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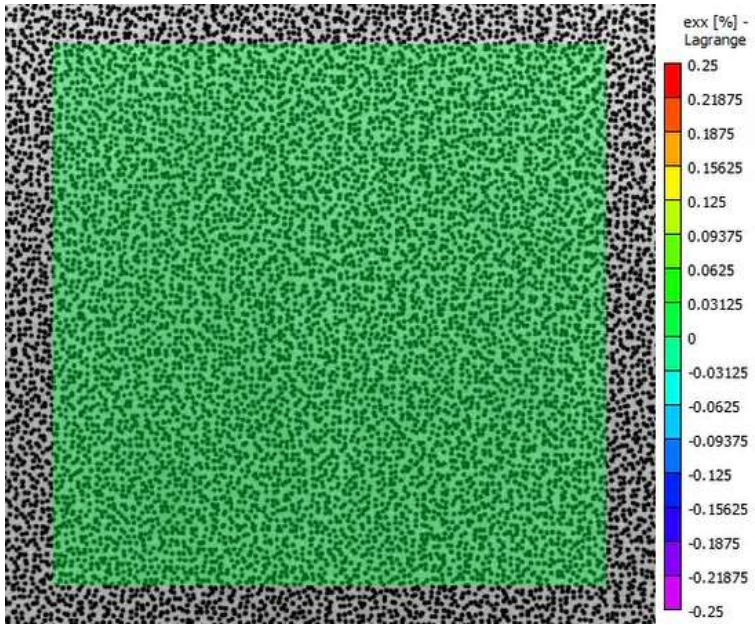

Distortion of DIC Measurements from Heat Waves

Elizabeth M. C. Jones, Phillip L. Reu,
Tim O'Hern and Bill Sweatt

U.S. DEPARTMENT OF ENERGY | NNSA

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There are many sources of error in a DIC experiment.

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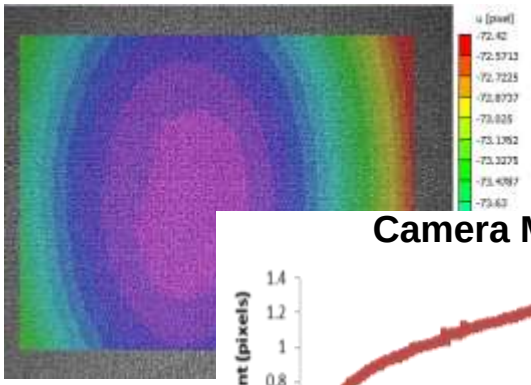
Experimental Setup
- Lens distortion
- Camera motion
- Sample motion
- Air turbulence
- Image blur
- System resolution

Image Acquisition
- Noise
- Contrast
- Speckle size
- Aliasing

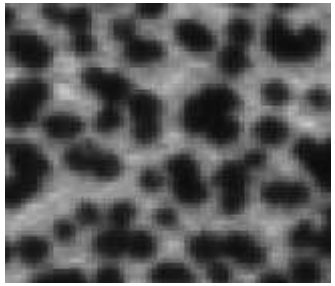
Image Correlation
- Interpolant
- Minimization
- Shape Function
- Subset size

2D Position, Motion, and Strain
- Filtering
- Strain calculation
- Coordinate system

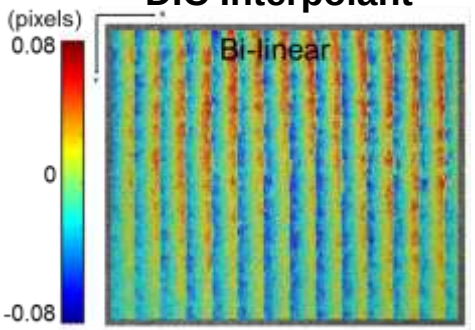
Lens Distortion



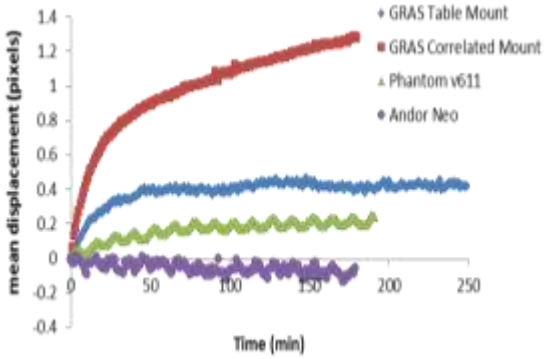
Good Contrast



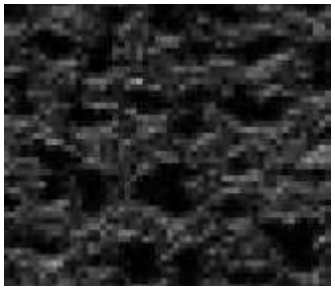
DIC Interpolant

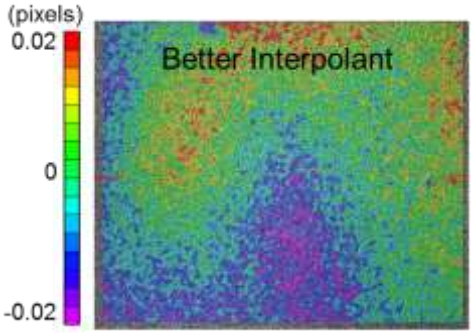


Camera Motion



Poor Contrast





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→

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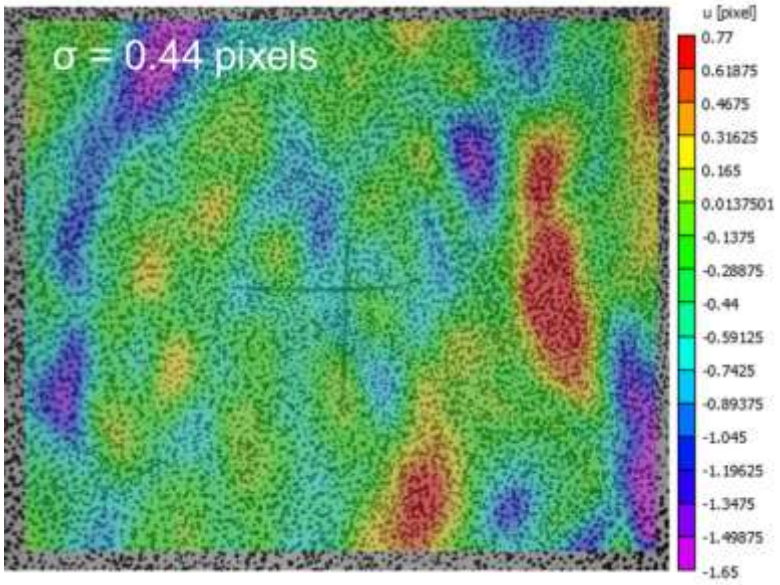
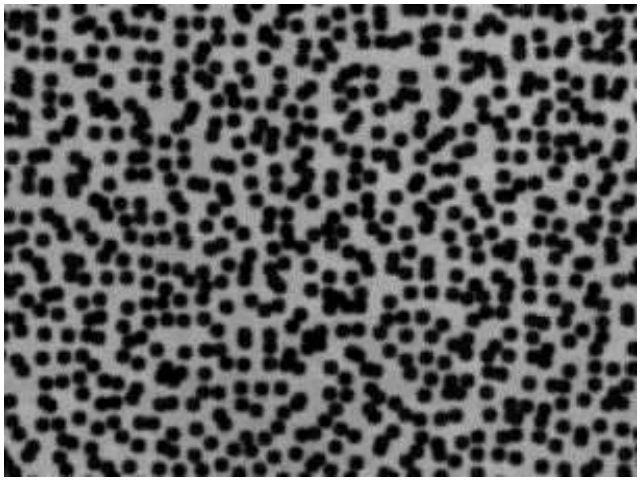
Heat Waves

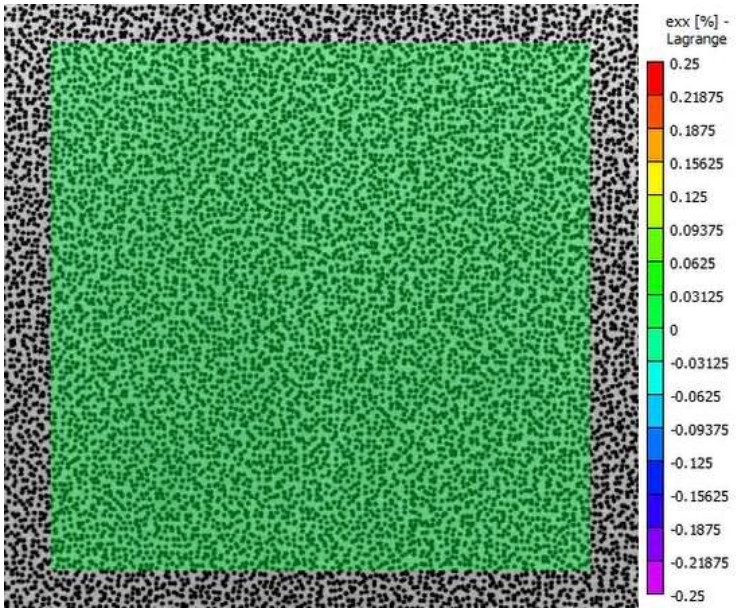


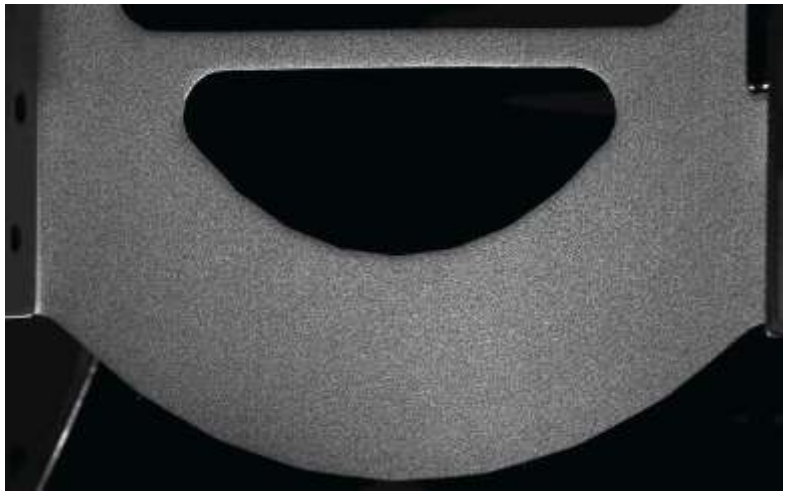
Sources

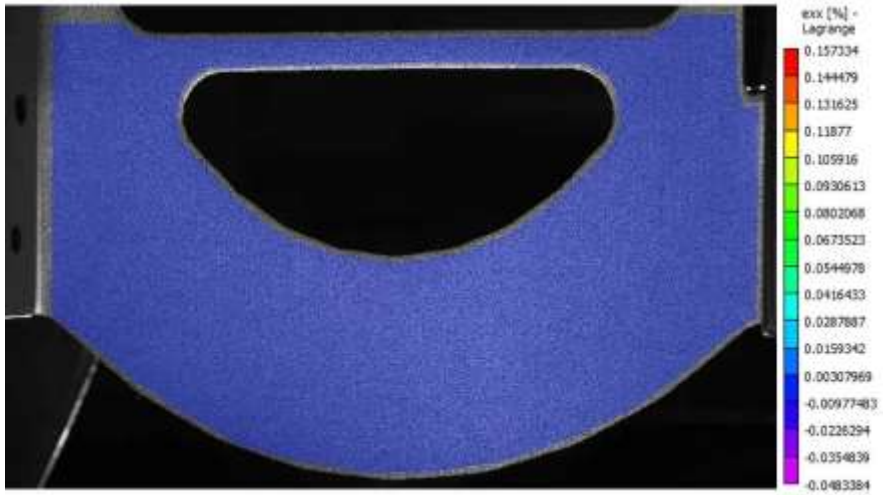
- Lights
  - LED: 40-100 C
  - Halogen: 160 C
- Cameras
  - High-speed cameras: 45-50 C
- Heated sample
- Outdoor natural temperature gradients

Heat waves can sometimes be seen with the naked eye.

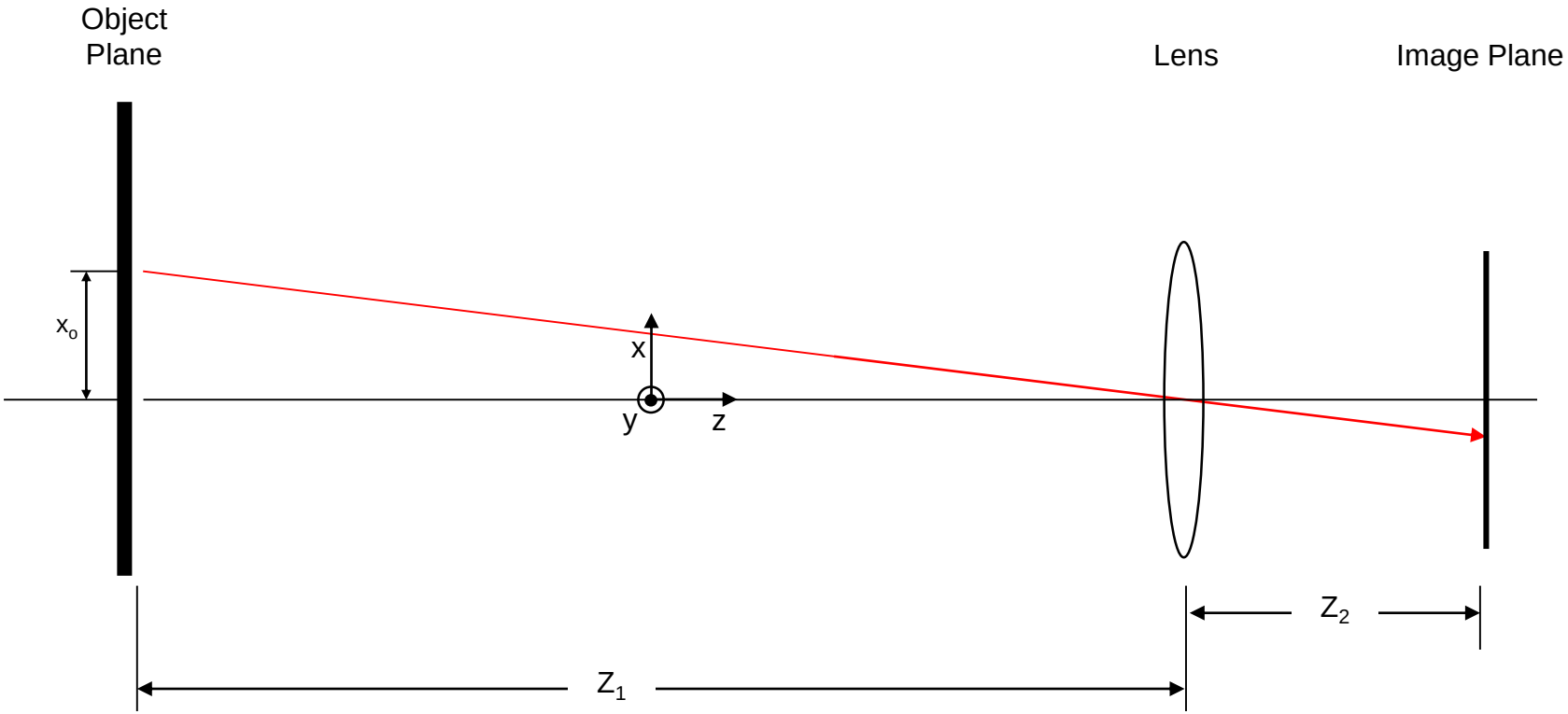








Index of refraction heterogeneity between the sample and camera will distort the image.



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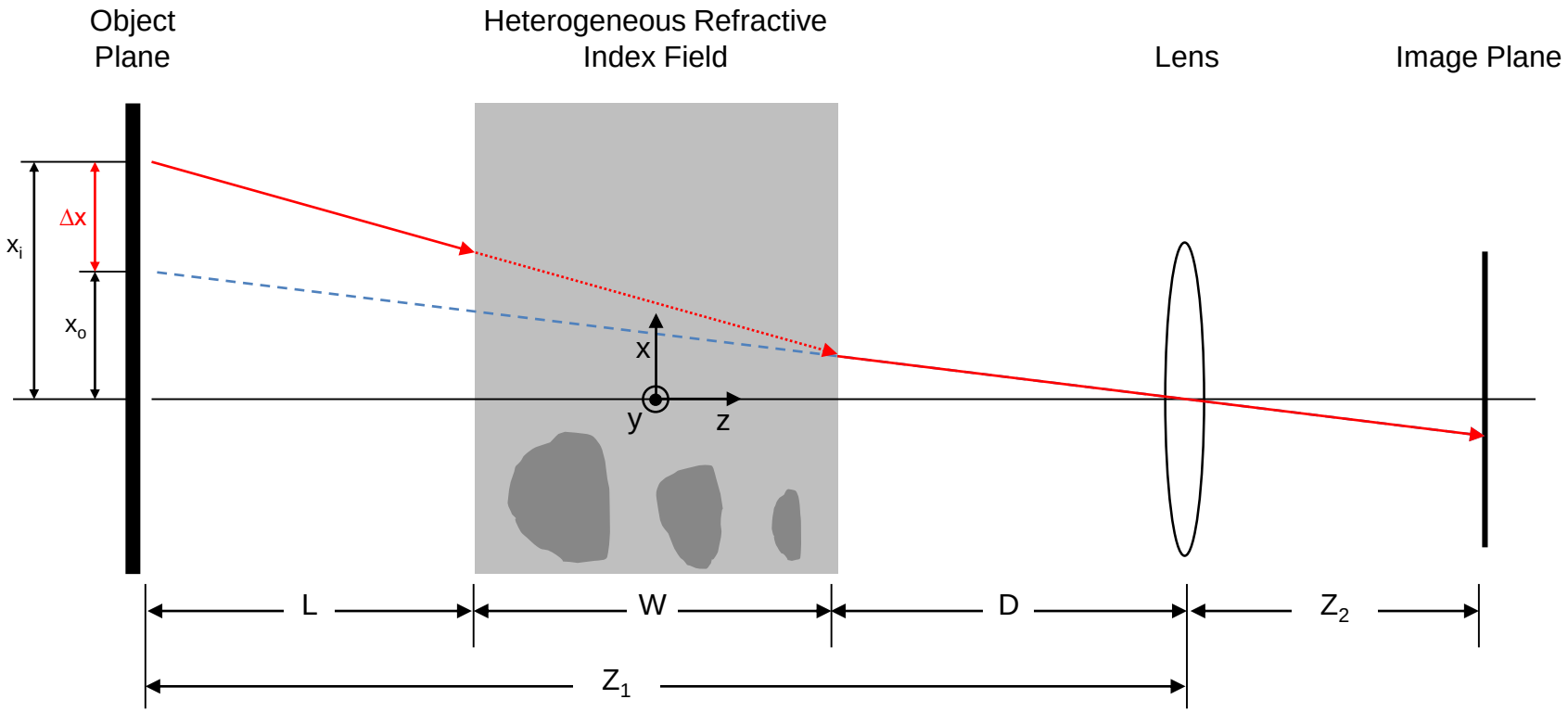

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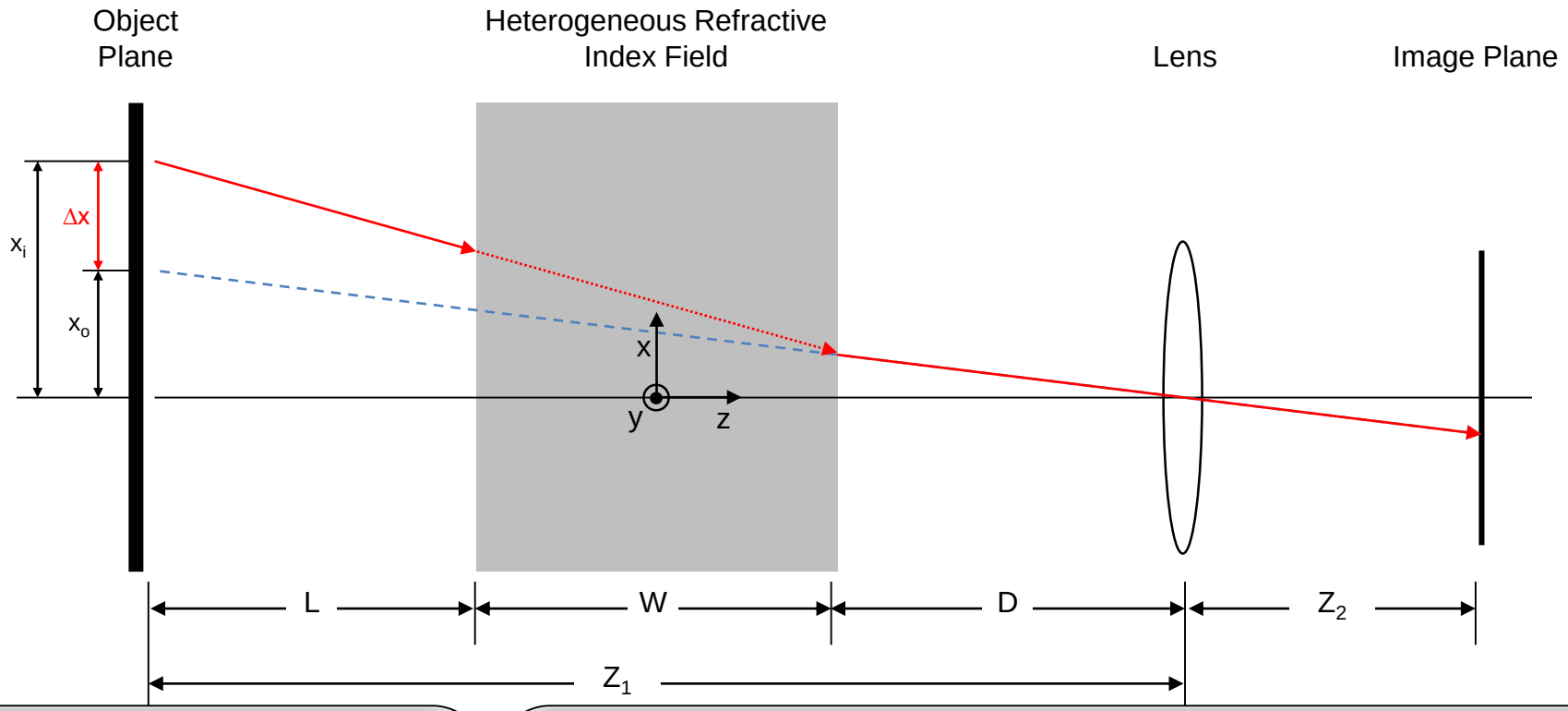
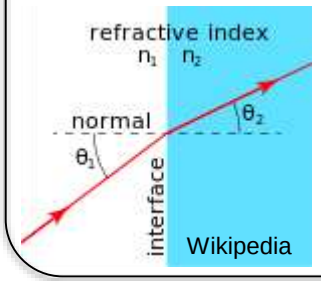


Refraction at an Interface

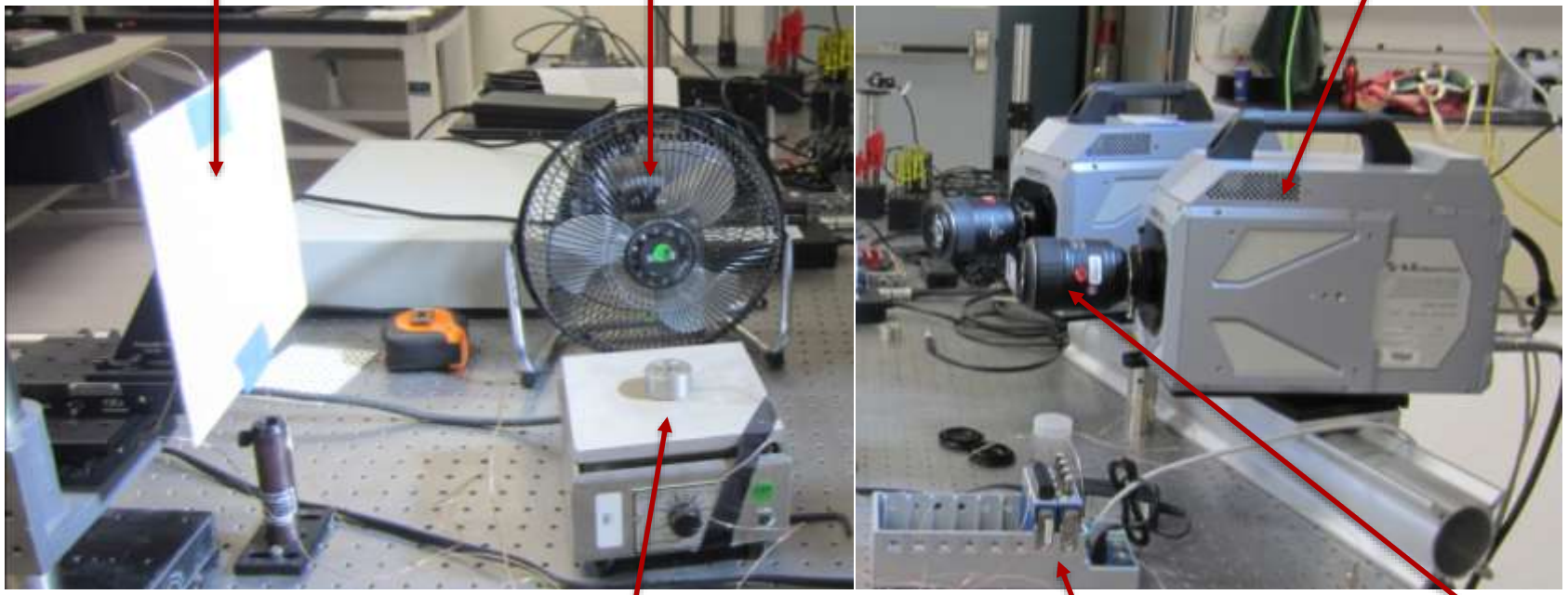


$$\frac{\sin(\theta_1)}{\sin(\theta_2)} = \frac{n_1}{n_2}$$

Refraction through a Heterogeneous Field

$$\frac{d^2x}{dz^2} = \left[1 + \left(\frac{dx}{dz}\right)^2 + \left(\frac{dy}{dz}\right)^2\right]\left[\frac{1}{n}\frac{\partial n}{\partial x} - \frac{dx}{dz}\frac{1}{n}\frac{\partial n}{\partial z}\right] \Rightarrow \Delta x \propto (L+W)\int_{-W/2}^{W/2}\left(\frac{\partial n}{\partial x}\right)dz$$

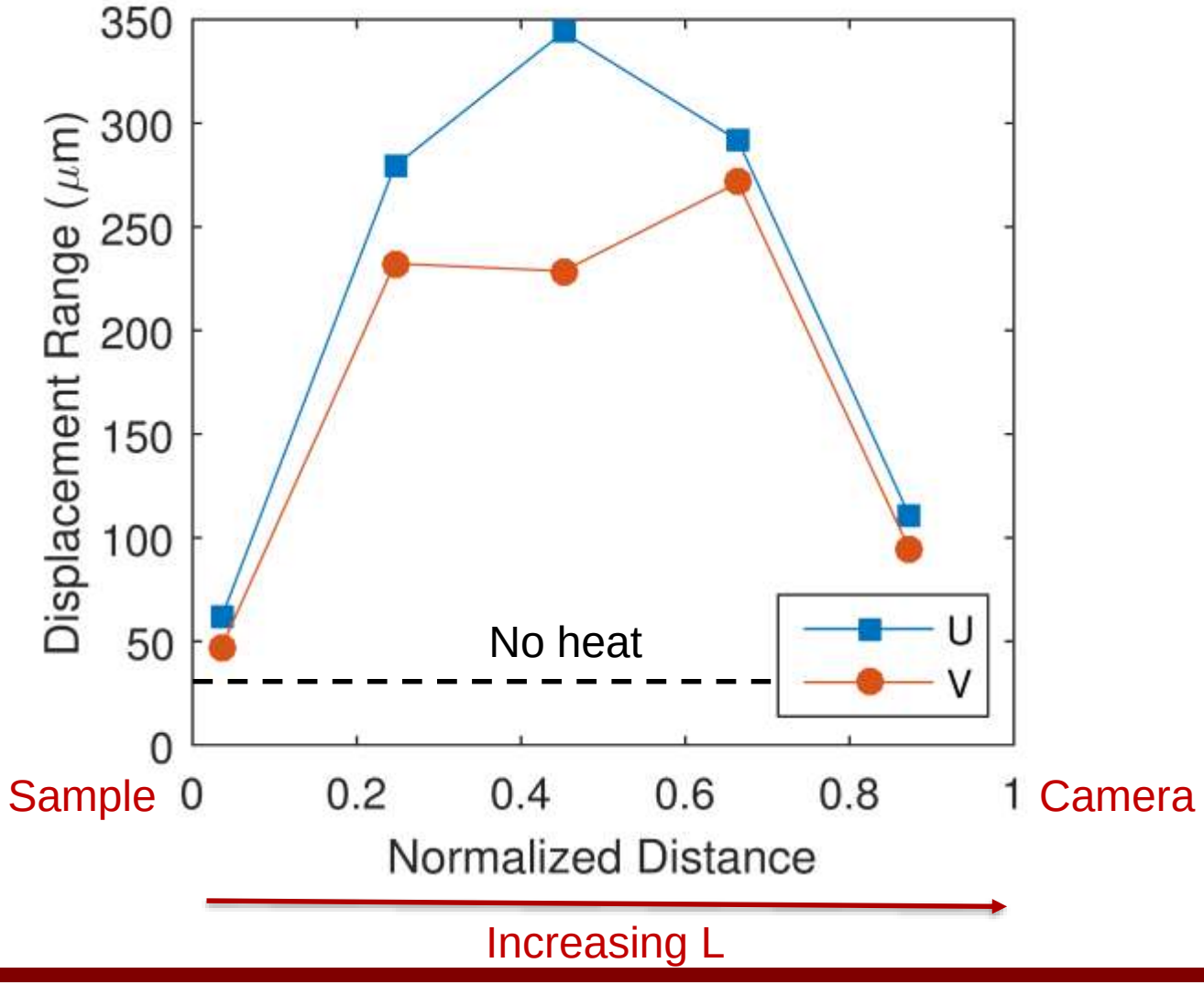
Heat wave properties are characterized with a model experimental setup.



- 2D DIC and stereo-DIC
- Metrics:
  - Displacement range: $U_{max} - U_{min}$; $V_{max} - V_{min}$
  - Displacement magnitude: $D = \sqrt{U^2 + V^2 + W^2}$

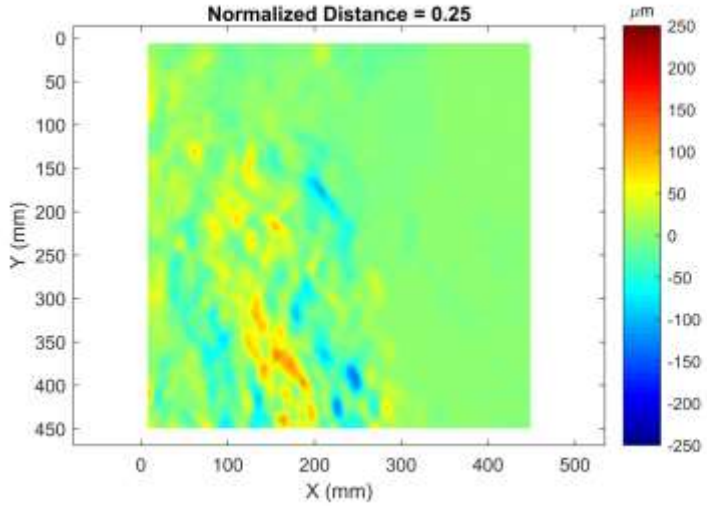
Location of the heat source strongly influences the results.

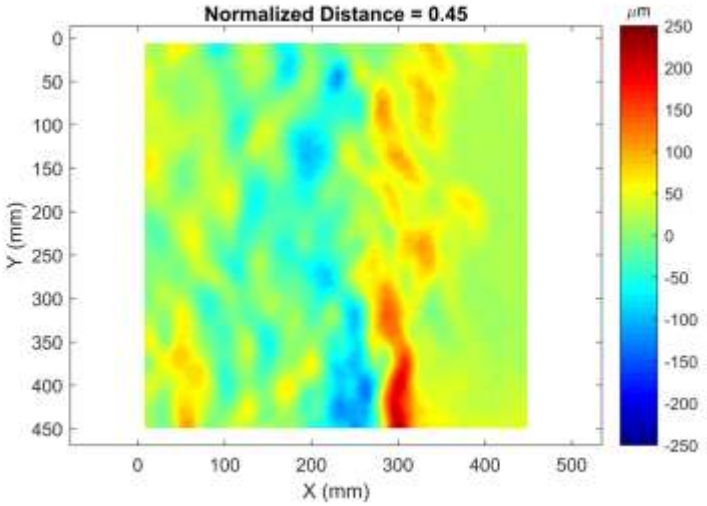
$$\Delta x \propto (L + W) \int_{-W/2}^{W/2} \left(\frac{\partial n}{\partial x}\right) dz$$

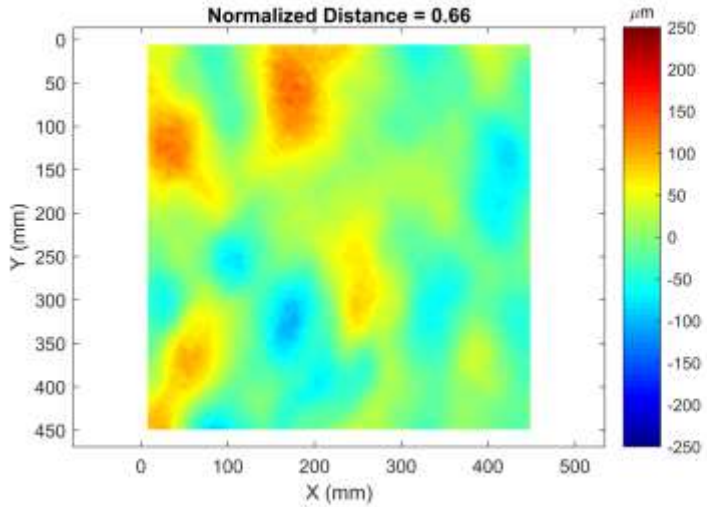


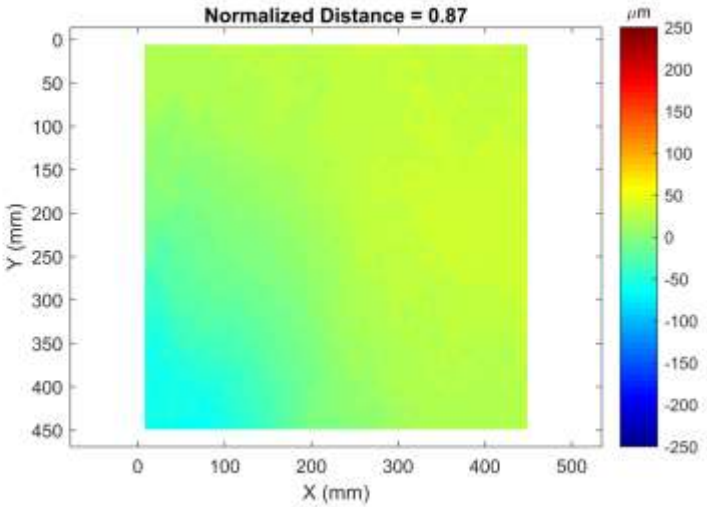
Spatial frequency of heat waves depends on relative hot plate location.

$$\Delta x \propto (L + W) \int_{-W/2}^{W/2} \left(\frac{\partial n}{\partial x} \right) dz$$



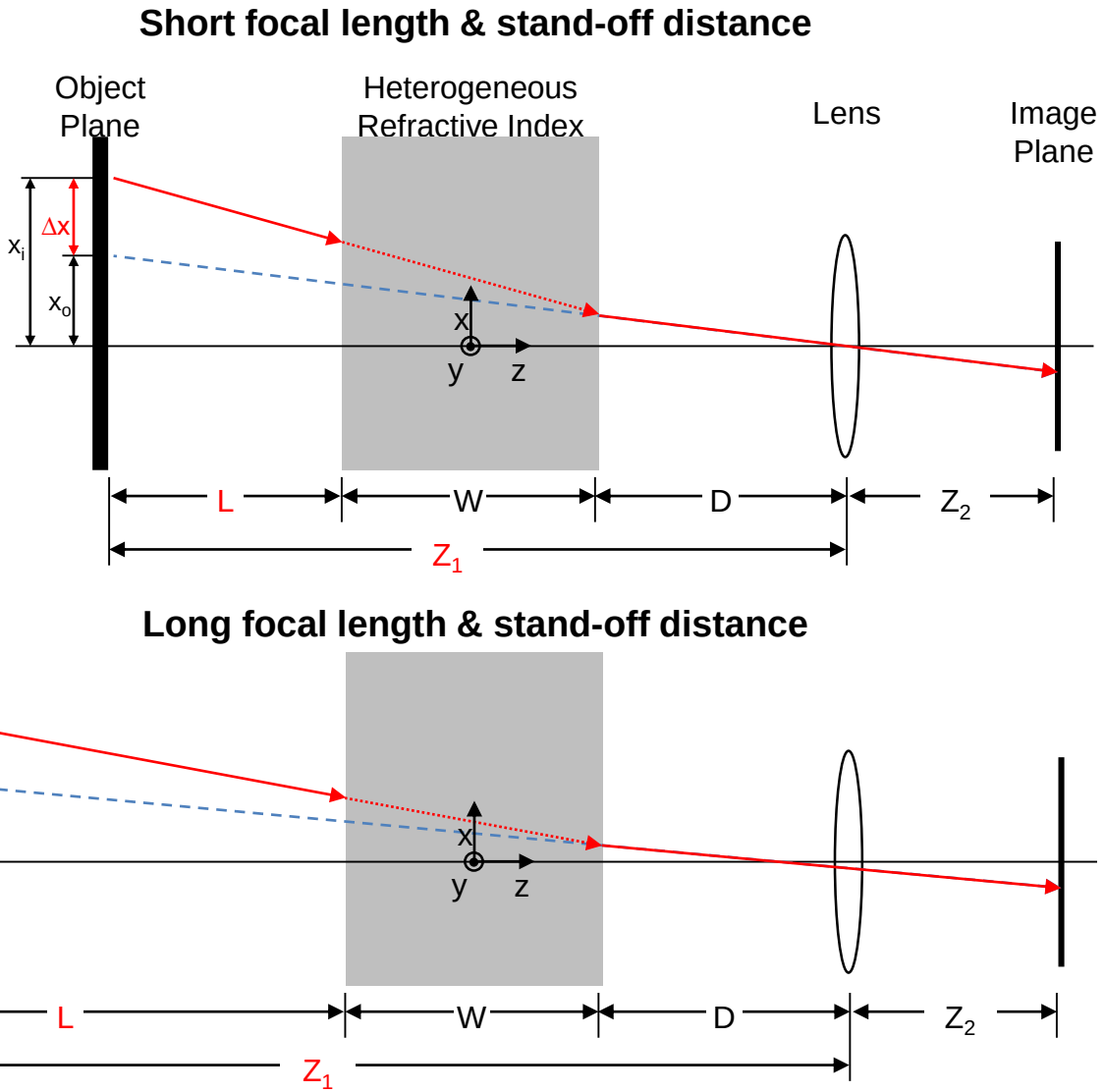






Focal length and stand-off also affect image distortion.

$$\Delta x \propto (L + W) \int_{-W/2}^{W/2} \left(\frac{\partial n}{\partial x}\right) dz$$



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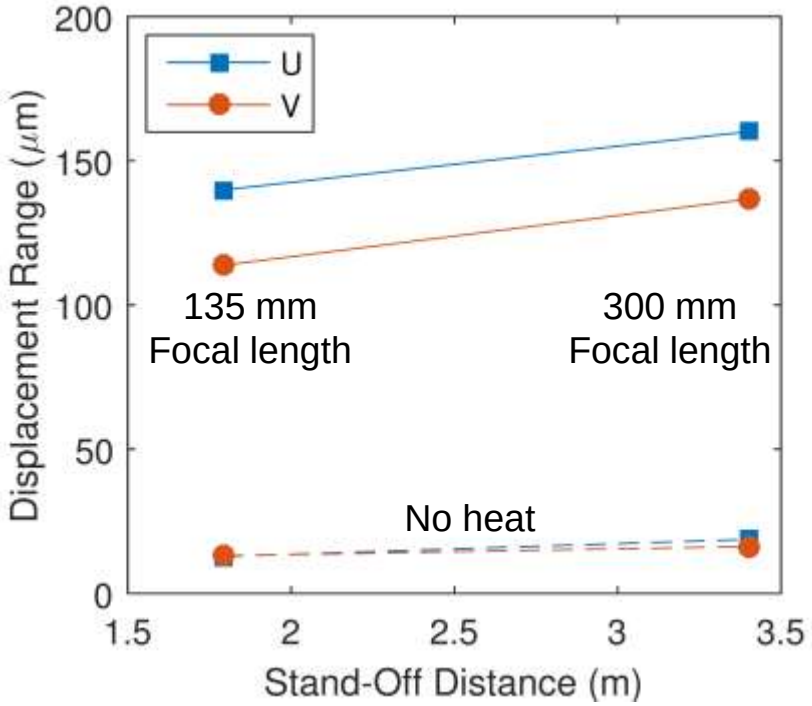
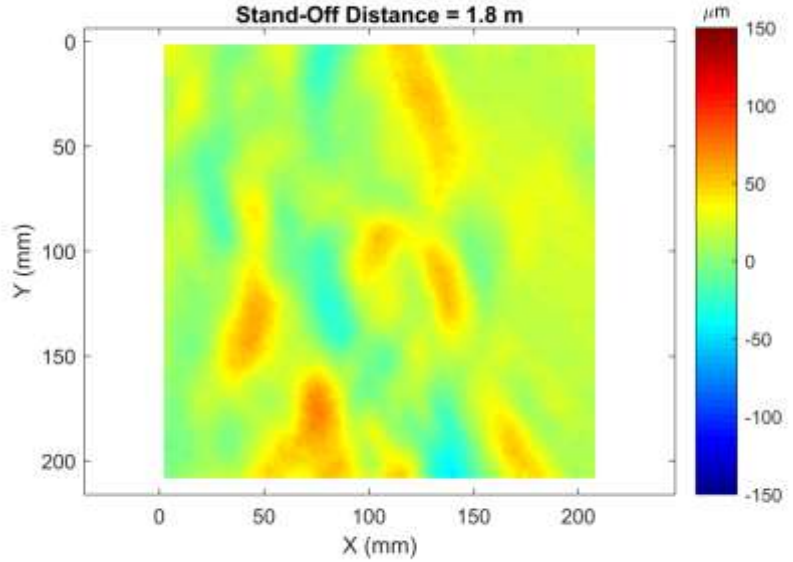
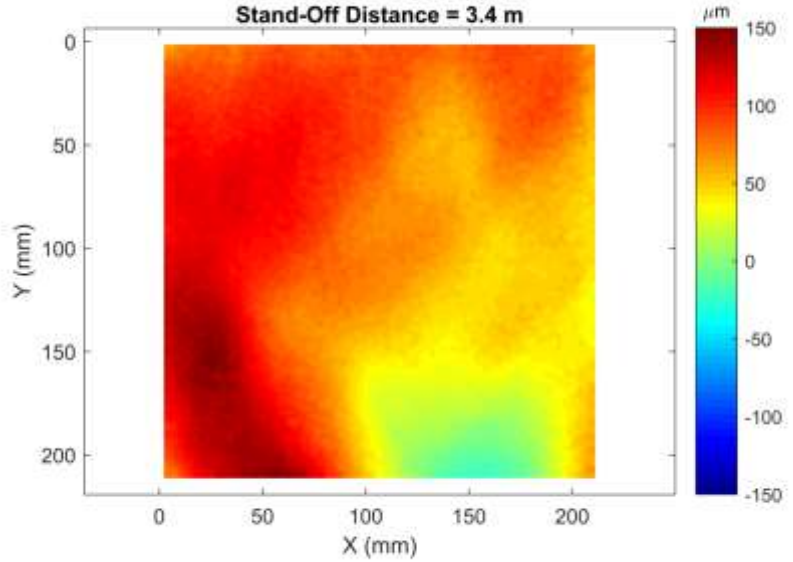
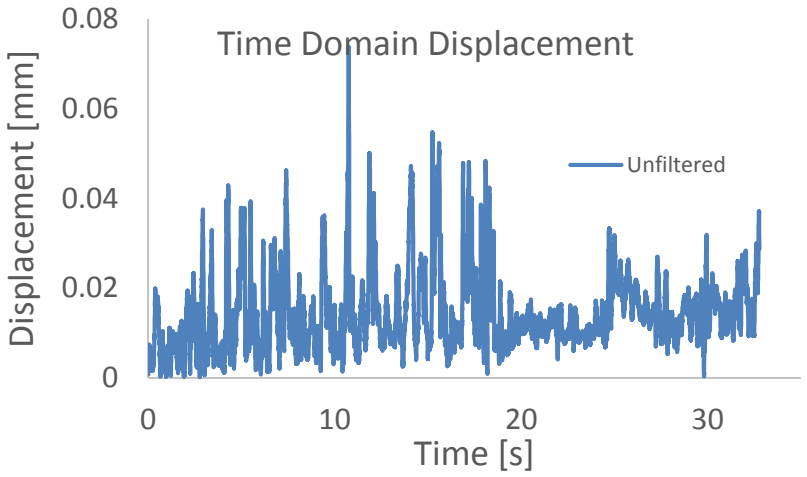


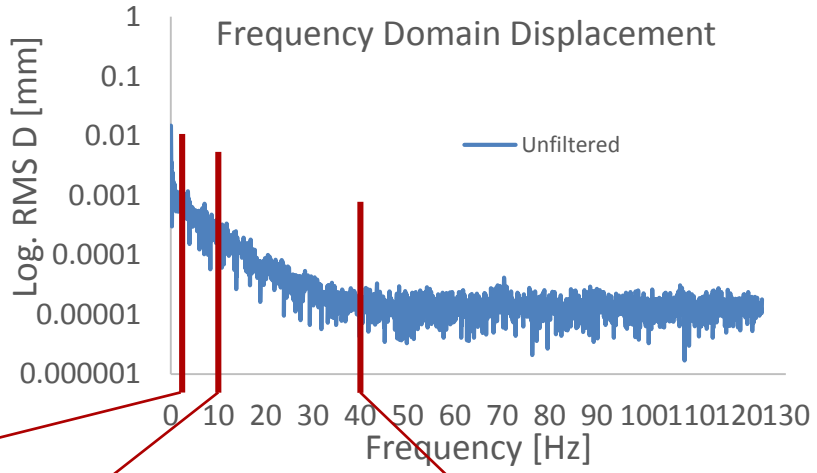




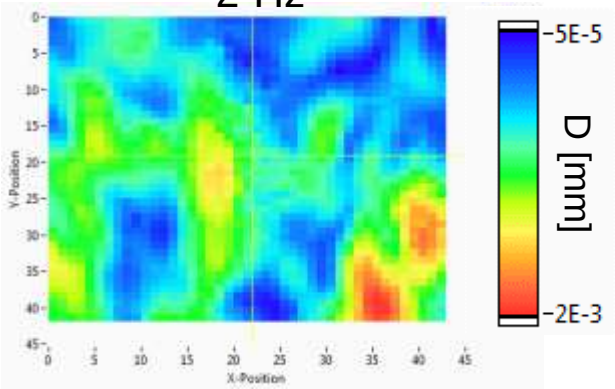
The frequency content of the heat waves is a key to eliminating them.

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

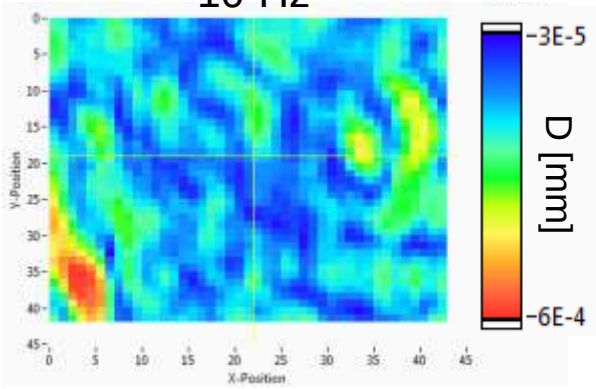




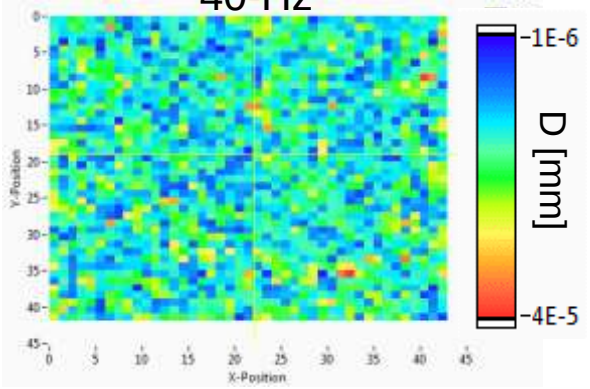
2-Hz



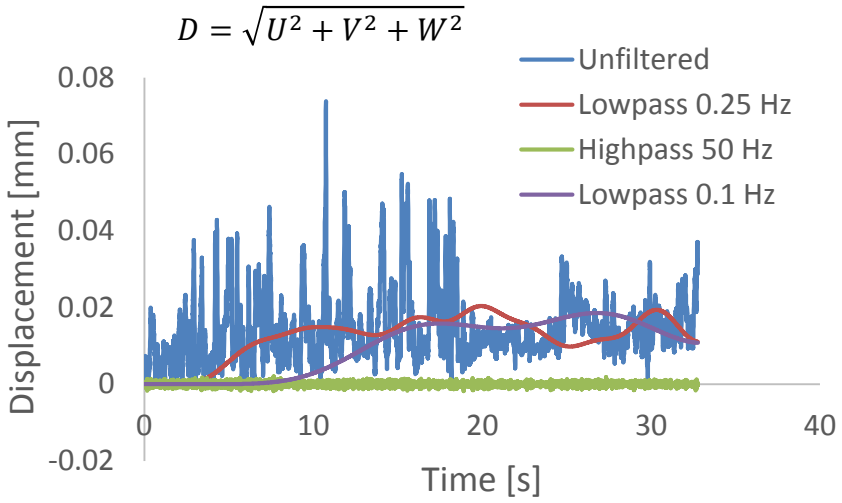
10-Hz

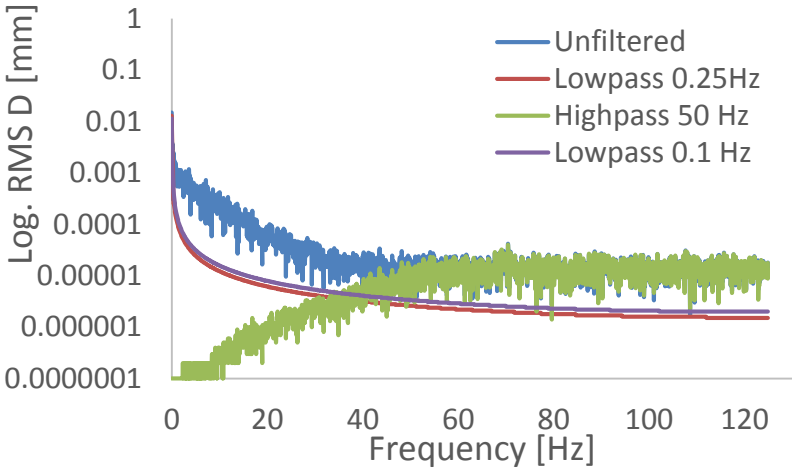


40-Hz

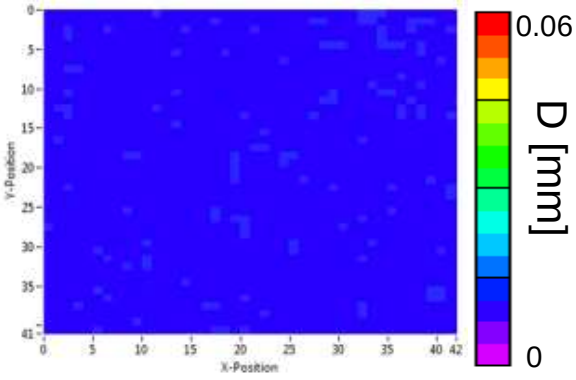


Band-pass filters can reduce the magnitude of heat waves.

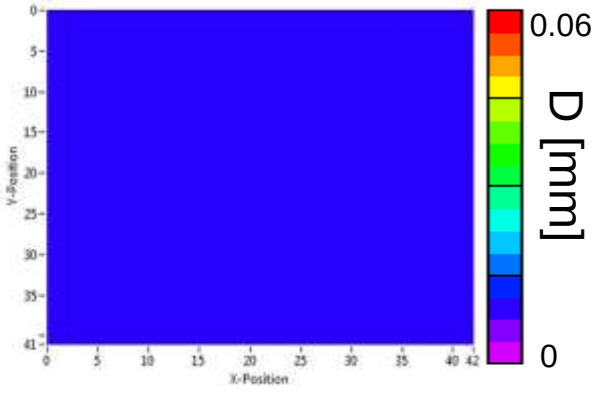




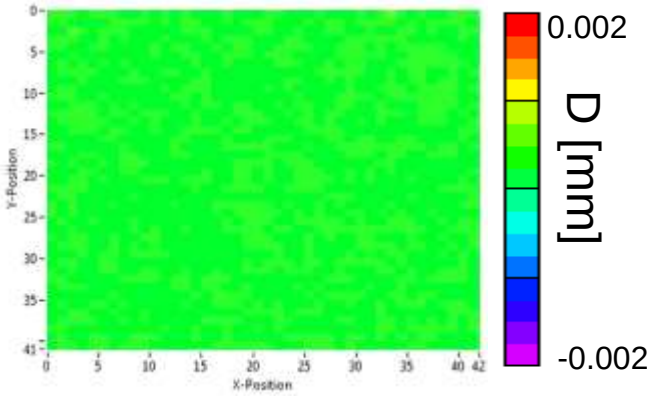
Unfiltered



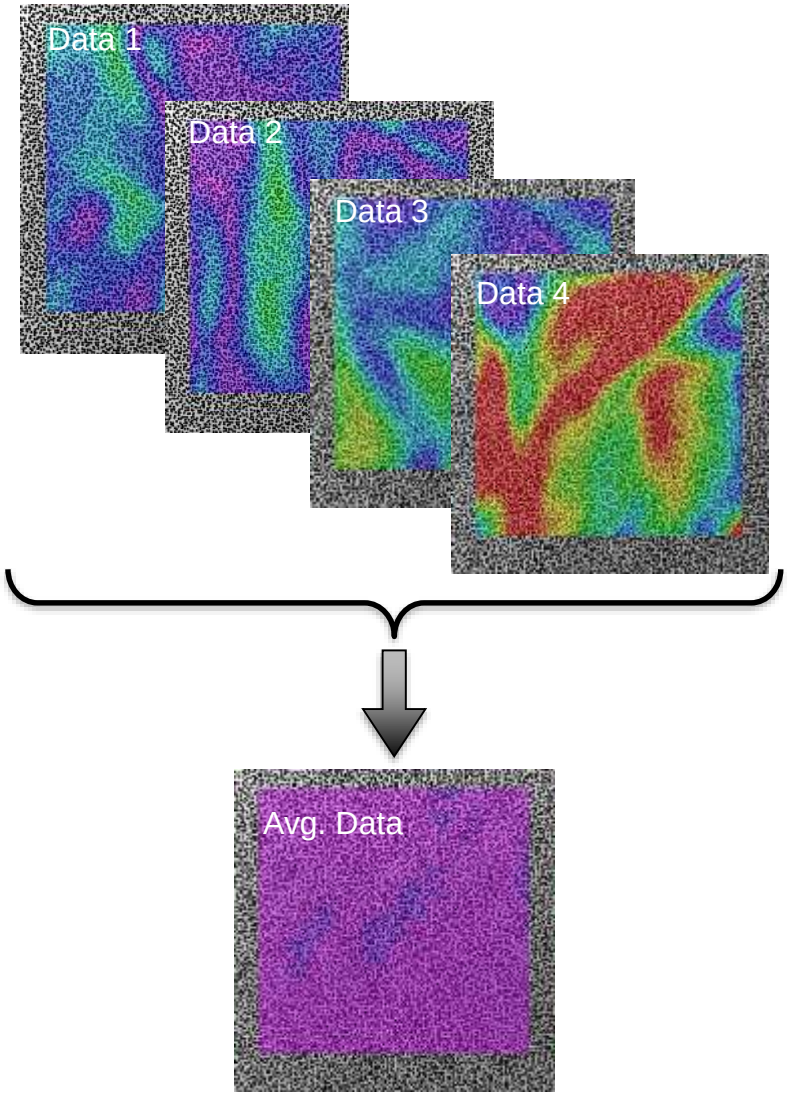
0.1 Hz Low Pass

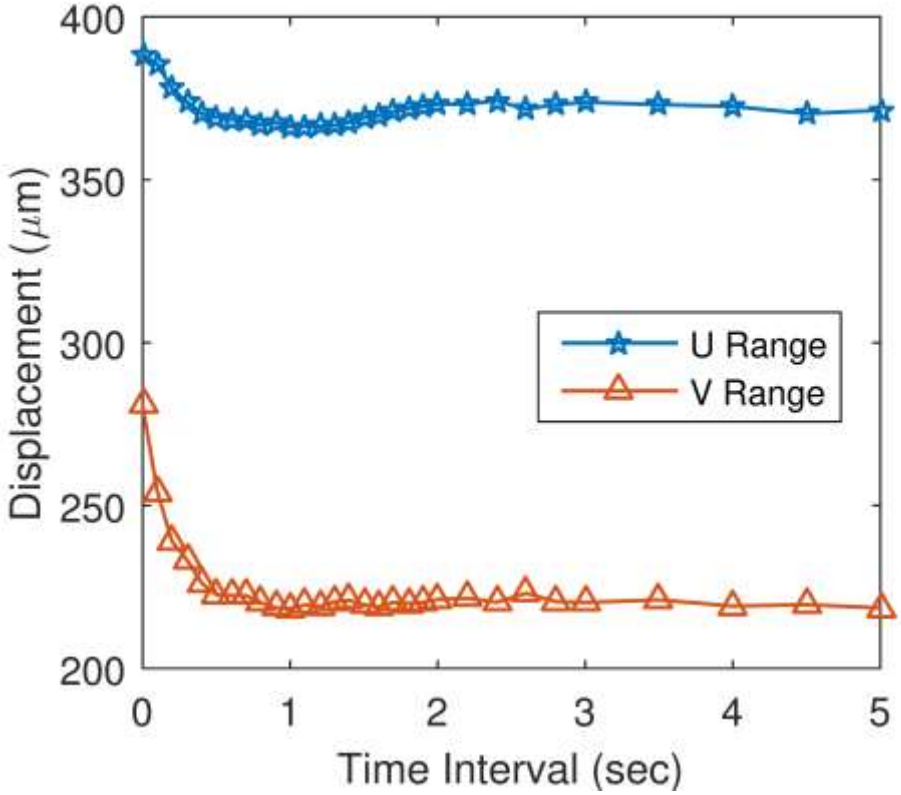


50 Hz High Pass

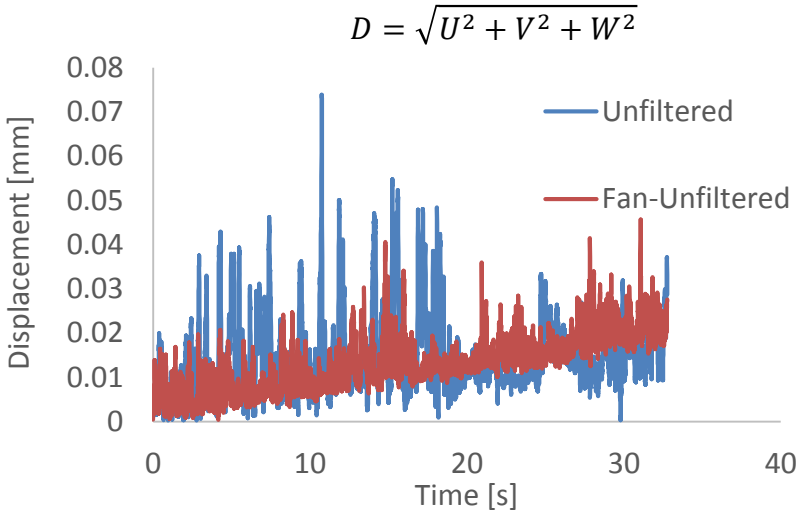


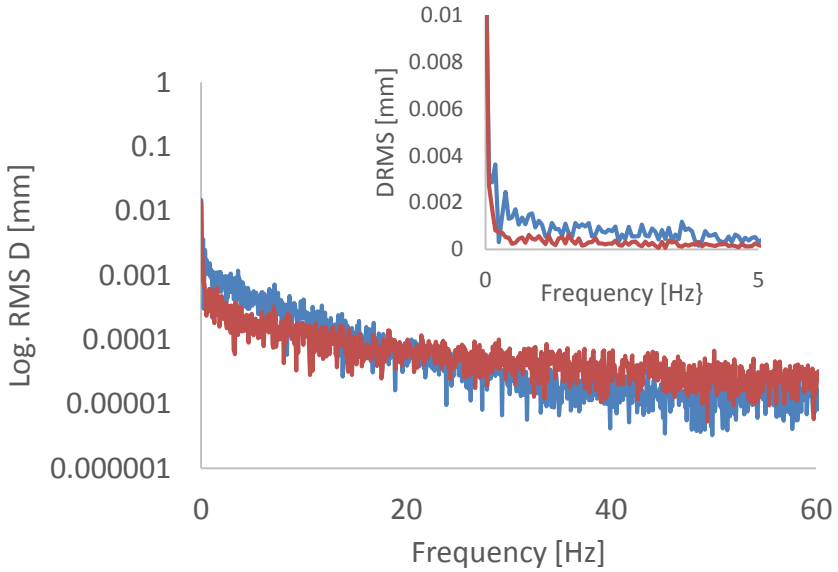
Temporal averaging provides limited improvement.

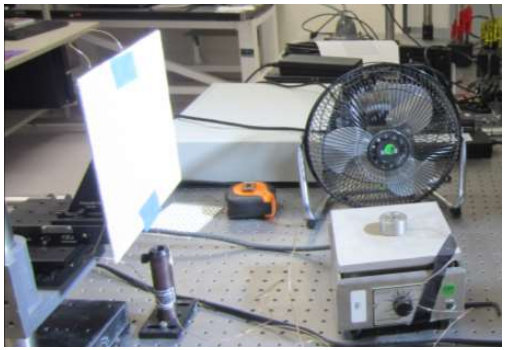


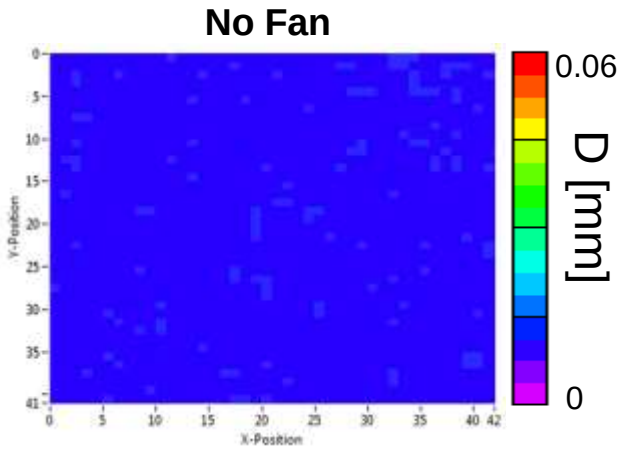


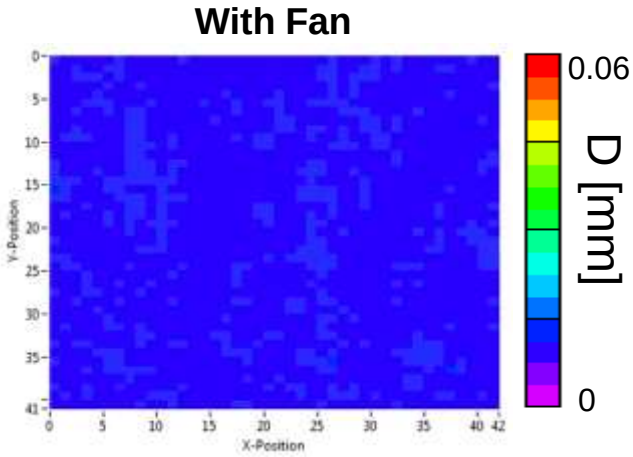
Fans can break up the heated zones.



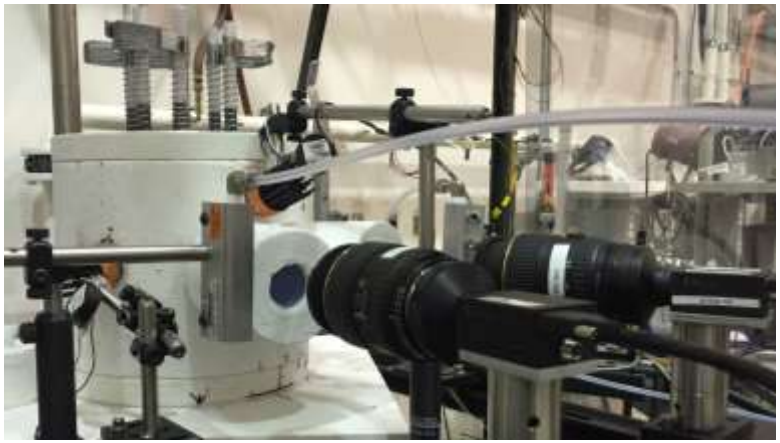


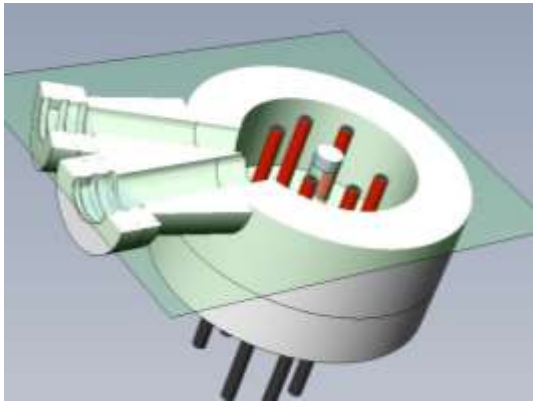


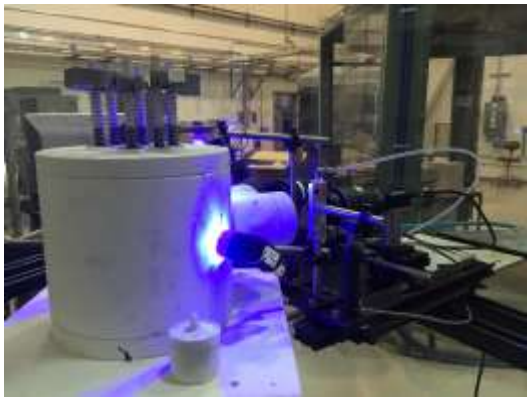


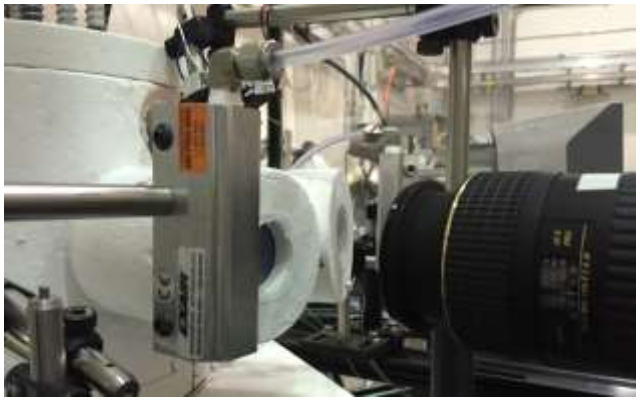


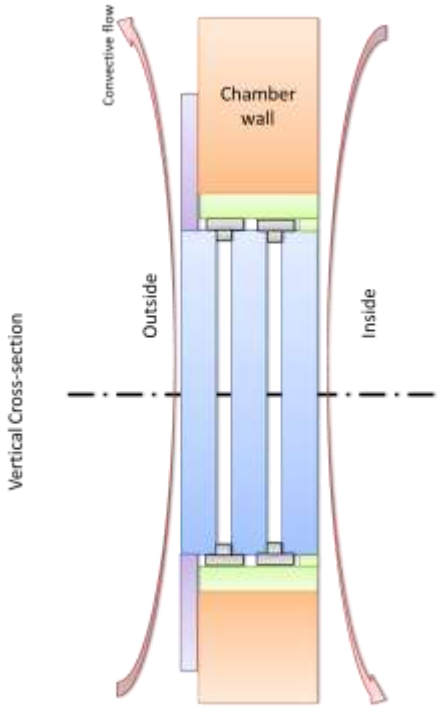
Carefully designed ovens aim to minimize thermal gradients.









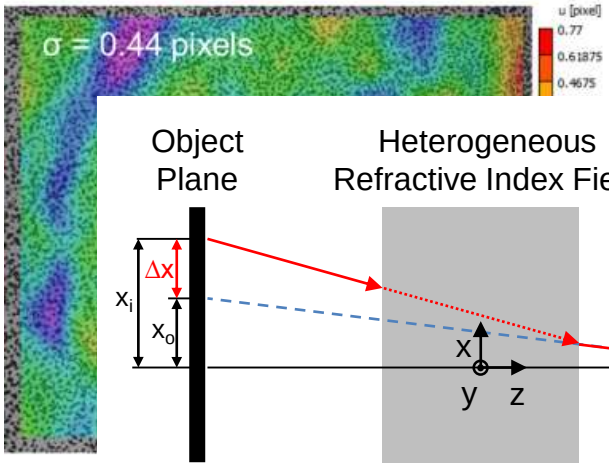


Selected References:

1. Berke, R.B. and J. Lambros, *Review of Scientific Instruments,* 2014. ***85(4):*** *p. 045121.*
2. Novak, M.D. and F.W. Zok, *Review of scientific instruments*, 2011. **82(11)**: p. 115101.
3. Lyons, J., J. Liu, and M. Sutton, *Experimental Mechanics*, 1996. **36(1**): p. 64-70.
4. Pan, B., et al., *Measurement Science & Technology*, 2011. **22(1)**.
5. De Strycker, M., et al., *Optics and Lasers in Engineering*, 2010. **48(10)**: p. 978-986.

Heat waves are often ubiquitous, but often overlooked

- Heat waves have many sources
  - Hot lights
  - Hot camera
  - Hot sample
  - Sunlight
- Image distortion caused by heterogeneous index of refraction
- Magnitude of false displacements depends on location of heat source and temperature gradients
- Post-processing filtering techniques are largely inadequate
- Best strategy is to eliminate/reduce heat waves experimentally



$$\Delta x \propto (L + W) \int_{-W/2}^{W/2} \left(\frac{\partial n}{\partial x} \right) dz$$