SIMULATION AND HARMONIC ANALYSIS OF K-SPACE READOUT

John Bodenschatz[1] and Daniel B. Rowe[1,2]

[1]Department of Mathematical and Statistical Sciences, Marquette University, Milwaukee, WI, USA
[2]Department of Biophysics, Medical College of Wisconsin, Milwaukee, WI, USA

KLINGLER College of Arts & Sciences
MARQUETTE UNIVERSITY

INTRODUCTION

To run magnetic resonance imaging (MRI) experiments is both financially and temporally costly; demanding machine time and obtaining Institutional Review Board (IRB) approvals can slow down the process of investigating new statistical interpretations of fMRI data. Consequently, researchers will test developing methods on simulated data as a cost-effective way of measuring potential. Currently, simulated fMRI data are largely developed in-house for each researcher using a variety of methods. We present the current work on a software package entitled Simulation and Harmonic Analysis of *k*-Space Readout (SHAKER) that aims to provide a one-stop shop for fMRI simulations. This package is designed to allow maximum flexibility in parameters set by the user, such as: T1 and T2* values, echo and repetition time, *k*-space trajectories and pulse sequences, task design and activation ROIs, etc. The tool will output simulated complex-valued k-space data (and, optionally, reconstructed magnitude and phase images) that can be internally analyzed or exported for further analysis using the researcher's preferred method and programming language. SHAKER is a unique entrance to the market of fMRI simulation tools in that it is both physics-based in its simulation methods and GUI-based (see Figure 1) for its operability (as compared to the more common statistics-based simulators that are operated via command line or inline coding). This allows for researchers, both new to and well-versed to the field, to be able to generate fMRI time series data with complete control and observability of how the data are created. A fully operational and standardized fMRI simulator supports the expedition of other research projects in the field. Current work on SHAKER can be found at https://github.com/bodensjc/kspace-simulator. SHAKER is made public to allow for a better understanding of the design structure and examples of *k*-space trajectories, MR signal equations, reconstruction methods, and statistical maps – all major functionalities that can be designed and altered by researchers.

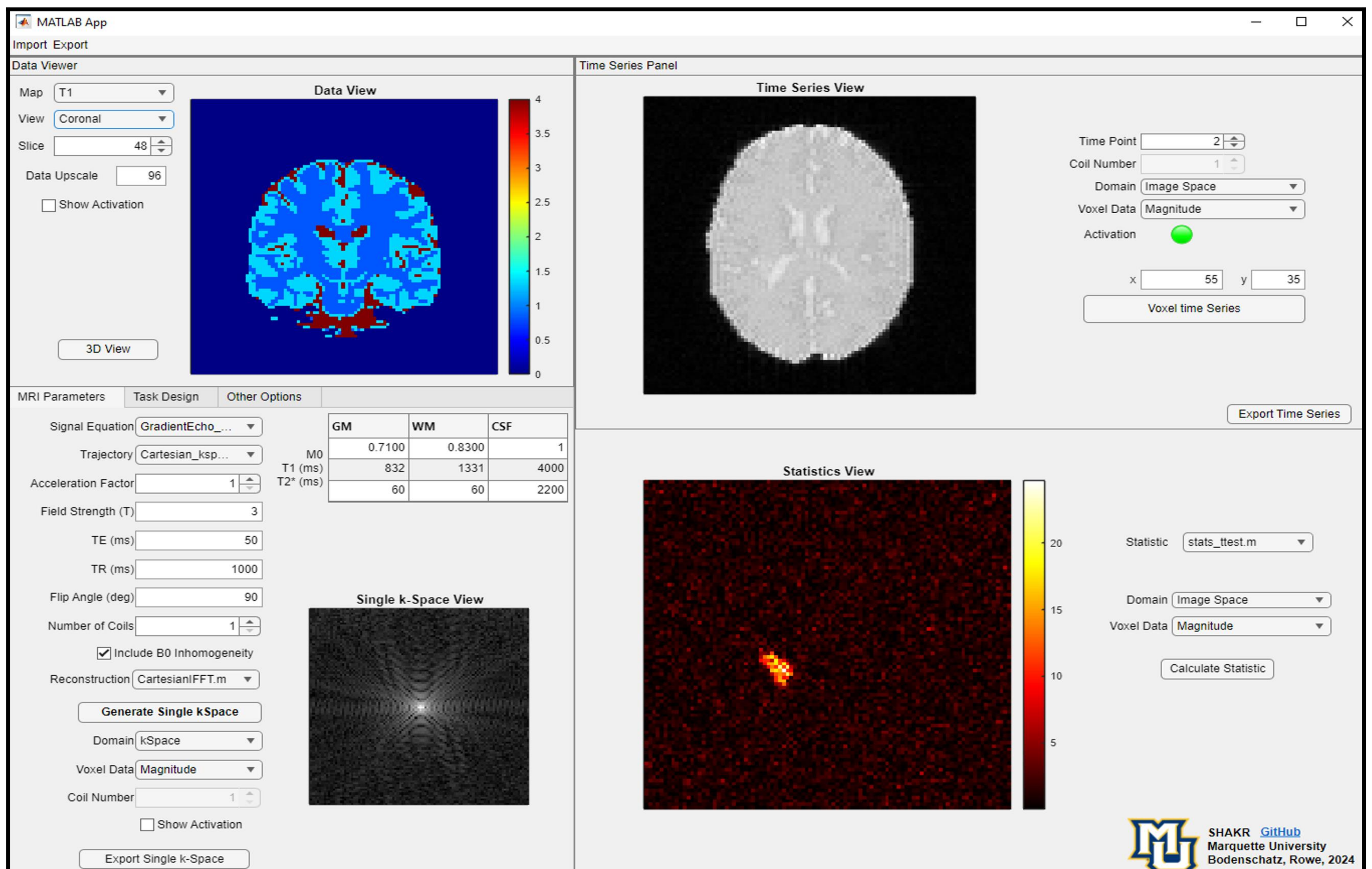
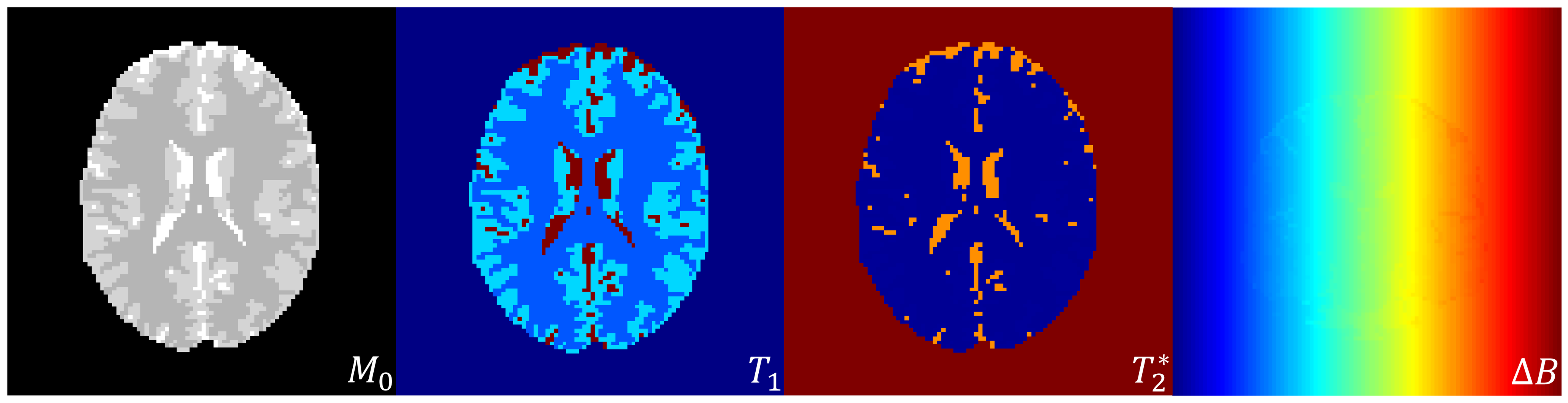


Figure 1: A screenshot of the working SHAKER GUI. In the top left pane, we can view the maps that will be input to the signal equation. In the bottom left pane, we have tunable (f)MRI parameters. The central pane displays two views: the top presents unaltered data from the simulated time series, and the bottom reflects an example of a statistical map created from the time series (e.g. *t*-statistic).

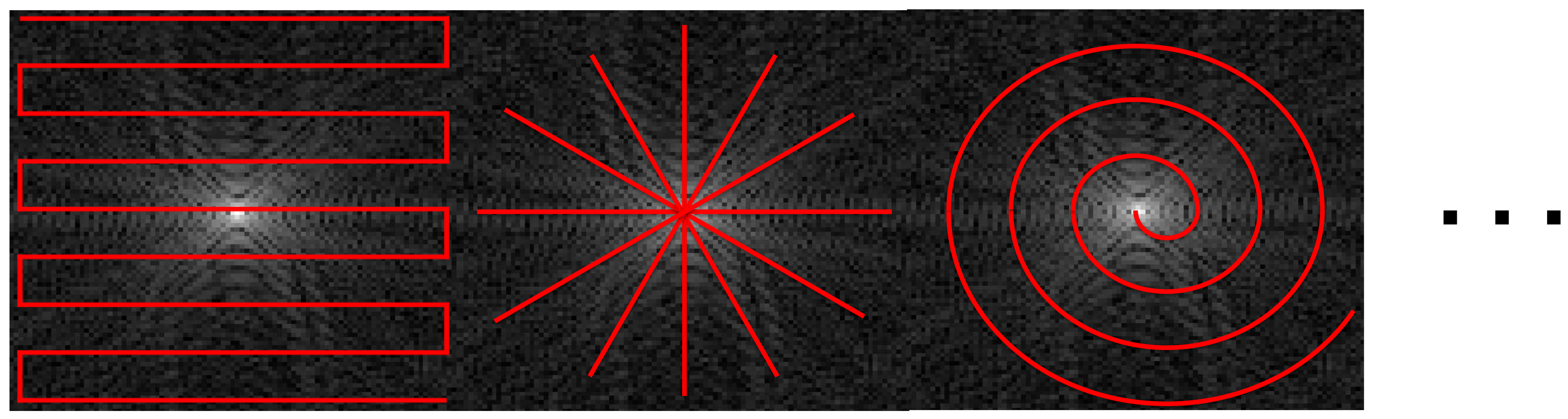
DESIGN



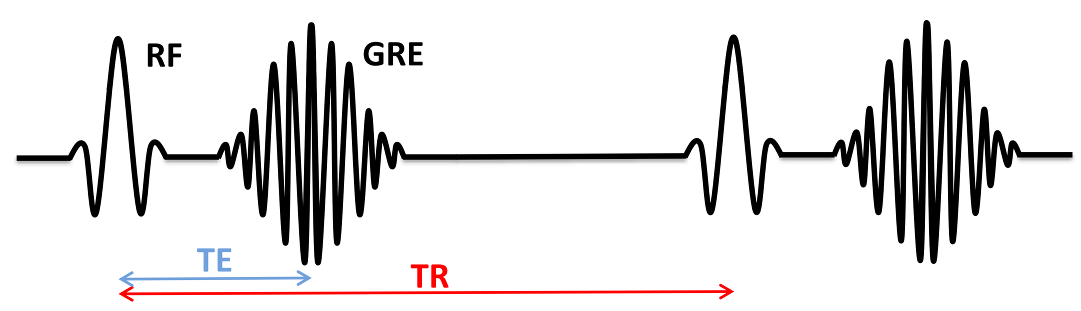
Net magnetization, relaxivity maps, and magnetic field inhomogeneity

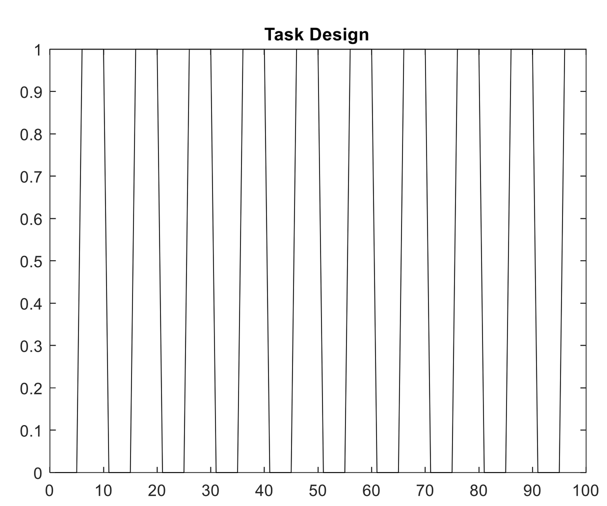
$$s(k_x,k_y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{M_0(x,y)\sin(\alpha)}{(1-\cos(\alpha)e^{-TR/T_1(x,y)})}\left(1-e^{-TR/T_1(x,y)}\right)e^{-t/T_2^*(x,y)}e^{i\gamma\Delta B(x,y)t}e^{-i2\pi(k_x x+k_y y)}\,dx\,dy$$

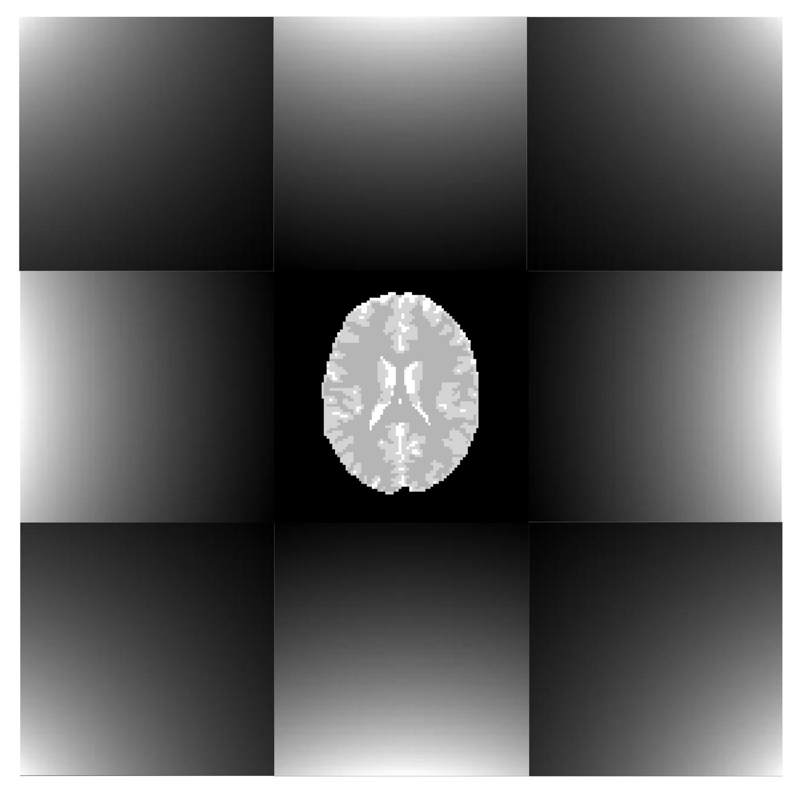
MR signal equation; gradient echo (GRE) with $\alpha = 90°$ is common for fMRI



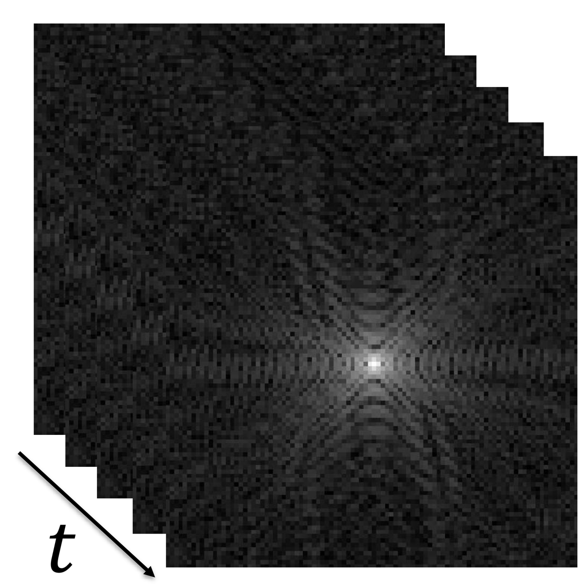
k-Space trajectory, follows a continuous path (turnaround points discarded)

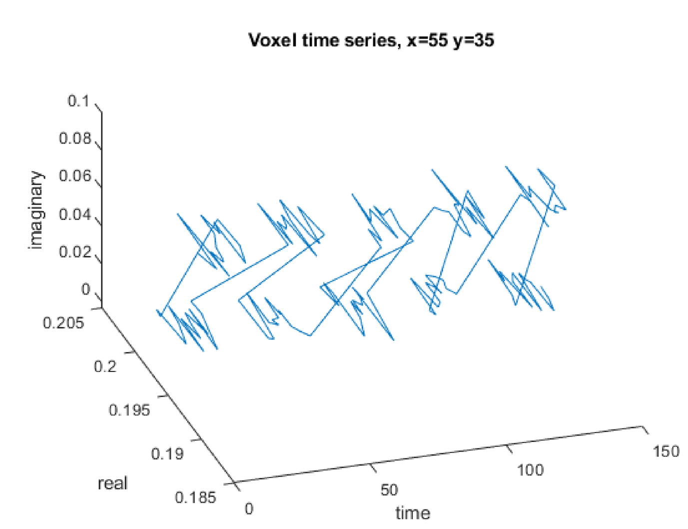






MRI machine parameters (TE, TR, …), fMRI experimental design, coils





k-Space and reconstructed image time series, image/voxel statistics, activation detection, etc.

REFERENCES

(1) Bernstein, M. A., King, K. F., and Zhou, X. J. *Handbook of MRI pulse sequences*, Elsevier Academic Press, 2004.
(2) Bruce, I.P., Karaman, M.M., and Rowe, D.B. *Incorporating relaxivities to more accurately reconstruct MR images*. Magnetic Resonance Imaging, 33(4):374-384, 2015.
(3) Comby, P.A., et al. *SNAKE-fMRI: A Modular fMRI Data Simulator from the Space-Time Domain to k-Space and Back*. arXiv:2404.08282, arXiv, 12 Apr. 2024.
(4) Rowe, D.B. *Modeling both magnitude and phase of complex fMRI data*. Neuroimage, 25:1310-24, 2005.
(5) Welvaert, M., et. al. *neurosim: An R package for generating fmri data*. *Journal of Statistical Software*, 44(10):1-18, 2011.

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