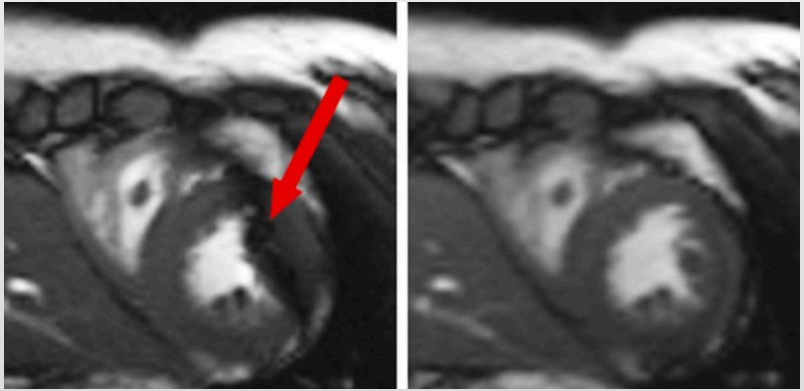
Constrained Model-based Relaxation Parameter Mapping using Balanced Steady State Free Precession

Zimu Huo[1], Minghao Zhang[2], Yiyun Dong[3], Joshua Kaggie[1], Pete Lally[4], Neal Bangerter[5], Michael Hoff[6], Martin Graves[1]

1. *Department of Radiology, University of Cambridge.*
2. *Wolfson Brain Imaging Centre, University of Cambridge.*
3. *Department of Physics, University of Washington.*
4. *Department of Bioengineering, Imperial College London.*
5. *Department of Electrical and Computer Engineering, Boise State University.*
6. *Radiology and Biomedical Imaging, University of California, San Francisco.*

Introduction

- The bSSFP sequence is widely used due to its high signal-to-noise ratio (SNR) efficiency. However, it suffers from signal losses in regions with large B_0 field inhomogeneity, resulting in banding artifacts.



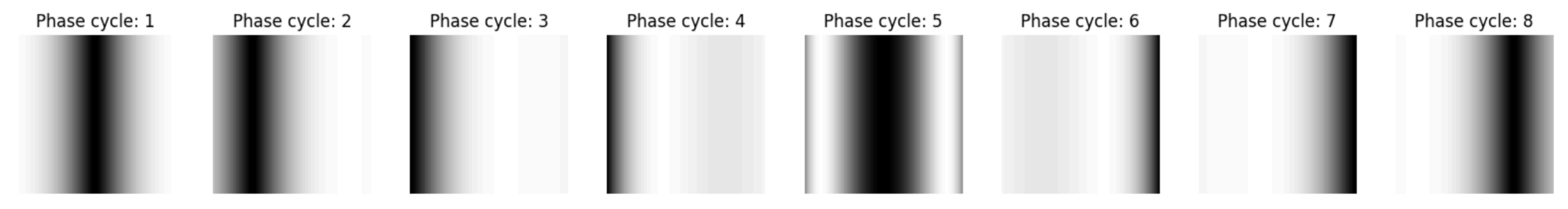
Highly interesting from a methodological standpoint

- Parameter mapping
- Super-resolution[1], and
- Parallel imaging[2]

1. Lally, P. Unbalanced SSFP for super-resolution in MRI. MRM
2. Berkin, B. Joint Reconstruction of Phase-Cycled Balanced SSFP with Constrained Parallel Imaging. ISMRM 2017

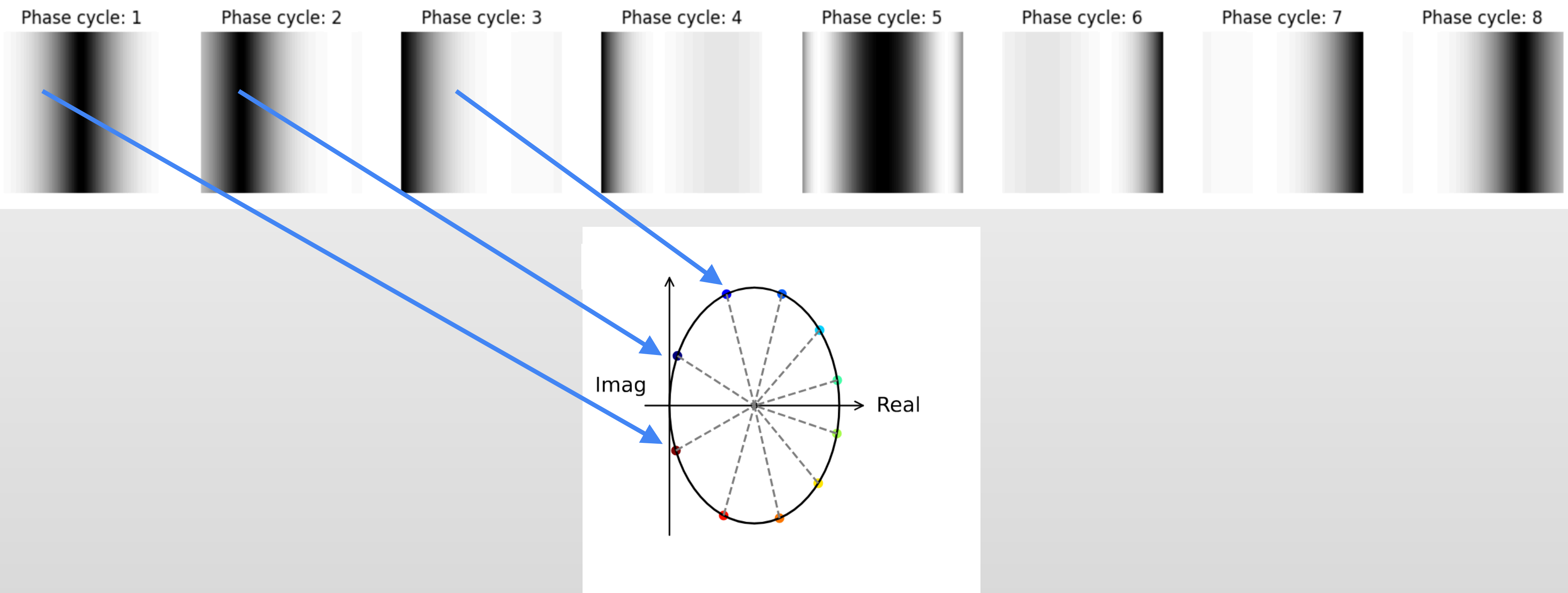
Introduction

- To mitigate these artifacts, typical bSSFP sequences acquire multiple linear phase-cycled images, each with a different linear RF phase increment, leading to the displacement of the banding artifacts in the spatial domain



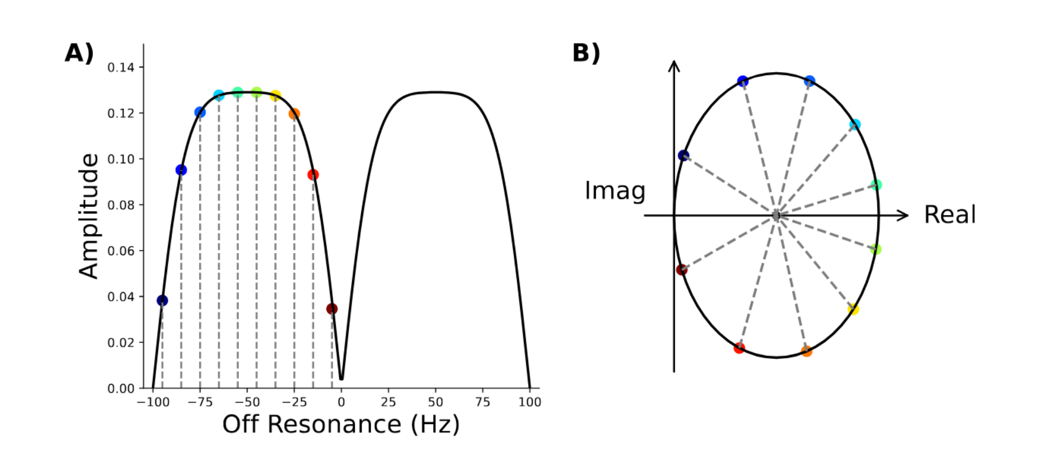
Introduction

- The real and imaginary components of the steady-state transverse magnetization form an ellipse across phase cycles on the complex plane.



Introduction

- Quantitative parameters may be derived using analytical expressions based on the geometric properties of this ellipse using a method referred to as PLANET[1]. However, voxel-wise fitting is sensitive to additive noise, leading to inaccuracies.



Y. Shcherbakova. MRM, vol. 81, no. 3, pp. 1534–1552, Oct. 2018

Theory

- We propose estimating relaxation parameters as a constrained nonlinear least square problem subject to data consistency costs in *k*-space to improve its noise robustness.
- Unlike traditional methods that extract quantitative relaxation parameters pixel by pixel, our approach leverages global information by jointly estimating T_1 and T_2 across the entire image and assessing reconstruction errors in k-space. Additionally, it supports flexible regularization options, such as total variation, which further mitigates noise sensitivity

$$
\begin{aligned}
\underset{T_1, T_2, M_0, B_0}{\text{minimize}} \quad & C = \| F \cdot \mathrm{M}(T_1, T_2, M_0, B_0) - y \|^2 \\
\text{subject to} \quad & p_i(T_1, T_2, M_0, B_0) = 0, \quad i = 1, \ldots, m, \\
& q_i(T_1, T_2, M_0, B_0) \leq 0, \quad i = 1, \ldots, n.
\end{aligned}
$$

Methods

- To evaluate noise sensitivity, we perform a Monte Carlo simulation by randomly generating T_1, T_2, and M_0 on a 16 by 16 image patch.
- T_1 is generated from 100 ms to 3000 ms, T_2 ranges from 1 ms and is upper bounded by the generated T_1 value, and M_0 values range from 0 to 2.
- B_0 map is generated based on low frequency noise in k-space to create smooth and slowly varying modulations in the image domain.
- We used a flip angle of 30 degrees, TR of 10 ms, TE of 5 ms.

Results: simulation

- The conventional approach fits each pixel individually across the phase cycle dimension (e.g., fitting through 6 complex data points for 6 phase cycles).
- In contrast, our method simultaneously fits the entire image by utilizing the entire k-space data across all phase cycles.

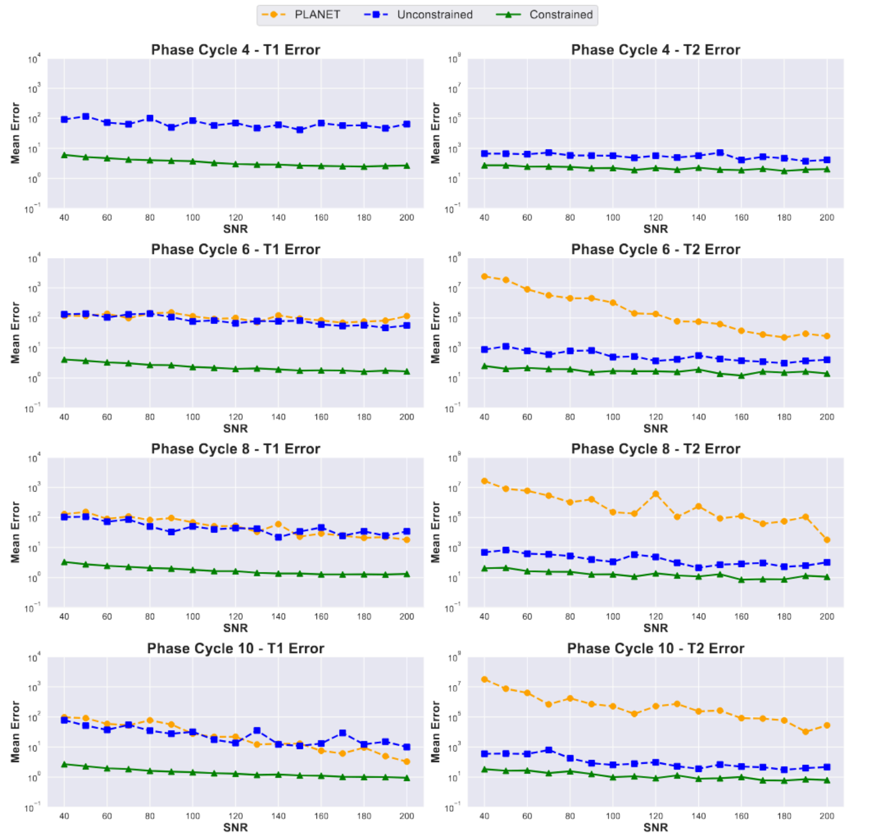
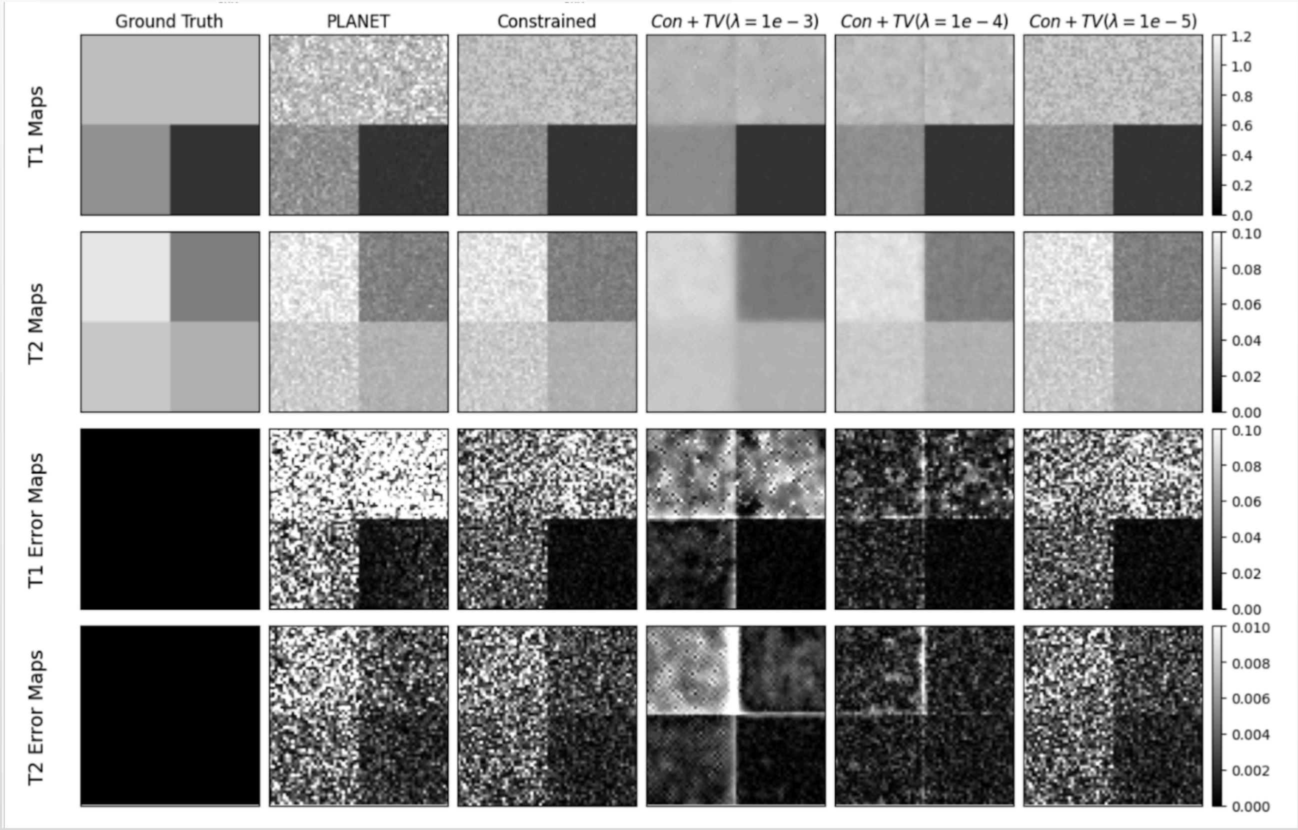


Figure 2: Simulation result.

Results: simulation (TV on T_1 and T_2)



Discussion

- The proposed method can be extended to multiple coils for parallel imaging. A key advantage is its ability to jointly solve for parameter maps by leveraging information across phase cycles and coils, effectively utilizing data redundancy.
- One limitation is the assumption of an ideal single-component relaxation model. Factors like diffusion, multi-compartment, and magnetization transfer can cause deviation and the steady state equation used in this work cannot fully capture this complexity[2].
- It is possible, at least partially, to include these secondary effects into the model.
- Future work will include phantom and in vivo acquisitions to validate the results.

2. K. Miller. MRM, vol. 63, no. 2, pp. 385–395, Jan. 2010

Conclusion

- The proposed constrained model-based fitting approach demonstrates robustness to noise across various phase cycles and SNR levels and outperforms the gold standard PLANET method.
- This is due to
    1. jointly solving parameter maps over an image,
    2. constraining the search space, and
    3. allowing additional regularizations.