



Simulation and Harmonic Analysis of k-Space Readout (SHAKER)

John Bodenschatz¹ and Daniel B. Rowe^{1,2}

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



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. There has been work to develop a more standardized method to simulate fMRI time series data [3,5]. However, many such methods disregard the complex-valued nature and true statistical properties of the data that is output by the machine, and instead return magnitude-only images for simulations. These methods and models often fail to include relevant nuclear magnetic resonance (NMR) physics such as the longitudinal and transverse relaxivities, as well as inhomogeneities in the magnetic field. It will be beneficial to provide researchers with a software tool that allows the simulation of complex-valued fMRI time series data with the ability to tune various parameters relating to the scan. 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.

DESIGN

SHAKER is an all-inclusive fMRI simulation software package built with the user in mind. SHAKER is built off the MATLAB programming language and presents as a GUI, with no scripting or external data required. The (optional) input data and output data are currently optimized for analysis in MATLAB, with future plans to support data structures that are operational in more general languages, like **R**. At every step of the simulation process and analysis (listed below) the user has complete observability of the functions and operations being applied to the data, as well as the option to implement their own pulse sequence, reconstruction method, statistical measure, etc.

1. Slice and view selection (axial, sagittal, coronal), activation structure
2. Pulse sequence and MR parameter selection (TE, TR, ...)
3. fMRI task sequence design (HRF, multiple tasks, ...)
4. Time series generation, (optional) image reconstruction
5. Statistical interpretation of complex-valued time series

This method will fully support reconstruction and analysis of complex-valued images that are representative of the underlying physics governing the signal attained from the machine. It is often the case that the phase data of Fourier reconstructed images is discarded and only the magnitude image is studied. However, it has been shown that the phase image contains information regarding the local and global inhomogeneities in the magnetic field as well as changes in venous blood-oxygenation [4].

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

DESIGN – CONT.

Figure 1 reflects the data flow of SHAKER, similarly to as was previously listed. While no external inputs are required, all can be altered to fit each investigator's needs for their specific projects. Current work on SHAKER is depicted in Figure 2. The various panes and regions of the GUI help to facilitate the simulation process in an organized, direct manner.

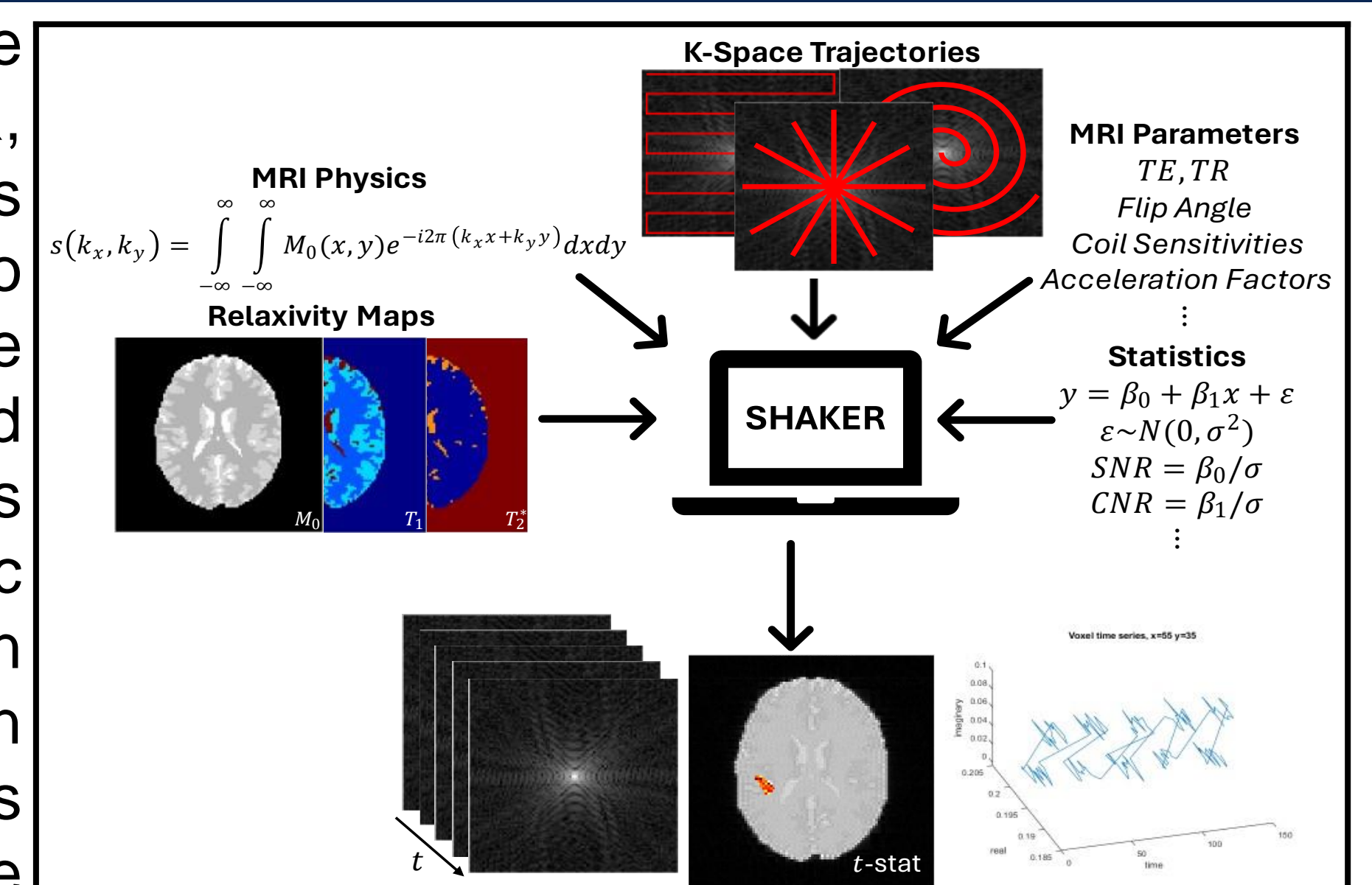


Figure 1: Display of various inputs to SHAKER and the output. SHAKER provides a wide range of common statistical analysis techniques, with the option to include researchers' own methods as well.

A fully operational and standardized fMRI simulator supports the expedition of other research projects in the field. 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 it is created. Future consideration for this work would involve the creation of an **R** Shiny app as a counterpart to the MATLAB app. This would expand the reach of the simulation package to those who are more accustomed to the **R** programming language or lack access to MathWorks software.

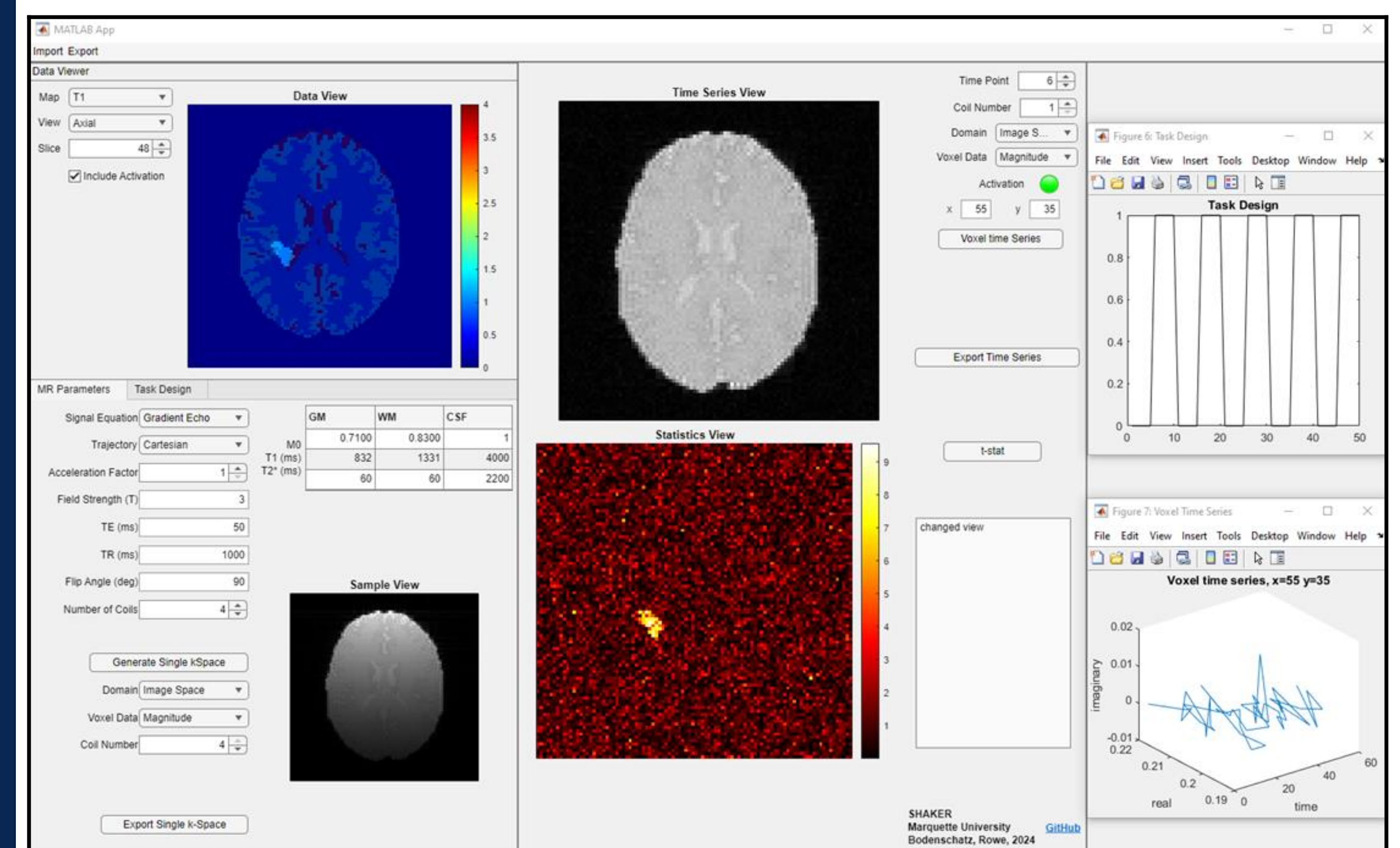


Figure 2: A screenshot of the working SHAKER GUI. In the top left pane, we can view the maps that will be input to the signal equation. In the bottom left pane, we have tunable (f)MRI parameters. The central pane displays two views: the top presents unaltered data from the simulated time series, and the bottom reflects an example of a statistical map created from the time series (t-statistic, in this case). The right pane shows two example plots (task design, single voxel time series) that can be created from within SHAKER.

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., 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. *SHAKE-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.