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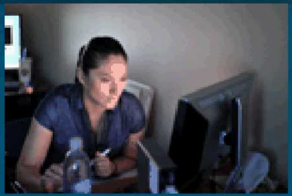
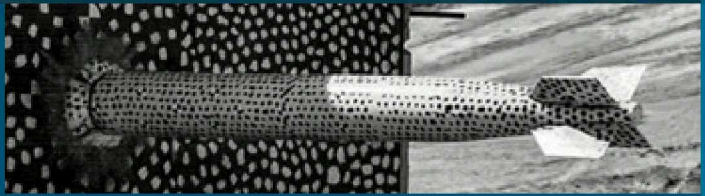
High-Fidelity Calibration and Characterization of the Hyperspectral Computed Tomography System





Isabel O. Gallegos, Gabriella M. Dalton, Adriana M. Stohn, Srivathsan Koundinyan, Kyle R. Thompson, Edward S. Jimenez

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Outline

- Hyperspectral Computed Tomography (H-CT)
- Linear Imaging System
- Discretized System Operator
- Technical Approach
- Results
- Conclusion
- Future Work

Current Challenges within Computed Tomography

- Traditional X-ray CT is typically performed with a polychromatic source that emits x-rays across a broad spectrum
  - Typically spans hundreds of keV to several MeV for industrial applications.
  - Highly non-linear relationship between material, thickness, geometry, and energy.
  - Beam filtering can help but is limiting in a number of ways.

- Beyond Qualitative Imaging
  - Advances in Deep Learning
  - Material characterization
  - Interface resolution
  - Verification and Validation Applications.

Hyperspectral Computed Tomography System

SNL has developed the ***world's only hyperspectral computed tomography (H-CT) system*** specifically engineered and designed for industrial and security applications.

- 500 mm field-of-view.
- 300keV maximum energy.
- 640x640 voxel slices with submillimeter resolution.
- Successfully demonstrated material identification across multiple materials.
- For a majority of NDE applications, low energy is not feasible due to lack of penetrating power.

Current Challenges within Hyperspectral Computed Tomography

- Although H-CT has shown to improve CT reconstruction, there exist a number of challenges.
  - System thermal stability
  - Photon-Counting Noise
  - Higher Dose
  - Long scan times
- Possible mitigations:
  - High-Fidelity Calibration
  - Iterative Reconstruction
  - Sparse Sampling
  - Pre-hardening beam
- Initial Investigation
  - This work will perform a numerical study to investigate the feasibility of improving H-CT system performance via system operator estimation.
  - System operator estimation will enable improved calibration, reconstruction, and system characterization.

Linear Imaging System

- ***Central Question:*** Is it possible to accurately model and characterize the nonlinear encoding system of the H-CT system as a sequence of linear operators?
  - ***If so, what does this mean?*** Simulating a sequence of measurements of point-response functions arranged into a 3-dimensional tensor array.

$$\vec{g} = \boldsymbol{H}\vec{f} + \vec{n}$$

Image Vector

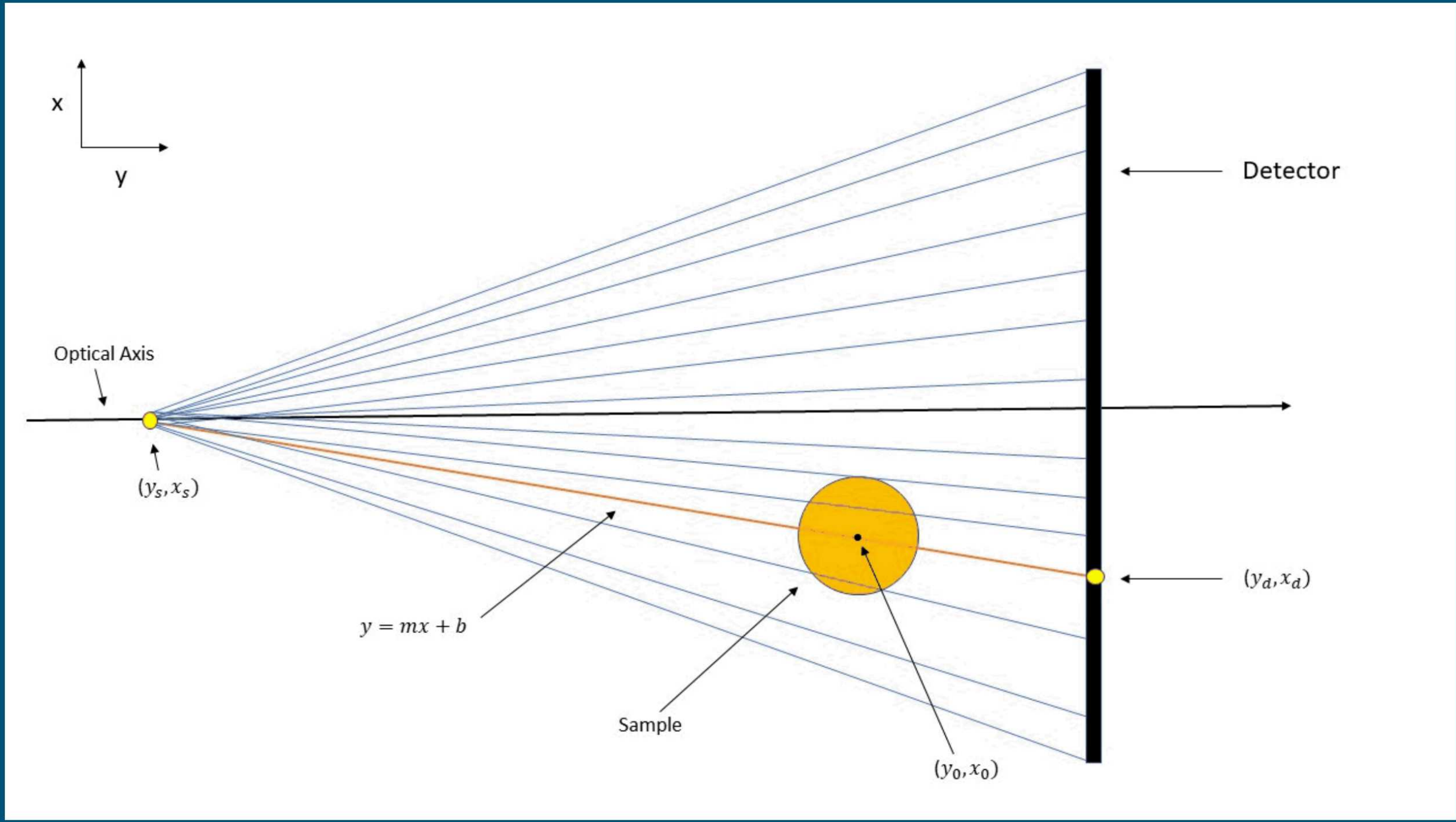
System Operator: responsible for mapping the object into the detected image

Object Vector

Noise Vector

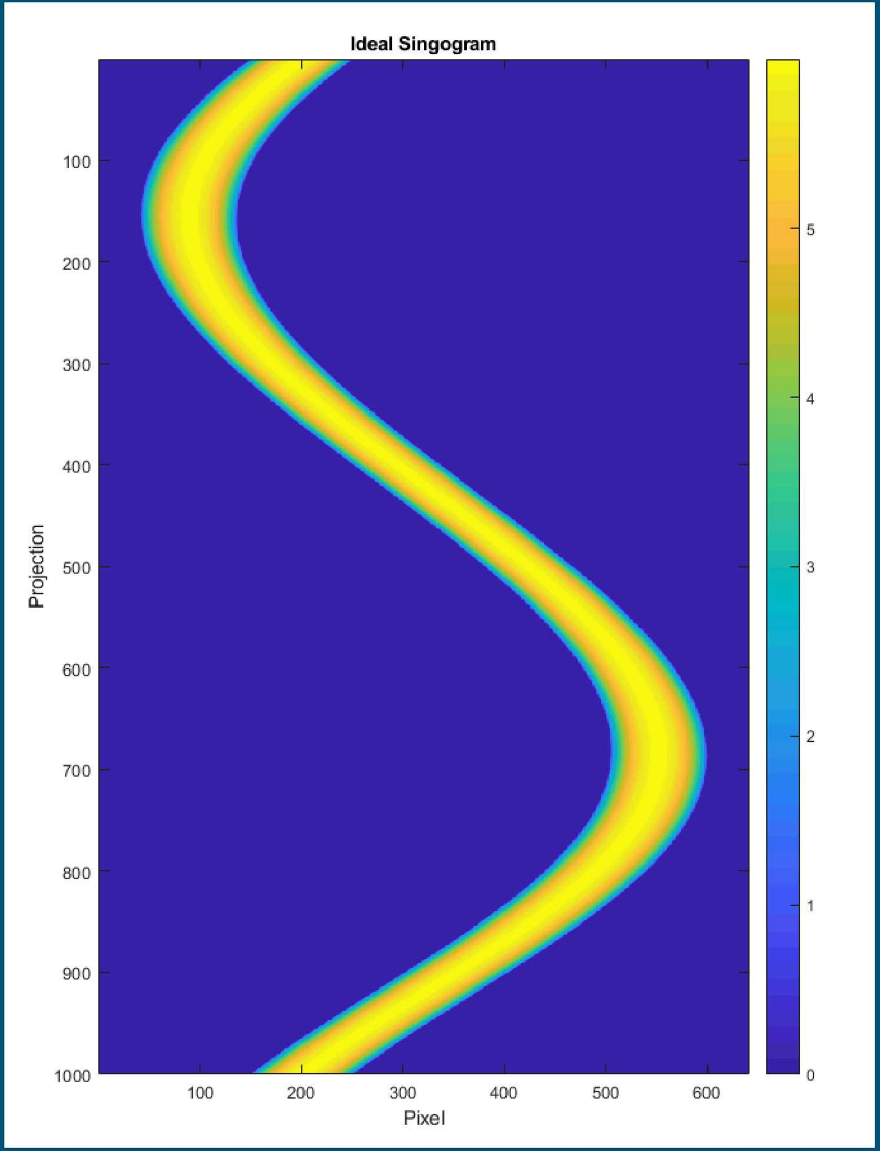
Discretized System Operator

- Define H-CT system geometry and discretize field-of-view (FOV).
- Distribute absorbers in the FOV and scan to estimate point-response function.



Approach: Data Acquisition via Numerical Study

- Ideal Data
  - Calculate path length through object.
  - No noise.
- PHITS: Particle and Heavy Ion Transport Code System
  - Monte Carlo particle transport simulation tool.
  - Provides realistic photon behavior and statistics.
- Each column of the system operator ***H***: sinogram of a single cylinder
- Each energy channel will have a system operator
- For this work, the system operator will have 640k rows and N columns, where N is the number of voxels in the FOV



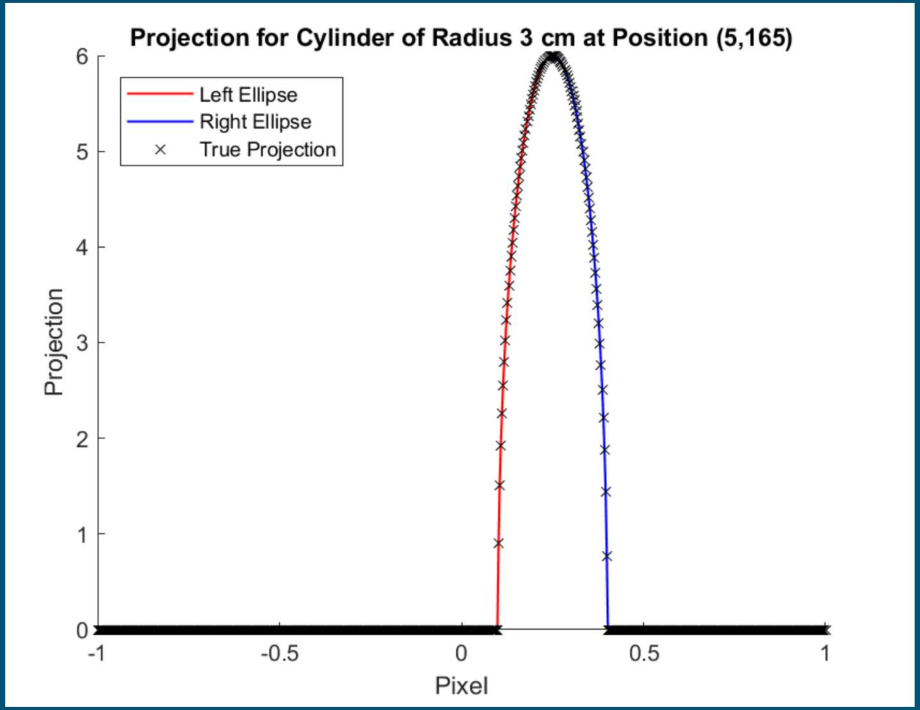
Compression: Estimated System Operator

- Without compression, the system operator approximately ***700 yottabytes.***
- Parametrize each projection by a given basis function.
- Use an optimization method to fit a parameterized basis function to each projection.
  - This work utilizes Nelder-Mead, a direct search method.

Basis Function	**Equation**	**Parameters**
Parabola	$y = a(x - x_0)^2 + b$	$[a, b, x_0]$
Ellipse	$y = \left(\frac{a^2 - (x - x_0)^2}{a^2}\right)^{\frac{1}{2}} \cdot b$	$[a, b, x_0]$
Ellipse Spline	$y = \left(\frac{{a_L}^2 - (x - x_0)^2}{{a_L}^2}\right)^{\frac{1}{2}} \cdot b$ for $x < x_0$ or $y = \left(\frac{{a_R}^2 - (x - x_0)^2}{{a_R}^2}\right)^{\frac{1}{2}} \cdot b$ for $x \geq x_0$	$[a_L, a_R, b, x_0]$

Compression: Estimated System Operator

Compress 640 values per projection to only 4 parameters per projection using an asymmetric ellipse as the basis function.



$$y_L = \left(\frac{a_L^2 - (x - x_0)^2}{a_L^2} \right)^{\frac{1}{2}} \cdot b$$

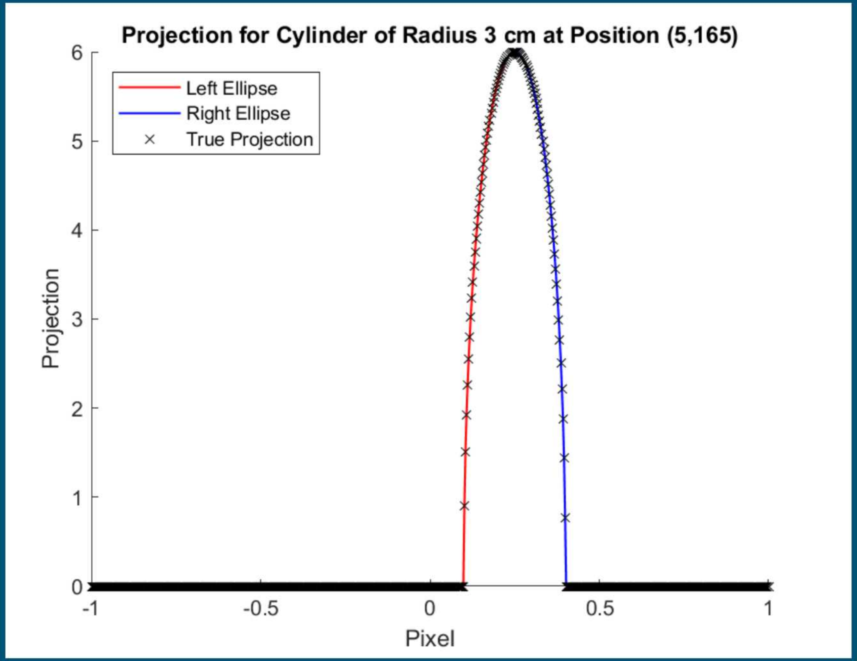
$$y_R = \left(\frac{a_R^2 - (x - x_0)^2}{a_R^2} \right)^{\frac{1}{2}} \cdot b$$

$$\rightarrow [a_L, a_R, b, x_0]$$

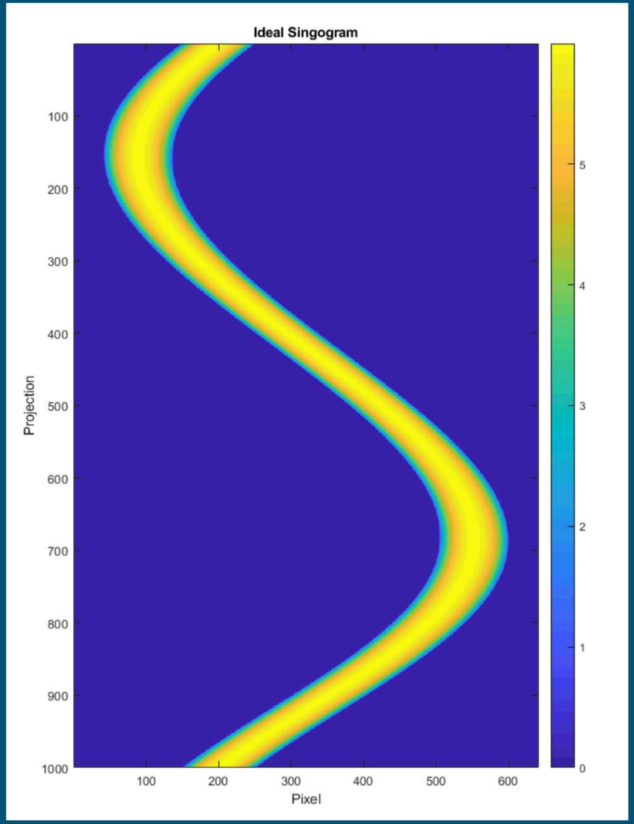
Decompression of Estimated System Operator

Image vector g calculated using parametrized system operator and discretized object vector f.

$[a_L, a_R, b, x_0]$ →



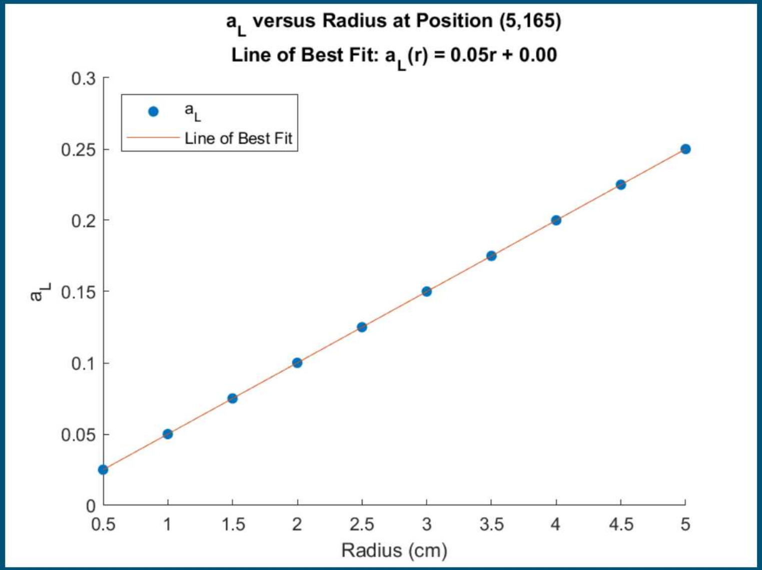
→

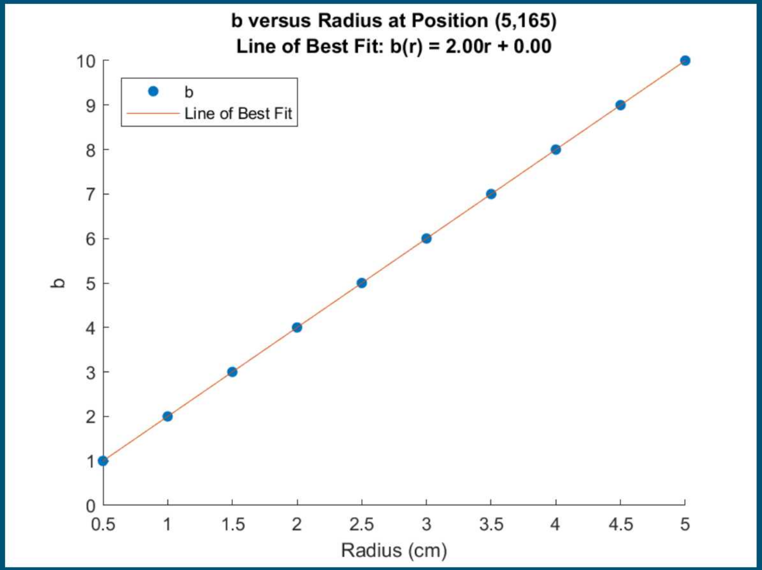


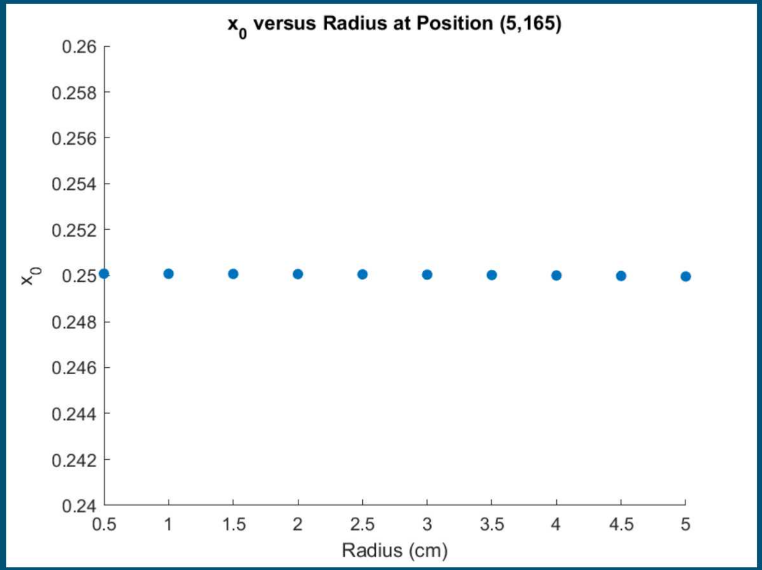
Extrapolation of Parameters

Extrapolating projection information mitigates inaccurate point response functions for cylinders of submillimeter radii.

1. Define a $n \times n$ grid of cylinders in the FOV.
2. Take one projection of each cylinder for two different radii, r_1 and r_2. For each radius, compress the projection into parameters $[a_L, a_R, b, x_0]$.
3. Fit a function to each parameter with respect to radius using Nelder-Mead.
4. For each cylinder position, extrapolate each parameter with respect to radius using the functions defined in Step 3.





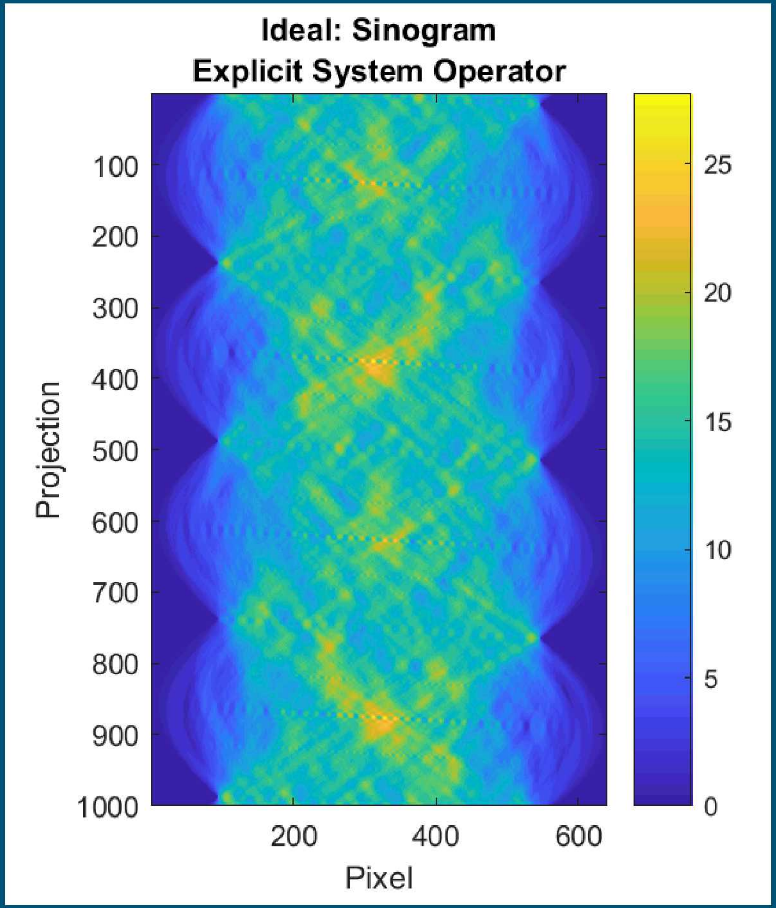


Interpolation of System Operator

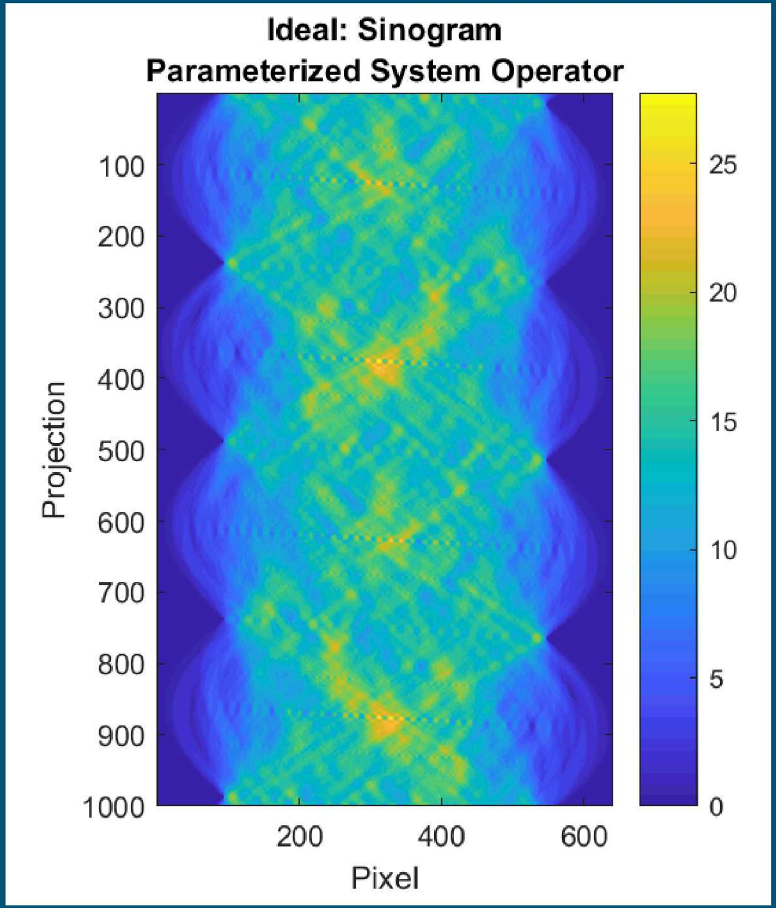
Interpolate the system operator to avoid measuring the point response at every voxel in the field of view.

1. Define a $m \times m$ grid of cylinders in the FOV.
2. For each cylinder:
   i. Calculate the location of every projection in the FOV.
   ii. For each projection location, use two-dimensional cubic spline interpolation of neighboring points to estimate the parameters $[a_L, a_R, b, x_0]$.

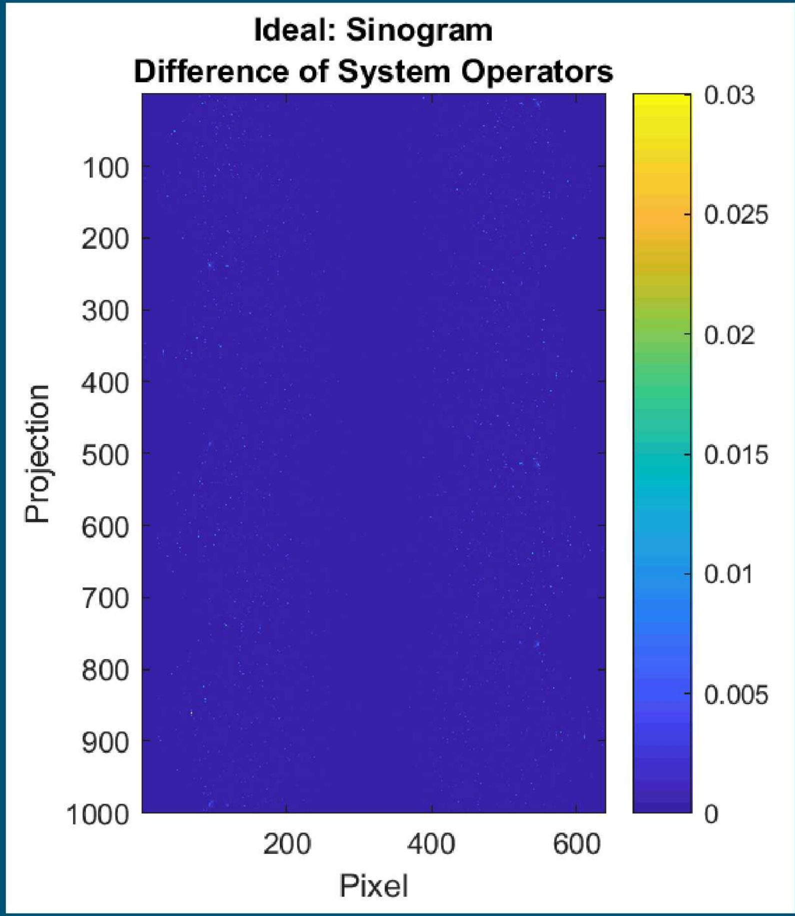
Comparison of the Ideal and Parameterized System Operators: Sinograms



Ideal System Operator

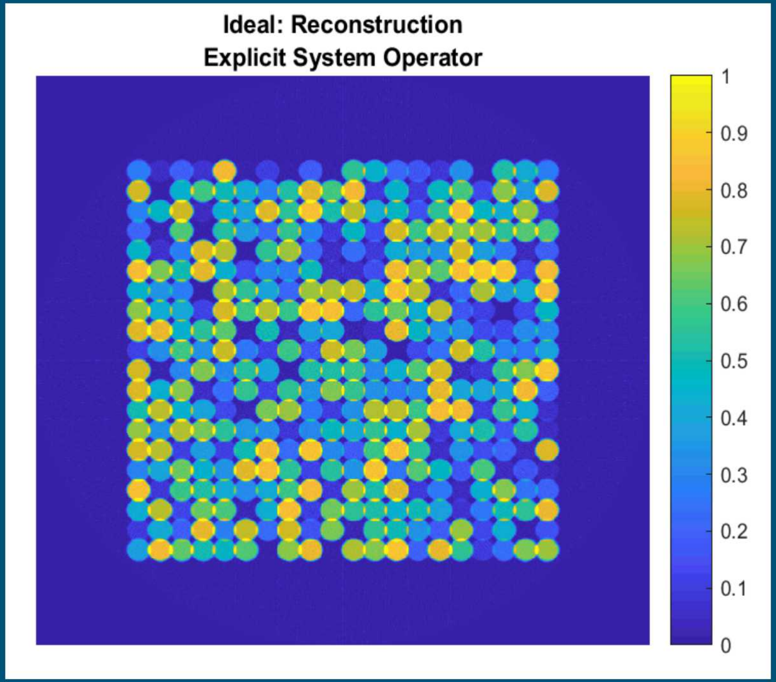


Parameterized System Operator

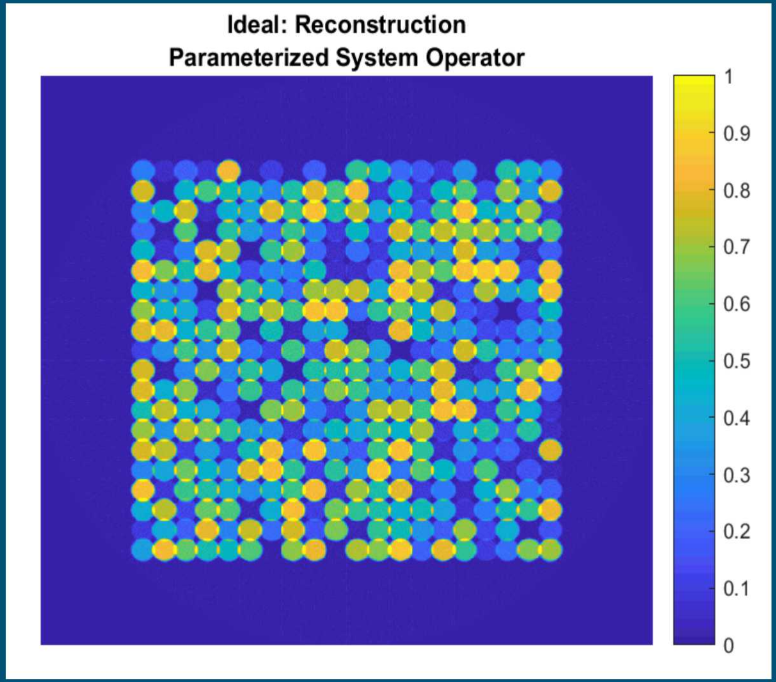


Difference

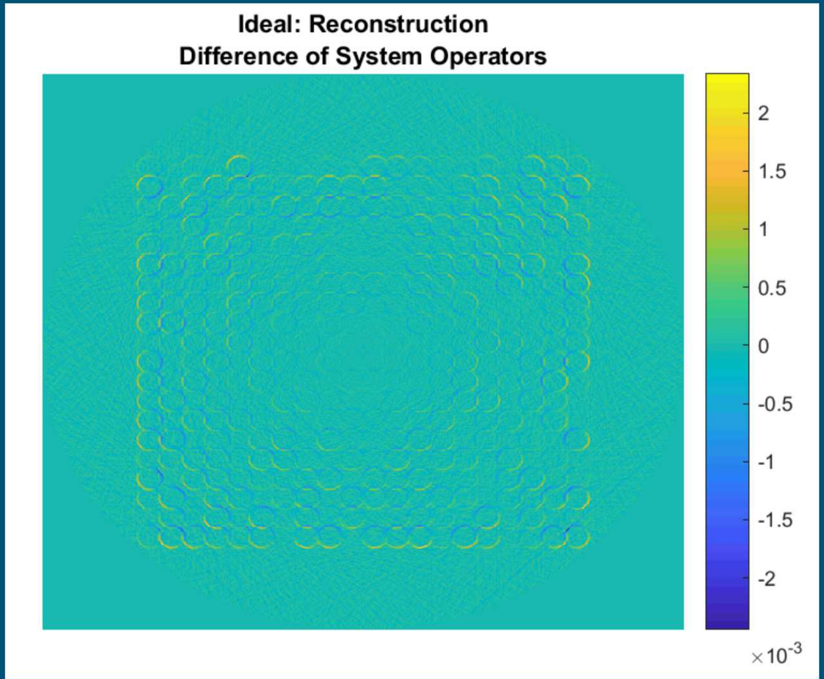
Comparison of the Ideal and Parameterized System Operators: Reconstructions



Ideal System Operator

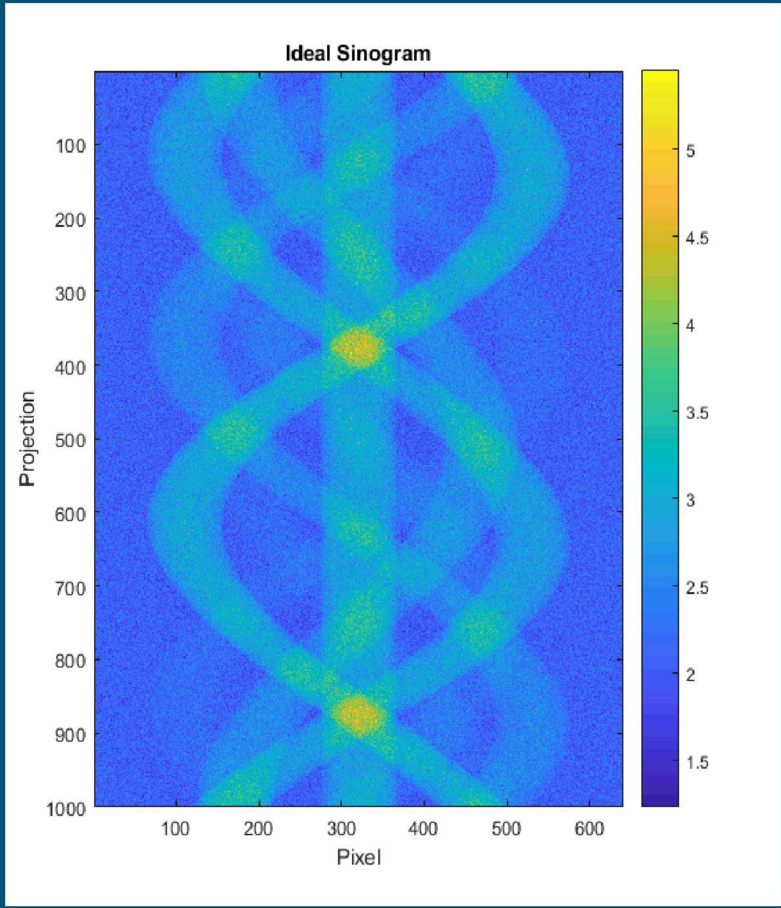


Parameterized System Operator

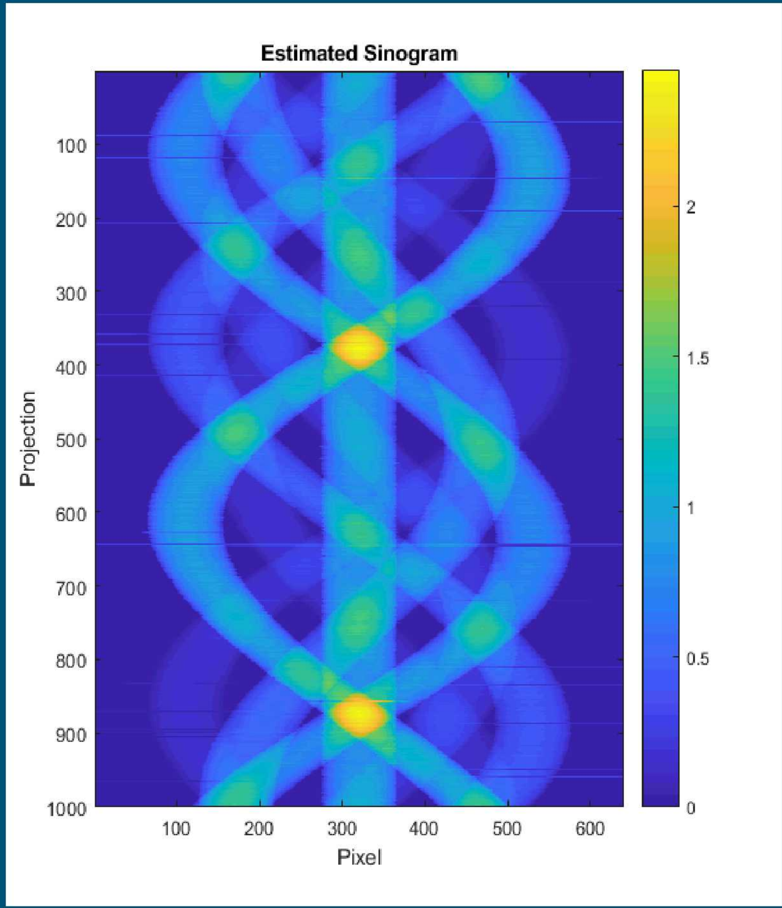


Difference

Comparison of the Ideal and Parameterized System Operators: Sinograms using PHITS Data

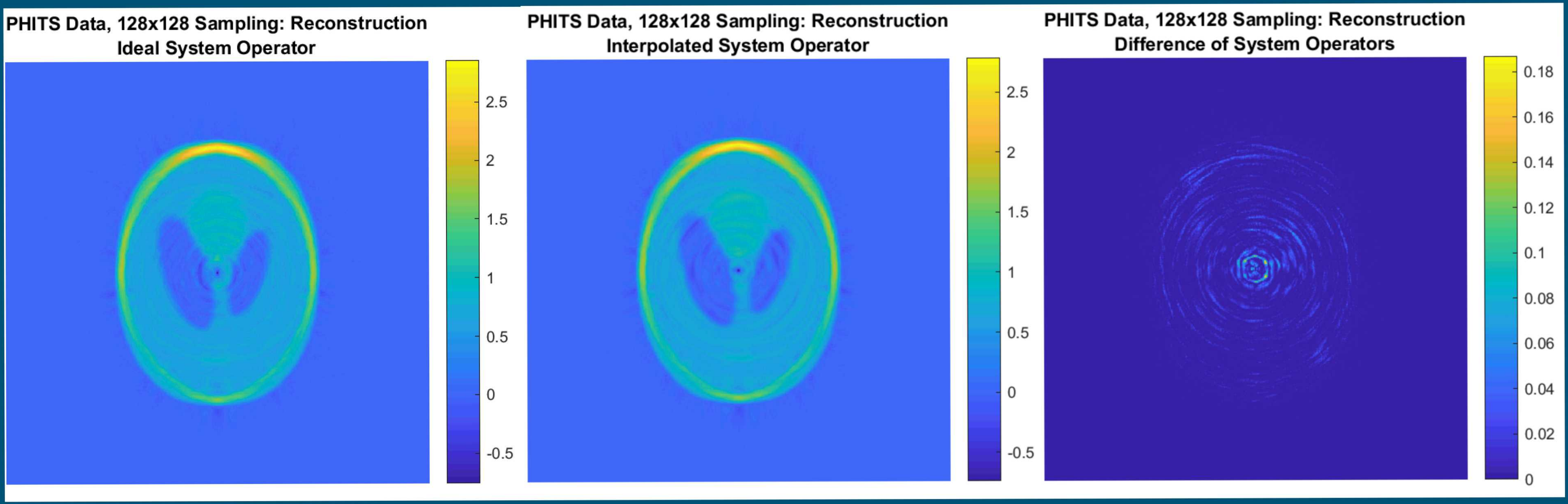


PHITS System Operator



Parameterized System Operator

Comparison of the Ideal and Parameterized System Operators: Reconstructions using PHITS Data



PHITS System Operator (128x128 Absorbers)

Parameterized System Operator (64x64 absorbers, Interpolated to 128x128)

Difference

Conclusion

- H-CT system characterization with a linear system operator seems to be feasible.
- Parametrization of system operator preserves system characteristics and optimizes data storage.
  - Challenges may exist with optimization routine
  - Extrapolation of parameters is feasible to allow for submillimeter estimation
  - Interpolation allows for fewer system measurements
- Applications for accurate simulated H-CT data:
  - Machine learning algorithms for data analysis.
  - Iterative reconstruction methods.
  - Material Characterization

Future Work

- Investigate Monte Carlo variance reduction methods to improve the data quality
  - Simulate frame averaging
- Characterize entire system by describing system operator with more samples
- Investigate other reconstruction algorithms and compare to FDK
- Investigate sparse sampling methods
- Investigate temporally dependent sources of noise (i.e. pulse-pile up)
- Characterize and calibrate real-world H-CT system.

References

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