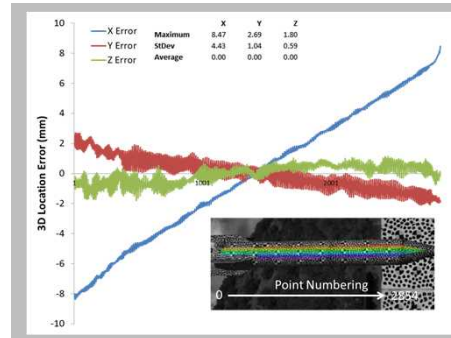
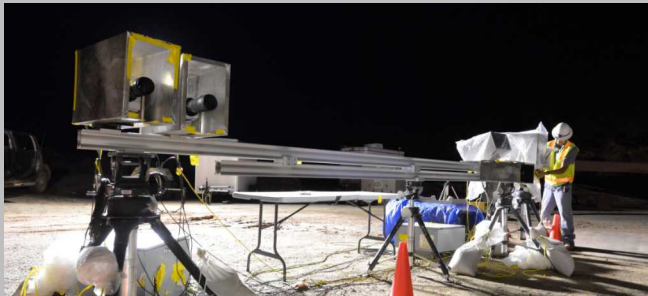


Exceptional service in the national interest

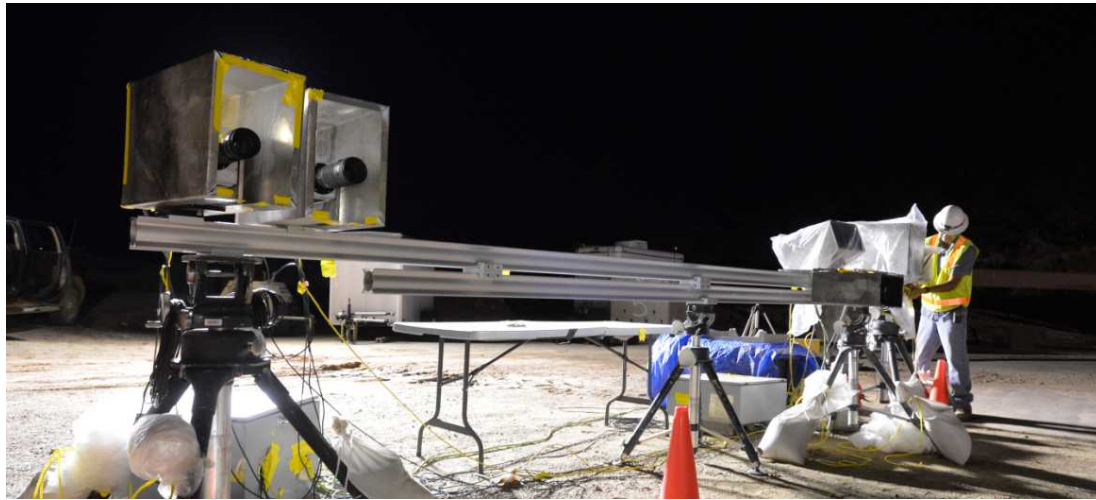


DIC Uncertainty Quantification for Large Scale Outdoor Testing

Phillip L. Reu, Timothy J. Miller

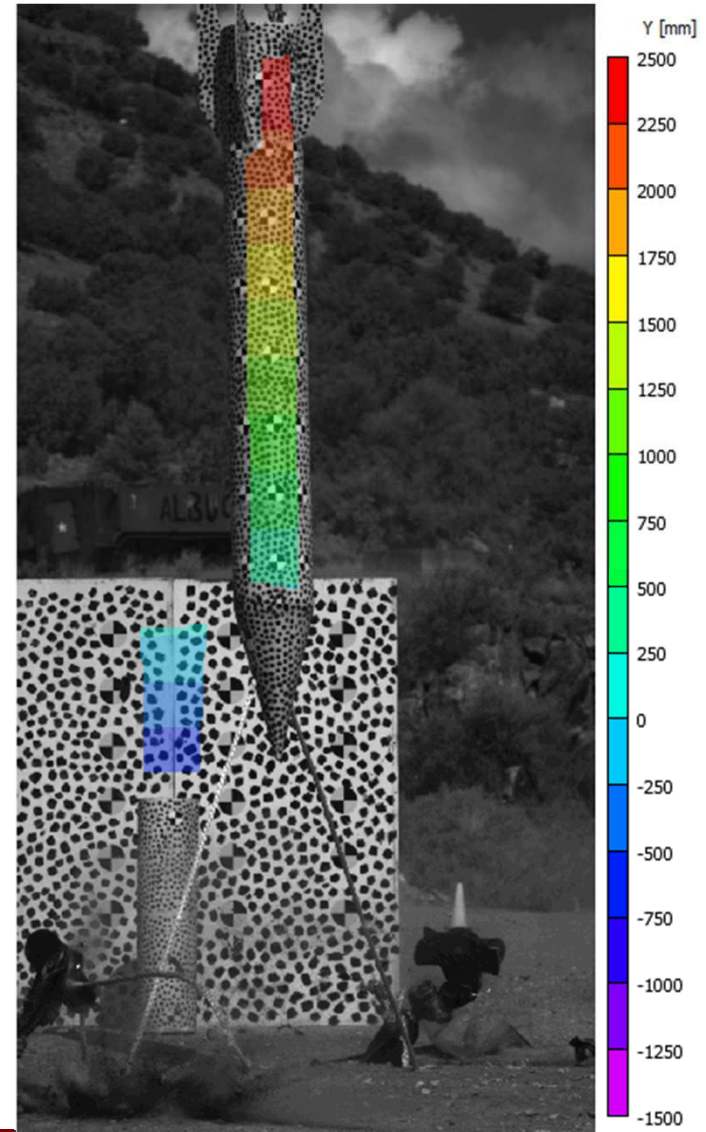
2014 SEM – Greenville, SC

3D-DIC has a complicated measurement chain from calibration to 3D-Position.

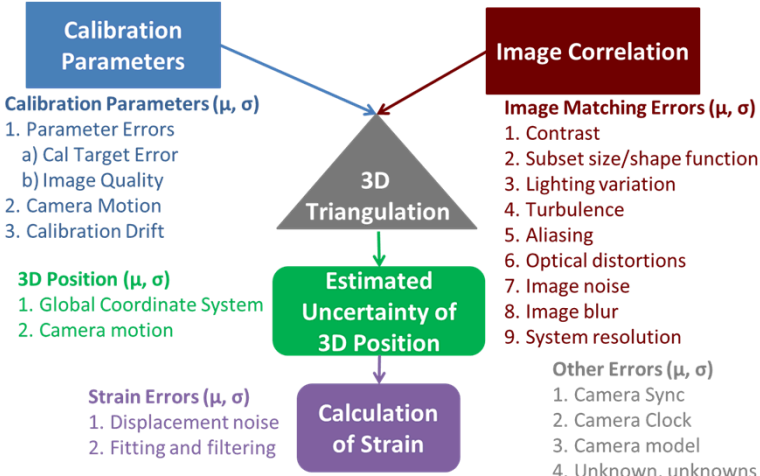


Goal: 1-mm resolution in 6 meters

- That is 0.02% error.
- 180 parts-per-million
- 0.25 pixel error (with the given setup)
- Can this be achieved?
- More importantly, can the actual error be quantified?

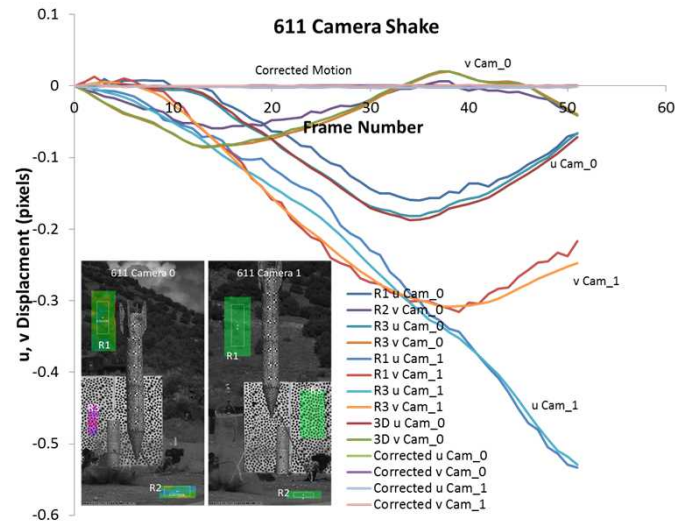


Tying all the errors together: Complete UQ approach

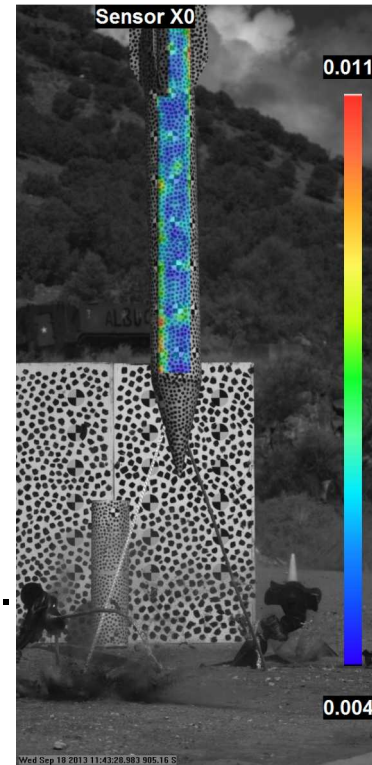


Understand the error sources

Calculate and propagate the errors



Gather other error sources.



Two types of errors: Random and Systematic



Accurate but not Precise

Large *Random* Error

Small *Systematic* Error



Precise but not Accurate

Small *Random* Error

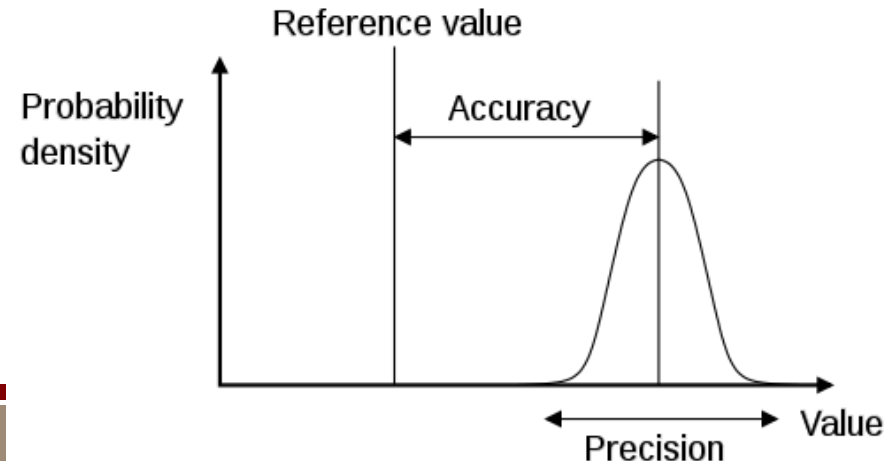
Large *Systematic* Error

Words used interchangeably

Bias = Systematic Error

Noise = Variance = Random Error

The new view is to categorize as Type A and Type B Errors



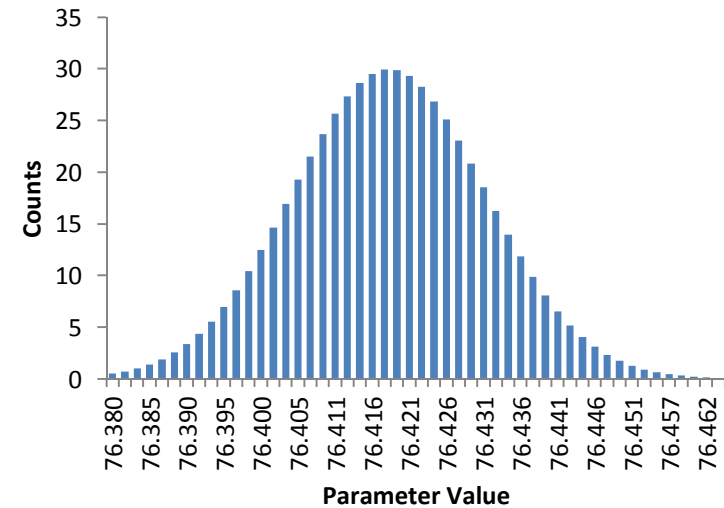
A newer approach categorizes errors into two types: Type A and Type B

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



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

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

Monte Carlo



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

Strain Errors

1. Displacement noise
2. Fitting and filtering

Matching Statistics



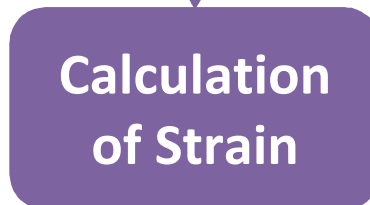
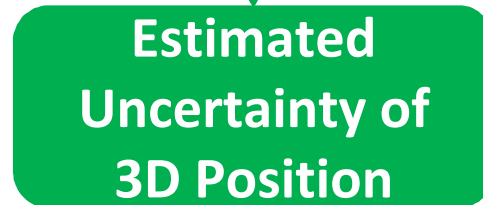
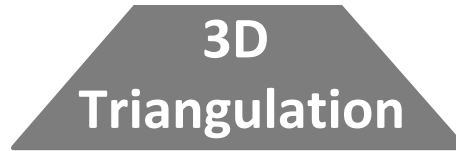
Image Matching Errors

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

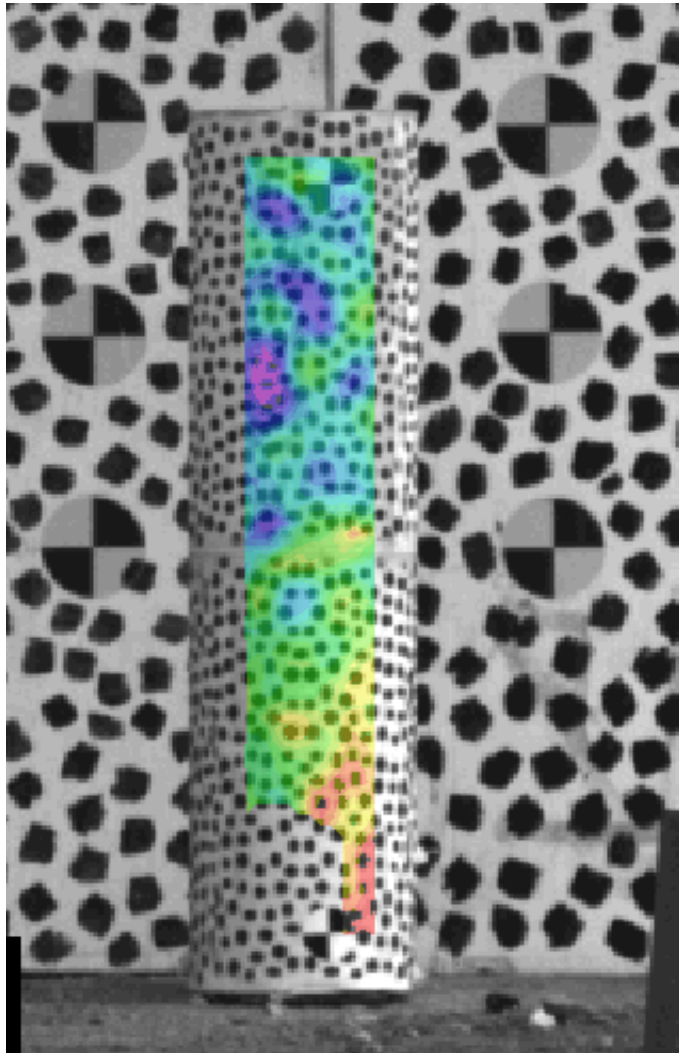
Other Errors

1. Camera Sync
2. Camera Clock
3. Camera model
4. Unknown, unknowns

Monte Carlo



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



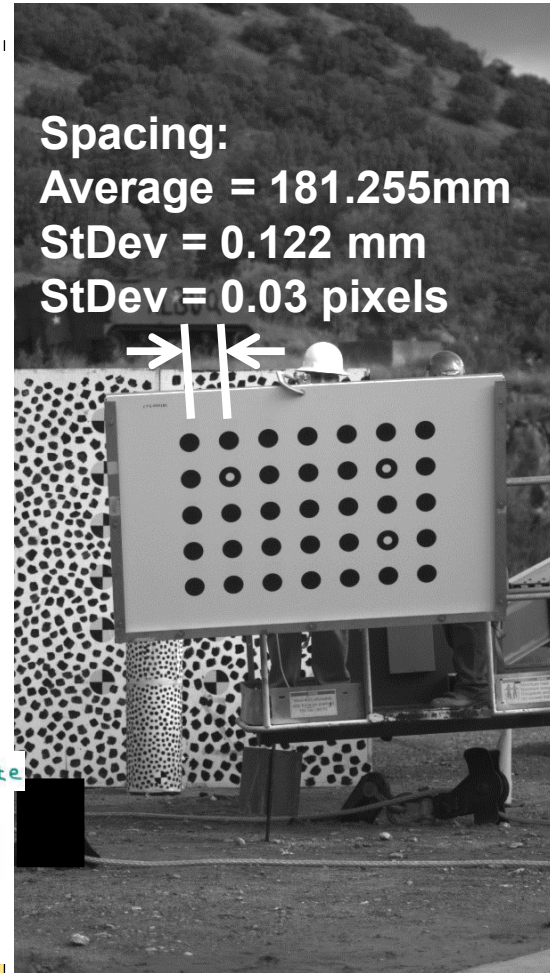
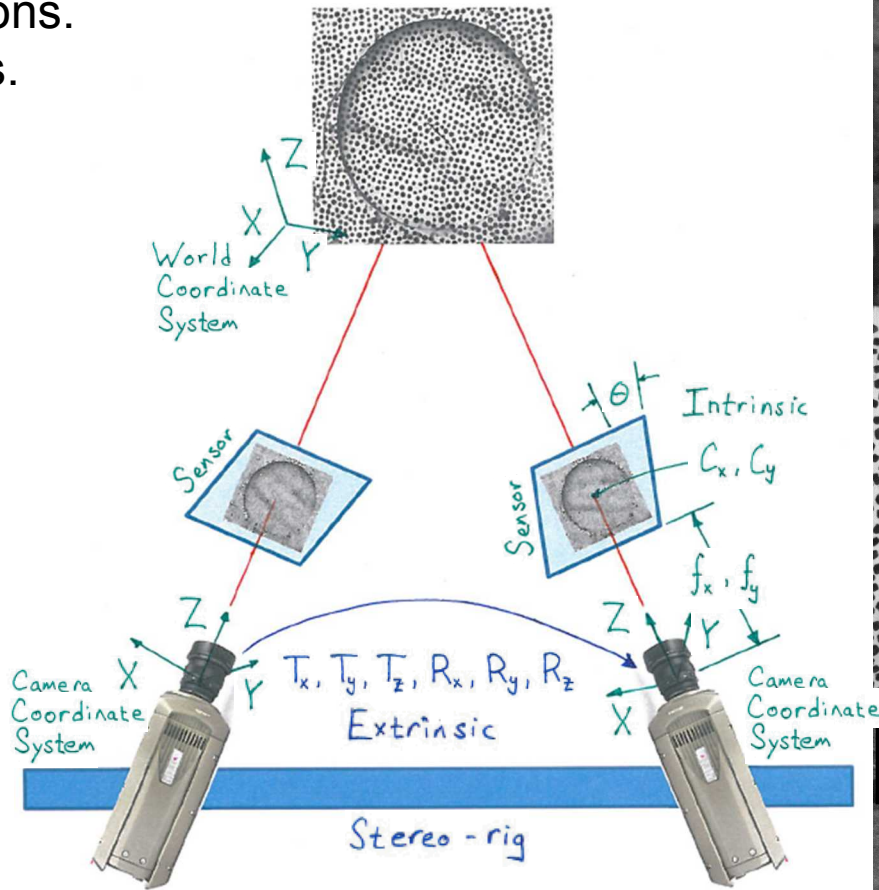
Estimated
Uncertainty of
3D Position

Übercalibration: Measuring the quality of the calibration.

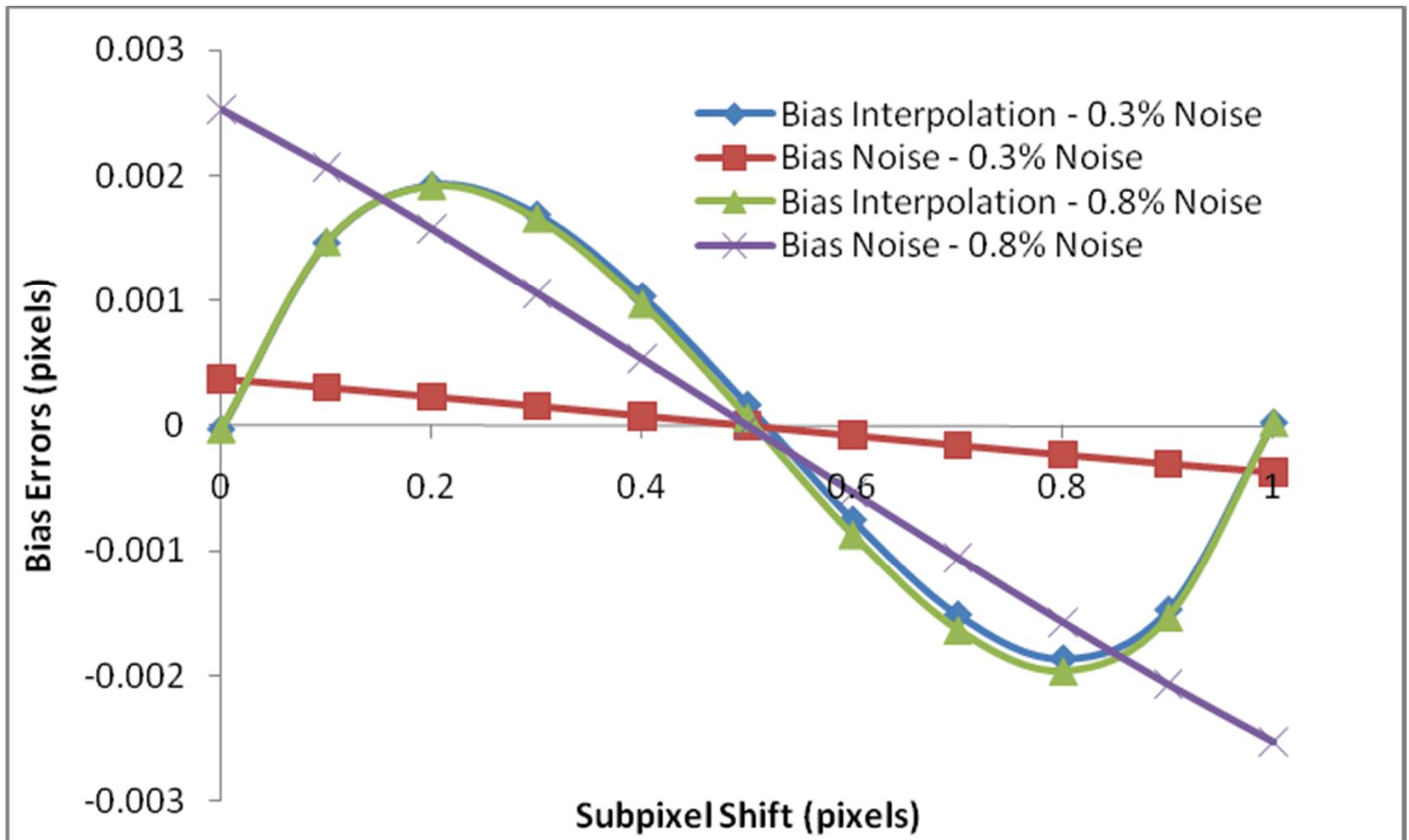
Monte Carlo Approach:

- Pick randomly from >1500 images.
- 150 Image calibrations.
- Save all parameters.

	Averages			Number of Calibrations
	Number of Images	Failed Images	Score	
611 181-mm Cal	150	6.00	0.04	1025

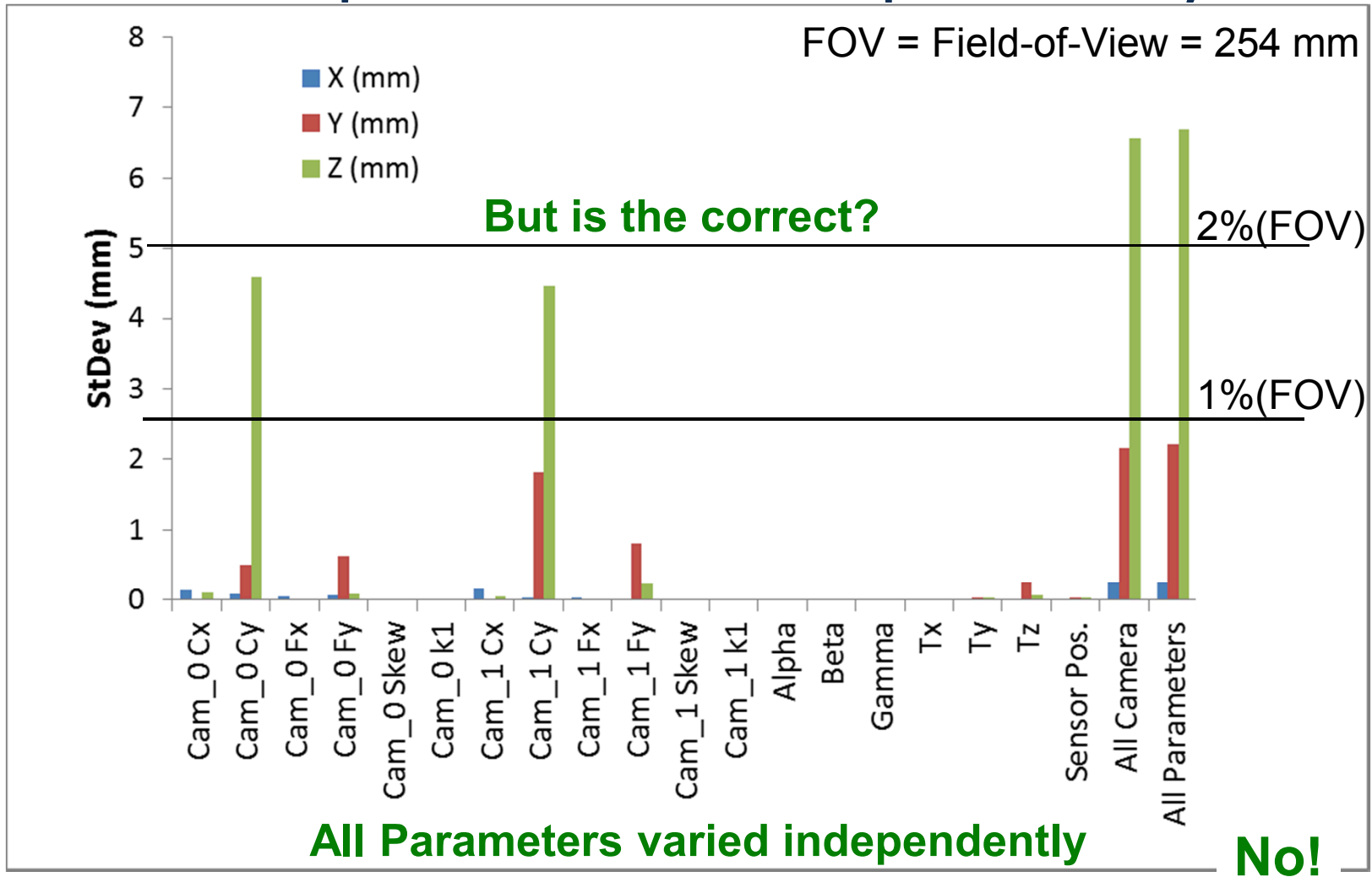


There are a large number of publications on assessing the 2D matching error.



Schreier, H. W. and M. A. Sutton (2002). Experimental Mechanics **42(3)**: 303-310.

The errors are propagated for all of the calibration parameters independently.



Calibration Parameters

Image Correlation

3D Triangulation

Estimated Uncertainty of 3D Position

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

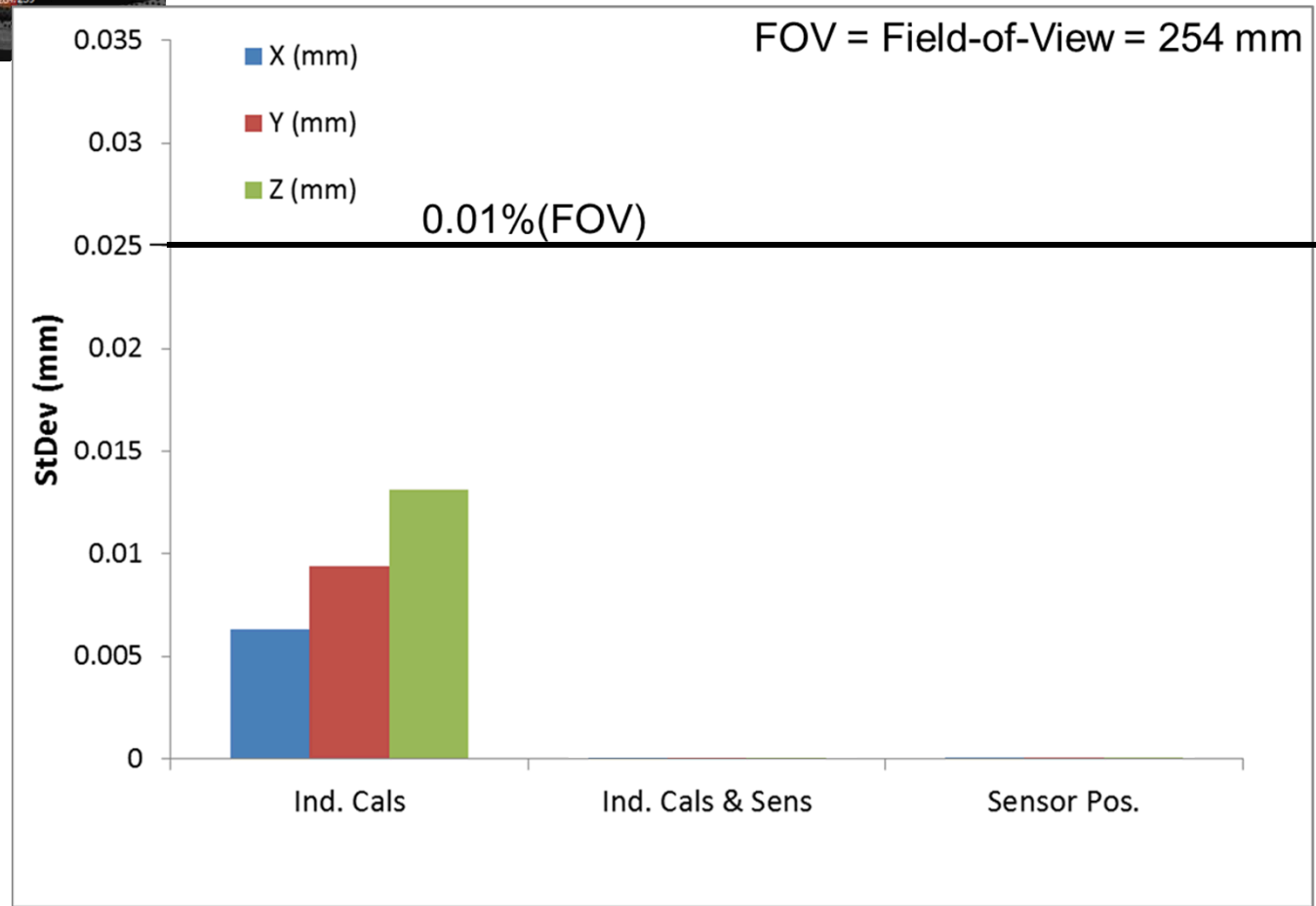
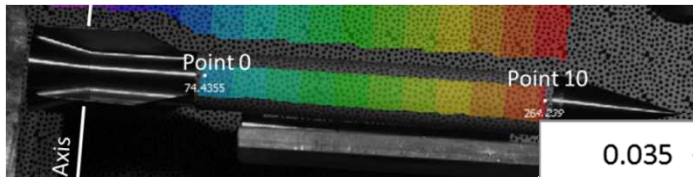


Image Correlation

Calibration parameters

3D Triangulation

Estimated Uncertainty of 3D Position

The sensor match contributes little to the position error.

Sensor Only

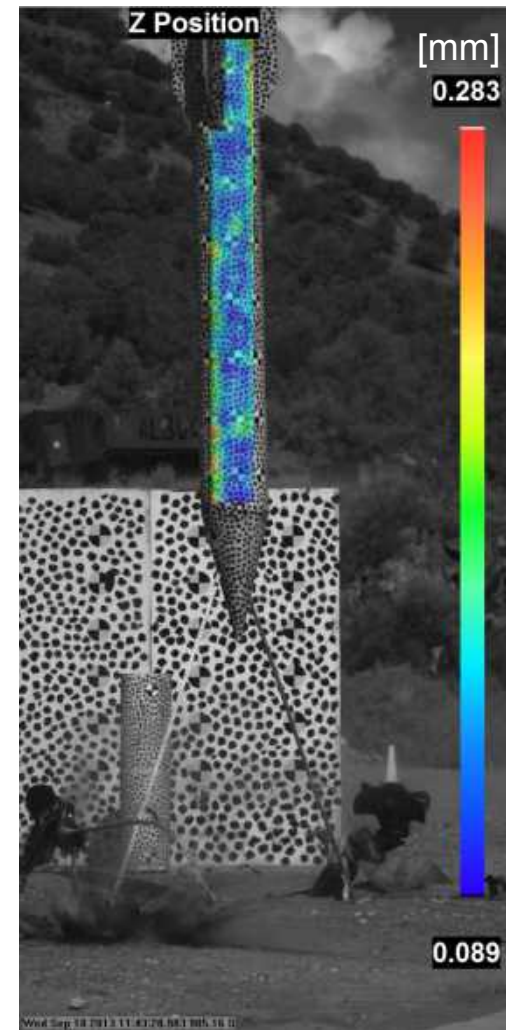
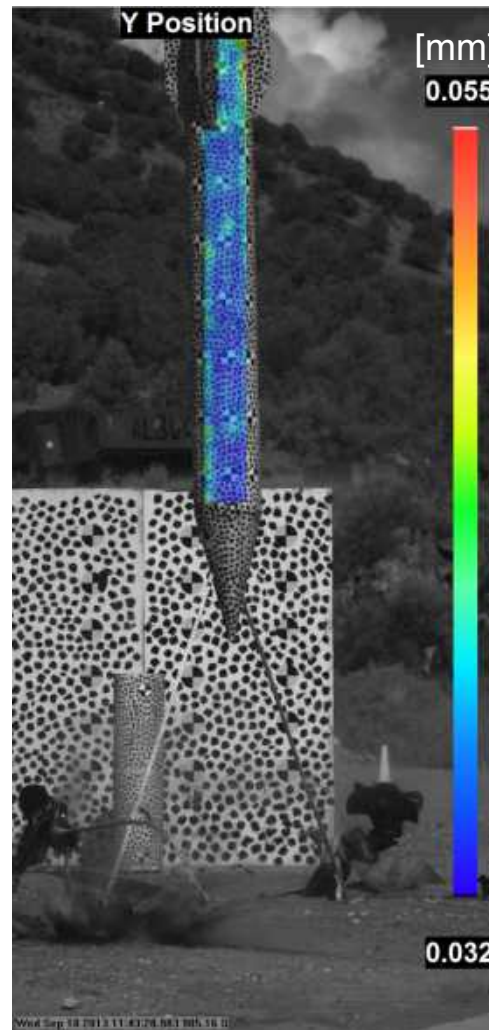
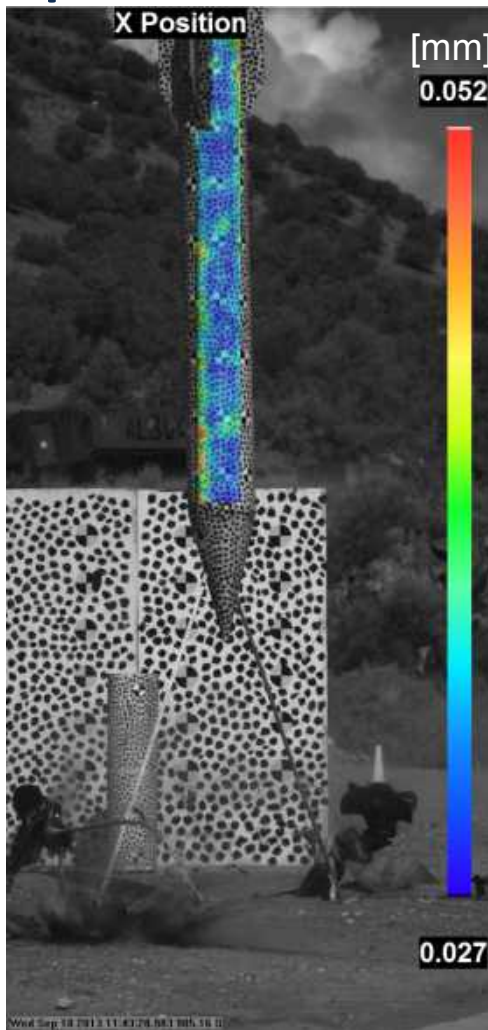


Image Correlation

3D Triangulation

Estimated Uncertainty of 3D Position

The largest source of 3D position error is due to our calibration.

Calibration and Sensor

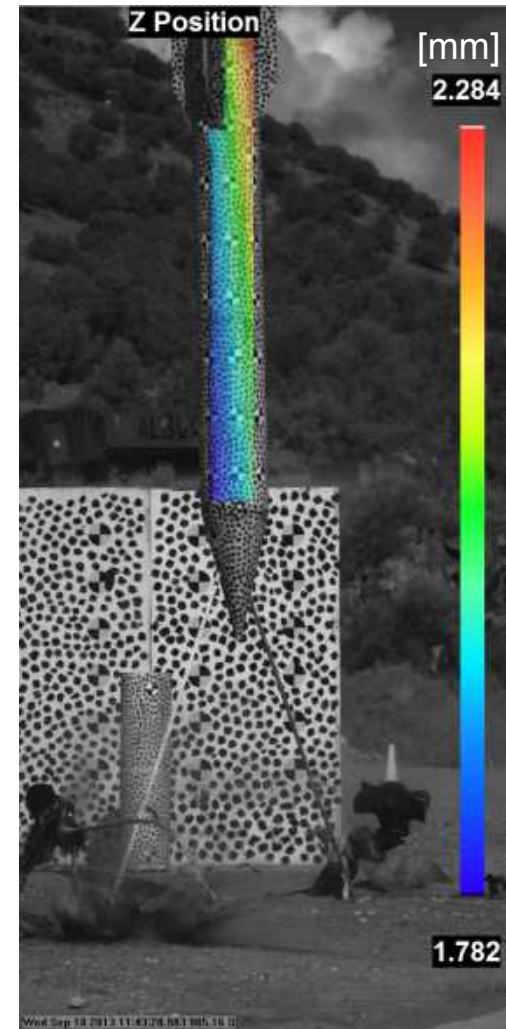
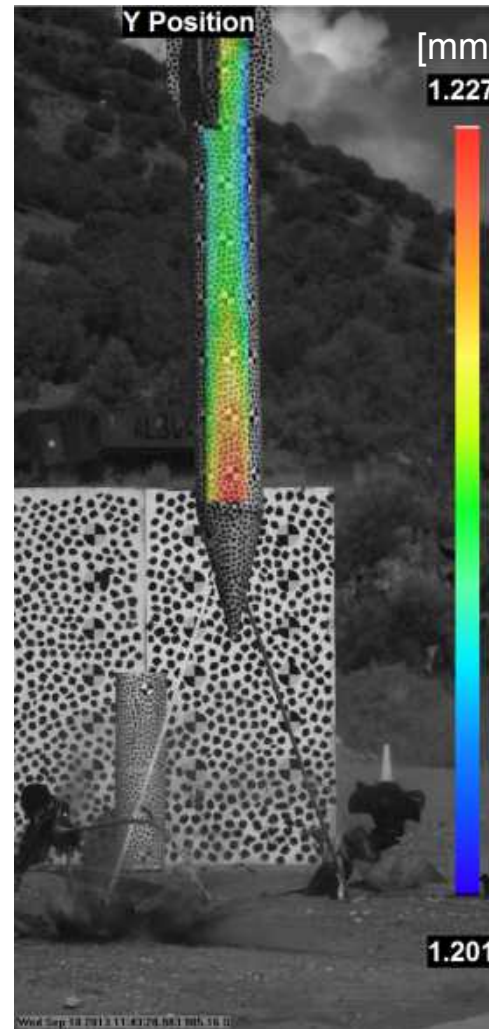
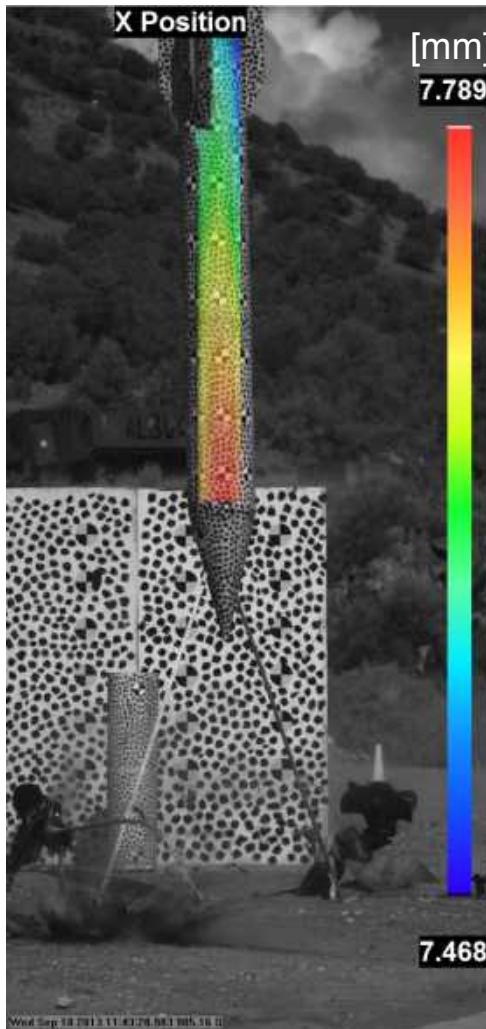


Image Correlation

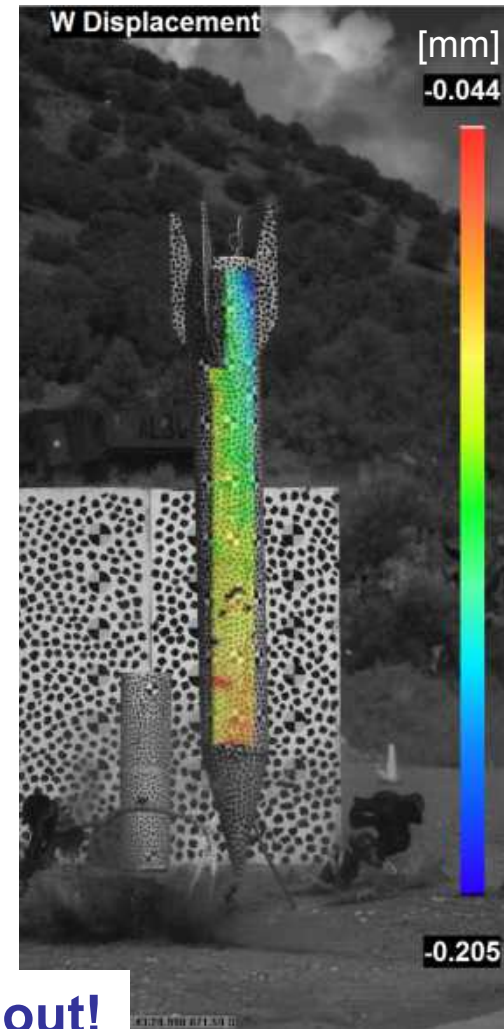
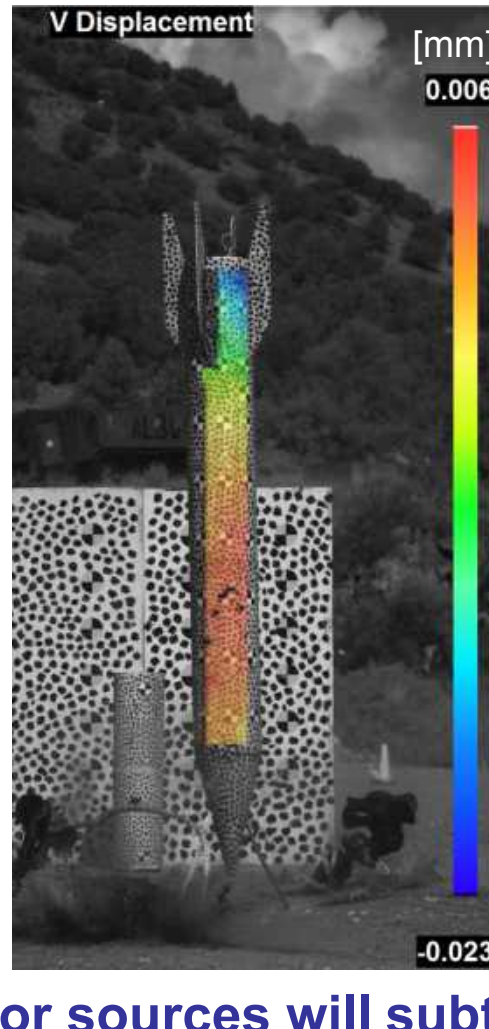
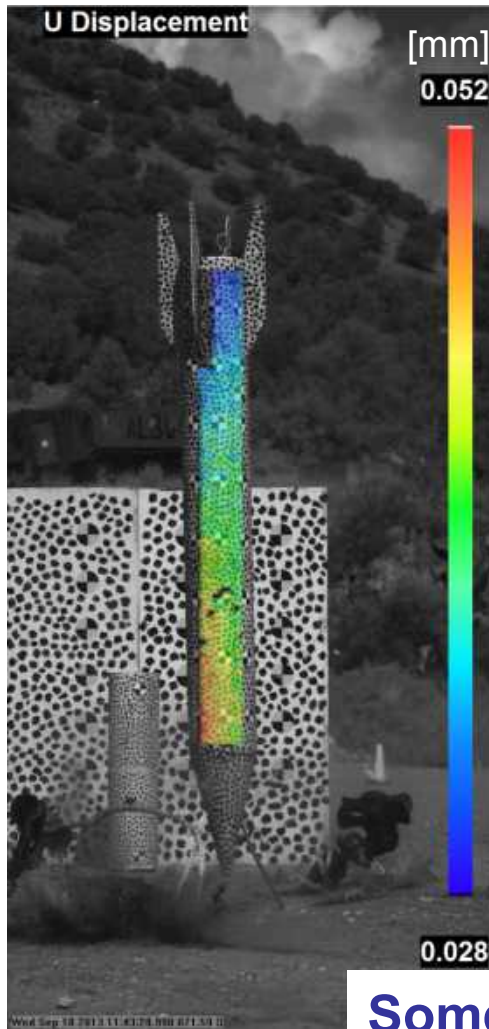
Calibration parameters

3D Triangulation

Estimated Uncertainty of 3D Position

Displacement is much less sensitive to calibration parameters.

Calibration and Sensor



Some error sources will subtract out!

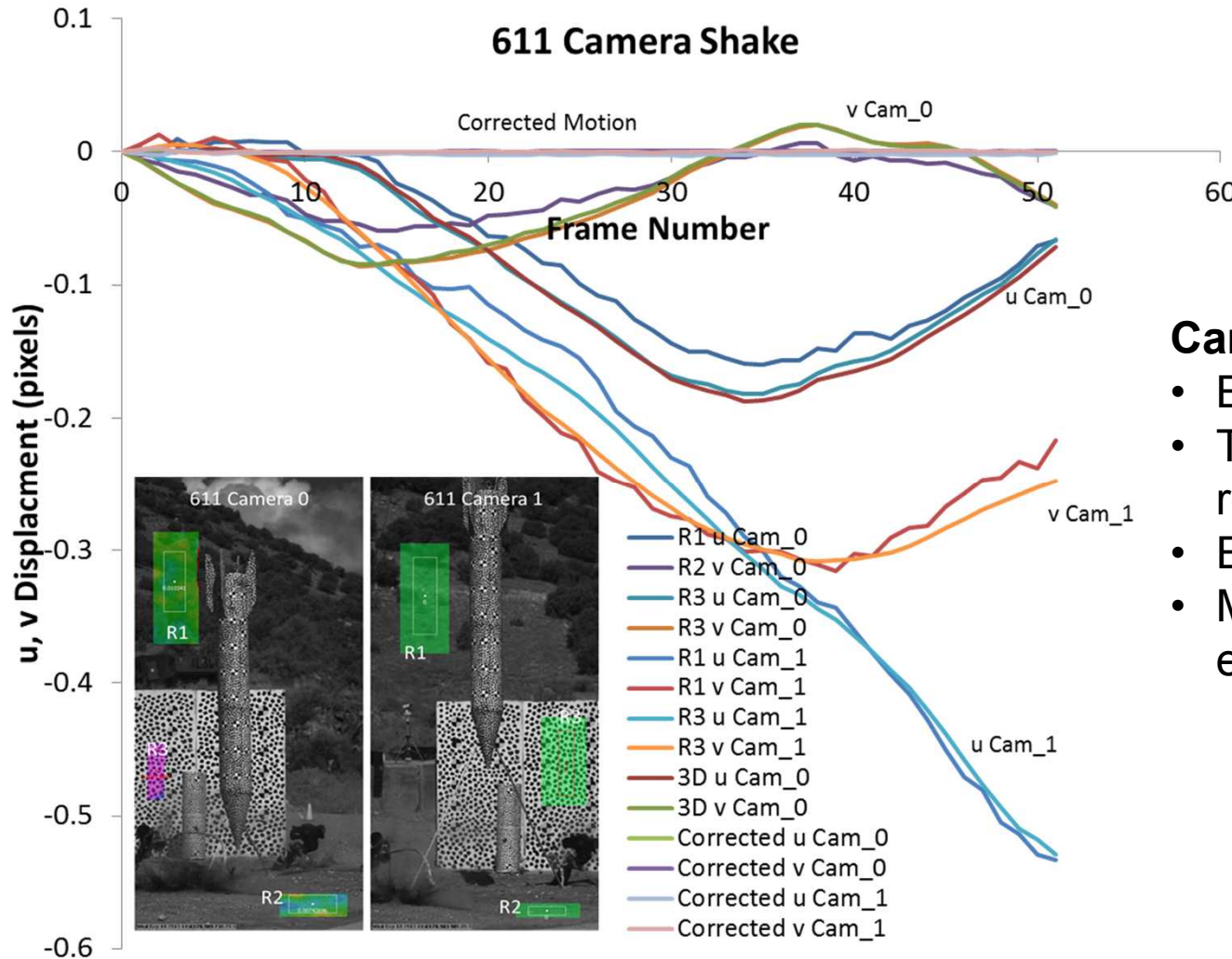
Image
Correlation

Calibration
parameters

3D
Triangulation

Estimated
Uncertainty of 3D
Position

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.

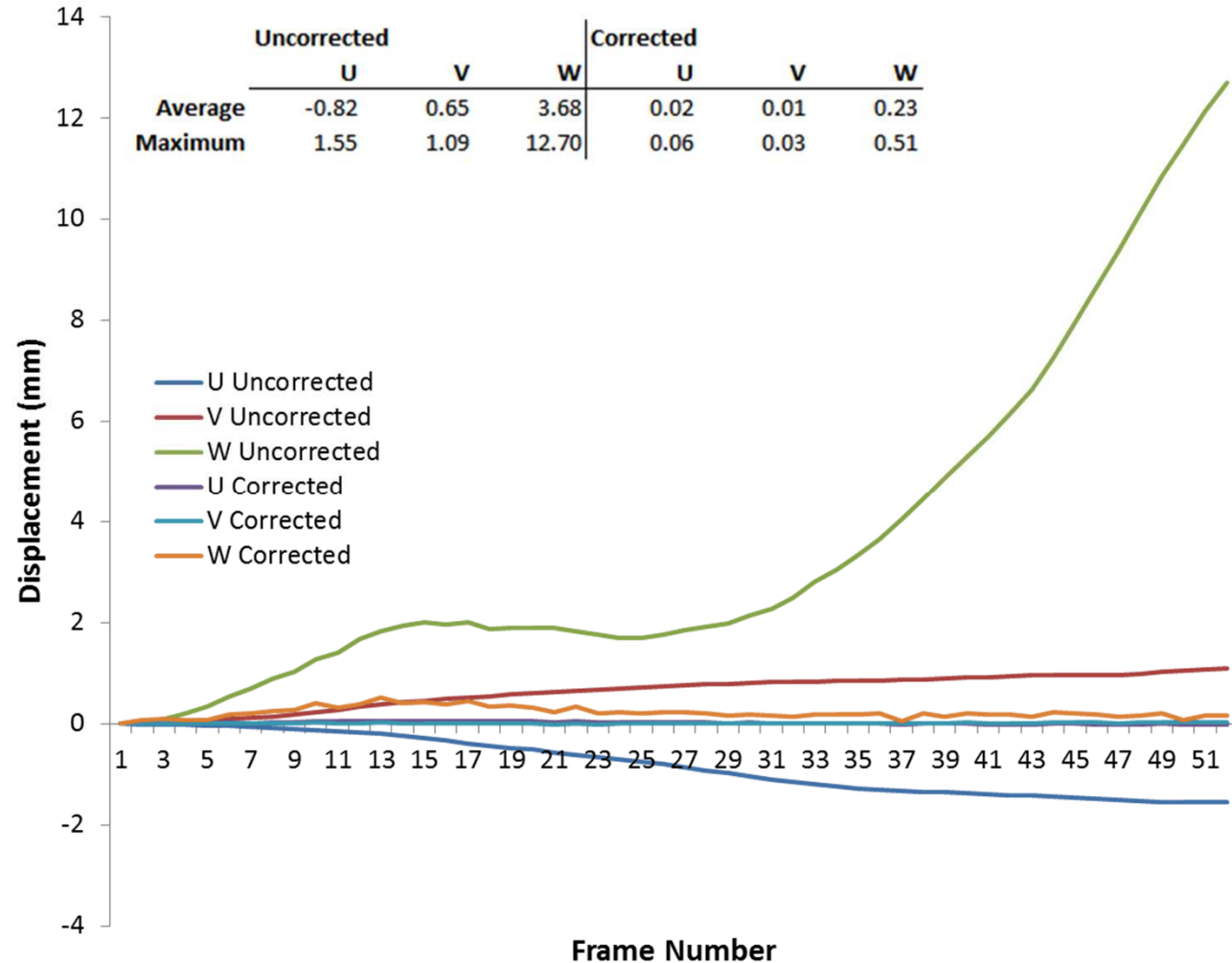
Camera shake can be corrected.

Type B
Camera Motion

The camera motion errors can be calculated in mm.

Camera Motion Notes:

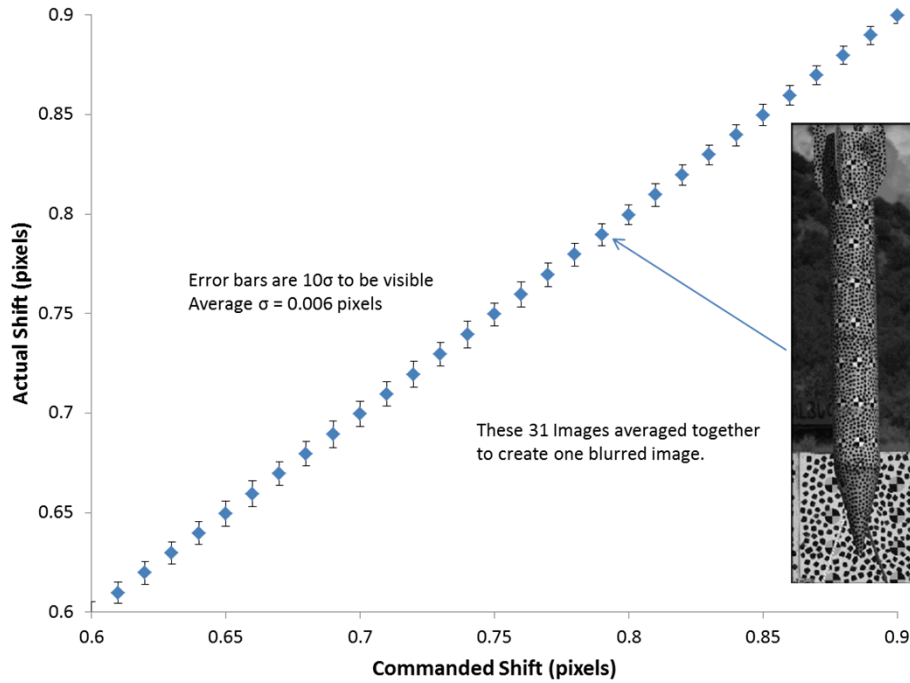
- Measured on the backboard (i.e. should have 0 displacement).
- Correction reduces the error to subpixel.
- This error will be an input for the Angle-of-attack calculation.
- This is in the backboard coordinates.



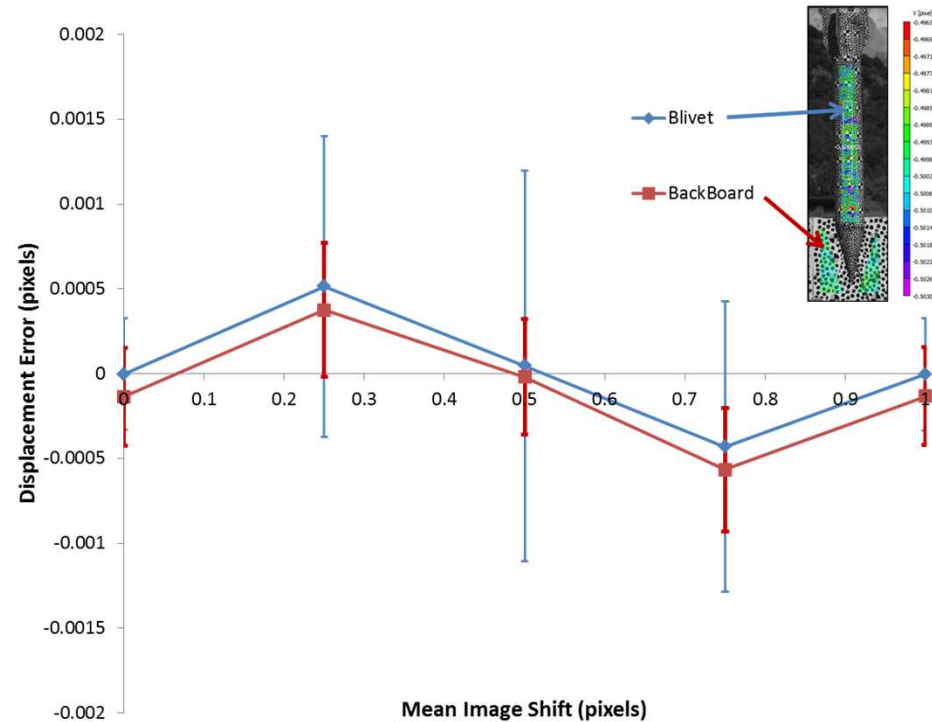
Type B
Camera Motion

Estimated
Uncertainty of 3D
Position

Blur is an unbiased filter in the phase space. It does not add any error.



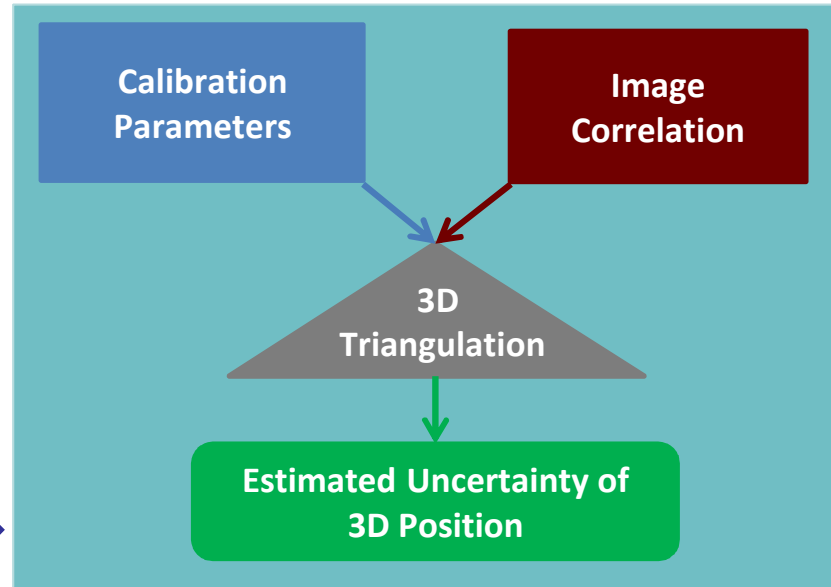
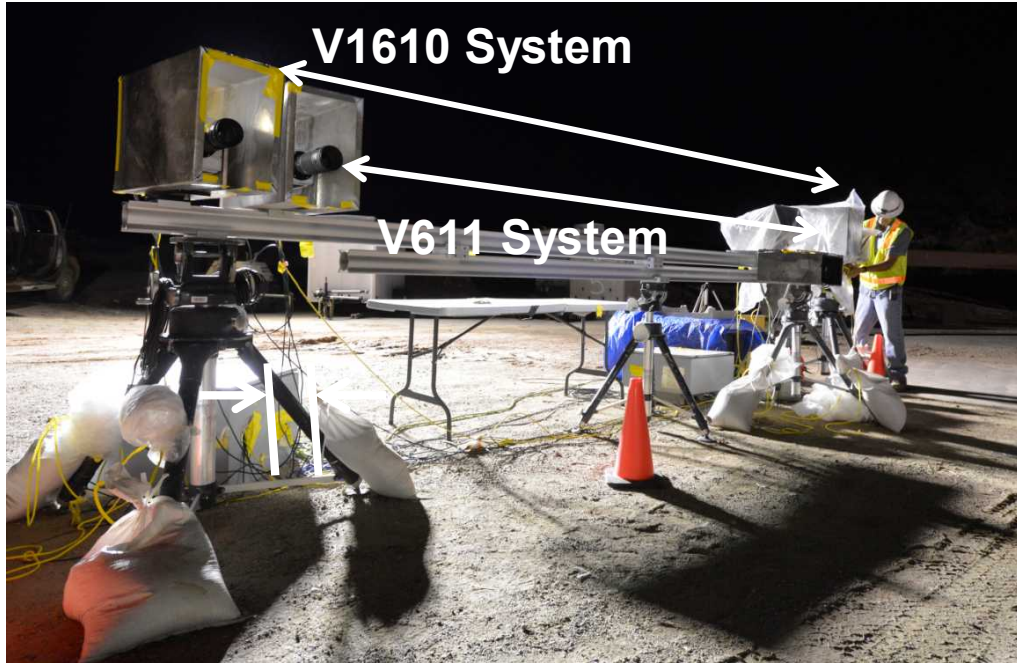
Used image shifting to create 31 images with a ± 0.15 shift. For a blur of 0.3 pixels.



This was done at 0, 0.25, 0.5, 0.75 and 1 pixel positions.

No bias error due to blur!

Multiple stereo-rigs and calibrations give us truly independent measurements.

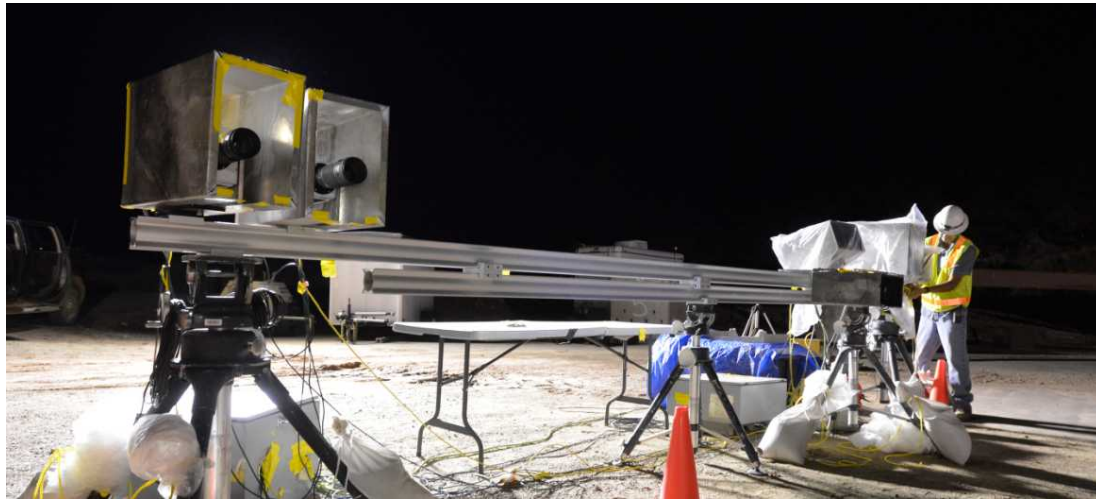


Possible stereo-rigs

1. V1610 – 181-mm & 184-mm Calibration
2. V611 – 181-mm & 184-mm Calibration
3. You could also combine one of each camera.

Bundle the Errors! 

Understanding the uncertainties of a DIC measurement is important for science.

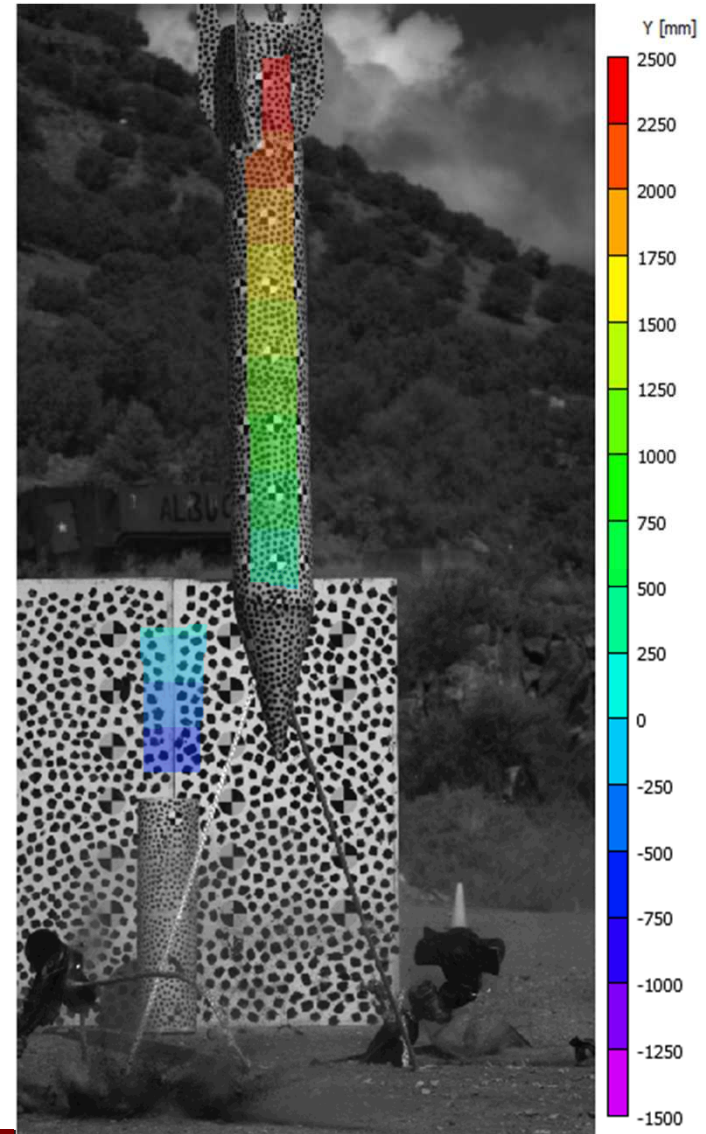


Goal: 1-mm resolution in 6 meters

Achieved: 7.5-mm in 6 meters

- 0.125% Field-of-View
- 1.9 pixel error.

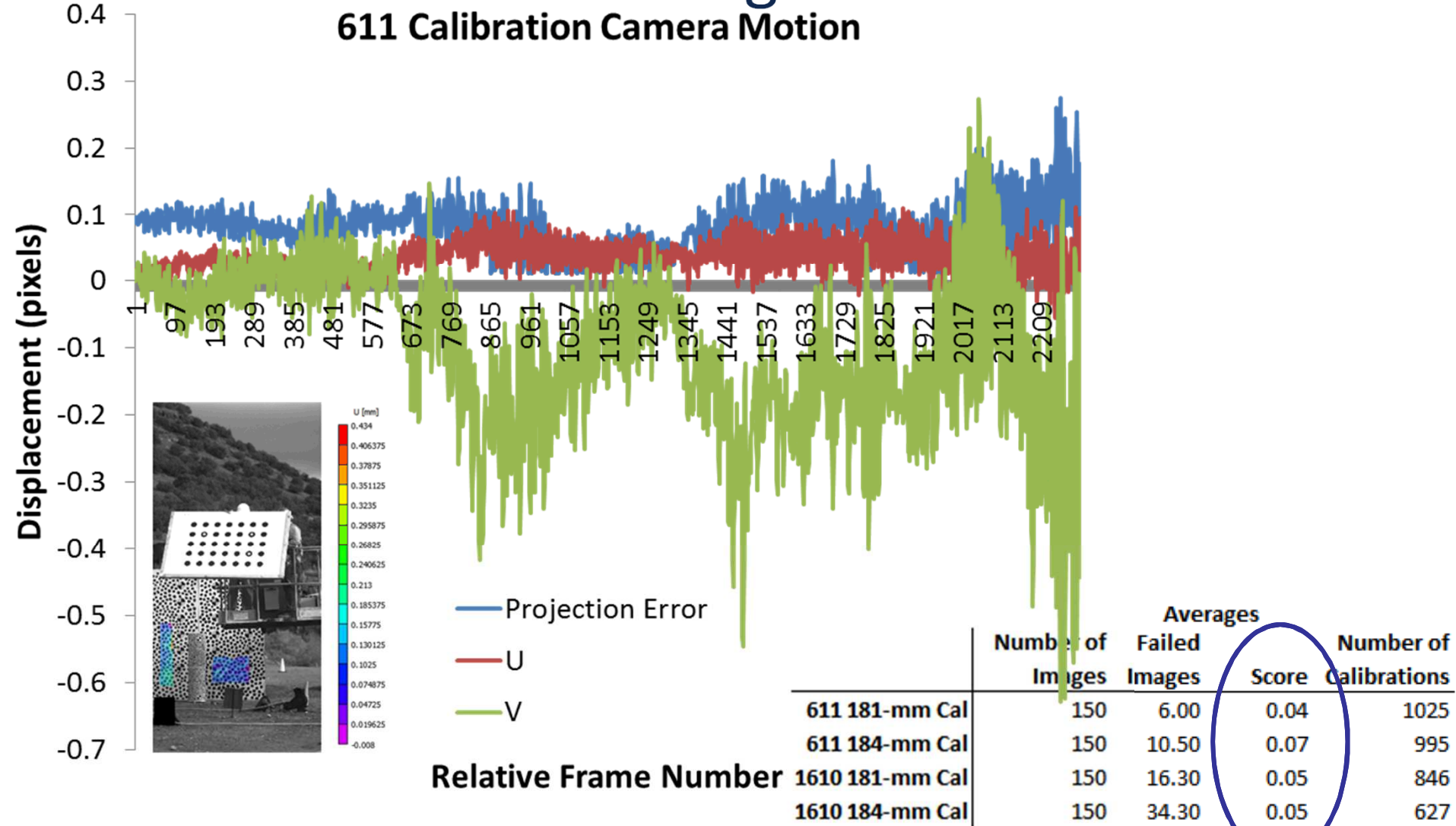
Most Importantly: I understood my uncertainties!



Bonus Slides!

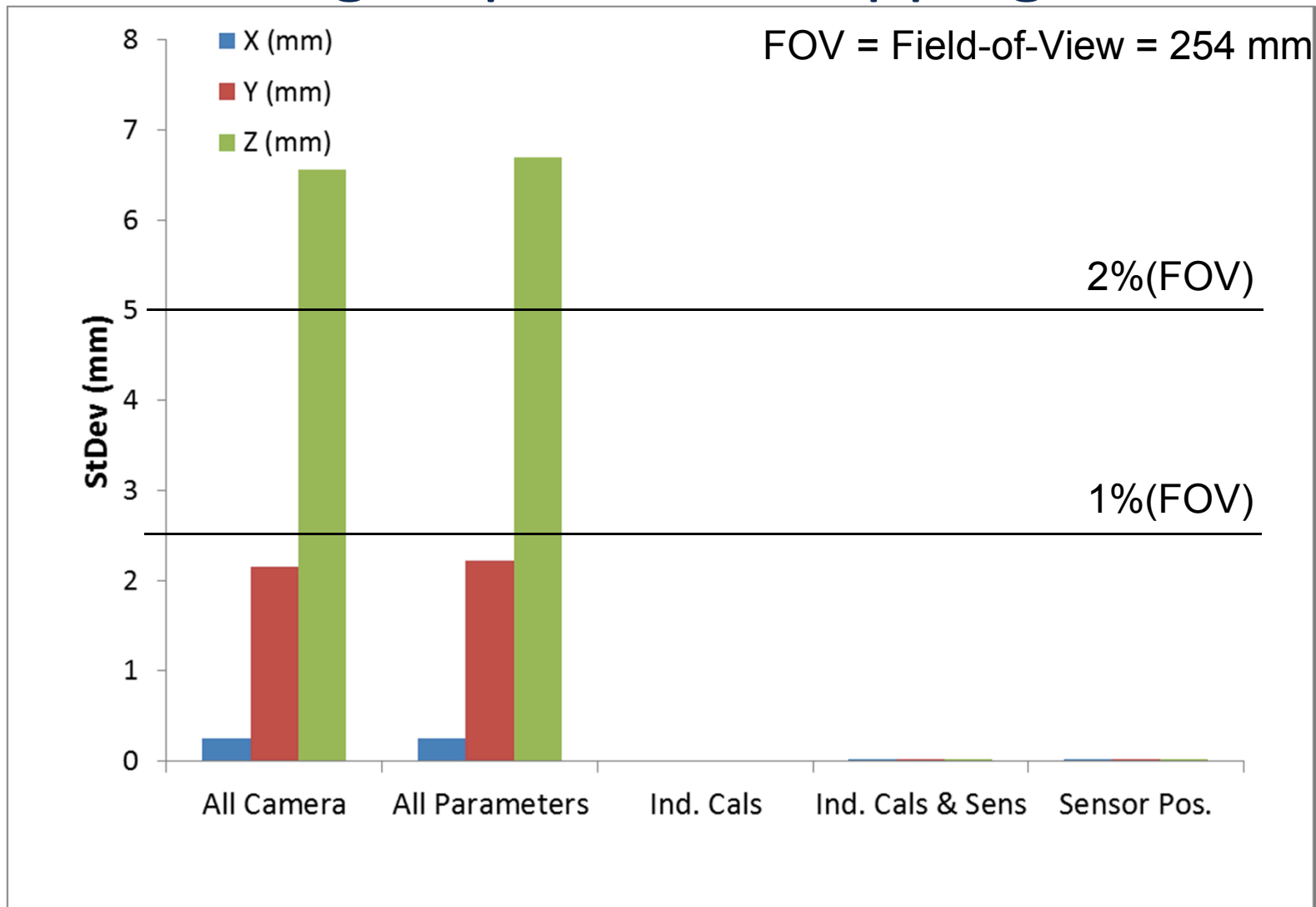
Our calibration scores were low because of camera motion during calibration.

611 Calibration Camera Motion



Rigid camera mounting is important!

The camera parameters co-vary and must be used as a group. Boot Strapping!



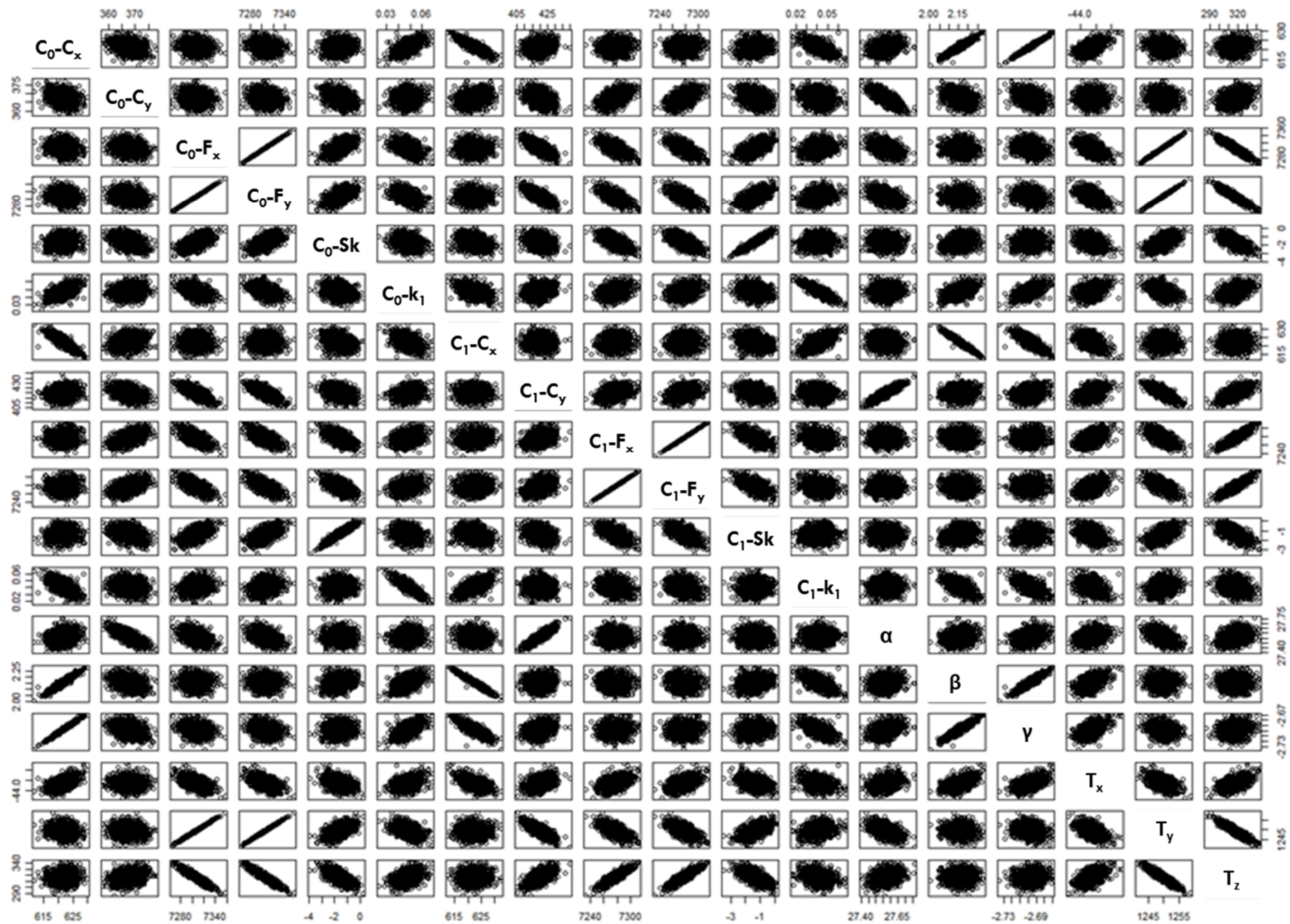
Calibration Parameters

Image Correlation

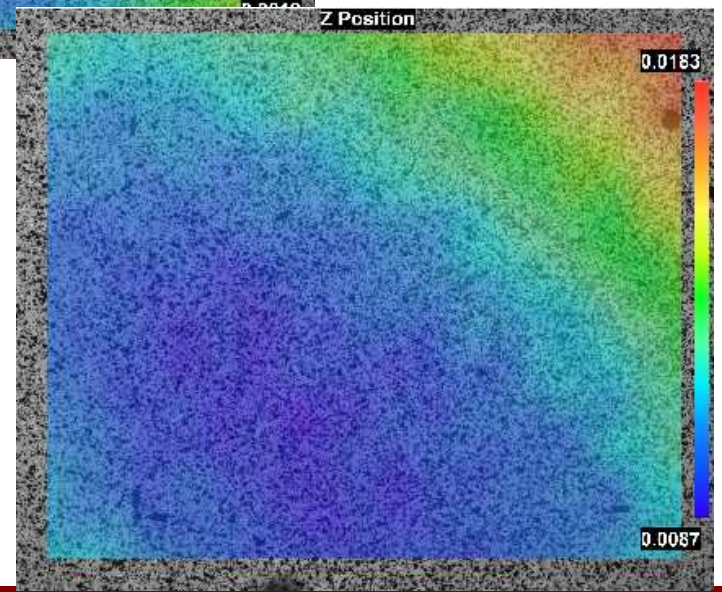
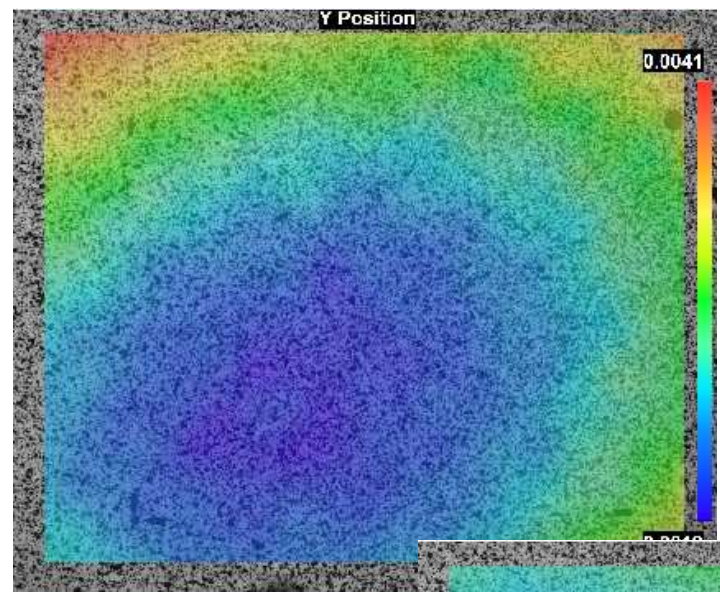
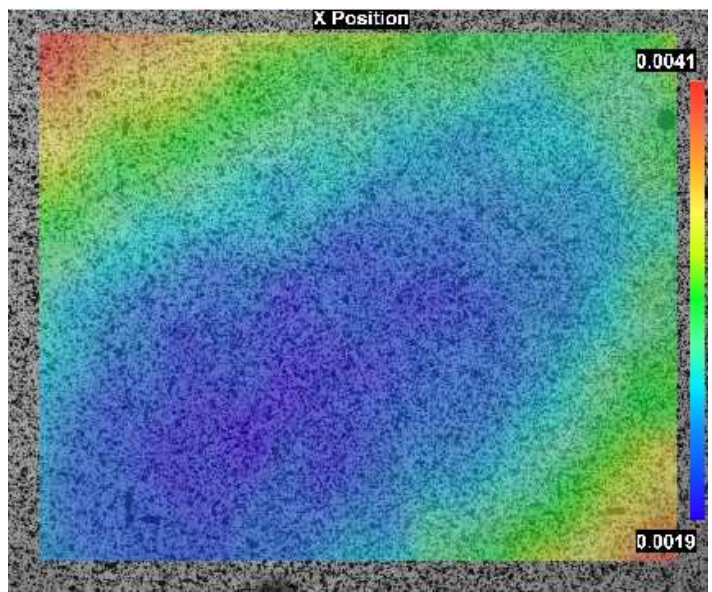
3D
Triangulation

Estimated Uncertainty
of 3D Position

Small 100, n = 1344



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



The calibration scale can be checked by measuring between two fiducials.

Known Distance = 1826.47 mm	Distance (mm)	Difference (mm)	Difference (pixels)	% Error
611 181-mm Cal	1829.71	3.24	0.81	0.18%
611 181-mm Cal Reorient	1826.44	-0.03	-0.01	0.00%
611 184-mm Cal	1829.82	3.35	0.84	0.18%
611 184-mm Cal Reorient	1826.14	-0.33	-0.08	-0.02%
1610 181-mm Cal	1828.84	2.37	0.59	0.13%
1610 181-mm Cal Reorient	1826.27	-0.20	-0.05	-0.01%
1610 184-mm Cal	1827.37	0.90	0.22	0.05%
1610 184-mm Cal Reorient	1826.87	0.40	0.10	0.02%

All of these are equally good. This is only as good as the fiducial measurement of $1/10^{\text{th}}$ of a pixel ($\pm 0.4\text{mm} \times 2$). Corrected *appear* lower because it was calculate at that sub-pixel location.

