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4D particle tracking using space-time interlaced tomography and apparent mass loss due to image blur

Benjamin R. Halls, Lucas K. Lebow, Enrico C. Quintana and Daniel R. Guildenbecher

Engineering Sciences Center, Sandia National Laboratories

Albuquerque, New Mexico 87185 USA

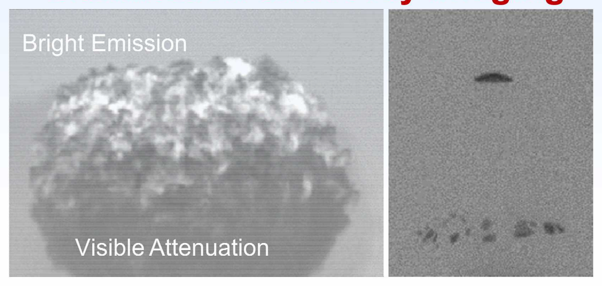
Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

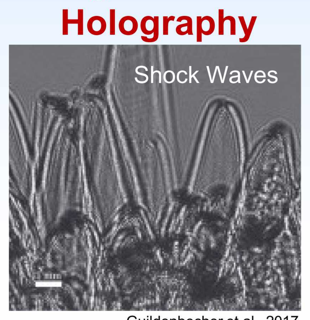
High-Speed, Polychromatic, Multi-Dimensional X-ray Imaging

High-speed x-ray radiography and tomography were used to track particles and quantify their mass during impulsively driven events. Because attenuation is the dominant interaction between x-rays and matter, refraction and multiple photon scattering events can be neglected. The resulting images are a function of the material properties and the x-ray spectrum. The main sources of uncertainty are the instrument function, out-of-plane motion (for radiography), and image blur, image parallax and the number of sources.

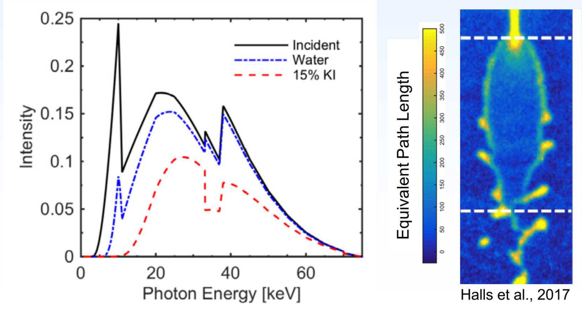
Simultaneous Diffuse Back-Illumination and X-ray Imaging



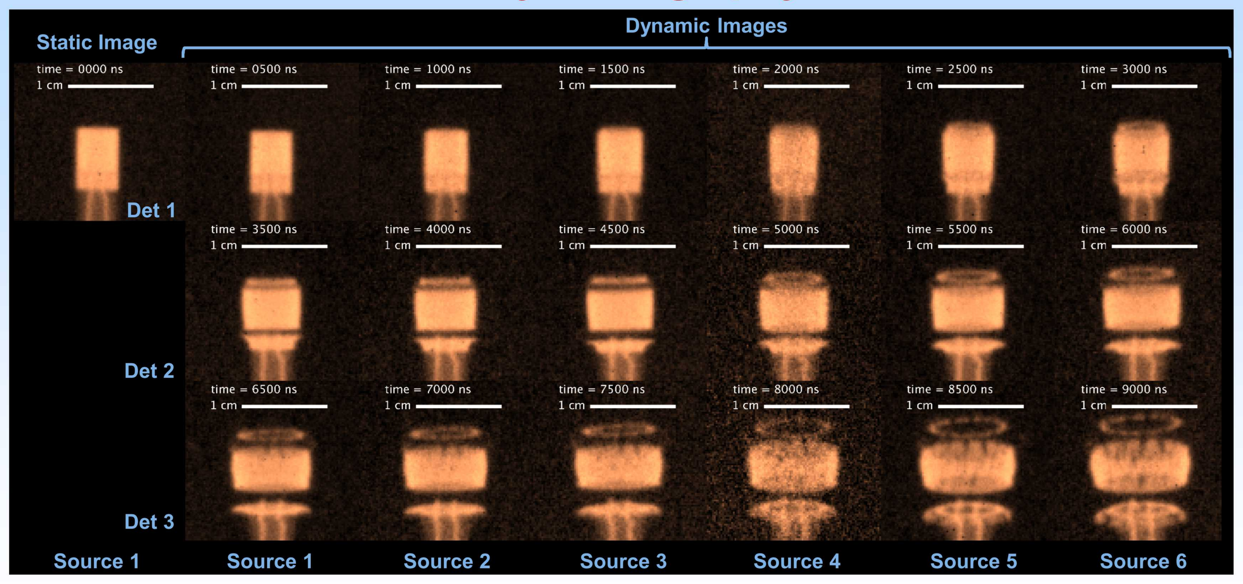
Digital Inline Holography



Quantitative Mass Distribution



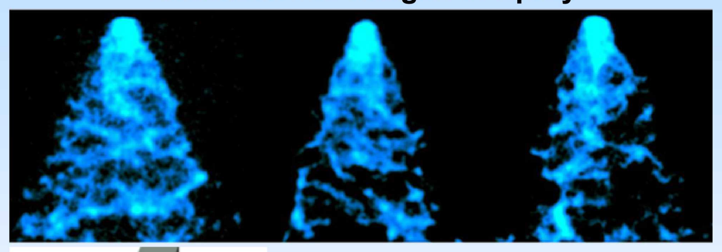
2 MHz Flash X-ray Radiography of Detonator

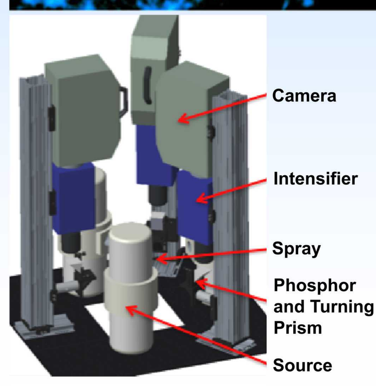


Images were phase matched over 3 detonators using six sources in each shot. Images from 7500 ns to 9000 ns display effect of image parallax, the detonator appears to rotate.

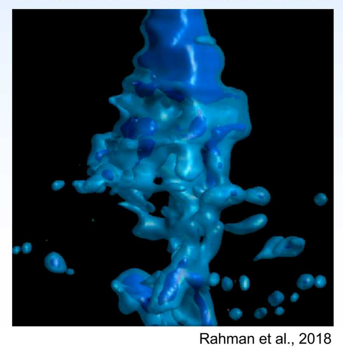
10 kHz X-ray Tomography using Iterative Reconstruction

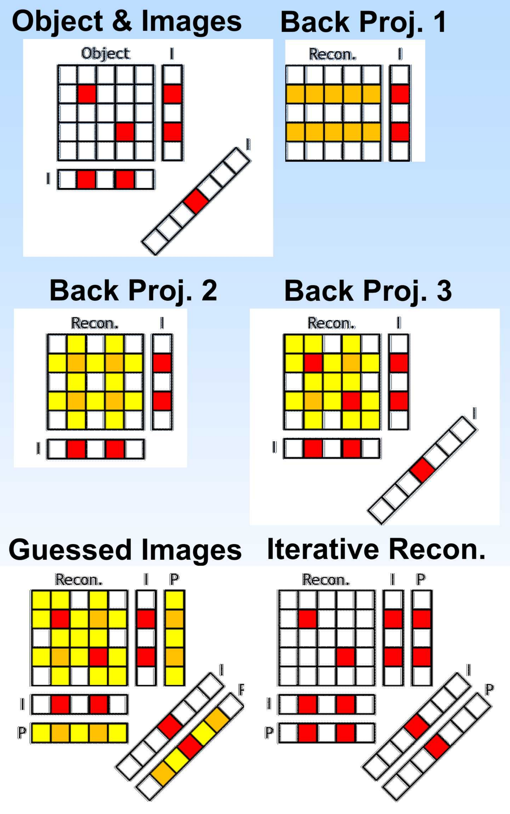
Simultaneous Images of Spray





Iterative Reconstruction





Space-Time Interlaced Tomography

Particles were tracked in three dimensions using space–time interlaced tomography. When a limited number of frames are available and linear trajectories are assumed, the three-dimensional particle locations can be determined by fitting a unique line to the possible particle locations. These particle locations are determined by interlacing the temporal and angular information of the scene.

Image parallax becomes a benefit

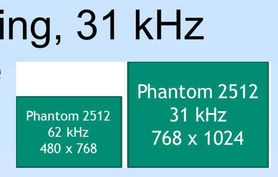
Flexible imaging systems

150 kVp x-ray sources

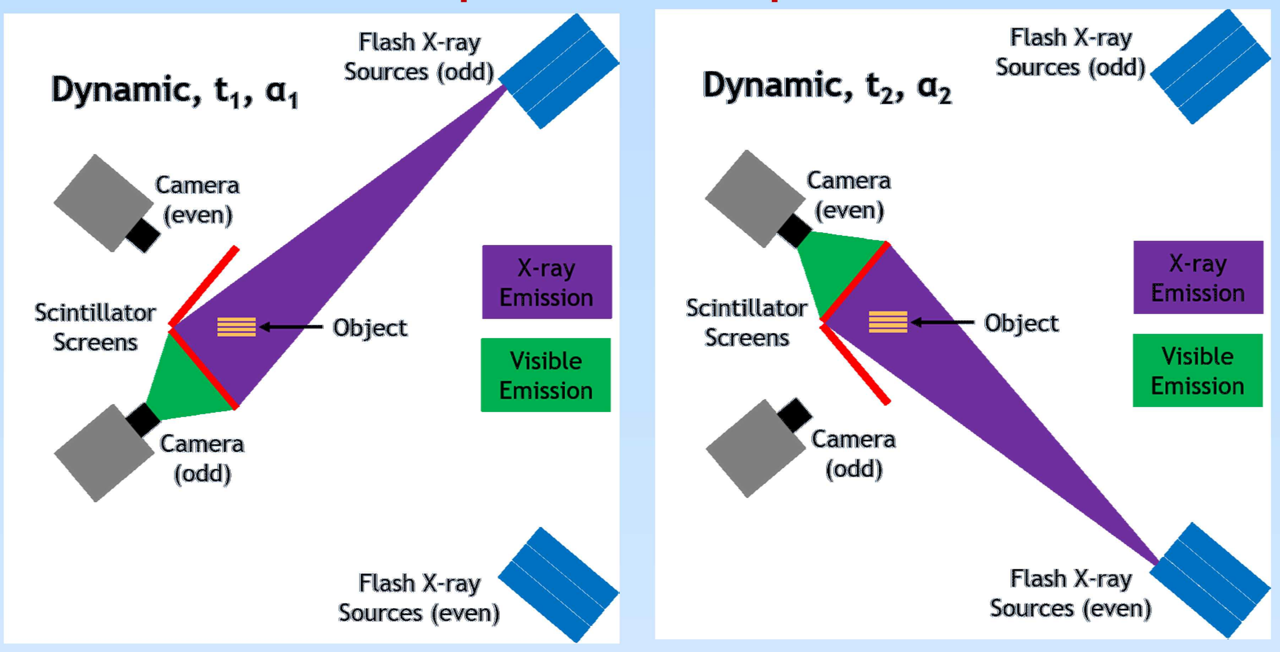
Spatial resolution of volume
- 10–90% Rise dist. = 1.6 mm

Scintillator screens
- GOS:Pr, ~4 μs decay time

High-speed cameras
- Phantom 2512, 50 mm f/1.4 Nikon
- 62 kHz x-ray imaging, 31 kHz camera frame rate

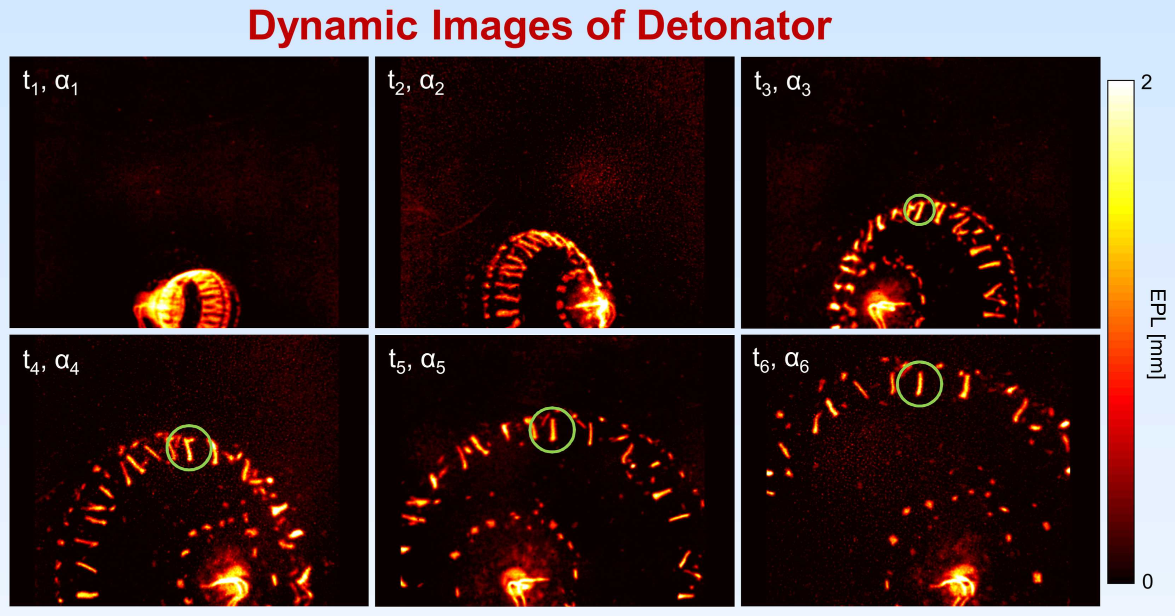


Experimental Setup

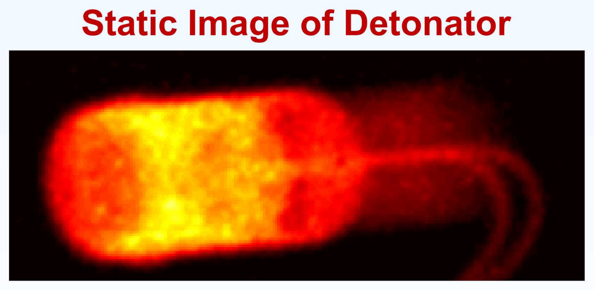


Data processing
- Dot target calibration
- Remove salt noise from images
- Normalize and convert images to Equivalent Path Length (EPL)
- Segment particles, images were binarized to isolate particles, particle location was determined by center of mass
- Possible particle locations were back projected through volume, no lines intersected because the particle has moved in time
- Unique linear trajectories were fit to the possible particle locations

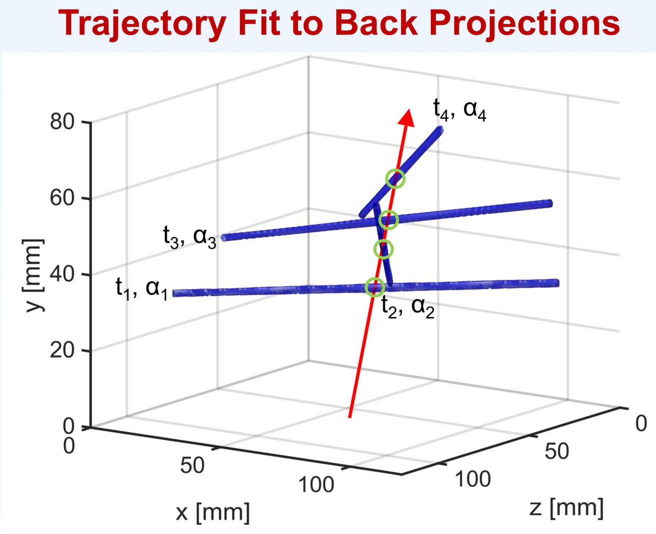
Dynamic Images of Detonator



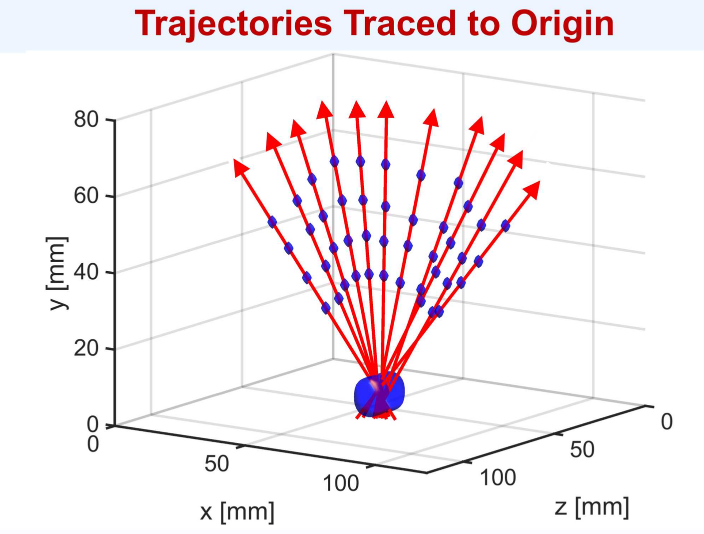
Static Image of Detonator



Trajectory Fit to Back Projections



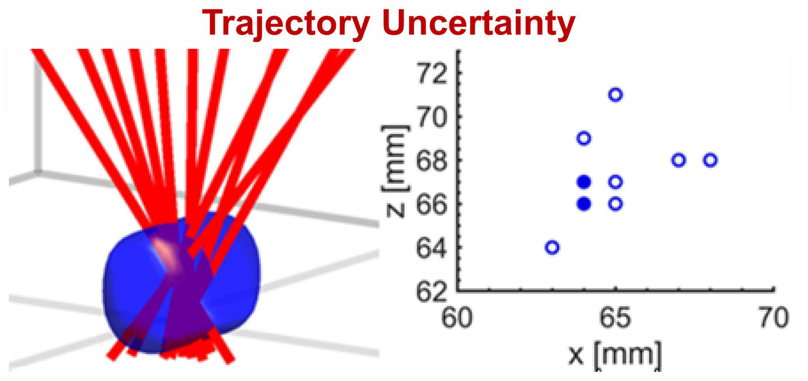
Trajectories Traced to Origin



Uncertainty
- Volume resolution ~1.6 mm, spread of trajectories ~5 mm

Causes of uncertainty:
- Velocity / Direction: calibration, particle segmentation, center of mass determination, spatial resolution
- Mass: atten. coeff., image blur, image characteristics, noise

Trajectory Uncertainty



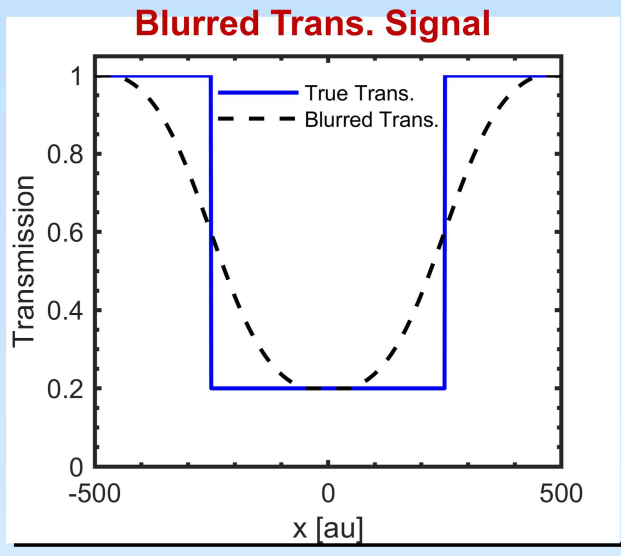
Apparent Mass Loss due to Image Blur

Image blur induces a bias error during the nonlinear conversion from transmission signal to path length when using a spectrally resolved version of Beer's Law. This bias error manifests as a measured mass less than the true mass. X-ray images were collected of objects of various sizes, shapes, and levels of spatial blur to investigate the uncertainty of measured mass. A numerical model of the imaging system investigated trends over a wide range of object shapes and sizes.

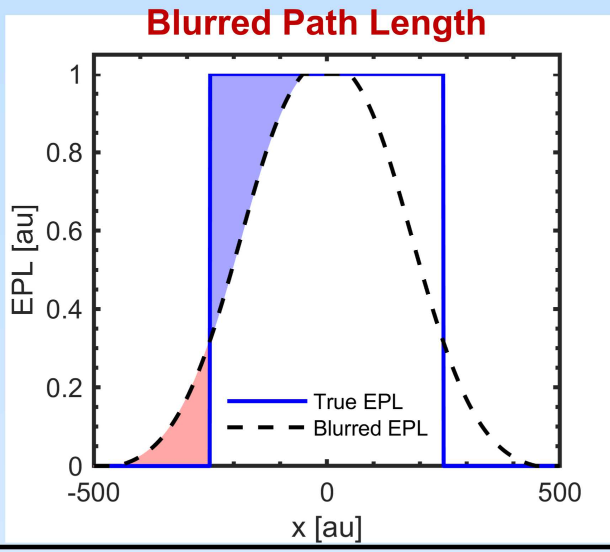
Effects to consider: Object size, Image blur, Level of transmission (degree of nonlinearity), Variance of trans., Pixel size, Noise (contrast-to-noise ratio of 5 results in mass gain of ~1%)

Sources of blur: penumbra (geometric blur), scintillator, intensifier, camera, lens

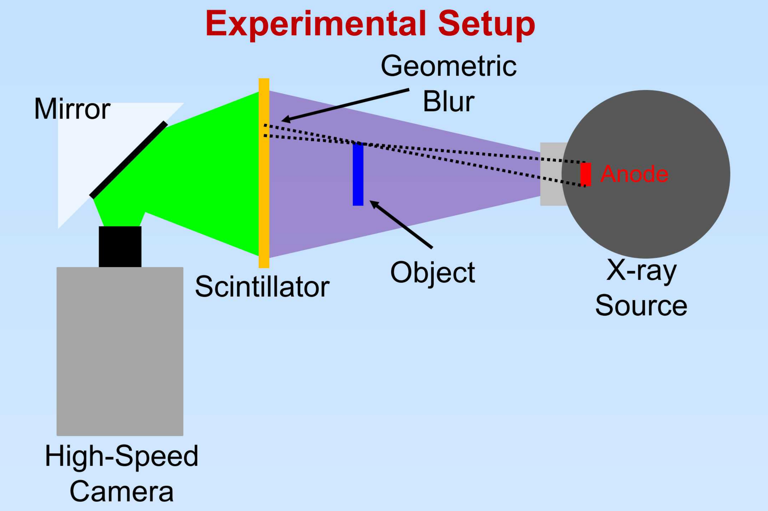
Blurred Trans. Signal



Blurred Path Length



Experimental Setup

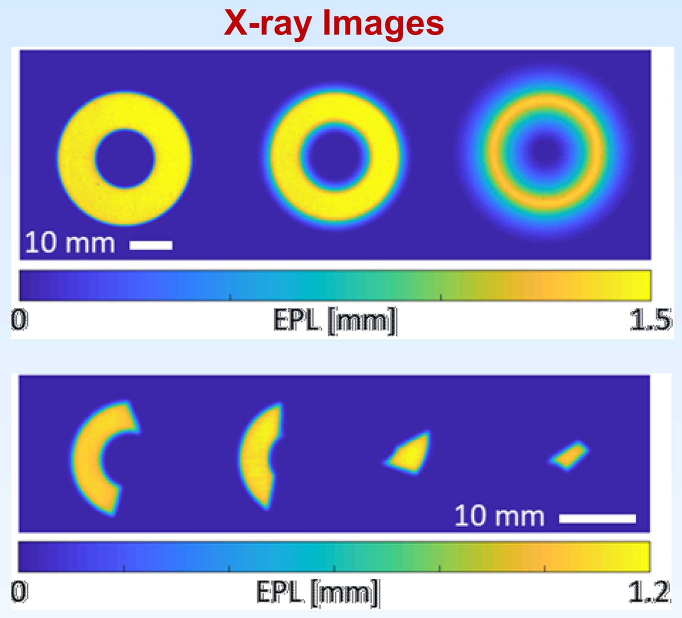


Experimental Results
- Objects of various shapes and area-to-perimeter ratios were images and their masses compared to that measured on a scale

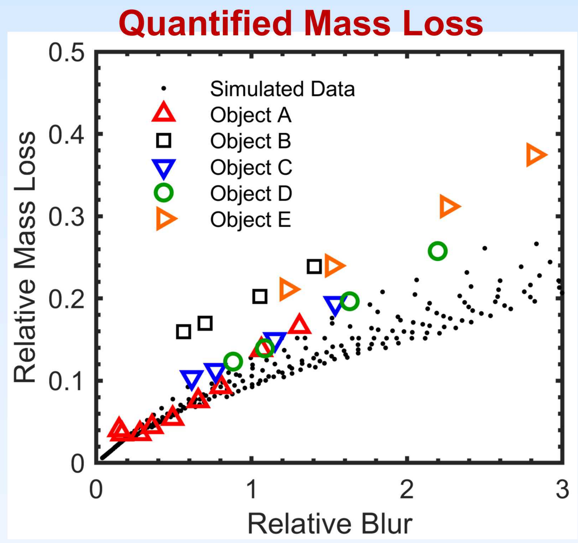
$$Rel.\,Mass\,Loss = \frac{(true - measured)}{true}$$

$$Rel.\,Blur = \frac{rise\ distance}{(area/perimeter)}$$

X-ray Images



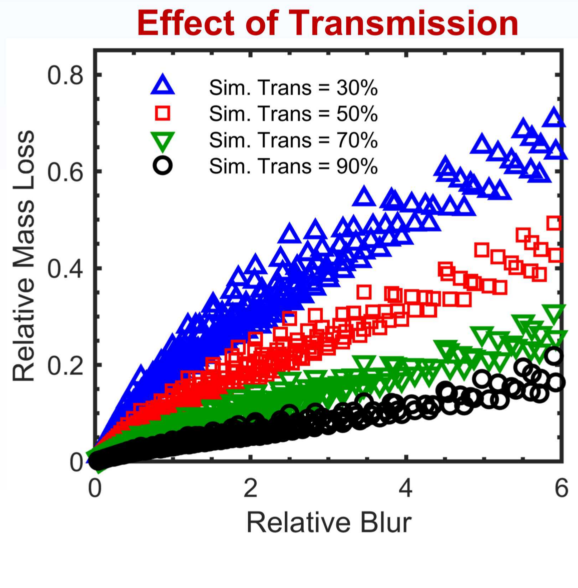
Quantified Mass Loss



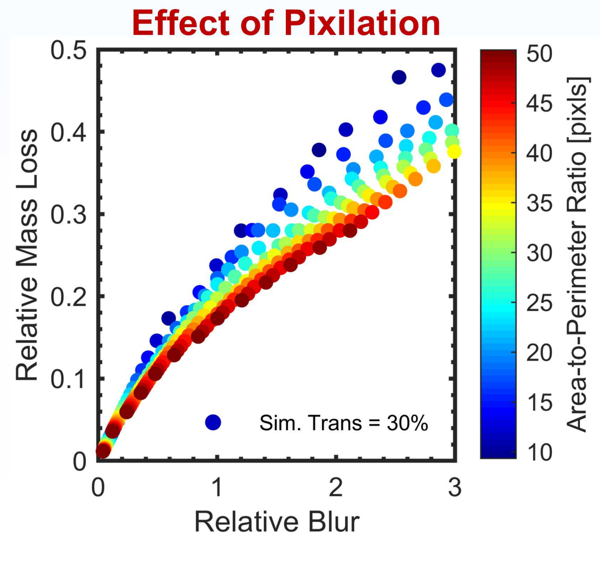
Discrepancy in objects B and E result of EPL conversion error

Numerical Imaging Results
- Variables: diameter, thickness (transmission), degree of spatial blur, and pixilation (secondary)
- Increased transmission leads to increased mass loss
- Spread in data attributed to degree of object pixilation
- Mass loss tracks well with average attenuation

Effect of Transmission



Effect of Pixilation



Combined Effects