SAND2016-2630C

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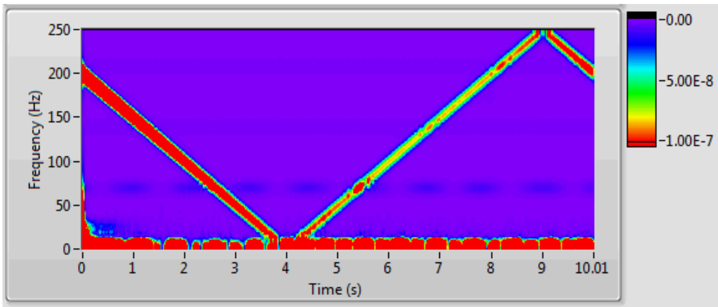
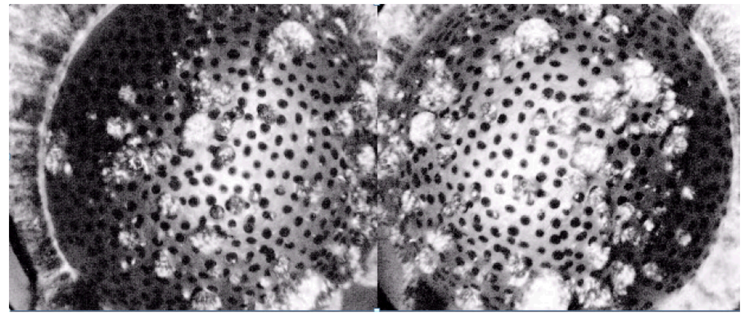
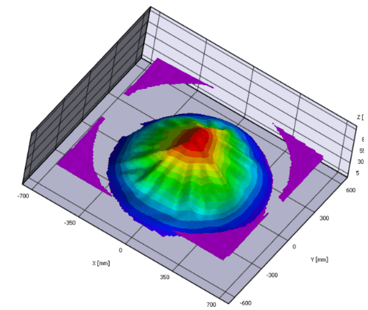
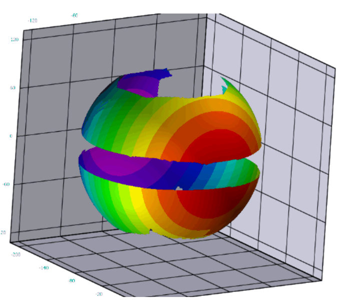






Digital Image Correlation (DIC) used for dynamic full-field deformation and strain measurements: Examples and applications



Phillip L. Reu, Daniel Rohe, Laura Jacobs and Dan Turner

AIAA SciTech 2016
San Diego, California

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Imaging technology is revolutionizing DIC by making new experiments possible.

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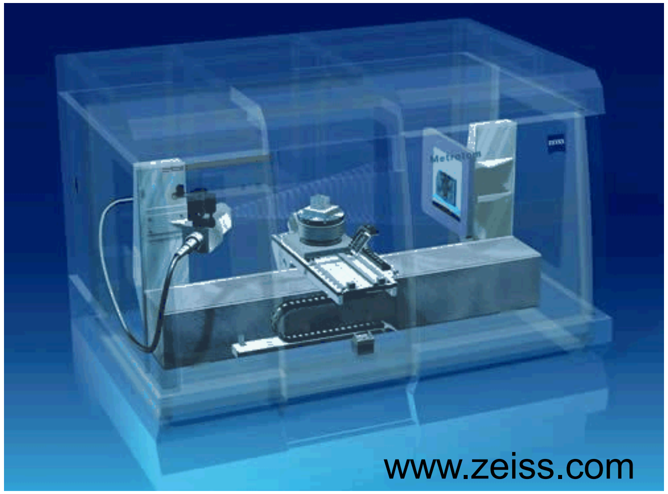
SEM/AFM

www.jeol.com

CT Scanner



High Resolution Machine Vision

http://www.alliedvisiontec.com

High and Ultra-high Speed Imaging

www.visionresearch.com

www.photron.com

www.shimadzu.com

The simulation repeatedly triangulates while varying one or more parameters

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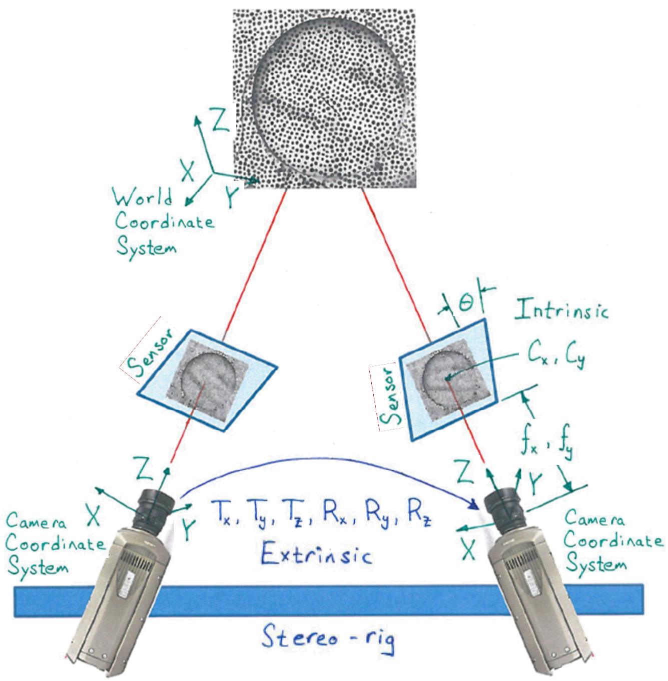
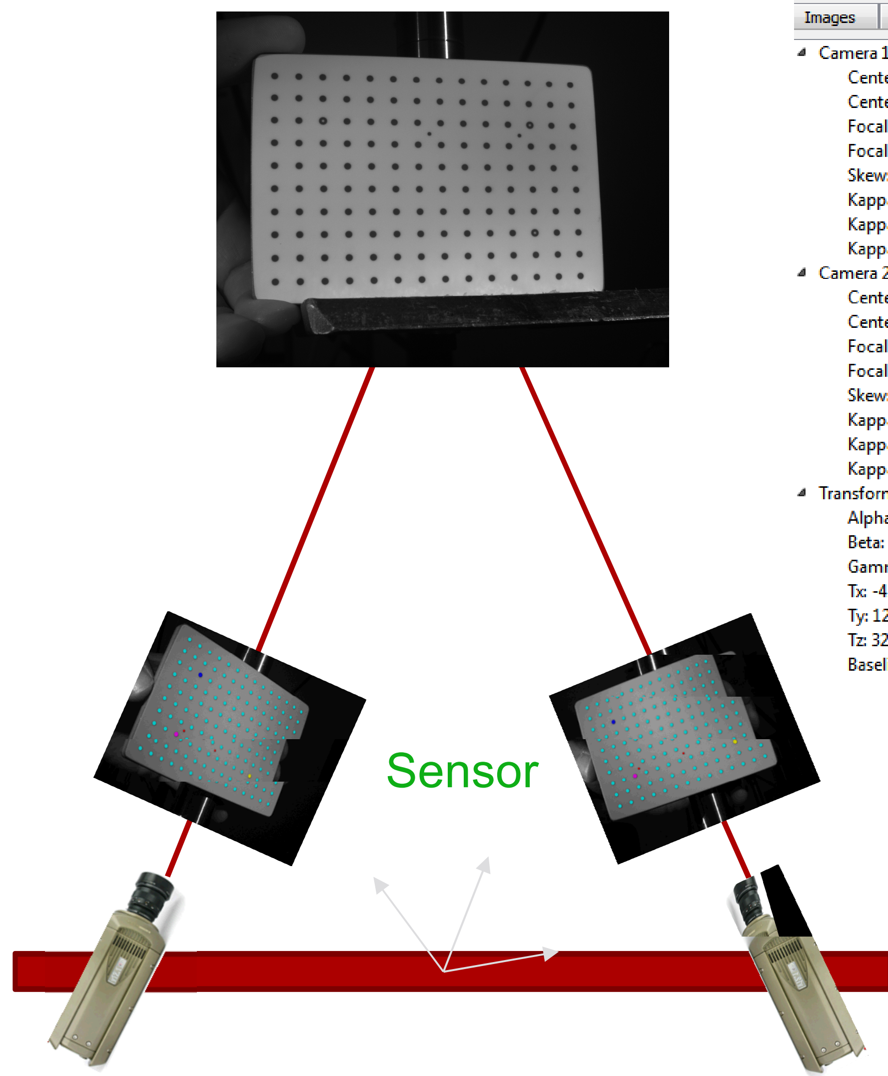


Hidden Components Stereo-DIC

1. **Calibration**
2. Subset shape function
3. Grey level interpolation
4. Subset matching
5. Triangulation
6. Post-processing

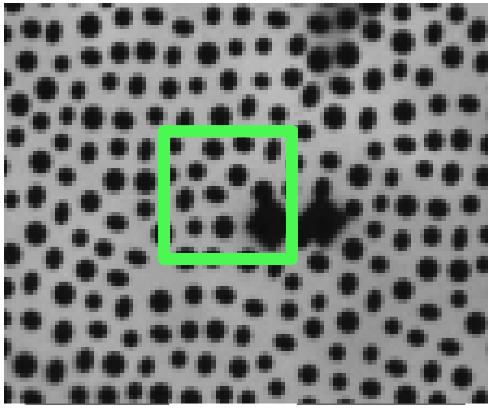


Images | Data | Calibration

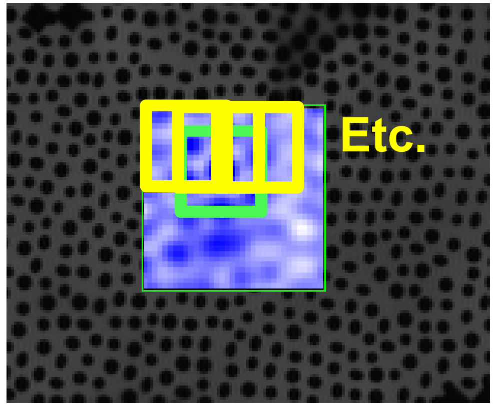
- Camera 1
  - Center x: 620.77 pixel
  - Center y: 368.819 pixel
  - Focal length x: 7300.19 pixel
  - Focal length y: 7298.06 pixel
  - Skew: -1.78958
  - Kappa 1: 0.0454422
  - Kappa 2: 0
  - Kappa 3: 0
- Camera 2
  - Center x: 621.265 pixel
  - Center y: 426.103 pixel
  - Focal length x: 7287.66 pixel
  - Focal length y: 7286.16 pixel
  - Skew: -1.35447
  - Kappa 1: 0.0363301
  - Kappa 2: 0
  - Kappa 3: 0
- Transformation
  - Alpha: 27.6014 deg
  - Beta: 2.1582 deg
  - Gamma: -2.70103 deg
  - Tx: -43.6947 mm
  - Ty: 1255.27 mm
  - Tz: 325.903 mm
  - Baseline: 1297.63 mm

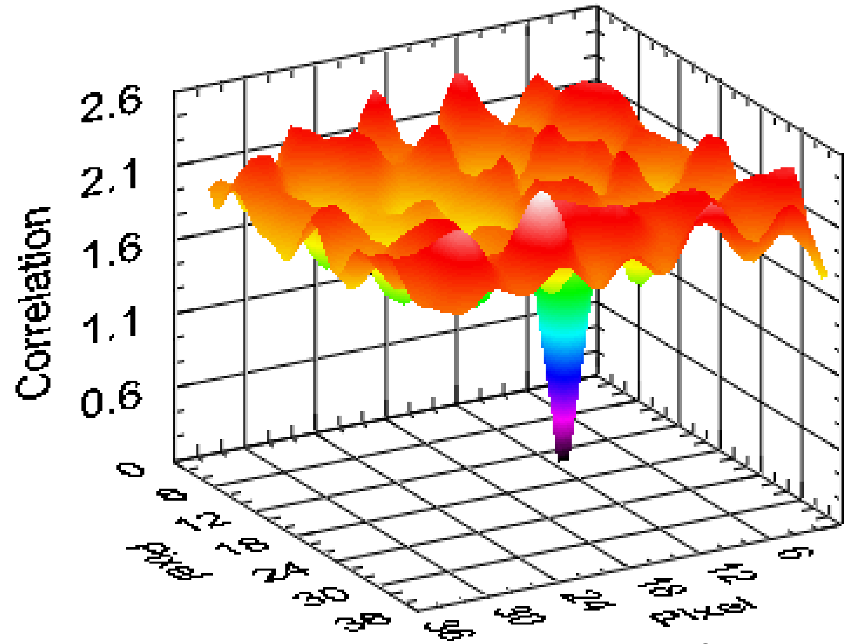
Using interpolation and the shape function a correlation criterion is used to find a subset match

Subset to find

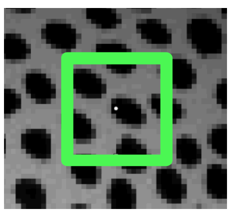


Region of Interest (ROI)



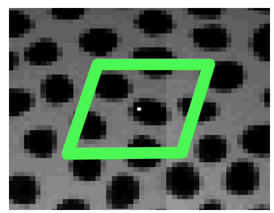


Reference Image (*F*)



Matching
- Cross-Correlation
- Time steps

Matched Image (*G*)

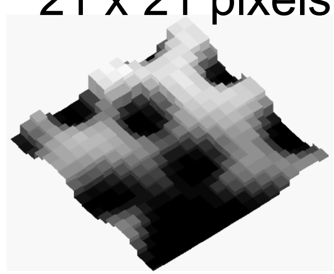


$$\chi^2 = \sum_i \left(G_i - F_i\right)^2$$

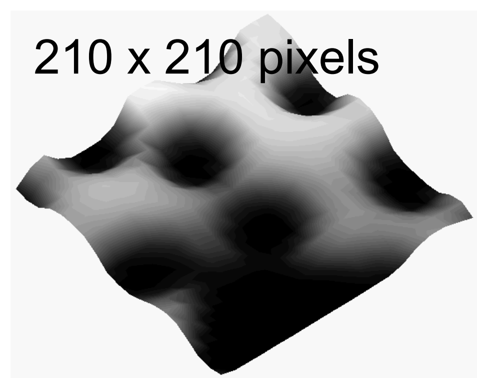
χ – is the function to minimize
F – is the reference image
G – is the deformed image
i – is the pixel in the subset

Hidden Components Stereo-DIC
1. Calibration
2. **Subset shape function**
3. **Grey level interpolation**
4. **Subset matching**
5. Triangulation
6. Post-processing

21 x 21 pixels



210 x 210 pixels



The simulation repeatedly triangulates while varying one or more parameters

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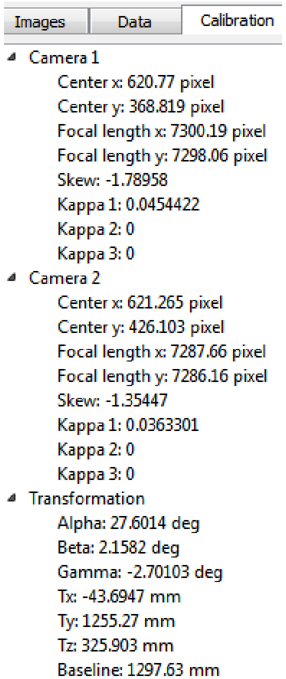
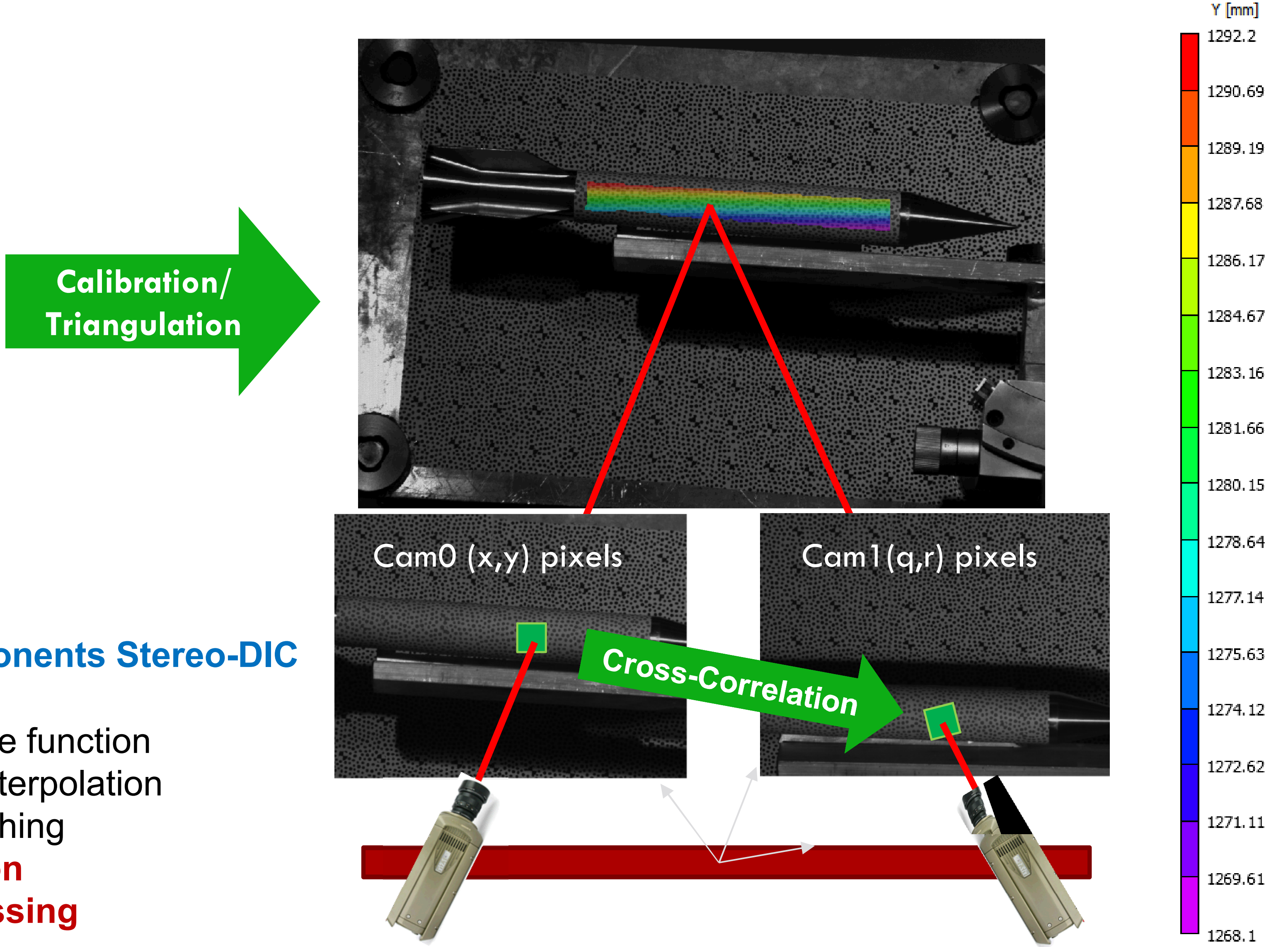
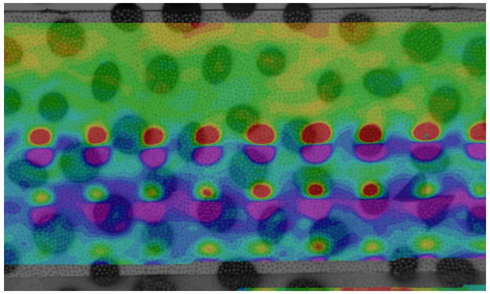




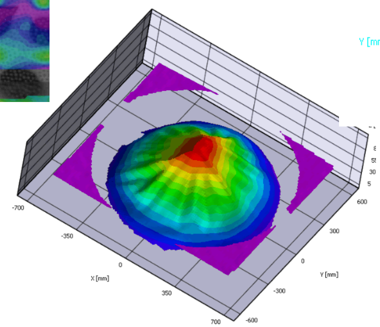
Hidden Components Stereo-DIC

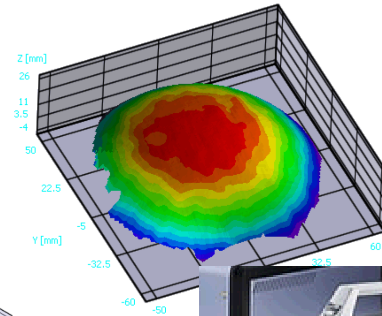
1. Calibration
2. Subset shape function
3. Grey level interpolation
4. Subset matching
5. **Triangulation**
6. **Post-processing**

There are many things we can do with these tools!

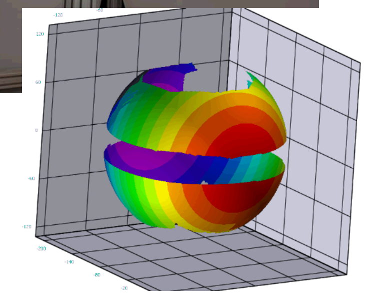


www.visionresearch.com





www.shimadzu.com

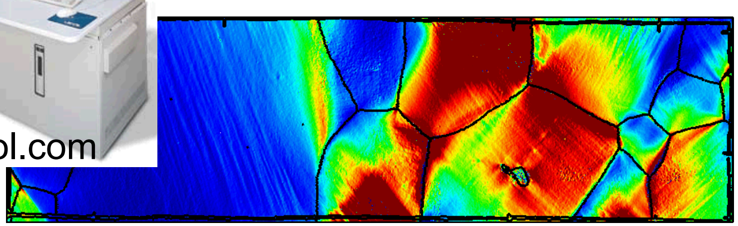


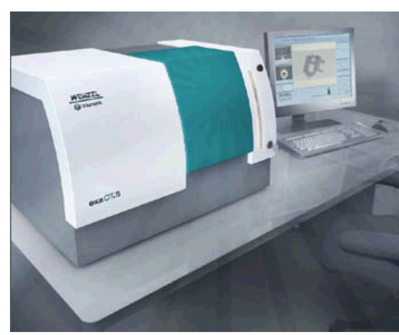
High Speed Displacement and Strain

1 Million FPS

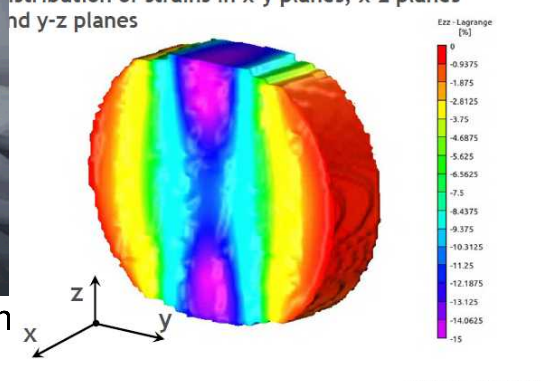
Multi-System

www.jeol.com





www.exactmetrology.com

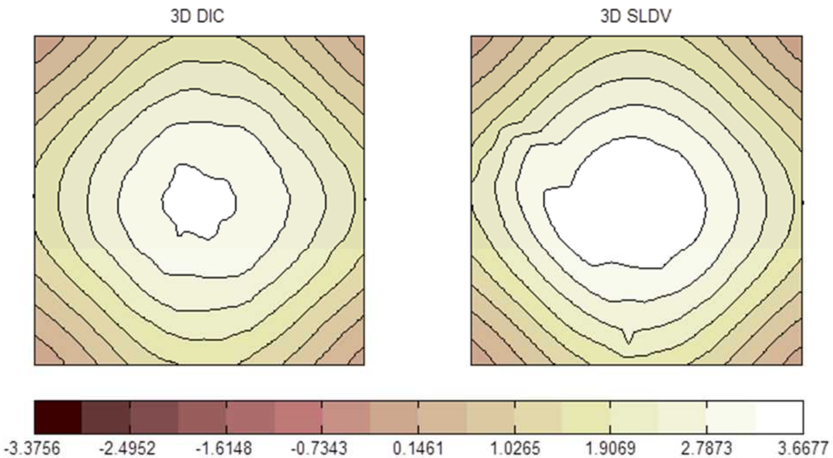


Grain scale strain measurement (optical)

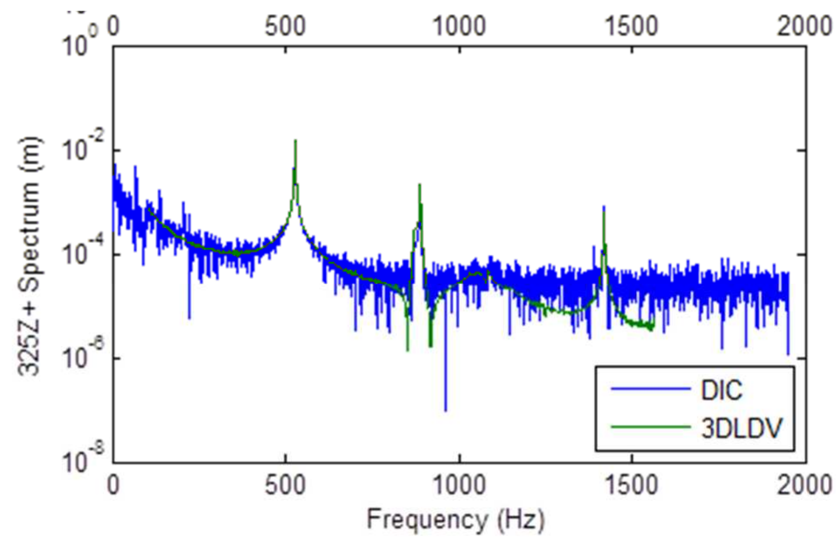
Volumetric strain fields

Grain Scale: J. Carroll Volumetric Image: M. Sutton – Murray lecture at SEM 2013

The goals of modal testing are determining the mode shape, frequency and damping.



Mode Shape
Modal Frequency = 529Hz



Damping = 0.0004

Note: Modal testing vibration amplitudes are small! Often nanometers.

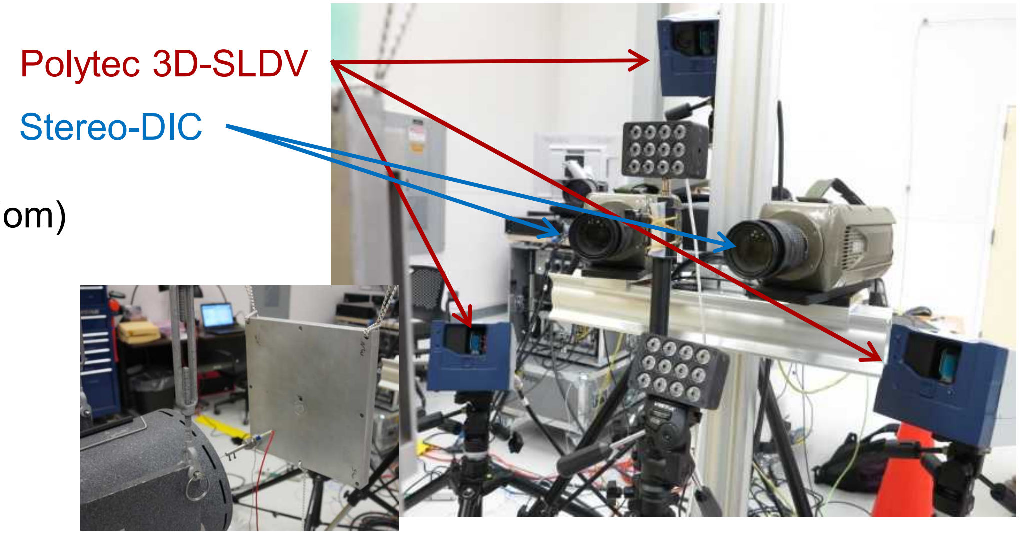
Modal Testing Reveals

- Frequencies that the object will vibrate (resonance) at and are to be avoided.
- The damping of the structure – how quickly vibrations die out.
- Needed for design of systems and structures.
- Can be used for FE model validation.
- Strain hot-spots or places for failure in the system.

How does DIC compare with scanning LDV? Does it have the displacement resolution?

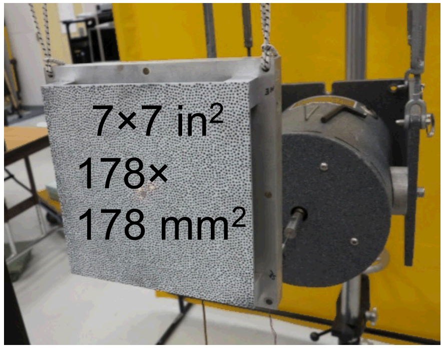
Experimental Setup

- Polytec PSV-500 3D-Scanning LDV system.
- Vic3D and Phantom 611 Cameras (800×800)
- 3906.25 Hz (200 μs exposure) to match LDV
- MB-50 Shaker on a shaker stand (Pseudo-Random)
- Speckle painted surface (not ideal for LDV)
- Retro surface (not possible for DIC)



Temporal DIC Resolution

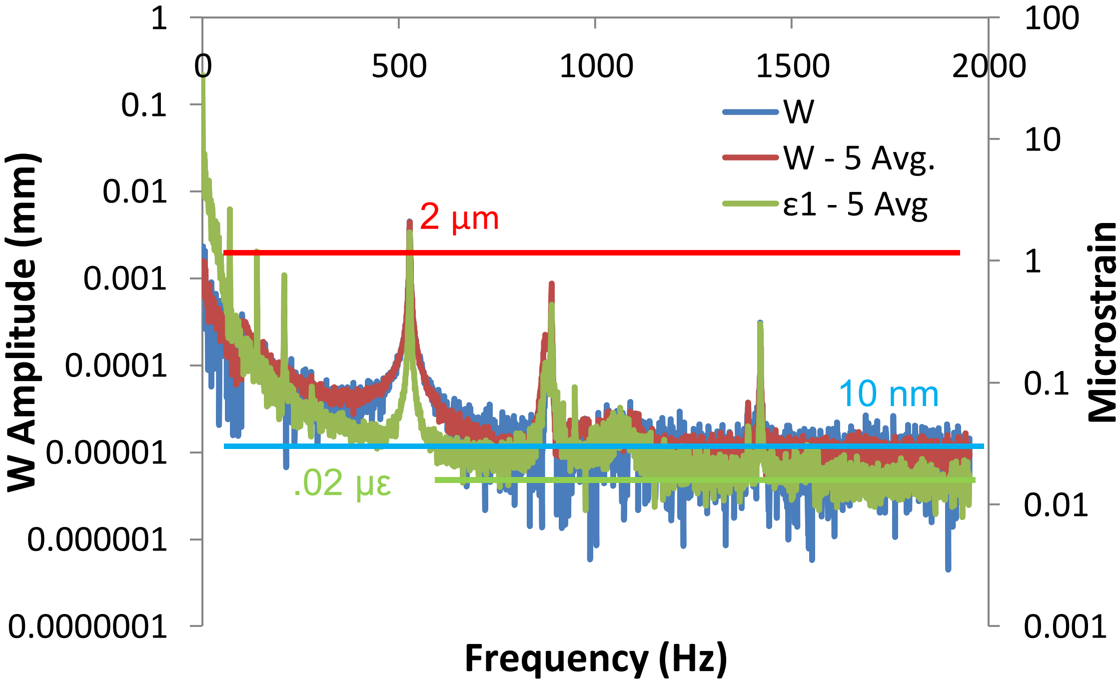
$$\frac{178\ mm}{800\ pixels} \cdot 0.01\ pixels = 2\ \mu m$$

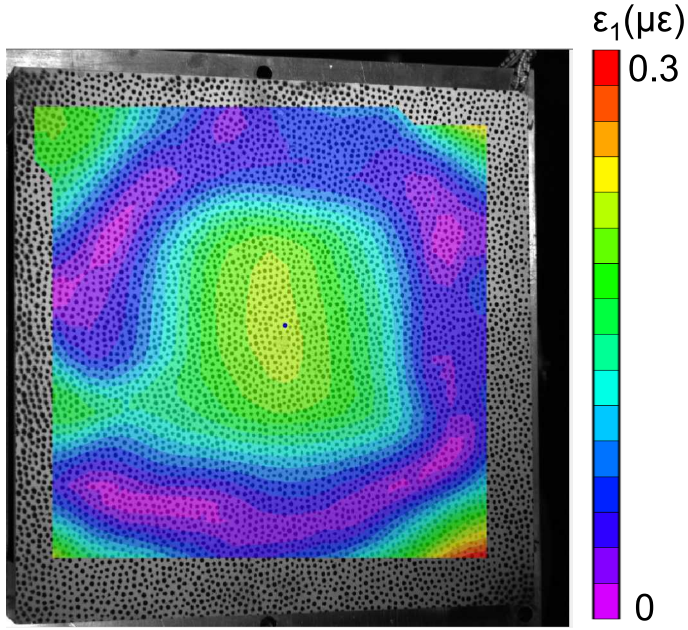


What we investigated

- Time to measurement (setup)
- Cost (not really)
- Measurement time
- Analysis time/data point
- Noise floor/resolution
- Ease of use (subjective)

The DIC noise floor is significantly better in the frequency domain than the time domain.

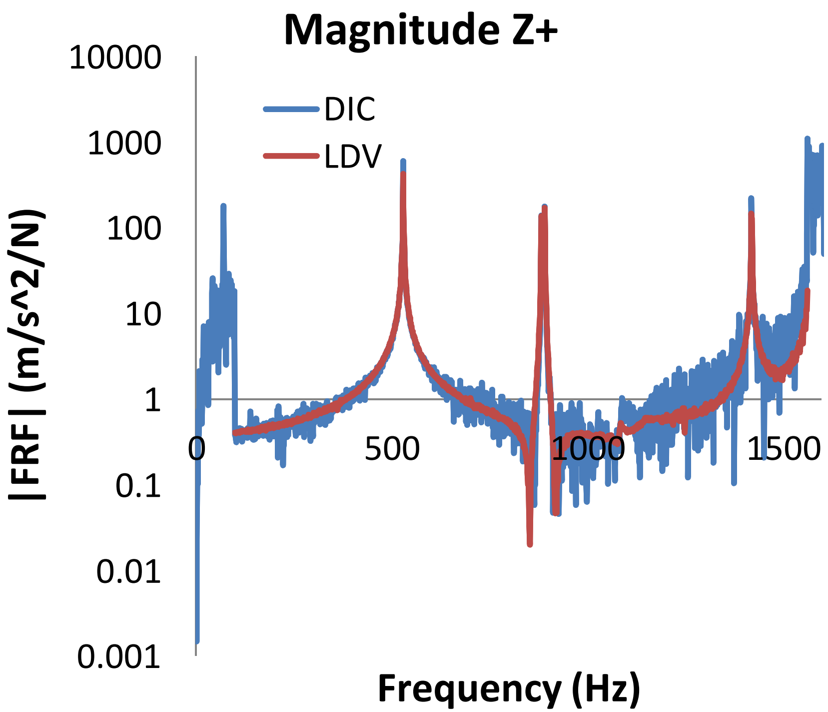


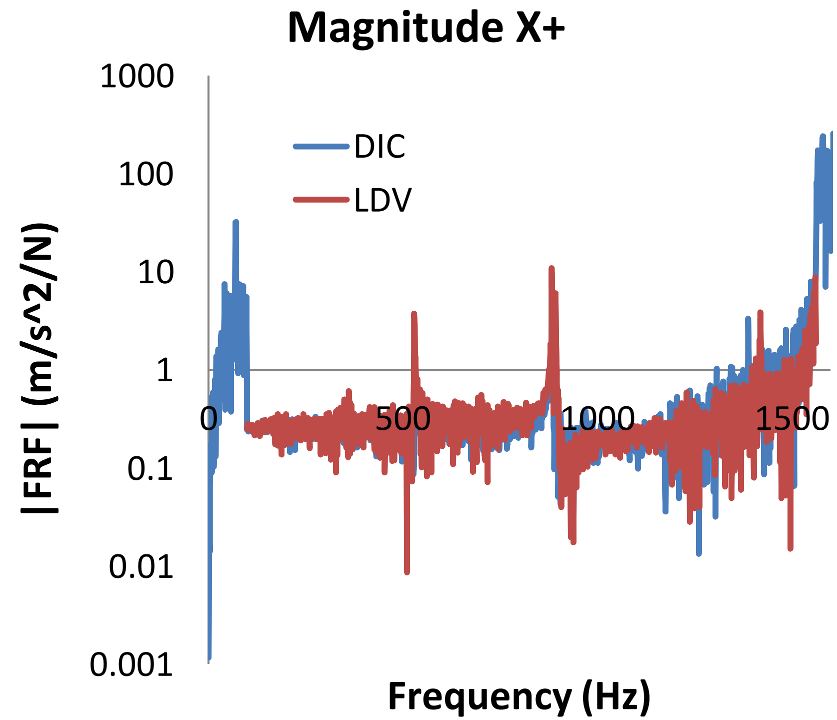


Notes on Resolution

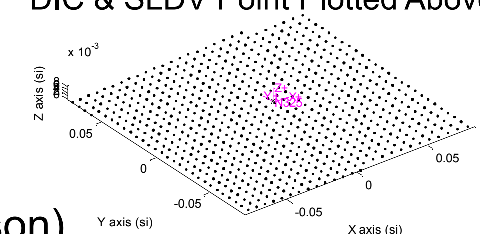
- Typical DIC resolution for a 7 inch FOV would be 2 μm or 200 με.
- The noise is distributed across all the frequencies – therefore lower at any given frequency band.
- Displacement resolution in the frequency domain is much better than that in the time domain.
- FFT averaging improves the noise even further (i.e. more images are better!), i.e. you can trade frequency resolution for noise reduction (i.e. more averaging).

LDV has a better noise floor than DIC in Z and comparable in X and Y.





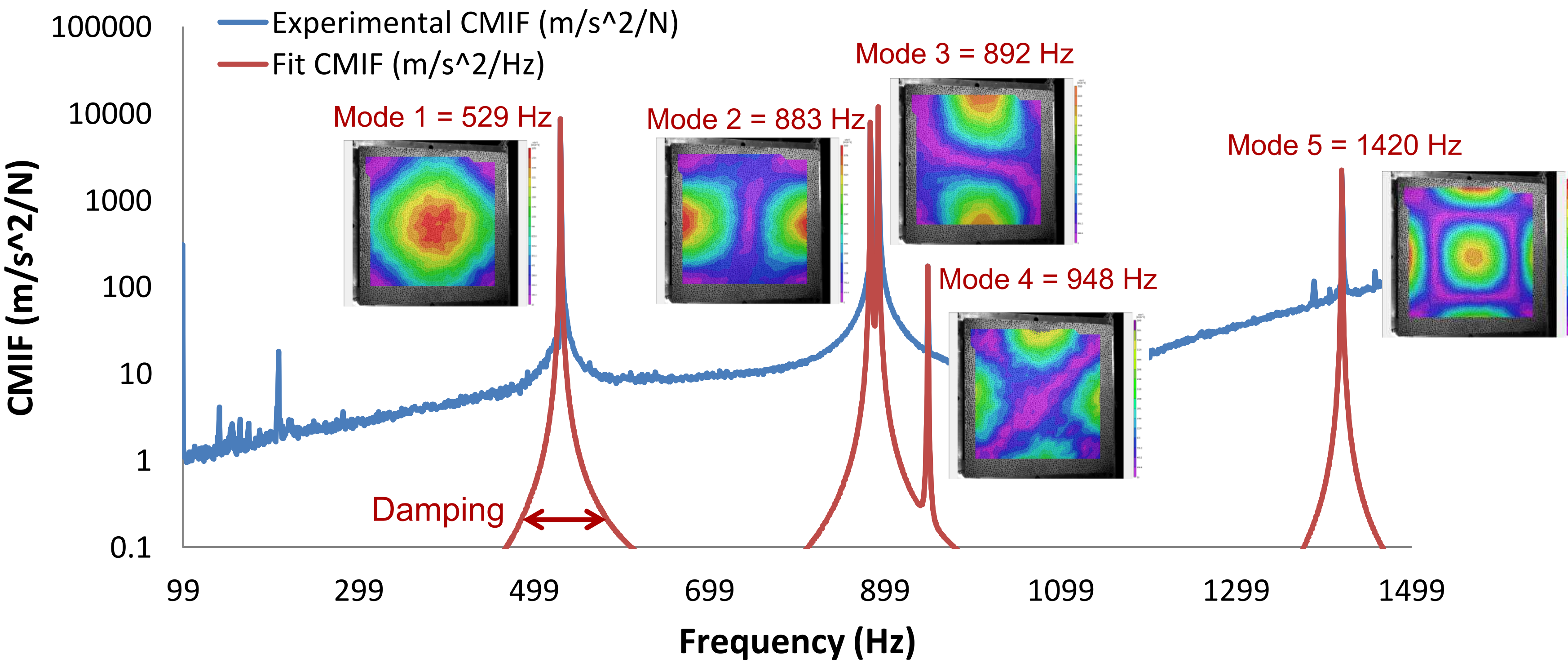
DIC & SLDV Point Plotted Above



Notes on the comparison

- Data at point near the middle of the plate.
- LDV is more sensitive out-of-plane, DIC is less sensitive.
- Not much in-plane motion at center (not important for this comparison)

Modal fitting analysis approach.



Modal Fitting Software

- SMAC† – Sandia's modal identification software
- There was some challenge with the large number of data points from the DIC software.
- CMIF is the Complex Mode Indicator Function.

†"Extending SMAC to Multiple Reference FRFs" by Daniel P. Hensley and Randy L. Mayes, Proceedings of the 24th International Modal Analysis Conference, January, 2006, St. Louis, Missouri.

Fitting results and comparisons. Show some mode shapes, damping and frequencies.

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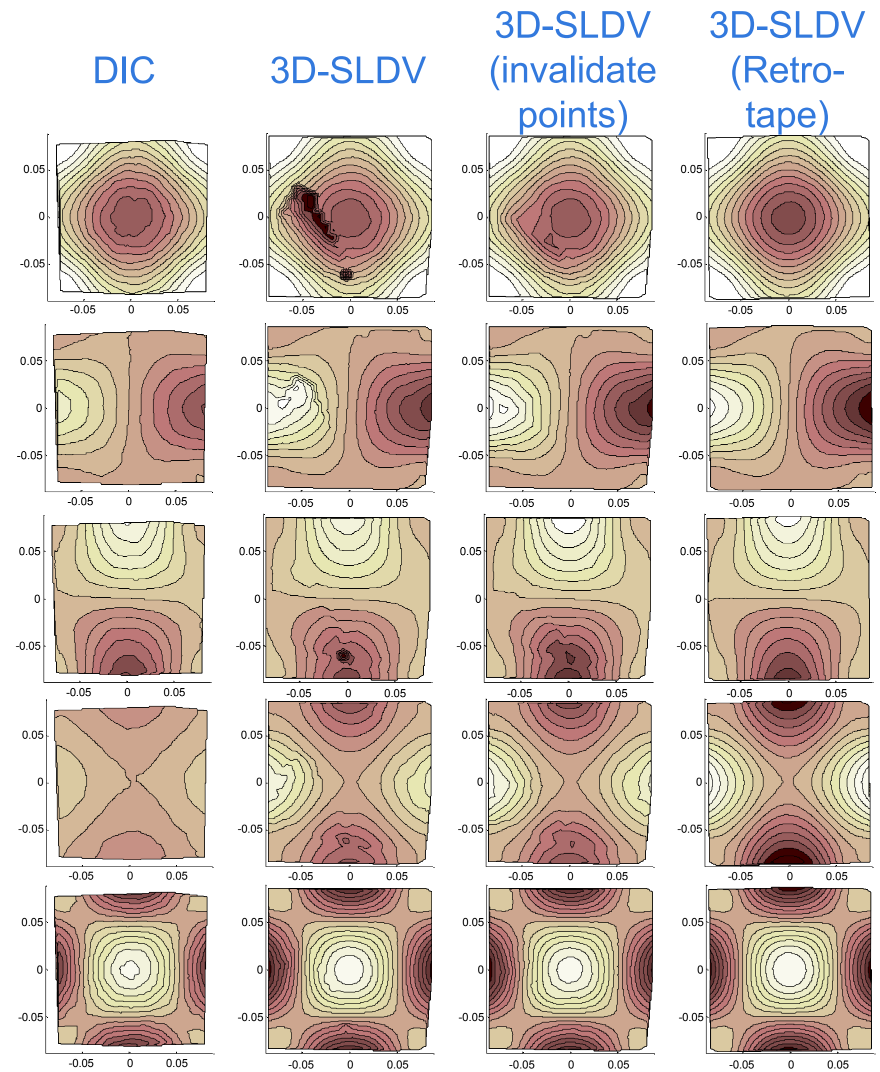
Mode	Frequency		Damping	
	DIC	LDV	DIC	LDV
1	529.4	529.5	0.042	0.042
2	883.0	883.1	0.022	0.024
3	891.7	891.7	0.015	0.026
4	948.3	948.4	0.019	0.019
5	1420.1	1420.4	0.015	0.020

Notes on the Results

- DIC = 715 Points, LDV = 545 Points
- Scale identical for each group of results
- DIC plots are from the speckled surface.
- 3D-SLDV are taken on the speckle surface.
- 3D-SLDV (invalidate points) removes “bad” data points from the analysis.
- 3D-SLDV (retro-tape) covered the speckle pattern with a retro tape to improve signal quality.



Temporal† anti-aliasing. It can be a big deal.

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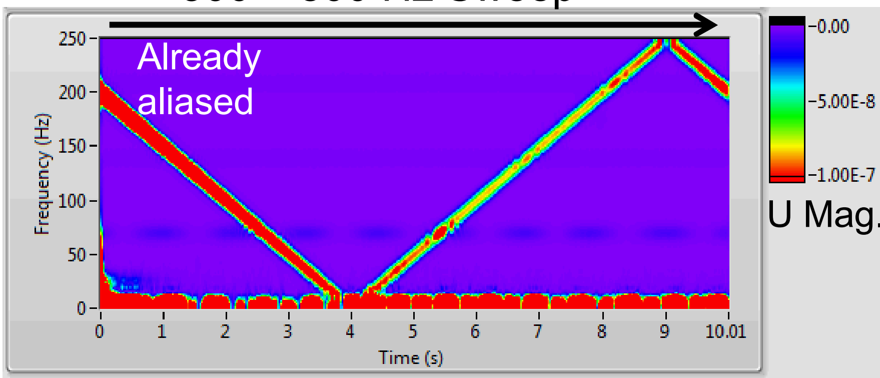
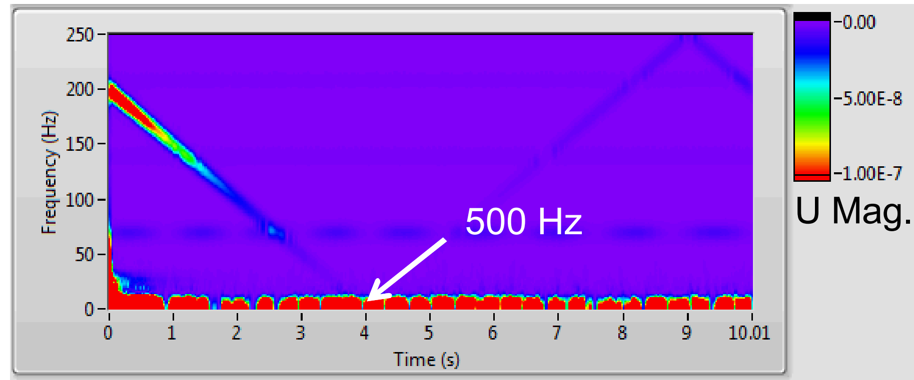
†Spatial aliasing is another completely different and important topic.

Frame Rate = 500 Hz: Nyquist = 250 Hz

300 – 800 Hz Sweep

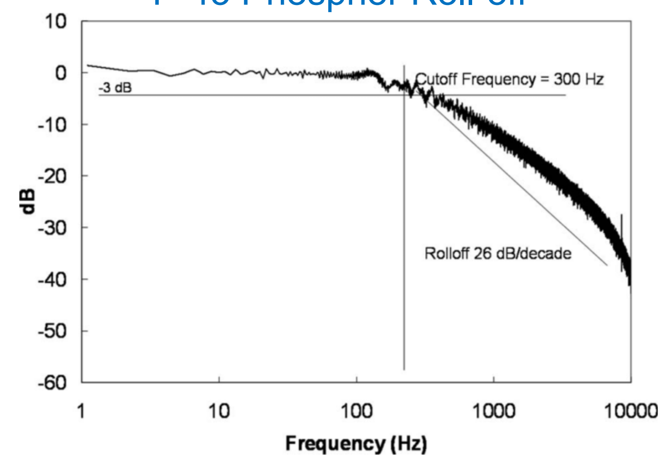




Exposure = 200 μs or 5000 Hz

Exposure = 1900 μs or 526 Hz

P-43 Phosphor Roll-off



Notes on aliasing

- With cameras – there are no good antialiasing filters. (Ideas do exist †)
- Long exposures provide some aliasing protection.
- Best solution: have a single point measurement (with antialiasing) to ensure the frequency content of the signal.
- With impact testing – the force profile rolls off gradually with frequency and will lead to aliasing issues.

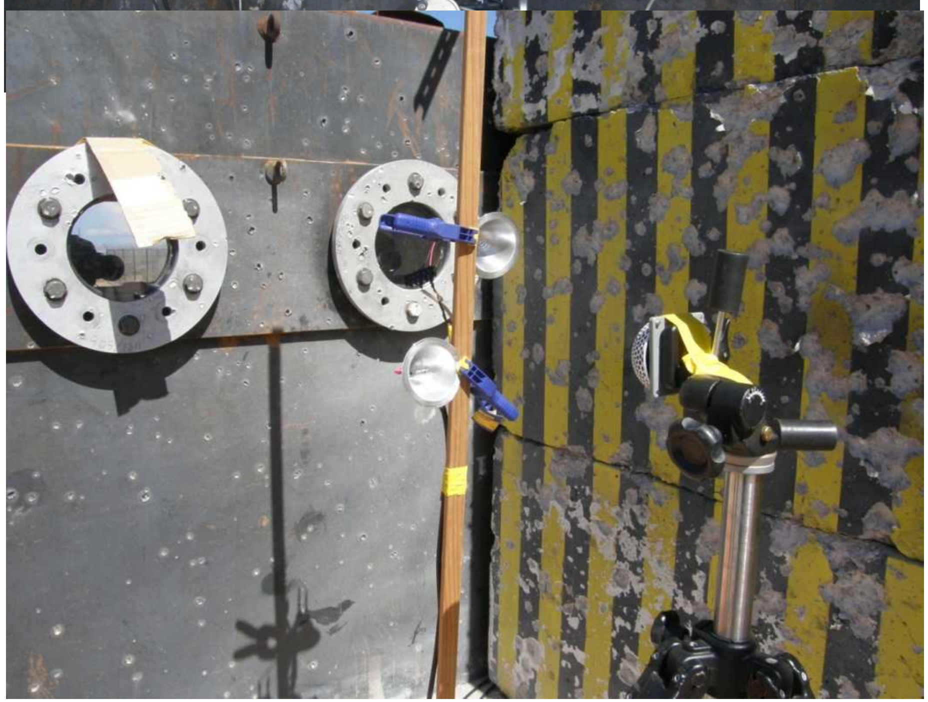
†Reu, P. L. and B. D. Hansche (2008). Optical Engineering **47(7).**

What are the pros and cons of the two methods. When do we use one or the other.

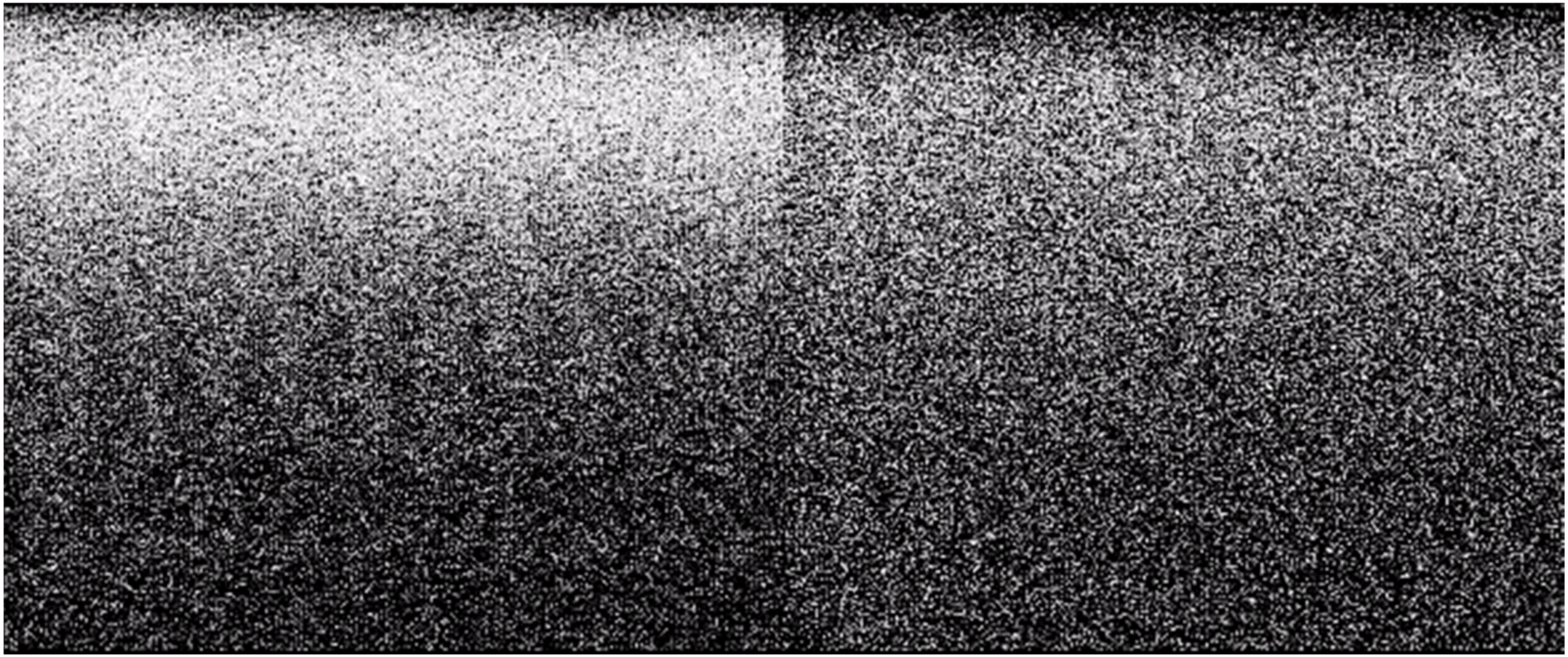
Comparison Metric†	LDV	DIC
Cost	≈$650k	≈$350k ✓
Setup time	2 hours	2 hours
Acquisition Time	Hours	Seconds ✓
Analysis Time	Seconds ✓	Hours
Disp. Resolution	≈ picometers ✓	≈ nanometers
Strain resolution	?	5 microstrain ✓
Strain Calculation	Integrated – but researchy	Seamlessly Integrated ✓
Anti-aliasing	Included ✓	Not possible at the moment
Data volume	Small (Mbytes) includes only frequency data	Large (Gbytes) but includes time history
Software	Designed for modal analysis. ✓	In its infancy.

†The comparison is for this test setup – but should be broadly accurate in many other situations.

Example: Cased explosive at 1 MHz



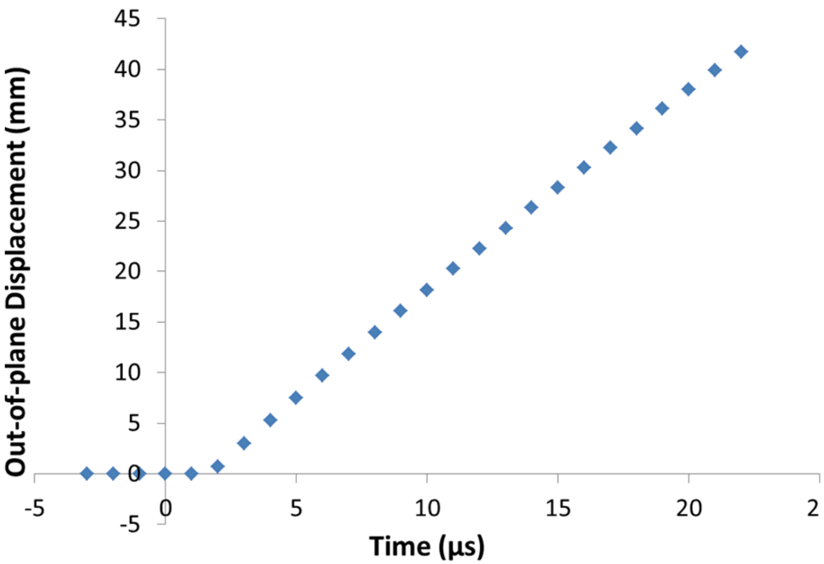
Optical distortions must be considered beyond the lens.

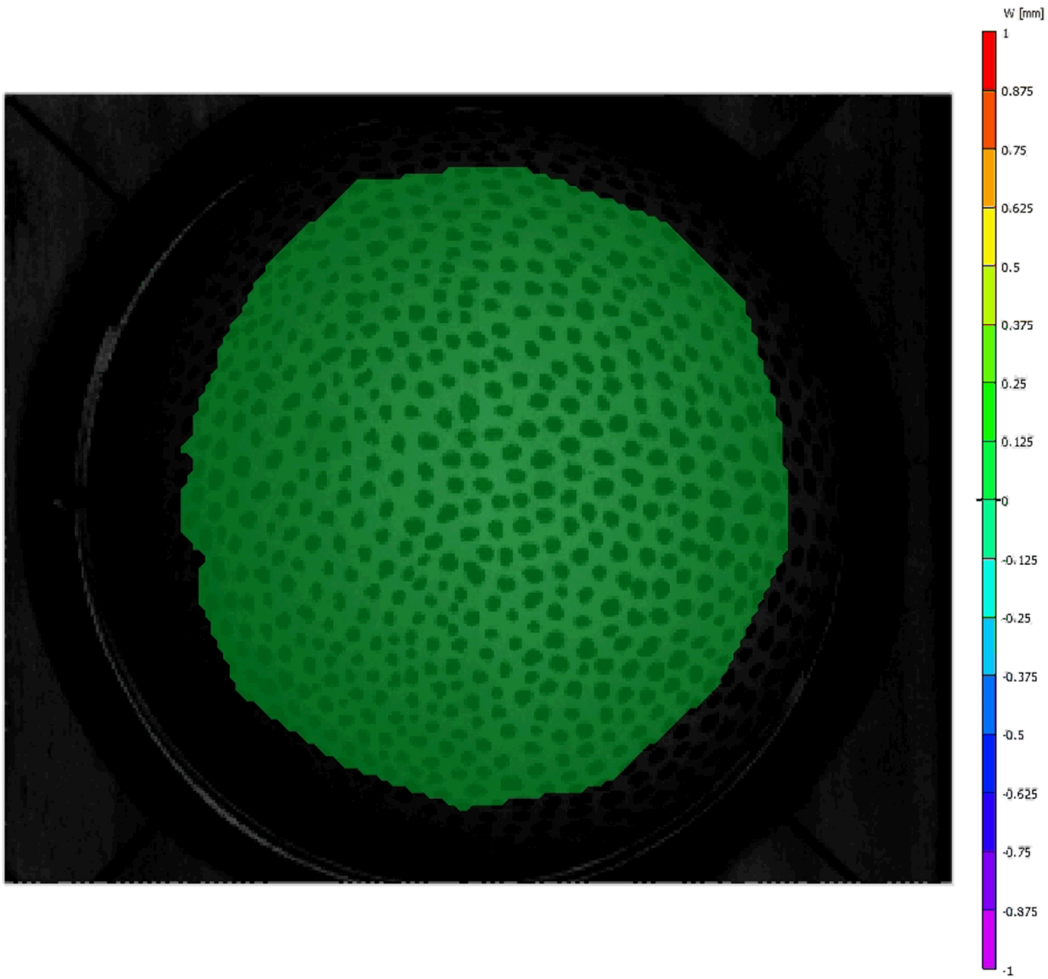


Type B
Optical Distortions

Estimated
Uncertainty of 3D
Position

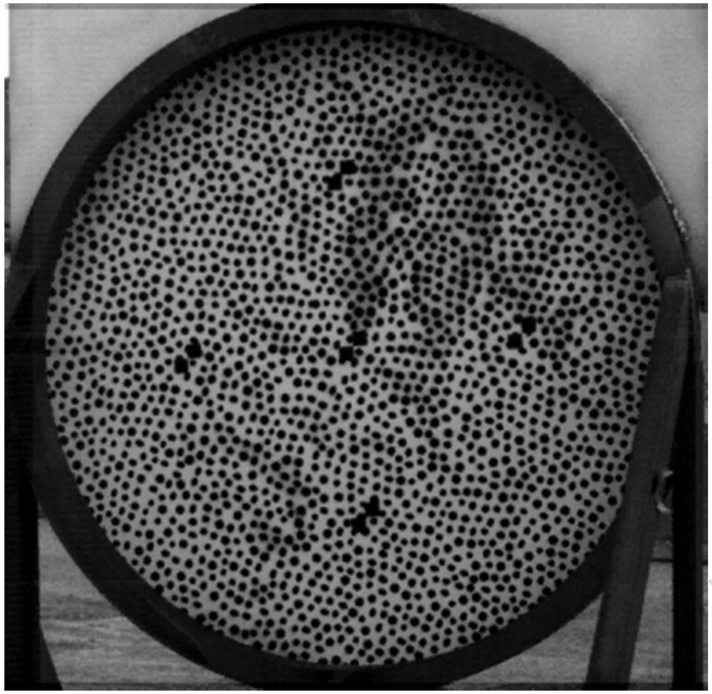
Typical displacement results at 1 Million frames per second

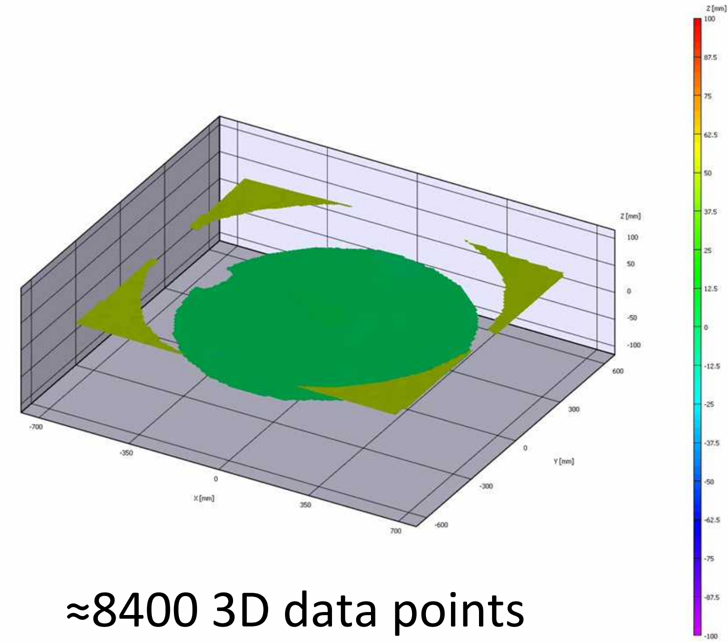




You can also get:
- 3D velocity
- Strain
- Strain rate

Example: Blast loaded plate at 35-kHz



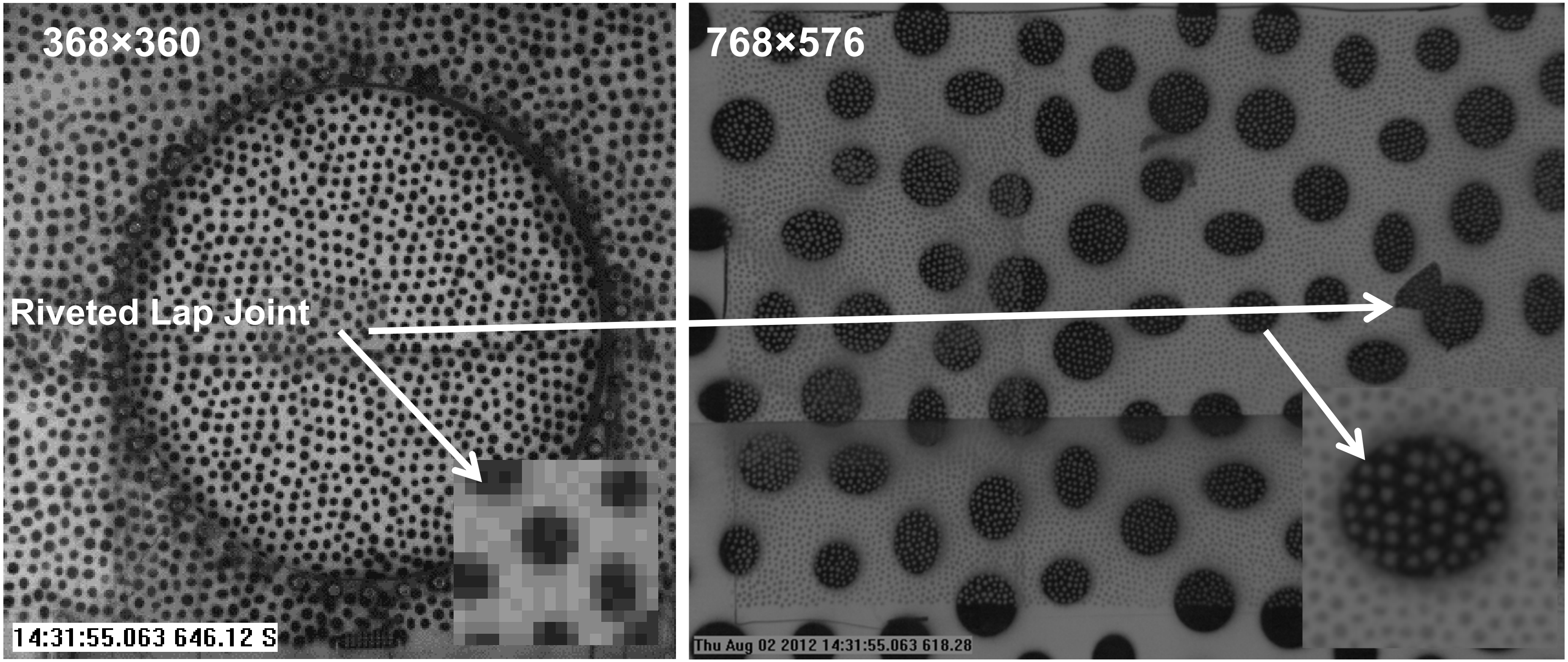


≈8400 3D data points

≈25 ft

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

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.

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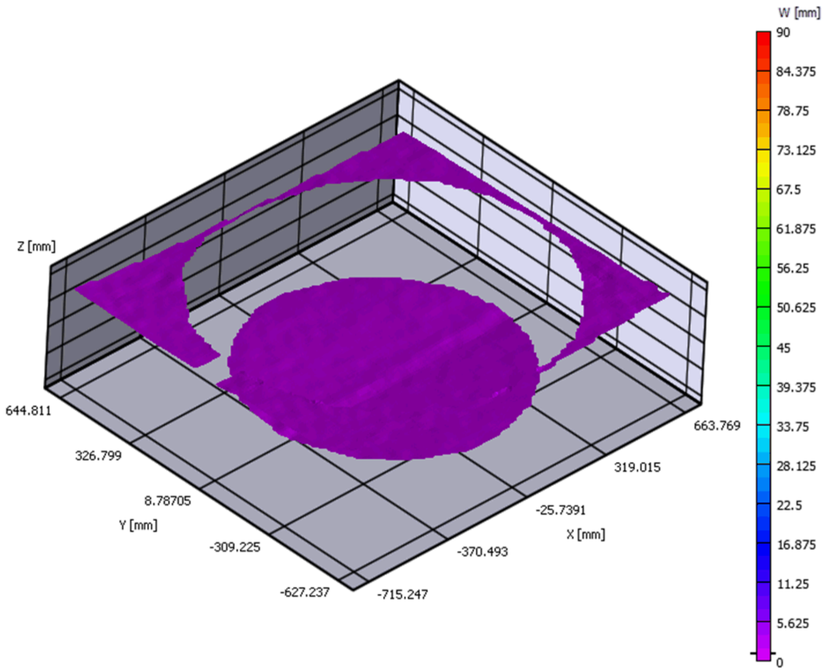
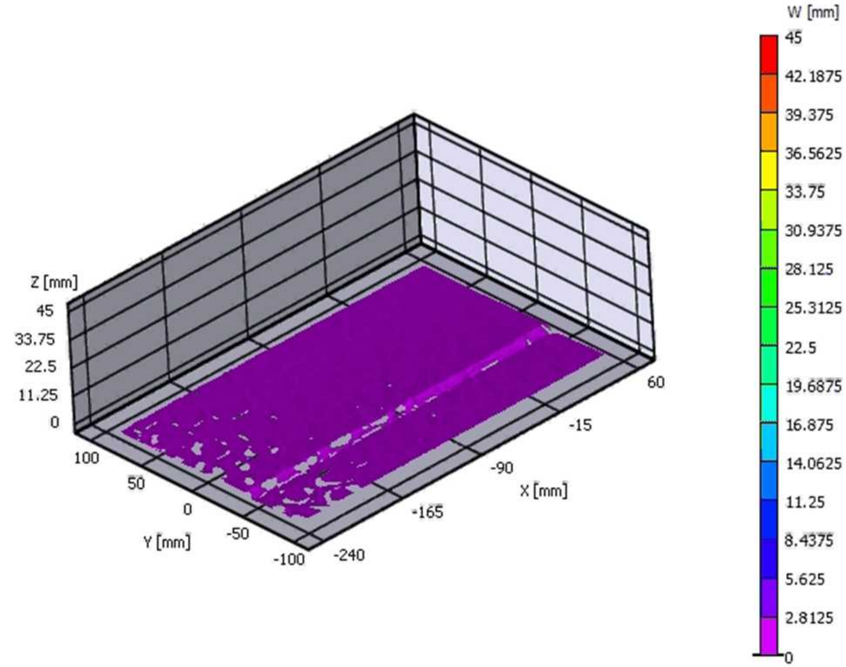
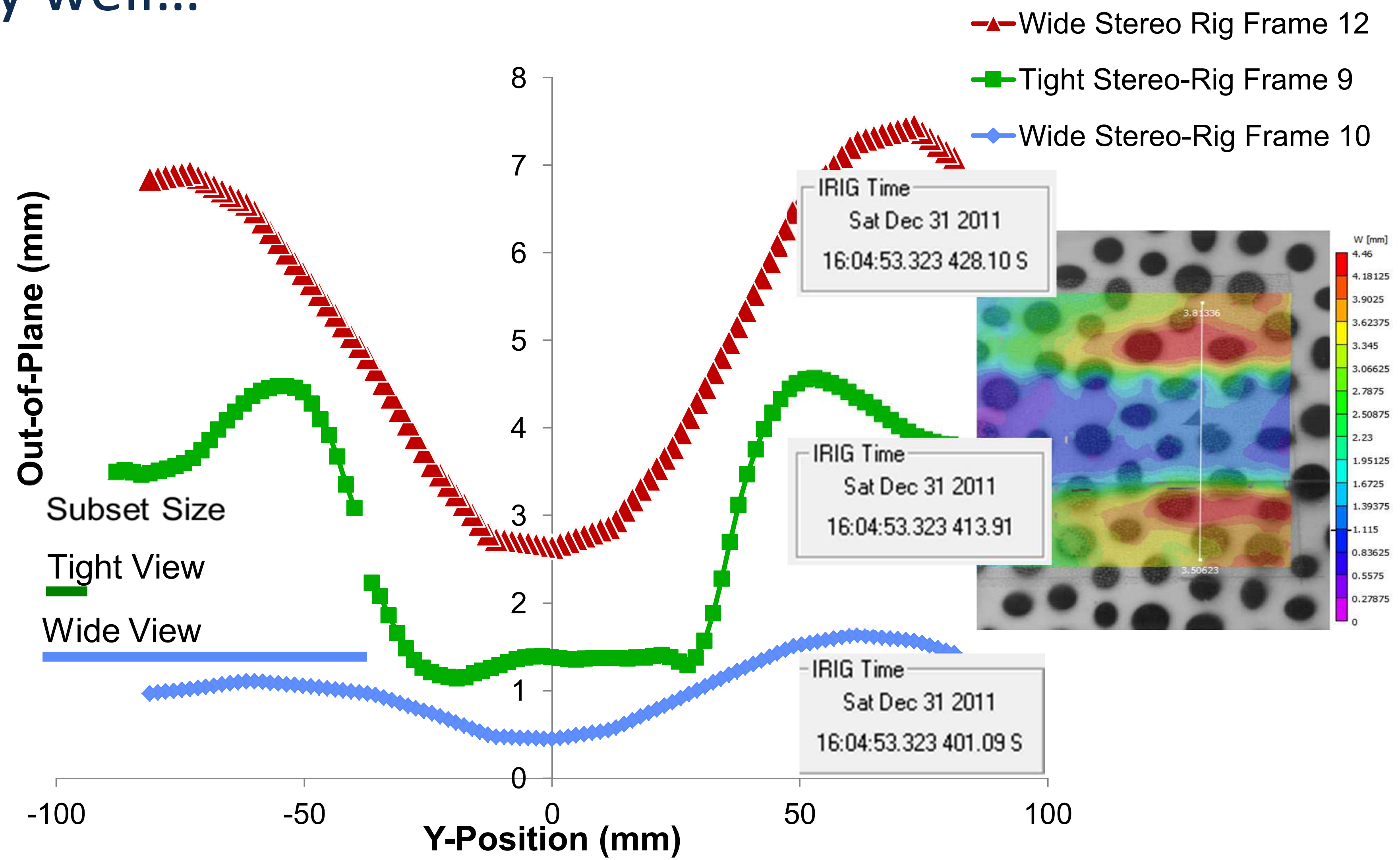




2 Stereo-DIC Systems
≈37,000 fps 368×360 Wide View
≈33,000 fps 768×576 Tight View

The overall and tight results compare very well…



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

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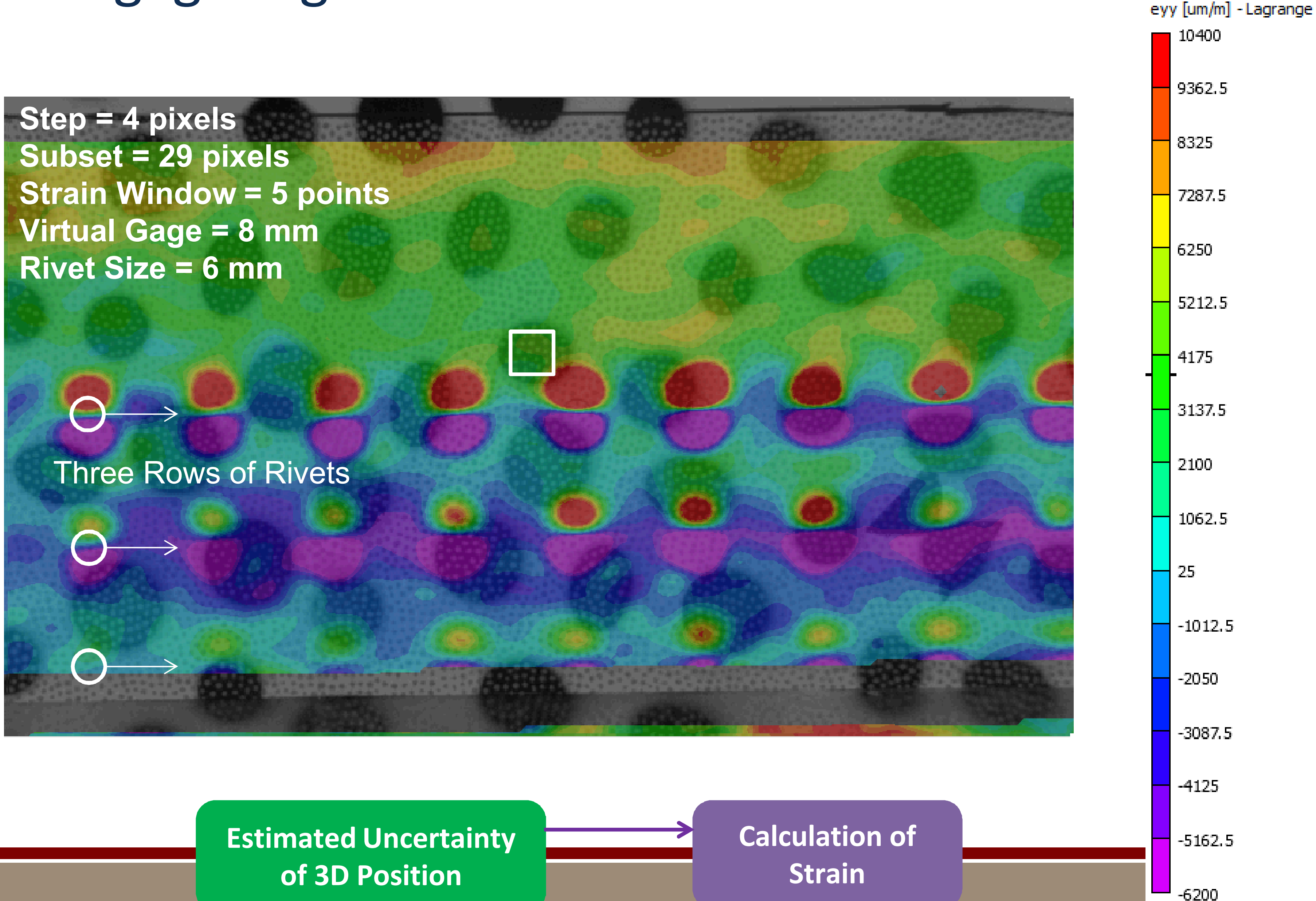

Estimated Uncertainty of 3D Position → **Calculation of Strain**

International Digital Image Correlation Society – Talks dedicated to DIC

Sandia National Laboratories

- A society dedicated to Digital Image Correlation.

November 8-10, 2016
Philadelphia, PA

- A conference covering the wide range of DIC applications.
- DIC best practices
- DIC Standards development
- Improved training beyond vendor provided – and agnostic of DIC software.

THE ART AND APPLICATION OF DIC

Calibration: Stereo Calibration

by Phillip Reu

SEM

DIC course
Metrology beyond colors

Developments, Applications and Tutorials in Experimental Mechanics Techniques
EXPERIMENTAL **TECHNIQUES**