Improved Primary Modulation Scatter Estimation (iPMSE) for Cone-Beam CT

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DEUTSCHES
KREBSFORSCHUNGSZENTRUM
IN DER HELMHOLTZ-GEMEINSCHAFT

Existing Scatter Correction Methods

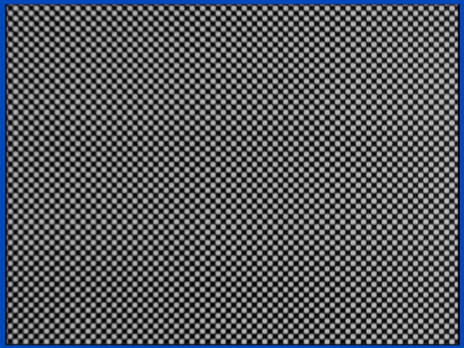
- **Remove or prevent scattered radiation (anti scatter grid, slit scan, large detector distance, …)**
- **Compute scatter to subtract it (convolution-based, Monte Carlo-based, …)**
- **Measure scatter distribution and subtract it (collimator shadow, beam blockers, primary modulators, …)**

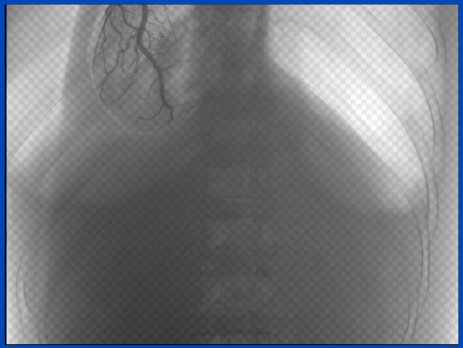
- **Literature:**

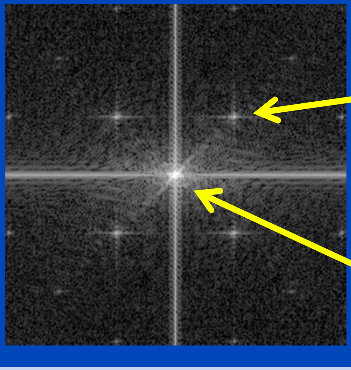
- E.-P. Rührnschopf and K. Klingenbeck, *"A general framework and review of scatter correction methods in x–ray cone–beam computerized tomography. Part 1: Scatter compensation approaches,"* Med. Phys., vol. 38, pp. 4296–4311, July 2011.
- E.-P. Rührnschopf and K. Klingenbeck, *"A general framework and review of scatter correction methods in x–ray cone beam CT. Part 2: Scatter estimation approaches,"* Med. Phys., vol. 38, pp. 5186–5199, Sept. 2011.

Primary Modulation-based Scatter Estimation (PMSE)

- **Idea: Insert a high frequency modulation pattern between the source and the object scanned**
- **Rationale: The primary intensity is modulated. The scatter is created in the object and only consists of low frequency components.**
- **Method: Estimate low frequency primary without scatter by Fourier filtering techniques**







Shifted primary

Scatter + primary

L. Zhu, R. N. Bennett, and R. Fahrig, “Scatter correction method for x–ray CT using primary modulation: Theory and preliminary results,” IEEE Transactions on Medical Imaging, vol. 25, pp. 1573–1587, Dec. 2006.

Primary Modulation-based Scatter Estimation (PMSE)

Key hypothesis: “Low-frequency components dominate the scatter distribution even if high-frequency components are present in the incident x-ray intensity distribution.“

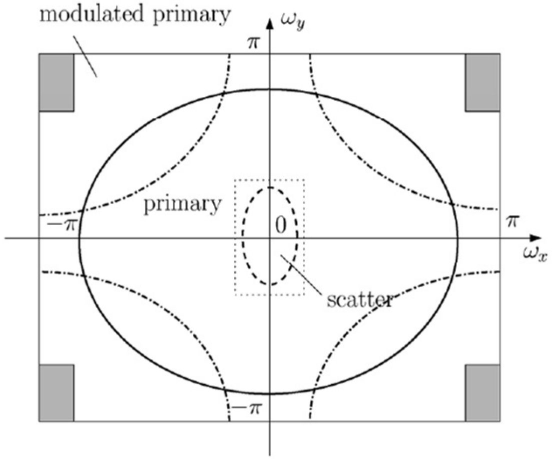
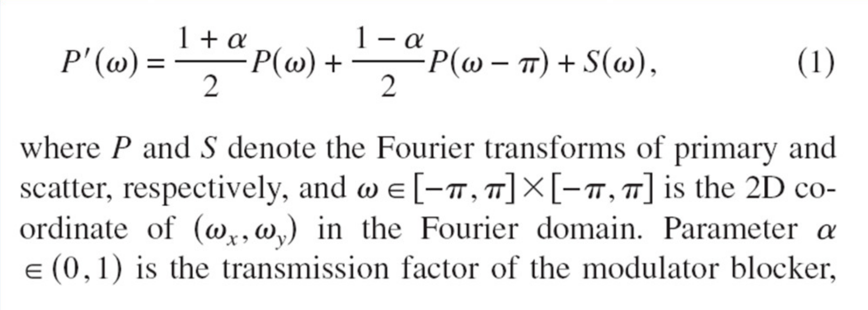


Fig. 3. Conceptual illustration of the primary and scatter distributions in the Fourier domain, with the primary modulator in place. The solid line indicates the primary distribution before modulation; the dot-dashed line indicates the modulated primary; the dashed line around the origin indicates the scatter distribution, which is mainly concentrated in the low-frequency region before and after primary modulation; the center region encompassed by the dotted line indicates the support of the low-pass filter used in Step 3.3 of the scatter correction algorithm proposed in Section II-D; the shaded region indicates the support of the high-pass filter used in Step 3.4.

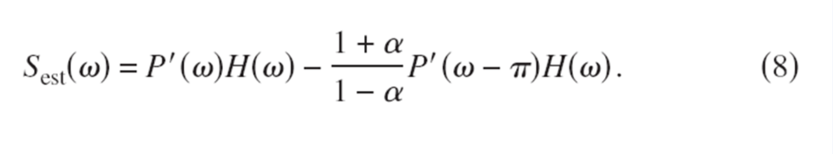
The measurement with a modulator can expressed in Fourier space with:



$$P'(\omega) = \frac{1+\alpha}{2}P(\omega) + \frac{1-\alpha}{2}P(\omega-\pi) + S(\omega), \qquad (1)$$

where P and S denote the Fourier transforms of primary and scatter, respectively, and $\omega \in [-\pi,\pi]\times[-\pi,\pi]$ is the 2D coordinate of (ω_x,ω_y) in the Fourier domain. Parameter $\alpha \in (0,1)$ is the transmission factor of the modulator blocker,

Scatter S can be estimated by



$$S_{\text{est}}(\omega) = P'(\omega)H(\omega) - \frac{1+\alpha}{1-\alpha}P'(\omega-\pi)H(\omega). \qquad (8)$$

with H(ω) being a low-pass filter

L. Zhu, R. N. Bennett, and R. Fahrig, “Scatter correction method for x–ray CT using primary modulation: Theory and preliminary results,” IEEE Transactions on Medical Imaging, vol. 25, pp. 1573–1587, Dec. 2006.

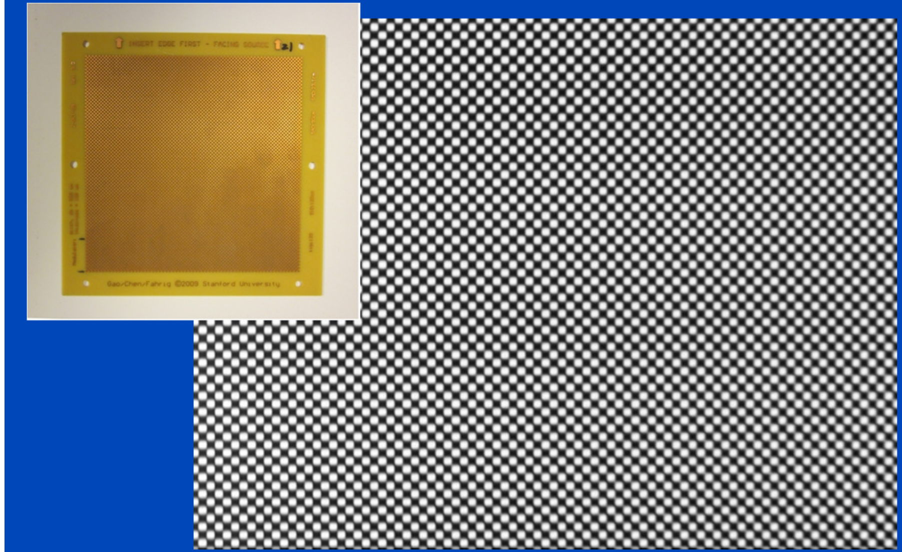
Primary Modulation-based Scatter Estimation (PMSE)

- **Advantages:**
  - Non-destructive measurement of the scatter distribution
  - Works with high accuracy on laboratory setups
  - Corrected projection data can be used for projective imaging (fluoroscopy) or for tomographic reconstruction
- **Drawbacks:**
  - Sensitive to non-linearities due to polychromaticity of x-rays. Ring artifacts are introduced[1]. Can be resolved using ECCP[2].
  - Requires exact rectangular pattern on the detector. Very sensitive to non-idealities of the projected modulation pattern (blurring, distortion, manufacturing errors of the modulator). Can be resolved using iPMSE (this work).

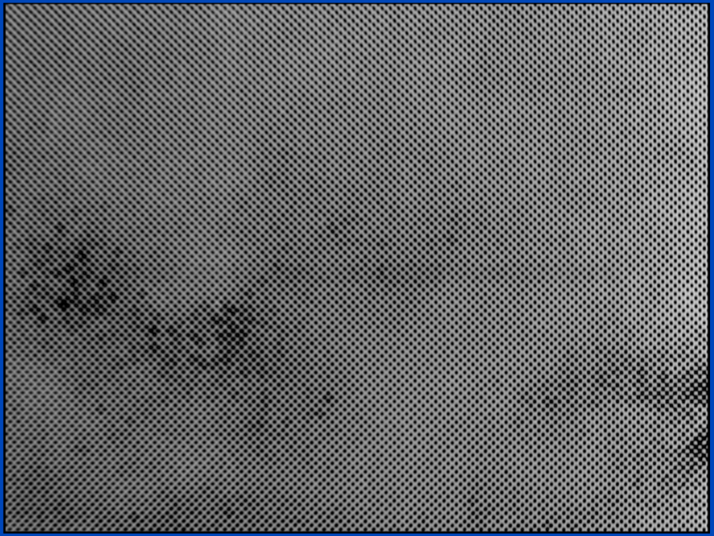
[1] H. Gao, L. Zhu, and R. Fahrig. *Modulator design for x-ray scatter correction using primary modulation: Material selection.* Med. Phys. 37:4029–4037, 2010.
[2] R. Grimmer, R. Fahrig, W. Hinshaw, H. Gao, and M. Kachelrieß. *Empirical cupping correction for CT scanners with primary modulation (ECCP)*. Med. Phys. 39:825-831, 2012.

Aim

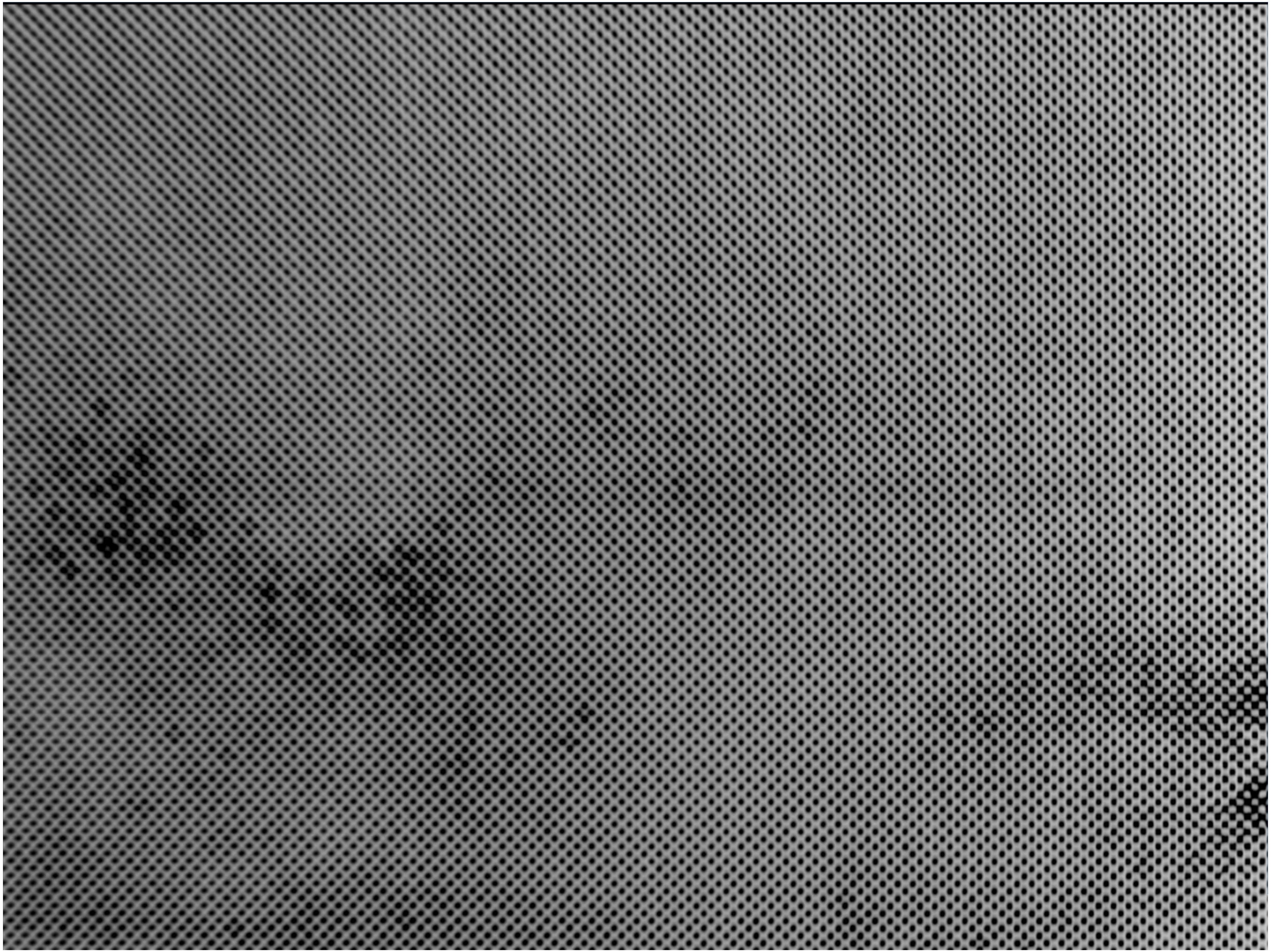
Create a robust scatter estimation method which is able to estimate the scatter distribution with high accuracy using a modulator with an arbitrary high frequency pattern.



“Ideal” modulator
(projection image of a
copper modulator)



Non-ideal modulator
(projection image of the
erbium modulator)



Modulation Process in the Rawdata Domain

- **Measured data:**

$$\underset{\text{Measured intensity}}{\boldsymbol{c}_{\mathrm{m}}} = \underset{\text{Modulation pattern}}{\boldsymbol{M}}\,\overset{\text{Primary intensity}}{\boldsymbol{c}_{\mathrm{p}}} + \underset{\text{Scatter intensity}}{\boldsymbol{c}_{\mathrm{s}}}$$

- **Solving for the primary intensity:**

$$\boldsymbol{c}_{\mathrm{p}} = \boldsymbol{M}^{-1}(\boldsymbol{c}_{\mathrm{m}} - \boldsymbol{c}_{\mathrm{s}})$$

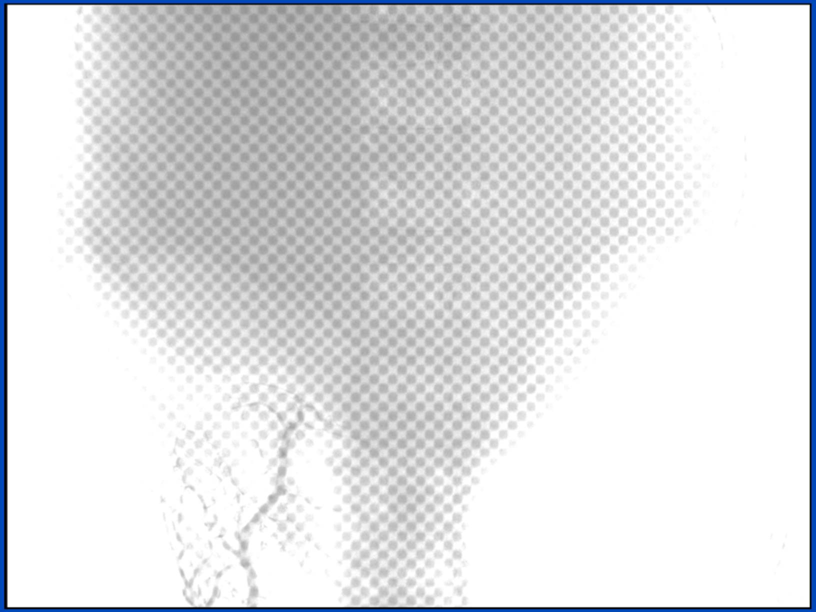
- **Error of primary estimate:**

$$\begin{aligned}\boldsymbol{c}_{\mathrm{p}}^{\mathrm{est}} &= \boldsymbol{M}^{-1}(\boldsymbol{c}_{\mathrm{m}} - \boldsymbol{c}_{\mathrm{s}}^{\mathrm{est}}) \\ &= \boldsymbol{c}_{\mathrm{p}} + \boldsymbol{M}^{-1}\underbrace{(\boldsymbol{c}_{\mathrm{s}} - \boldsymbol{c}_{\mathrm{s}}^{\mathrm{est}})}_{\text{Scatter estimate error}}\end{aligned}$$

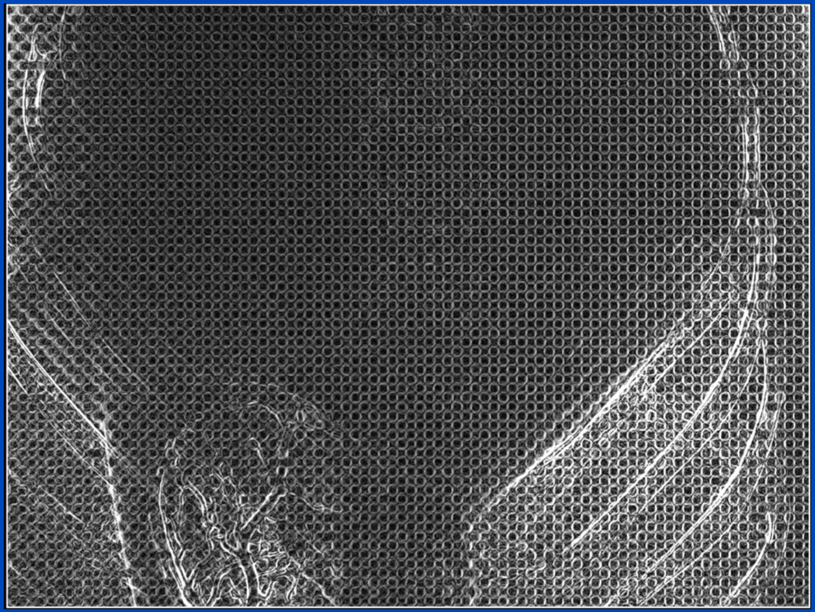
The modulation pattern remains visible if the scatter estimate error is not zero.

Is there a cost function which is sensitive to the modulation pattern?

Regard the image sequence $\boldsymbol{c}_{\mathrm{p}}(t) = \boldsymbol{M}^{-1}(\boldsymbol{c}_{\mathrm{m}} - t)$**:**



$\boldsymbol{c}_{\mathrm{p}}(t)$



$\|\boldsymbol{\nabla} \cdot \boldsymbol{c}_{\mathrm{p}}(t)\|_1$

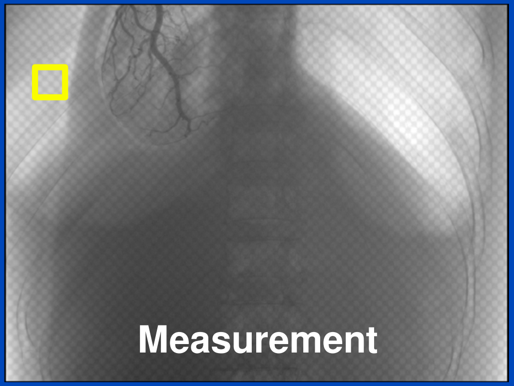
Optimization Problem

- **Subject to $H \cdot \boldsymbol{c}_\mathrm{s}^\mathrm{est} = 0$ solve:**

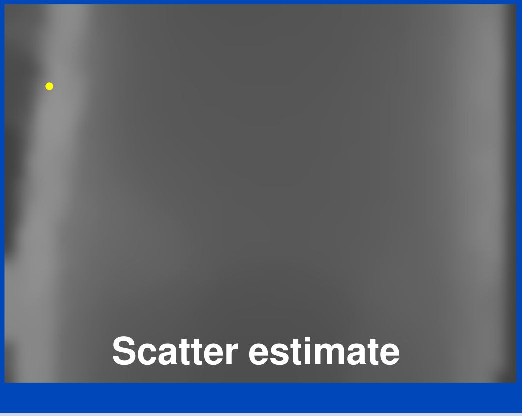
$$C(\boldsymbol{c}_\mathrm{p}^\mathrm{est}) = \|\nabla \cdot \boldsymbol{c}_\mathrm{p}^\mathrm{est}\|_1 = \|\nabla \cdot \boldsymbol{M}^{-1}(\boldsymbol{c}_\mathrm{m} - \boldsymbol{c}_\mathrm{s}^\mathrm{est})\|_1$$

- **Assumption:**
  In a sufficiently small and sufficiently large sub image the constraint can be satisfied by assuming c_s = const.

- **Solution:**
  Solve cost function for each possible sub image separately.



Measurement

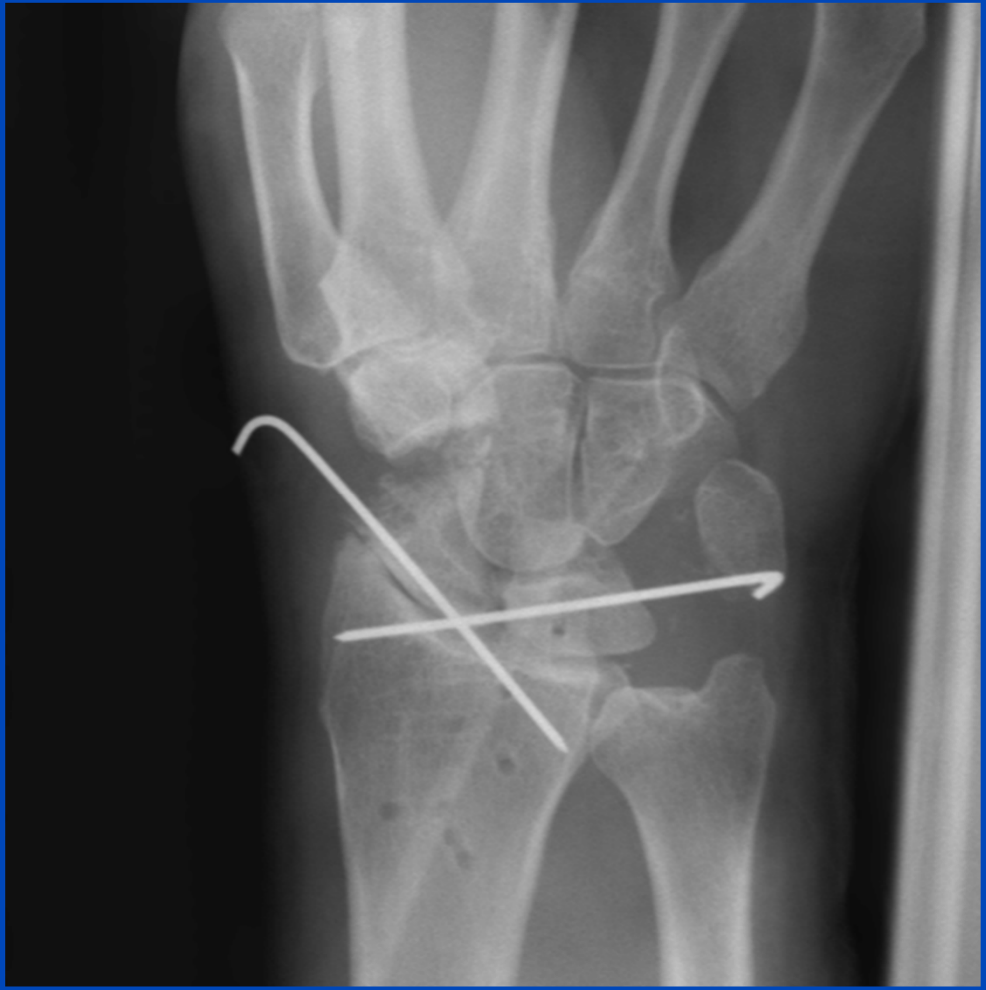


Scatter estimate

Results

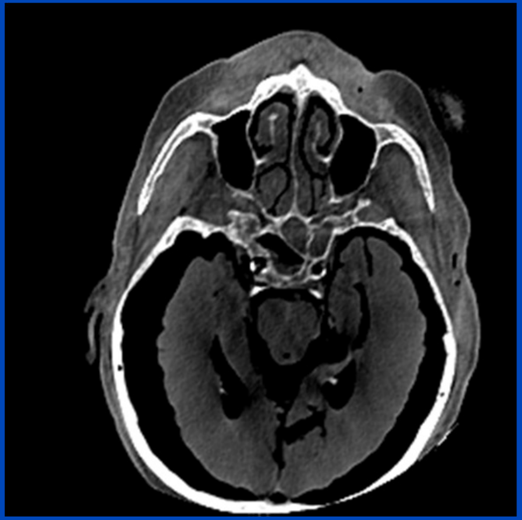
Measured Intensity

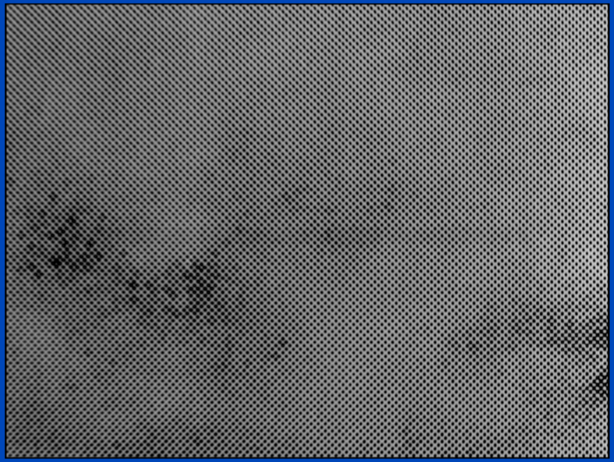
iPMSE Estimation



Parameters: Cadaver Head

- Scan parameters
  - 80 kV
  - 30 mA
  - 13 ms pulse length
  - 625 projections of 360°
  - 244 mAs
- No antiscatter grid
- Modulator
  - Material: Erbium
  - Thickness: 0.0254 mm
  - Pattern size: 0.457 mm
- ECCP[1] preprocessing
- iPMSE scatter removal
- FDK reconstruction





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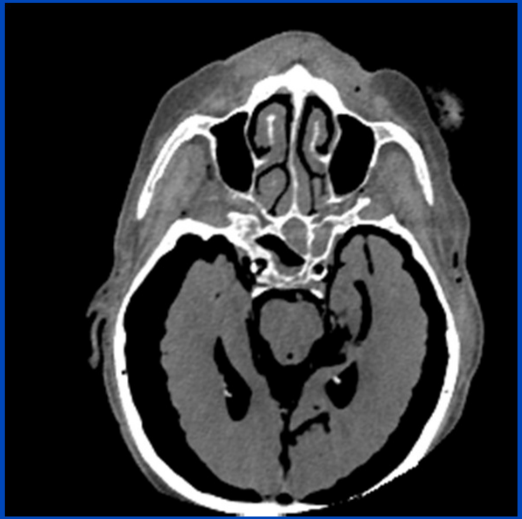
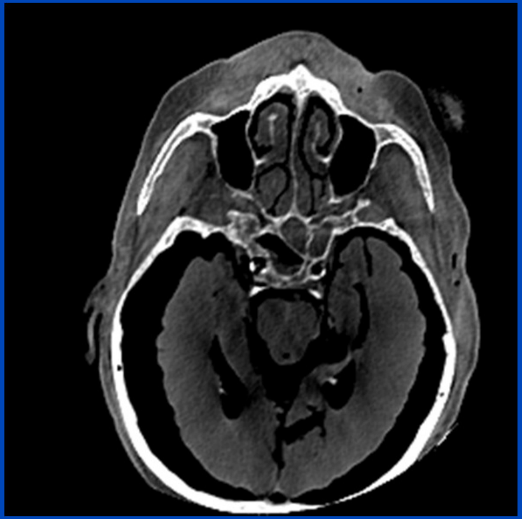
[1] R. Grimmer, R. Fahrig, W. Hinshaw, H. Gao, and M. Kachelrieß. *Empirical cupping correction for CT scanners with primary modulation (ECCP)*. Med. Phys. 39:825-831, 2012.

Cadaver Head Axial Slice



Slitscan

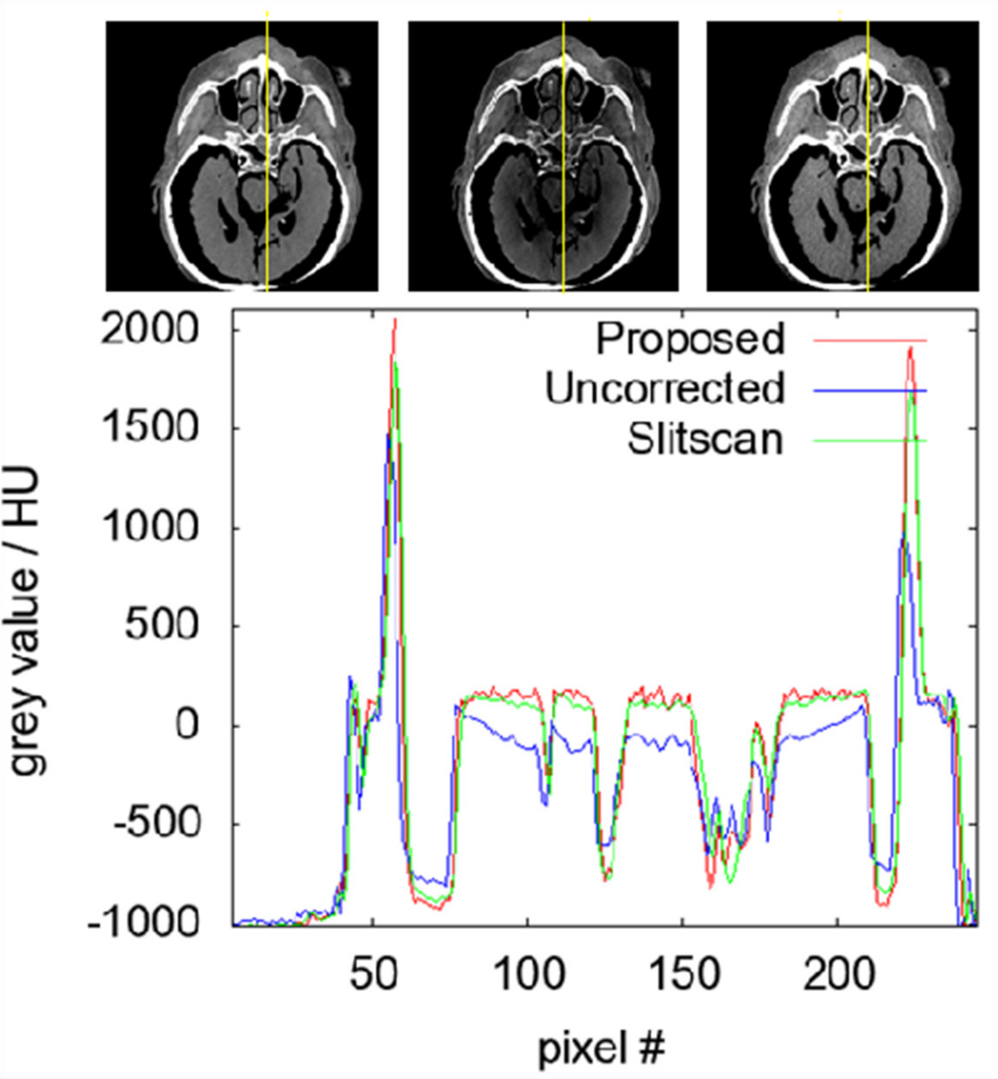


Uncorrected

iPMSE

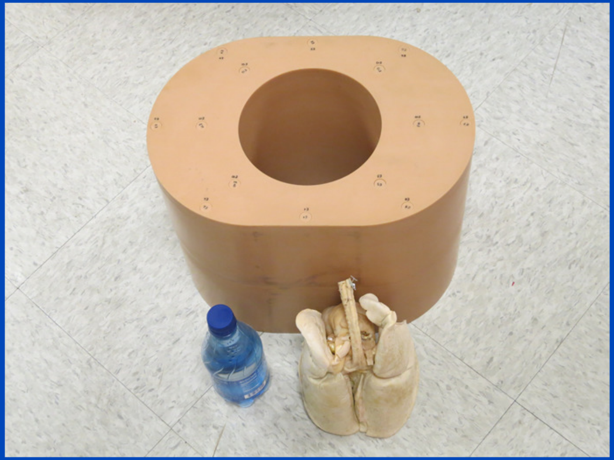
C/W = 200 HU / 800 HU

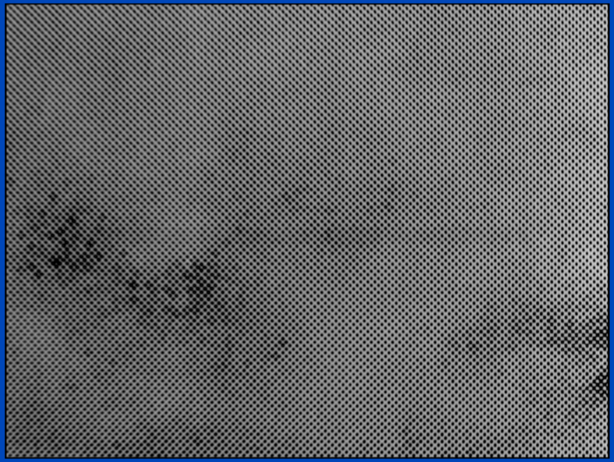
Profile Through Axial Slices



Parameters: Lung Phantom

- Scan parameters
  - 100 kV
  - 30 mA
  - 13 ms pulse length
  - 625 projections of 360°
  - 244 mAs
- No antiscatter grid
- Modulator
  - Material: Erbium
  - Thickness: 0.0254 mm
  - Pattern size: 0.457 mm
- ECCP[1] preprocessing
- iPMSE scatter removal
- FDK reconstruction





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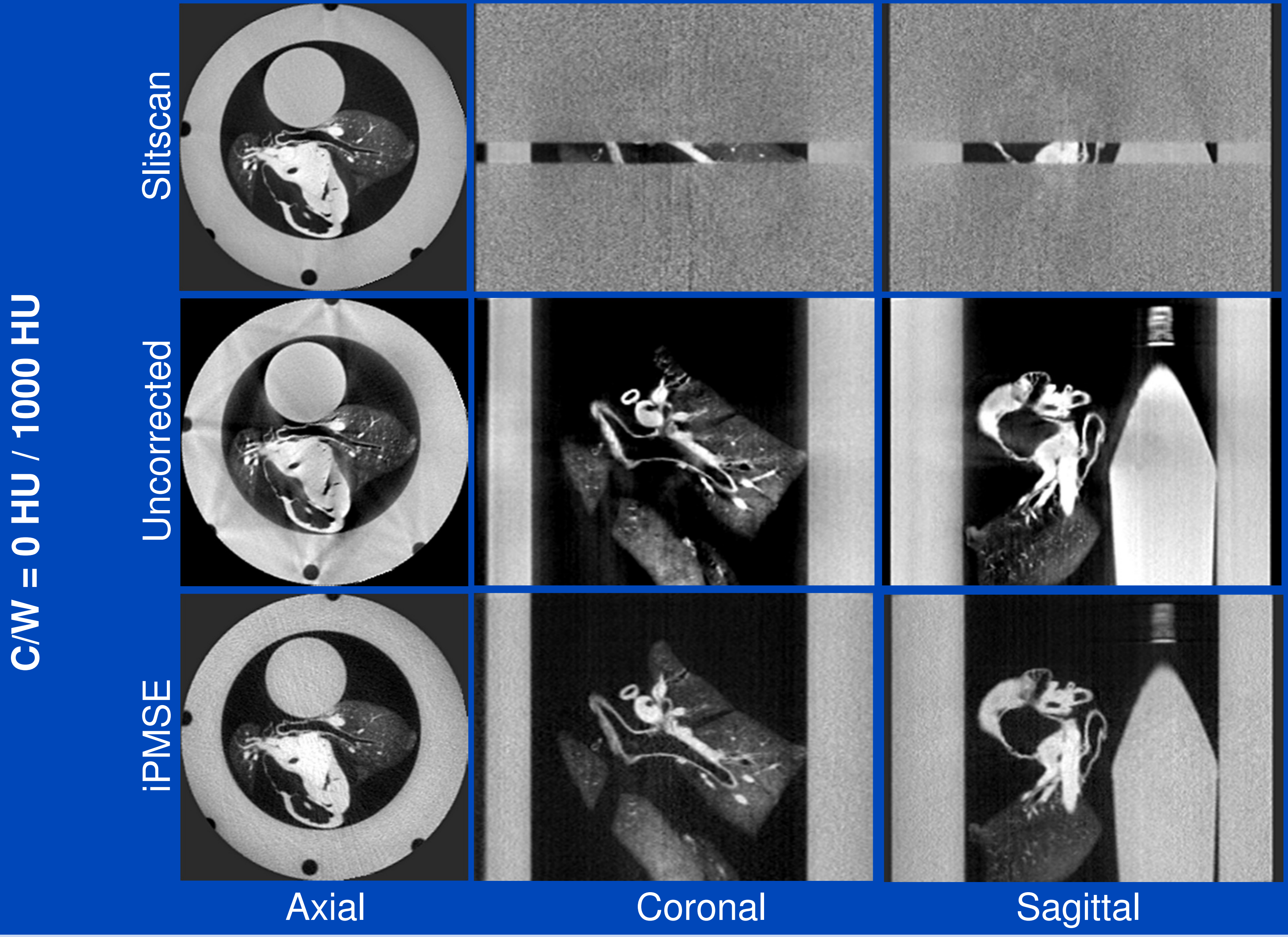
Lung Phantom Scan



Discussion

- Highly accurate scatter estimation and removal is also possible using irregular modulation patterns.
- Non-idealities of the modulation pattern and penumbra effects are optimally handled with iPMSE.
- The combination ECCP and iPMSE guarantees quantitative flat detector images without scatter artifacts.
- Accurate scatter correction opens the field of quantitative flat detector CT.

Thank you!

This presentation will soon be available at www.dkfz.de/ct.