A new calibration-free beam hardening reduction method for industrial CT

ECC^2 for industrial CT

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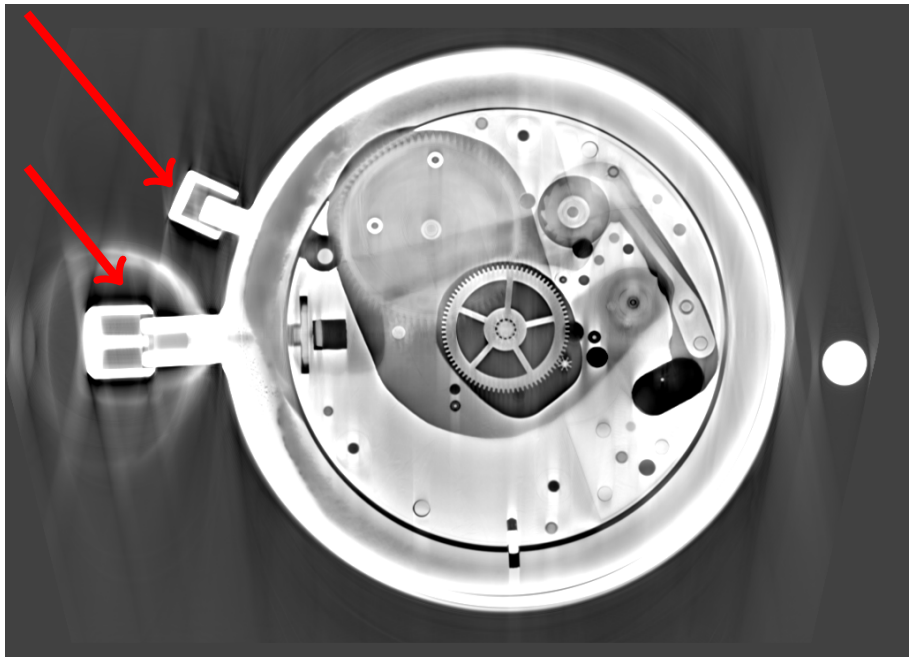
Beam Hardening

Standard Reconstruction

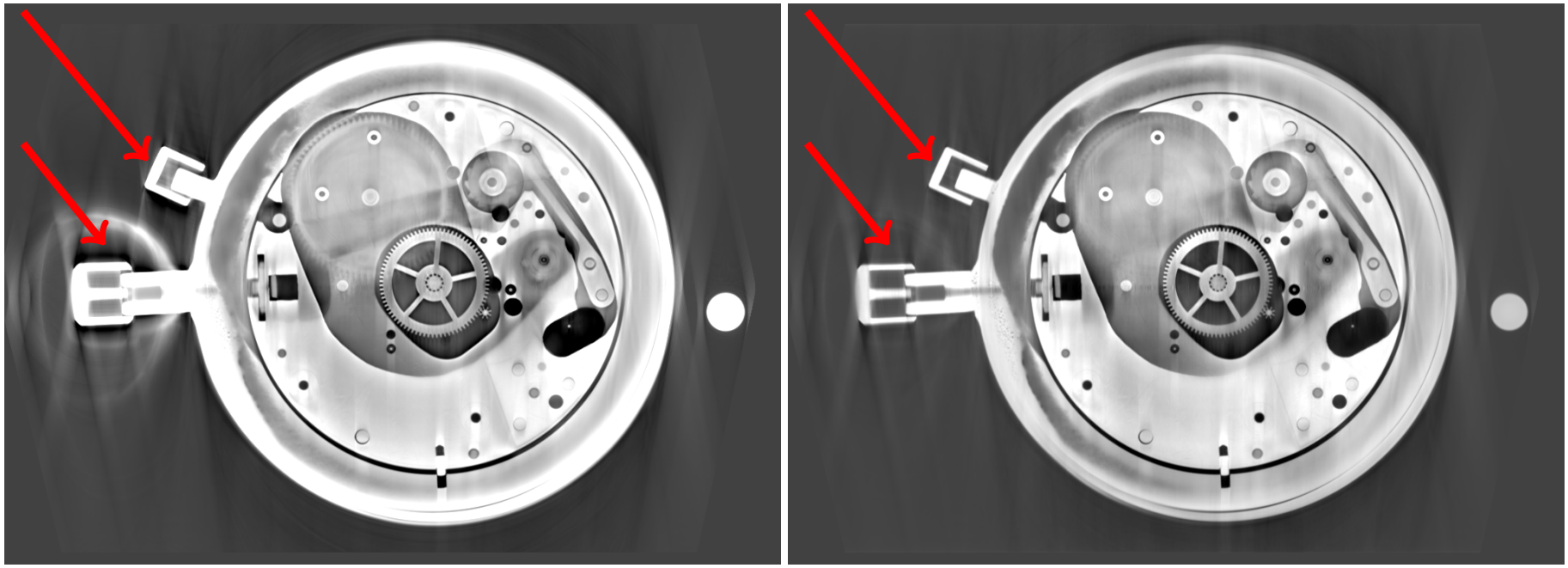


- Beam hardening appears when using polychromatic X-rays

➔ Causes artifacts like cupping and streaks

Beam Hardening

Standard Reconstruction | **Beam Hardening Reduced**



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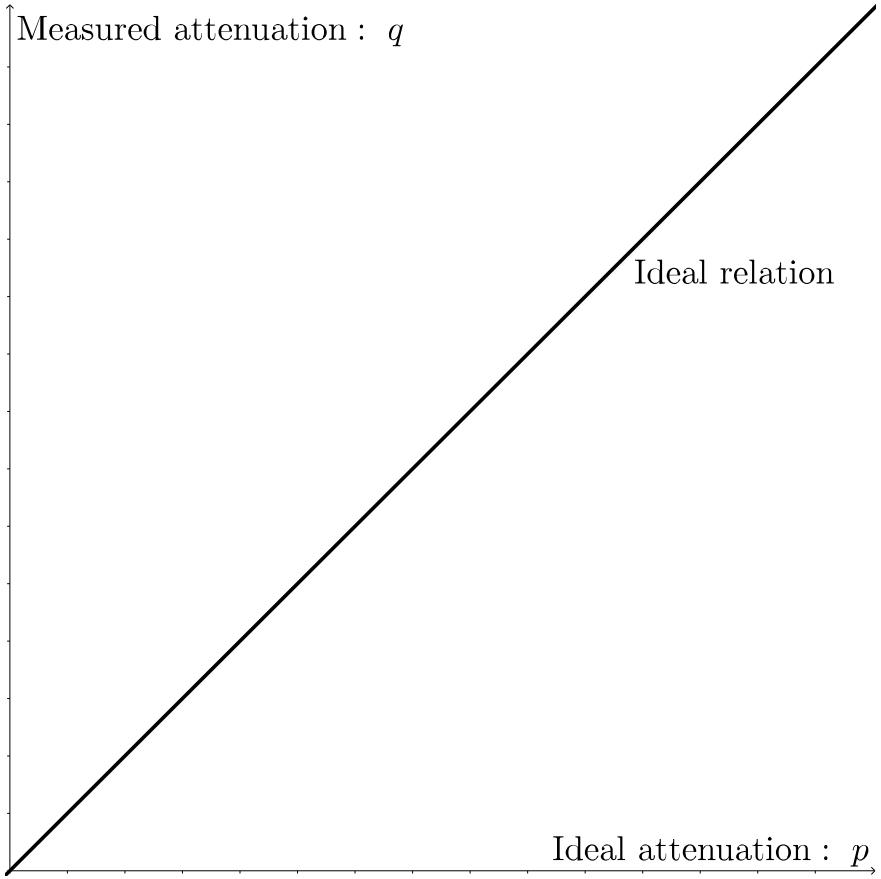
➔ Causes artifacts like cupping and streaks

- Can be reduced by software methods

Artifact Reduction

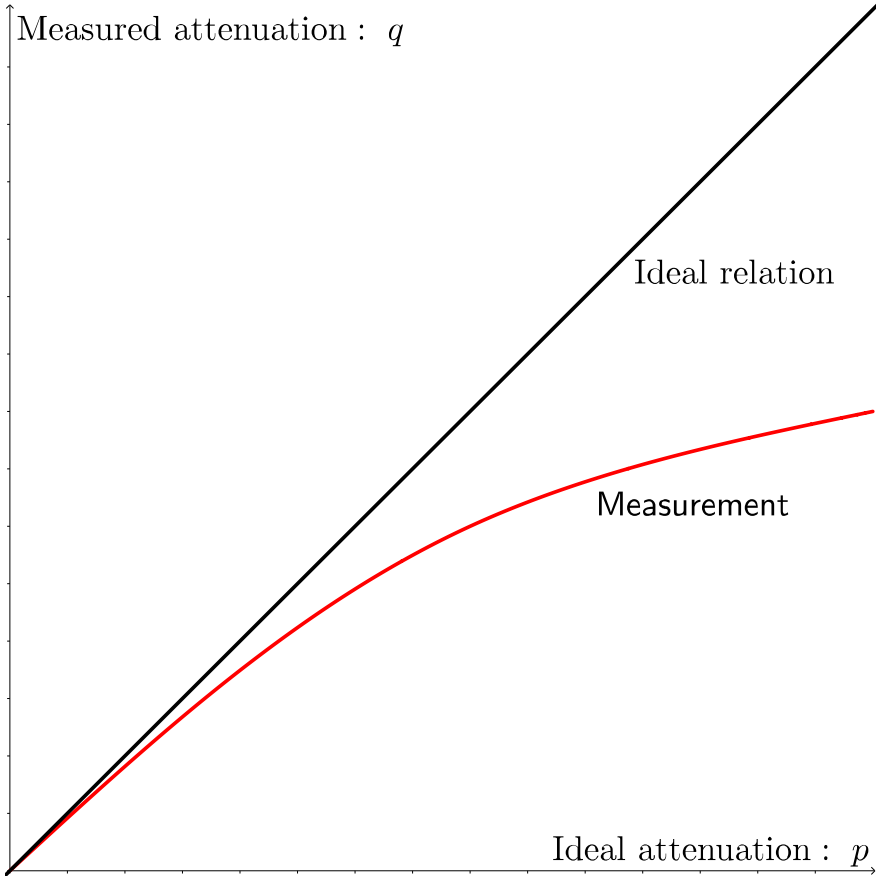
Mono material compensation



Artifact Reduction

Mono material compensation

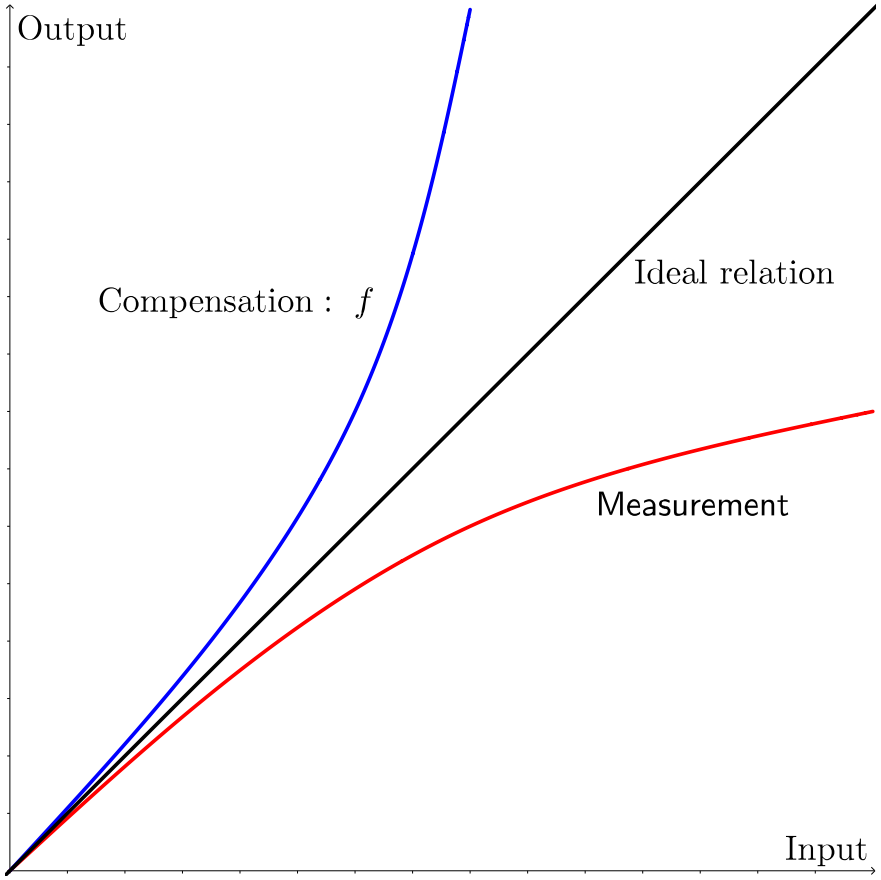
- Well posed function inversion problem
- Function can be obtained by **material** absorption properties



Artifact Reduction

Mono material compensation

- Well posed function inversion problem
- Function can be obtained by **material** absorption properties
- Compensation function can be obtained
  - by inversion of the function
  - by direct fitting



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➔ Achieve competitive image quality based on measurement itself

Reference-free Algorithms

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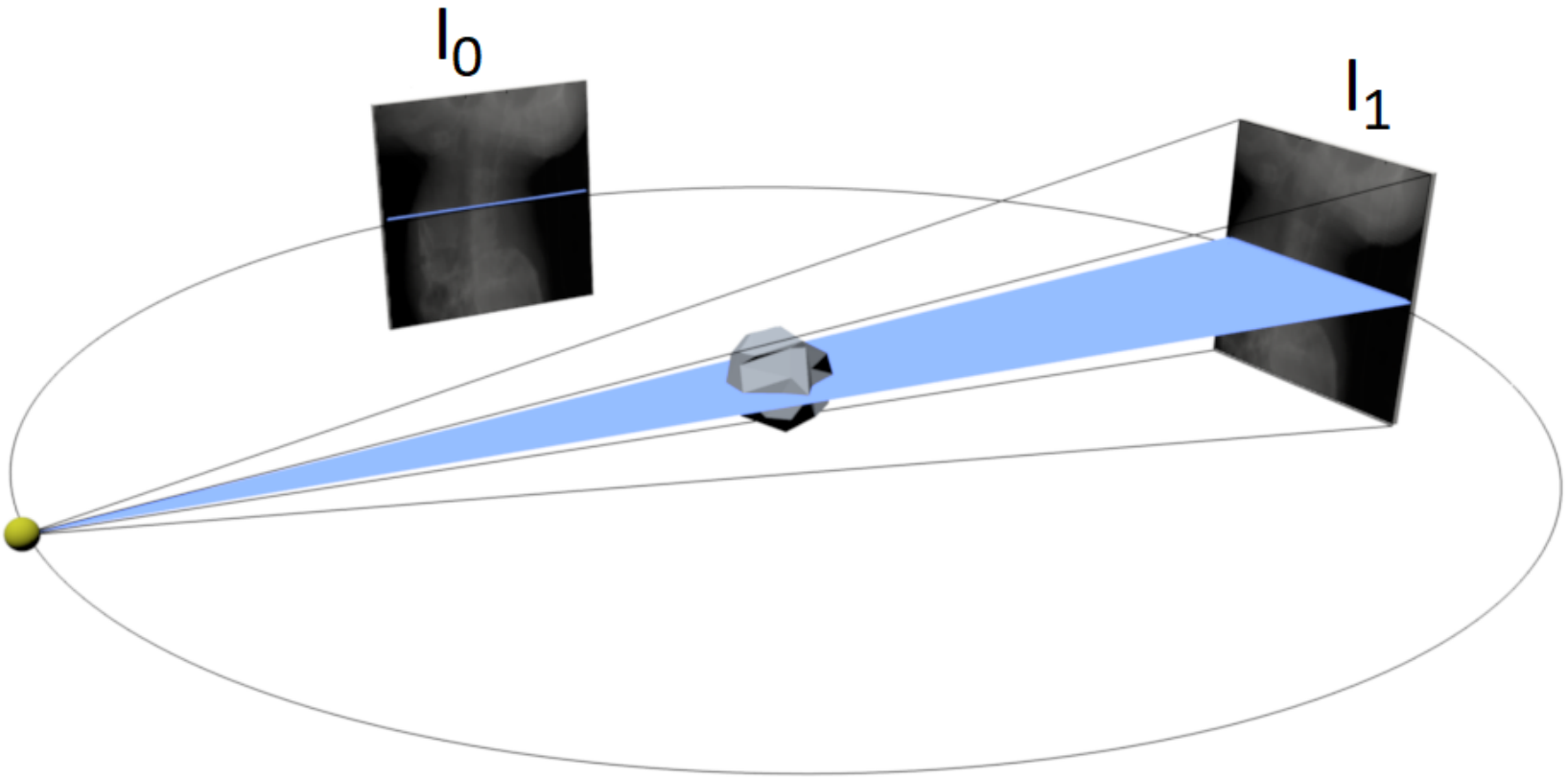
- Iterative algorithms with a realistic forward model
  - ➔ are even more computationally expensive
  - ➔ rely on tuning of parameters
- Projection-based consistency conditions
  - do not need reconstruction ➔ computationally efficient
  - ➔ are mathematically well founded
  - ➔ are available for cone-beam geometry [1]

➔ We use the Epipolar Consistency Condition (ECC) [3]

- Algorithm introduced in

  T. Würfl, N. Maaß, F. Dennerlein, X. Huang, and A. Maier, "Epipolar Consistency Guided Beam Hardening Reduction - ECC^2", in *Fully Three-Dimensional Image Reconstruction in Radiology and Nuclear Medicine*, G. Wang and X. Mou, Eds., 2017, pp. 181–185

Epipolar Geometry



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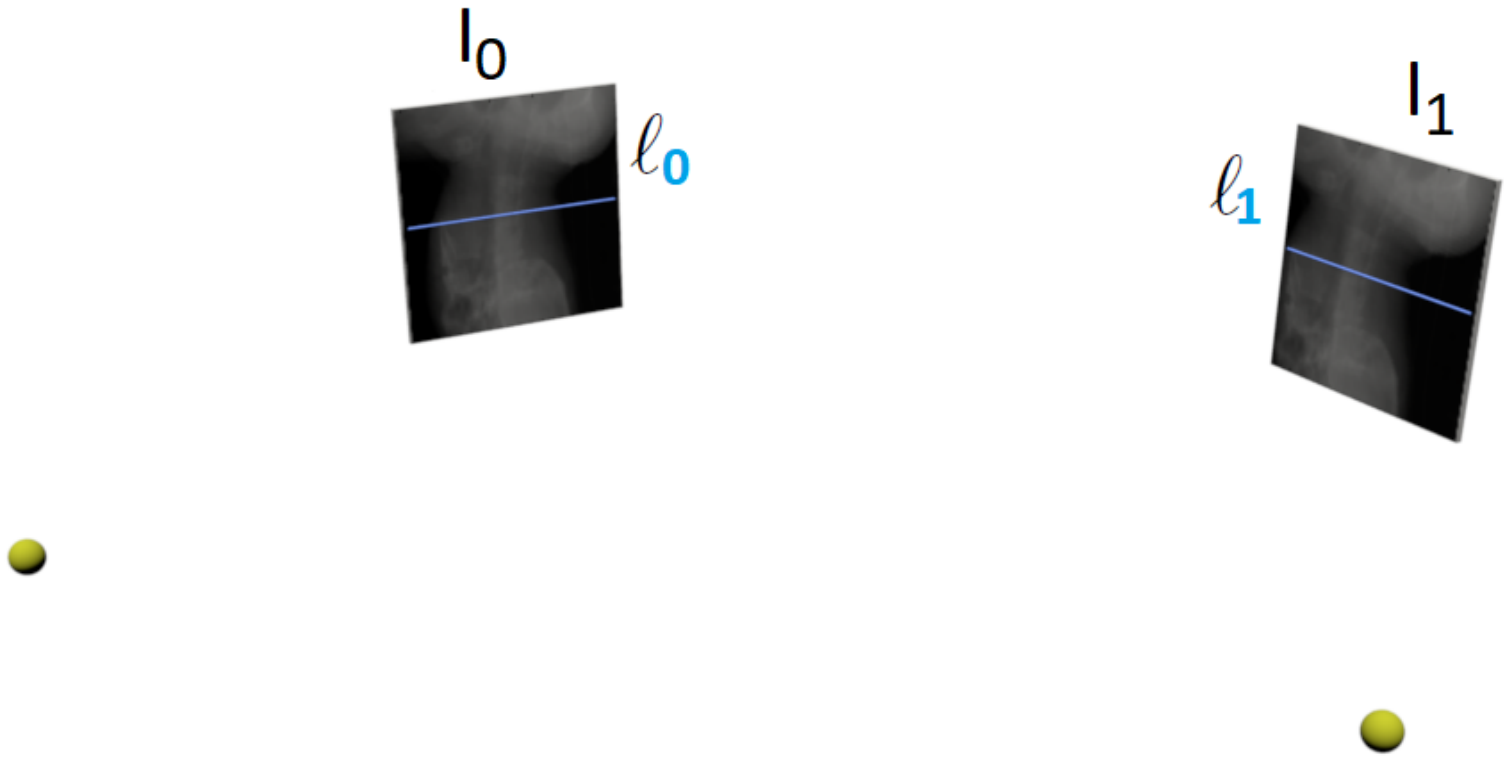

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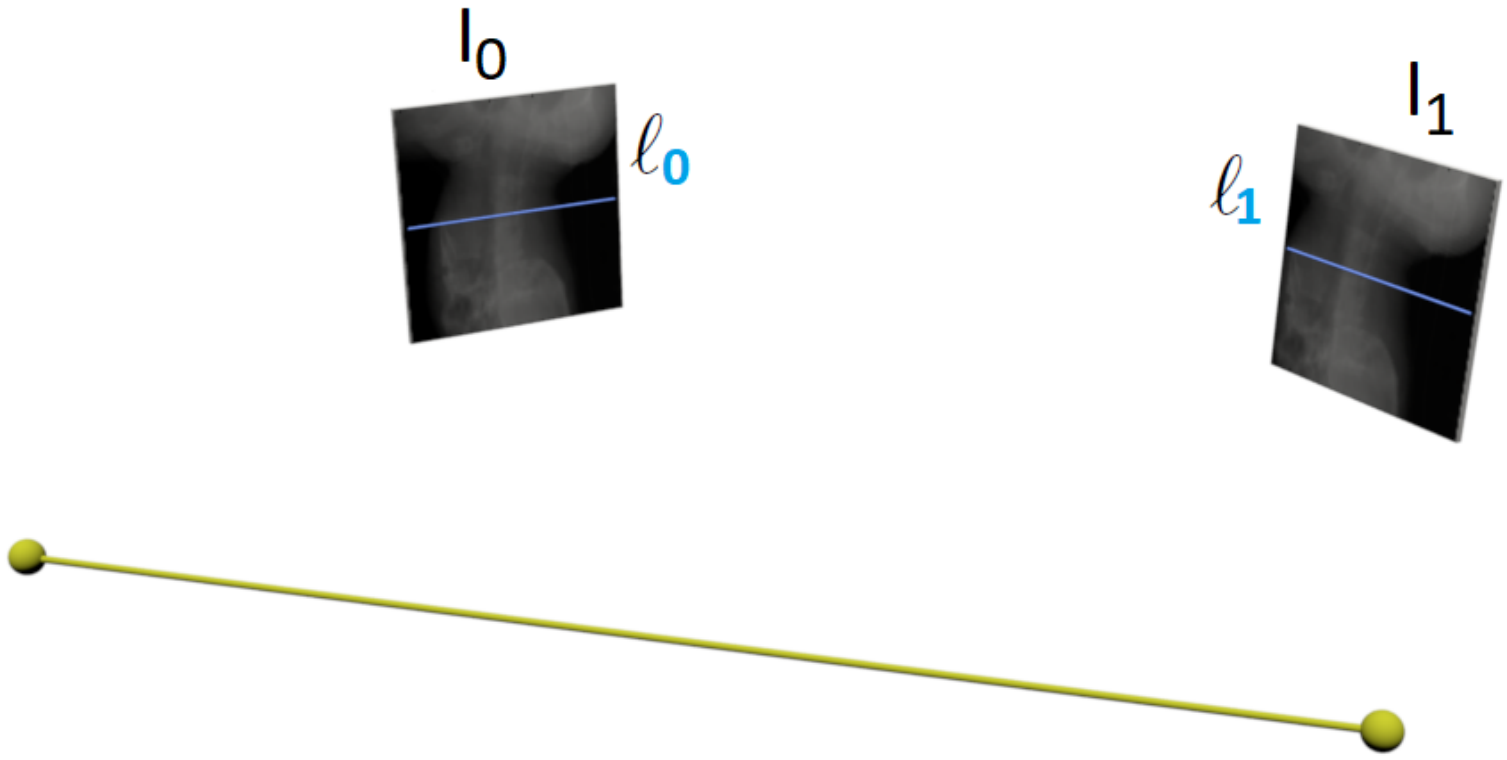

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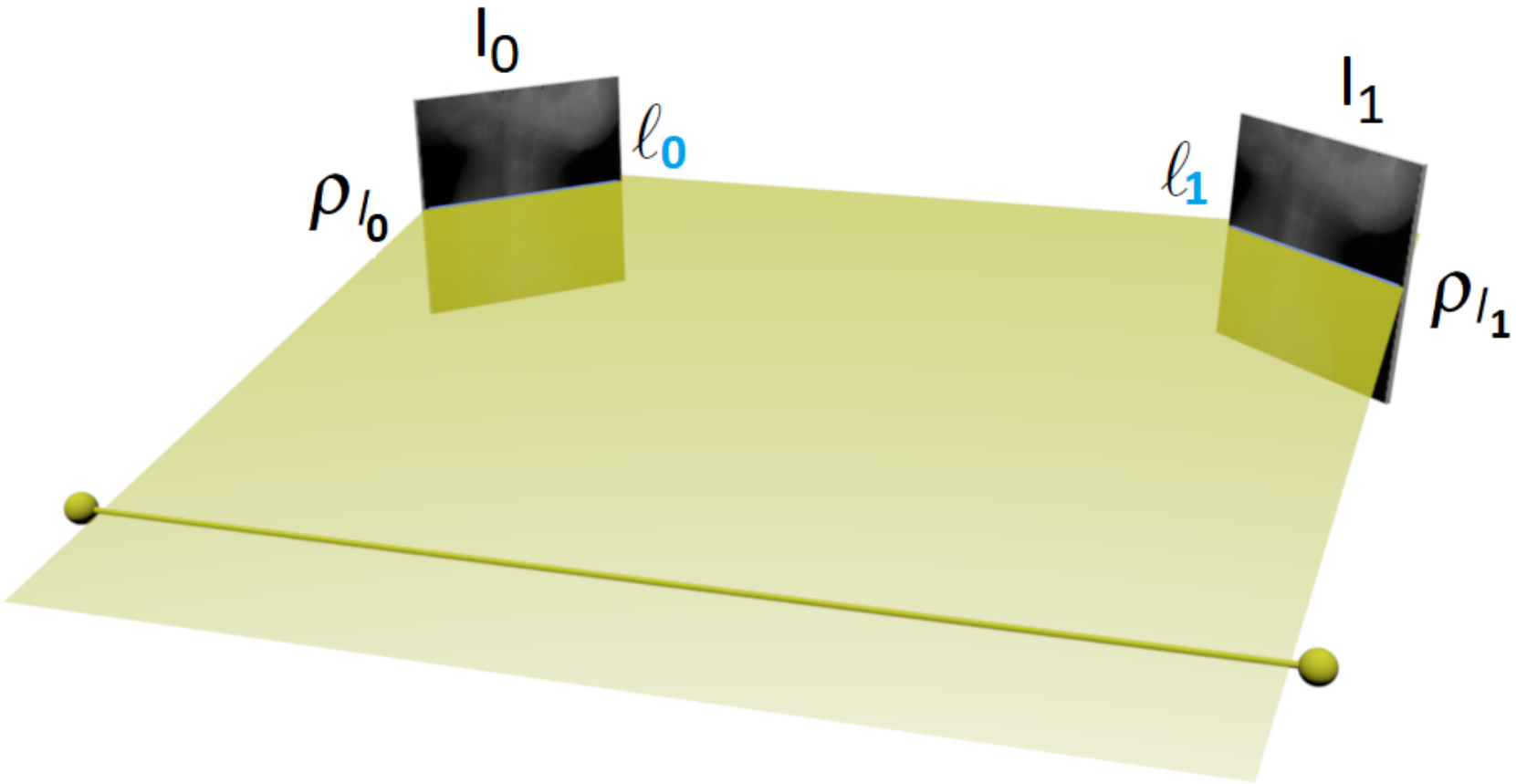

Epipolar Consistency

- Plane integrals $\rho_{\mathbf{l}}(\ell)$ can only be obtained in 3D parallel beam geometry
- In cone-beam geometry only their derivatives $\frac{\partial}{\partial t}\rho_{\mathbf{l}}(\ell)$ can be obtained
- Multiple measurements of the same plane integral derivative should be equal:

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→Inequality shows data inconsistency and serves as cost function

- We need a suitable model for beam hardening reduction
- **Polynomial model** adapted from [2]

$$f(q, \mathbf{w}) = \sum_{n=1}^{N} w_n q^n, \quad w \geq 0 \quad \forall w \in \mathbf{w}$$

- **Linear** in its parameters
- The constraint on the coefficients enforces **monotone** and **convex** solutions

ECC^2 - Epipolar Consistency Condition * Empirical Cupping Correction

- Use the **linearity** of Radon transform and derivative operator:

$$\sum_{n=1}^{N} w_n \left(\frac{\partial}{\partial t} \rho_{\mathbf{I}_0^n}(\ell_0) \right) \approx \sum_{n=1}^{N} w_n \left(\frac{\partial}{\partial t} \rho_{\mathbf{I}_1^n}(\ell_1) \right) + e$$

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- For one projection pair $\{\mathbf{I}_0, \mathbf{I}_1\}$ and one epipolar line set $\{\ell_0, \ell_1\}$:

$$e = \sum_{n=1}^{N} w_n a_n \quad \text{with: } a_n = \left(\frac{\partial}{\partial t} \rho_{\mathbf{I}_0^n}(\ell_0) - \frac{\partial}{\partial t} \rho_{\mathbf{I}_1^n}(\ell_1) \right)$$

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- Considering many projection pairs and epipolar lines produces M such equations:

$$\min \left(\|\mathbf{A}\mathbf{w}\|_2^2 \right) \quad \text{s.t. } \mathbf{w}^T \mathbf{b} = \beta \,, \quad w \geq 0 \quad \forall\, w \in \mathbf{w}$$

- b and β determine the **effective energy**
- Solved by general-purpose non-linear optimizer, supporting constraints, e.g. Method of Moving Asymptotes (MMA)[5]

Evaluation of ECC^2 for Industrial CT

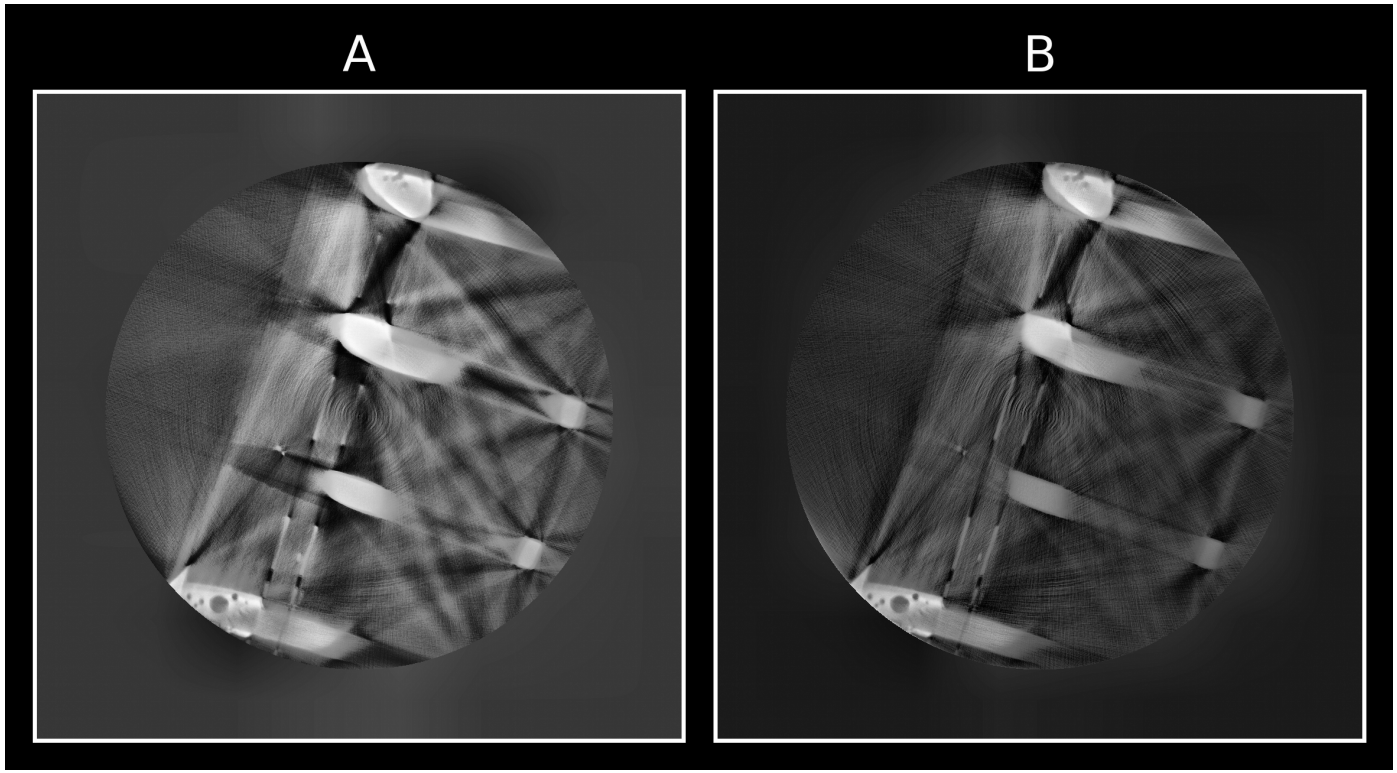

Figure: Example from the user study.

- **Comparison** to **manual** optimization using 3 reduction strength presets

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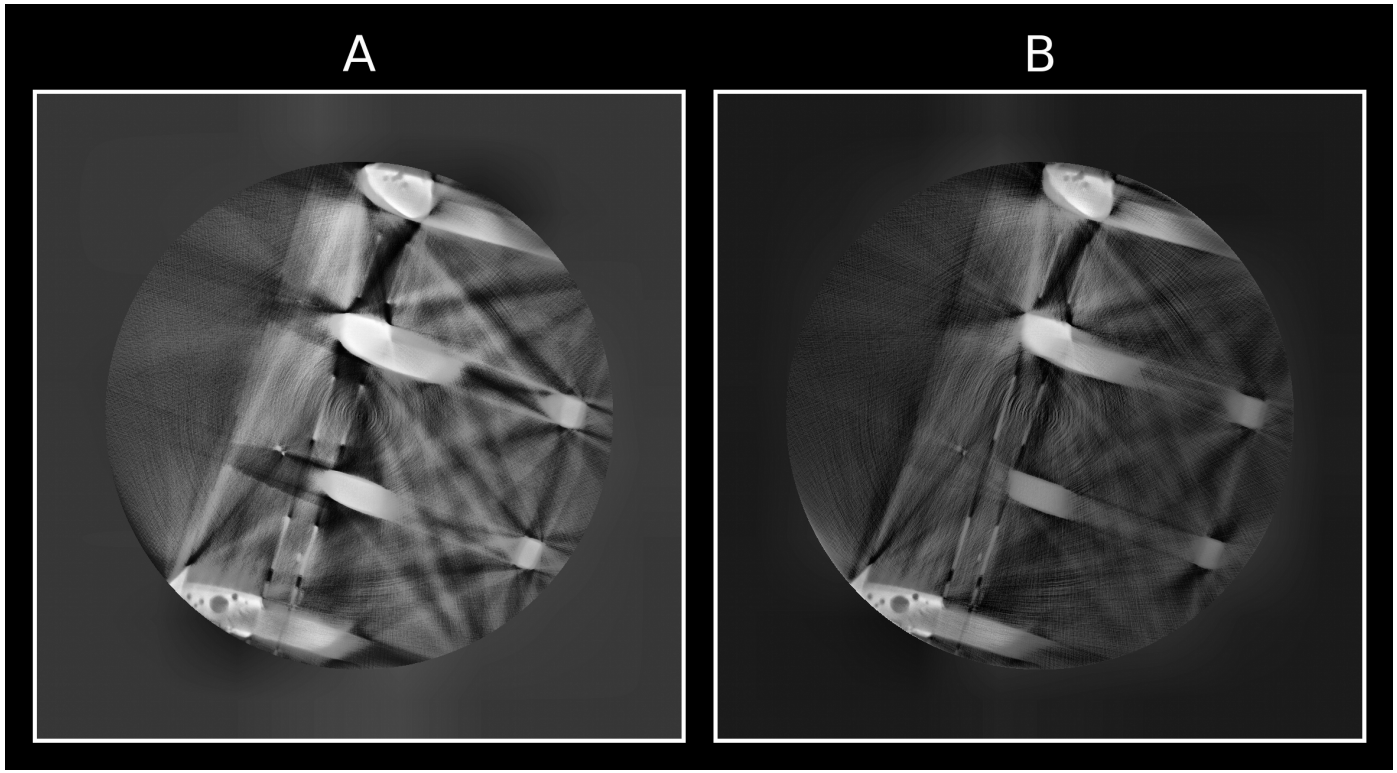
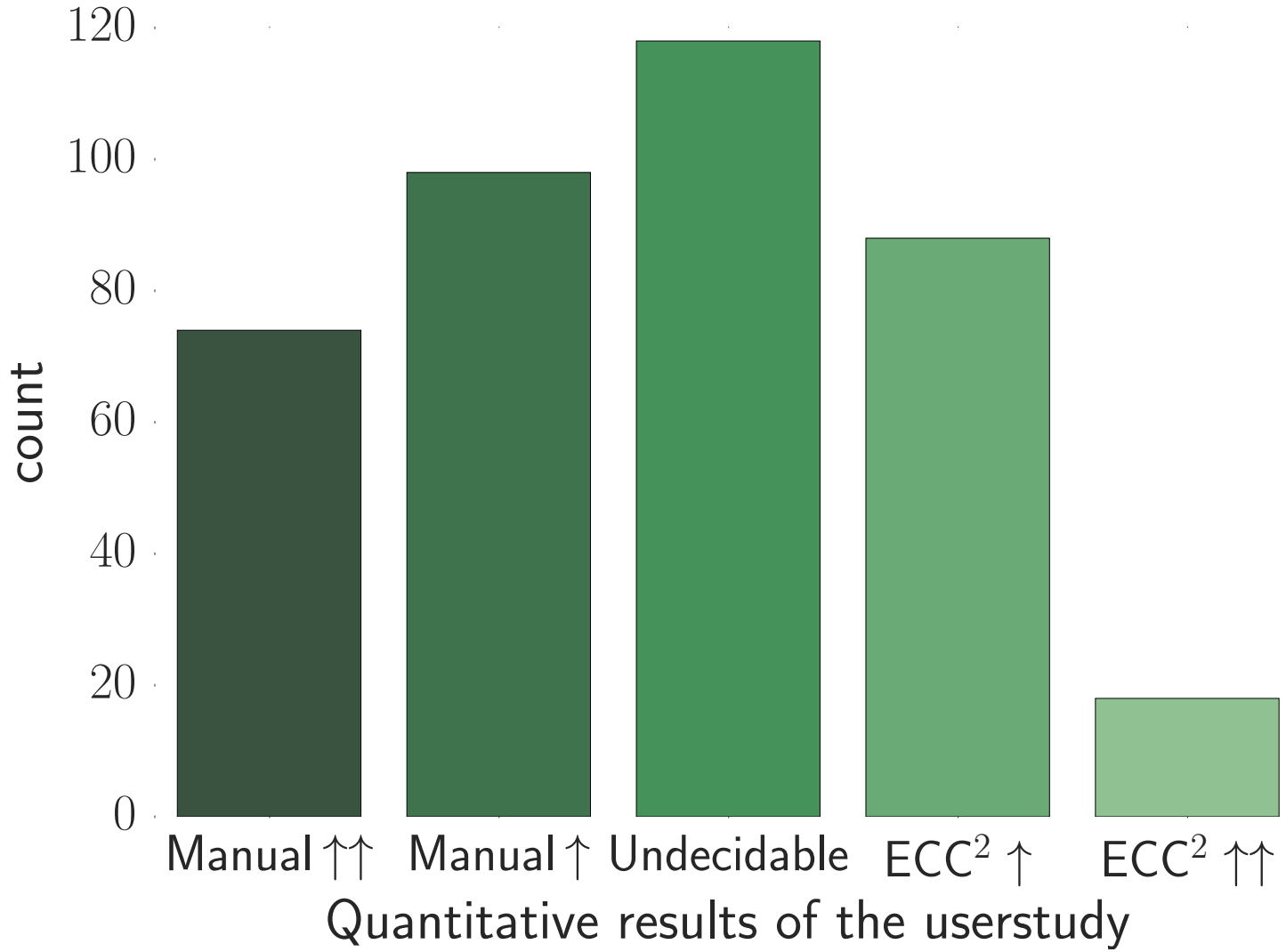


Figure: Example from the user study. B is the result using ECC^2.

- **Comparison** to **manual** optimization using 3 reduction strength presets
- User study conducted as a **randomized**, **blind** A-B test; **5 ordinal** levels
- **Ten** CT expert raters, three from an industrial CT background
- **40 diverse datasets**: Circuit board, metal stopwach, capacitor ...

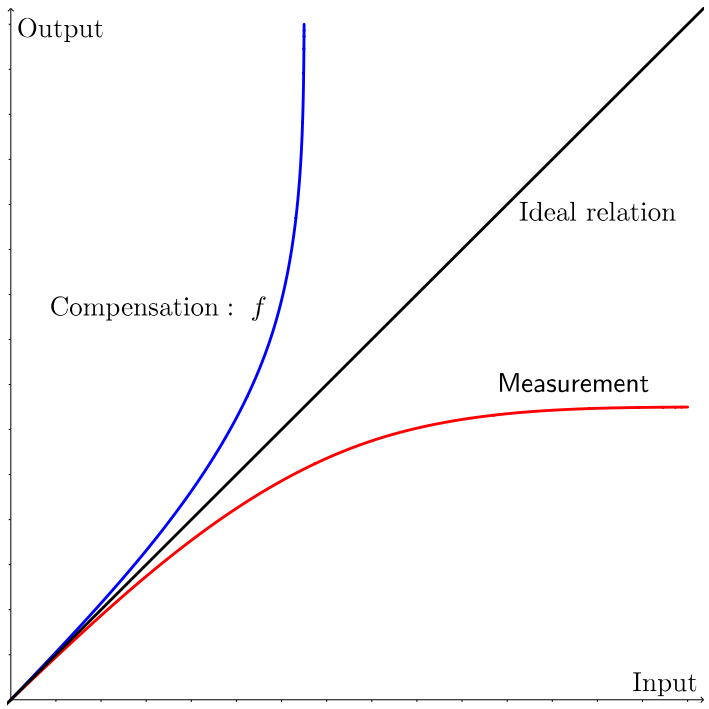
Results


120
100
80
60
40
20
0
count
Manual ↑↑
Manual ↑
Undecidable
ECC² ↑
ECC² ↑↑
Quantitative results of the userstudy

Photon Starvation

- Most common problem in low quality results
- Vanishing slope leads to an infinite slope in the inverse function

➔ ECC^2 overestimates beam hardening



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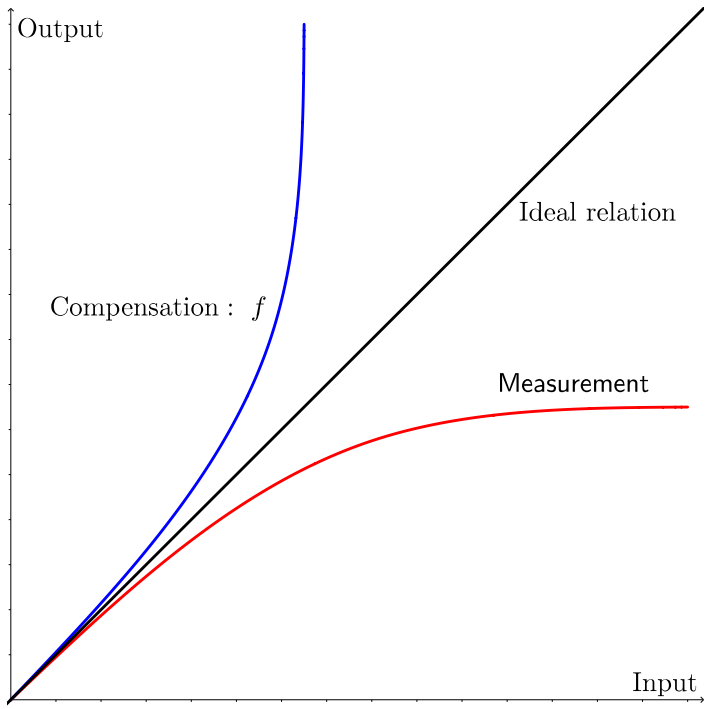
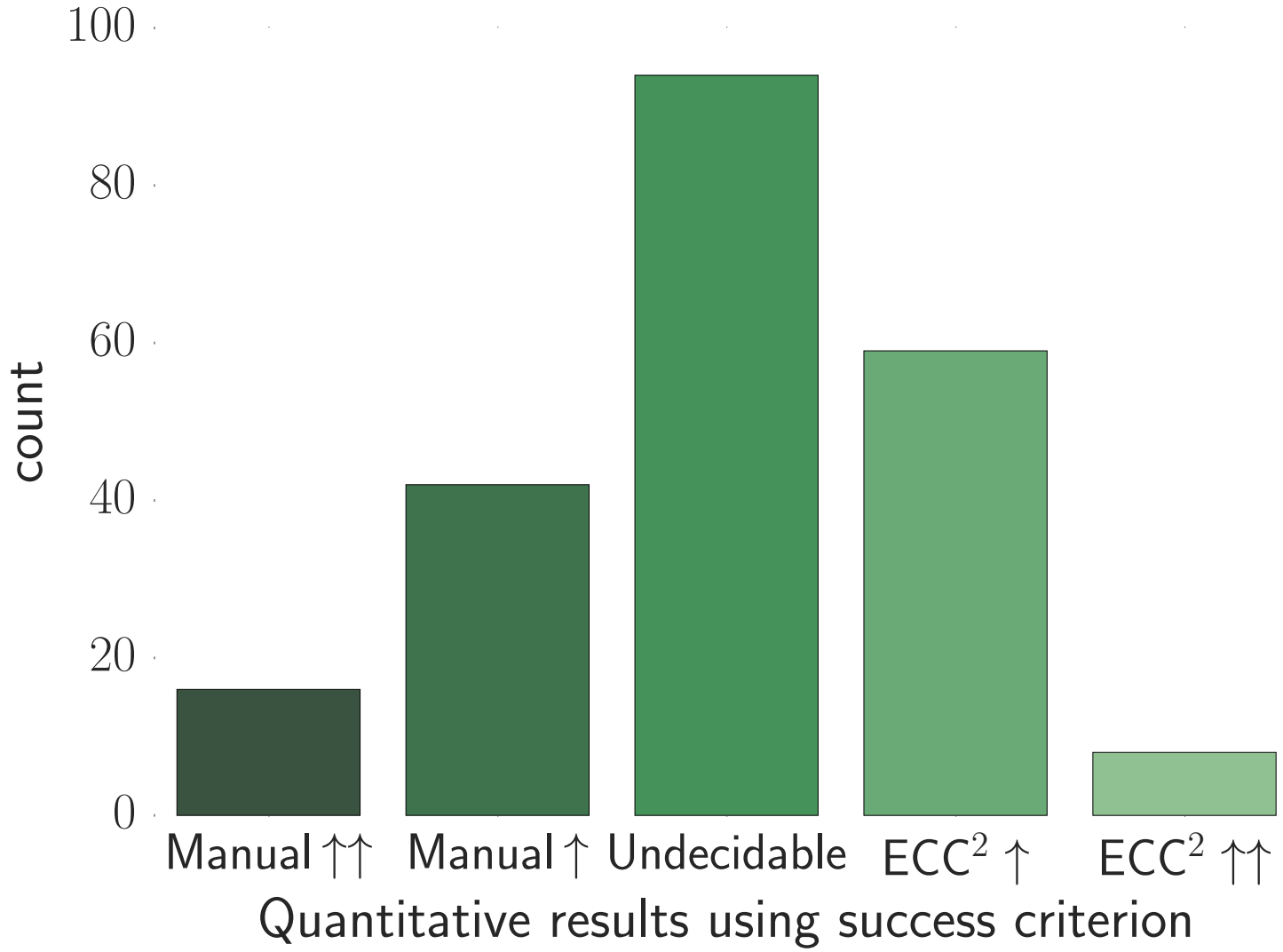


Success criterion

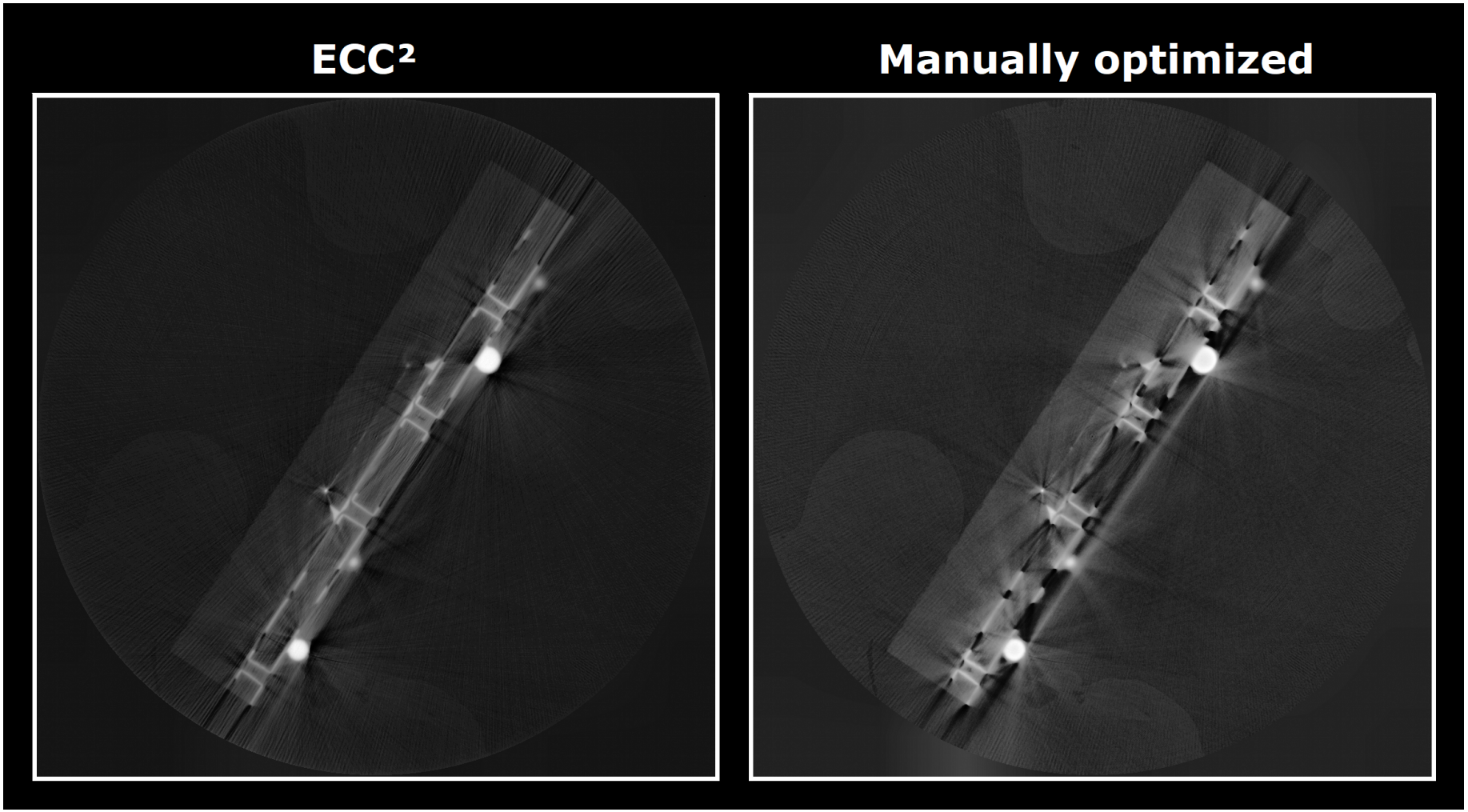
- Can be detected because the maximum possible curvature is estimated
- Equivalent to the coefficient w_N being the only non-zero component

➔ Mark those results as failure cases

Results Using the Success Criterion



Example Result



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Outlook

- Increase **robustness** to photon starvation
- Extend to the **multi-material** scenario
- Reduce **scatter** using a consistency-based algorithm

Thanks for listening.

Any questions?

References I

[1] C. Debbeler, N. Maaß, M. Elter, F. Dennerlein, and T. M. Buzug, "A new ct rawdata redundancy measure applied to automated misalignment correction", in *Fully Three-Dimensional Image Reconstruction in Radiology and Nuclear Medicine*, 2013, pp. 264–267.

[2] M. Kachelrieß, K. Sourbelle, and W. A. Kalender, "Empirical cupping correction: A first-order raw data precorrection for cone-beam computed tomography", *Medical Physics*, vol. 33, no. 5, pp. 1269–1274, 2006.

[3] A. Aichert, M. Berger, J. Wang, *et al.*, "Epipolar consistency in transmission imaging", *IEEE Transactions on Medical Imaging*, vol. 34, no. 11, pp. 2205–2219, 2015.

[4] T. Würfl, N. Maaß, F. Dennerlein, X. Huang, and A. Maier, "Epipolar Consistency Guided Beam Hardening Reduction - ECC^2", in *Fully Three-Dimensional Image Reconstruction in Radiology and Nuclear Medicine*, 2017, pp. 181–185.

References II

[5] K. Svanberg, “The method of moving asymptotes-a new method for structural optimization”, *International journal for numerical methods in engineering*, vol. 24, no. 2, pp. 359–373, 1987.