Knowing the unknowns : Quantifying uncertainties in DIC using synthetic images

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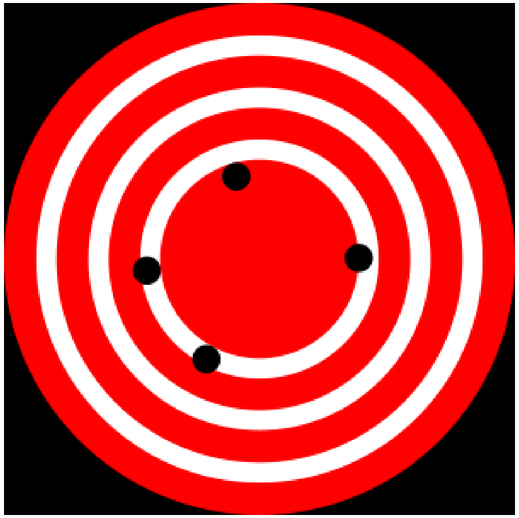
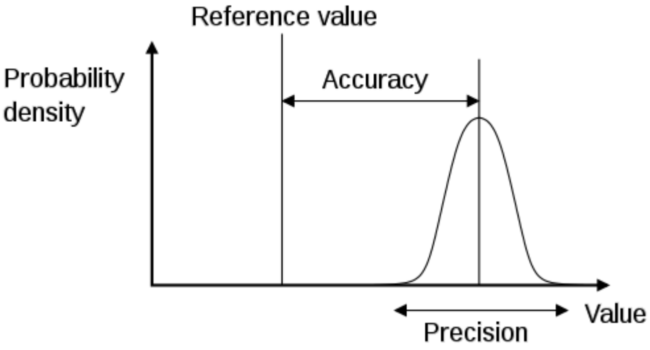
Uncertainty Quantification in Digital Image Correlation
The National Physical Laboratory, Hampton Rd, Teddington, TW11 0LW, UK. *22nd February 2017*

Two types of errors: Random and Systematic

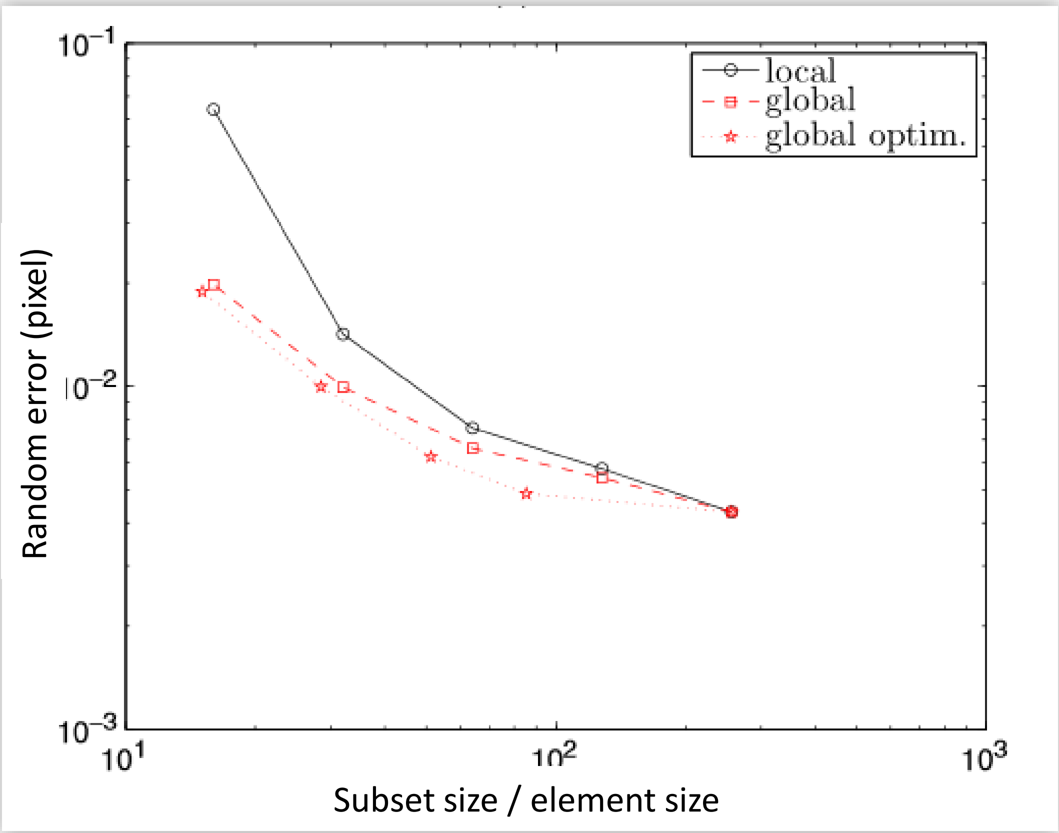


Small *Systematic* Error
Large *Random* Error

Small *Random* Error
Large *Systematic* Error



The random error due to camera noise

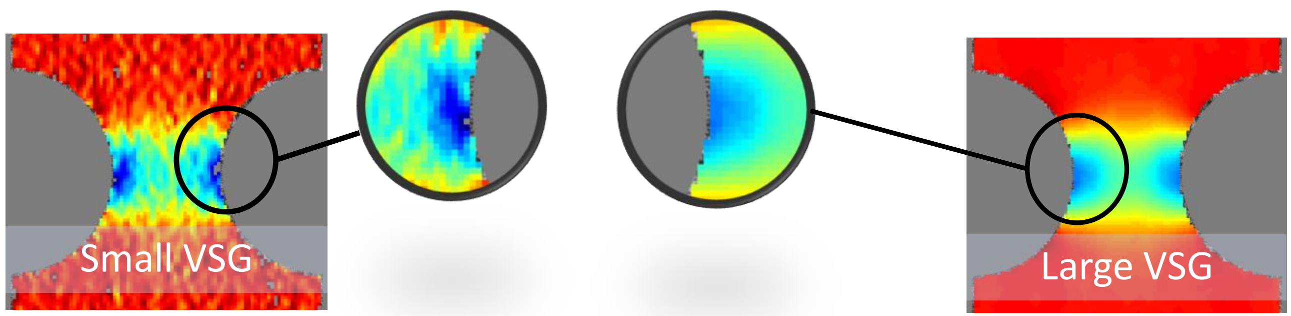


- Explored via “static” images containing no signal
- Reduces with imposed filter size
- Algorithmic noise robustness?

F Hild and S Roux. Comparison of local and global approaches to digital image correlation *Experimental Mechanics*, 52:1503–1519, 2011.

The systematic error: a much more difficult story

DIC filtering

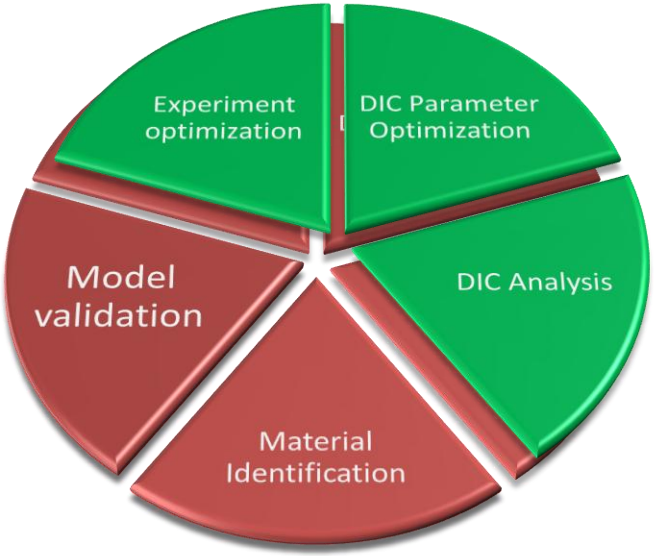


Good signal reconstruction

Small random error

What is the actual true signal? → **A benchmark is needed with known values**

Generation of ground-truth images with known signal

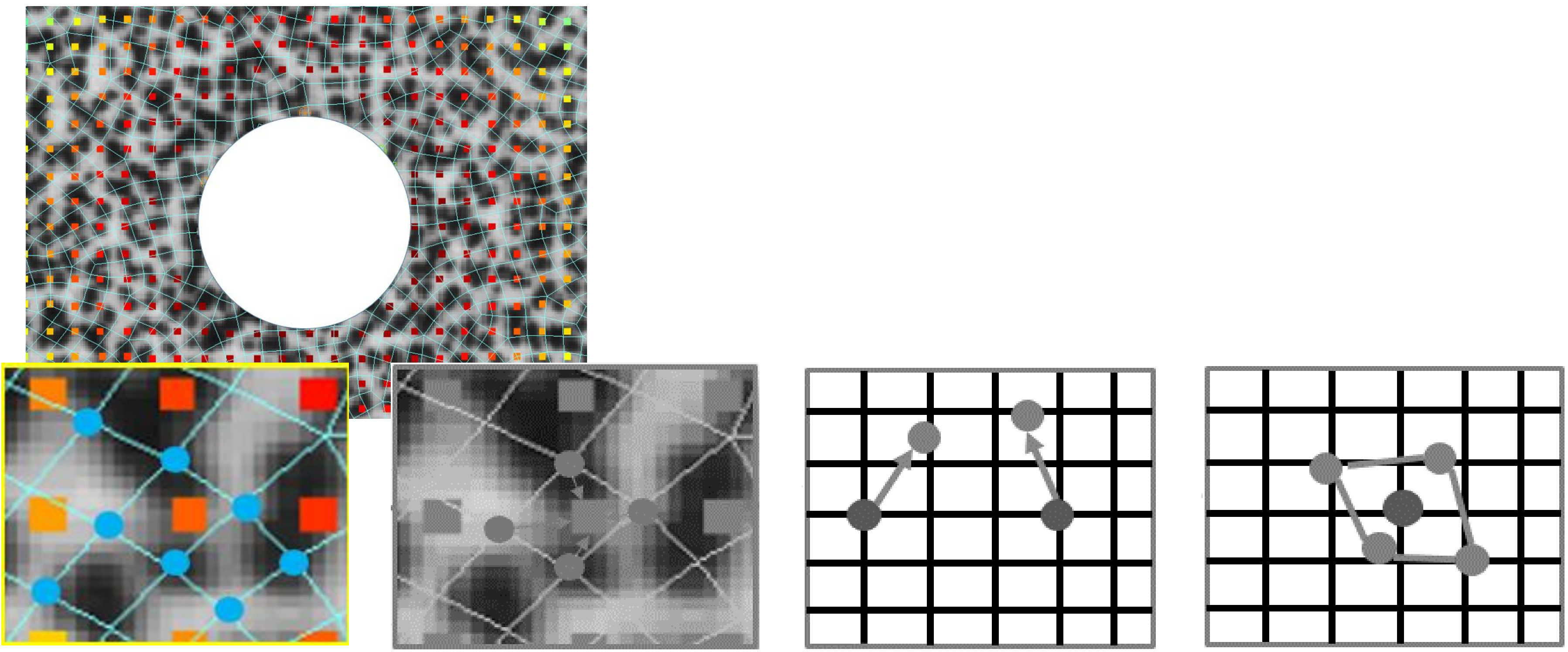


- Procedure
- Validation
- Examples
  - Sinusoidal field
  - Actual FEA field

Synthetic images: a brief history

[1] Bornert et al., Exp Mech 49(3):353-370, 2009.
[2] Lava et al., Opt Las Eng 47(7-8):747-753, 2009.
[3] Rossi et al., IJSS 49(3-4): 420-453,2012.
[4] Garcia et al., Photomechanics 2013.
[5] Wang et al., Strain 48(6): 453-462, 2012.
[6] Wittevrongel L., PhD thesis, KU Leuven.
[7] Sutton, Orteu, Schreier, Springer 2009.
[8] Reu, Exp Mech 51: 443-452, 2011.
[9] Wang et al., Strain 45(2): 160-178, 2009.
[10] Rossi et al., Strain 51(3): 206-222 , 2015.
[11] Balcaen et al., Exp Mech 2017.
[12] …

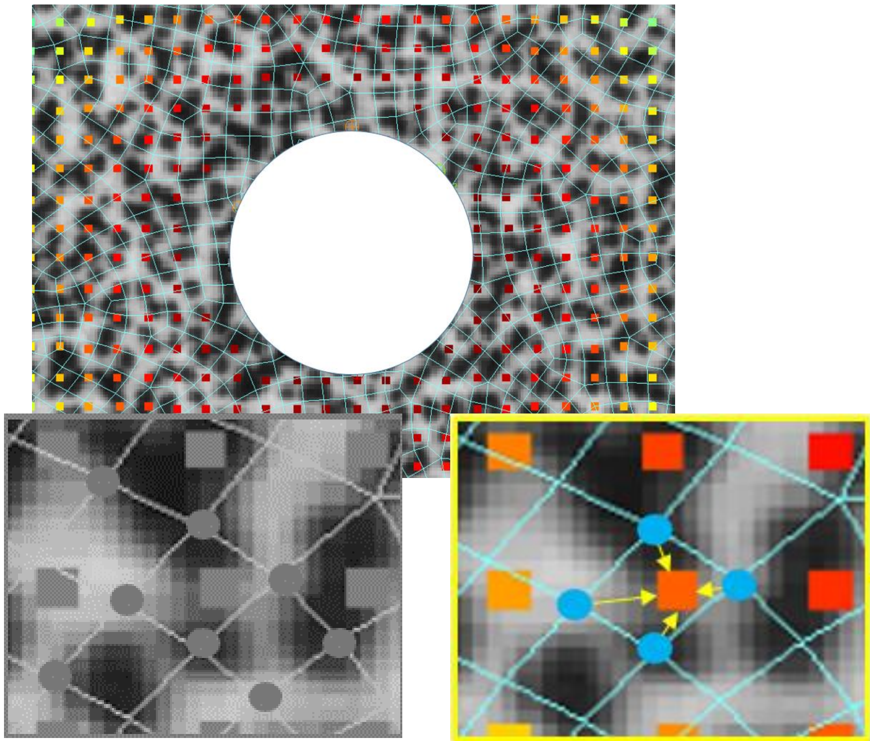
Synthetic image generation: procedure



U(x,y), V(x,y)

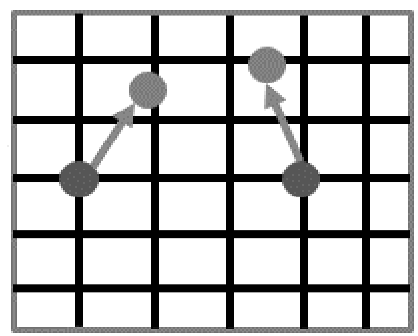
Imposed data

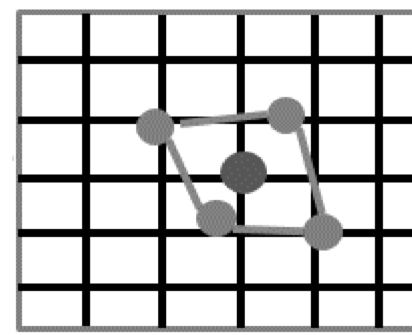
Synthetic image generation: procedure



$U(x,y)$, $V(x,y)$
Imposed data

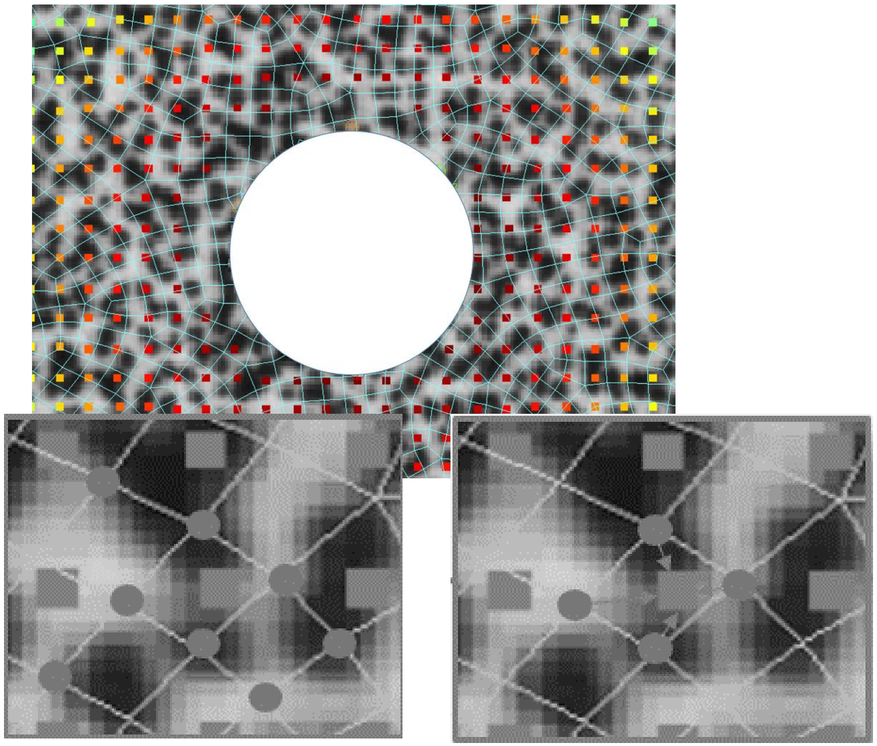
$U_p(x_0,y_0)$, $V_p(x_0,y_0)$
Data at pixel locations

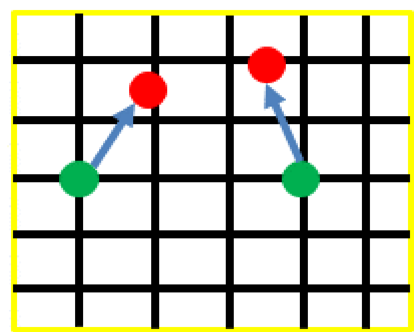


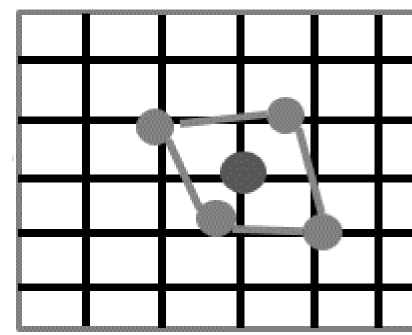


Interpolation!

Synthetic image generation: procedure







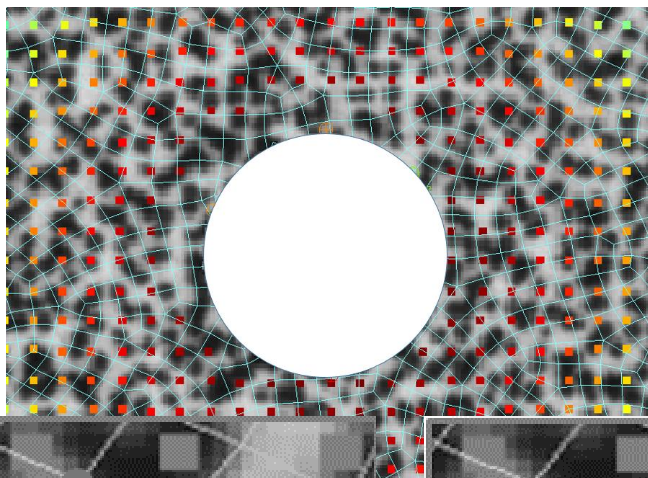
$U(x,y)$, $V(x,y)$
Imposed data

$U_p(x_0,y_0)$, $V_p(x_0,y_0)$
Data at pixel locations

$G(x_0+U_p,y_0+V_p)$
non-integer locations

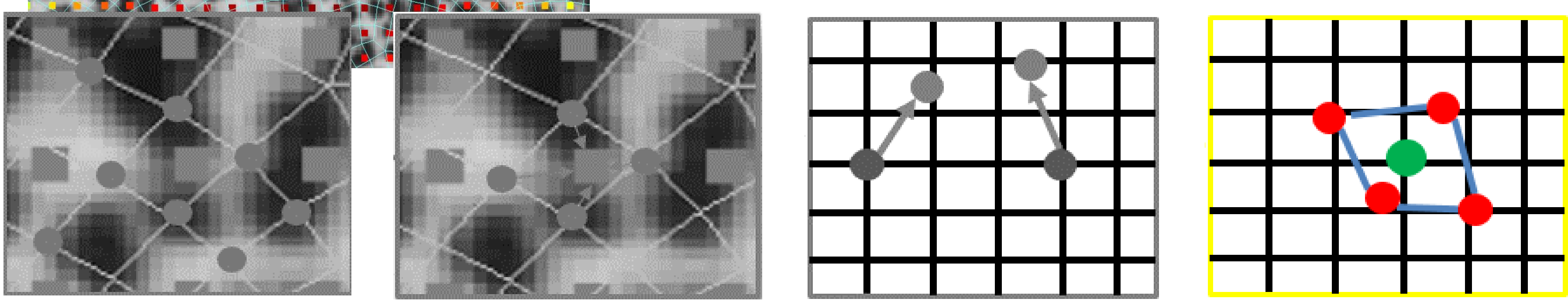
Interpolation!

Synthetic image generation: procedure



Involve multiple interpolation steps!

Bias due to these must be as minimal as possible!



$U(x,y)$, $V(x,y)$
Imposed data

$U_p(x_0,y_0)$, $V_p(x_0,y_0)$
Data at pixel locations

$G(x_0+U_p,y_0+V_p)$
non-integer locations

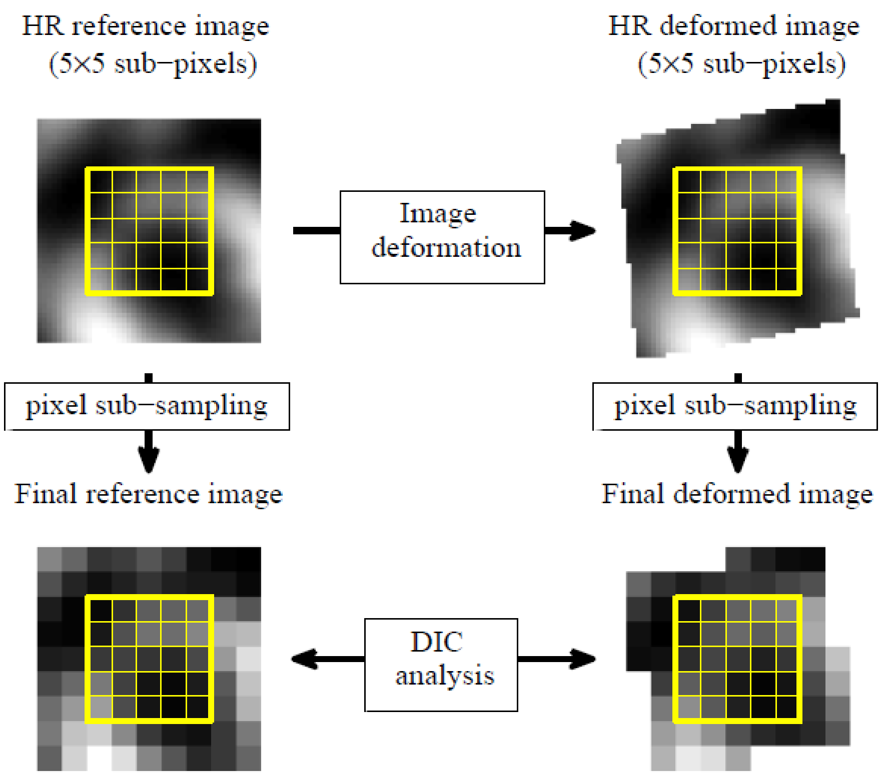
$G(x_0,y_0)$
Deformed image

Interpolation!

Interpolation!

Synthetic image generation: procedure

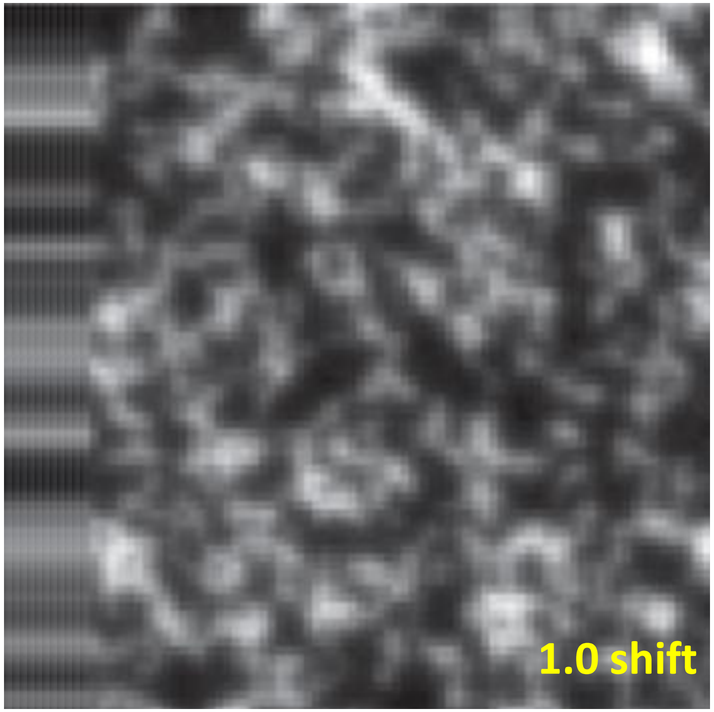
Numerical deformation bias errors should be as low as possible



Rossi M., Lava P., Pierron F., Debruyne D., Sasso M. Strain, 2015.

Synthetic image generation: validation

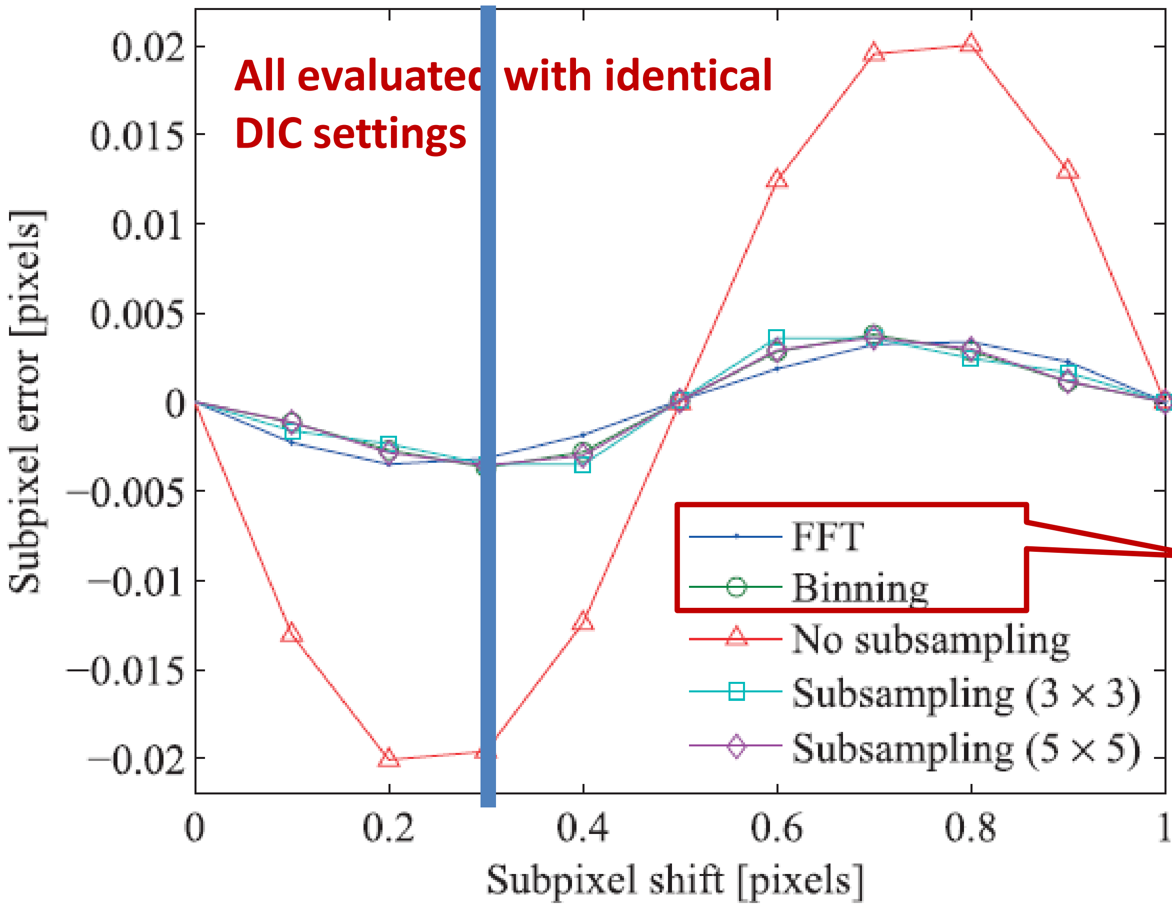
1D Translation "Experiment"



Evaluate difference between **Imposed shift** and *measured* **DIC shift**

P. Reu, *Experimental and numerical methods for exact subpixel shifting,* Experimental Mechanics 51 (2011) 443-452

Synthetic image generation: validation

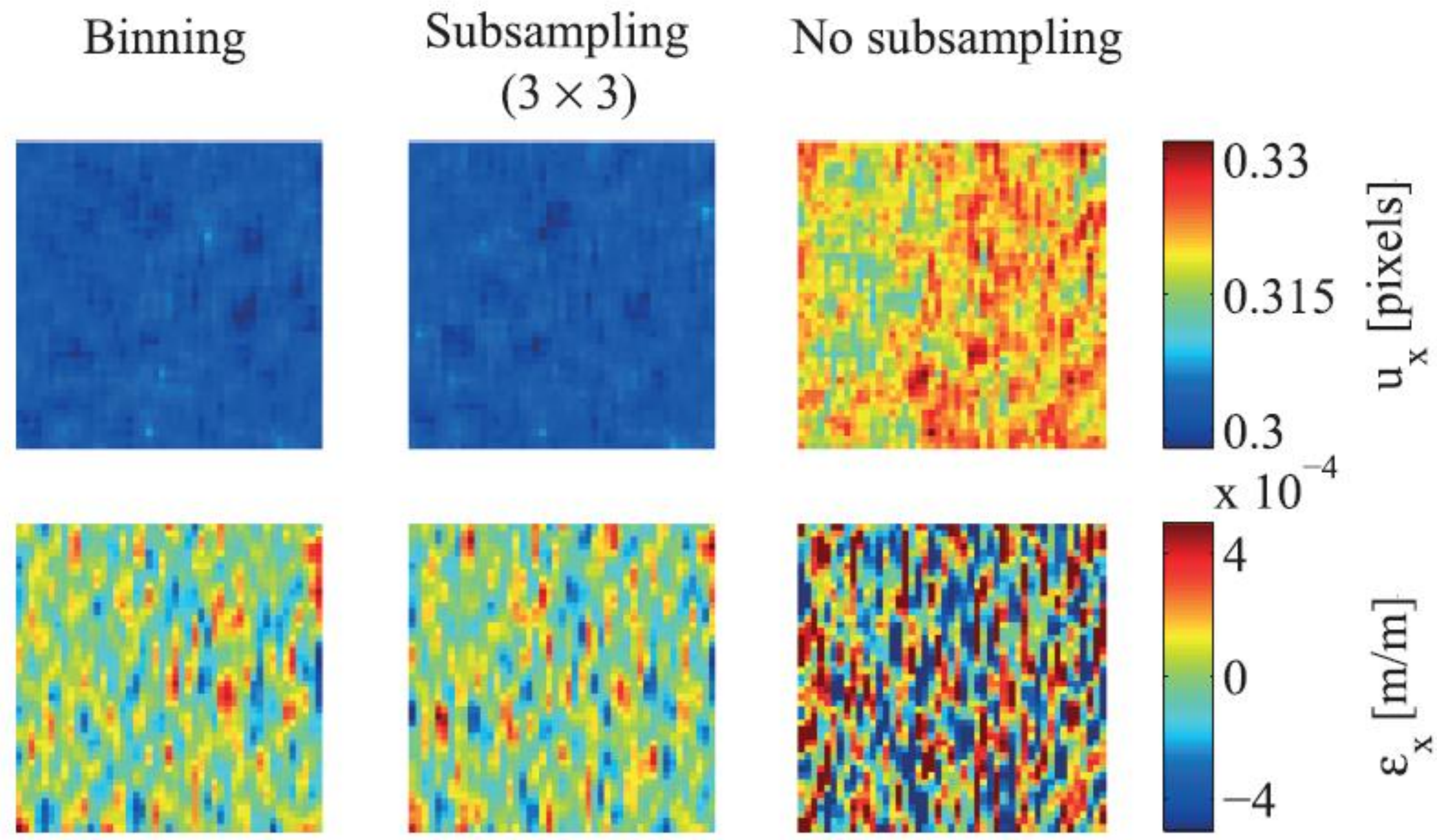


Optimal image shifting algorithms

P. Reu, *Experimental and numerical methods for exact subpixel shifting*, Experimental Mechanics 51 (2011) 443-452

Synthetic image generation: validation

Spatial distribution at 0.3 subpixel shift

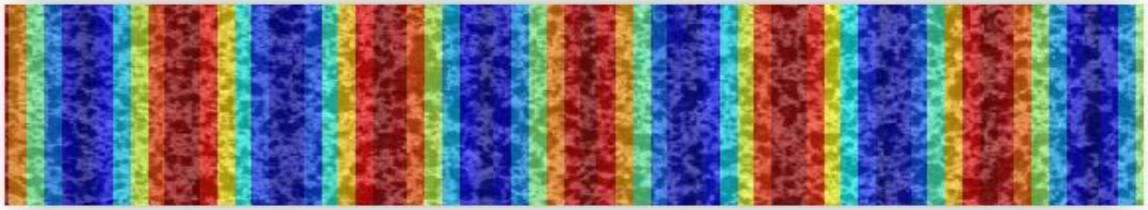


A first application: sinusoidal displacement field

- Reference image deformed using sine wave displacements of varying frequencies

$$u_x = \cos\left(\frac{2\pi n}{L}x\right) \qquad \varepsilon_{xx} = -\frac{2\pi n}{L}\sin\left(\frac{2\pi n}{L}x\right)$$

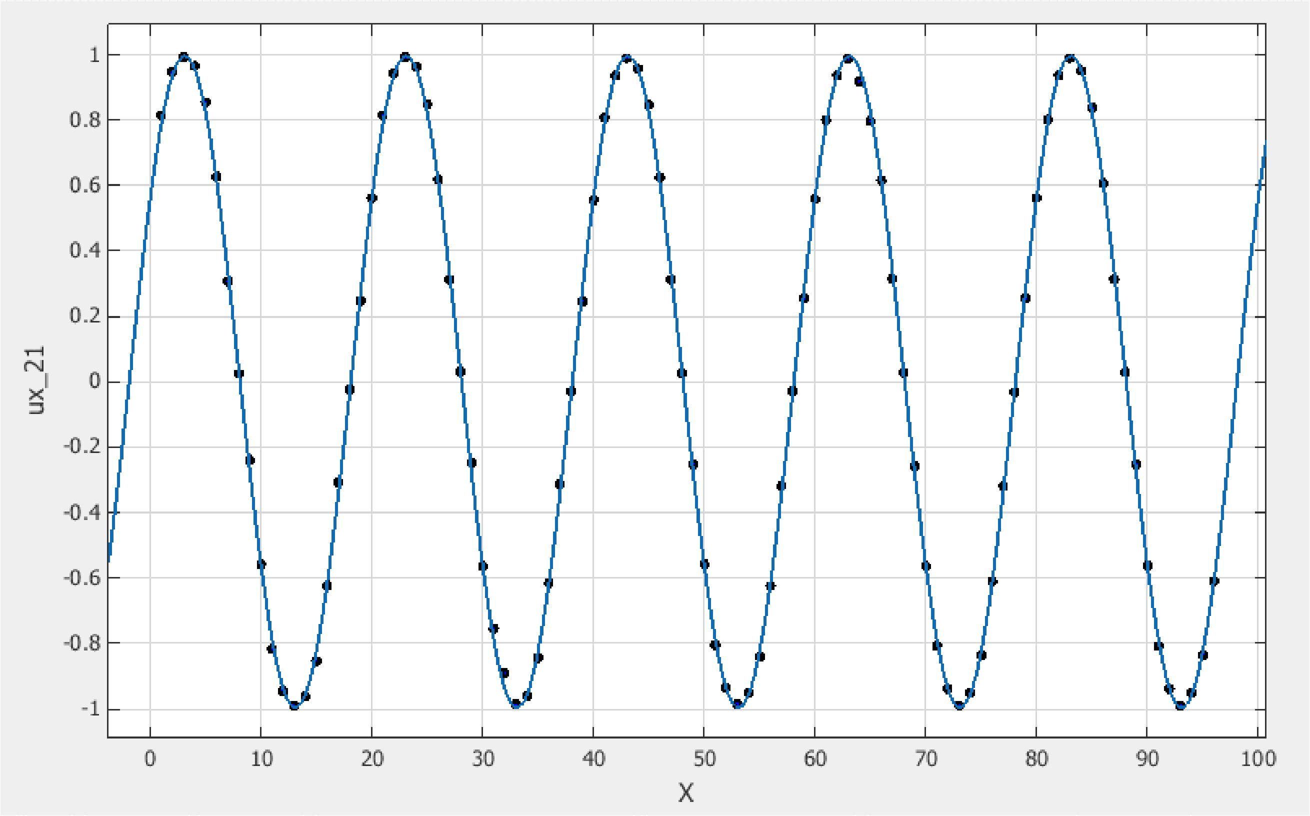
- Perform DIC
- Average displacements computed across y
- Fit best sine function to resulting 1D data
- Calculate amplitude
- **Study impact of DIC settings**



Effect of subset size: subset = 21 pixels

Amplitude: 0.996
Loss: 0.4%

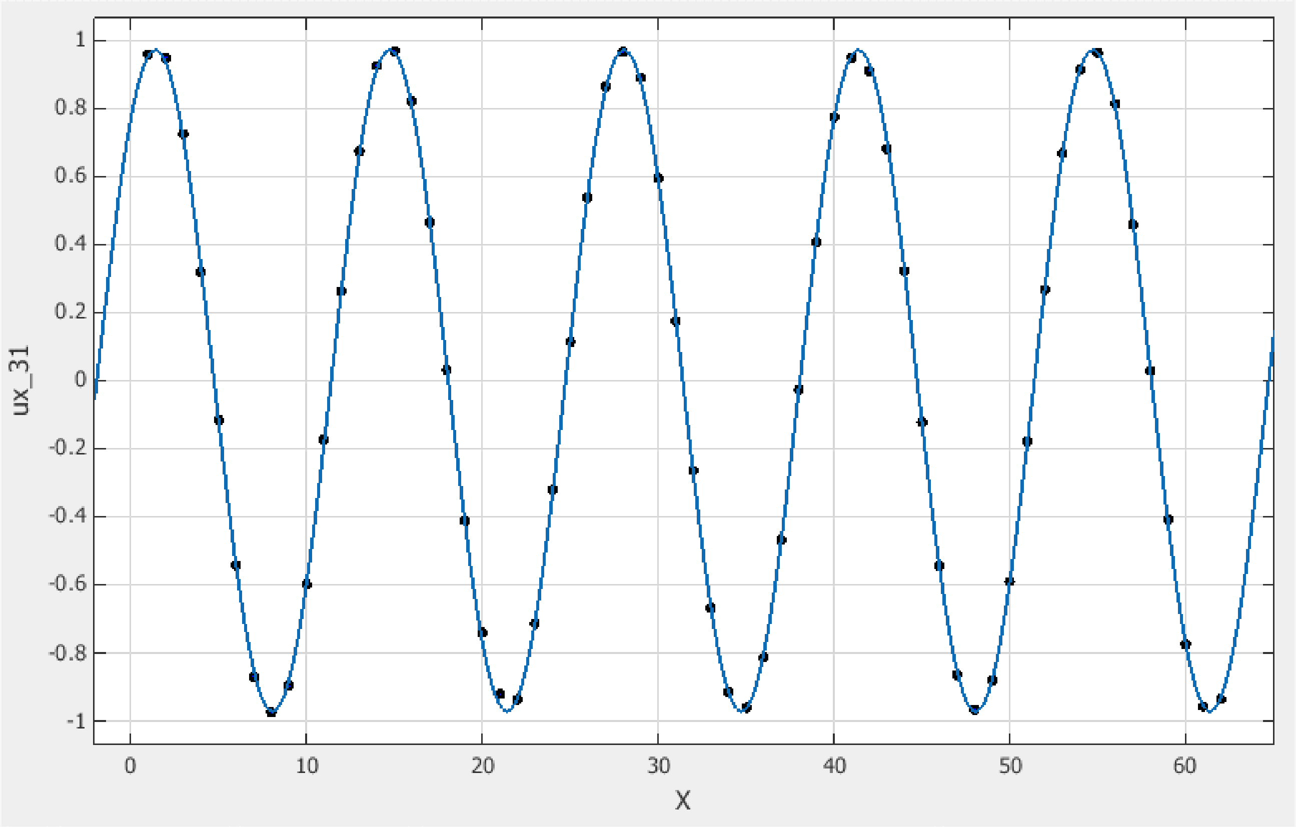
Black dots: DIC results
Blue curve: curve fitting



Effect of subset size: subset = 31 pixels

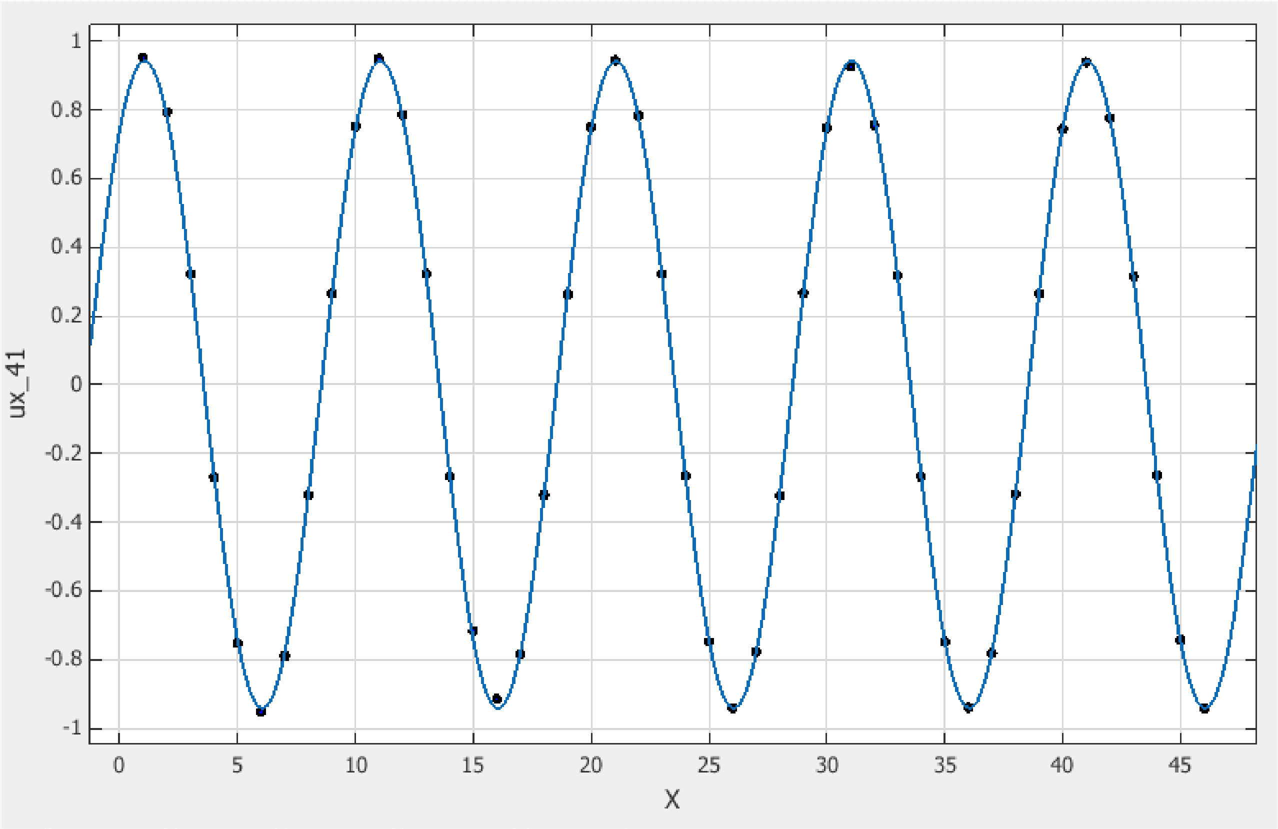
Amplitude: 0.972

Loss: 2.8%

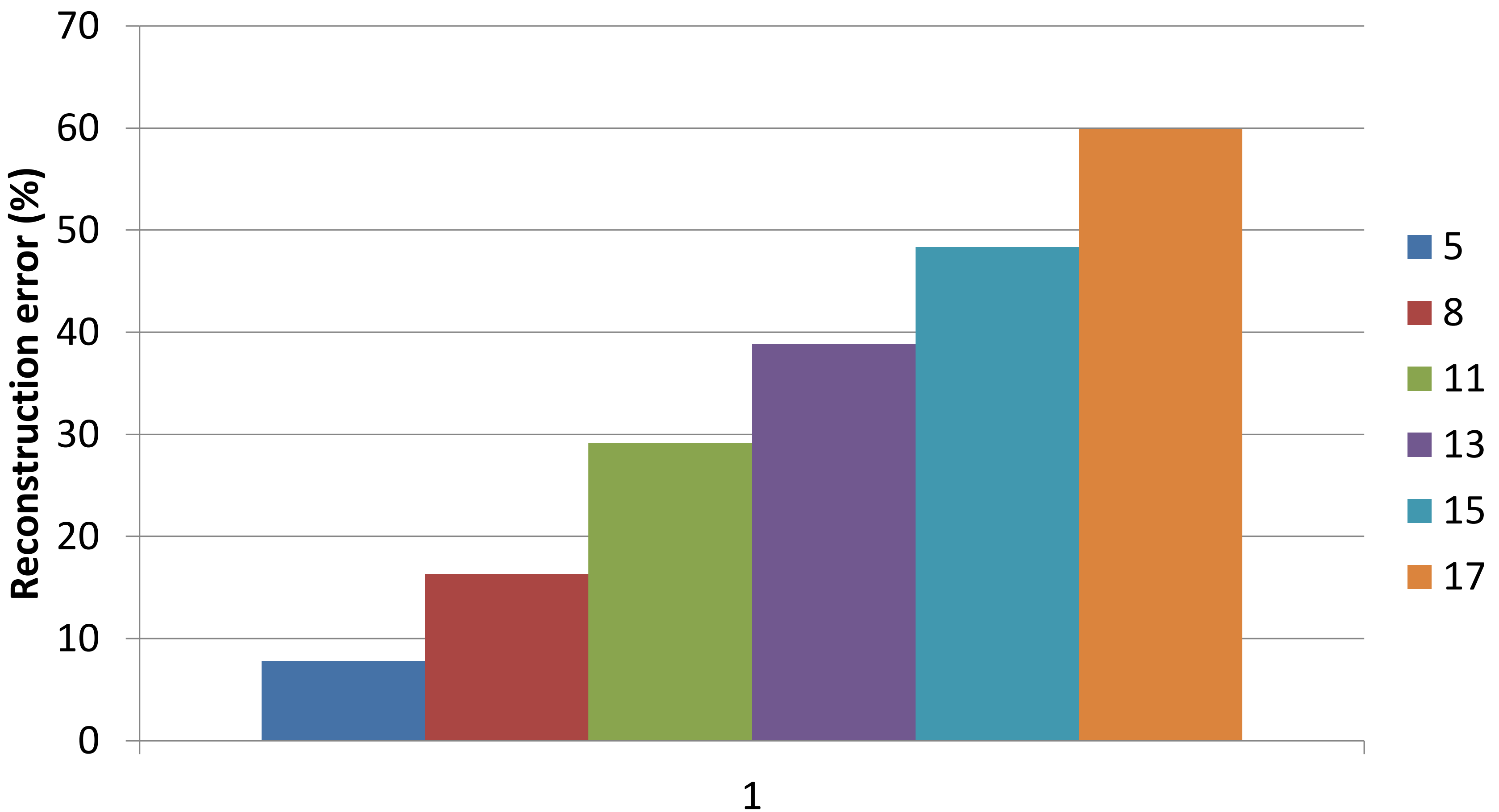


Effect of subset size: subset = 41 pixels

Amplitude: 0.942
Loss: 5.8%



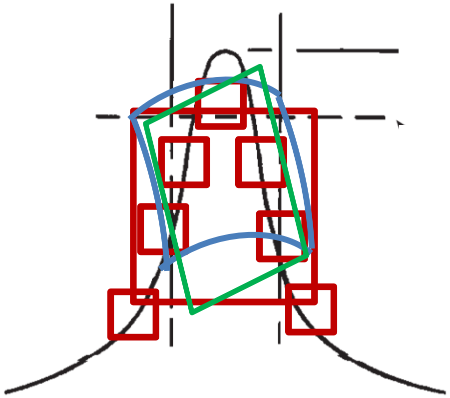
Affine shape function, subset 41 pixels



Random error: 0,012 (standard deviation of displacement noise map, max of components)

Why?

Peak displacement



How large should my subset be?

Large?

- \+ Average out image noise, improvement of noise floor
- \- Average out deformation, decrease of the reconstructed signal

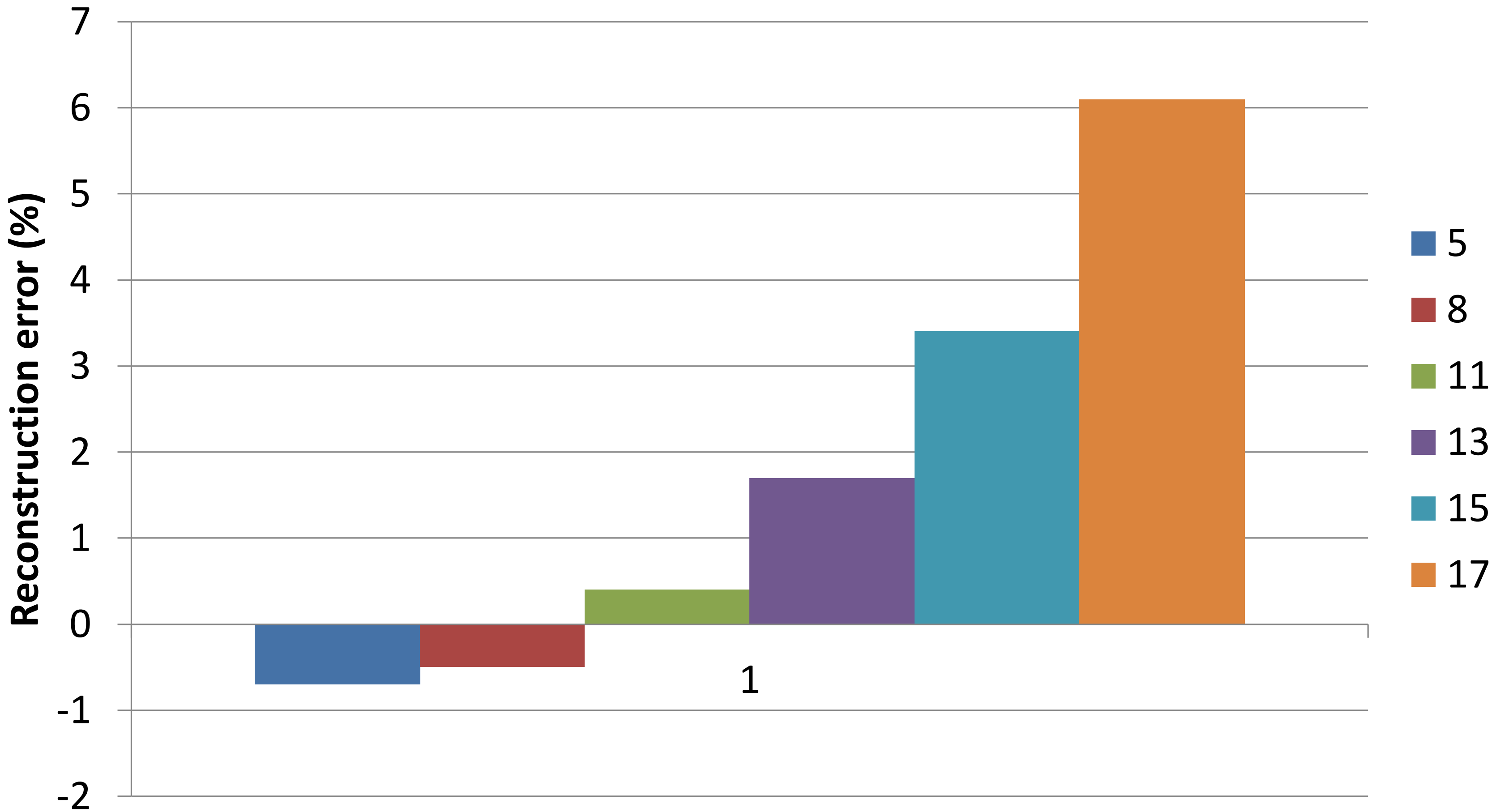
Small?

- \+ Increase of signal reconstruction (less averaging)
- \- Less averaging of noise, more influence of noise

An affine (first order) subset describes a linear varying displacement field

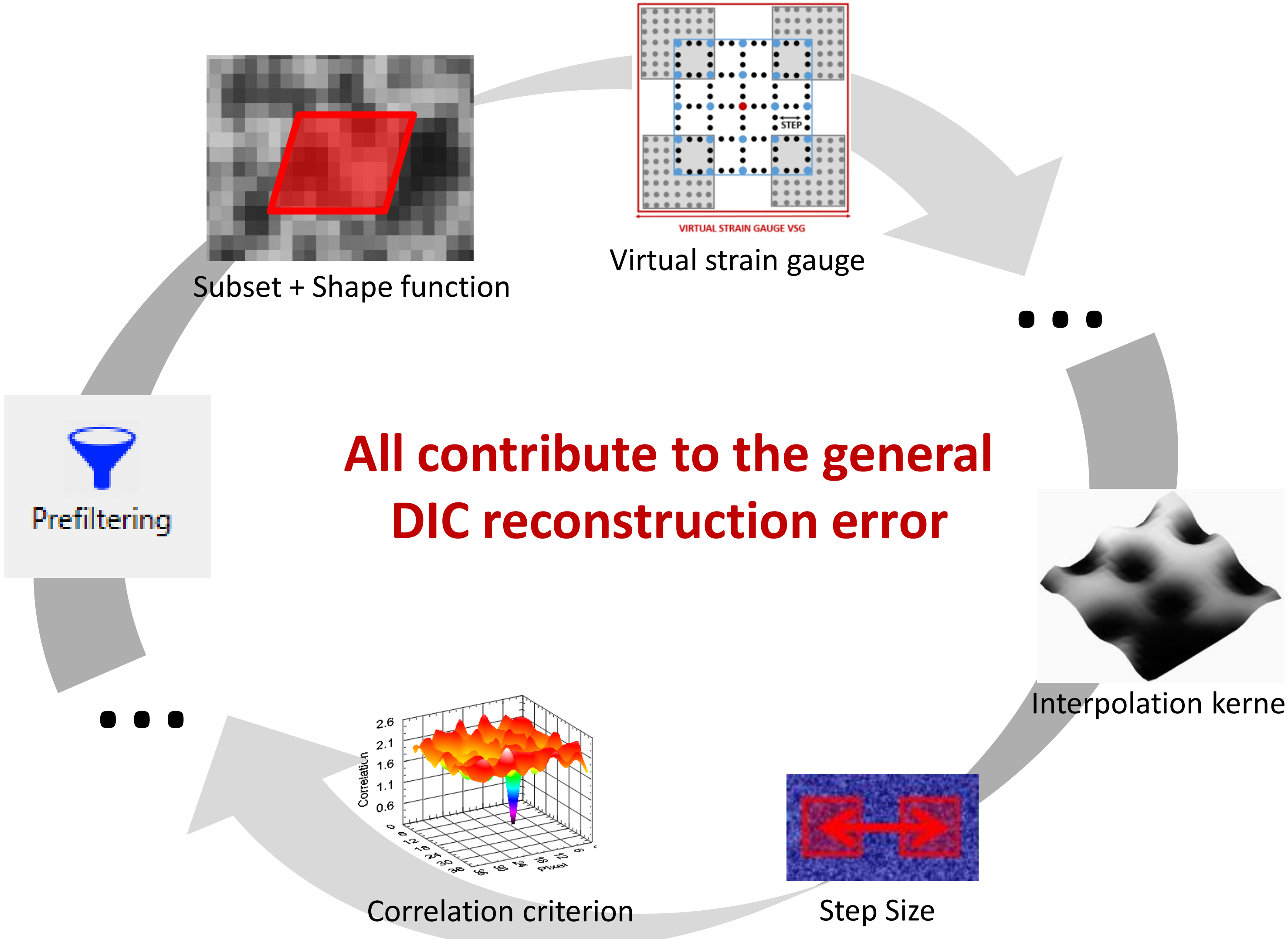
Introduce **higher order shape functions** to describe more complex deformation fields

Quadratic shape function, subset 41 pixels



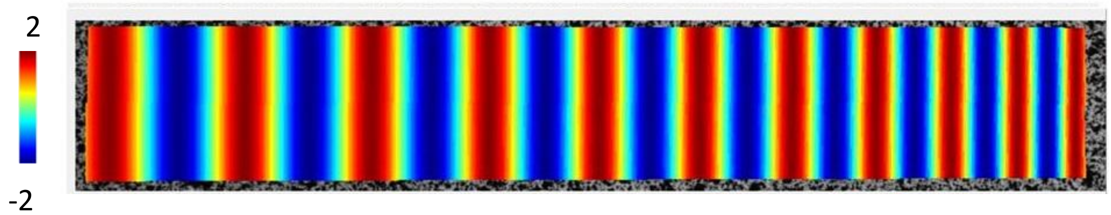
Random error: 0.041 (vs 0.012 for affine shape function)

And even more ...



All contribute to the general DIC reconstruction error

An approach to quantify the spatial resolution?



$$\Phi_D(\mathrm{x}) = \begin{cases} d_x = a \cdot sin[\frac{2\cdot\pi}{P_0} \cdot x + (\frac{2\cdot\pi}{P_1} - \frac{2\cdot\pi}{P_0}) \cdot \frac{x^2}{2L}] \\ d_y = 0 \end{cases}$$

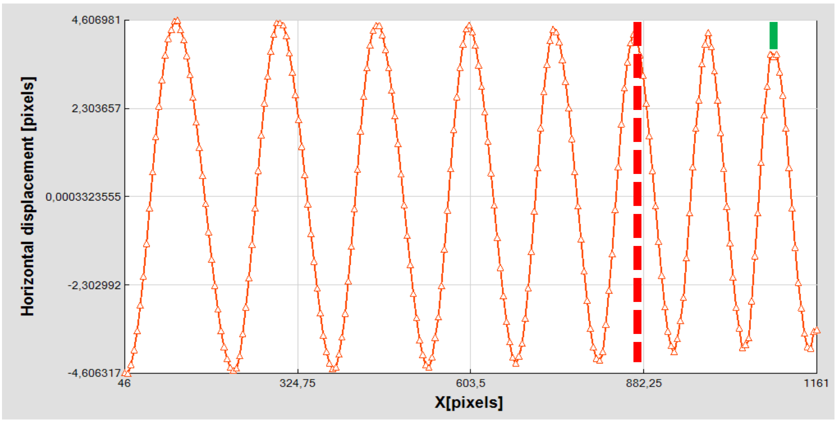
Change in frequency

↓

Change in spatial resolution

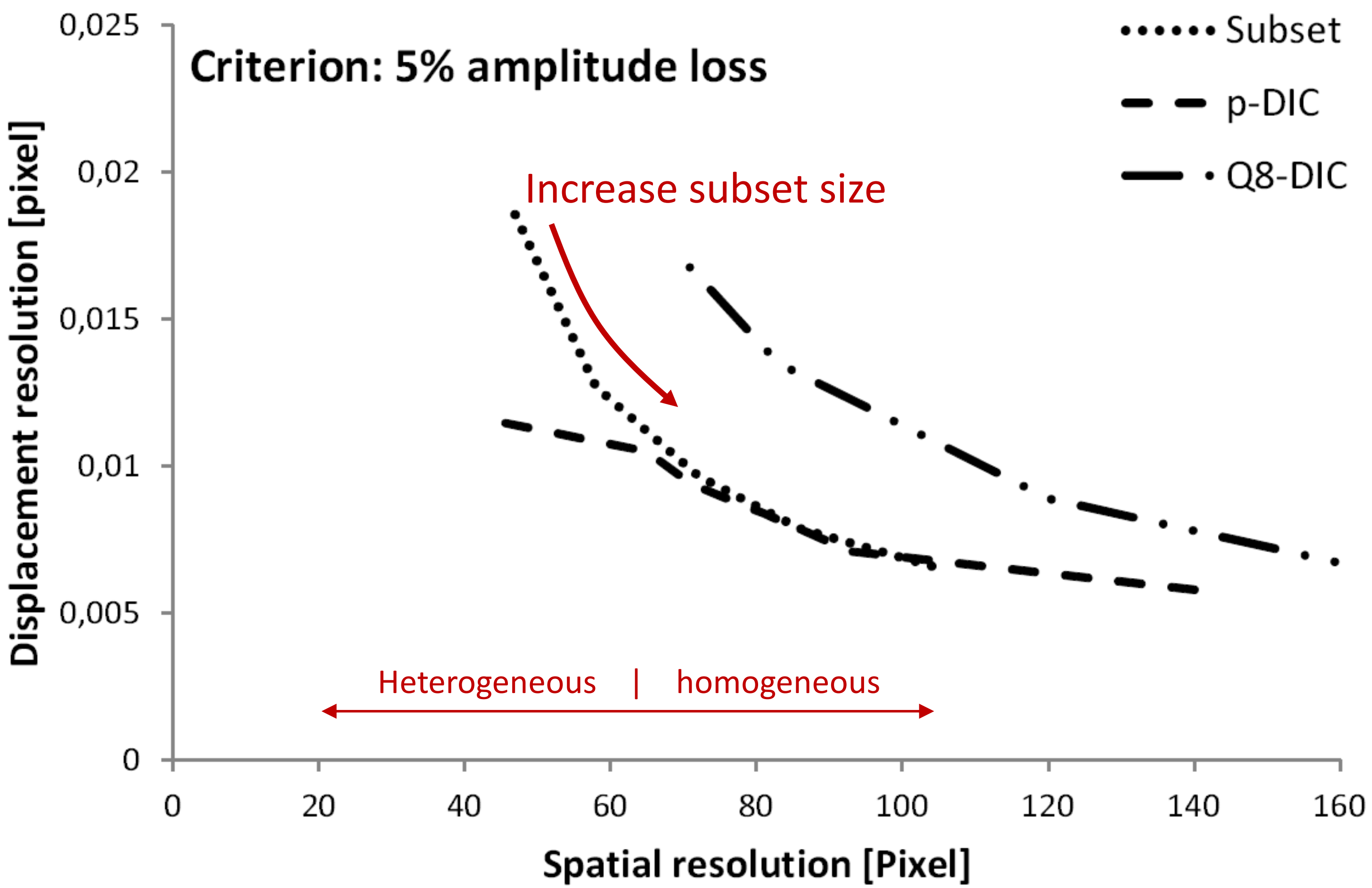
How good can gradients be quantified?

Measured sine wave



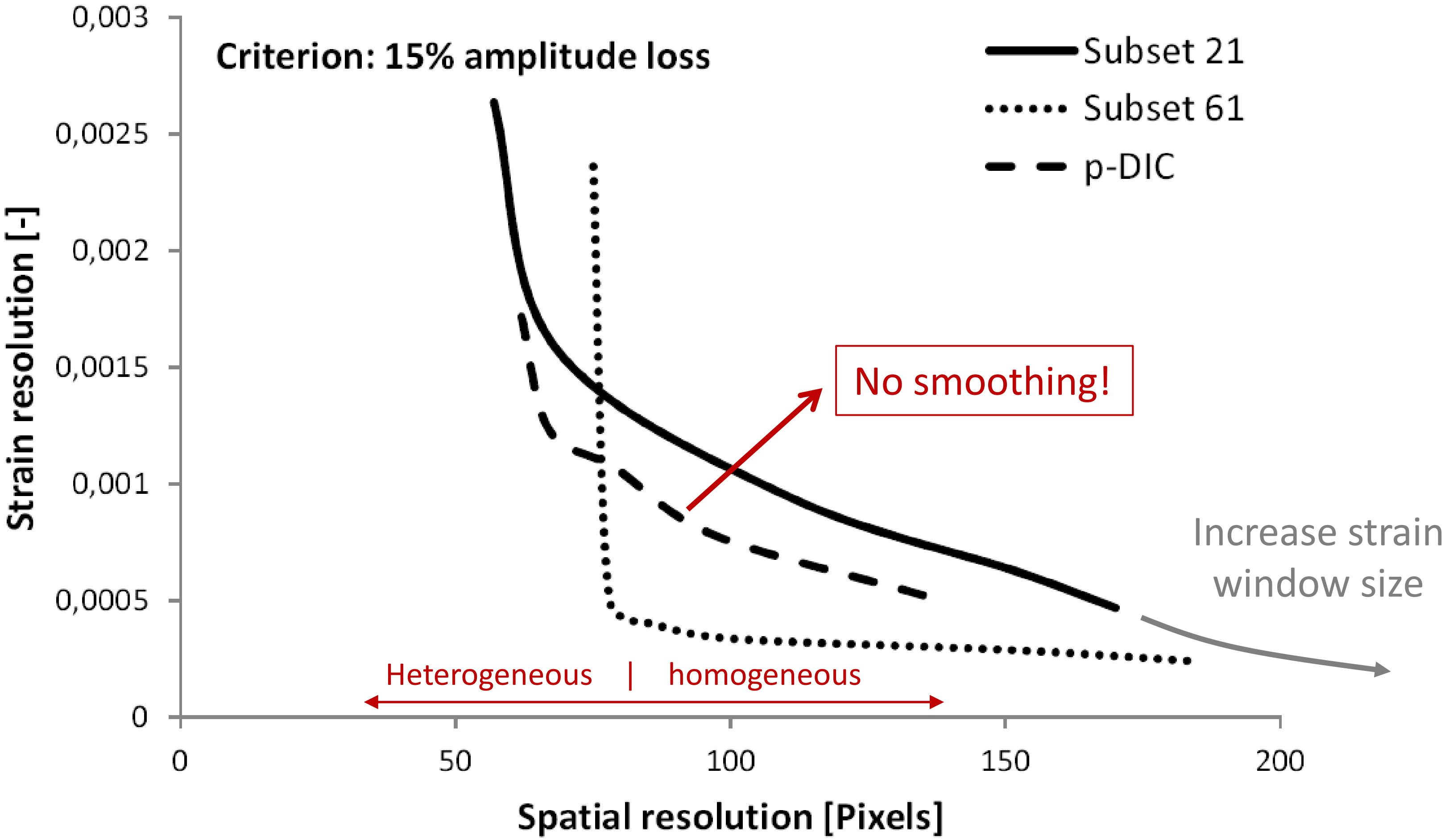
Minimum wave length =? the *Spatial resolution*

Displacements



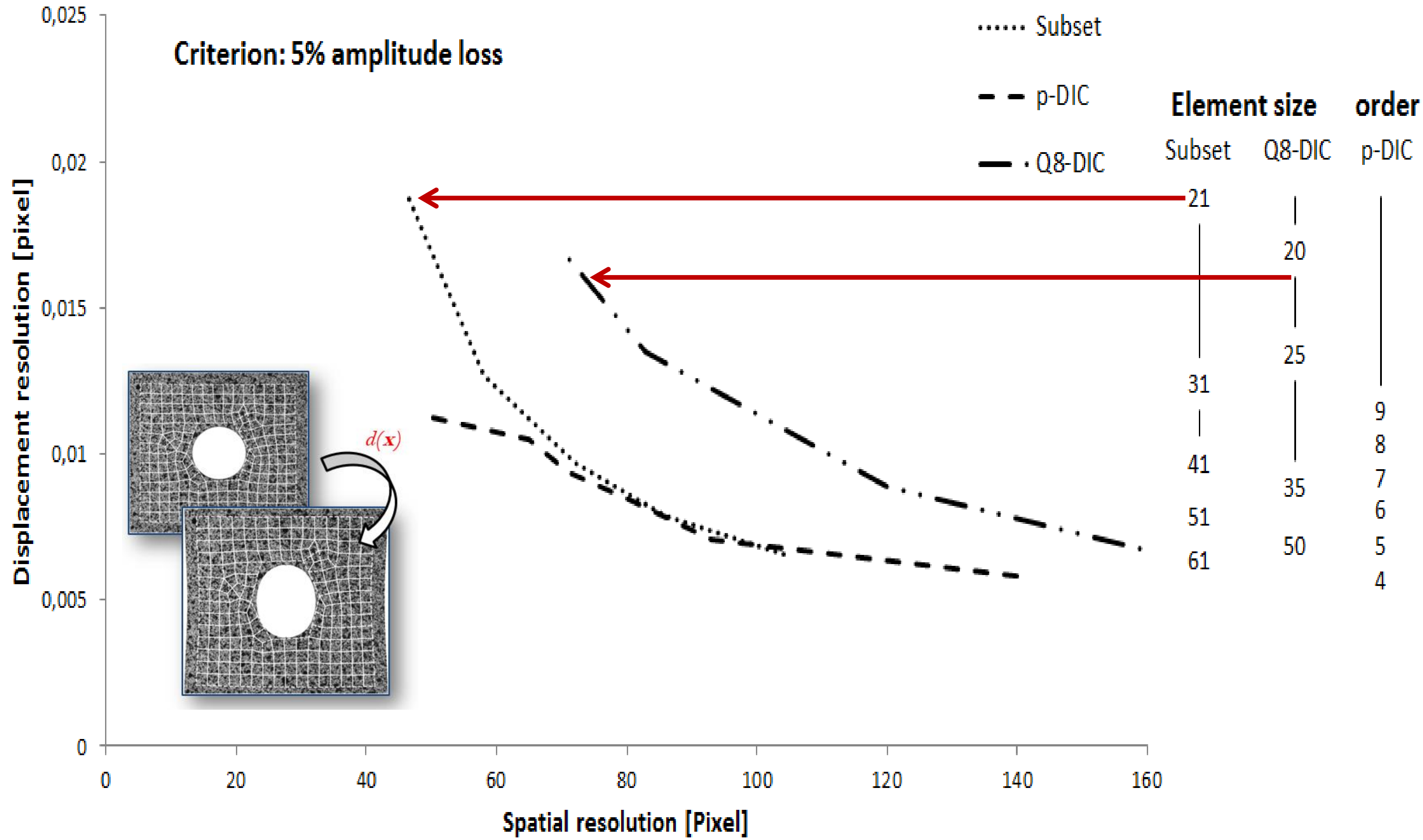
Wave length able to reproduce

Strains



Wave length able to reproduce

Local vs. Global DIC



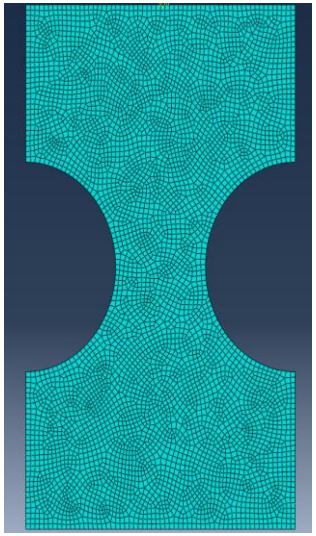
Spatial resolution is not really element or subset size

Problem statement

- Spatial resolution is not really element or subset size … many DIC settings contribute
- What cut-off frequency should I adopt?
- How do I translate gradients in a sinusoidal field to my true application?

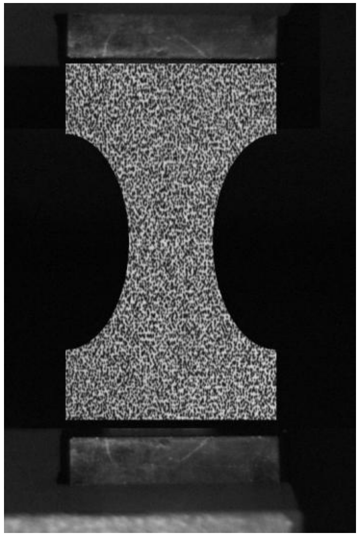
A more practical approach: Finite element based deformation fields

FEA nodal displacements



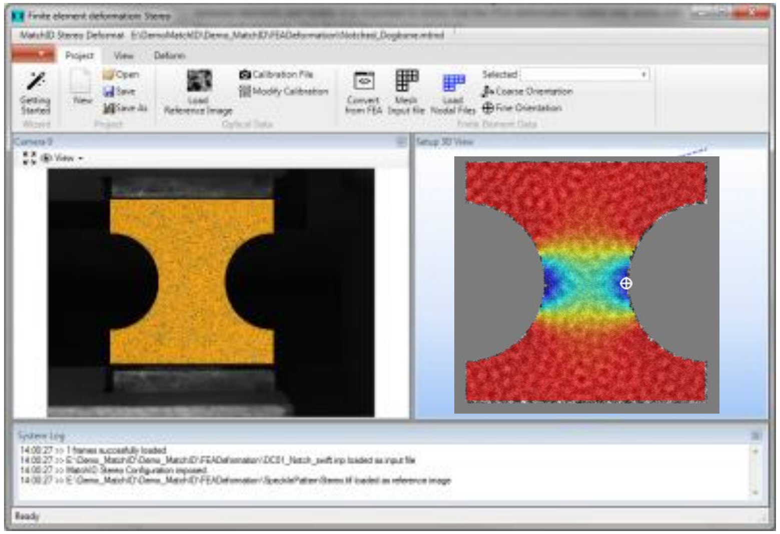
\+

Import DIC image



→

Align mesh/image and Generate deformed image



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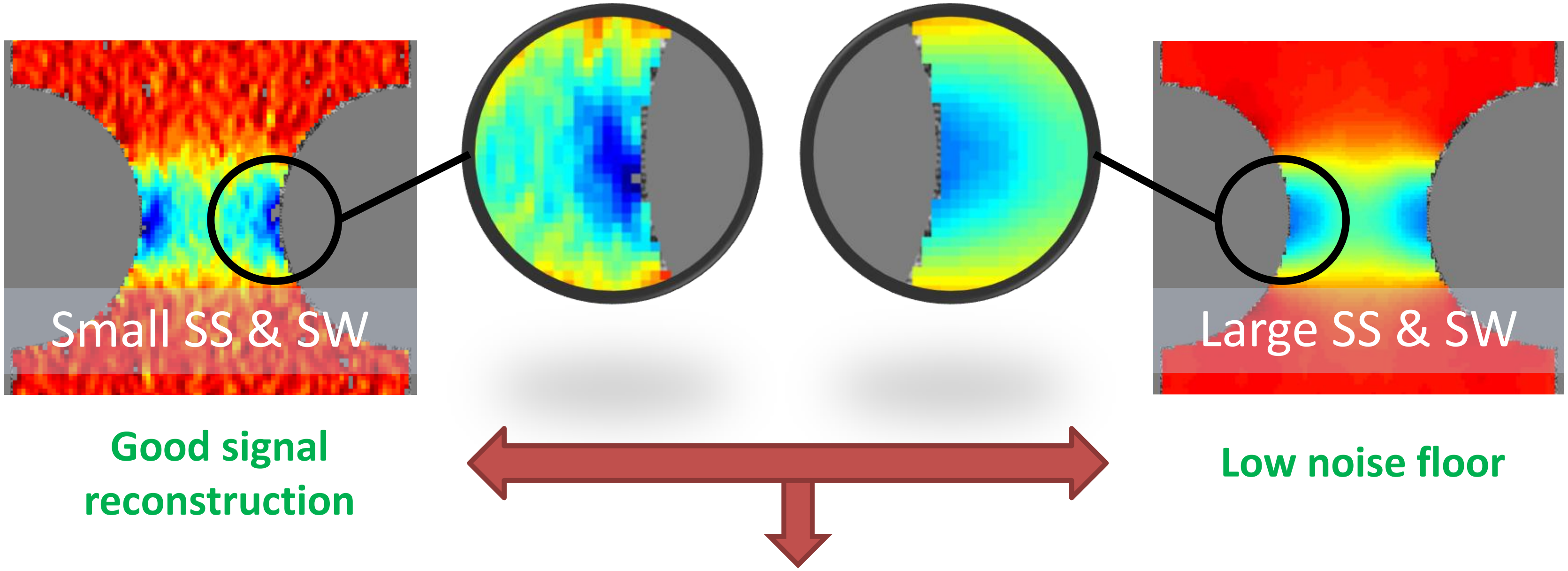
Influence of DIC Parameters

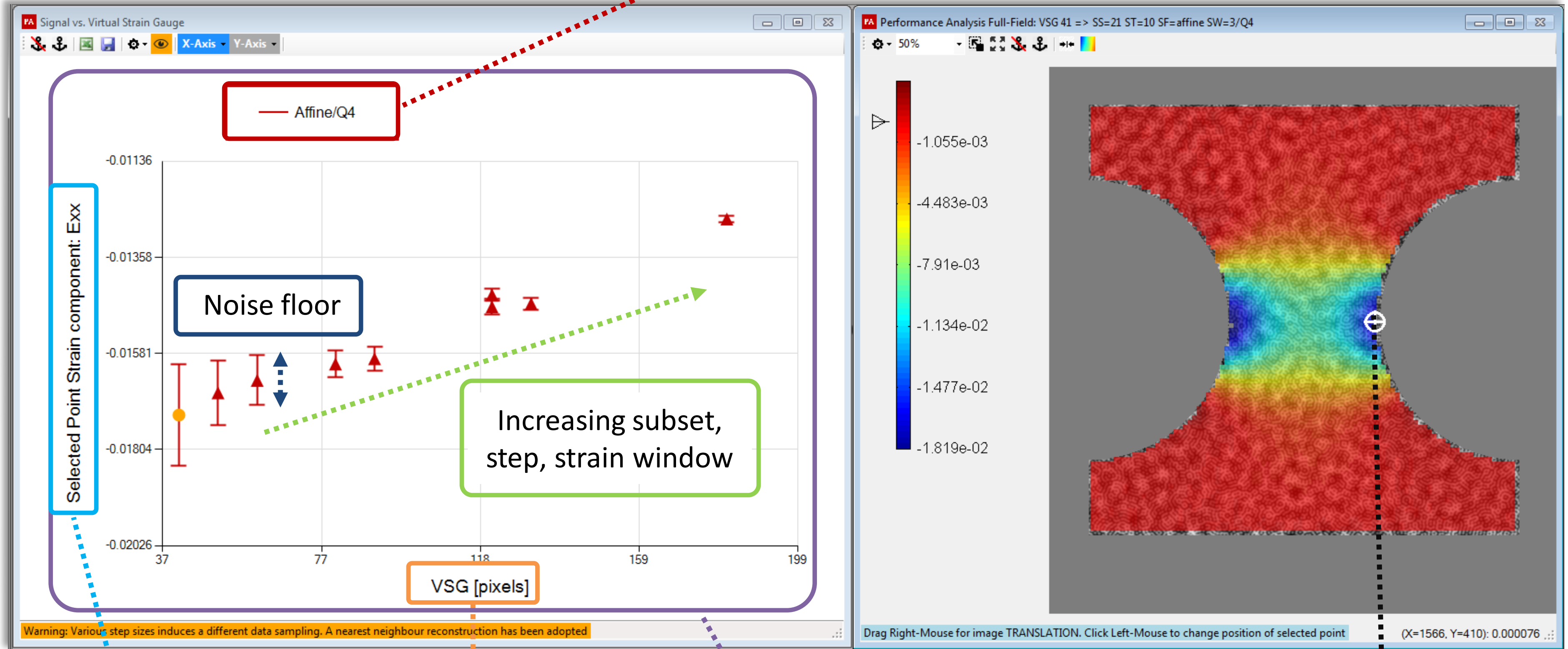
Selection of DIC parameters is an optimum between noise reduction and signal reconstruction



MatchID 's performance analysis module helps you to find that optimum!

A quick example

Subset shape function: Affine
Strain window order: Q4



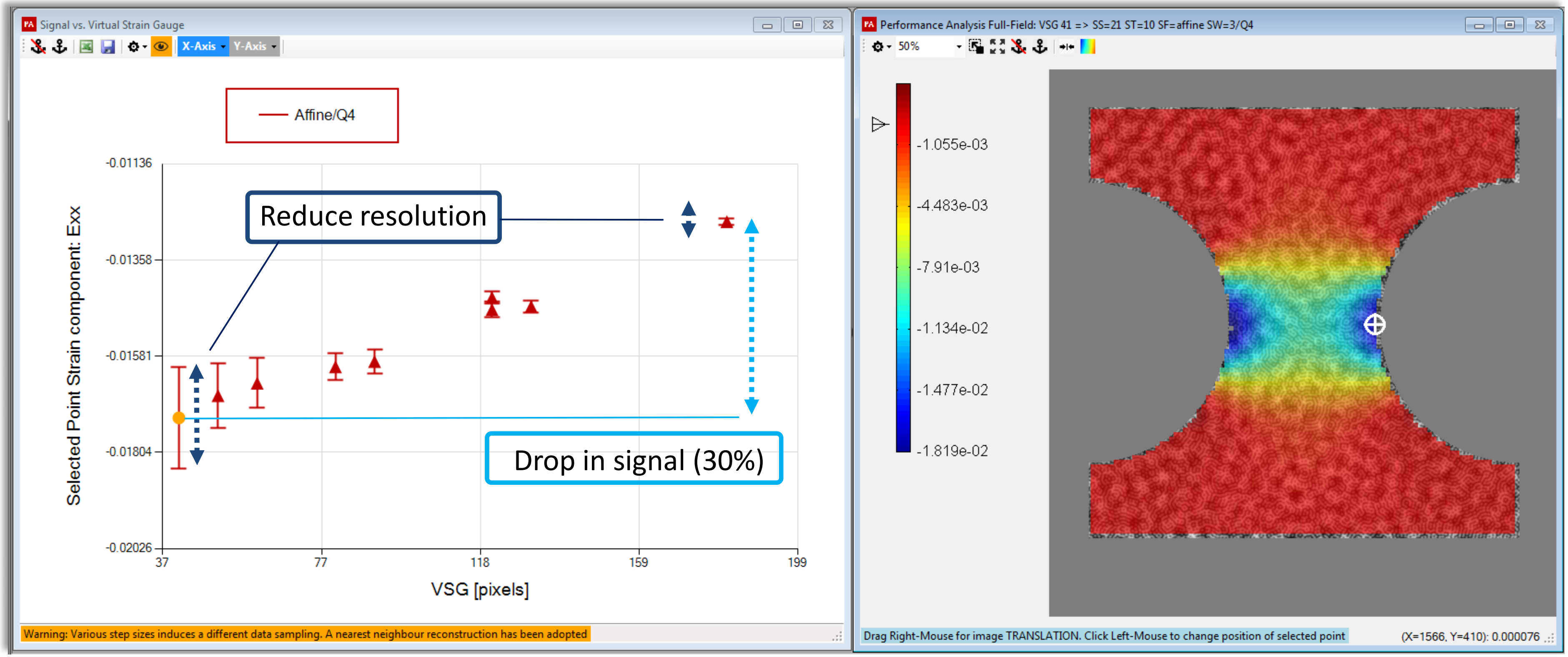
Strain peak in selected point (signal)

VSG is combination of:
- Subset size
- Step
- Strain window

Signal vs Noise floor, in function of VSG

Selected point (POI)

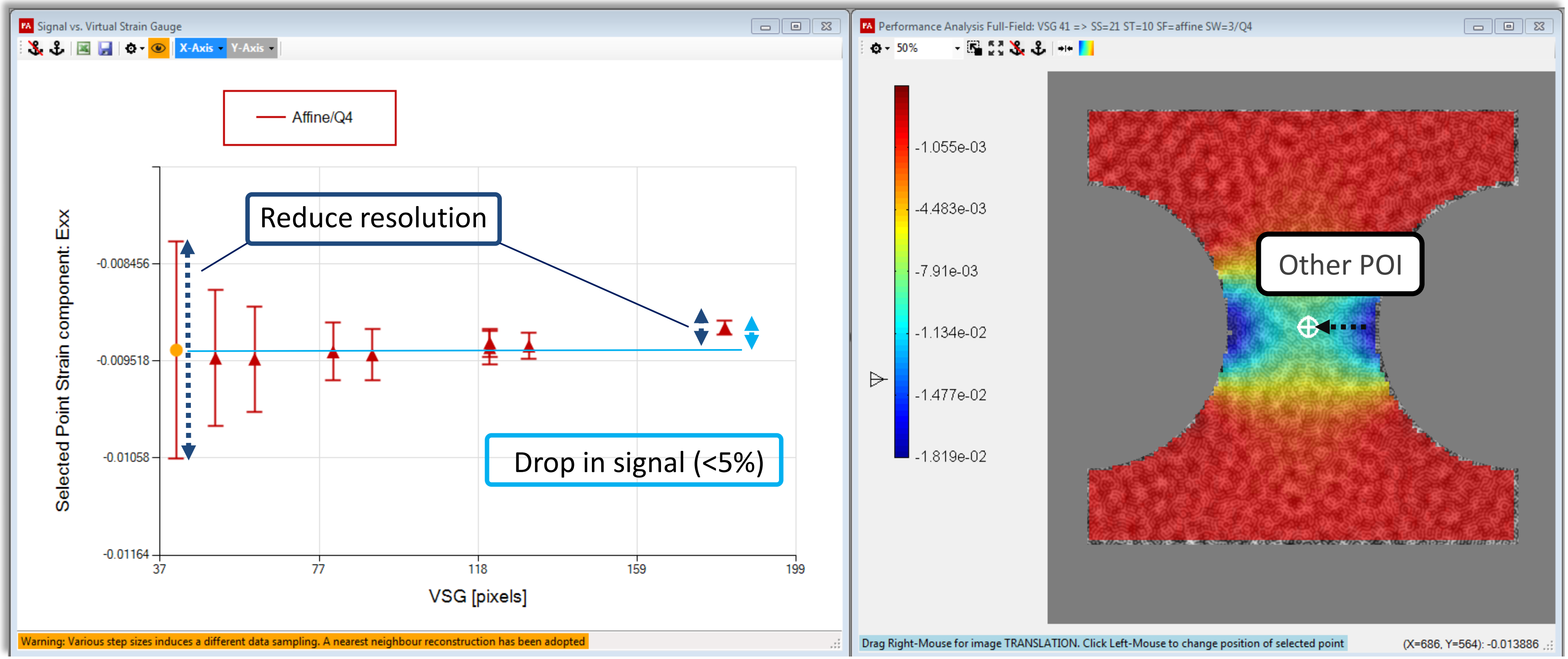
A quick example



For the selected point in the strain peak:

Increase of the subset and/or step and/or strain window size will reduce the resolution, but will also result in a considerable drop in reconstructed strain peak

A quick example



When your point of interest is in the center:

Increase of the subset and/or step and/or strain window size will still reduce the resolution, but because the deformation is uniform (almost) no signal loss will occur!

Conclusions

- Ground-truth images allow to investigate the accuracy of DIC in both 2D and Stereo and as such helps you to optimize your test setup
- The selection of DIC parameters will define both the resolution and signal reconstruction.
- An attempt to approach the spatial resolution of DIC.
- The optimum selection of your parameters depend both on your test and your point of interest.

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