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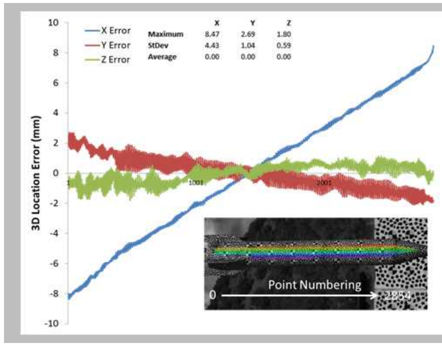

A Comprehensive Look at Stereo-DIC Uncertainty Quantification

Phillip L. Reu

2014 Vic3D Users Conference – Dublin, Ireland

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Imaging equipment has revolutionized experimental measurements.

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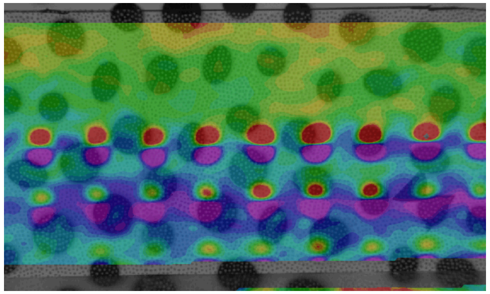
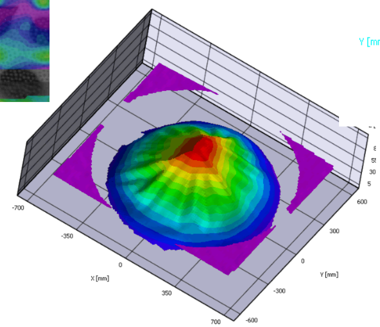
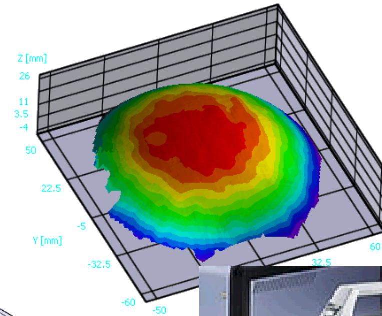
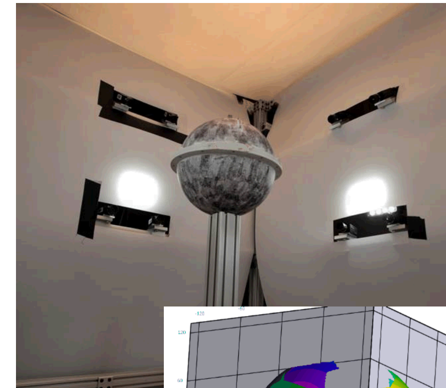
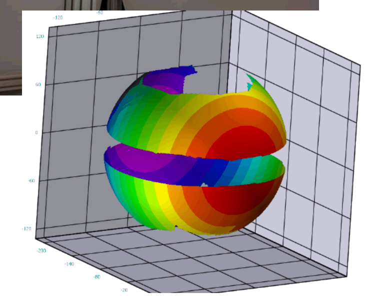



www.visionresearch.com


www.shimadzu.com

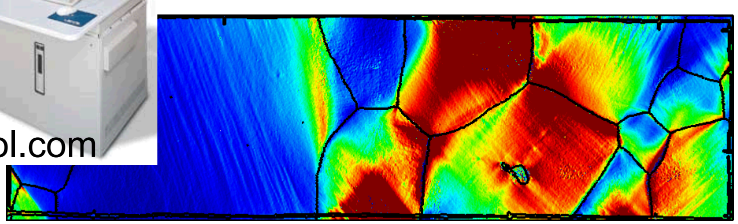



High Speed Displacement and Strain

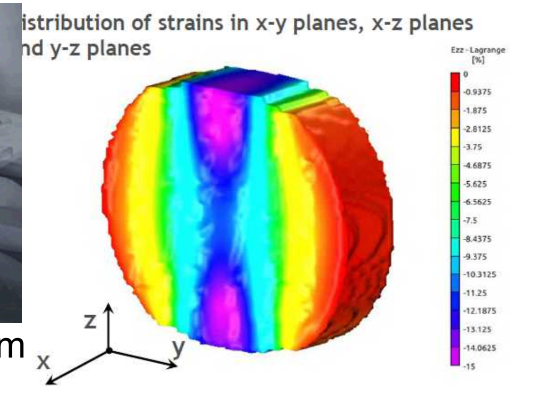
1 Million FPS

Multi-System

www.jeol.com




www.exactmetrology.com



Grain scale strain measurement (optical)

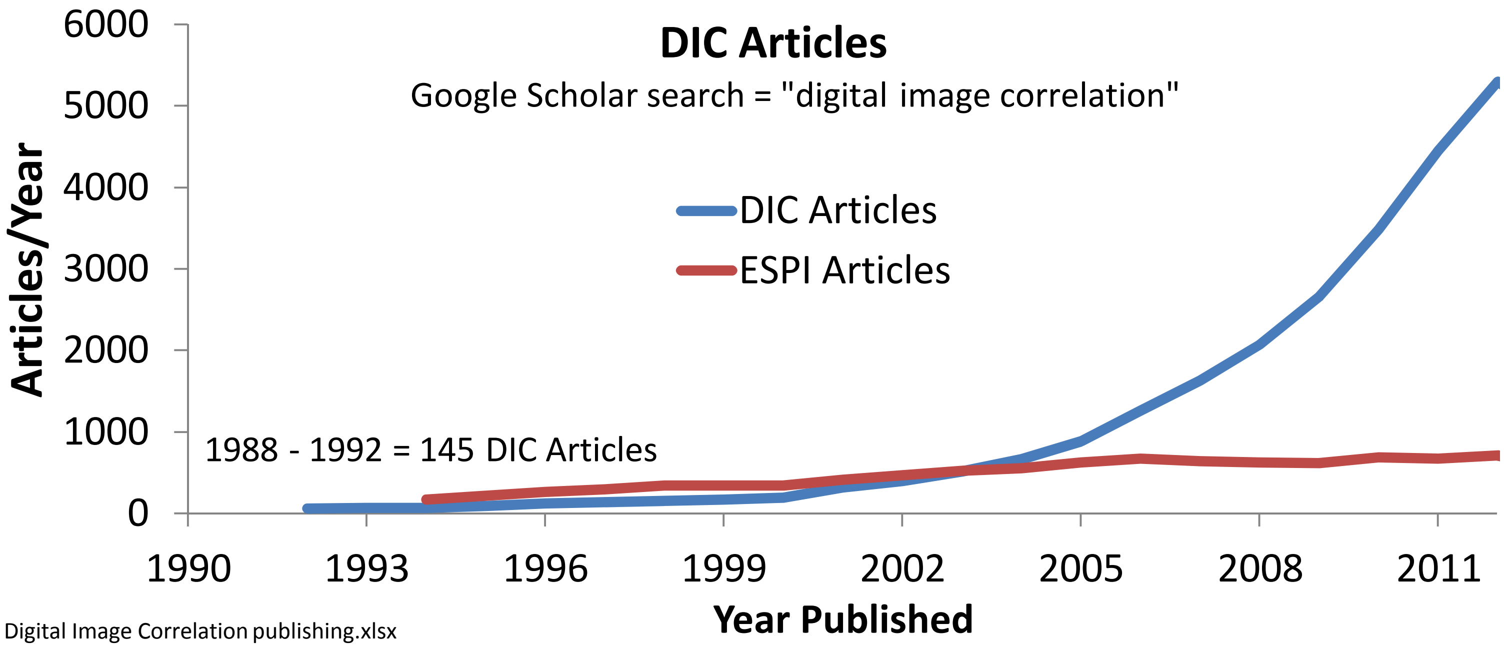
Volumetric strain fields

Grain Scale: J. Carroll

Volumetric Image: M. Sutton – Murray lecture at SEM 2013

DIC has become a standard experimental measurement technique.

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).

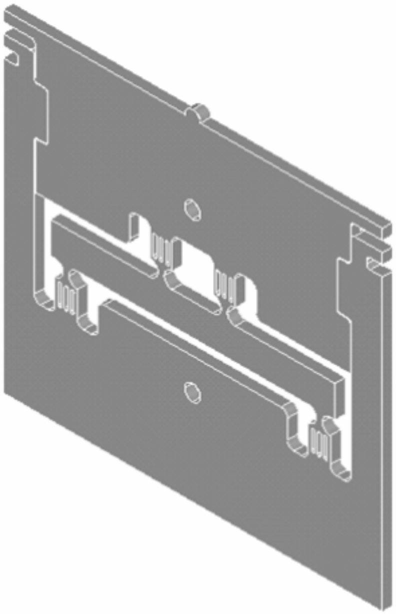


Digital Image Correlation publishing.xlsx

DIC standardization is important for industry, government and academia.

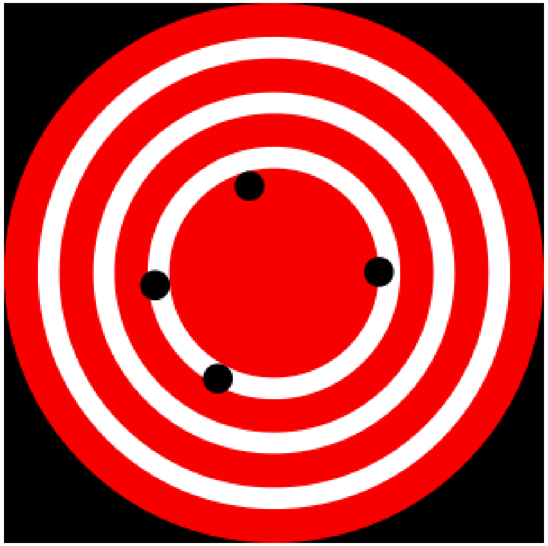
Standardization efforts

- SPOTS – European project for full-field measurements.
- German government program?
- DIC Challenge - SEM
- BSSM and strain gage type groups for DIC
- International training program (both general and vendor specific) “Metrology Beyond Colors”
- Publication guidelines and definitions (to be written by a large group of DIC experts)
- Journal reviewer guidelines
- Guide to uncertainty measurement (GUM)



Patterson, E. A., et al. (2007). "Calibration and evaluation of optical systems for full-field strain measurement." Optics and Lasers in Engineering **45(5): 550-564**

Two types of errors: Random and Systematic

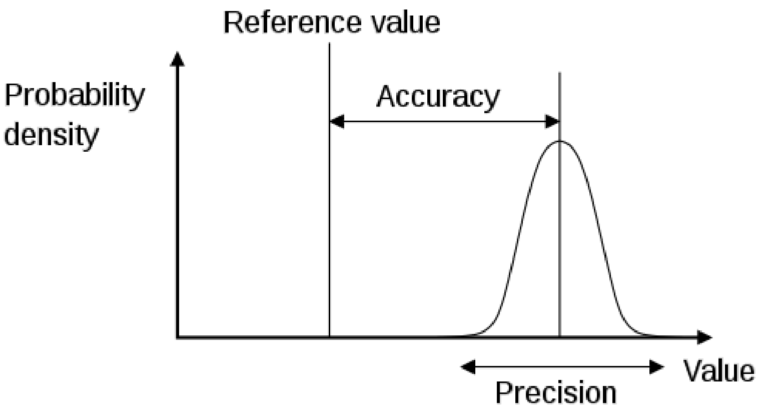


Accurate but not Precise
Large *Random* Error
Small *Systematic* Error
Aleatoric Uncertainty

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

Words used interchangeably
Bias = Systematic Error
Noise = Variance = Random Error = Repeatability

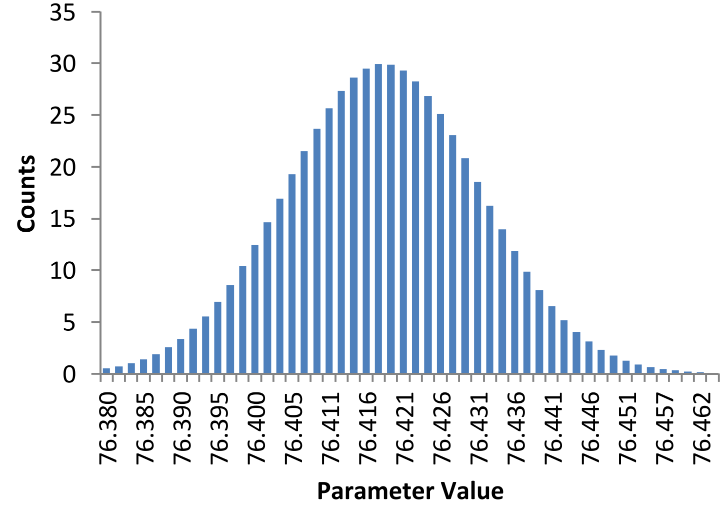
The new view is to categorize as:
Type A and **Type B** Errors.
Why no bias errors? A known bias is removed and it becomes a variance error.



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

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.

Categories → Type B (Other)/Type B (Monte Carlo)
Type A (Statistics)

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Monte Carlo

Calibration Parameters

Image Correlation

Calibration Parameters
1. Parameter Errors
   a) Cal Target Error
   b) Image Quality
2. Camera Motion
3. Calibration Drift

3D Position
1. Global Coordinate System
2. Camera motion

Monte Carlo

3D Triangulation

Estimated Uncertainty of 3D Position

Image Matching Errors
1. Contrast
2. Image noise
3. Lighting variation
4. Subset size/shape function
5. Turbulence
6. Aliasing
7. Optical distortions
8. Image blur
9. System resolution

Strain Errors
1. Displacement noise
2. Fitting and filtering

Calculation of Strain

2D Displacement

Other Errors
1. Camera model
2. Unknown, unknowns

2D matching is fundamental to both 2D-DIC and stereo-DIC.

Image Correlation

Image Matching Errors

1. Contrast
2. Image noise
3. Lighting variation
4. Subset size/shape function
5. Turbulence
6. Aliasing
7. Optical distortions
8. Image blur
9. System resolution

2D Displacement

Calculation of Strain

Strain Errors

1. Displacement noise
2. Fitting and filtering

2D matching errors – should the research stop?

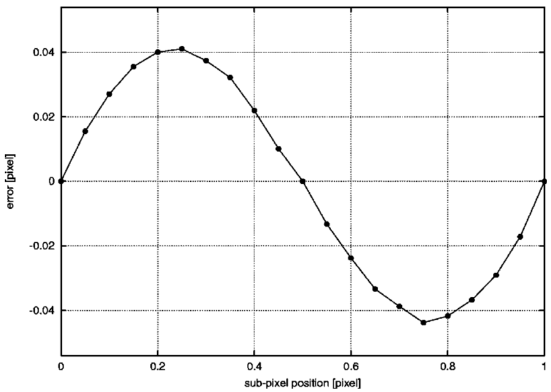
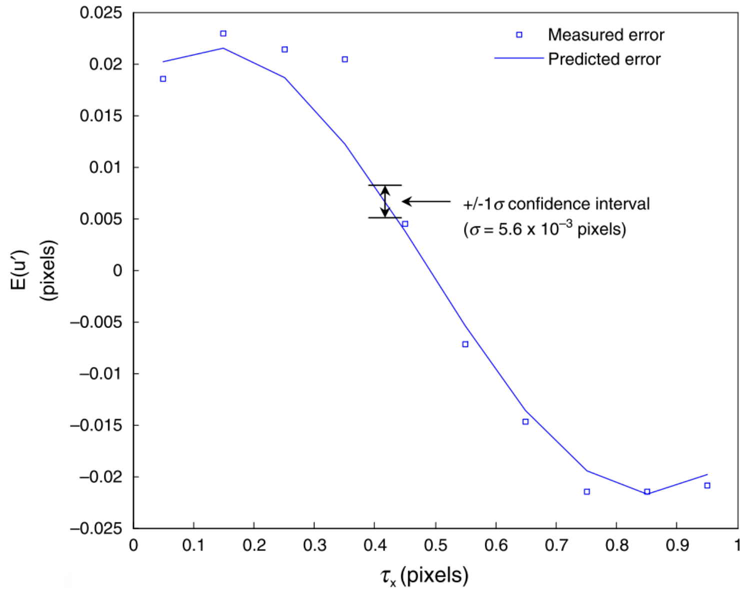


Fig. 1 Typical correlation error as a function of the subpixel position of the displaced subset.

Schreier HW, Braasch JR, Sutton MA (2000). Opt Eng 39 (11):2915-2921



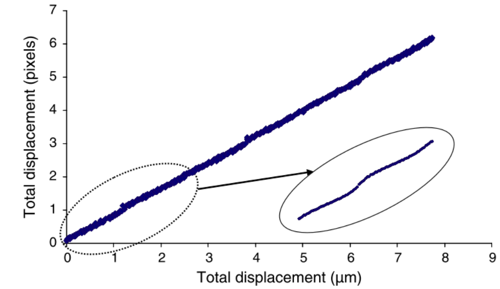
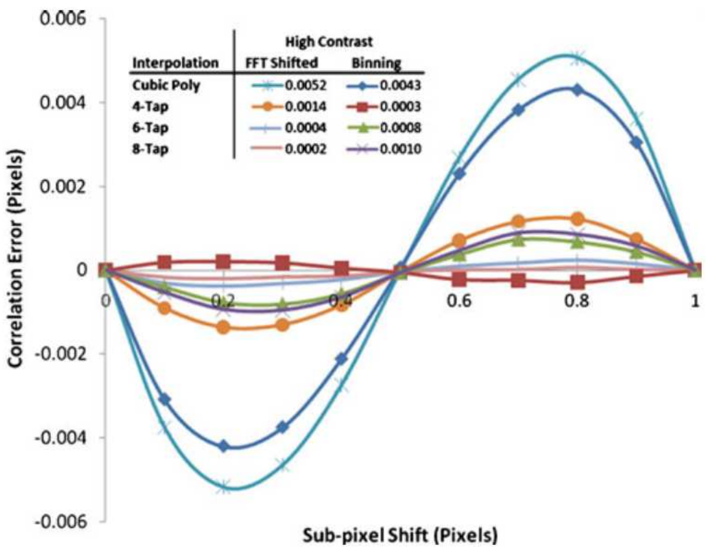


Figure 8: Measured horizontal image-based translation as a function of time. Measurements obtained using 2D digital image correlation with Point Grey camera images and a 209 × 209 subset

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



Are bias errors a problem anymore?

- Depends on the interpolant really.
- With good interpolants bias errors (for reasonable noise levels) are a small error source.

Matching error predictors

$$\sigma_u^{th} \propto \frac{\sigma_n}{d\sqrt{\overline{\nabla I^2}}}$$

Roux S, Hild F (2006) Int J Fracture 140 (1-4):141-157.

M. Bornert PD, J.-C. Dupré, C. Poilâne, L. Robert, E. Toussaint and B. Wattrisse In: 15th International Conference on Experimental Mechanics (ICEM'15), Porto, Portugal, 22-27 Juillet 2012, Porto, Portugal, 2012. EURASEM.

$$\sigma(\Delta u') \approx \left(\frac{D(\eta)}{\sum\sum (f_x)^2} \right)^{1/2}$$

$$\sigma(\Delta v') \approx \left(\frac{D(\eta)}{\sum\sum (f_y)^2} \right)^{1/2}$$

Pan B, Xie HM, Wang ZY, Qian KM (2008) Opt Express 16 (10):7037-7048

$$Var(t) = \frac{\sum |G - F|^2}{NH_{11}} = \frac{2\sigma^2}{\sum(\partial F / \partial x)^2}$$

From the covariance matrix.

Sutton DA, Orteu JJ, Schreier HW (2009) Image Correlation for Shape, Motion and Deformation Measurements. Springer, New York, NY

$$\mathrm{Var}(u_e) = \frac{2\sigma^2}{\sum_{i=1}^{N} \sum_{j=1}^{N} [\nabla I_x(\mathbf{x}_{ij})]^2}$$

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

The matching error is composed of a bias and variance term

Systematic Bias

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

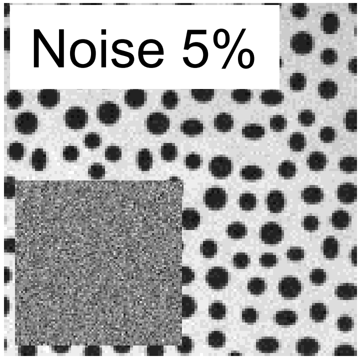
Interpolation Bias **Noise Bias**

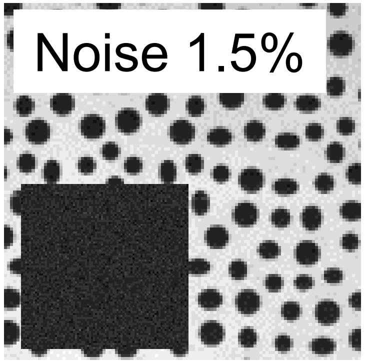
Random Variance

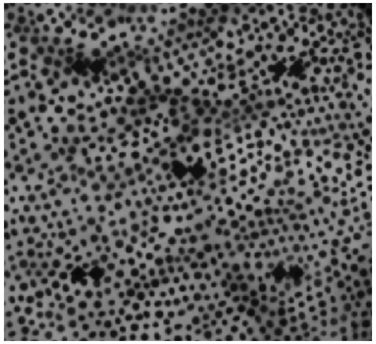
$$\mathrm{Var}(t) \cong \frac{2\sigma^2}{\sum_i \left[\nabla T(x_i) \right]^2}$$

Measurement Variance

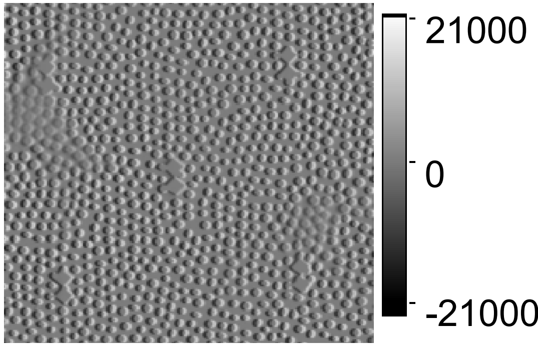
$\sigma \propto$





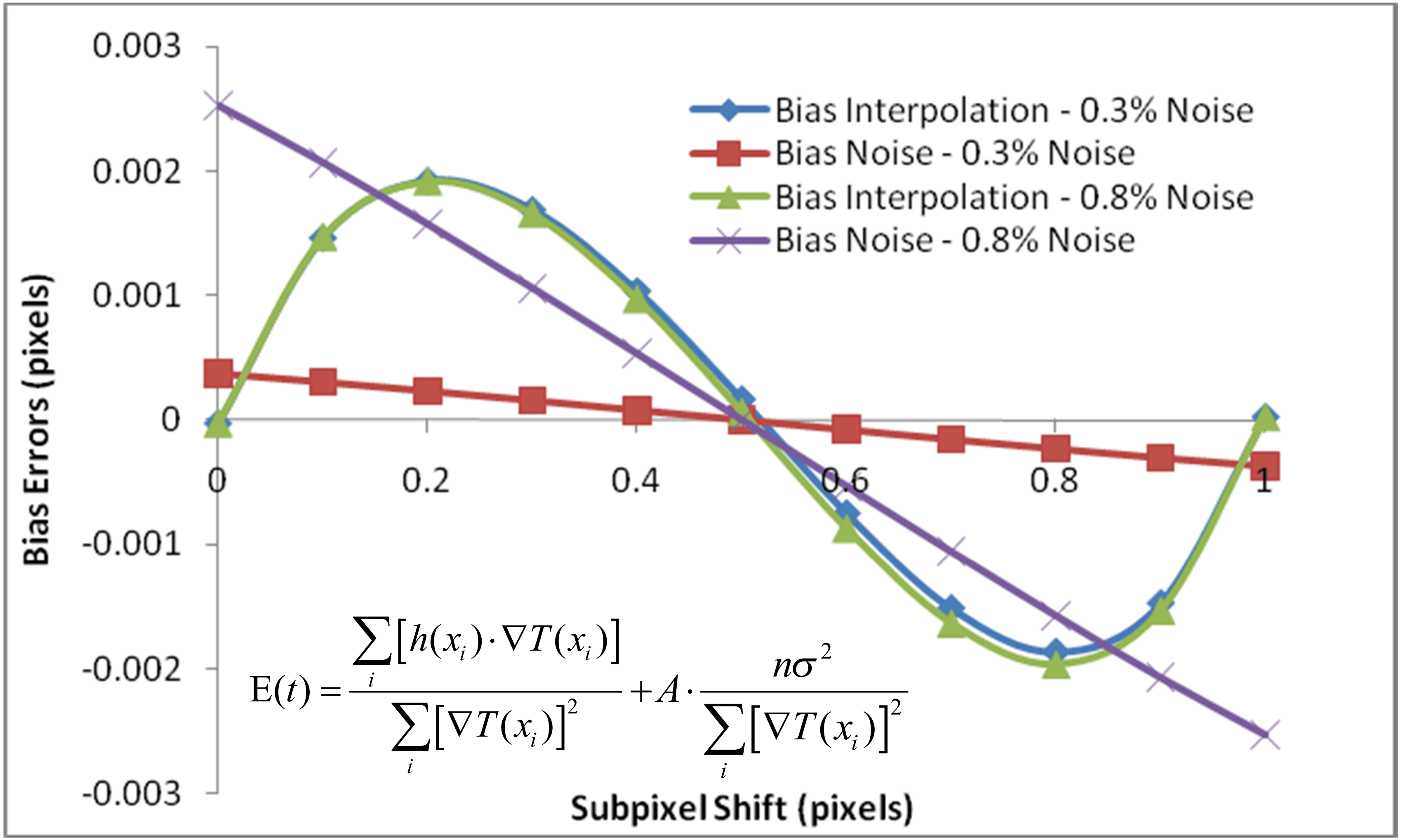


Gradients = $\sum_i \left[\nabla T(x_i) \right]$ **=**

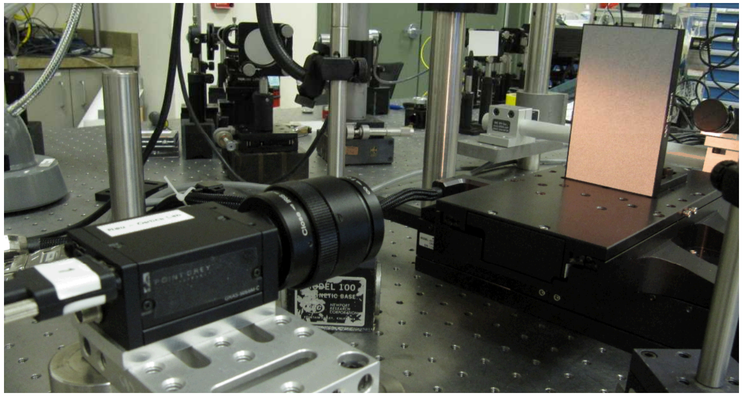


Wang, Y.Q. Strain, 2009. **45**(2): p. 160-178.

Bias and noise errors calculated in software agree with earlier publications

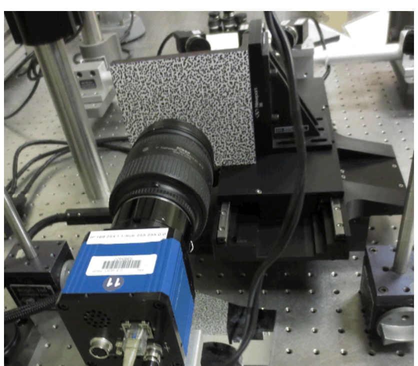


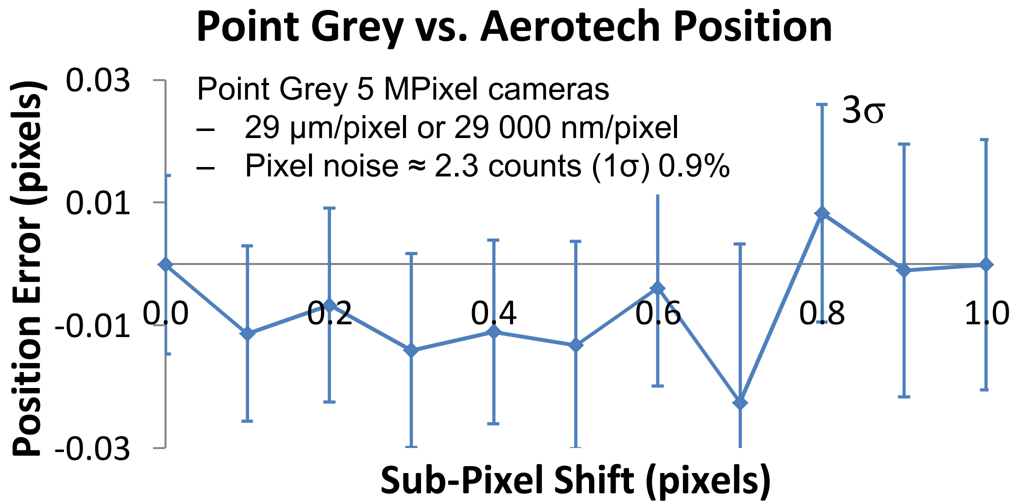
Experimentally finding the bias errors is difficult.



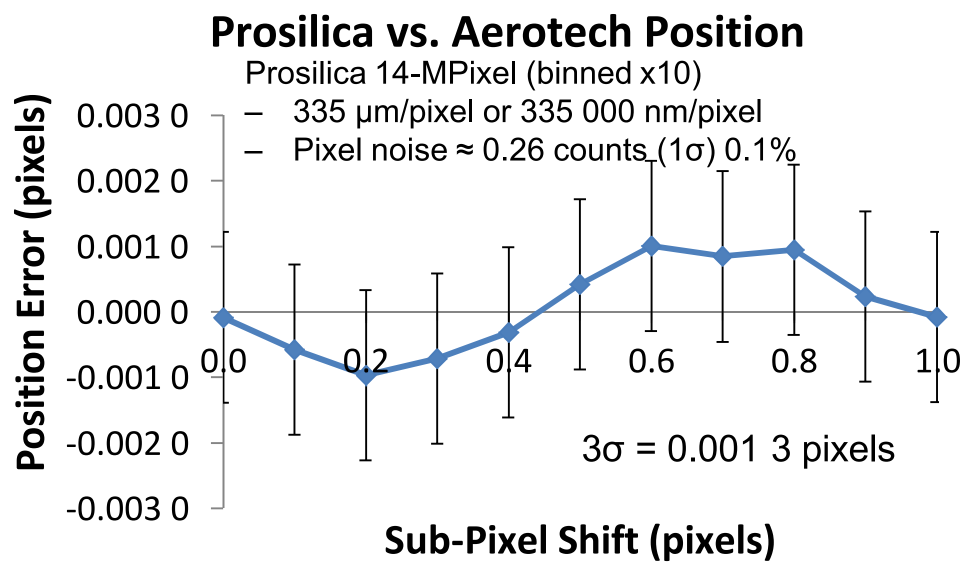
Experimental Setup

- 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)
- Floating optical table
- Standard climate controlled room

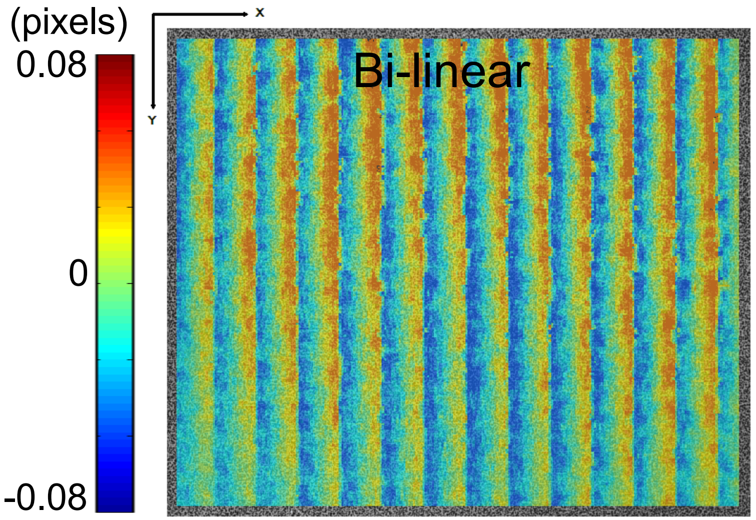


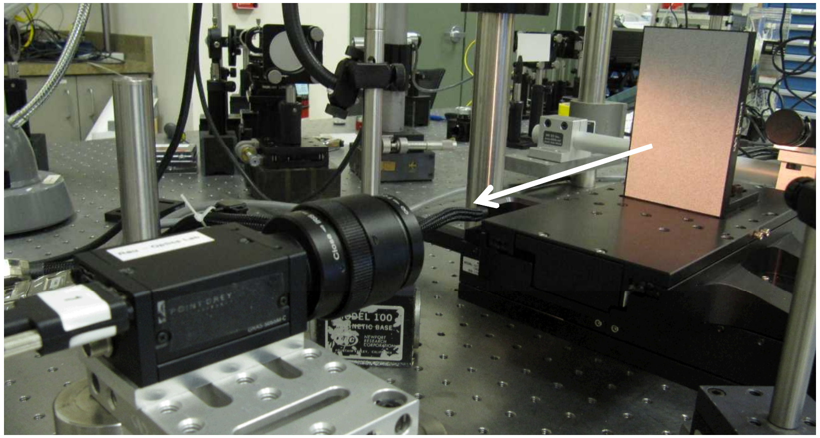


Variance errors dominate bias errors!

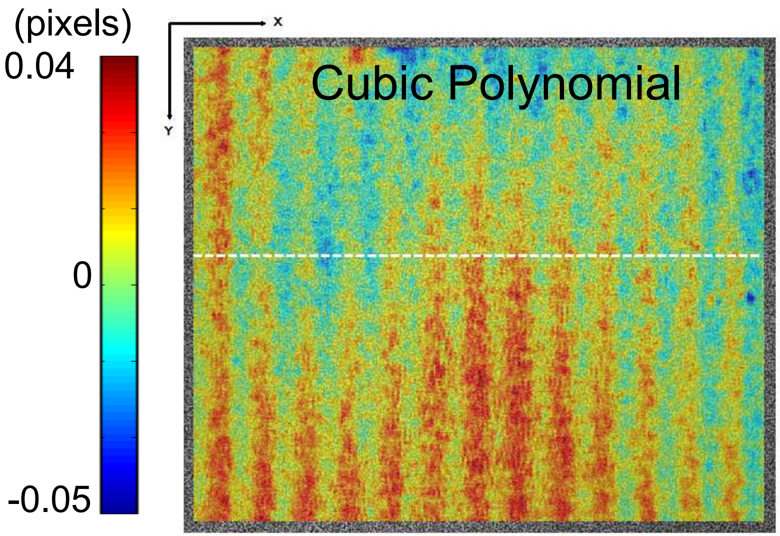


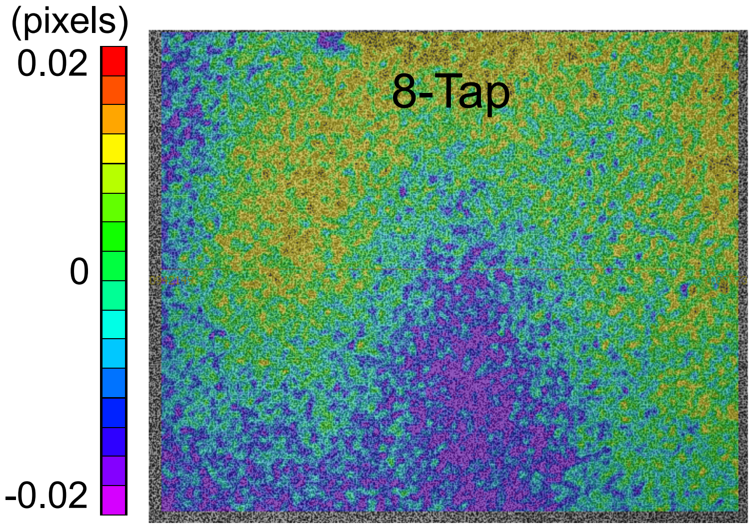
The bias error is much easier to find with out-of-plane motion.



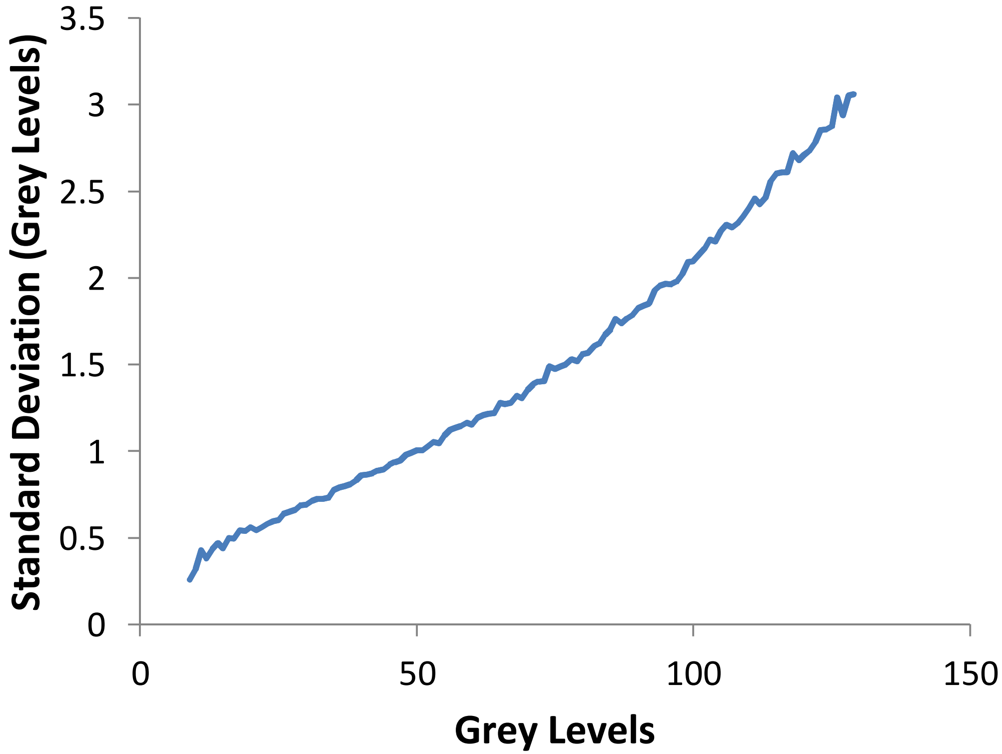


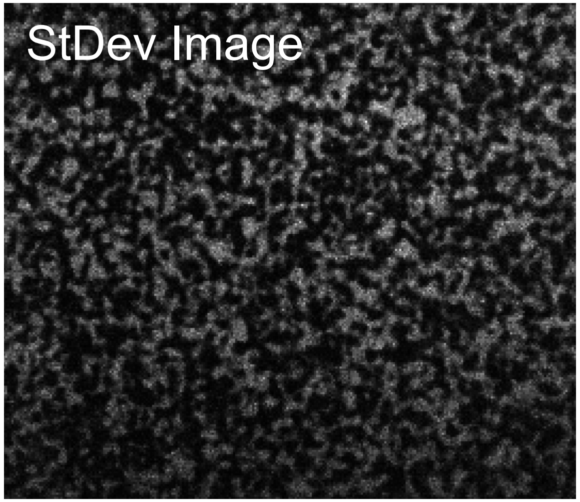
This simulates a biaxial strain, but uniaxial would cause the same issues!

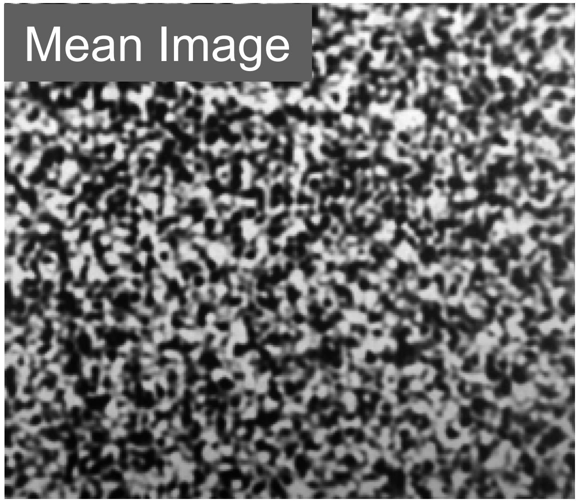




The true distribution of noise is not Gaussian across the entire detector.



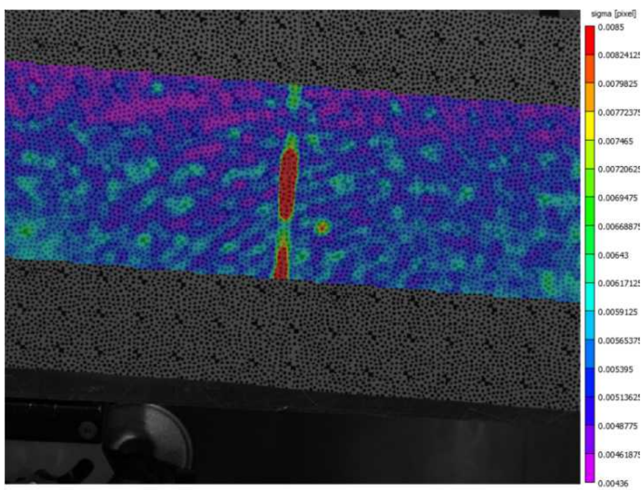


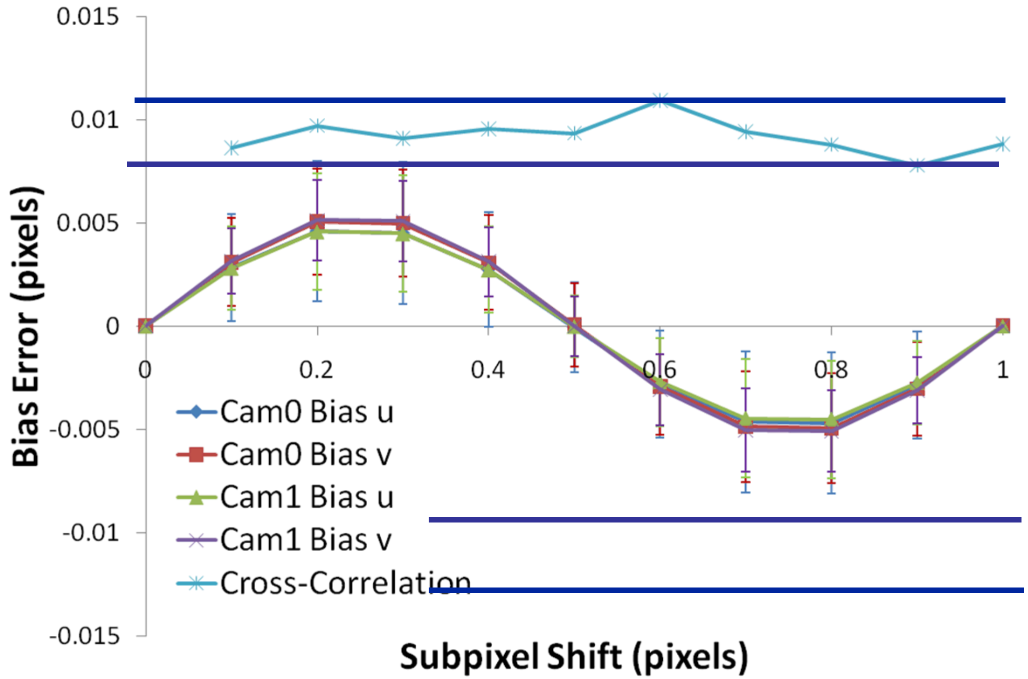


Prosilica camera (with high gain).

Finding 2D matching errors. A pseudo-experimental approach.

1. Numerically shift the images
2. Find the bias and variance using the 2D correlation software for a given interpolation, subset, etc.
3. Use the 2D software to do a cross-correlation and find the matching error. This includes the bias.
4. The maximum of these two is the worst case matching error.

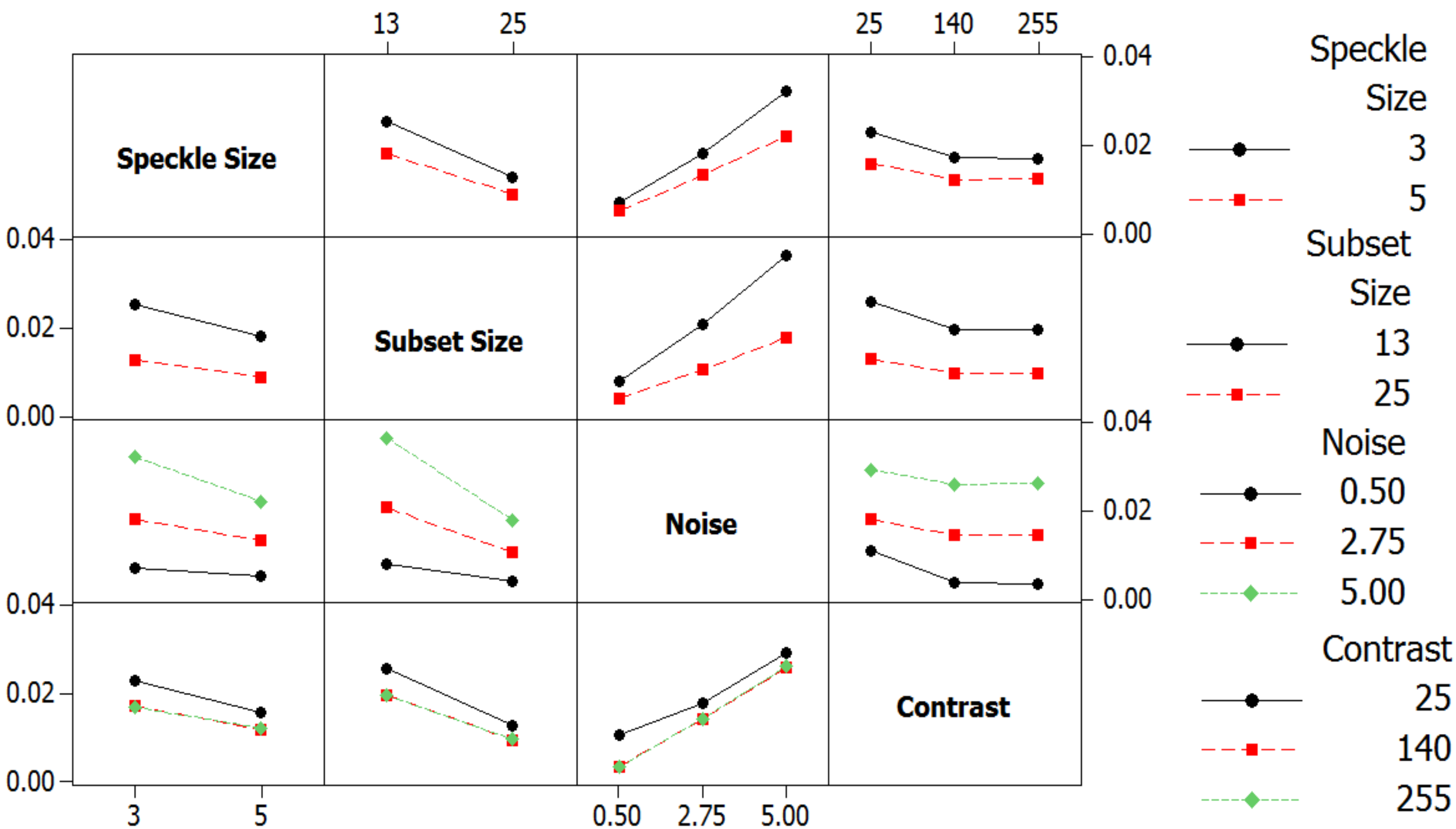




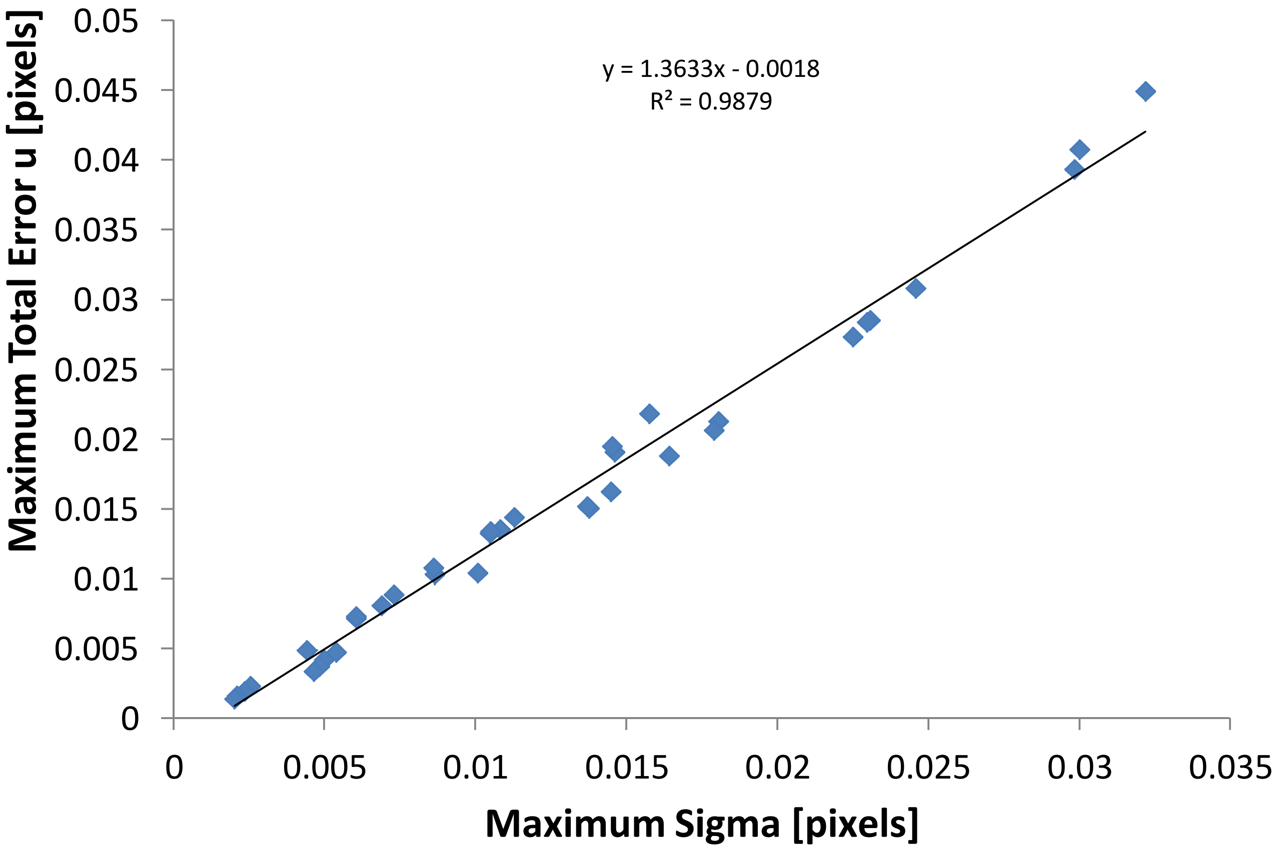
Worst case matching	± 0.009
Cross-Correlation (2σ)	± 0.011

A reliable numerical subpixel shifting is required!

A sensitivity study shows that camera noise and subset size are key.



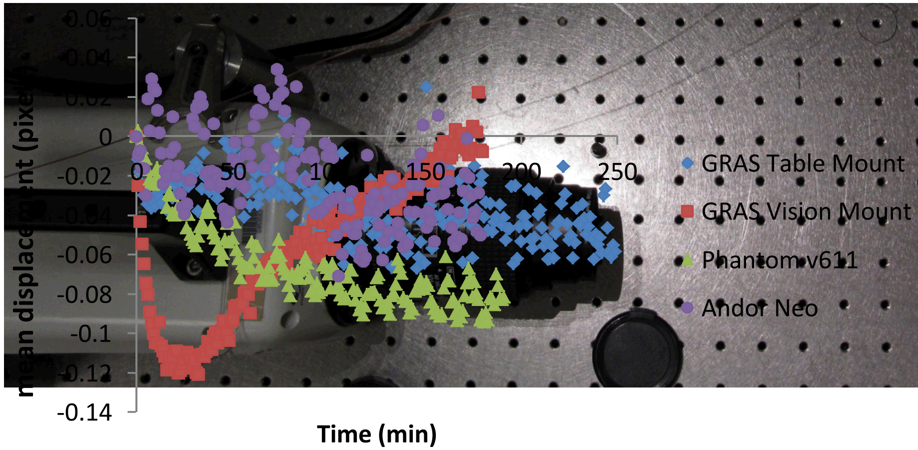
Vic3D predicted matching error works very well over a range of conditions.



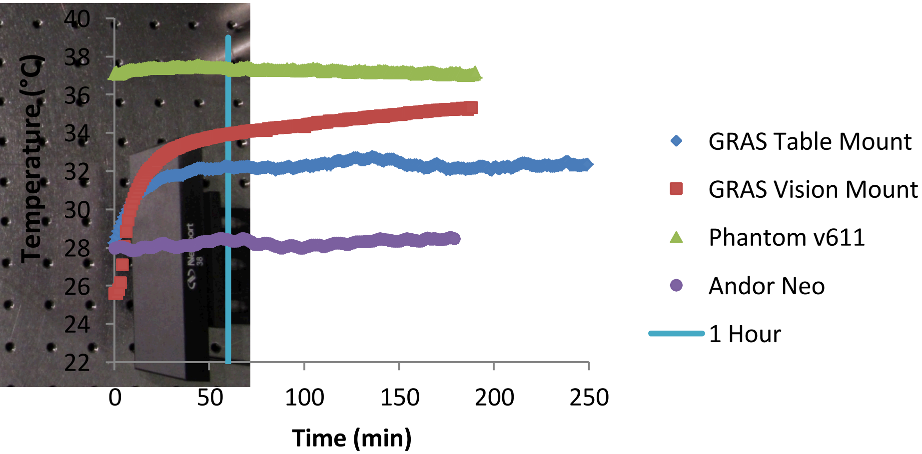
2D Displacement

What does a stationary camera mean?

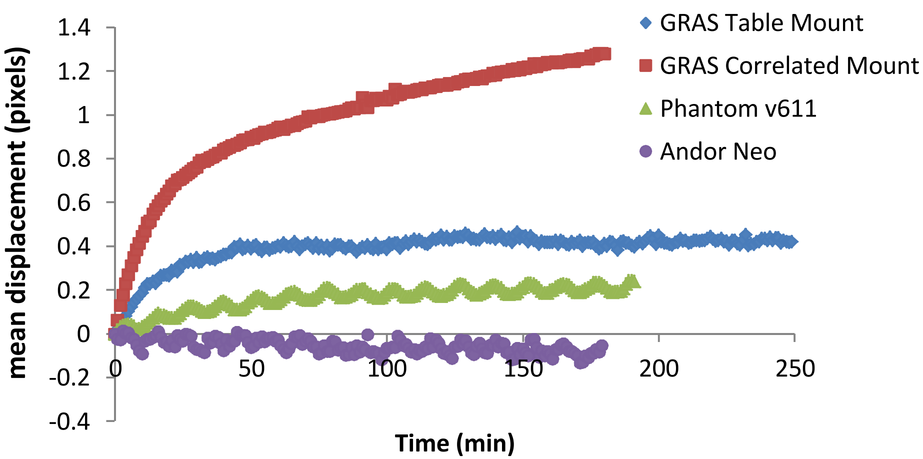
mean(u)

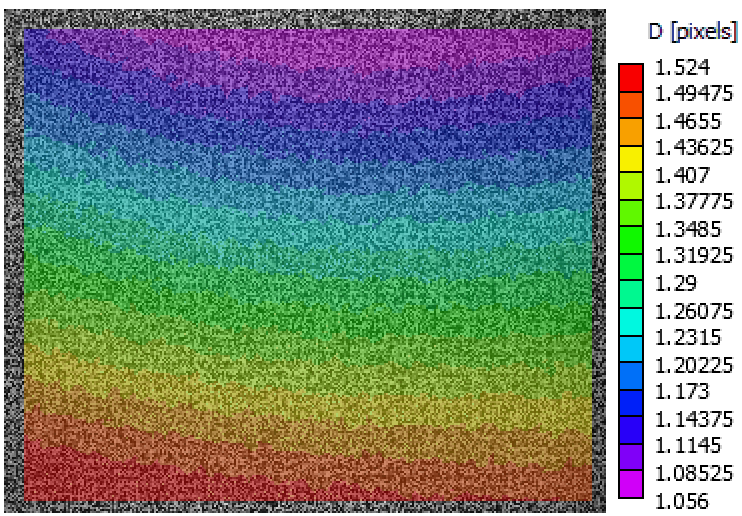


Camera Temperature



mean(v)

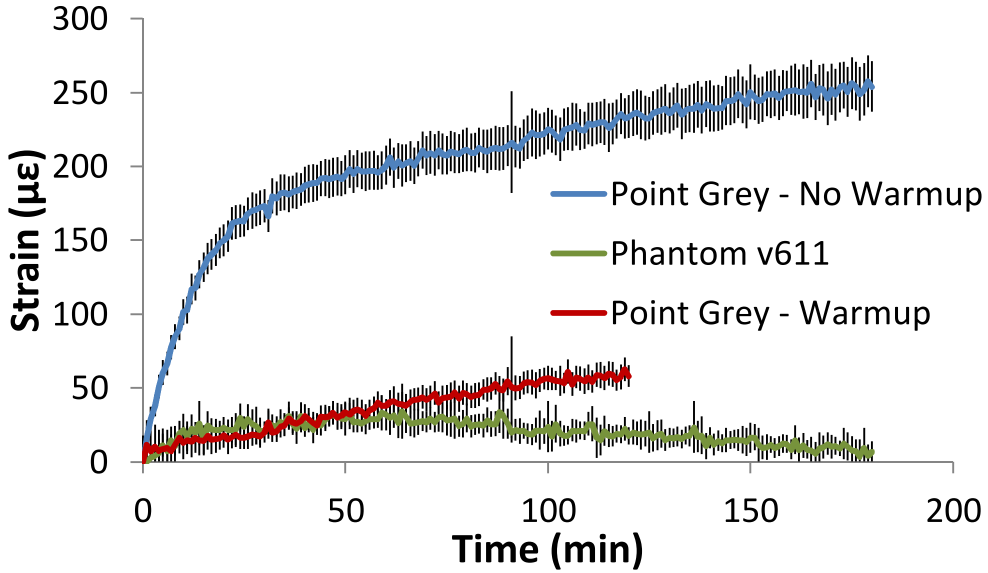


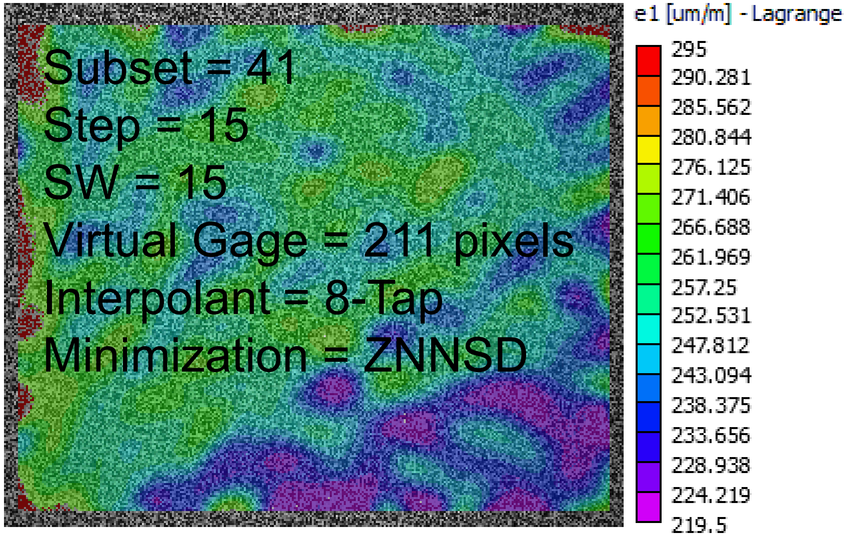


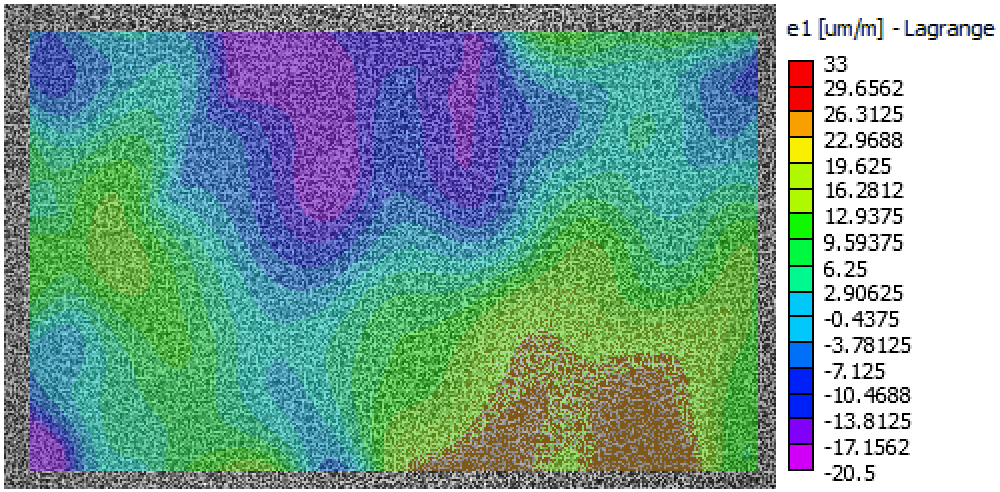
The same speckle pattern was used for all cameras, and the speckle size was maintained (~ 3 to 5 pixels), therefore equal pixel/mm for all cameras.

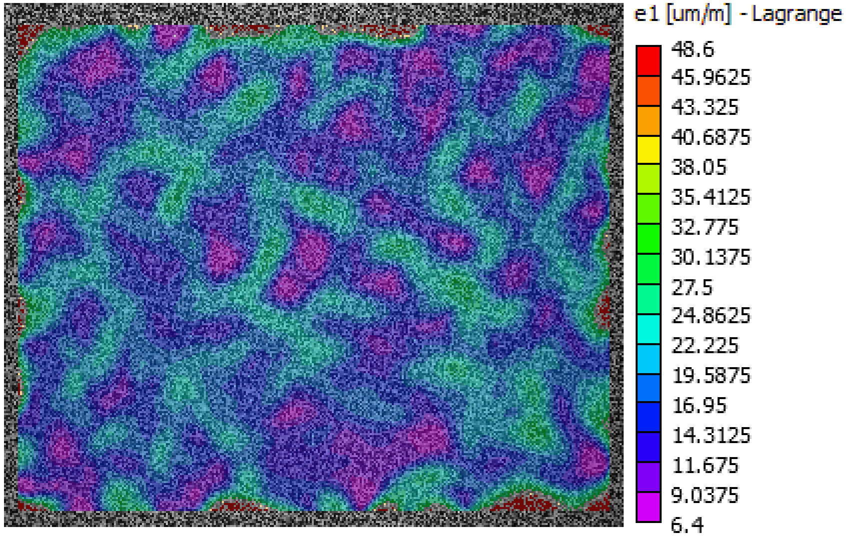
The effect is smaller after camera warmup.

VSG = [(SW-1) x ST] + 1

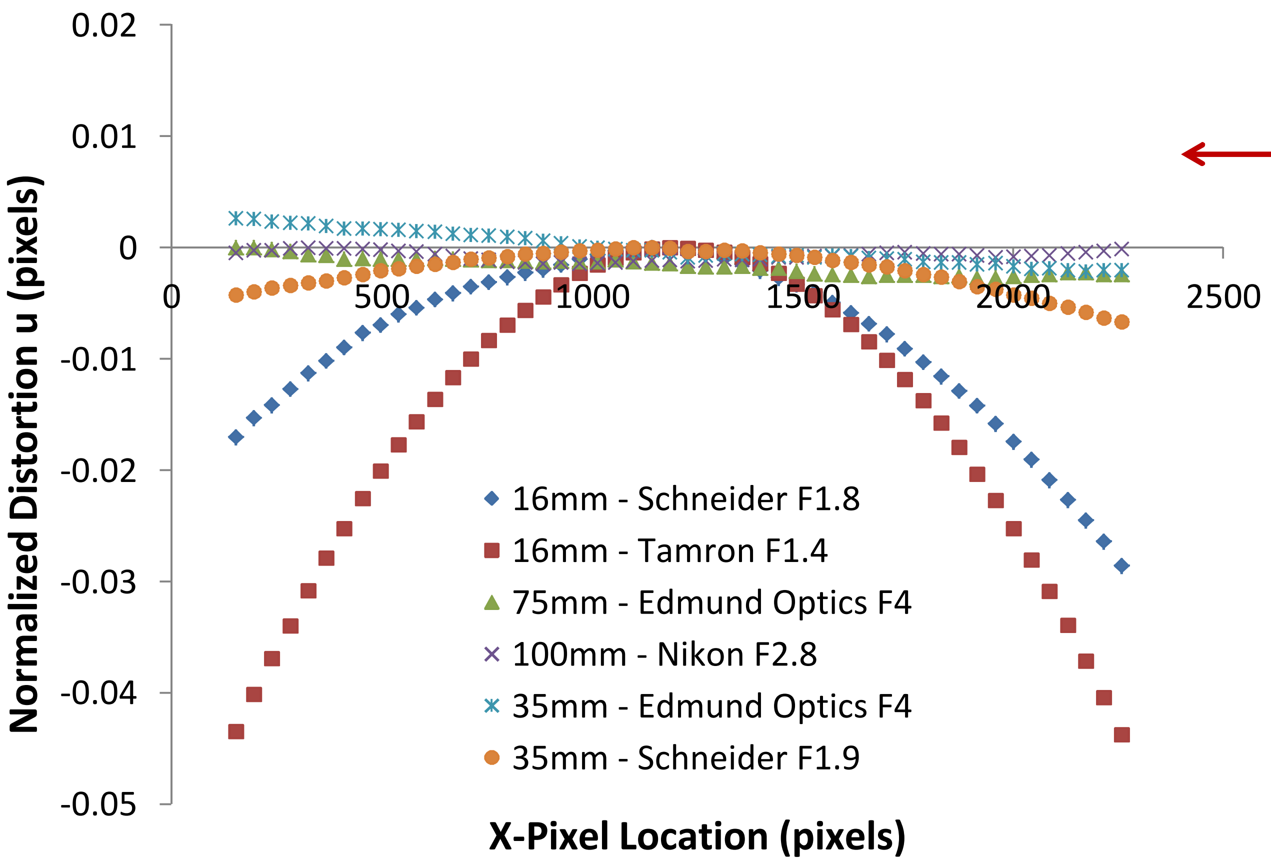


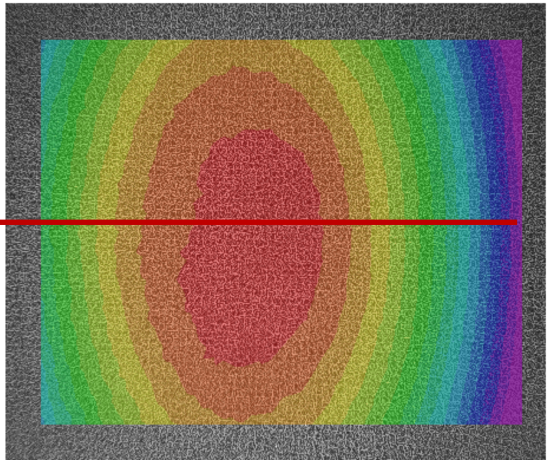






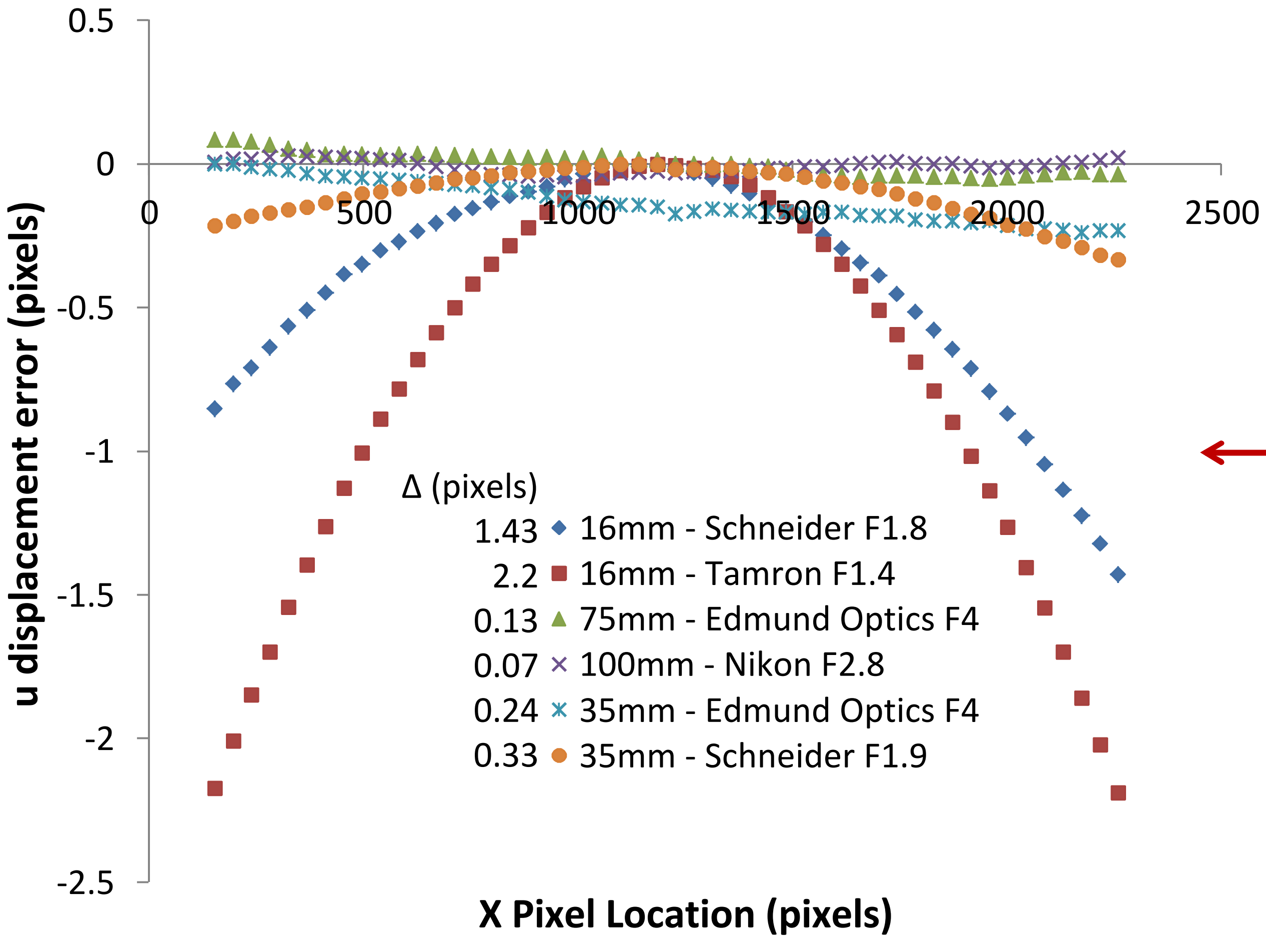
Lens distortions can also cause large errors, particularly with large distortions!

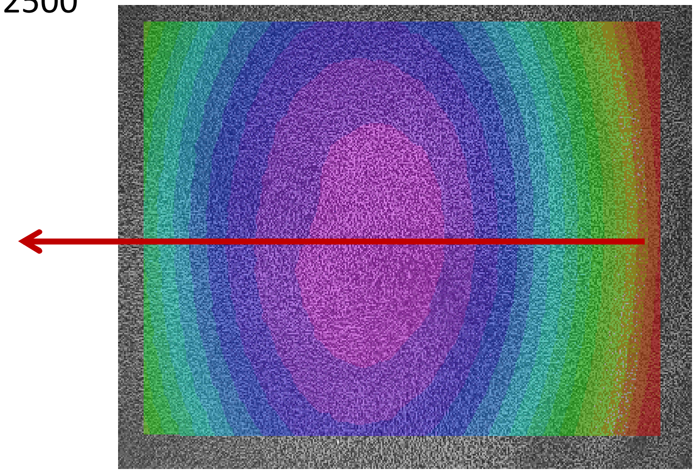




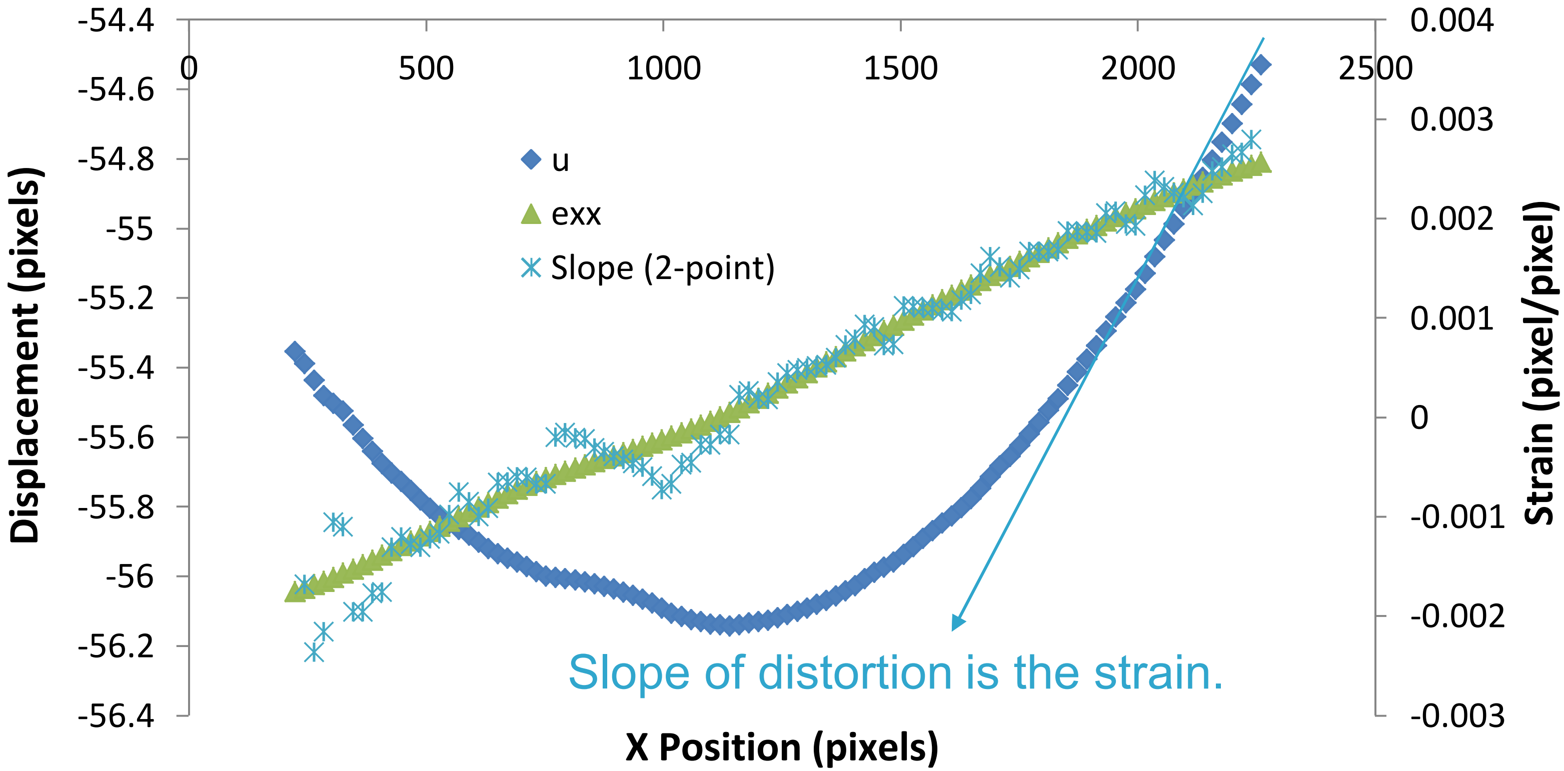
$$u_{normalized} = \frac{u_i - u_{max}}{u_{max}}$$

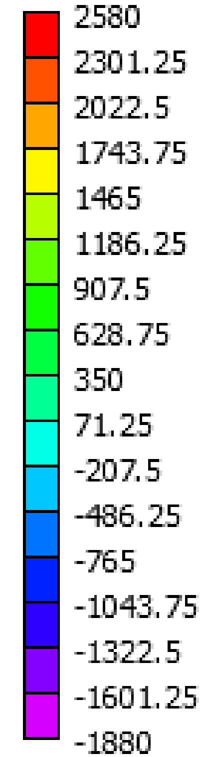
A 50 pixel shift yields a 2-pixel error!



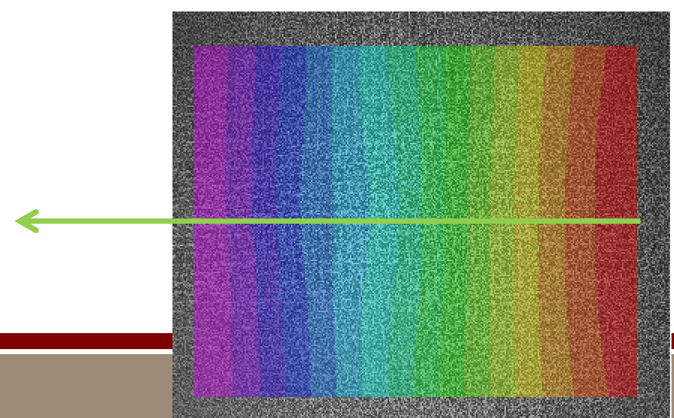


The slope of the distortion curve also means there will be a strain error.





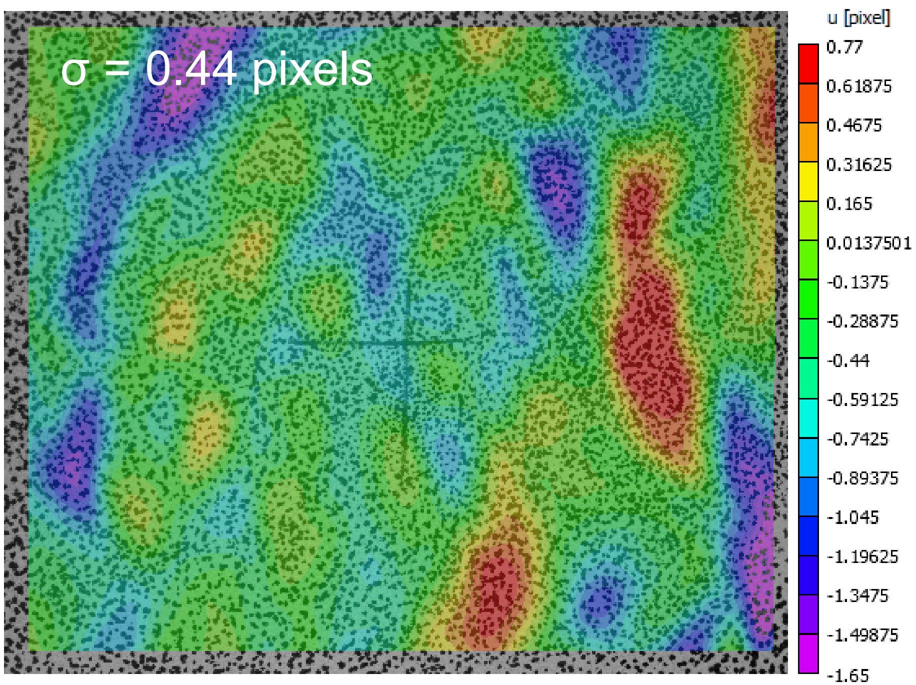
Subset = 43
Step = 43
SW = 15
Virtual Gage = 603 pixels
Interpolant = 8-Tap
Minimization = ZNNSD



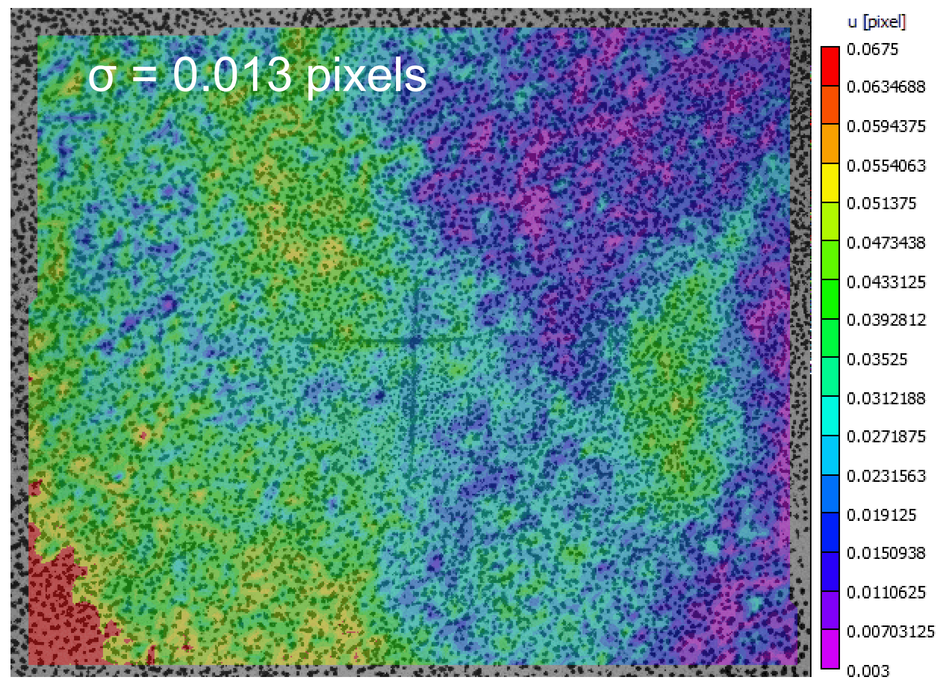
2D Displacement

Air turbulence (density changes) can cause false displacements.

With heat waves.



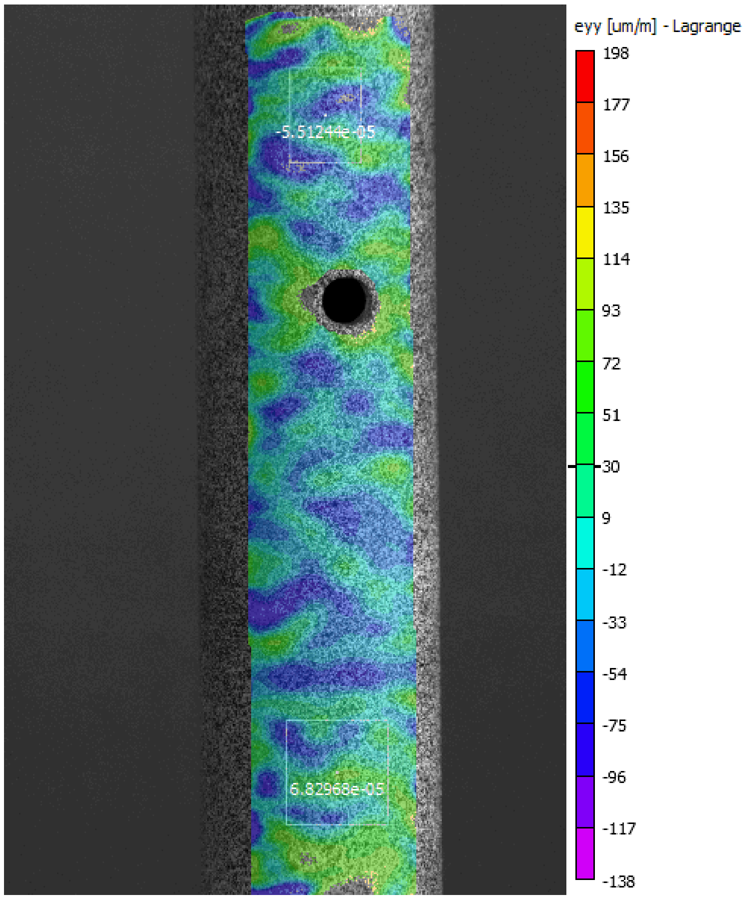
Normal lab environment.



Out-of-plane motion can cause large errors!

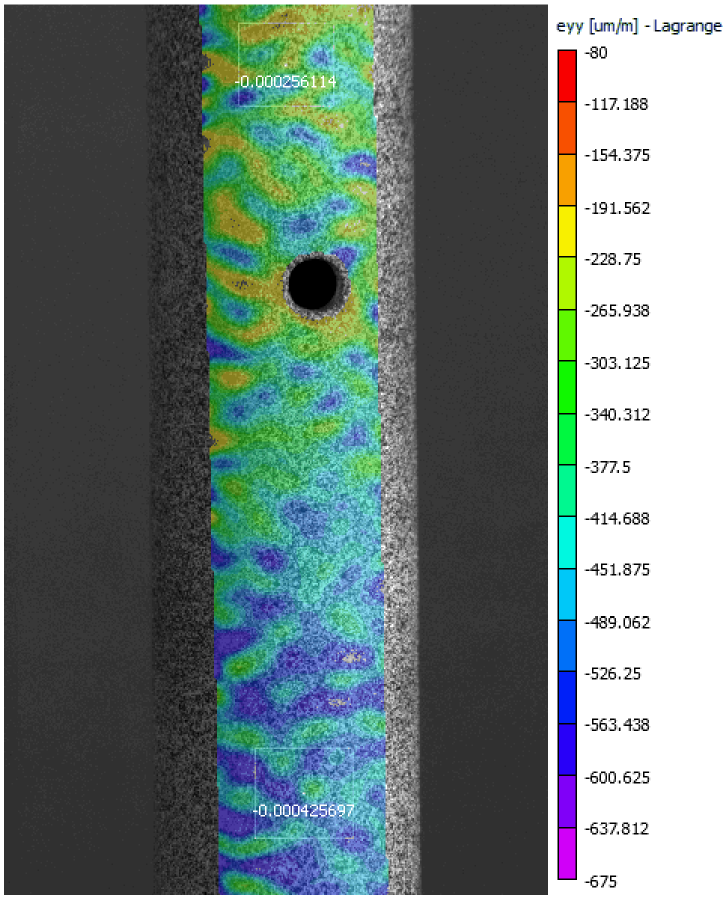
3D Strain (Mean = 5με)

Stand-Off (z)



2D Strain (Mean = -300 με)

Motion out-of-plane (Δz)



$\Delta z/z$ = -0.2/645*1e6= -310 με

2D Image Correlation

2D Error	Estimated Error (pixels)	Notes
Contrast/Noise	0.01	Easiest to determine and minimize.
Interpolant bias	0.01 to 0.001	Depends on noise and interpolant.
Lighting variation	0.005	If using ZNNSD.
Subset size/Shape function	Linear fit to displacement field	Depends on underlying displacement field.
Optical distortions (w/o calibration)	~ Pixels	Depends on lens and distance moved.
Image blur	0.001	If blur is constant for all frames
Turbulence/Shockwaves	~ 0.01 to 2+ pixels	Depends on lighting and lab environment.
Out-of-plane	~0.5	Depends on magnification and motion.
Lack of perpendicularity	~0.5	Depends on tilt and sample motion
System resolution	Small	Increases subset size.
Aliasing	~0.005	Adds noise to the image (see above)

Estimates for a ~100-mm field-of-view

Categories → Type B (Other)/Type B (Monte Carlo)

Type A (Statistics)

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Calibration Parameters

Image Correlation

3D Triangulation

Estimated Uncertainty of 3D Position

Calculation of Strain

Calibration Parameters

1. Parameter Errors
   a) Cal Target Error
   b) Image Quality
2. Camera Motion
3. Calibration Drift

3D Position

1. Global Coordinate System
2. Camera motion

Image Matching Errors

1. Contrast
2. Image noise
3. Lighting variation
4. Subset size/shape function
5. Turbulence
6. Aliasing
7. Optical distortions
8. Image blur
9. System resolution

Strain Errors

1. Displacement noise
2. Fitting and filtering

Other Errors

1. Camera model
2. Unknown, unknowns

There is not much literature on stereo-DIC errors.

Wang YQ, Sutton M, Ke XD, Schreier H, Reu P, Miller T (2011) On Error Assessment in Stereo-based Deformation Measurements. Exp Mech 51 (4):405-422.

Ke XD, Schreier H, Sutton M, Wang Y (2011) Error Assessment in Stereo-based Deformation Measurements. Exp Mech 51 (4):423-441.

Hu Z, Xie H, Lu J, Wang H, Zhu J (2011) Appl Opt 50 (33):6239-6247

Di Leo G, Liguori C, Paolillo A (2011) Instrumentation and Measurement, IEEE Transactions on 60 (5):1664-1673

Reu PL (2013) Exp Mech 53 (9):1661-1680.

- Add a quick summary of each paper.
- What does "unbiased" calibration mean.
- Non-linear optimized solutions hard to work with (ke)

Many things were studied.

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Calibration Parameters

- Calibration parameter variation and normality
- Calibration target size
- Number of calibration images
- Calibration image noise
- Calibration image contrast
- Calibration dot spacing uncertainty
- Independent calibration variation
- Lens distortion parameters
- 24 hour and 8 hour calibration interval

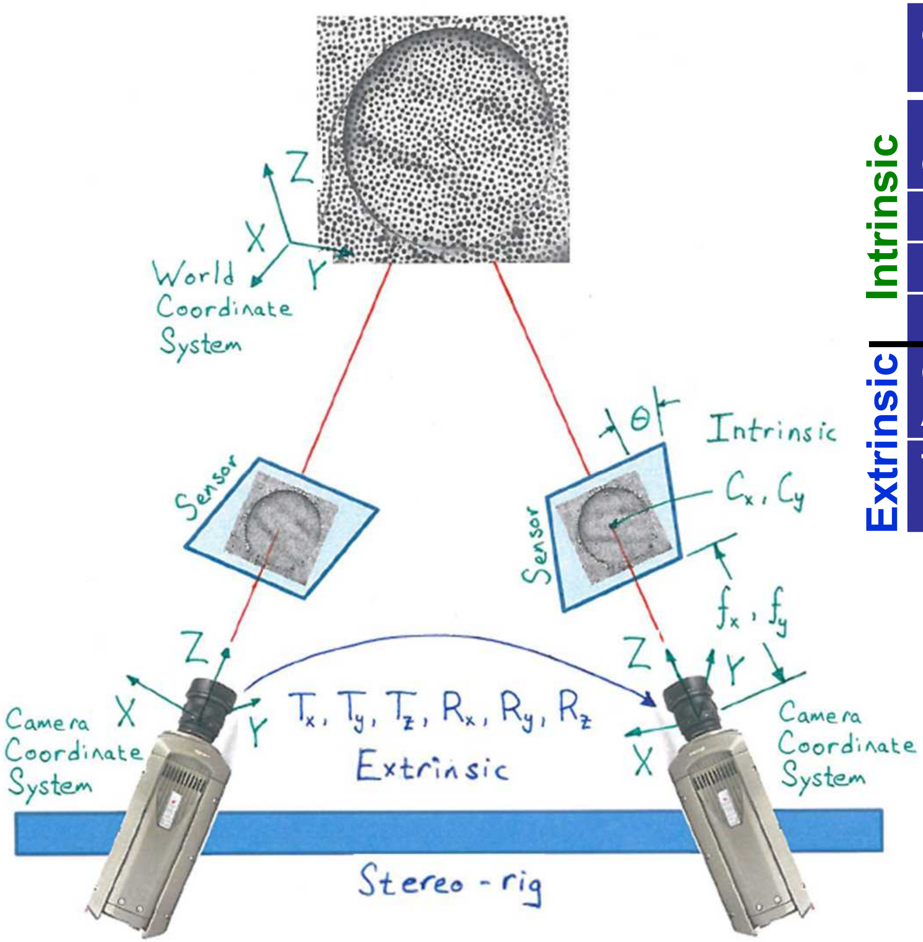
Image Correlation

- Matching uncertainty
- Sensor errors only
- Interpolation method
- Image noise
- Image contrast

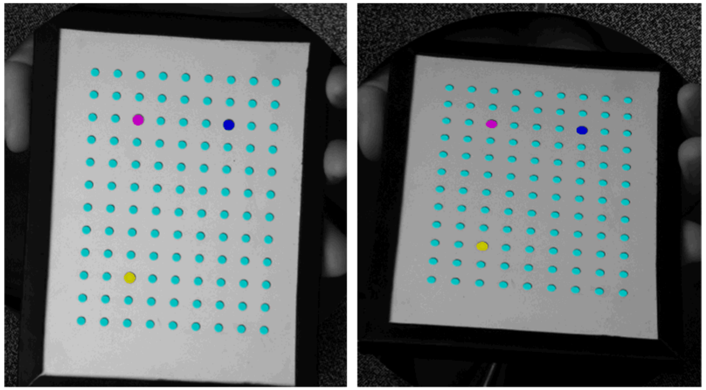
Estimated Uncertainty of 3D Position

- Calibration error versus matching error
- Comparing different systems
- Full-field error distribution
- Software calibration error versus actual calibration error

A stereo-rig has both intrinsic and extrinsic parameters that may have errors

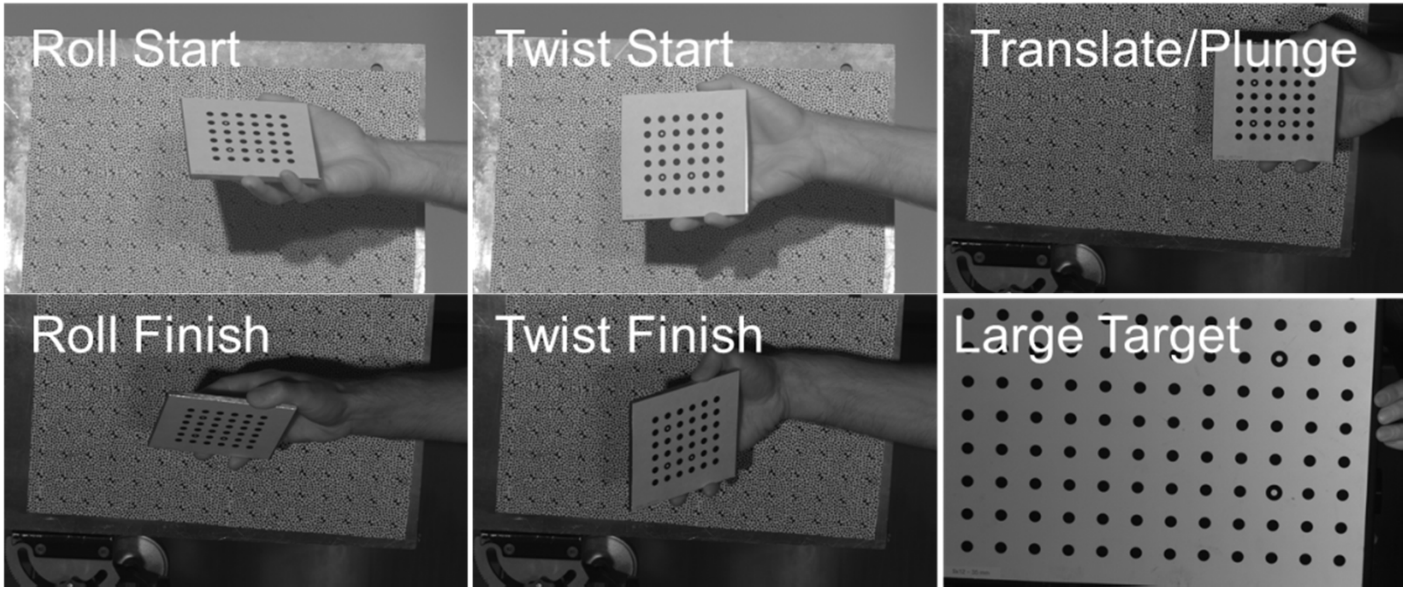


	Camera Parameter	Name	Units
Intrinsic	Image Plane Center	Cx and Cy	Pixels
	Focal Length	Fx and Fy	Pixels
	Image Skew Angle	Skew	Degrees
	Lens Distortions	k1, k2, k3	Pix^{-2}, Pix^{-3}, Pix^{-4}
Extrinsic	Camera Rotation Angles	Alpha (Rx), Beta (Ry), Gamma (Rz)	Degrees
	Translation Between Cameras	Tx, Ty and Tz	mm



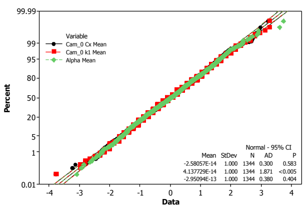
A Monte Carlo approach was used to find the calibration errors.

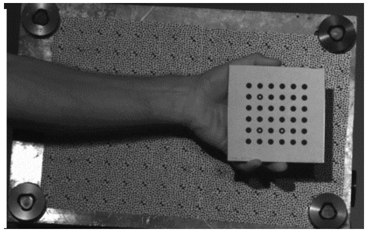
> 1000 Images each motion



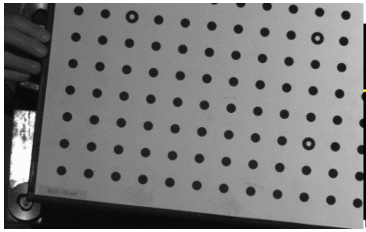
- Images selected at random from the 3 directories
- Independent calibrations run using a different number of images

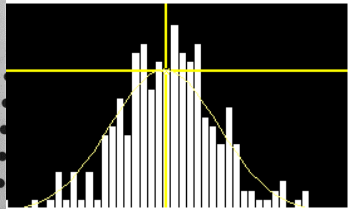
Most of the parameters were normally distributed.





100-Image Calibrations





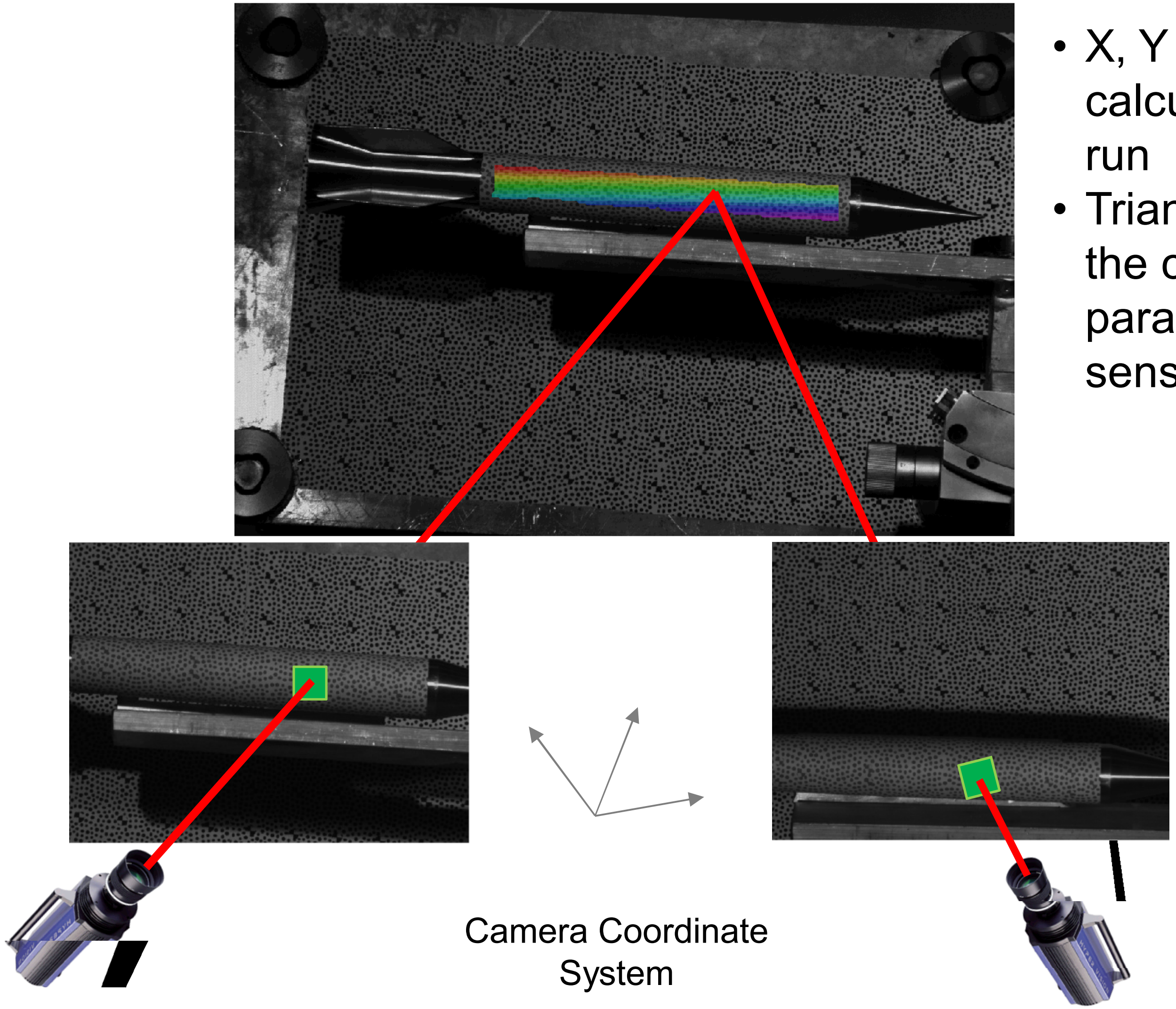
	Parameter (N=1345)	Mean	StDev	SftWr σ	AD	P-Value
Intrinsic Parameters	Cam_0 Cx	621.49	2.577	46.37	0.3	0.583
	Cam_0 Cy	367.53	3.143	117.70	0.347	0.48
	Cam_0 Fx	7306.58	12.870	1021.00	0.307	0.562
	Cam_0 Fy	7306.15	12.704	1027.39	0.293	0.603
	Cam_0 Skew	-1.63	0.570	10.32	0.724	0.059
	Cam_0 k1	0.05	0.006	0.00	1.871	0
	Cam_1 Cx	622.46	3.116	40.43	0.422	0.321
	Cam_1 Cy	420.06	4.772	140.44	0.173	0.928
	Cam_1 Fx	7276.41	11.088	1025.51	0.329	0.516
	Cam_1 Fy	7276.29	11.347	1070.81	0.352	0.467
	Cam_1 Skew	-1.34	0.519	10.32	1.648	0
	Cam_1 k1	0.04	0.008	0.00	1.366	0
Extrinsic Parameters	Alpha (Rx)	27.57	0.052	0.00	0.38	0.404
	Beta (Ry)	2.15	0.041	0.00	0.6	0.119
	Gamma (Rz)	-2.70	0.010	0.00	0.858	0.027
	Tx	43.66	0.232	0.48	0.756	0.049
	Ty	1249.59	2.326	28.99	0.352	0.467
	Tz	316.84	8.056	213.72	0.389	0.385

Red = Not Normal

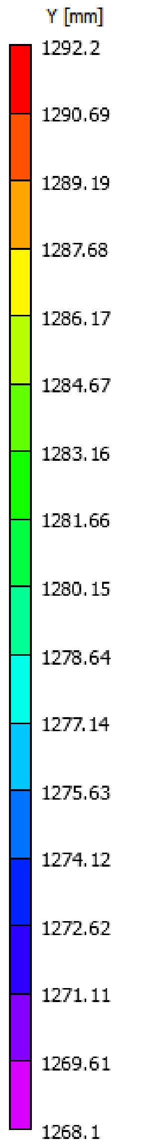
	Parameter (N=1522)	Mean	StDev	SftWr σ	AD	P-Value
Intrinsic Parameters	Cam_0 Cx	623.81	1.894	15.25	0.462	0.258
	Cam_0 Cy	366.01	3.044	62.00	0.495	0.215
	Cam_0 Fx	7299.04	1.426	13.62	0.289	0.614
	Cam_0 Fy	7297.00	1.340	13.53	0.389	0.385
	Cam_0 Skew	-1.98	0.378	1.23	3.009	0
	Cam_0 k1	0.05	0.003	0.00	7.767	0
	Cam_1 Cx	623.82	1.888	17.03	0.477	0.237
	Cam_1 Cy	423.74	3.006	59.04	0.896	0.022
	Cam_1 Fx	7289.85	1.761	20.13	0.322	0.528
	Cam_1 Fy	7288.38	1.801	20.36	0.526	0.179
	Cam_1 Skew	-1.45	0.332	1.23	2.364	0
	Cam_1 k1	0.04	0.003	0.00	10.401	0
Extrinsic Parameters	Alpha (Rx)	27.61	0.006	0.00	2.125	0
	Beta (Ry)	2.16	0.005	0.00	2.627	0
	Gamma (Rz)	-2.69	0.007	0.00	1.977	0
	Tx	-43.75	0.113	0.09	0.38	0.404
	Ty	1255.28	0.231	0.37	0.801	0.038
	Tz	326.67	0.756	2.46	0.304	0.571

AD – Anderson-Darling Normality Test (Smaller is better)

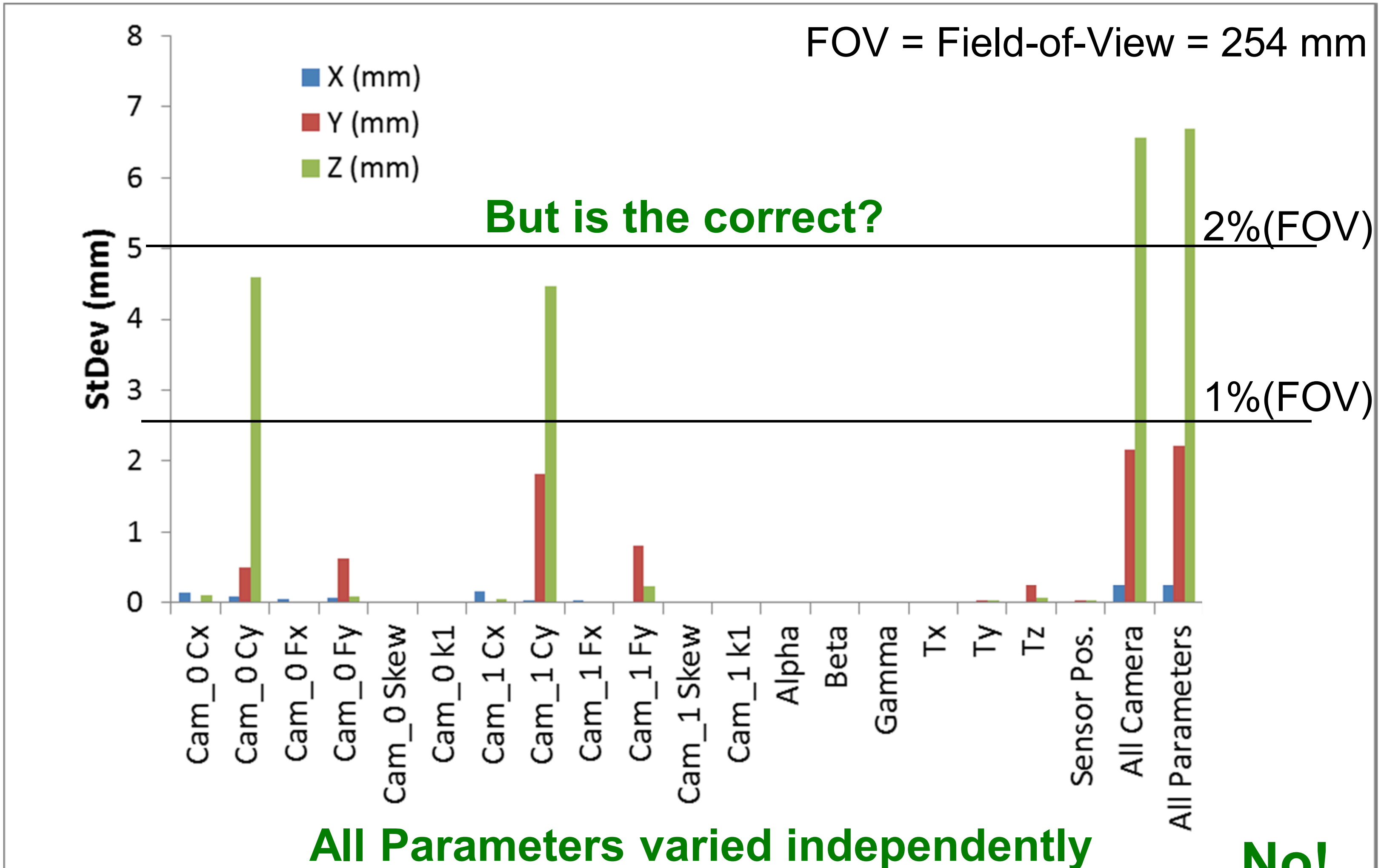
The simulation repeatedly triangulates while varying one or more parameters



- X, Y and Z are calculated for each run
- Triangulation uses the calibration parameters and sensor positions.



The parameter variation is not what matters: It is the final position in space!



The calibration parameters are not independent and *must* be used together

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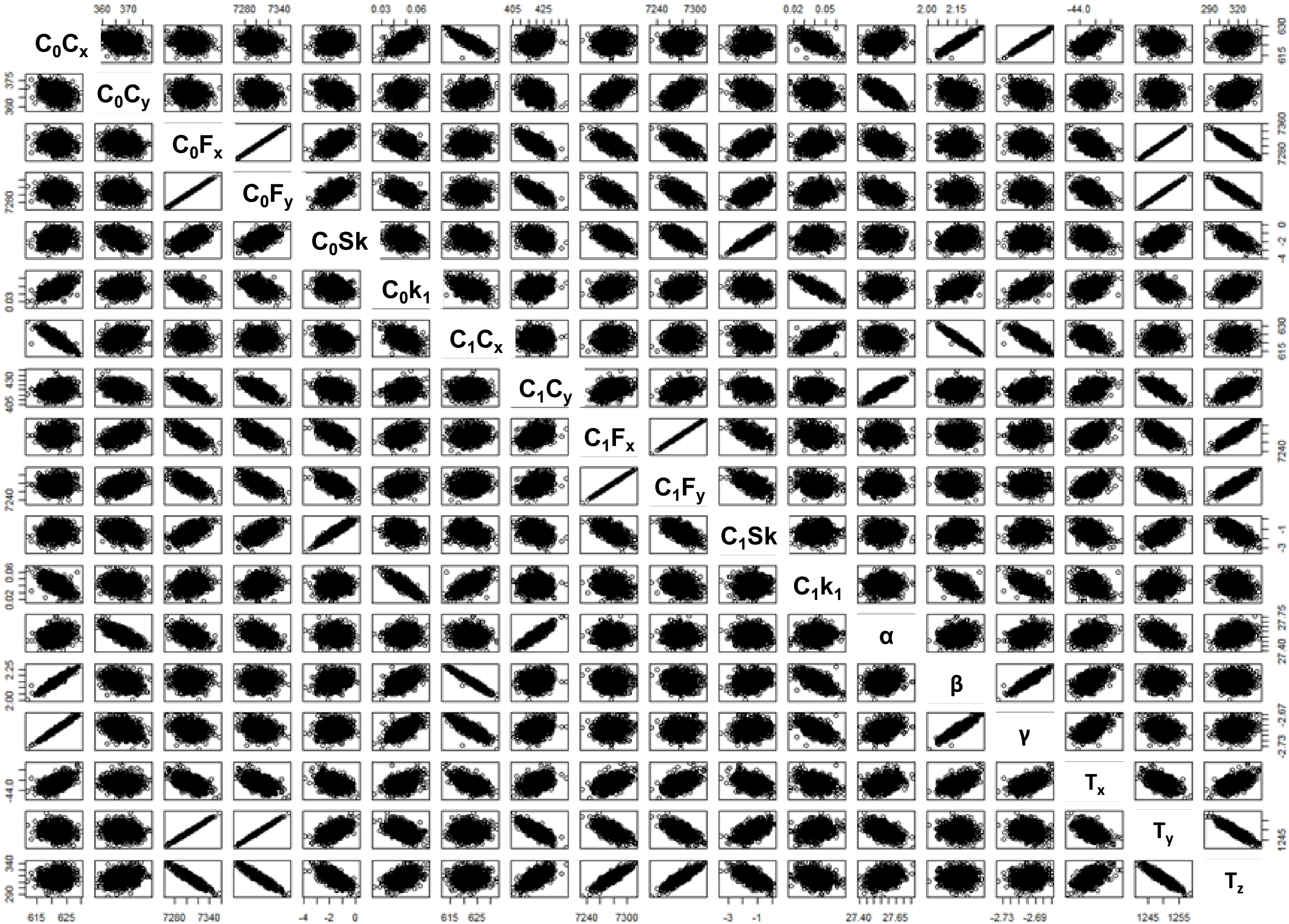
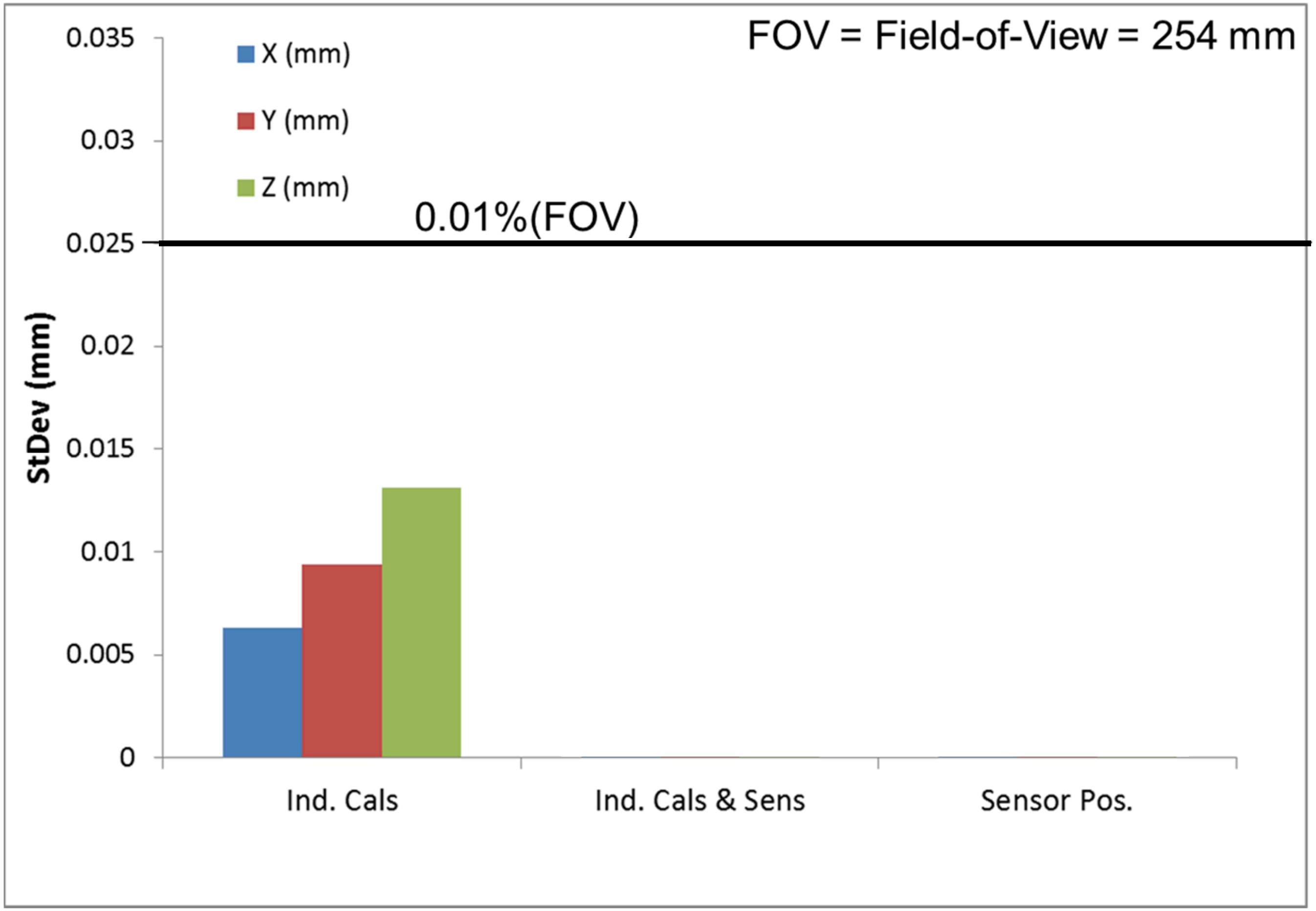


The sensor error tends to dominate the error (with a good calibration)



The covariance matrix is not a good estimation of the actual parameter variation

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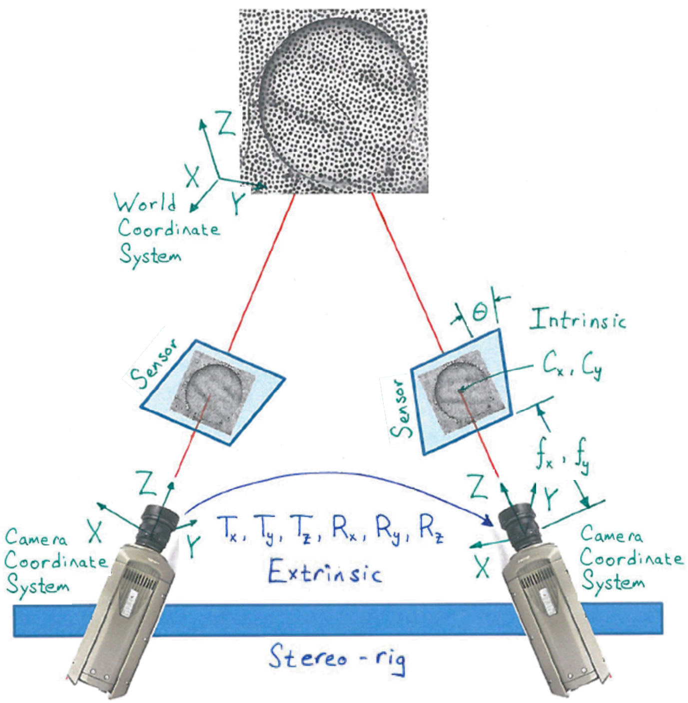
- Calibration covariance matrix is conservative (usually)
- Reprojection error is not very sensitive



	25 Image StDev		1000 Image StDev	
Parameter	**Actual**	**CoVar**	**Actual**	**CoVar**
Cam_0 Cx Mean	1.15	5.08	0.12	0.08
Cam_0 Cy Mean	1.12	4.89	0.15	0.09
Cam_0 Fx Mean	2.61	27.97	0.20	0.43
Cam_0 Fy Mean	2.52	29.31	0.18	0.45
Cam_0 Skew Mean	0.79	5.25	0.11	0.11
Cam_0 k1 Mean	0.00	0.00	0.00	0.00
Cam_1 Cx Mean	2.00	7.47	0.12	0.10
Cam_1 Cy Mean	0.98	7.69	0.11	0.15
Cam_1 Fx Mean	2.21	35.68	0.24	0.53
Cam_1 Fy Mean	2.28	38.77	0.25	0.58
Cam_1 Skew Mean	0.78	5.25	0.12	0.11
Cam_1 k1 Mean	0.01	0.00	0.00	0.00
Alpha Mean	0.03	0.00	0.00	0.00
Beta Mean	0.04	0.00	0.00	0.00
Gamma Mean	0.01	0.00	0.00	0.00
Tx Mean (Negated)	4.23	69.63	0.32	1.14
Ty Mean	0.60	2.98	0.07	0.05
Tz Mean	9.51	669.30	1.18	10.92

You need a *large* number of images to minimize the calibration variance

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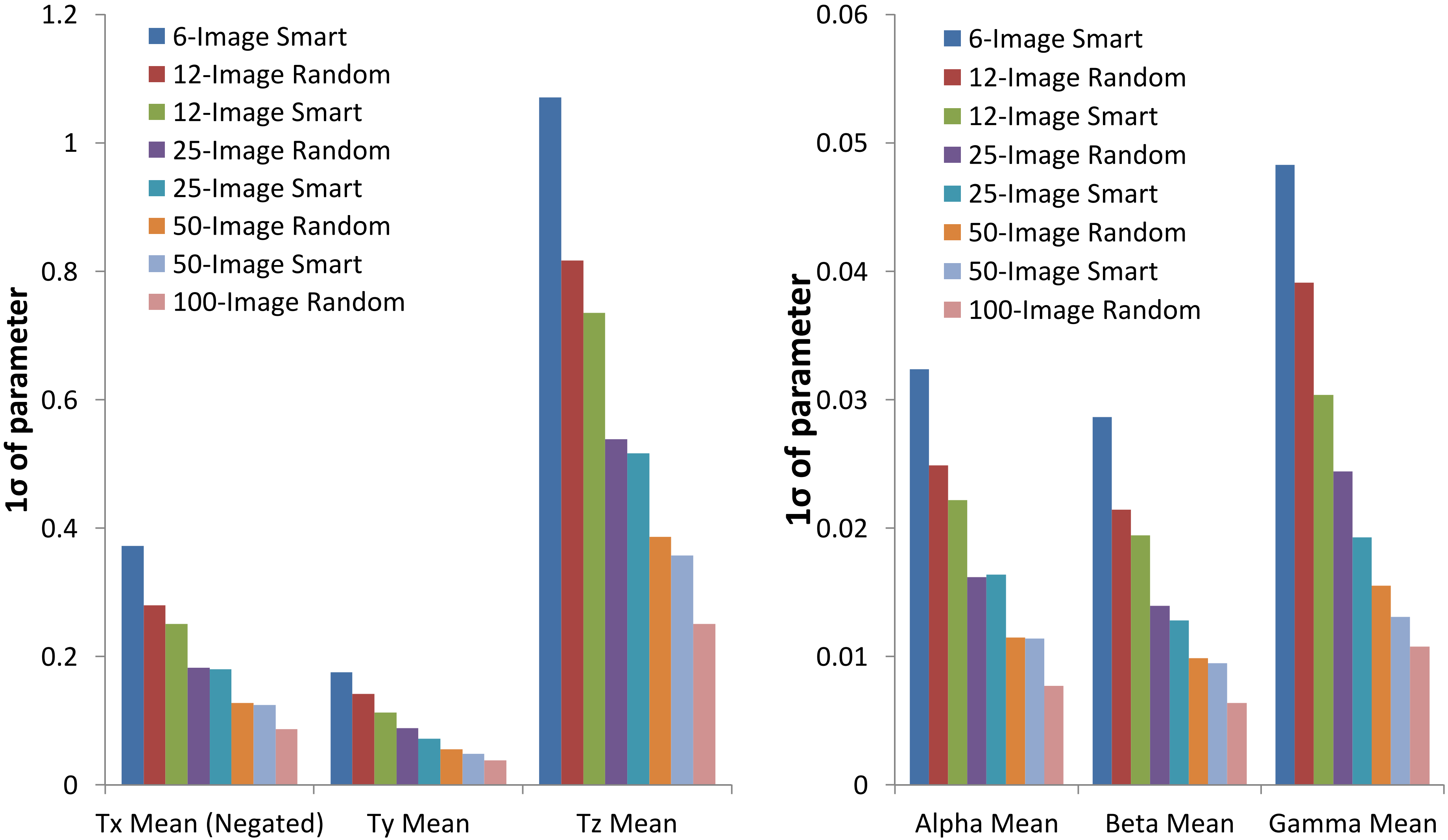
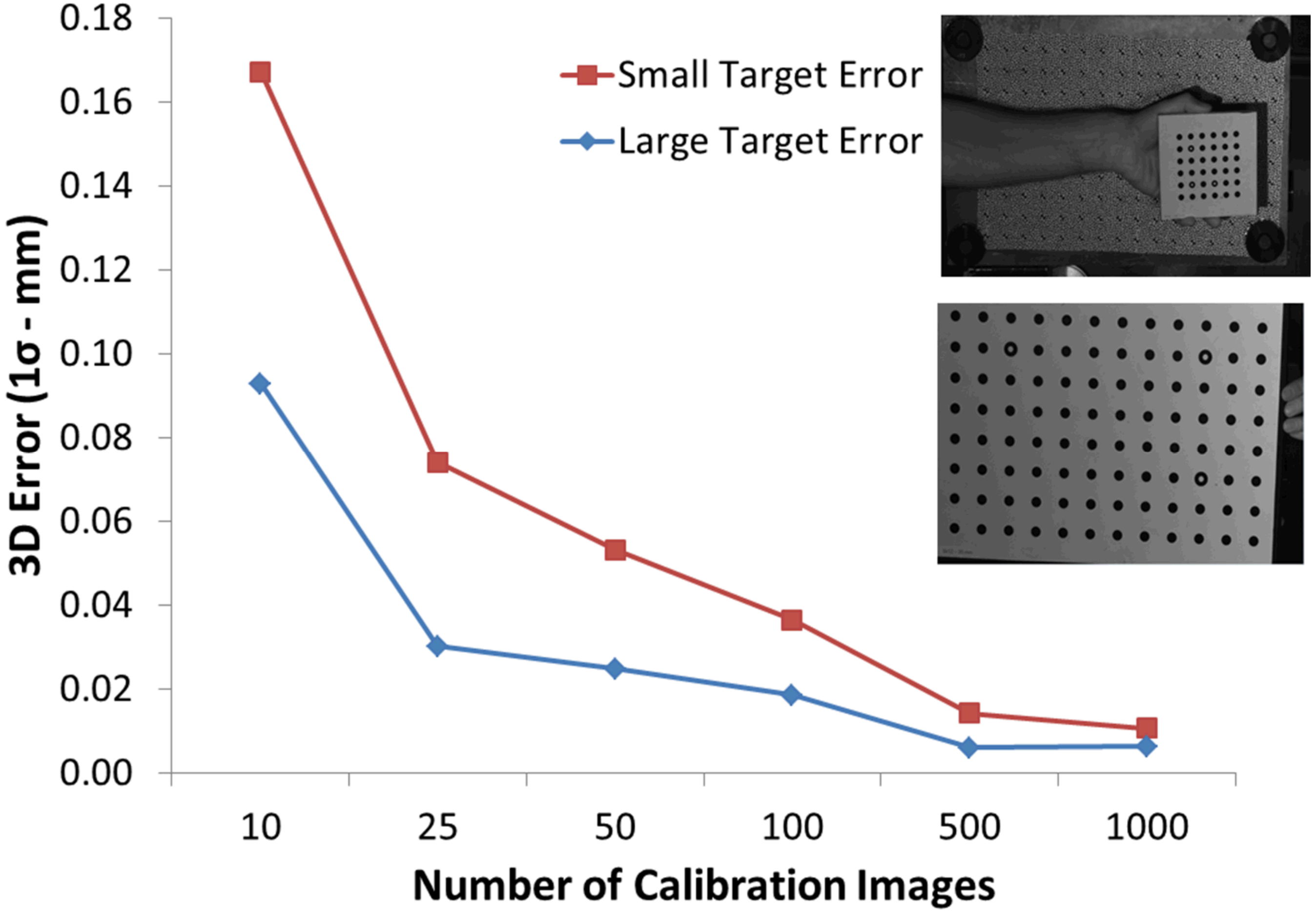
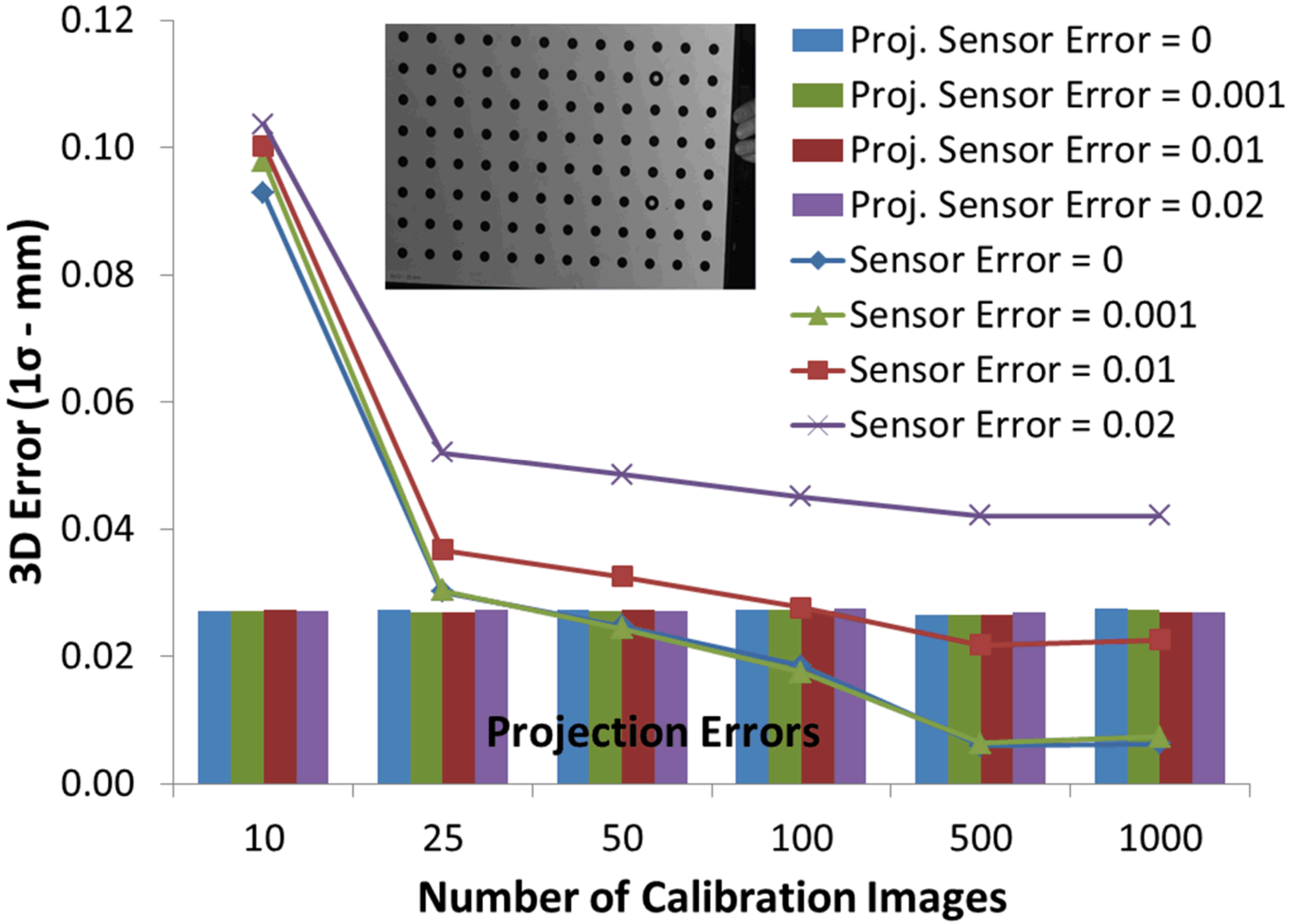


The others behave similarly.

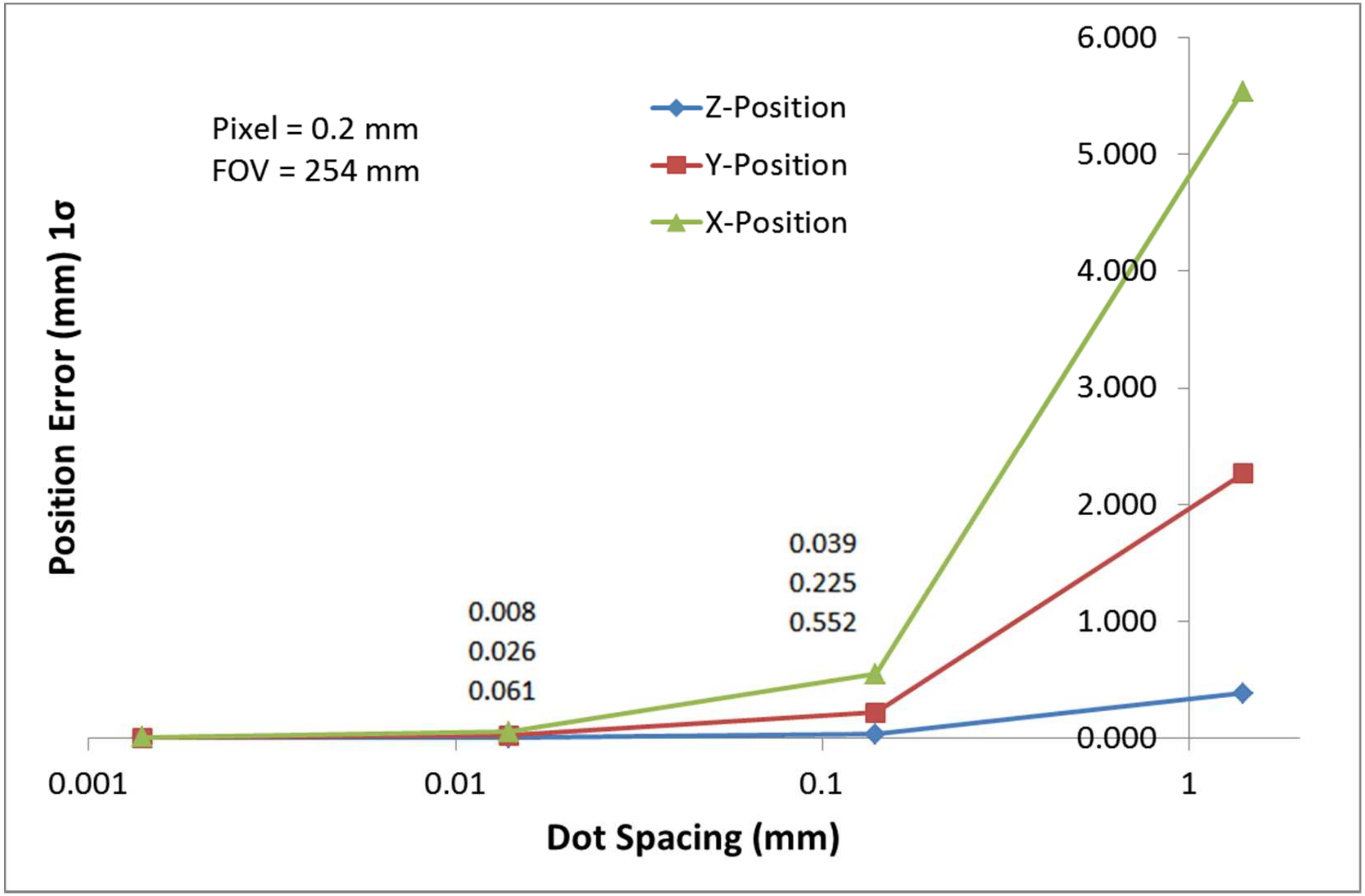
A target that fills the FOV is better and requires less images.



Projection error may not be sensitive enough to calibration issues.

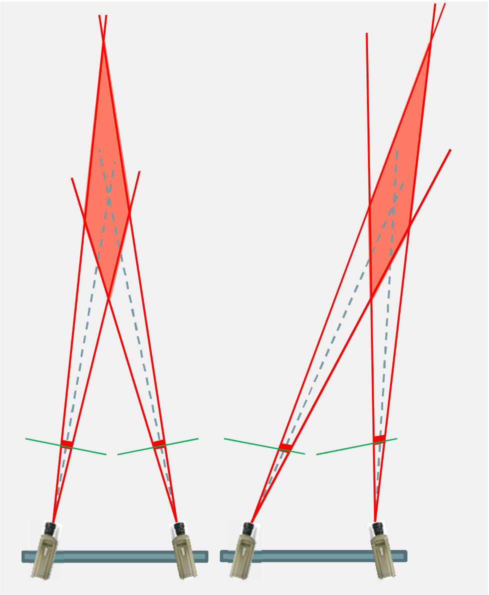


Cal target dot spacing only needs to be known to ~1/10th of a pixel.

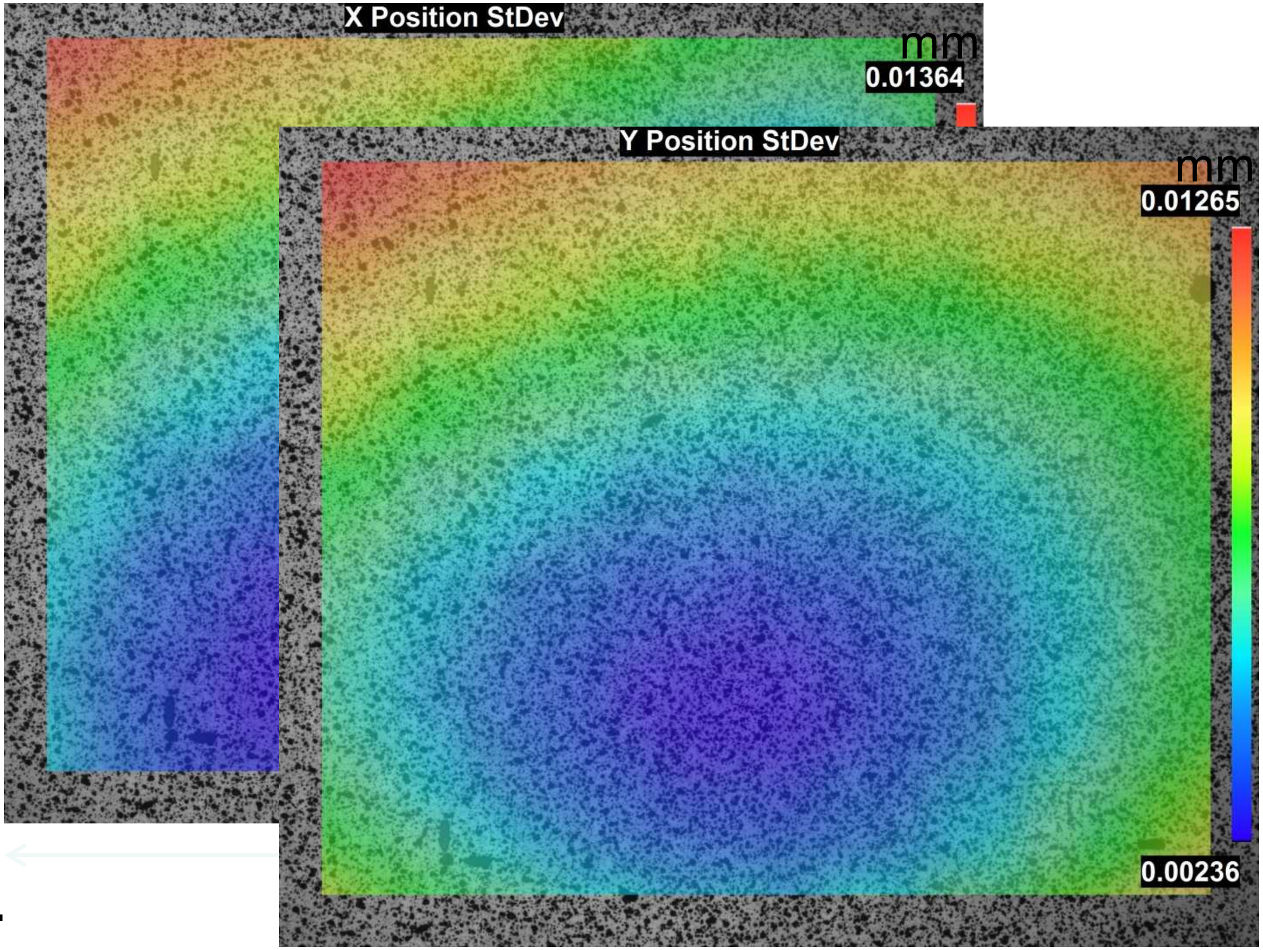


Full-field UQ results may also be calculated with the same techniques.

75-mm Lens
6 Calibration Images
Sensor = 0 (1σ)

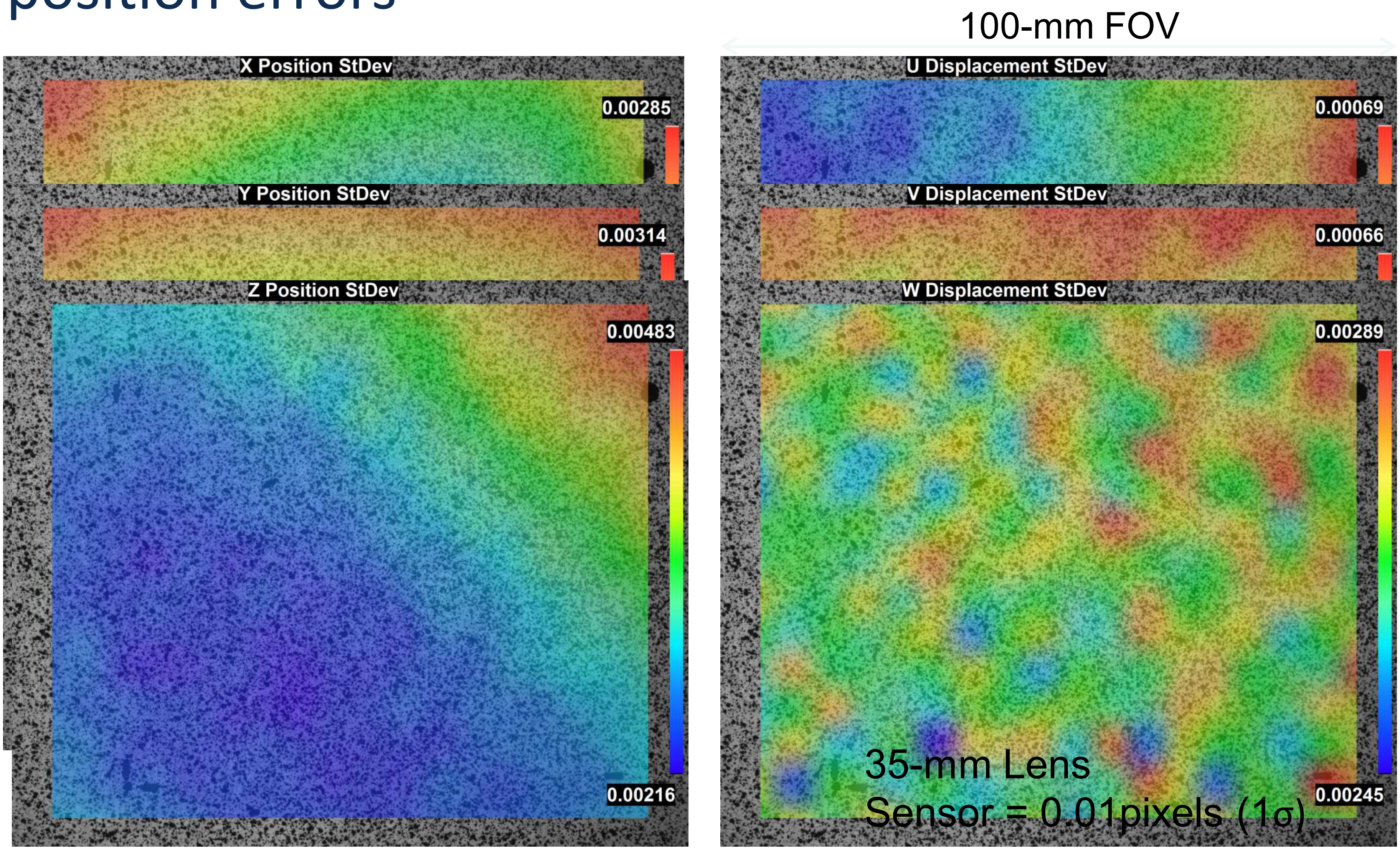


Edges Are Worse.



100-mm FOV

Displacement errors are lower than absolute position errors



Units are mm

At the center – the matching error dominates the error.

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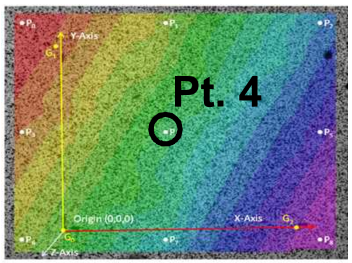
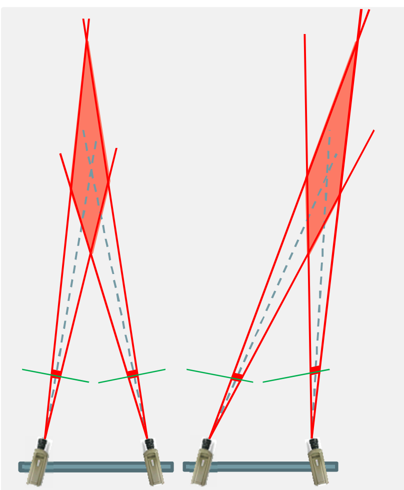
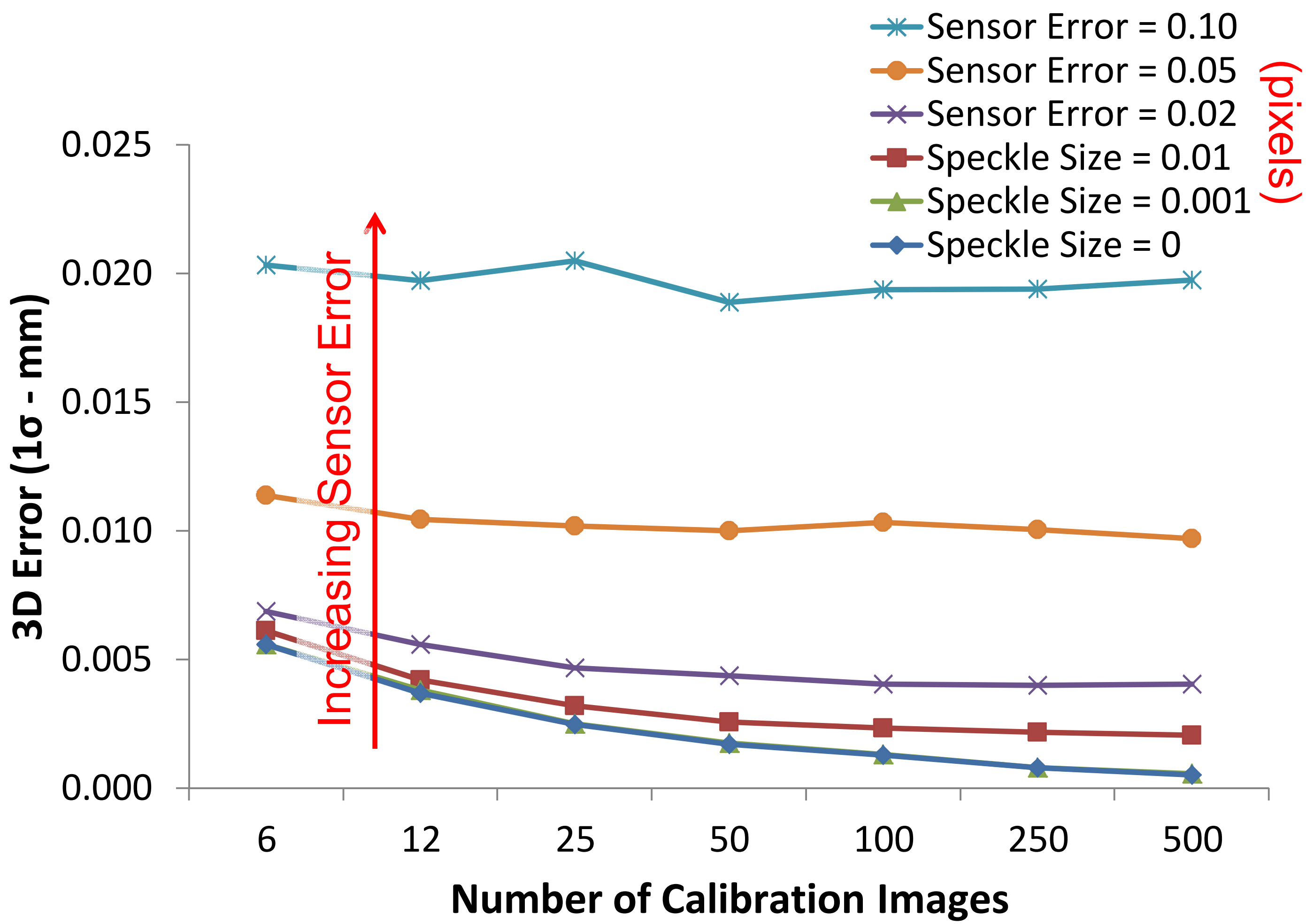
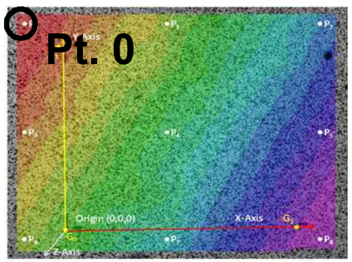


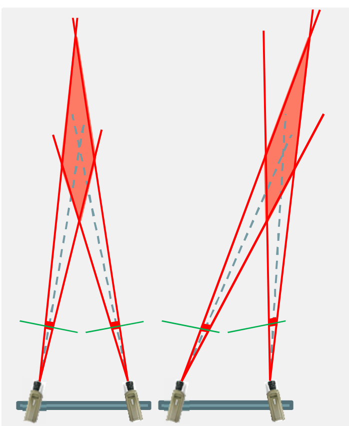


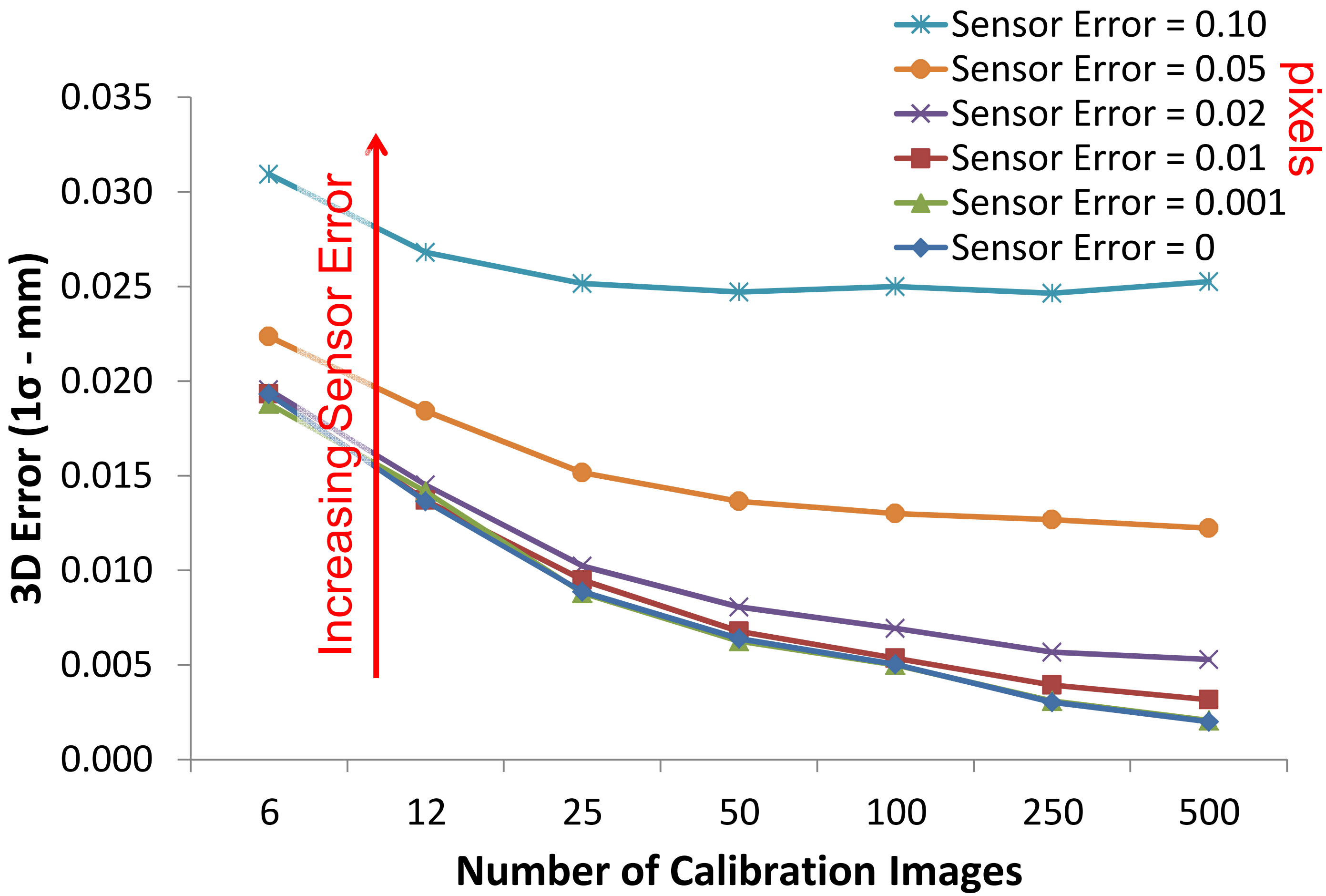


75-mm Lens – 100-mm FOV
Sensor Error = Matching Error (pixels)

At the edge of the FOV, the calibration dominates the uncertainty.

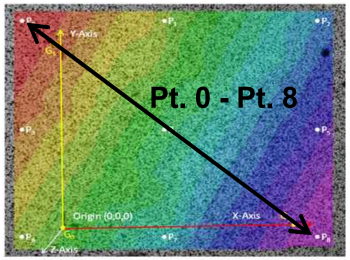


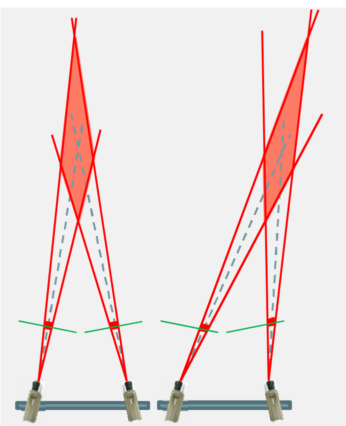


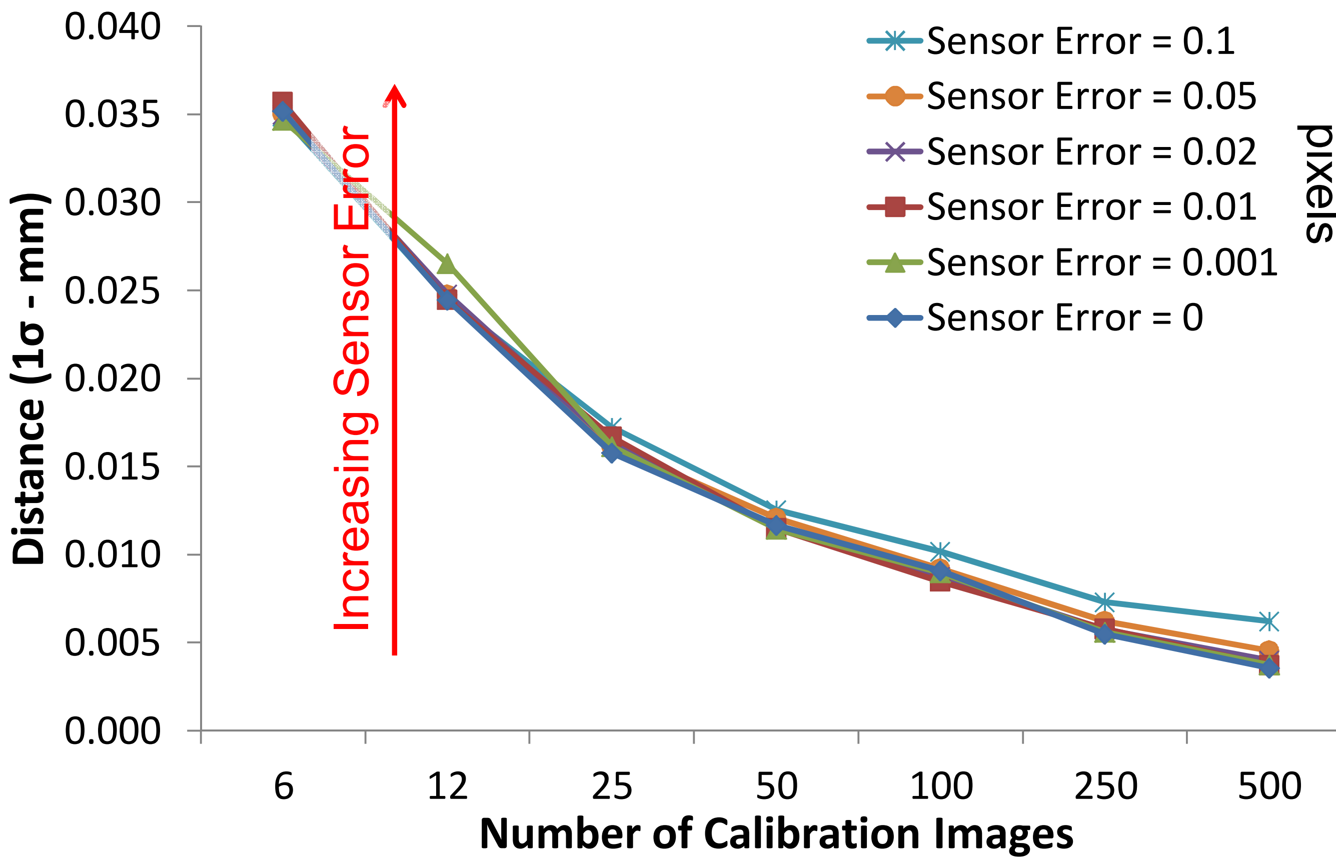


75-mm Lens – 100-mm FOV
Sensor Error = Matching Error (pixels)

The edges are dominated by the calibration.



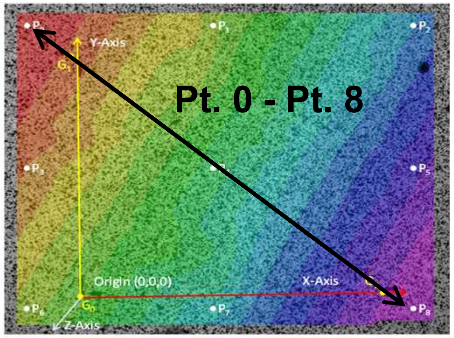


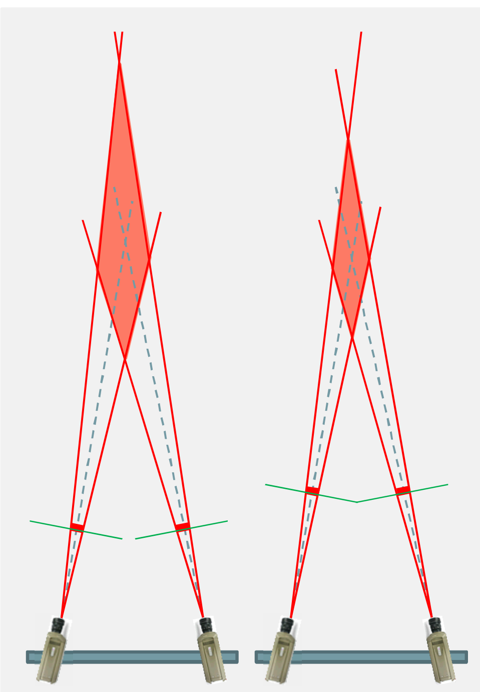


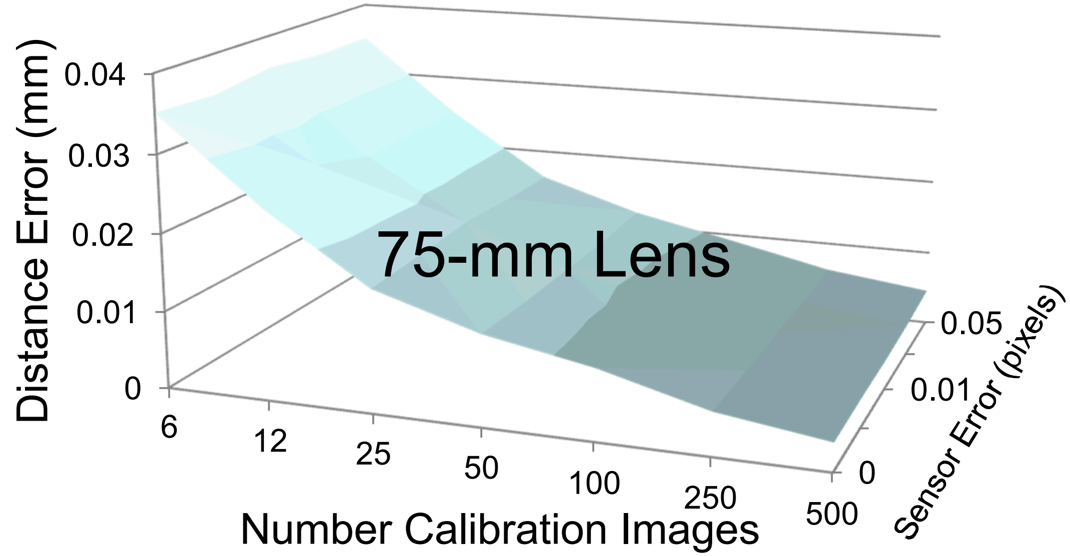
75-mm Lens – 100-mm FOV

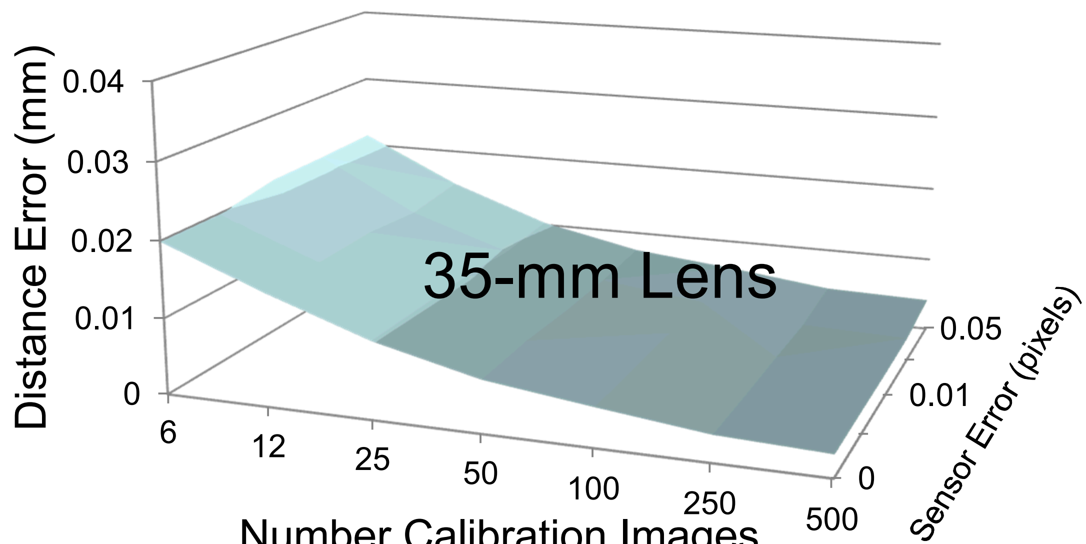
Sensor Error = Matching Error (pixels)

Longer lenses have lower errors.

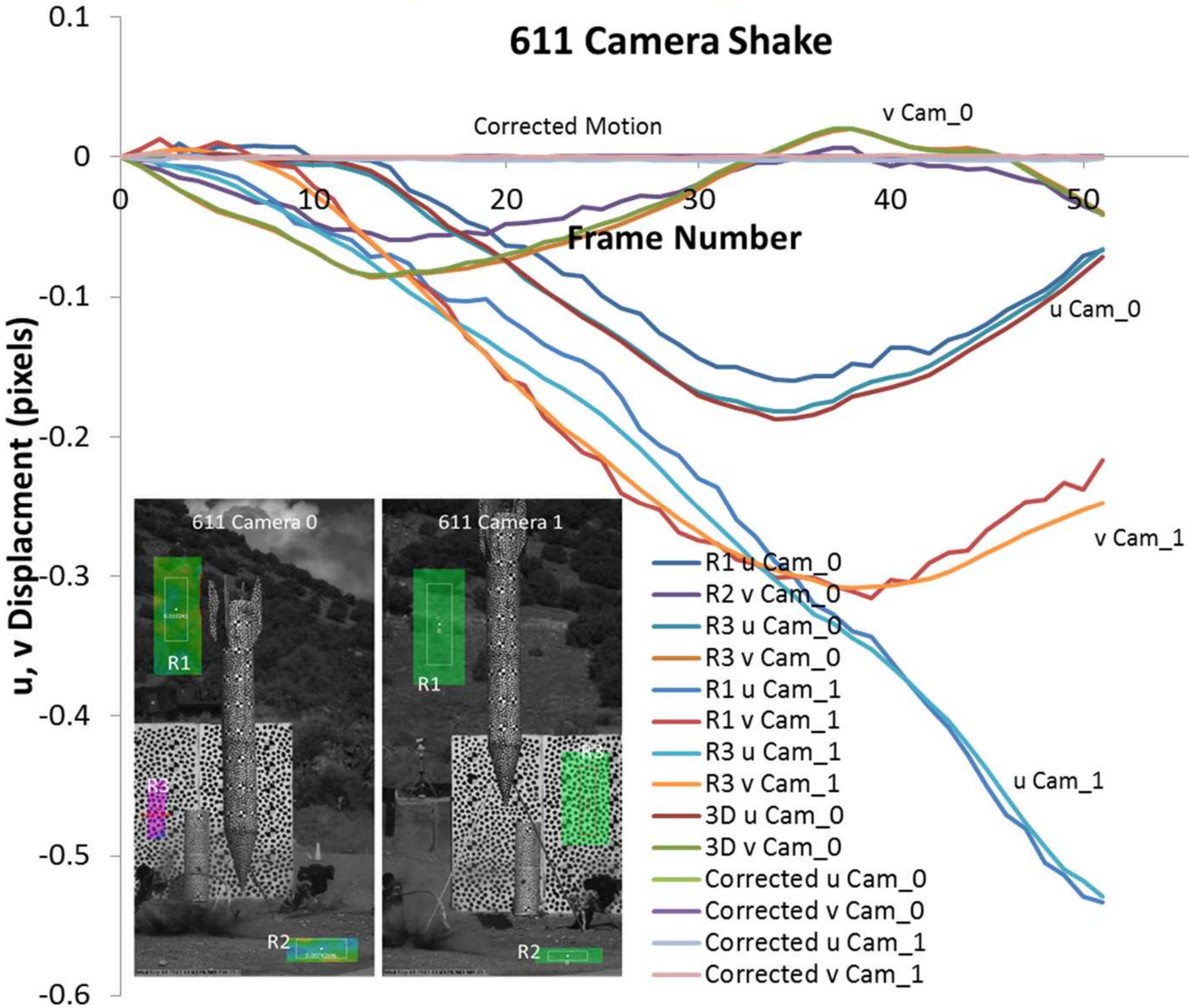








For outdoor testing, camera shake is most likely the largest error term.



Camera Shake Notes:
- Backboard is stationary
- There is no camera rotation (this is good!)
- Error is up to 0.5 pixels!
- My not be noticeable by eye.

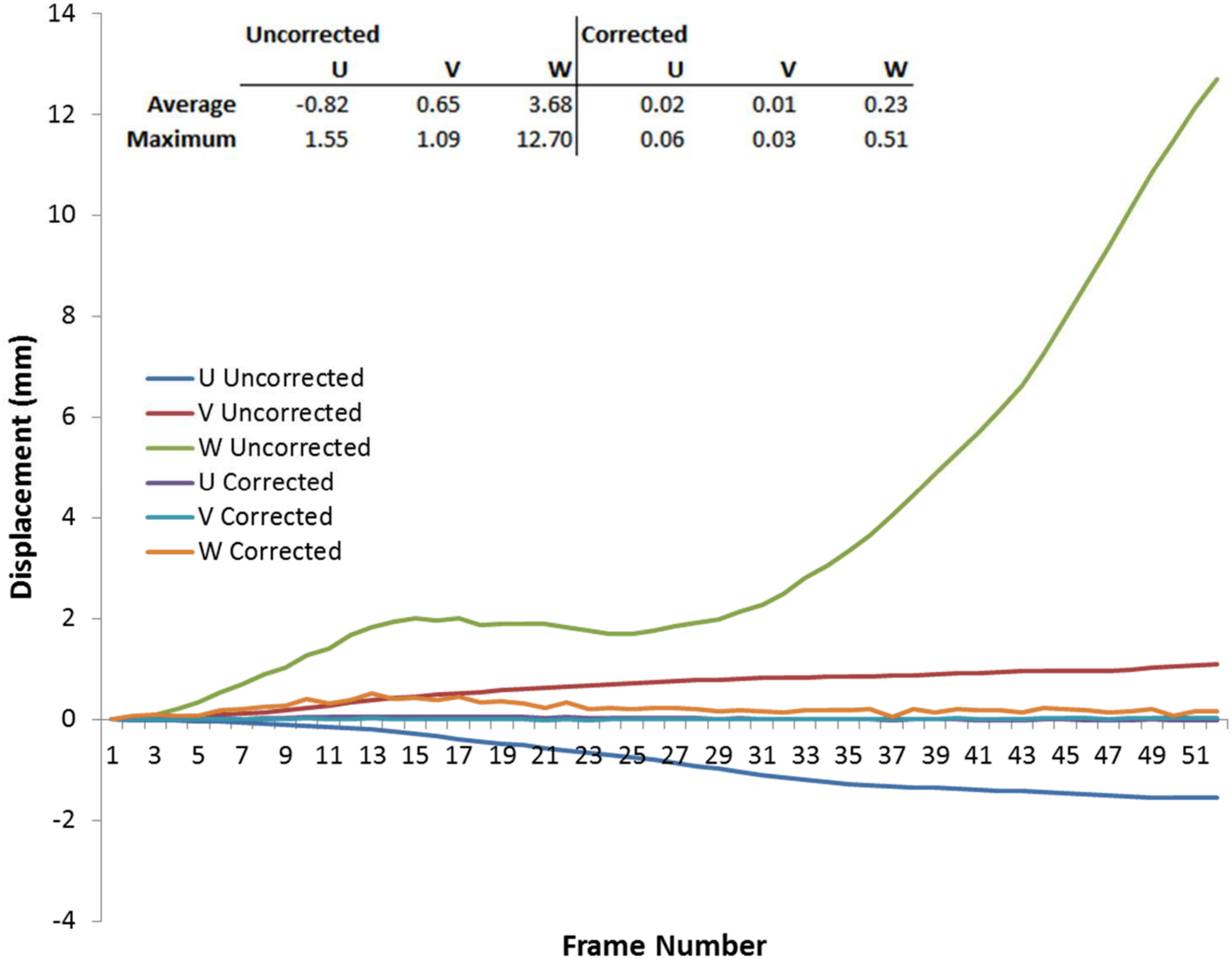
Camera shake can be corrected.

The camera motion errors can be calculated in mm.

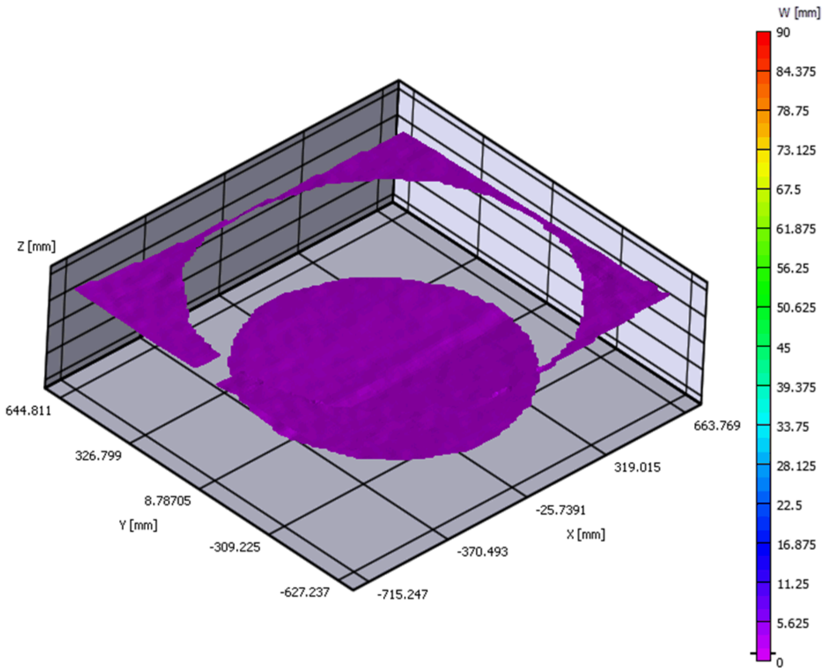
Camera Motion Notes:

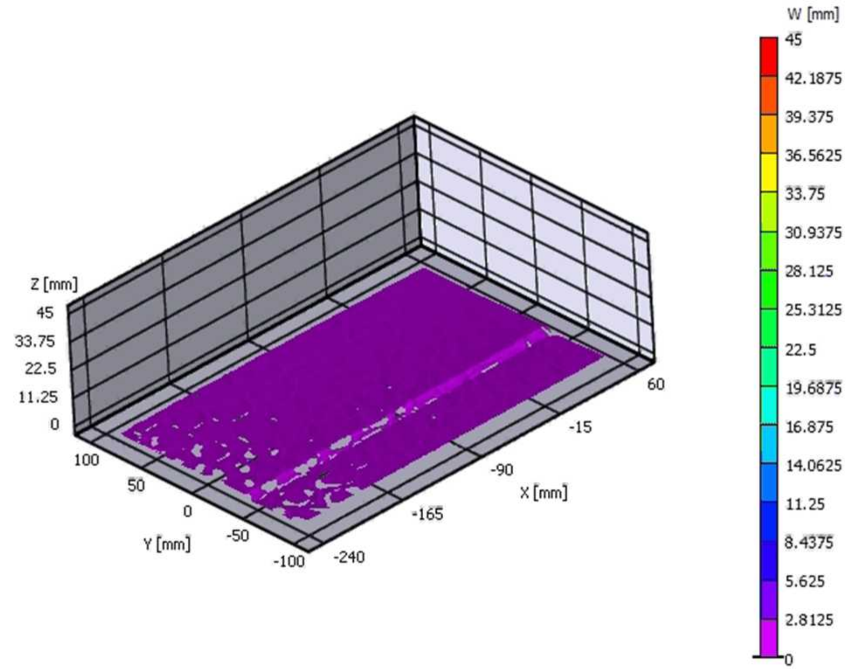
- Measured on the backboard (i.e. should have 0 displacement).
- Correction reduces the error to subpixel.
- This error will be an input for the Angle-of-attack calculation.
- This is in the backboard coordinates.

	Uncorrected U	Uncorrected V	Uncorrected W	Corrected U	Corrected V	Corrected W
Average	-0.82	0.65	3.68	0.02	0.01	0.23
Maximum	1.55	1.09	12.70	0.06	0.03	0.51

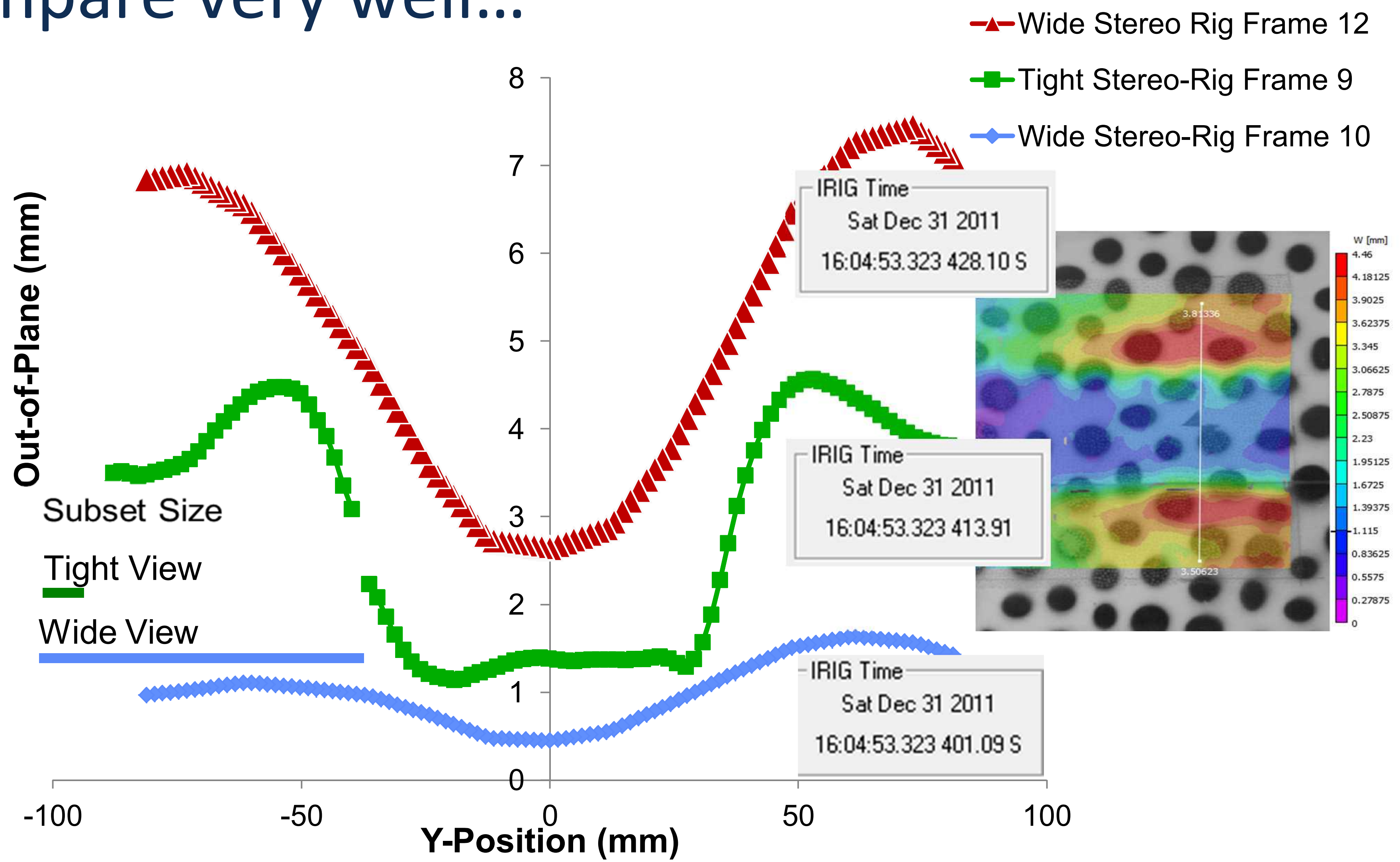


Conflicting requirements require two different fields-of-view

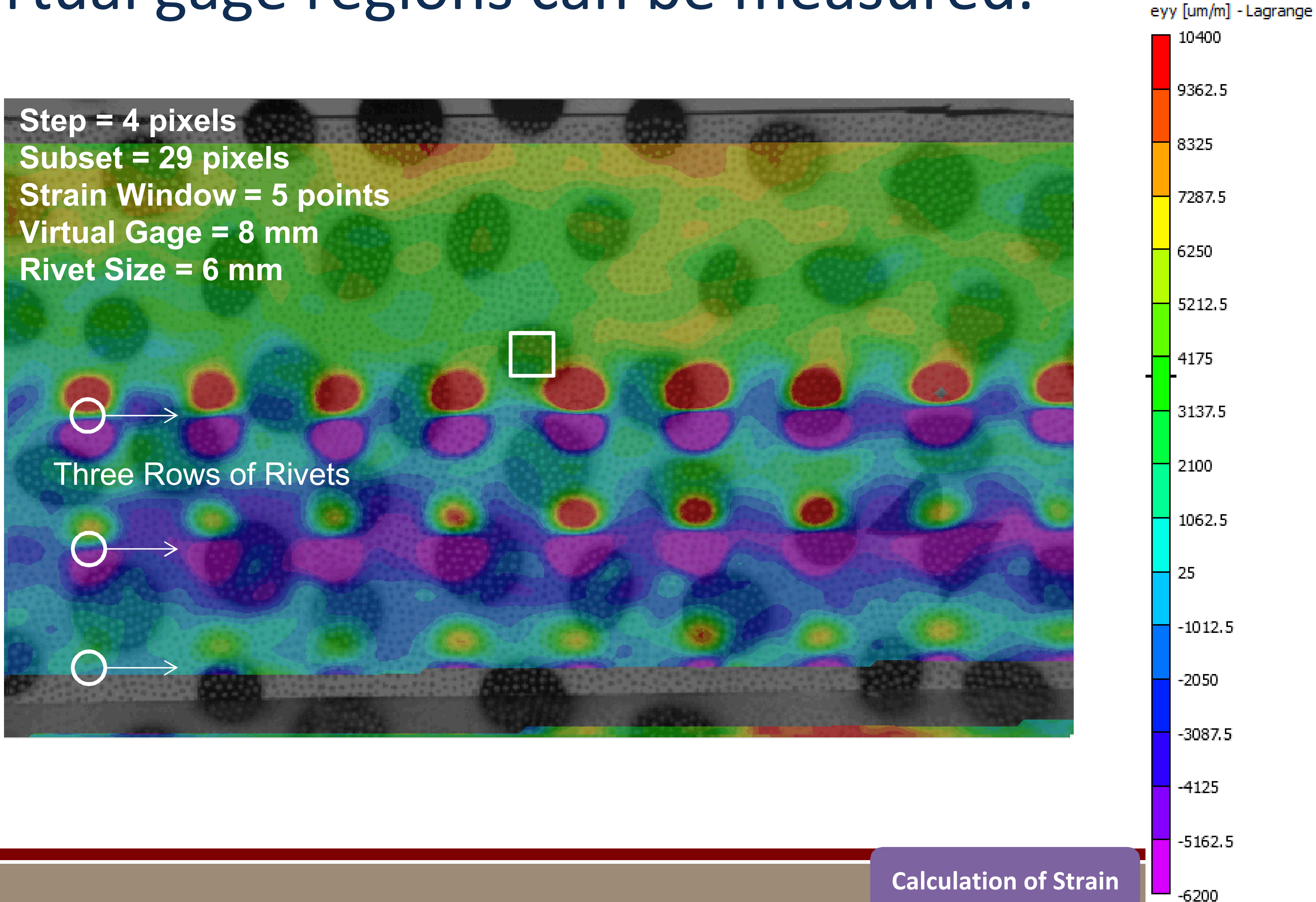




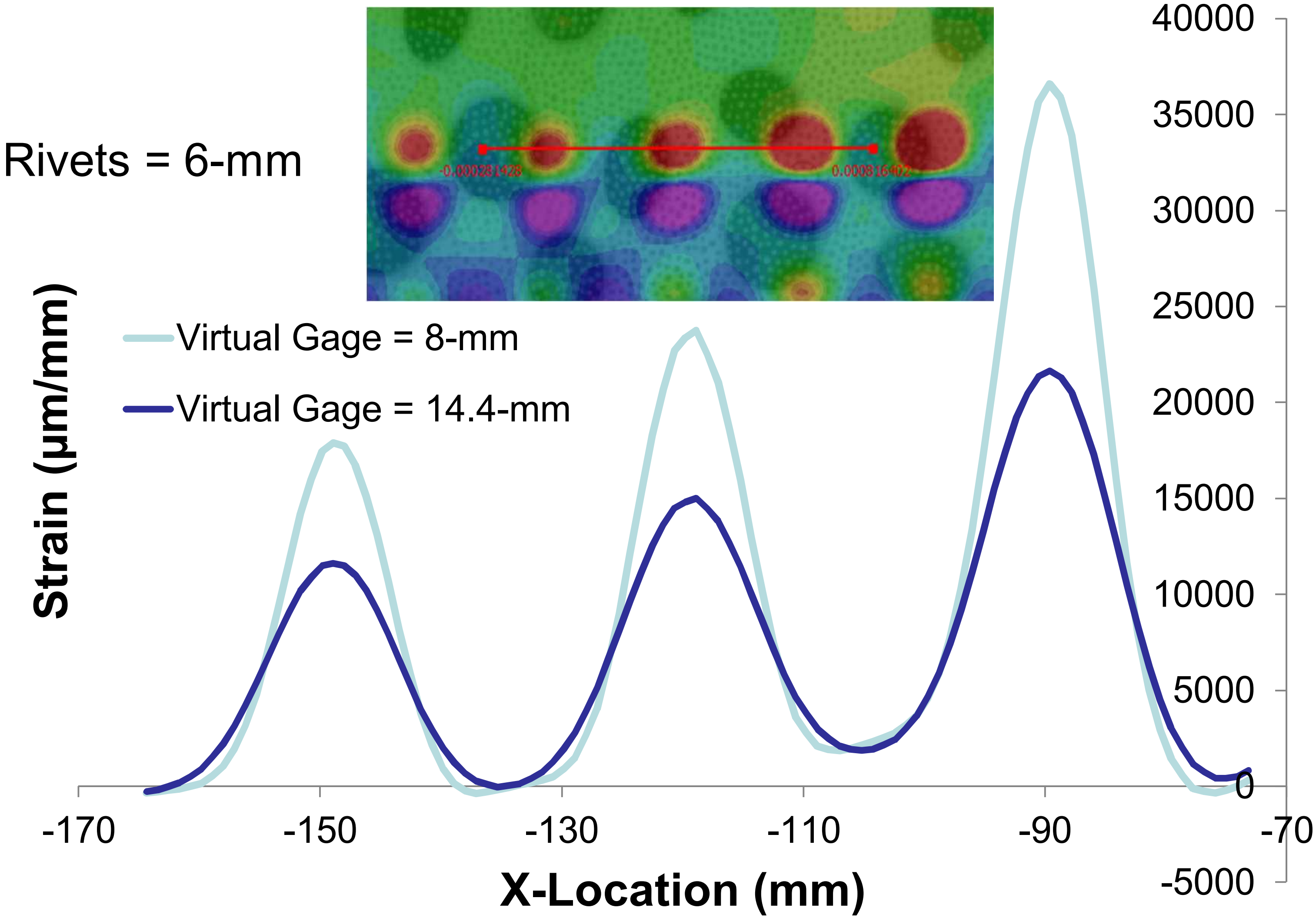
The overall and tight results compare very well…



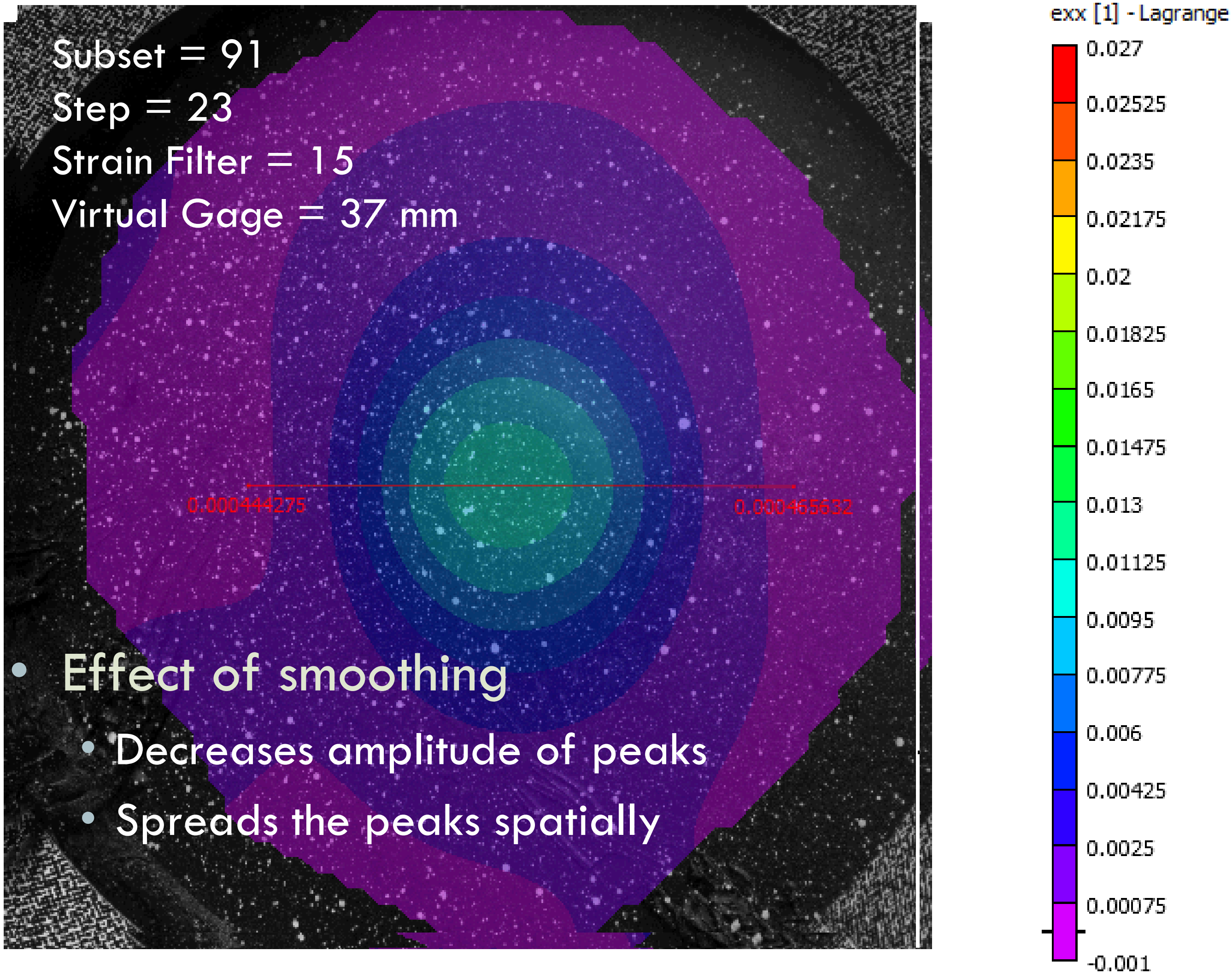
With proper experimental design small virtual gage regions can be measured.



Strain profiles across rivets.

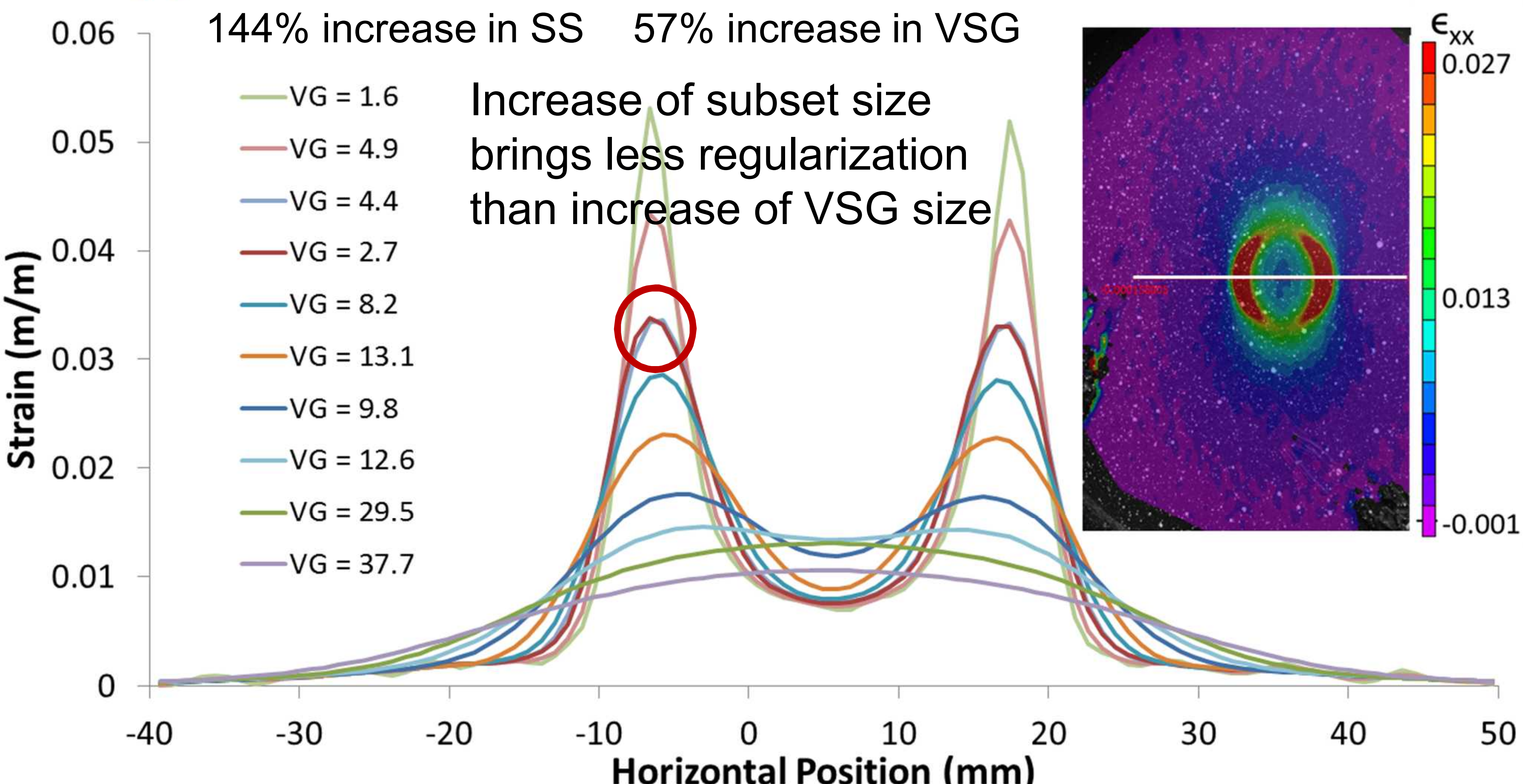


Strain sensitivity case study using real data

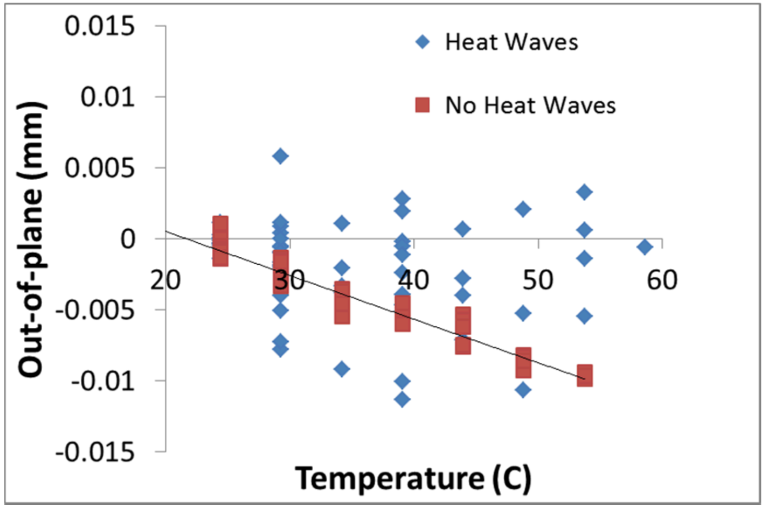


- Effect of smoothing
  - Decreases amplitude of peaks
  - Spreads the peaks spatially

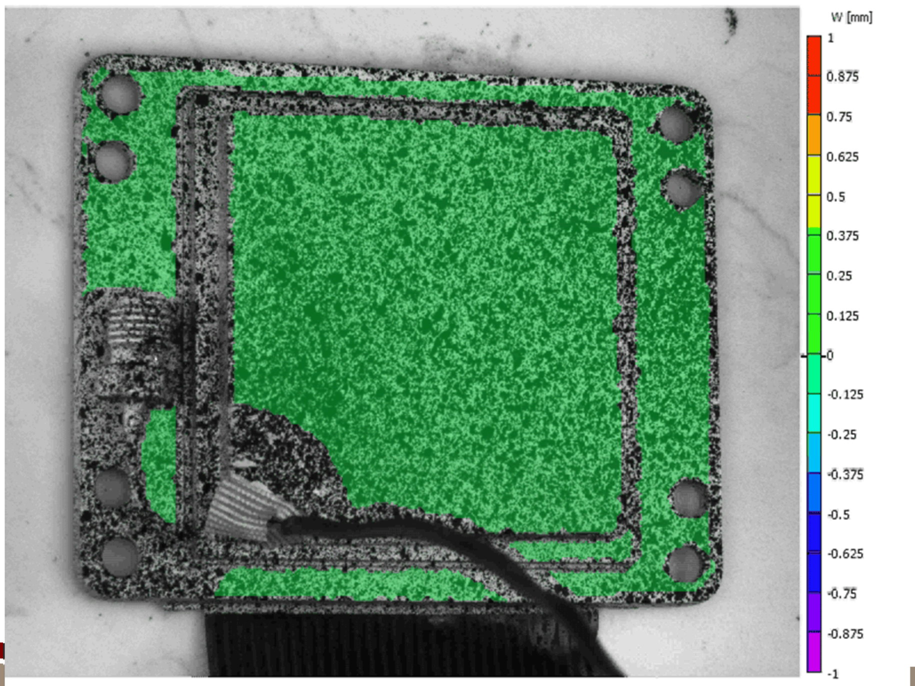
Subset Size	29	71	29	29	71	71	91	29	71	91
Step Size	3	5	8	3	5	18	23	8	18	23
Strain Window	5	5	5	15	15	5	5	15	15	15
Virtual Gage (pixels)	13	21	33	43	71	73	93	113	253	323
Interpolant	4-Tap	4-Tap	4-Tap	4-Tap	4-Tap	4-Tap	4-Tap	4-Tap	4-Tap	4-Tap
Virtual Gage (mm)	1.6	2.7	4.4	4.9	8.2	9.8	12.6	13.1	29.5	37.7
Noise (StDev - με)	174	54	59	93	47	30	22	41	18	15
Max Strain (με)	53109	33811	33589	43392	28645	17607	14555	23094	13039	10586

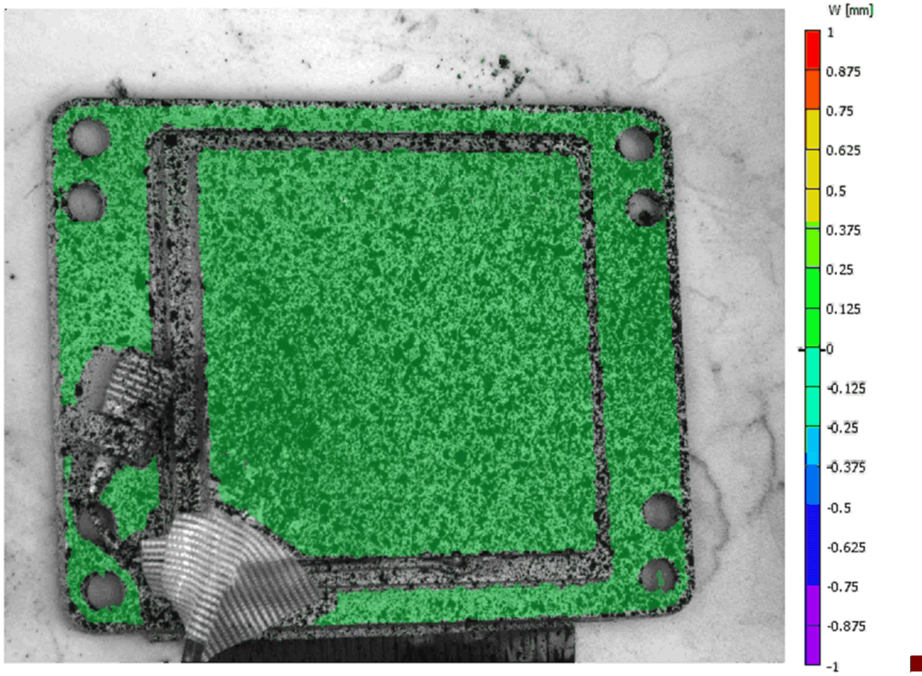


Thermal waves will cause issues

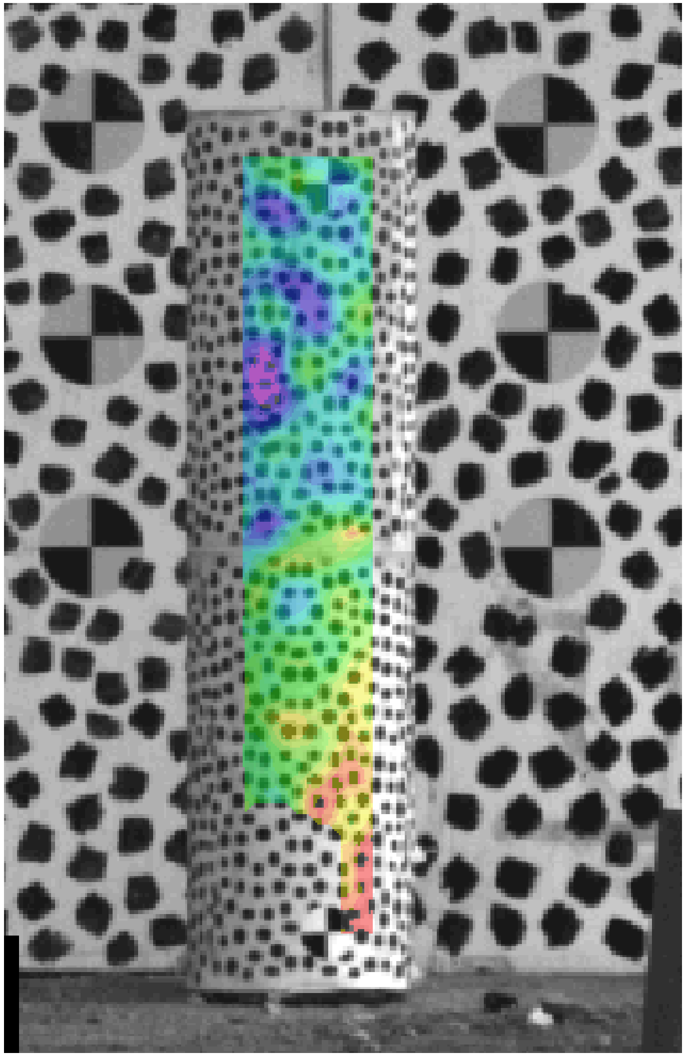


Watch these movies carefully





The noise floor gives you a some of the uncertainty parameters.



Standard Deviation

U [mm]	V [mm]	W [mm]	Matching [pix]
0.038	0.035	0.249	0.005

Absolute Maximum

U [mm]	V [mm]	W [mm]	Matching [pix]
0.52	1.38	2.82	0.01

Included
- Matching quality
- Pattern quality

Some portion of
- Calibration quality

Can be added with extended noise floor
- Lens distortions
- Camera motion

Estimated Uncertainty of 3D Position

Estimated Uncertainty of 3D Position

Sandia National Laboratories

Estimates for a ~100-mm field-of-view

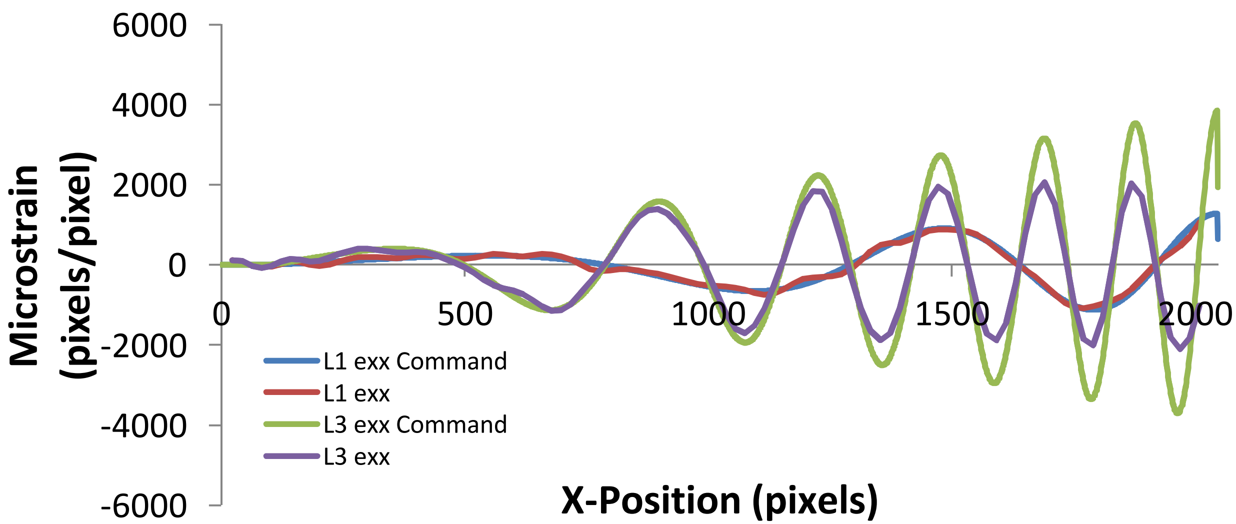
3D Error	Position Error (mm)	Notes
Calibration Errors		
Number of images	0.01	> 25 Images at center
Calibration target quality	0.5 or better	Better than 1/10th pixel
Lens distortions	0.02	Depends on number of calibration images and lens quality.
Thermal Errors	0.01 ??	Depends on lens length and air column between sample and camera.
Matching Errors	0.01	Depends on where in image. Not additive with calibration error.
Subset size	0.2 ??	Depends on underlying shape and displacement field.
Camera Motion	0.15? (0.5 pixel motion)	Depends on magnitude and direction of camera motion
Strain Error	??	Depends on filtering and underlying strain field.

Displacement errors an order of magnitude less.

The DIC community needs, training, standardization and guidelines.

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

- Publication requirements to provide important DIC information.



- A real definition of spatial resolution is needed.

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

DIC Challenge

The DIC Challenge seeks to:

- 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.

- Phillip Reu – Chairman (US – FFT Shifting)
- Bertrand Wattrisse
- Evelyne Toussaint (EU – Data Analysis)
- Wei-Chung Wang (Asia)
- Laurent Robert (EU - TexGen)
- 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