Image Quality Models and Performance Measurement in X-ray Differential Phase Contrast Imaging

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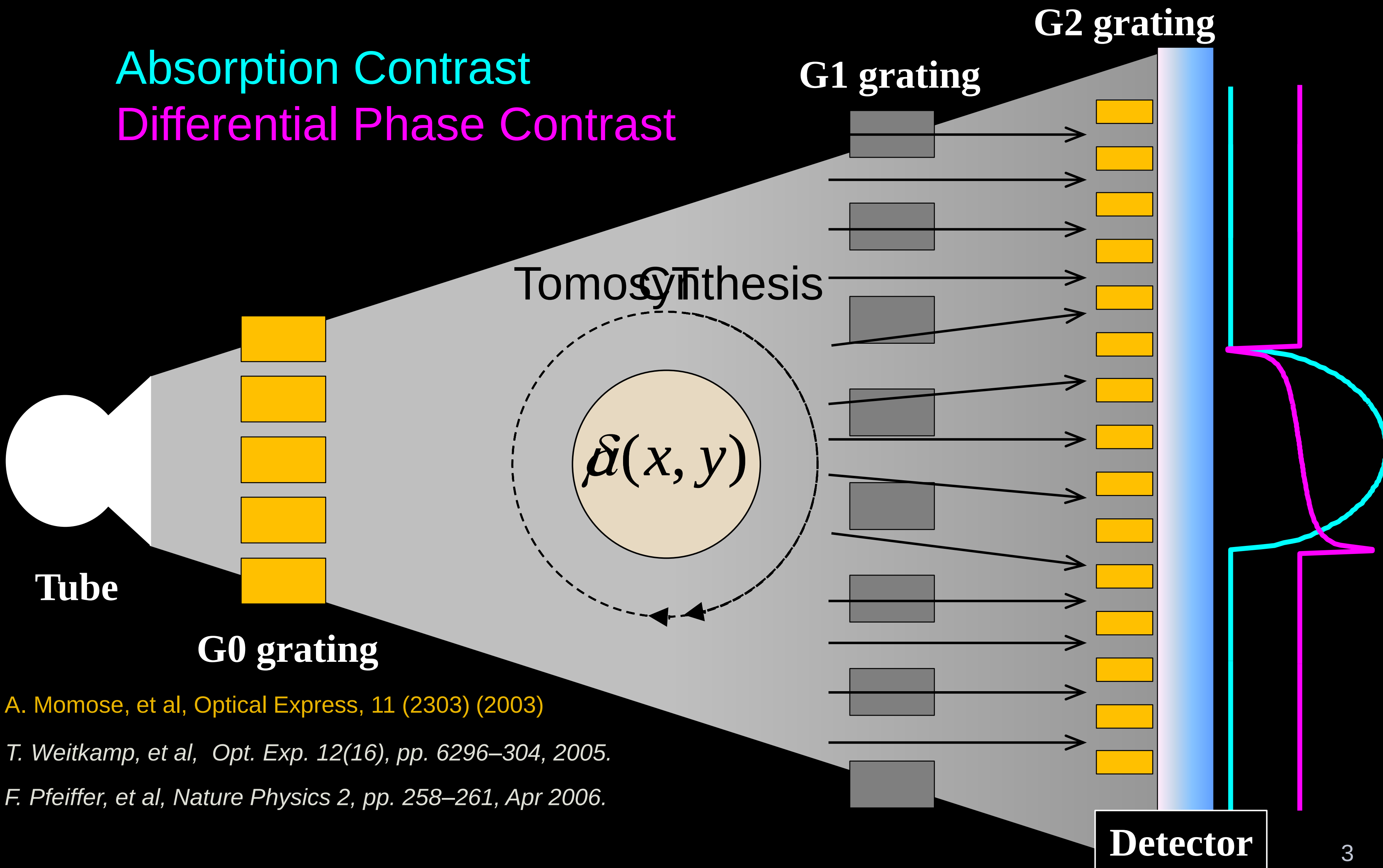
Outline

- Brief introduction of x-ray differential phase contrast (DPC) imaging
- Intrinsic noise relationship between DPC imaging and absorption imaging
- Task-based model observer studies for DPC imaging
- Summary

X-Ray Differential Phase Contrast Imaging

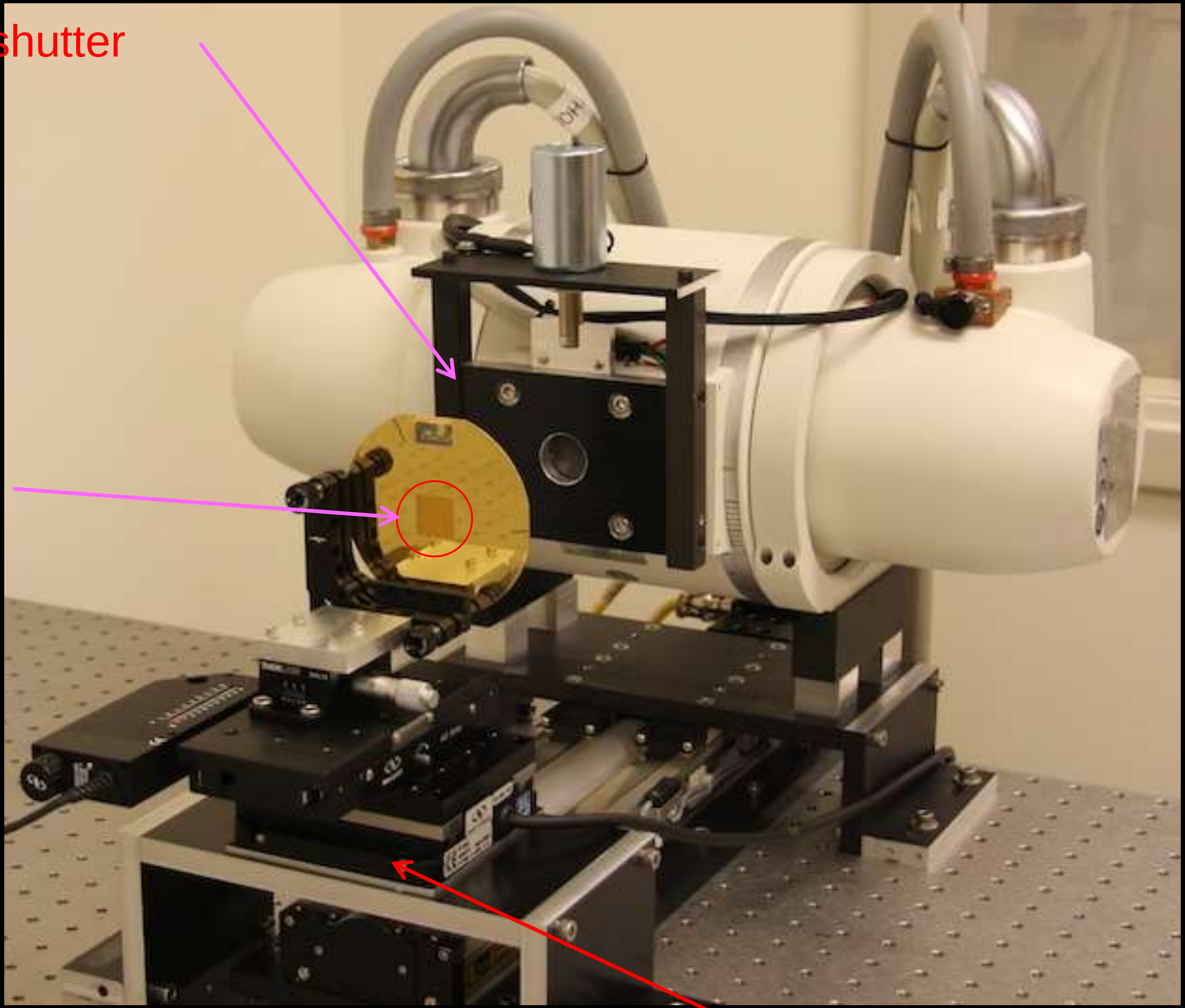


A. Momose, et al, Optical Express, 11 (2303) (2003)

T. Weitkamp, et al, Opt. Exp. 12(16), pp. 6296–304, 2005.

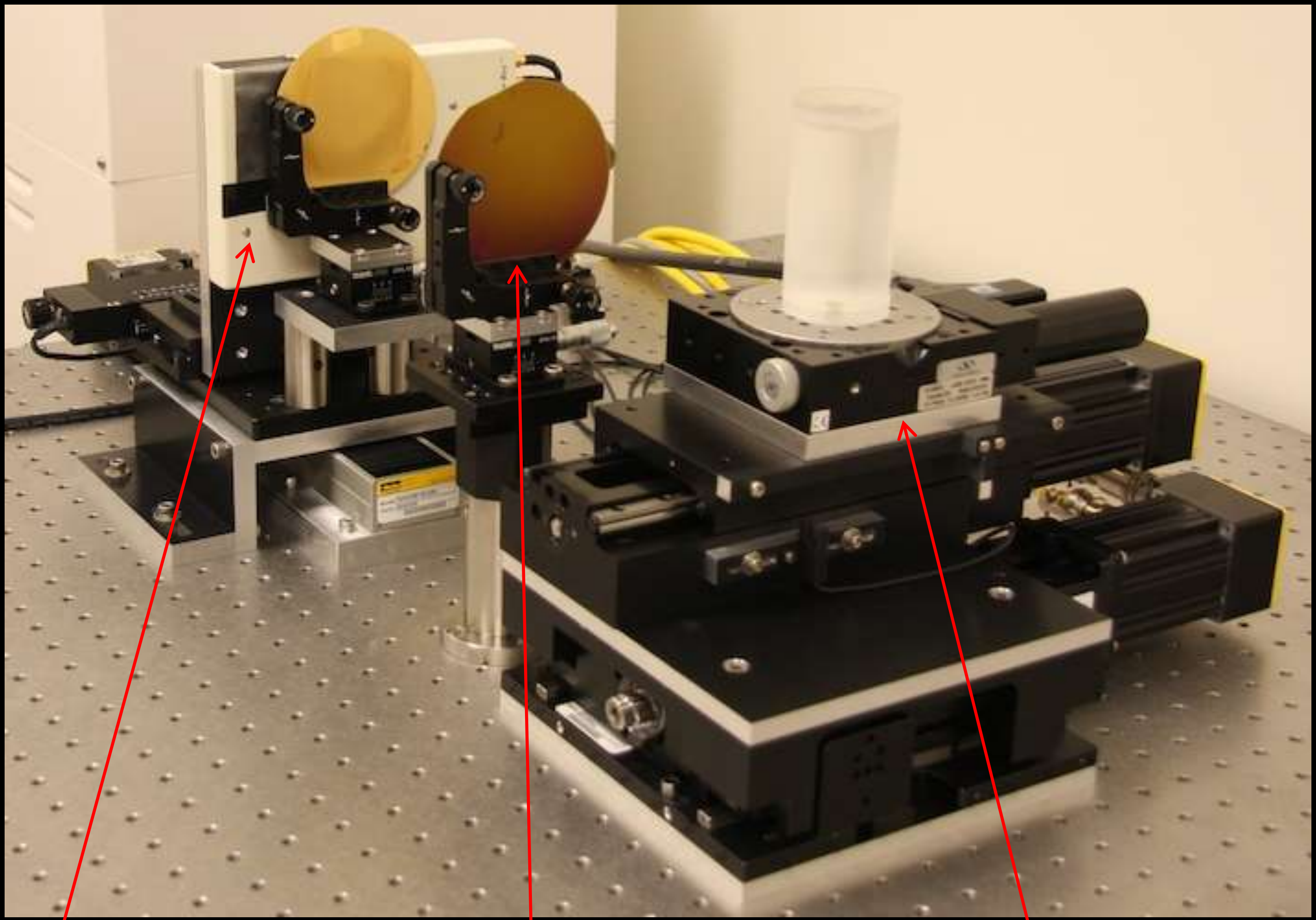
F. Pfeiffer, et al, Nature Physics 2, pp. 258–261, Apr 2006.

Experimental System at UW-Madison



Zambelli *et al*.," Med. Phys., 2010, Vol. 37, pp. 2473-2479

Experimental System at UW-Madison



Zambelli *et al*.," Med. Phys., 2010, Vol. 37, pp. 2473-2479

X-ray Grating Specifications

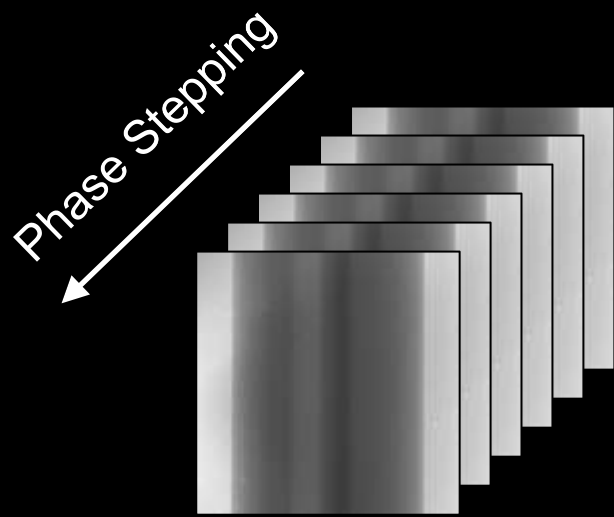
- G_0 – Absorption Grating
  - 15 µm opening
  - 37 µm pitch
  - 2 cm x 2 cm
  - 60 µm Au depth
- G_1 – Phase Grating (π differential shift for 50% of beam)
  - 4 µm opening
  - 8 µm pitch
  - 7 cm x 7 cm
  - 40 µm etch depth
- G_2 – Absorption Grating
  - 2.25 µm opening
  - 4.5 µm pitch
  - 7 cm x 7 cm size
  - 30 µm Au depth

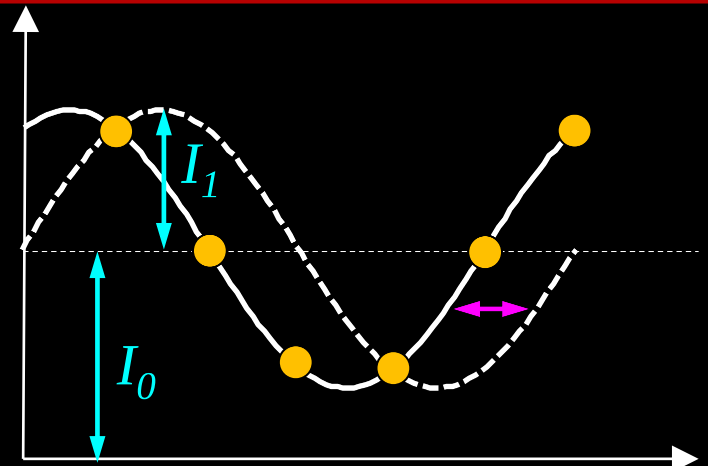
All gratings were made by Joe Zambelli and Ke Li using the on-campus micro-fabrication facility: Wisconsin Center for Microelectronics (WCAM) at UW-Madison.

Absorption and Phase contrast signals from the same set of intensity measurements

Absorption

Phase





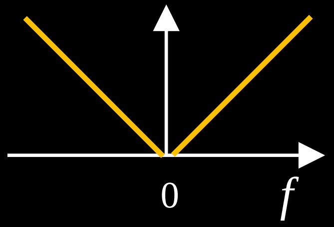
$$I(m,n;x_g) = I_0(m,n) + I_1(m,n)\cos\left[\frac{2\pi}{p_2}x_g + \varphi_d(m,n)\right]$$

Signal Models and Recon Kernels

- Absorption: $\mathrm{Proj}_{\mathrm{A}}(\rho)=\int_l \mu(x,y)\,\mathrm{d}l$

Convolution kernel: $|f|$

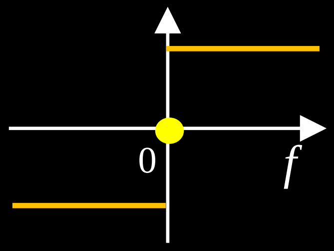
Ramp filter



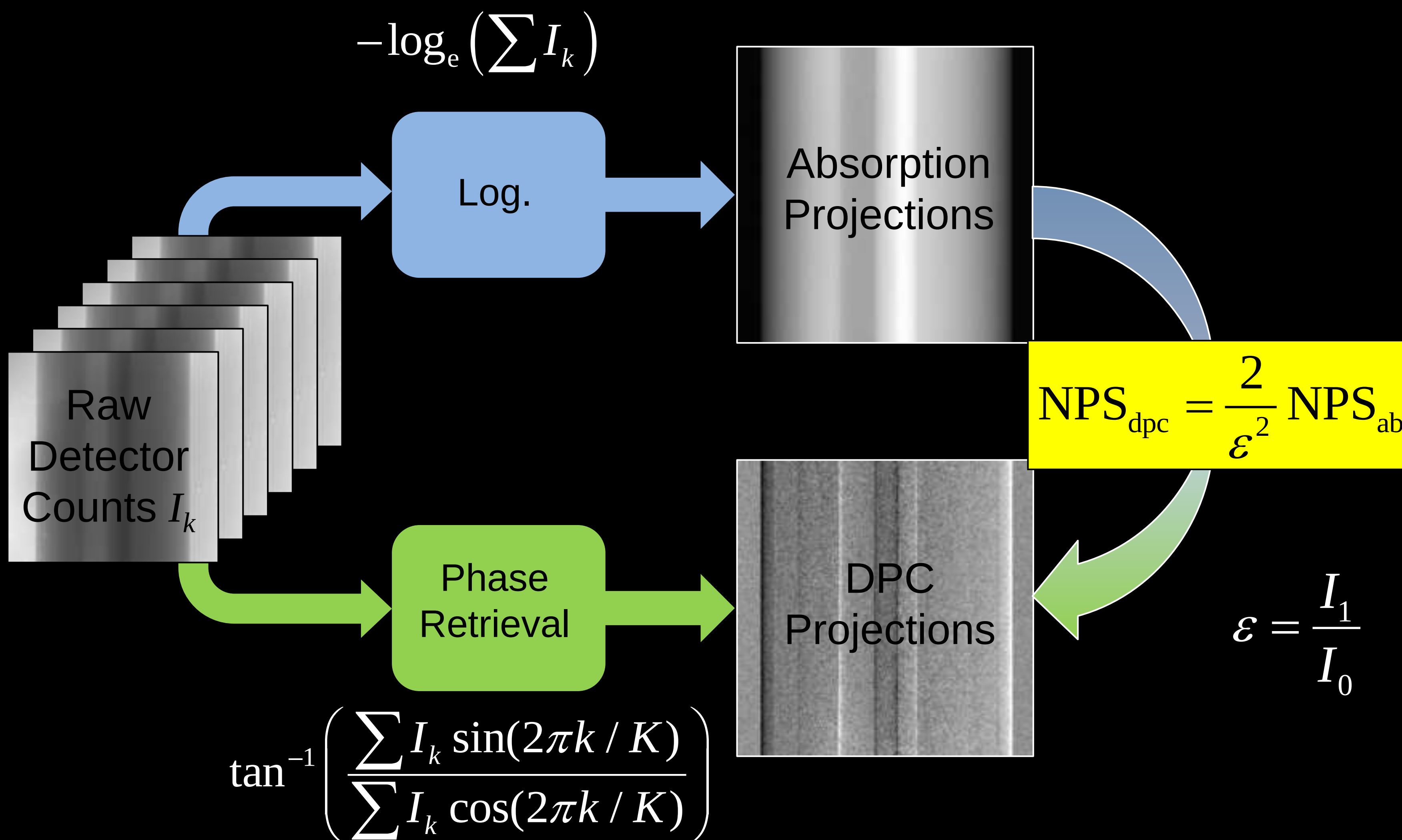
- DPC: $\mathrm{Proj}_{\mathrm{DPC}}(\rho)=\frac{2\pi d}{p_2}\frac{\partial}{\partial\rho}\int_l \delta(x,y)\,\mathrm{d}l$

Convolution kernel: $\frac{p_2}{2\pi d}\frac{\mathrm{sgn}(f)}{2\pi \mathrm{i}}$

Hilbert filter



Noise Relationship in Projection Images



$$-\log_e\left(\sum I_k\right)$$

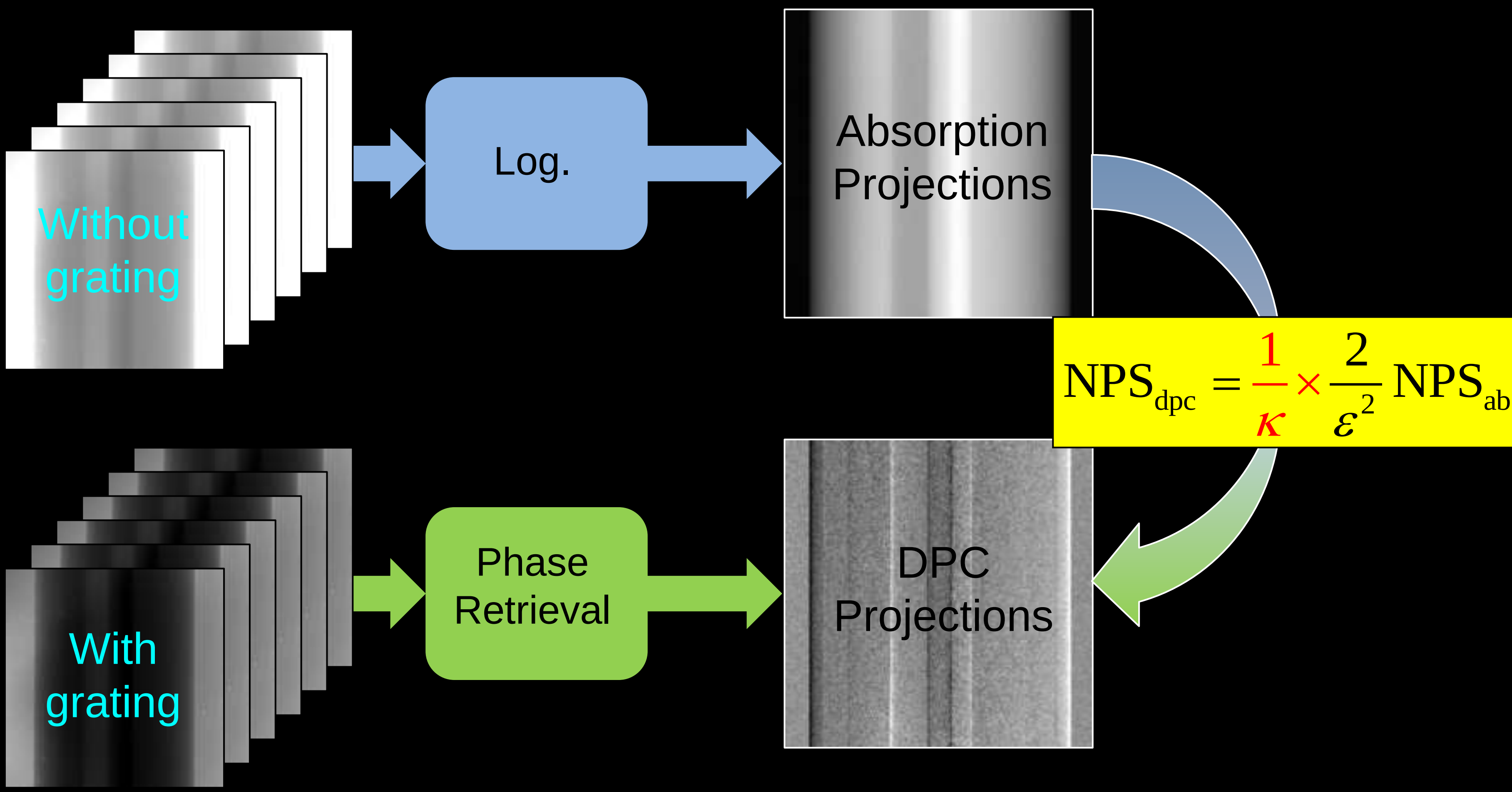
$$\tan^{-1}\left(\frac{\sum I_k \sin(2\pi k/K)}{\sum I_k \cos(2\pi k/K)}\right)$$

$$\mathrm{NPS}_{\mathrm{dpc}} = \frac{2}{\varepsilon^2}\mathrm{NPS}_{\mathrm{ab}}$$

$$\varepsilon = \frac{I_1}{I_0}$$

G.-H. Chen et. al, *Med. Phys*. (2010)

Noise Relationship in Projection Images



Noise relationship in CT Images: DPC-CT and ACT

- The NPS of DPC-CT can be quantitatively determined from the NPS of the associated ACT (and vice-versa)

$$NPS_{DPC} = C_g \frac{1}{f^2} NPS_{ab}$$

where

$$C_g = \frac{1}{2\kappa\pi^2\varepsilon^2}\left(\frac{p_2}{2\pi z_T}\right)^2$$

- This relationship independent of:
  - Dose
  - and X-ray tube/detector (except their geometric setup)

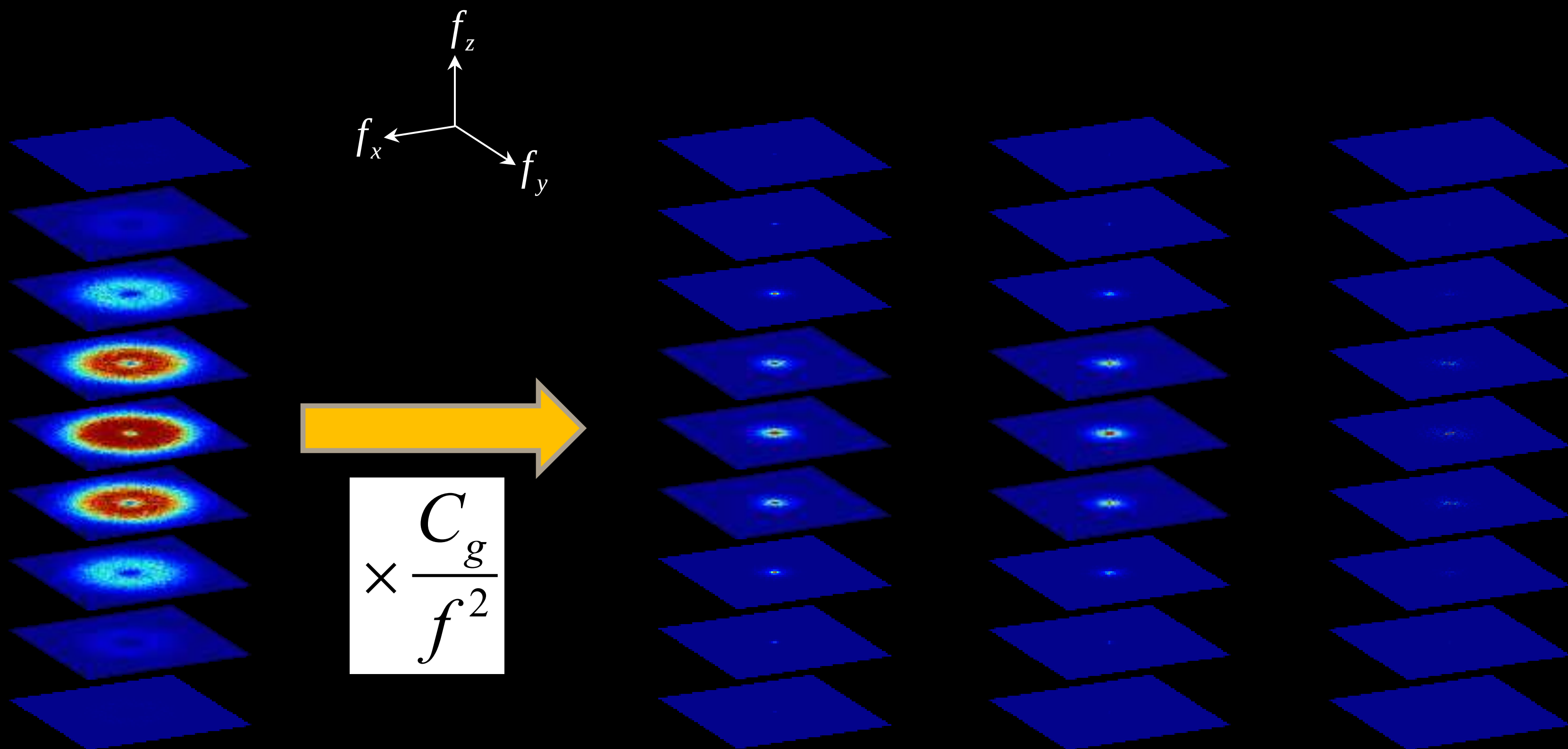
K. Li, N. Bevins, J. Zambelli, G.-H. Chen, *Med. Phys*. **40**, p 021908 (2013)

How to Predict the NPS of DPC-CT?

- Method A: Image-based approach
  - 1. Calculate the NPS of absorption CT
  - 2. Scale the NPS of absorption CT by the ratio of C_g / f^2
  - *Subject to errors caused by aliasing*

- Method B: Projection-based approach
  - 1. Scale the absorption projections by a factor of $\frac{\sqrt{2}}{\varepsilon}$
  - 2. Reconstruct DPC-CT using these scaled absorption projections
  - 3. NPS calculation
  - *Immune to aliasing*

Experimental Validation – Method A



Absorption CT NPS w/o gratings

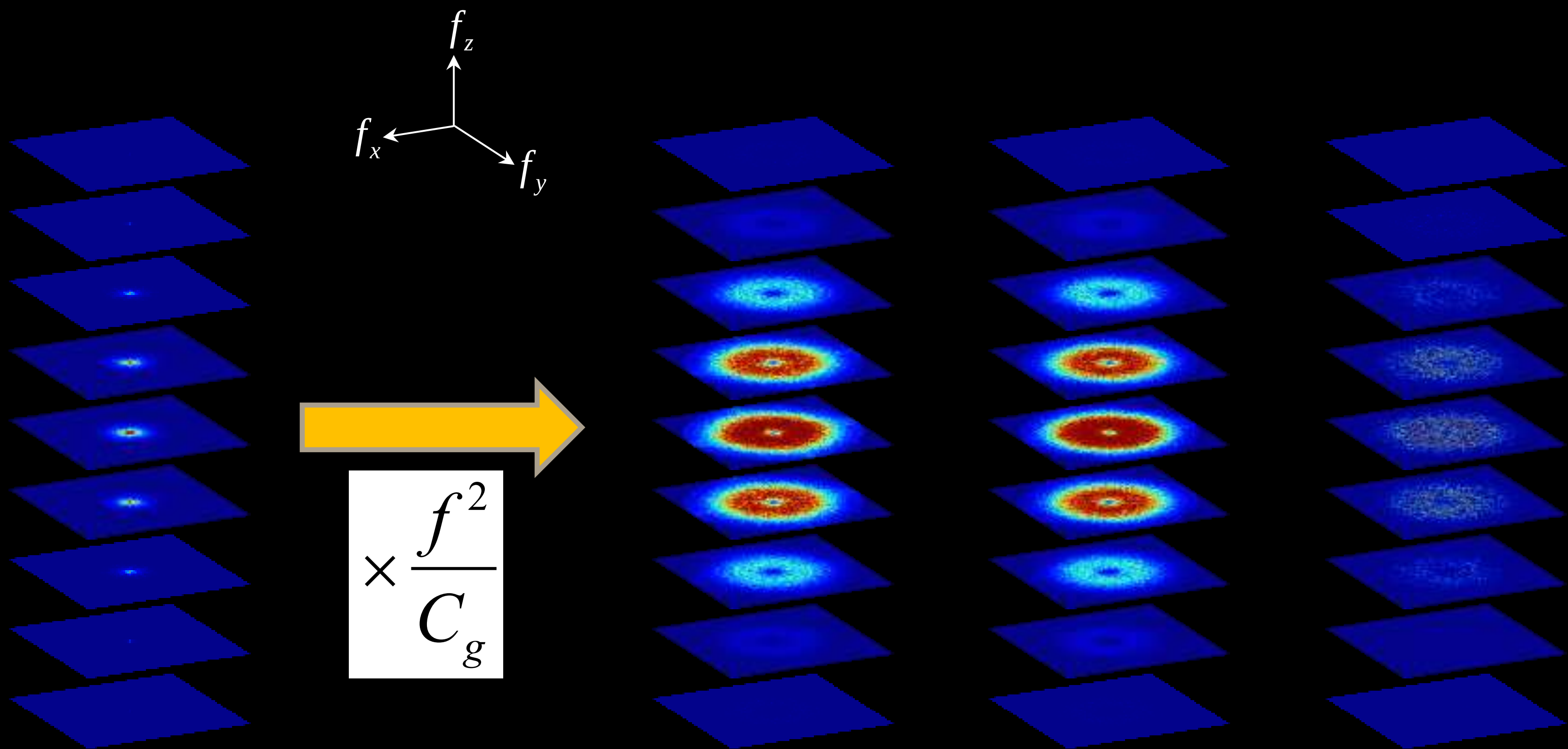
DPC-CT NPS (predicted)

DPC-CT NPS (Measured)

Magnitude of Difference

K. Li *et al.* SPIE 8668, Medical Imaging 2013.

Experimental Validation – Method A



DPC-CT NPS

Absorption CT NPS (predicted)

Absorption CT NPS (Measured)

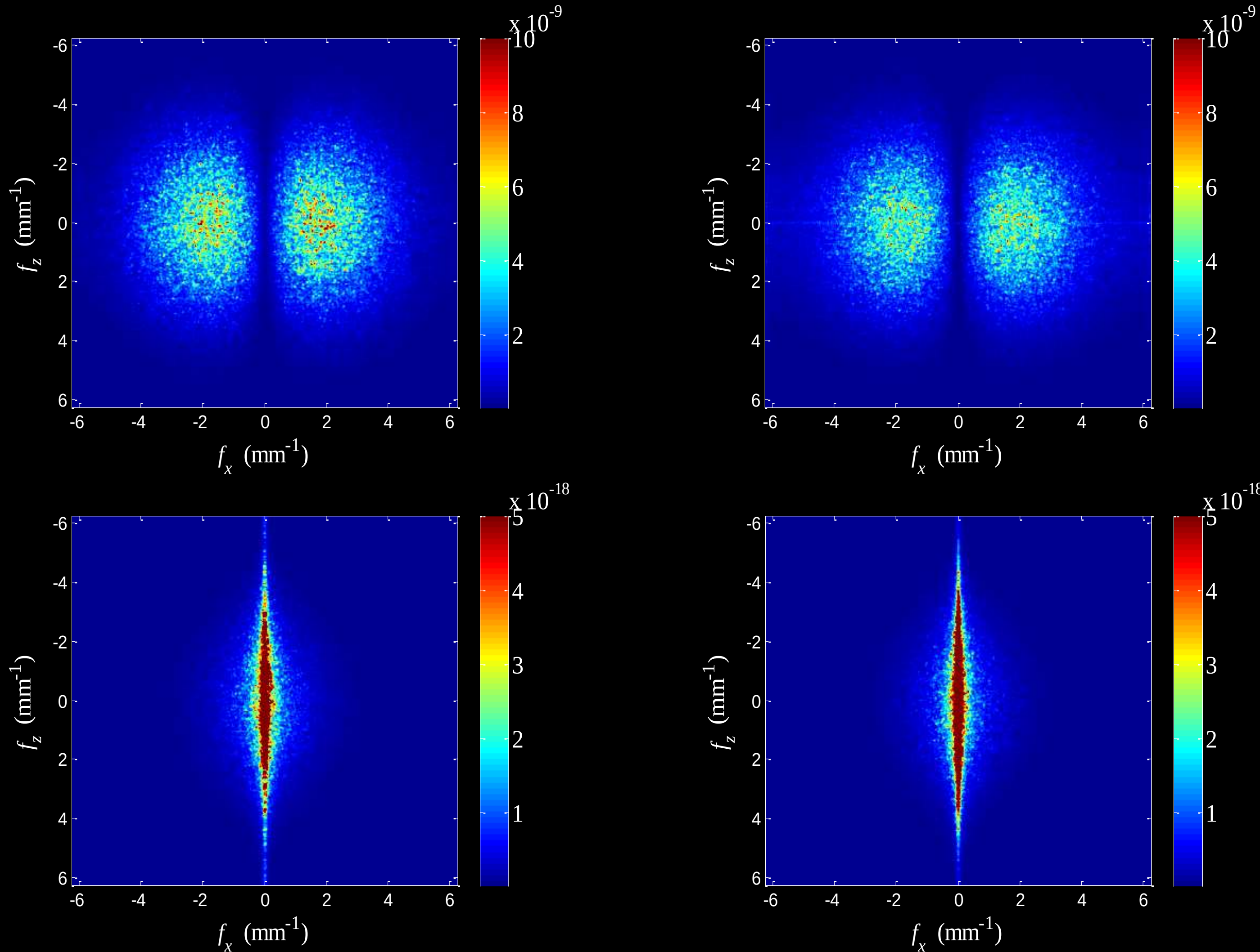
Magnitude of Difference

Sagittal Cuts through the 3D NPS

Measured | Predicted

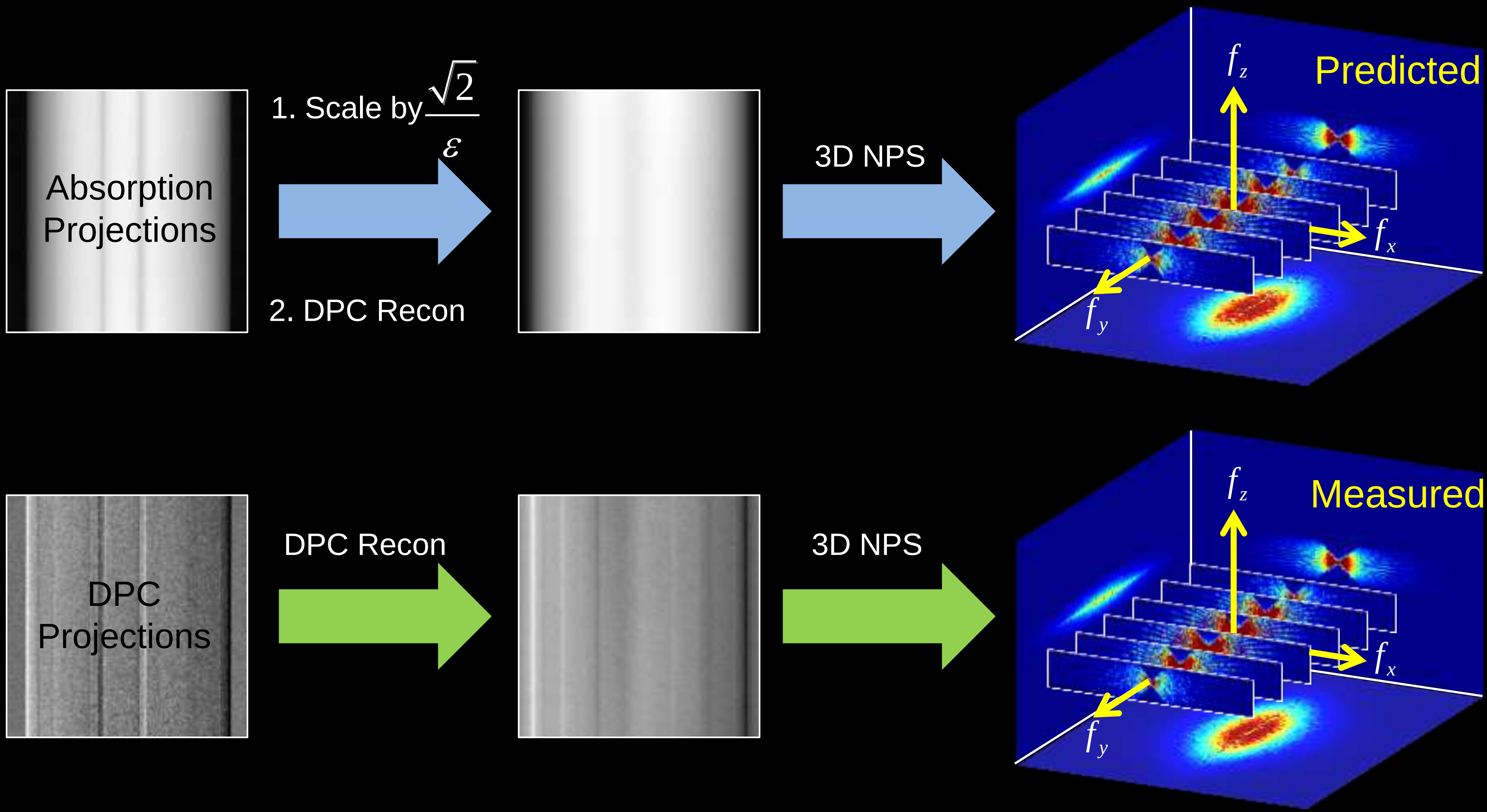
Absorption CT

DPC-CT



Experimental Validation – Method B

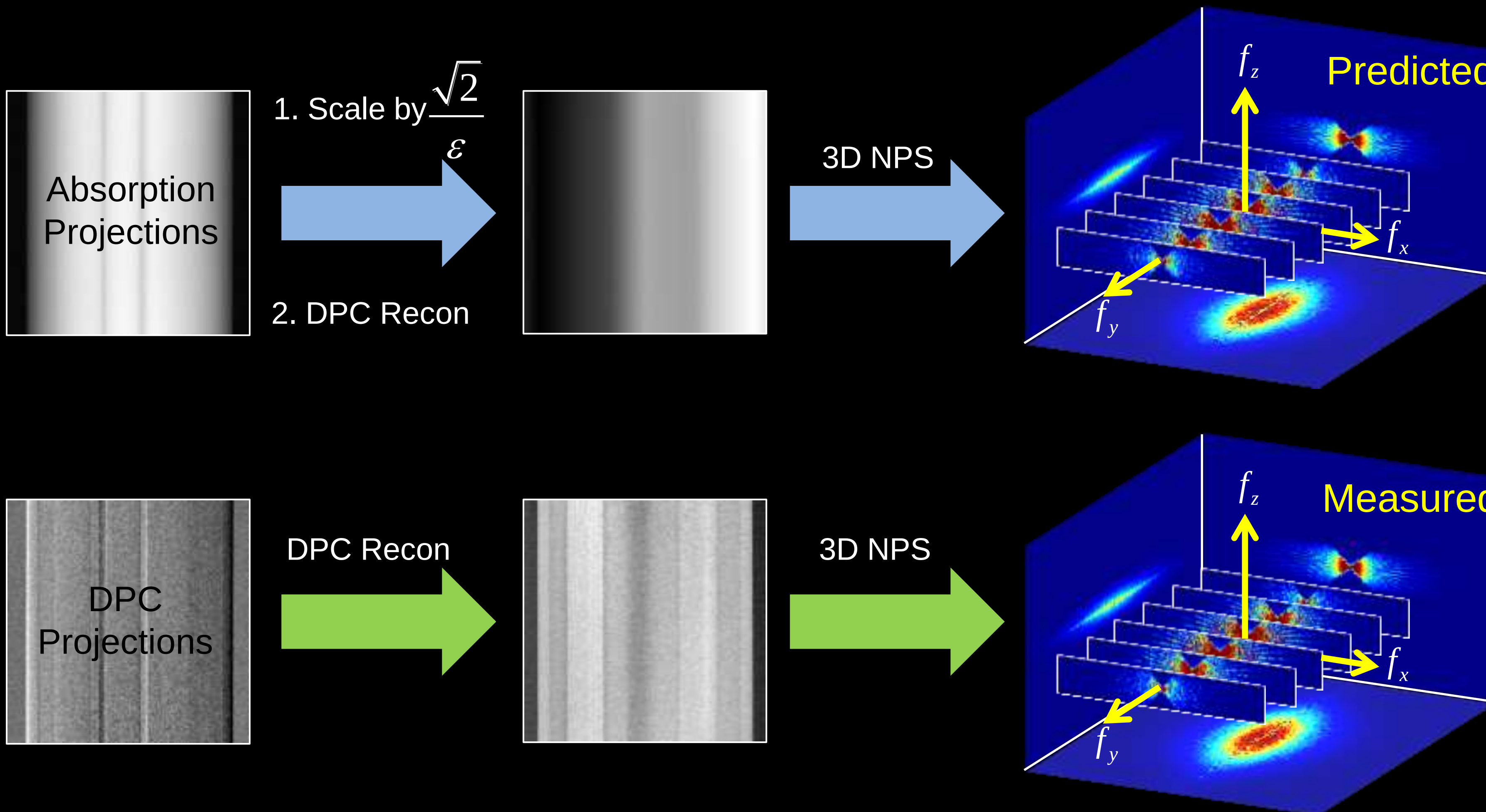
- DPC tomosynthesis reconstructed by shift-and-add



K. Li, J. Garrett, Y. Ge, G.-H. Chen, *Wednesday 4:50, Room 103*

Experimental Validation – Method B

- DPC tomosynthesis reconstructed by FBP



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Model observer performance studies

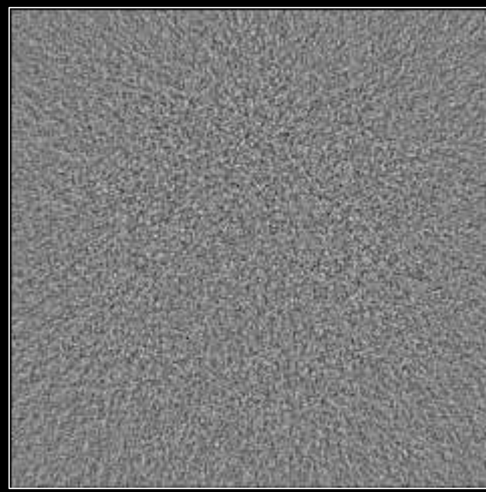
- We considered the five commonly used model observers in x-ray absorption imaging:
  - Ideal observer
  - Non-prewhitening (NPW) observer
  - Non-prewhitening observer with eye filter and internal noise (NPWEi)
  - Prewhitening observer with eye filter and internal noise (PWEi)
  - Channelized Hotelling Observer (CHO) (with Gabor basis functions)

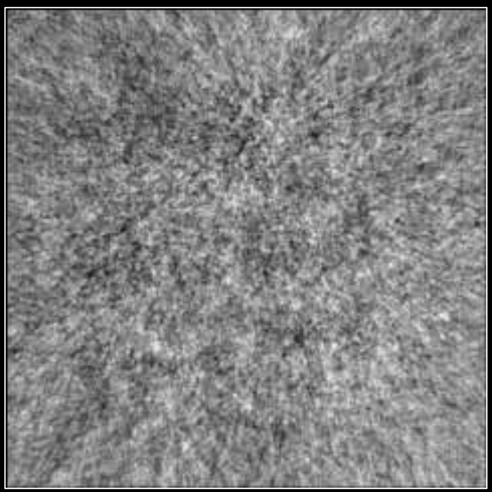
Difference in Noise Properties between DPC-CT and ACT

Absorption CT

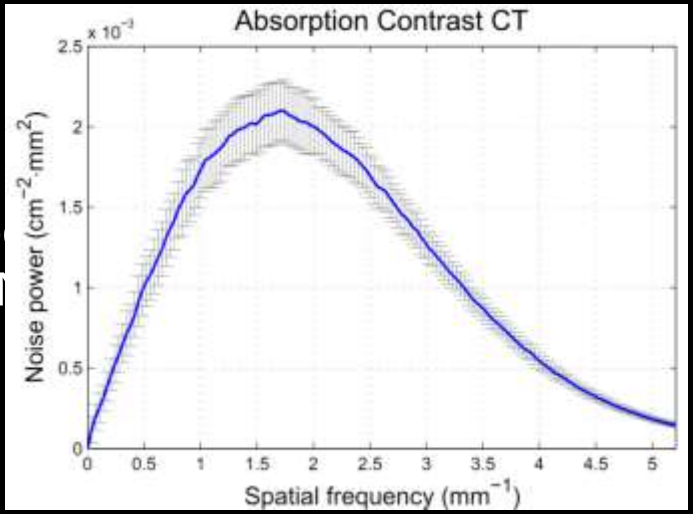
DPC-CT

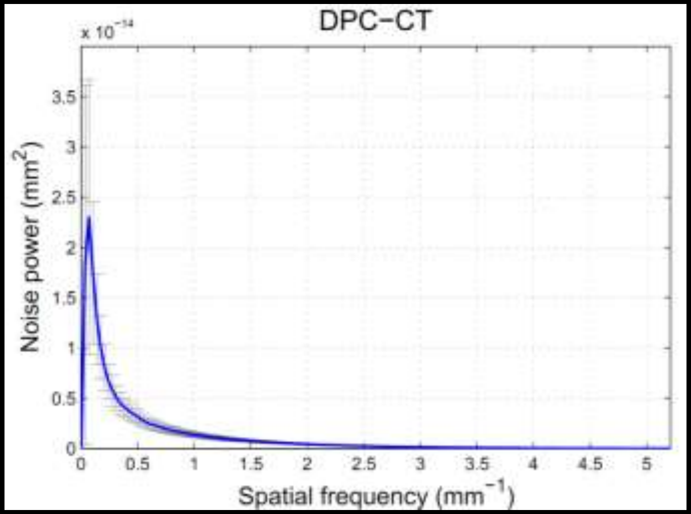
Noise-only image





2D noise p
spectrum (N





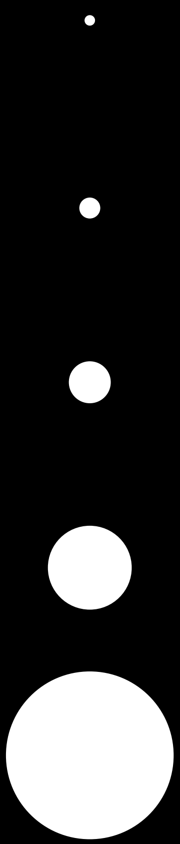
Zambelli, *et al*. Proc. SPIE, **7961**, p79613N (2011)

How to choose a model observer?

- A model observer should predict human performance, but each model observer will behave differently.
- This then motivates the following question:
  - Given the peculiar noise power spectrum in DPC tomographic imaging, which model observer should be used to assess the performance of DPC imaging?

SKE Imaging Tasks

1. Detection of circular object



8 pixels (0.64 mm)

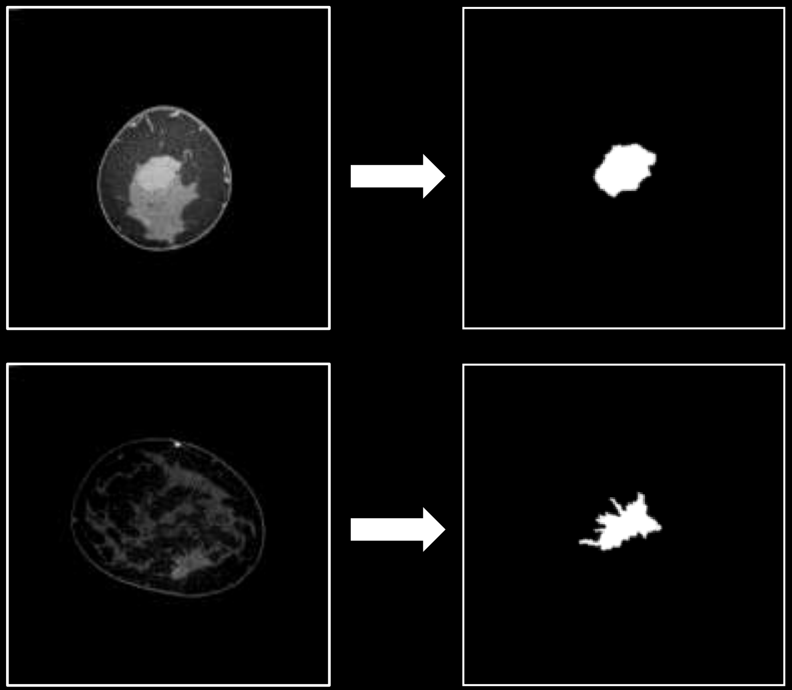
16 pixels (1.28 mm)

32 pixels (2.56 mm)

64 pixels (5.12 mm)

128 pixels (10.24 mm)

2. Detection of breast lesion*



Original

Segment, MTF blurring

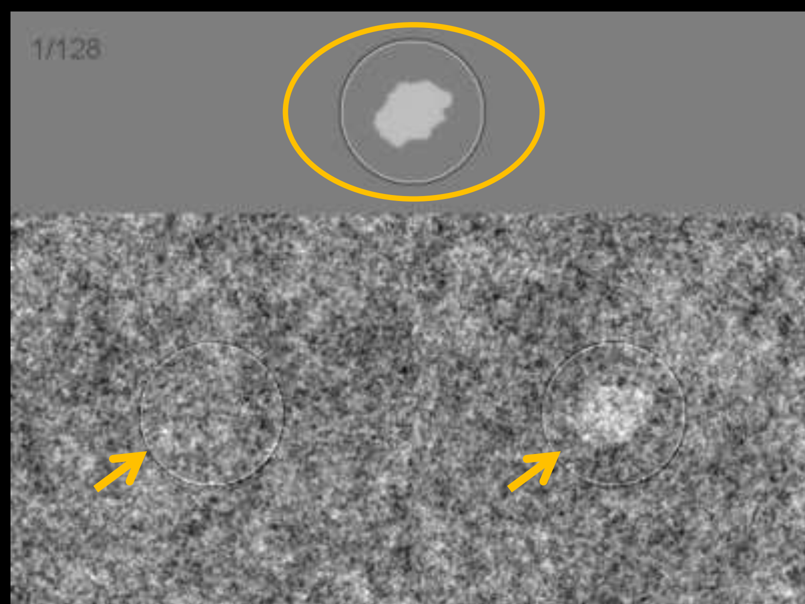
*N. Prionas, *et al*., *Radiology*, **256**, p714 (2010)

Breast CT data courtesy of John Boone

Human Observer Experiments

- 2AFC: two-alternative forced-choice
- SKE: signal-known exactly
  - The ground truth (lesion size and shape) and circular cues (lesion location) were provided to the observers

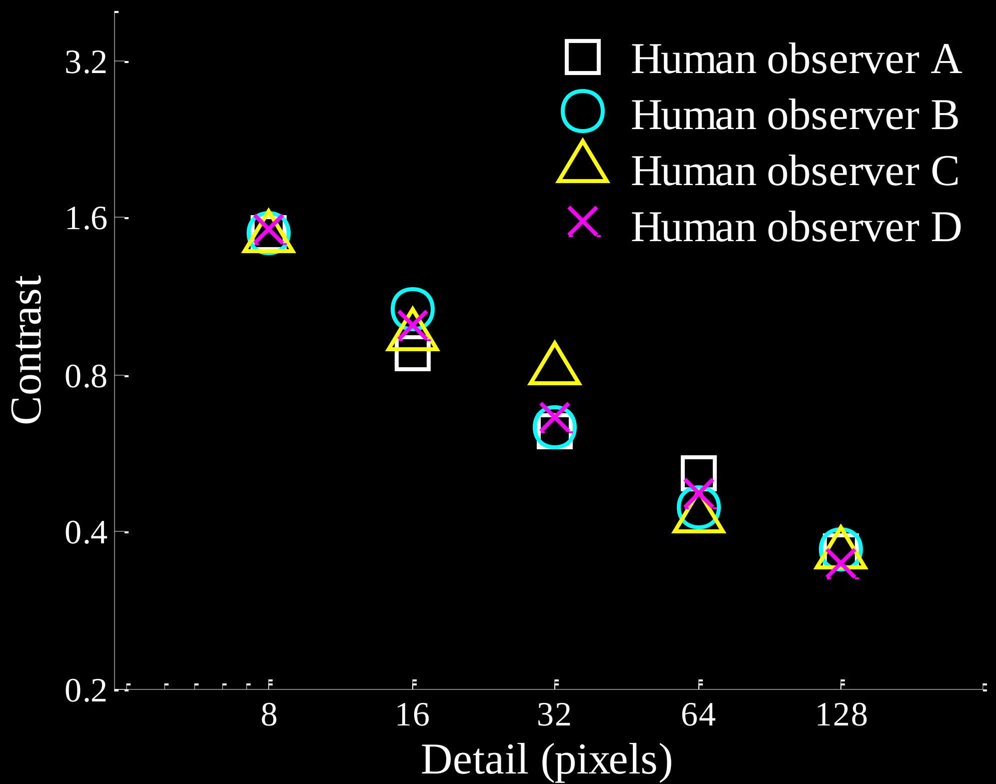
Left or right? (you must choose one)



Human Observer Trials

- Four physicist observers
  - Each read 256 trials x 7 tasks (5 discs, 2 breast lesions)
- Training session prior to actual trial
- Monochrome diagnostic quality monitor (Coronis 5MP Mammo, Barco Inc.)
- Responses recorded by mouse/keyboard input
- 70 cm viewing distance
- W/L: [mean-4σ, mean-4σ]
- Dark reading room

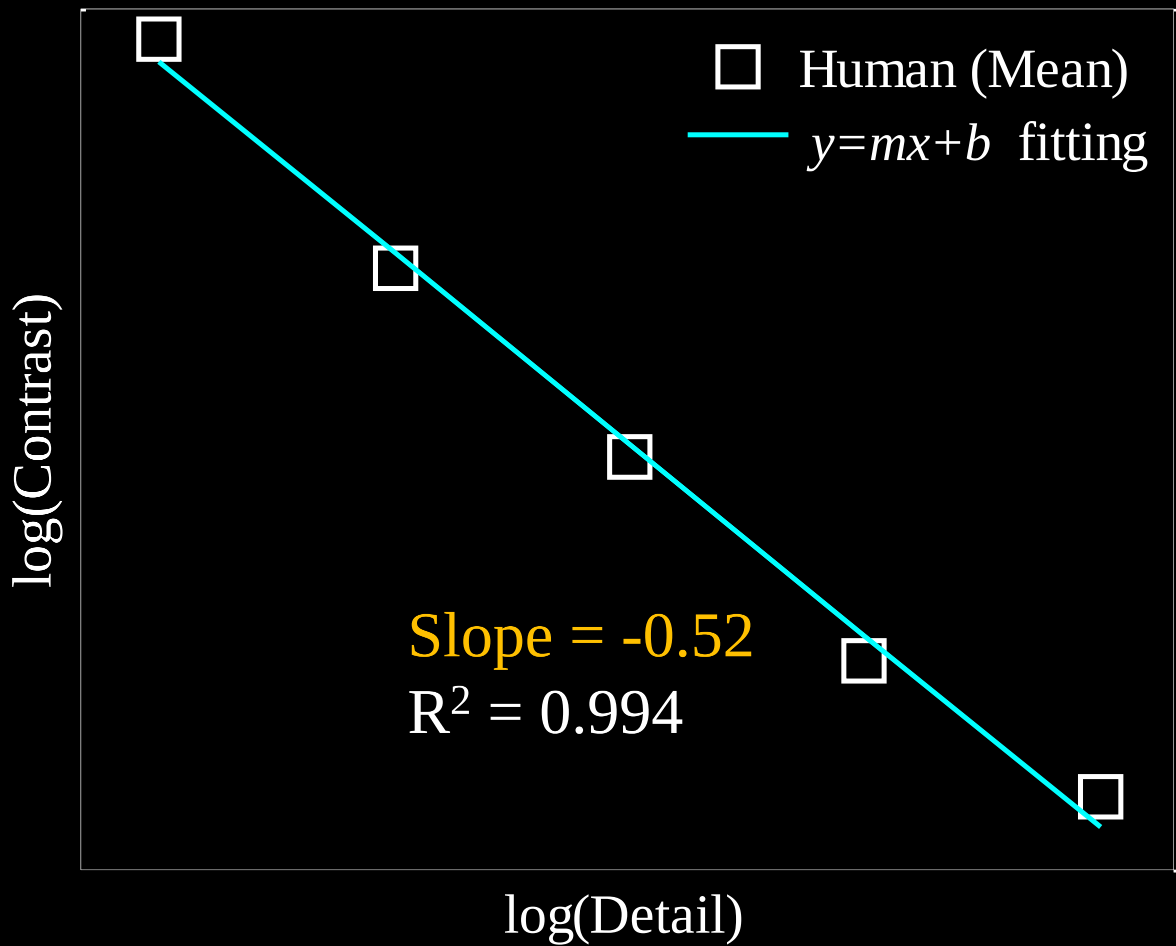
Results: Human Observer (Disc detection task)



Inter-observer variation< 5%

Linear Regression

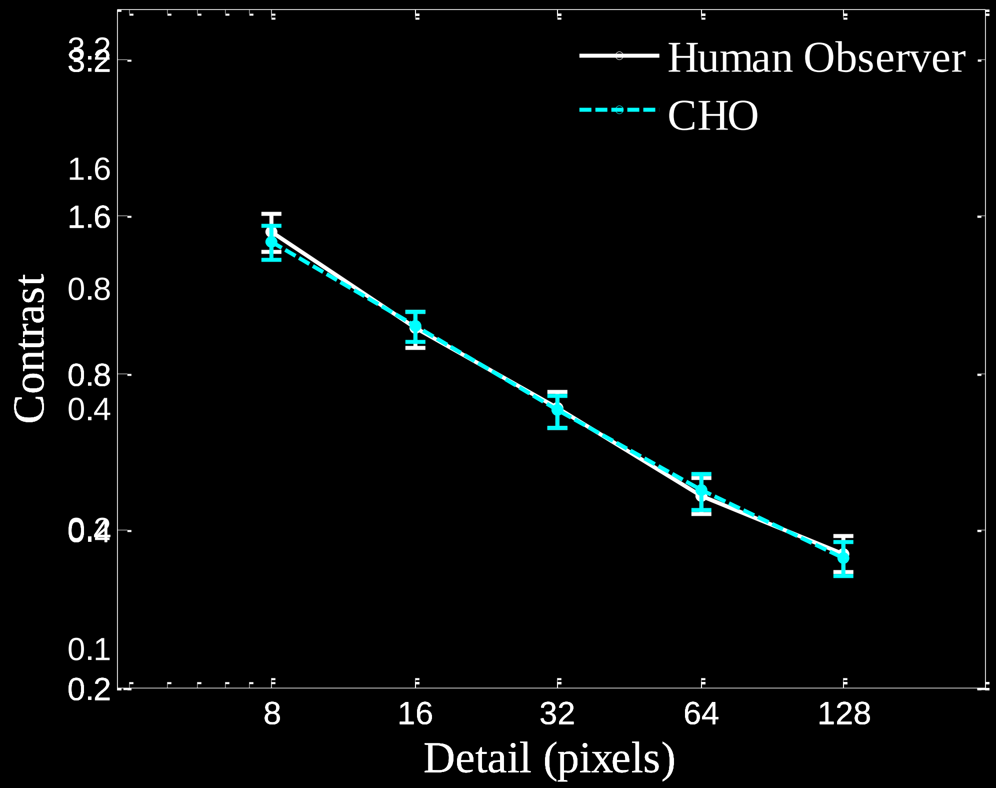
DPC CD curve:



$$\text{contrast} \propto \frac{1}{\sqrt{\text{detail}}}$$

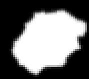
K. Li *et al.* SPIE 8668, Medical Imaging 2013.

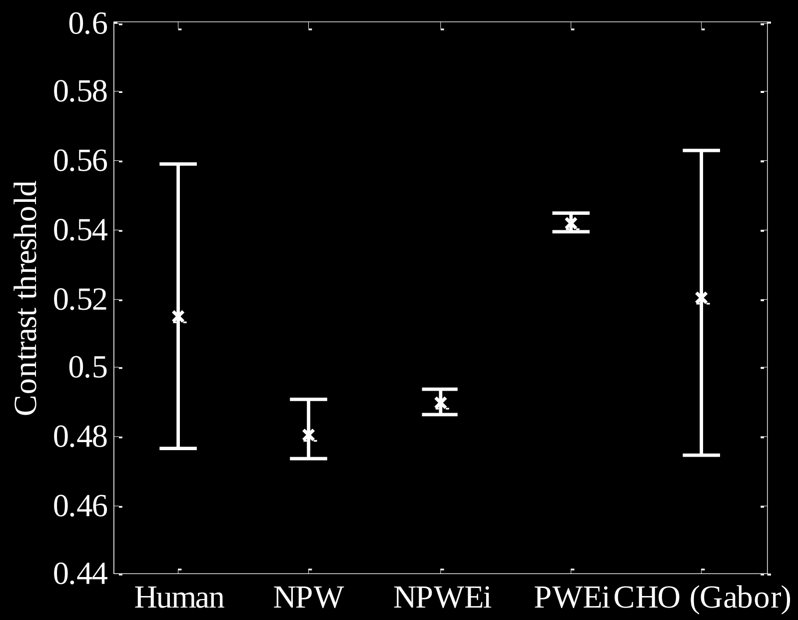
Disc detection Results



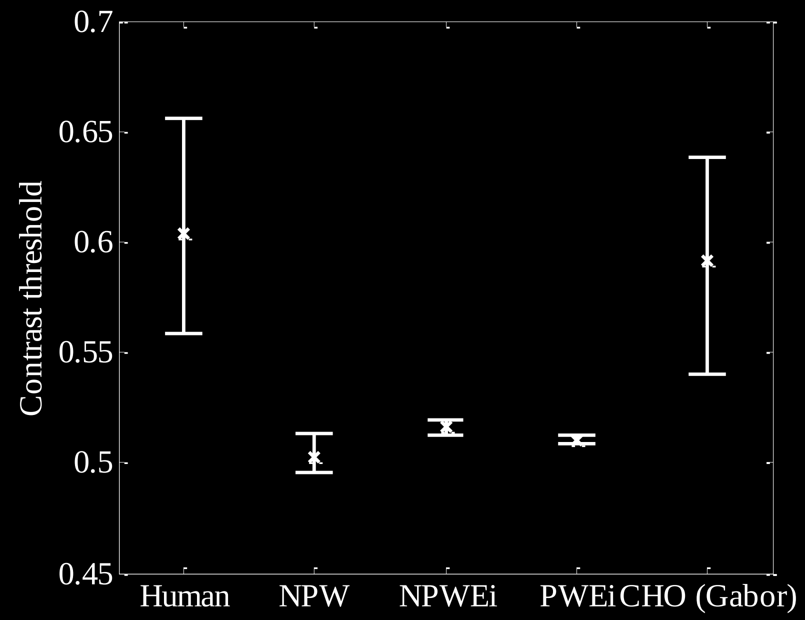
Breast Lesion Results

Lesion 1





Lesion 2



Minimum Equivalence Tolerance Range for Each Observer Model

Signal	Model Observer				
	Ideal	NPW	NPWEi	PWEi	CHO
Disc (d=8)	[-72%, 72%]	[-16%, 16%]	[-81%, 81%]	[-17%, 17%]	[-9%, 9%]
Disc (d=16)	[-71%, 71%]	[-11%, 11%]	[-19%, 19%]	[-13%, 13%]	[-10%, 10%]
Disc (d=32)	[-72%, 72%]	[-13%, 13%]	[-9%, 9%]	[-9%, 9%]	[-9%, 9%]
Disc (d=64)	[-72%, 72%]	[-12%, 12%]	[-9%, 9%]	[-9%, 9%]	[-9%, 9%]
Disc (d=128)	[-75%, 75%]	[-23%, 23%]	[-20%, 20%]	[-17%, 17%]	[-11%, 11%]
Lesion 1	[-39%, 39%]	[-9%, 9%]	[-9%, 9%]	[-9%, 9%]	[-9%, 9%]
Lesion 2	[-53%, 53%]	[-18%, 18%]	[-15%, 15%]	[-16%, 16%]	[-11%, 11%]

Take-Home Message

- DPC-CT or DPC-Tomo imaging does not need new image quality metrics; existing performance metrics from x-ray absorption imaging can be directly applied;
- Given x-ray absorption imaging performance and grating quality factors (visibility and transmission rate), one can quantitatively determine the corresponding performance of a corresponding DPC imaging system for grating based DPC imaging system.
- The model observer method can be used to predict human performance for relatively simple SKE tasks; Among all model observer investigated in this study, CHO model yields the best overall agreement with human observer performance.

Future work

- Using model observer performance as a metric to optimize DPC imaging system;
- Determine the pros and cons for DPC imaging system for a given clinical task and radiation dose constraint.

Acknowlegement

- Dr. Zambelli, Dr. Bevins, John Garrett
- Physicist observers who participated in the human observer experiments

Thank You

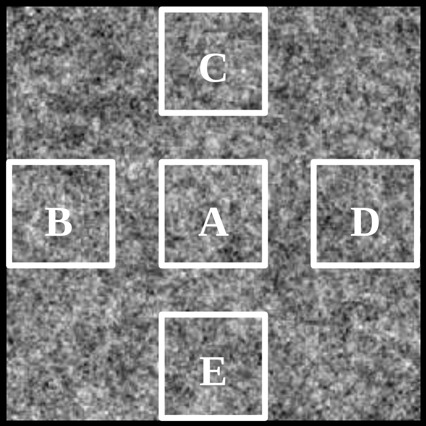
UW CT Research

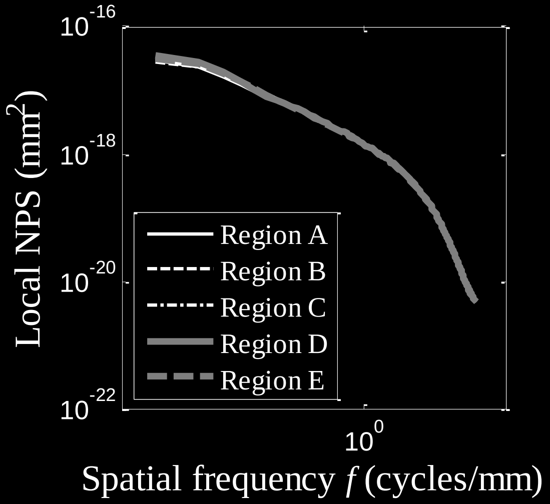
www.medphysics.wisc.edu/research/ct/

gchen7@wisc.edu

Cascaded Linear System Analysis

- Basic requirement
  - System is linear and shift-invariant
- DPC imaging system meets this requirement
  - Because it does not require any non-linear stage to be added to the imaging chain
  - Example: Experimental demonstration of noise stationarity





Noise propagation during image Recon

Absorption projections		DPC projections
Ramp $T_1^{\mathrm{ab}} = \lvert f \rvert$	1. Filtering	Modified Hilbert $T_1^{\mathrm{dpc}} = \frac{p_2}{2\pi d} \frac{\mathrm{sgn}(f)}{2\pi}$
e.g., de-noise filter	2. Additional Filtering	e.g., de-noise filter
$T_3^{\mathrm{ab}} = \mathrm{sinc}^2(\pi f \Delta x)$ for bilinear	3. Interpolation	$T_3^{\mathrm{dpc}} = \mathrm{sinc}^2(\pi f \Delta x)$ for bilinear
$T_4^{\mathrm{ab}} = \frac{\pi M^2}{n_\theta} \frac{1}{\lvert f \rvert}$ or projection matrix	4. Backprojection	$T_4^{\mathrm{dpc}} = \frac{\pi M^2}{n_\theta} \frac{1}{\lvert f \rvert}$ or projection matrix
Convolution with the 3D comb III	5. Resampling	Convolution with the 3D comb III
Absorption CT images $\mathrm{NPS}_{\mathrm{CT}}^{\mathrm{ab}} = \mathrm{NPS}_{\mathrm{proj}}^{\mathrm{ab}} \left[T_1^{\mathrm{ab}} T_2^{\mathrm{ab}} T_3^{\mathrm{ab}} T_4^{\mathrm{ab}} \right]^2 * \mathrm{III}$		DPC CT images $\mathrm{NPS}_{\mathrm{CT}}^{\mathrm{dpc}} = \mathrm{NPS}_{\mathrm{proj}}^{\mathrm{dpc}} \left[T_1^{\mathrm{dpc}} T_2^{\mathrm{dpc}} T_3^{\mathrm{dpc}} T_4^{\mathrm{dpc}} \right]^2 * \mathrm{III}$

D. Tward and J. Siewerdsen, *Med. Phys.* (2008)

K. Li, N. Bevins, J. Zambelli, G.-H. Chen, *Med. Phys*. (2013)

Noise Relationship in the Final Image

NPS of Absorption CT

$$\mathrm{NPS}_{\mathrm{CT}}^{\mathrm{ab}} = \mathrm{NPS}_{\mathrm{proj}}^{\mathrm{ab}} \left[T_1^{\mathrm{ab}} T_2^{\mathrm{ab}} T_3^{\mathrm{ab}} T_4^{\mathrm{ab}} \right]^2 * \mathrm{III}$$

NPS of DPC CT

$$\mathrm{NPS}_{\mathrm{CT}}^{\mathrm{dpc}} = \mathrm{NPS}_{\mathrm{proj}}^{\mathrm{dpc}} \left[T_1^{\mathrm{dpc}} T_2^{\mathrm{dpc}} T_3^{\mathrm{dpc}} T_4^{\mathrm{dpc}} \right]^2 * \mathrm{III}$$

$$\mathrm{NPS}_{\mathrm{proj}}^{\mathrm{dpc}} = \frac{2}{\varepsilon^2} \mathrm{NPS}_{\mathrm{proj}}^{\mathrm{ab}}$$

NPS of Absorption CT

$$\mathrm{NPS}_{\mathrm{CT}}^{\mathrm{ab}} = \frac{\varepsilon^2}{2} \mathrm{NPS}_{\mathrm{proj}}^{\mathrm{dpc}} \left[T_1^{\mathrm{ab}} T_2^{\mathrm{ab}} T_3^{\mathrm{ab}} T_4^{\mathrm{ab}} \right]^2 * \mathrm{III}$$

NPS of DPC CT

$$\mathrm{NPS}_{\mathrm{CT}}^{\mathrm{dpc}} = \frac{2}{\varepsilon^2} \mathrm{NPS}_{\mathrm{proj}}^{\mathrm{ab}} \left[T_1^{\mathrm{dpc}} T_2^{\mathrm{dpc}} T_3^{\mathrm{dpc}} T_4^{\mathrm{dpc}} \right]^2 * \mathrm{III}$$

Materials

- Experimental 2D axial DPC-CT noise images
  - Acquired from a benchtop DPC-CT system
  - 80 µm pixel size
  - 360 x 360 image matrix size
- Digital signals were blurred by the system MTF before being added to the experimental noise background

Human Observer Trails

- Responses from the 2AFC experiments generated the portion of correct response (P_c), which is related to the model observer d' by

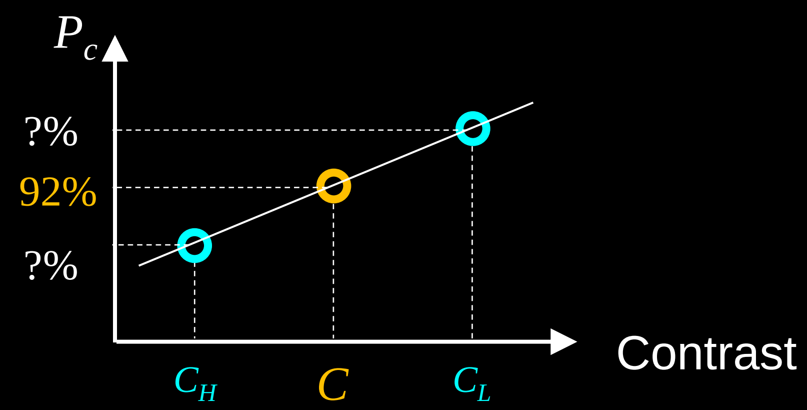
$$P_c = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{d'}{2}\right)\right], \quad \text{where } \mathrm{erf(x)} = \frac{2}{\sqrt{\pi}}\int_0^x \mathrm{e}^{-t^2}\,\mathrm{d}t$$

- To minimize sampling errors due to the finite number of trails, the expected value of P_c should be close to 92% in 2AFC experiments*

* A. Burgess, *Med. Phys.*, **22**, p643 (1995)

Contrast Setting of the Objects

- In order to get an P_c close to 92% for each task
  - Two contrast levels to achieve $P_c \in$ [88%, 92%] and $P_c \in$ [92%, 96%] were determined by training trail results
  - The 2AFC experiments were repeated at each of the two contrast levels to get two P_c values
  - The contrast threshold to achieve $P_c = 92\%$ was determined by linear interpolation



A. Burgess *et al.*, *Med. Phys*. **28**, p419 (2001)

Data Analysis

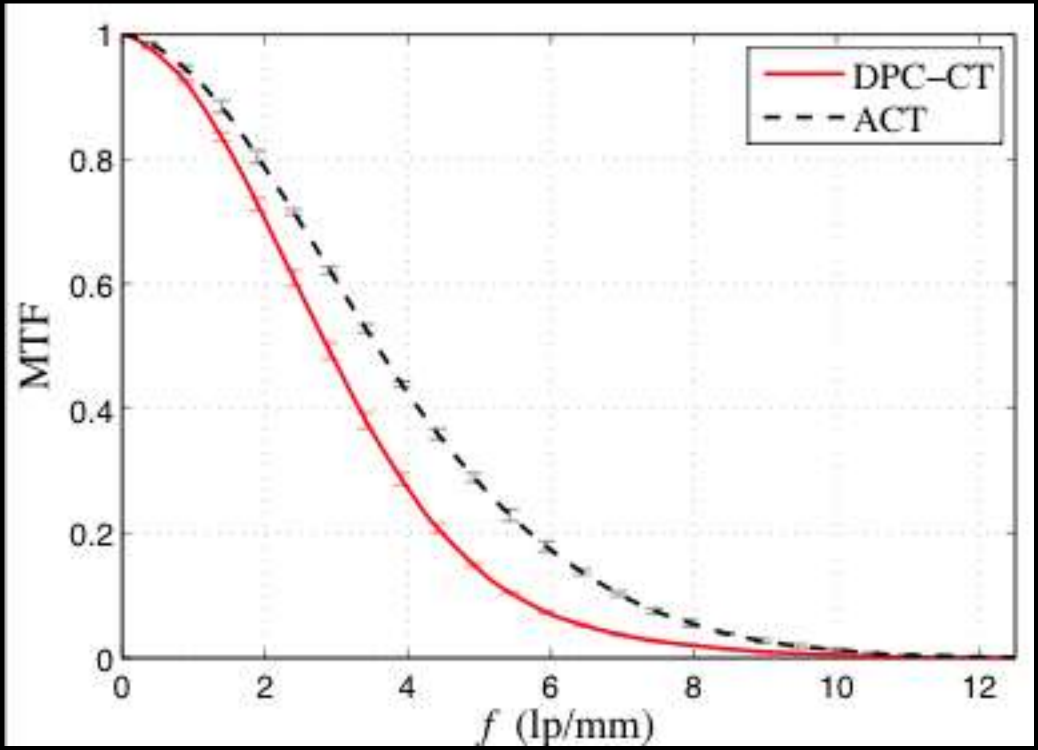
- Error bars of human results: Sampling error

$$\sigma^2(P_c) = \frac{P_c(1-P_c)}{N}$$

- Error bars of model observer results: Uncertainty in the NPS/covariance measurement (measured using bootstrapping)*
- Results were reported as contrast-detail curves
  - x-axis: Object size (in pixels)
  - y-axis: Contrast threshold to achieve 92% P_c

* I. Reiser and R. Nishikawa, *Med. Phys*. **37** (2010)

Measured MTF for both ACT and DPC-CT



Ke Li, et al, Phys. Med. Biol. (2013)