Exceptional service in the national interest

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iDICs INTERNATIONAL DIGITAL IMAGE CORRELATION SOCIETY

The story of DIC Uncertainty Quantification, thus far…

Layer up on layer of complication that makes you want to cry

Phillip L. Reu

London 2017

U.S. DEPARTMENT OF ENERGY   NNSA National Nuclear Security Administration

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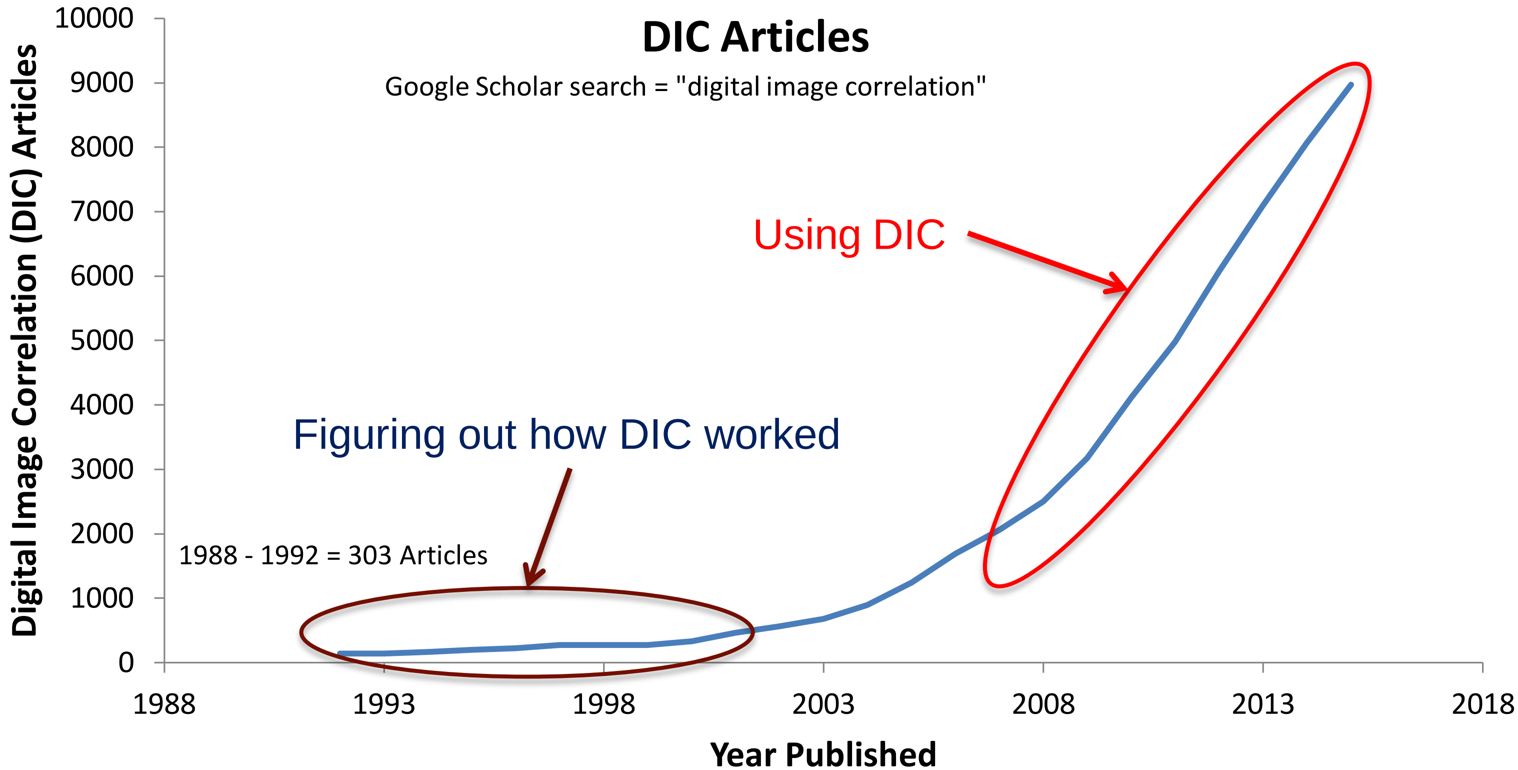
DIC has changed the way we do experimental mechanics.



Digital Image Correlation publishing.xlsx (OneNote)

"DIC Uncertainty" Quantification Publications

- Almost no publications before 2005
- 2005 to 2017 there are 30 publications
- I started pushing the issue for the 2009 SEM in Albuquerque where we had the first session.

Digital Image Correlation – Phil and Sandia

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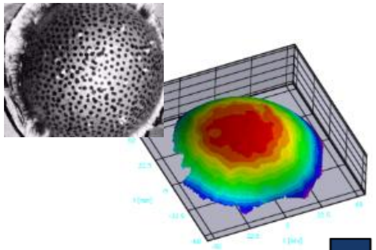
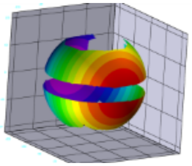
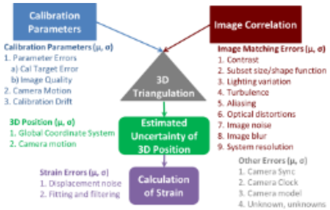
Displacement, velocity and strain



360º coverage

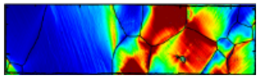


Stereo-DIC Uncertainty Quantification
From colors to metrology.



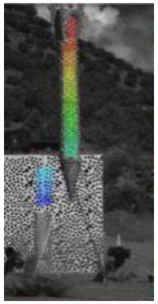
DIC for Material Properties
- Quantified Uncertainty
- More parameters per test
- Parameter interaction
- High-throughput
- Model validation

Grain Scale strain

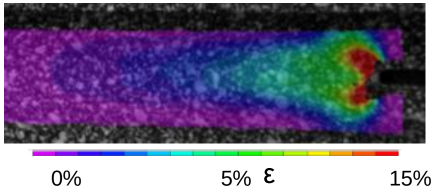


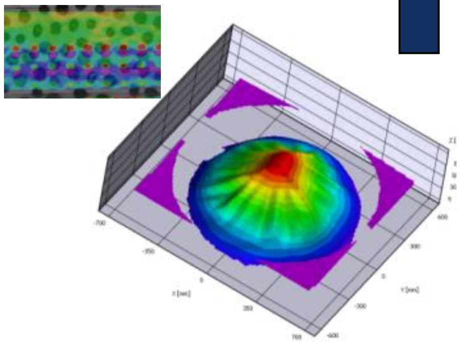
2005 2007 2009 2011 2013 2015

Introduction of DIC to Sandia

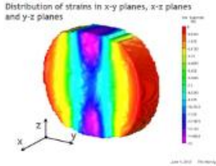


Crack-tip and Fracture Strain





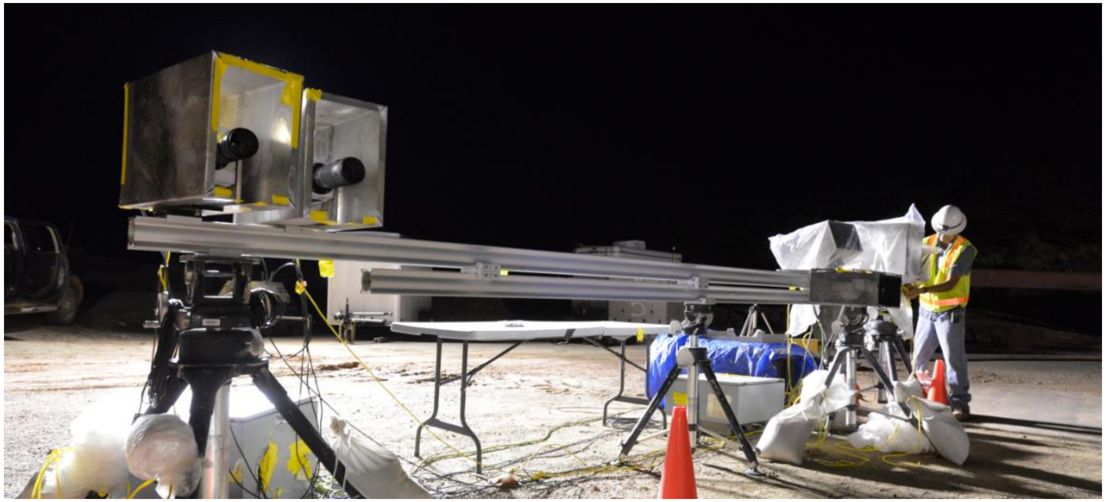
Explosive Panel Deformation

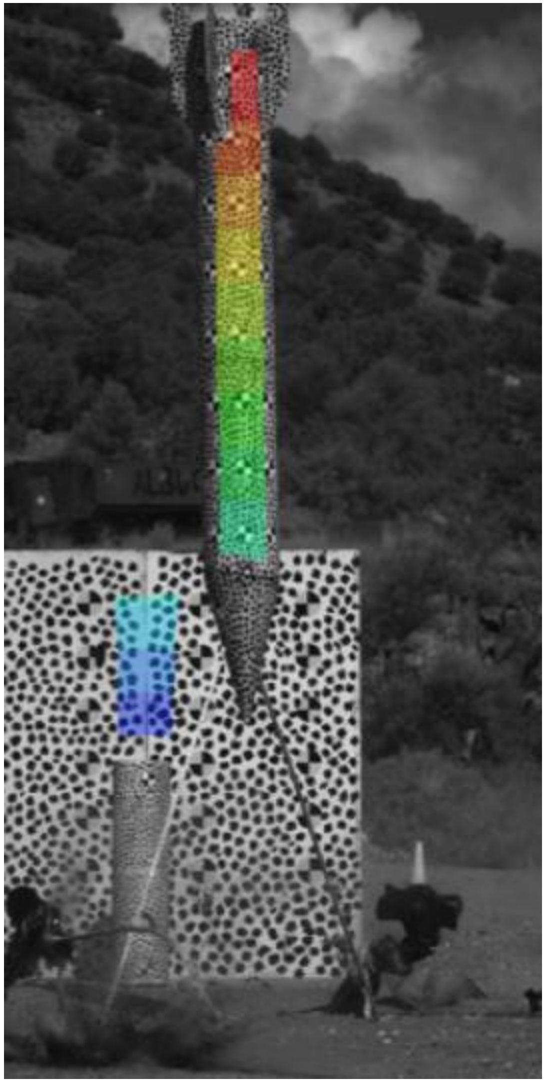


Volumetric DIC

Sandia's growing use of quantitative image based measurements.

Sandia required "NIST traceable" measurements with UQ





- Complicated experimental setup and environments
- Understand the error sources (bottom-up)
- Must quantify uncertainty
  - 0.125% Field-of-View (or full-range)
  - 1.9 pixel error

Reu, P.L., *Experimental Mechanics, 2013.* ***53(9): p. 1661-1680.***

There is an important difference between the definition of "error" and "uncertainty".

Error

- Difference between the measured value and the "true" value (often unknown).
- Sometimes described as bias (persistent) and random (volatile).

Uncertainty[†]

- "Is the doubt that exists about the result of any measurement".
- Determined using standard methods: Type A and Type B.
- Expressed using an interval, standard uncertainty, and a confidence level.
- Standard uncertainty (*u*) is the standard deviation (*s*) divided by square root of number of samples (*N*).
- Traceability is assumed.

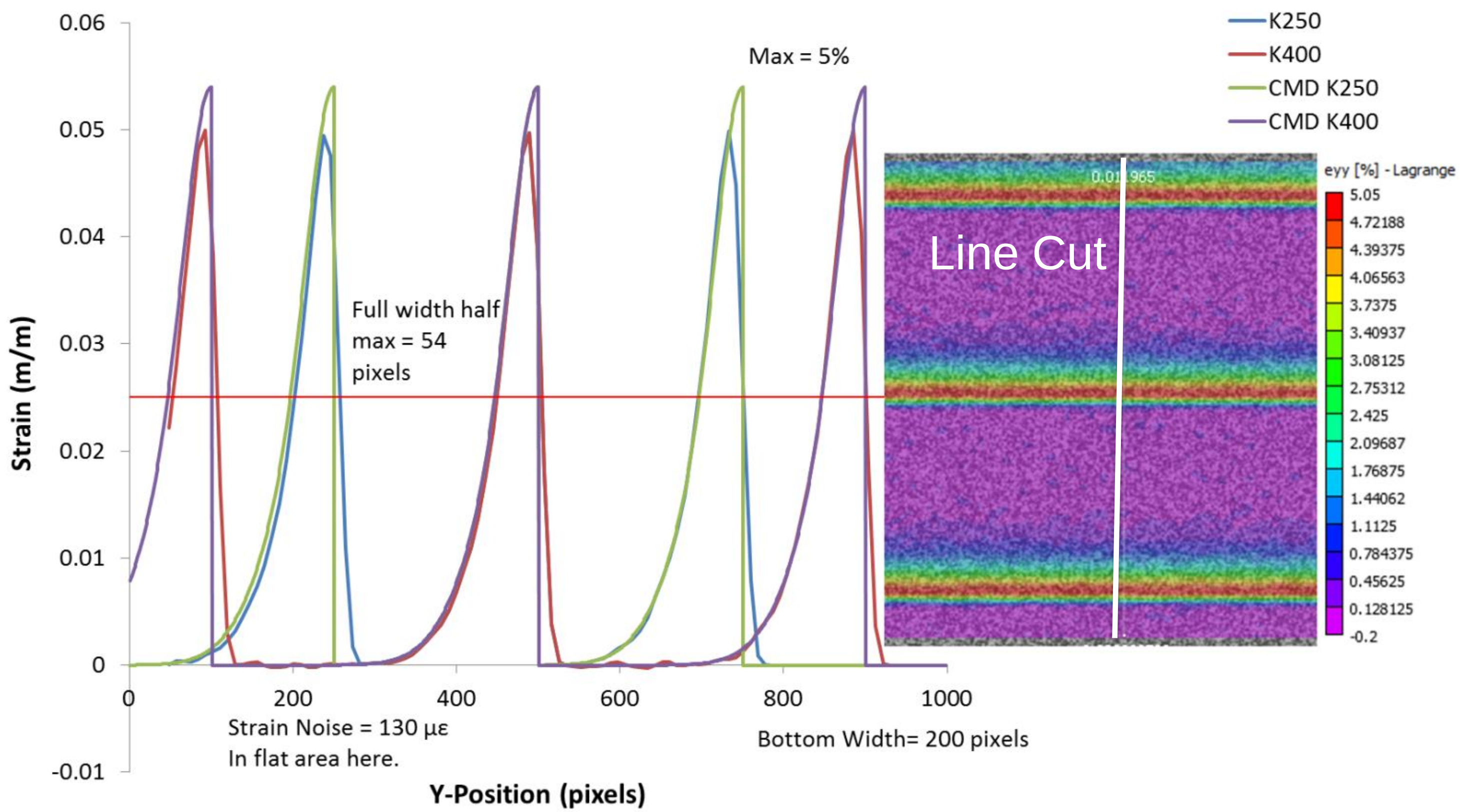
$$u = \frac{s}{\sqrt{N}}$$

A measurement to be useful must have an associated uncertainty!

[†]**Bell, S.** (1999). A beginner's guide to uncertainty of measurement. N. P. Laboratory. UK.

Error: Difference between a known and measured value.

Simulated or synthetic images provide a "known" displacement field



Advantages/Problems with simulated or synthetic images

- You know the answer
- Verifies the DIC code
- Investigates numerical issues
- Errors in synthetic image creation.
- **What errors have I missed?**

DIC UQ literature is very thin, particularly for stereo-DIC.

Verification

- Are we solving the equations correctly (optical flow)?
- Do we converge to the correct answer?
- Is the software written correctly?
- Comparison with **synthetic** images.

90% of the published papers (and nearly all 2D!)

Validation

- Are the measurements an accurate representation of the real world?
- Comparisons with a 2nd measurement.
- Credibility and uncertainty quantification.

Small number of comparison papers

A simulation approach may be useful in quantifying errors.

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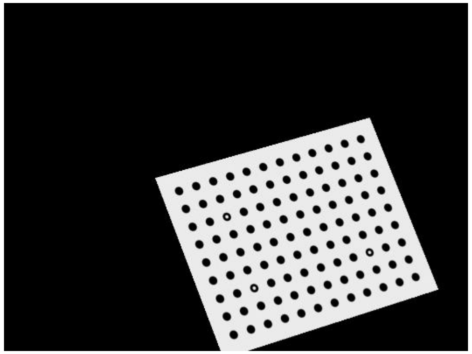
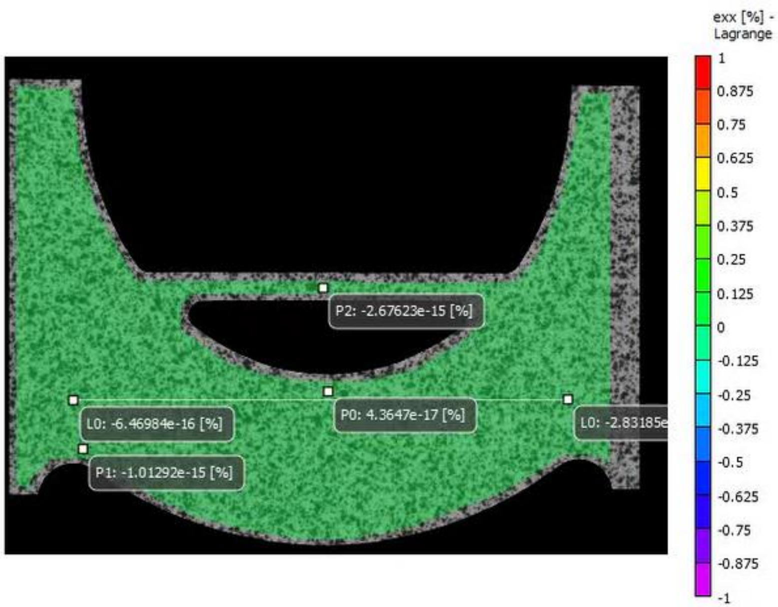
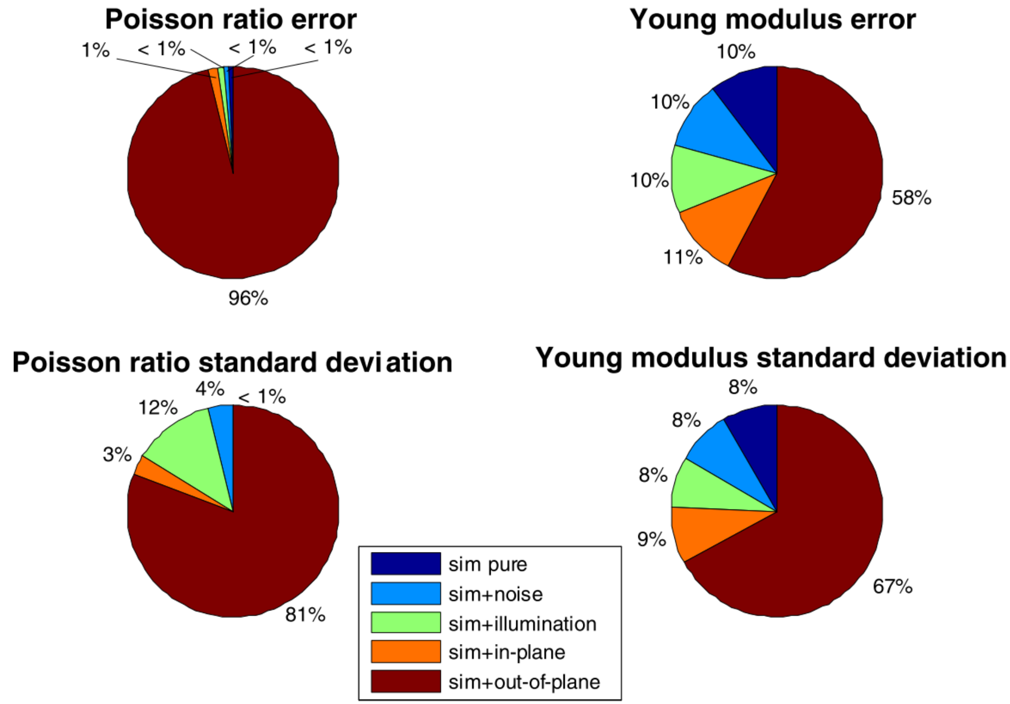






Examples of problem with leaving off different error sources in the simulation‡.

Ruben Balcaen, EM to be published.

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

Top-down versus *bottom-up* uncertainty quantification approach[†].

Top-Down Evaluation

- Does not require study of contributing sources
- Inter-laboratory studies
- Comparisons with a standard
  - Displacement tests
  - Strain gages
  - Shape measurements

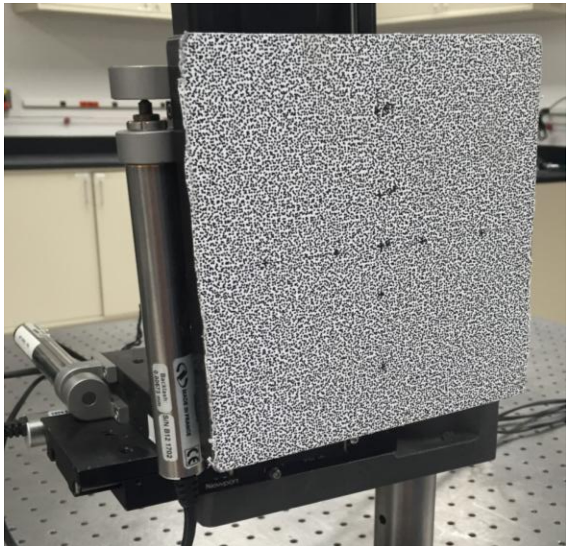
Bottom-Up Evaluation

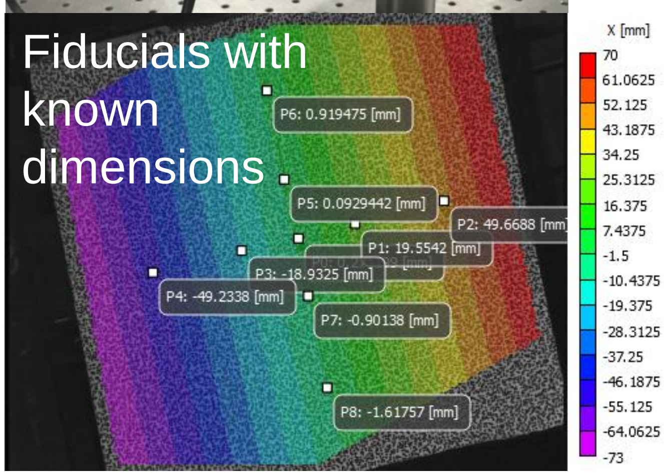
- Complete enumeration of all relevant sources of uncertainty.
- Description of their interplay and UQ influence.
- Characterization of contributions to uncertainty

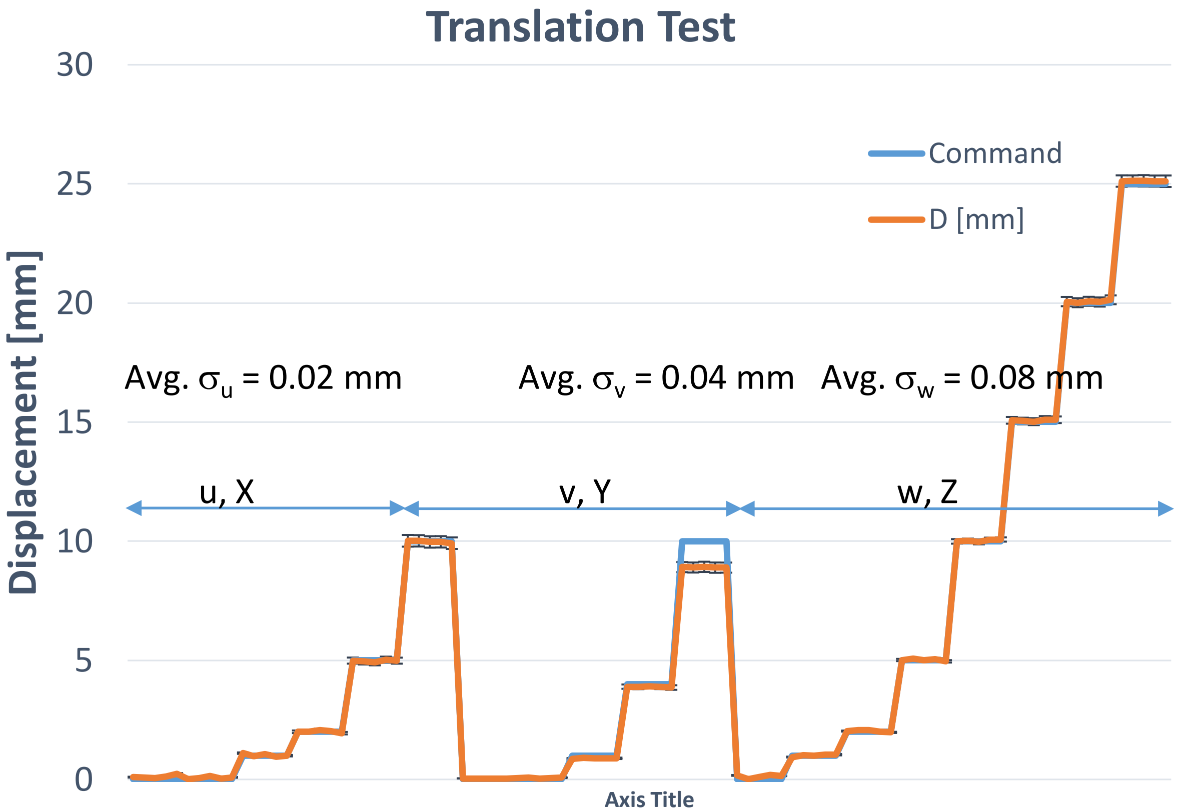
[†]**Possolo, A.** (2015). Simple Guide for Evaluating and Expressing the Uncertainty of NIST Measurement Results Technical Note 1900. NIST.

Top-Down evaluation attempts to quantify all the error sources “experimentally”

X, Y, Z Translation Stage







Bottom-up Methods: Compare DIC results to

- Known shape measurements
- Known fiducial locations
- Known translations

Bottom-up: Comprehensive list of errors

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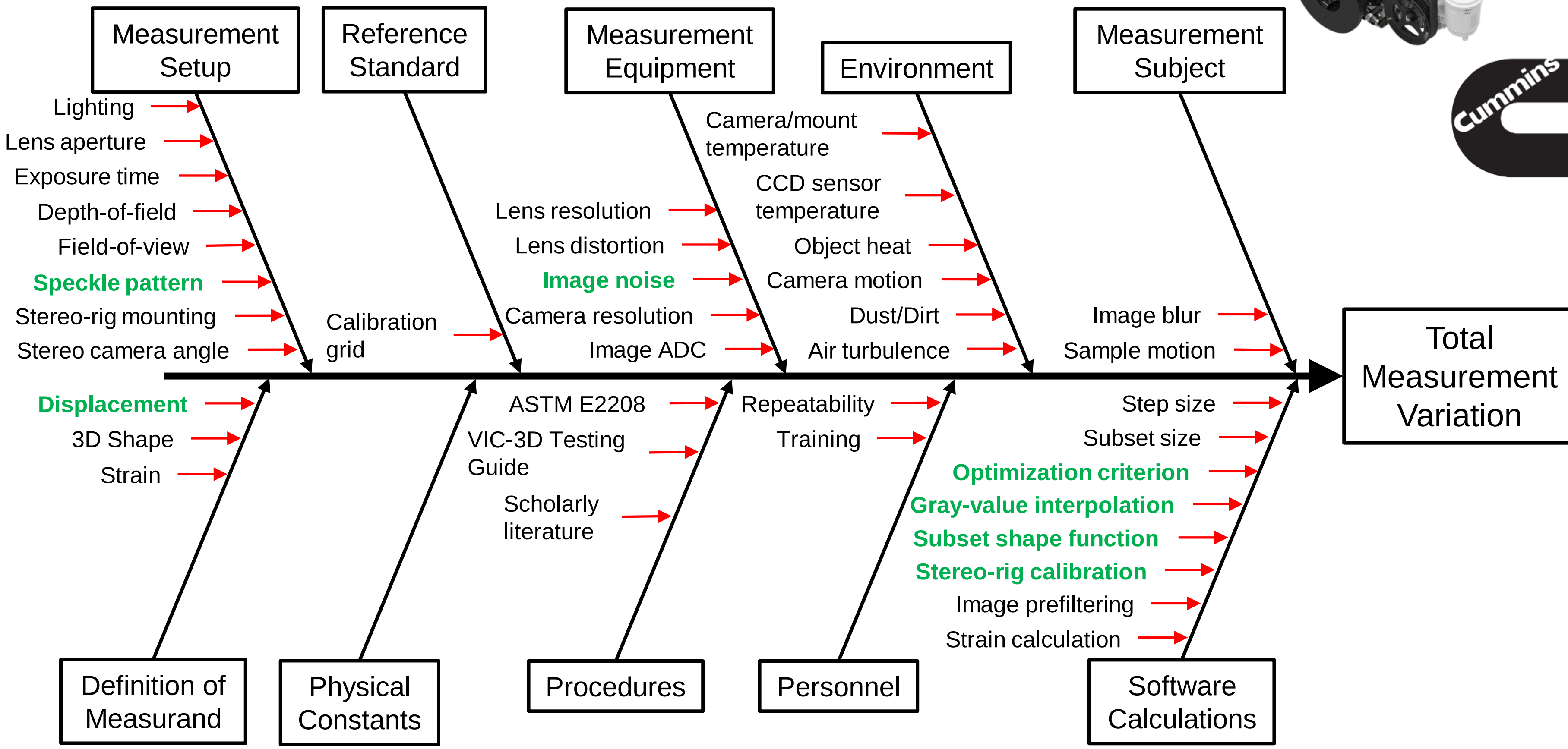
$$D = \sqrt{U^2 + V^2 + W^2}$$

2D Error Source	Type	Assessment Method/Comments	|D| ≈ mm	|D|≈pixels
Lens distortion	B	Previous calibration 100-mm Lens Not motion	<0.001	0.009
Camera motion	A,B	Stationary pattern – See later in slides	<0.02	0.18
Sample motion	B	Fixed target on table	0	0
Turbulence	A,B	This presentation for 50 C heat source	0.01 – 0.07	0.09 – 0.6
Image blur	B	Stationary	0	0
Resolution	B	Adequate pixel size	0	0
Image noise	A	Noise floor (5 frames at start of experiment)	0.001	0.009
Speckle contrast	A	Contrast ≈ 160 counts (Included in noise floor)	Noise floor	
Speckle size	B	Direct measure of speckle size (μ=6.9; σ=1.2 pixels)	Noise floor	
Aliasing	A,B	Noise floor (not aliased)	Noise floor	
Interpolant	B	Synthetic and experimental image studies for optimum	0.0001	0.0009
Minimization	B	DIC parameter study, synthetic and exp. image studies	0.0001	0.0009
Shape function	B	DIC parameter study, synthetic and exp. image studies	0	
Subset size	B	DIC parameter study, synthetic and exp. image studies	Noise floor	
Filtering	B	DIC parameter study		
Strain calculation	B	DIC parameter study		
Coord. system	B	Other means		

The fundamental problem of DIC-UQ is that there are many variables to consider.



Jordan E. Kelleher, Paul J. Gloeckner, An Applications-Oriented Measurement System Analysis of 3D Digital Image Correlation, 2016 SEM Annual Conference & Exposition on Experimental & Applied Mechanics

There were few (or no) experimental validations 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

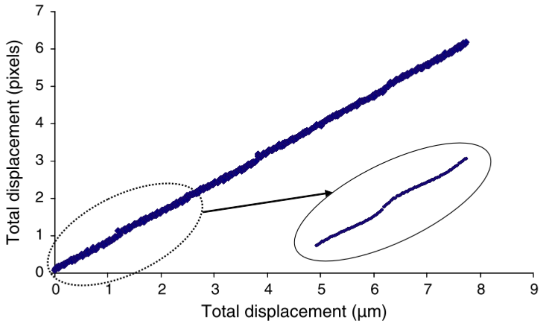
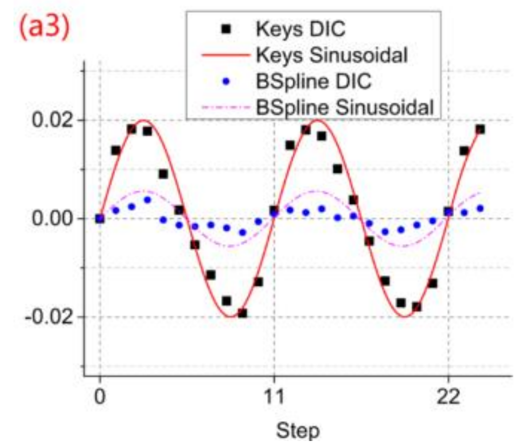


Figure 8: Measured horizontal image-based translation as a function of time. Measurements obtained using 2D digital image correlation with Point Grey camera images and a 209 × 209 subset

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

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



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

In-plane translation test with high-precision stage.

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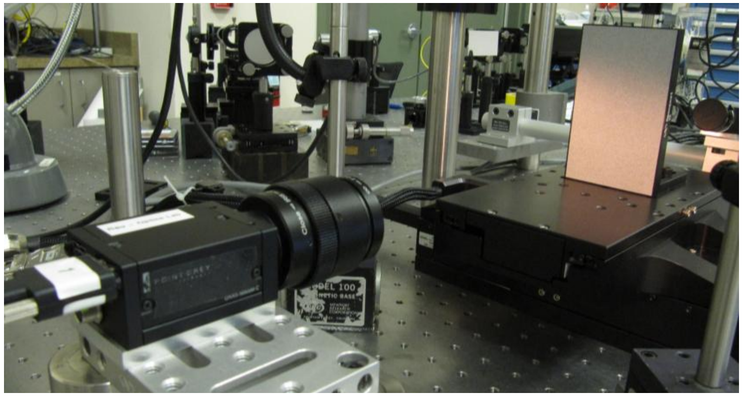
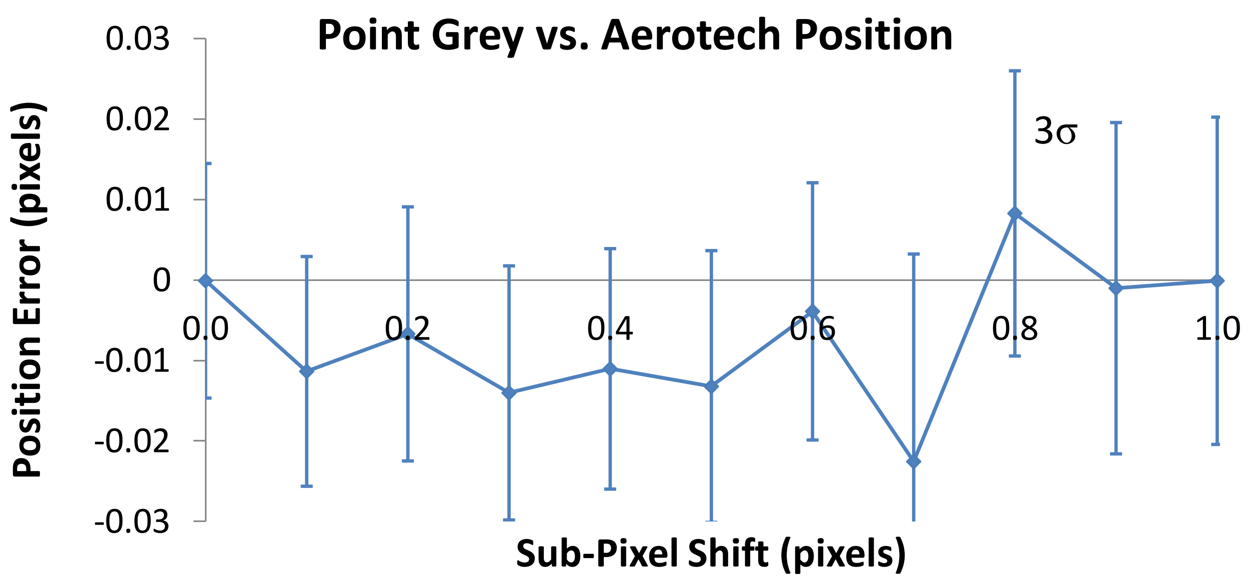


Aerotech ultra-precision x-y stage

- ±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)

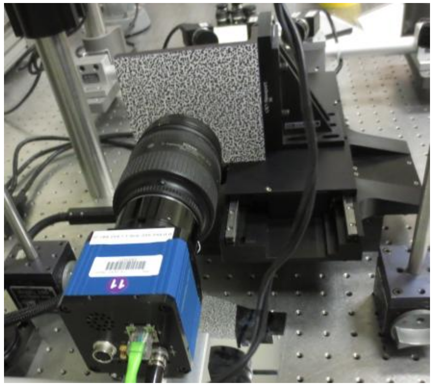
Point Grey 5 MPixel cameras

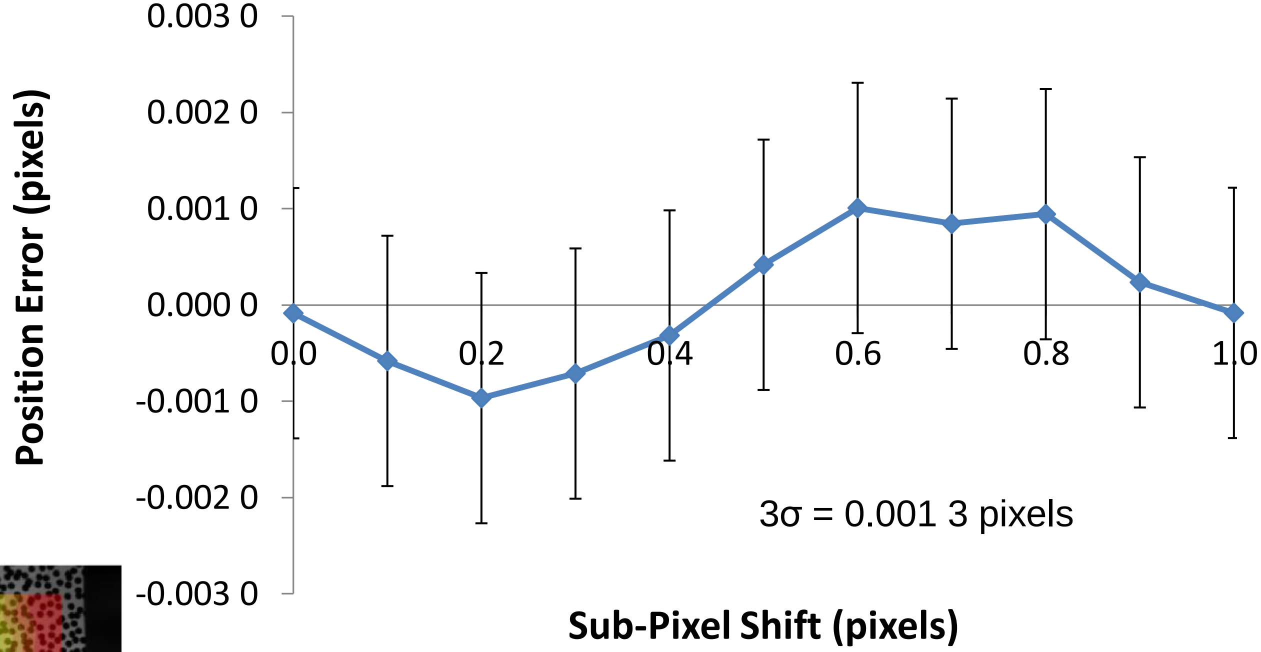
- 29 μm/pixel or 29 000 nm/pixel
- Stage error max. 6 nm or 0.000 2 pixels
- Pixel noise ≈ 2.3 counts (1σ) 0.9%

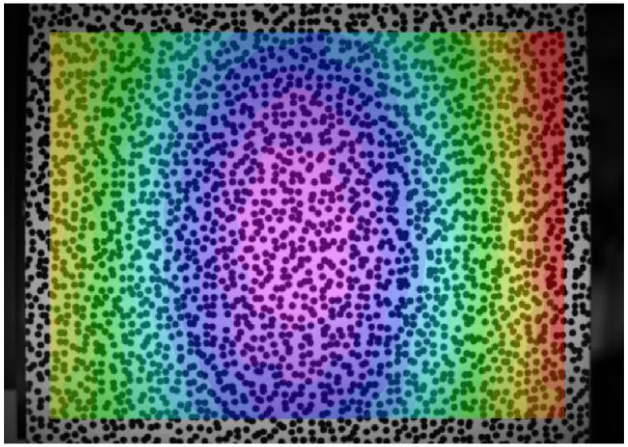


Variance errors dominate bias errors!

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





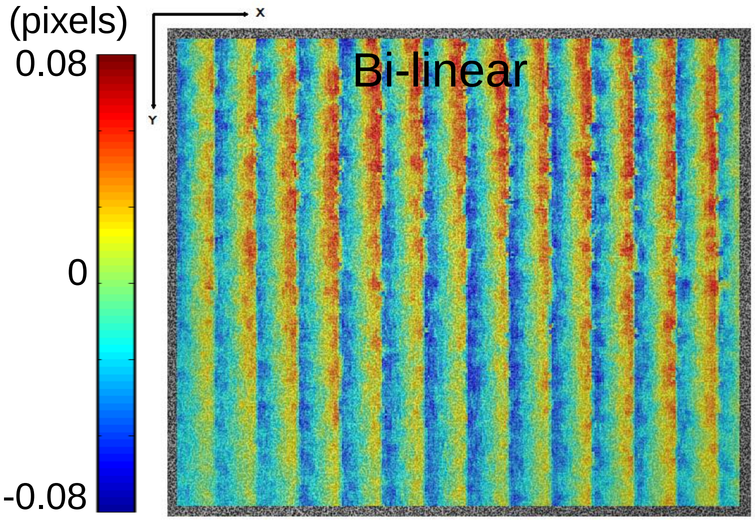


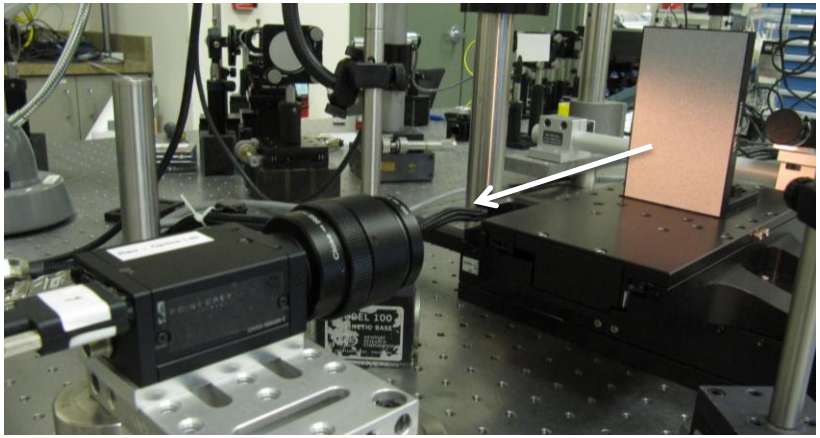
Prosilica 14-MPixel (binned x10)

- 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%

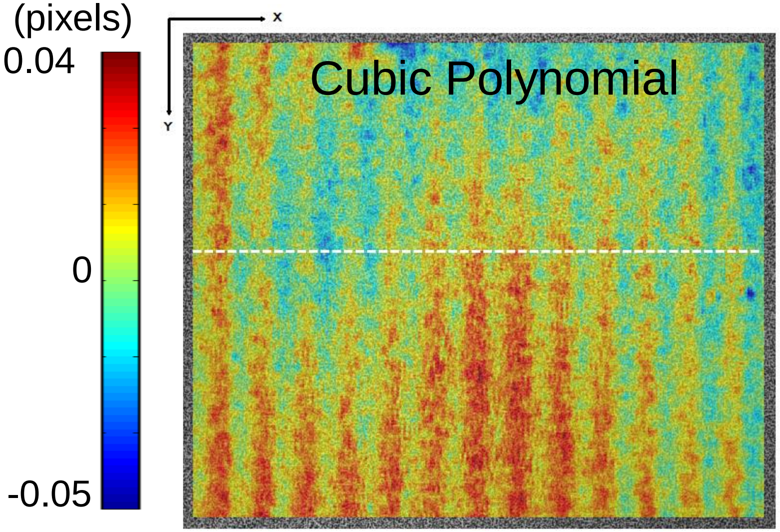
At this point – The lens distortion started to contribute.

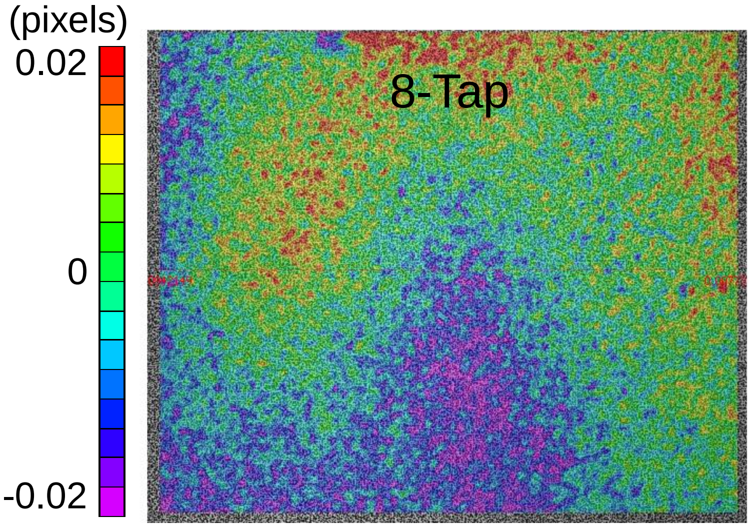
The bias error is much easier to find with out-of-plane motion.



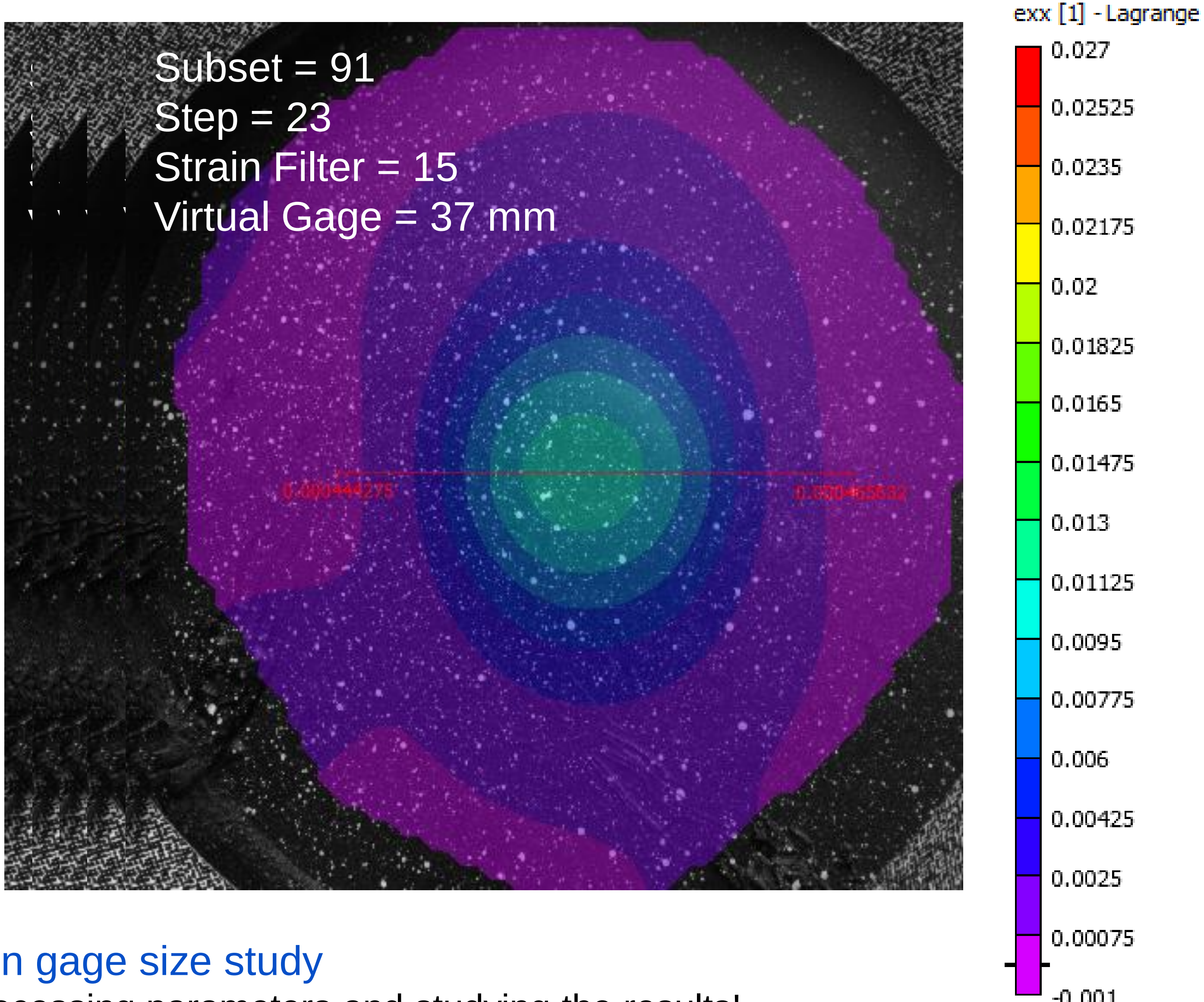


This simulates a biaxial strain, but uniaxial would cause the same issues!





The user is a weak link in the system. Training!



Virtual strain gage size study

- Varying processing parameters and studying the results!

The DIC community needs, training, standardization and guidelines.

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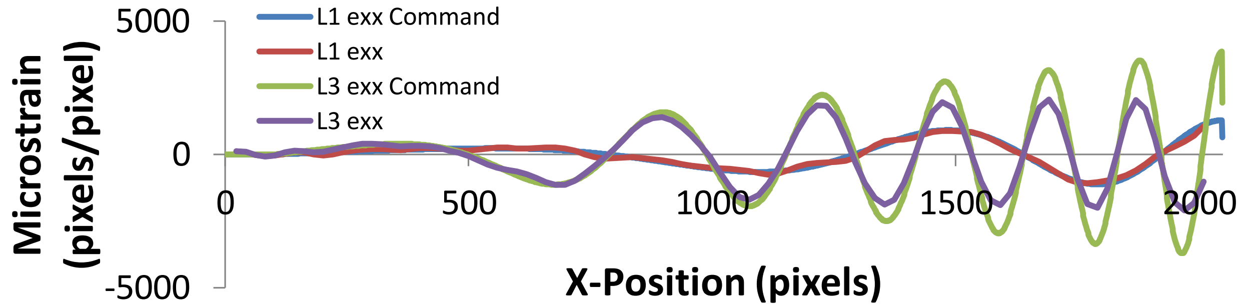
- Publication requirements to provide important DIC information.

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

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Annual International DIC Society Conference

November 6 – 9, 2017 in Barcelona Spain

http://idics.org

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Wei-Chung Wang

General Call

The International Digital Image Correlation Society (iDICs) is inviting your participation in its annual conference in Barcelona Spain. We welcome you to join this society aimed at inspiring their members to continually improve their application and development of image correlation methods. The board invites you to join in presenting, organizing sessions, and participating in the active committees to help guide DIC into the future.

Active Committees

- Applications (Chair: Dave Dawicke)
- University Education (Chair: Mark Pankow)
- Training & Certification (Chair: Tim Schmidt)
- Standards & Best Practices (Chair: Mark Iadicola)

Monday Courses (November 6)

- To be determined

Mission: Extend – Improve – Train

Extending the Frontiers: Training the next Generation:
Standardizing for Industry: Improving our Practice

Important Dates
Abstract due July, 2017
Early Registration until Sept. 1