Dictionary-Based Oscillating Steady State fMRI Reconstruction

Shouchang Guo, Douglas C. Noll and Jeffrey A. Fessler

UNIVERSITY OF MICHIGAN

May 16, 2019

Declaration of Financial Interests or Relationships

Speaker Name: Shouchang Guo

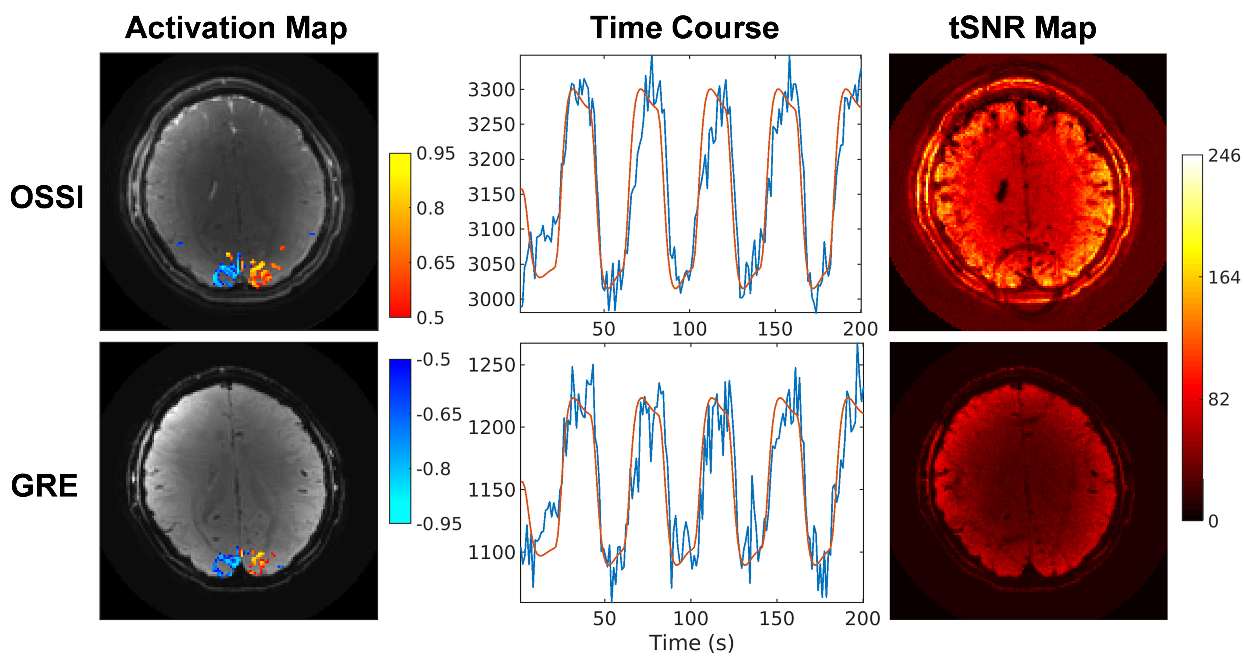
I have no financial interests or relationships to disclose with regard to the subject matter of this presentation.

Oscillating Steady-State Imaging (OSSI)[1]

A new fMRI acquisition method exploits a large, oscillating signal

compared to GRE

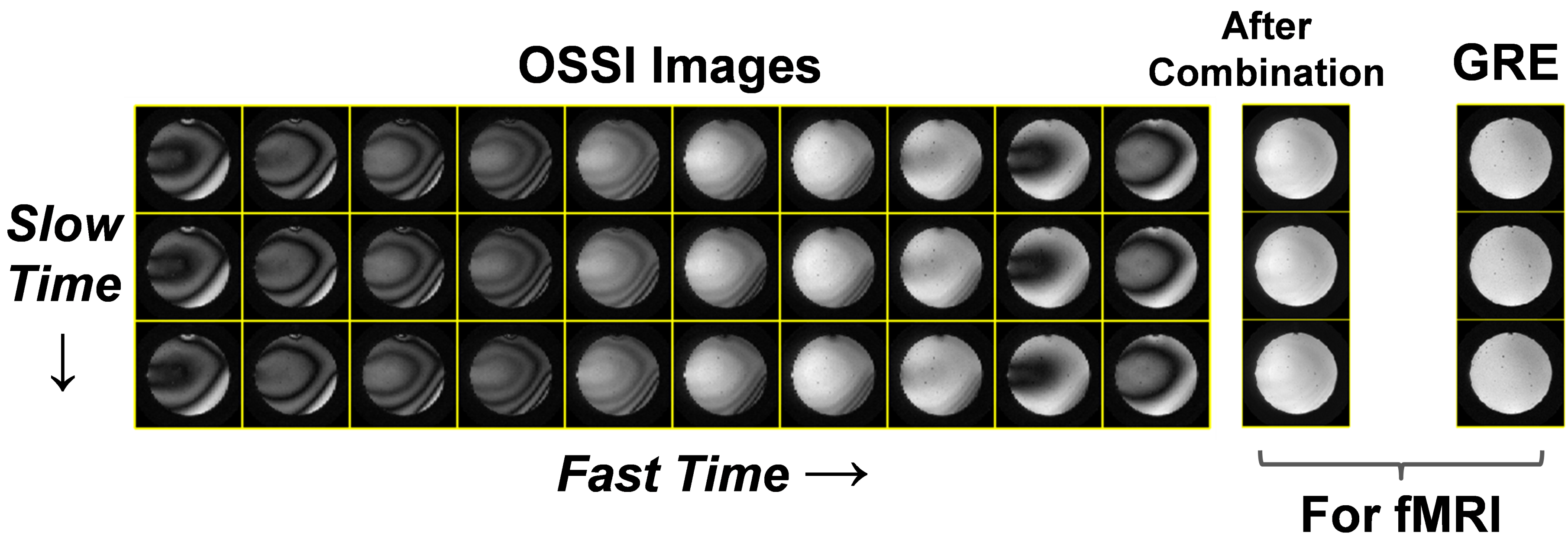
- 2 times higher SNR
- high-resolution fMRI



[1] Guo and Noll, ISMRM, 2018 #5441, 2019 #1170

Need for k-Space Undersampling

RF phase cycling with cycle length n_c, OSSI signal oscillates with period n_cTR

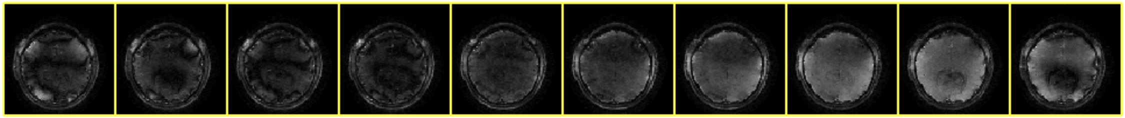


- $n_c = 10$ times more images would compromise temporal resolution
- short TR $=$ 15 ms limits single-shot spatial resolution

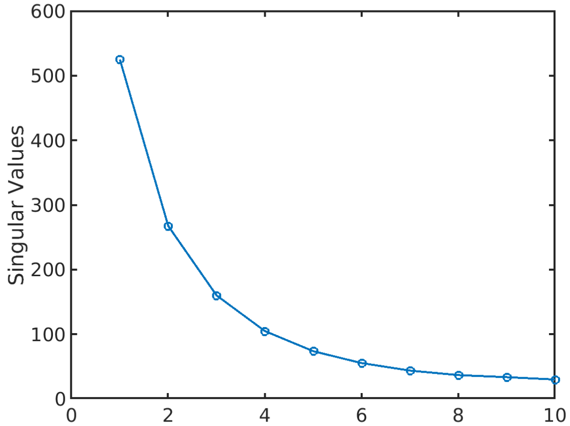
Need for Nonlinear Dimension Reduction

Not very low-rank along fast time[2], linear subspace model may not help much

1 slow-time image set = 10 fast-time images



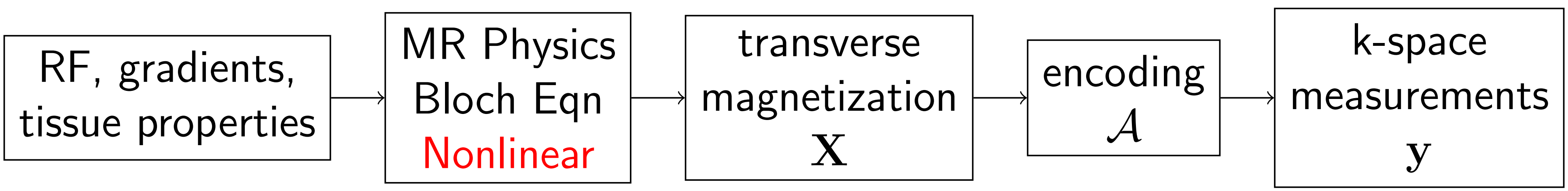
⟶



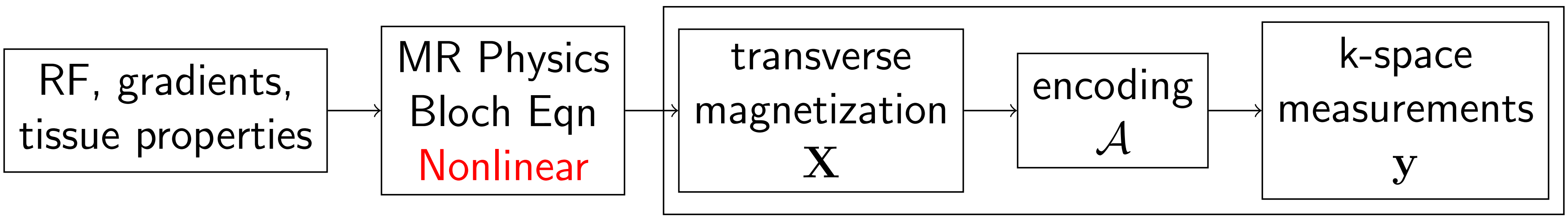
- nonlinearity of the OSSI signal
- dimension reduction for undersampling

[2] Guo and Noll, ISMRM, 2018 #3531

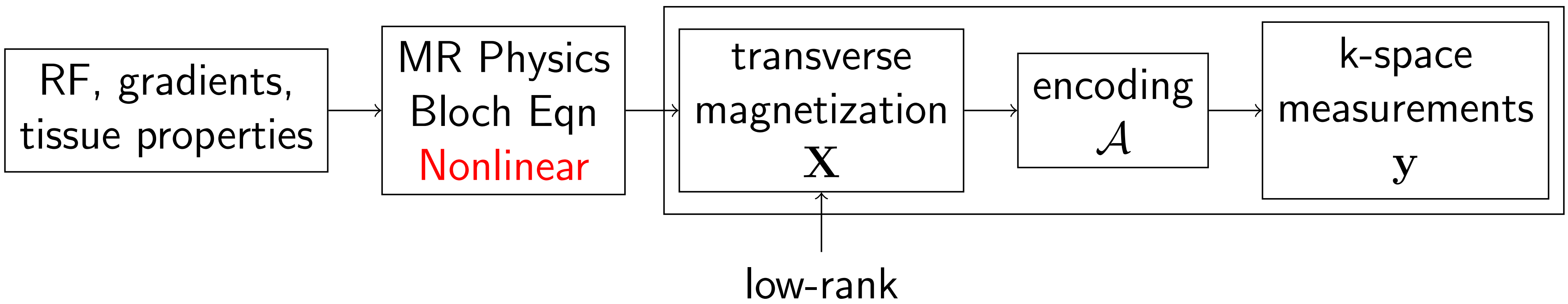
OSSI Manifold Model



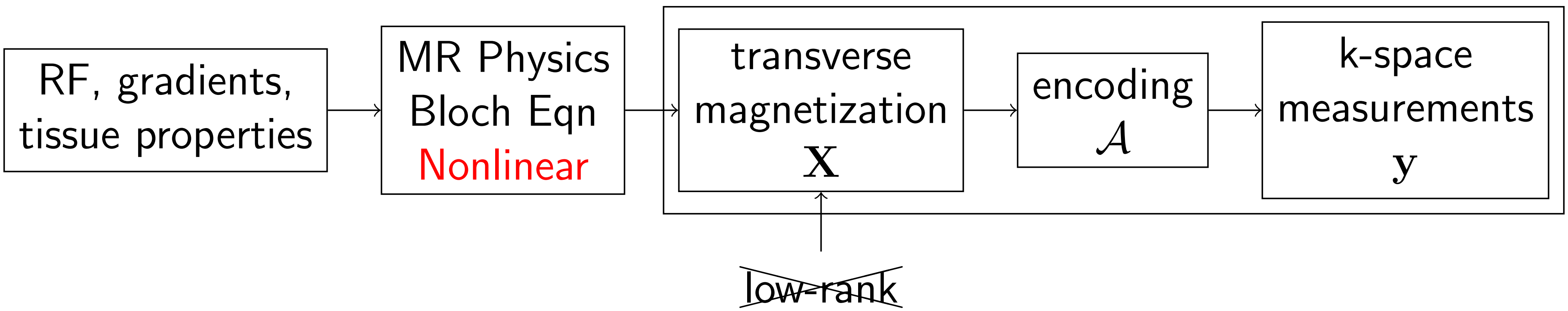
OSSI Manifold Model



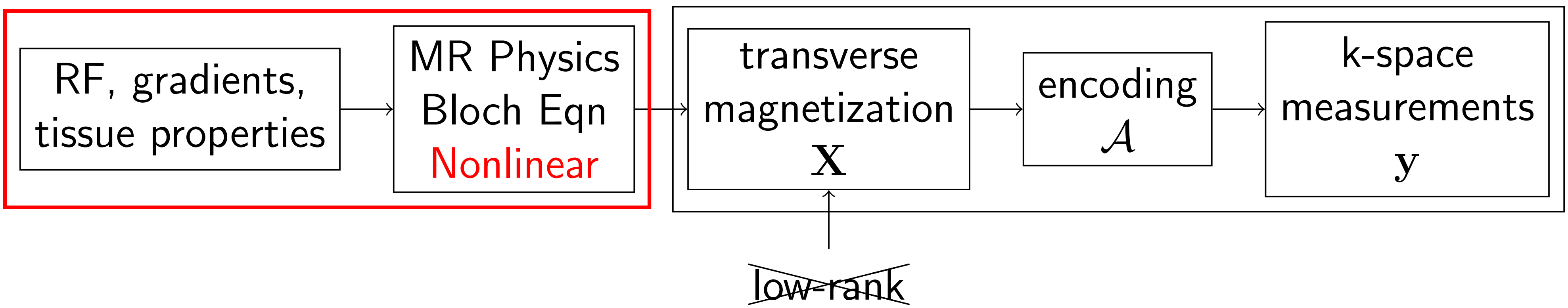
OSSI Manifold Model



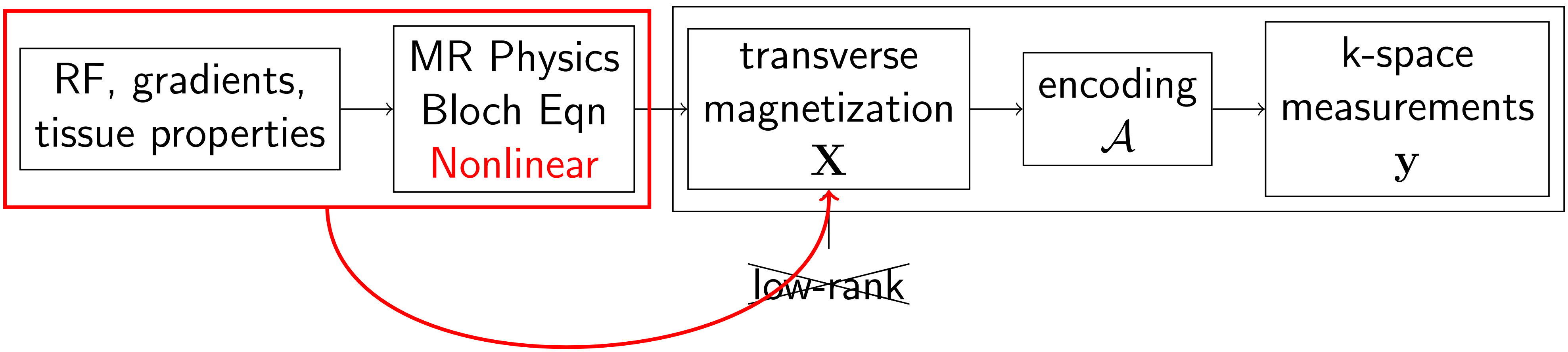
OSSI Manifold Model



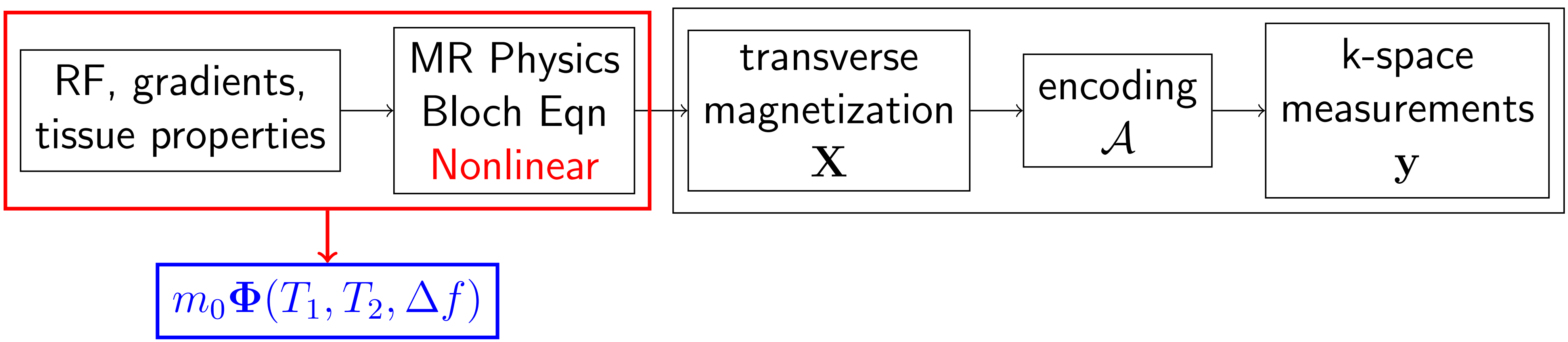
OSSI Manifold Model



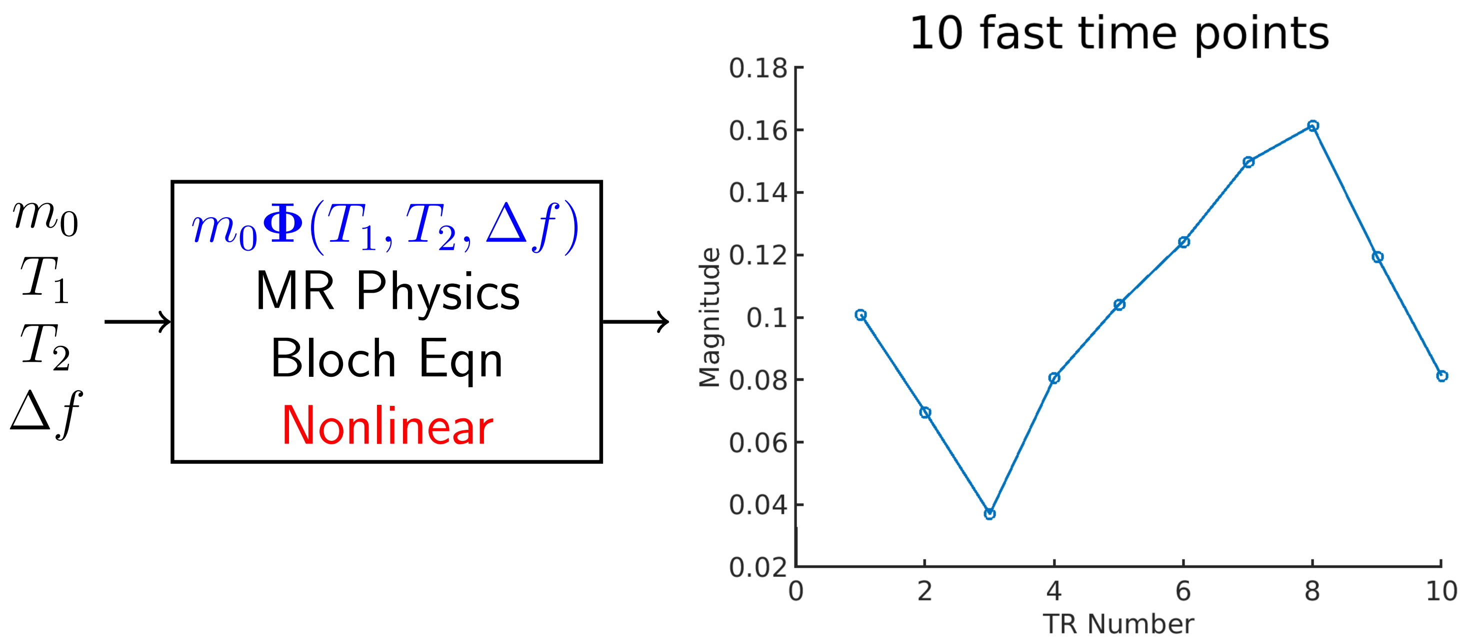
OSSI Manifold Model



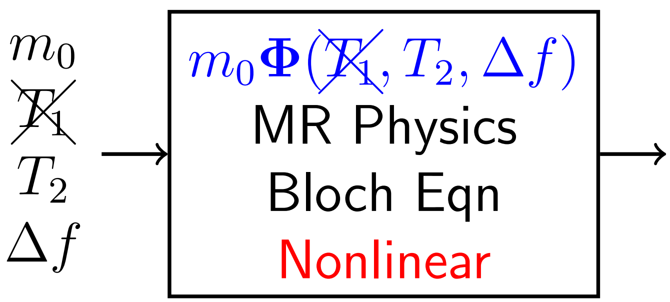
OSSI Manifold Model

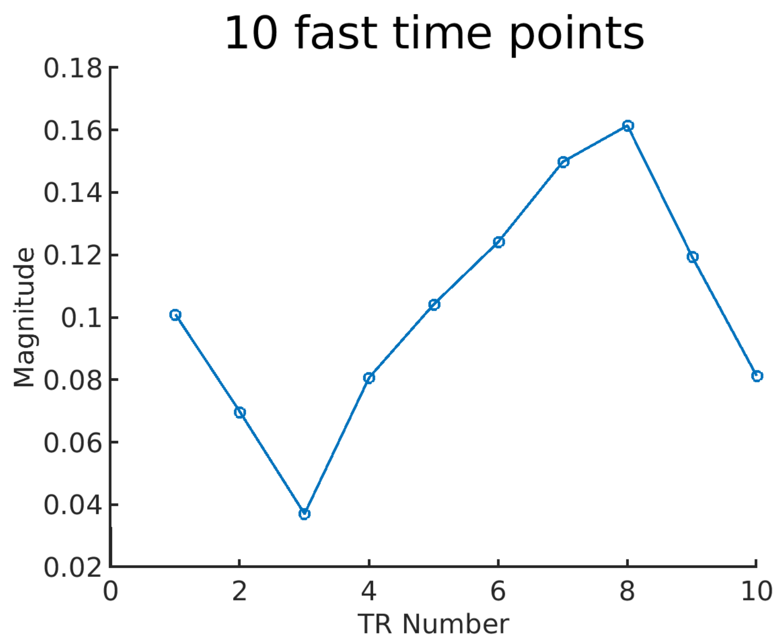


Parameterization of OSSI Signal



Parameterization of OSSI Signal

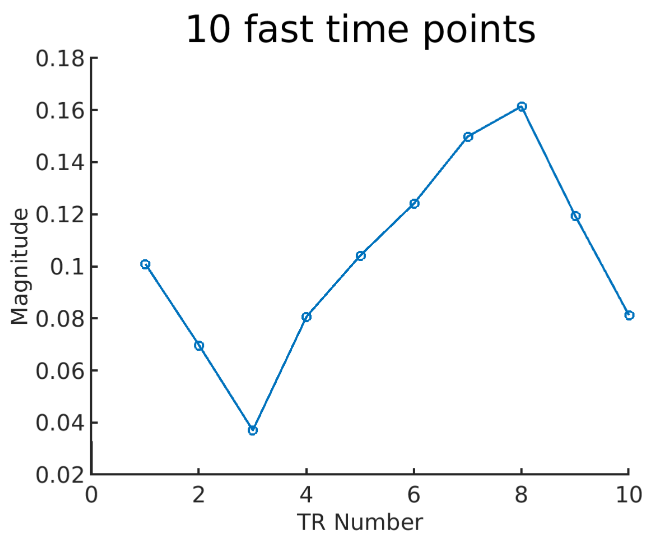




Parameterization of OSSI Signal

m_0 signal magnitude
T_2 tissue properties
Δf off-resonance frequency

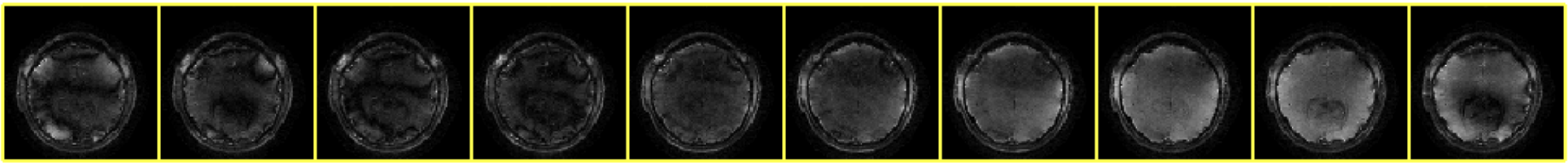
→ $m_0 \mathbf{\Phi}(T_2, \Delta f)$
MR Physics
Bloch Eqn
Nonlinear →



- effectively 3 physical parameters $\Rightarrow$ 10 time points
- nonlinear dimension reduction

Voxel-Wise Near Manifold Regularizer

- One slow-time image set $\mathbf{X} \in \mathbb{C}^{N_x \times N_y \times n_c}$, $n_c = 10$



- Voxel-wise

  $\mathbf{v} = \mathbf{X}[i, j, :] \in \mathbb{C}^{n_c}$ is a vector of 10 fast-time image values

Voxel-Wise Near Manifold Regularizer

- Problem formulation for one slow-time image set $\mathbf{X} \in \mathbb{C}^{N_x \times N_y \times n_c}$,

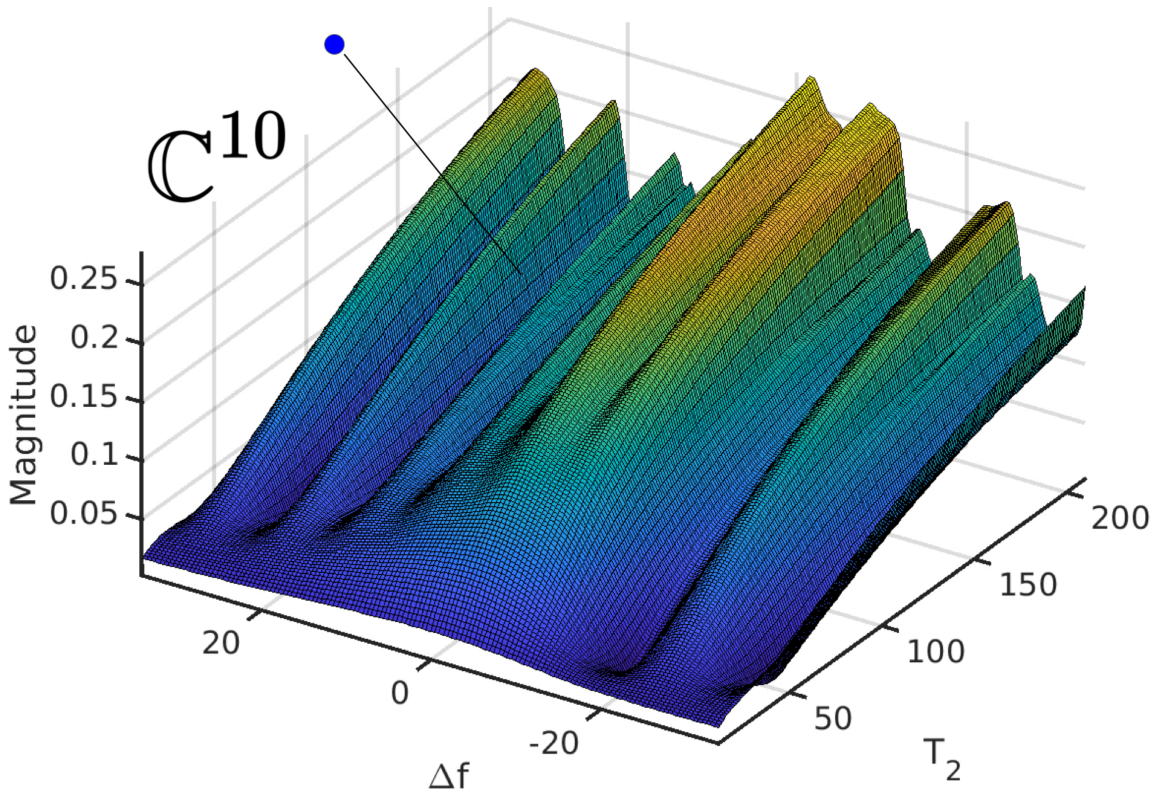
$$\hat{\mathbf{X}} = \arg\min_{\mathbf{X}} \frac{1}{2}\|\mathcal{A}(\mathbf{X}) - \mathbf{y}\|_2^2 + \beta \sum_{i,j} R\left(\mathbf{X}[i, j, :]\right),$$

$$R(\mathbf{v}) = \min_{m_0, T_2, \Delta f} \|\mathbf{v} - m_0 \mathbf{\Phi}(T_2, \Delta f)\|_2^2,$$

  - $\mathcal{A}(\cdot)$ is the encoding operator,
  - $\mathbf{y}$ denotes undersampled k-space measurements,
  - β is the regularization parameter.

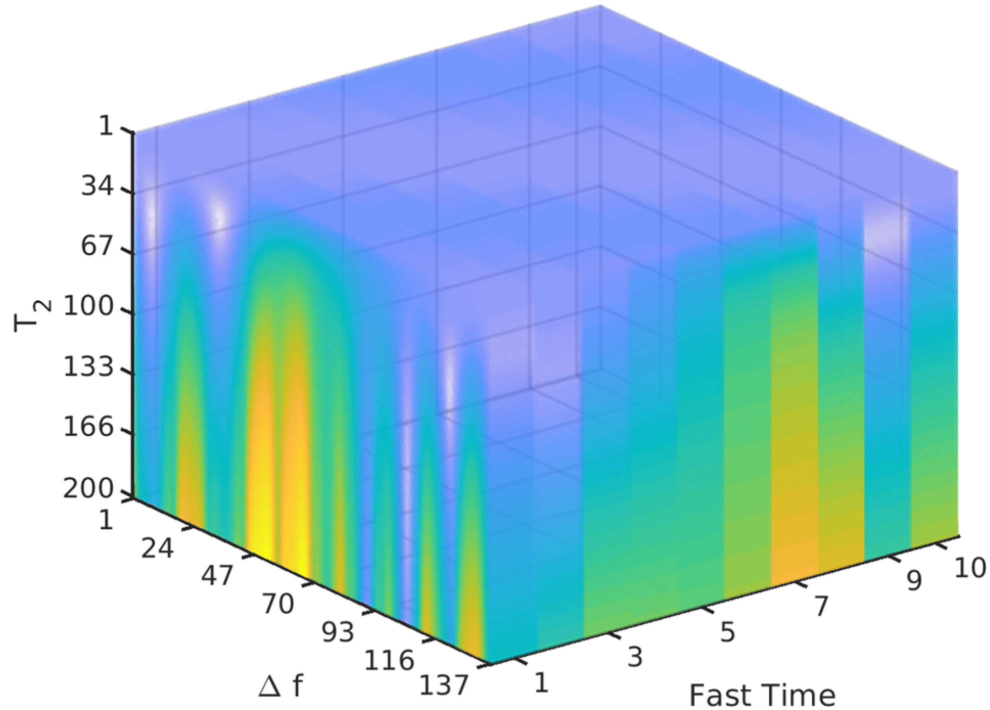
$$R(\mathbf{v}) = \min_{m_0, T_2, \Delta f} \|\mathbf{v} - m_0 \boldsymbol{\Phi}(T_2, \Delta f)\|_2^2$$

- $\{m_0 \boldsymbol{\Phi}(T_2, \Delta f) \in \mathbb{C}^{10} : m_0 \in \mathbb{C}, T_2, \Delta f \in \mathbb{R}\}$



$$R(\mathbf{v}) = \min_{m_0, T_2, \Delta f} \|\mathbf{v} - m_0 \boldsymbol{\Phi}(T_2, \Delta f)\|_2^2$$

- nonlinear least square $\Longrightarrow$ dictionary fitting via VARPRO[3]



[3] Golub and Pereyra, Inverse problems, 2003

MR Physics Based Reconstruction

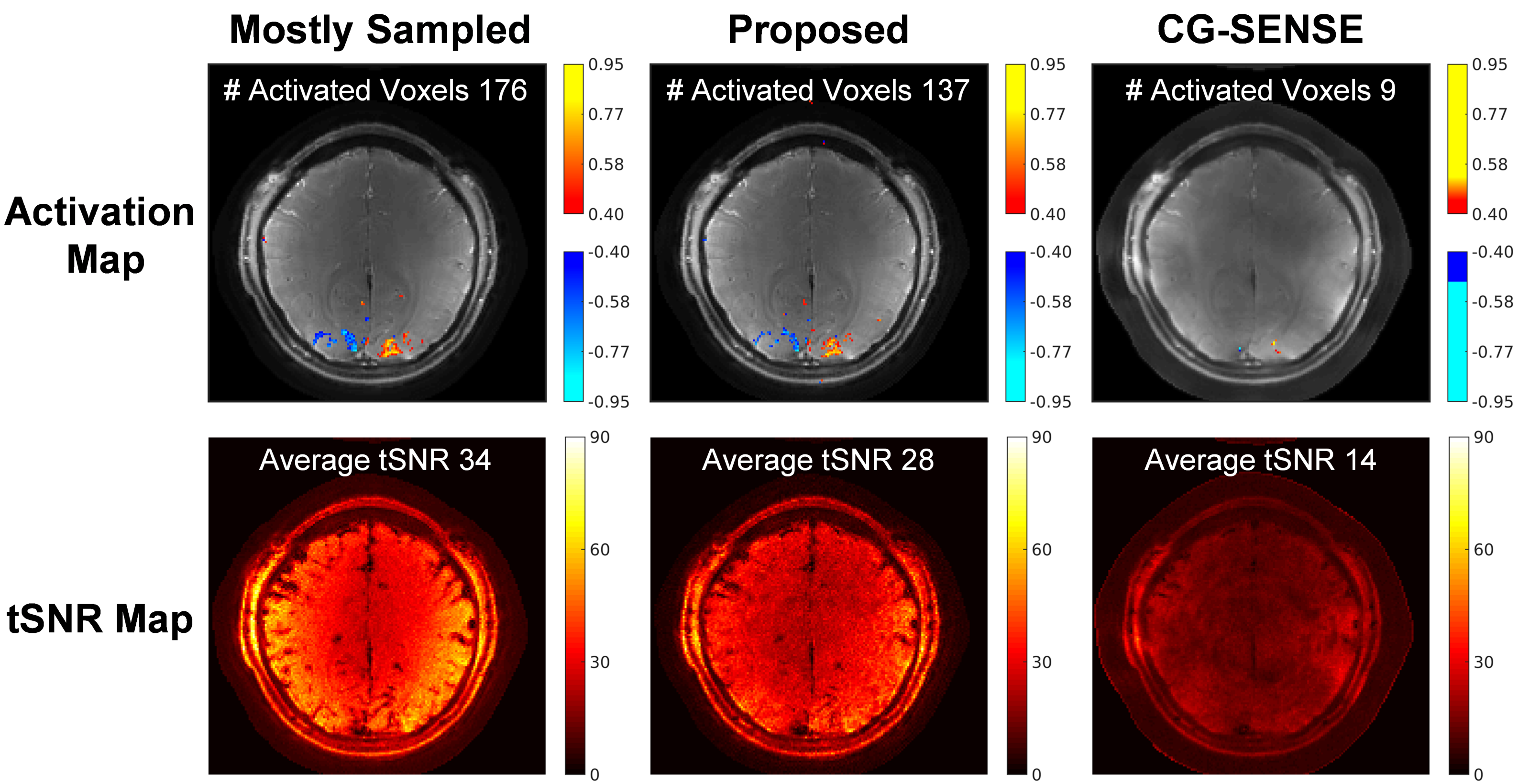
$$\hat{\mathbf{X}} = \arg\min_{\mathbf{X}} \frac{1}{2}\|\mathcal{A}(\mathbf{X}) - \mathbf{y}\|_2^2 + \beta \sum_{i,j} R\left(\mathbf{X}[i,j,:]\right),$$

$$R(\mathbf{v}) = \min_{m_0, T_2, \Delta f} \|\mathbf{v} - m_0 \mathbf{\Phi}(T_2, \Delta f)\|_2^2,$$

- alternating minimization
- $\mathbf{X}$ update $\rightarrow$ the conjugate gradient method
- regularizer update $\rightarrow$ dictionary fitting
- easily parallelized for all slow-time points

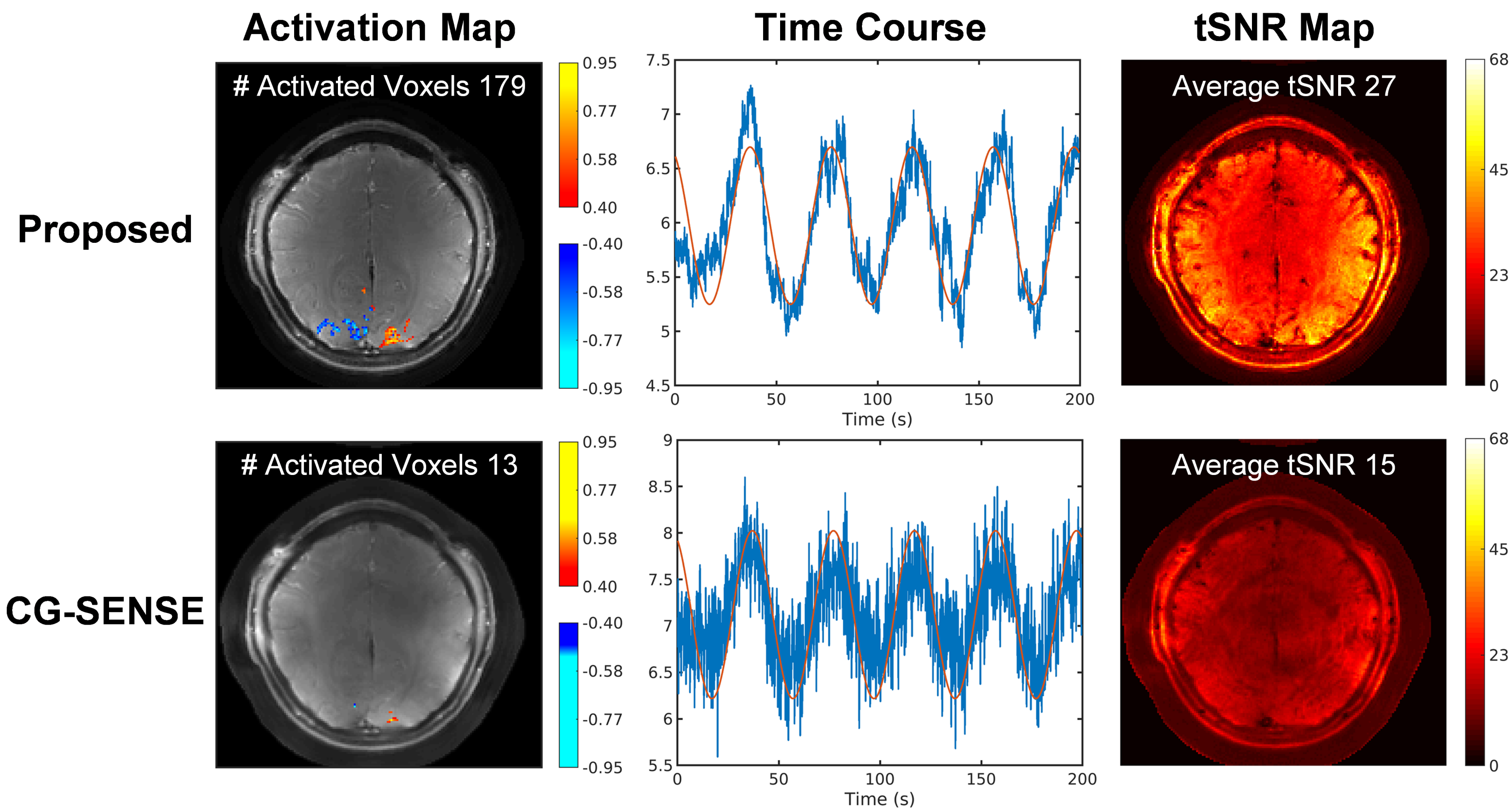
2D Human Retrospective Undersampling

- acceleration factor 12, NRMSD 5.6%, spatial resolution = 1.3 mm



2D Human Prospective Undersampling

- acceleration factor 12, spatial resolution = 1.3 mm, temporal resolution = 150 ms



Dictionary-Based Oscillating Steady State fMRI Reconstruction

- MR physics based signal model for reconstruction
  as a voxel-wise parametric regularizer
- Nonlinear dimension reduction for OSSI
- Acceleration factor of 12 with NRMSD 5.6%
- No spatial or temporal smoothing
- Joint undersampled reconstruction and parameter estimation

Future Work

- More accurate parameterization, T_2 or T_2^*
- More exploration of the manifold
- Combine with other regularizers
  (for both undersampled reconstruction and parameter estimation)

Acknowledgement

We thank NIH Grants R01EB023618 and U01EB026977 for supporting our work.

UNIVERSITY OF MICHIGAN