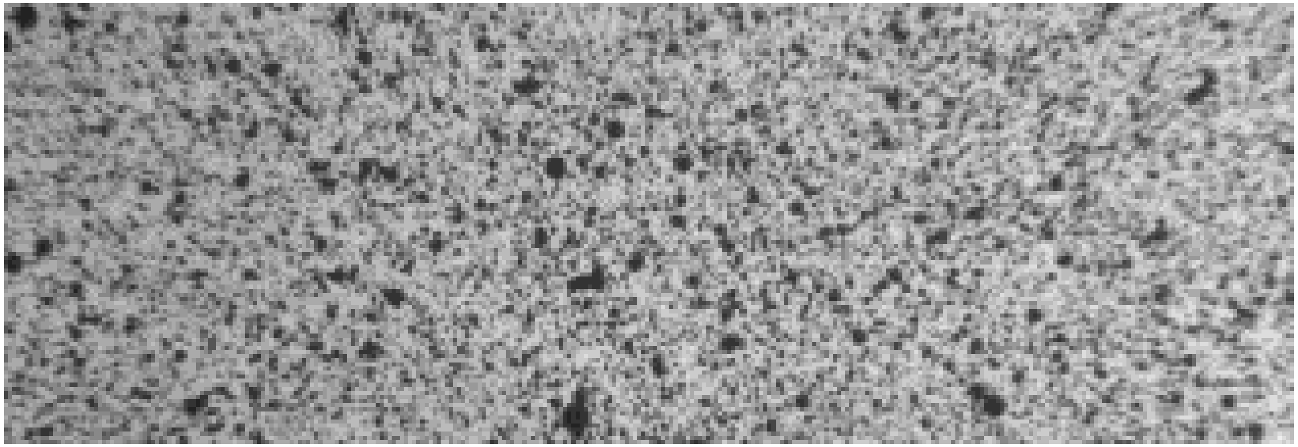
- Laser printer
- CSI target generator
- Good contrast
- Consistent size

A typical painted pattern



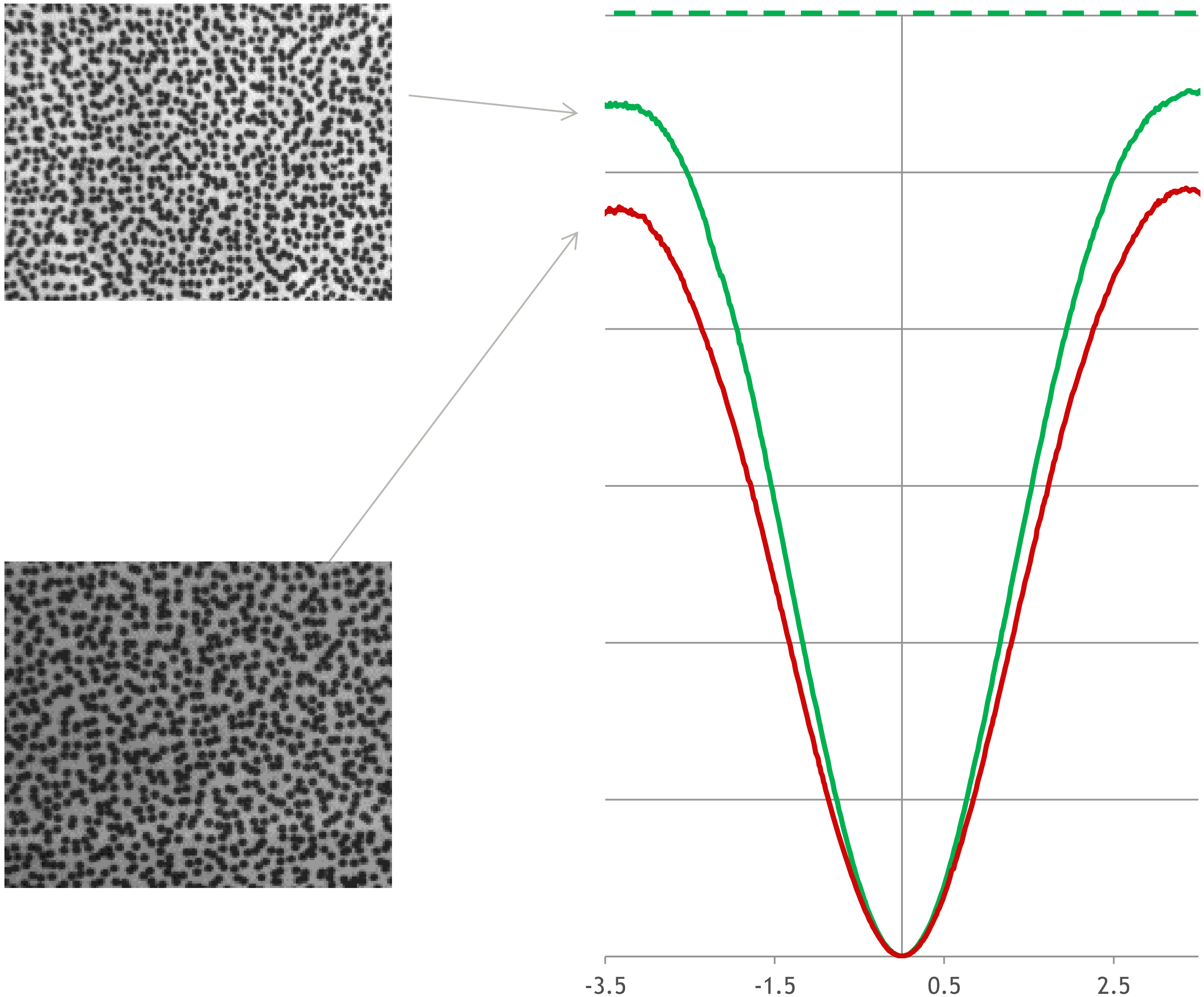


A typical painted pattern



- Inconsistent size
- No bright white areas
- Soft edges

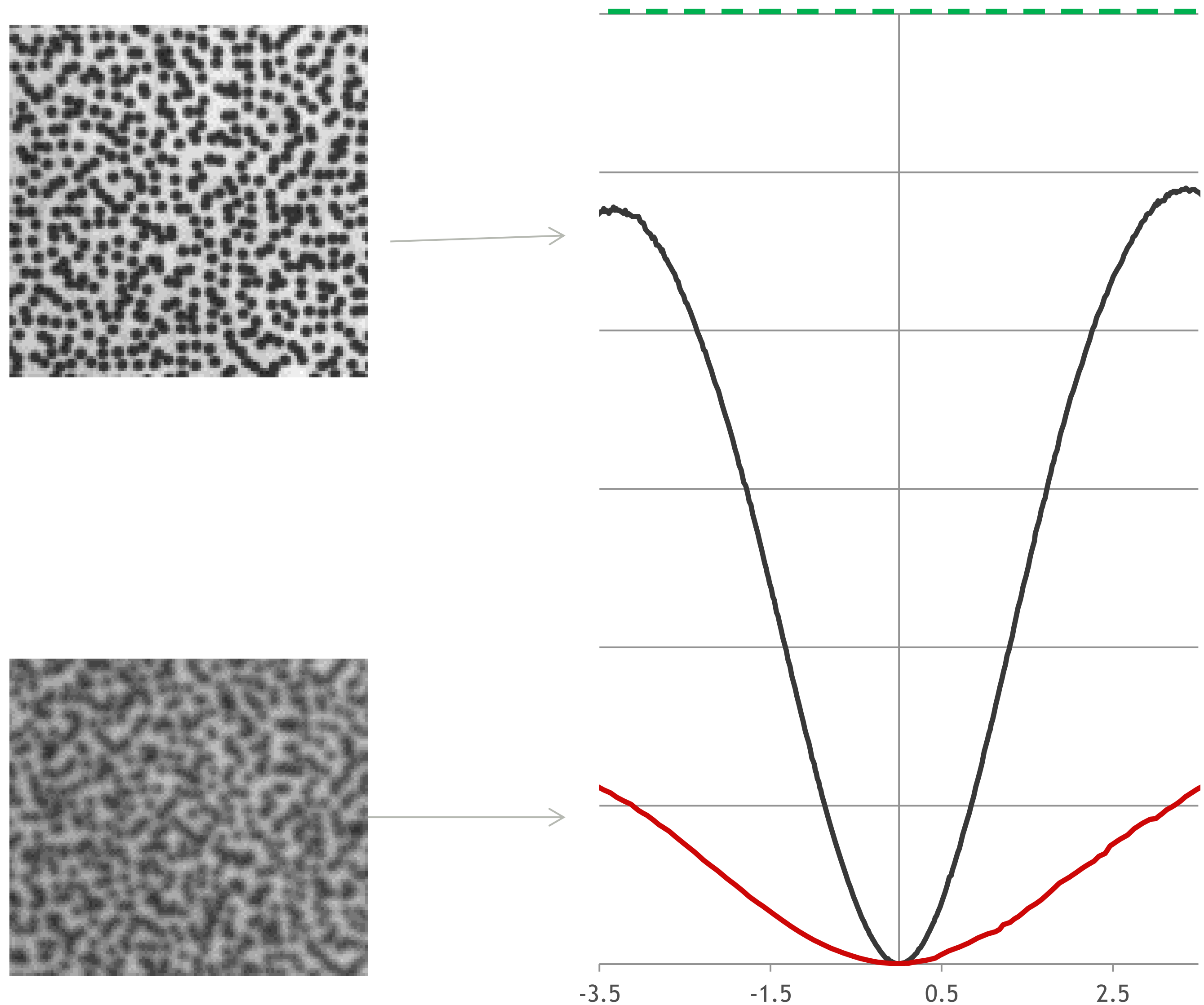
Effect of reduced contrast



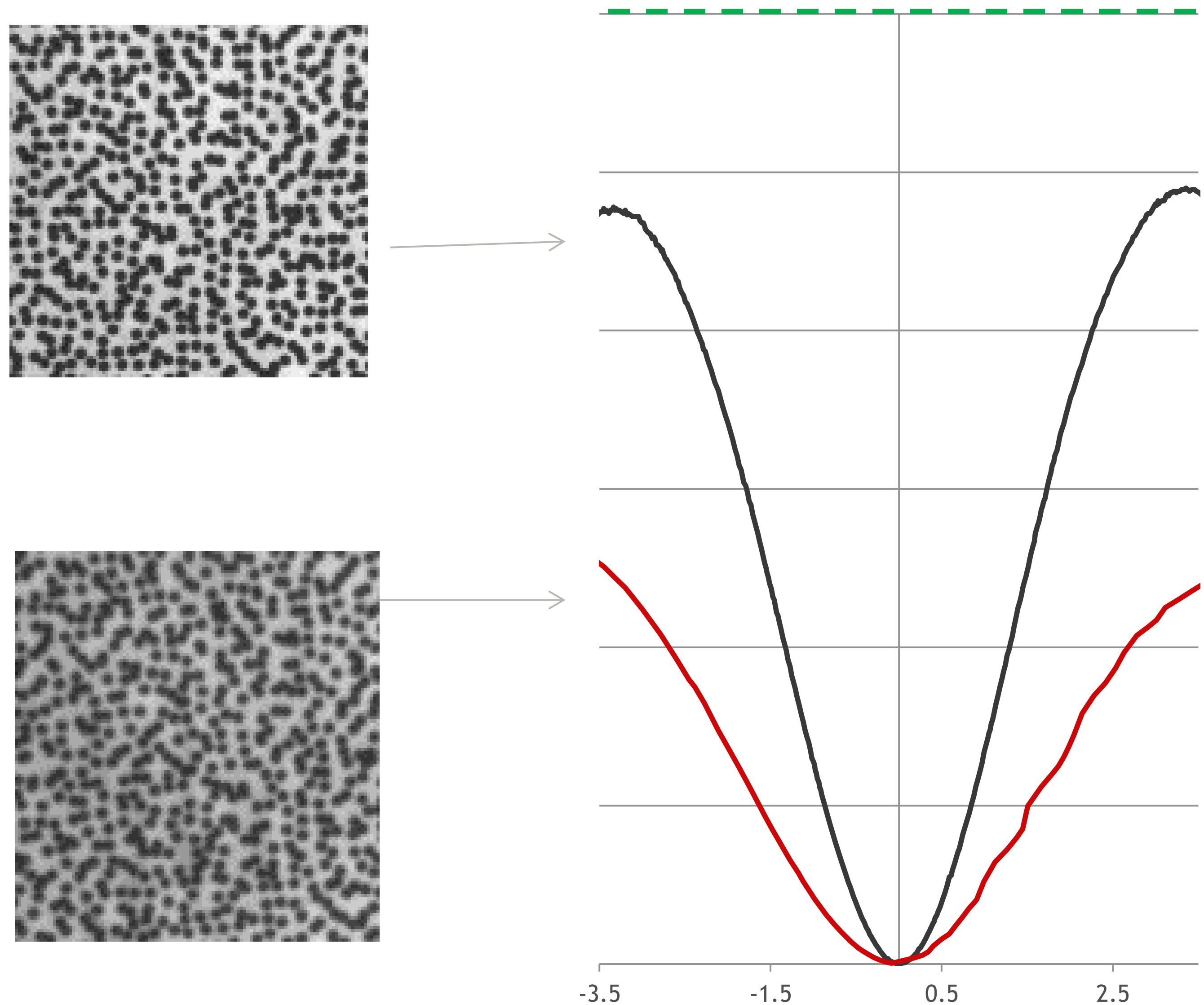
Other considerations

- Focus
- Brightness
- Glare
- F-stop

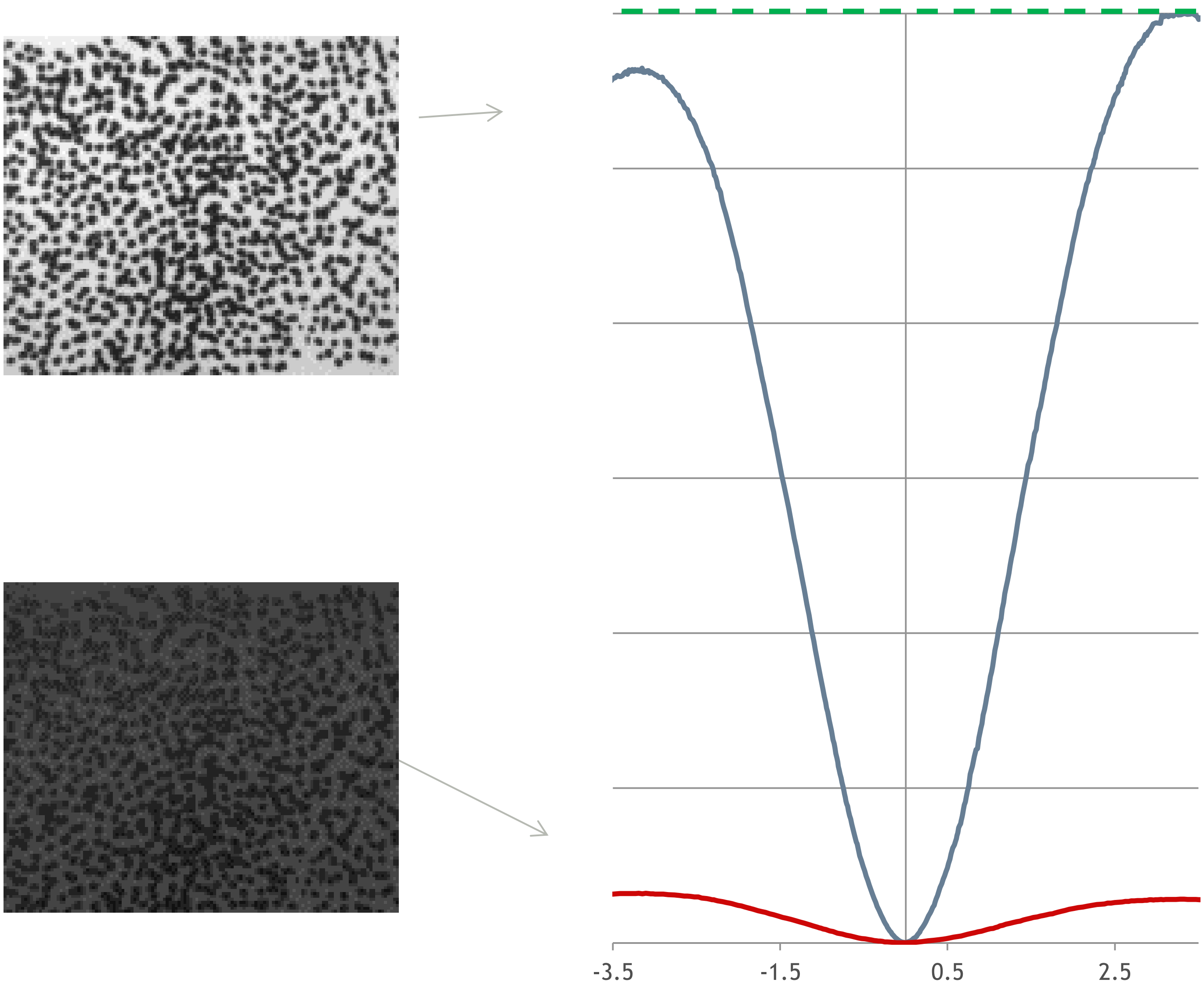
Effect of reduced focus



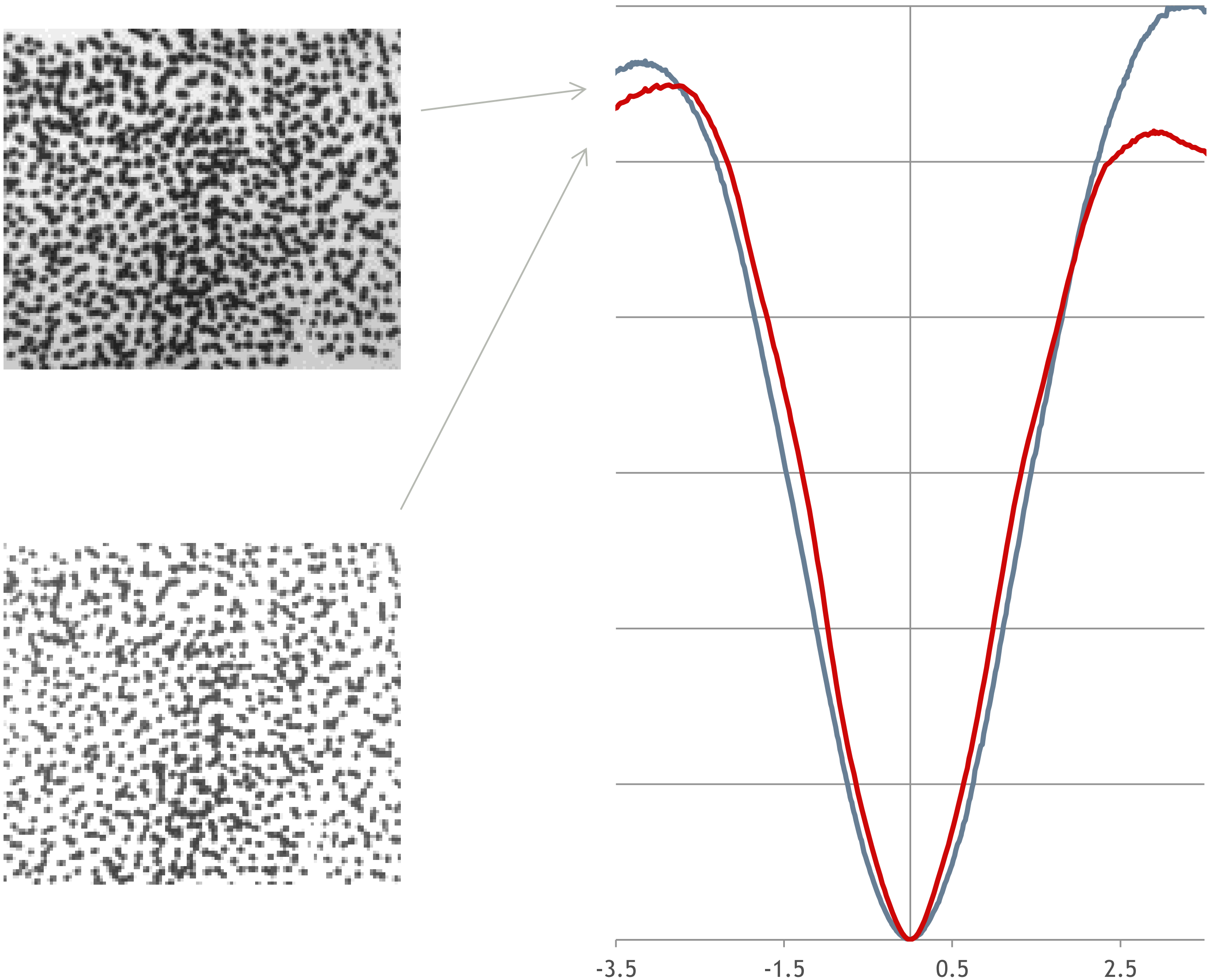
Aperture too small



Effect of low light

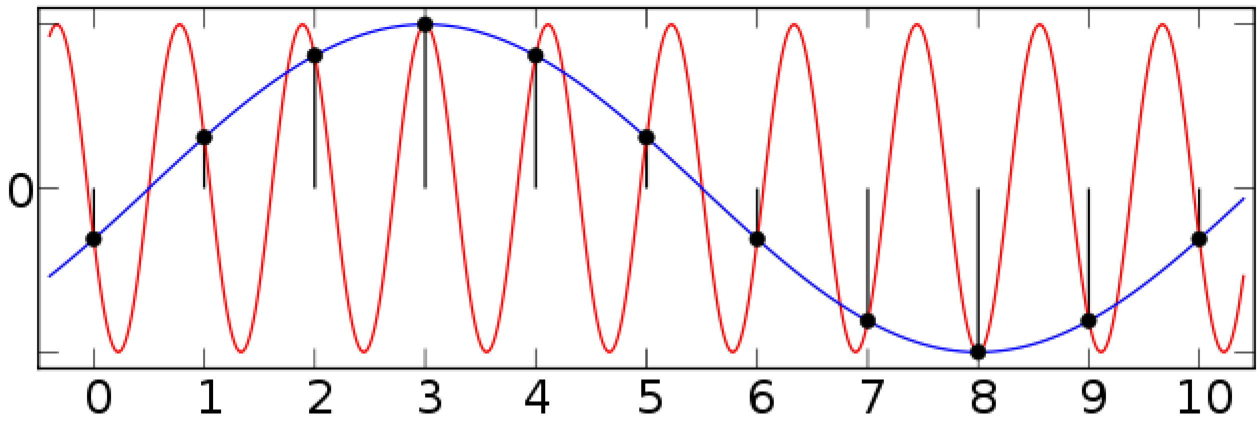


Effect of too much light



Effect of Aliasing

- Aliasing occurs when a signal isn’t sampled frequently enough to represent it.
- Aliasing in a 1D signal:

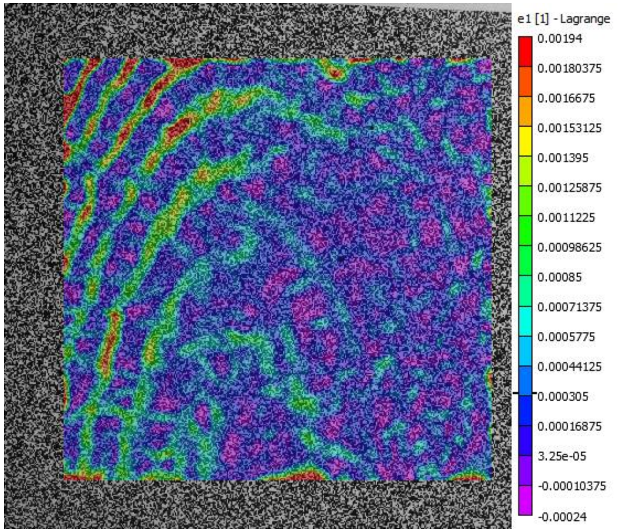


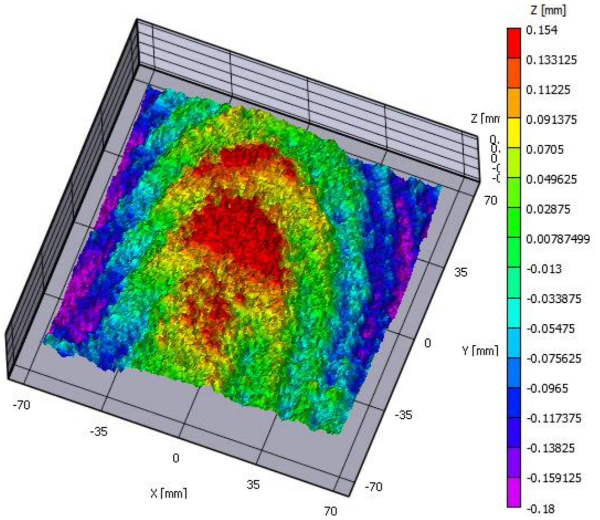
Effect of aliasing

- Aliasing occurs when the scene contains high-frequency content that cannot be represented by the pixel resolution of the image

Effect of aliasing

- Aliasing is dangerous because it **does not always** appear in the “sigma” value
- We can sometimes see aliasing in the result

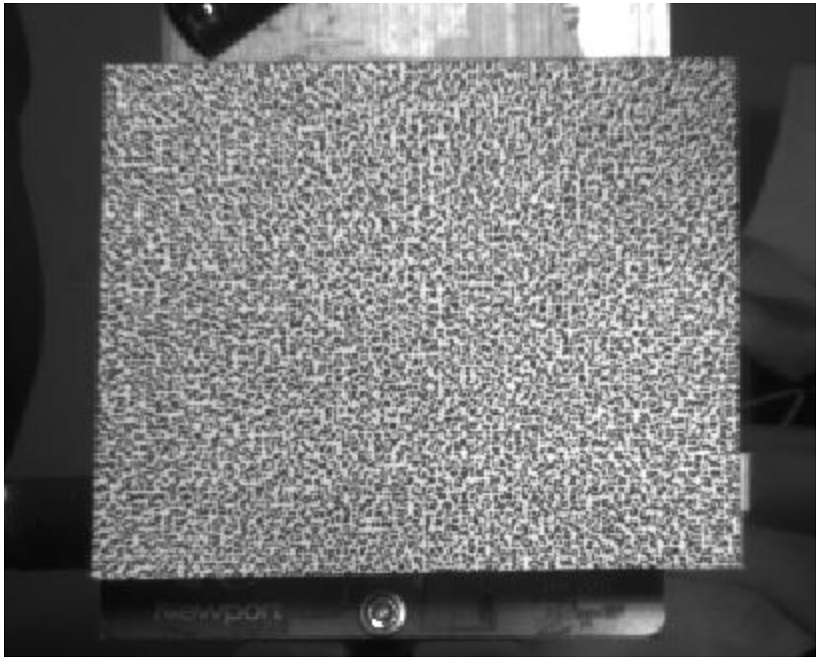




- This is both a bias and an accuracy problem even when not apparent!

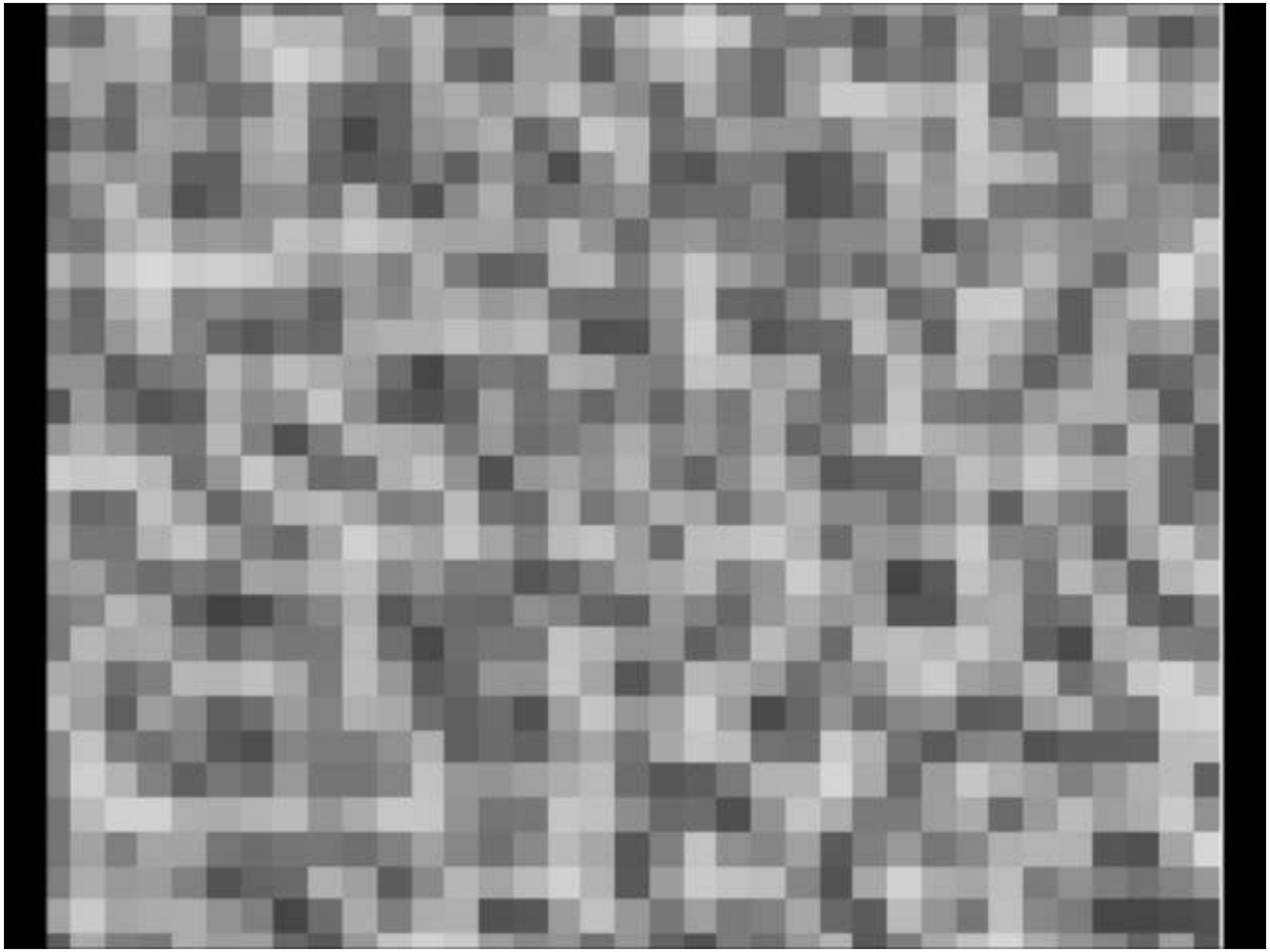
Effect of aliasing

- Overly fine pattern



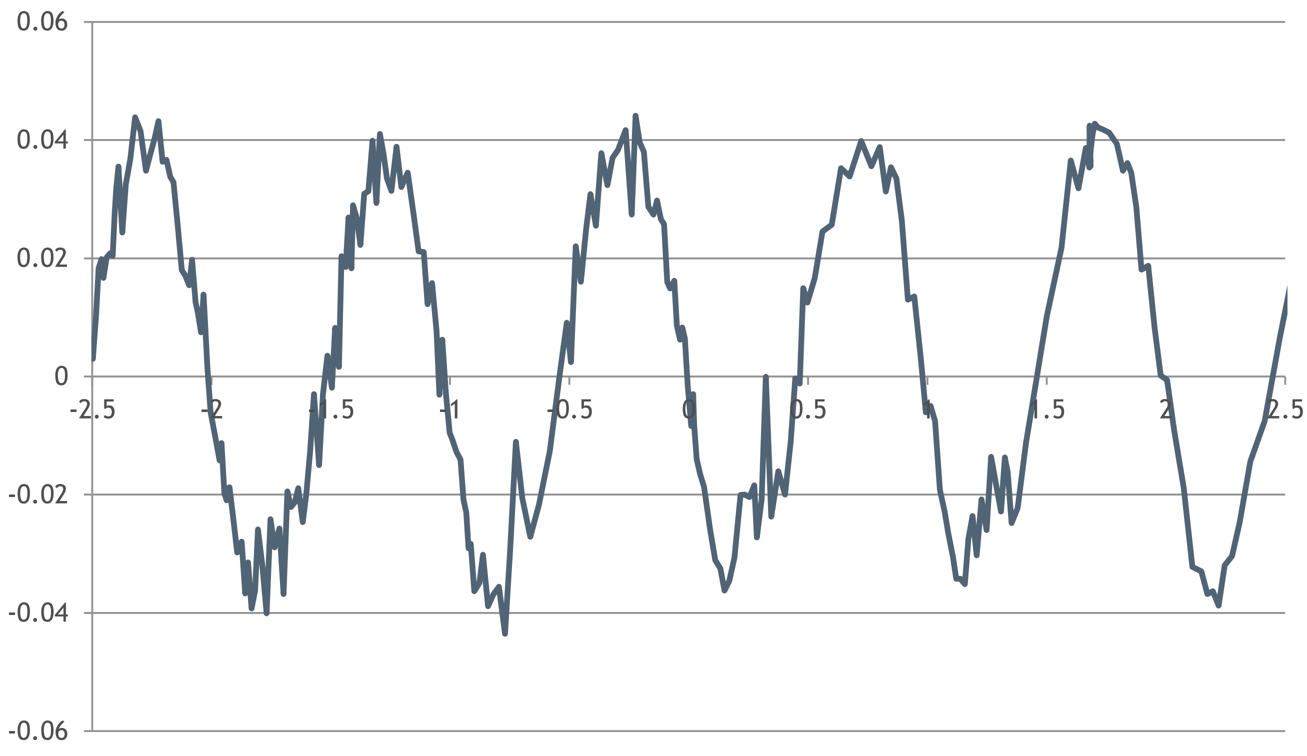
Effect of aliasing

- Showing translation



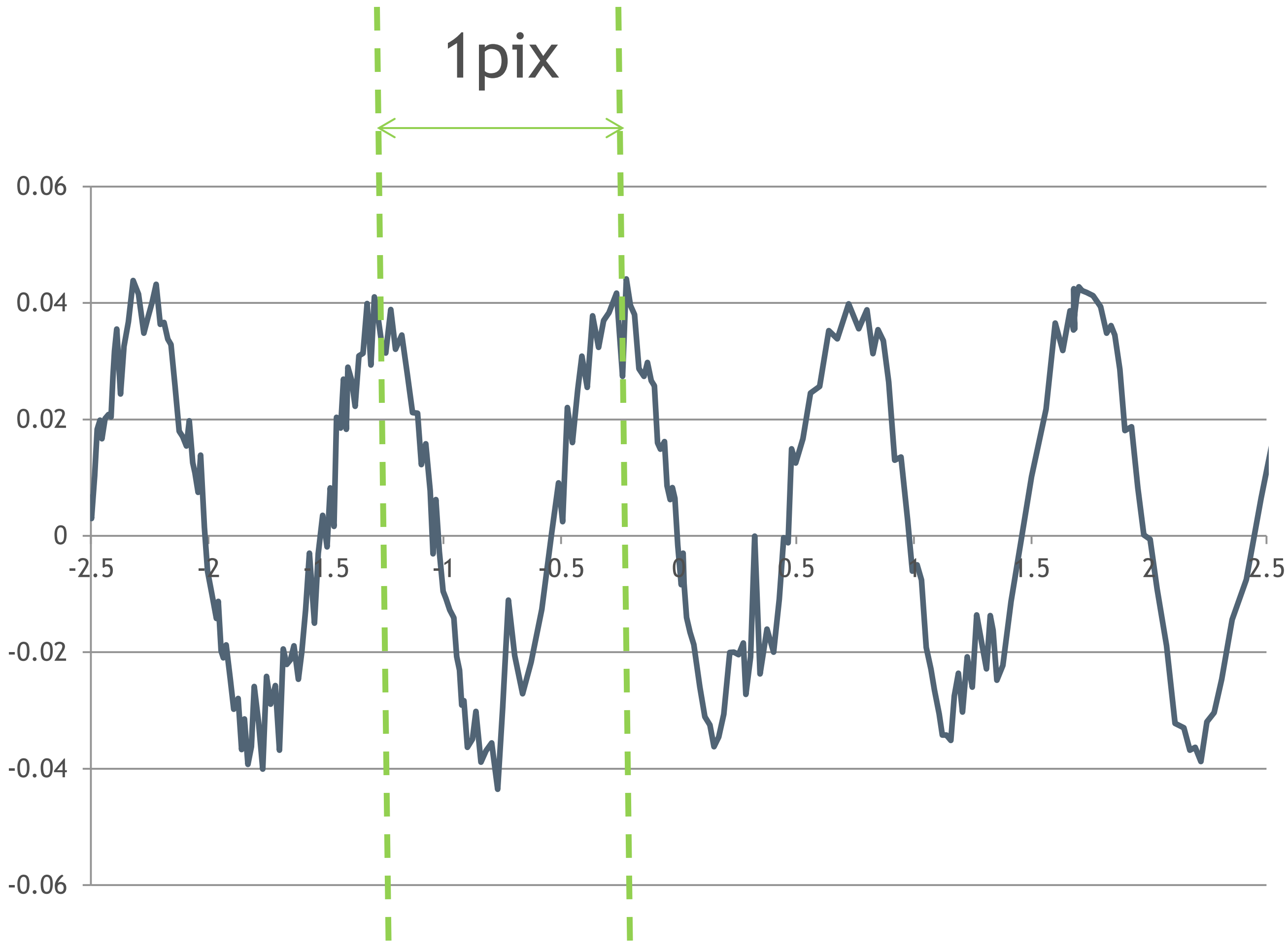
Displacement error from aliasing

- We calculate the **actual** displacement vs. the local **measured** displacement
- The error is plotted vs. position



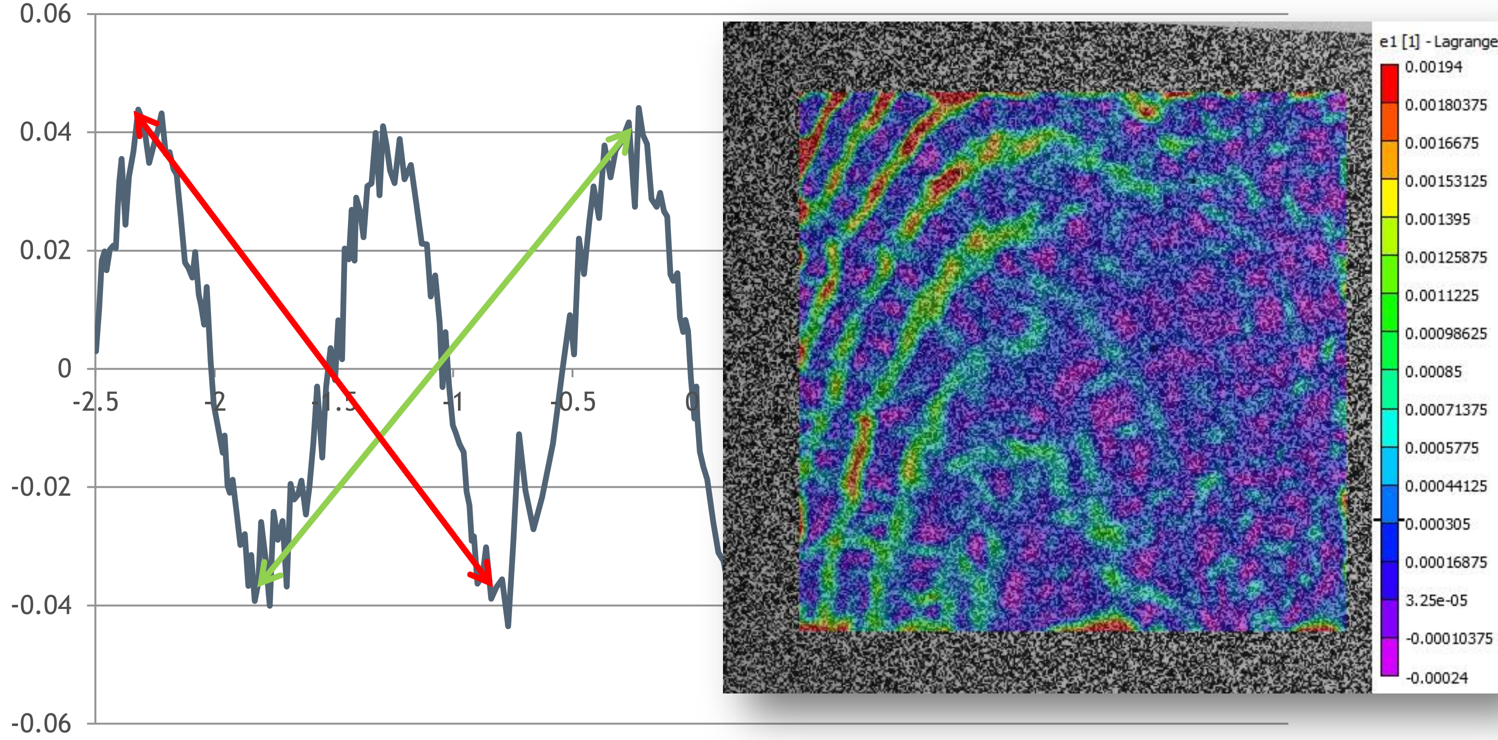
Displacement error from aliasing

- The error varies with the pixel position
- This causes the moiré effect seen before



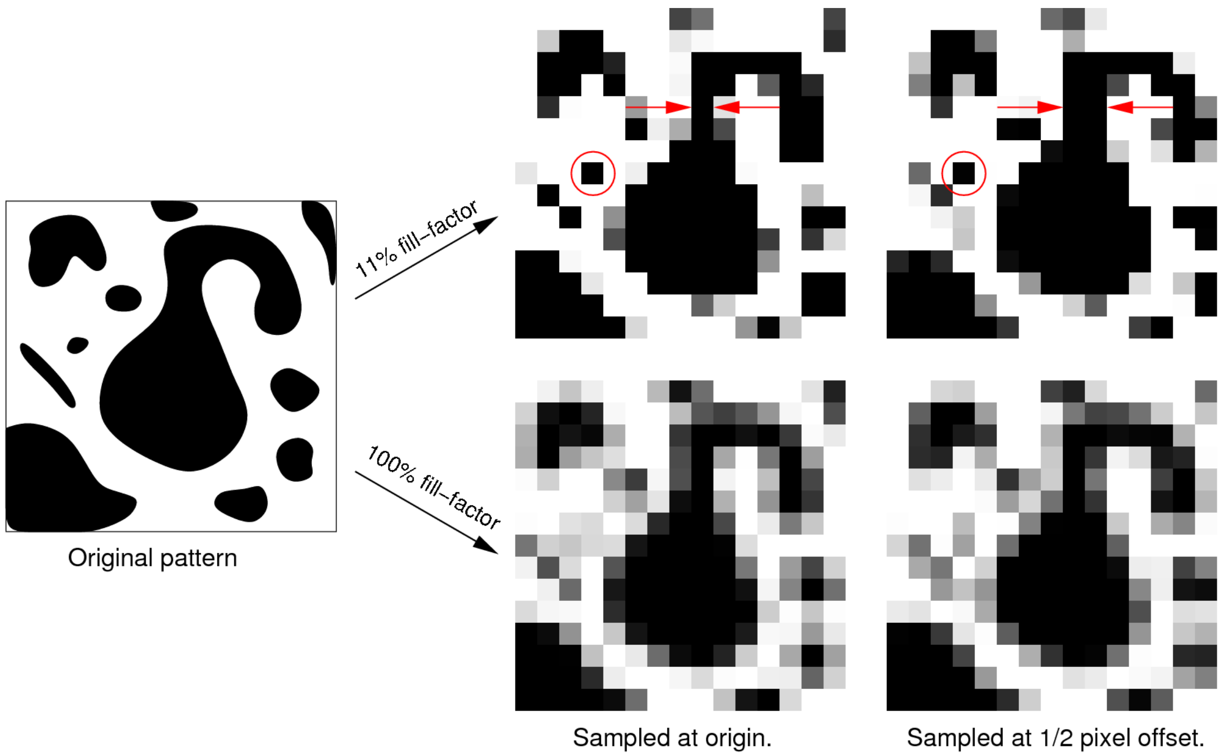
Strain error from aliasing

- This can cause very serious strain errors!
- Waves of compressive strain and tensile strain cause ripples



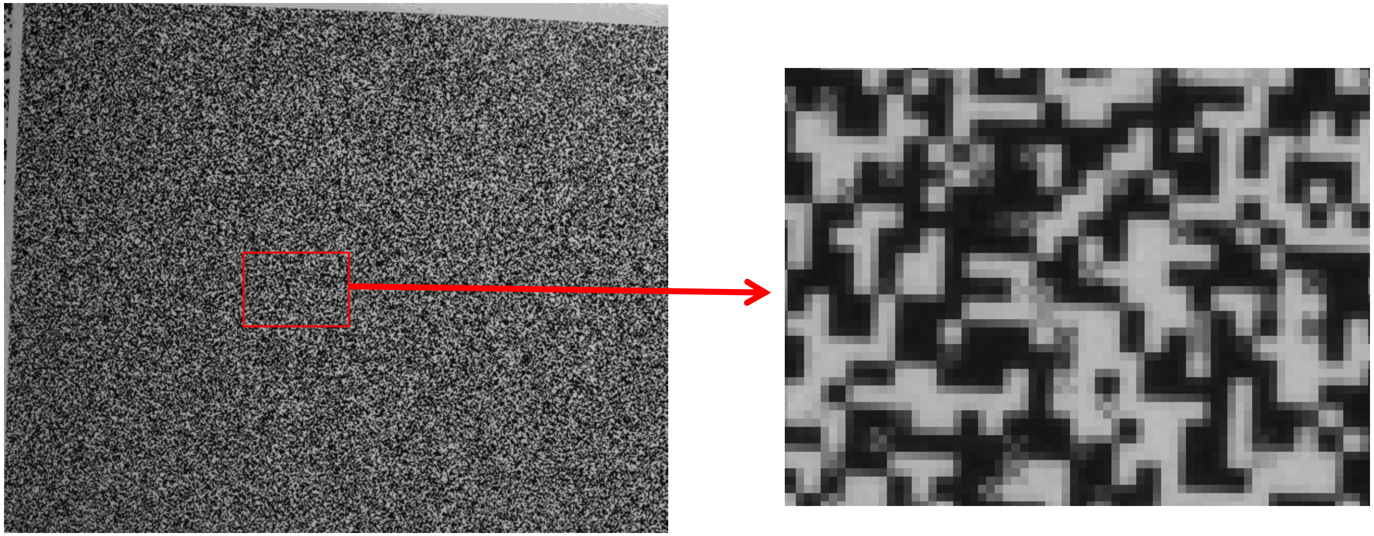
Noise and Bias Due to Aliasing

- Low fill factors can exacerbate the aliasing issue for a given pattern



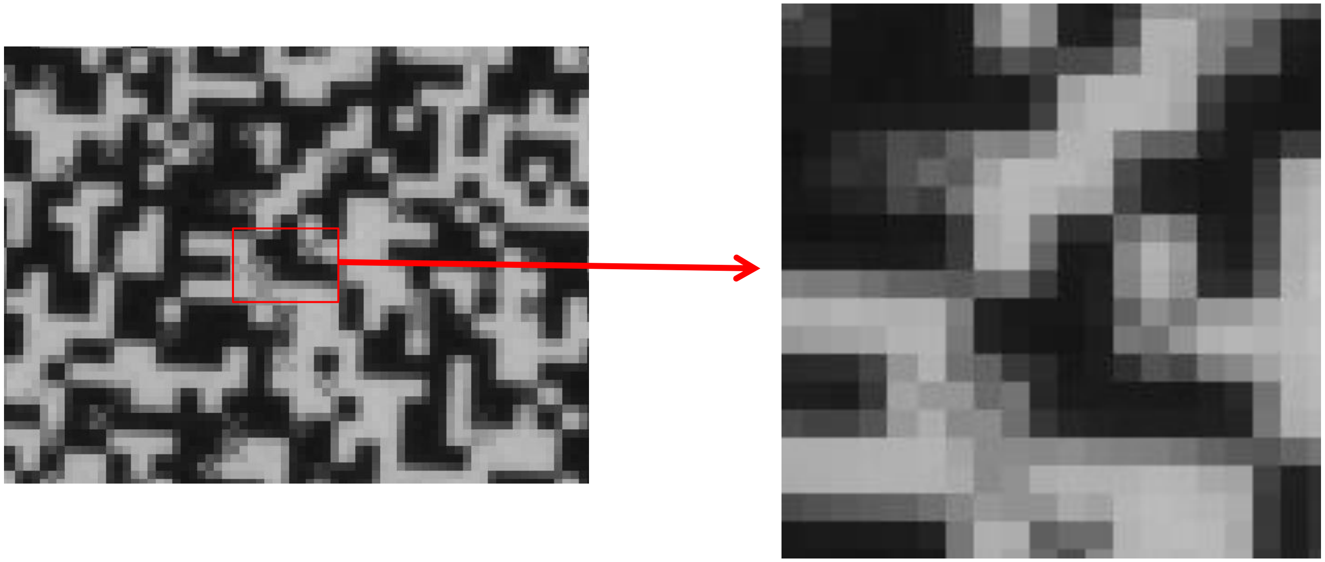
Bias Due to Aliasing

- An example of an extremely aliased image – due to dithering from a laser printer

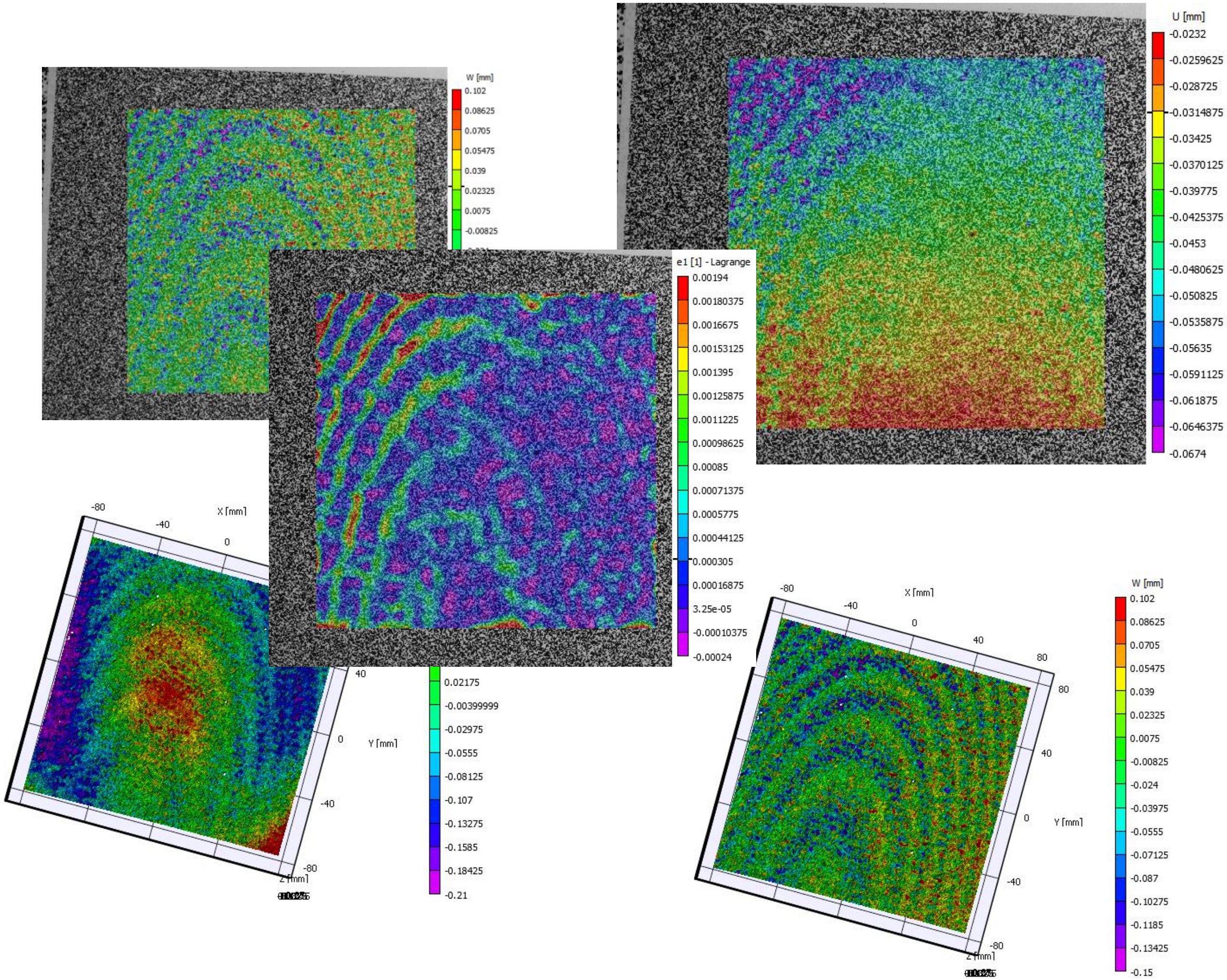


Noise and Bias Due to Aliasing

- An example of an extremely aliased image – due to dithering from a laser printer

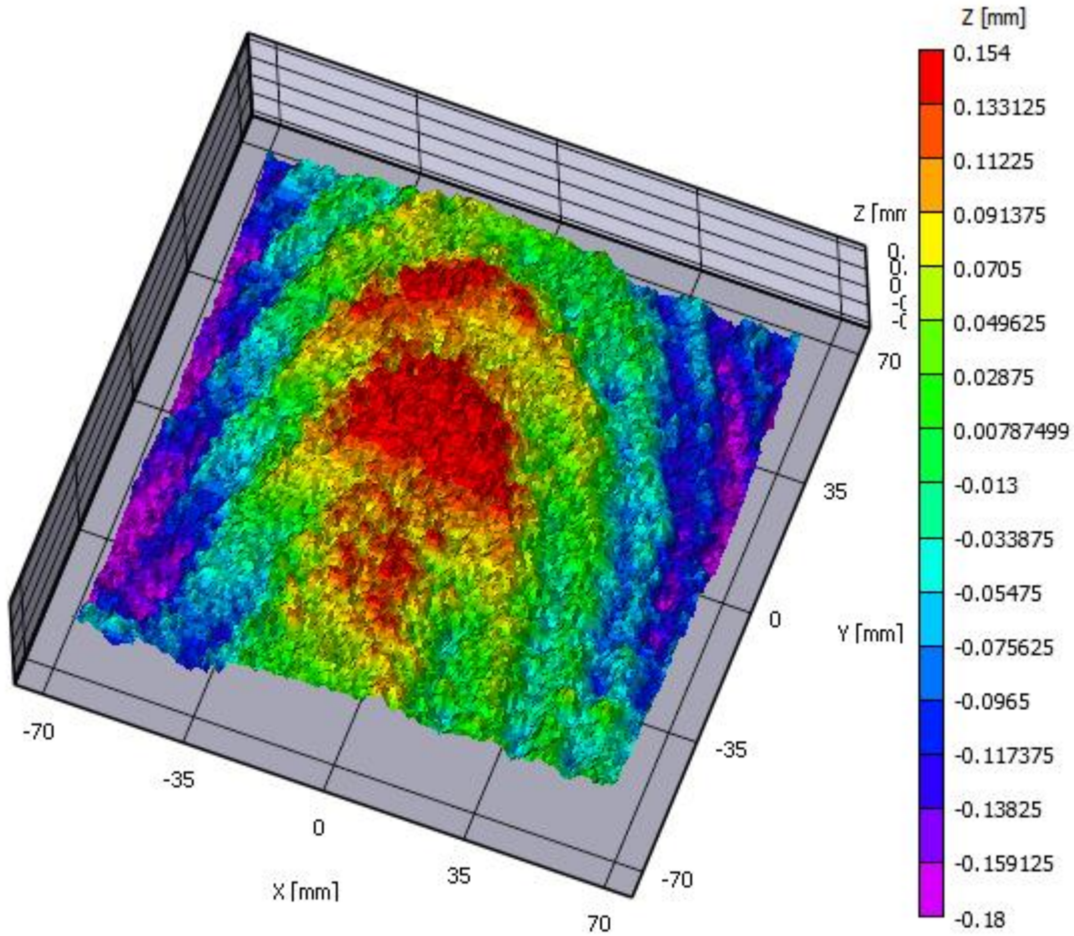


Noise and Bias Due to Aliasing



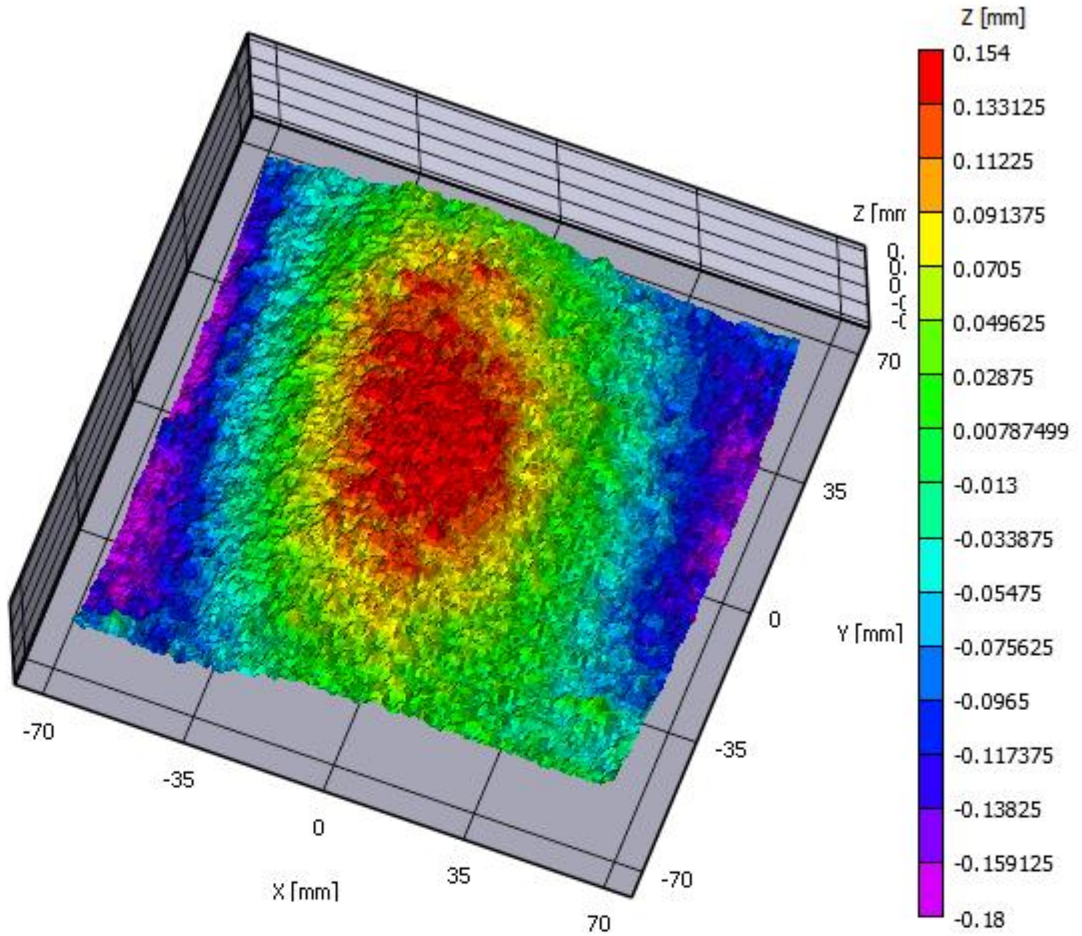
Noise and Bias Due to Aliasing

- Aliased shape



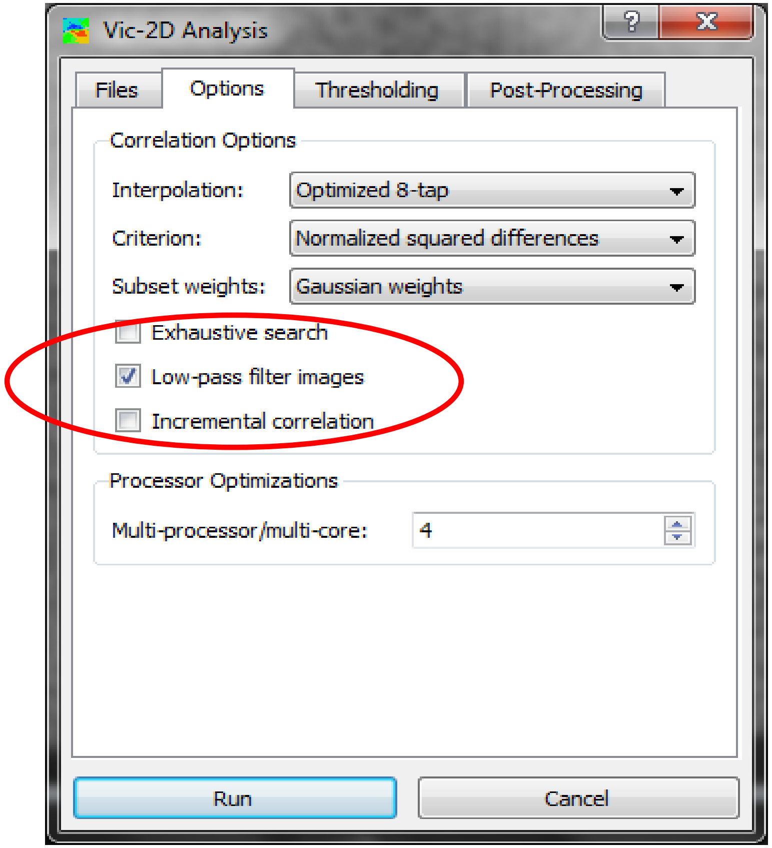
Noise and Bias Due to Aliasing

- With low-pass filtering of image



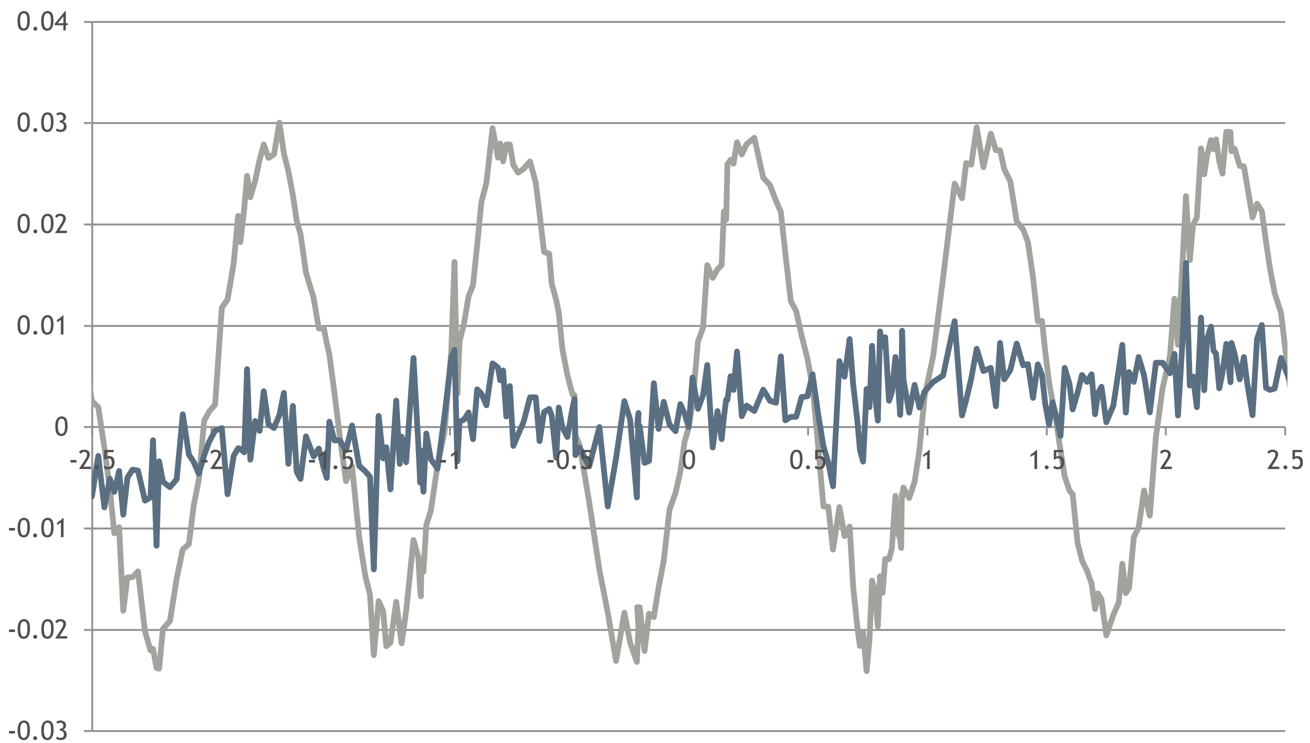
Effects of Aliasing

- Greatly reduces aliasing - at the expense of actual accuracy



Effects of Aliasing

- Use of low pass filter can help

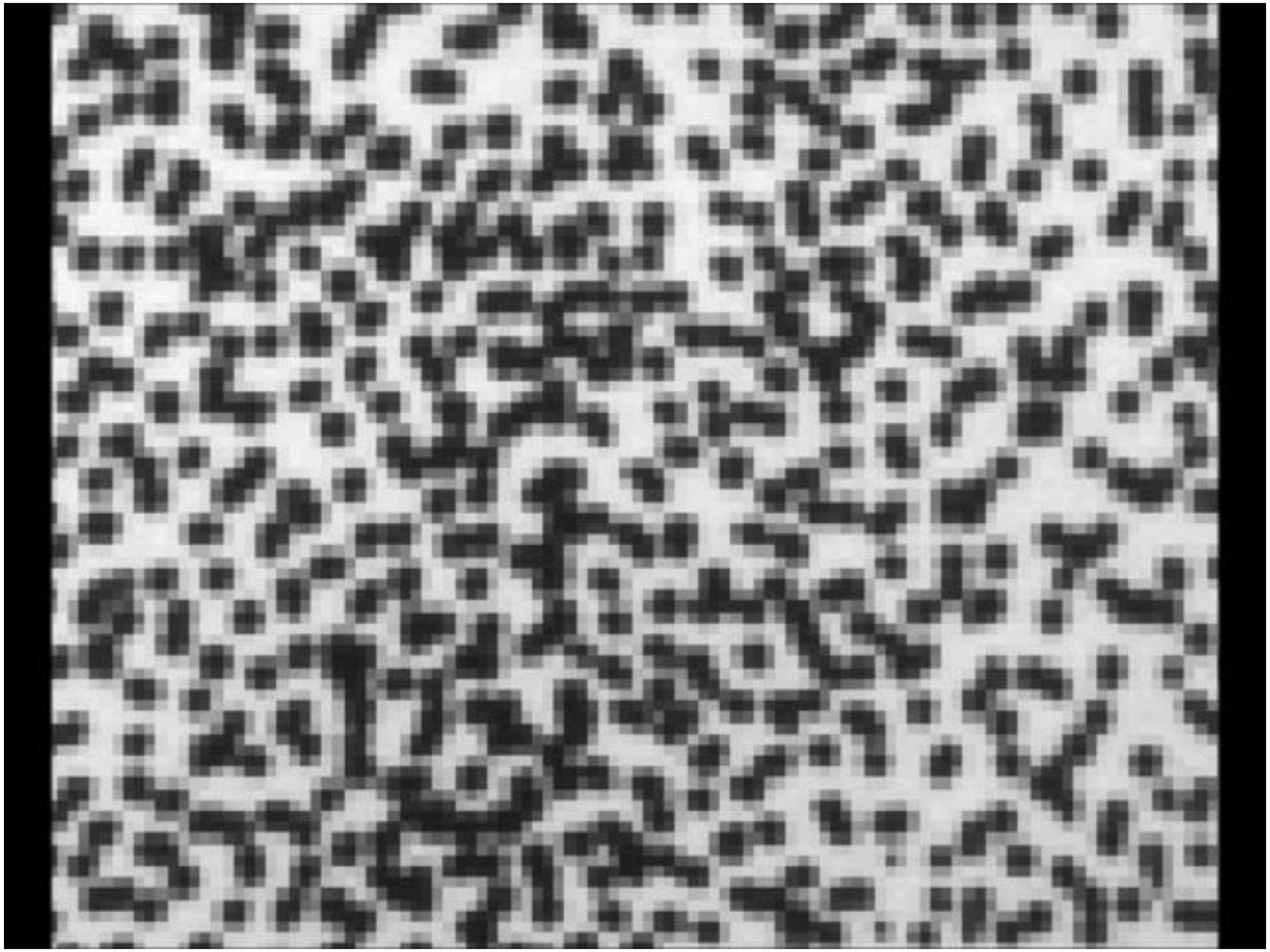


Noise and Bias Due to Aliasing

- Aliasing can cause severe biases and noise in displacement and strain
- Best to avoid in the first place – bigger patterns or more magnification
- Can be mitigated
  - Low-pass image filter
    - This comes at the expense of resolution
  - Higher order interpolation

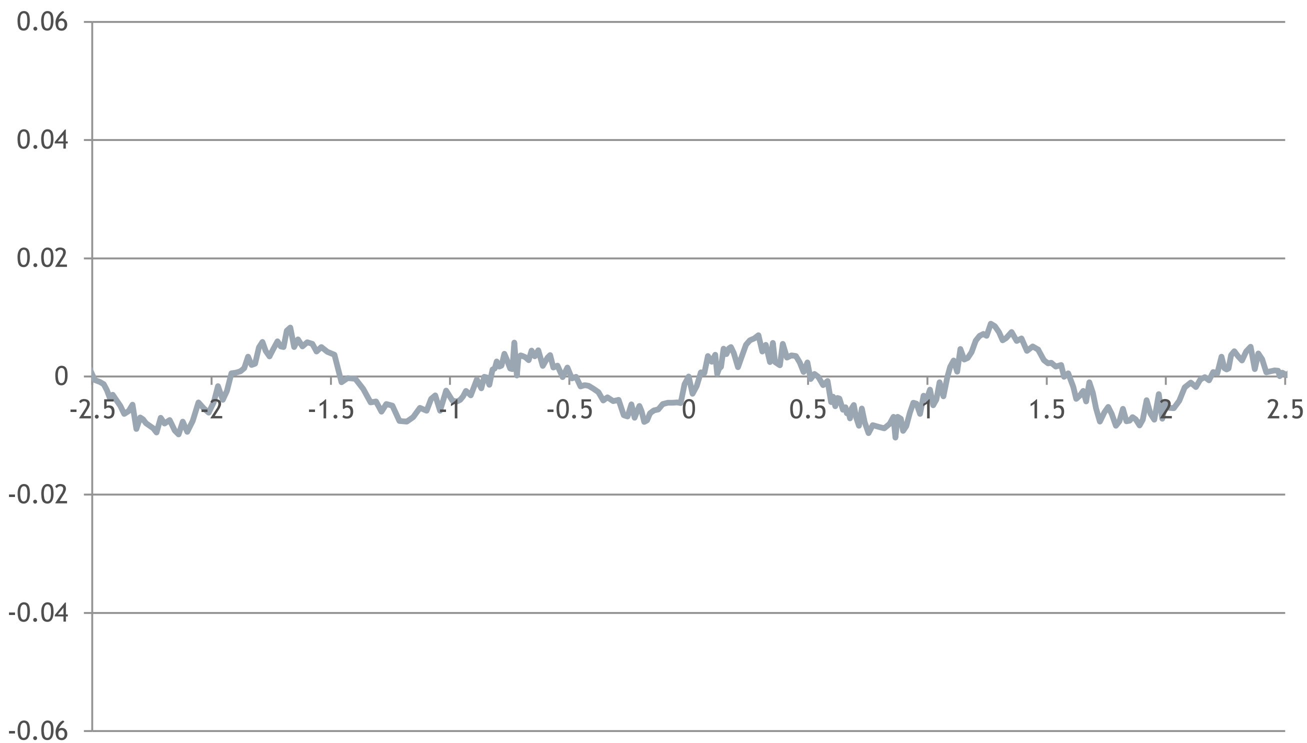
A better pattern

- Showing translation

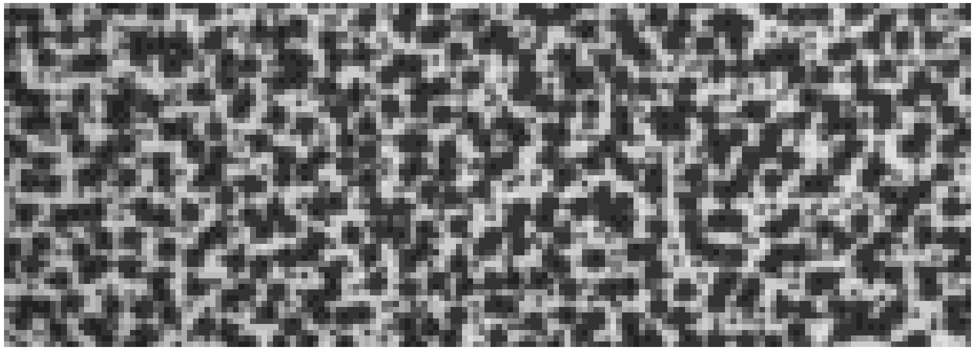


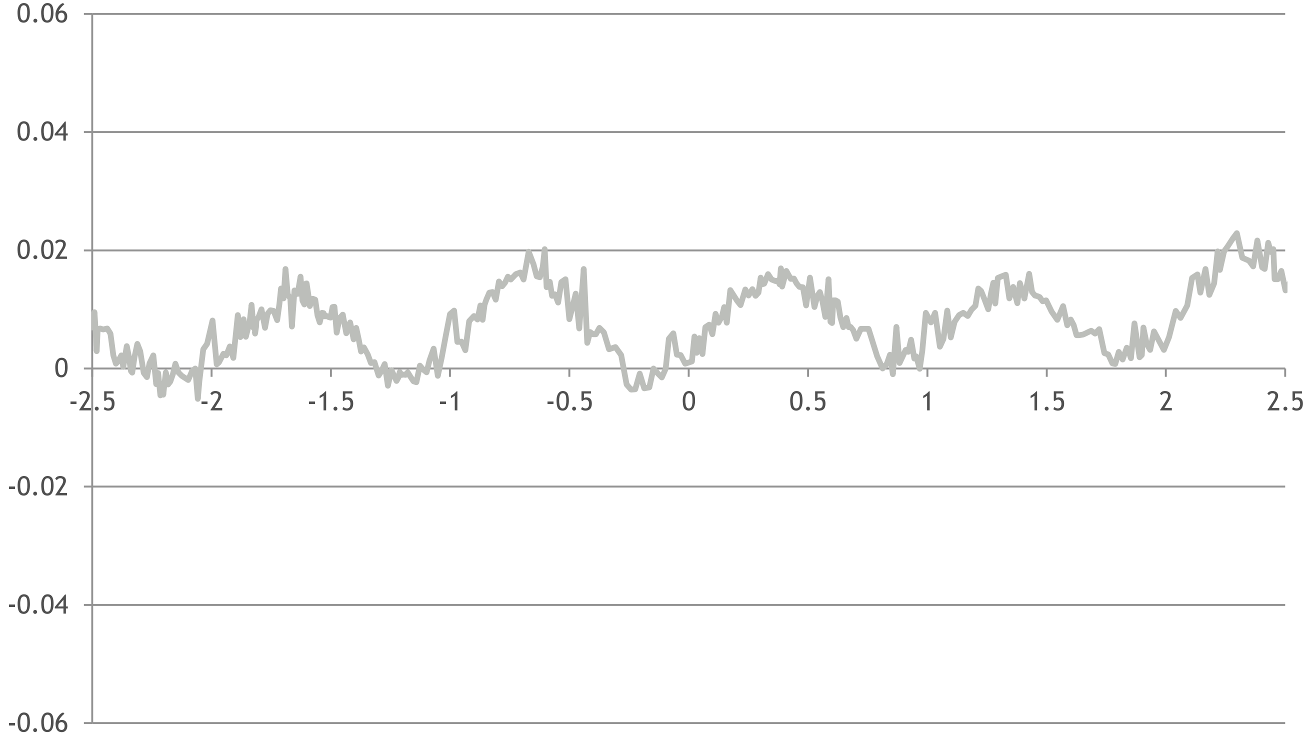
A better pattern

- Stronger pattern – aliasing still visible (low quality camera) but much weaker

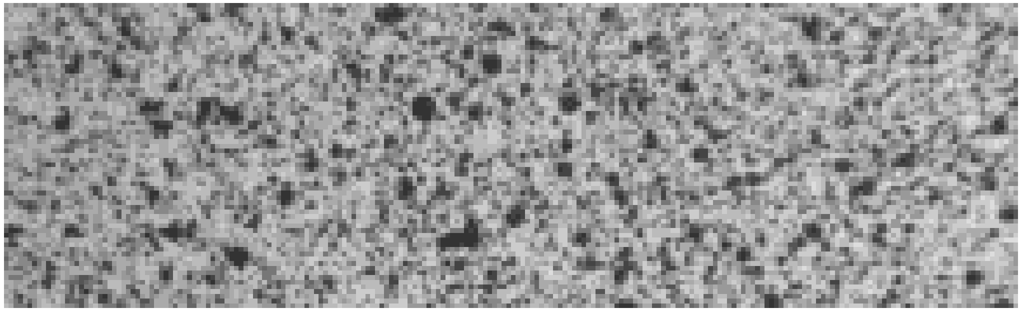


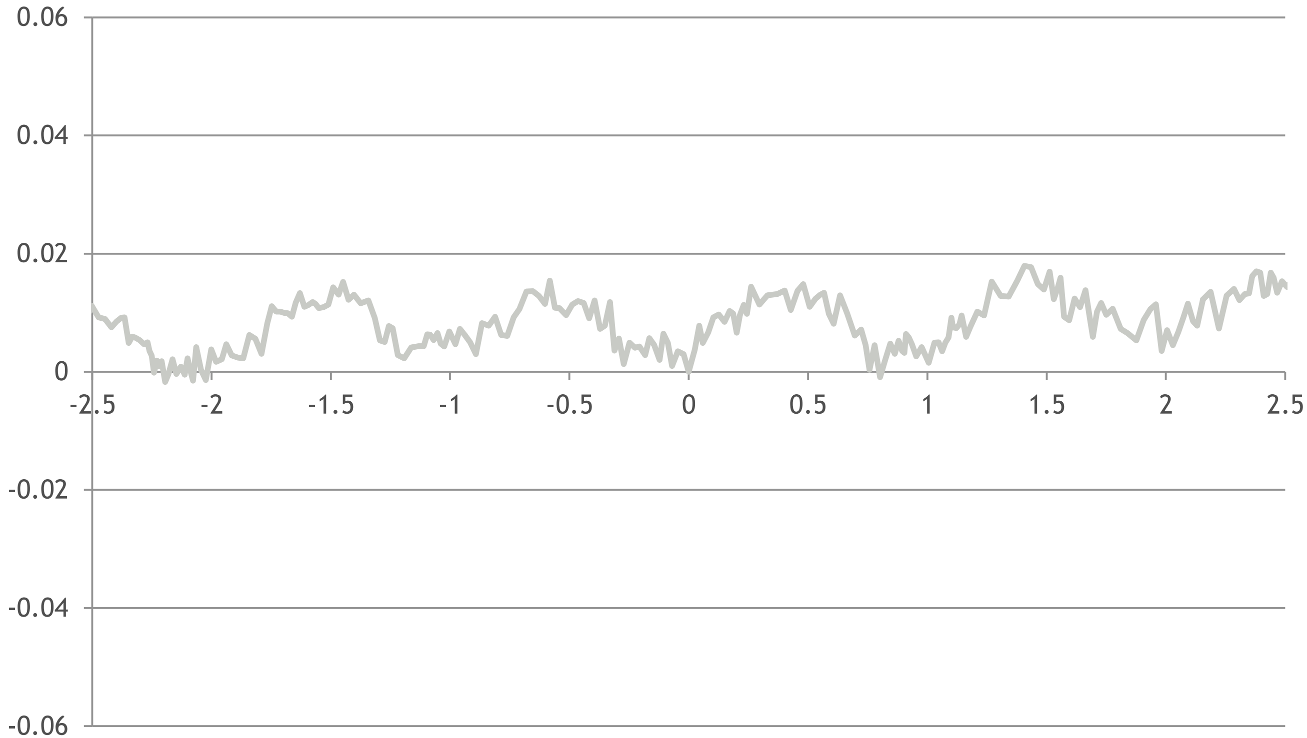
Mixed sizes - synthetic





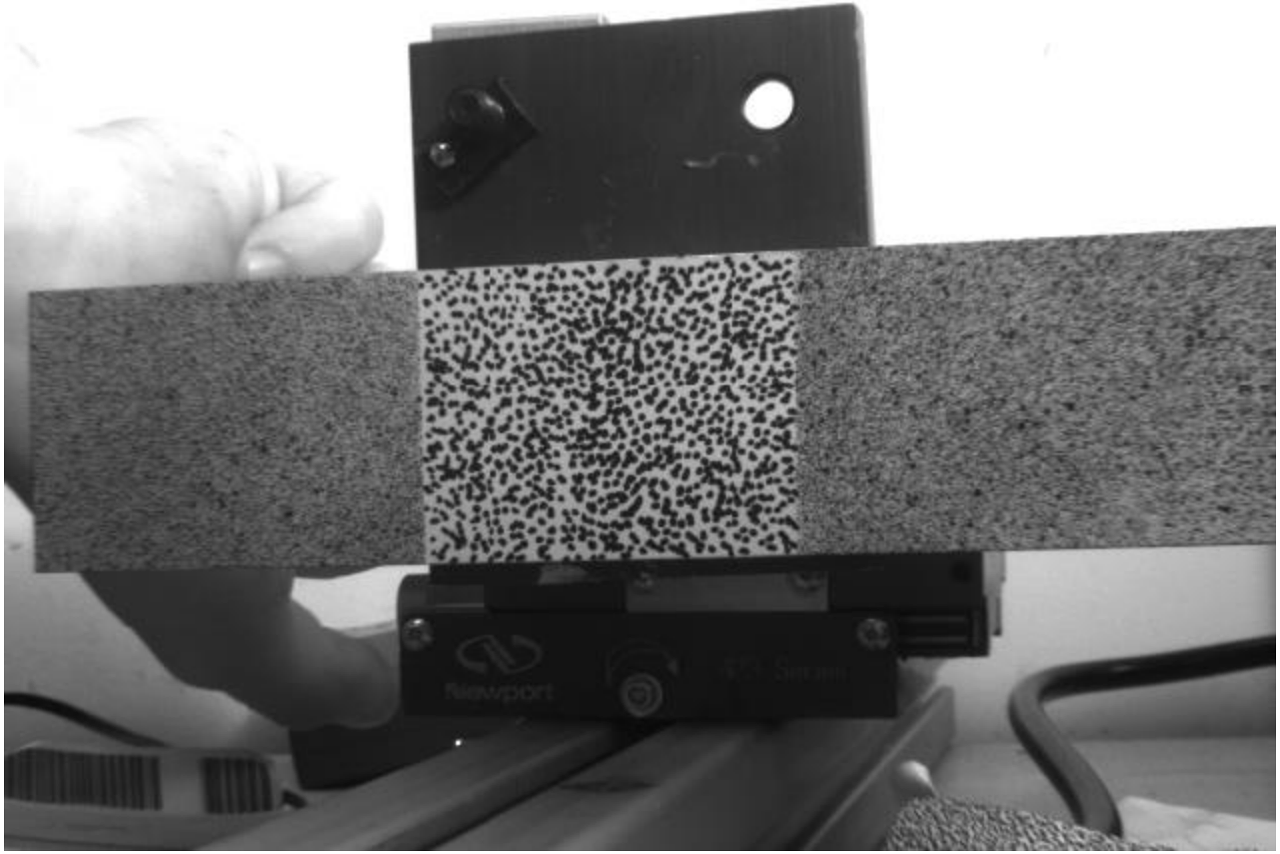
Mixed sizes - real





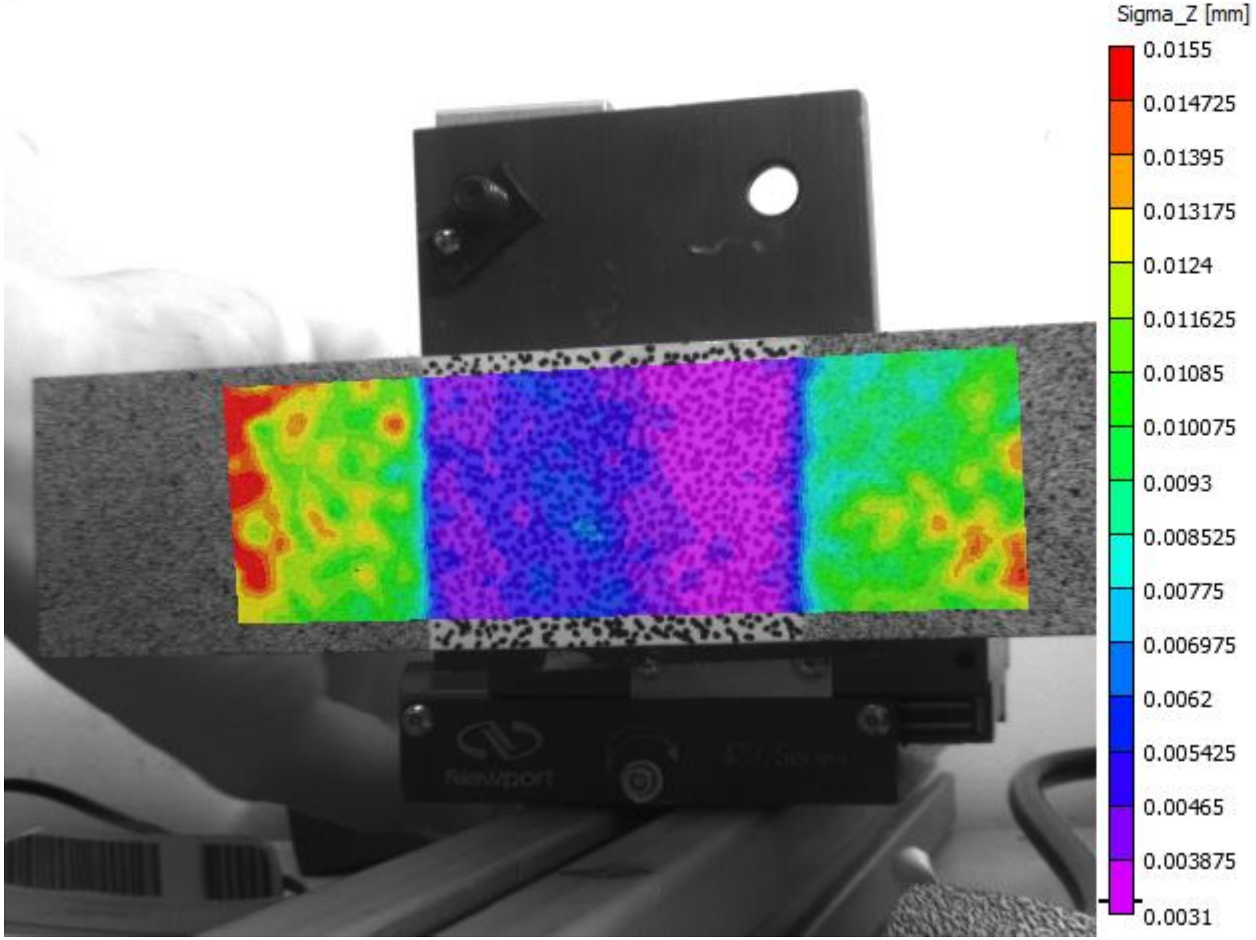
Speckle Pattern Conclusions

- Why is this important?



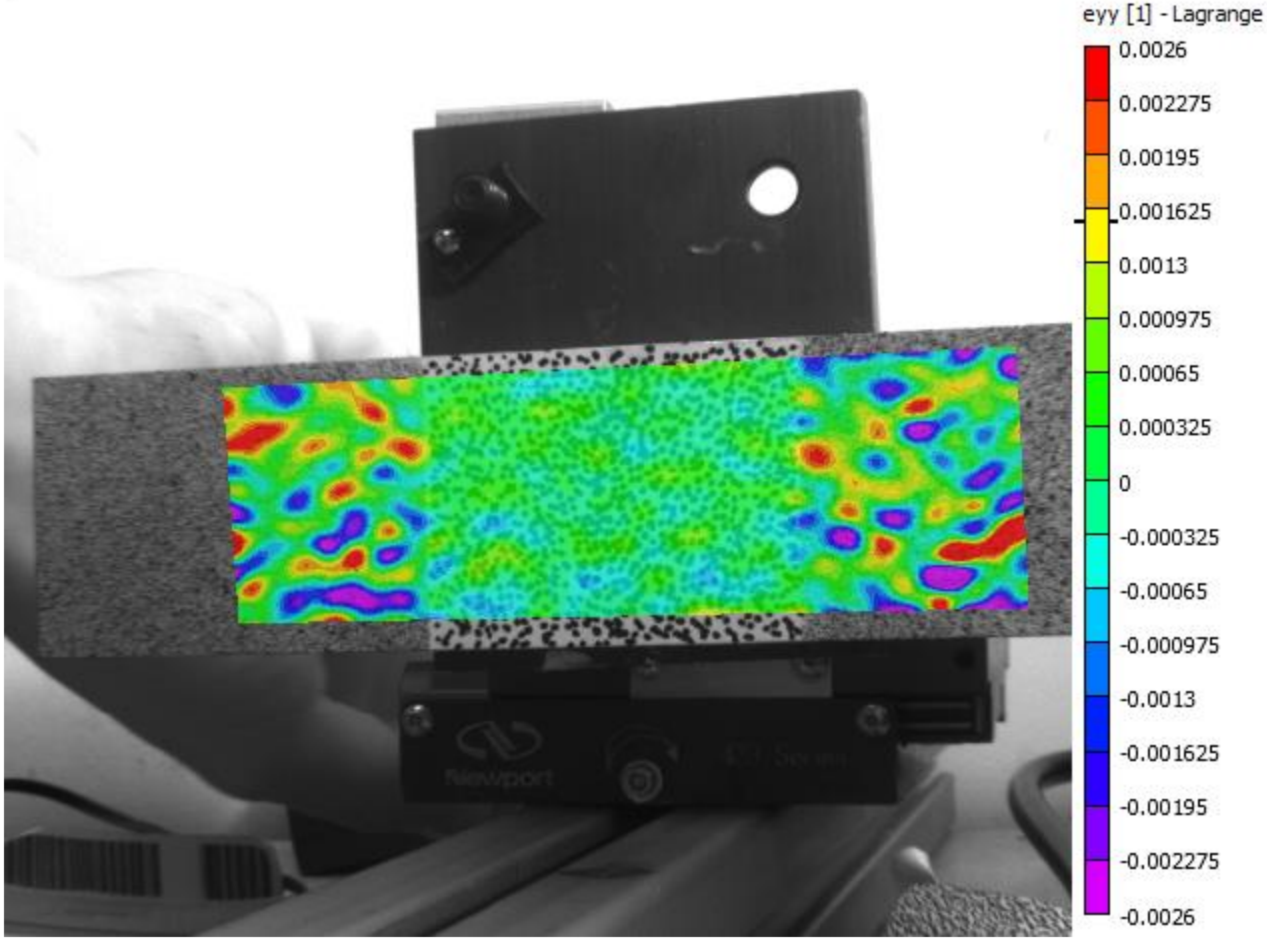
Conclusions

- Z-accuracy



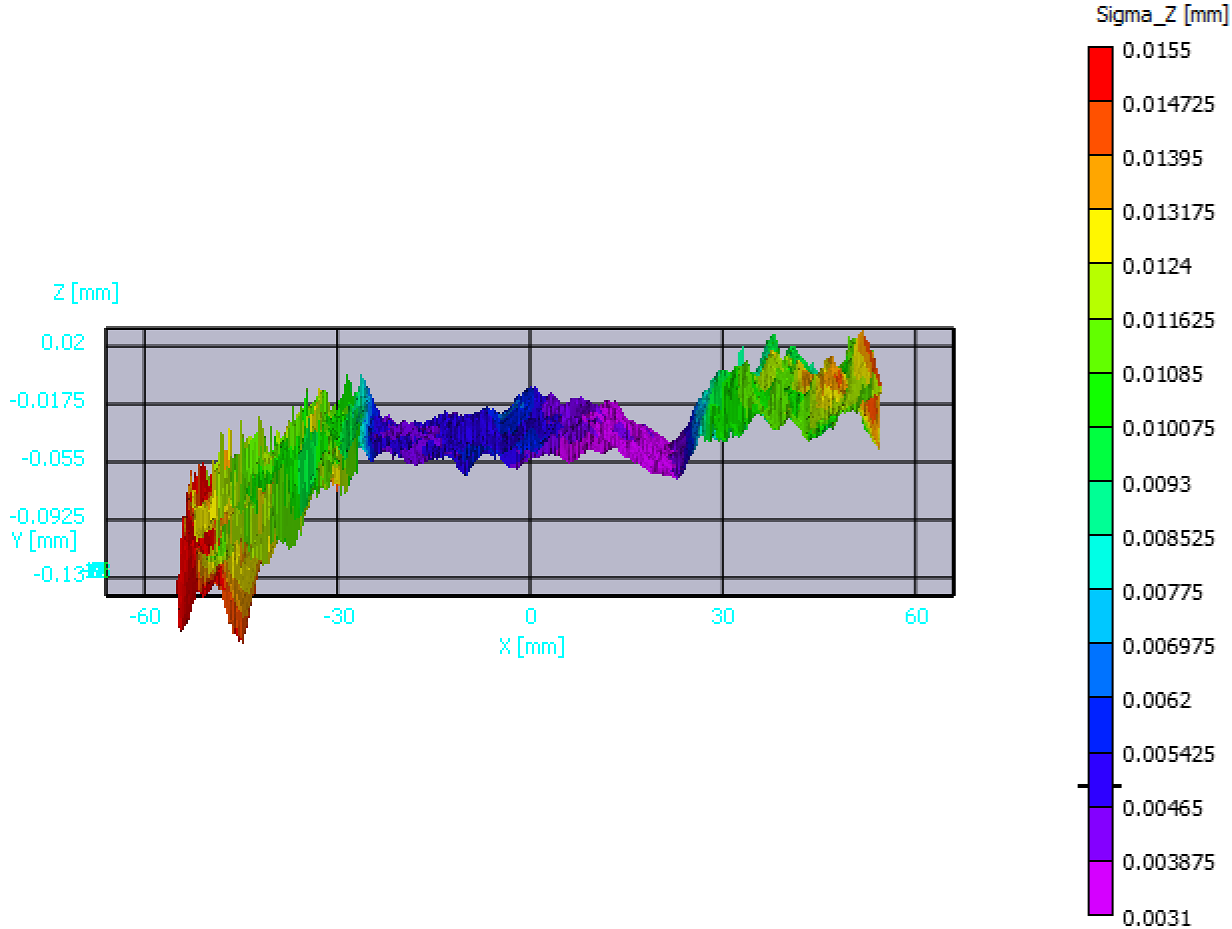
Speckle Pattern Conclusions

- False strain (300uε vs 1300uε)



Speckle Pattern Conclusions

- Shape accuracy



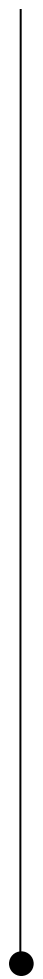
Confidence Margins in 3D

- 3D image correlation contains another important step
- We want to minimize our Sigma_X/Y/Z
  - This will minimize our strain noise
  - Two components
    - Low pixel sigma
    - Proper test setup

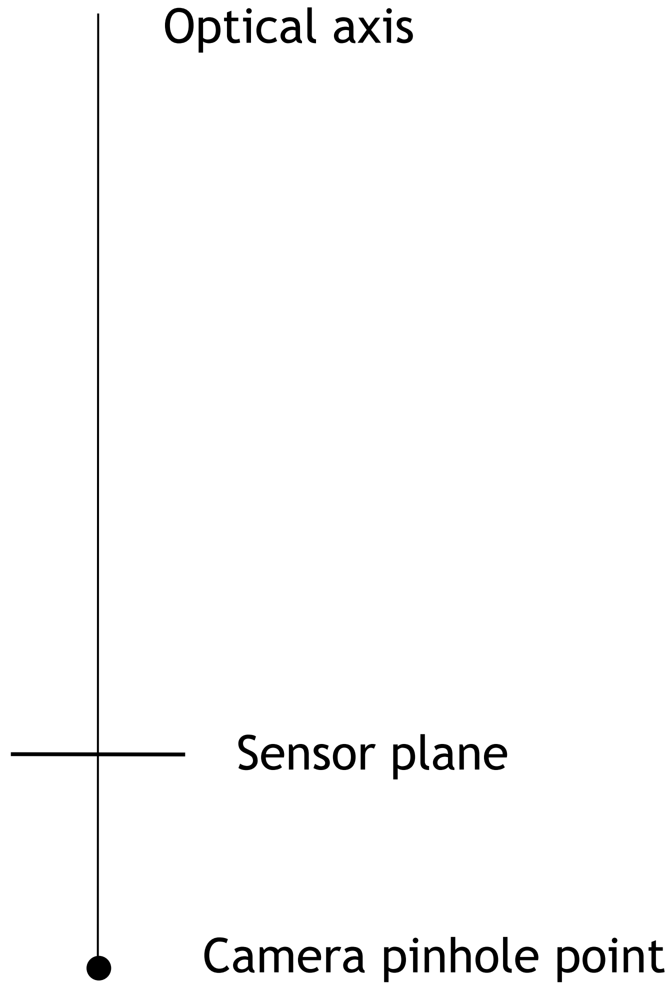
Confidence Margins in 3D

• Camera pinhole point

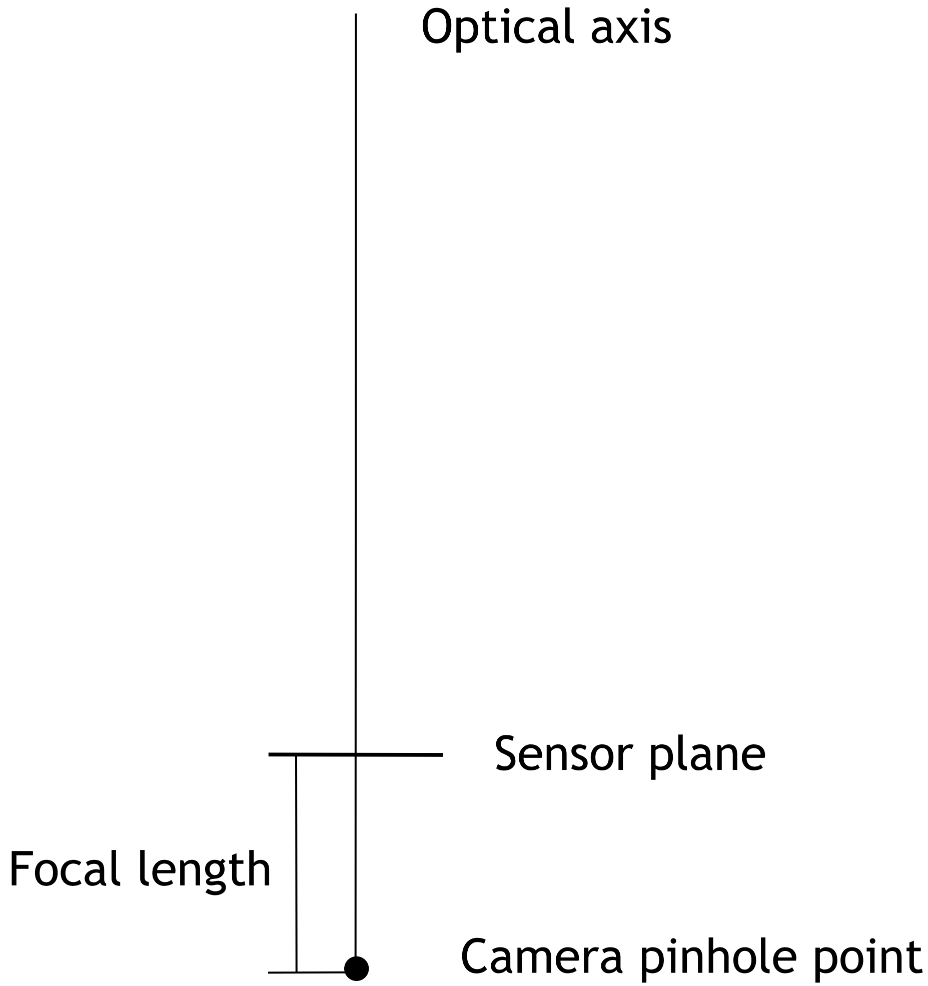
Confidence Margins in 3D



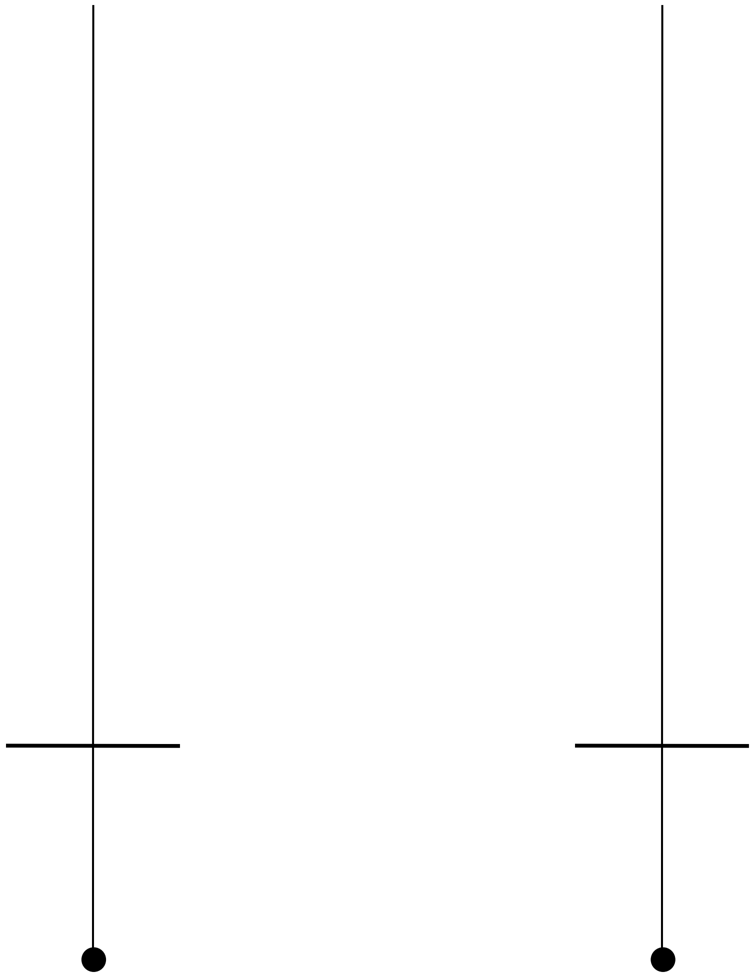
Confidence Margins in 3D



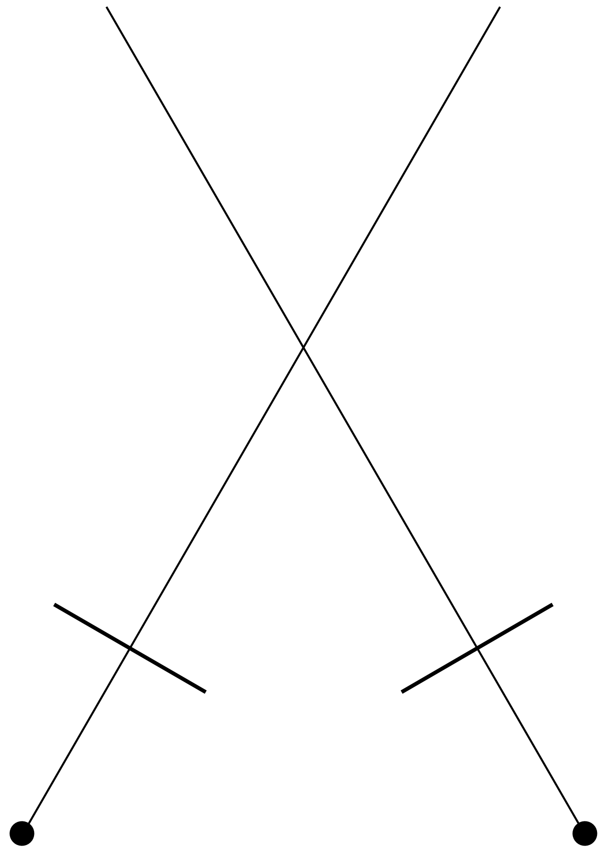
Confidence Margins in 3D



Confidence Margins in 3D



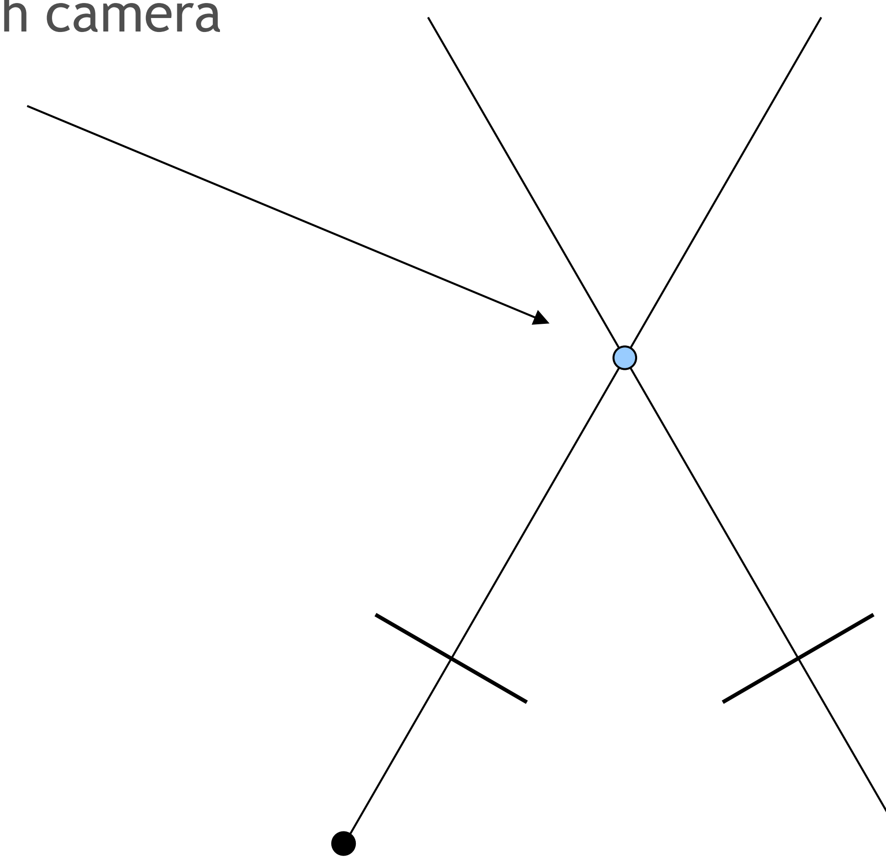
Confidence Margins in 3D



Stereo system

Confidence Margins in 3D

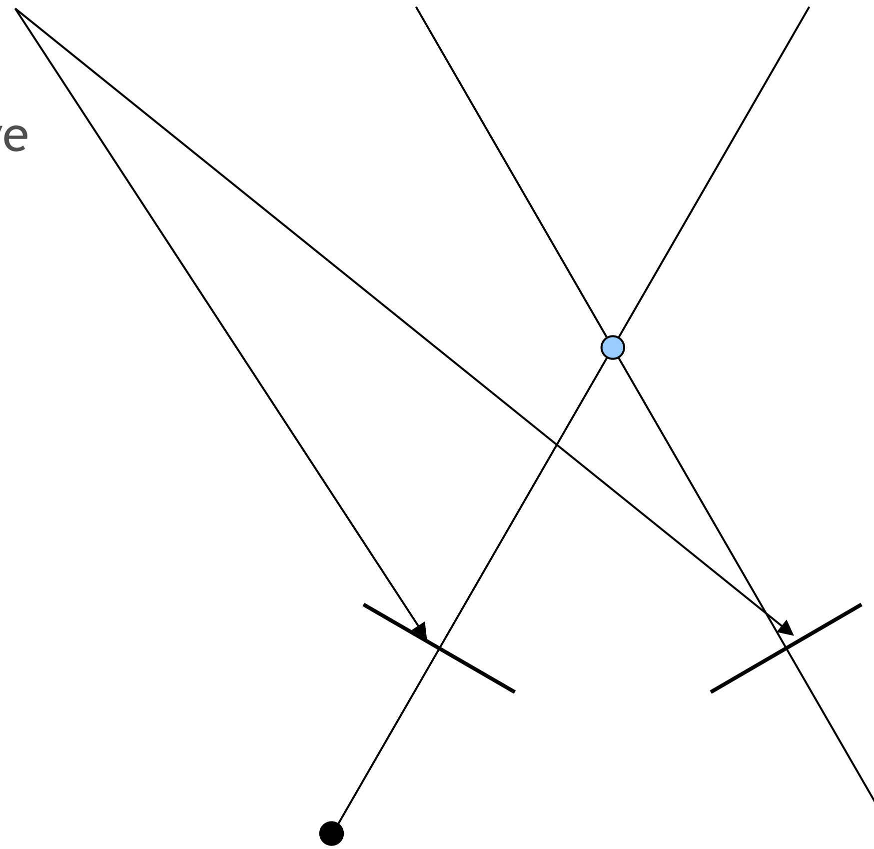
Triangulate point located on
optical axis of each camera



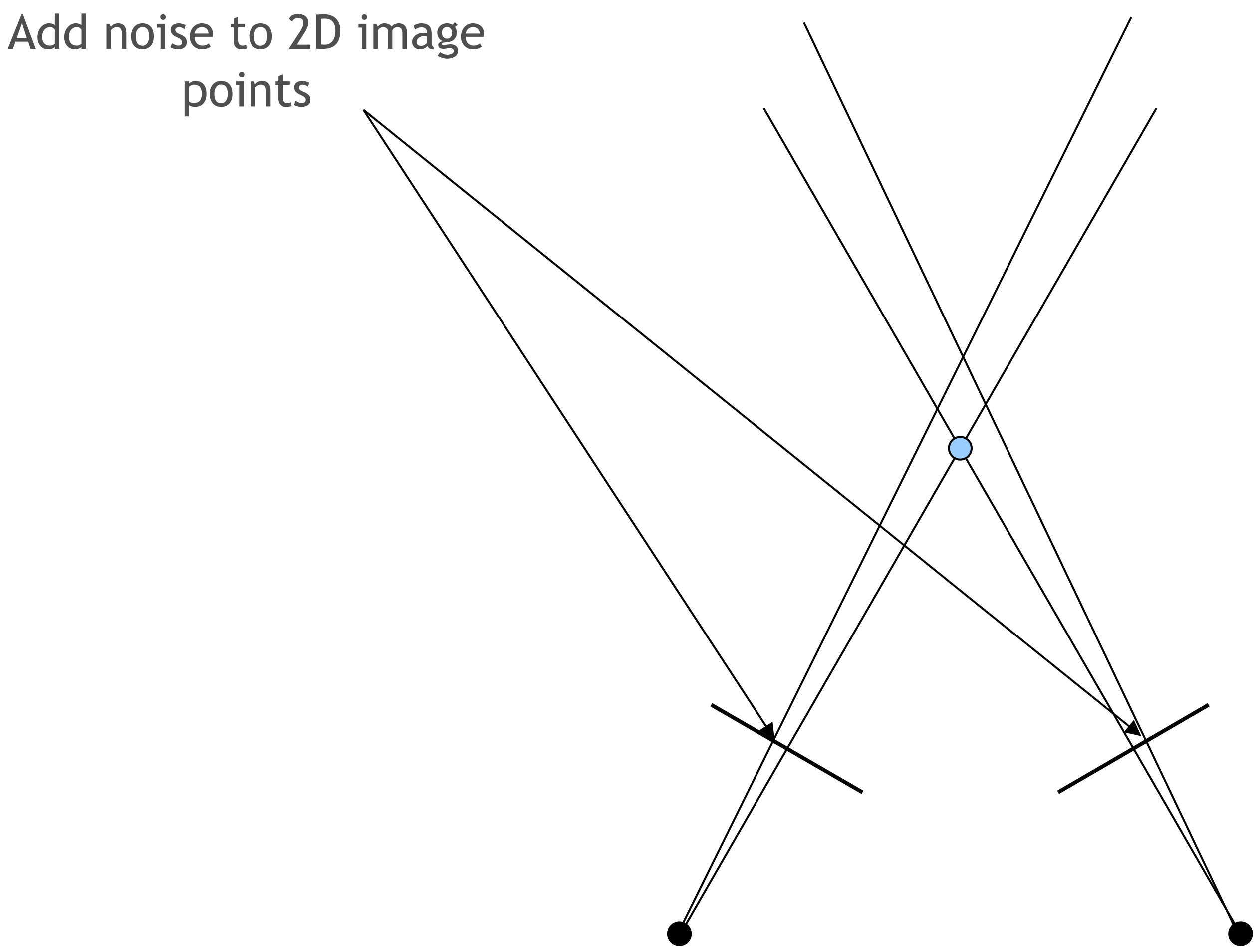
Confidence Margins in 3D

Add noise to 2D image points:

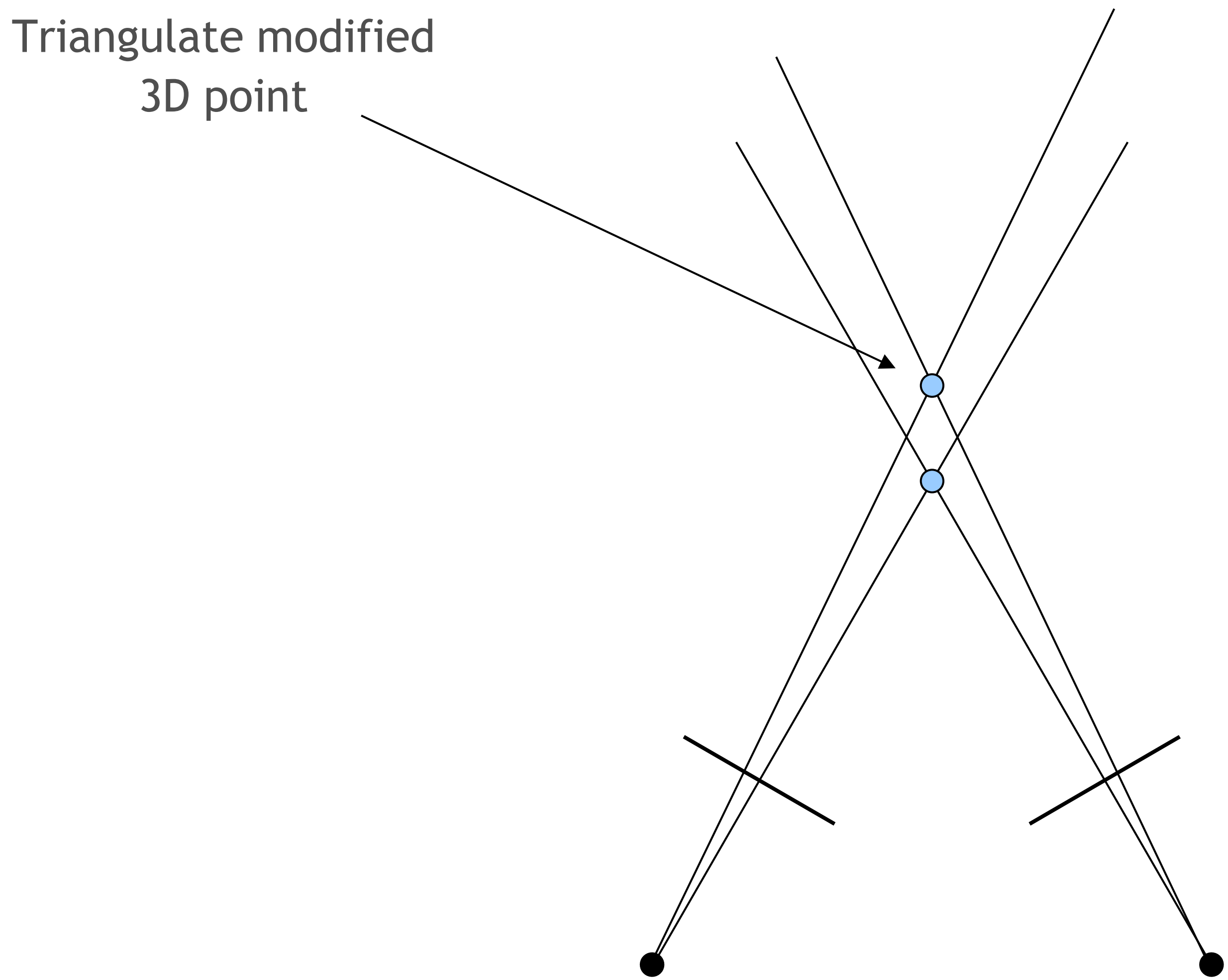
This is the noise we have discussed so far in this presentation



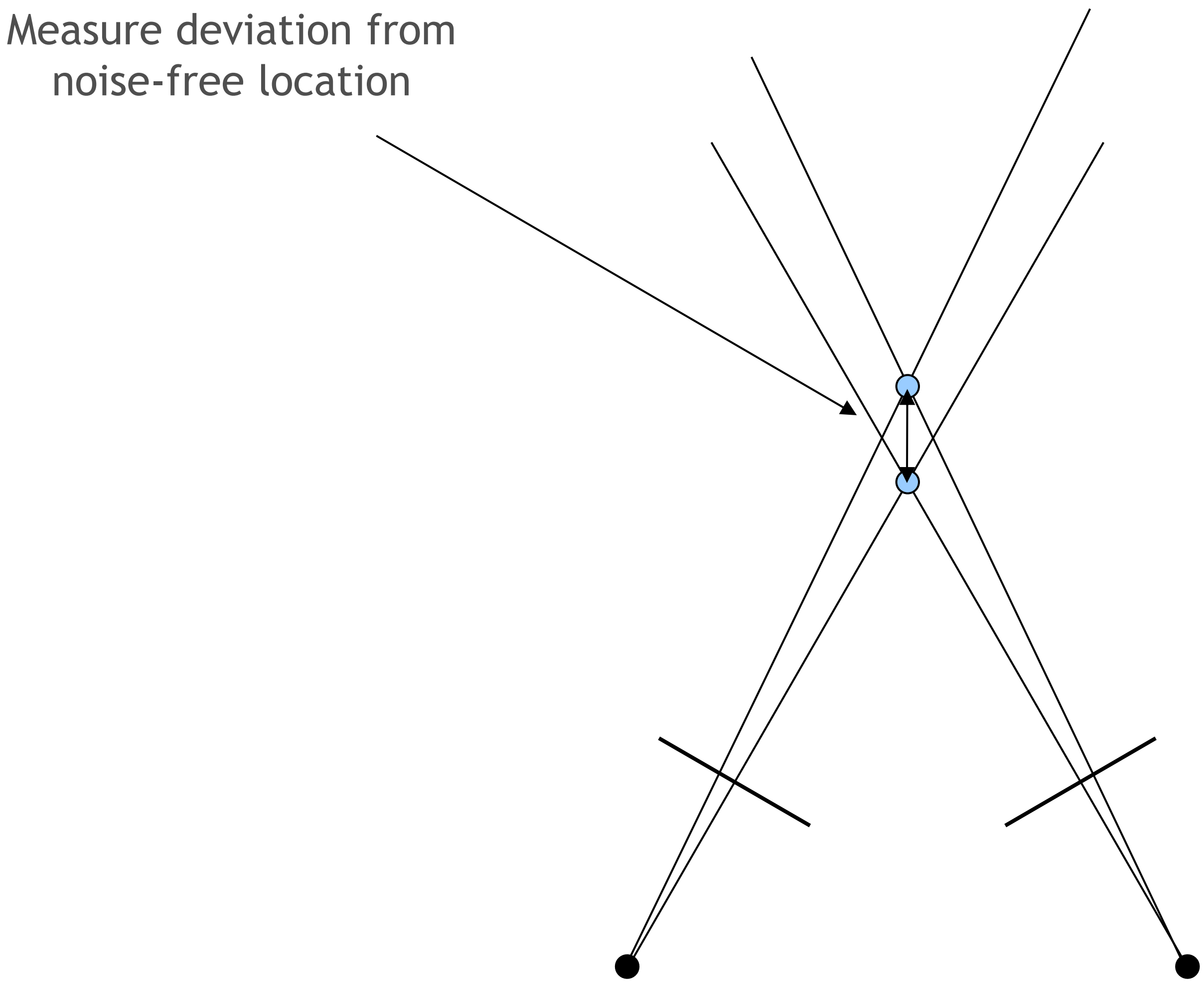
Confidence Margins in 3D



Confidence Margins in 3D

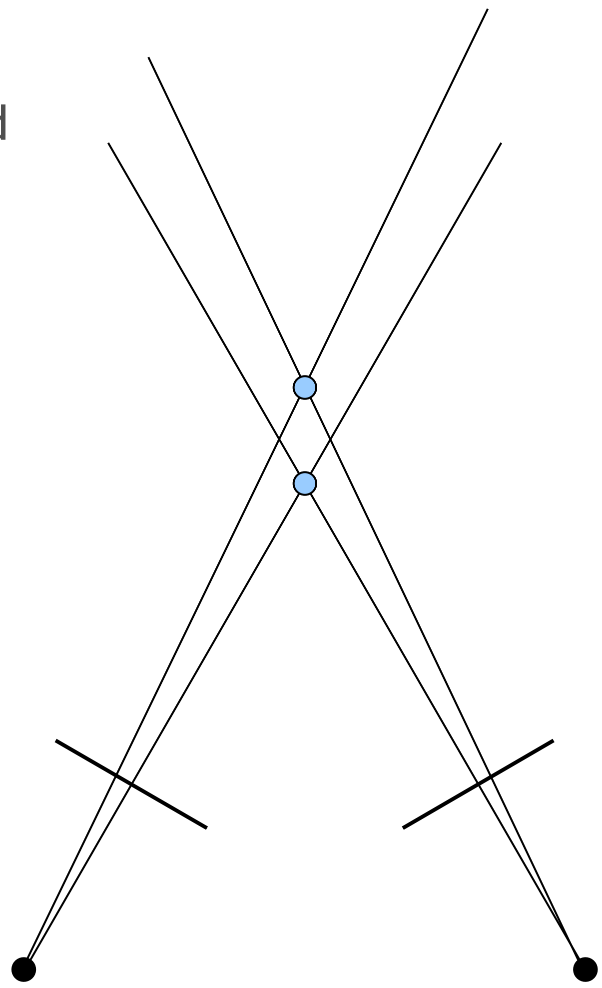


Confidence Margins in 3D



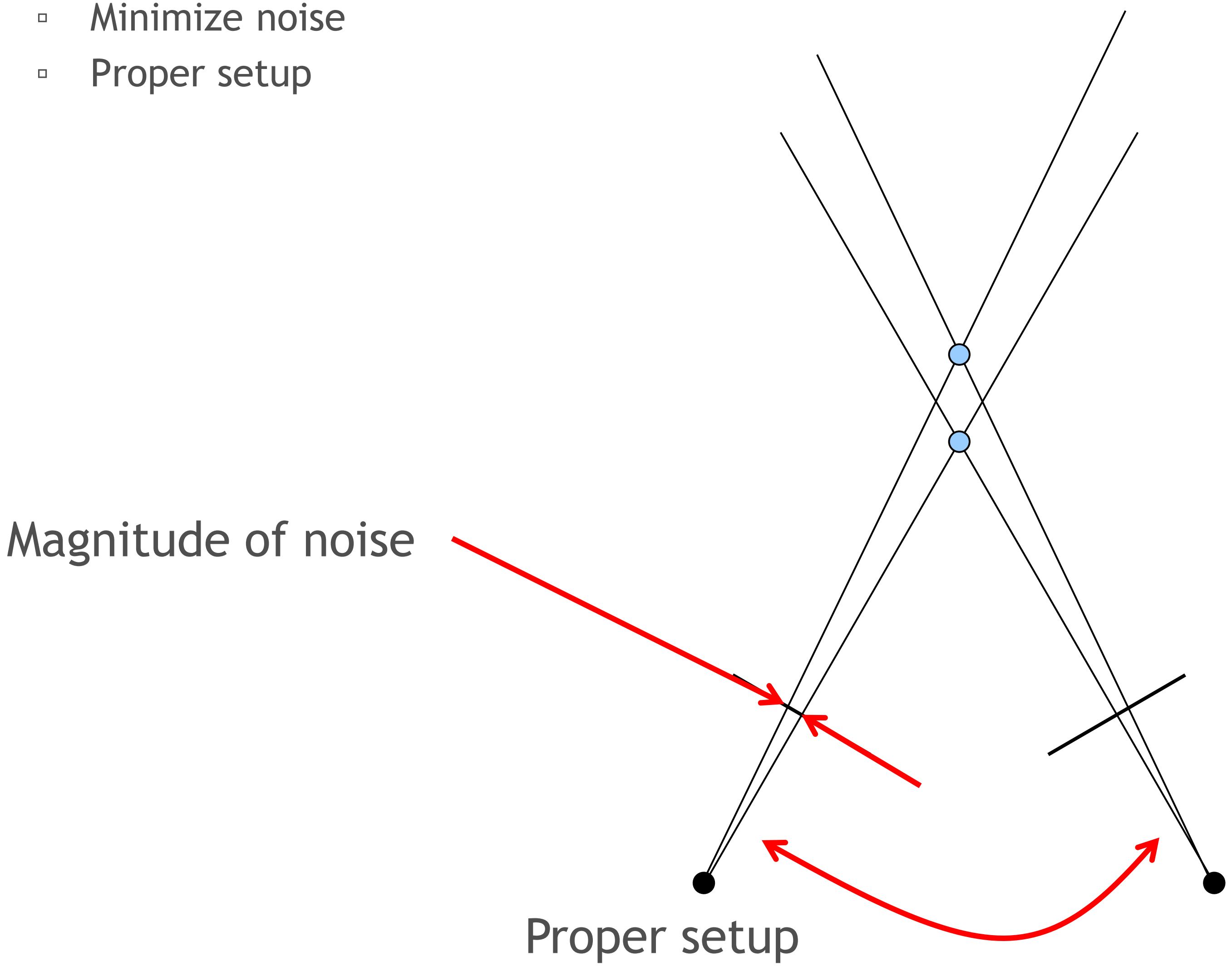
Confidence Margins in 3D

- By taking the set of all possible points, we generate a 3D volume in space.
- The volume has a height (Sigma_Y), a width (Sigma_X), and a depth (Sigma_Z)

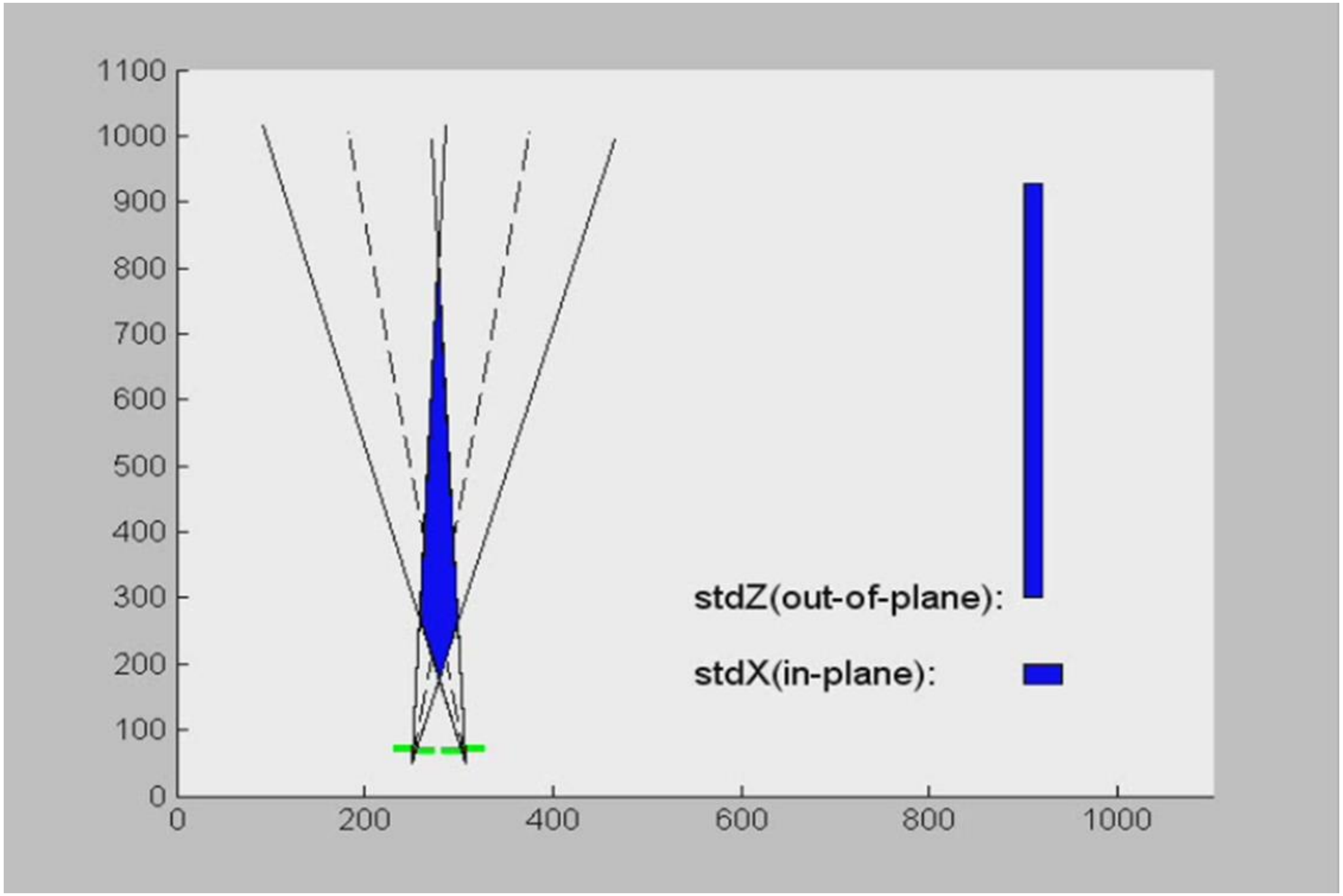


Confidence Margins in 3D

- How to minimize the error volume?
  - Minimize noise
  - Proper setup

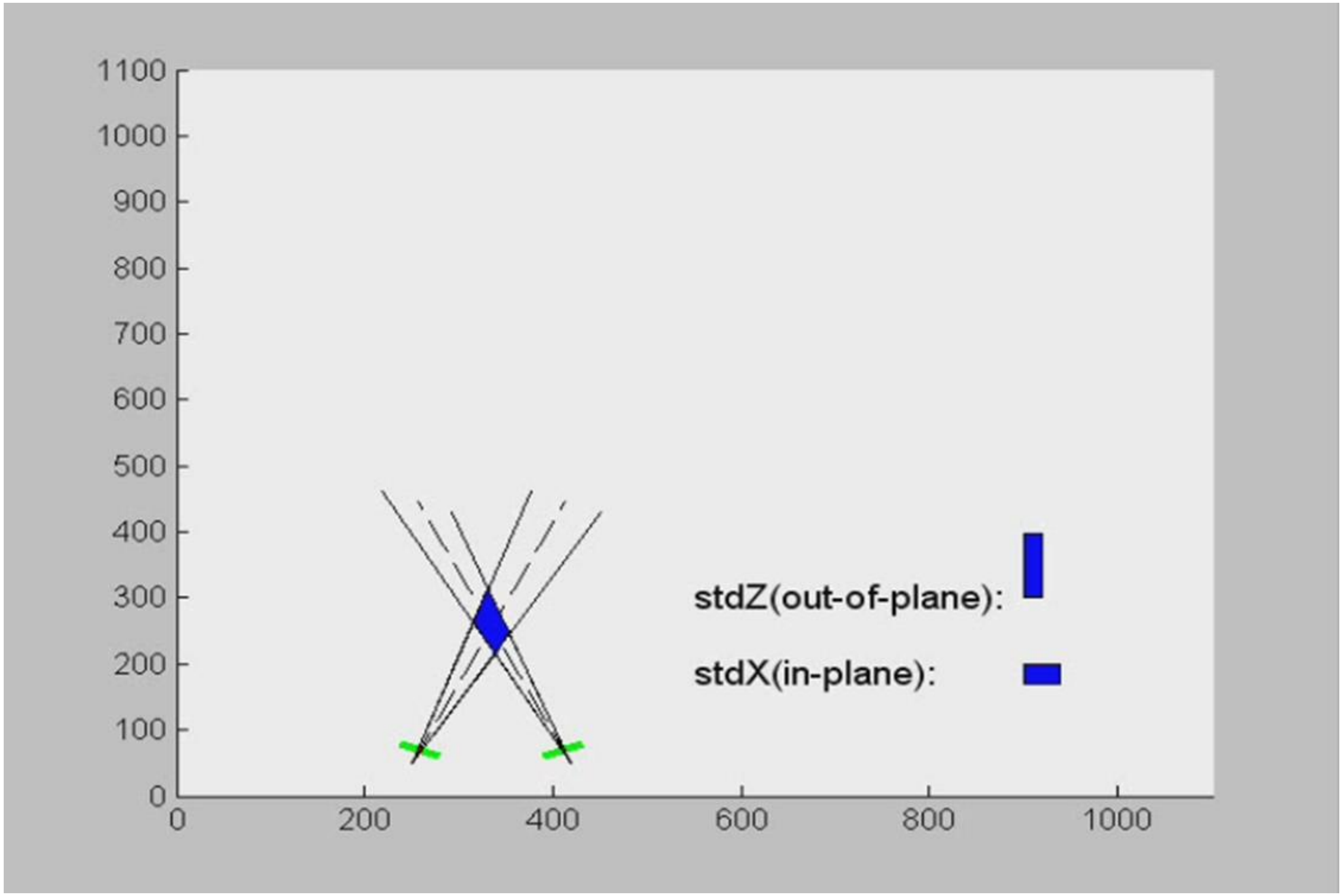


Effects of setup



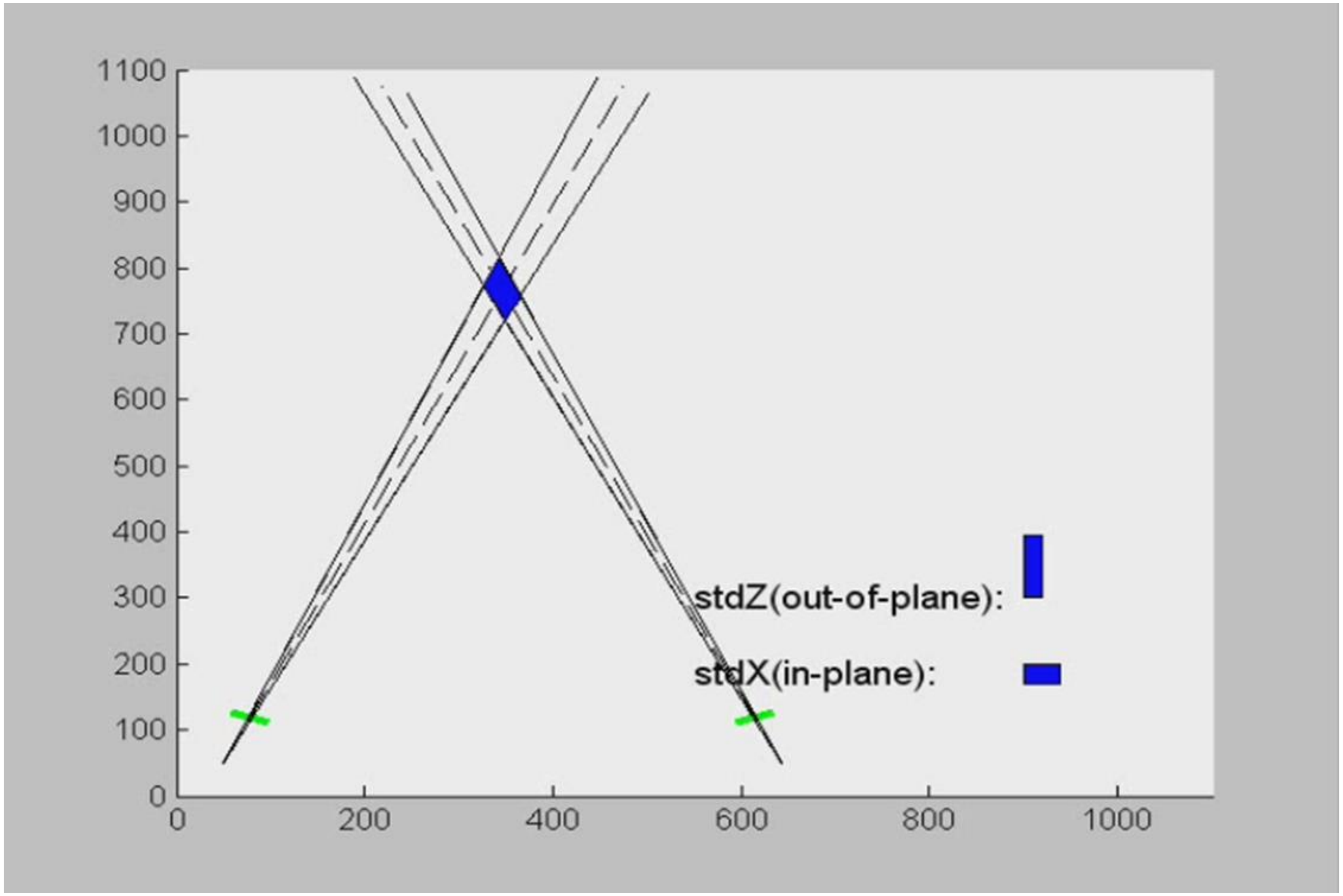
Short focal length; small angle

Effects of setup



Short focal length; large angle

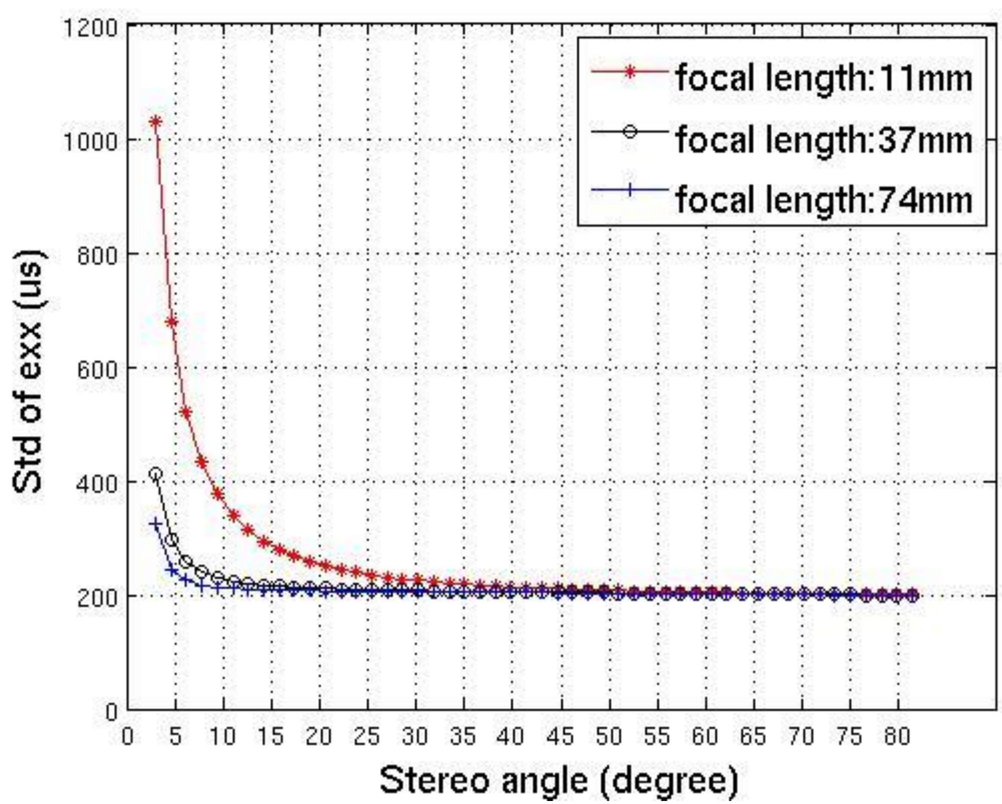
Effects of setup



Long focal length; large angle

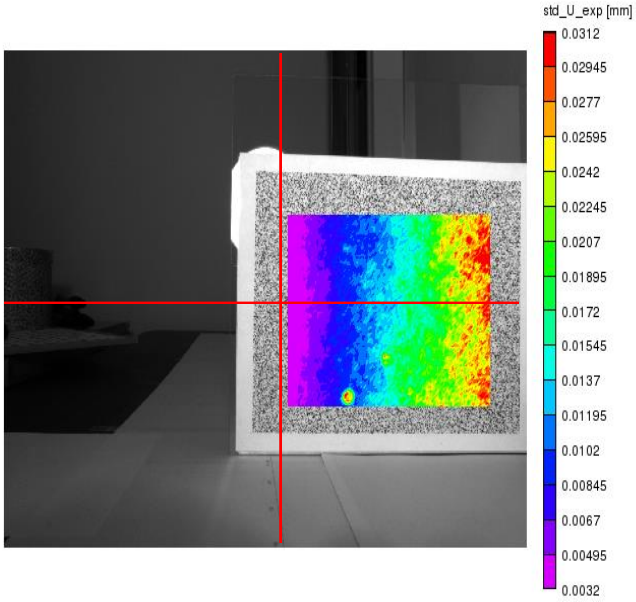
Minimizing Bias & Noise

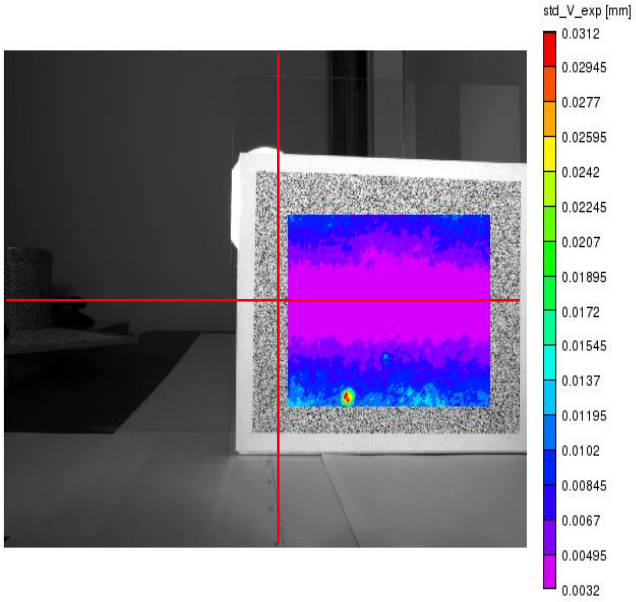
- Noise in displacement and strain is strongly dependent on stereo angle



Minimizing Bias & Noise

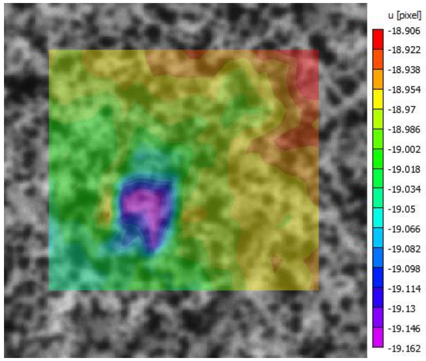
- Noise is lowest near the optical axis



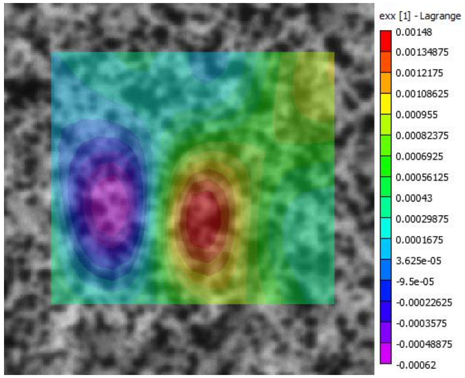


Bias Due to Contaminations

- Contamination can cause severe biases in displacement (u shown):



- This bias will have a strong effect on calculated strains (exx shown):



Bias Due to Contaminations

- Contaminations (e.g., dust on sensor) cause large localized bias in displacement estimates
- Typically, a large erroneous strain concentration results
- Not possible to mitigate through processing techniques
- Always check before taking measurements

Bias Due to Poor Calibration

- A low calibration score is indicative of a good calibration IF we have enough information in the calibration images
  - Large grid that fills up entire image
  - Very large grid tilts (tilt it until it starts to go out of focus)
  - 15-25 calibration image sets
- If using short focal length lenses (8mm, 12mm), you might need to change the distortion order to 2 or 3 in the distortion window.
- In high magnification applications, you might need to select “High Mag” in the calibration window.

Bias Due to Poor Calibration

- Distortion order for short lenses
  - Calibrate at distortion order 1. Look at your kappa 1 (a lens distortion parameter) in your calibration results.
  - Calibrate at distortion order 2. You'll have a kappa 2 now, but if your kappa 1 is the same as what you got for a distortion order of 1, then the distortion order of 1 was OK.
  - If the kappa 1 changed, then repeat for an order of 3 and see if kappa 2 changed.
  - Once you figure out the distortion order, you can use that that order anytime you use that camera-lens combination

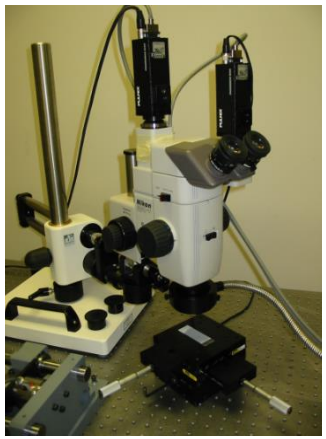
Bias Due to Poor Calibration

- High Magnification
  - For high magnification instances you might see very large calibration errors.
  - This is because the limited depth of field doesn't allow us to tilt the grid enough in order to extract the camera sensor positions.
  - Check your center x, center y for each camera in your calibration results
  - The centers should be ROUGHLY the centers of the sensors (i.e. for 5MP cameras that are 2448x2048 pixels, you should see centers of 1224,1024)
  - If centers are WAY off (by more than 50%; maybe even negative), select "high mag"
  - This will force the centers to the center of the sensor (1224x1024 in this case).
  - Only use the high mag option when completely necessary because it forces the software to make some assumptions that we'd rather extract from the calibration image.
  - "High mag" is not an option for the stereo microscope module; we use a different calibration method (see next slides)

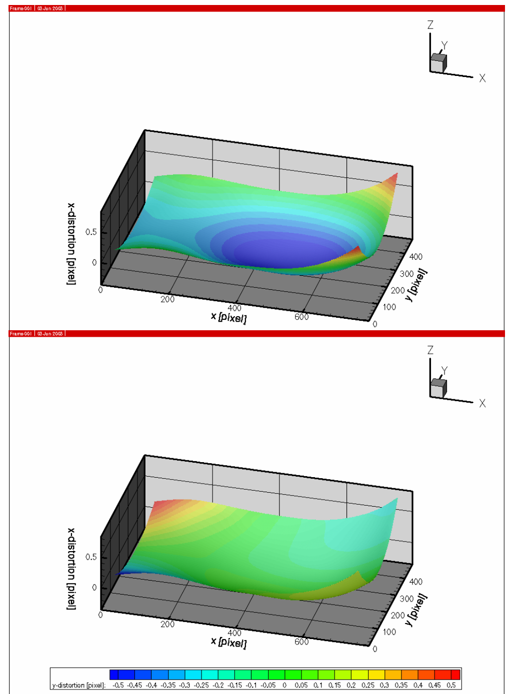
Stereo Microscope

- For simple lenses the calibration error is typically not a concern when using proper calibration techniques
- For complex optics, such as the stereo microscope, parametric distortion models are typically not sufficient and severe bias results
- For accurate measurements using stereo microscopes (or SEMs), a non-parametric distortion calibration technique is required
- DIC can be used to calibrate such distortions using a simple motion constraint scheme

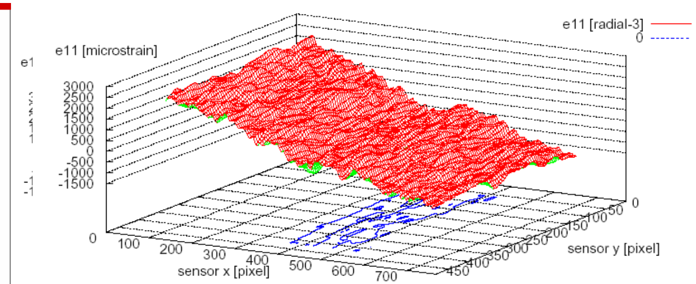
Stereo Microscope



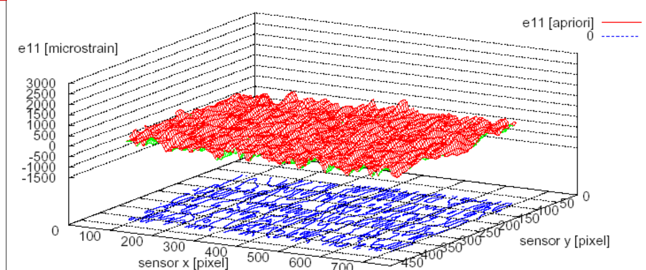
Setup: optical stereo-microscope



True X and Y-distortion fields (computed by inverse mapping)



No distortion correction

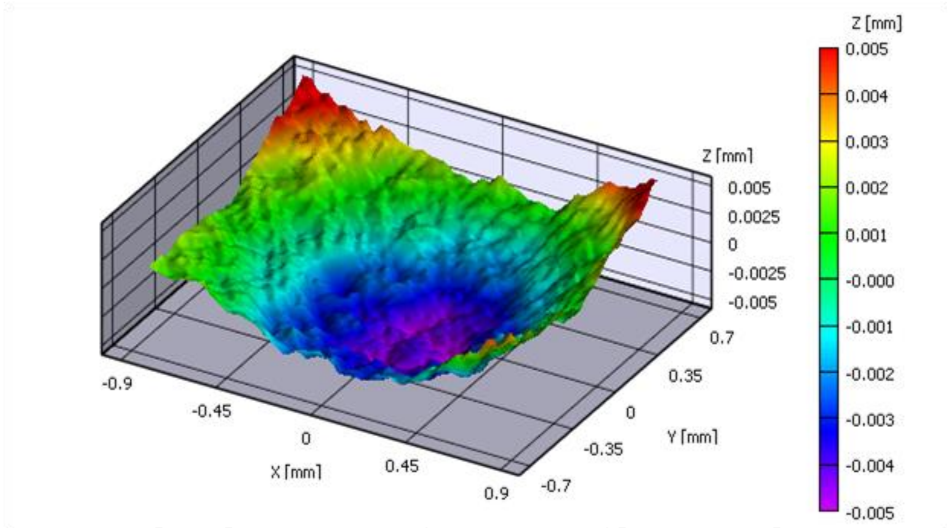


Distortion corrected

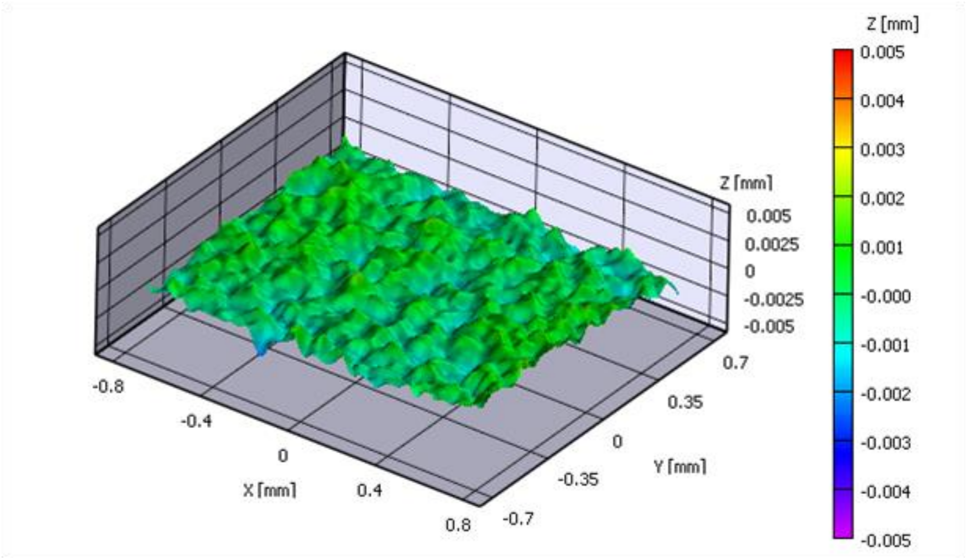
Measured principal strain (rigid-body motion)

Stereo Microscope

- Uncorrected shape for a flat plate

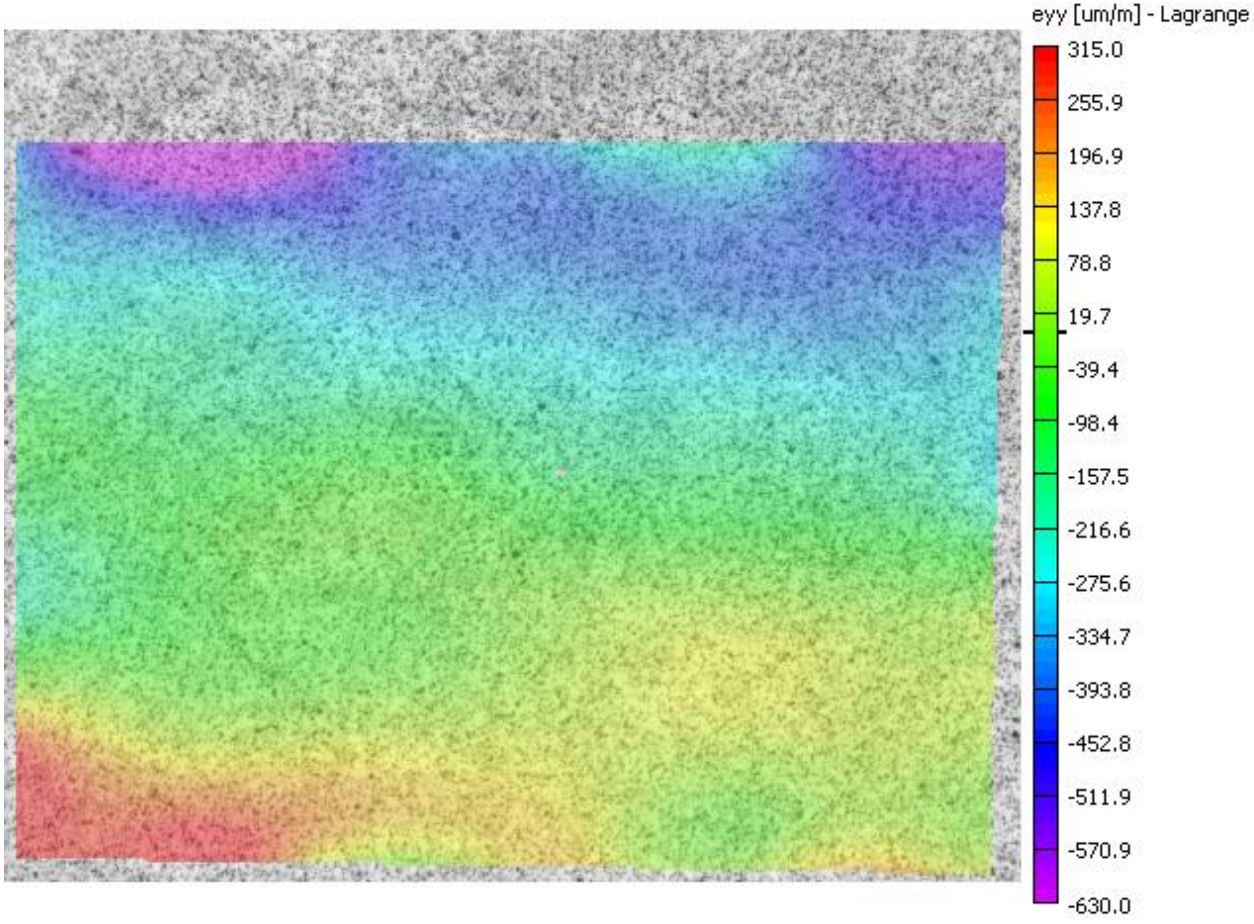


- Corrected shape for a flat plate



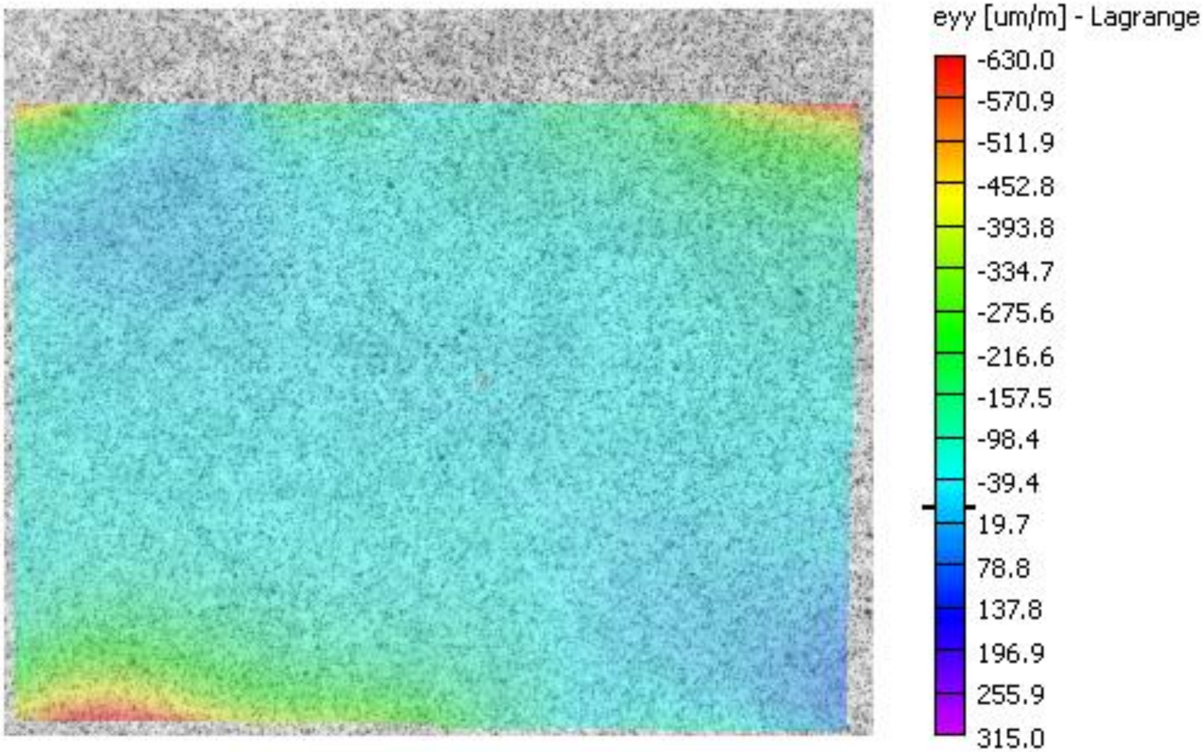
Stereo Microscope

- Uncorrected strain for rigid motion



Bias Elimination

- Corrected strain for rigid motion



Conclusions

- With proper set-up, we can eliminate bias and minimize noise.
- Front-end reductions
  - Proper test setup (focal length, stereo angle, clean lens/sensor, good lighting, correct F-stop, well focused, no blur, no glare)
  - Good speckle pattern (consistent speckle pattern, 50% coverage, good contrast, sharp speckle edges)
  - Good calibration (good tilt in calibration images, select high magnification or distortion order if necessary)
- Back-end reductions
  - Correct subset sizes
  - Low-pass filtering, if necessary
  - Distortion correction for stereo microscope applications