A Count Rate-Dependent Method for Spectral Distortion Correction in Photon Counting CT

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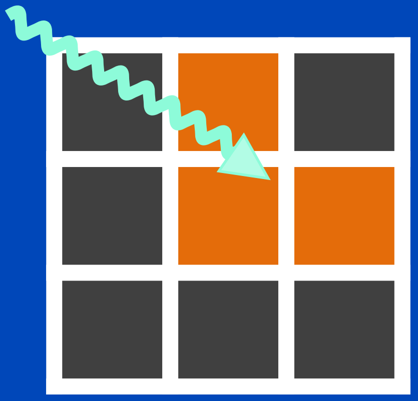
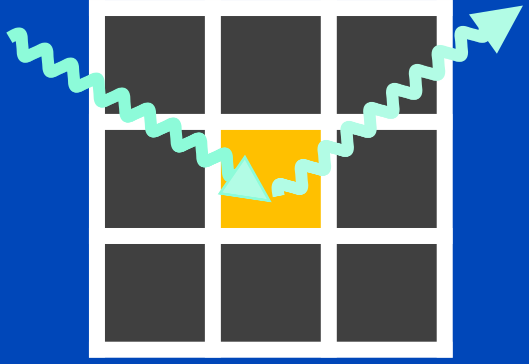
Aim

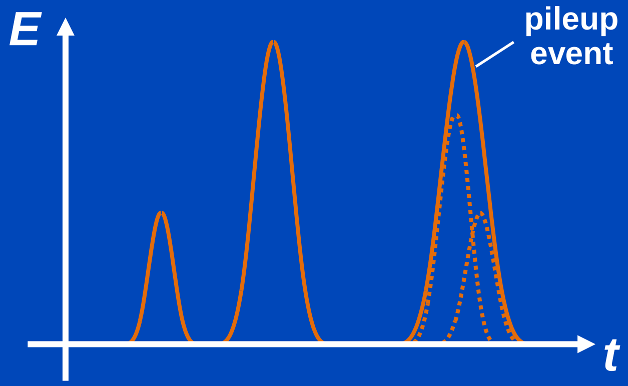
- Material decomposition of spectral CT data into contributions of iodine and water
- Table-top setup with a prototype photon-counting detector (PCD)
- Calibration of spectral response to account for…
  - Spectral distortions: charge sharing, K-escape
  - Count rate-dependent distortions: pulse pileup



Charge Sharing

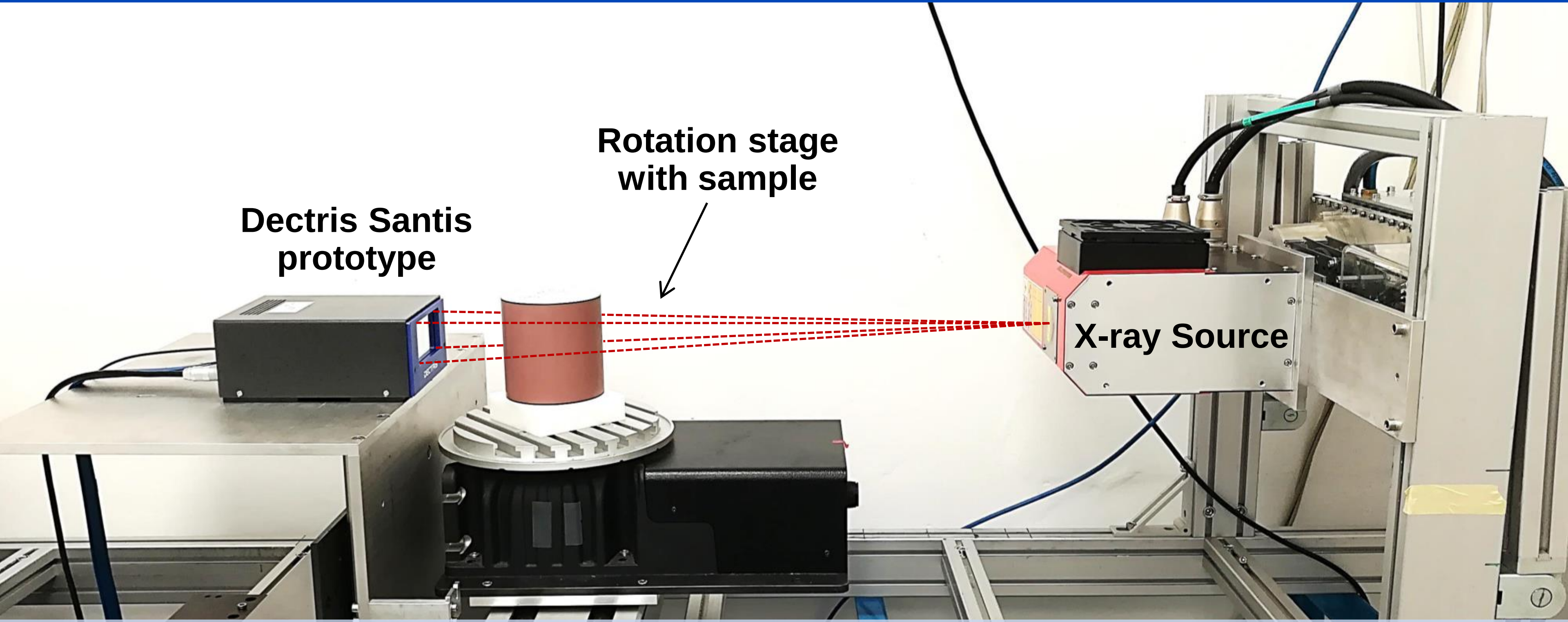


K-Escape, Compton



Pulse Pileup

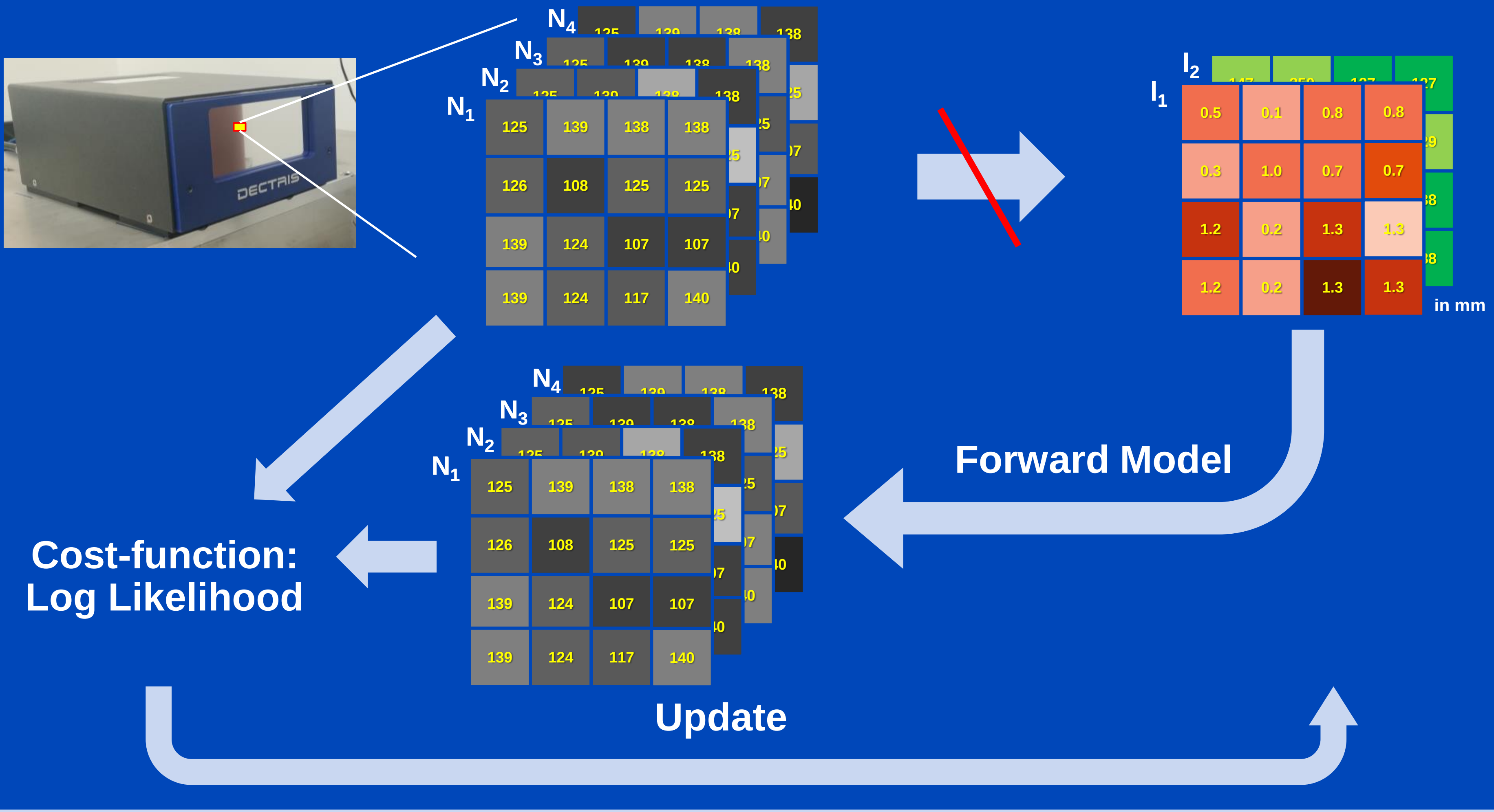
Table-Top Photon Counting CT



Pixel	512 x 256
Pixel size	150 x 150 μm^2
Sensor thickness	1.0 mm CdTe

Material Decomposition

$$N_b(l_{1,\ldots,M}) \propto N_{0,b} \int dE \; w(E) \cdot S_b(E) \cdot \exp\left(-\sum_{m=1}^{M} \mu_m(E) \cdot l_m\right)$$



125	139	138	138
126	108	125	125
139	124	107	107
139	124	117	140

0.5	0.1	0.8	0.8
0.3	1.0	0.7	0.7
1.2	0.2	1.3	1.3
1.2	0.2	1.3	1.3

in mm

Forward Model

125	139	138	138
126	108	125	125
139	124	107	107
139	124	117	140

Cost-function:
Log Likelihood

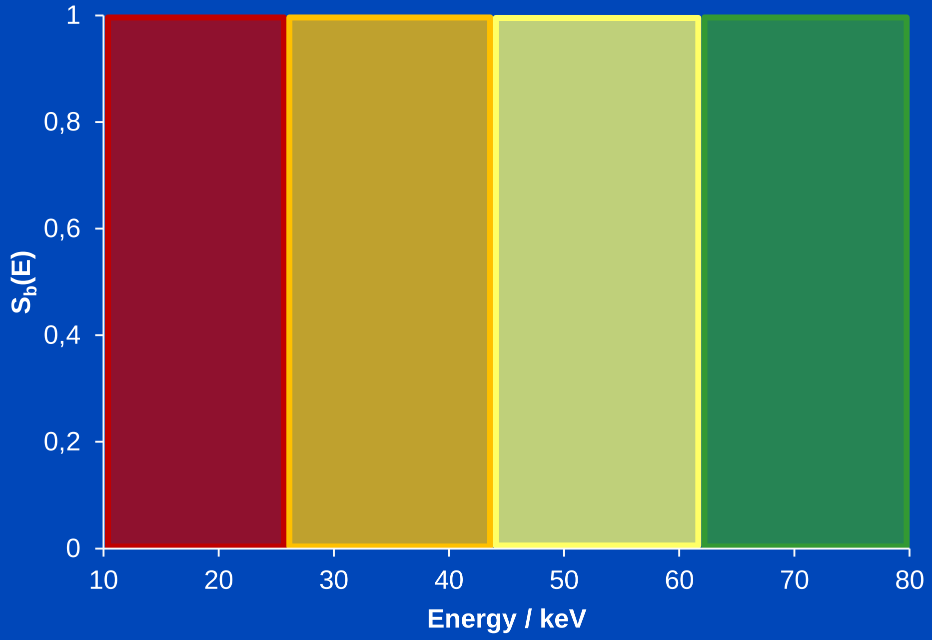
Update

Schlomka et al. (2008) “Experimental feasibility of multi-energy photon-counting K-edge imaging in pre-clinical computed tomography” *Physics in Medicine and Biology*, 53(15), 4031–4047.

Material Decomposition

- The detection process of a PCD is described using the bin sensitivity function $S_b(E)$.

$$N_b(l_{1,\ldots,M}) \propto N_{0,b} \int dE \;\; w(E) \cdot S_b(E) \cdot \exp\left(-\sum_{m=1}^{M} \mu_m(E) \cdot l_m\right)$$



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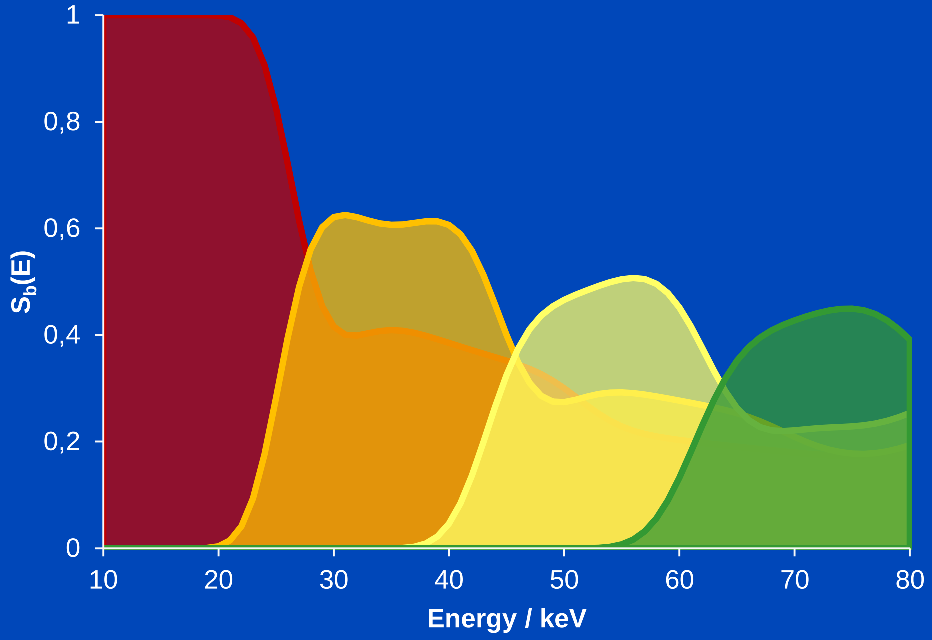

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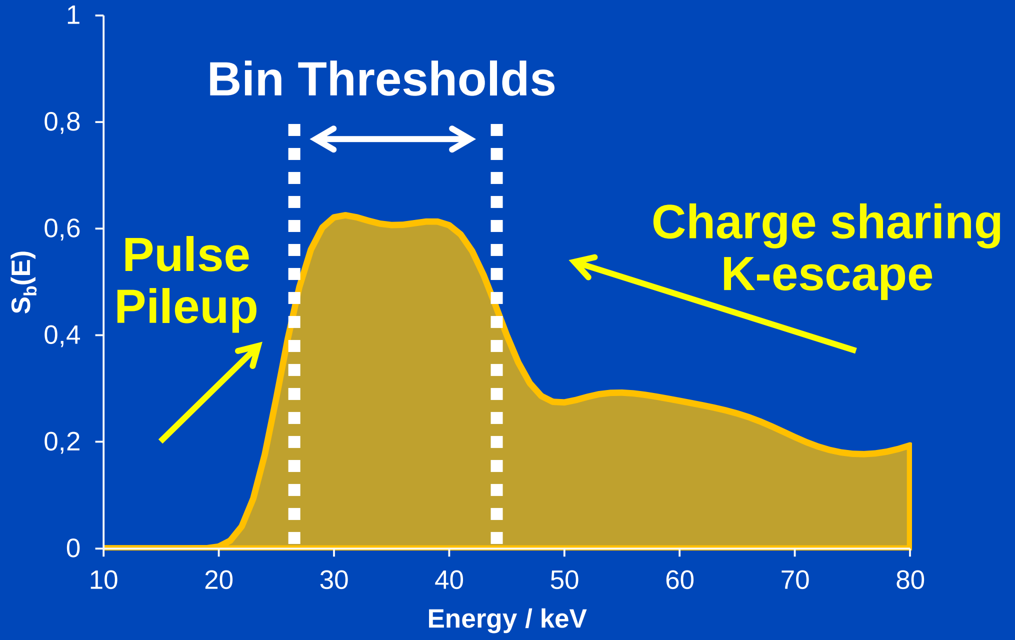
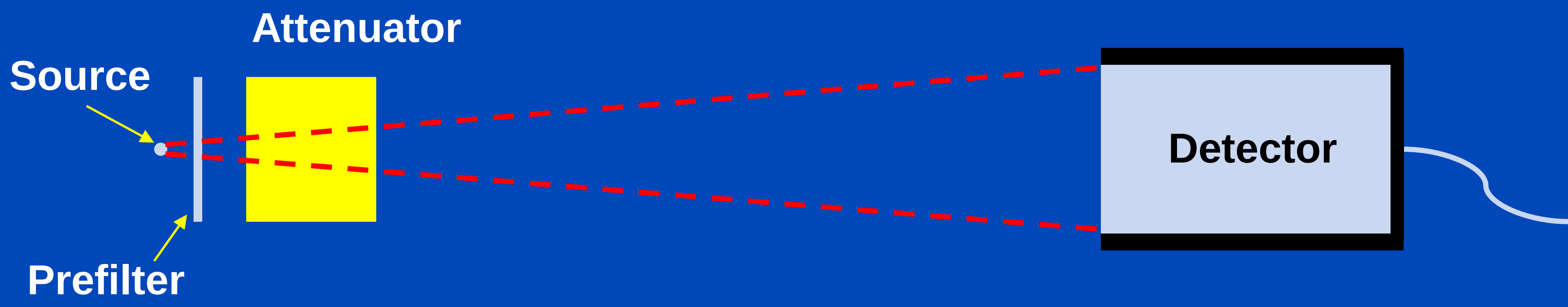


Schlomka et al. (2008) “Experimental feasibility of multi-energy photon-counting K-edge imaging in pre-clinical computed tomography” *Physics in Medicine and Biology*, 53(15), 4031–4047.

Calibration Measurements

- Measure transmission through slabs of aluminum and POM
- Adapt forward model for each patch of 10x10 pixels such that it reproduces the calibration measurement



Reference Methods

- **Method 1 by Liu et al. (2015)**

$$N_b(l_{1,\ldots,M}) \propto N_{0,b} \cdot C_b\Big(\int dE \;\; w(E) \cdot S_b(E) \cdot \exp\Big(-\sum_{m=1}^{M} \mu_m(E) \cdot l_m\Big)\Big)$$

$$C_b(N) = \frac{\alpha_b + \beta_b \cdot N}{1 + \gamma_b \cdot N}$$

- **Method 2 by Sidky et al. (2005)**

$$N_b(l_{1,\ldots,M}) \propto N_{0,b} \cdot \int dE \;\; \underbrace{w(E) \cdot S_b(E)}_{= w_b(E)} \cdot \exp\Big(-\sum_{m=1}^{M} \mu_m(E) \cdot l_m\Big)$$

Liu, et al. (2015) “Spectral response model for a multibin photon-counting spectral computed tomography detector and its applications”. *Journal of Medical Imaging*, 33502

Sidky et al. (2005) “A robust method of x-ray source spectrum estimation from transmission measurements: Demonstrated on computer simulated, scatter-free transmission data”. *Journal of Applied Physics*, 97(12), 124701.

Count Rate-Dependent Spectral Calibration

- Include a multiplicative correction function P$_b$(E,N$_b$) to account for spectral distortions and effects depending on the count-rate N_b

$$N_b(l_{1,\dots,M}) \propto N_{0,b} \int dE \ \ w(E) \cdot S_b(E) \cdot P_b(E, N_b) \cdot \exp\left(- \sum_{m=1}^{M} \mu_m(E) \cdot l_m \right)$$

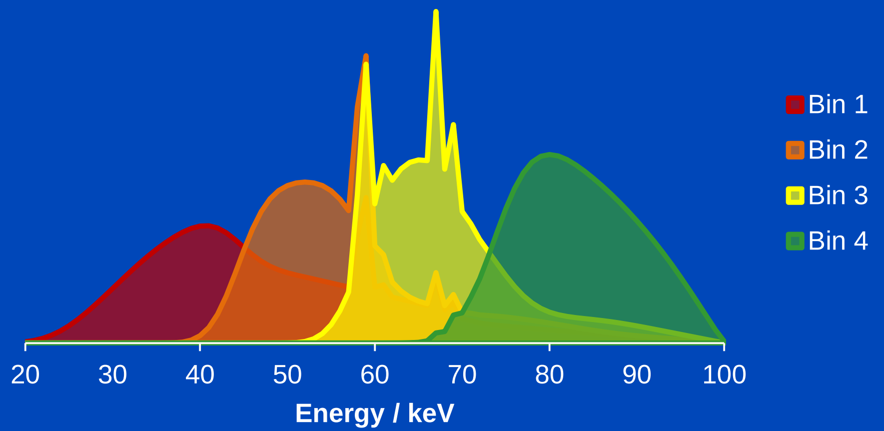
- Model the correction function as a polynomial of order K

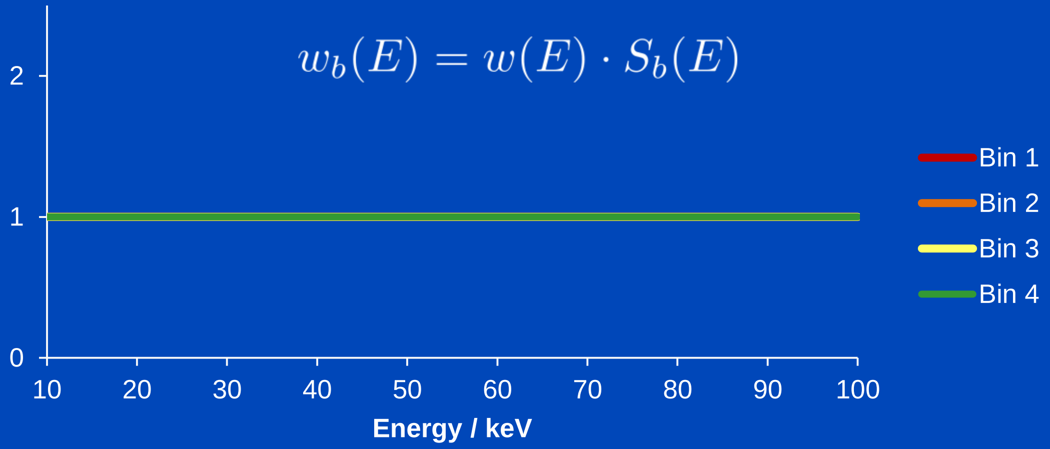
$$P_b(E, N_b) = 1 + (E - E_{\min})(E - E_{\max}) \cdot \sum_{k=0}^{K-2} c_{kb}(N_b) E^k$$

where the coefficients depend linearly on the count-rate

$$c_{kb}(N_b) = c_{kb}^{(0)} + c_{kb}^{(1)} \cdot N_b$$

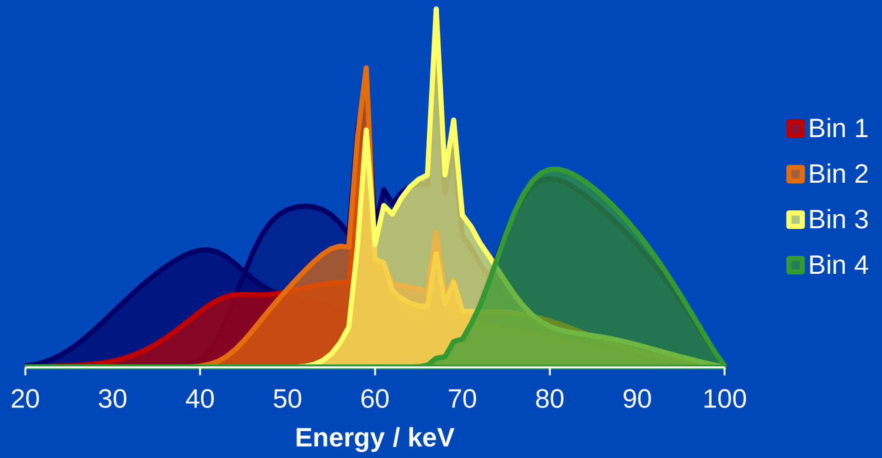
Count Rate-Dependent Spectral Calibration

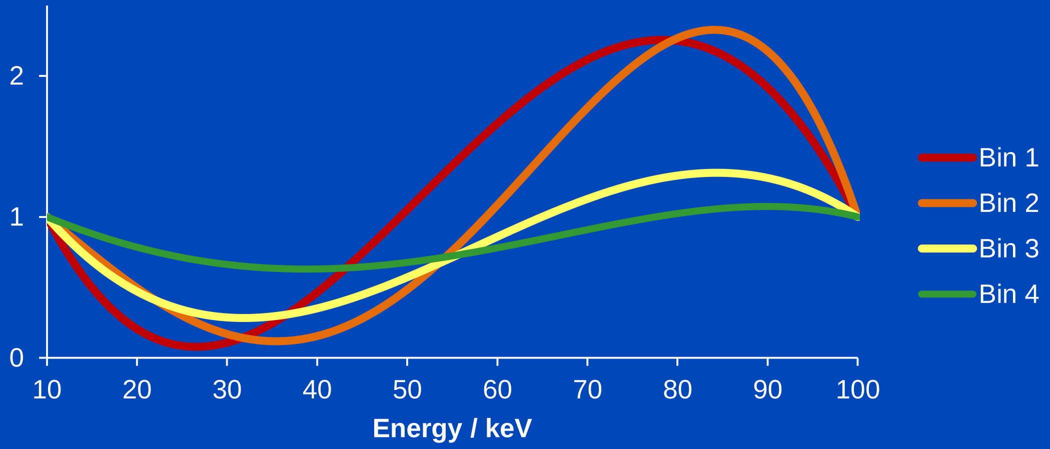


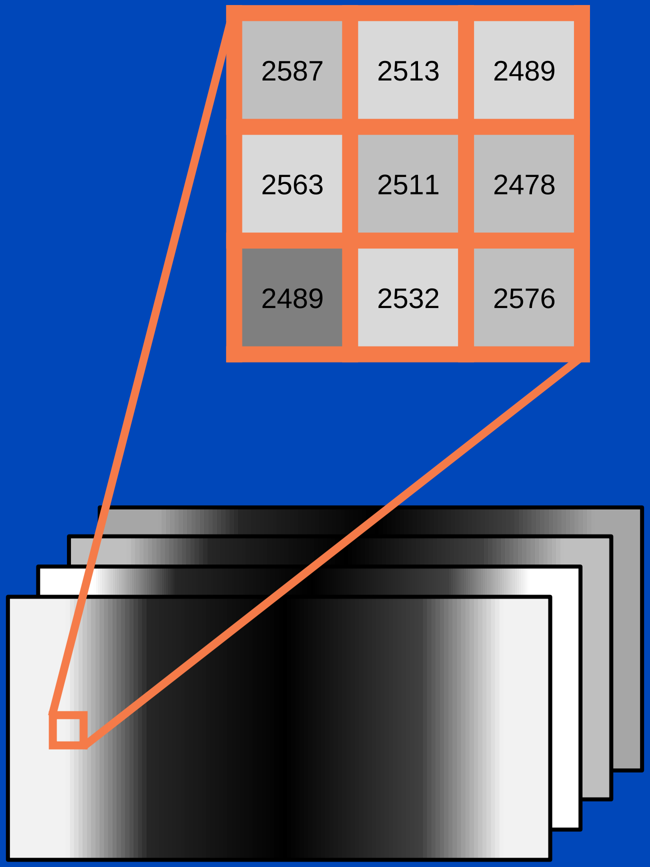


$$w_b(E) = w(E) \cdot S_b(E)$$

Count Rate-Dependent Spectral Calibration

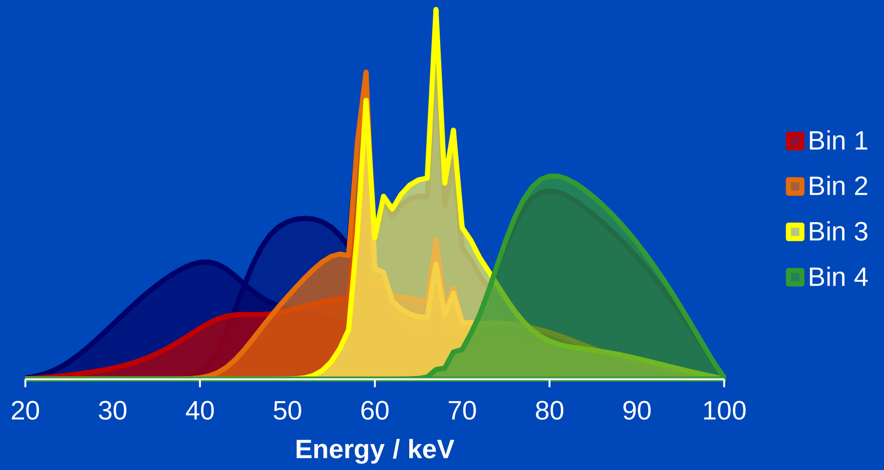


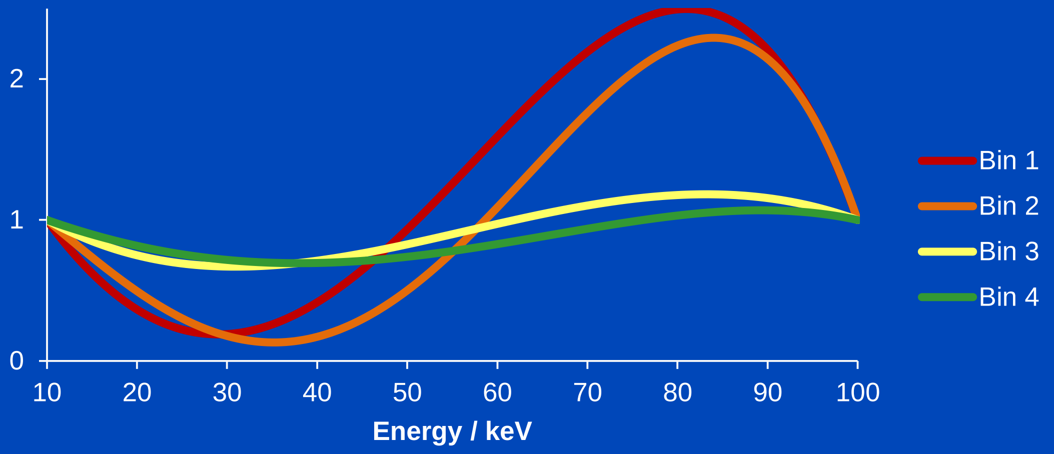


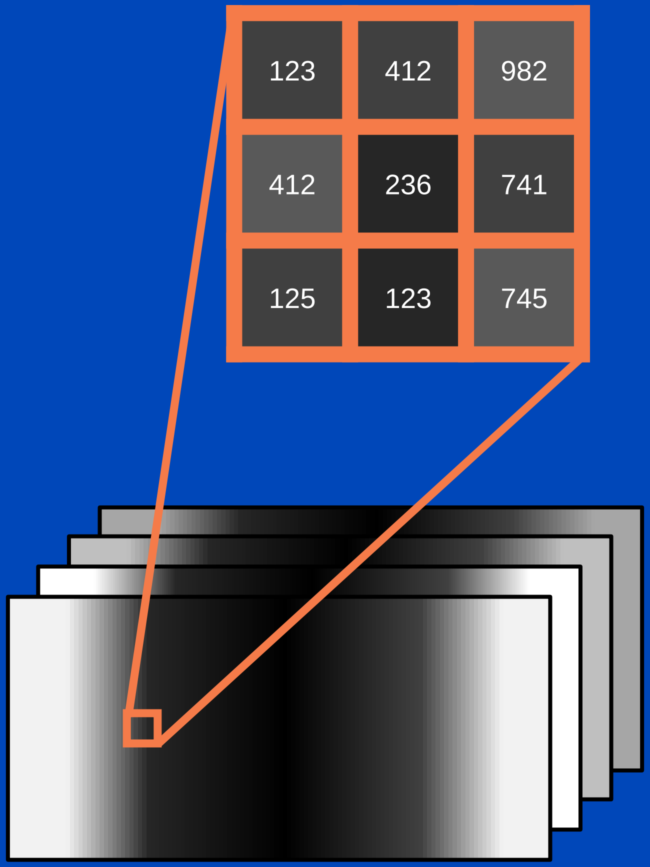


2587	2513	2489
2563	2511	2478
2489	2532	2576

Count Rate-Dependent Spectral Calibration







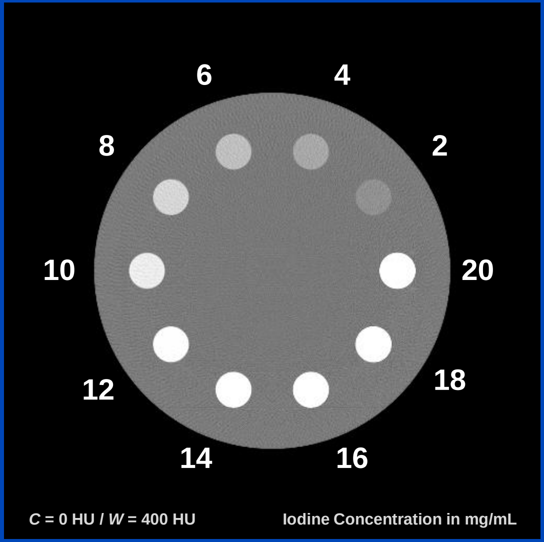
123	412	982
412	236	741
125	123	745

Simulation Study

- Material decomposition into iodine and water
- Spectrum 80 kV, 6 mm Al prefiltration

a) Distorted bin sensitivity function for decomposition

b) Simulated pulse pileup for paralyzable detector and rectangular shaped pulses



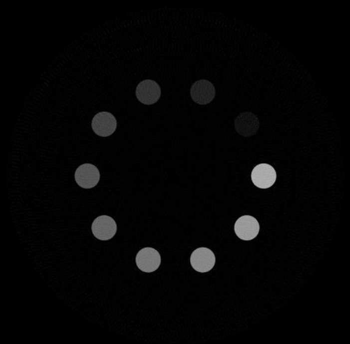
Faby et. al. (2016). “An efficient computational approach to model statistical correlations in photon counting x-ray detectors”. *Medical Physics*, 43(7), 3945–3960

Schlomka et. al. (2008) “Experimental feasibility of multi-energy photon-counting K-edge imaging in pre-clinical computed tomography” *Physics in Medicine and Biology*, 53(15), 4031–4047

Frey et. al. (2007). “Investigation of the use of photon counting x-ray detectors with energy discrimination capability for material decomposition in micro-computed tomography”. *Proceedings of SPIE Medical Imaging*, 65100A

Simulation Study

Ground Truth

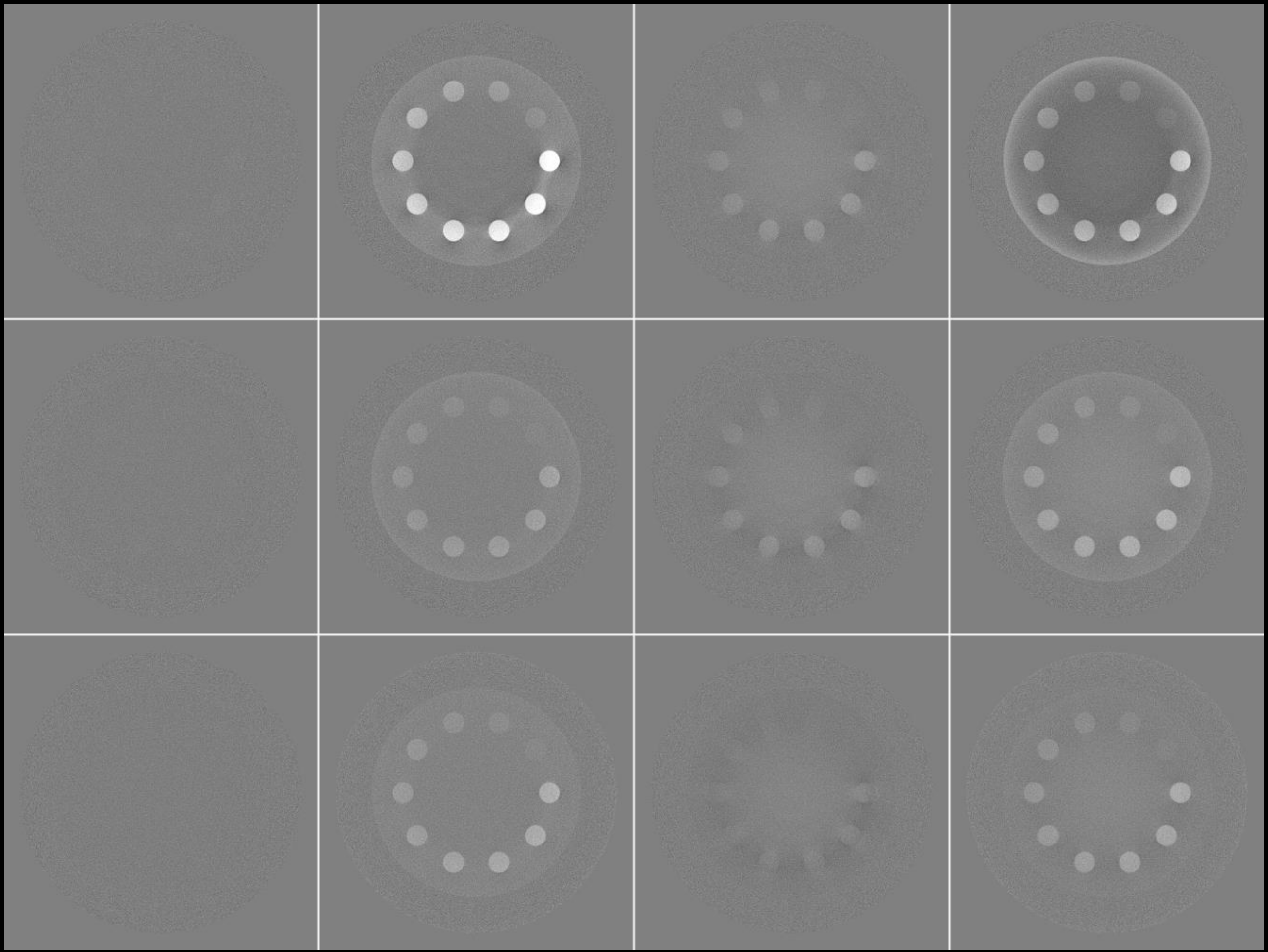


Iodine
C = 15 mg/mL, *W* = 30 mg/mL

Iodine Image (Difference to ground truth)

No pulse pileup | **With pulse pileup**

ideal | *distorted* | *ideal* | *distorted*



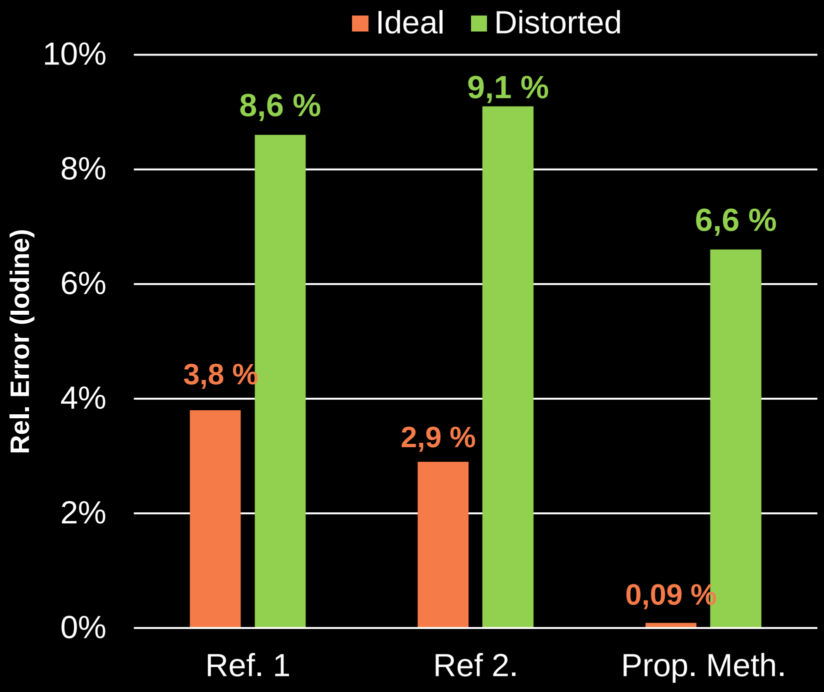
Ref. 1

Ref. 2

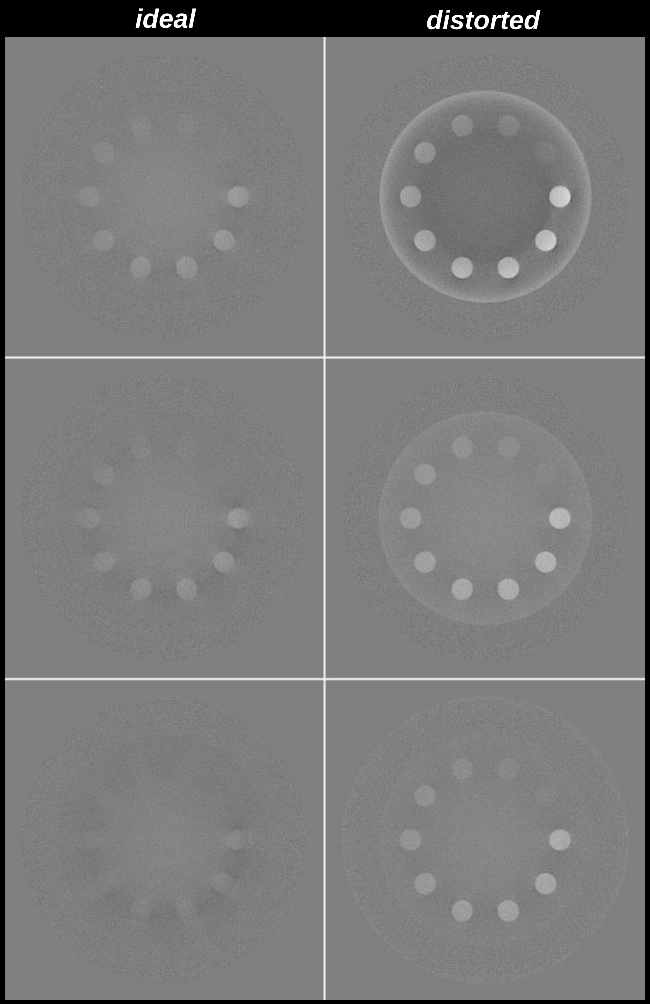
Prop. Meth.

C = 0 mg/mL, *W* = 4 mg/mL

Simulation Study



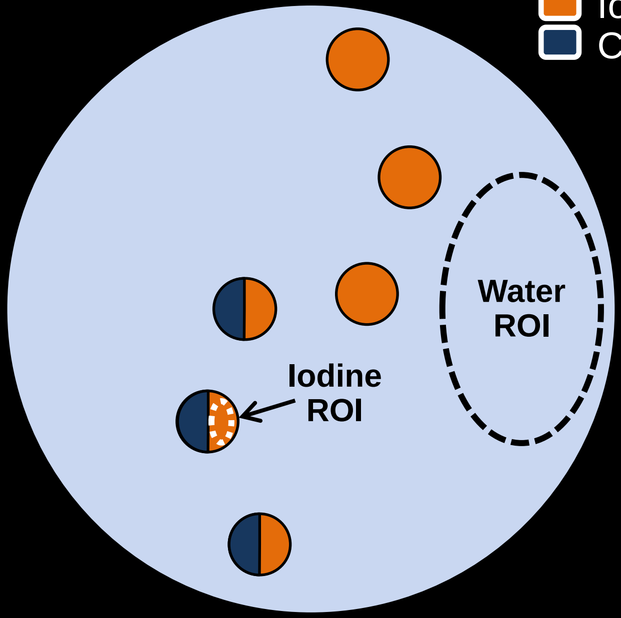
With pulse pileup



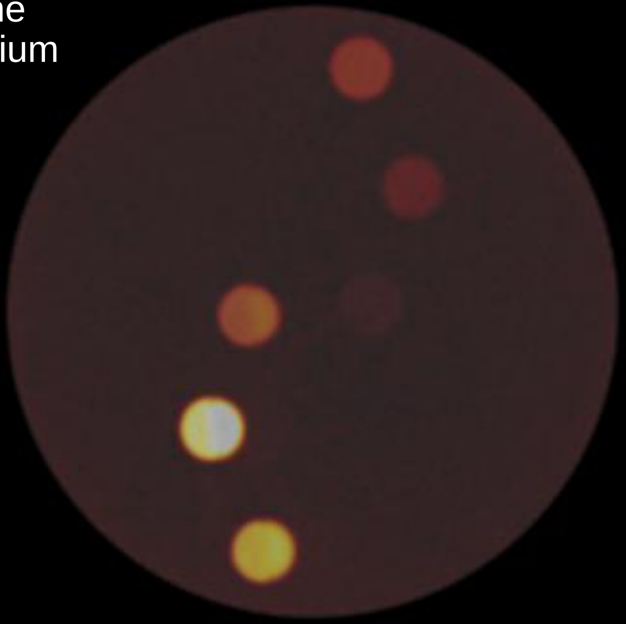
C = 0 mg/mL, *W* = 4 mg/mL

Phantom Measurements

- QRM dual energy phantom DEP-002.
- Reference concentration determined with Siemens Somatom Definition Flash scanner.



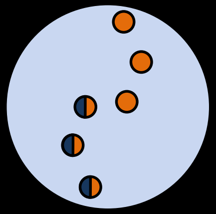
▢ Water
🟧 Iodine
🟦 Calcium

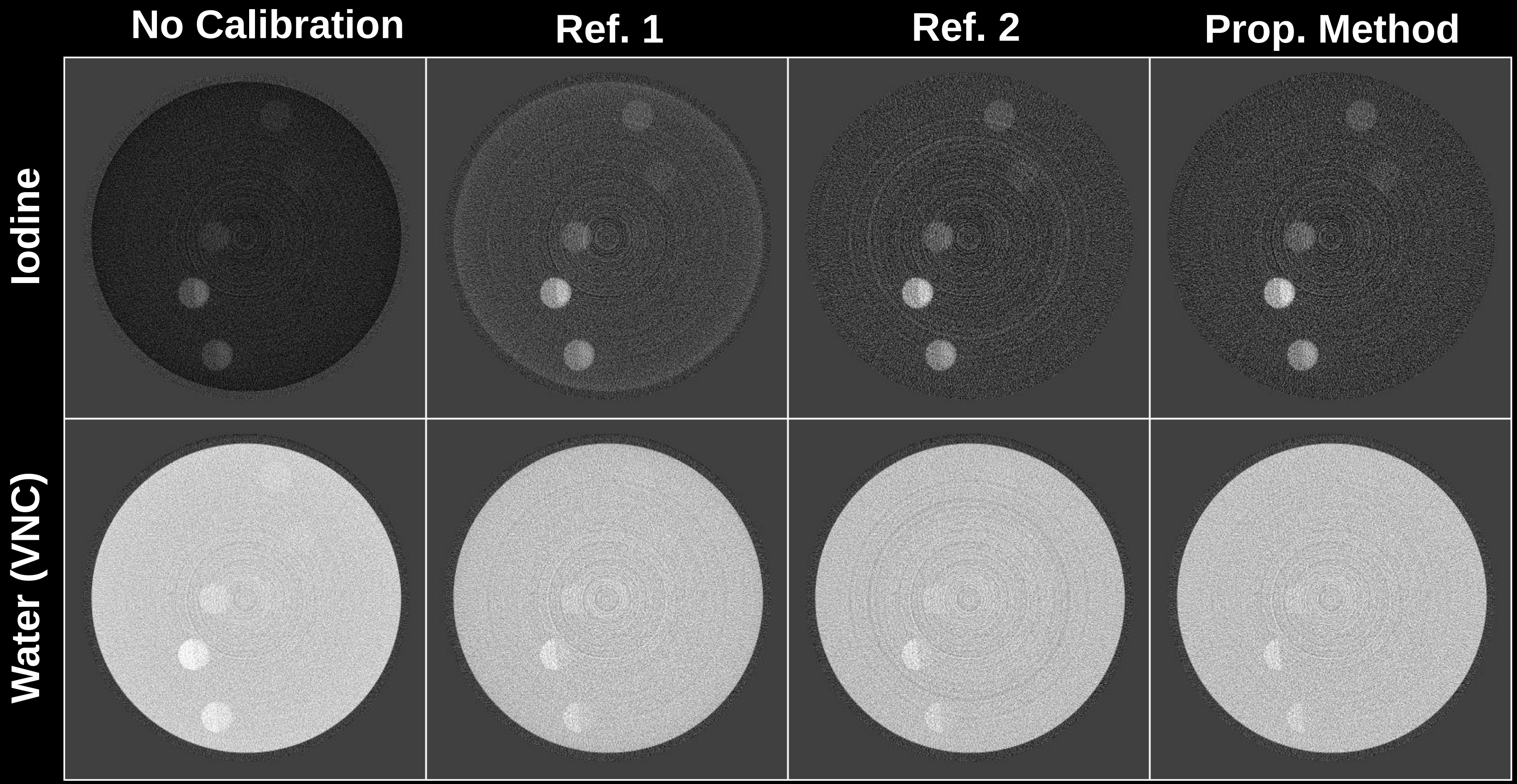


2 cm

Iodine ROI: 21.5 mg/mL
Water ROI: 0.6 mg/mL

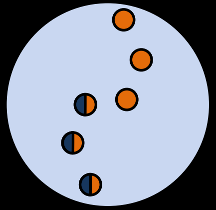
Phantom Measurements



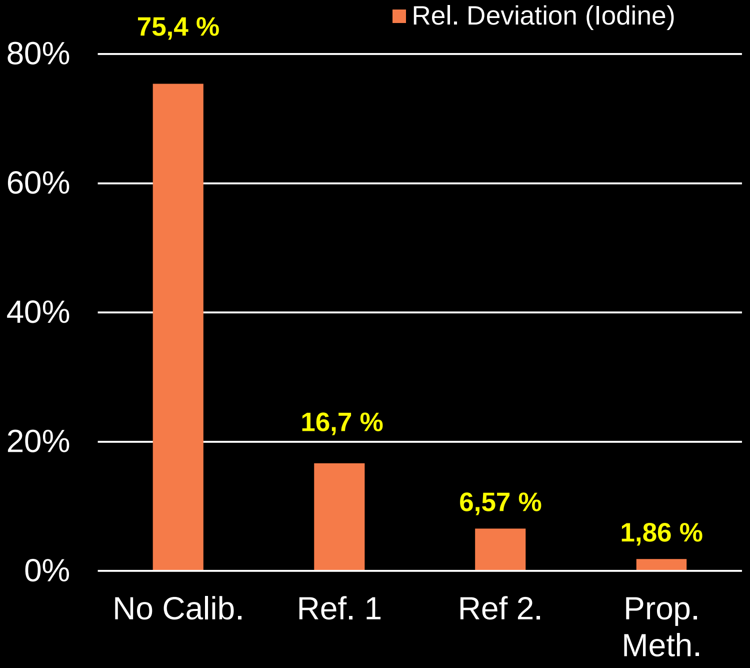


C = 10 mg/mL, *W* = 40 mg/mL
C = -500 HU, *W* = 2000 HU

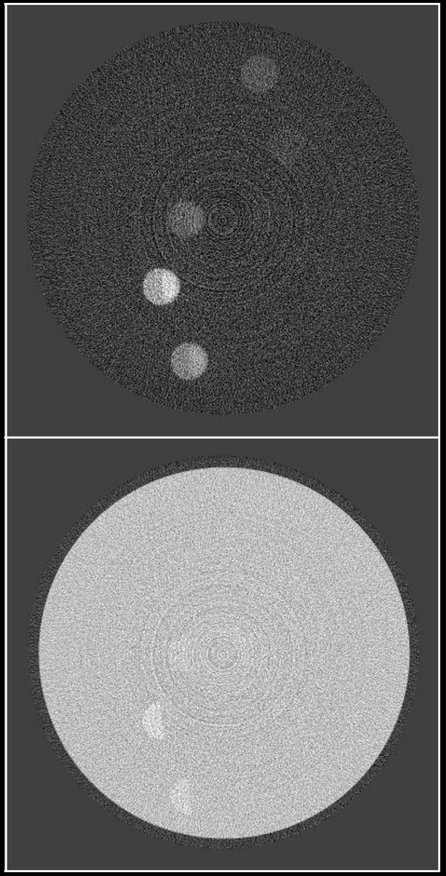
Phantom Measurements



Deviation from Reference Scan



Prop. Method



5 cm

C = 10 mg/mL, *W* = 40 mg/mL
C = -500 HU, *W* = 2000 HU

Conclusions

- The count rate-dependent spectral calibration can accommodate both for spectral distortions and count rate-dependent effects.
- Not only pulse pileup is count rate-dependent, also effects like scatter correlate with the local count rate.
- In measurements, artifacts in material images were down to noise level.
- Agreement with clinical CT system within 2% for iodine quantification.

Thank You!

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

The high-speed image reconstruction software RayConStruct®-IR was provided by RayConStruct GmbH, Nürnberg, Germany.

The prototype photon-counting x-ray detectors were provided by Dectris Ltd., Baden, Switzerland.