

SMS-NLINV




Simultaneous Imaging of Multiple Slices

Sebastian Rosenzweig
Diagnostic and Interventional Radiology
University Medical Center Göttingen

May 29, 2020

Magnetic Resonance in Medicine 79:2057–2066 (2018)

Simultaneous Multi-Slice MRI Using Cartesian and Radial FLASH and Regularized Nonlinear Inversion: SMS-NLINV

Sebastian Rosenzweig ^{1,*} Hans Christian Martin Holme ^{1,2} Robin N. Wilke,^{1,2}
Dirk Voit,³ Jens Frahm,^{2,3} and Martin Uecker ^{1,2}

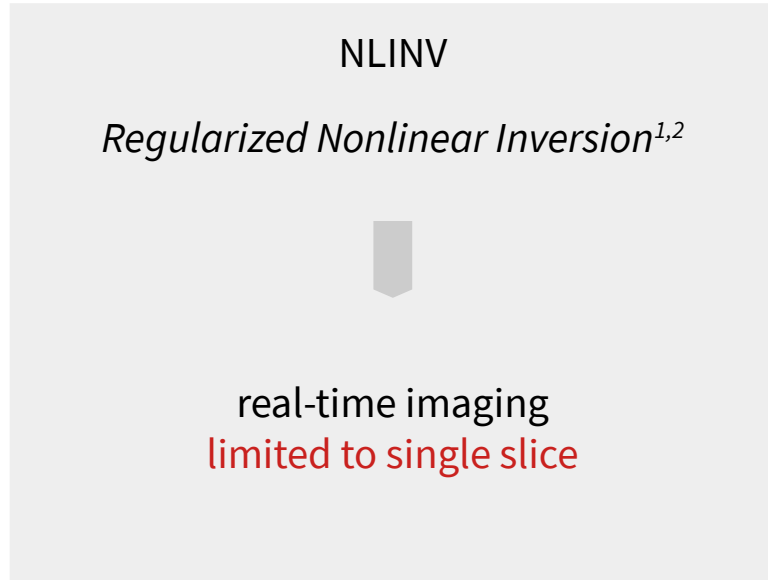
Purpose: The development of a calibrationless parallel imaging method for accelerated simultaneous multi-slice (SMS) MRI based on Regularized Nonlinear Inversion (NLINV), evaluated using Cartesian and radial fast low-angle shot (FLASH).

Theory and Methods: NLINV is a parallel imaging method

consist of a calibration from reference lines followed by linear reconstruction (1–4). In contrast, Regularized Nonlinear Inversion (NLINV) (5) does not require a calibration step but simultaneously computes image content and coil sensitivities from all available data. Because

SMS-NLINV

Motivation



[1] Uecker et al., Magn. Reson. Med. (2008)

[2] Uecker et al., NMR Biomed (2010)

SMS-NLINV

Motivation

NLINV

Regularized Nonlinear Inversion^{1,2}



real-time imaging
limited to single slice

SMS

*Simultaneous Multi-Slice*³



less data demand
time-consistent slices

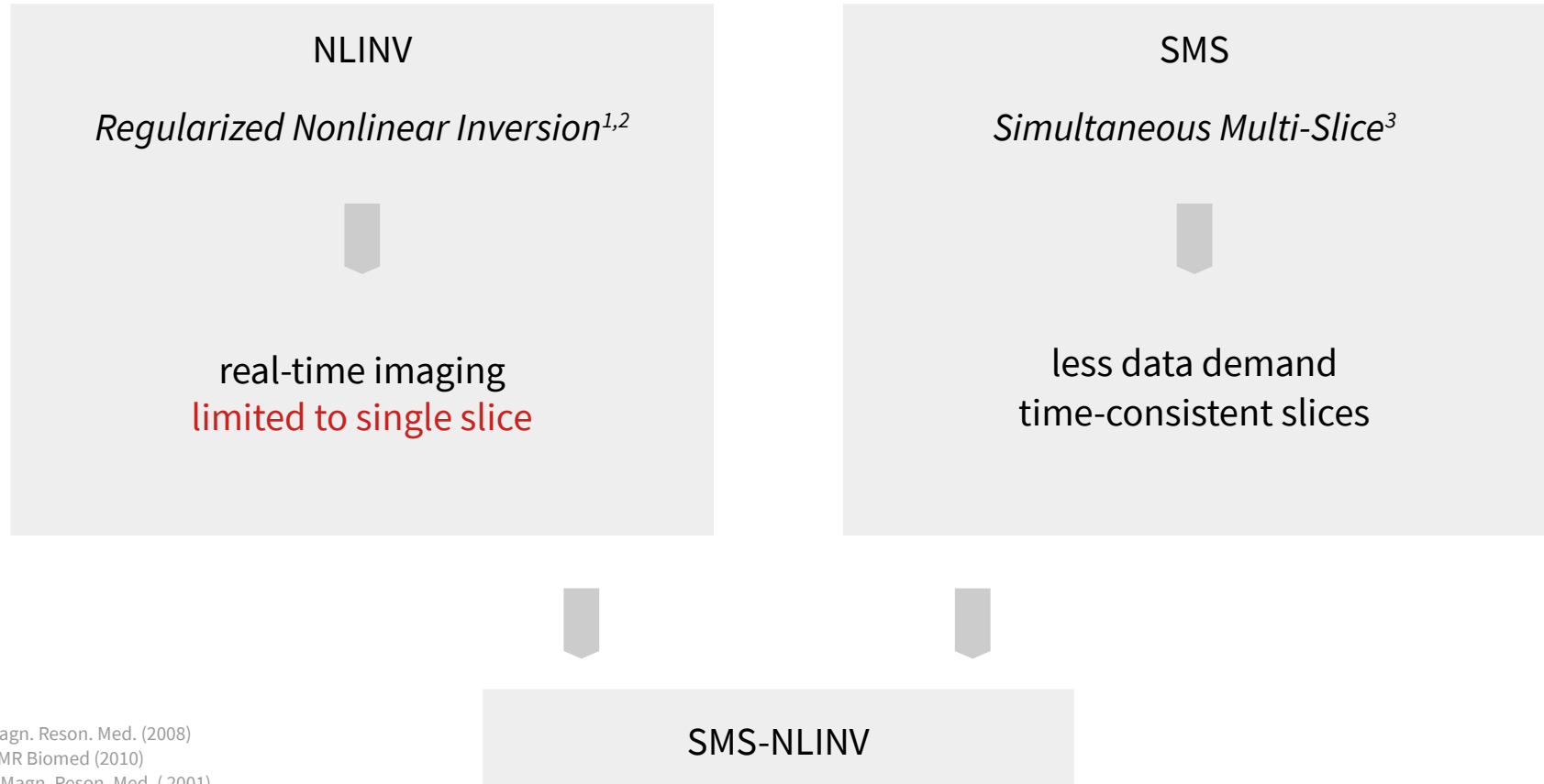
[1] Uecker et al., Magn. Reson. Med. (2008)

[2] Uecker et al., NMR Biomed (2010)

[3] Larkman et al., Magn. Reson. Med. (2001)

SMS-NLINV

Motivation

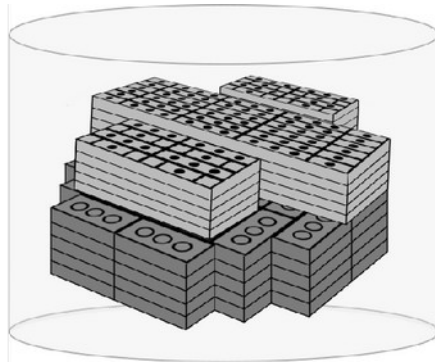


[1] Uecker et al., Magn. Reson. Med. (2008)

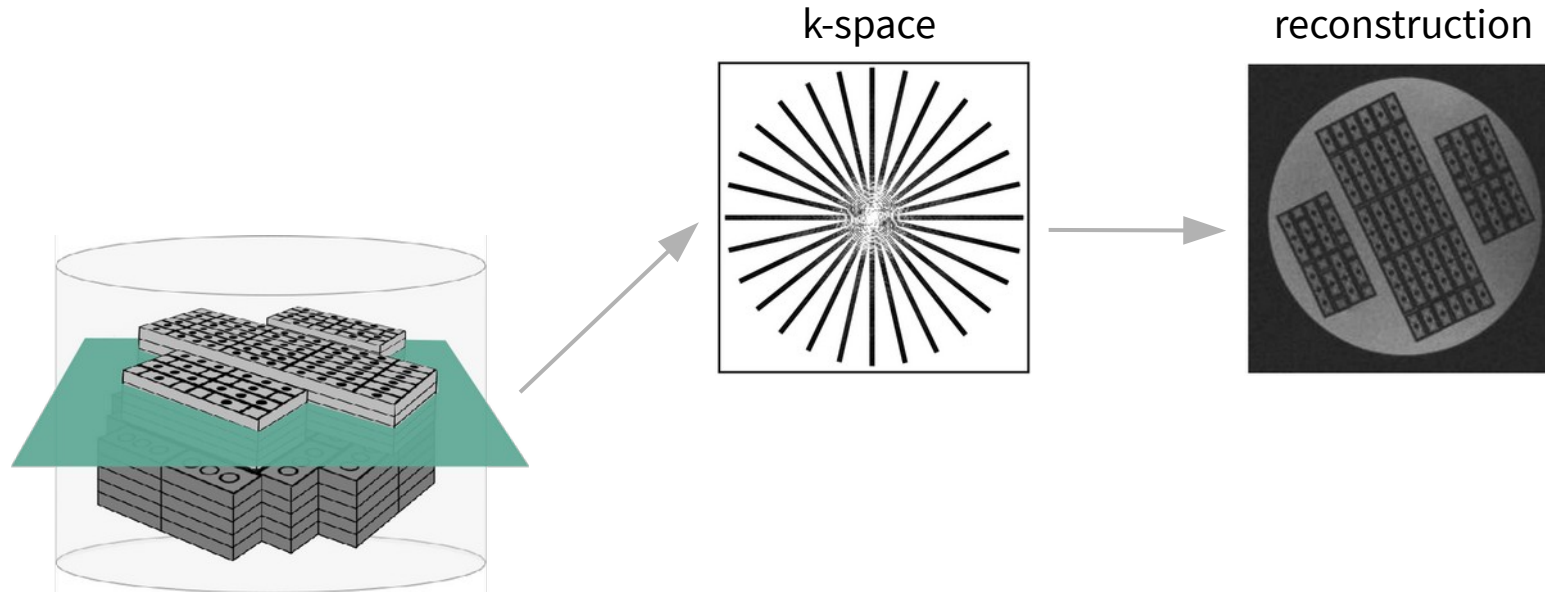
[2] Uecker et al., NMR Biomed (2010)

[3] Larkman et al., Magn. Reson. Med. (2001)

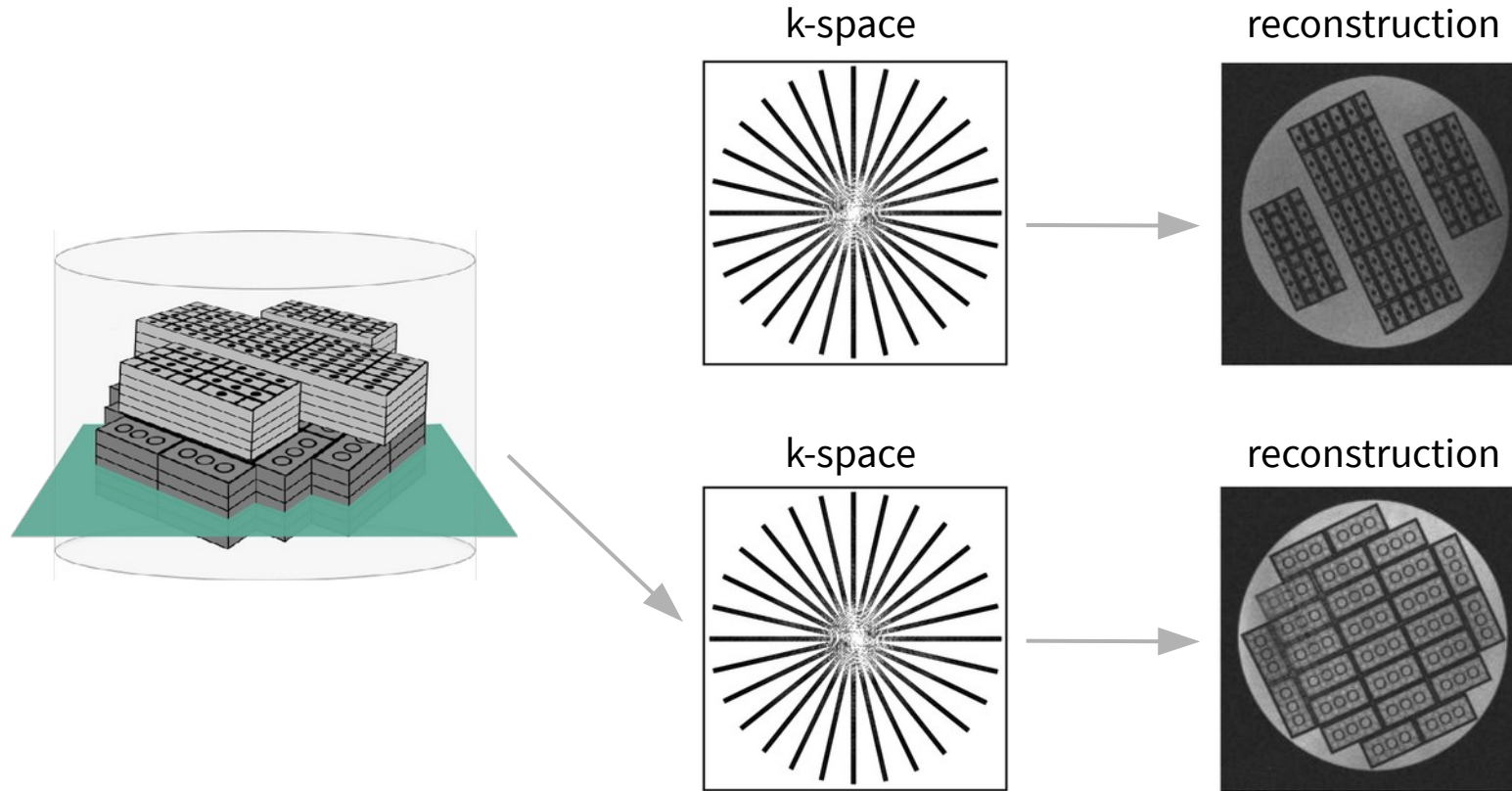
Conventional Multi-Slice Imaging



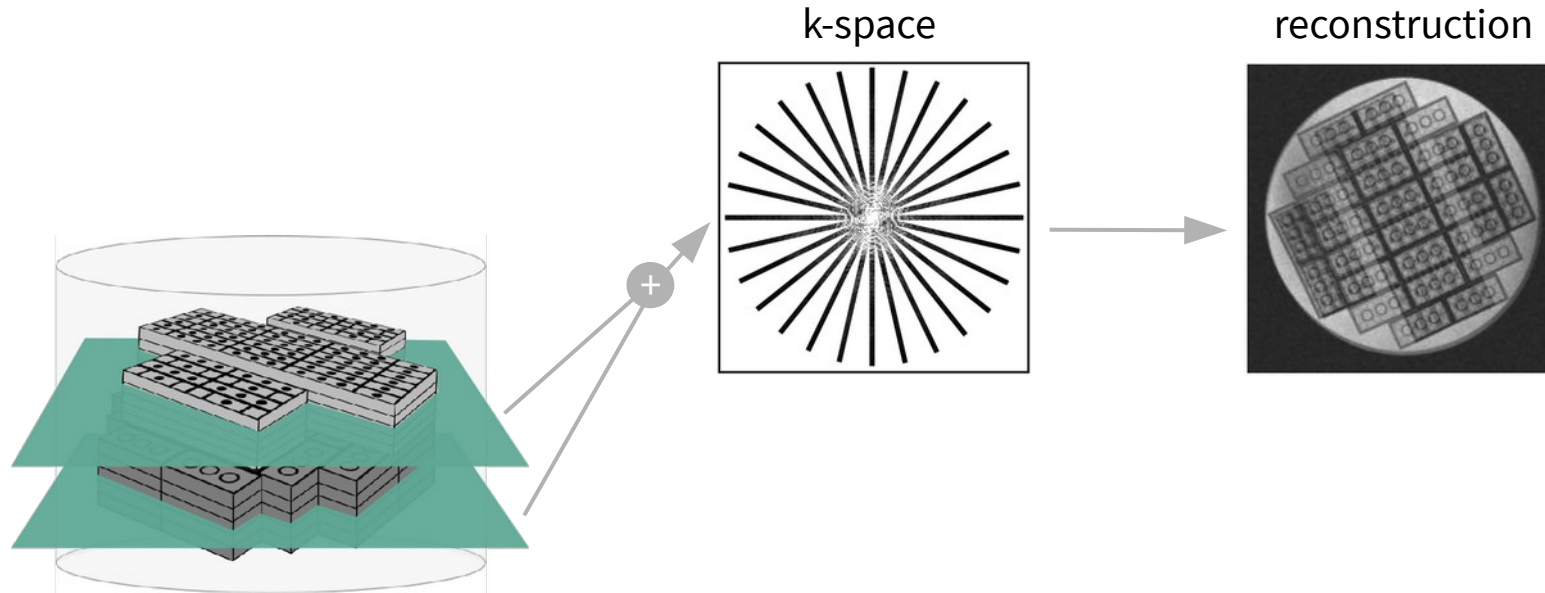
Conventional Multi-Slice Imaging



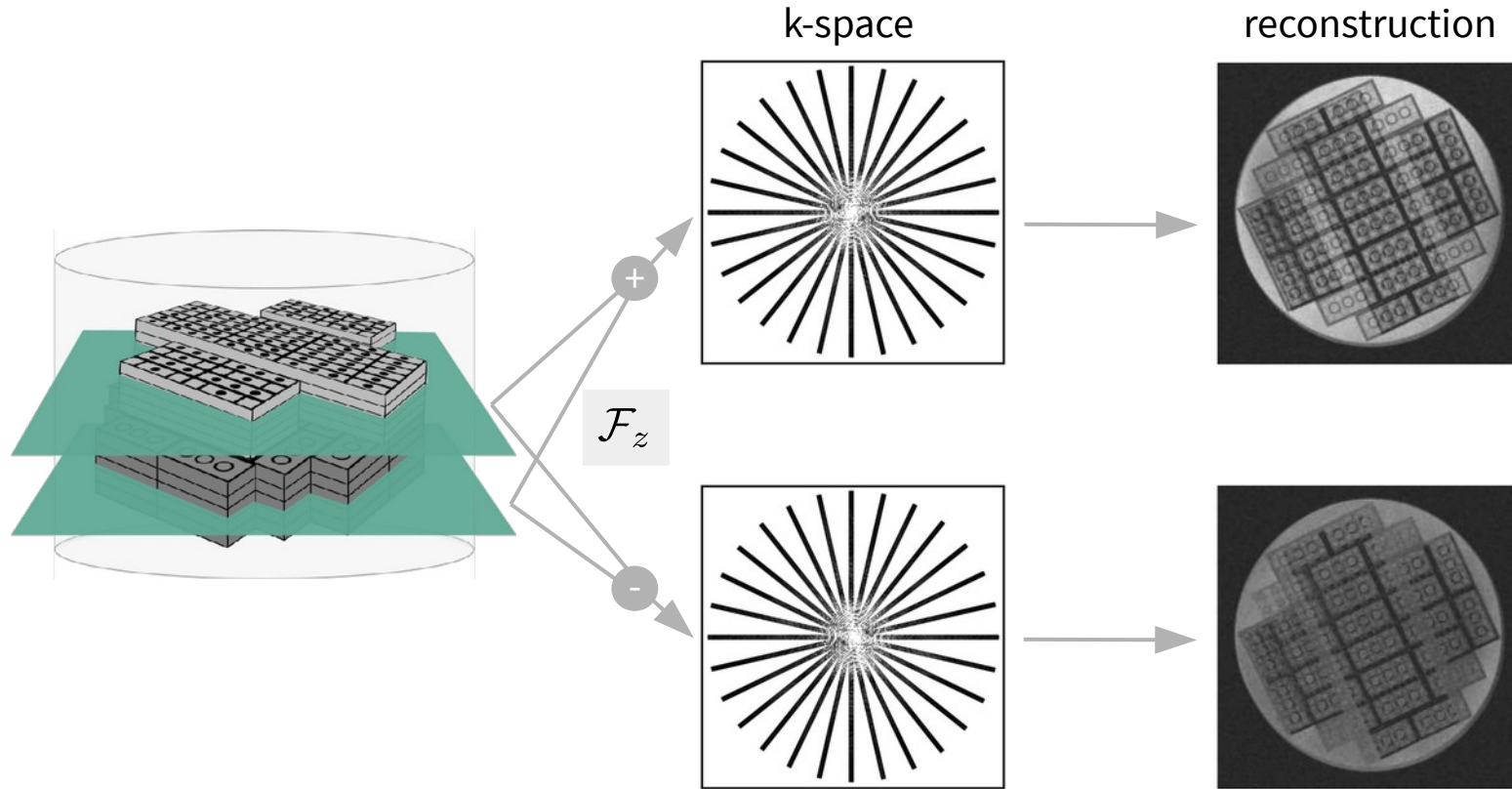
Conventional Multi-Slice Imaging



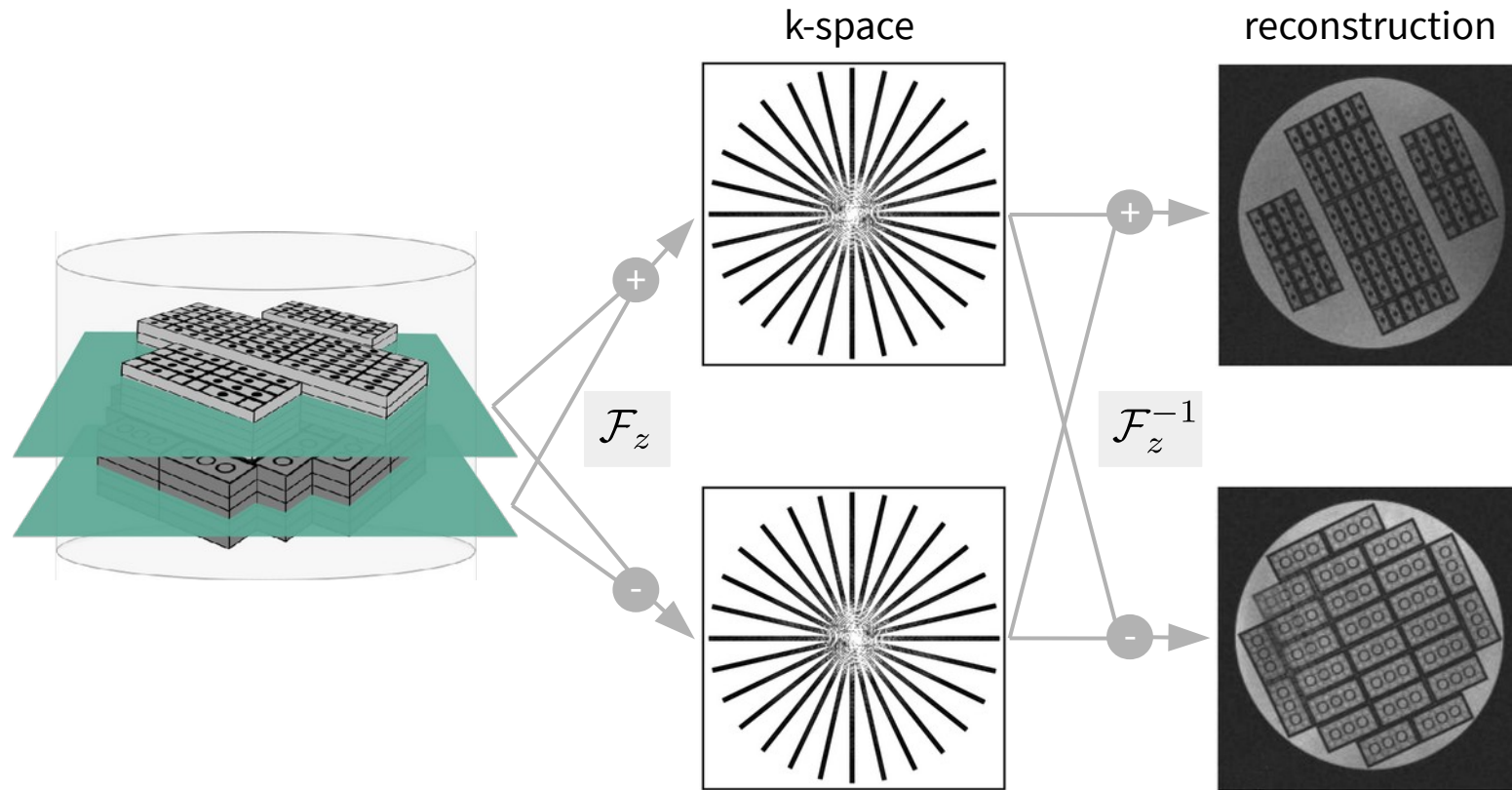
Simultaneous Multi-Slice Imaging



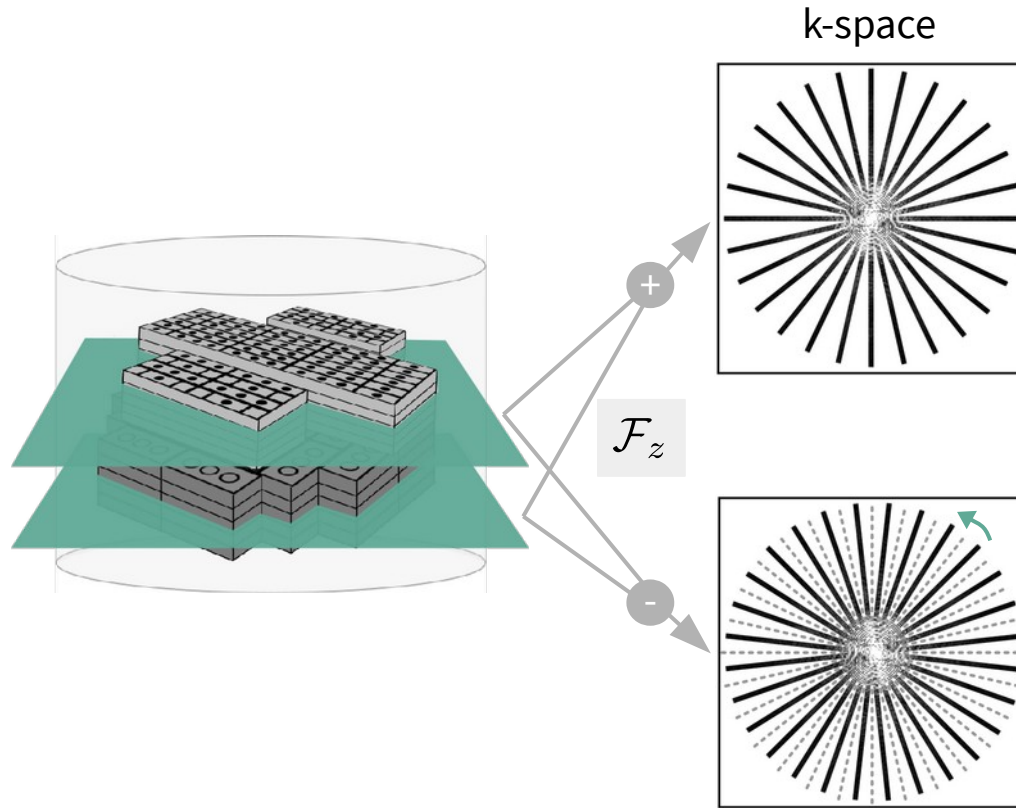
Simultaneous Multi-Slice Imaging



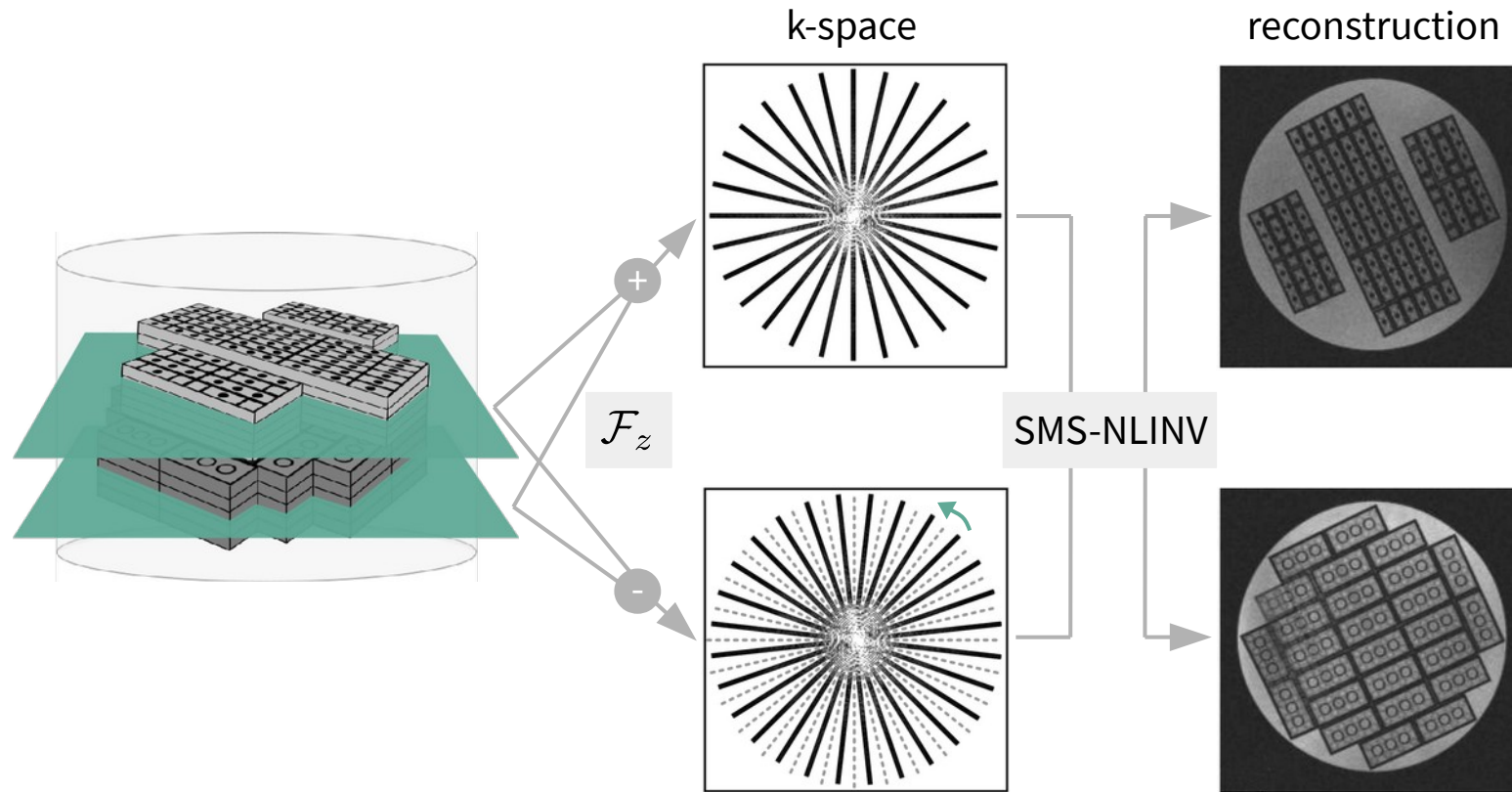
Simultaneous Multi-Slice Imaging



Simultaneous Multi-Slice Imaging



Simultaneous Multi-Slice Imaging



Optimization Problem

$$\operatorname{argmin}_{\mathbf{x}} \|\mathcal{PFC}\mathbf{x} - \mathbf{y}\|^2 + R(\mathbf{x})$$

Optimization Problem

$$\operatorname{argmin}_{\mathbf{x}} \|\mathcal{P}\mathcal{F}C\mathbf{x} - \mathbf{y}\|^2 + R(\mathbf{x})$$

$$\mathcal{F} := \mathcal{F}_{3D}$$

$$\mathbf{X} := (C, \mathbf{x})$$

$$F := \mathcal{P}\mathcal{F}_{3D}$$

Optimization Problem

$$\operatorname{argmin}_{\mathbf{X}} \|\mathbf{F}(\mathbf{X}) - \mathbf{y}\|^2 + R(\mathbf{X})$$

Optimization Problem

$$\operatorname{argmin}_{\mathbf{X}} \|\mathbf{F}(\mathbf{X}) - \mathbf{y}\|^2 + R(\mathbf{X})$$

$$F(\mathbf{X}_n + d\mathbf{X}) \approx F(\mathbf{X}_n) + DF(\mathbf{X}_n)d\mathbf{X}$$

Optimization Problem

$$\operatorname{argmin}_{\underline{d\mathbf{X}}} \left\| F(\mathbf{X}_n) + DF(\mathbf{X}_n)\underline{d\mathbf{X}} - \mathbf{y} \right\|^2 + \alpha_n \left\| \mathbf{X}_n + \underline{d\mathbf{X}} \right\|^2$$

- solve for update $\underline{d\mathbf{X}}$ in each Newton-step
- iterative update
 $\mathbf{X}_{n+1} = \mathbf{X}_n + \underline{d\mathbf{X}}$
- Tikhonov regularization

SMS-NLINV

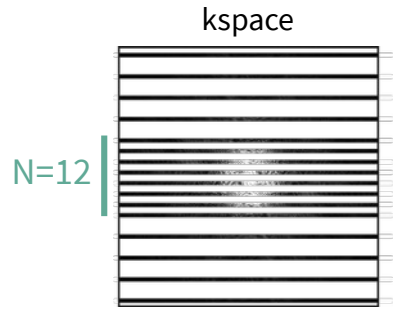
Benefits

- non-linear formulation
- complementary k-space samples

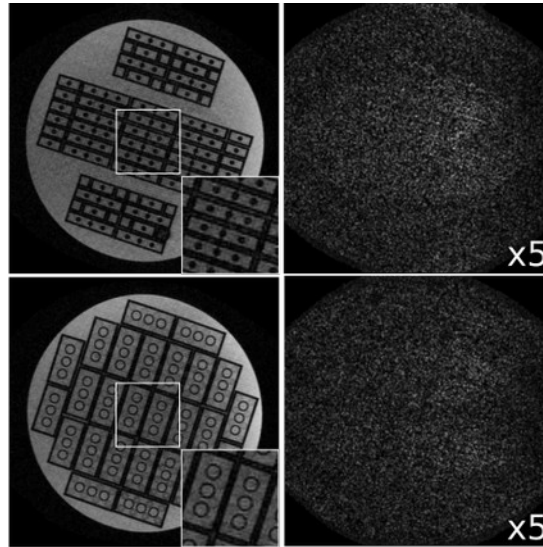


SMS-NLINV

Cartesian | 2 slices

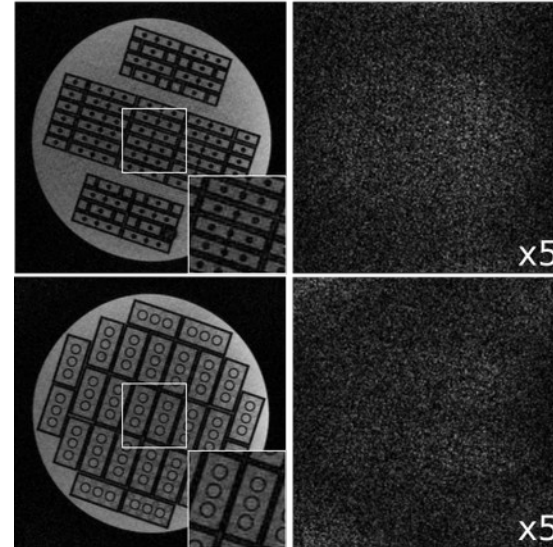


ESPIRiT₁
linear reconstruction
(additional coil calibration)



difference to
reference

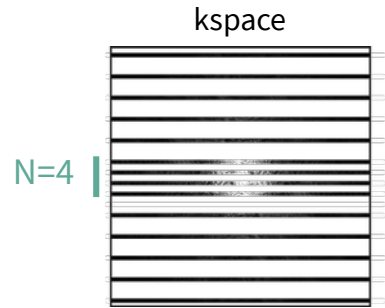
SMS-NLINV
non-linear reconstruction
(calibration-less)



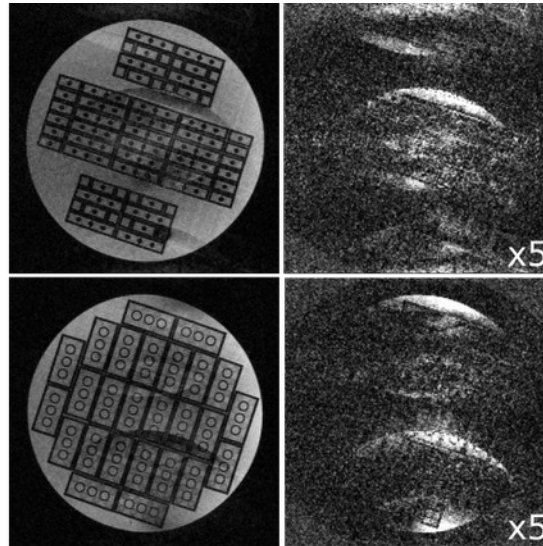
difference to
reference

SMS-NLINV

Cartesian | 2 slices

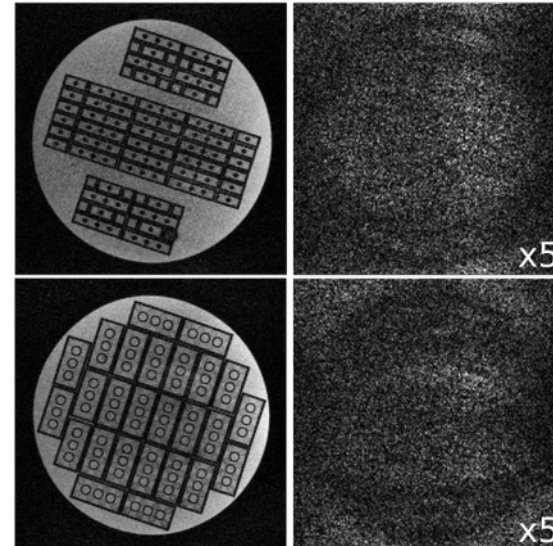


ESPIRiT₁
linear reconstruction
(additional coil calibration)



difference to
reference

SMS-NLINV
non-linear reconstruction
(calibration-less)

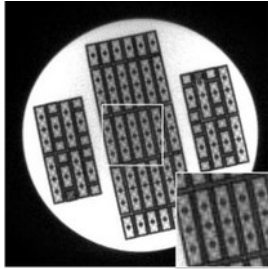


difference to
reference

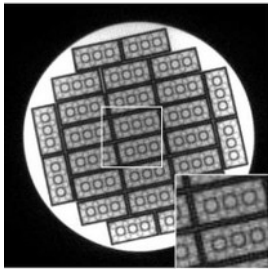
SMS-NLINV

Radial | 3 slices

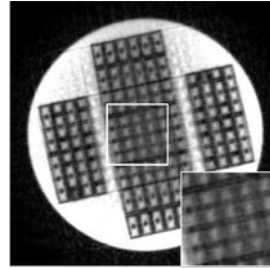
NLINV



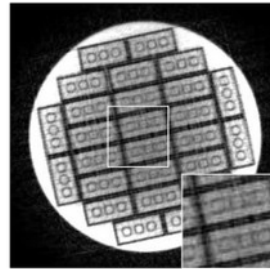
⋮



fully sampled

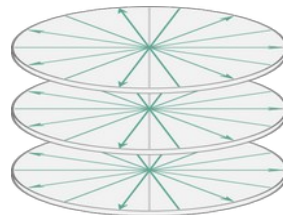
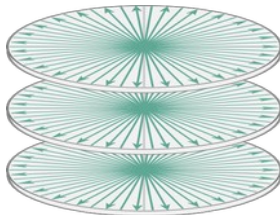


⋮



undersampled (10x)

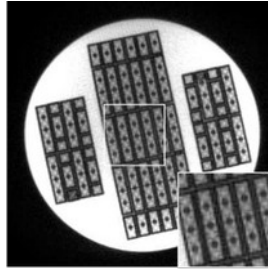
slice



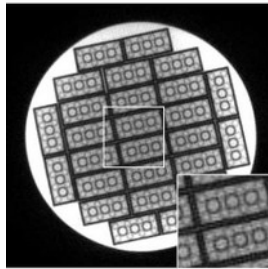
SMS-NLINV

Radial | 3 slices

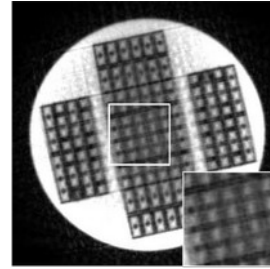
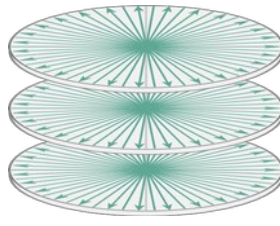
NLINV



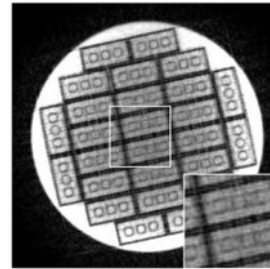
⋮



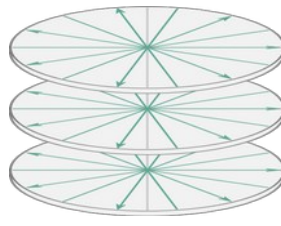
fully sampled



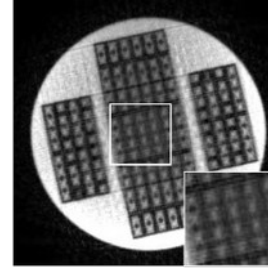
⋮



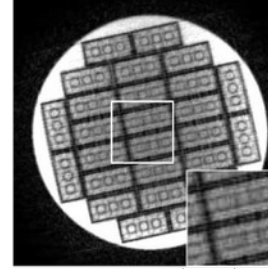
undersampled (10x)



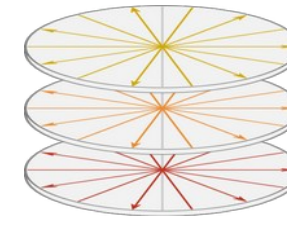
SMS-NLINV



⋮



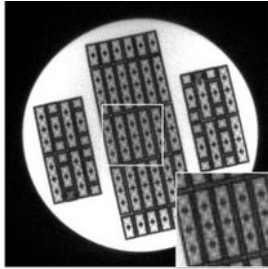
aligned (10x)



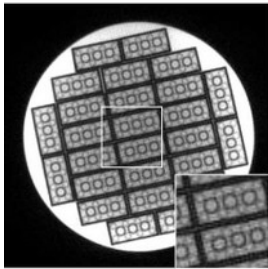
SMS-NLINV

Radial | 3 slices

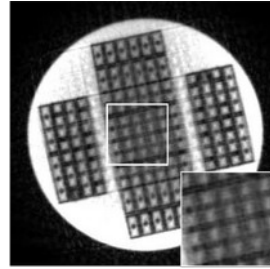
NLINV



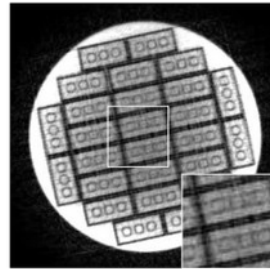
⋮



fully sampled

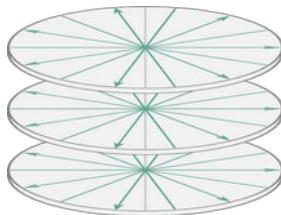
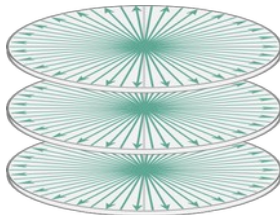


⋮

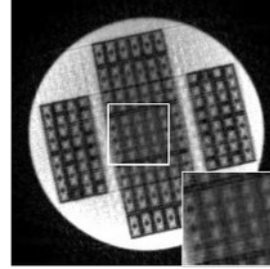


undersampled (10x)

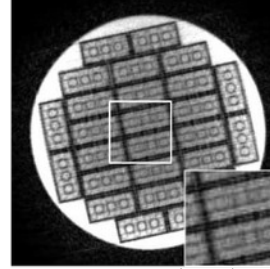
slice



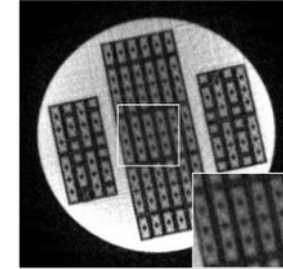
SMS-NLINV



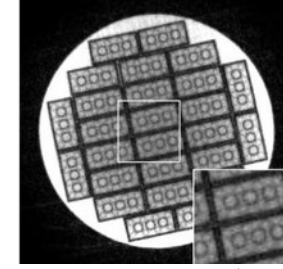
⋮



aligned (10x)

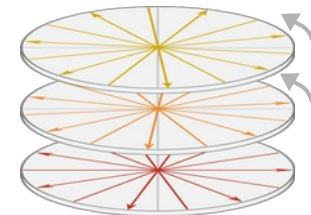
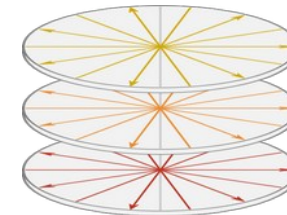


⋮



complementary (10x)

k_z

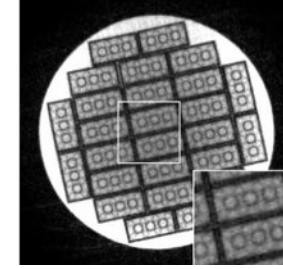
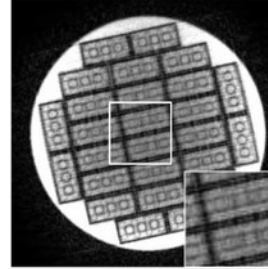
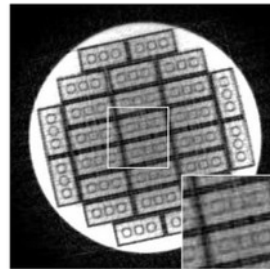
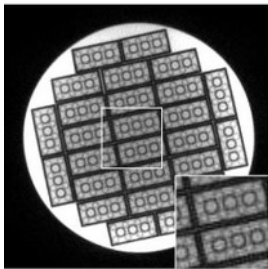
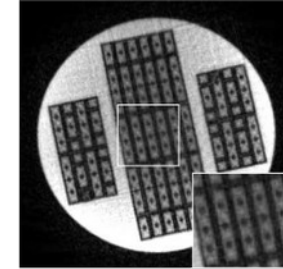
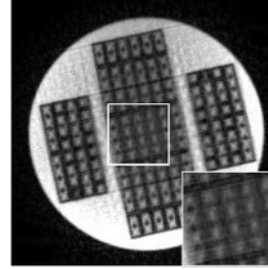
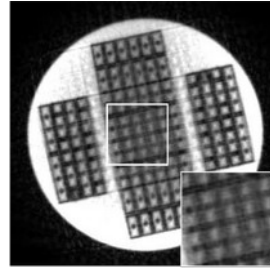
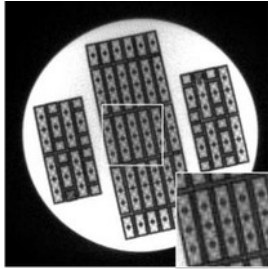


SMS-NLINV

Radial | 3 slices

NLINV

SMS-NLINV

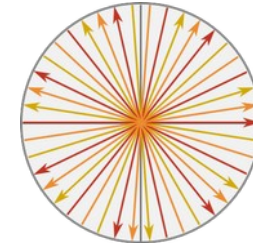
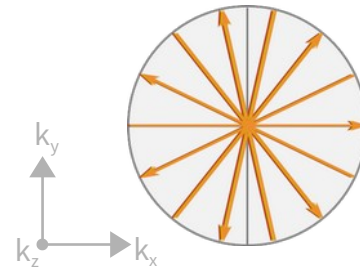
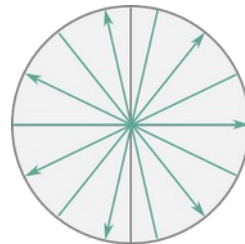
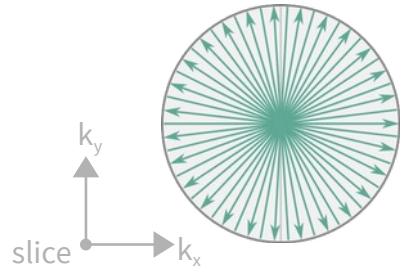


fully sampled

undersampled (10x)

aligned (10x)

complementary (10x)



Temporal Regularization

$$\operatorname{argmin}_{d\mathbf{X}^{(t)}} \|F(\mathbf{X}_n^{(t)}) + DF(\mathbf{X}_n^{(t)})d\mathbf{X}^{(t)} - \mathbf{y}\|^2 + \alpha_n \|\mathbf{X}_n^{(t)} + d\mathbf{X}^{(t)}\|^2$$

Temporal Regularization

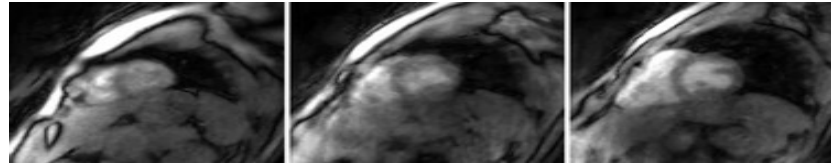
$$\operatorname{argmin}_{d\mathbf{X}^{(t)}} \left\| F(\mathbf{X}_n^{(t)}) + DF(\mathbf{X}_n^{(t)})d\mathbf{X}^{(t)} - \mathbf{y} \right\|^2 + \alpha_n \left\| \mathbf{X}_n^{(t)} + d\mathbf{X}^{(t)} \right\|^2$$

Temporal Regularization

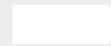
$$\operatorname{argmin}_{d\mathbf{X}^{(t)}} \left\| F(\mathbf{X}_n^{(t)}) + DF(\mathbf{X}_n^{(t)})d\mathbf{X}^{(t)} - \mathbf{y} \right\|^2 + \alpha_n \left\| \mathbf{X}_n^{(t)} + d\mathbf{X}^{(t)} - \underline{\mathbf{X}^{(t-1)}} \right\|^2$$

penalize the difference
to the previous frame

SMS-NLINV
SMS real-time MRI



5 spokes
per partition & frame

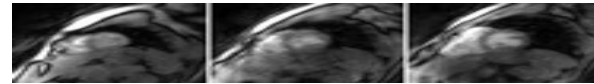


3 slices & 29 frames
per second

SMS-NLINV Wrap Up

SUMMARY

- joint estimation of images and coils
- improved image quality
- time-consistency
- multi-slice real-time MRI



LIMITATIONS

- ~ 2 - 5 slices
- problem size
- SMS-FLASH study

OUTLOOK

- SMS-bSSFP sequence
- T1 mapping^{1,2}

SMS-NLINV T1 mapping^{1,2}

