Exceptional service in the national interest

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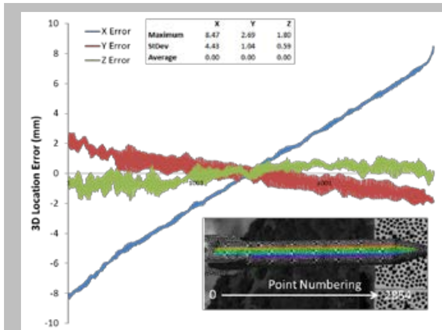

The evolution of high and ultra-high speed imaging from qualitative to quantitative

“Seeing is Believing”
“Measuring is Understanding”

Phillip L. Reu and Mark Nissen

BSSM High Speed Imaging – London England

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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

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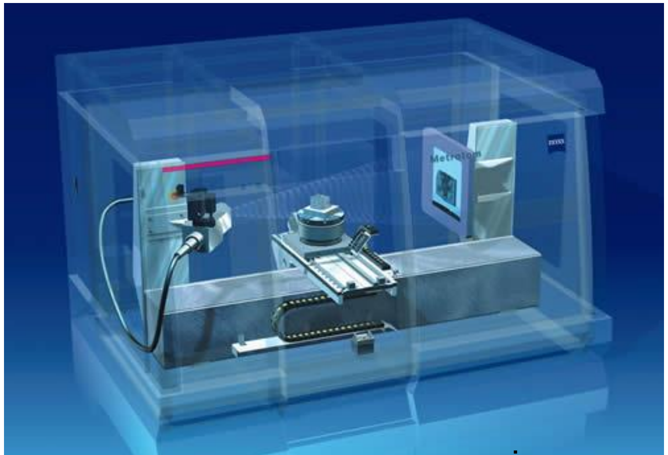
SEM/AFM

www.jeol.com

CT Scanner



www.zeiss.com

High Resolution Machine Vision

http://www.alliedvisiontec.com

High and Ultra-high Speed Imaging

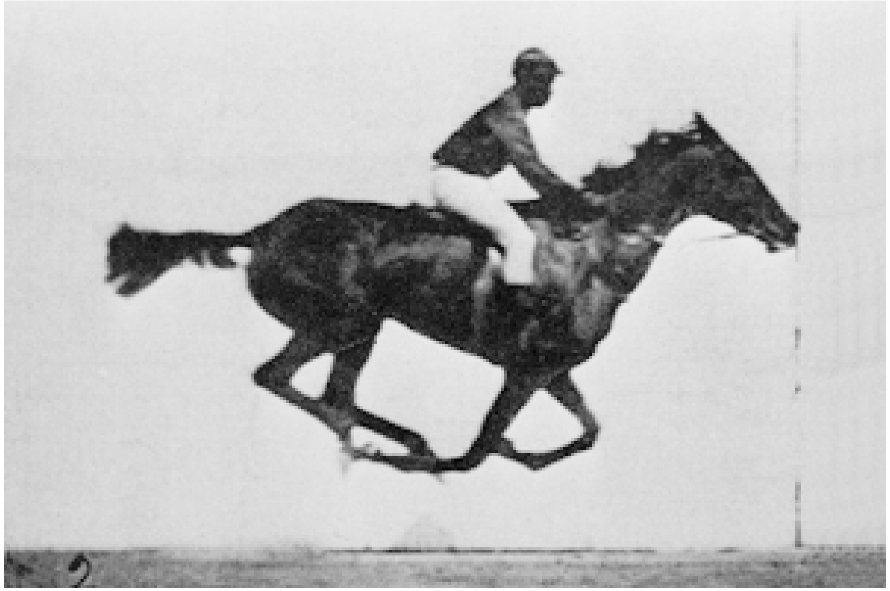
www.visionresearch.com

www.photron.com

www.shimadzu.com

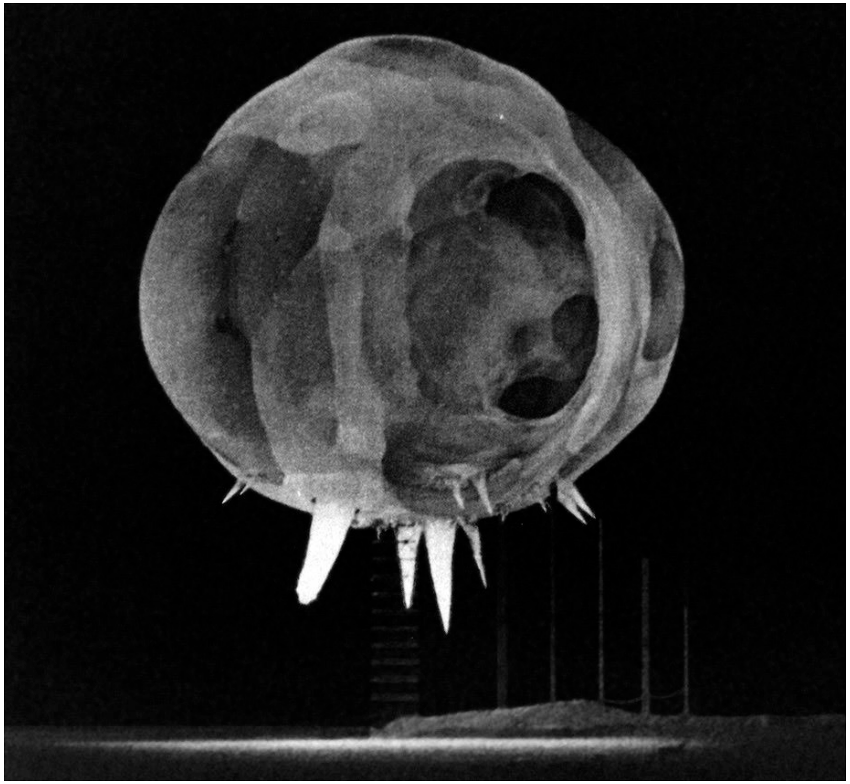
Why we need high speed.

High speed helps to understand things too fast for human perception.



Eadweard Muybridge (1878)

- Multiple cameras lined up and triggered by a thread.
- Later used clock work timing.



Harold Edgerton (1940s)

- Nanosecond to microsecond exposures.
- Done with polarization and Faraday or Kerr cells for shuttering.

http://en.wikipedia.org/wiki/High-speed_photography

Some vintage high-speed cameras

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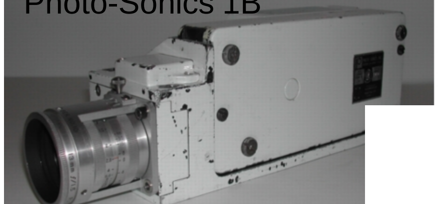
Cameras in picture:

1. Redlake Hycam II (16-mm @ 1000fps)
2. Sandia Image Motion (127-mm film)
3. Fastax Camera (35-mm also streak)
4. Kodak HG2000 Digital 1000 fps (512x386)

Other early Sandia Cameras:

1. Photo-Sonics 1B (16-mm @ 1000fps)
2. Photo-Kinetics Nova (film)

Photo-Sonics 1B



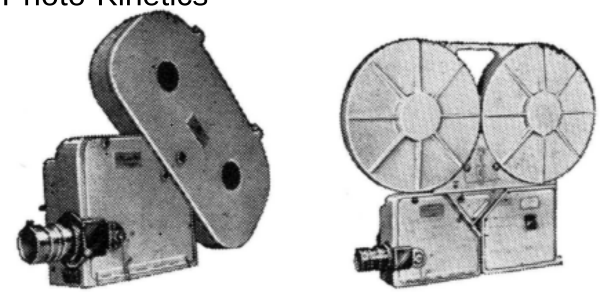
rocketryphotography.com

Kodak HG2000

Anfoworld.com

Vision Research – V7

Photo-Kinetics

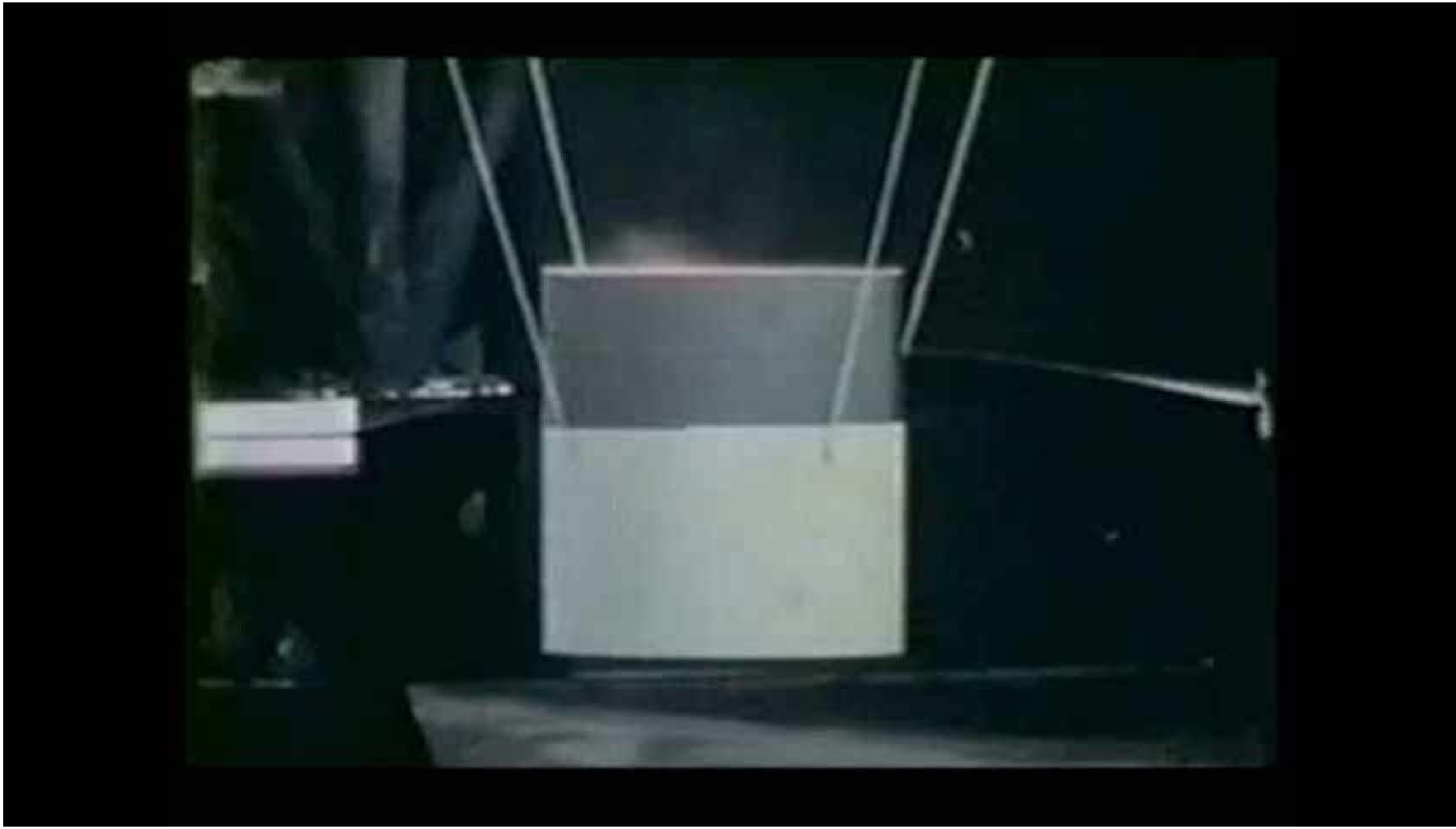


Spiedigitallibrary.org

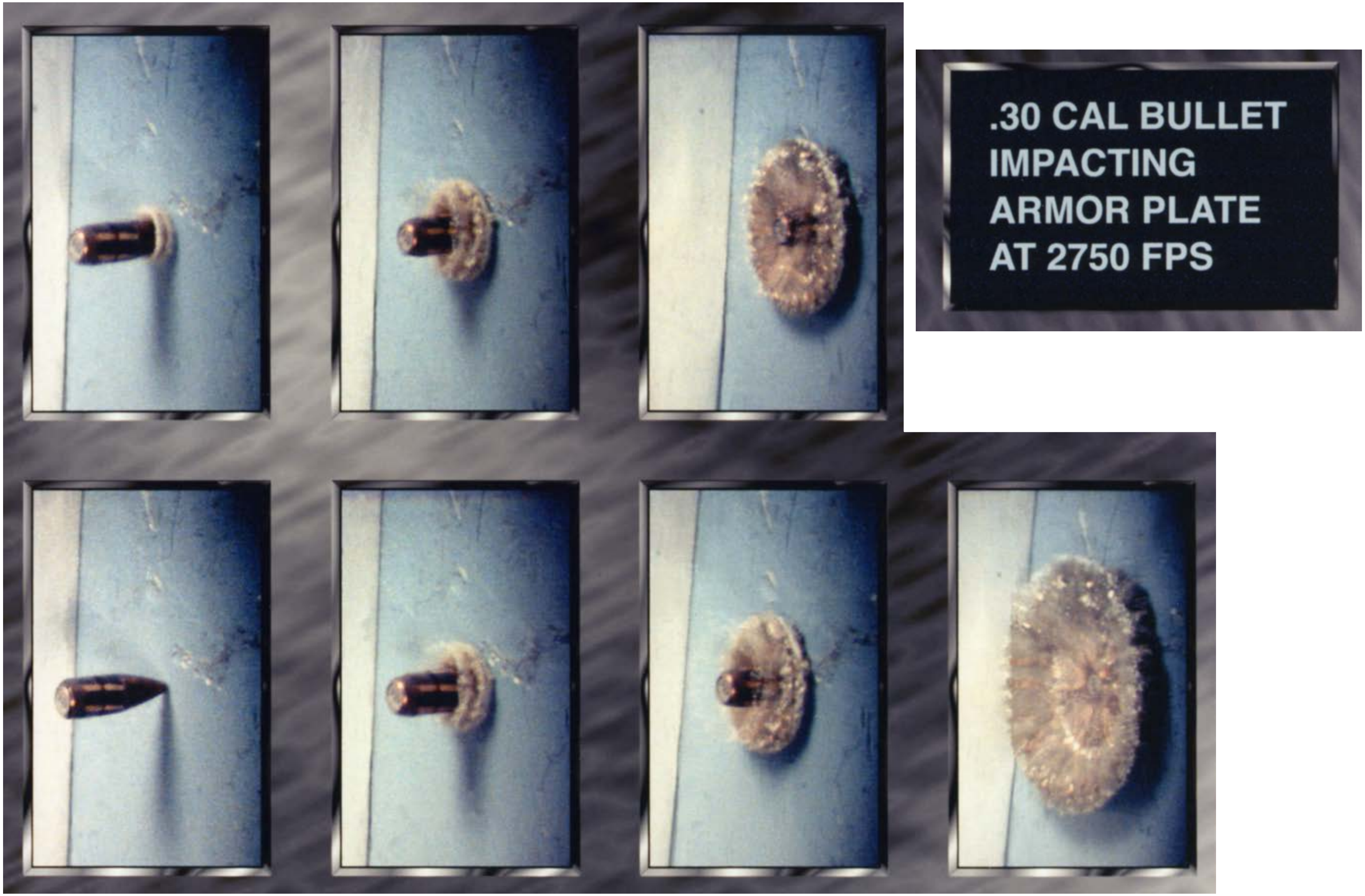
Film cameras

Rocket rail tests.

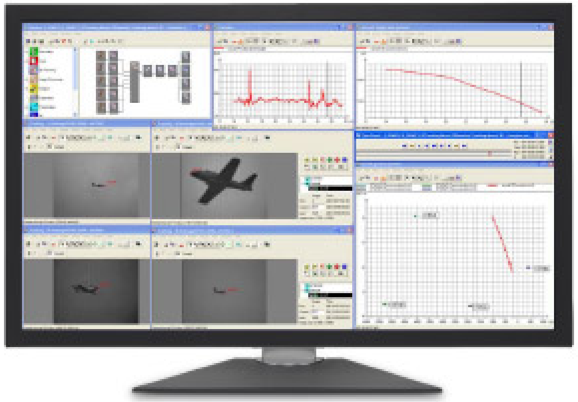
Tests using Film



1-Mfps film camera.

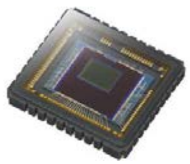


Scanning of film and extraction of fiducials was used for a few years.



Digital high speed imaging technology is quite varied.

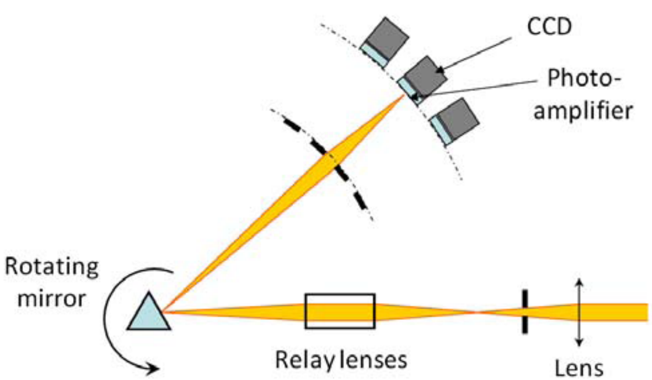
High-Speed Imaging



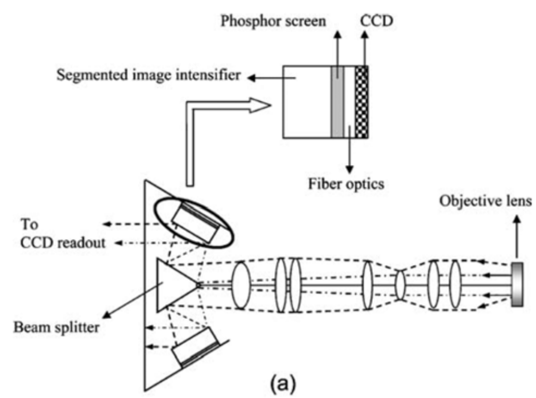
High-speed CMOS detector. Image off load rate from chip is the limiting factor.

Ultra High-Speed Imaging

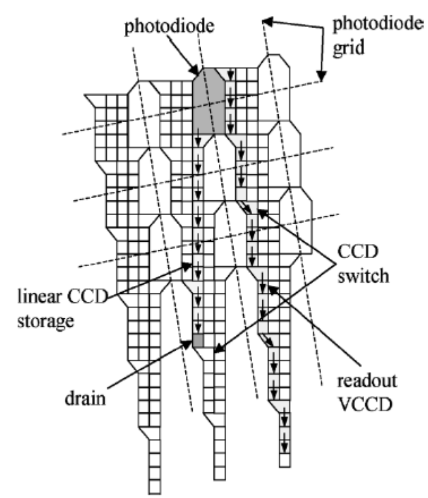
Rotating mirror (CORDIN)



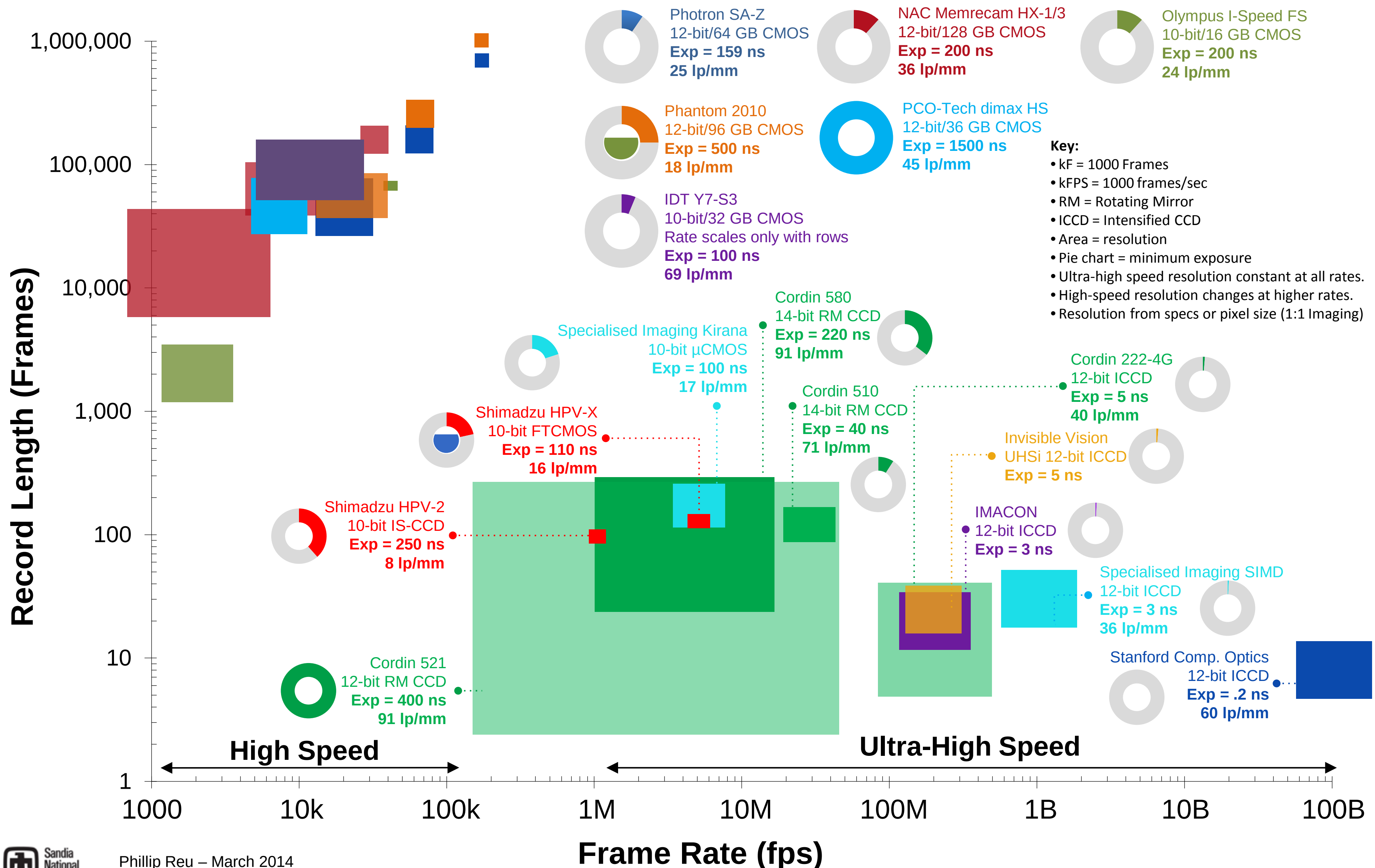
Beam splitting



On chip storage



The state of high-speed imaging



Photogrammetry and DIC have moved high speed imaging from qualitative to quantitative.

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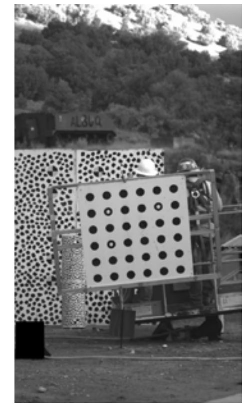
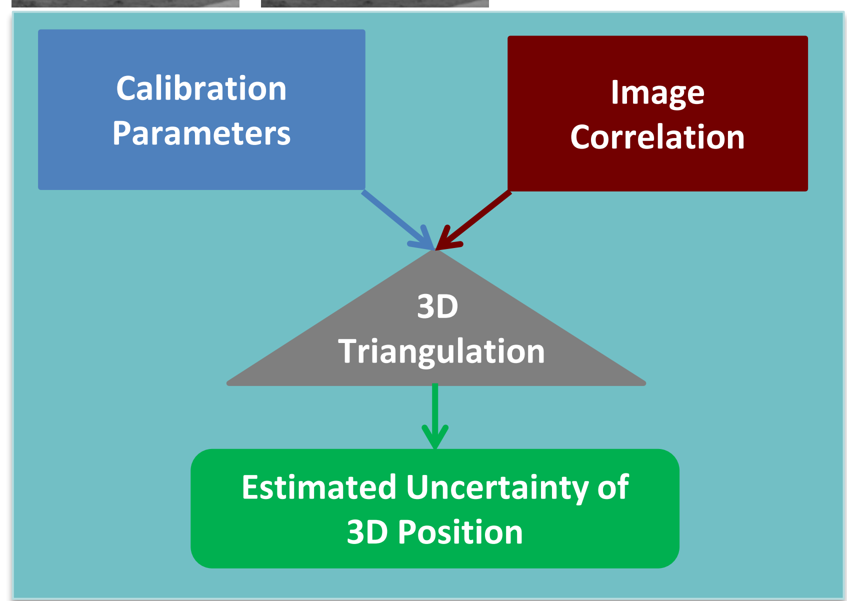
The difference is uncertainty quantification!



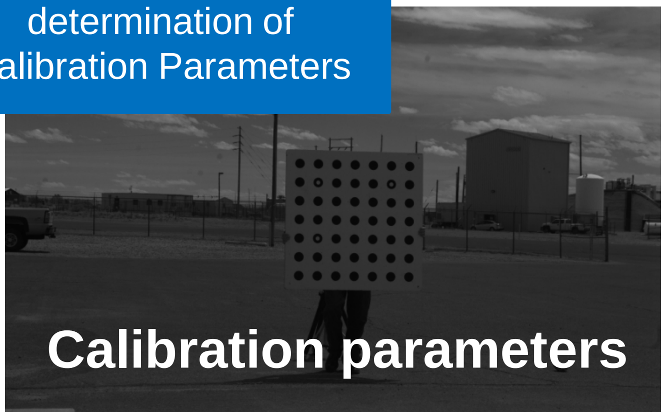
Possible stereo-rigs

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



How do you turn camera images into quantitative measurements?

Monte Carlo determination of Calibration Parameters

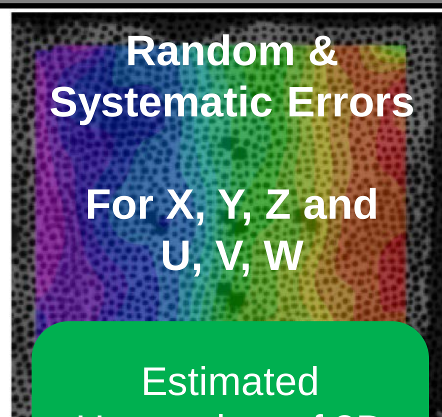


Determination of 2D and Cross-correlation Matching Errors

Random & Systematic Errors

Random & Systematic Errors

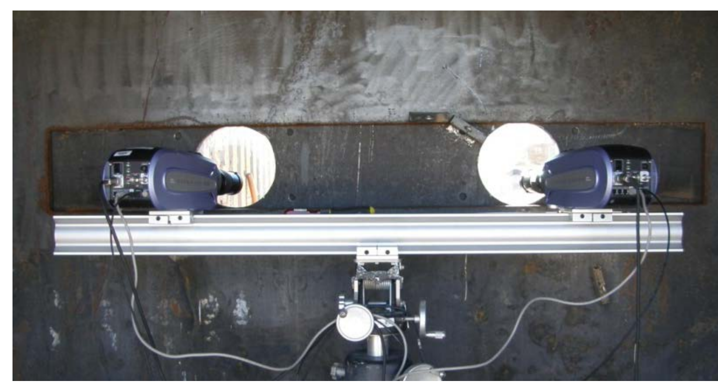
3D Triangulation



Estimated Uncertainty of 3D Position

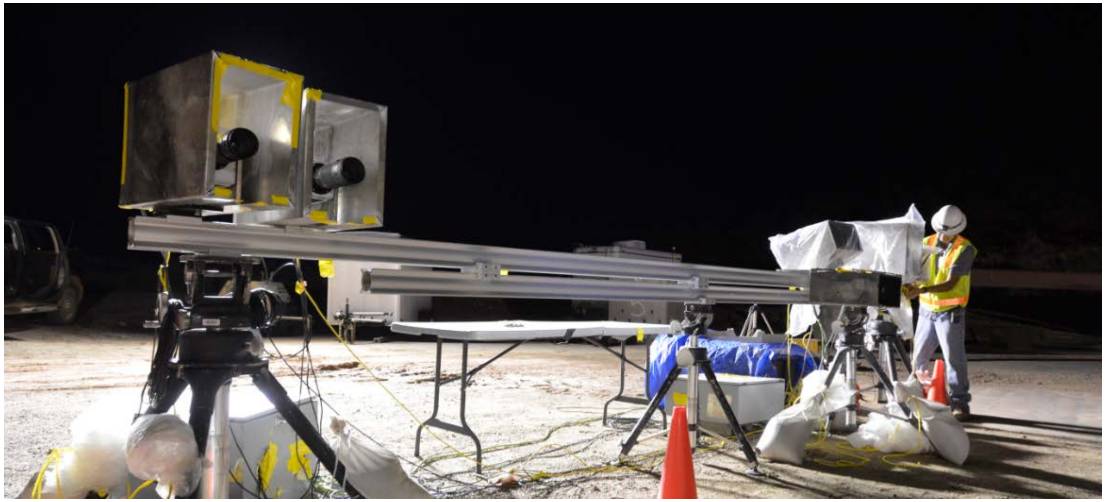
Ignoring:

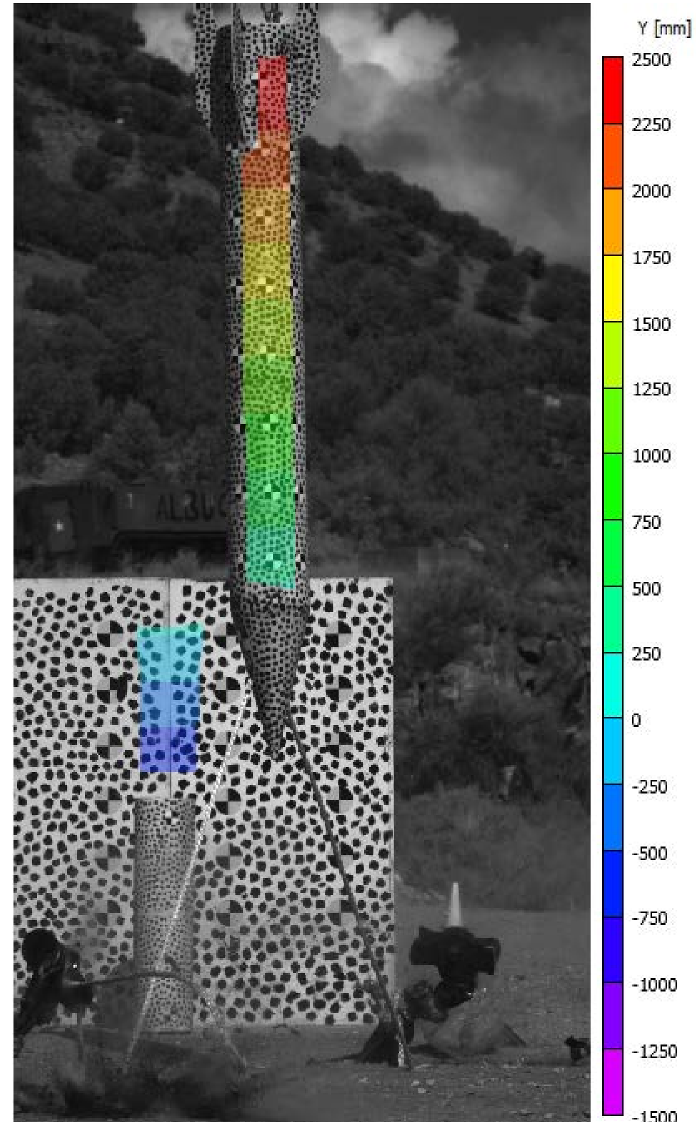
1. **Camera model problems**
2. **Shape function bias**
3. **Aliasing bias**
4. **Unknown unknowns**



Example: Quantitative high speed measurements at 6 kHz

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?

The simulation repeatedly triangulates while varying one or more parameters

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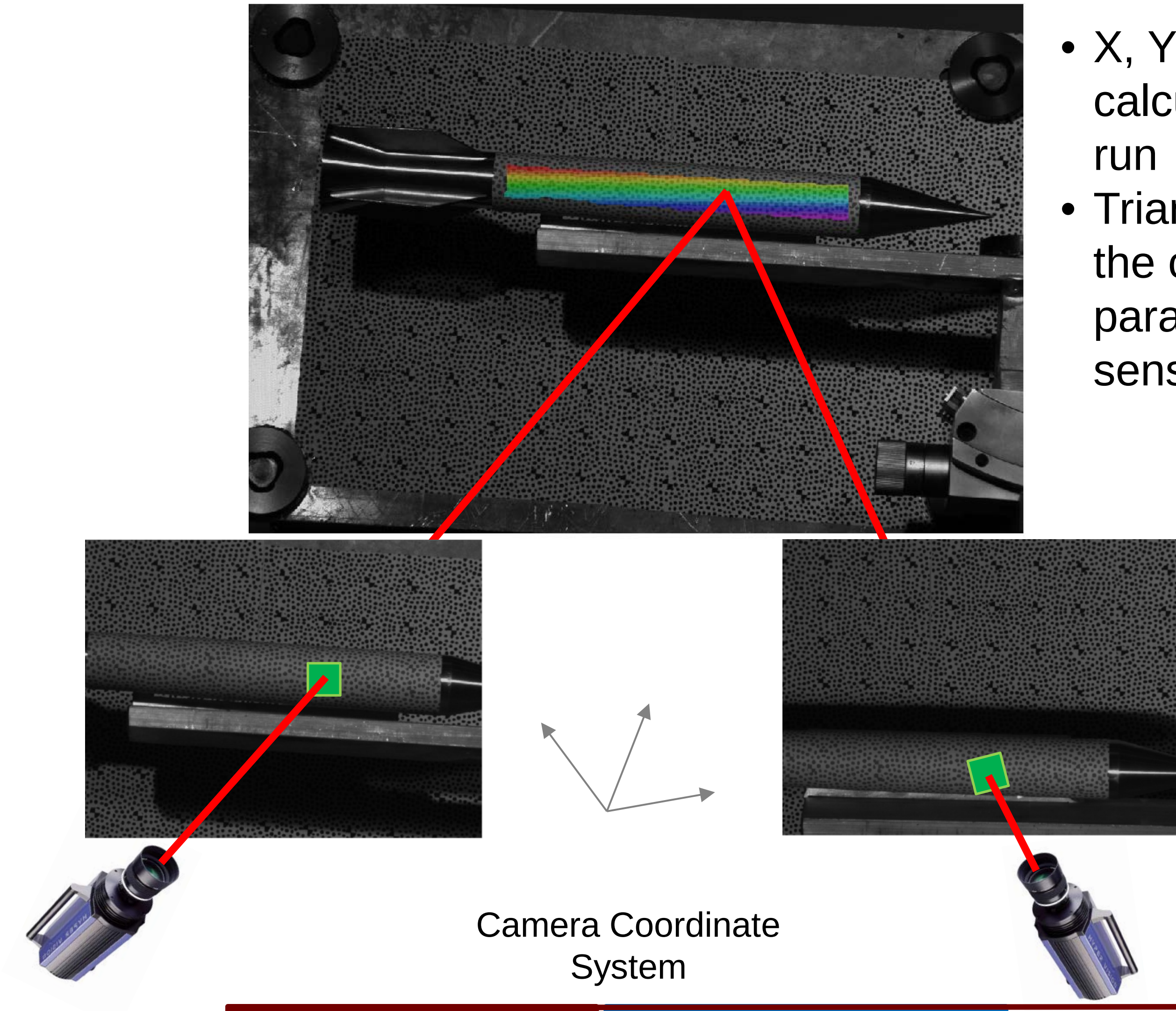
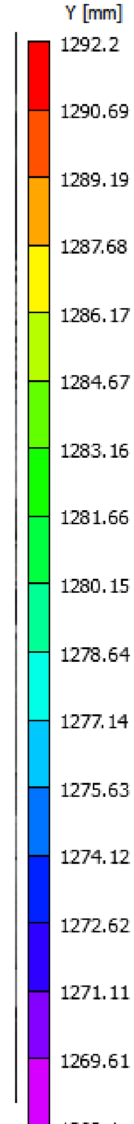


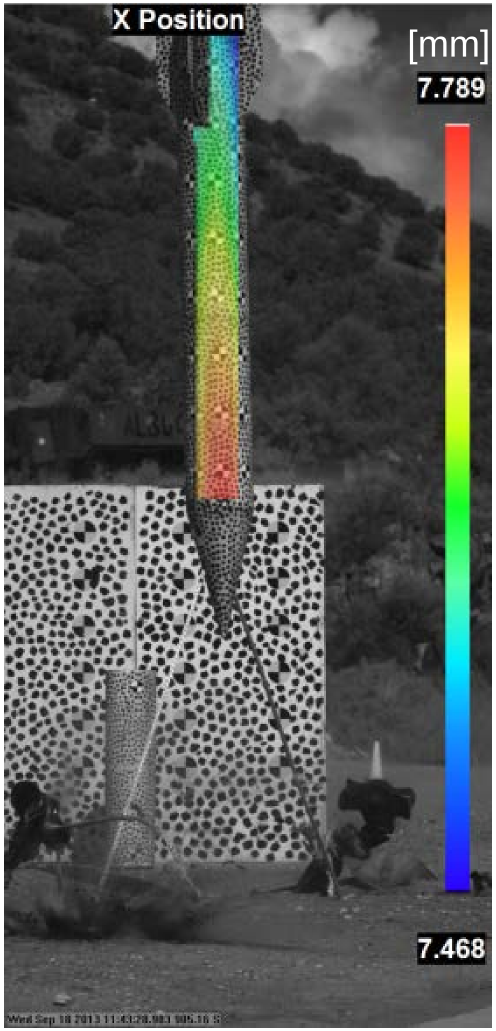
- X, Y and Z are calculated for each run
- Triangulation uses the calibration parameters and sensor positions.

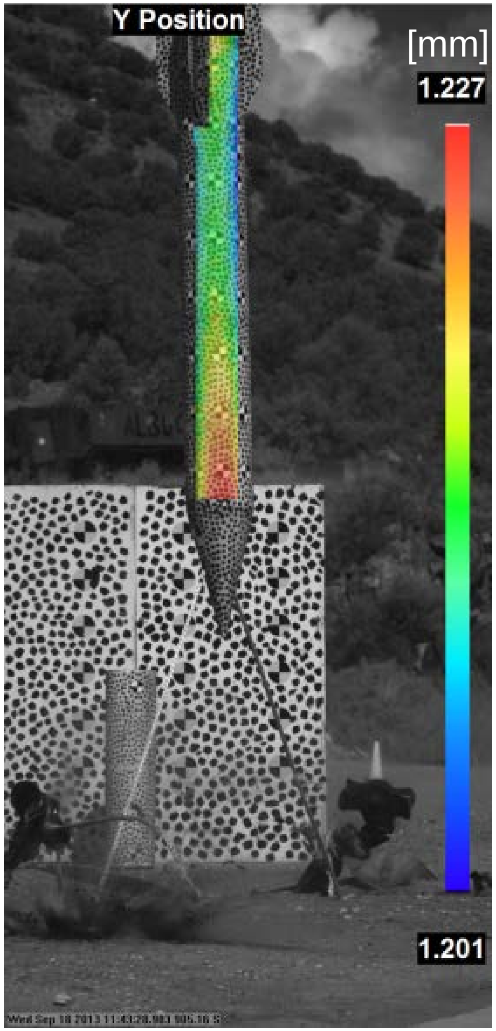


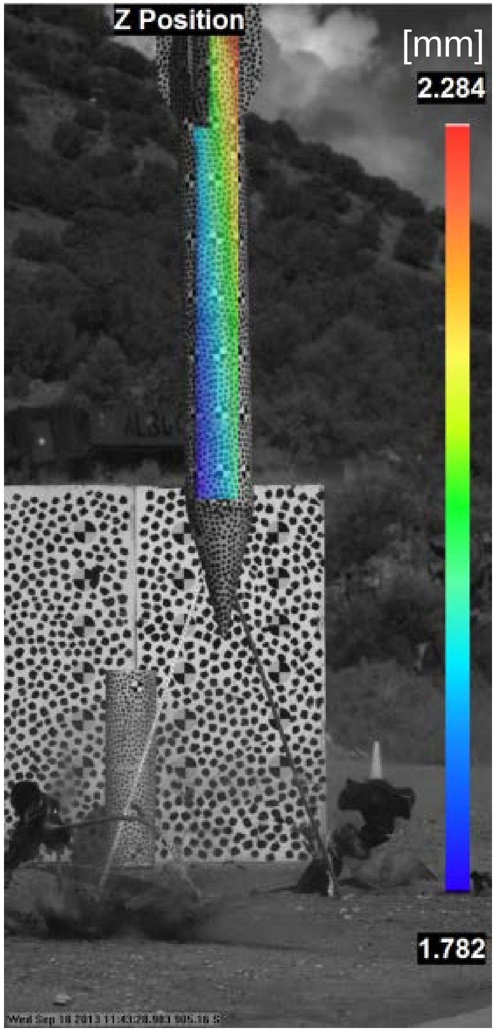
Determination of 2D and Cross-correlation Matching Errors → Monte Carlo determination of Calibration Parameters → 3D Triangulation → Estimated Uncertainty of 3D Position

The errors can be propagated to calculate a 3D uncertainty.

Includes Calibration and Sensor







Example: Cased explosive at 1 MHz

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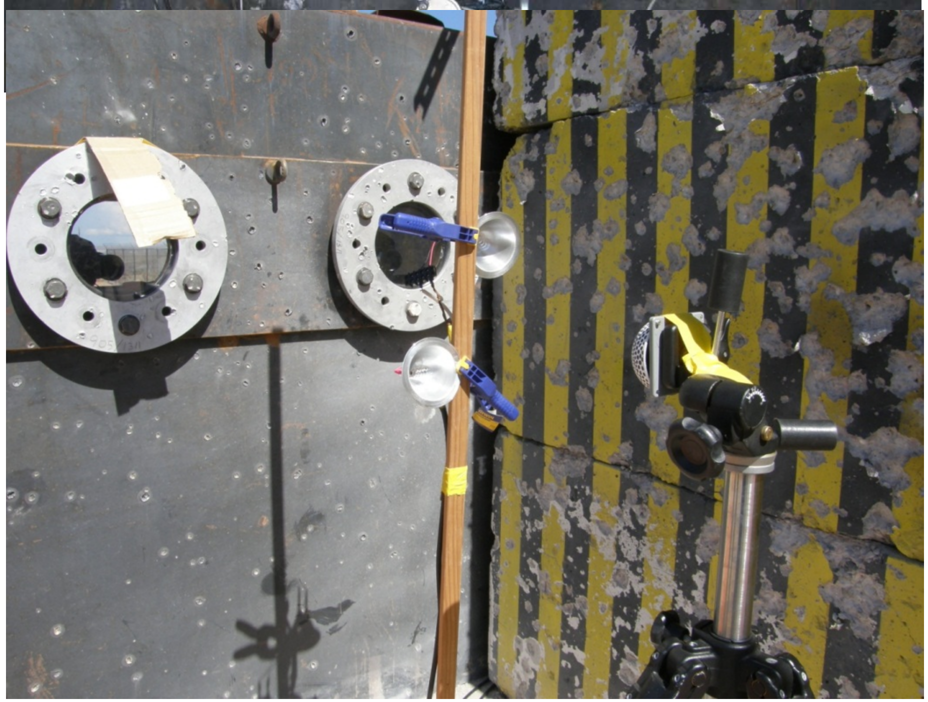

Optical distortions must be considered beyond the lens.

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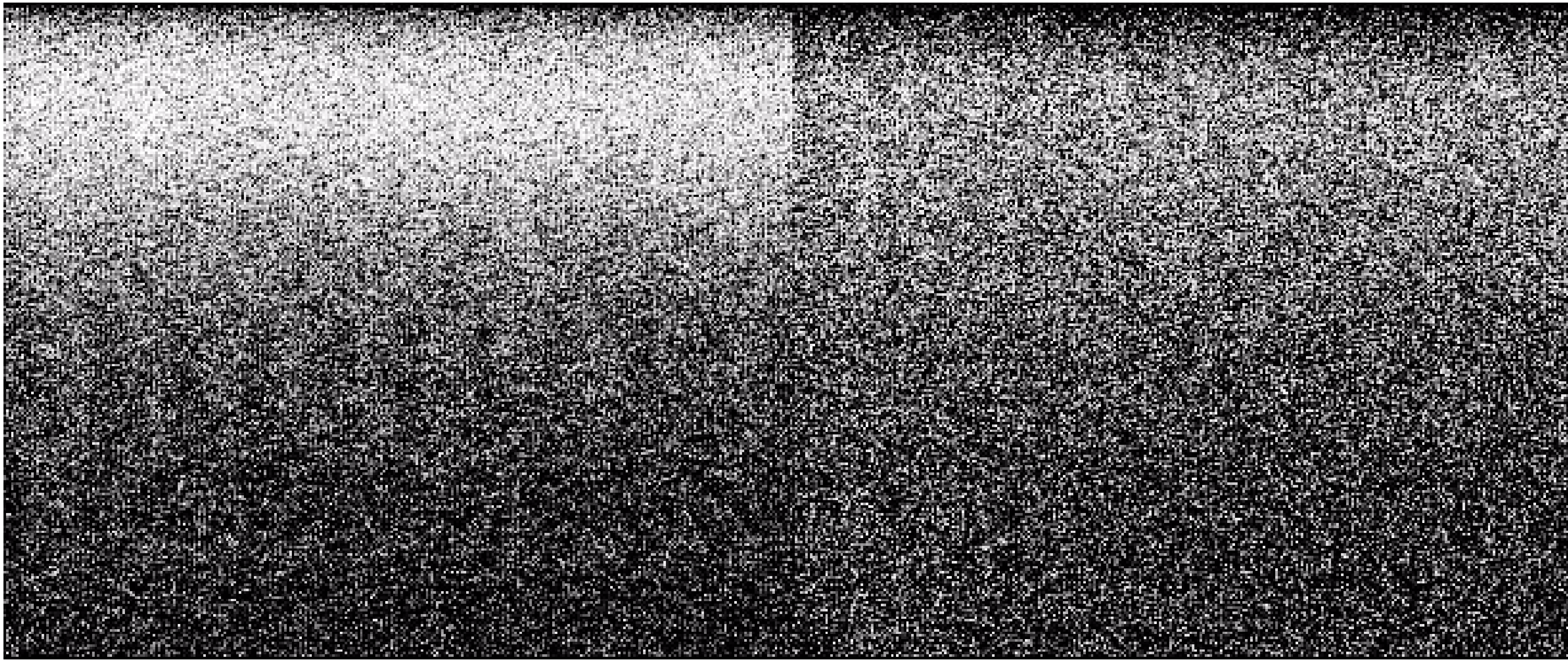
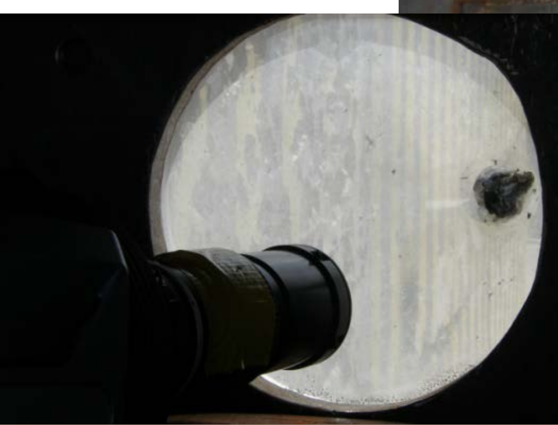


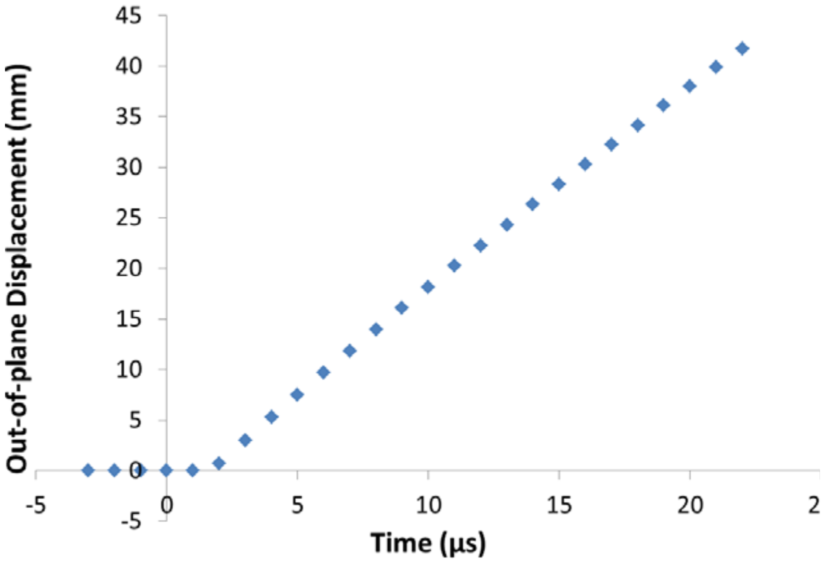


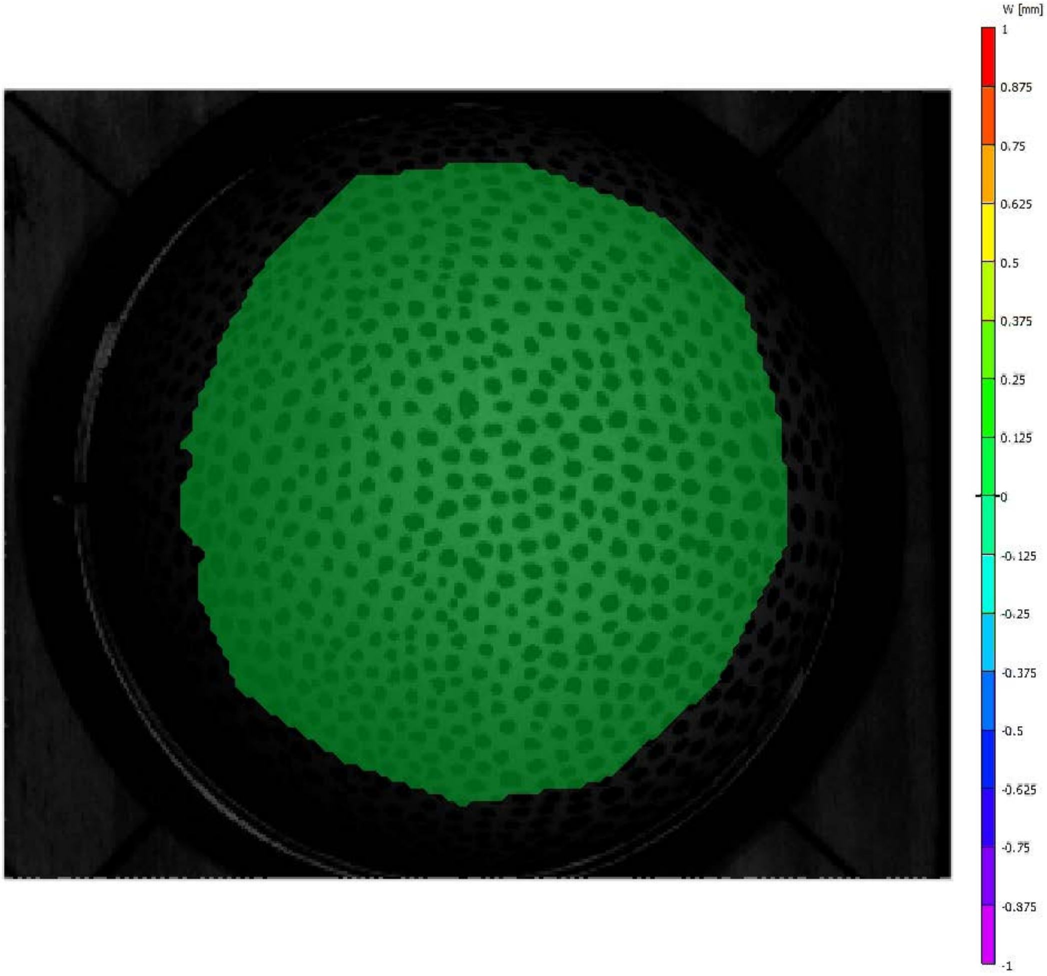
Type B
Optical Distortions

→

Estimated Uncertainty of 3D Position

Typical displacement results at 1 Million frames per second

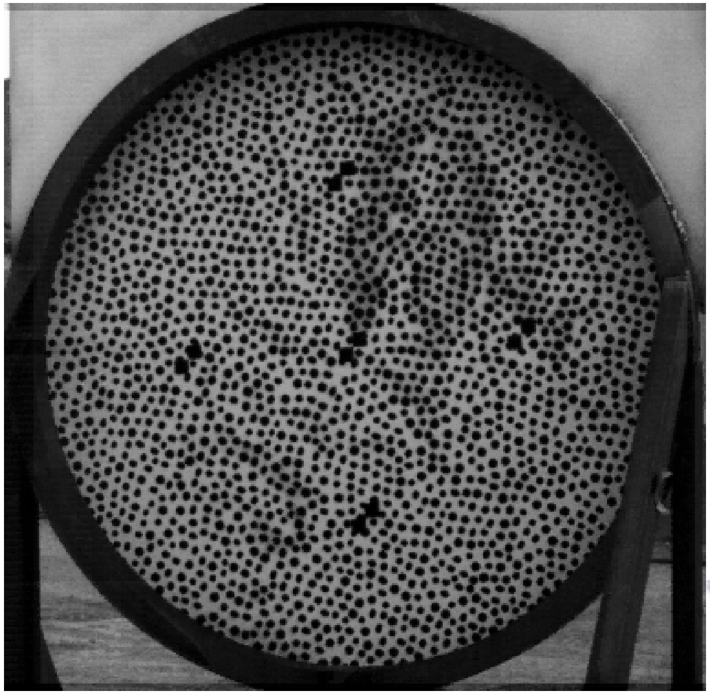


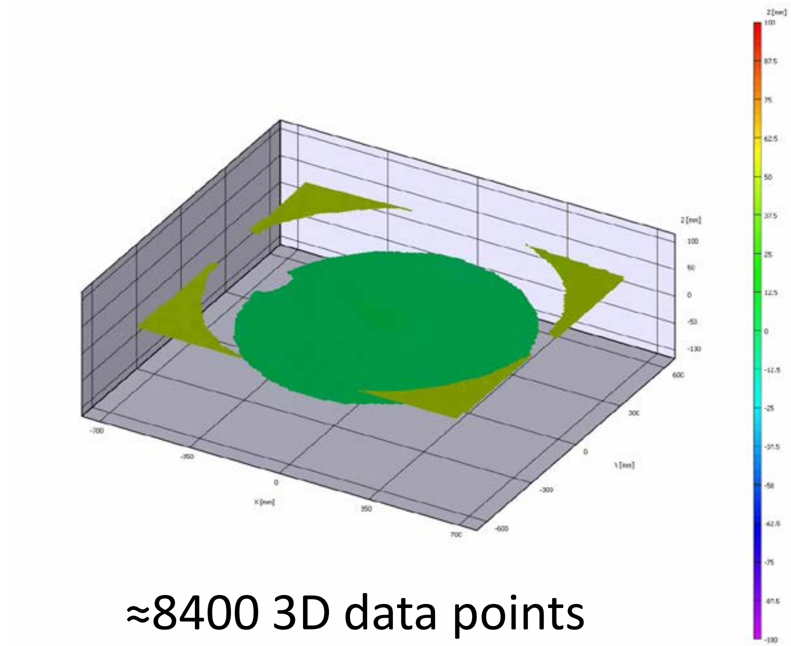


You can also get:

- 3D velocity
- Strain
- Strain rate

Example: Blast loaded plate at 35-kHz



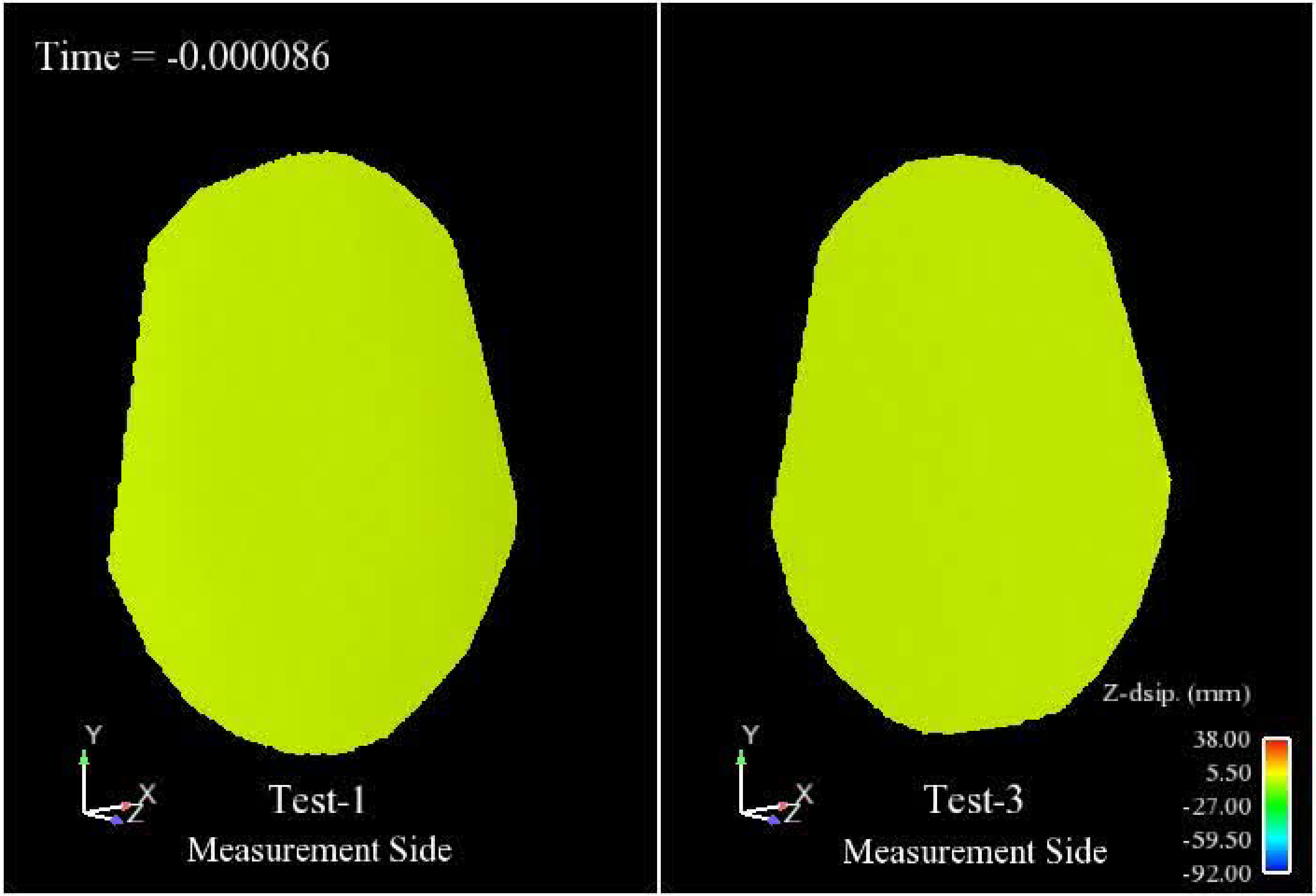


≈8400 3D data points

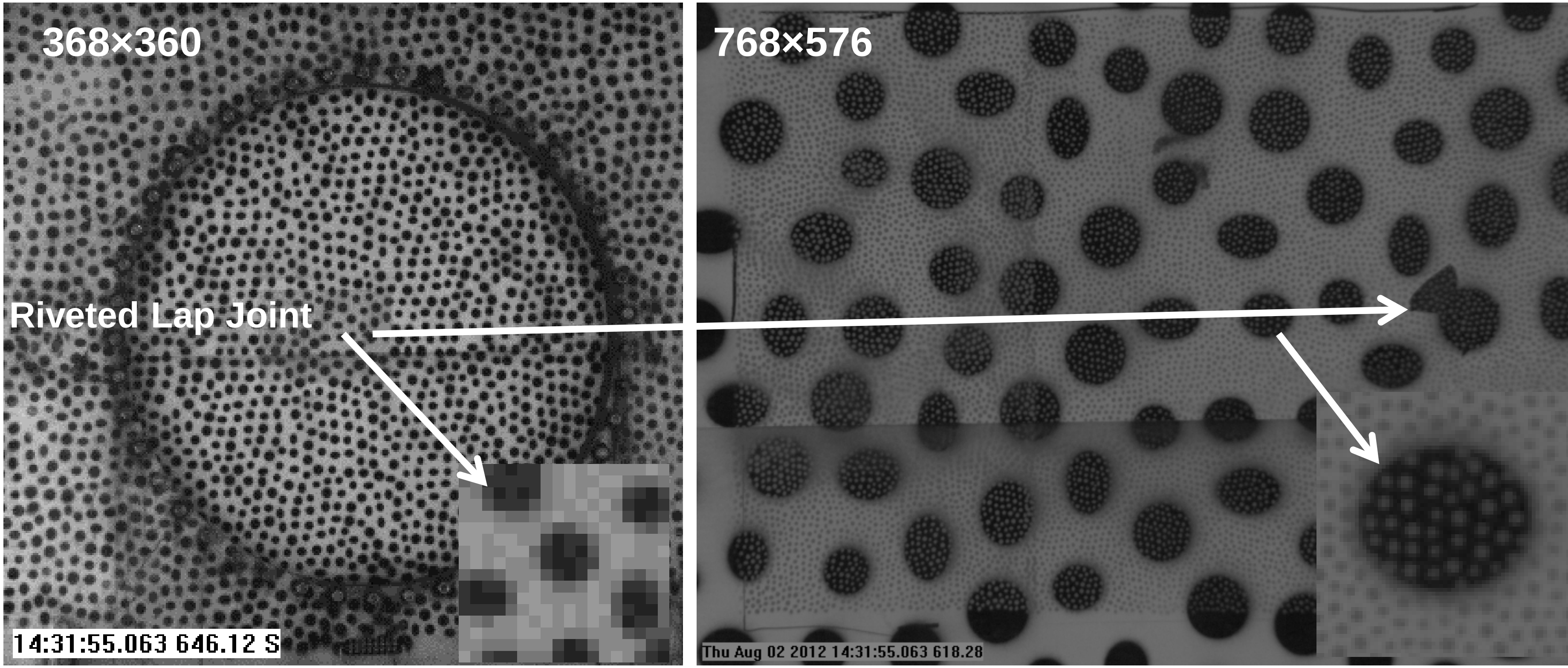
≈25 ft

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

Full-field data helps with understanding the experiment.



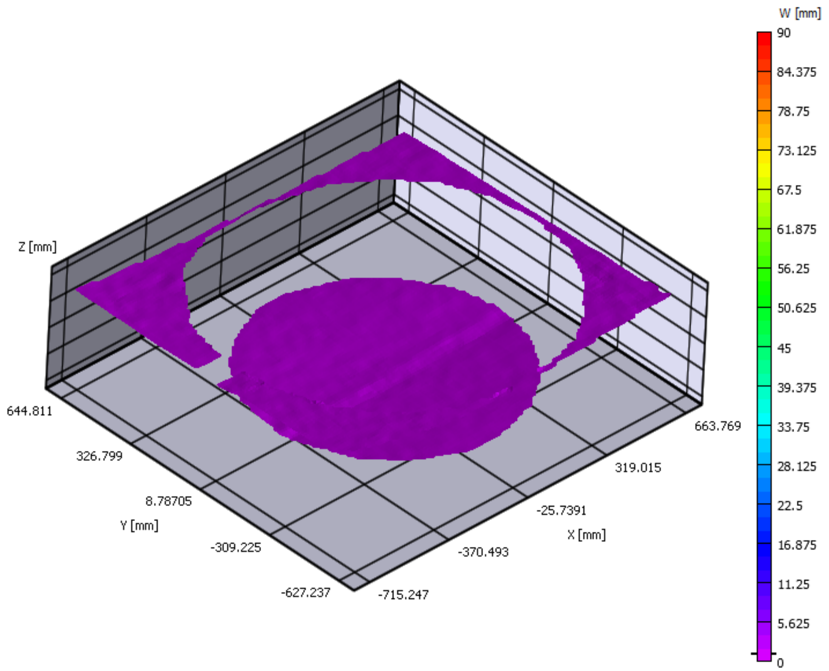
Example: Simultaneous strain and displacement at 36 kHz.

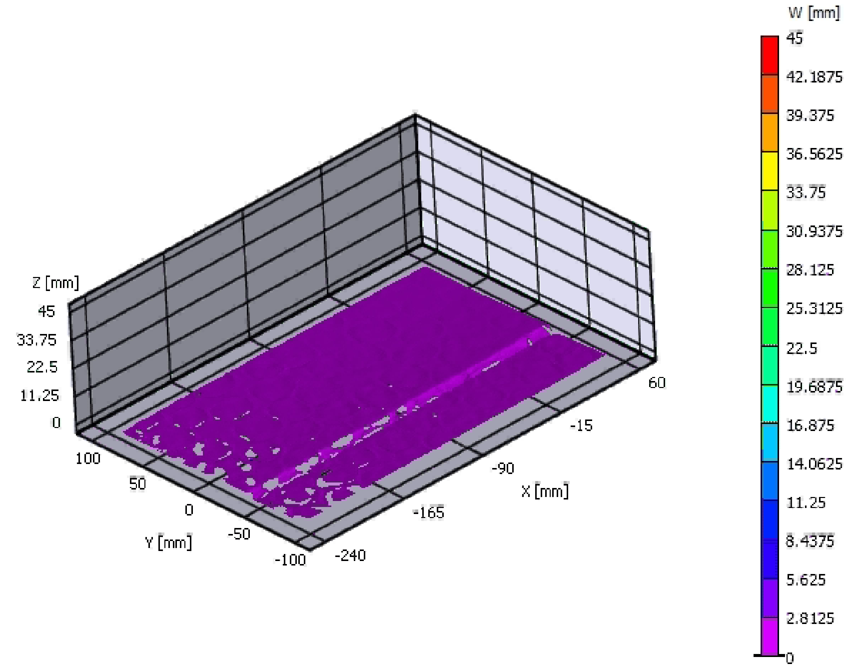


4 mm/pixel **0.4 mm/pixel**

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

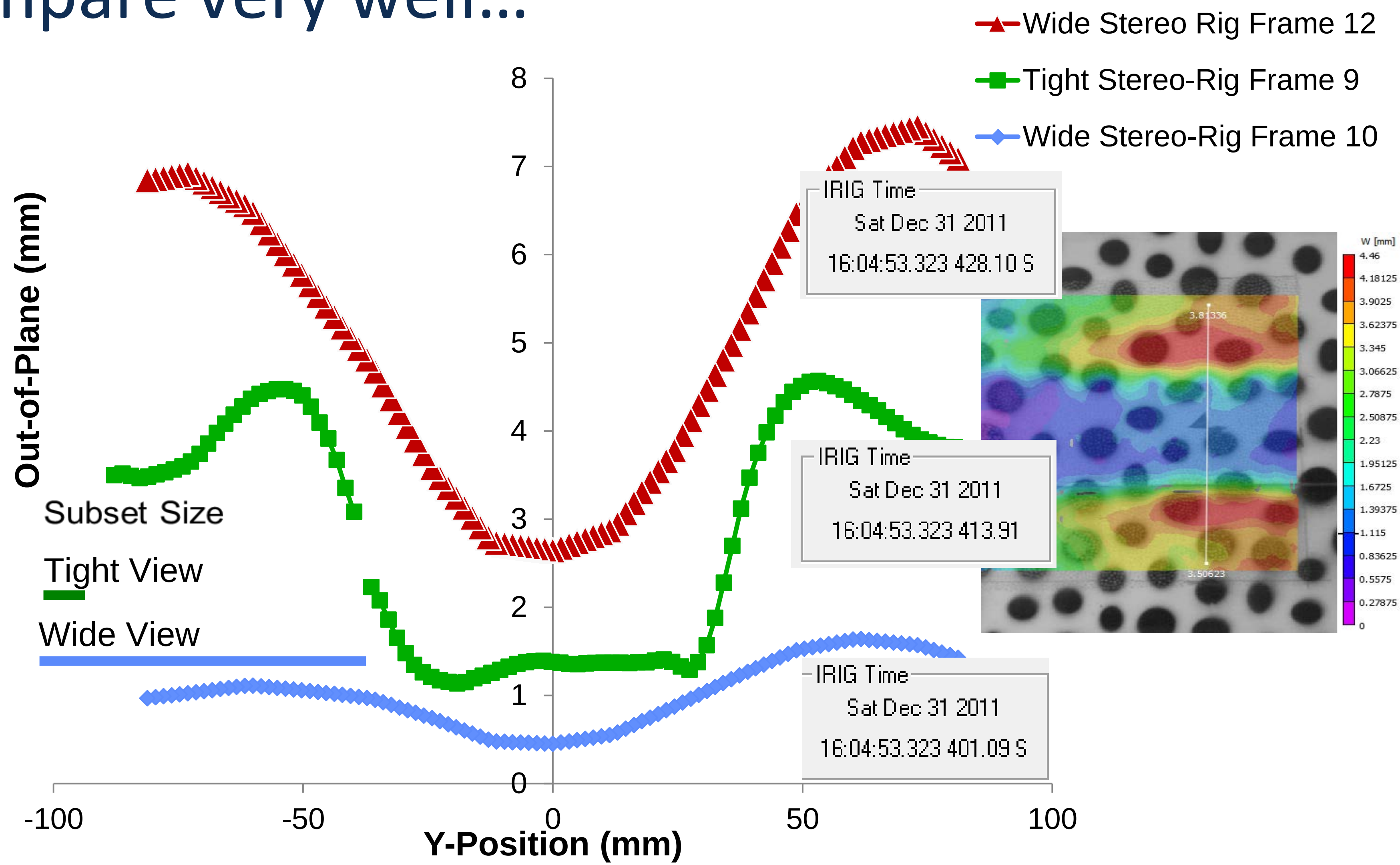
We have two systems to measure at two different spatial resolutions.



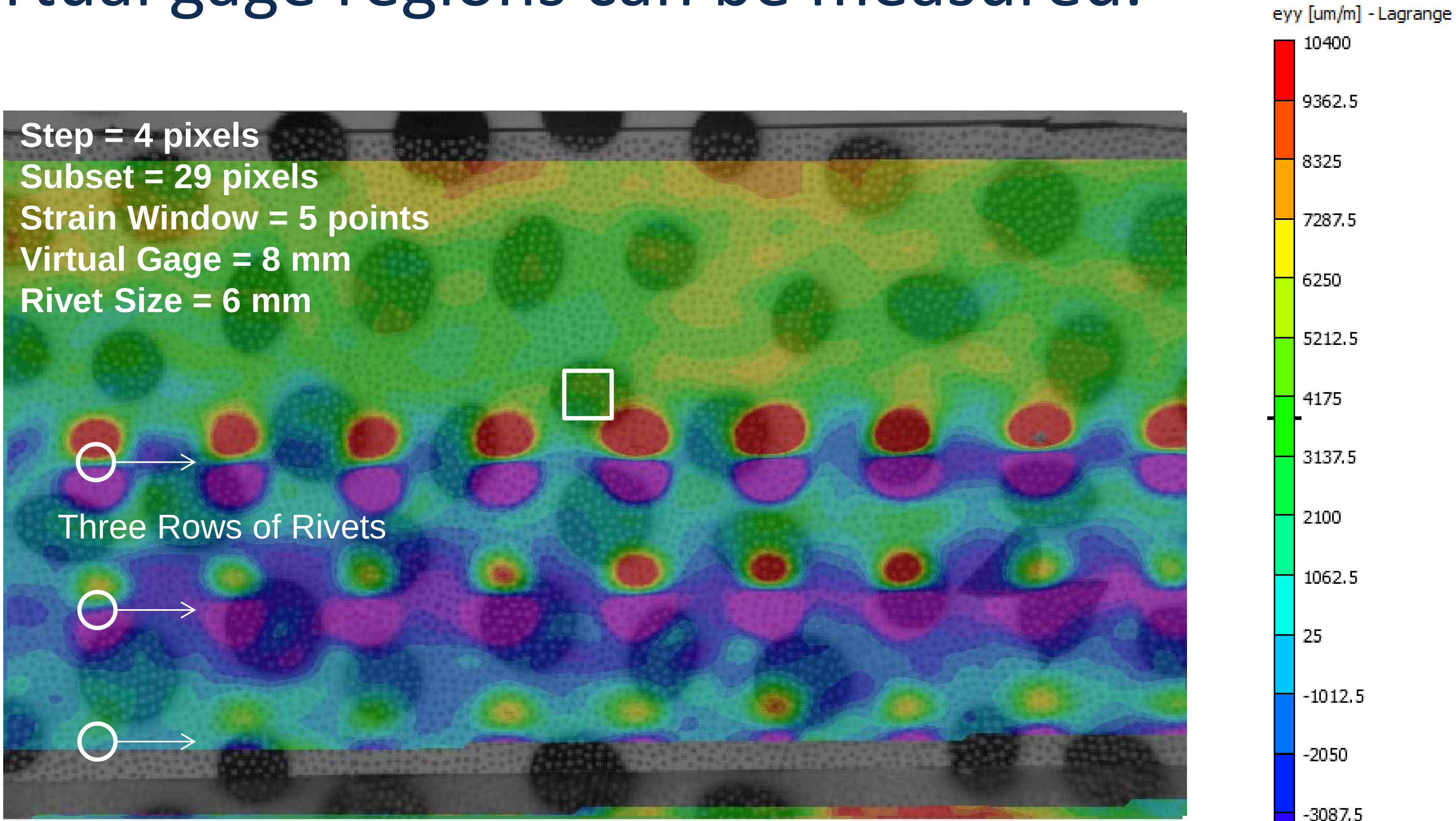


2 Stereo-DIC Systems
≈37,000 fps 368×360 Wide View
≈33,000 fps 768×576 Tight View

The overall and tight results compare very well…

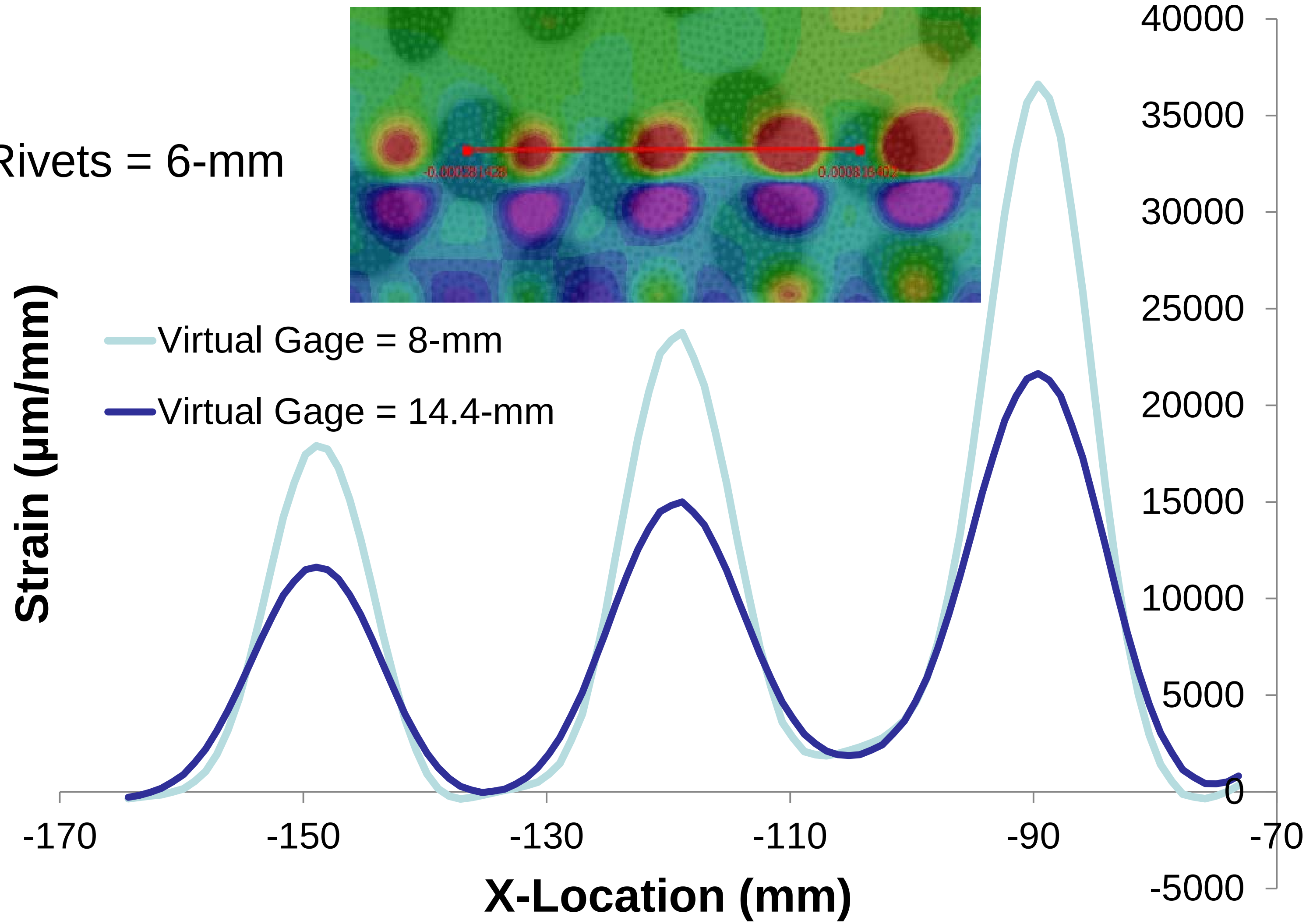


With proper experimental design small virtual gage regions can be measured.



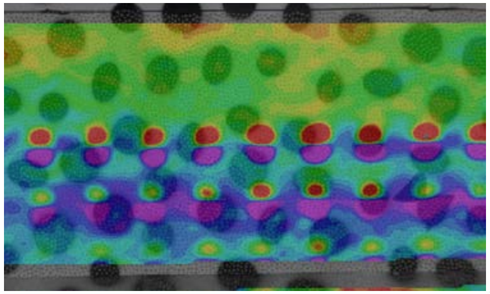
Estimated Uncertainty of 3D Position → Calculation of Strain

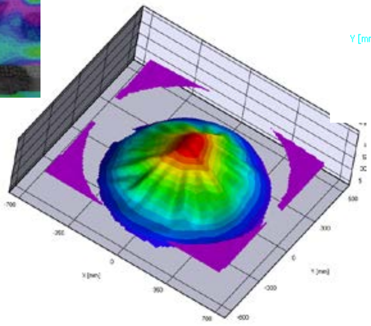
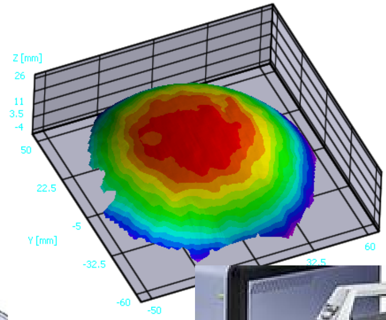
Strain profiles across rivets.



Estimated Uncertainty of 3D Position → Calculation of Strain

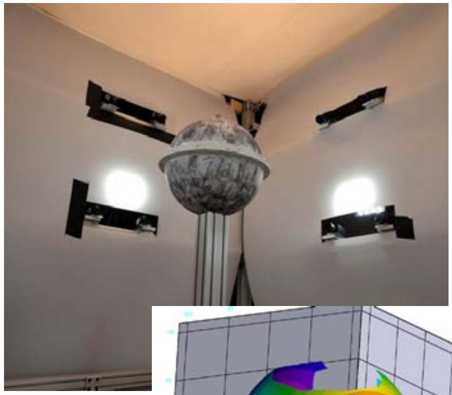
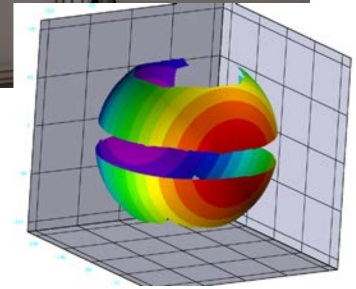
Imaging equipment has revolutionized experimental measurements.



www.visionresearch.com

www.shimadzu.com

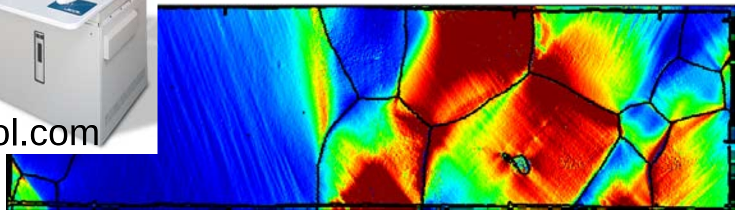



High Speed Displacement and Strain

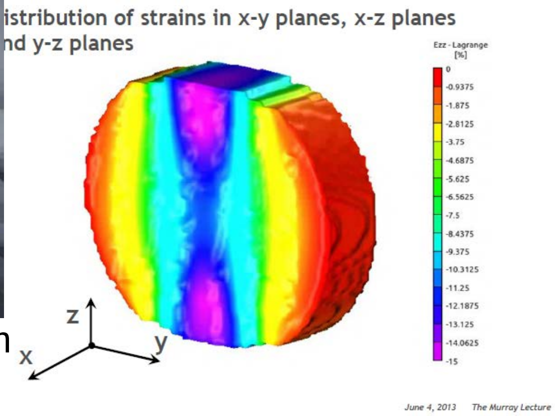
1 Million FPS

Multi-System

www.jeol.com



www.exactmetrology.com



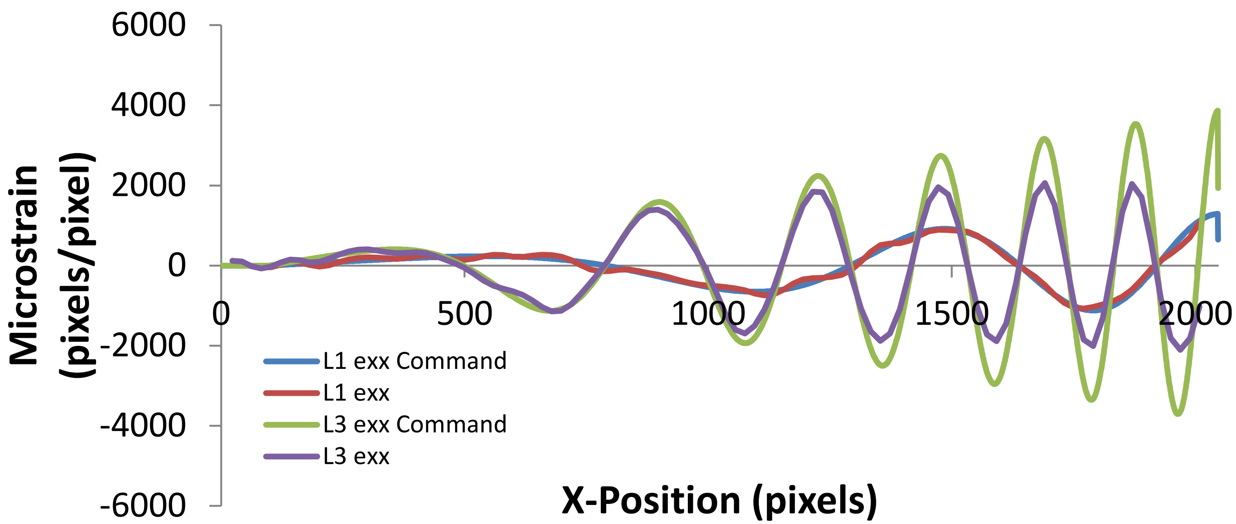
Grain scale strain measurement (optical)

Volumetric strain fields

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

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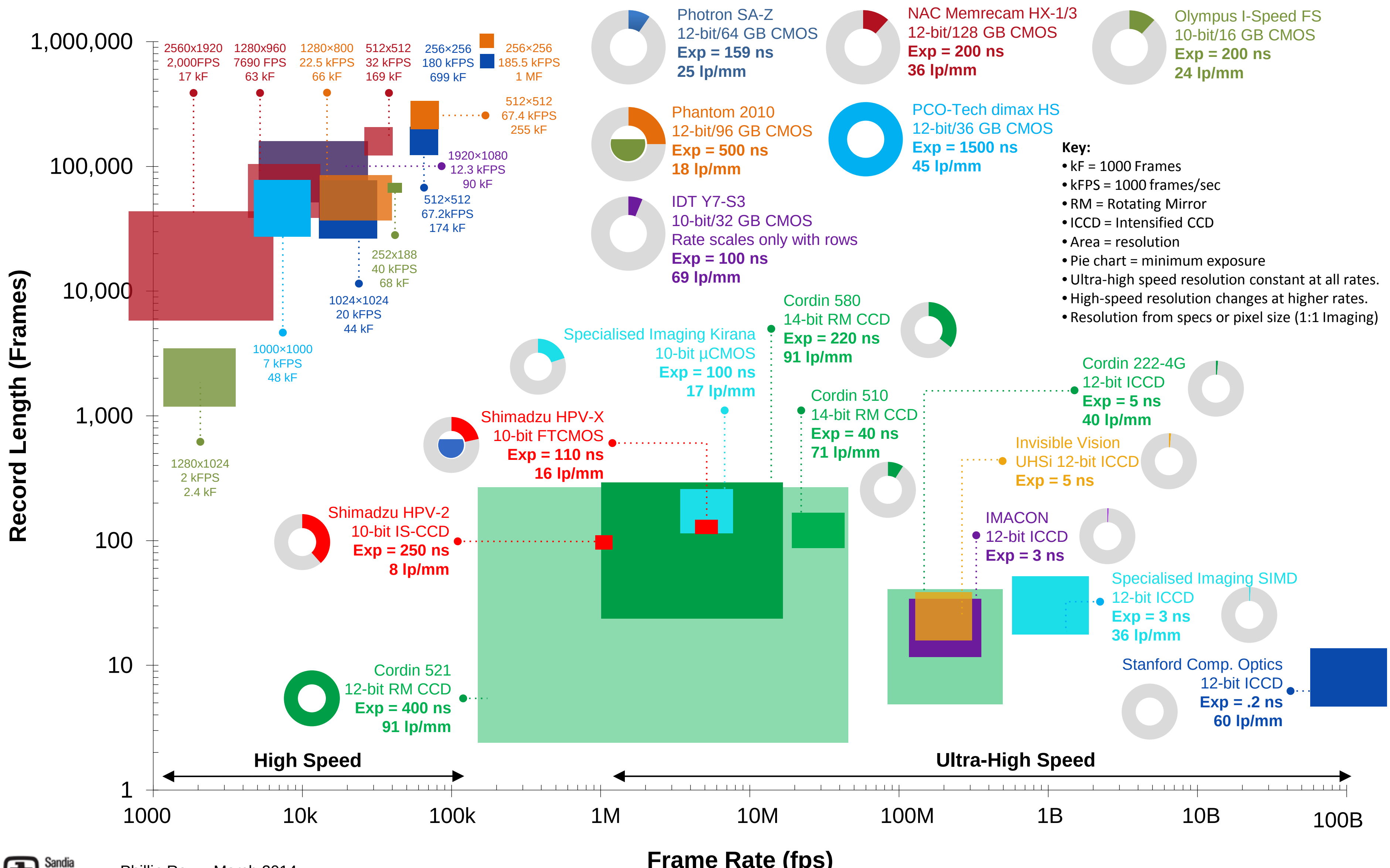
The DIC Challenge seeks to:

- 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.

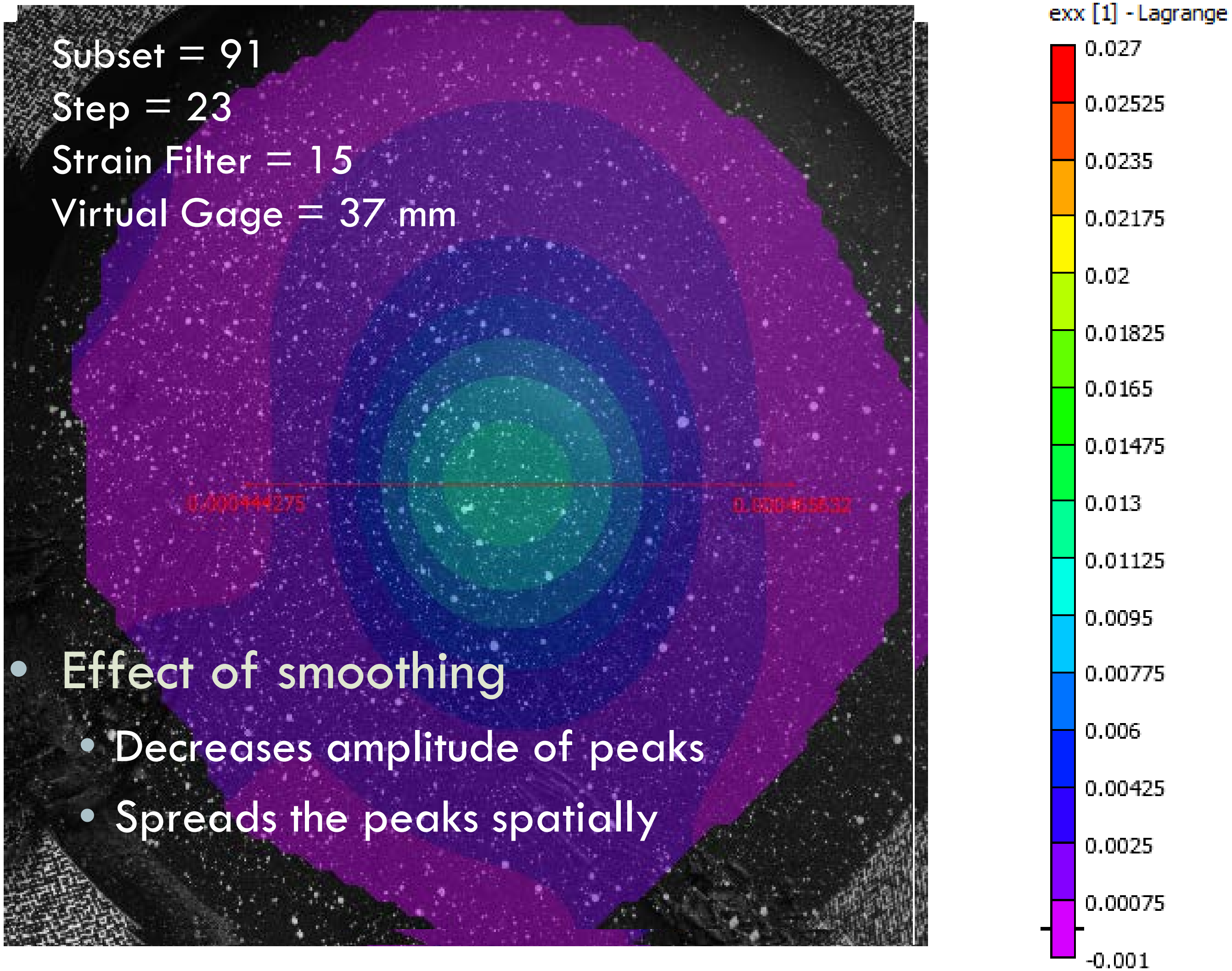
- Phillip Reu – Chairman (US – FFT Shifting)
- Bertrand Wattrisse
- Evelyne Toussaint (EU – Data Analysis)
- Wei-Chung Wang (Asia)
- Laurent Robert (EU - TexGen)
- Hugh Bruck (US)
- Sam Daly (US)
- Ramon Rodriguez-Vera (Latin/South America)

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

The state of high-speed imaging



Strain sensitivity case study using real data



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