



Exceptional service in the national interest

Insight with X-rays

Imaging and Quantifying Obscured Deformation

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Benjamin Halls, [Caroline Winters](#)

Society of Experimental Mechanics Annual Conference

5-8 June 2023

SAND2023-XXXX

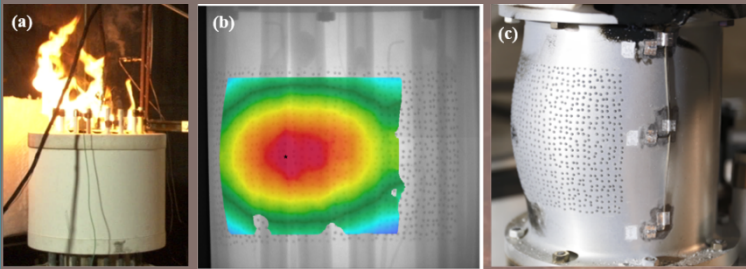
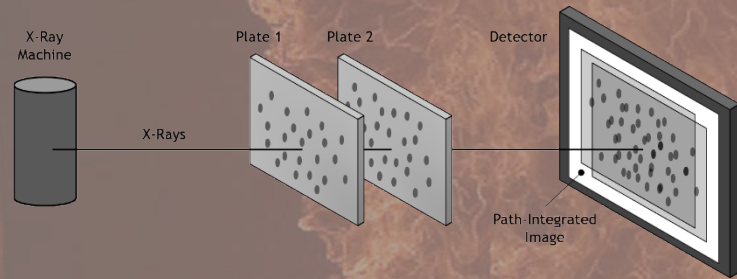
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Optical strain measurements in complex environments can be hindered by obscurations, where UV/visible radiation is readily absorbed or occluded

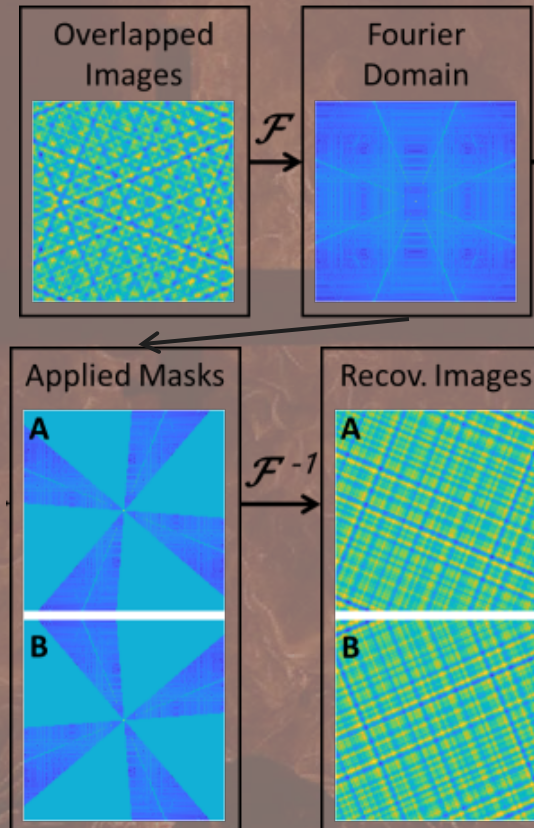
Incident and scattered x-rays have high penetrating power in optically thick environments

Path-integrated Digital Image Correlation (PI-DIC)

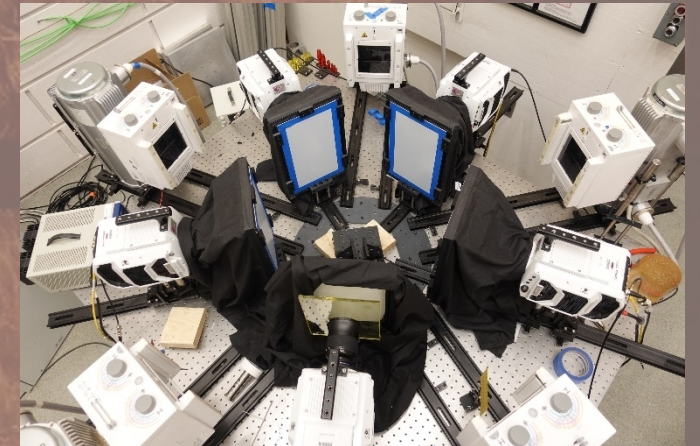


5000 fps

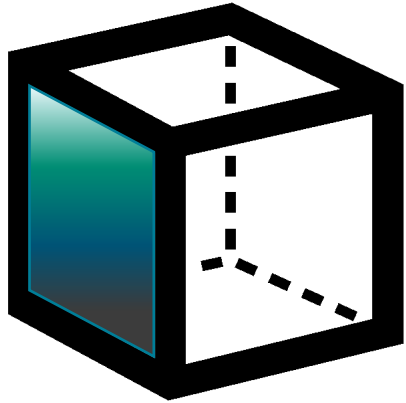
Frequency Multiplexed DIC (FM-DIC)



Time-resolved Digital Volume Correlation (T-DVC)

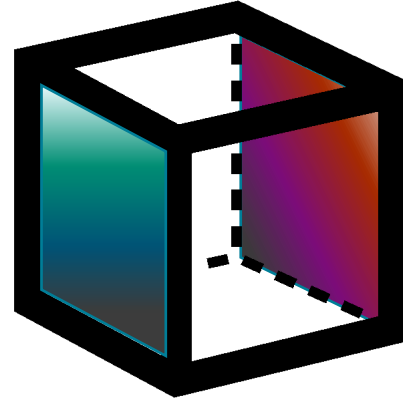


X-rays offer a spectrum of non-contact, full-field strain mapping



Single-surface X-ray DIC

- S.S. Russell, Strain-field analysis acquired through correlation of X-ray radiographs of a fiber-reinforced composite laminate, 1989
- P. Synnergren, Application of digital speckle photography to flash x-ray studies of internal deformation fields in impact experiments, 1999
- S.G. Grantham, Digital speckle radiography-a new ballistic measurement technique, 2003
- E.M.C. Jones, X-ray stereo DIC, 2019.
- J.W. James, High-speed x-ray stereo DIC in a shock tube, 2021.
- D.P. Rohe, Structural dynamic measurements using high-speed x-ray DIC, 2020.

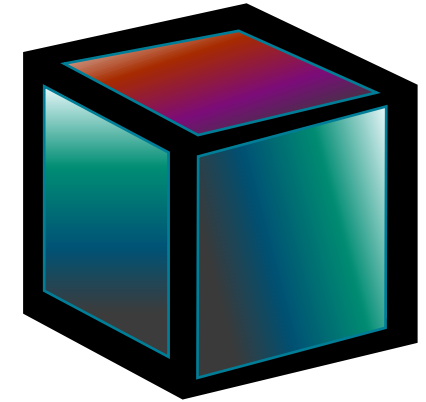


FRAME technique

- V. Kornienko, Beyond MHz image recordings using LEDs and the FRAME concept, 2020.

Path-Integrated DIC

- E.M.C. Jones, Path-Integrated X-Ray Images for Multi-Surface DIC (PI-DIC), 2023



Digital Volume Correlation

- Buljac A, Digital Volume Correlation: Review of Progress and Challenges, 2018

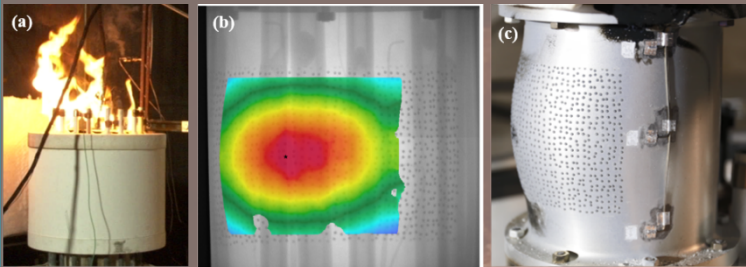
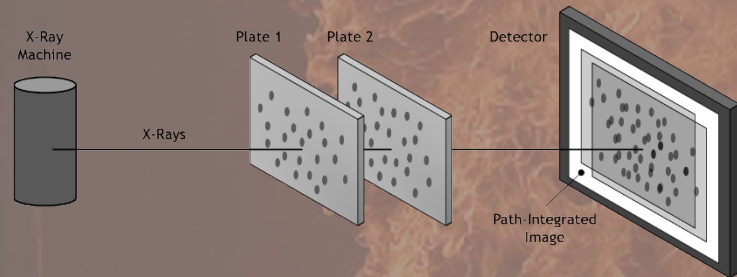
Few-view Reconstruction

- E.Y. Sidky, Accurate image reconstruction from few-views and limited-angle data in divergent-beam CT, 2006
- S. J. LaRoque, Accurate image reconstruction from few-view and limited-angle data in diffraction tomography, 2008
- S. Moser, Investigation of fragment reconstruction accuracy with in situ few-view flash x-ray high-speed computed tomography (HSCT), 2019

Optical strain measurements in complex environments can be hindered by obscurations, where UV/visible radiation is readily absorbed or occluded

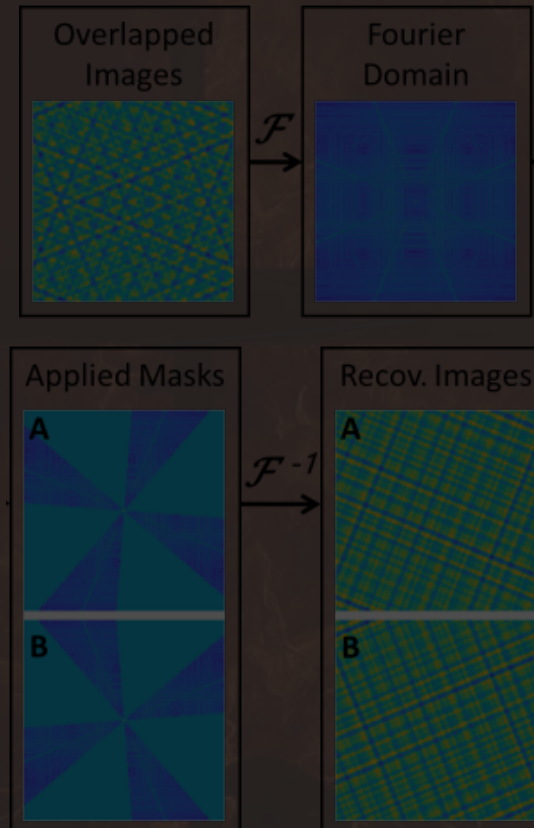
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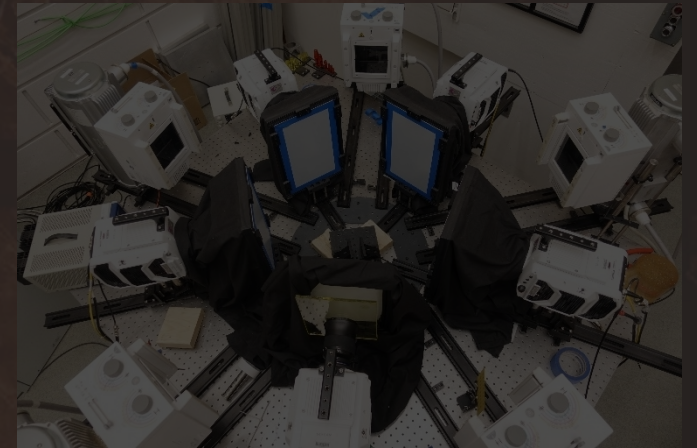


5000 fps

Frequency Multiplexed DIC (FM-DIC)



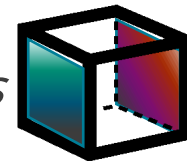
Time-resolved Digital Volume Correlation (T-DVC)



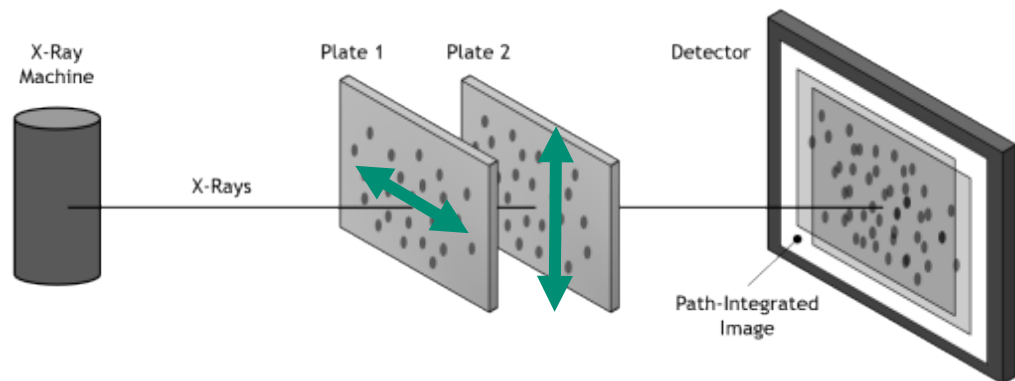


Path-Integrated DIC¹ (PI-DIC): optical flow re-written using a Beer-Lambert approximation

Work led by Elizabeth Jones



Experimental Schematic



- The cost function is re-written to resolve the conservation of intensity violation
- A two-step process tracks points in an Lagrangian framework → repeated for both surfaces
- Synthetic images w/1.5% noise demonstrated the technique in rigid translation, rigid rotation, and uniform stretching conditions
- All motion was recovered with error ≤ 0.03 pixels

Plate 1; Stretch 1.00 along x

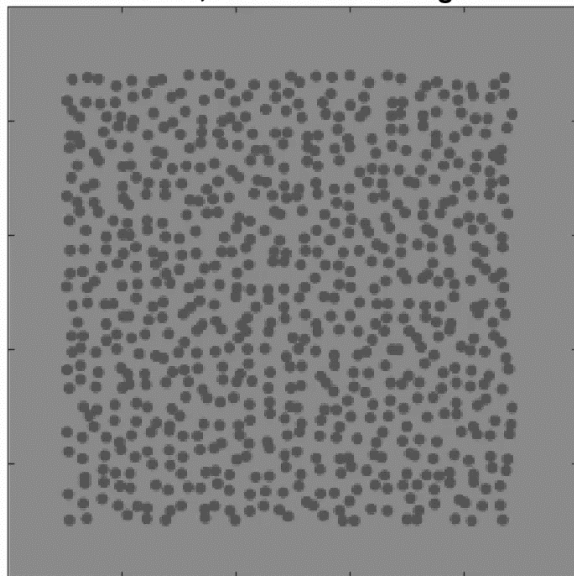
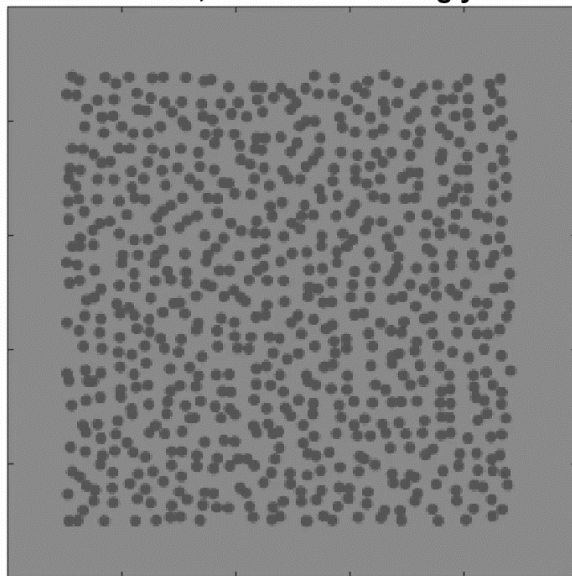
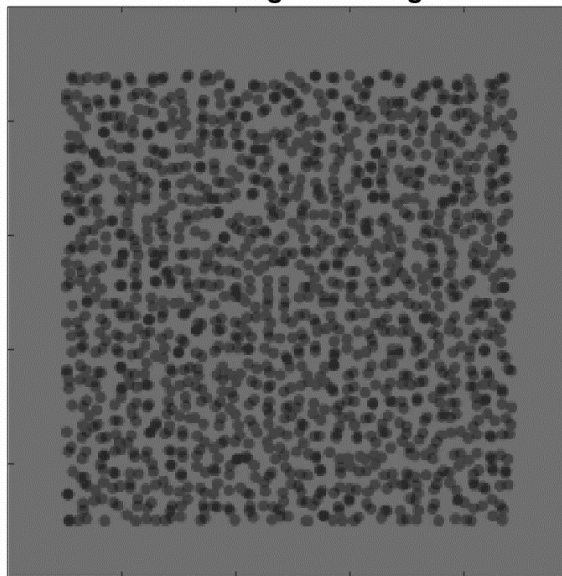


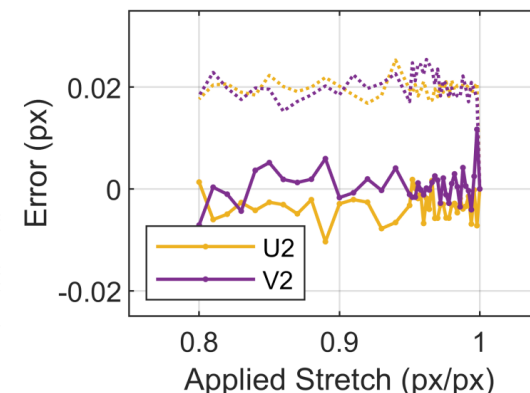
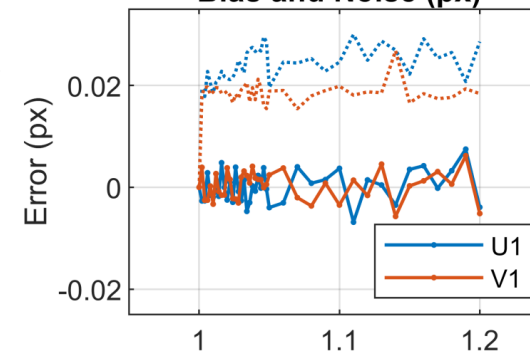
Plate 2; Stretch 1.00 along y



Path-Integrated Image



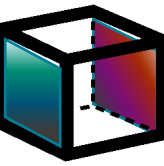
Bias and Noise (px)



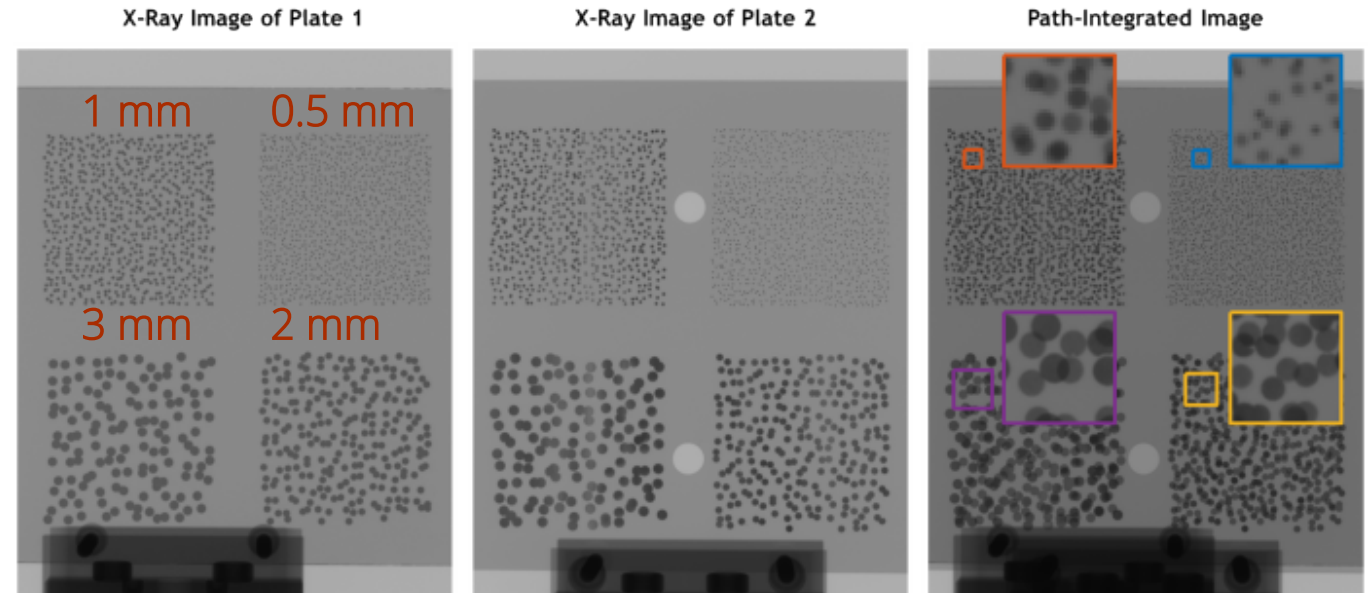
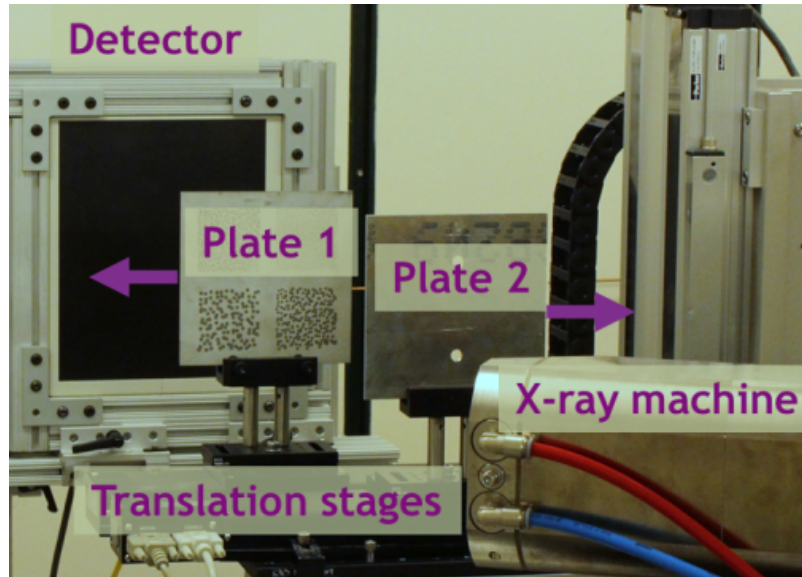


Path-integrated, multi-plane X-ray DIC was also demonstrated with experimental images¹

Work led by Samuel Fayad & Elizabeth Jones

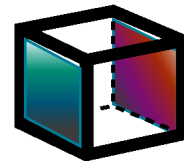


Rigid Translations: Benchtop Demonstration



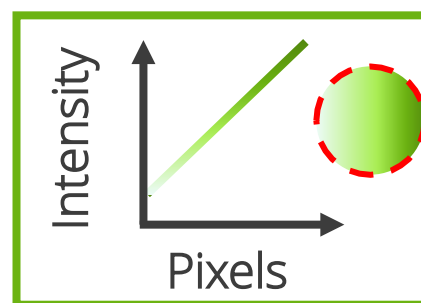
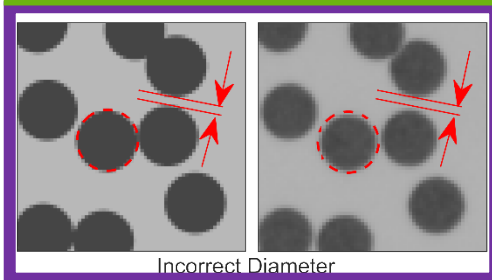
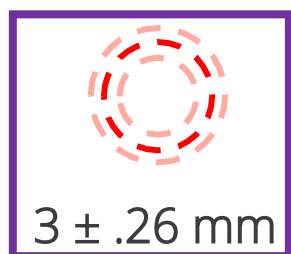
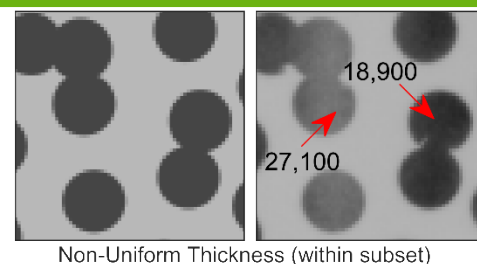
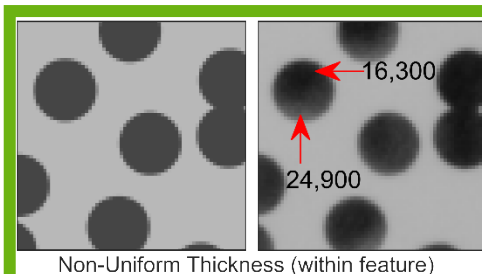
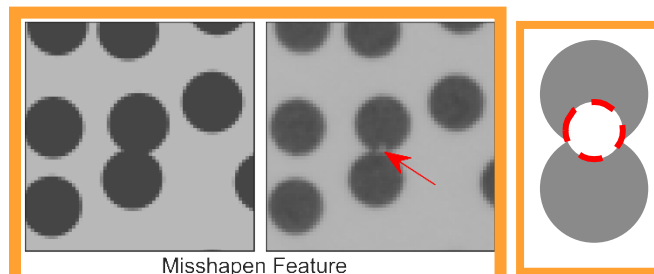
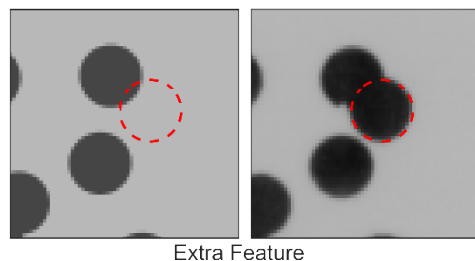
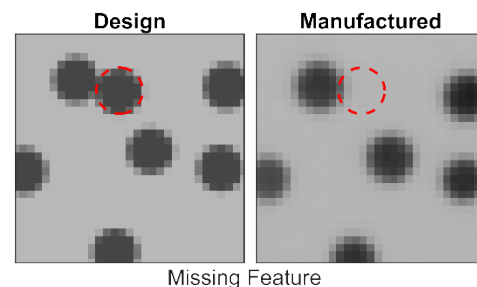
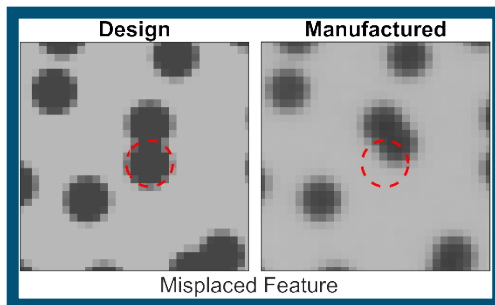
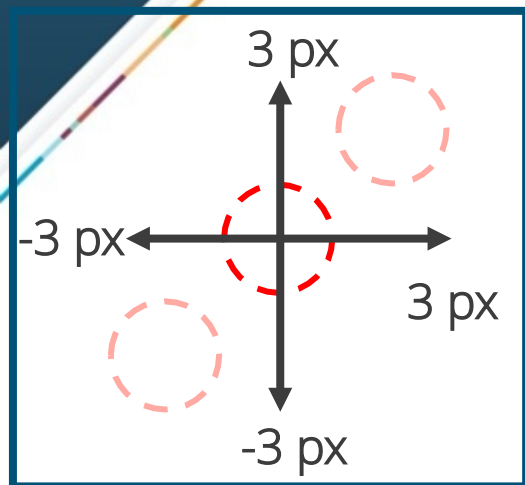
- Aluminum plates were patterned with tantalum & rigidly translated 0:0.1:1 then 1:1:10 px increments
→ ~0.05 px error

Can synthetic reference images be applied, when experimental is impractical?

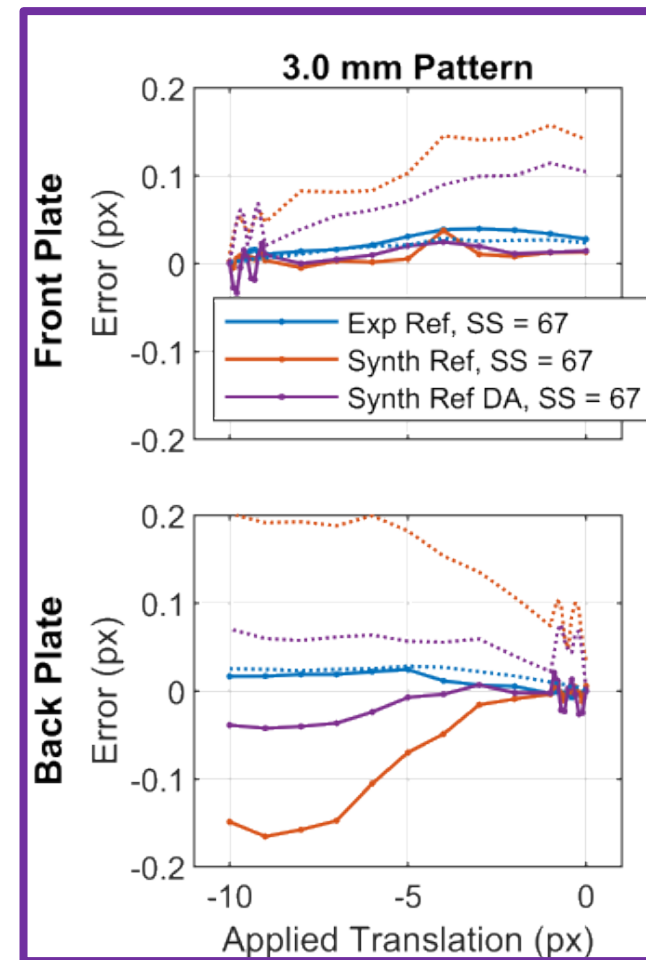


Manufacturing defects must be considered for PI-DIC reference images²

As-manufactured plate inspection



Error in Recovered Motion

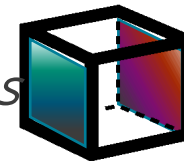


Work led by Samuel
Fayad & Elizabeth Jones

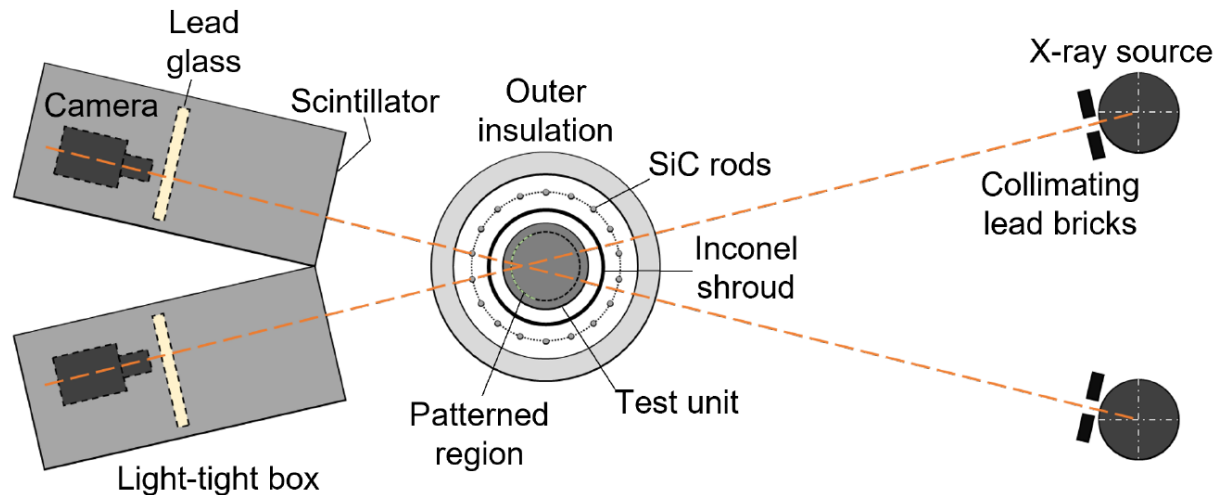


Stereo PI-DIC in real test environments can account for background objects³

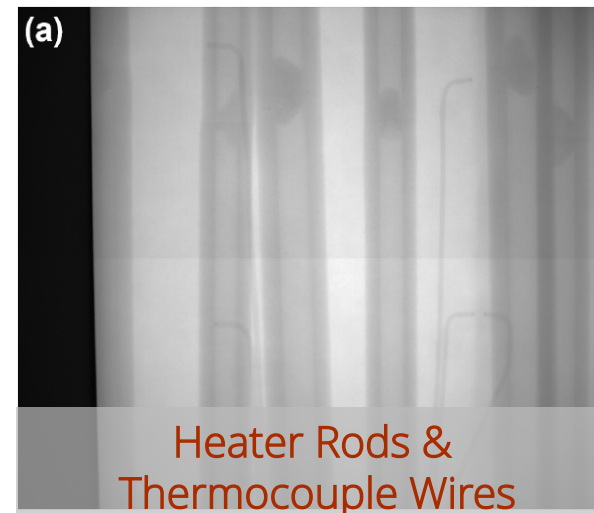
Work led by Elizabeth Jones



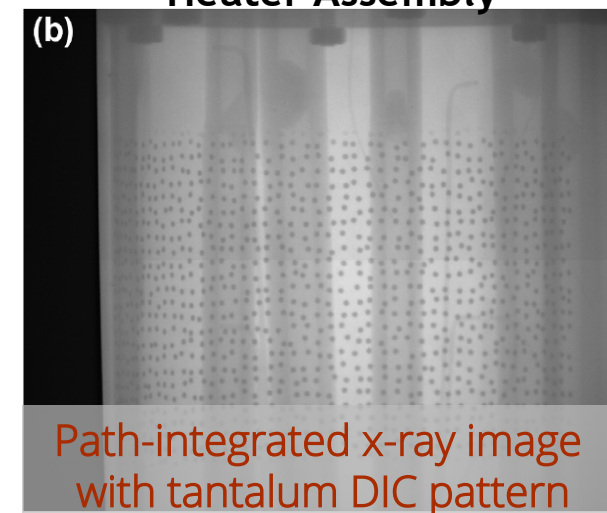
Experimental Schematic



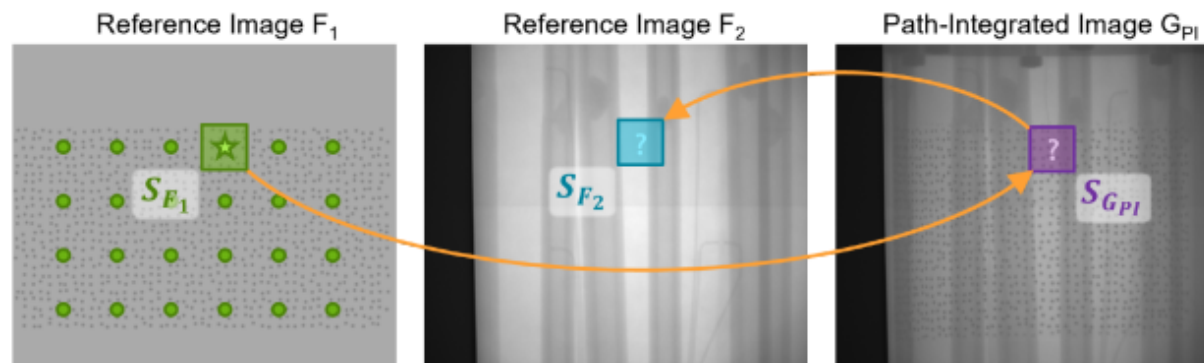
X-ray Image Heater Assembly



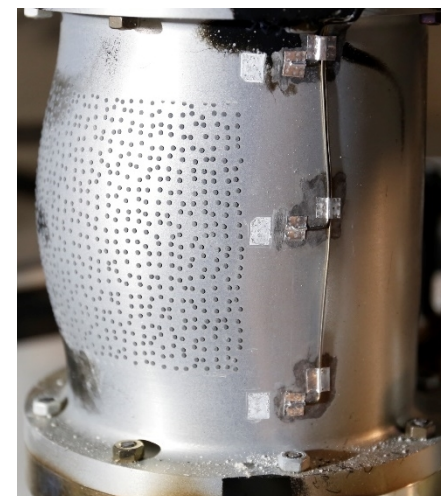
X-ray Image Test Unit in Heater Assembly



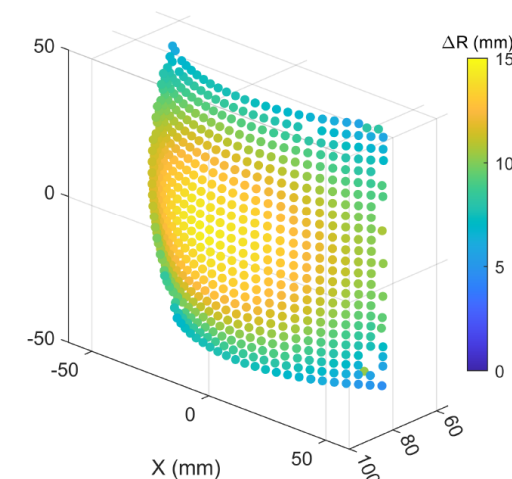
Lagrangian point tracking



Post-test photo



Recovered Radial Change

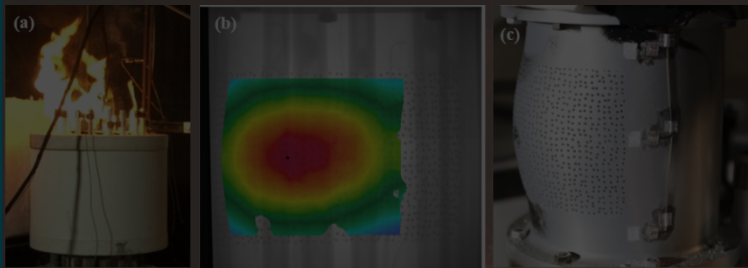
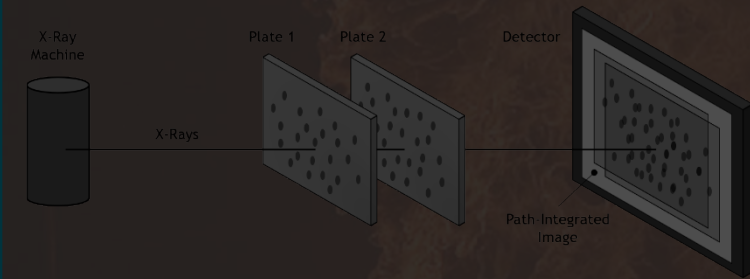


[3] Jones, E. M. C., Resolving the Violation of Conservation of Intensity for Path-Integrated X-ray Digital Image Correlation in Extreme Environments. *Experimental Mechanics*, in preparation

Optical strain measurements in complex environments can be hindered by obscurations, where UV/visible radiation is readily absorbed or occluded

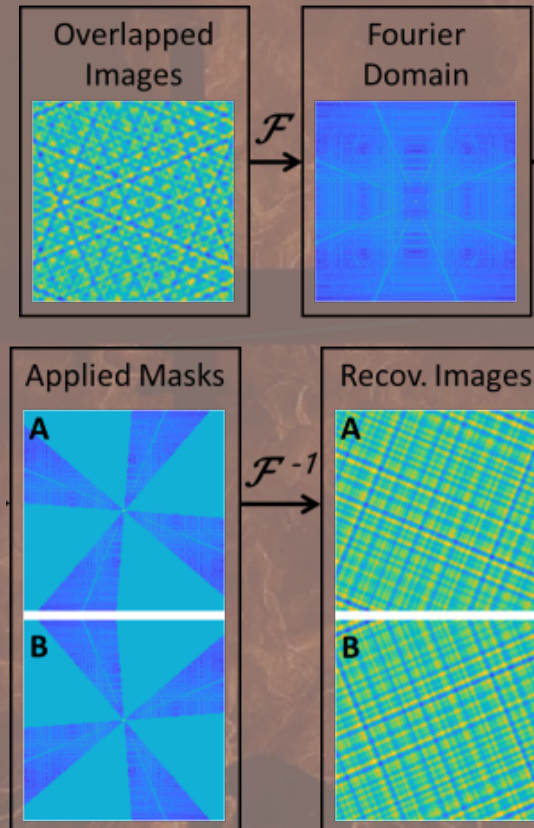
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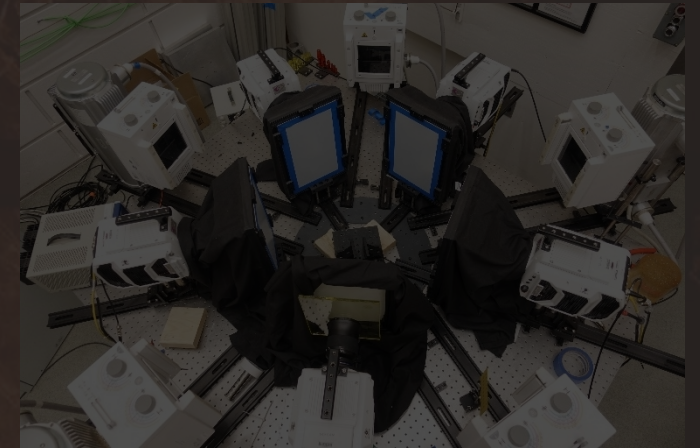


5000 fps

Frequency Multiplexed DIC (FM-DIC)



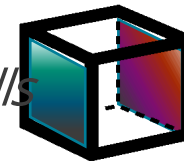
Time-resolved Digital Volume Correlation (T-DVC)



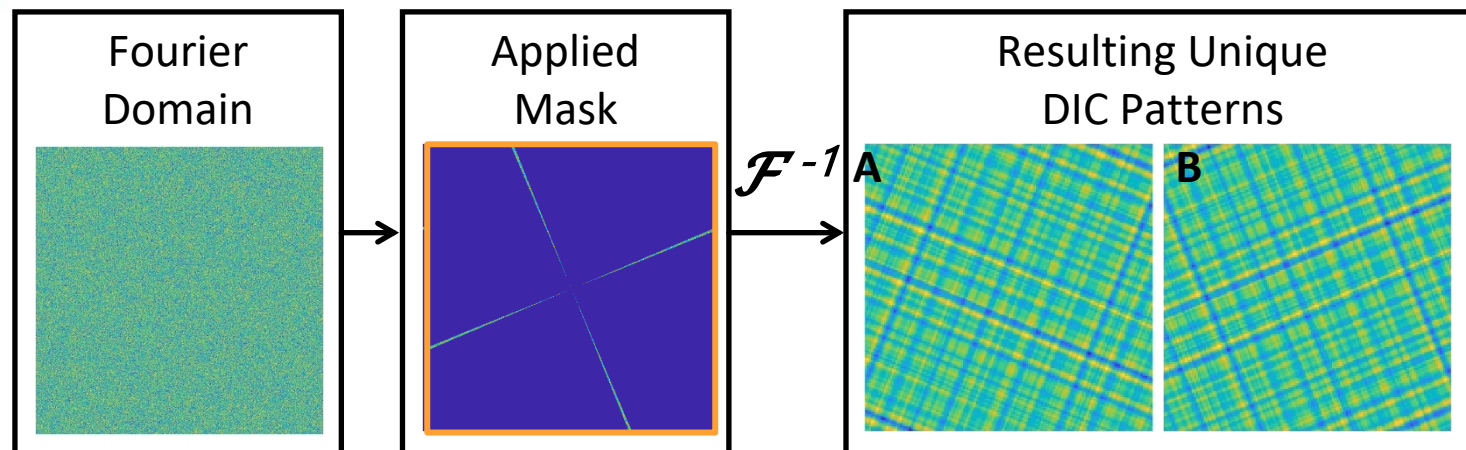


Frequency Multiplexed DIC (FM-DIC): Fourier masking generates unique extrinsic patterns for multiple surfaces⁴

Work led by Ben Halls
& Elizabeth Jones

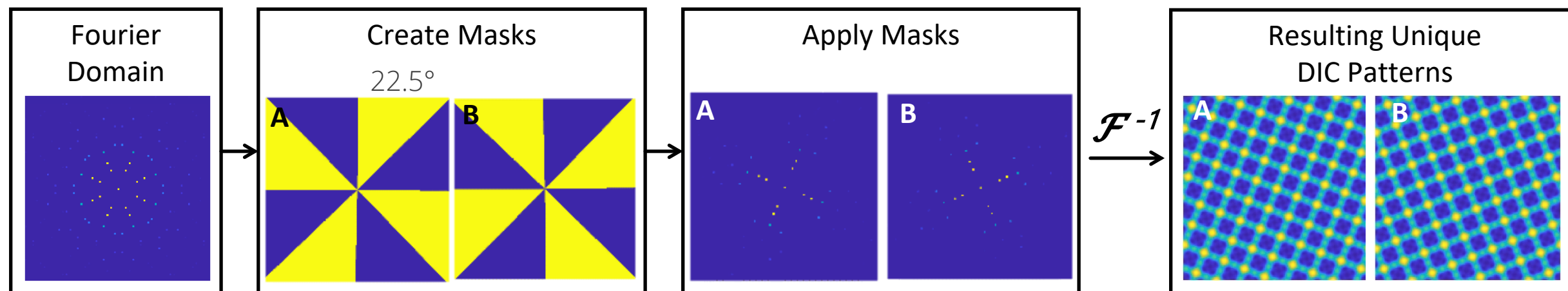


White Noise Patterning



- Idealized (noise and blur free) images
- Full pixel depth of a 16-bit camera
- Tunable parameters:
 - Blade Number
 - Blade Width
 - Clocking Orientation

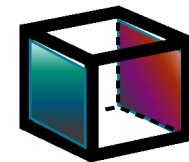
Sine Wave, Controlled Patterning



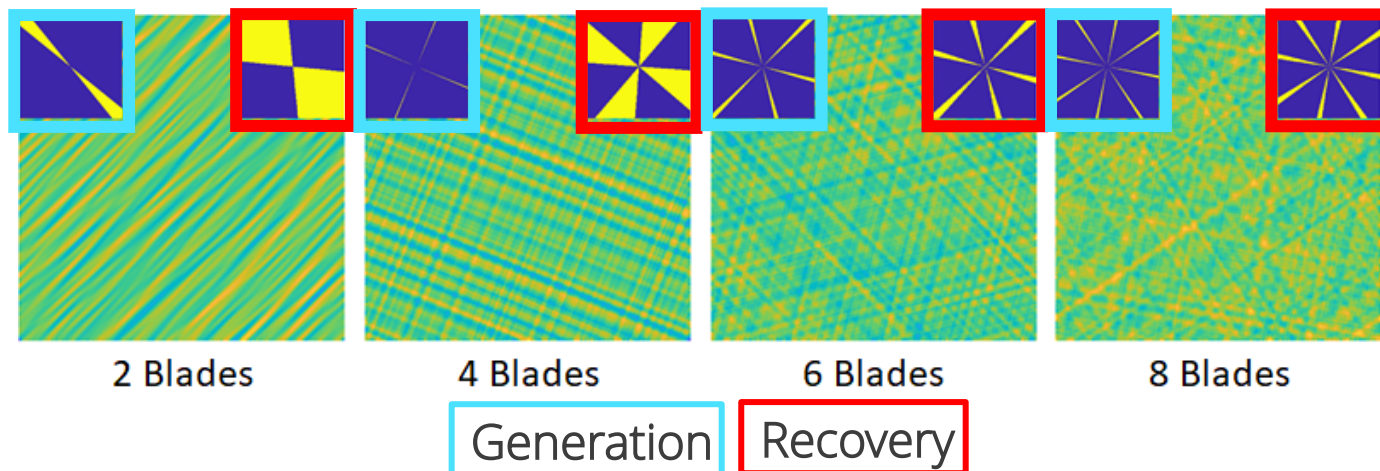


Fourier filtering of extrinsic features allows optical processing of x-ray images⁴

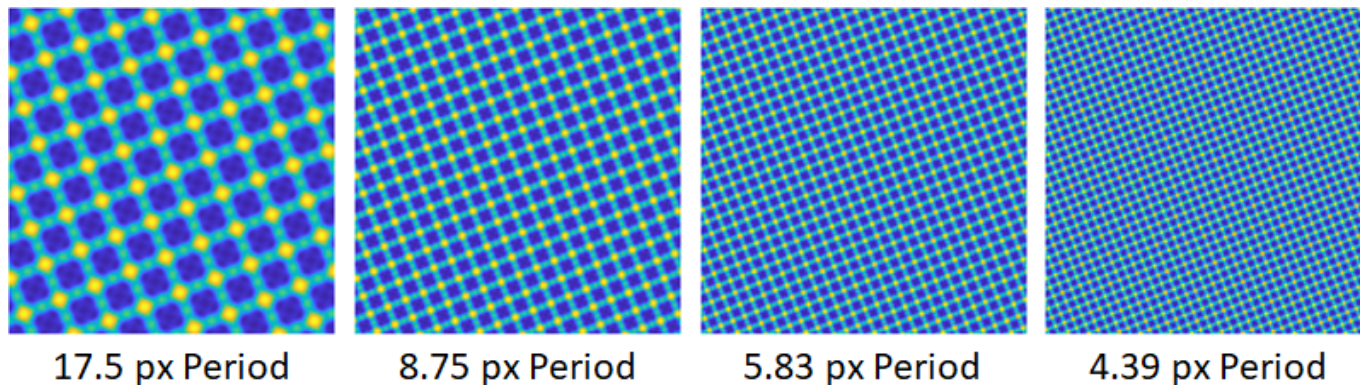
Work led by Ben Halls
& Elizabeth Jones



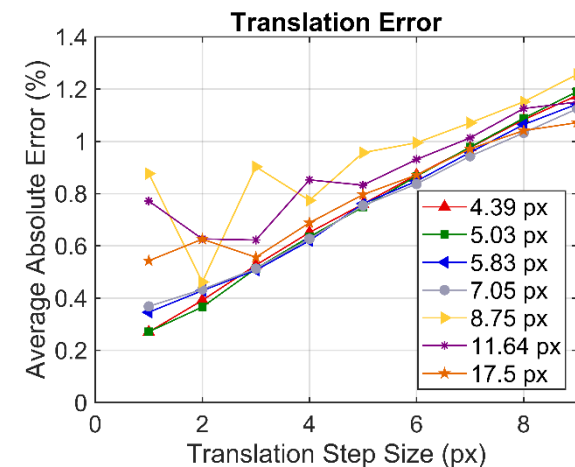
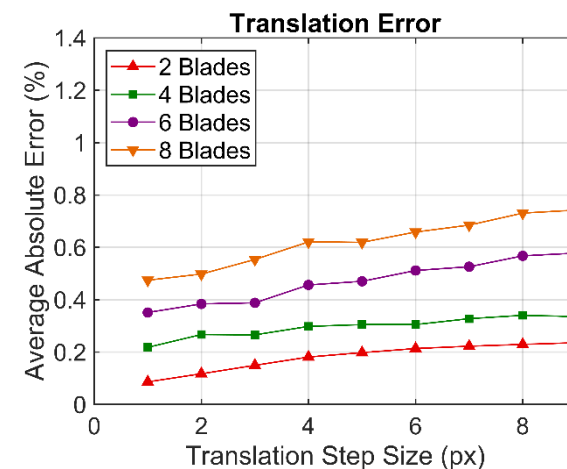
Optimization for Recovering Movement



Sine Wave Patterns



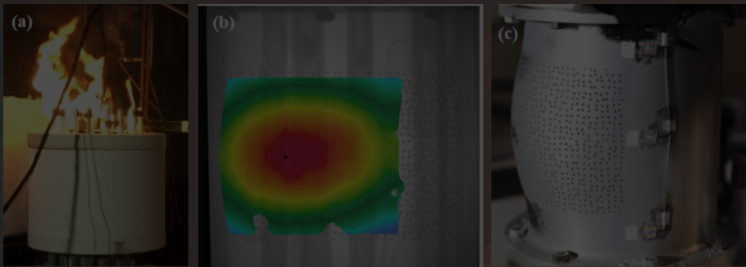
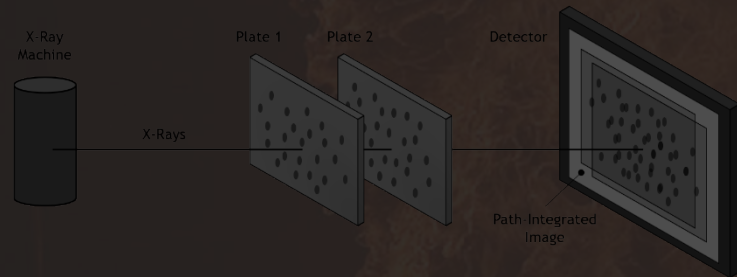
DIC Performance



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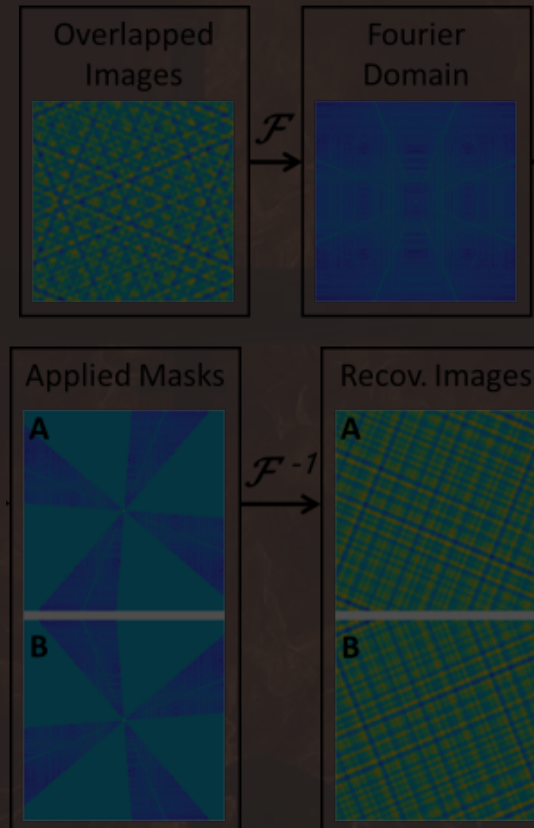
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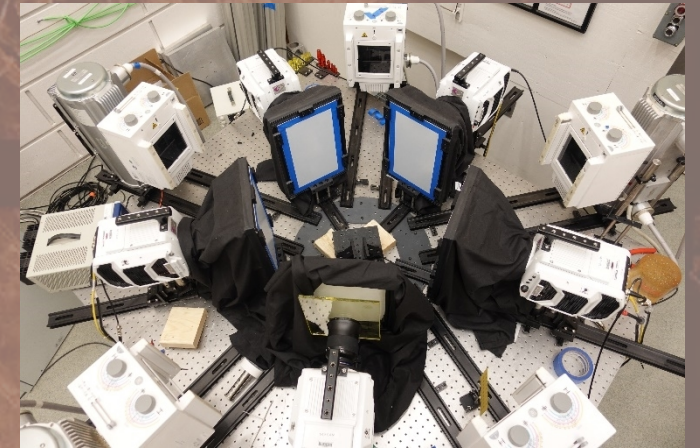


5000 fps

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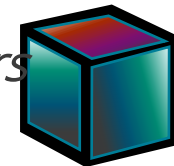




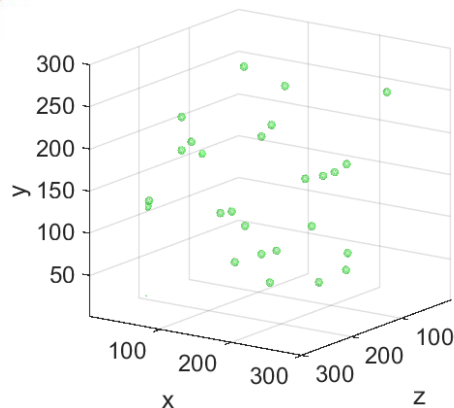
Time-resolved Digital Volume Correlation (T-DVC): limited-view reconstruction of synthetic 3D volumes

Easy to Reconstruct

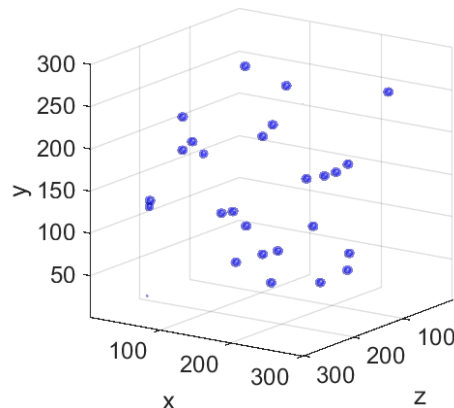
Work led by John Miers
& Ben Halls



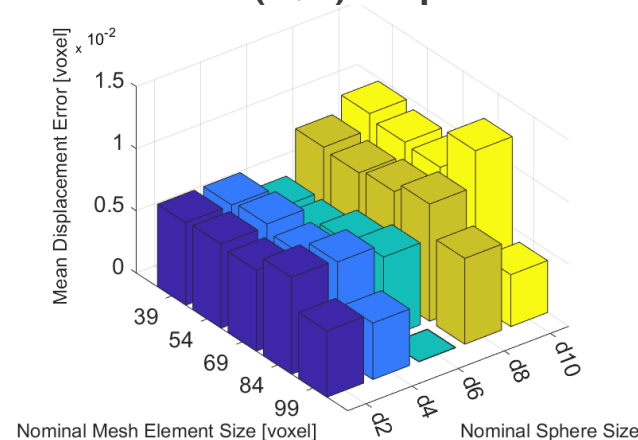
True Volume



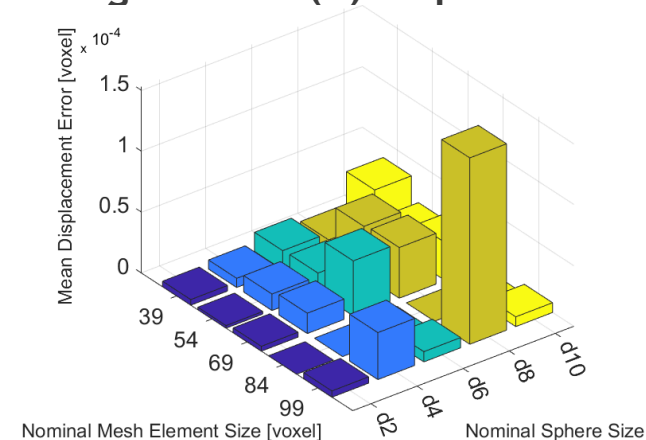
Reconstruction



Sub-voxel (0.7) Displacement



Integer-voxel (7) Displacement

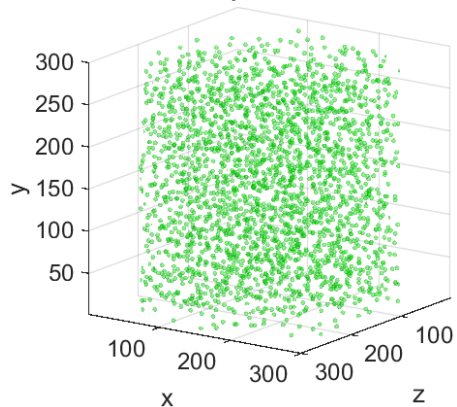


Noise-free images to isolate reconstruction errors

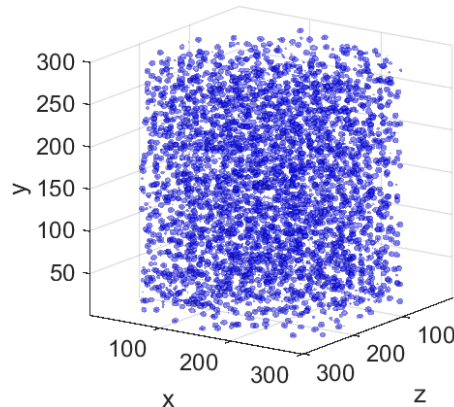


Better DVC Resolution

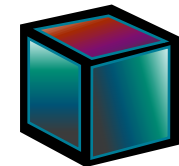
True Volume



Reconstruction



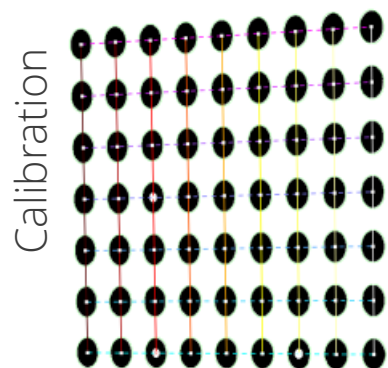
- These volumes are reconstructed from 5-views representing the current Sandian capability
- Whereas Computed Tomography (CT) scans use 100s-1000s of views to reconstruct volumes
- Digital Volume Correlation from tomographically reconstructed volumes is accurate to a sub-voxel level



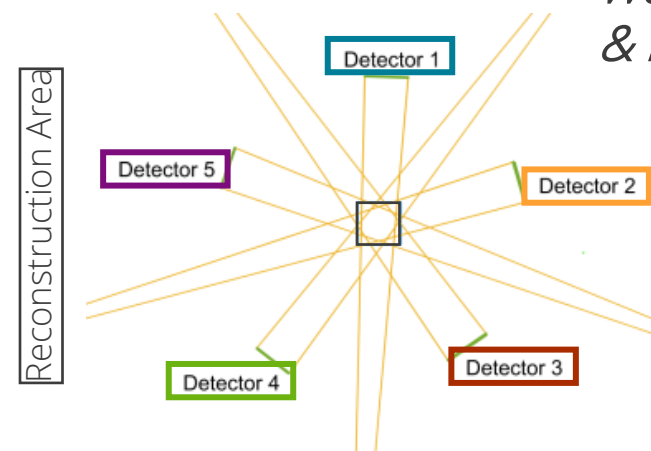
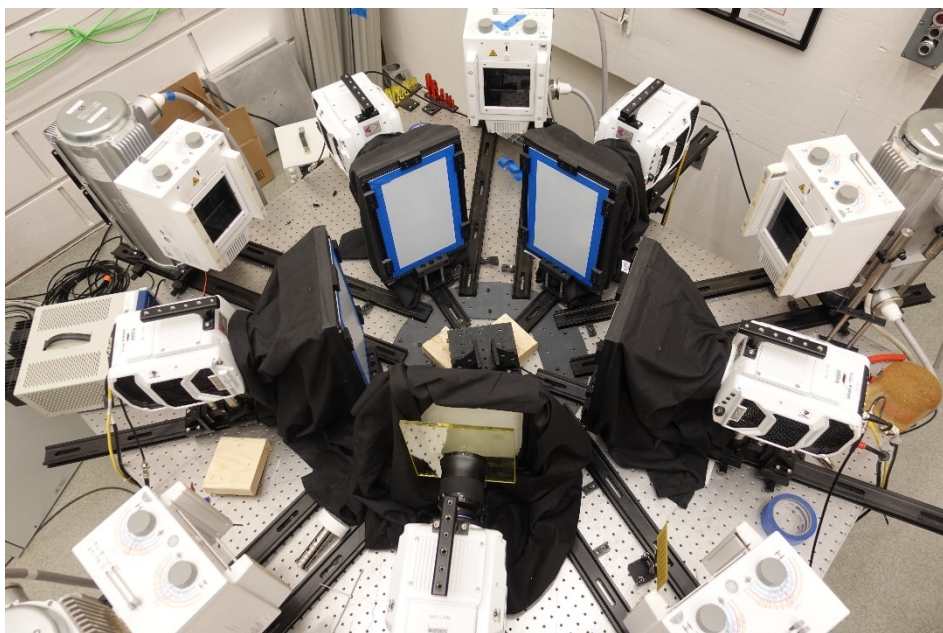
Time-resolved Digital Volume Correlation (T-DVC): development of multiple projection reconstruction to capture dynamic behavior

Work led by John Miers & Ben Halls

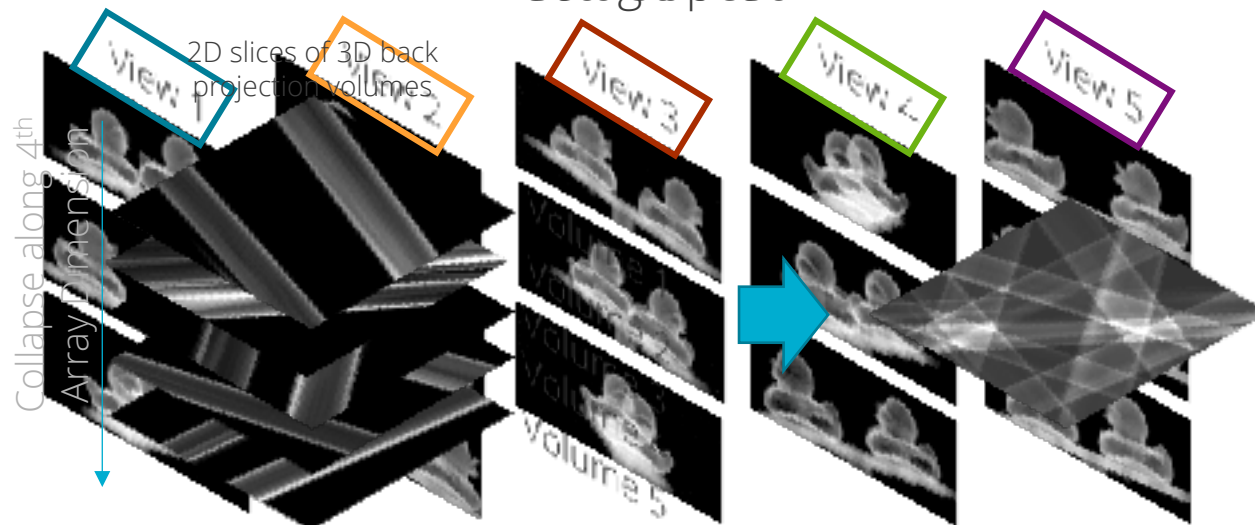
Experimental Overview

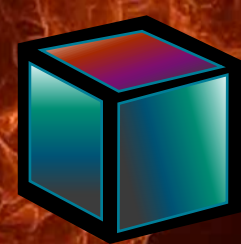
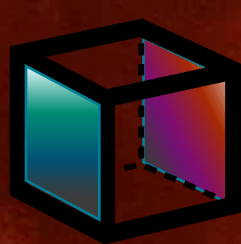
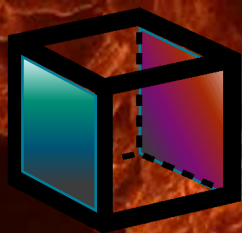


Five-source system

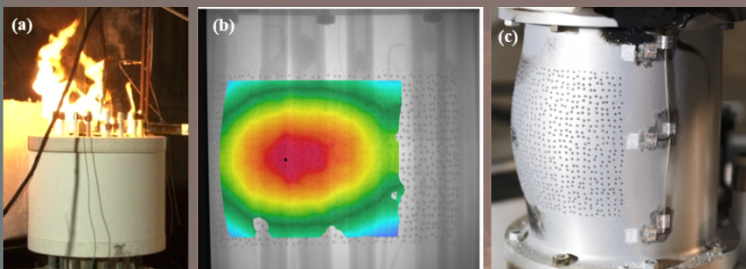
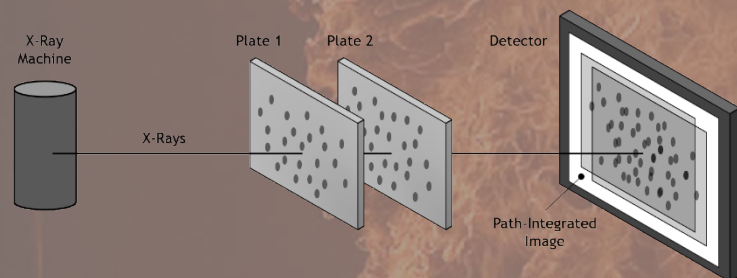


Radiograph



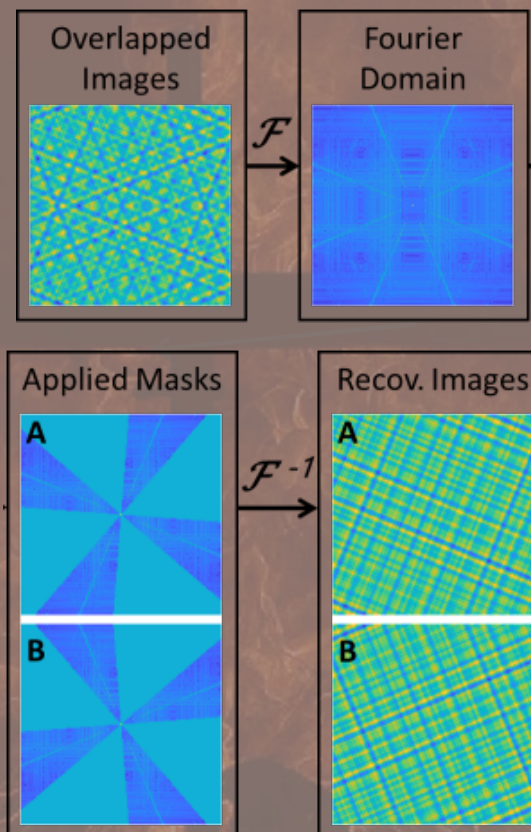


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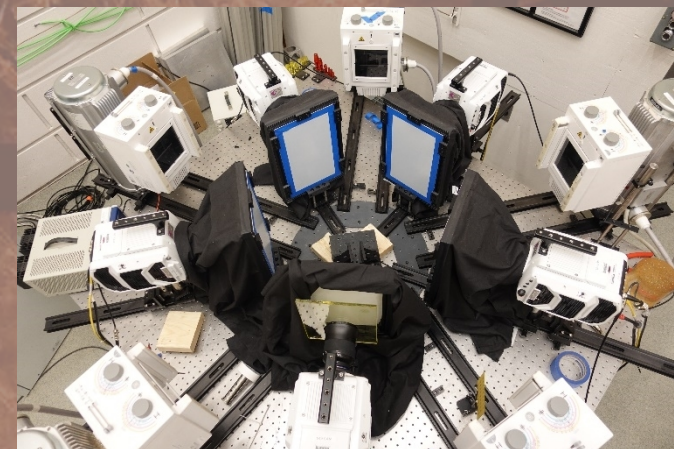


5000 fps

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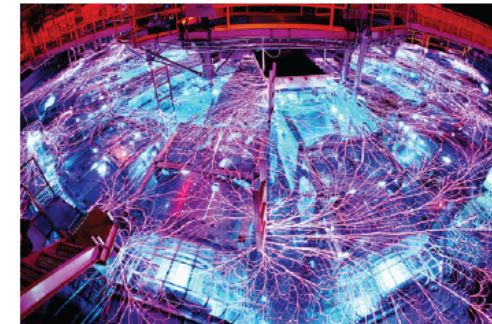
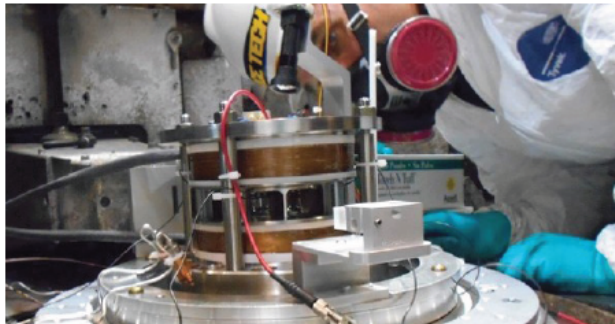


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Insight with X-rays

*Imaging and
Quantifying Obscured
Deformation*

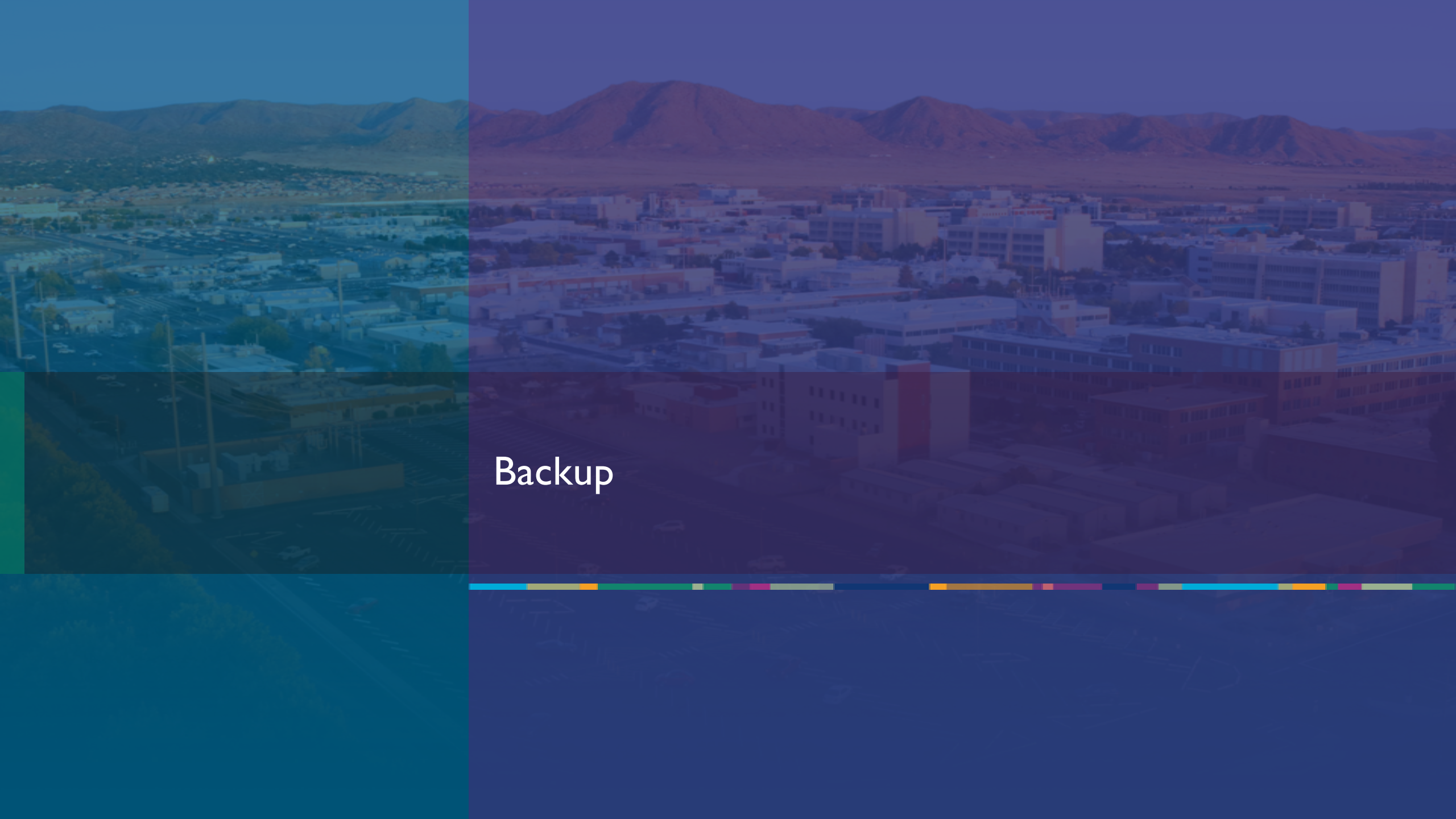
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National Laboratories.**

Thank you!

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DE-NA0003525.**

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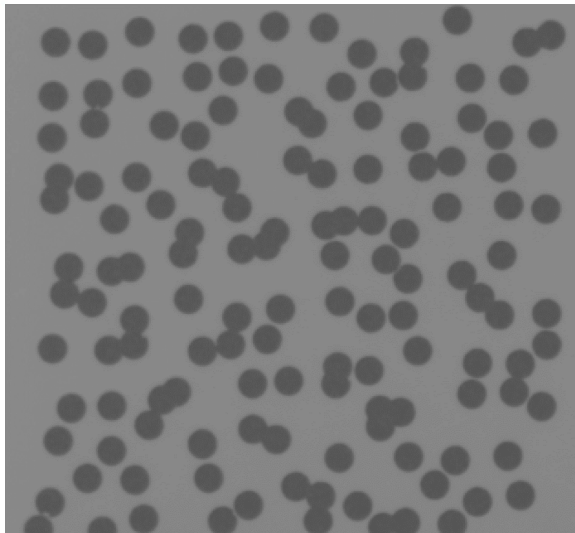
Backup



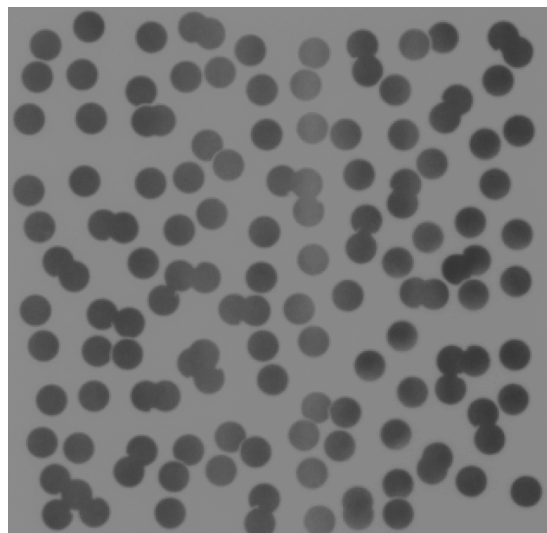


The Beer-Lambert approximation has < 3% error.

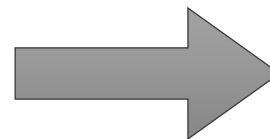
Exp. Ref. Image F_1



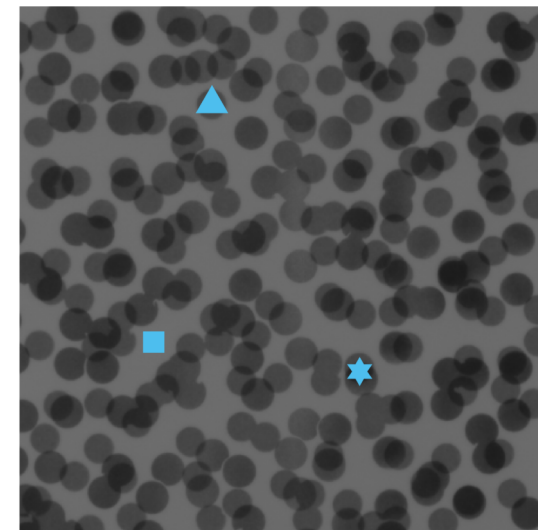
Exp. Ref. Image F_2



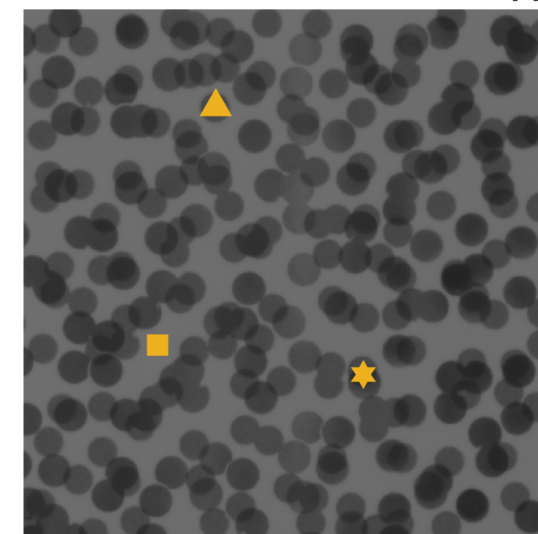
$$F_{PI}^C = \frac{1}{I_0} F_1 F_2$$






Composed PI Image F_{PI}^C



Experimental PI Image F_{PI}^E



Point location	Symbol	Composed PI Image	Experimental PI Image	Percent Error
Aluminum only		27886	28241	0.54%
Aluminum + 1 Tantalum feature		18518	18857	0.52%
Aluminum + 2 Tantalum features		8461	10501	3.1%