The feasibility of dynamic full-field earthquake measurements from space: a laboratory study

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Acknowledgments:
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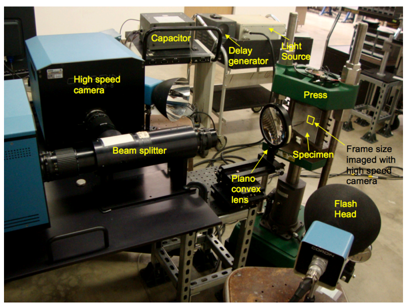
Laurence Bodelot, Vahe Gabuchian

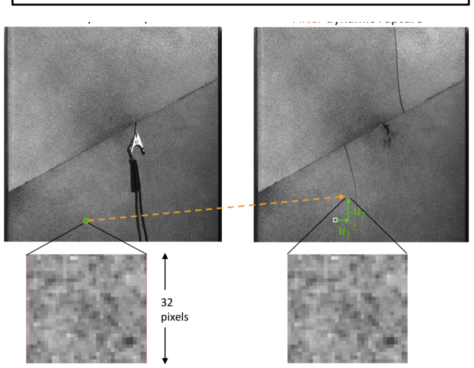
Summary

Background

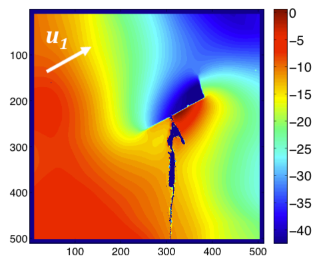
Experimental setup

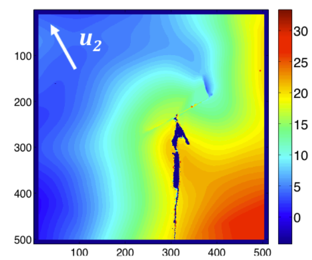


Experimental Method:
Digital Image Correlation

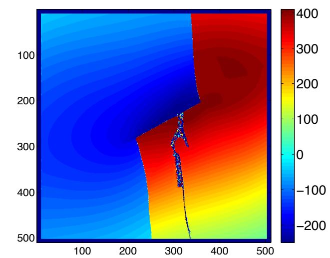


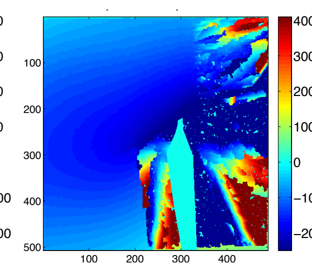
Displacement field – Test1
The importance of filtering data



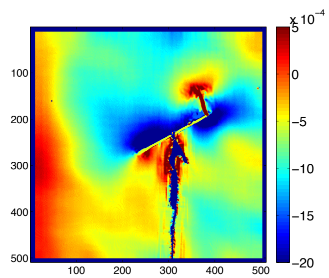


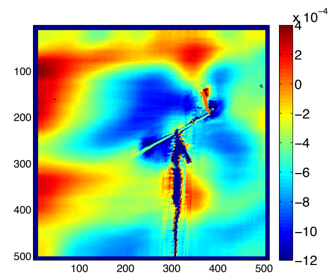
Displacement field – Test2
COSI-Corr vs. VIC-2D



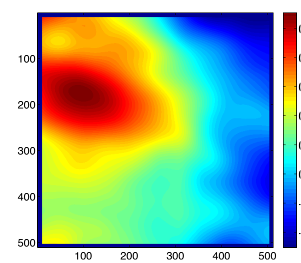


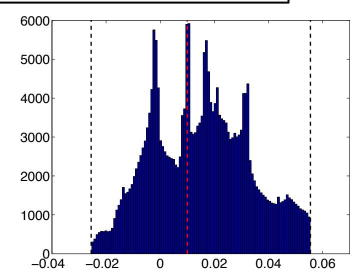
Strains– Test1



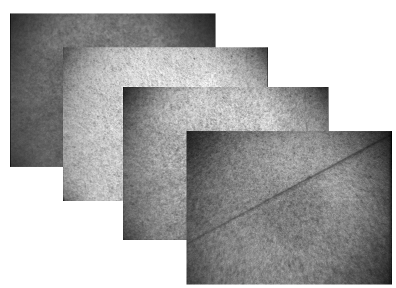


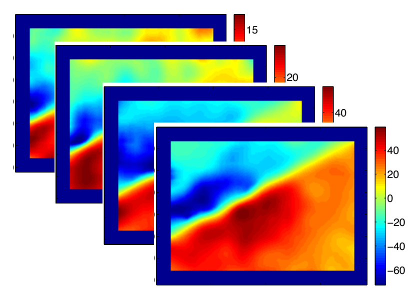
How accurate are our results
Error analysis

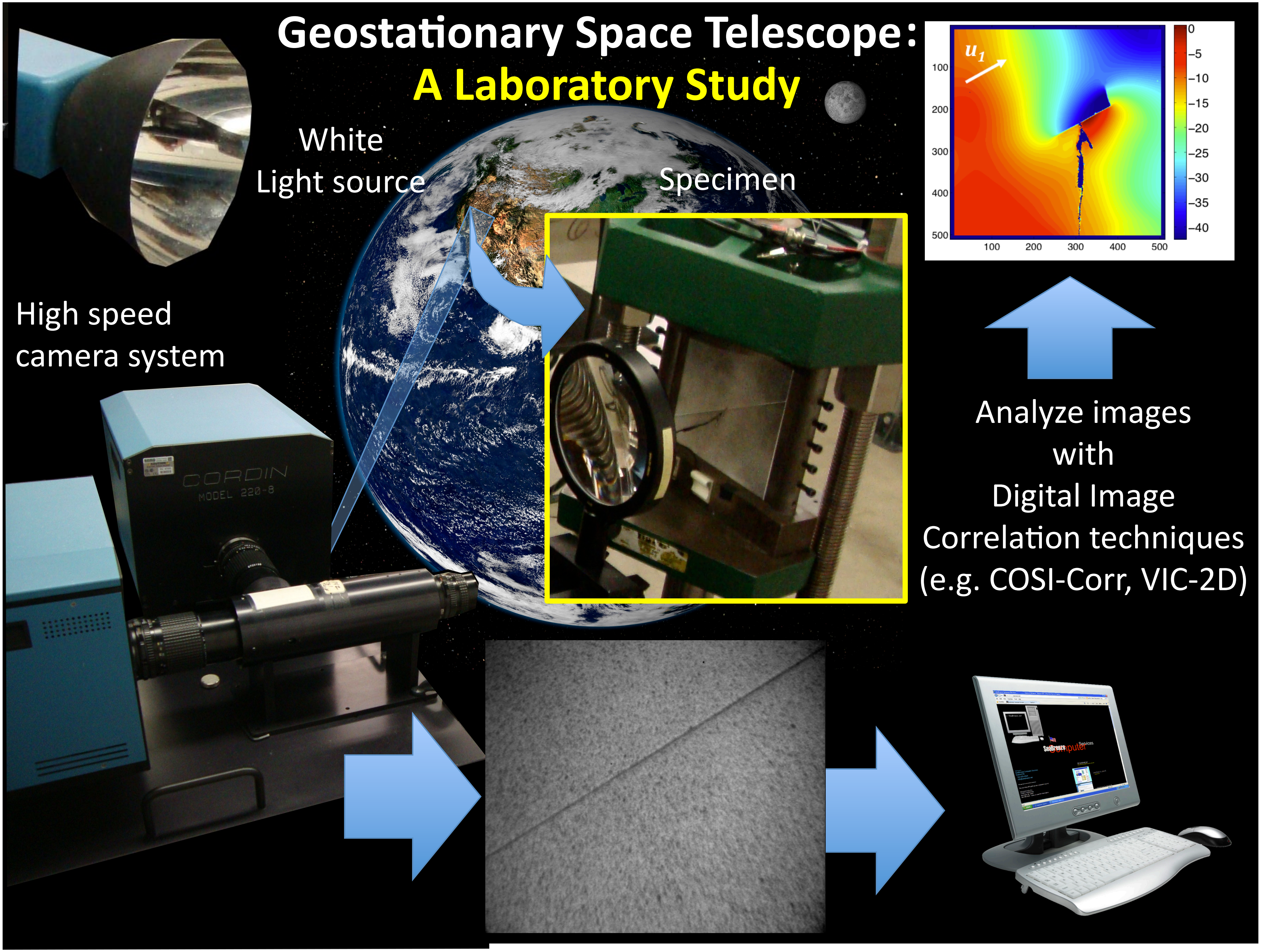


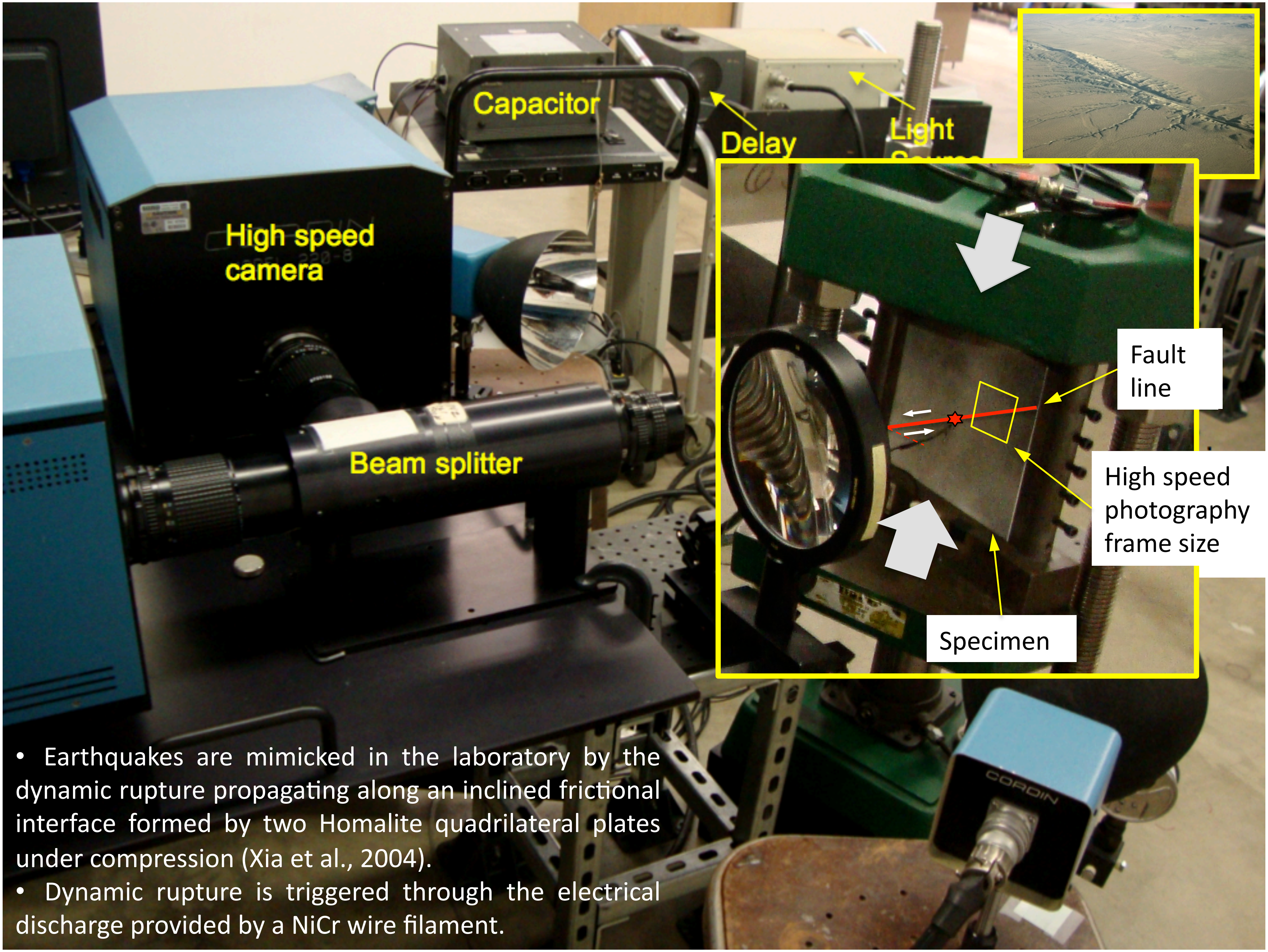


High Speed Photography
Preliminary results



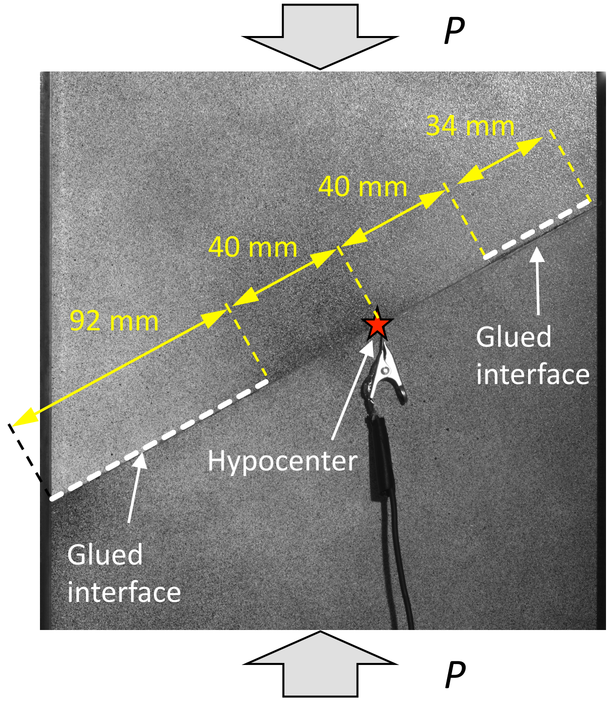



Geostationary Space Telescope:
A Laboratory Study
White
Light source
Specimen
High speed
camera system
Analyze images
with
Digital Image
Correlation techniques
(e.g. COSI-Corr, VIC-2D)



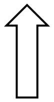
- Earthquakes are mimicked in the laboratory by the dynamic rupture propagating along an inclined frictional interface formed by two Homalite quadrilateral plates under compression (Xia et al., 2004).
- Dynamic rupture is triggered through the electrical discharge provided by a NiCr wire filament.

Geometry and Loading Configuration



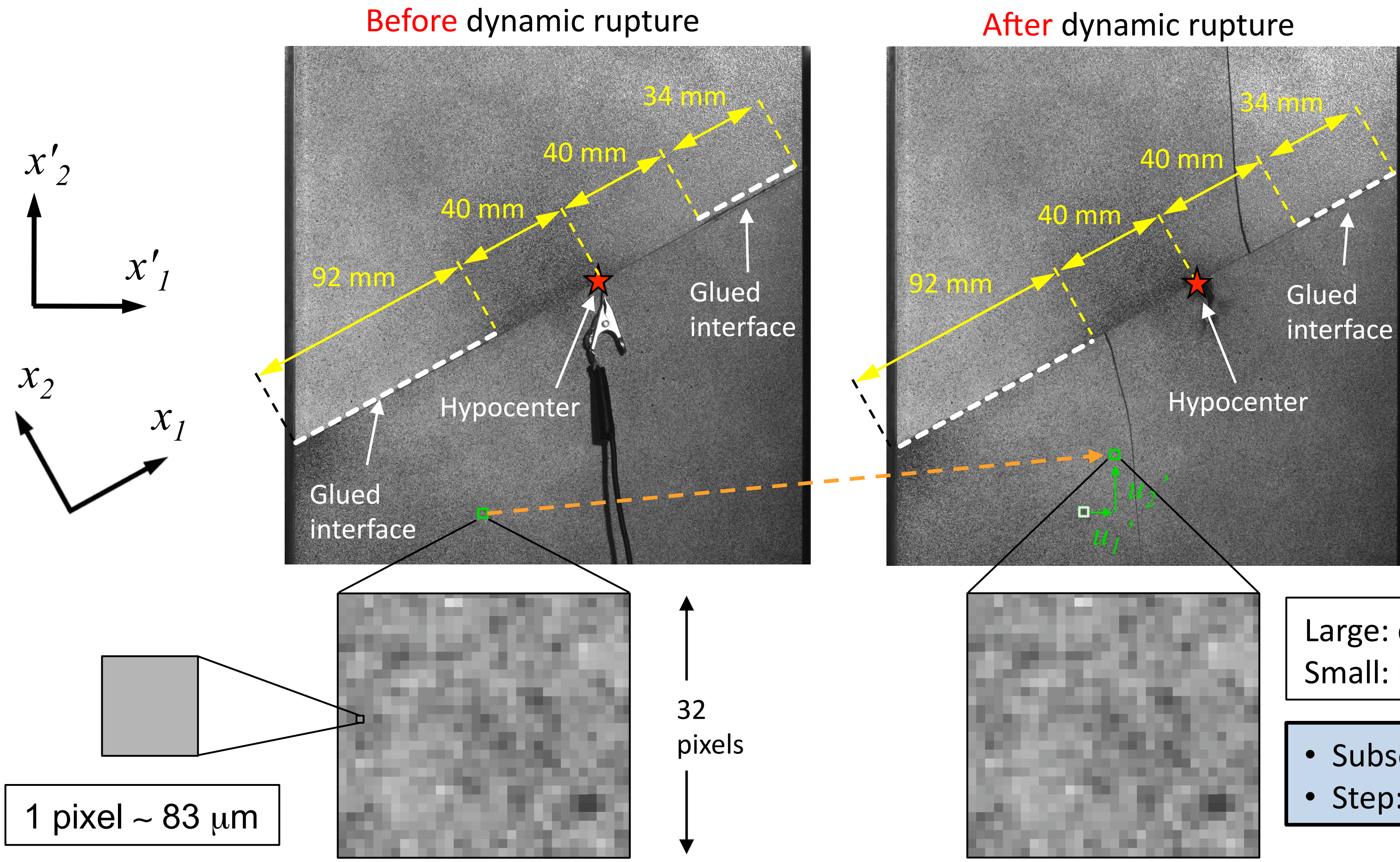
We will discuss two tests:

- *P* = 5 MPa (subRayleigh)
- *P* = 15 MPa (supershear)



Expected rupture speed (from previous experiments)

The Digital Image Correlation Method



CCD Camera:
JAI Pulnix/TM4200CL
2048 x 2040 pixels

High Speed Camera:
Cordin 220
767x 574 pixels

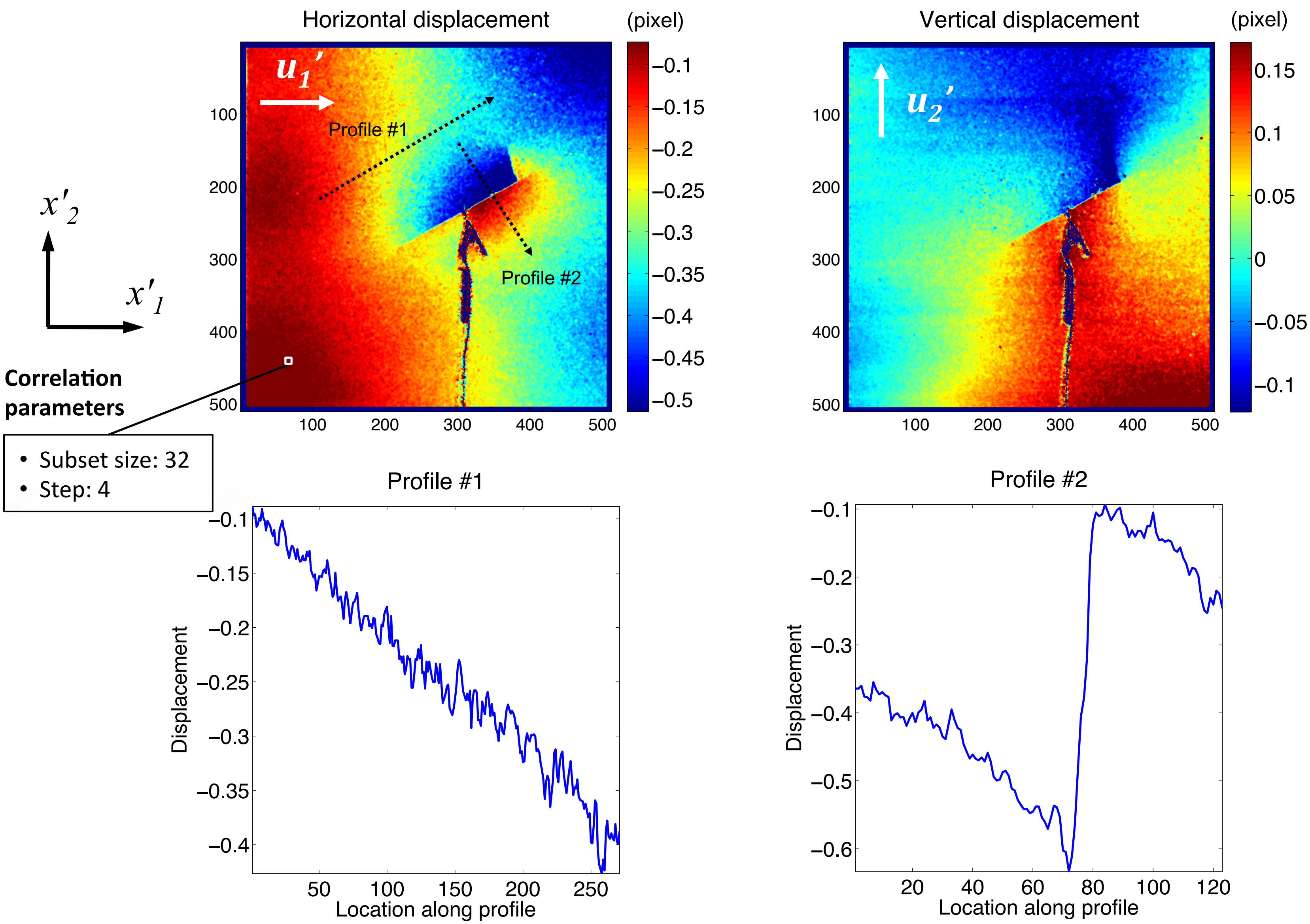
Large: characteristic pattern
Small: high resolution

- Subset size: 32x32
- Step: 4

- Digital Image Correlation (DIC) is an optical method to measure the deformation on a specimen surface.
- DIC technique identifies gray level patterns in small pixel subsets and tracks their motion during deformation.
- Two methods are used in this study:
  - COSI-Corr (Leprince et. al, 2007).
  - VIC-2D (Correlated Solutions Inc.)

Displacement Field - *Unfiltered*

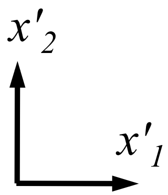
Test 1, P = 5 MPa



Displacement Field - *Filtered*

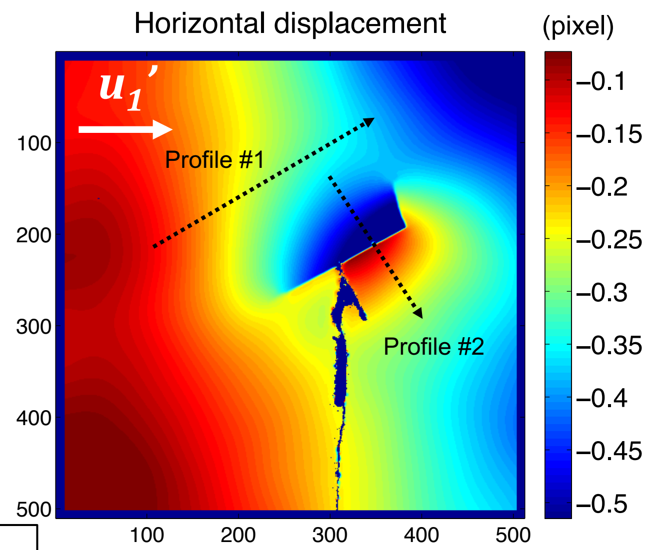
← **Non local means filter (Buades et al., 2008)**

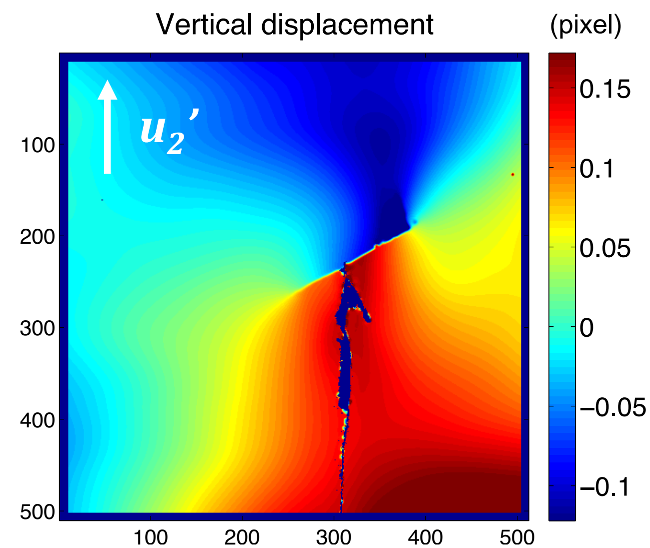
Test 1, P = 5 MPa

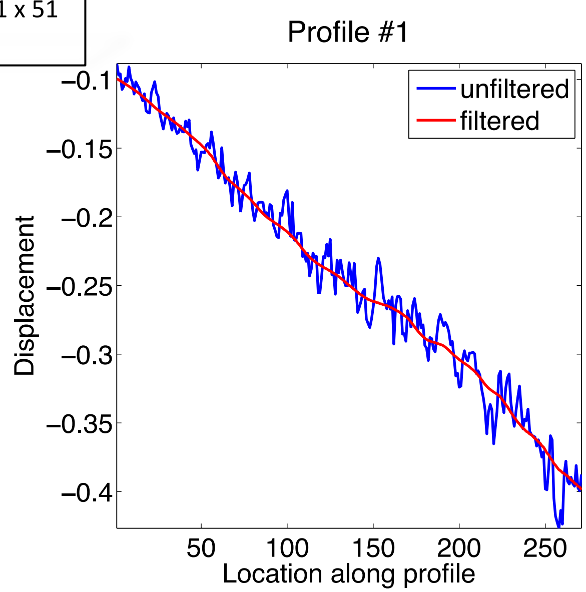


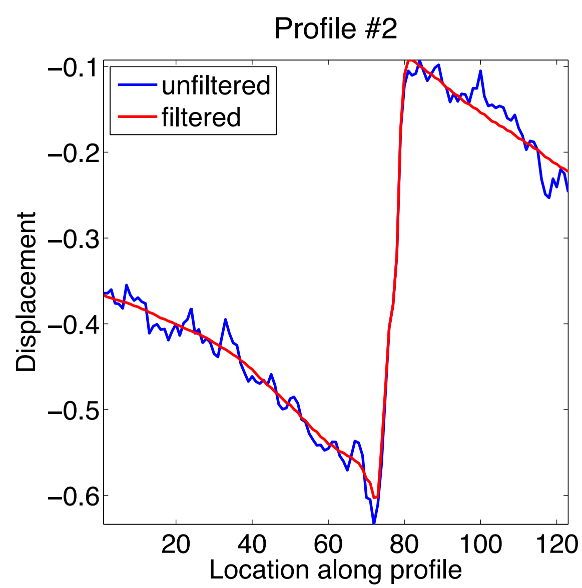
Filtering parameters

- Noise param.: 0.1
- Window size: 51 x 51
- Patch size: 5 x 5



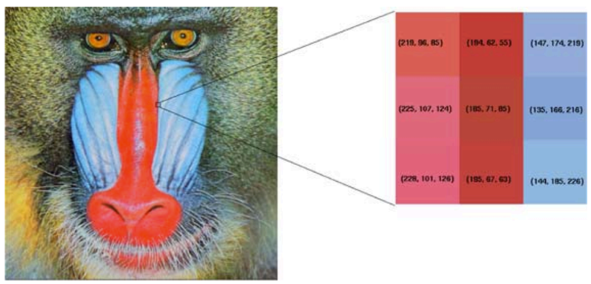




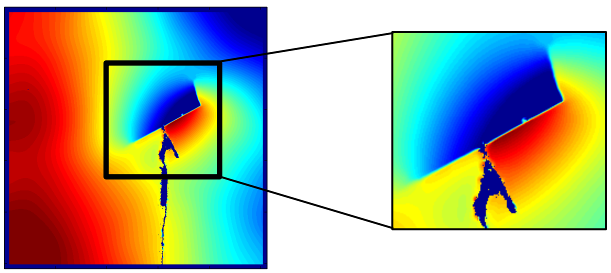


The Non Local Means Filter (NL-Means)

(Buades et al., 2008; Goosens et al. 2008)

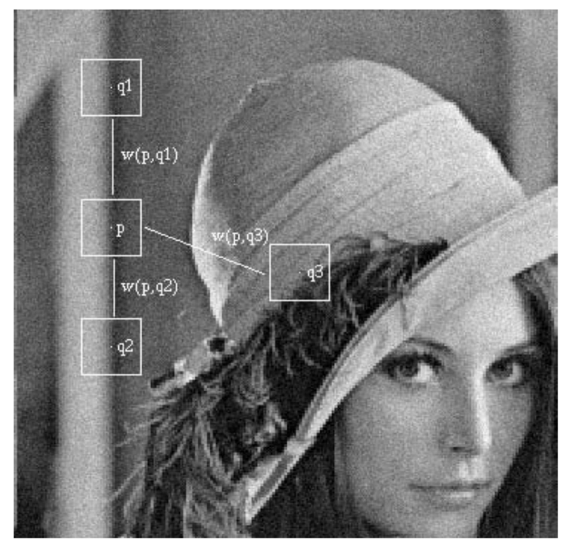


- Local smoothing filters give blurred edges
- In contrast the NL-means filter avoids the blurring effect

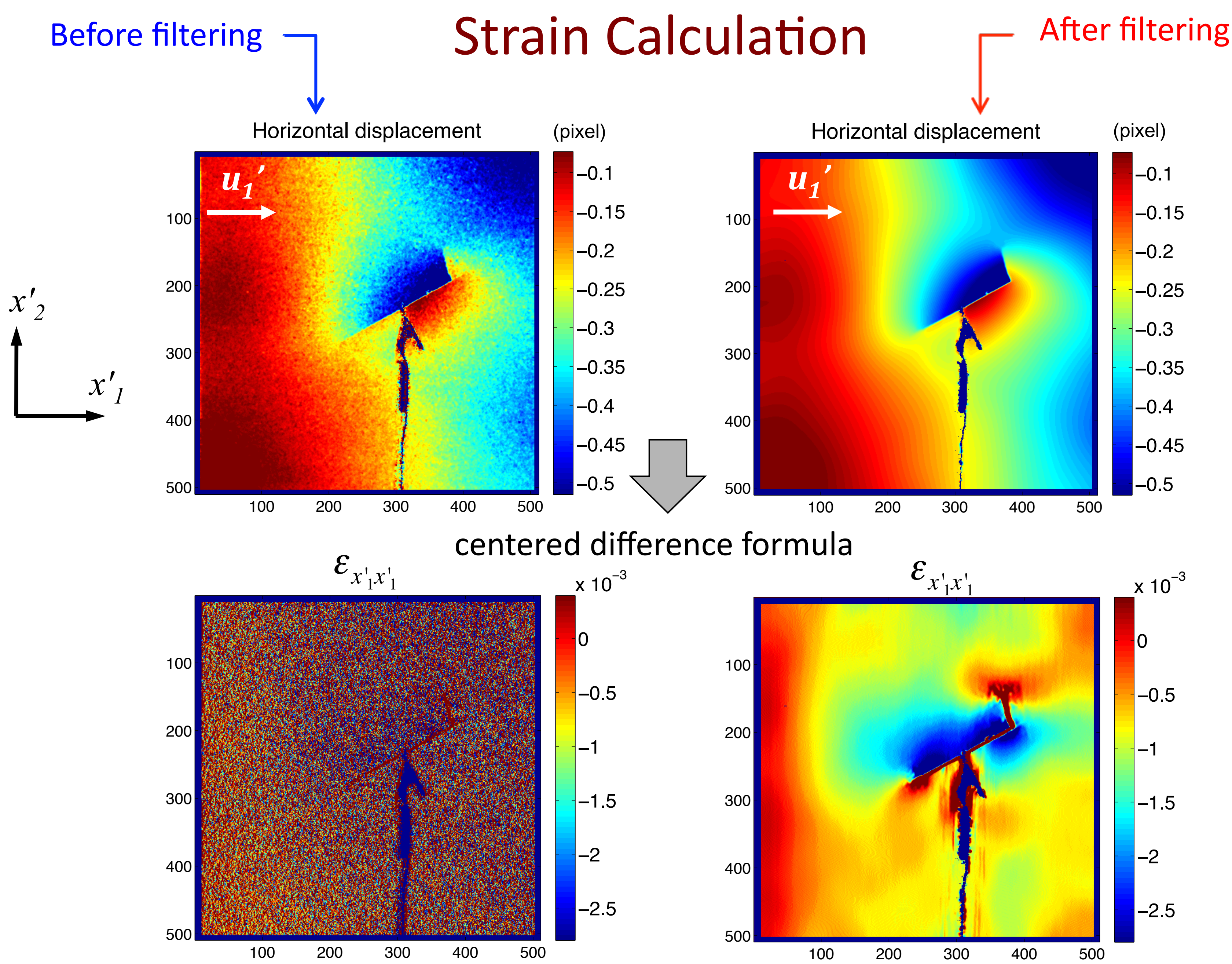


- It is very useful to accurately reproduce the displacement field of our experiments, which contains sharp edges near the interface and wing cracks.

- In an image, most details occur repeatedly.
- For example, each color box in the image to the left refers to a group of squares which are almost indistinguishable
- The NL-means filter exploits this property of image self-similarity to eliminate noise
- The squares similar to each other are averaged out.



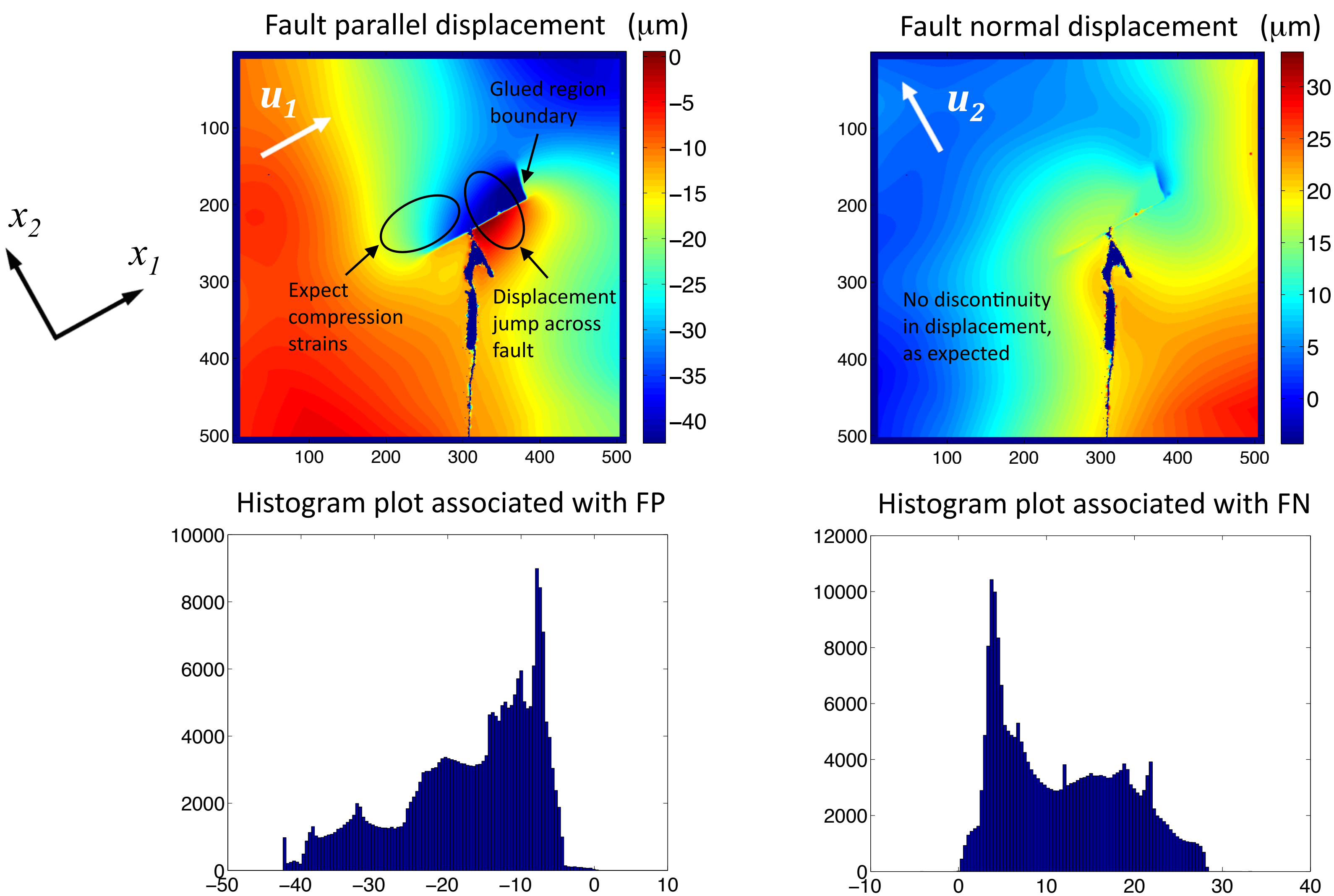
COSI-Corr includes in its tools an implementation of the Non-Local Means algorithm for denoising datasets and images, based on Buades et al., 2008 and Goosens et al., 2008.



Strain Calculation
Before filtering
After filtering
Horizontal displacement
(pixel)
Horizontal displacement
(pixel)
u1'
u1'
x'2
x'1
centered difference formula
εx'1x'1
x 10^-3
εx'1x'1
x 10^-3

Fault parallel and fault normal displacements

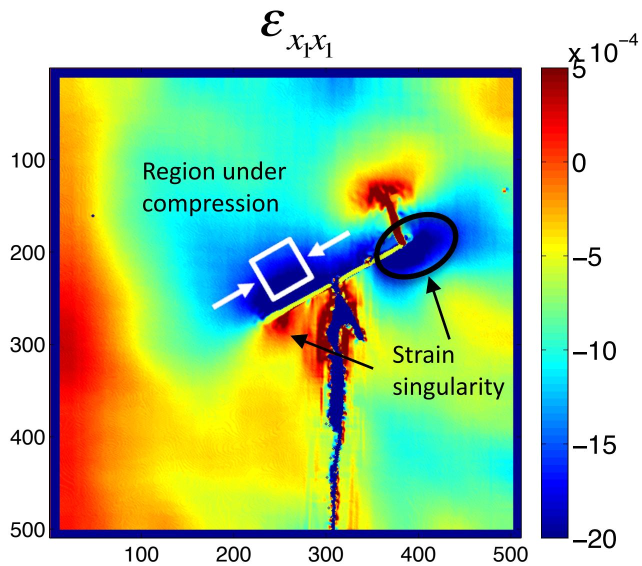
Test 1, P = 5 MPa

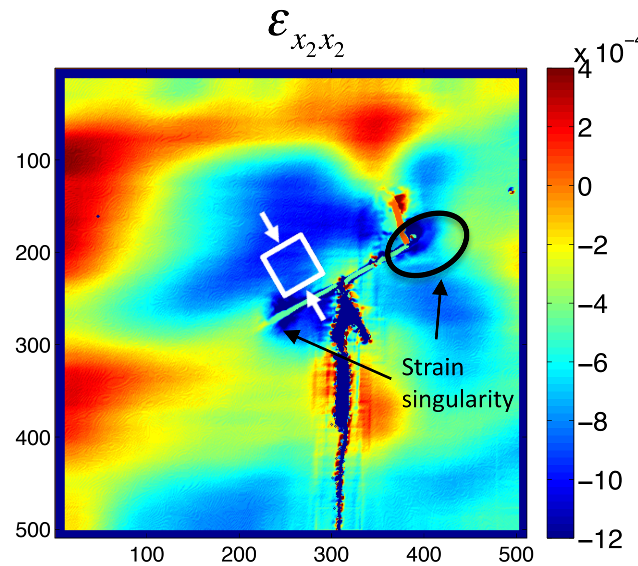


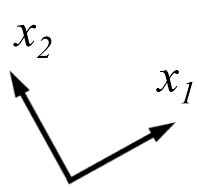
Overall the results show that rupture has propagated along the frictional interface, consistent with Rosakis et al. (2007), but has been stopped at the glued boundaries.

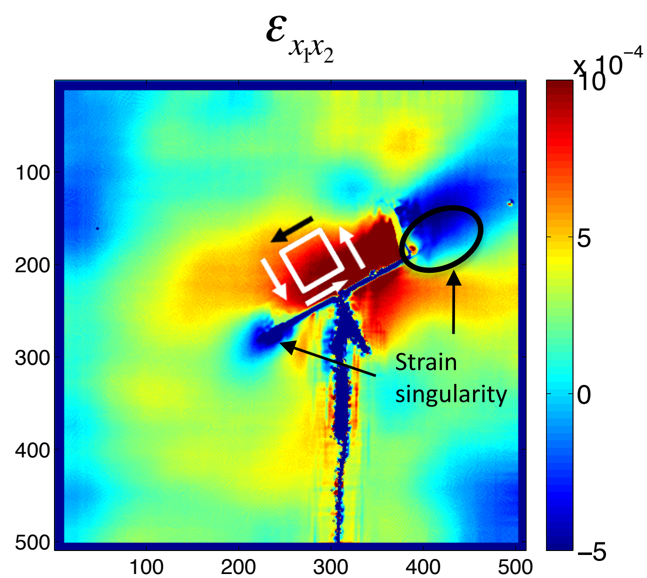
Normal and Shear Strains

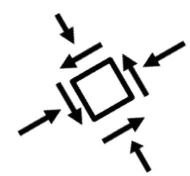
Test 1, *P* = 5 MPa







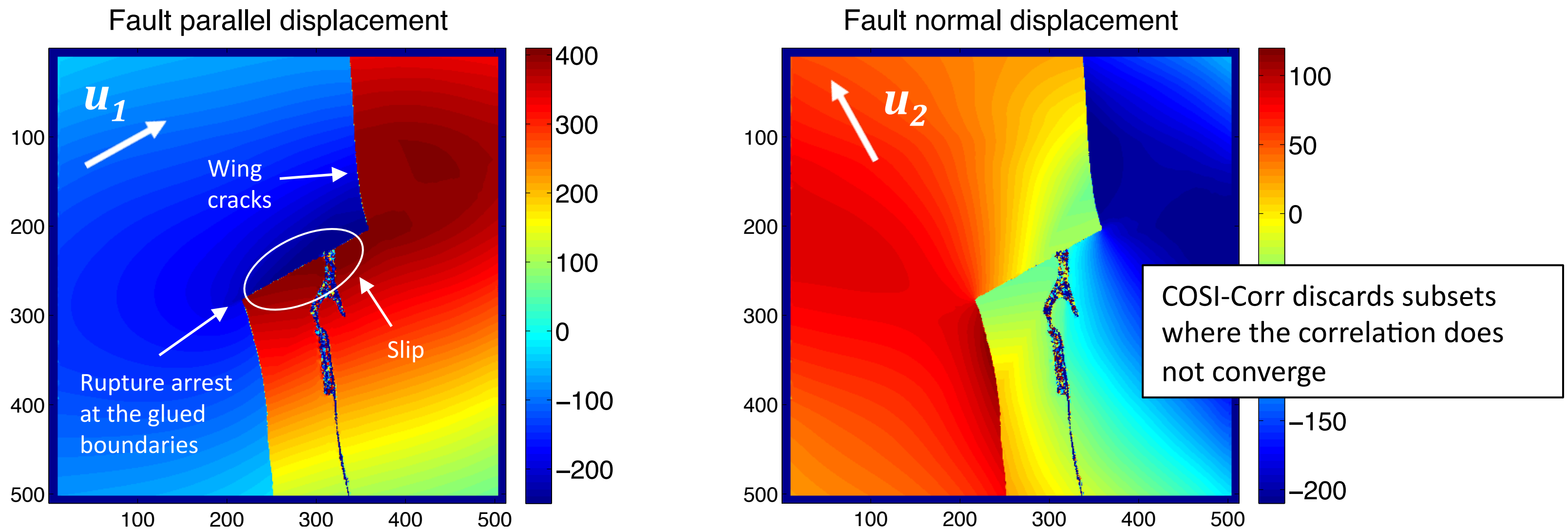


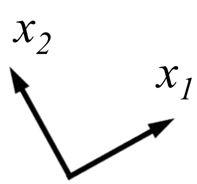


The method allows to determine the complete state of strain (and stress) of virtually any point within the field of view.

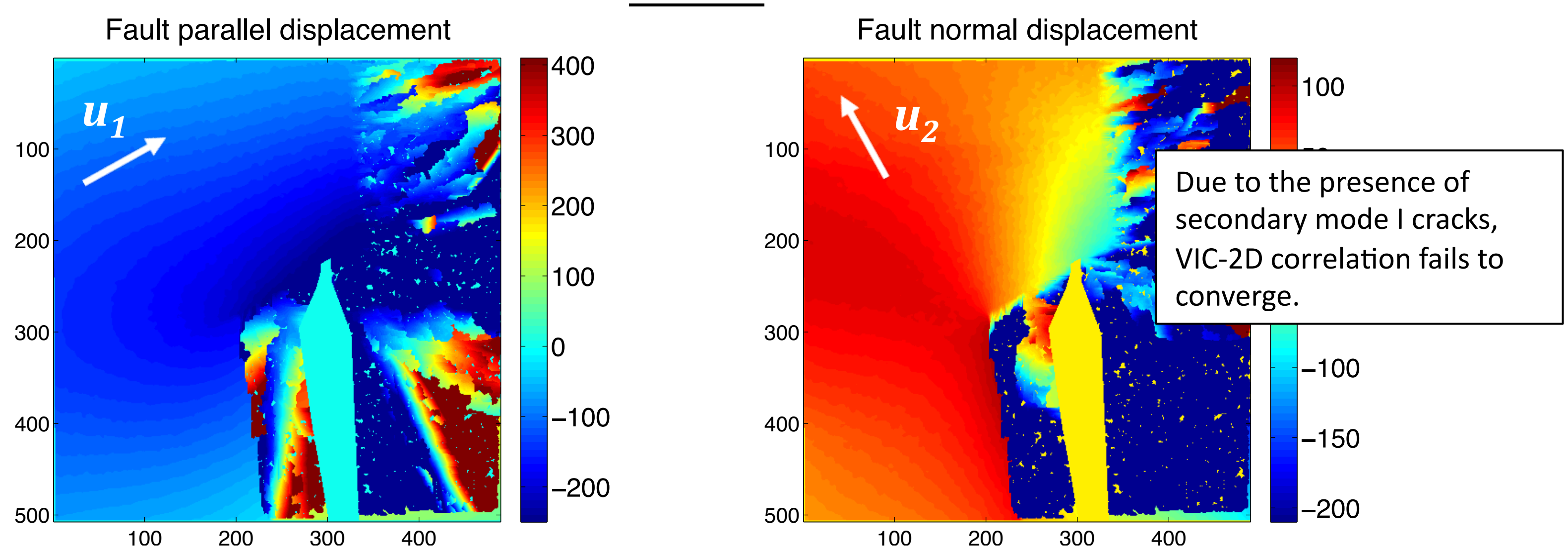
COSI-Corr vs. VIC-2D (Test 2, *P* = 15 MPa)

COSI-Corr



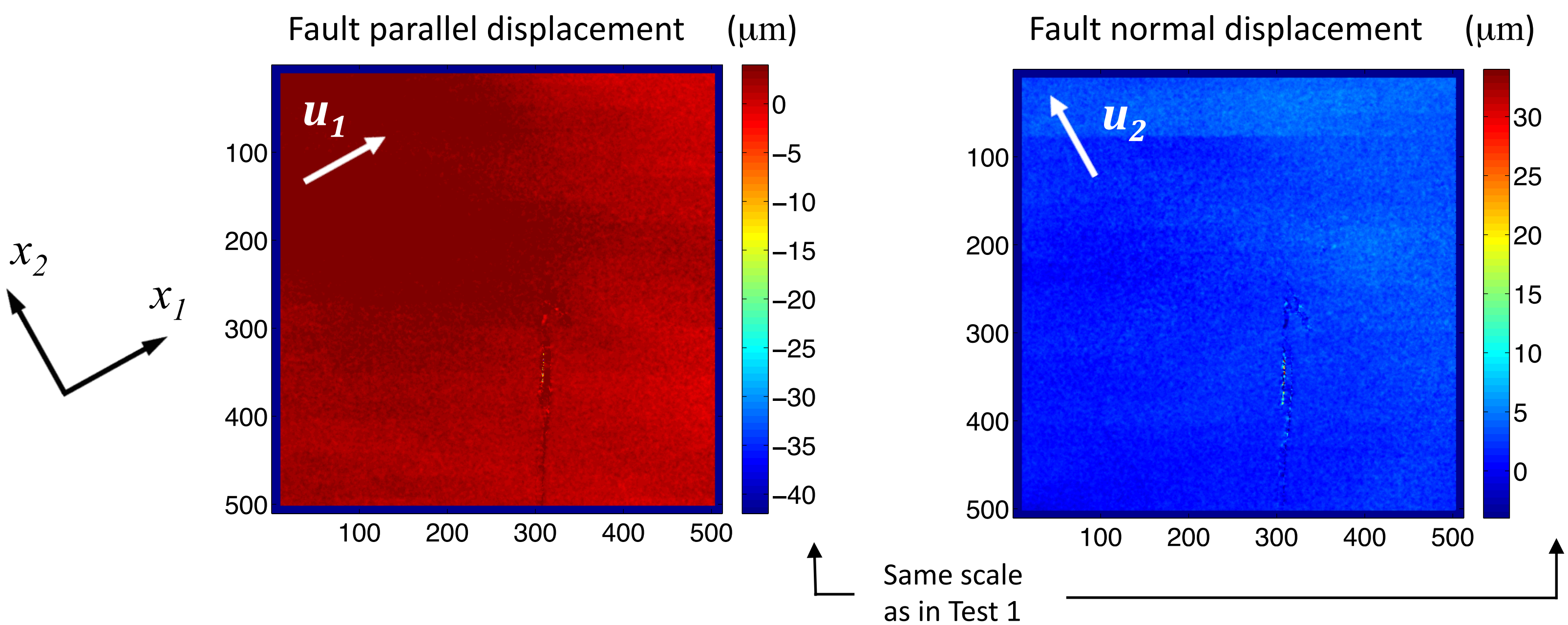


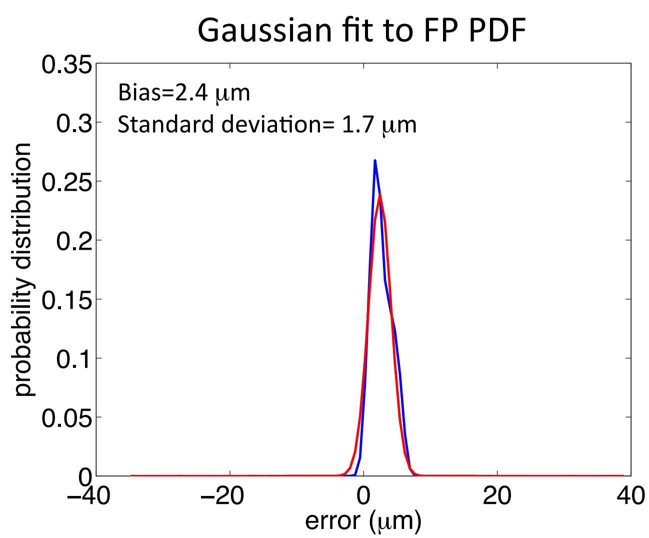
VIC-2D

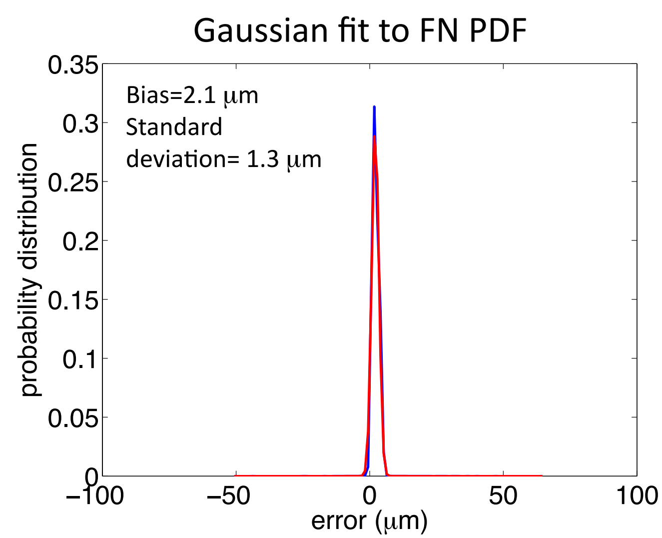


Error Analysis

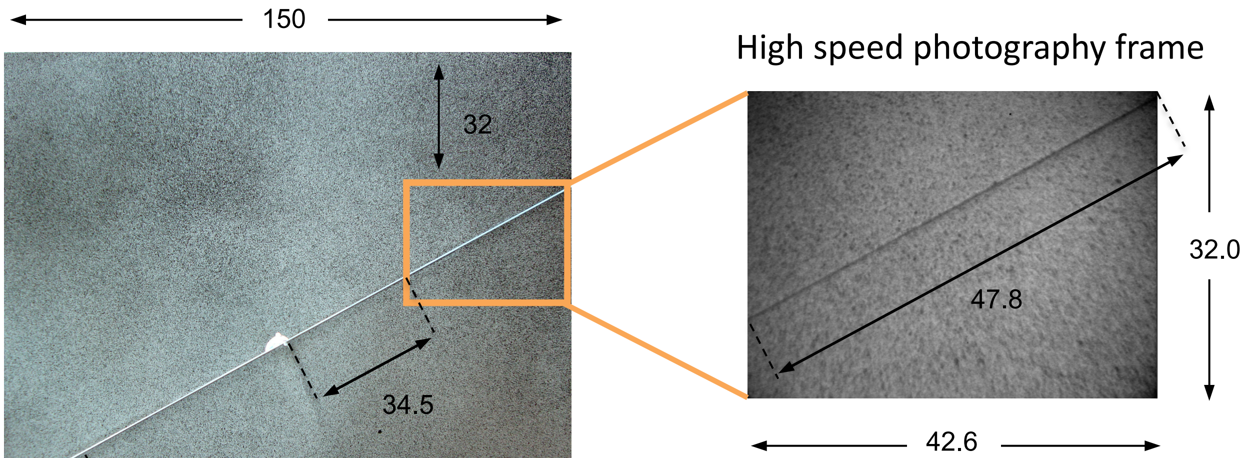
Correlation of two nominally identical images







High speed digital image correlation



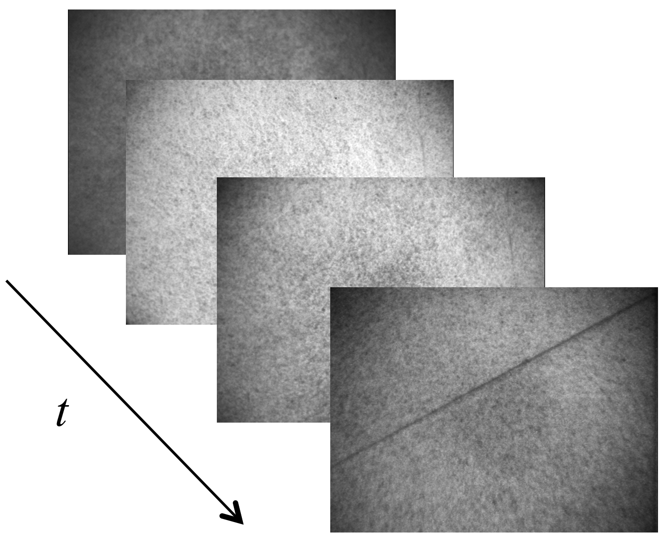
1 pixel ~ 83μm (Before)

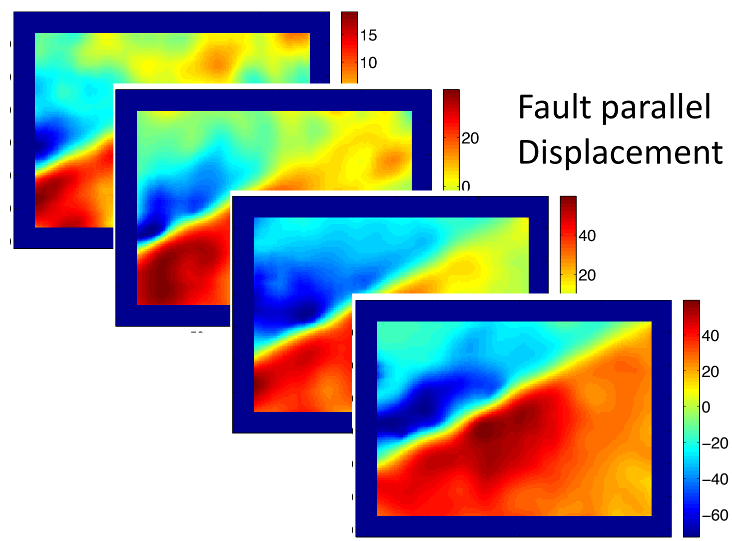
1 pixel ~ 55 μm (Now)

- **Problem**: Reduce method's error in μm
- **Solution**: Reduce pixel size by reducing the field of view

Quotes in mm

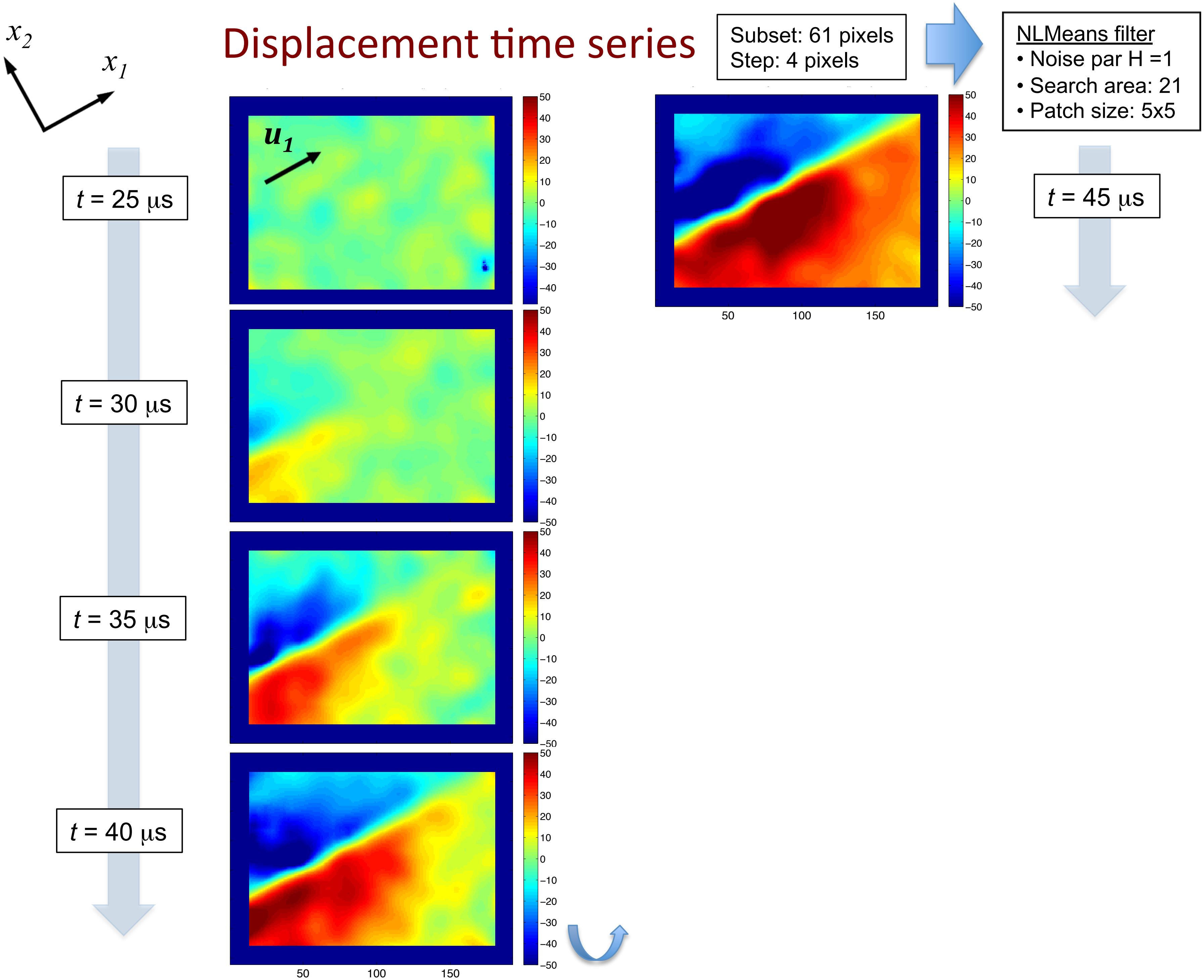
Time-series of displacement fields





Fault parallel Displacement (μm)

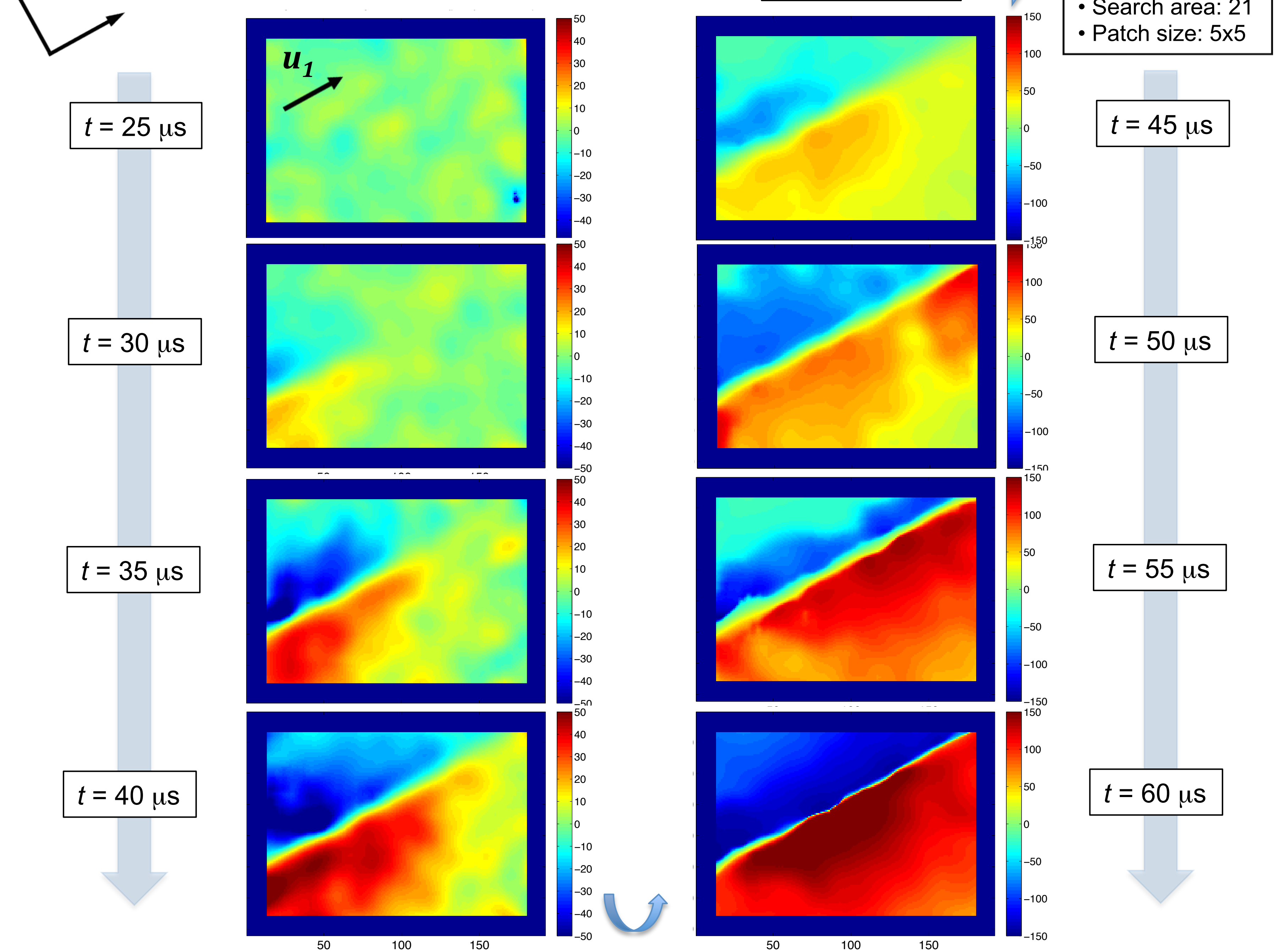
Displacement time series



Displacement time series

Subset: 61 pixels
Step: 4 pixels

NLMeans filter
- Noise par H =1
- Search area: 21
- Patch size: 5x5



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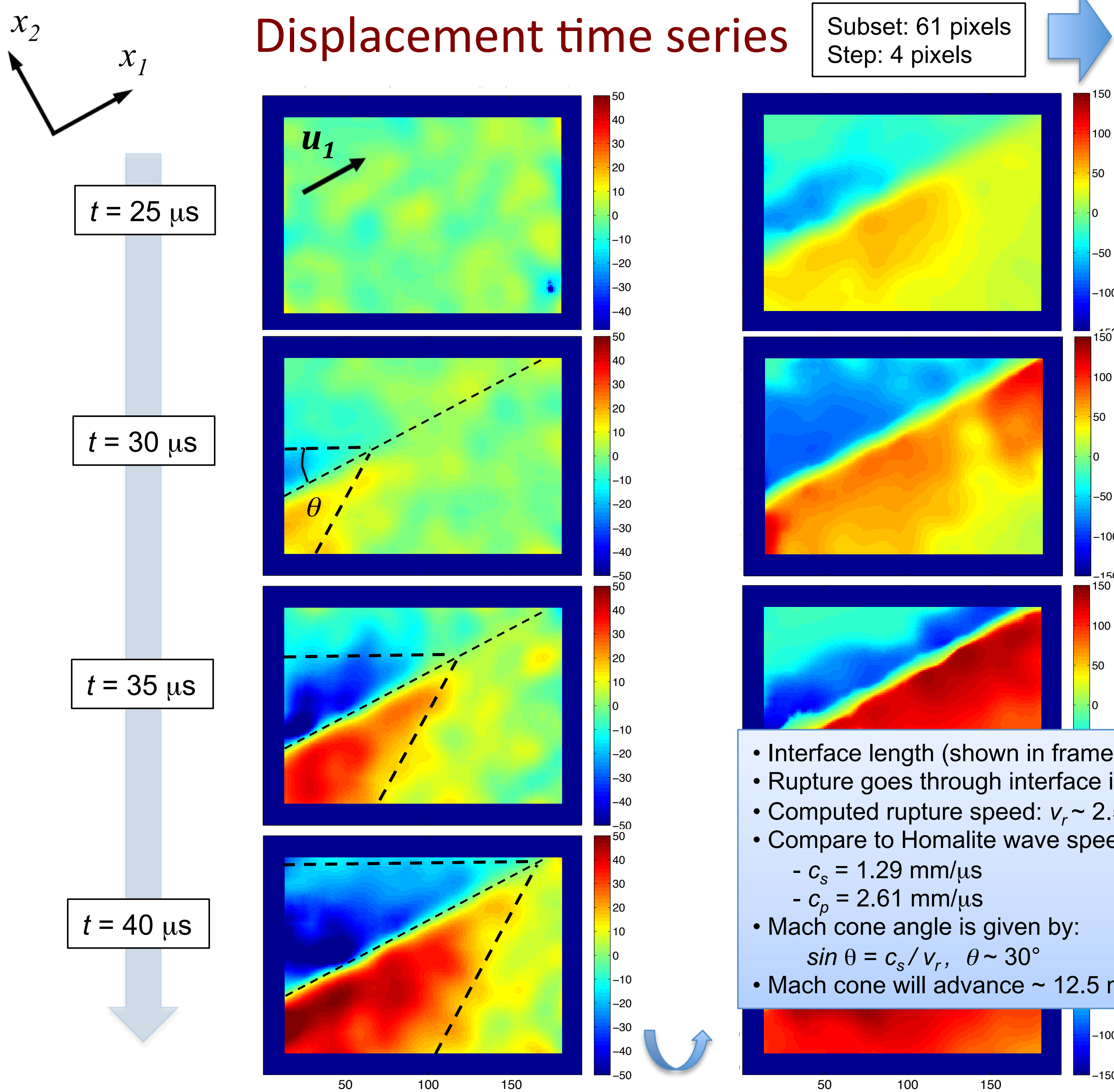
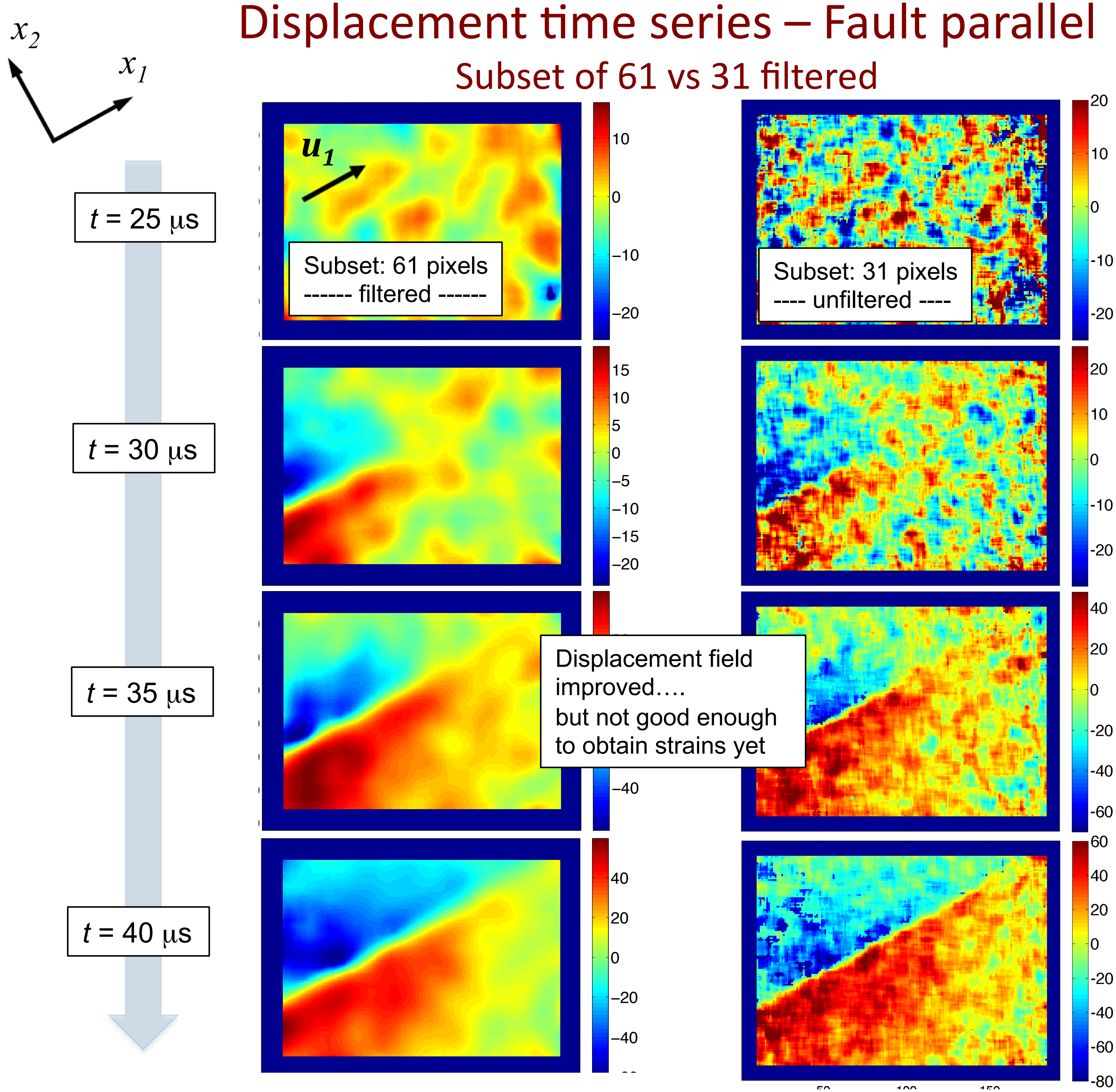


- Interface length (shown in frame): ~40 mm
- Rupture goes through interface in t < 20 μs
- Computed rupture speed: v_r ~ 2.5 mm/μs
- Compare to Homalite wave speeds:
  - c_s = 1.29 mm/μs
  - c_p = 2.61 mm/μs
- Mach cone angle is given by:
  $\sin\theta = c_s / v_r$, $\theta \sim 30°$
- Mach cone will advance ~ 12.5 mm

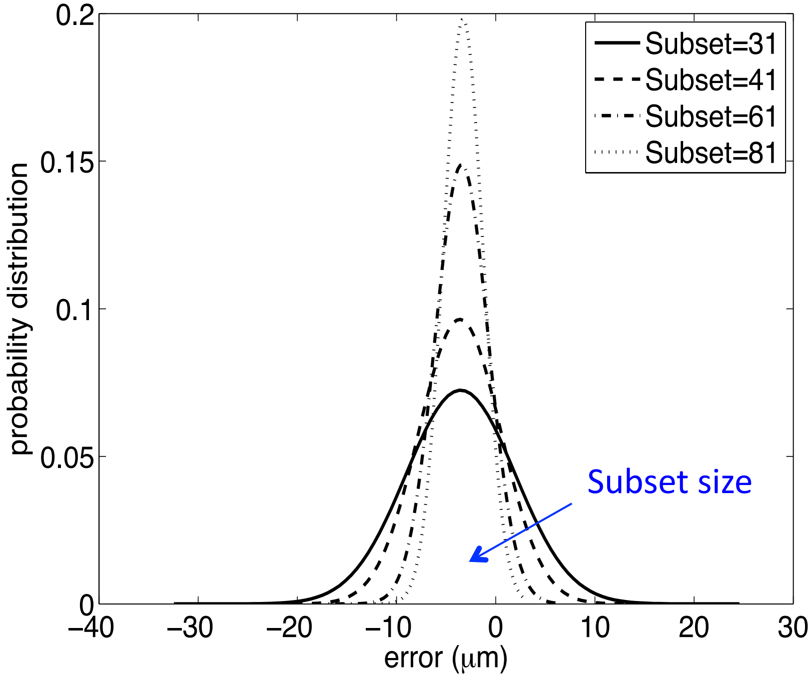
Displacement time series – Fault parallel

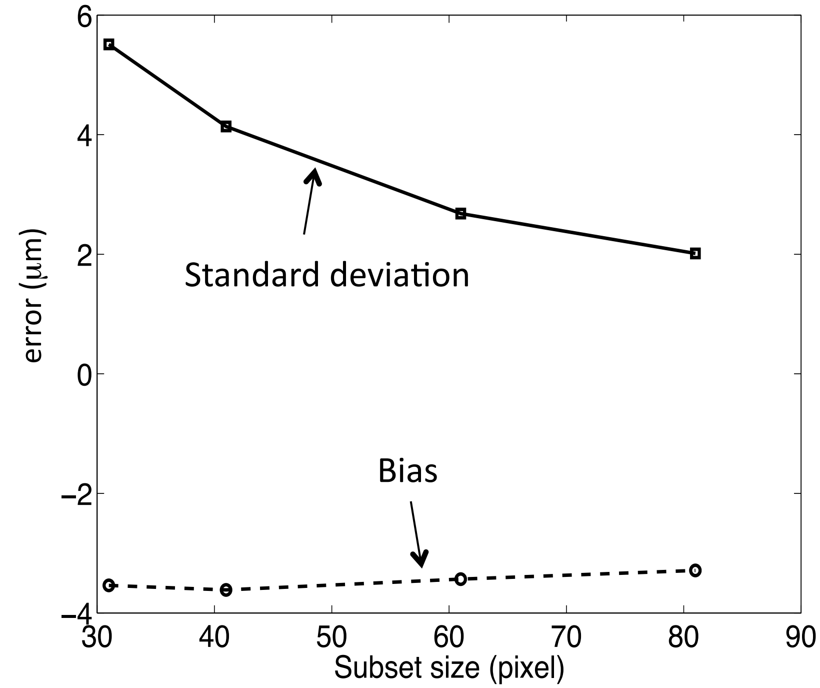
Subset of 61 vs 31 filtered



Quantifying errors (from gaussian fits)

Effect of subset size



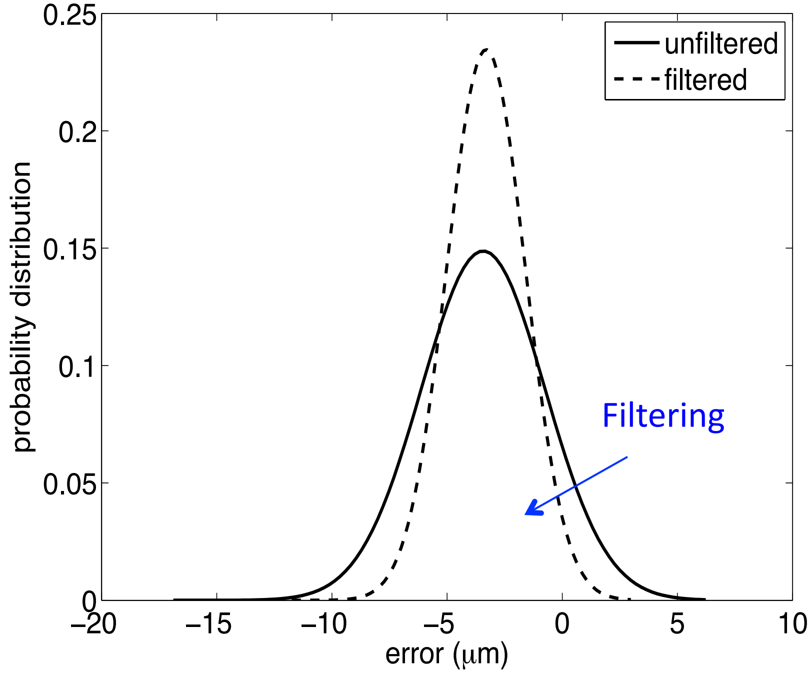


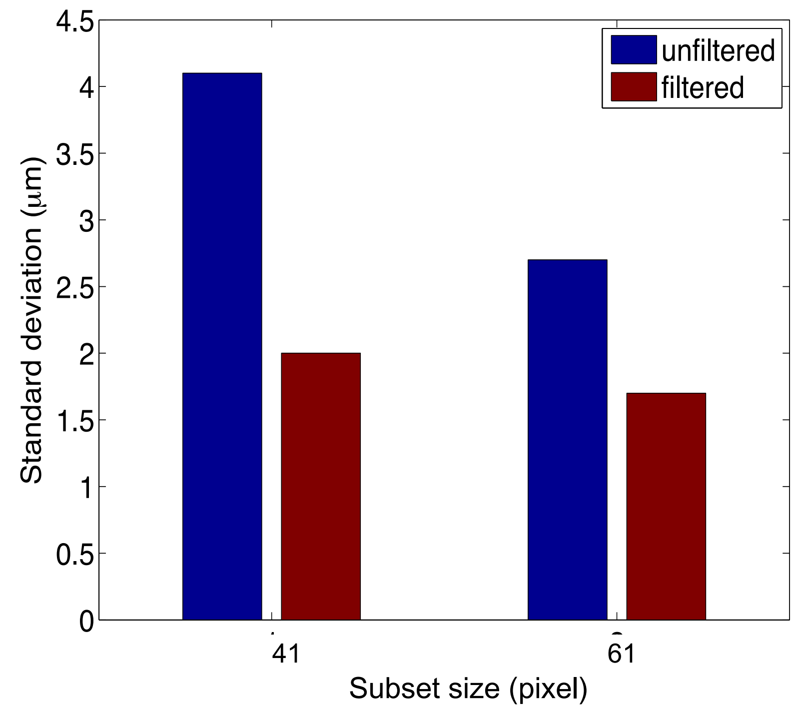
Fault parallel component of displacement, similar results for fault normal

- Correlate two nominally identical images
- The displacement field obtained is taken as a measure of the method's error
- Increasing the subset size has he effect of reducing the error standard deviation but not the bias

Quantifying errors (from gaussian fits)

Effect of filtering





Fault parallel component of displacement,
similar results for fault normal

- Correlate two nominally identical images
- The displacement field obtained is taken as a measure of the method's error
- Filtering with the NLMeans has he effect of reducing the error standard deviation but not the bias

Standard deviation can be reduced by filtering and increasing subset size, how about the bias?

How can we reduce the bias?

BIAS
due to

- Interpolation
- Noise
- Mismatched shape functions
- Image contamination (e.g. dust on sensor)
- Aliasing -> speckle pattern
- Other causes e.g. lighting change, pattern degradation

Sutton et al., 2009

Static vs. Dynamic Bias

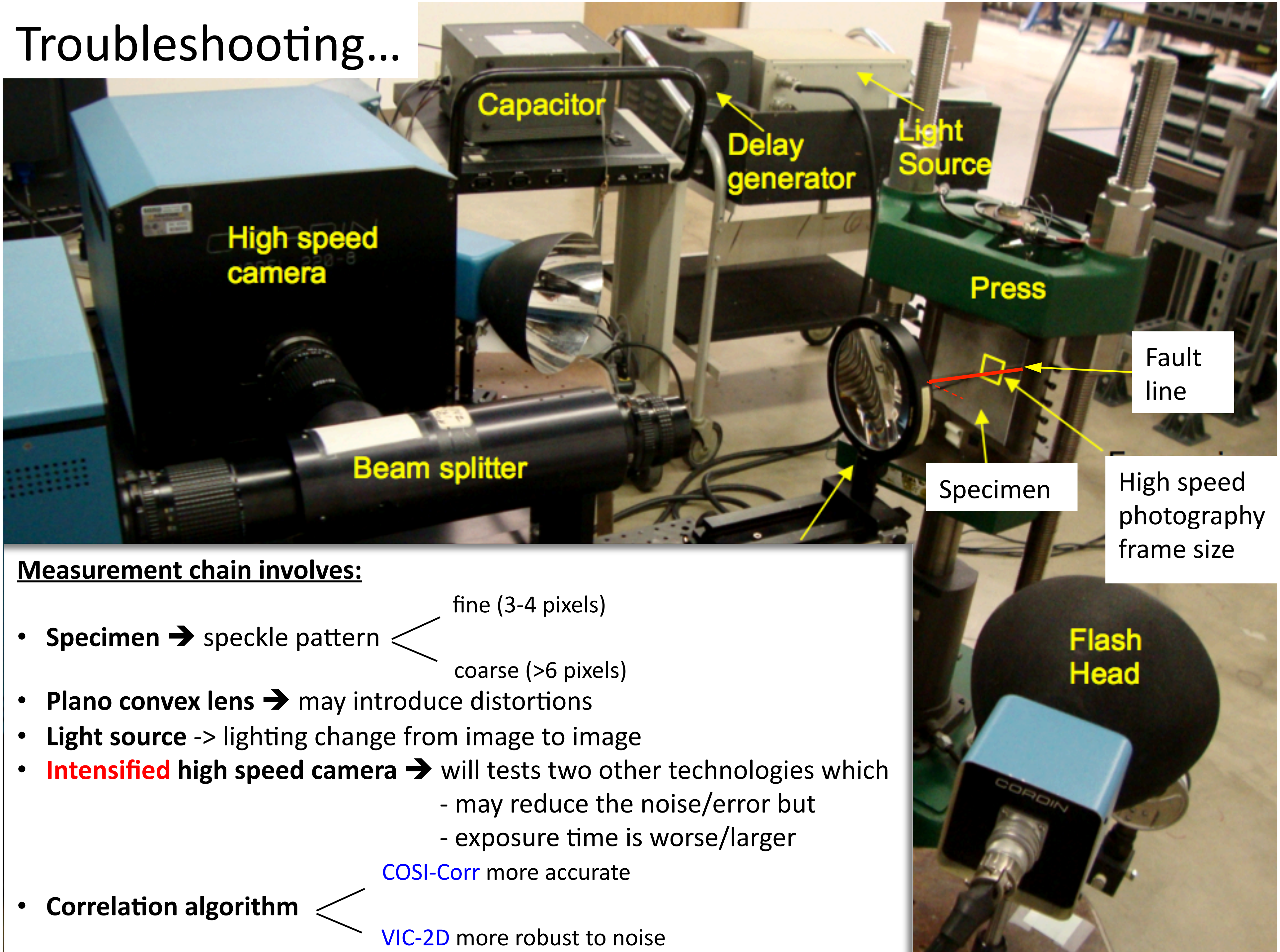
Regime	**Static**	**Dynamic**
Pixel size	83 μm	83 μm
Bias (μm)	2.4 μm	3.5 μm
Bias (pixel)	1/35 pixel	1/16 pixel

$$2.4\ \mu m \times \frac{1}{83}\frac{pixel}{\mu m} = 0.0289$$

Dynamic bias is ~ 2.2 times larger than static

How can we do better?

Troubleshooting…

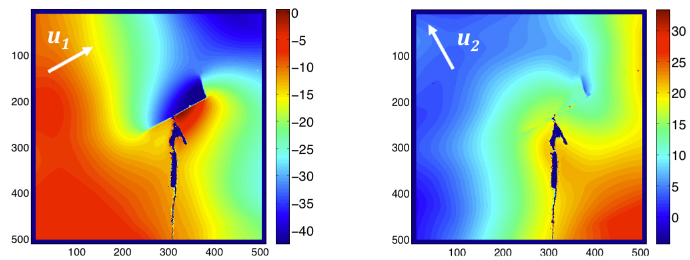


Measurement chain involves:

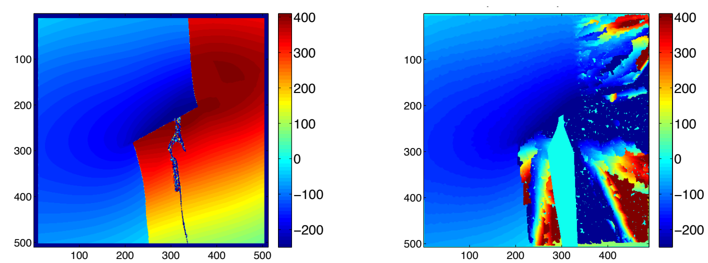
- **Specimen ➔** speckle pattern < fine (3-4 pixels) / coarse (>6 pixels)
- **Plano convex lens ➔** may introduce distortions
- **Light source** -> lighting change from image to image
- **Intensified high speed camera ➔** will tests two other technologies which
  - may reduce the noise/error but
  - exposure time is worse/larger
- **Correlation algorithm** < COSI-Corr more accurate / VIC-2D more robust to noise

Conclusions and Future Work

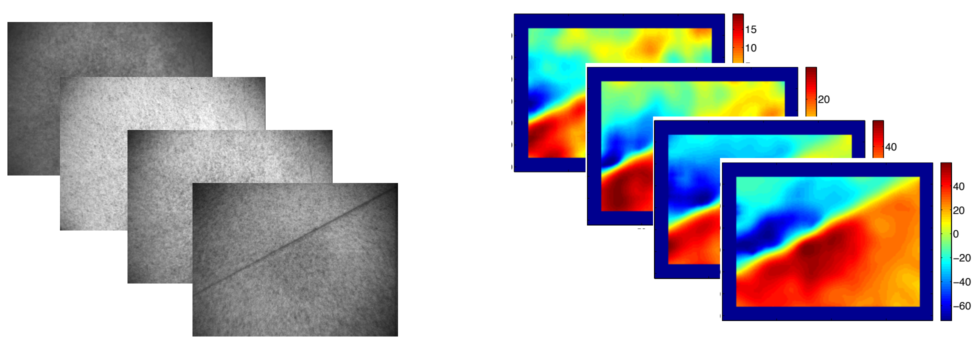
• Successfully characterized full-field static displacements and strain of a dynamic crack with digital image correlation techniques.



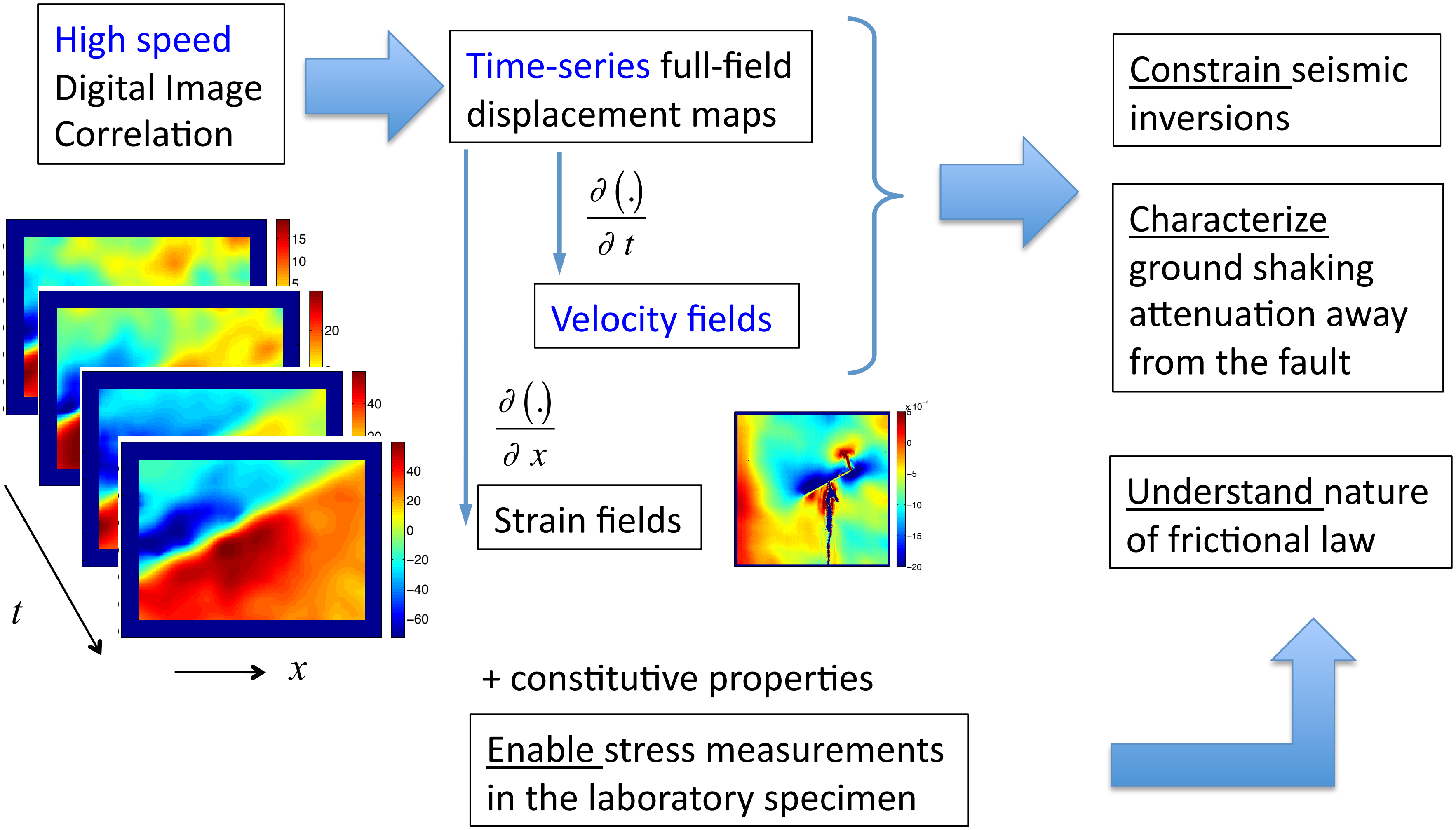
• Two DIC software packages have been tested: COSI-Corr outperforms VIC-2D, especially in the presence of opening cracks, such as in Test 2.



• Performed dynamic measurements with high speed camera to capture the time dependent behavior.



Broader goals of the project



- Study the effects of surface roughness and variability, material inhomogeneity, etc.
- Include spontaneous nucleation