

A comparison of direct reconstruction algorithms in proton CT

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List-mode proton CT for most-likely path (MLP) estimation

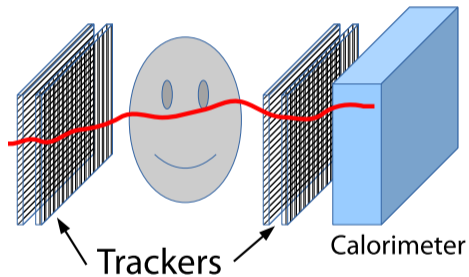


Figure from [Krah et al., 2018]

Direct reconstruction algorithms based on filtered backprojection

- Filtering according to the distance to a straight line [Cirrone et al., 2011],
- Distance driven binning [Rit et al., 2013],
- Backprojection then filtering [Poludniowski et al., 2014],
- Differentiated backprojection [Rit et al., 2015],
- Maximum likelihood high resolution radiographies [Collins-Fekete et al., 2016],
- Directional ramp filter (new).

Iterative reconstruction algorithms

- ART [Li et al., 2006],
- Total variation superiorization [Penfold et al., 2010], DROP [Penfold, 2010],
- Statistical reconstruction [Hansen, 2014],
- ...

Comparison of reconstruction algorithms

Existing comparisons between

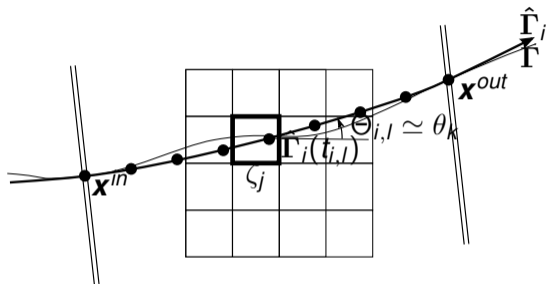
- iterative algorithms [Penfold and Censor, 2015]
- iterative algorithms + one direct algorithm [Hansen et al., 2016].

Comparison of 4 direct reconstruction algorithms from simulated data:

- Distance driven binning [Rit et al., 2013],
- Backprojection then filtering [Poludniowski et al., 2014],
- Differentiated backprojection [Rit et al., 2015],
- Directional ramp filter (new).

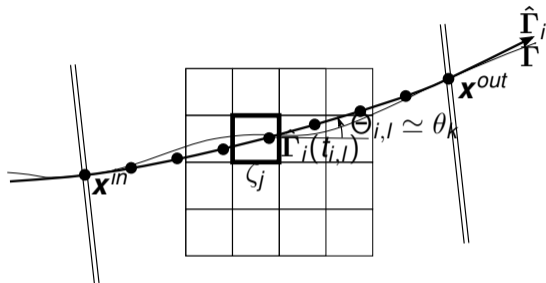
- Monte Carlo simulations with Gate [Jan et al., 2011] (based on Geant4 [Agostinelli et al., 2003])
- Most likely path estimation of [Schulte et al., 2008]
- Two phantoms for the assessment of the spatial resolution [Rit et al., 2013]
 - Catphan resolution phantom
 - Water cylinder with inserts at different depths

Backprojection/binning in list-mode pCT



- Discretize space, voxel index j
- Discretize directions, direction index k
- Sample the most-likely path $\hat{\Gamma}_i$, position index l

Backprojection/binning in list-mode pCT

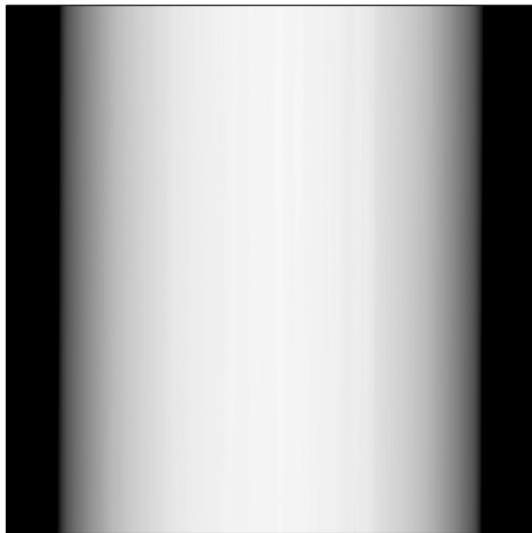


- Average measurement $b_{j,k}$ of protons going through the same voxel j with the same direction k according to their most-likely path

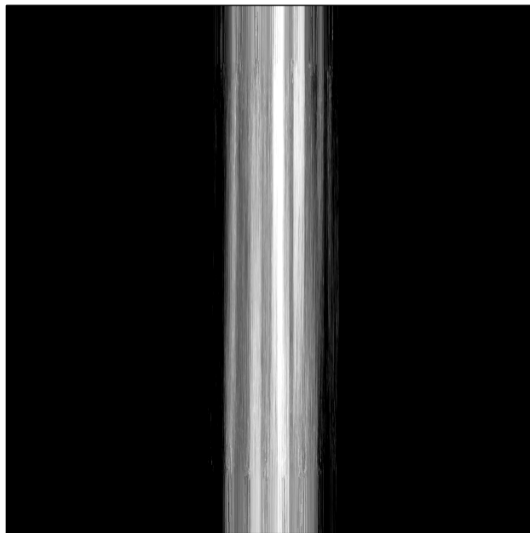
$$b_{j,k} = \frac{\sum_{i,l} \zeta_j(\hat{\Gamma}_i(t_{i,l})) \xi_k(\Theta_{i,l}) g_i}{\sum_{i,l} \zeta_j(\hat{\Gamma}_i(t_{i,l})) \xi_k(\Theta_{i,l})} \quad (1)$$

Backprojection/binning in list-mode pCT

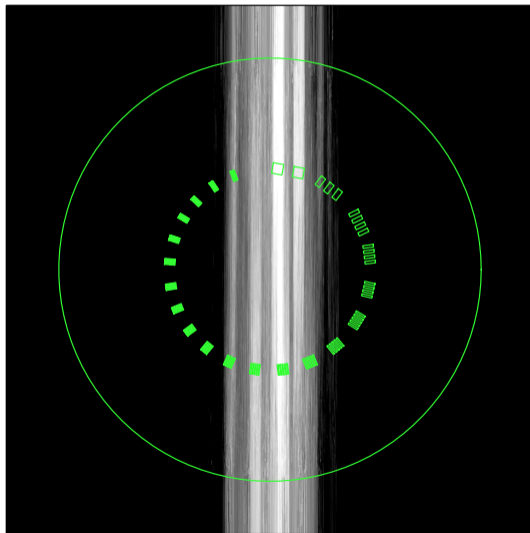
Backprojection/binning in list-mode pCT



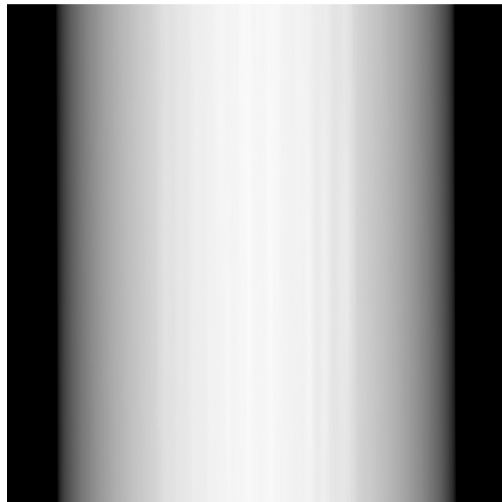
Backprojection/binning in list-mode pCT



Backprojection/binning in list-mode pCT

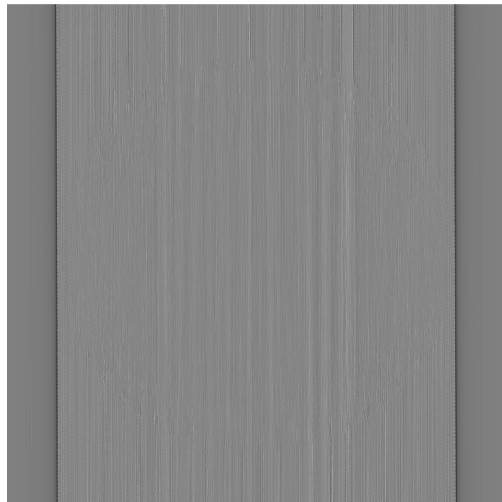


- Backprojection/binning of each direction on a grid parallel to the detector,



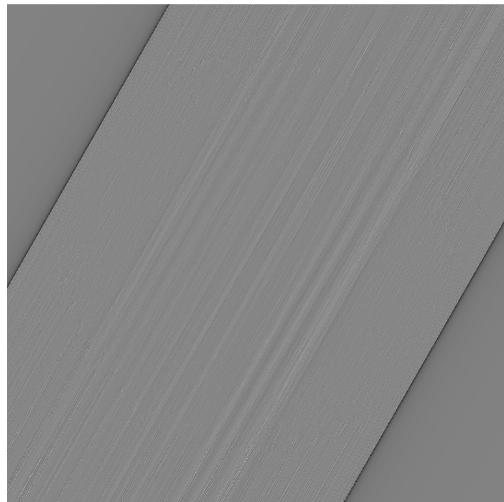
Distance driven binning [Rit et al., 2013]

- Backprojection/binning of each direction on a grid parallel to the detector,
- Ramp filtering of each line,



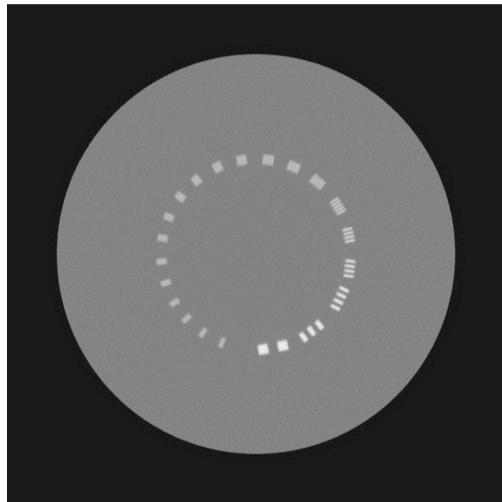
Distance driven binning [Rit et al., 2013]

- Backprojection/binning of each direction on a grid parallel to the detector,
- Ramp filtering of each line,
- Rotate,



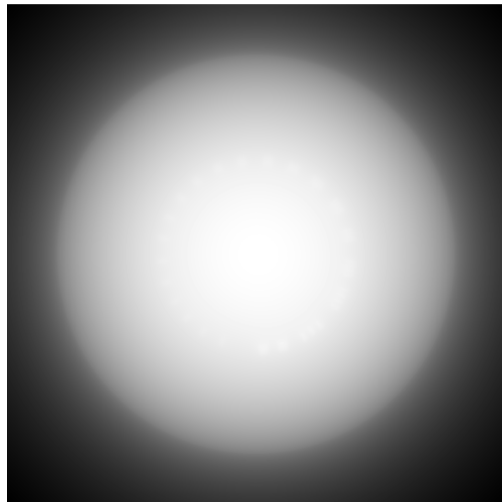
Distance driven binning [Rit et al., 2013]

- Backprojection/binning of each direction on a grid parallel to the detector,
- Ramp filtering of each line,
- Rotate,
- Sum.



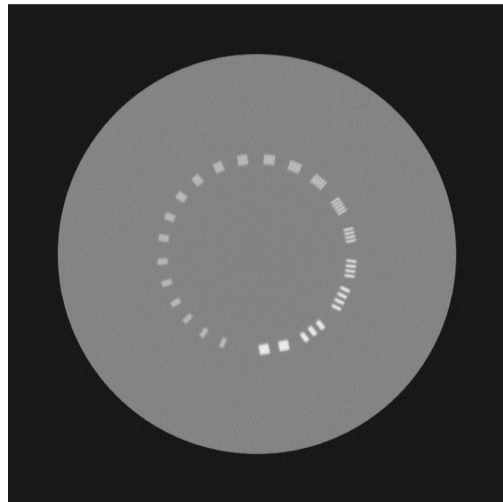
Backprojection then filtering [Poludniowski et al., 2014]

- Sum all directions of the backprojection/binning,



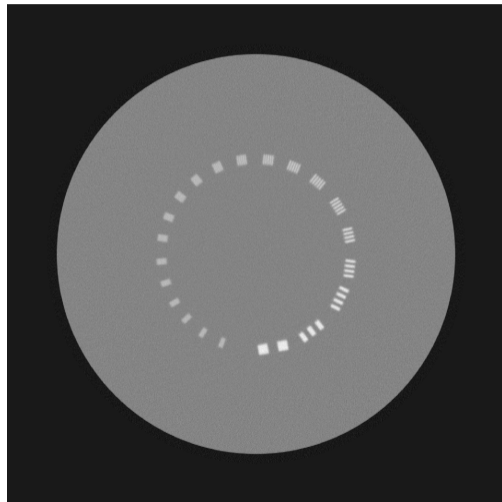
Backprojection then filtering [Poludniowski et al., 2014]

- Sum all directions of the backprojection/binning,
- 2D filtering,



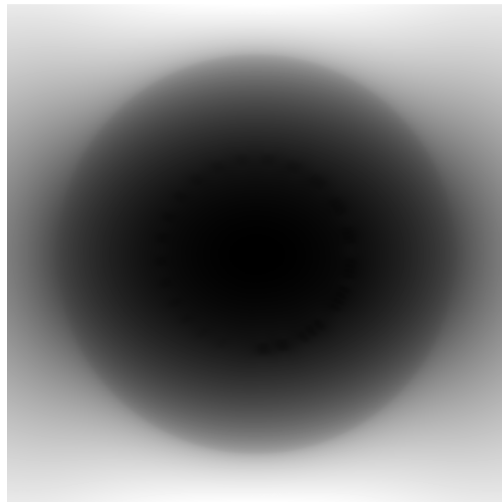
Backprojection then filtering [Poludniowski et al., 2014]

- Sum all directions of the backprojection/binning,
- 2D filtering,
- Correction of DC offset (truncated backprojection).



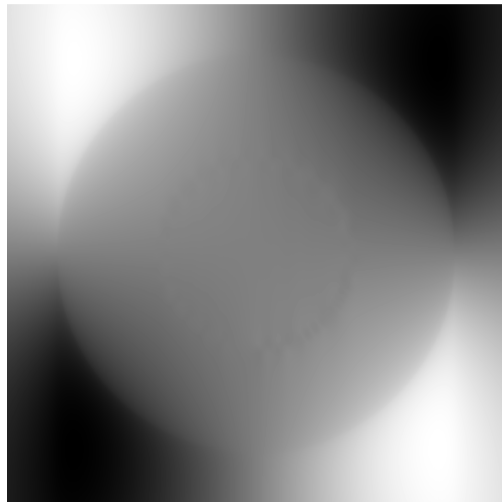
Based on [Zeng, 2007]

- Two weighted sum of the backprojection/binning,



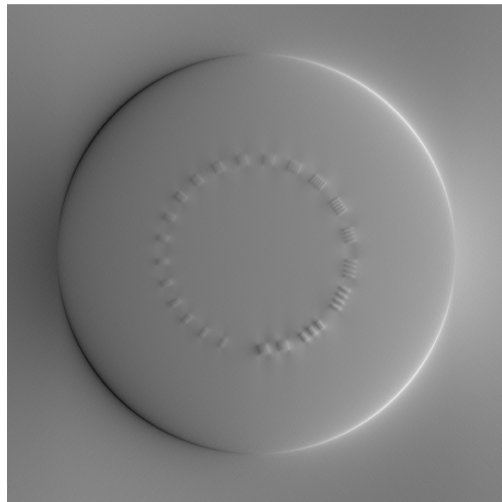
Based on [Zeng, 2007]

- Two weighted sum of the backprojection/binning,



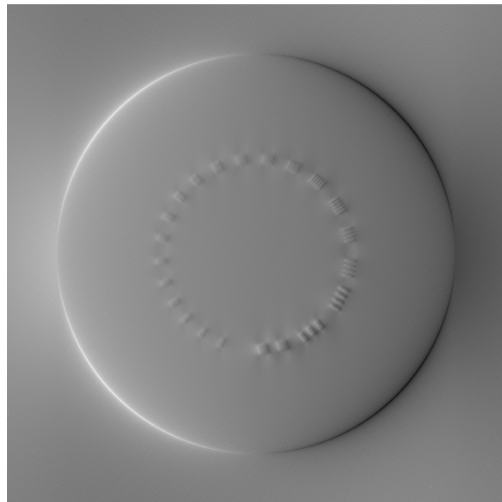
Based on [Zeng, 2007]

- Two weighted sum of the backprojection/binning,
- Derivatives along lines / columns,



Based on [Zeng, 2007]

- Two weighted sum of the backprojection/binning,
- Derivatives along lines / columns,



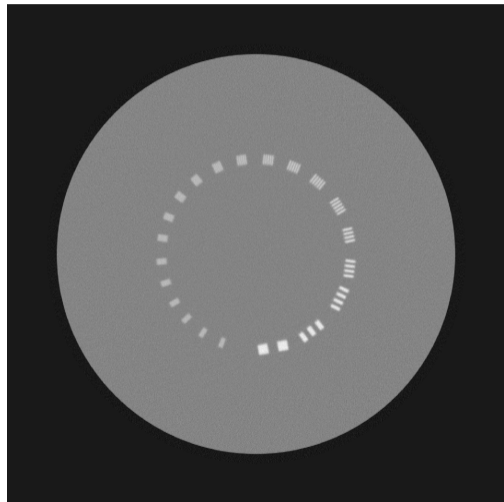
Based on [Zeng, 2007]

- Two weighted sum of the backprojection/binning,
- Derivatives along lines / columns,
- Sum and finite Hilbert inverse.



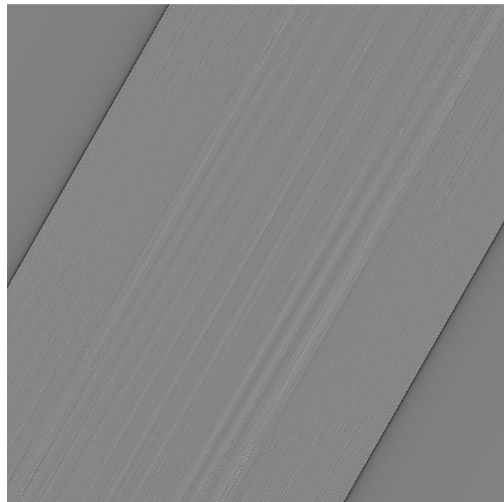
Based on [Zeng, 2007]

- Two weighted sum of the backprojection/binning,
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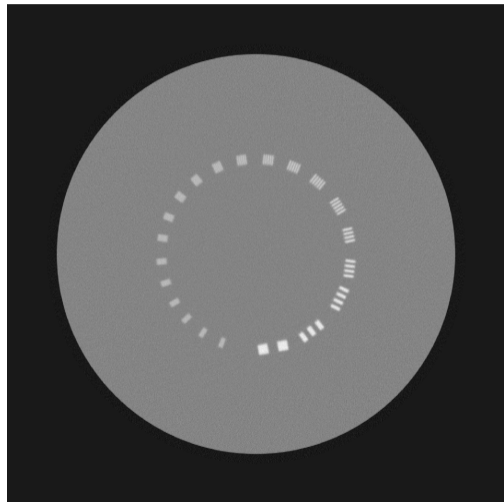
Directional ramp filter

- Ramp filtering each direction of the backprojection/binning in an oblique direction,



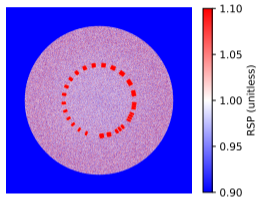
Directional ramp filter

- Ramp filtering each direction of the backprojection/binning in an oblique direction,
- Sum.

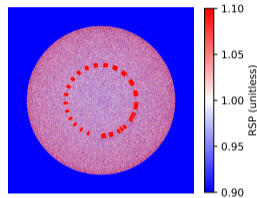


Results: spatial resolution

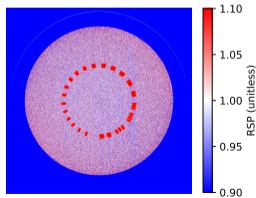
DD



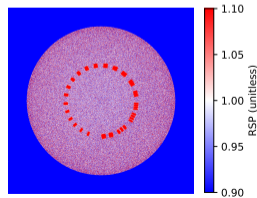
BPF



DBP

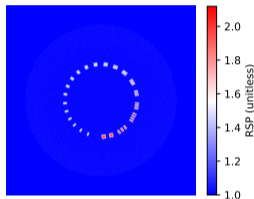


DR

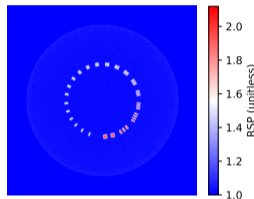


Results: spatial resolution

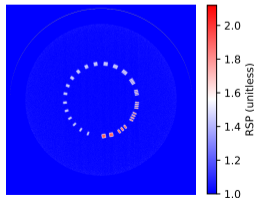
DD



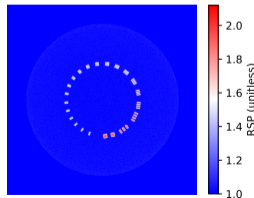
BPF



DBP

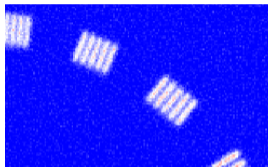


DR

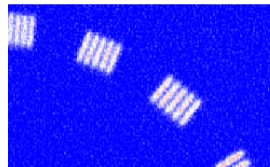


Results: spatial resolution

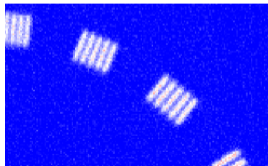
DD



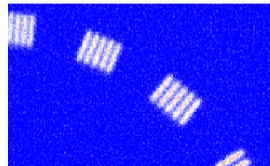
BPF



DBP

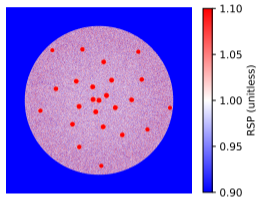


DR

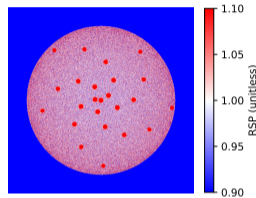


Results: spatial resolution

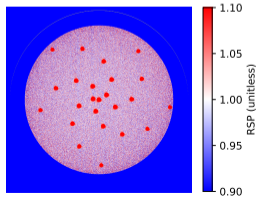
DD



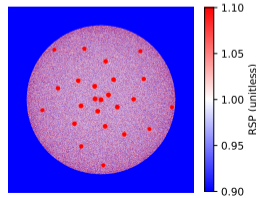
BPF



DBP

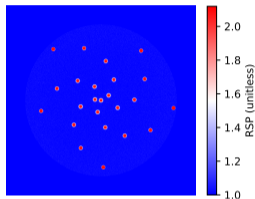


DR

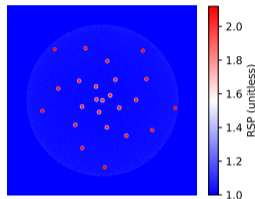


Results: spatial resolution

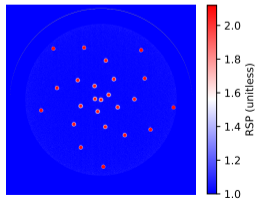
DD



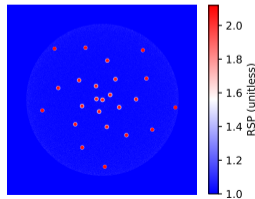
BPF



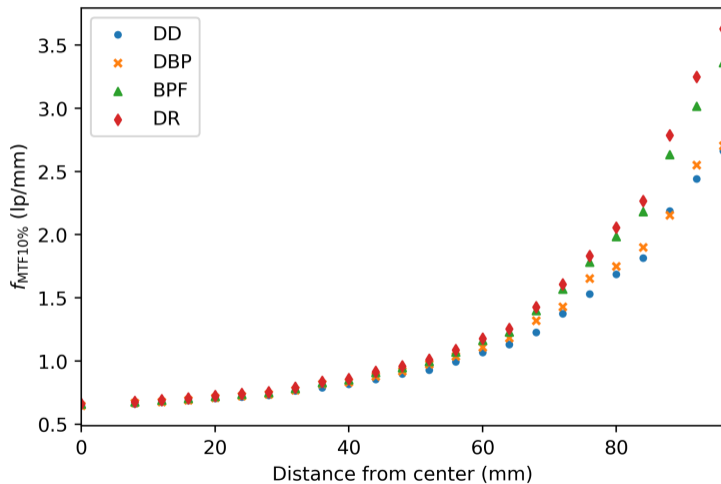
DBP



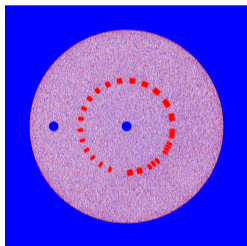
DR



Results: spatial resolution

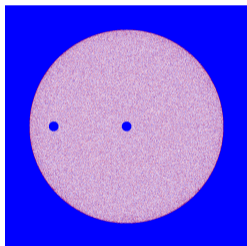


Results: accuracy and precision



	ROI ₁		ROI ₂	
	mean	std	mean	std
DD	0.997	0.043	0.986	0.046
BPF	1.004	0.049	0.989	0.056
DBP	0.997	0.040	0.987	0.046
DR	0.996	0.053	0.988	0.058

Results: accuracy and precision



	ROI ₁		ROI ₂	
	mean	std	mean	std
DD	0.999	0.037	0.999	0.037
BPF	1.005	0.040	0.998	0.039
DBP	0.997	0.032	0.998	0.033
DR	0.998	0.042	0.998	0.043

Conclusions

- Comparison of four direct reconstruction algorithms
 - On-going work to include other algorithms
- Small differences in spatial resolution where MLP uncertainty is small
 - Will likely vanish when accounting for tracker uncertainty
- Comparable accuracy except for a slight bias in BPF
- Better precision when spatial resolution is less good
- Differences in computational times: $DD / DR \gg BPF / DBP$

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