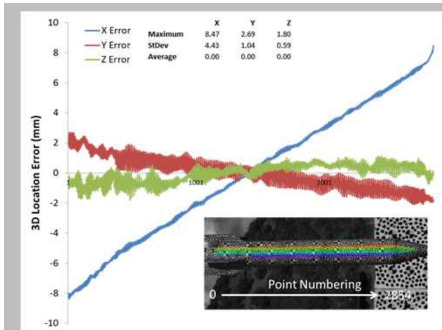
Exceptional service in the national interest

SAND2015-7021C

Sandia National Laboratories



Quantifying errors in image based measurements

Phillip L. Reu

"Seeing is believing but measuring is understanding"

ISEM-SOI Guanajuato, Mexico 2015

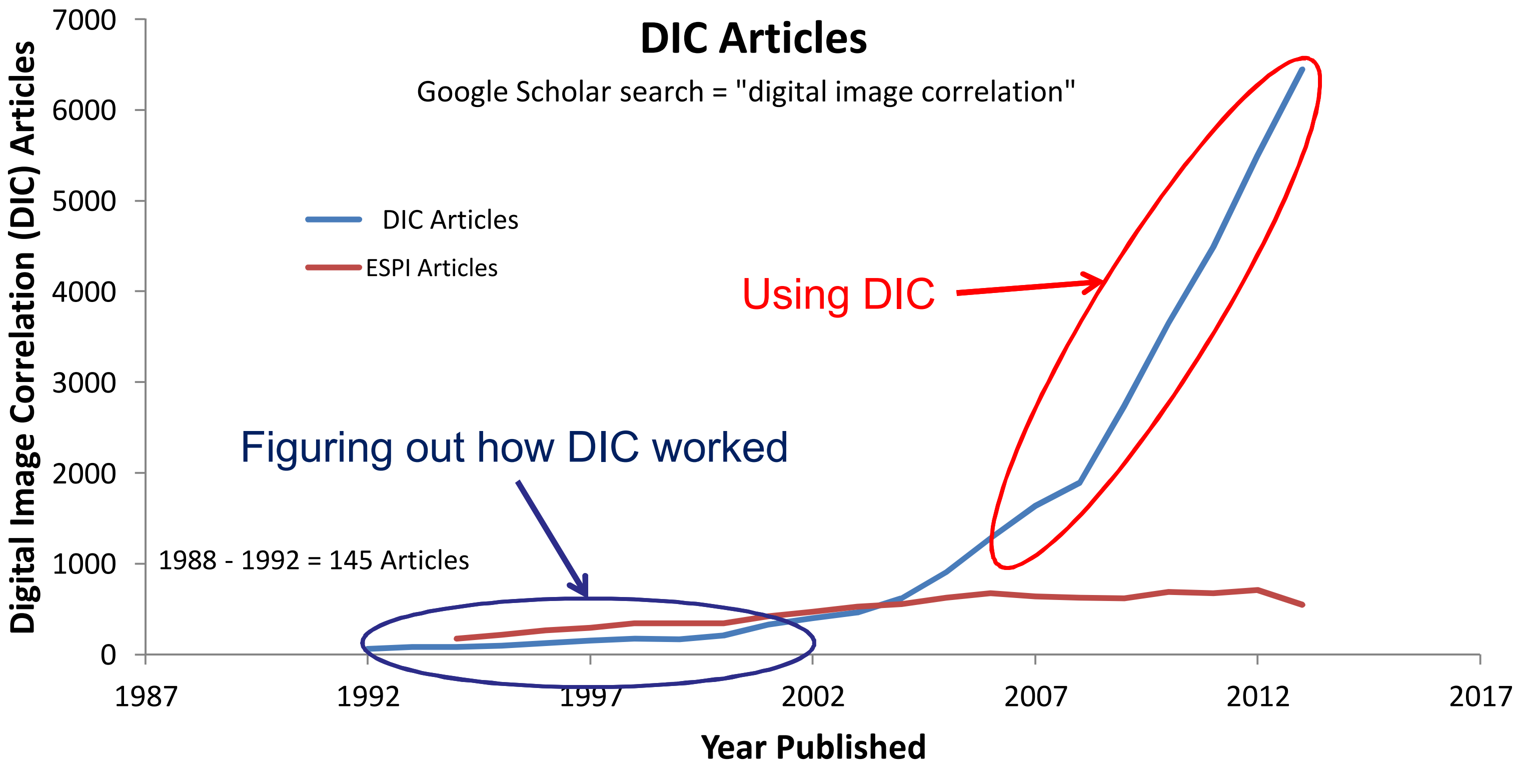
U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

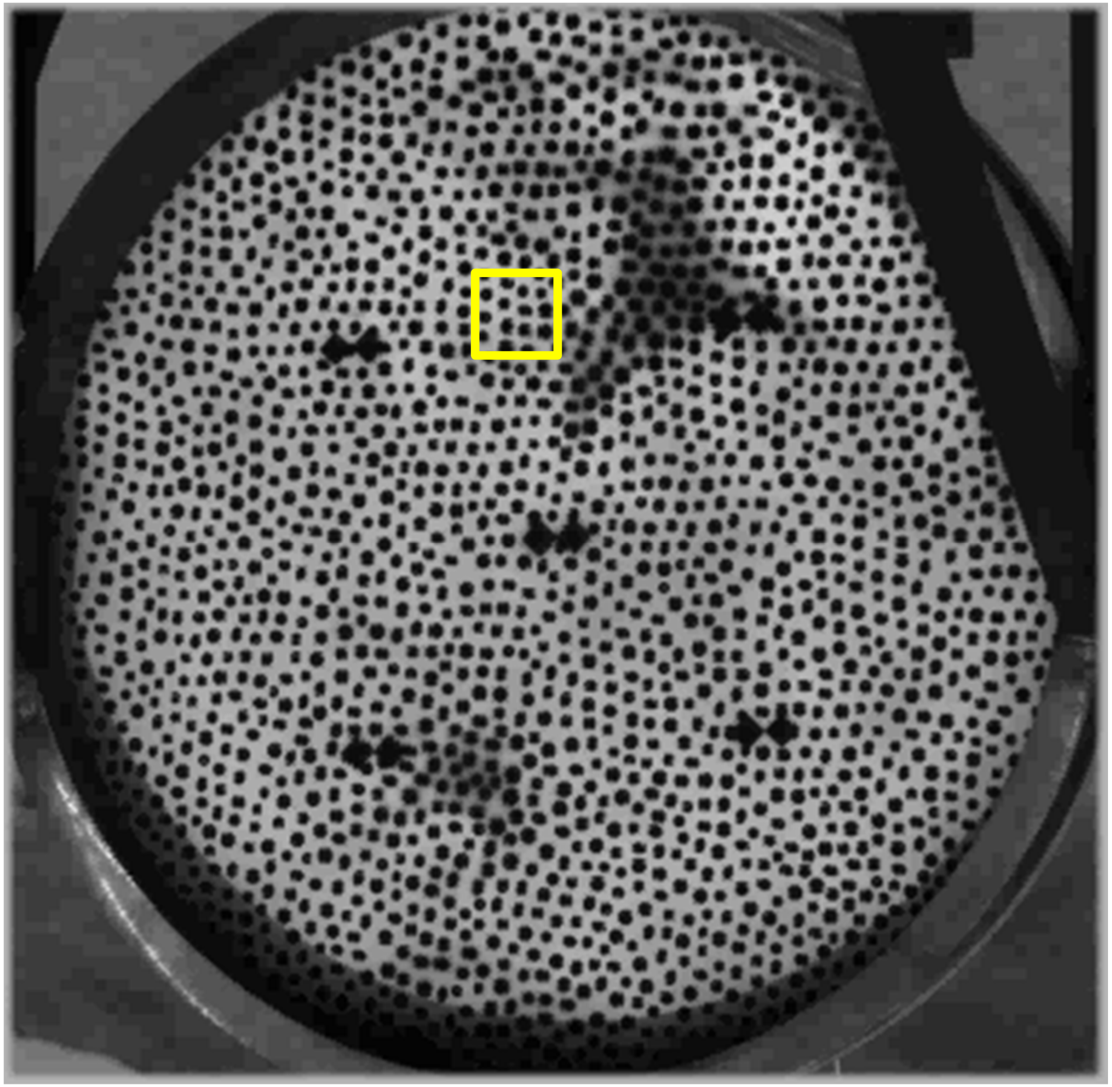
DIC has changed the way we do experimental mechanics.

1. **Ranson & Peters** (1980) – Digitized ultrasound images.
2. **Cheng & Sutton; Sutton & Wolters** (1982) – Non-linear least squares to find local displacements.
3. **Chu, Ranson, Sutton, Peters** (1985) – Digital camera and algorithms conclusively demonstrate the use of the method.
4. Many others began to pick up the idea at this point (many graduate students of Sutton).



Digital Image Correlation publishing.xlsx (OneNote)

2D-DIC is a pattern “tracking” method.



Hidden components of DIC

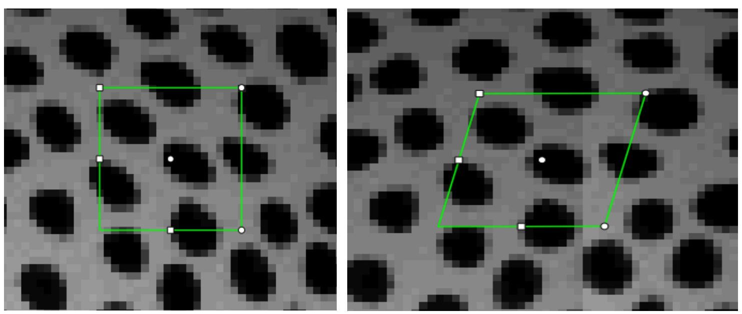
- Uses a region to **match** a pattern between 2 images.
- Image **interpolation** is used to obtain subpixel results.
- A **shape function** allows the subset to deform as the sample deforms.

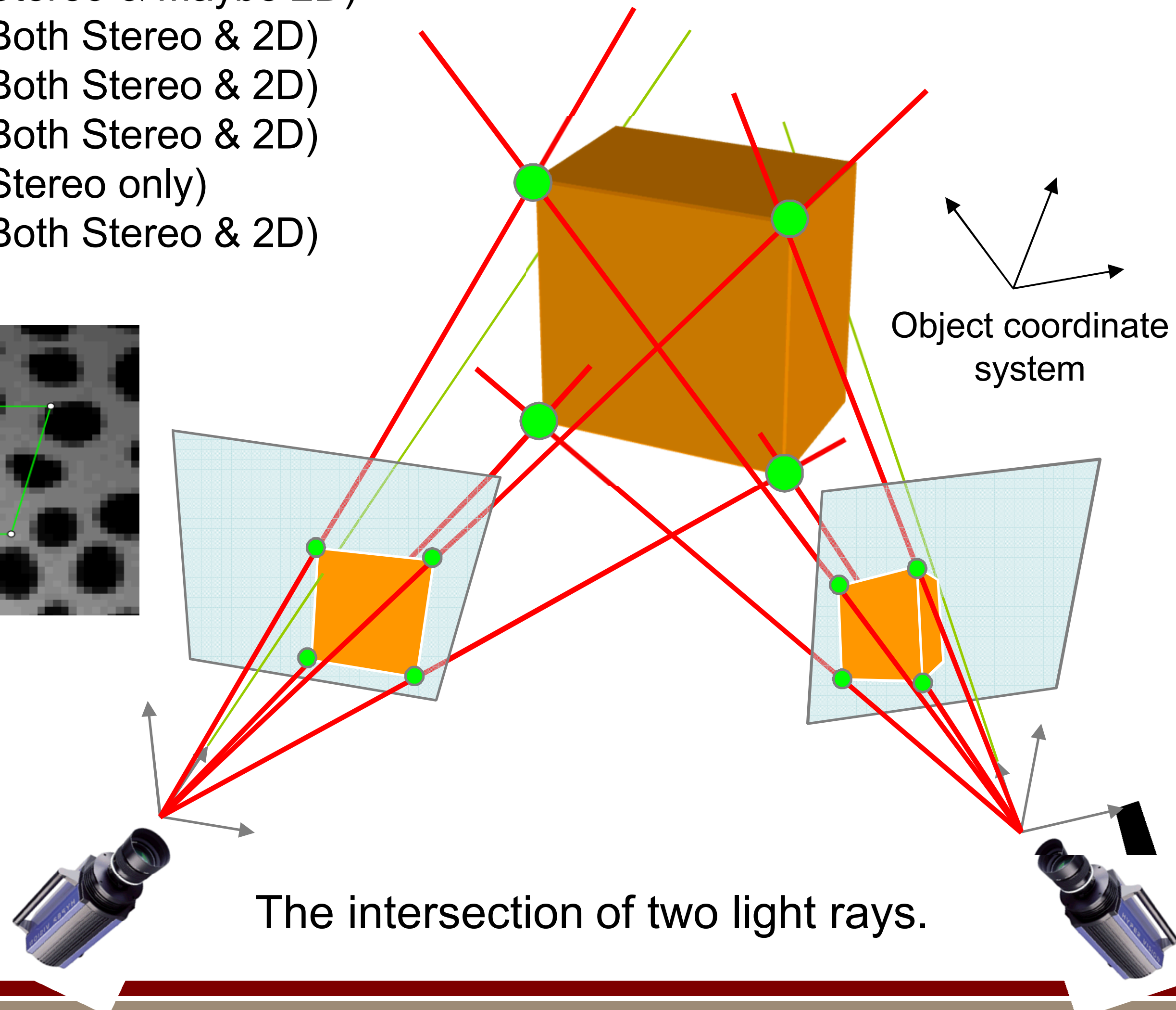
DIC is different from photogrammetry:
we *require* subpixel accuracy.

Similar to human vision, two views can be combined to yield 3D shape.

The “hidden components” of DIC

1. Calibration	(Stereo & Maybe 2D)
2. Subset shape function	(Both Stereo & 2D)
3. Grey level interpolation	(Both Stereo & 2D)
4. Subset matching	(Both Stereo & 2D)
5. Triangulation	(Stereo only)
6. Post-processing	(Both Stereo & 2D)





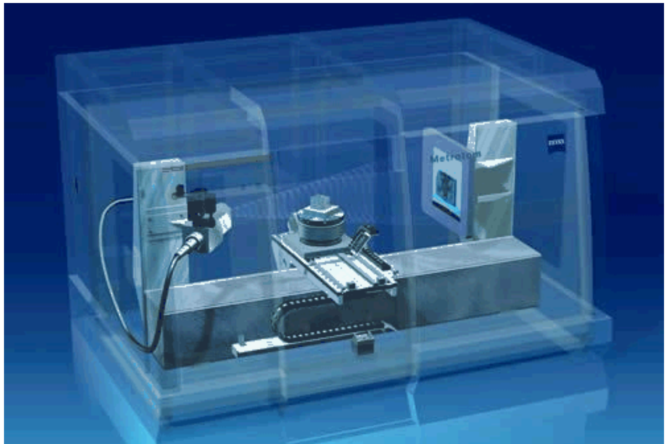
Imaging technology is improving DIC. This is both a gift and a problem.

Sandia National Laboratories

SEM/AFM

www.jeol.com

CT Scanner



www.zeiss.com

High Resolution Machine Vision

http://www.alliedvisiontec.com

High and Ultra-high Speed Imaging

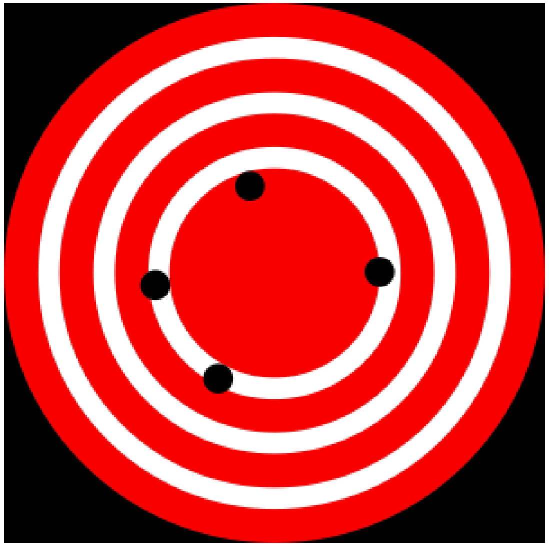
www.visionresearch.com

www.photron.com

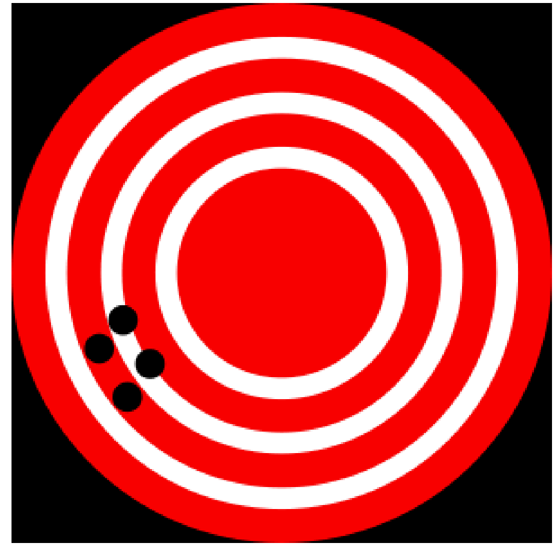
www.shimadzu.com

Problem: We are now using these for metrology – not imaging!

Two types of errors: Random and Systematic



Accurate but not Precise
Large *Random* Error
Small *Systematic* Error
Noise, repeatability,
Aleatoric Uncertainty



Precise but not Accurate
Small *Random* Error
Large *Systematic* Error
Bias Error
Epistemic uncertainty

The new view is to categorize as:
Type A and **Type B** Errors.
Why no bias errors? A known bias is removed and it becomes a variance error.

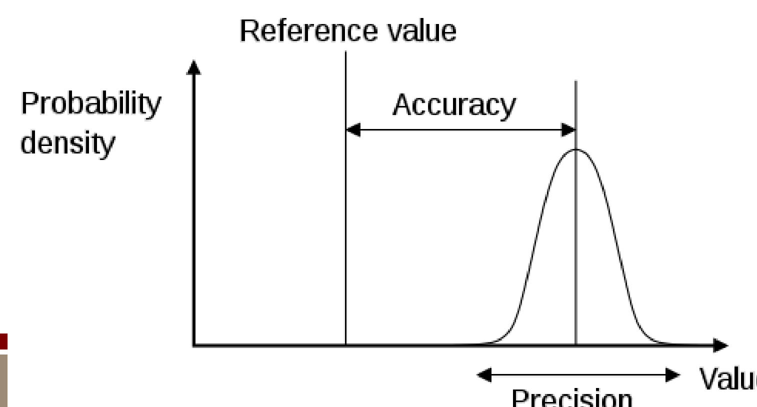


Image from Wikipedia

A newer approach categorizes errors into two types: Type A and Type B

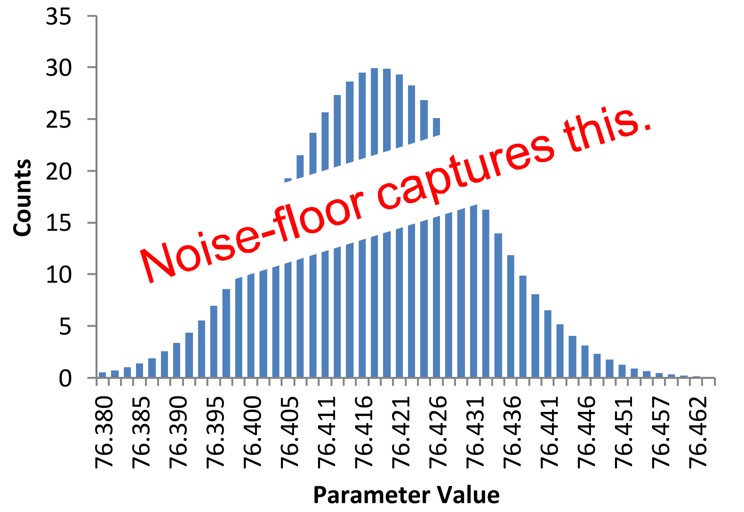
Sandia National Laboratories

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



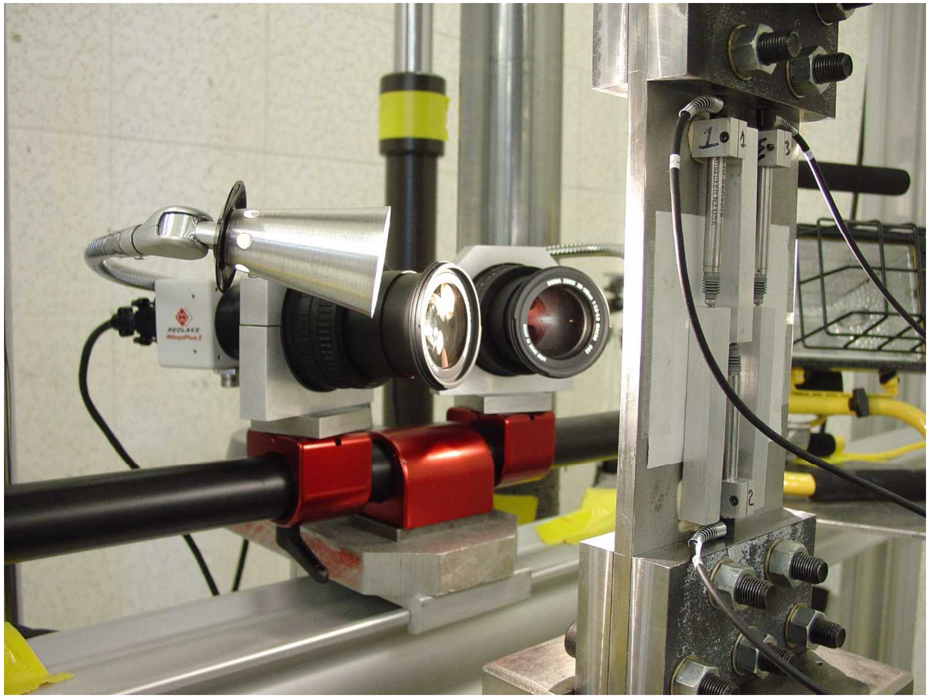
$$Y = f(X_1, X_2, \ldots, X_N)$$

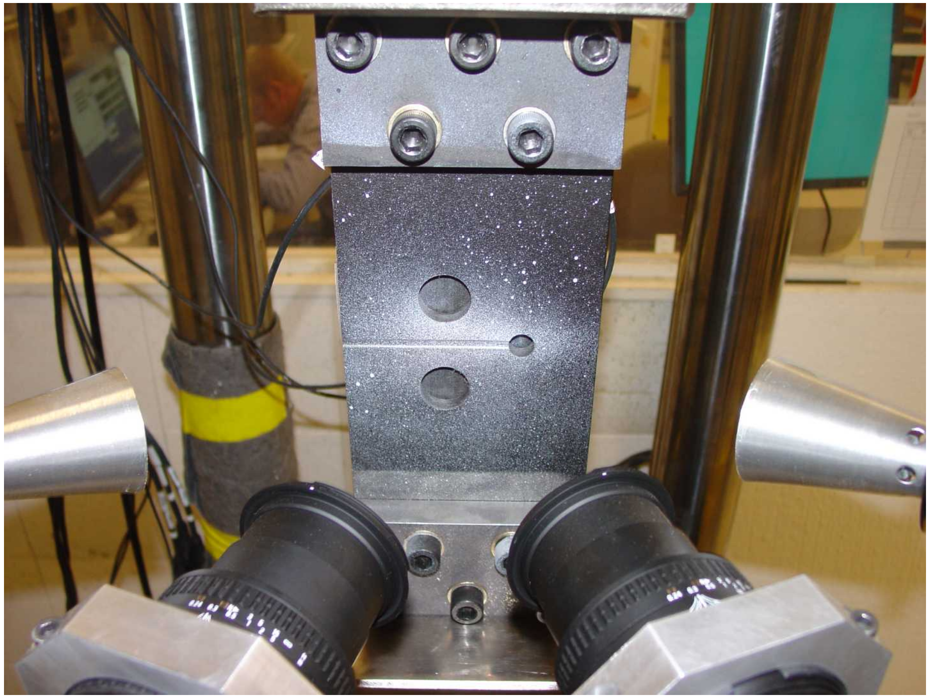
The measurand Y is made up of X other input quantities. The function may be so complicated that it cannot be written down (Section 4.1.2).

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.

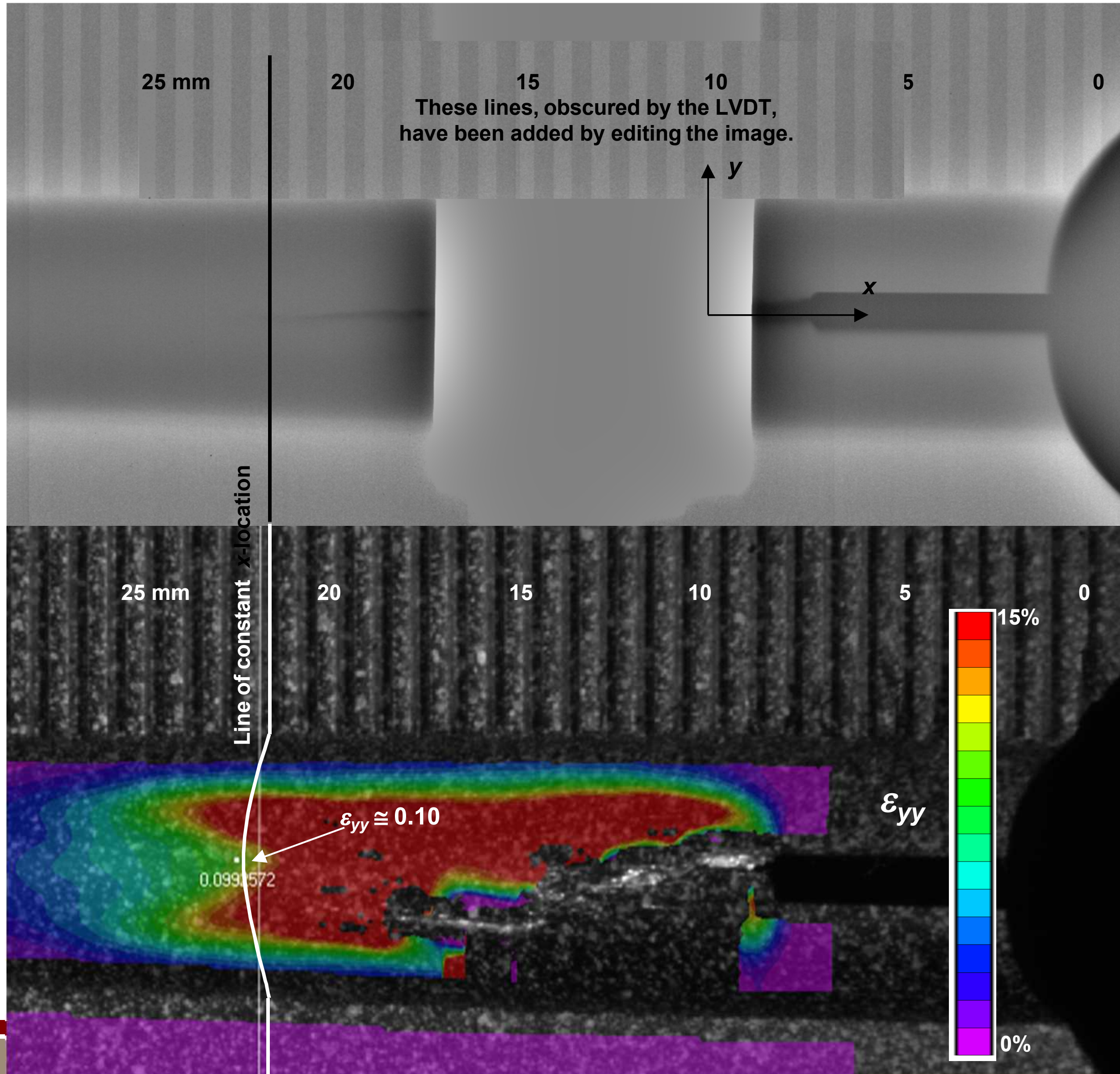
An early stereo-DIC experiment using the newly found power DIC.



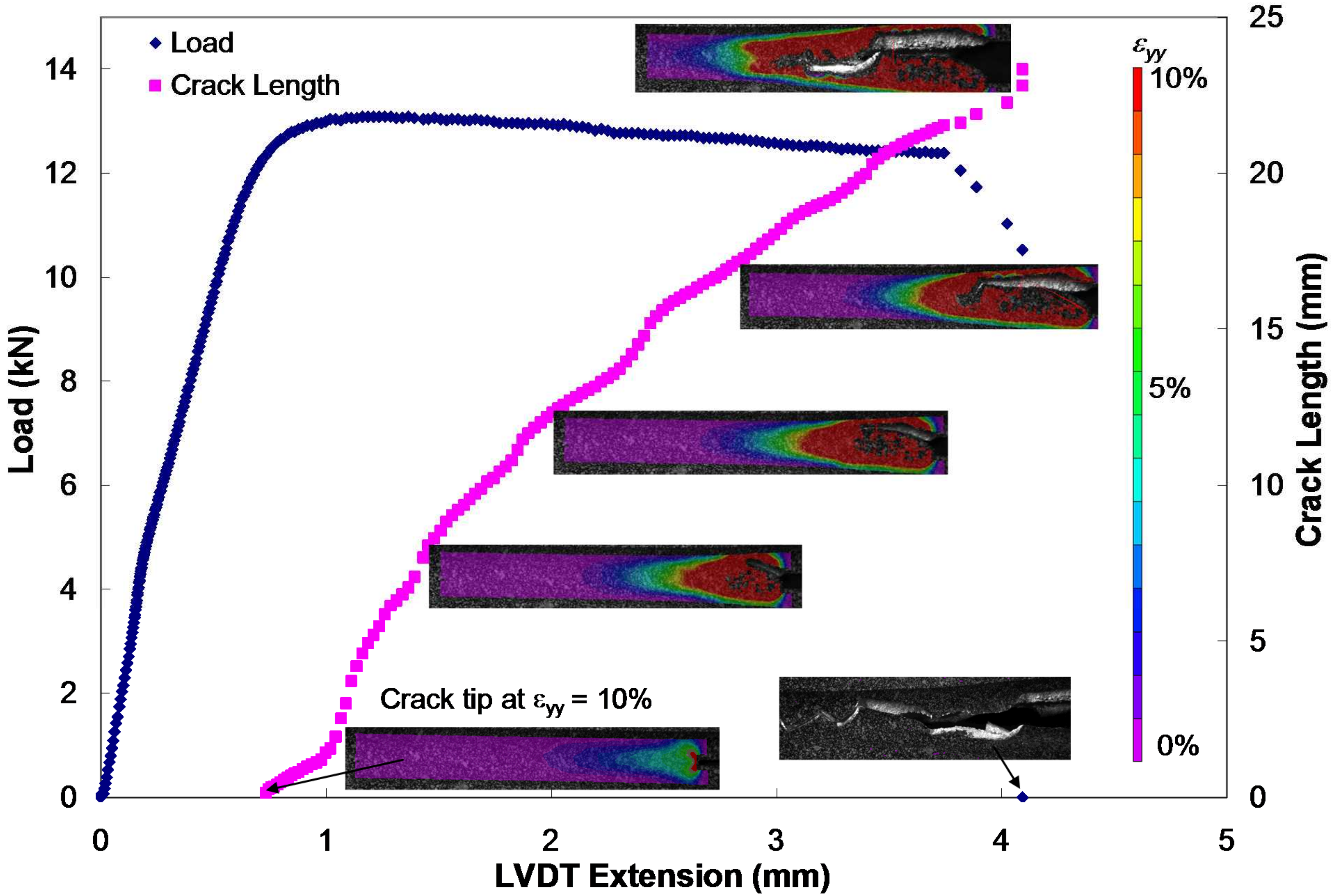


Reu, P. L., et al. (2007). Stable Crack Growth Measurement Using DIC as a Tool for Model Validation SEM Annual Conference & Exposition on Experimental and Applied Mechanics, Springfield, MA.

The crack length from the x-ray was aligned with a "strain"



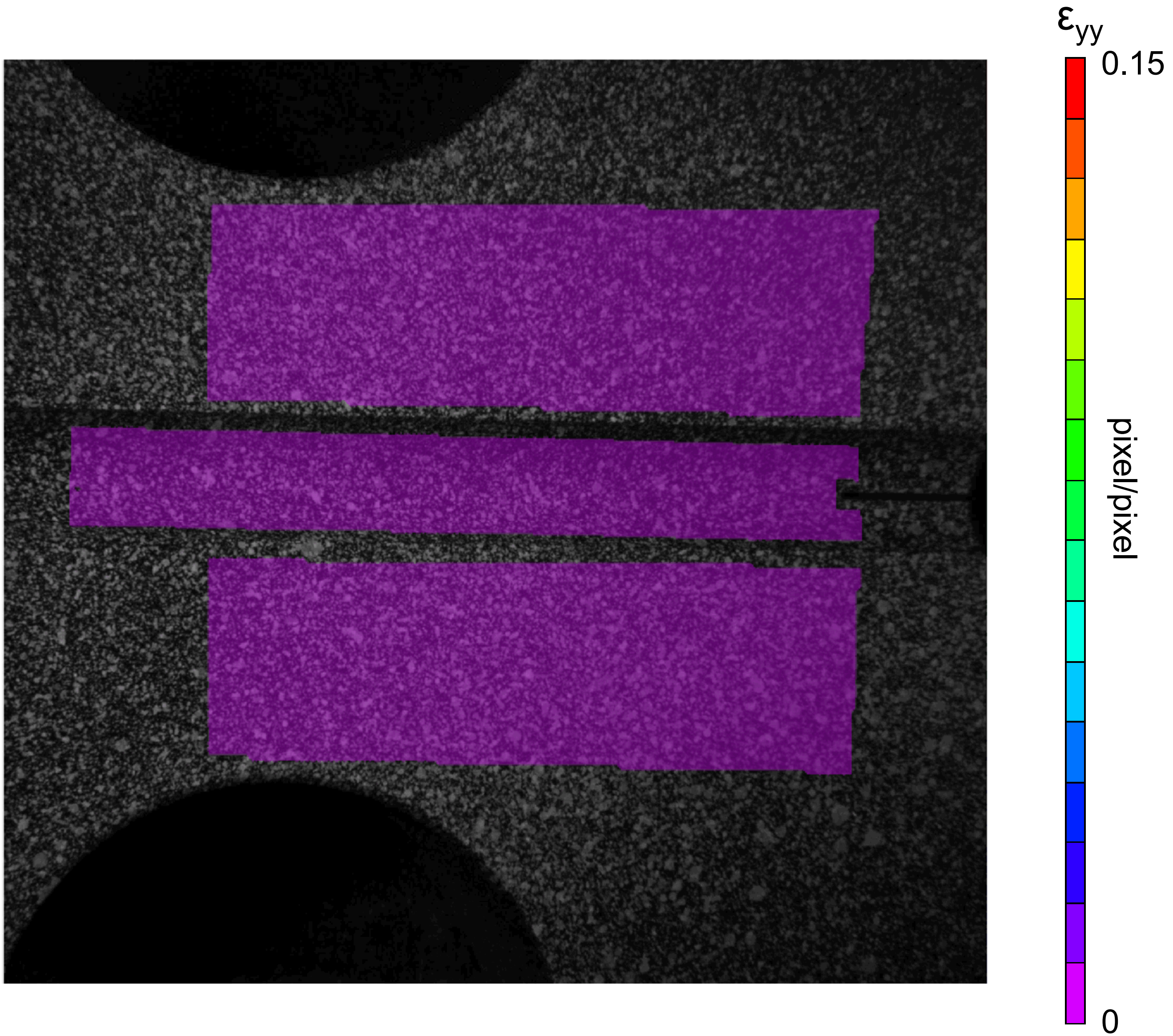
The crack length can then be tracked at 10% strain location.



The “strain field” was measured using DIC.

What is missing here?
- Any information on the DIC settings.
- What is the uncertainty?
- What is the spatial resolution?

This experimental series raised many questions
- Can we predict the uncertainty?
- What are the error sources in a DIC experiment.
- Can DIC be quantitative rather than qualitative?



Year: 2007

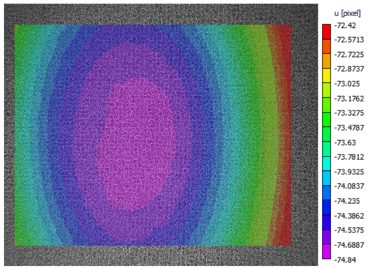
Are you worrying about the wrong error source?

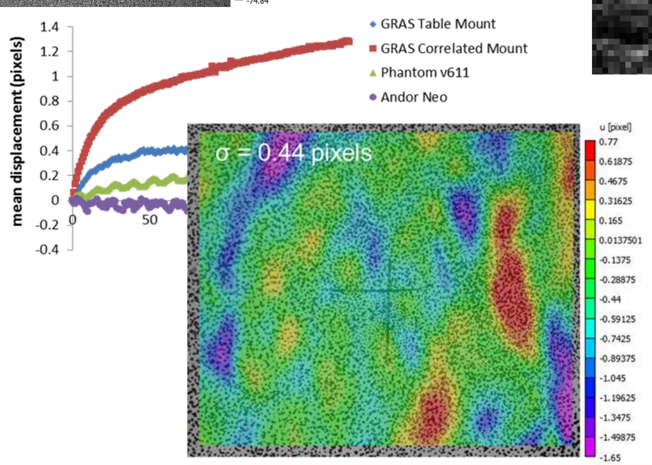
Experimental Setup
- Lens distortion
- Camera motion
- Sample motion
- Air turbulence
- Image blur
- System resolution

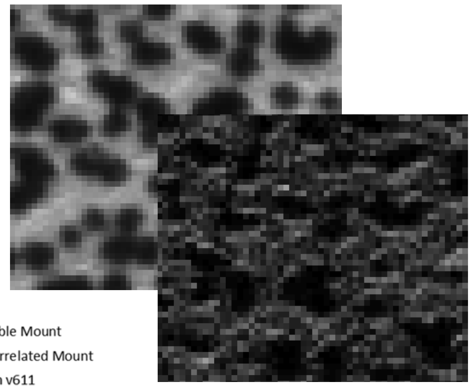
→ **Image Acquisition**
- Noise
- Contrast
- Speckle size
- Aliasing

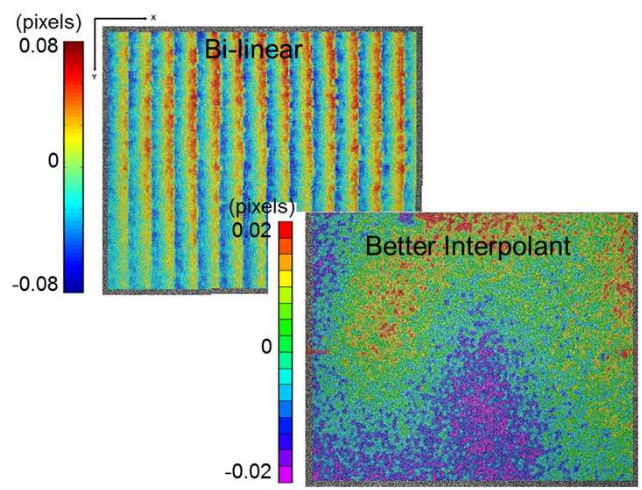
→ **Image Correlation**
- Interpolant
- Minimization
- Shape Function
- Subset size

→ **2D Position, Motion, and Strain**
- Filtering
- Strain calculation
- Coordinate system









For the stereo-DIC story see:
Reu, P. L. (2013). Experimental Mechanics **53(9): 1661-1680.**

Analytic equations to predict the matching error.

Systematic Bias

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

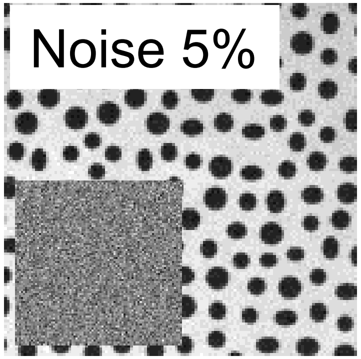
Interpolation Bias **Noise Bias**

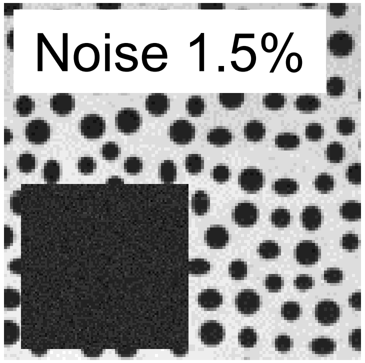
Random Variance

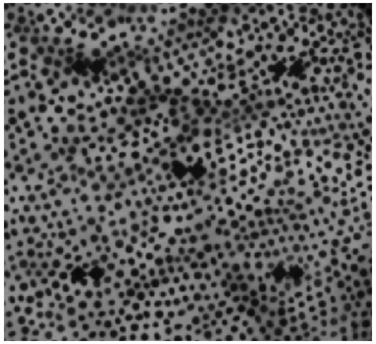
$$\mathrm{Var}(t) \cong \frac{2\sigma^2}{\sum_i \left[\nabla T(x_i) \right]^2}$$

Measurement Variance

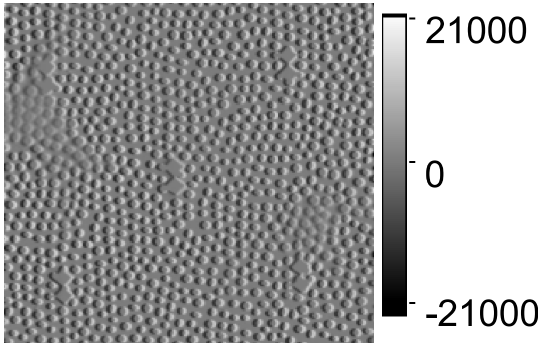
$\sigma \propto$



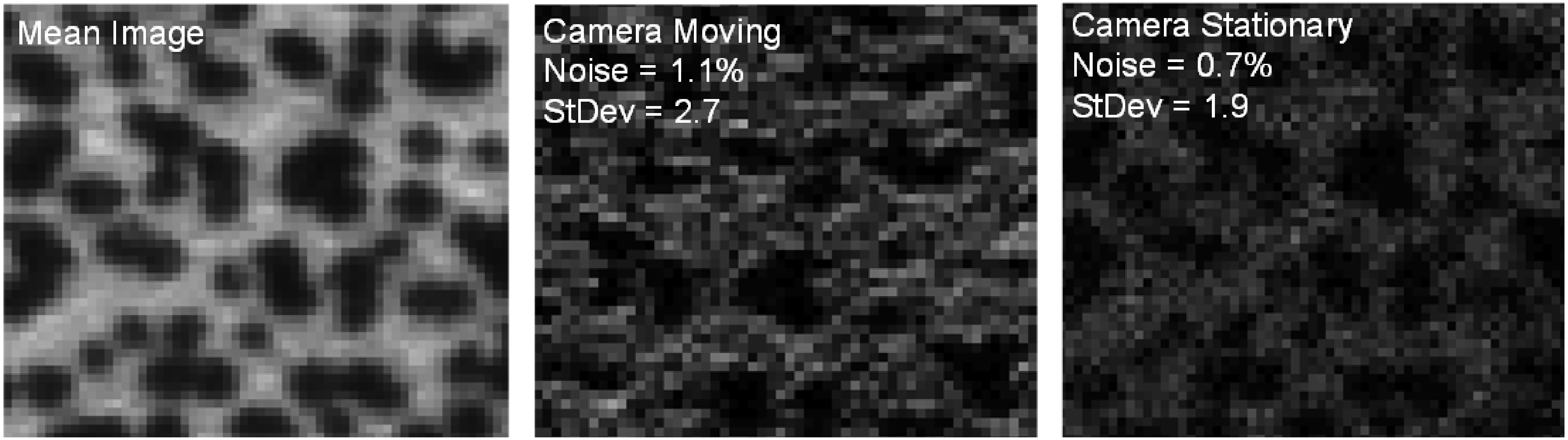


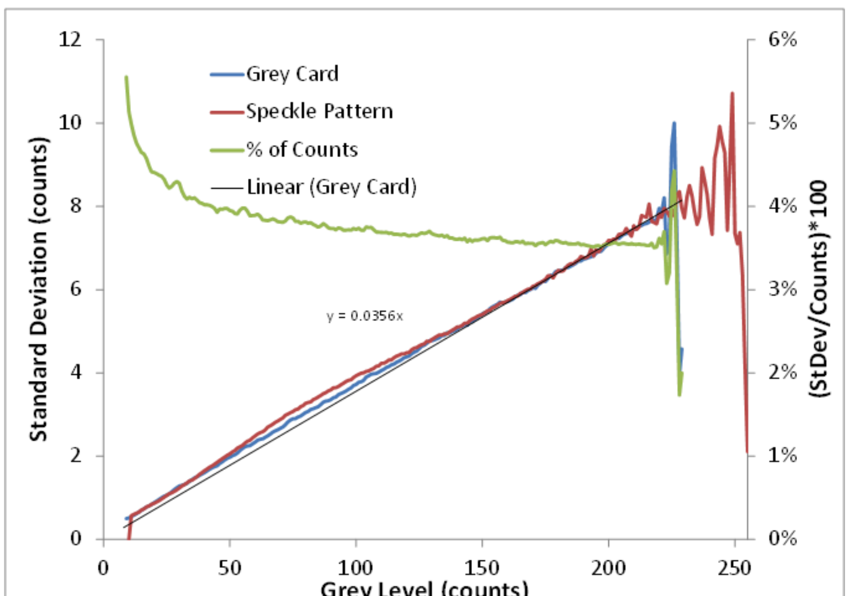


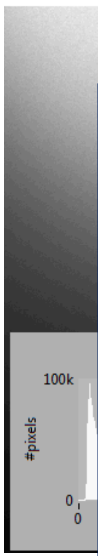
Gradients = $\sum_i \left[\nabla T(x_i) \right]$ **=**



Quantifying the noise of the camera and results may include camera shake.



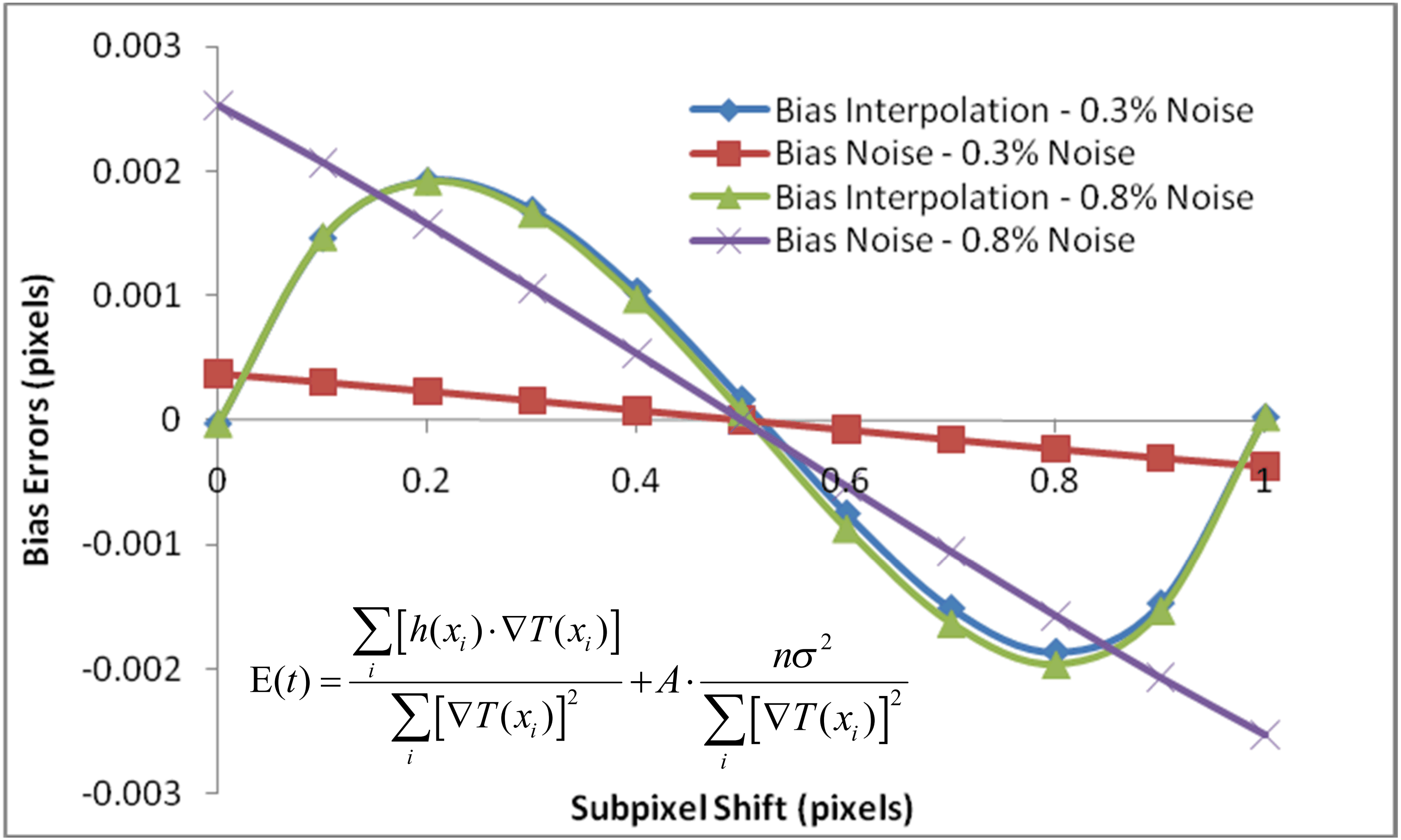




Camera	%Noise	StDev (cts)
PointGrey GRAS (5MP)	0.82	1.56
PointGrey GX (5MP)	0.46	1.17
AVT Prosilica GX (5MP)	1.7	4.1
Prosilica GE4900 (16MP)	0.86	0.34
Prosilica Binned (0.1MP)	0.1	0.28
Phantom v611 (1MP)	0.78	1.84
Andor Neo (5MP)	0.60	1.51

Sur, F. and M. Grediac (2014). IEEE Signal Proc. Letters 21(4): 432-436.

Bias and noise errors calculated in software agree with earlier publications



How do we validate this?

There were few (or no) experimental verifications of the bias and noise error.

Experimental validation is very hard!

- Constant velocity test (leaves lots of questions)
- Super-resolution (next slides – still questions)
- Really expensive stages.
- Out-of-plane motion

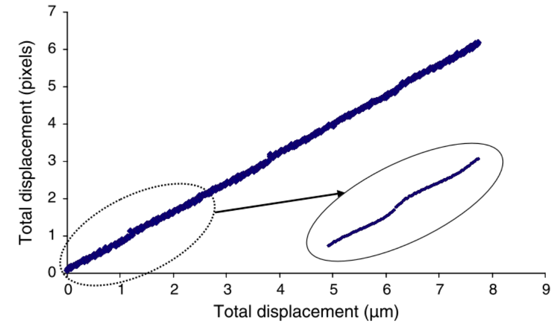


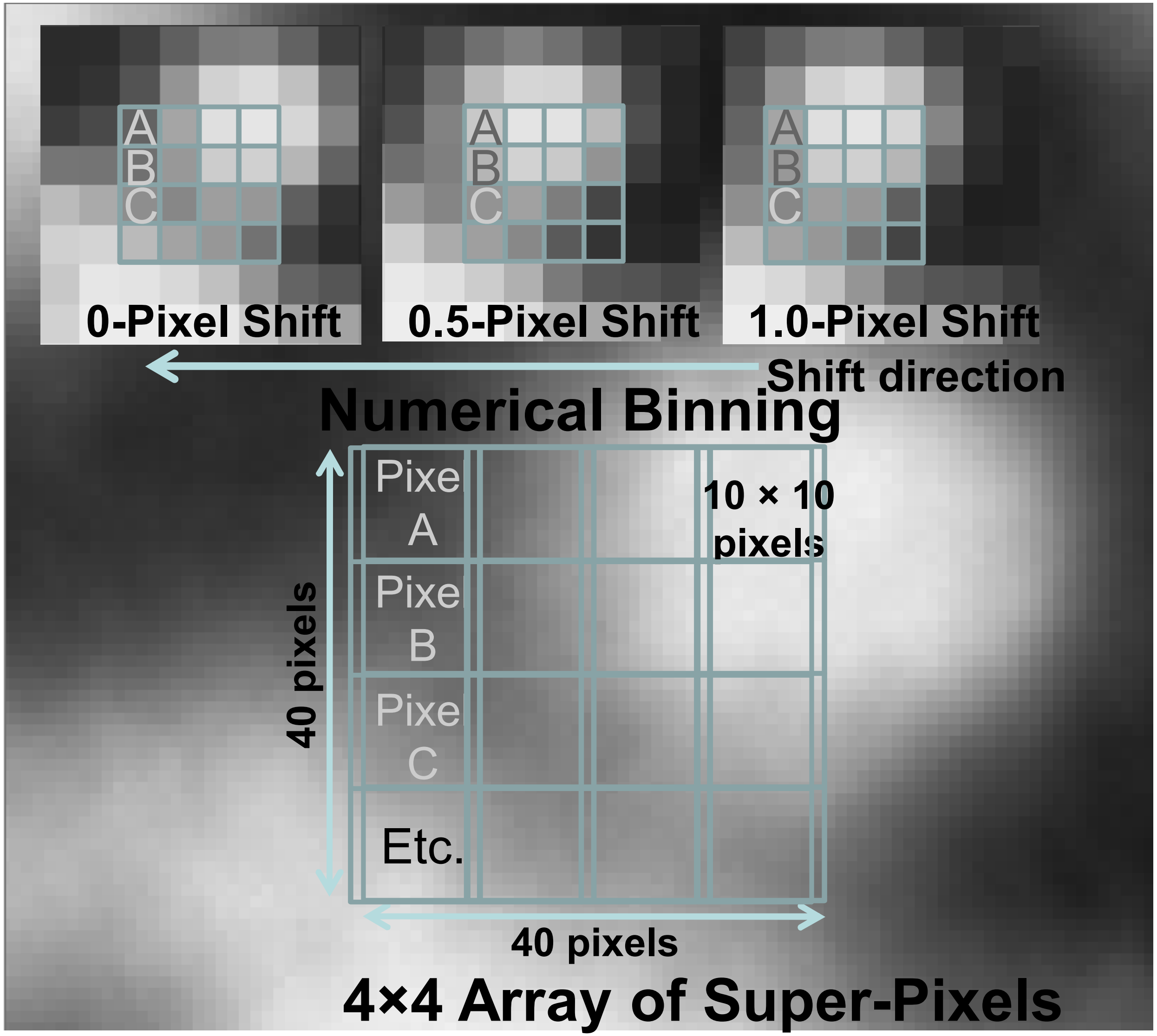
Figure 8: Measured horizontal image-based translation as a function of time. Measurements obtained using 2D digital image correlation with Point Grey camera images and a 209 × 209 subset

Wang YQ, Sutton MA, Bruck HA, Schreier HW (2009). Strain 45 (2):160-178.

Su, Y., et al. (2015). Optics Express **23(15): 19242-19260.**

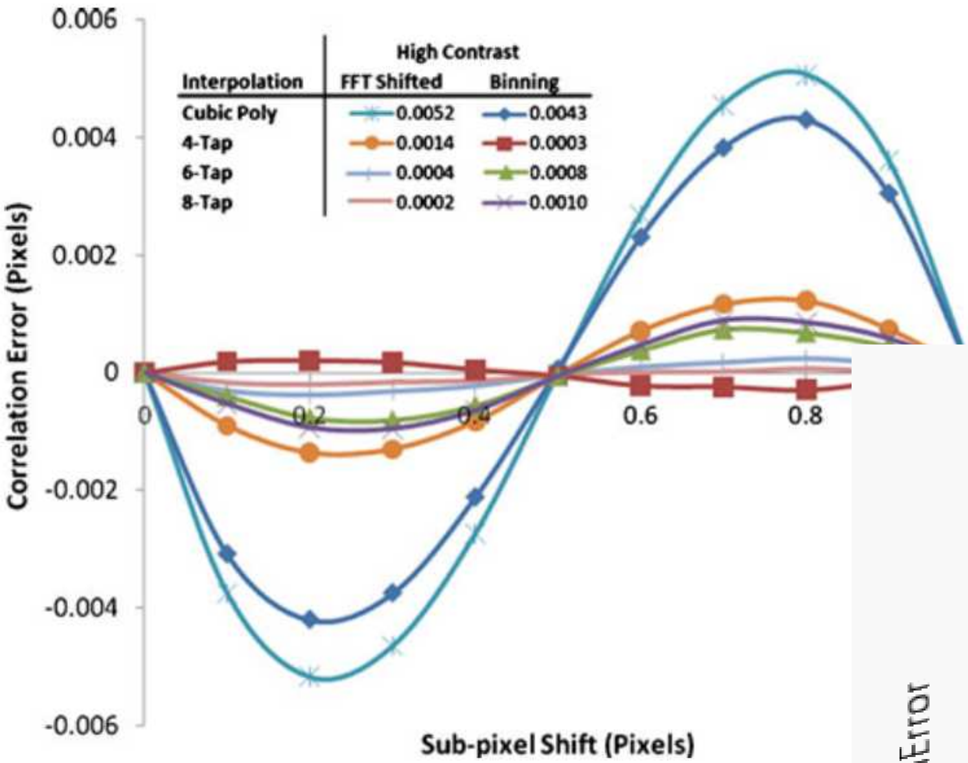
Reu P (2011). Exp Mech 51 (4):443-452.

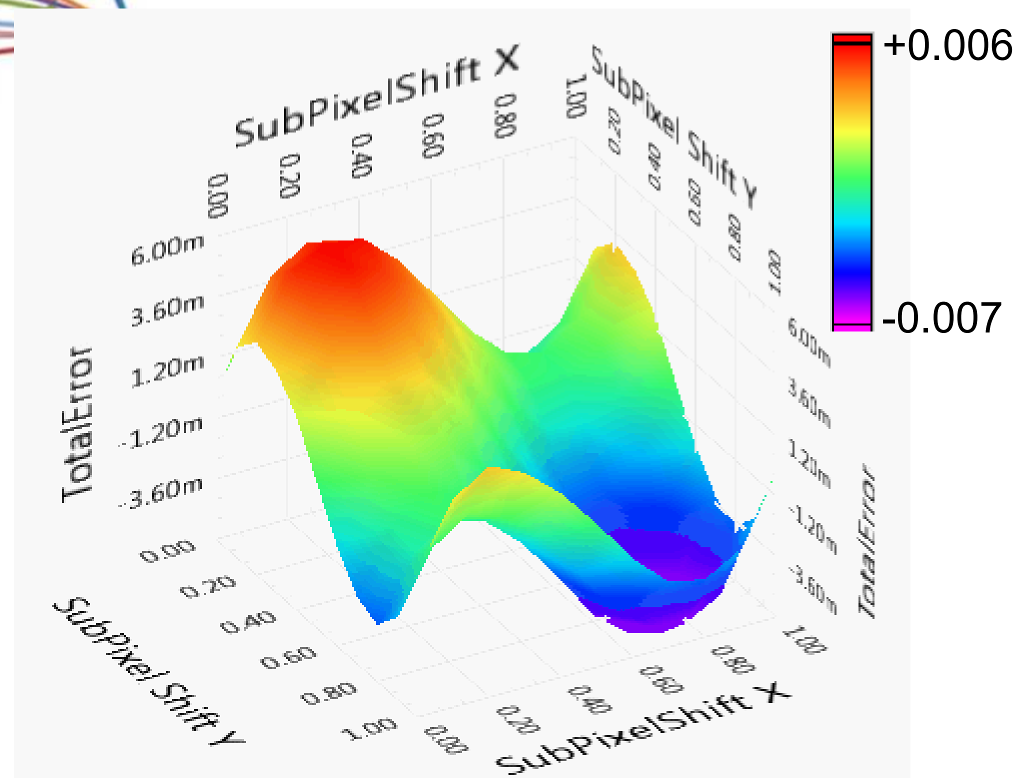
Numerical binning uses a super-pixel averaged to create on image pixel



Reu, P. (2011). "Experimental and Numerical Methods for Exact Subpixel Shifting." Experimental Mechanics **51(4): 443-452.**

Super-resolution exact sub-pixel shifting reproduces the bias error.



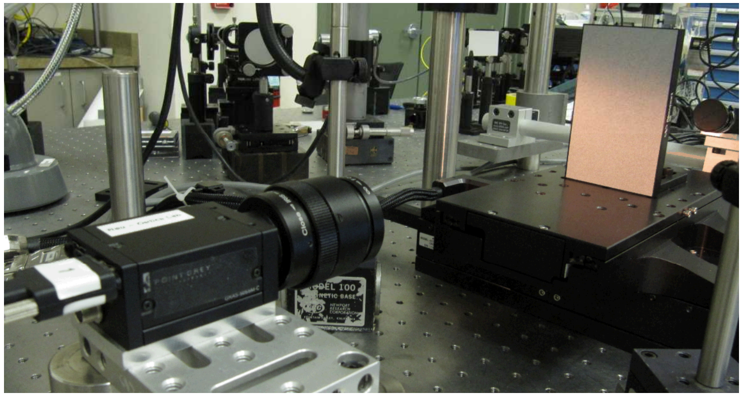


Possible problems

- Is the image band limited i.e. aliasing during decimation.
- Filter then decimate.

In-plane translation test with high-precision stage.

Sandia National Laboratories

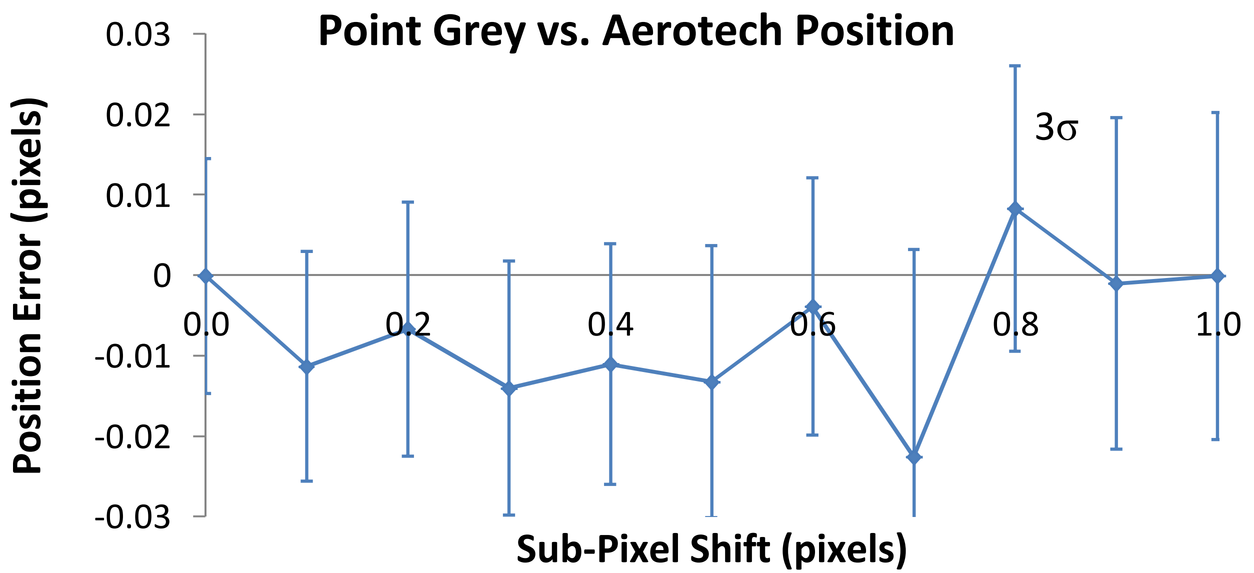


Aerotech ultra-precision x-y stage

- ±1 nm encoder resolution (0.000 03 pixels)
- ±21 nm (3σ) position stability (0.000 7 pixels)
- ±75 nm bi-directional repeatability (0.002 5)
- ±300 nm accuracy (0.01 pixels)

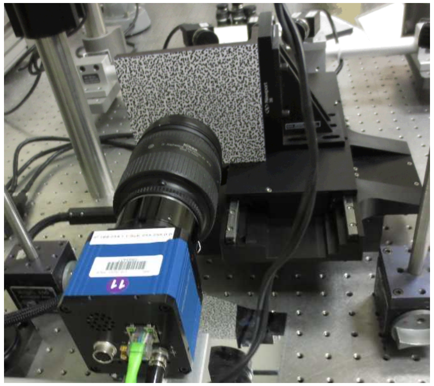
Point Grey 5 MPixel cameras

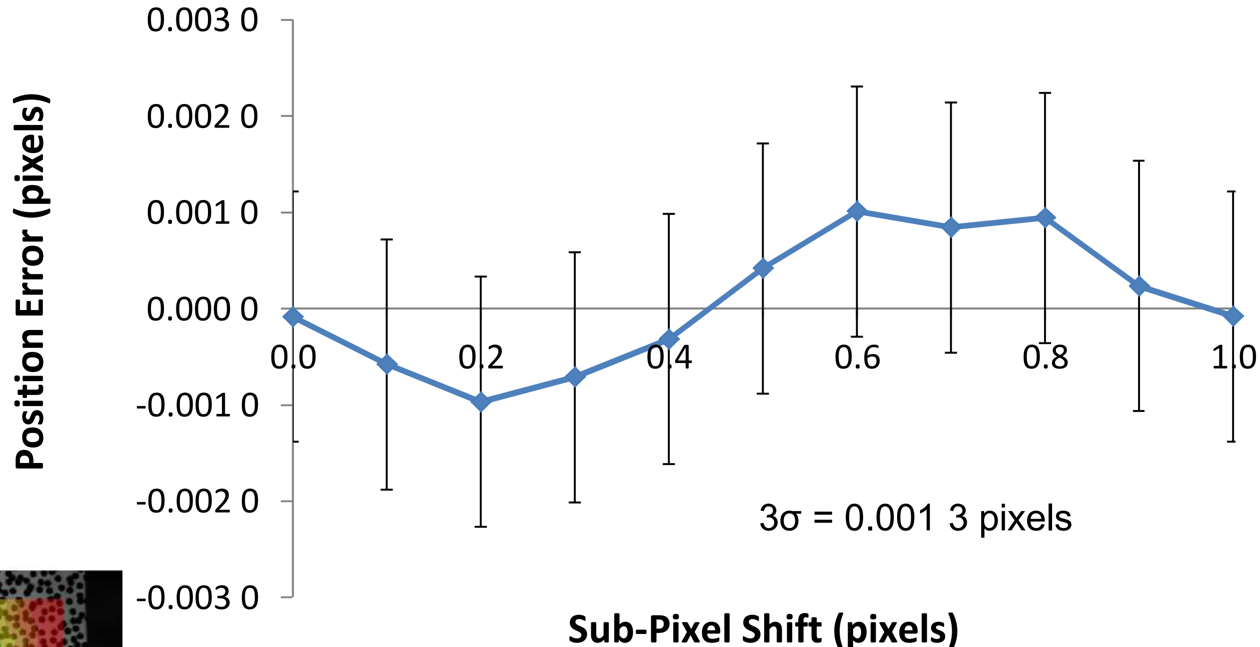
- 29 µm/pixel or 29 000 nm/pixel
- Stage error max. 6 nm or 0.000 2 pixels
- Pixel noise ≈ 2.3 counts (1σ) 0.9%

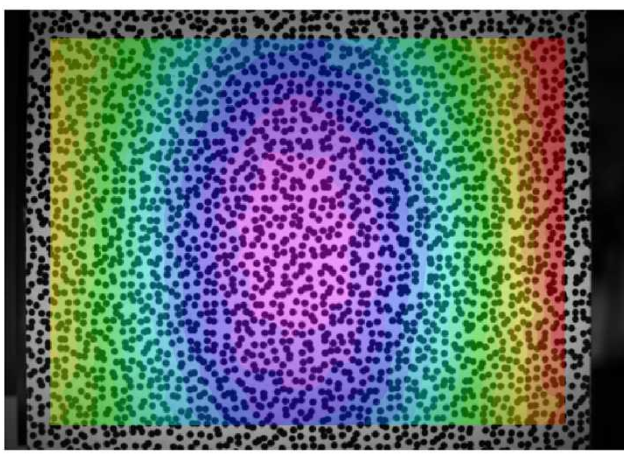


Variance errors dominate bias errors!

An experimental demonstration of the interpolation bias error using in-plane translation.





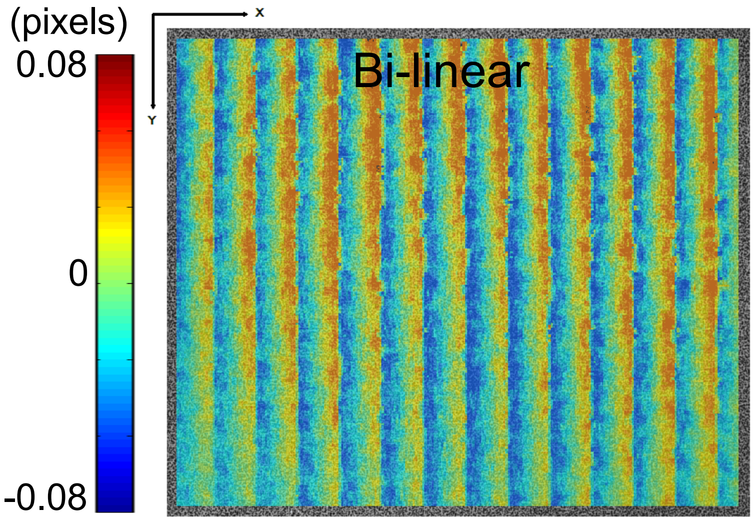


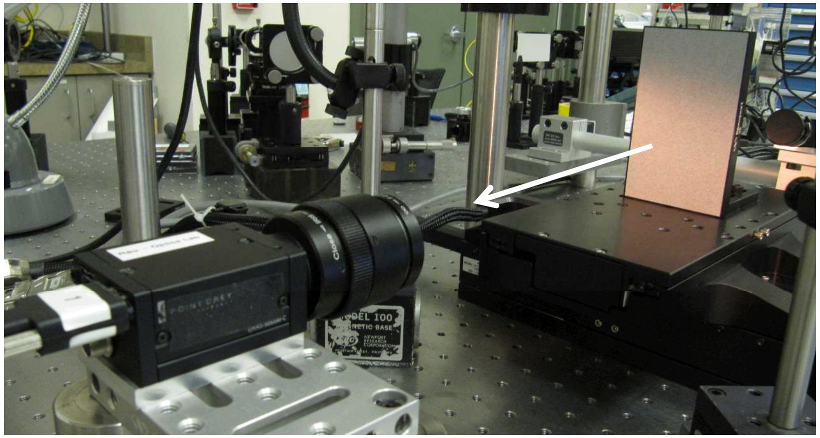
Prosilica 14-MPixel (binned x10)

- 335 µm/pixel or 335 000 nm/pixel
- Stage error max. 6 nm or 4e-6 pixels
- Pixel noise ≈ 0.26 counts (1σ) 0.1%

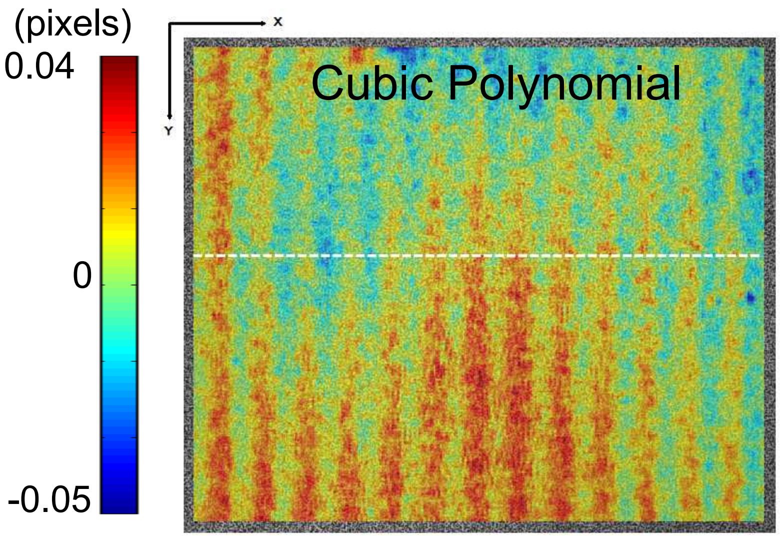
At this point – The lens distortion started to contribute.

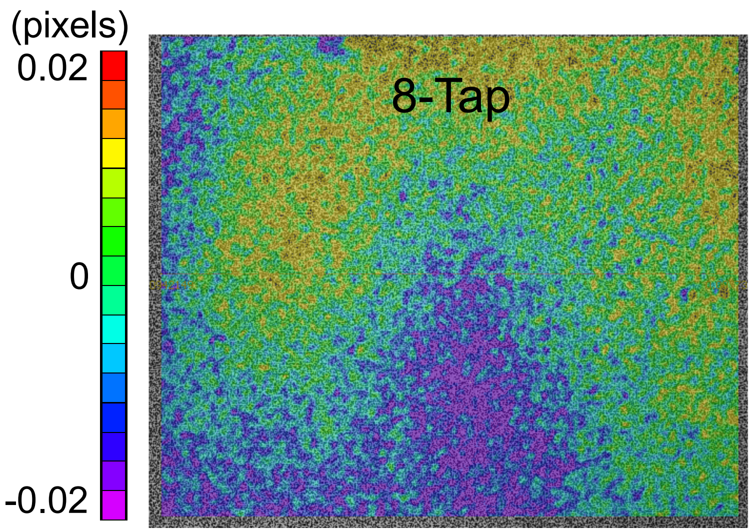
The interpolation bias error is much easier to find with out-of-plane motion.





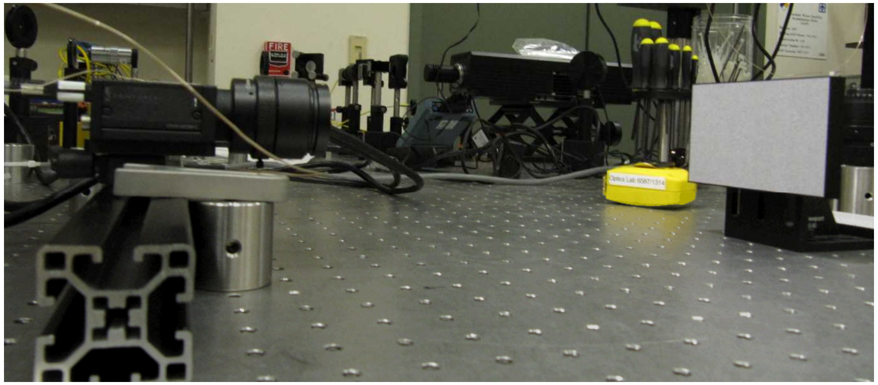
This simulates a biaxial strain, but uniaxial would cause the same issues!

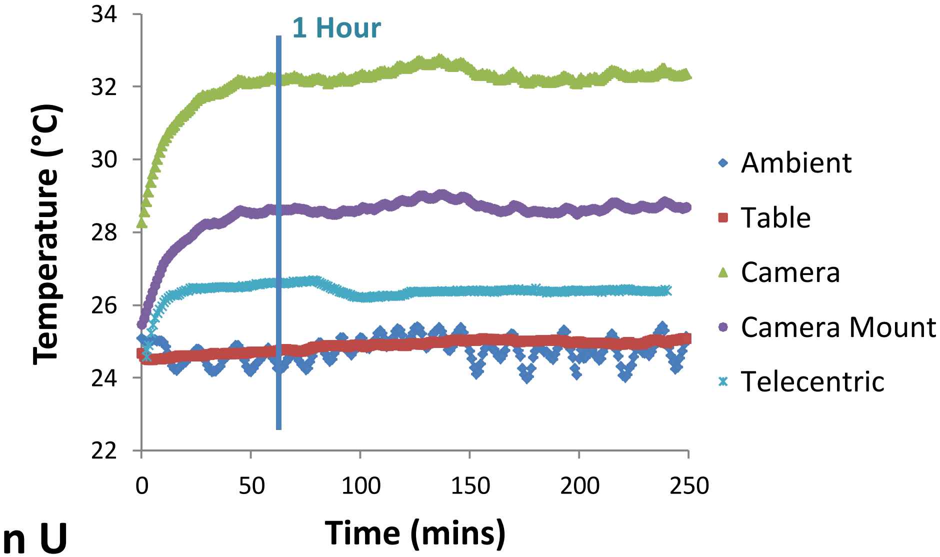


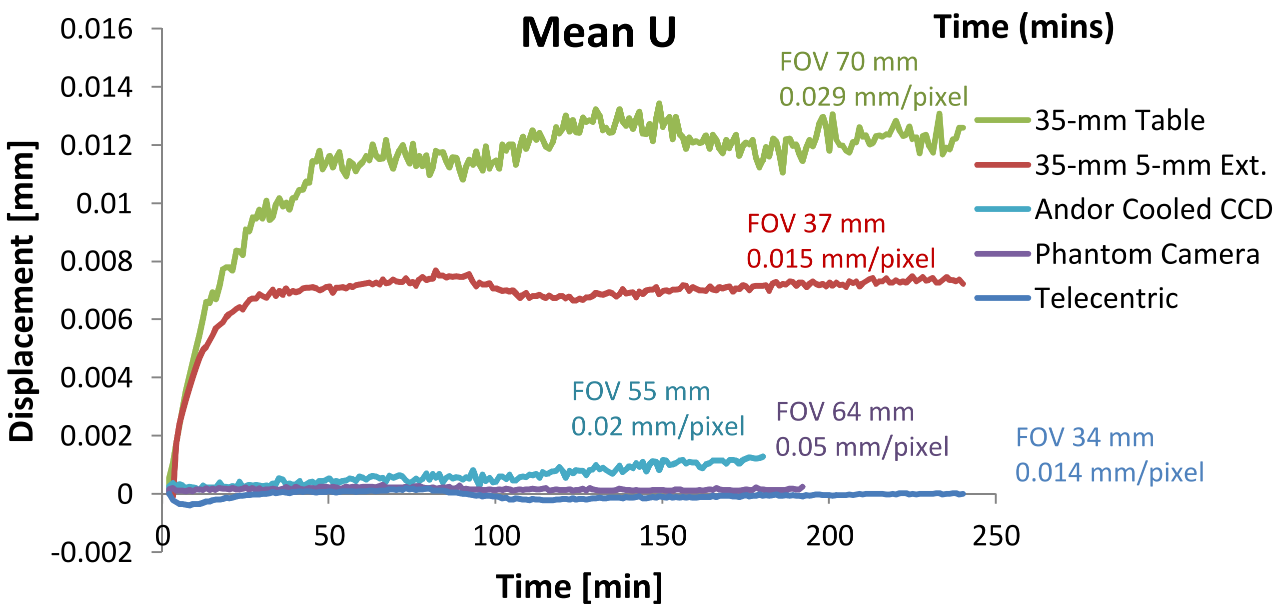


The experimental setup will contribute bias errors to the results.

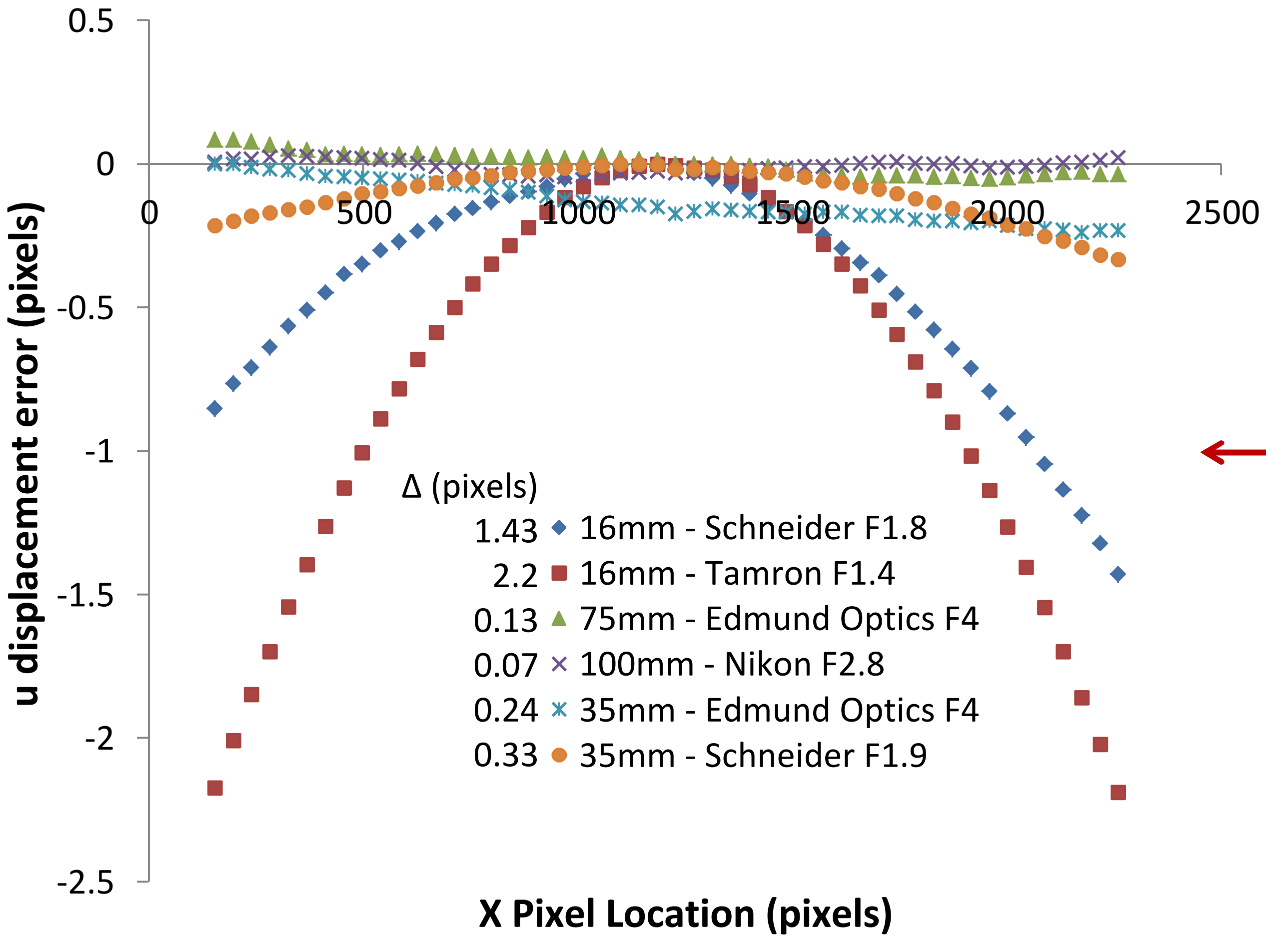
Sandia National Laboratories

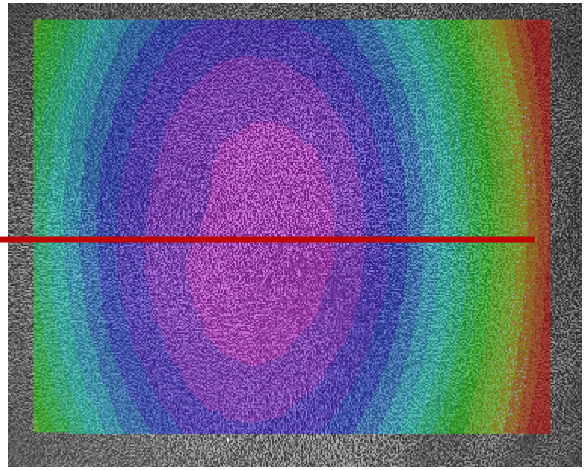






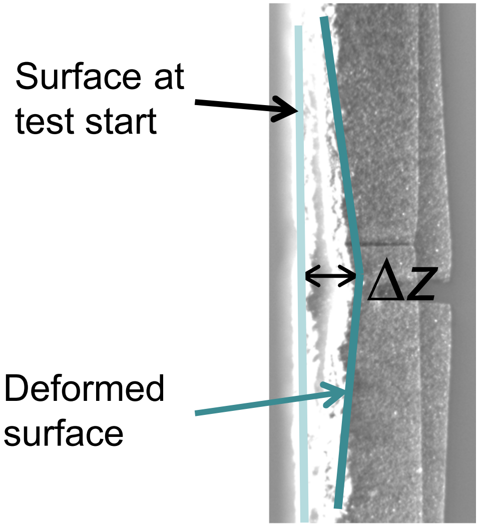
Lens distortions may cause problems with the displacement results.

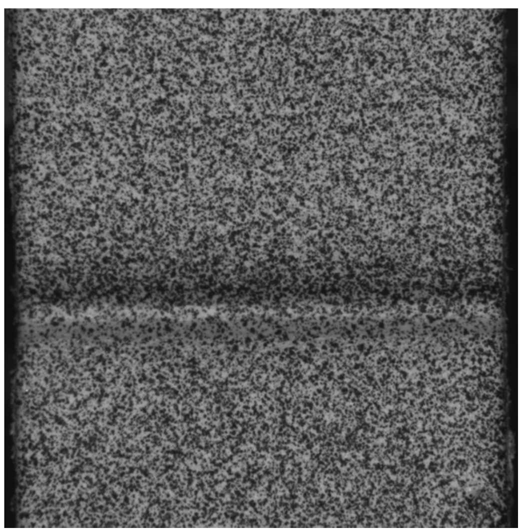




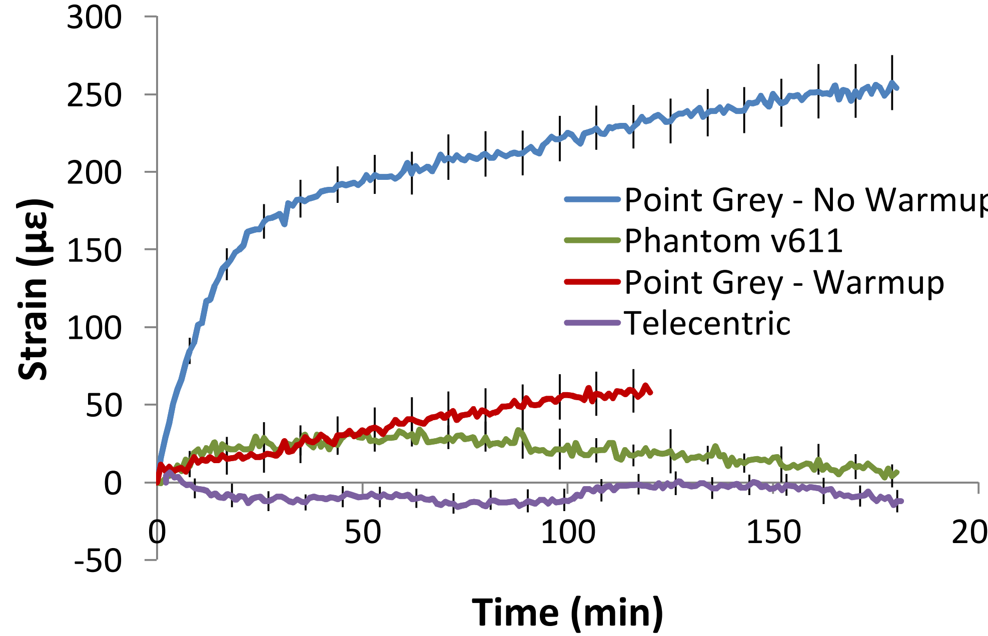
A 50 pixel shift yields a 2 pixel error at the edges.

Bi-Telecentric lens will aid in removing out-of-plane errors.





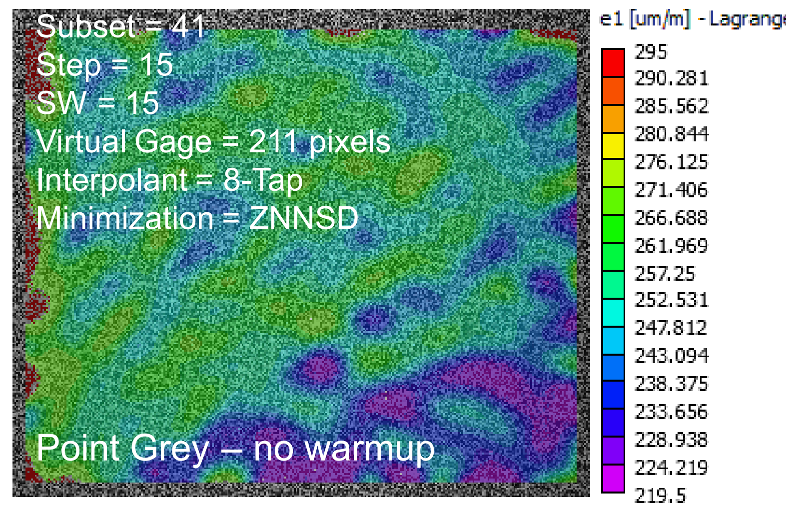
Sutton, M. A., et al. (2008). Optics and Lasers in Engineering **46(10): 746-757.**



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

Max out-of-plane, Δz = 0.41 mm

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



Pan, B., et al. (2014). Applied Optics **53(19): 4216-4227**

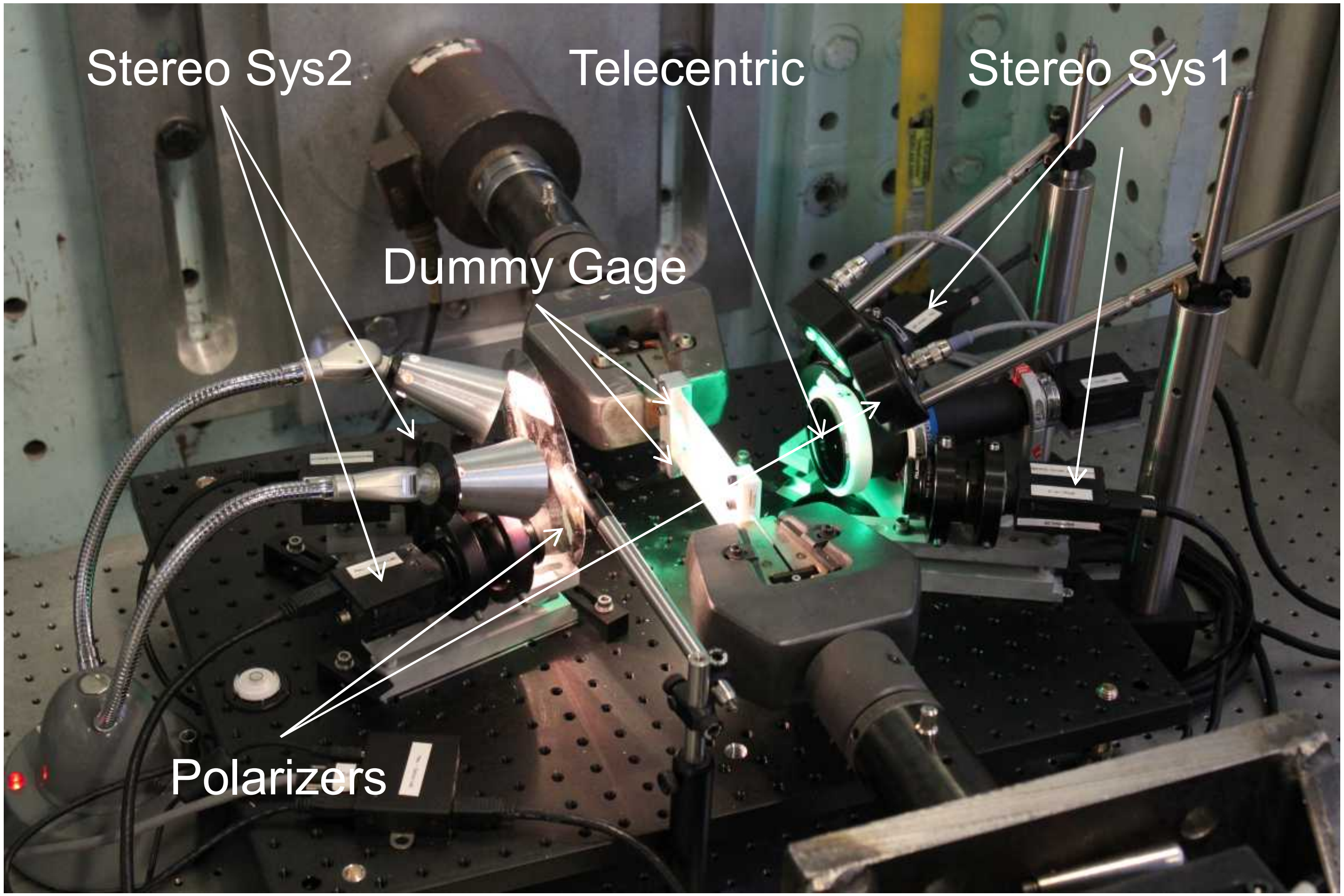
Everyone should create an error table!

Sandia National Laboratories

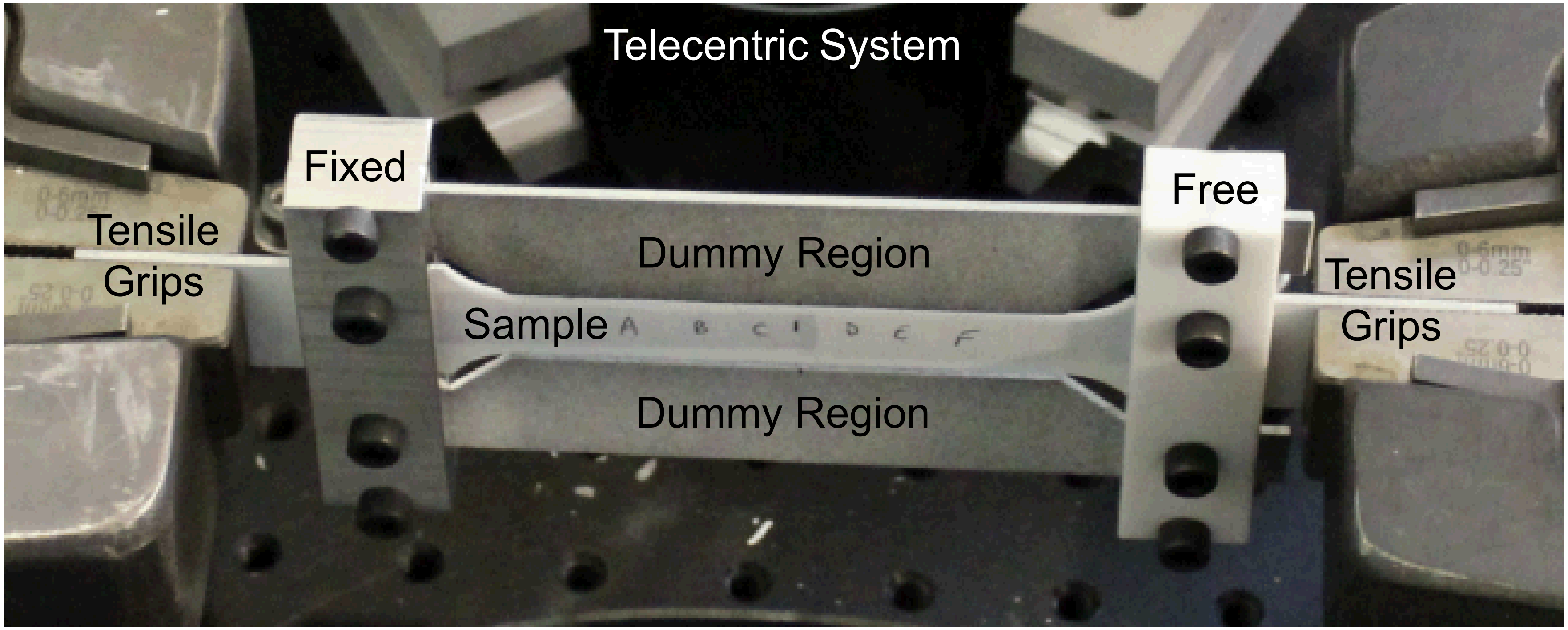
2D Error Source	Type	Assessment Method	≈ |pixels|
Lens distortion	B	Either camera calibration (grids) or speckle translation.	Pixels (w/o Calib.)
Camera motion	A,B	Noise Floor or static “dummy” region.	0.5
Sample motion	B	Dummy region or other measurement method	0.5
Turbulence	A,B	Noise floor (must have same environment as test)	0.01 to pixels
Image blur	B	Estimated from synthetic images	0.001
Resolution	B	Estimated via experiments and synthetic images	0.001 (contrast)
Image noise	A	Noise floor	0.01
Speckle contrast	A	Noise floor	0.01
Speckle size	B	Direct measure of speckle size, noise floor, parameter study	0.02 (w/o aliasing)
Aliasing	A,B	Noise floor	0.005
Interpolant	B	Synthetic and experimental image studies for optimum.	0.001 to 0.01
Minimization	B	DIC parameter study, synthetic and exp. image studies	0.005
Shape function	B	DIC parameter study, synthetic and exp. image studies	Linear fit
Subset size	B	DIC parameter study, synthetic and exp. image studies	Noise vs filtering
Filtering	B	DIC parameter study	Spatial resolution
Strain calculation	B	DIC parameter study	Spatial resolution
Coord. system	B	Other means	

A 2D-DIC exemplar experiment: Trying to eliminate, control and quantify the errors.

Goal: Measure the elastic modulus of a tensile specimen.



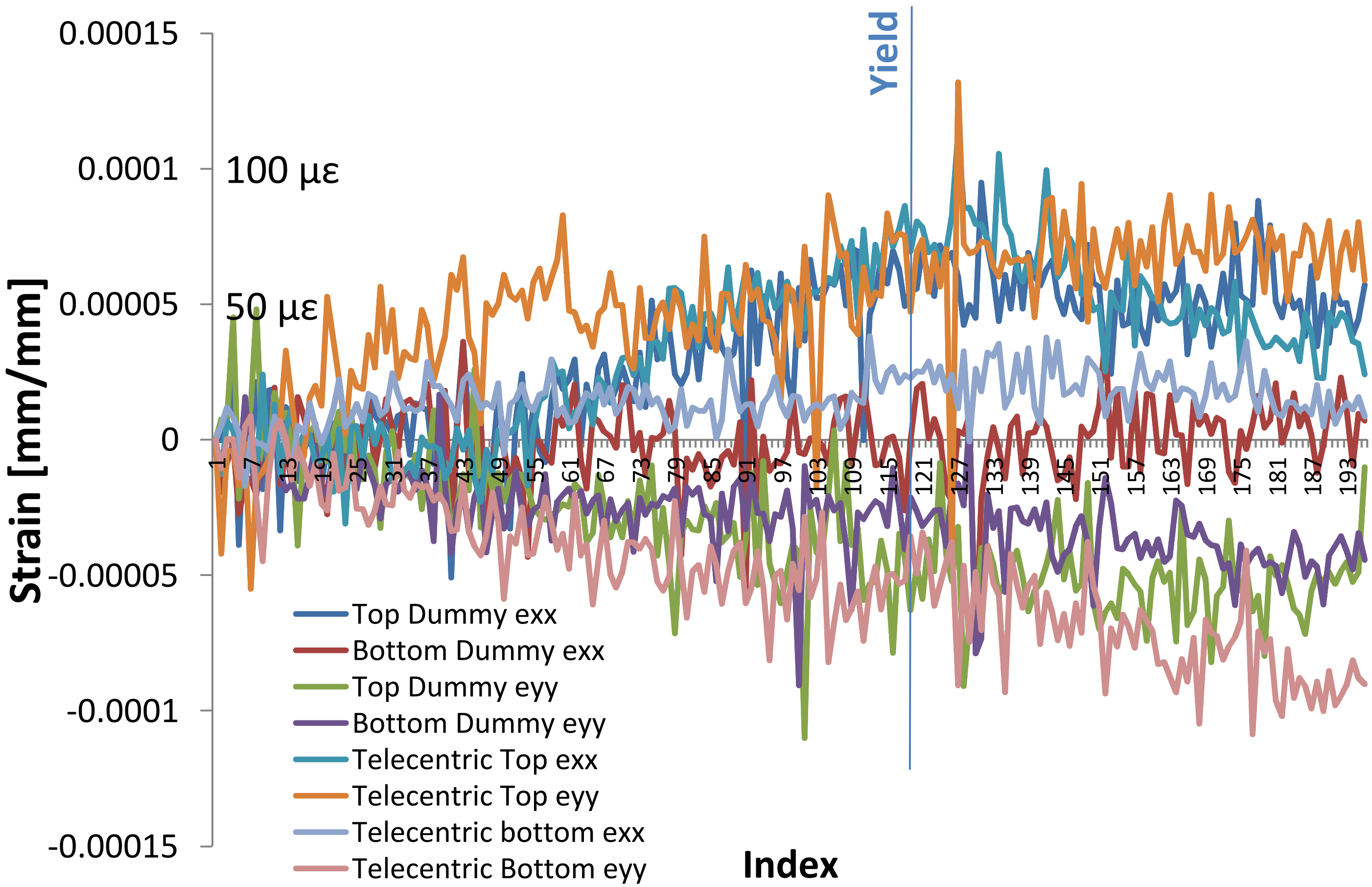
Dummy gage† region allows a number of errors to be quantified.



Software Settings
ZNSSD, 4-Tap, No Filtering
SS = 29, ST = 7, SW=15

†Pan, B., et al. (2014). Measurement Science & Technology **25(2).**

Dummy region can be used to look at the strain noise floor plus bias errors.

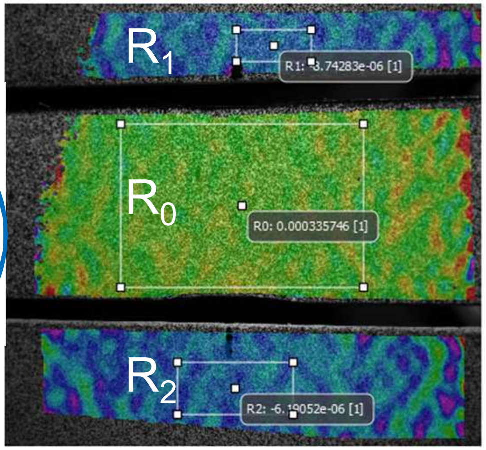


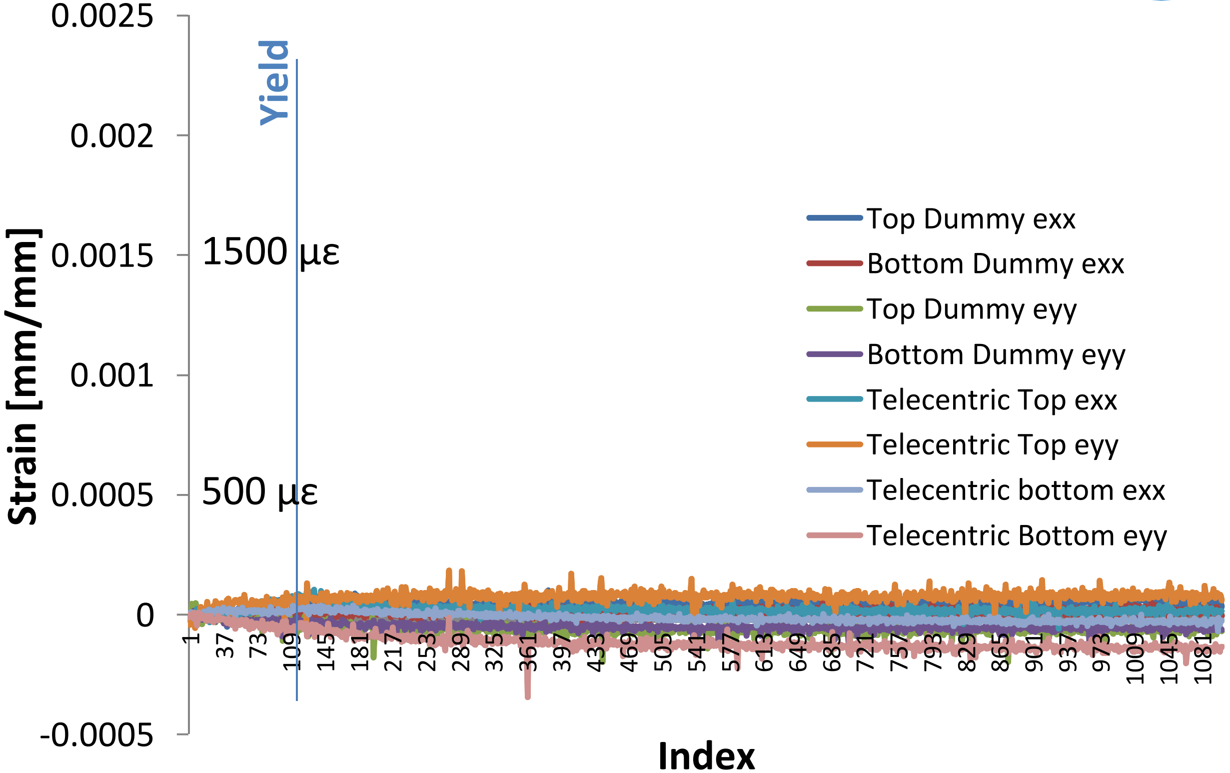
Telecentric lens is important to correcting the out-of-plane errors.

(all με)	Up to Yield				Entire Run				Entire Run			
	Top		Bottom		Top		Bottom		Top		Bottom	
	exx	eyy	exx	eyy	exx	eyy	exx	eyy	σ(exx)	σ(eyy)	σ(exx)	σ(eyy)
System 1	10	-15	-2	-20	45	-61	10	-49	18	23	15	16
Telecentric	9	33	11	-29	22	73	-12	-113	18	23	18	36

Bias

Noise



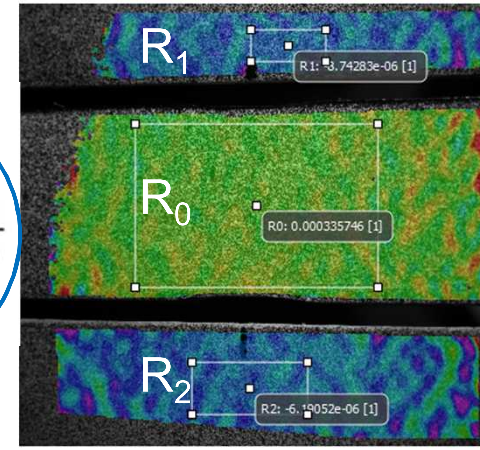


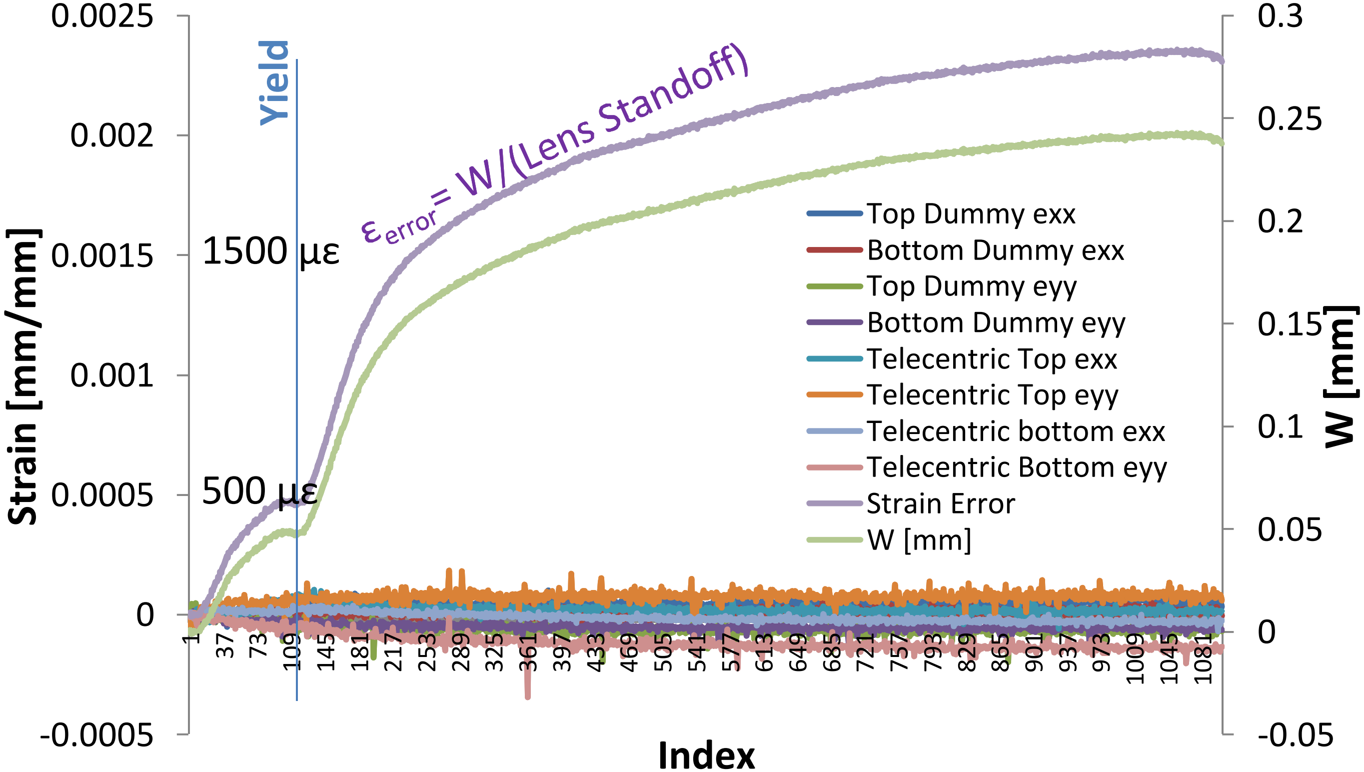
Out-of-plane motion can create a large error source in 2D-DIC.

(all με)	Up to Yield				Entire Run				Entire Run			
	Top		Bottom		Top		Bottom		Top		Bottom	
	exx	eyy	exx	eyy	exx	eyy	exx	eyy	σ(exx)	σ(eyy)	σ(exx)	σ(eyy)
System 1	10	-15	-2	-20	45	-61	10	-49	18	23	15	16
Telecentric	9	33	11	-29	22	73	-12	-112	18	23	18	36

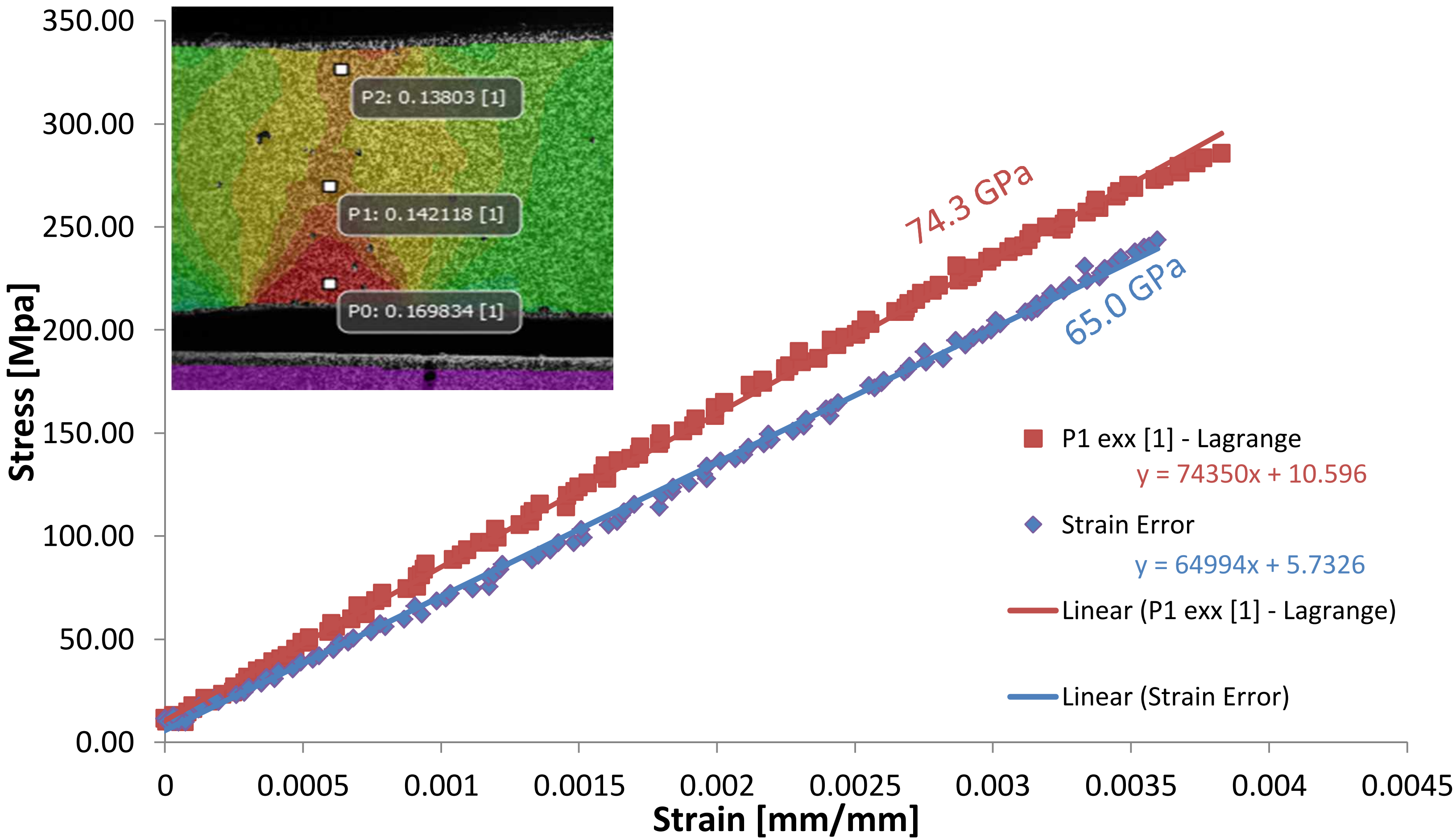
Bias

Noise





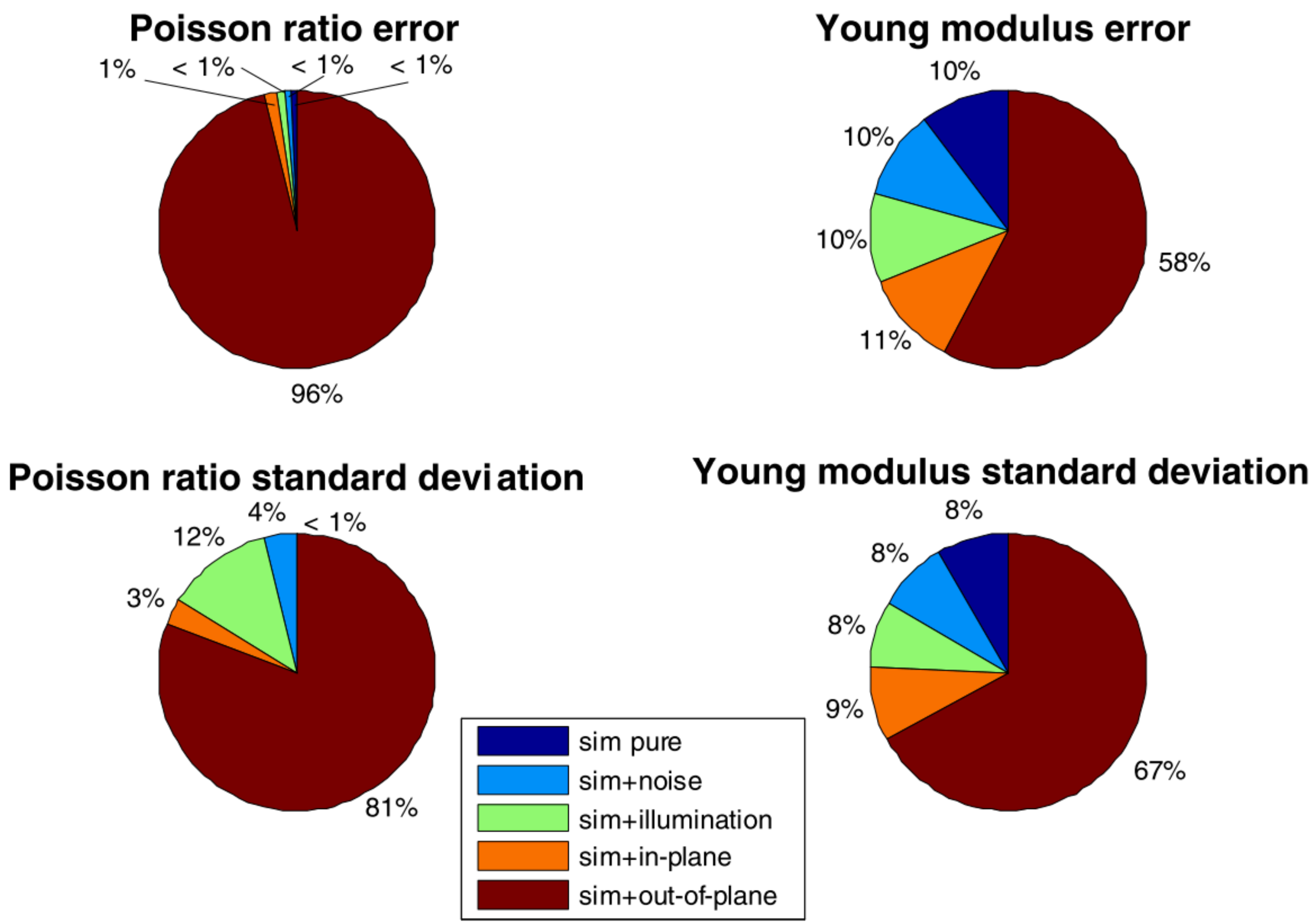
Out-of-plane motion can cause large errors in material ID.



13% error for a 0.25-mm out-of-plane motion!

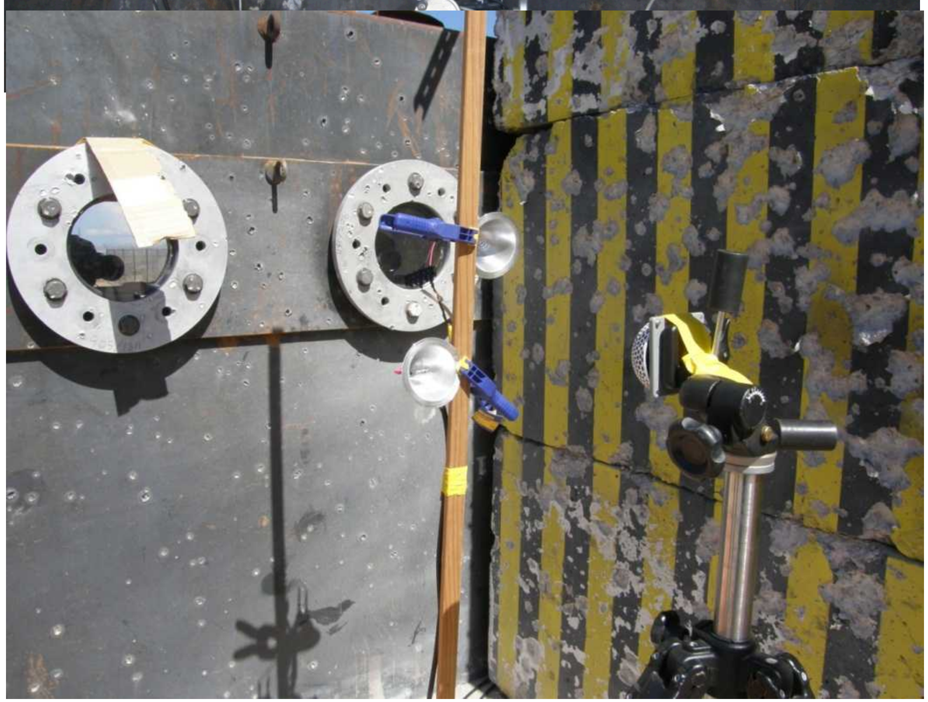
A simulation approach may be useful in quantifying errors.

Fig. 18 The pie chart shows the impact of the different key elements in the identification in term of means and standard deviations



Badaloni, M., et al. (2015). Experimental Mechanics: 1-16.

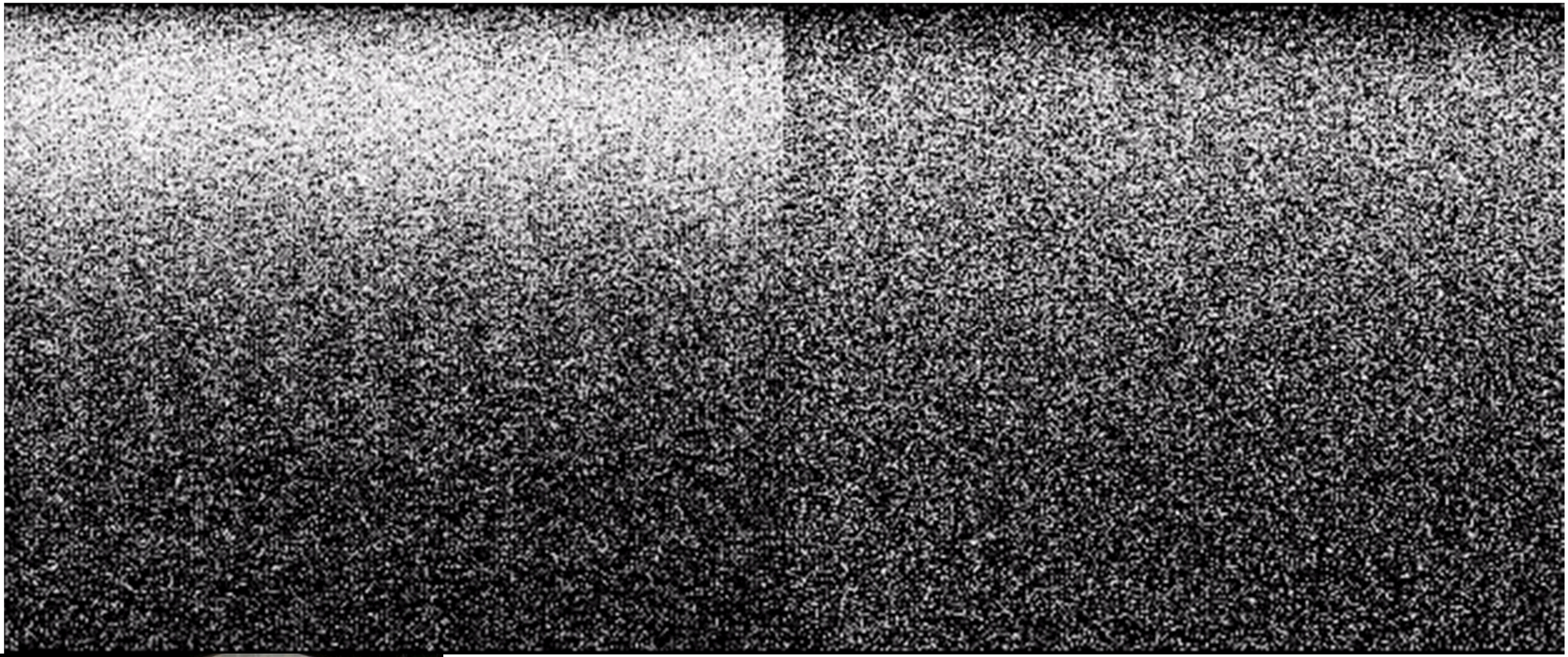
Example: Cased explosive at 1 MHz

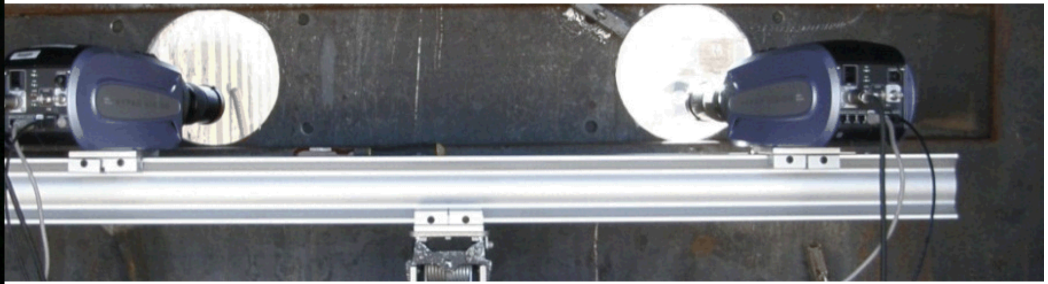


Reu, P. L. and T. J. Miller (2008). "The application of high-speed digital image correlation." Journal of Strain Analysis for Engineering Design **43(8): 673-688.**

Cooper, M. A., Reu, P.L. Miller, T.J. (2010). 14th International Detonation Symposium, Coeur d'Alene, Idaho.

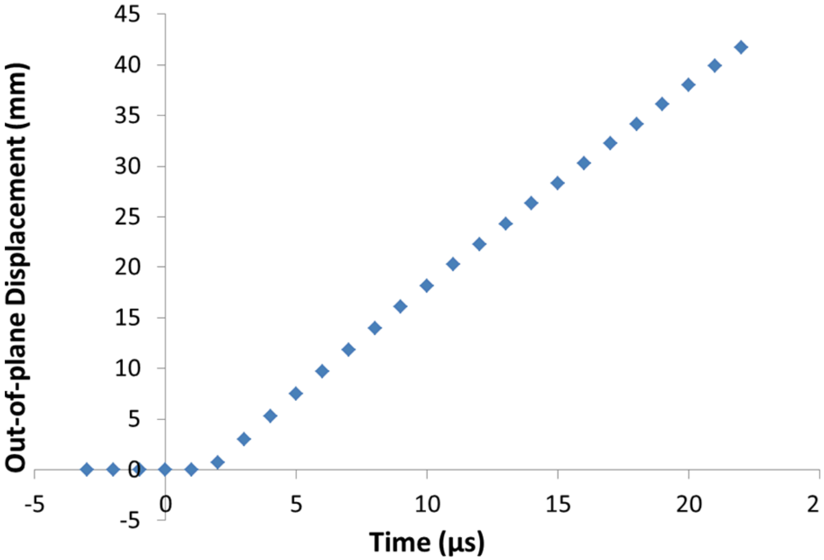
Stereo-DIC of cased explosive at 1 MHz

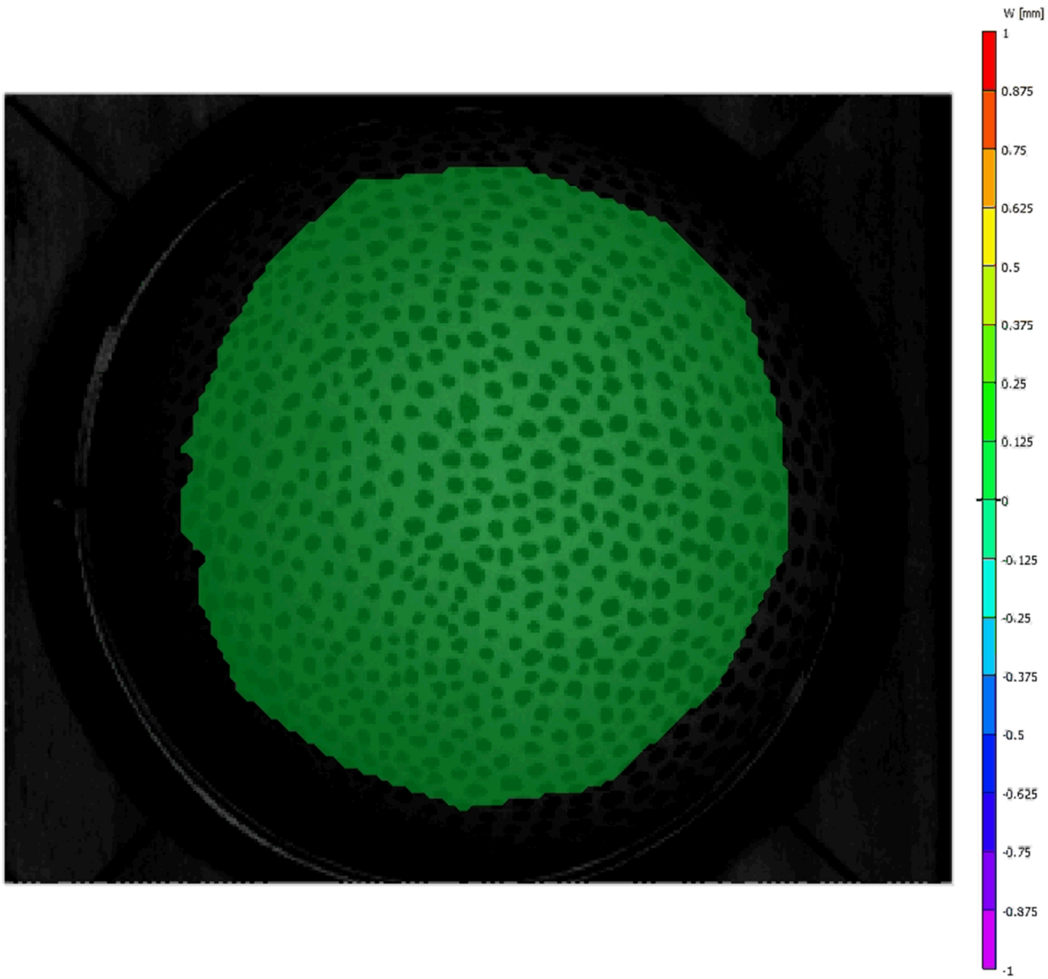




Reu, P. L. (2011). Advances in Experimental Mechanics Viii. Trans Tech Publications Ltd. **70: 69-74.**

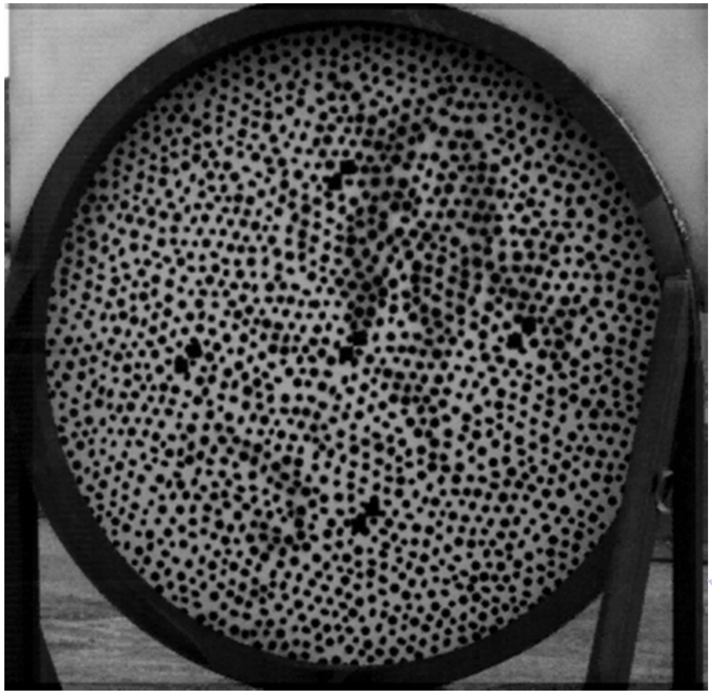
Typical displacement results at 1 Million frames per second

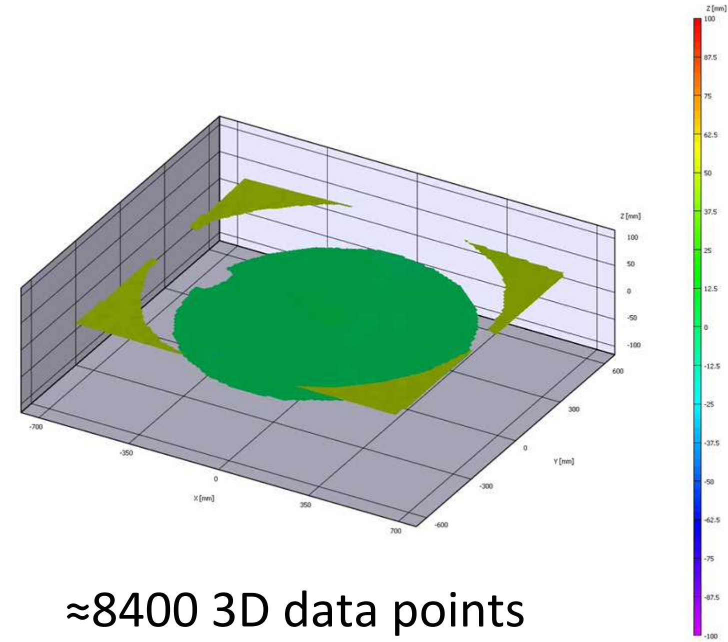




You can also get:
- 3D velocity
- Strain
- Strain rate

Example: Blast loaded plate at 35-kHz





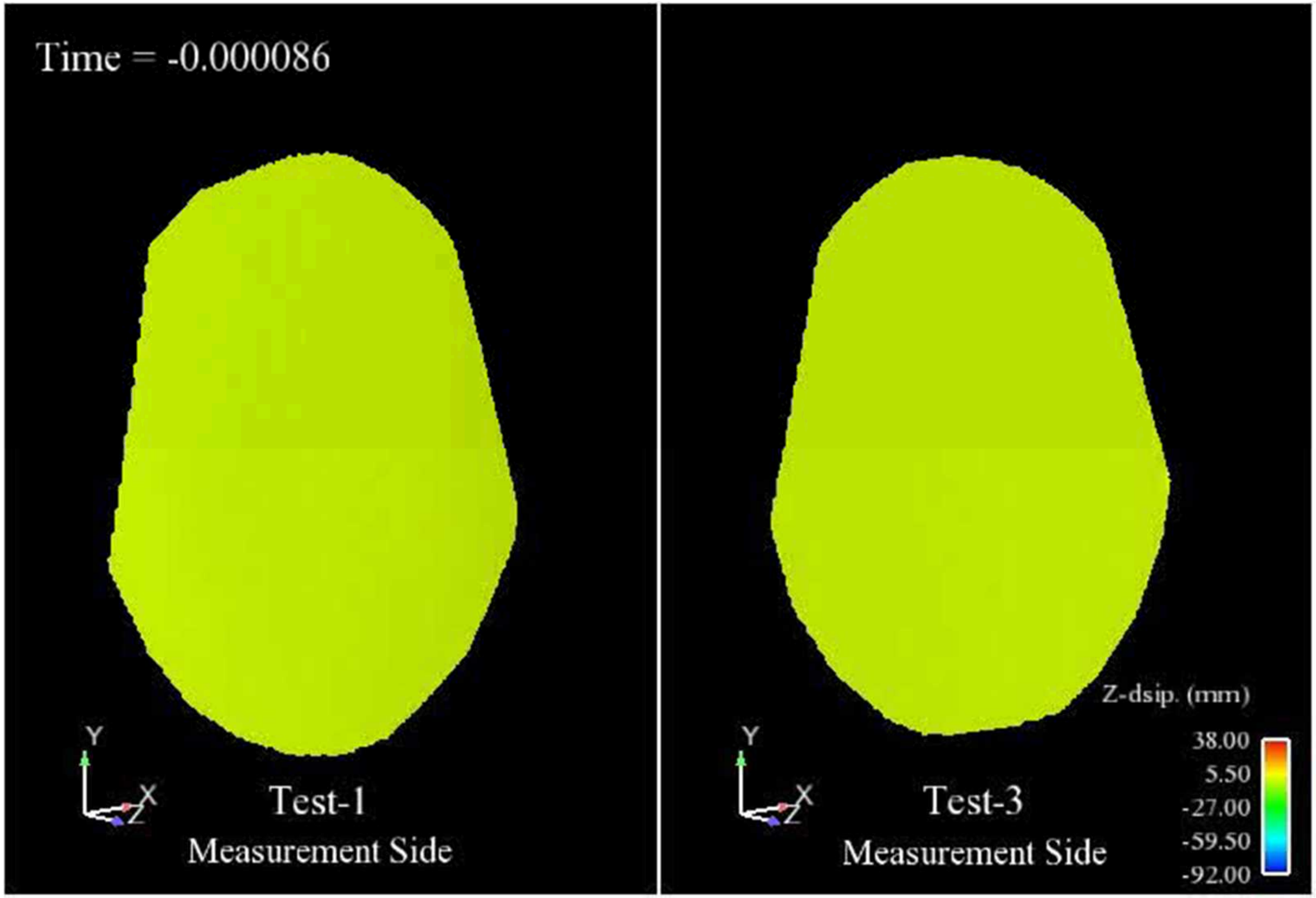
≈8400 3D data points

≈25 ft

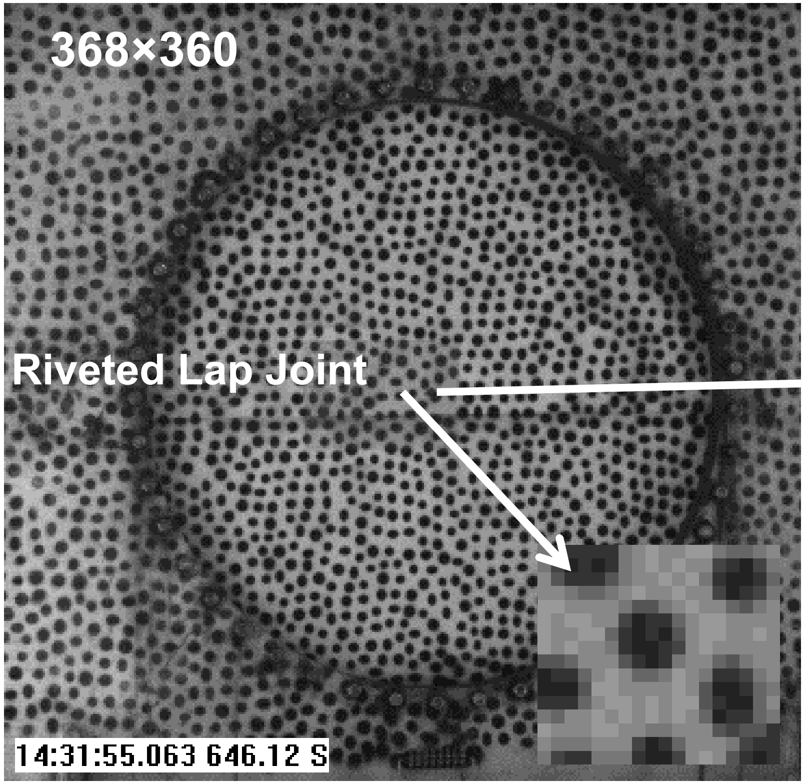
1 Stereo-DIC System
≈37,000 fps 368×360 Wide View

Reu, P. L. (2014). Advancement of Optical Methods in Experimental Mechanics, Volume 3., Springer International Publishing: 119-124.

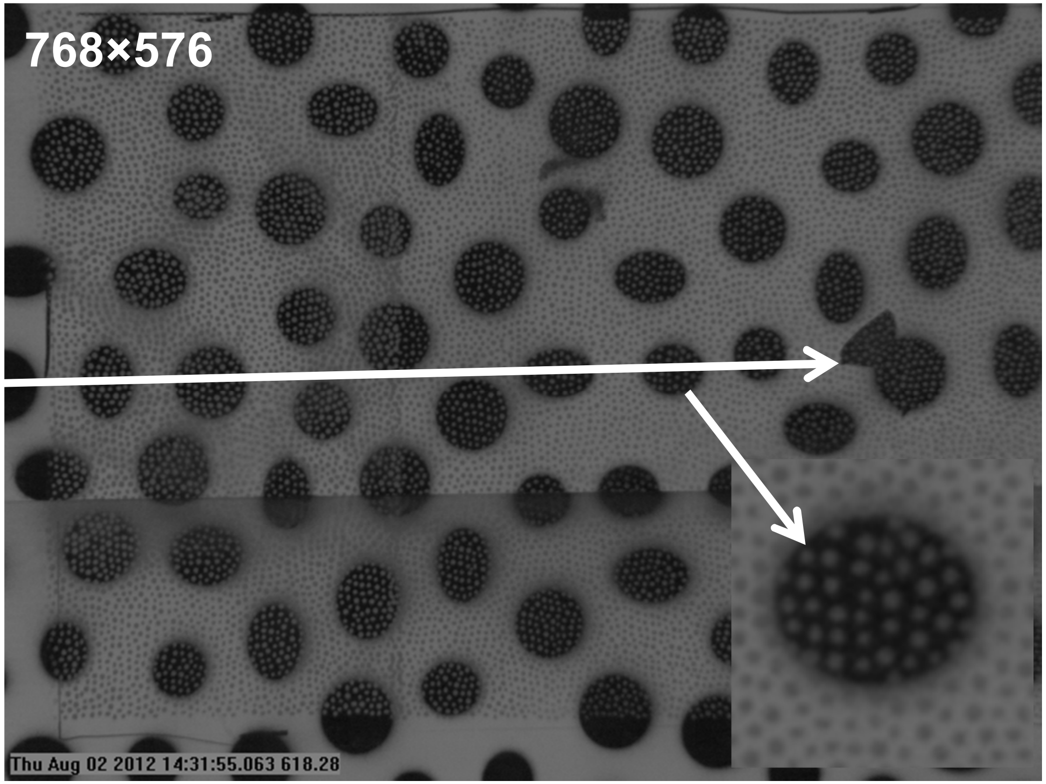
Full-field data helps with understanding the experiment.



Example: Simultaneous strain and displacement at 36 kHz.



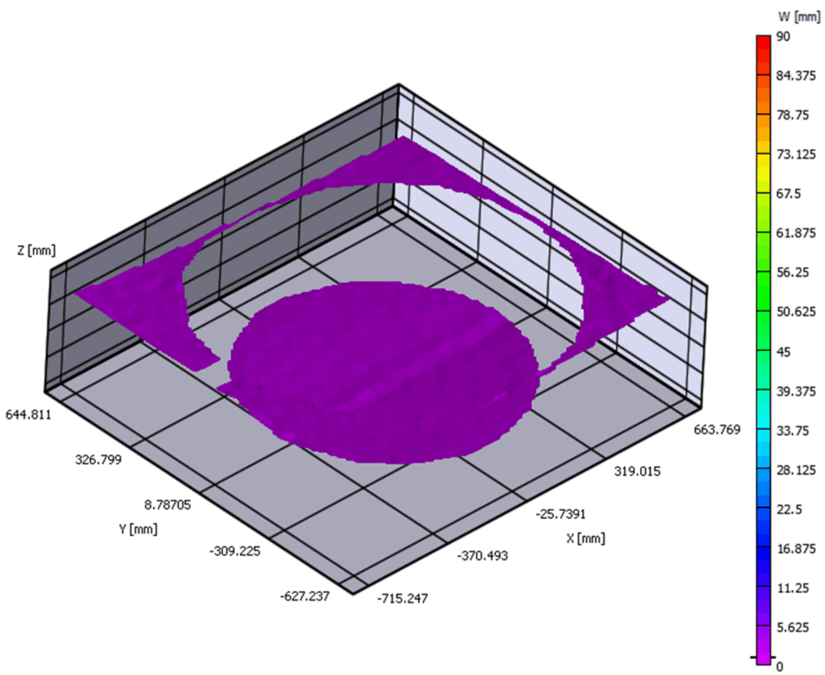
4 mm/pixel

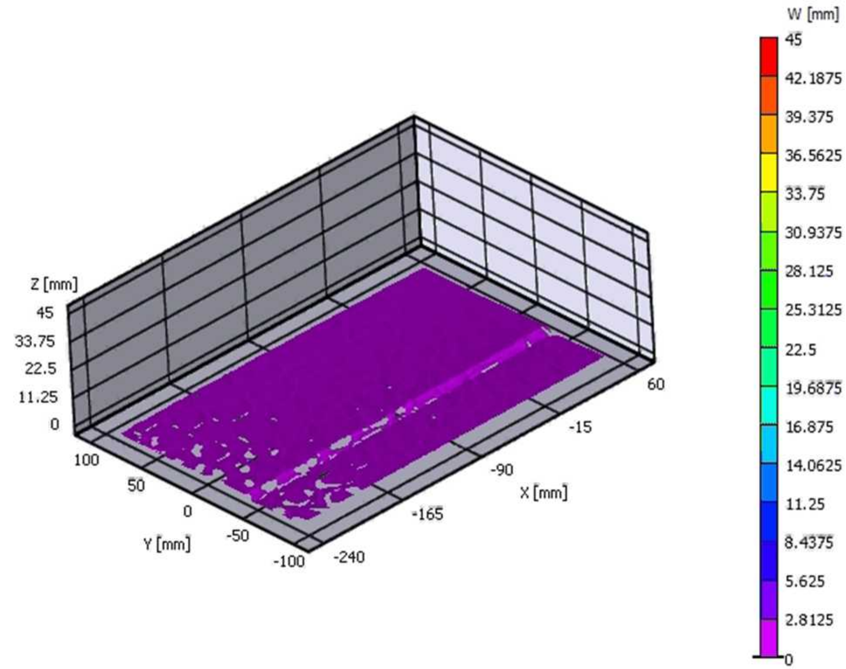


0.4 mm/pixel

This works because the small speckles are severely aliased in the wide FOV.

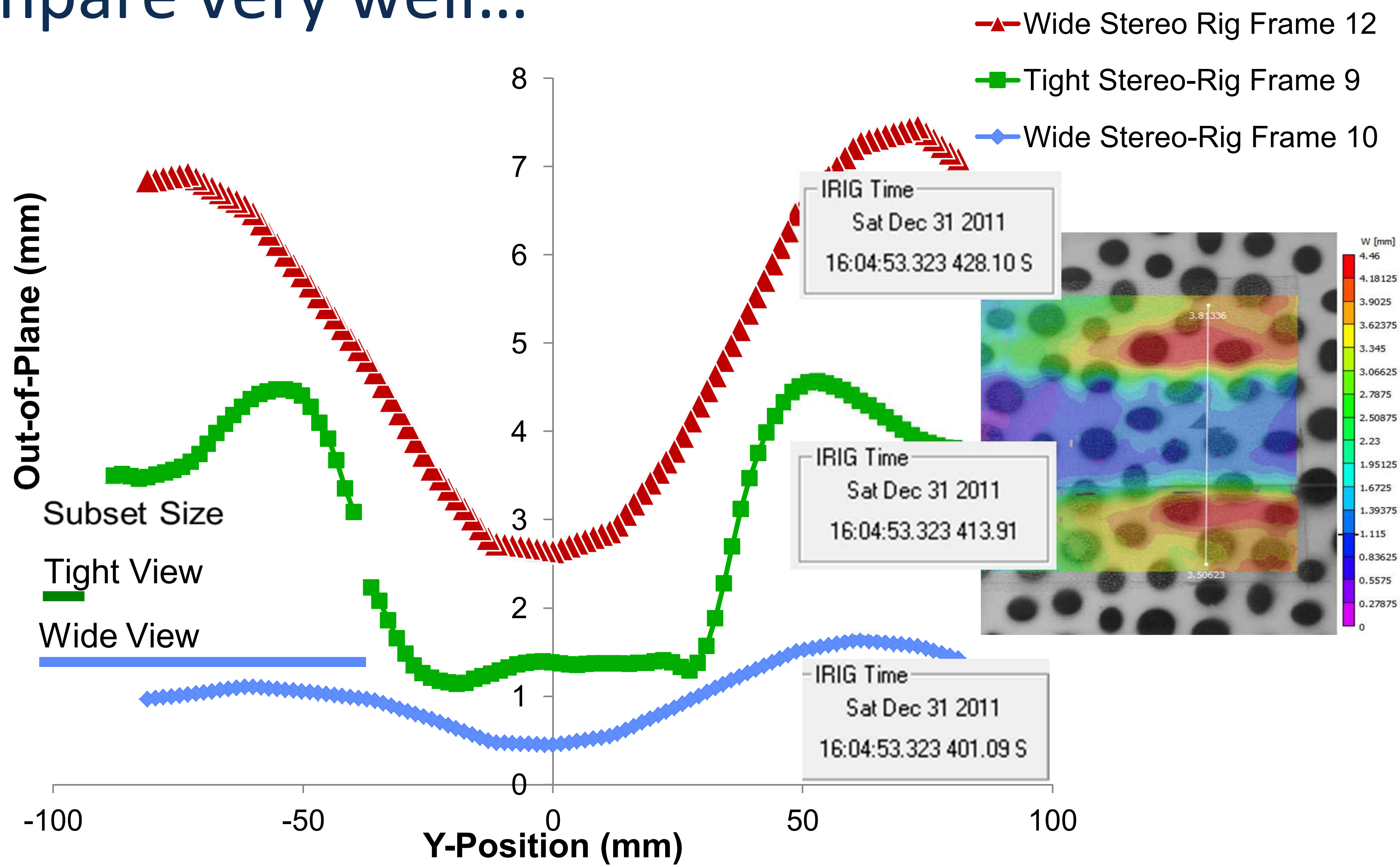
We have two systems to measure at two different spatial resolutions.



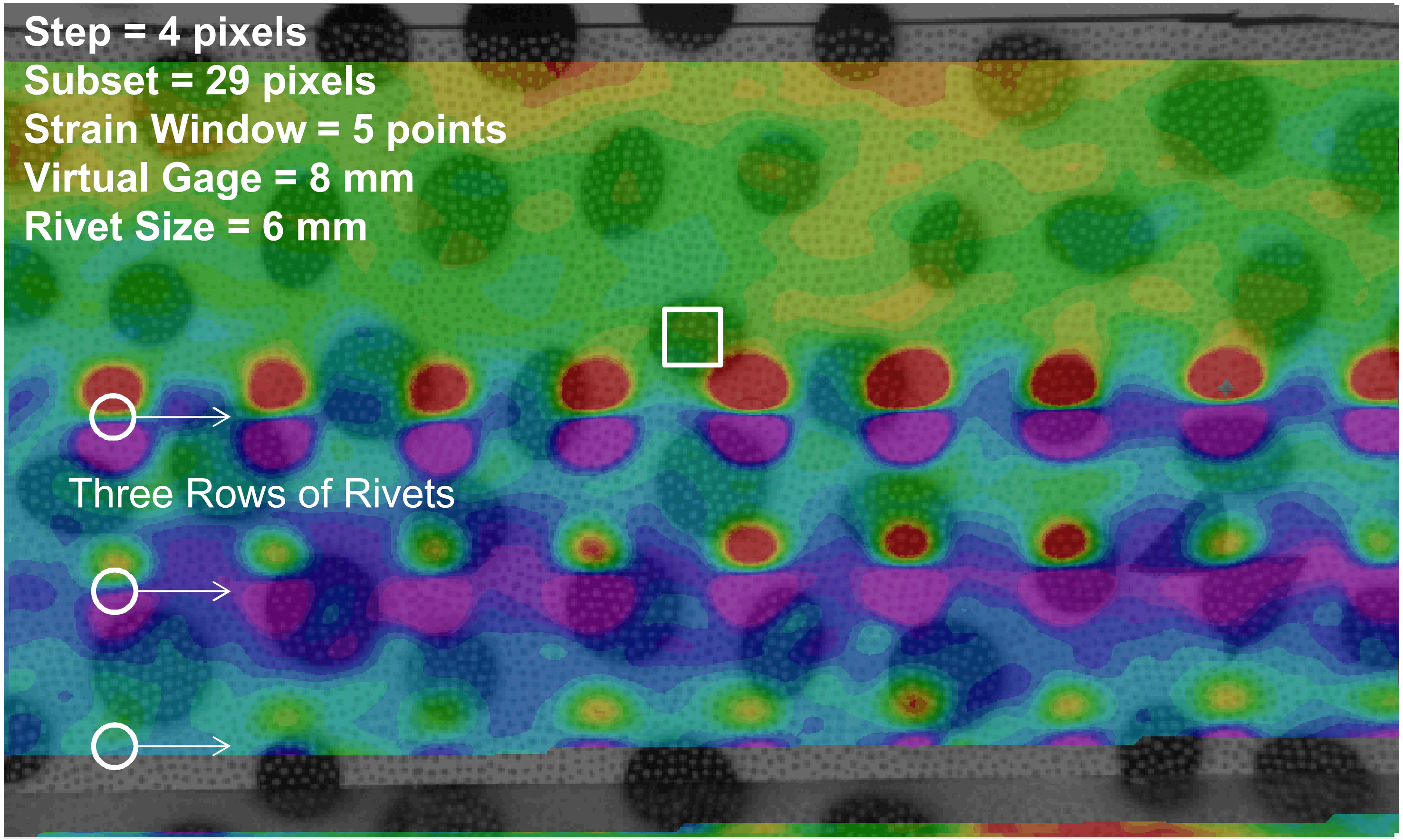


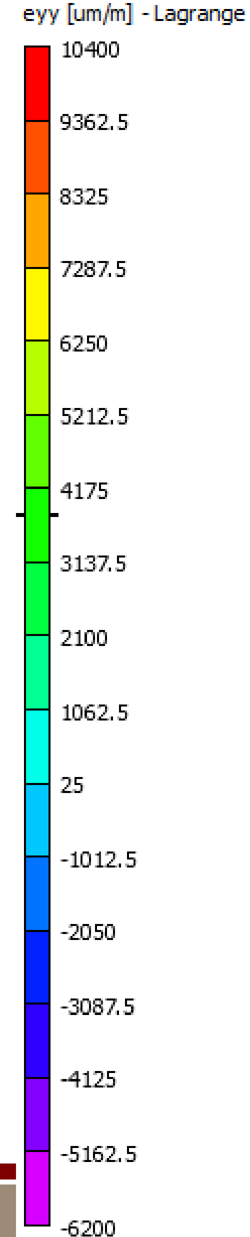
2 Stereo-DIC Systems
≈37,000 fps 368×360 Wide View
≈33,000 fps 768×576 Tight View

The overall and tight results compare very well…



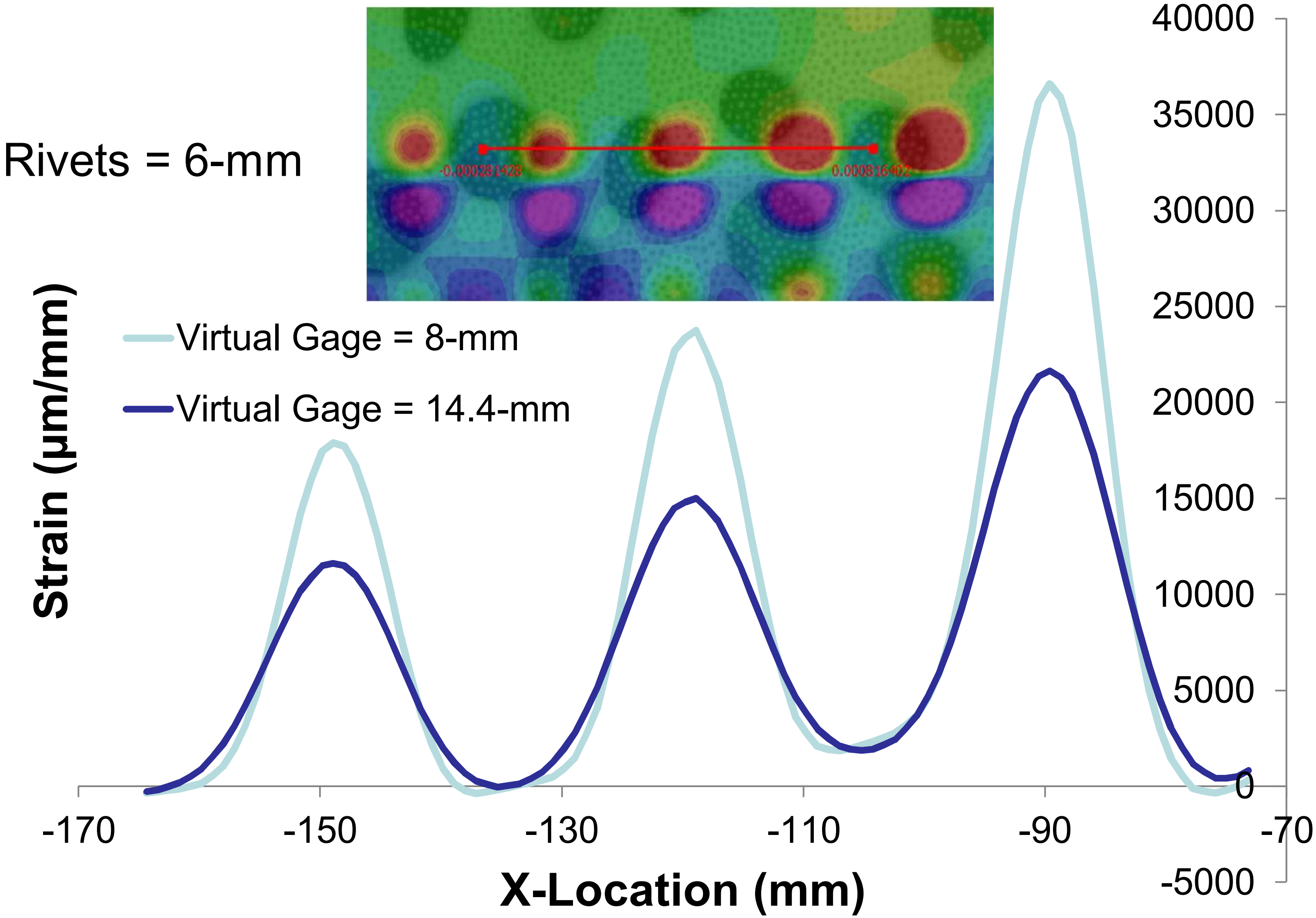
With proper experimental design small virtual gage regions can be measured.





Estimated Uncertainty of 3D Position → Calculation of Strain

Strain profiles across rivets.



Estimated Uncertainty of 3D Position → Calculation of Strain

DIC Challenge

- Provide sample images for code verification and development.
- Benchmarked results for the sample images – published and peer-reviewed.
- A forum for the discussion and improvement of DIC.

Challenge Board

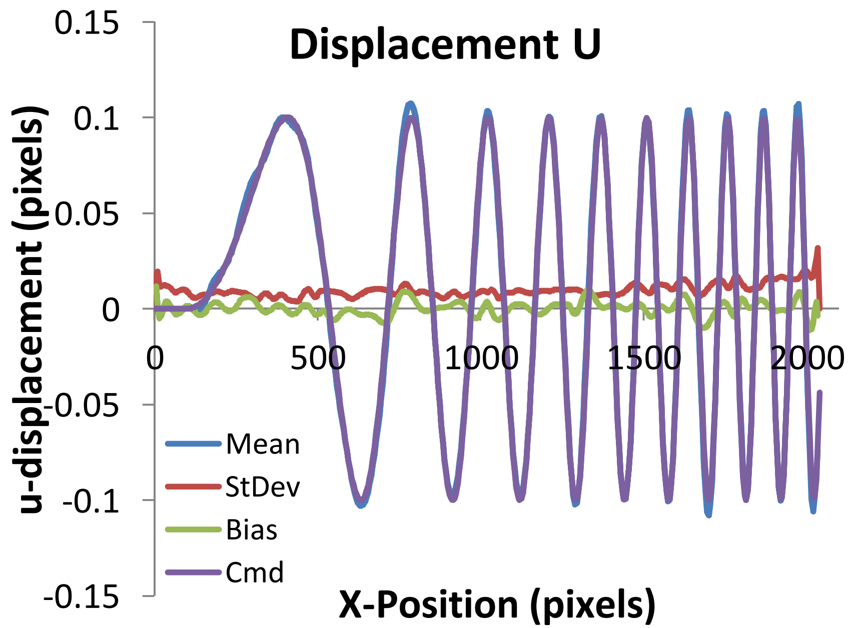
- Phillip Reu – Chairman (US – FFT Shifting)
- Bertrand Wattrisse
- Evelyne Toussaint (EU – Data Analysis)
- Wei-Chung Wang (Asia)
- Hugh Bruck (US)
- Sam Daly (US)
- Ramon Rodriguez-Vera (Latin/South America)

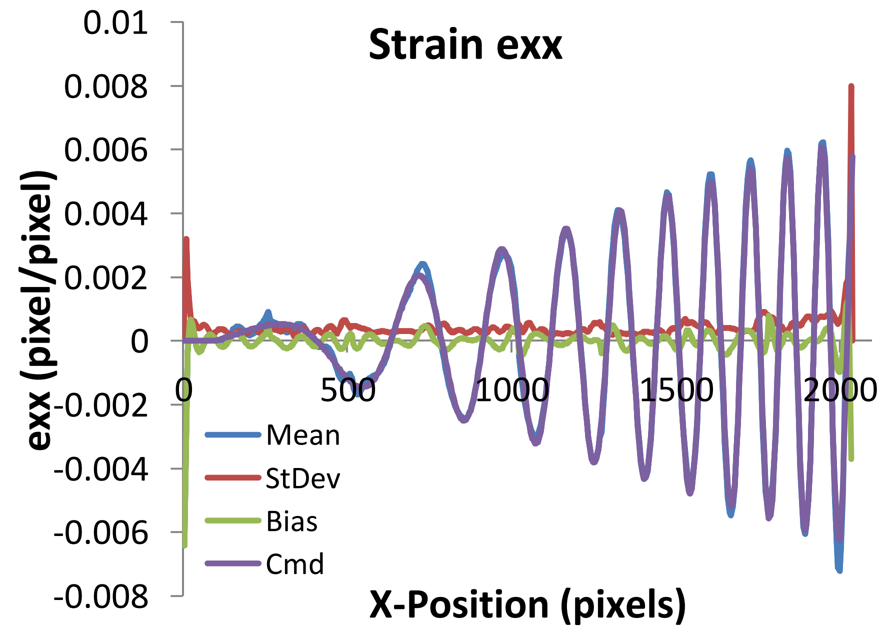
Description	Set Name	Method‡	Contrast	Subset Size*	Noise σ (GL)	Shift (pixels)	# Images
TexGen Shift X,Y	Sample1	TexGen	Varying	Specify	1.5	X=Y=0.05	20
TexGen Shift X,Y	Sample2	TexGen	0 to 50	Specify	8	X=Y=0.05	20
FFT Shift X,Y	Sample3	FFT Shift	0 to 200	Specify	1.5	X=Y=0.1	10
FFT Step Shift	Sample3b	FFT Shift	0 to 200	User	1.5	0.05 to 0.5	5
FFT Shift x and y	Sample4	FFT Shift	0 to 50	Specify	8	X=Y=0.1	10
FFT Shift x and y	Sample5	FFT Shift	Varying	Specify	1.5	X=Y=0.1	10
Prosilica Bin	Sample6	Binning	0 to 200	21	Low	X=Y=0.1	10
Prosilica Bin	Sample7	Binning	0 to 50	Specify	High	X=Y=0.1	10
Rotation TexGen	Sample8	TexGen	0 to 100	Specify	2	Θ by 1	10
Rotation FFT	Sample9	FFT	0 to 100	Specify	2	Θ by 1	10
Strain Gradient	Sample10	TexGen	0 to 200	User	2	Sinusoid	10
Strain Gradient	Sample11	TexGen	60 to 130	User	2	Sinusoid	10
Strain Gradient	Sample11b	FFT	0 to 200	User	1.5	Tri. .01 to 1	6
Ex1 – Plate Hole	Sample12	Exper.	Good	User	Low	N/A	12
Ex2 – Weld	Sample13	Exper.	Poor	User	Low	N/A	52
Varying Strain	Sample 14	FFT	0 to 200	User	5	N/A	4
Varying Strain	Sample 15	TexGen	80 to 180	User	2	N/A	9
Rigid motion	Sample 16	Exper.	0 to 254	User	0.26	≈0.1	11
Out-of-plane	Sample 17	Exper.	15 to 210	User	≈1.3	N/A	6

Sample analysis participants

- Two university codes
  - Elizabeth Jones (Urbana-Illinois, now at Sandia) and Stephane Roux/Francois Hild (LMT Cachan)
- All 5 commercial vendors (In random order)
  - Dantec
  - CSI
  - LaVision
  - MatchID
  - GOM
- Two global codes
  - Stephane Roux/Francois Hild (LMT Cachan)
  - AdaptID (Lukas Wittevrongel and Pascal Lava)

Sample 14 – Average noise

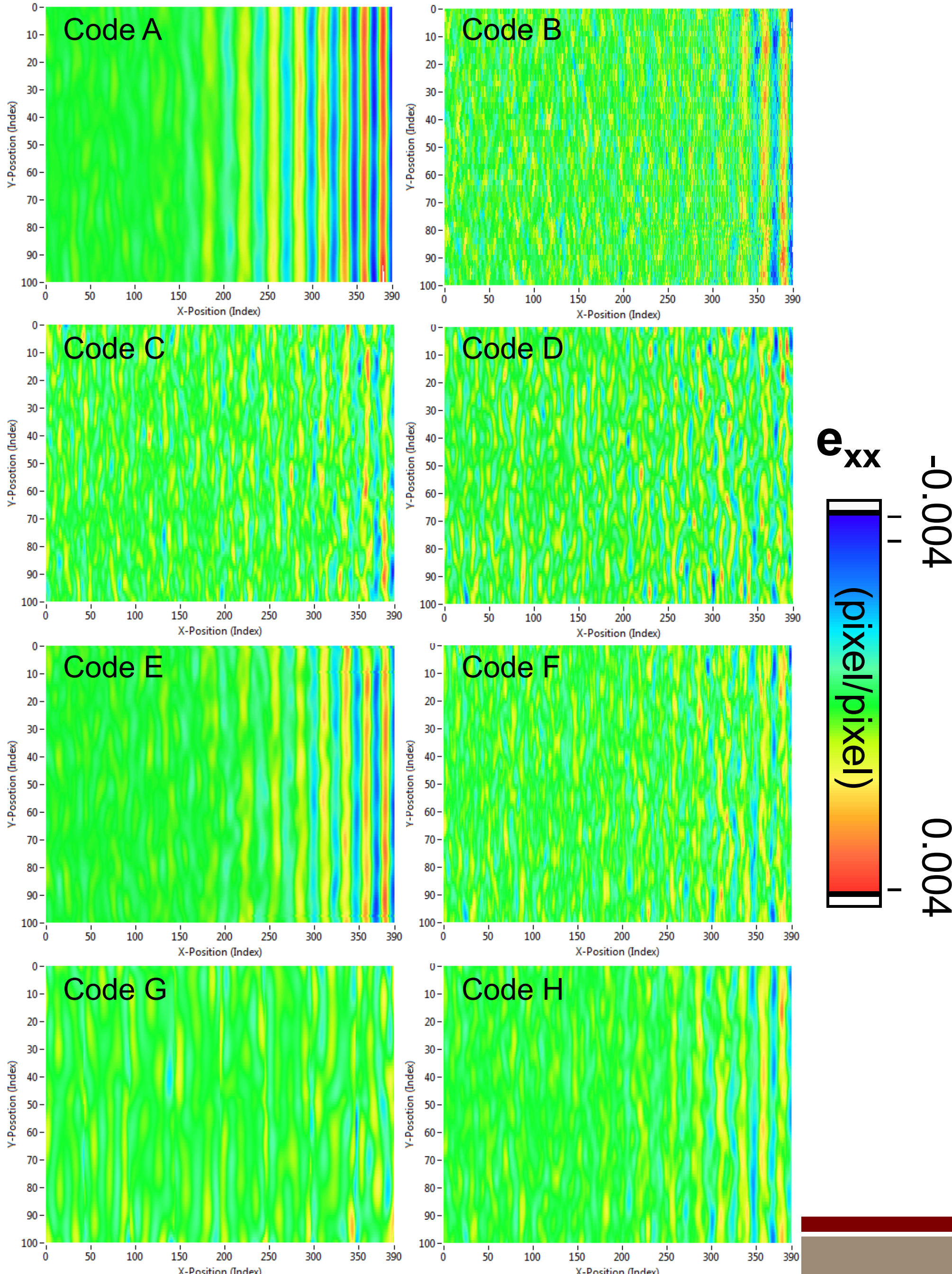




	u StDev	μe_{xx} StDev
Code A	0.005	172
Code B	0.010	676
Code C	0.010	578
Code D	0.011	686
Code E	0.015	256
Code F	0.011	542
Code G	0.010	429
Code H	0.011	341

- Standard deviation of each point from the 50 line cuts is averaged.
- Both displacement and strain.

(Command) – (DIC Results)



Sandia National Laboratories

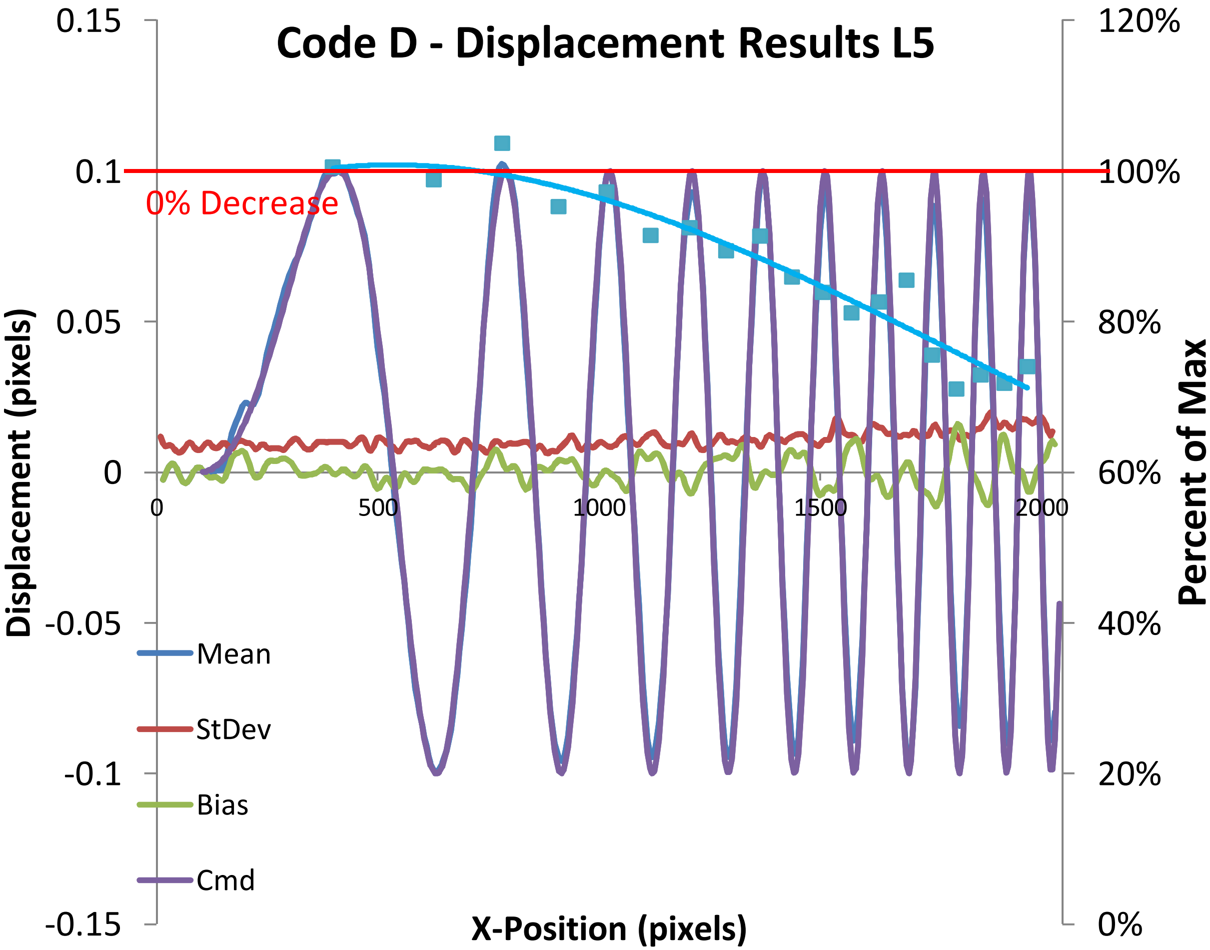
$$RMSE = \sqrt{\frac{1}{n}\sum_{x,y}[\Delta u(x,y)]^2}$$

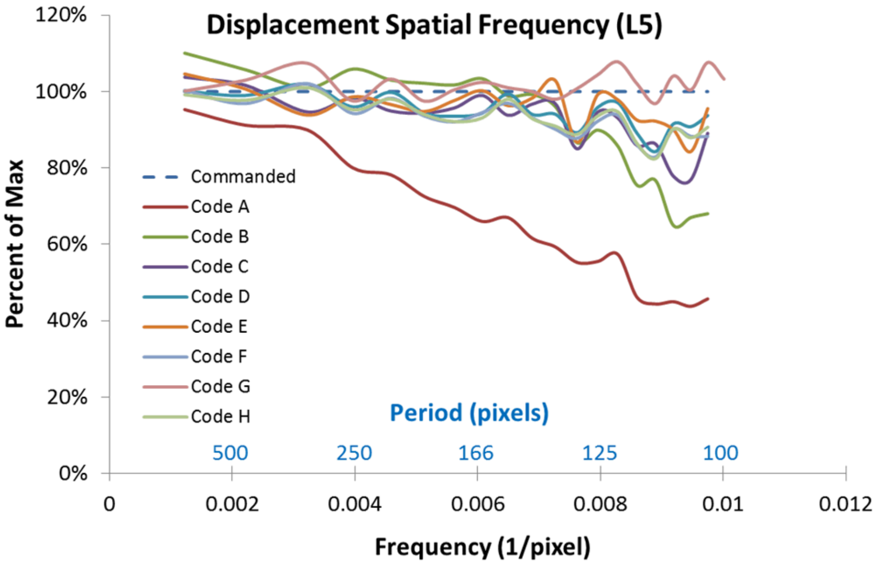
- RMSE measures the average error.
- Maximum bias measures the worst point in the measured area.

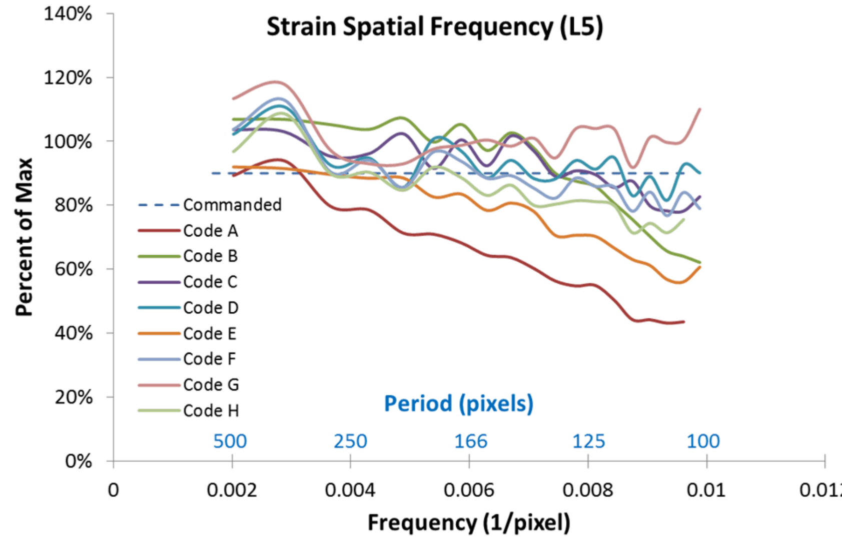
	RMSE u	Max Bias u	RMSE μe_{xx}	Max Bias μe_{xx}
Code A	0.022	0.076	1131	4129
Code B	0.014	0.068	854	4657
Code C	0.012	0.060	686	3846
Code D	0.012	0.058	754	3958
Code E	0.016	0.098	795	3405
Code F	0.013	0.074	665	3985
Code G	0.010	0.056	453	2593
Code H	0.013	0.070	601	3022

A proposed measure of the spatial resolution using the roll-off.

	u StDev	μe_{xx} StDev
Code A	0.005	172
Code B	0.010	676
Code C	0.010	578
Code D	0.011	686
Code E	0.015	256
Code F	0.011	542
Code G	0.010	429
Code H	0.011	341







	Displacement Resolution			Strain Resolution		
Cutoff	100%			90%		
	Frequency (1/pixel)	**Spatial Res. (pixel)**	**u StDev (pixel)**	**Frequency (1/pixel)**	**Spatial Res. (pixel)**	**$\mu\varepsilon_{xx}$ StDev (pix/pix)**
Code A	0.0010	986	0.005	0.0025	396	166
Code B	0.0048	208	0.010	0.0067	149	675
Code C	0.0032	316	0.010	0.0072	138	573
Code D	0.0022	455	0.011	0.0081	123	678
Code E	0.0030	336	0.015	0.0037	267	252
Code F	0.0019	521	0.011	0.0063	159	536
Code G	0.0100	100	0.010	0.0250	40	383
Code H	0.0017	594	0.011	0.0050	202	338

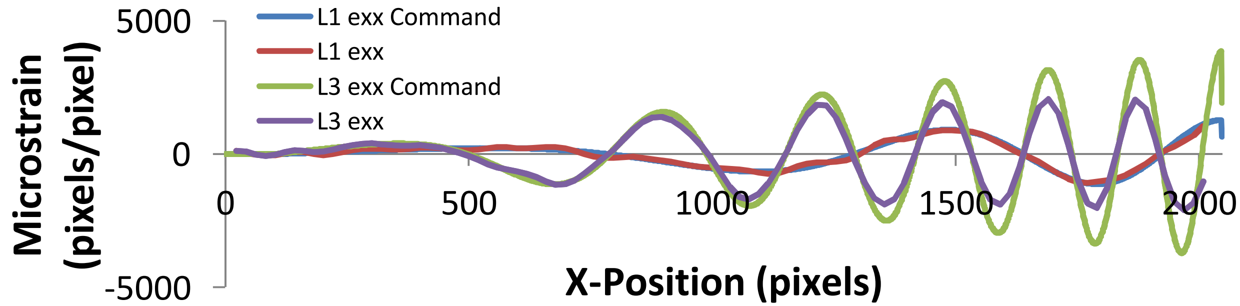
The DIC community needs, training, standardization and guidelines.

Sandia National Laboratories

- Publication requirements to provide important DIC information.

Strain	
Smoothing technique	Local polynomial - affine
VSG	10 data points, 8.5 mm
Spatial resolution	111 pixels, 9.4 mm
Resolution	2.3 10^{-4}

- A real definition of spatial resolution is needed.



- Improved training beyond vendor provided – and agnostic of DIC software.

THE ART AND APPLICATION OF DIC

Calibration: Stereo Calibration

by Phillip Reu

DIC course

Metrology beyond colors

Developments, Applications and Tutorials in Experimental Mechanics Techniques

EXPERIMENTAL **TECHNIQUES**

SEM

- A society dedicated to training and DIC standards.

IDICS International Digital Image Correlation Society

www.idics.org