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# Minimizing Pattern Induced Bias in Digital Image Correlation

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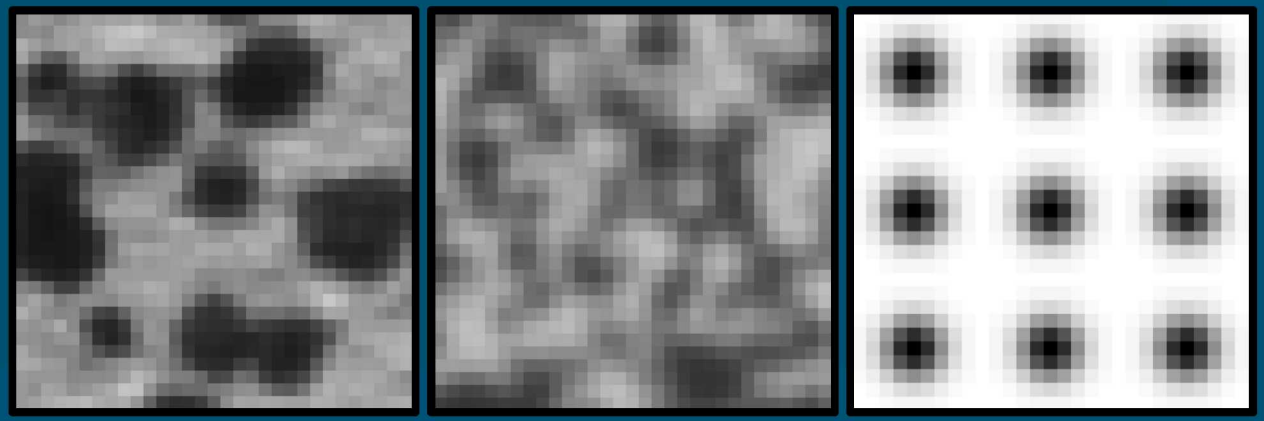

iDICs 2019

Portland, Oregon

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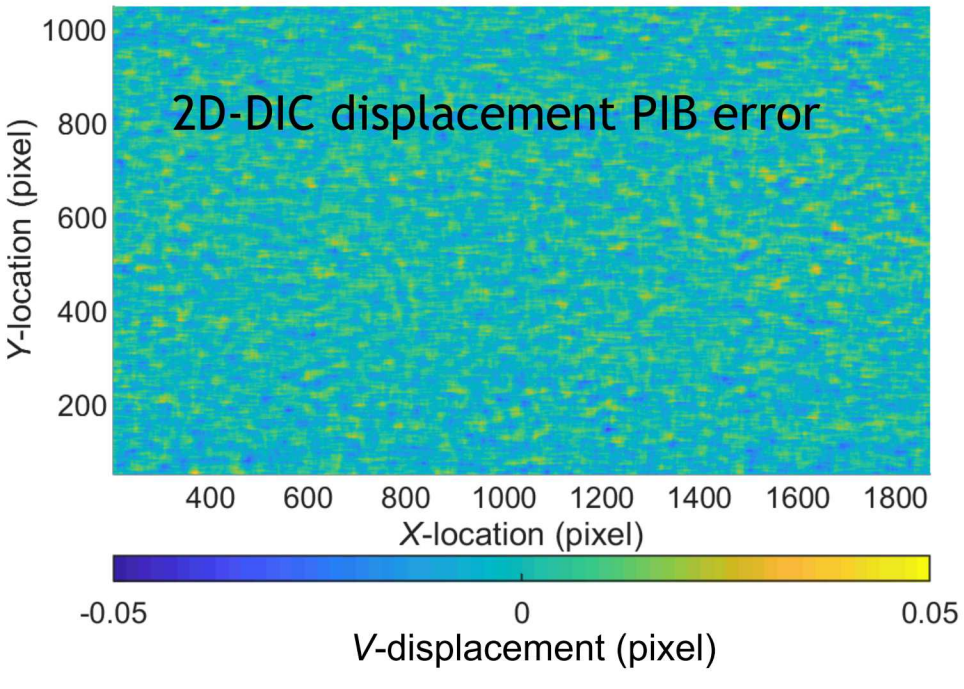
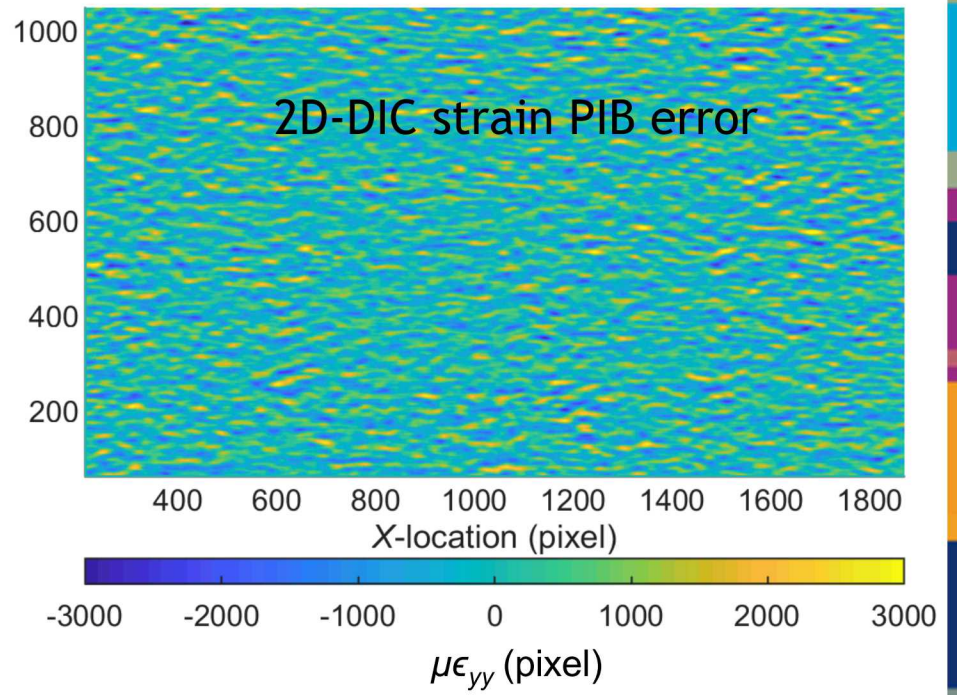
DIC has a spatial bias error caused by the interaction of the: Pattern, deformation field, and any DIC error terms, mainly that from an undermatched shape function.

## Pattern Induced Bias (PIB) Error




Until now*, this term was only briefly mentioned in literature[].

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

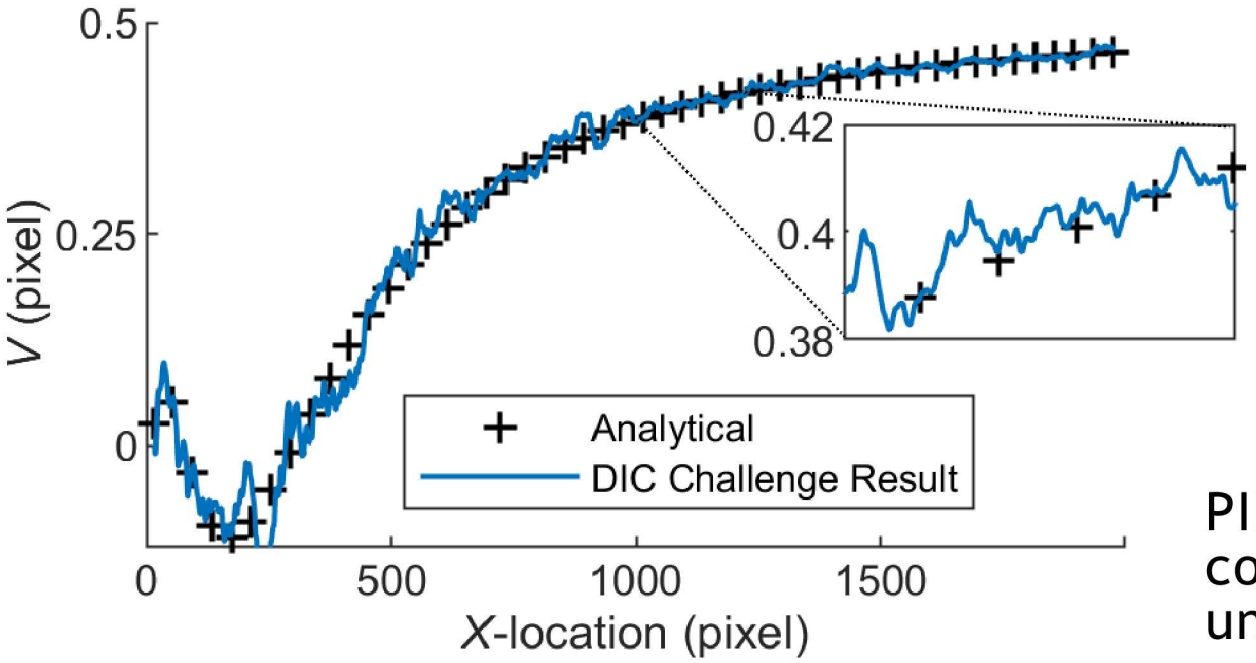
*SS. Fayad, DT Seidl, PL Reu, ExpMech, doi.org/10.1007/s11340-019-00553-9

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

# This error was first noticed in the DIC Challenge image set

Expected DIC Solution
(black crosses)

$$v(X_0) \cong \frac{1}{\Omega K(X_0)} sin\left(\frac{\Omega K(X_0)}{2}\right)$$




PIB causes the deviation of the blue line from the expected solution

PIB magnitude is loosely correlated with how undermatched the SF is.

# It was also noticed the bias was unique to the pattern

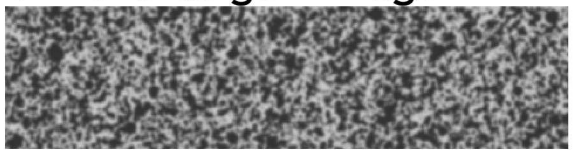
Unique Image number

1

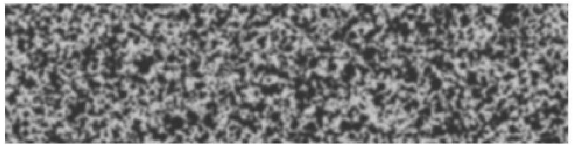
⋮

50

100 pixel x 400 pixel samples from the larger image



⋮



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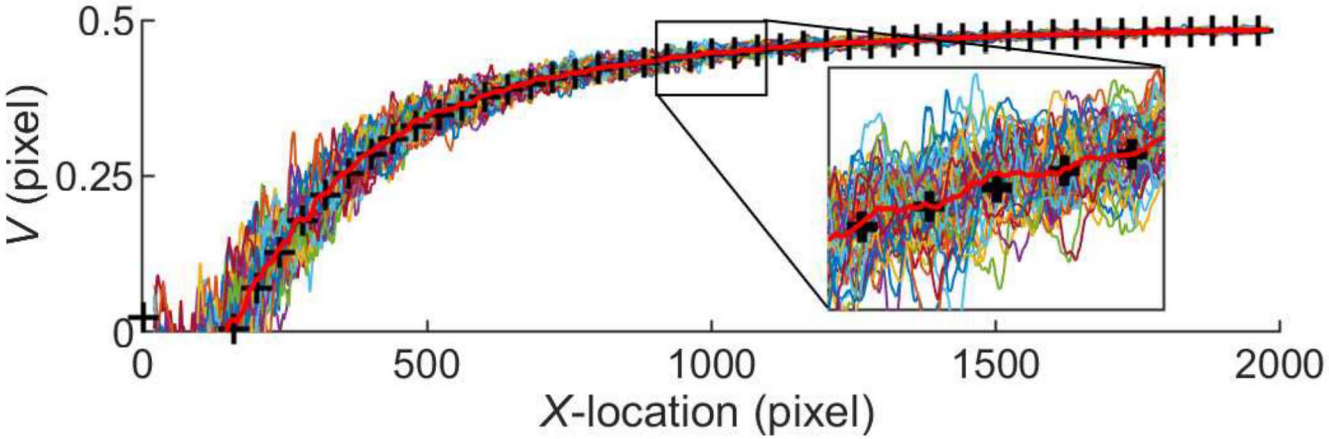
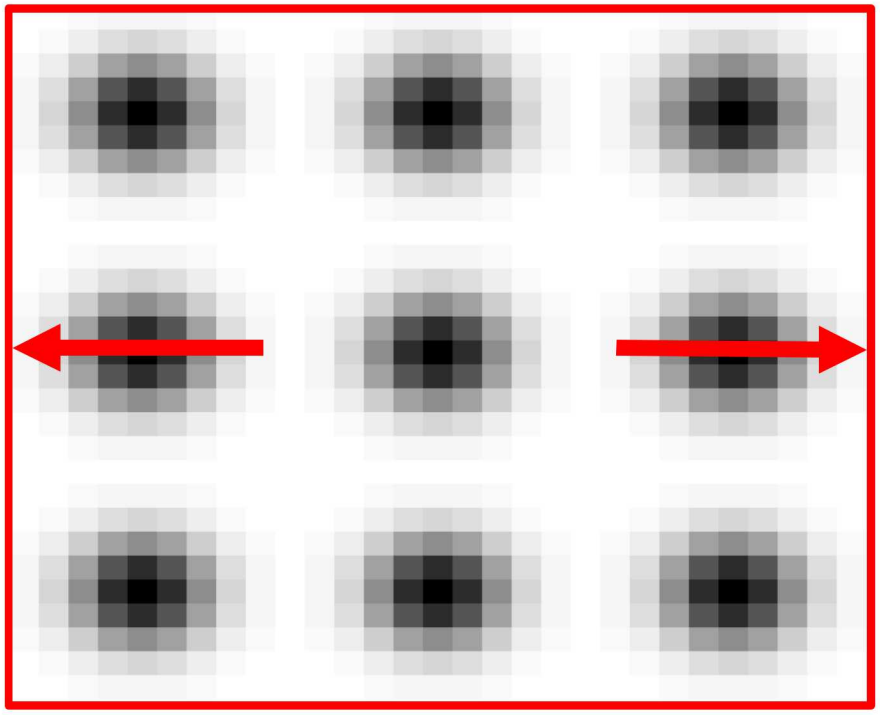


# Simple intuition of PIB using a double precision pattern:

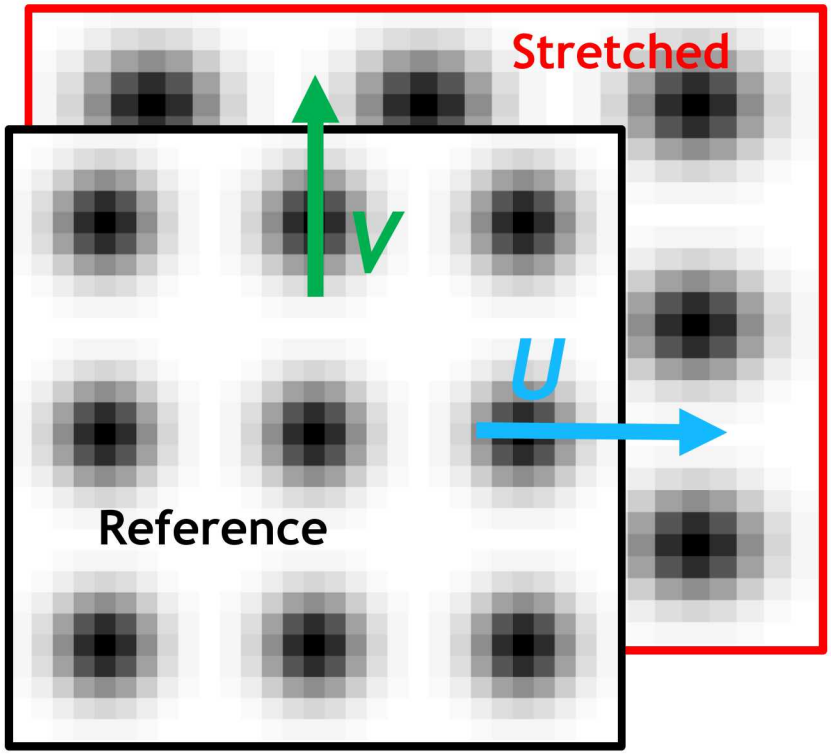
A continuous pattern sampled at 31 “pixels”

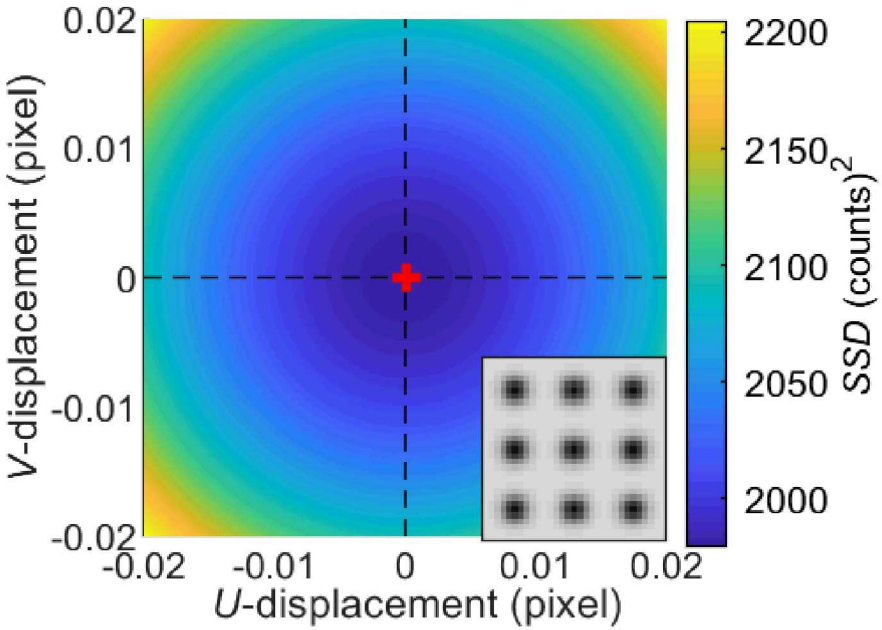
1%  uniform horizontal stretch



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

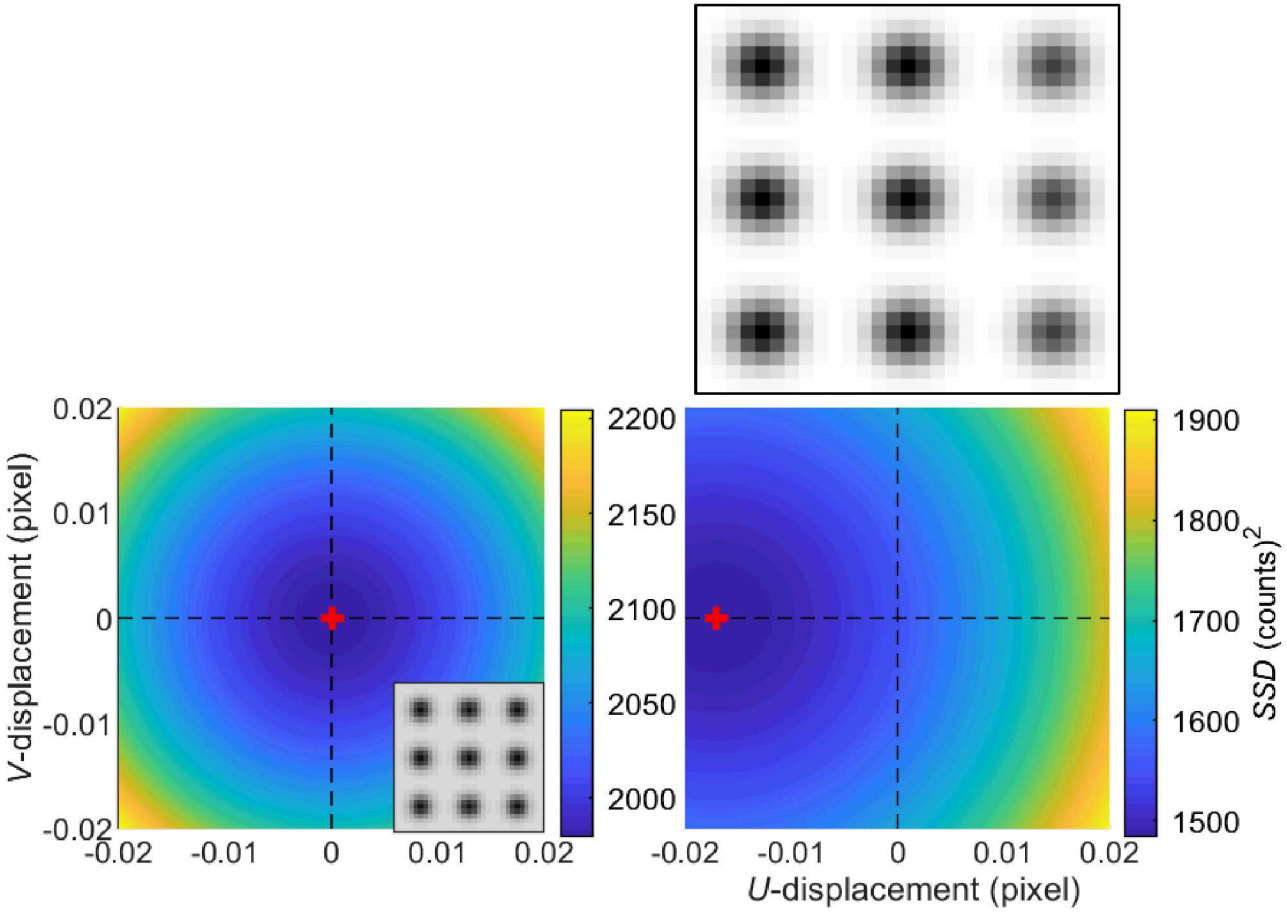
$$SSD \equiv \frac{1}{2}\sum_{x=-M}^{M}\sum_{y=-M}^{M} \boldsymbol{w}(\boldsymbol{x})\big(I(\boldsymbol{x}) - G(\boldsymbol{x}+\boldsymbol{U})\big)^2$$



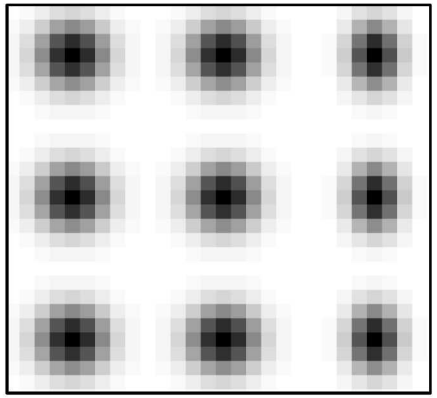

The perfectly symmetric pattern is an unlikely case

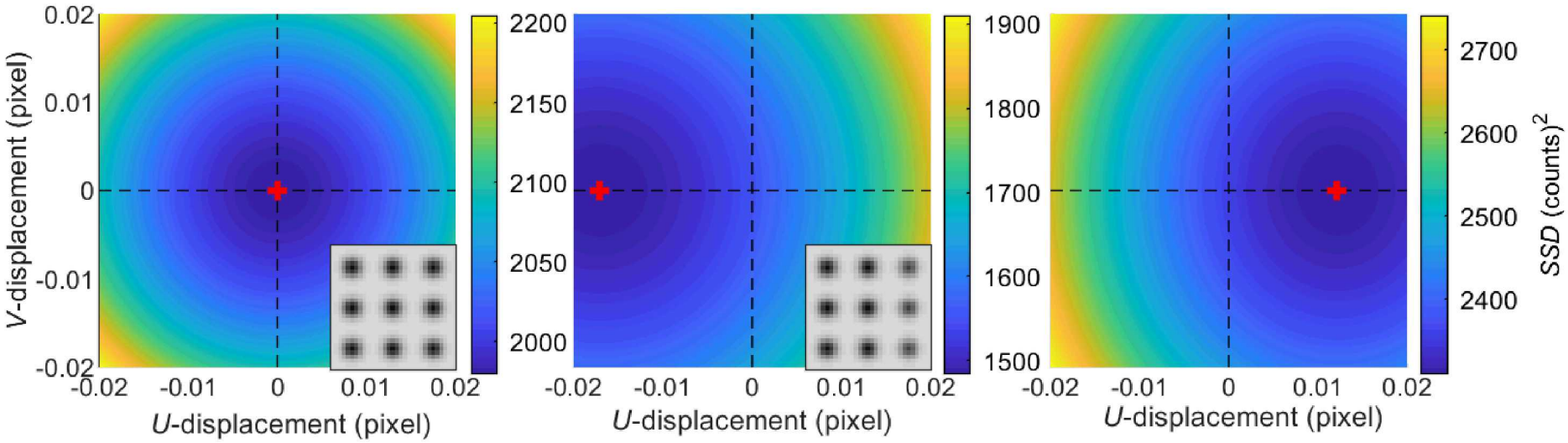
PIB is influenced by the characteristics of the features within a pattern such as contrast (gradient magnitude), geometry, position,…



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

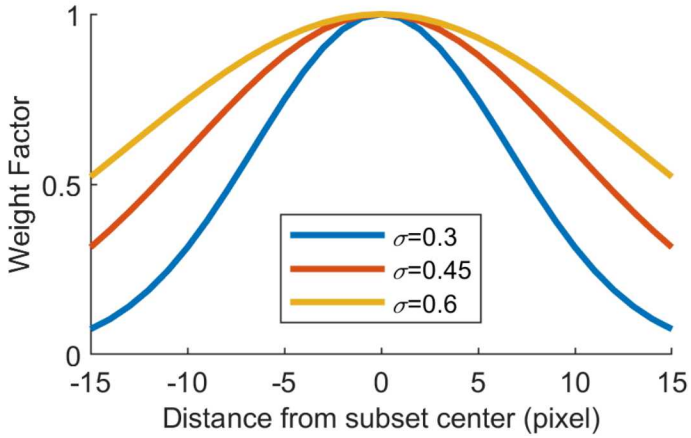
- The DIC solution is biased by higher contrast (gradient) features.

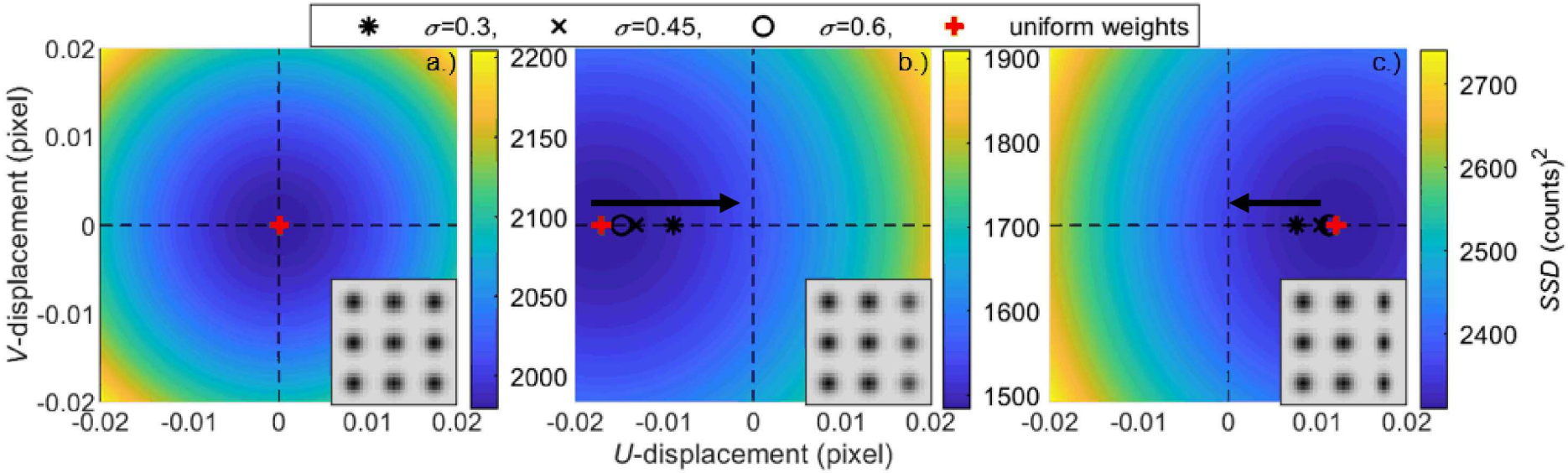




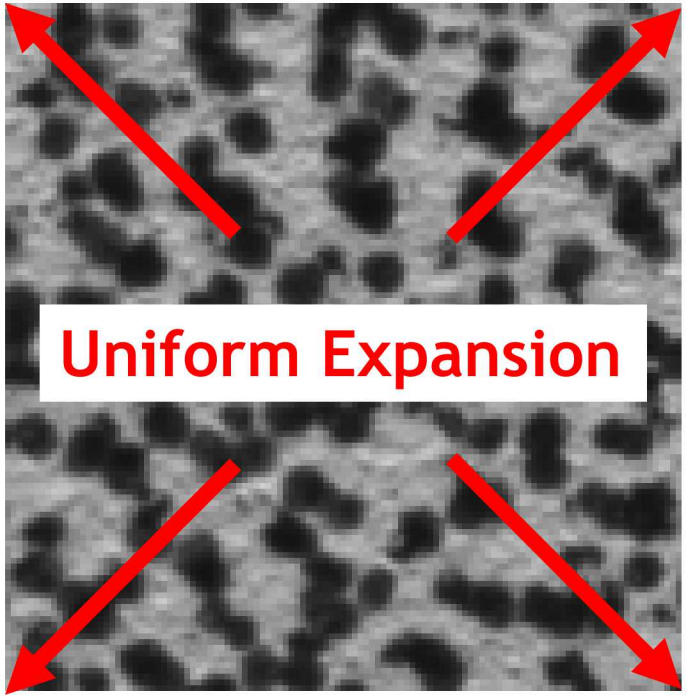
# PIB is influenced by the characteristics of the features within a pattern such as contrast(gradient magnitude), geometry, position,…

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



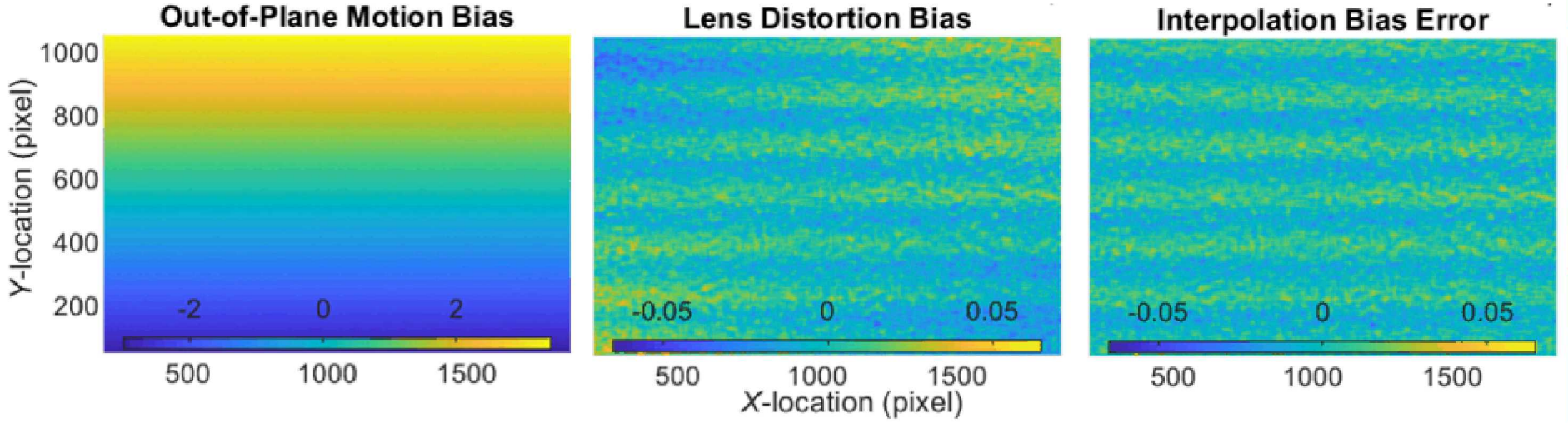



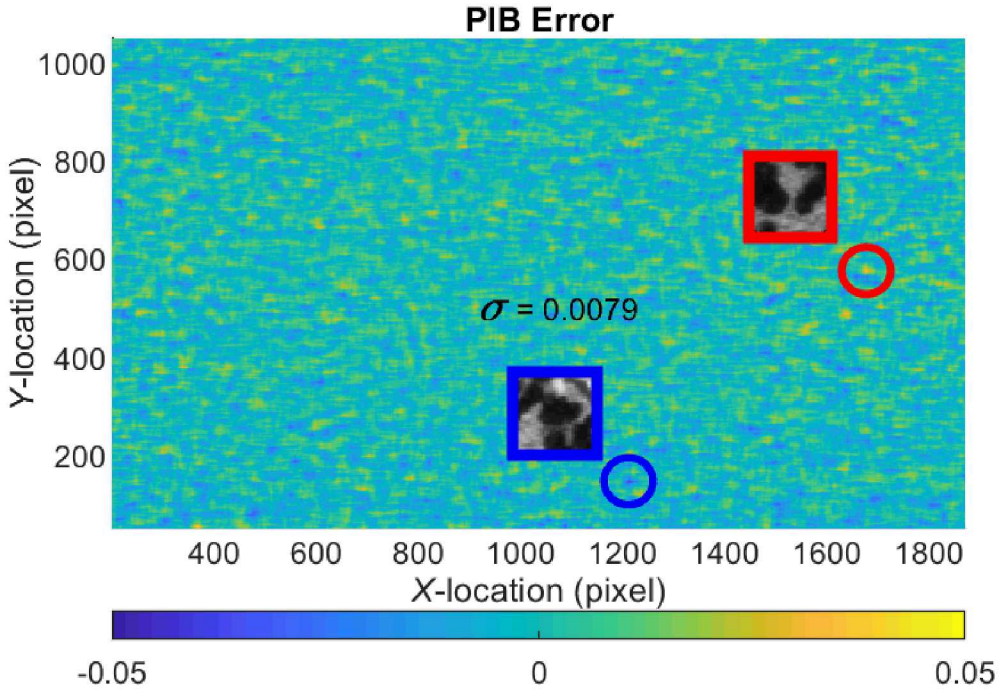
# PIB error is demonstrated in a simple out-of-plane motion experiment.

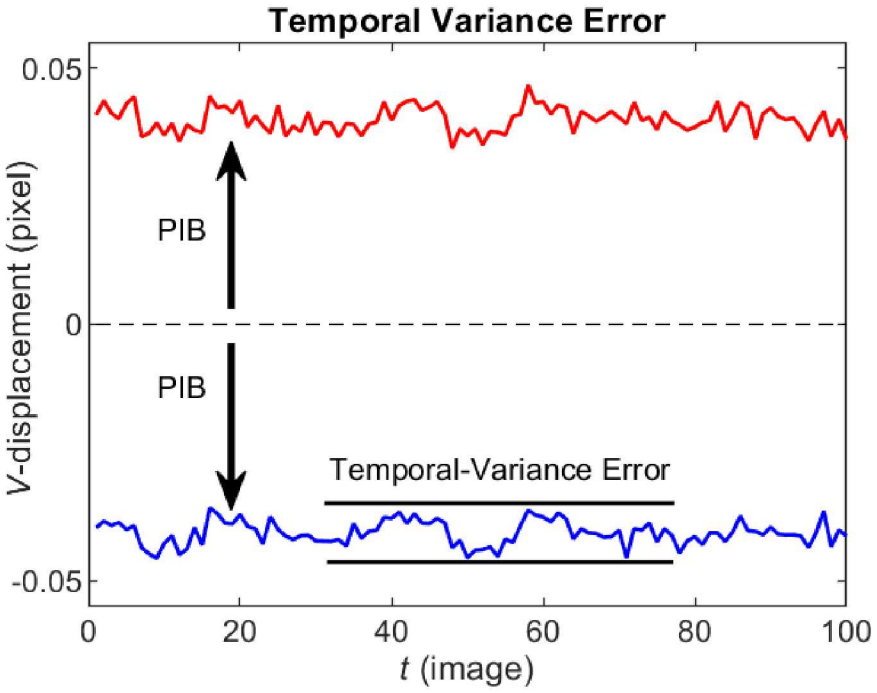




- Stereo set-up for 3D DIC, Orthogonal camera for 2D DIC
- A floating vacuum chamber was used to prevent vibrations and index of refraction changes in the air (largest error source).
- Out-of-plane motion used to create a perfectly uniform expansion (largest 2D error source)
- Experimental images were averaged to remove the temporal-variance error

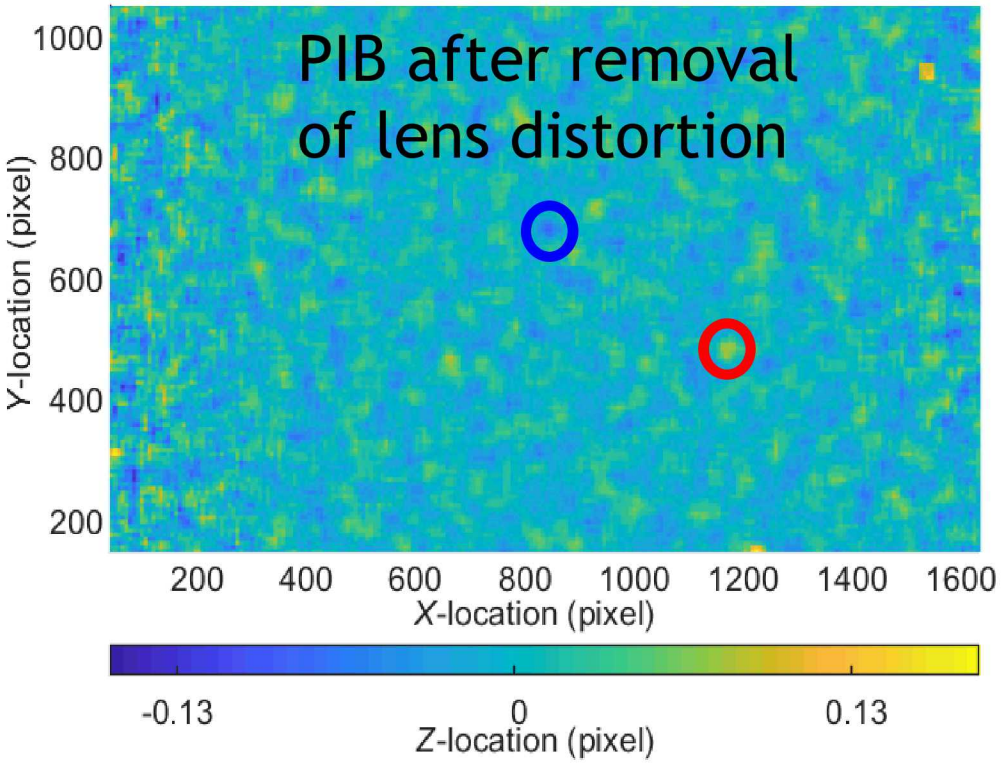
# The PIB error is the 2nd or 3rd most important DIC error.



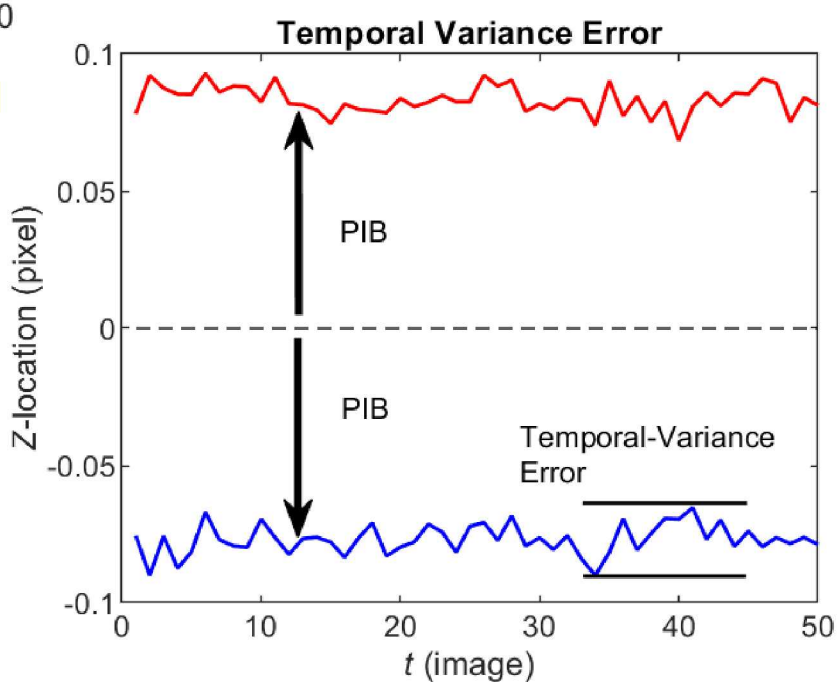



# PIB exists in Stereo-DIC




Again, the error is spatially variant, but not temporally variant

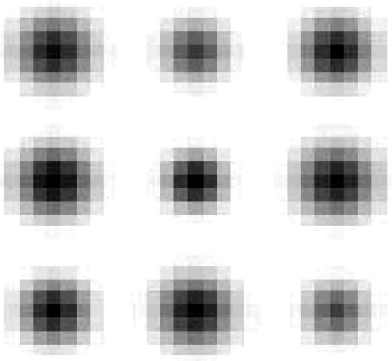


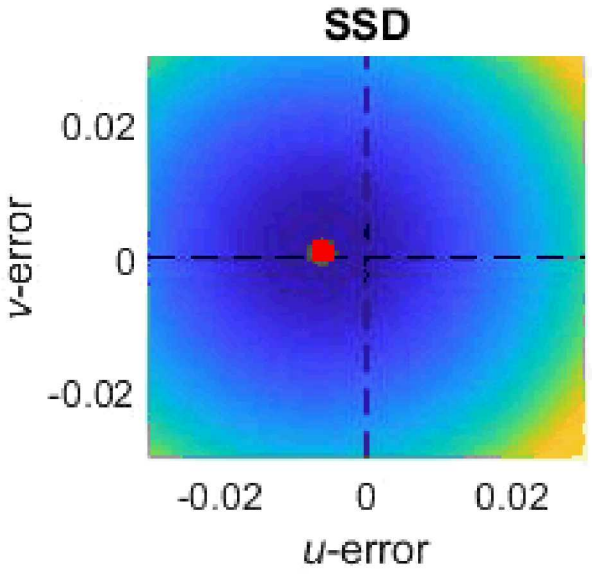
This error can be modeled

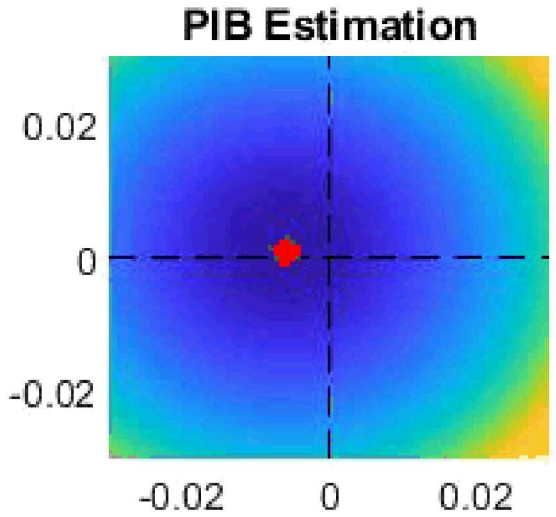
$$\boldsymbol{U}_{PIB} = u(\mathbf{0}, \underset{\boldsymbol{p}}{\operatorname{argmin}} \frac{1}{2} \sum_{\Omega} (\nabla I(\boldsymbol{X}_0 + \boldsymbol{x}) \cdot \boldsymbol{\delta})^2) - [\boldsymbol{u}(\mathbf{0}, \boldsymbol{q}) + \boldsymbol{E}(\boldsymbol{X}_0)]$$

PIB is related to the image gradient, and any errors within the gradient such as image noise, heat haze, etc.
-$\nabla I$ Acts as weight

Therefore, it is unique for different DIC patterns. Even under the same noise, undermatched shape function, etc.

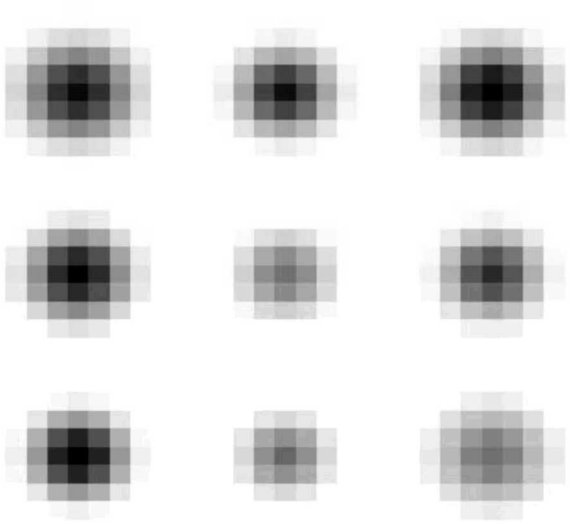


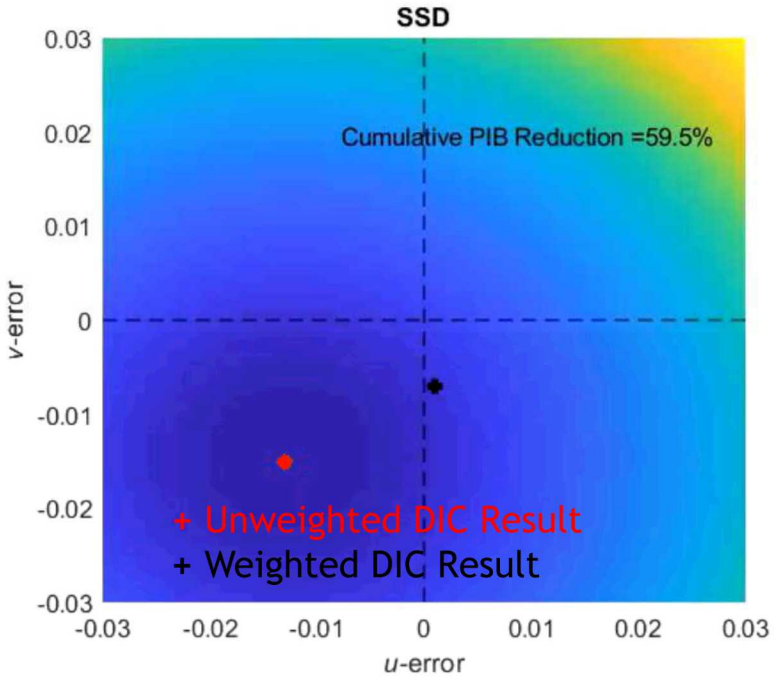


# The PIB error can be minimized within the correlation algorithm

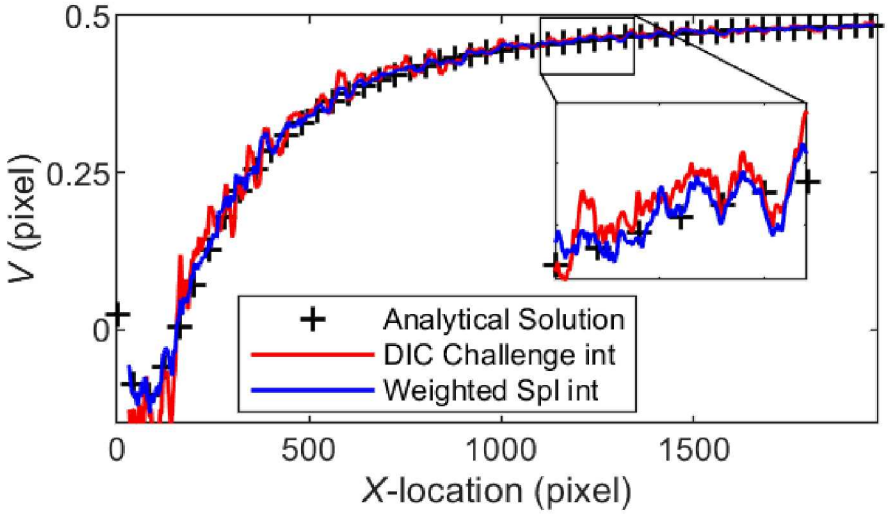
$$W_{SSD}^{i}(\boldsymbol{x}) = \frac{\beta}{|\nabla I^{i}(\boldsymbol{X}_0 + \boldsymbol{x})| + \beta}$$






The gradient based weighting is more effective with larger PIB errors.

# The improvement of PIB can also be seen in the DIC Challenge image

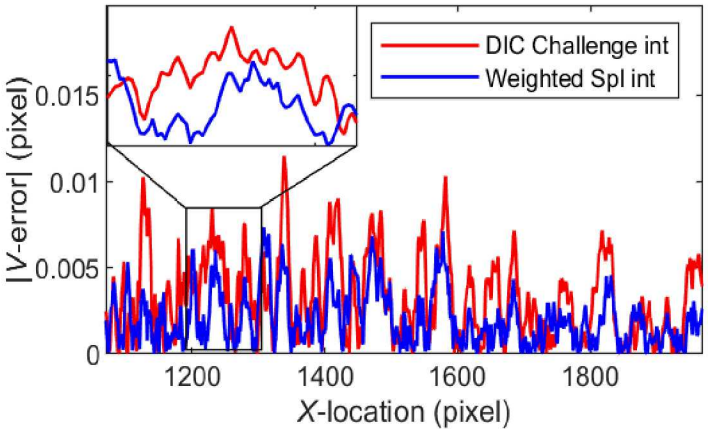


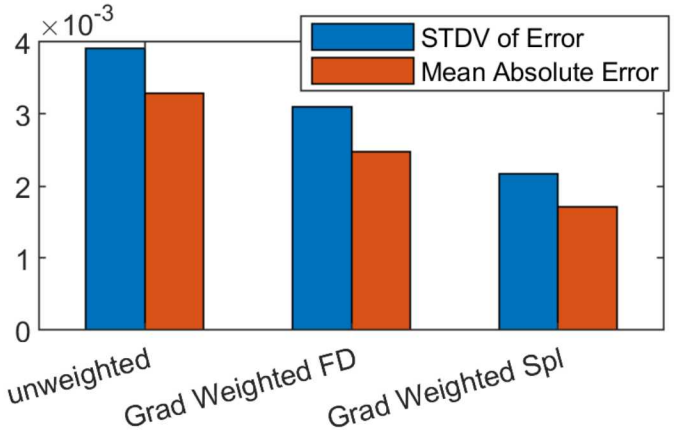

This method is highly effective in the unresolvable region

Applications in deconvolution techniques[1]

[1]Grediac, DOI:10.1007/s11340-018-00461-4

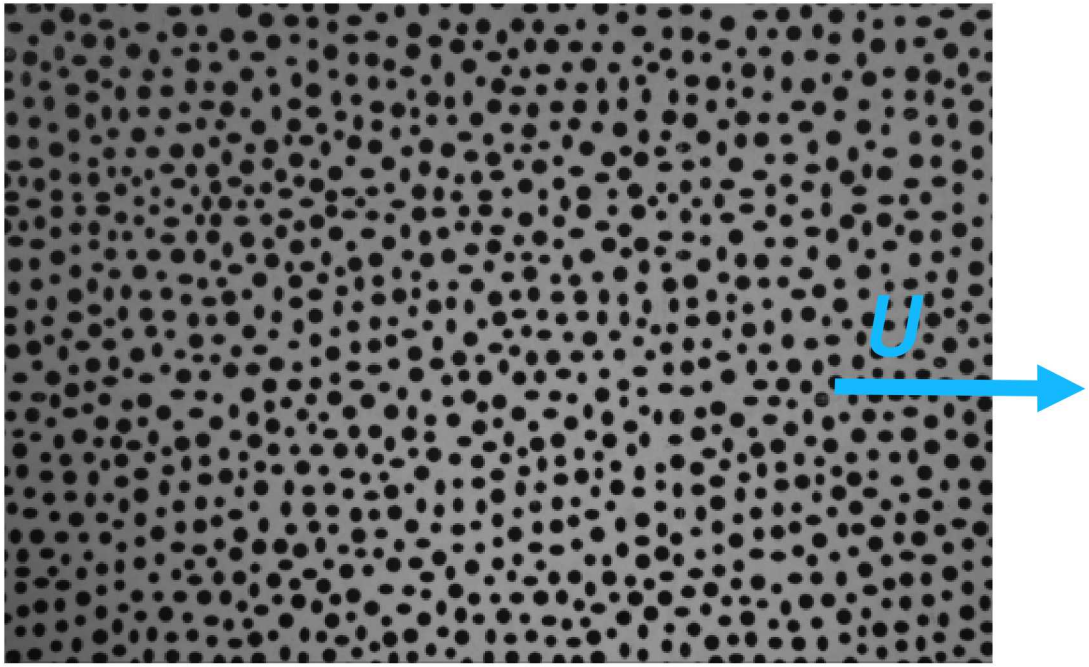
The improvement in the resolvable region is less pronounced but is improved with better estimates of the gradient ~50% improvement



# The weighting leads to the increase of other errors, especially when the subset shape function is well matched

Rigid body motion experiment: DIC Challenge FFT Shift (0.1px increments)



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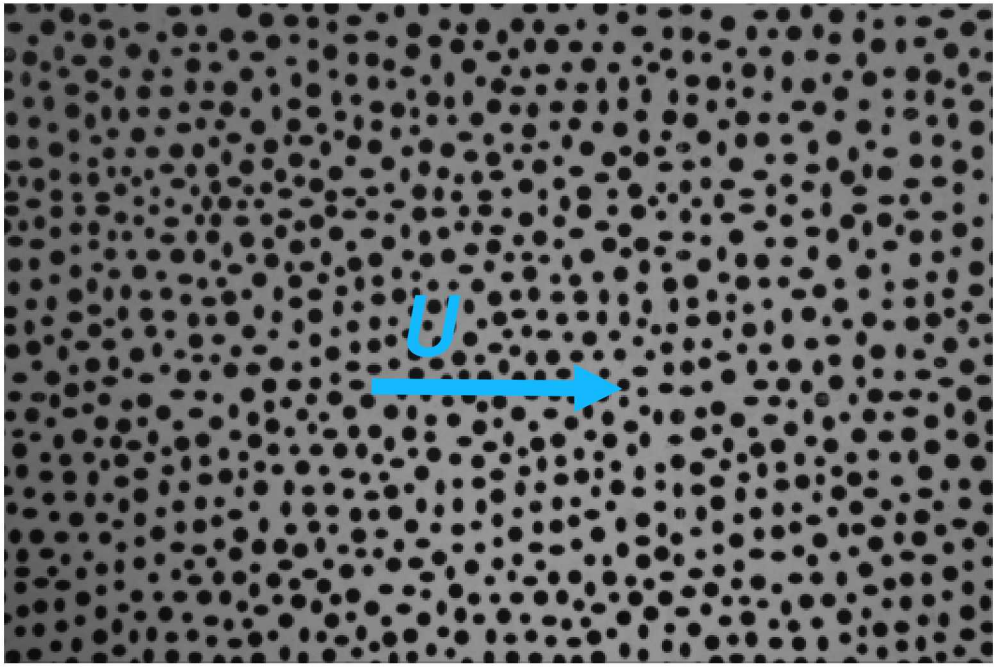

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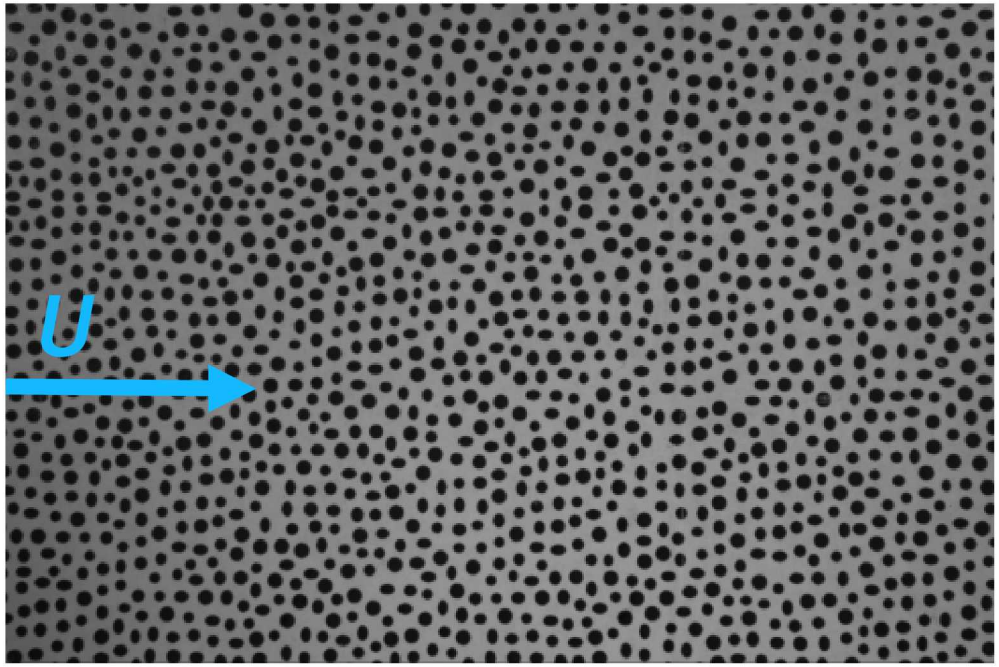
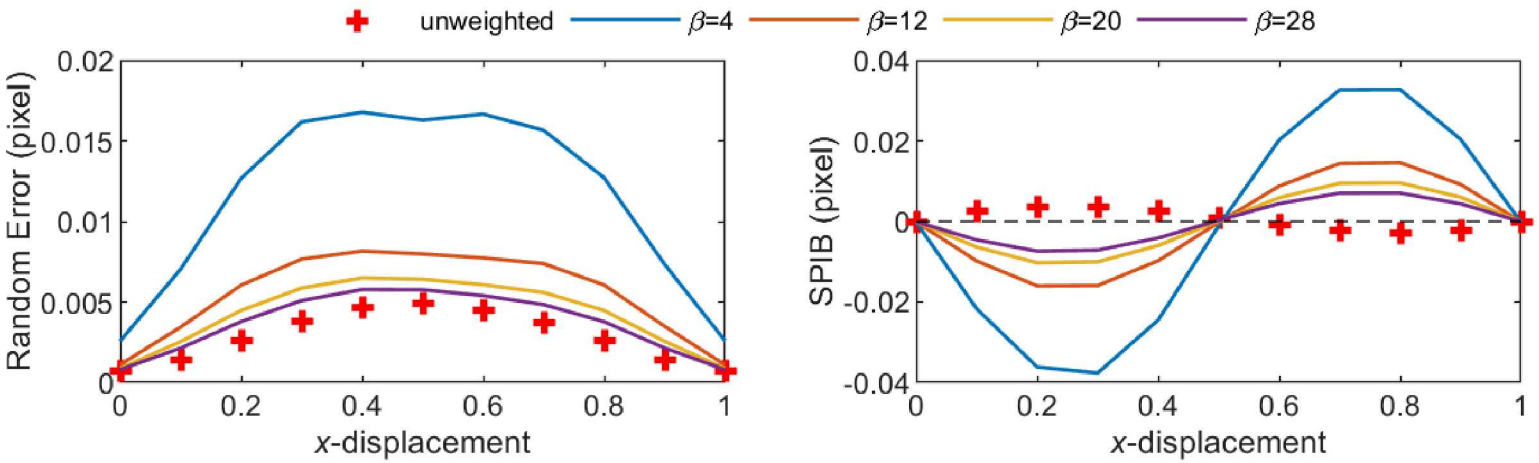


# The weighting leads to the increase of other errors, especially when the subset shape function is well matched

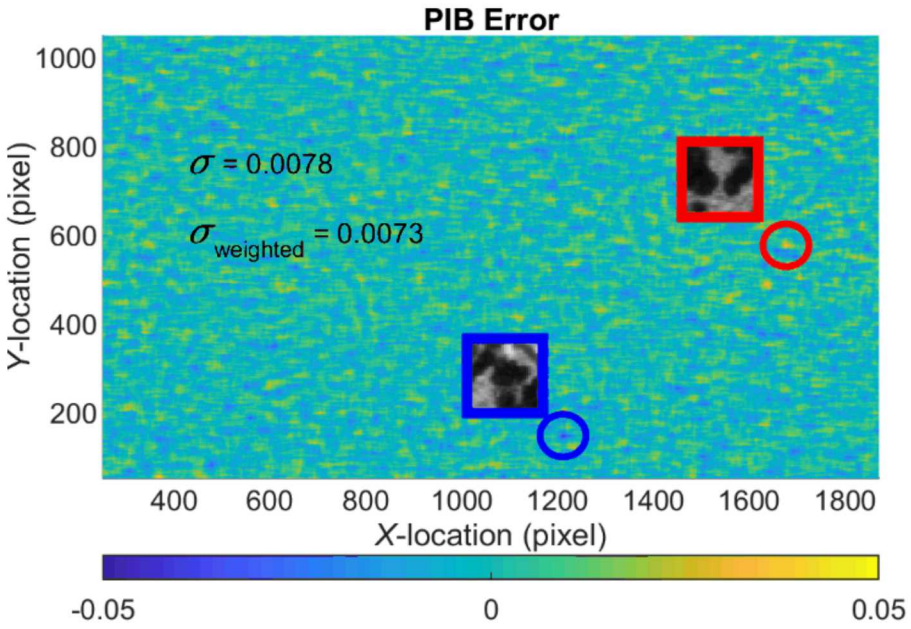
$$W_{SSD}^{i}(\boldsymbol{x}) = \frac{\beta}{|\nabla I^{i}(\boldsymbol{X}_0 + \boldsymbol{x})| + \beta}$$

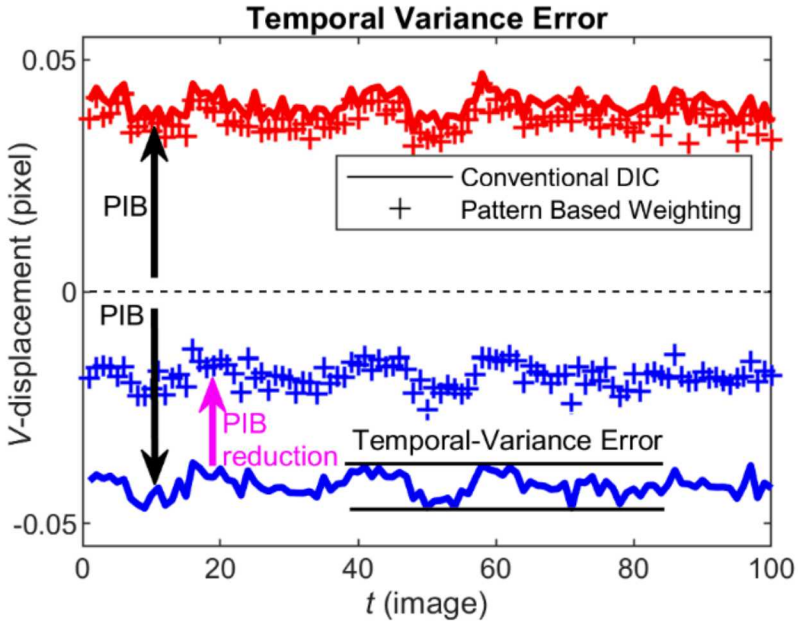



Random error measured as the full-field standard deviation of error

Error from gray-value interpolation also increases due to the uniform decrease of matching contrast.

# The improvement in PIB error is heavily negated by the relative increase of these other error terms in experimentation



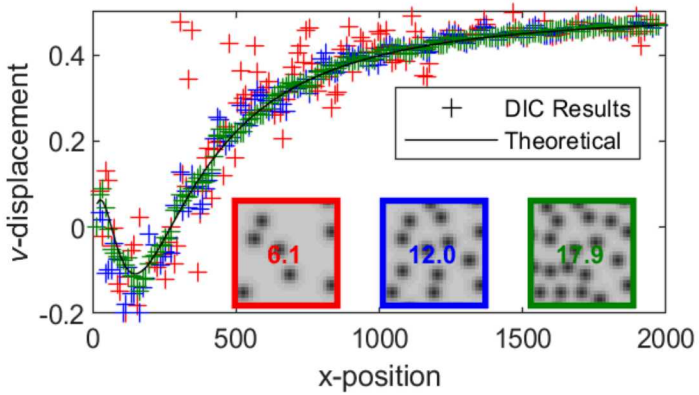
# The error also decreases as a function of pattern density

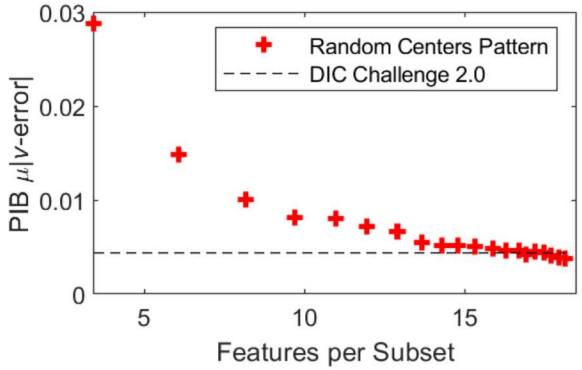
$$\boldsymbol{U}_{PIB} = u(\mathbf{0}, \underset{\boldsymbol{p}}{\operatorname{argmin}} \frac{1}{2} \sum_{\Omega} (\nabla I(\boldsymbol{X}_0 + \boldsymbol{x}) \cdot \boldsymbol{\delta})^2) - [\boldsymbol{u}(\mathbf{0}, \boldsymbol{q}) + \boldsymbol{E}(\boldsymbol{X}_0)]$$

The PIB error decreases as the pattern density is increased. (as long as the features are similar)

i.e. the feature frequency>>displacement frequency.

$$\boldsymbol{U}_{PIB} \cong u(\mathbf{0}, \underset{\boldsymbol{p}}{\operatorname{argmin}} \frac{1}{2} \sum_{\Omega} (\boldsymbol{\delta})^2) - [\boldsymbol{u}(\mathbf{0}, \boldsymbol{q})] \cong \mathbf{0}$$



# Conclusions

- PIB results in a spatial bias error
- PIB is not temporally-variant
- PIB is dependent on the pattern
- PIB occurs for all implementations of DIC due to the ubiquity of intensity patterns and experimental/systematic errors.
- PIB error can be reduced through:
  - Denser patterns
  - Center weighting subsets
  - Gradient-based weighting, at the cost of an increase in other error terms

Contact Information:
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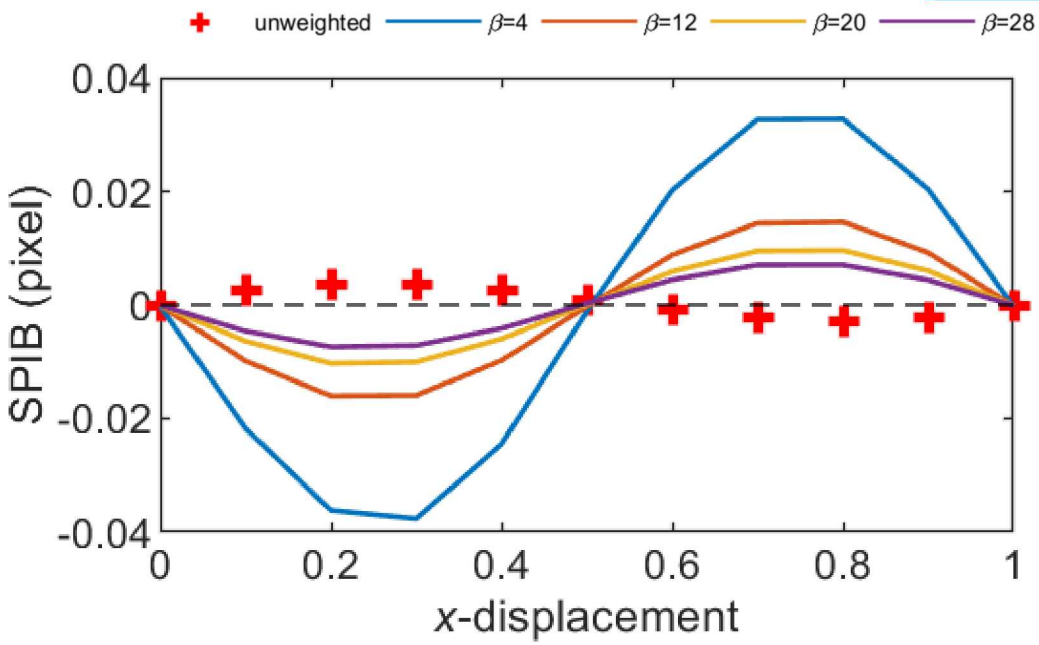
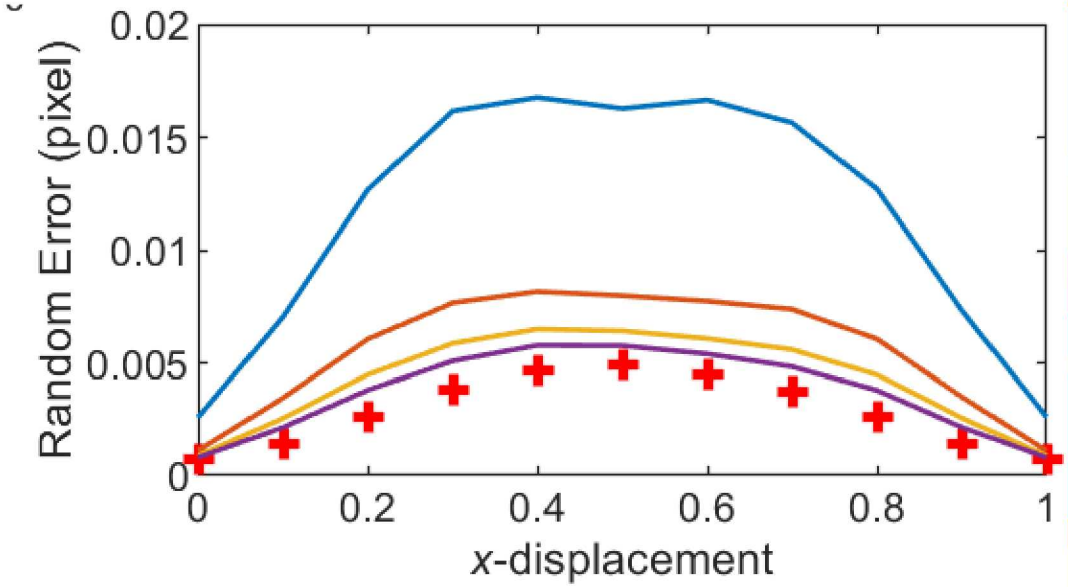
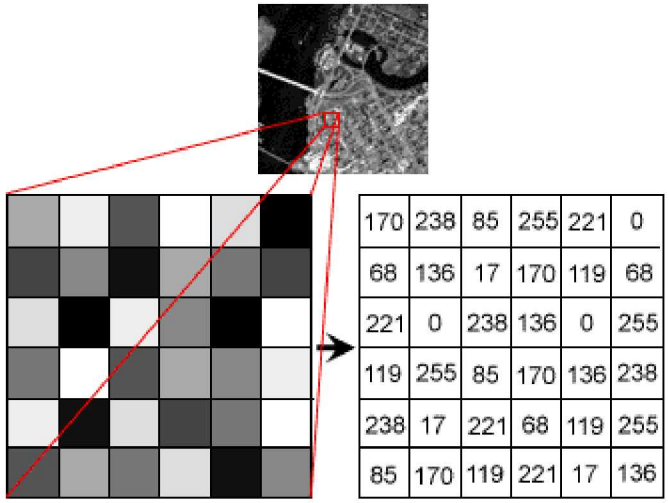
ssfayad@sandia.gov



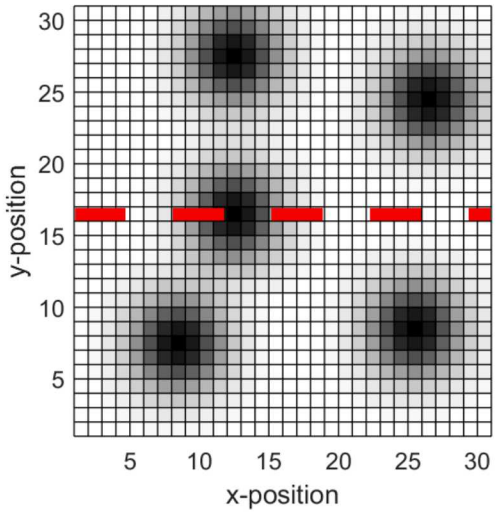



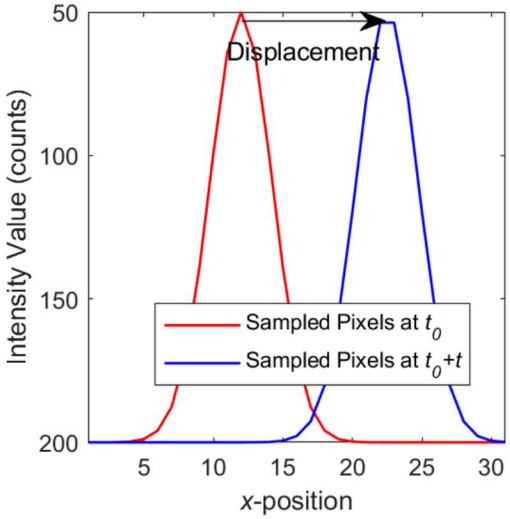
# Supplemental Material- DIC Basics

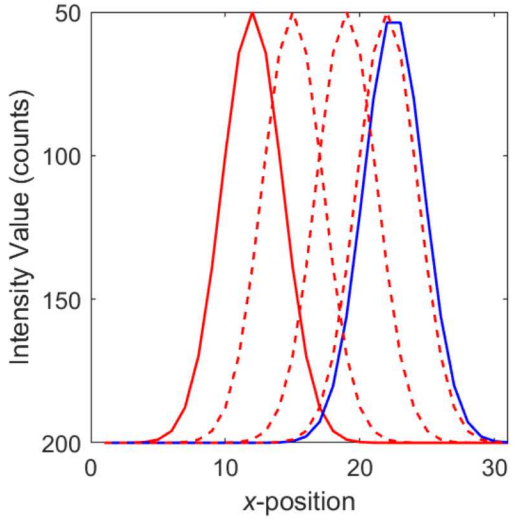


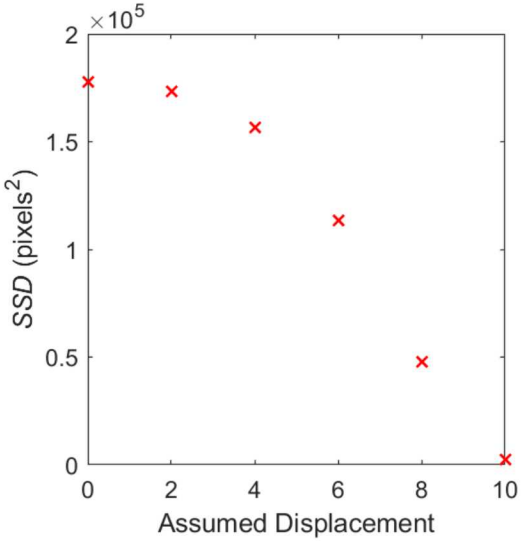
| | | | | | |
|---|---|---|---|---|---|
| 170 | 238 | 85 | 255 | 221 | 0 |
| 68 | 136 | 17 | 170 | 119 | 68 |
| 221 | 0 | 238 | 136 | 0 | 255 |
| 119 | 255 | 85 | 170 | 136 | 238 |
| 238 | 17 | 221 | 68 | 119 | 255 |
| 85 | 170 | 119 | 221 | 17 | 136 |

Spatially discrete integer values representing an 8-bit digital image. The zoomed in shows 6x6 pixels with their corresponding intensities which range from 0 to 255. (CCRS Tutorial, 1998)



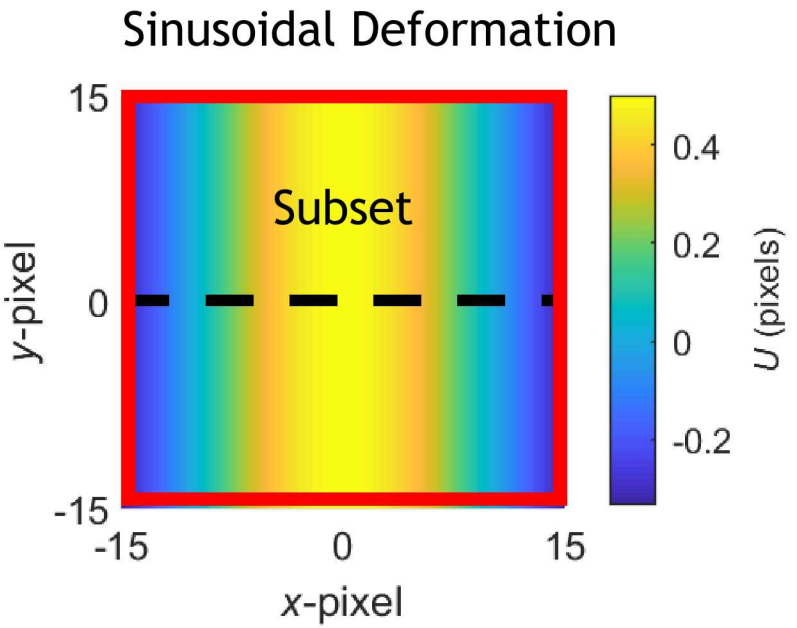



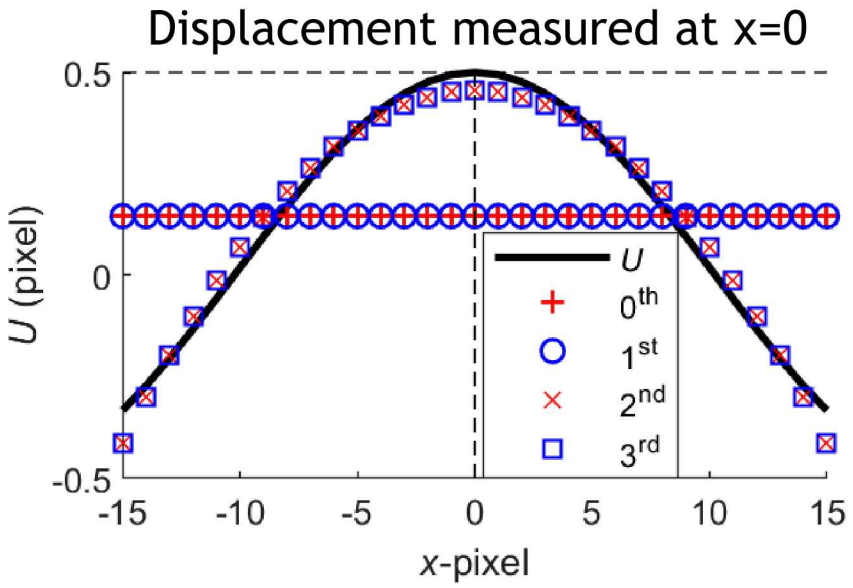



# This error was initially noticed when the shape function was undermatched.

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



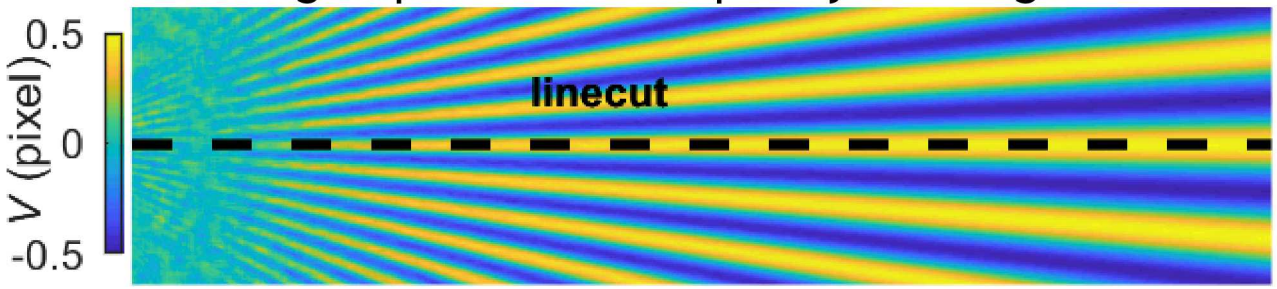




Deviation from true deformation (black line) is shape function attenuation bias

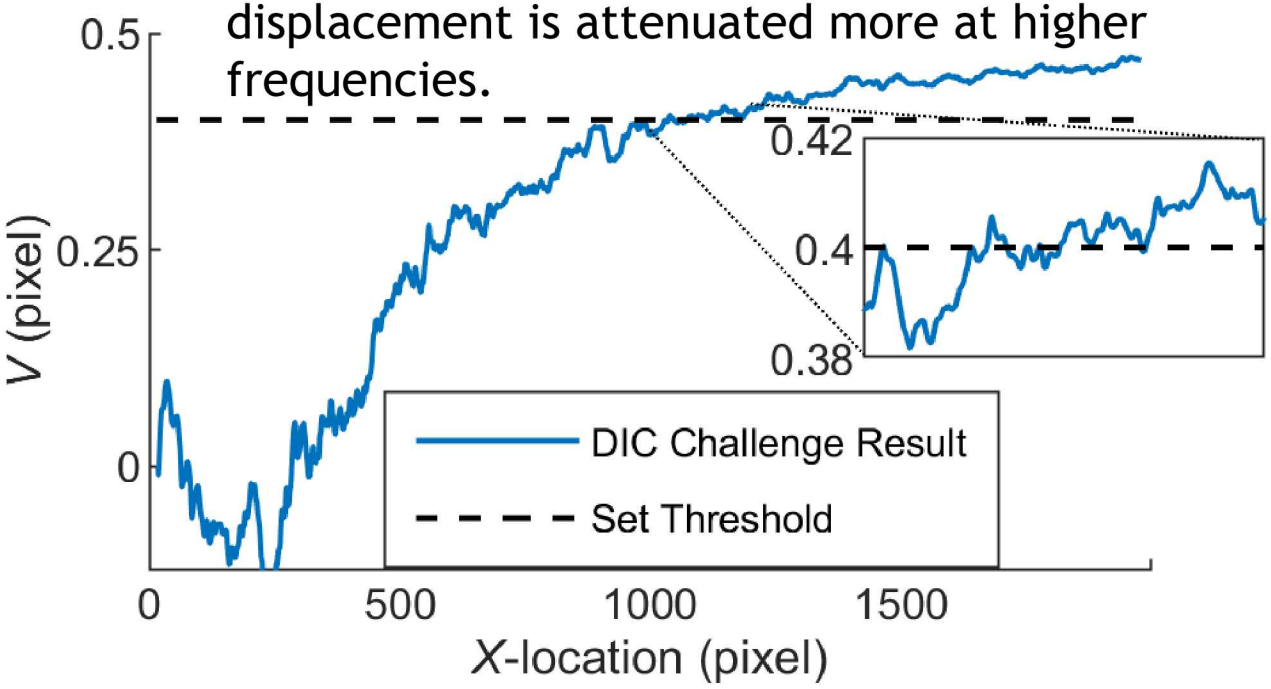
# Shape function attenuation bias dictates the correlation results in the DIC Challenge 2.0 images.

Image Characteristics:

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

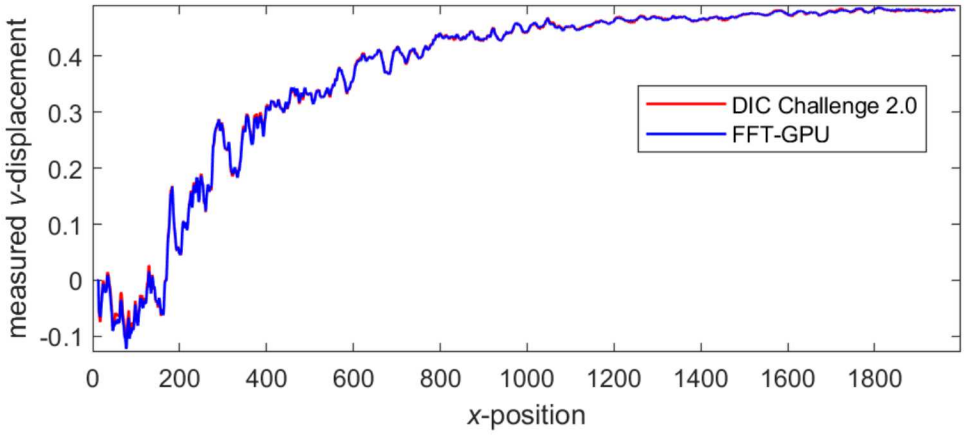


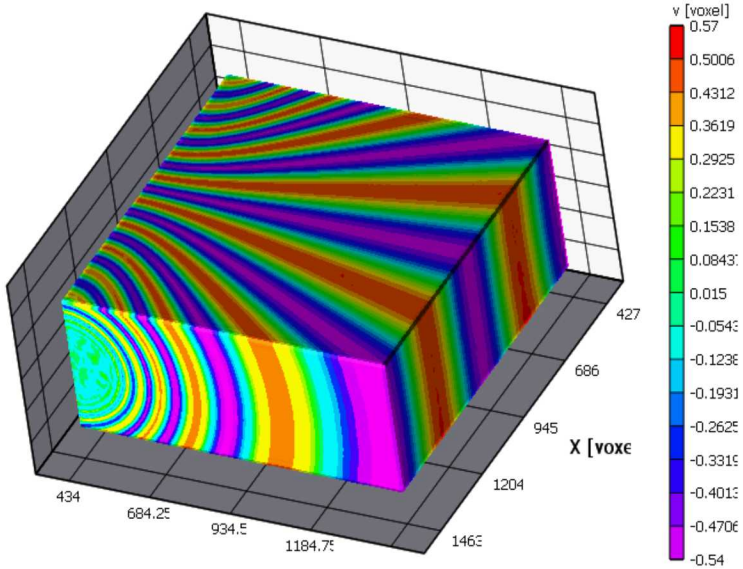

Due to shape function attenuation bias, the displacement is attenuated more at higher frequencies.



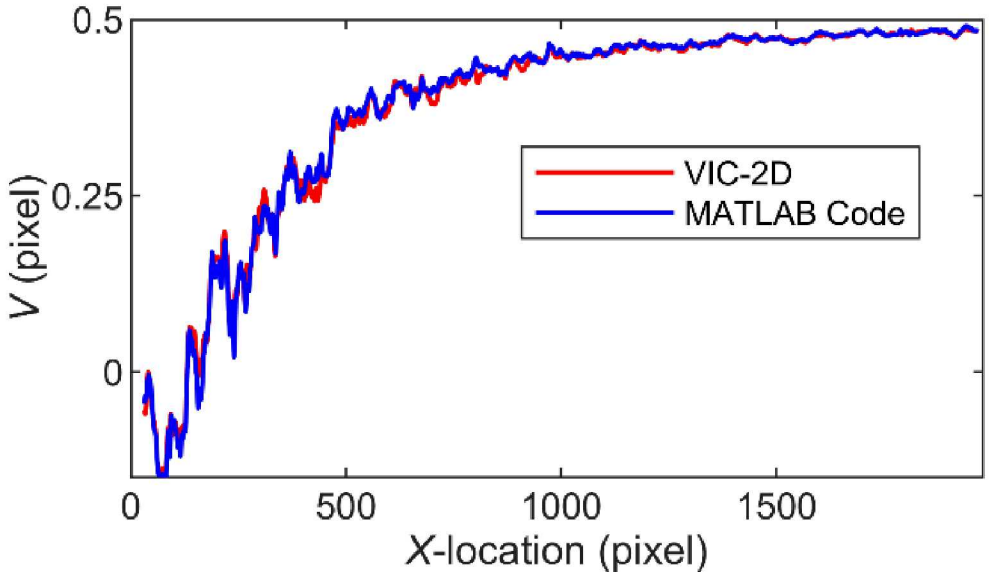

The DIC solution crosses the threshold multiple times, obfuscating the resolution limit.

# Supplemental Material – Deformation code validation

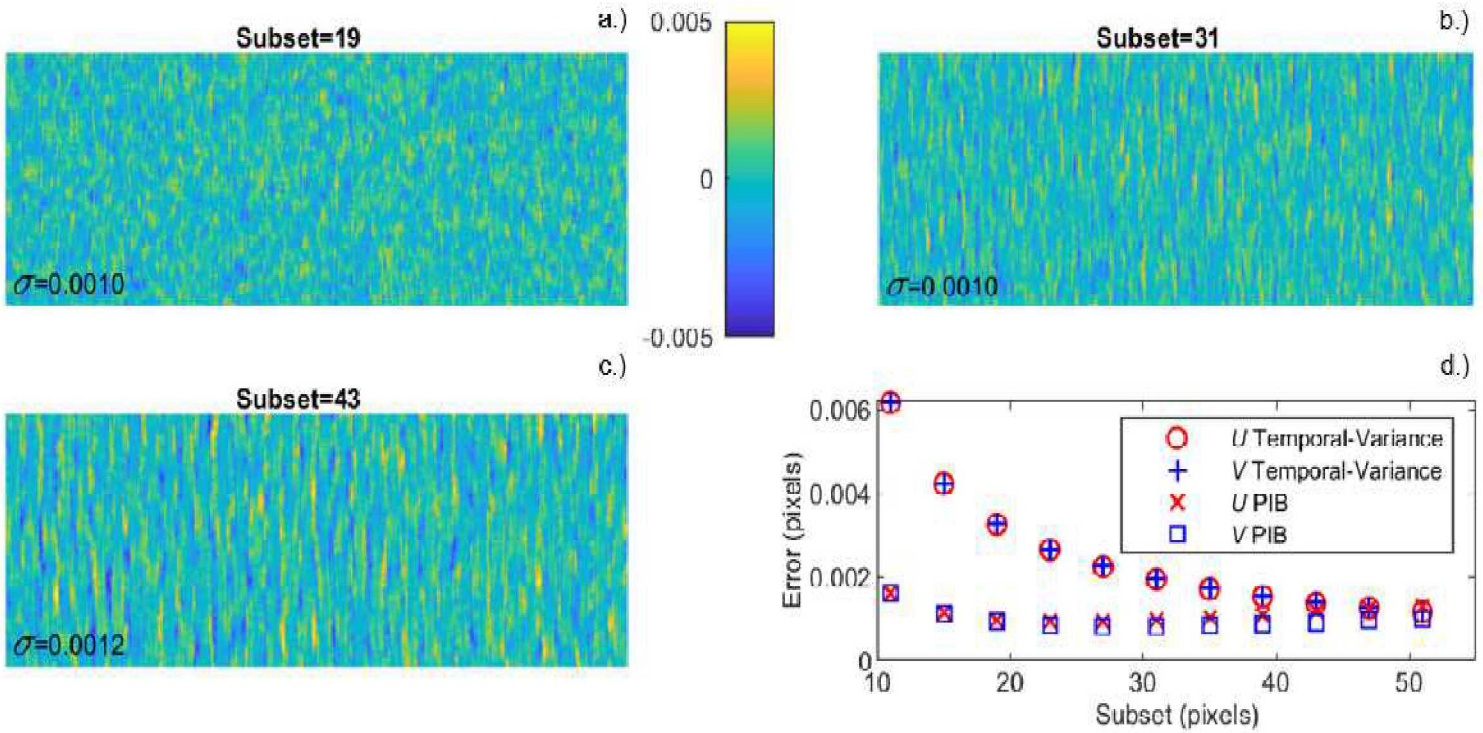


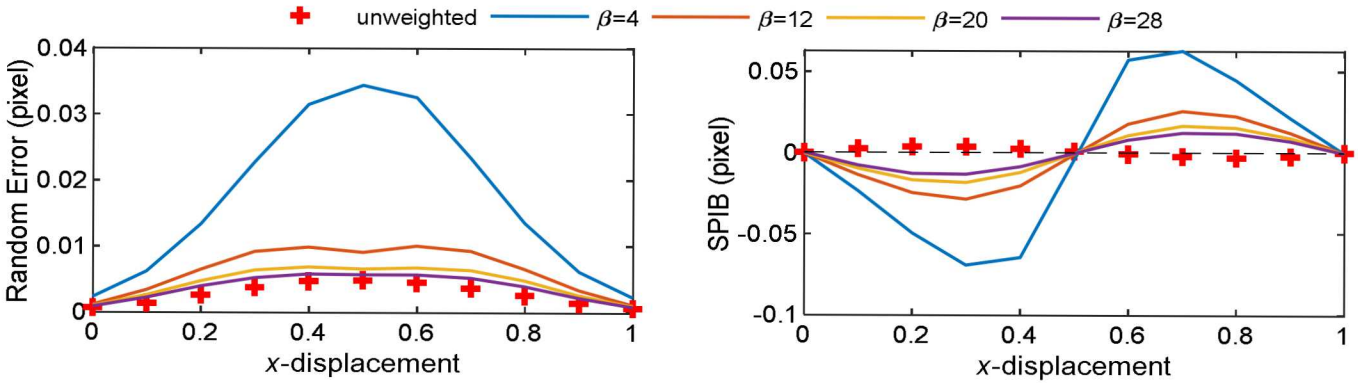
# Supplemental Material – DIC code validation

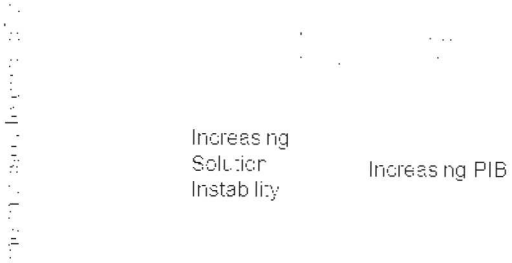


# Supplemental Material – pib vs subset

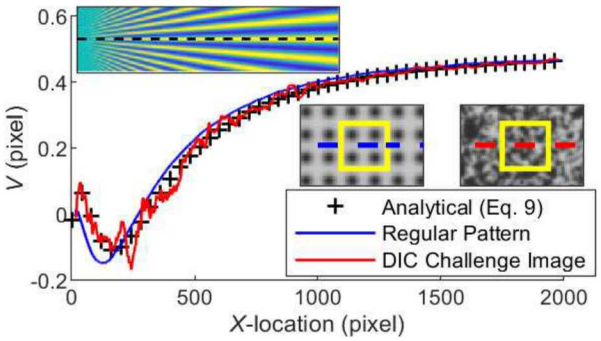


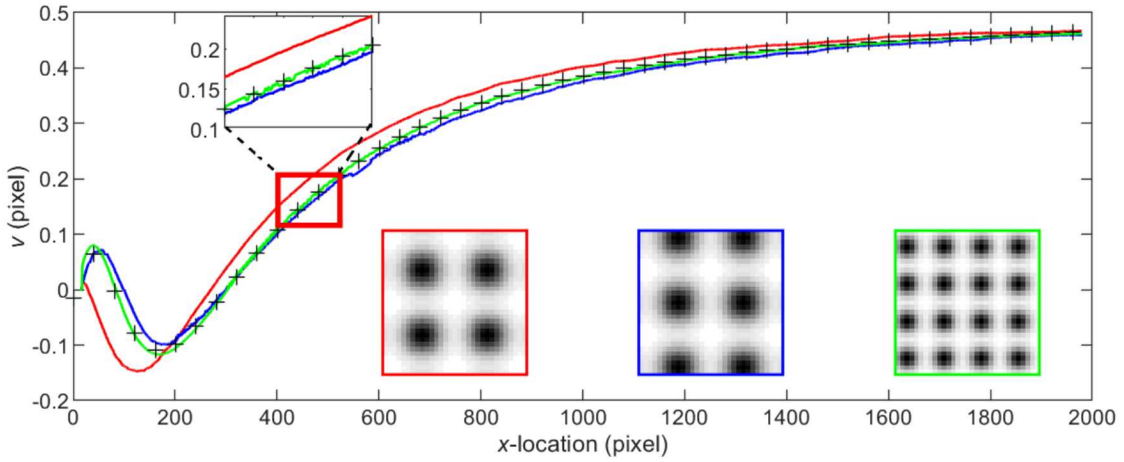
# Supplemental Material – Improvement with GBW, DIC Chal

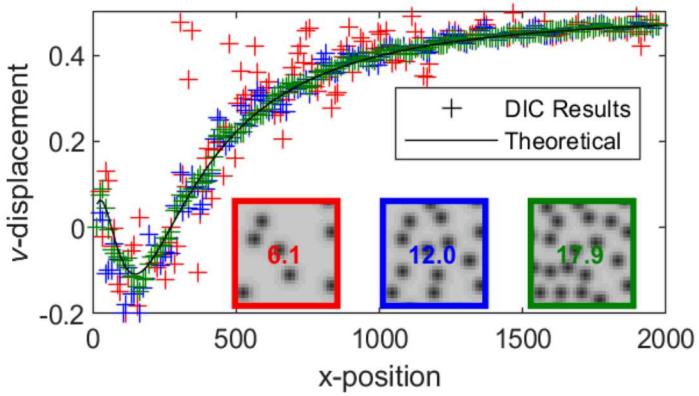


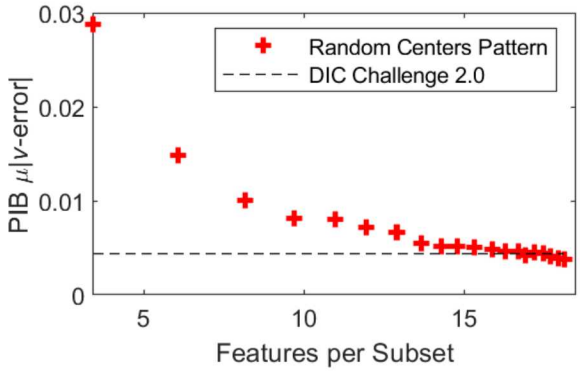



# Supplemental Material – high frequency pattern



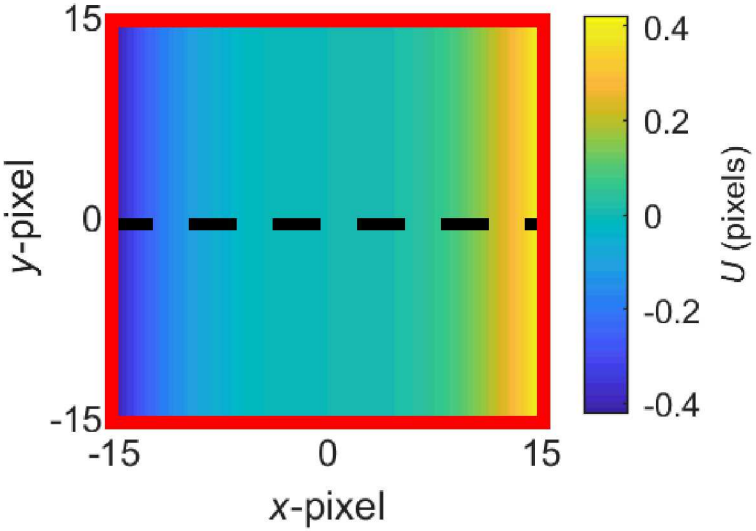



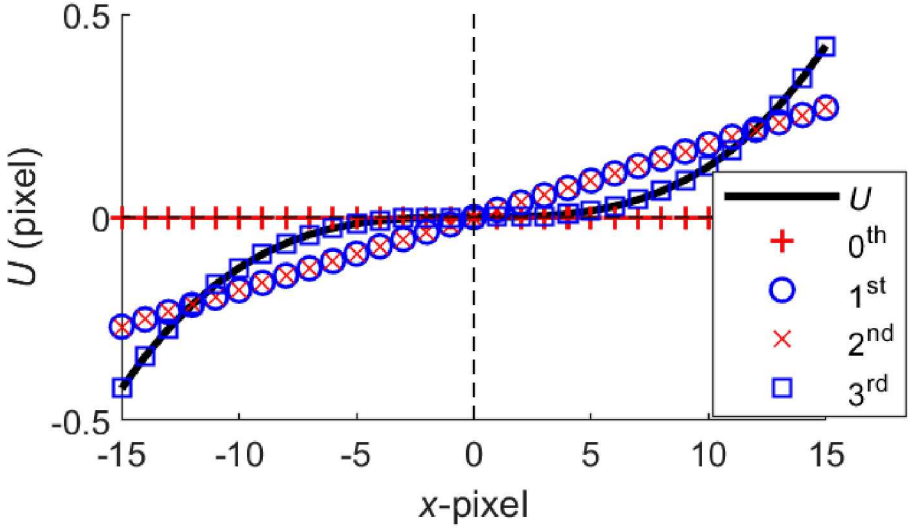
# Antisymmetric deformations are undermatched, but don't produce shape function attenuation bias

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