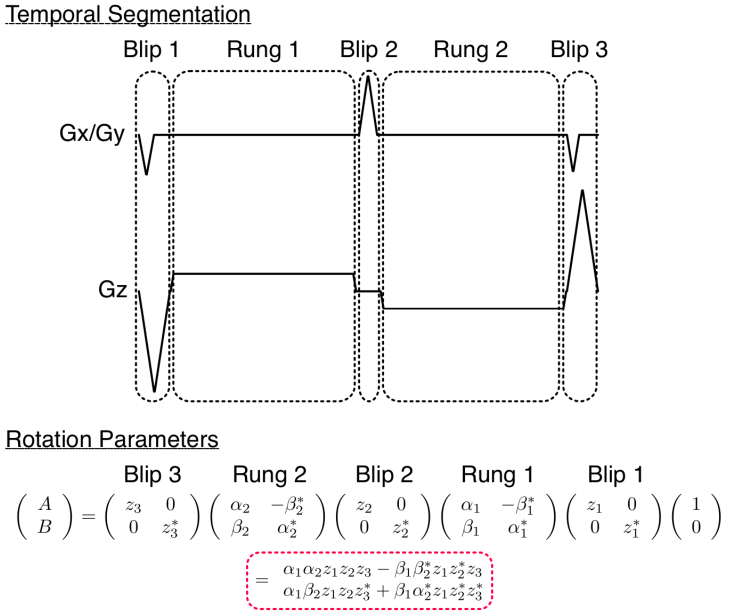
# Joint Design of Dual-Band Large-Tip-Angle RF and Gradient Waveforms in Parallel Excitation

**W. A. Grissom[1], A. B. Kerr[2], P. P. Stang[3], G. C. Scott[3], I. Hancu[4], M. W. Vogel[5], and J. M. Pauly[3]**
[1]Electrical Engineering and Radiology, Stanford University, Stanford, CA, United States, [2]Stanford University, Stanford, CA, United States, [3]Electrical Engineering, Stanford University, Stanford, CA, United States, [4]GE Global Research, Niskayuna, NY, United States, [5]Advanced Medical Applications Laboratory, GE Global Research, Munich, Bavaria, Germany

**Introduction** Determining optimal phase encoding locations for two and three dimensional parallel excitation pulses is a non-trivial problem, due to the non-Fourier spatial encoding in parallel excitation and the non-linear relationship between an excitation pattern and excitation gradient waveforms. Several algorithms for optimizing phase encoding locations have been developed for small-tip-angle parallel excitation (e.g., [1,2]), however, no method has yet been introduced for large-tip-angle excitation. Here we present a framework for large-tip-angle phase encode optimization, with experimental results demonstrating improved performance of dual-band echo-volumar spin echo pulses designed using the framework in conjunction with large-tip-angle RF design.

**Theory** Figure 1 illustrates the main idea behind our method. We temporally segment a blipped trajectory into 'rungs' and 'blips'. Assuming the RF is zero during the blips, the Cayley-Klein parameter $\alpha$ due to blip $j$ is given analytically by $z_j = e^{i\frac{\gamma}{2}\mathbf{x}\cdot\int_0^{T_j}\mathbf{g}(t)dt}$, where $T_j$ is the duration of the blip, while $\beta$=0 [3]. Concatenating the rung and blip rotation matrices and multiplying them out yields expressions for a pulse's net parameters ($A$,$B$), such as that shown in Fig. 1, whose relationship to blip areas are readily apparent. This permits straightforward optimization of the blips using, e.g., gradient descent [1] or optimization transfer [4].

**Experiments** We performed parallel excitation on a 1.5T GE Signa Excite scanner (GE Healthcare, Waukesha, WI, USA) using a 4-channel vector modulator-driven Tx array [5]. $B_1$+ maps were measured in a 12cm bottle phantom, and 4 sets of pulses were designed to excite uniform patterns over the phantom: 90/180° shimmed slice-selective pulses, and 2 sets of 7-rung flyback echo-volumar (EV) dual-band (water and fat) slice-selective spin echo (SE) pulses (13.9ms duration). The pulses were parameterized by SLR-designed subpulses (1cm slices, TB 2) [3]. In the first EV set, the RF weights and gradient blips were initially optimized in the small-tip regime using the method in [1]. The gradients were then fixed (i.e., remained 'small-tip optimal'), and RF weights were refined using the fast optimal control method [6]. A second 'large-tip-optimal' set was designed using the same small-tip initialization, but fast optimal control iterations were interleaved with gradient descent phase encode updates, using our described optimization framework. Target phase profile relaxation was used in all designs.



$$\begin{pmatrix} A \\ B \end{pmatrix} = \begin{pmatrix} z_3 & 0 \\ 0 & z_3^* \end{pmatrix}\begin{pmatrix} \alpha_2 & -\beta_2^* \\ \beta_2 & \alpha_2^* \end{pmatrix}\begin{pmatrix} z_2 & 0 \\ 0 & z_2^* \end{pmatrix}\begin{pmatrix} \alpha_1 & -\beta_1^* \\ \beta_1 & \alpha_1^* \end{pmatrix}\begin{pmatrix} z_1 & 0 \\ 0 & z_1^* \end{pmatrix}\begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$= \begin{matrix} \alpha_1\alpha_2 z_1 z_2 z_3 - \beta_1\beta_2^* z_1 z_2^* z_3 \\ \alpha_1\beta_2 z_1 z_2 z_3^* + \beta_1\alpha_2^* z_1 z_2^* z_3^* \end{matrix}$$

***Figure 1**: Segmentation of a two-rung EV trajectory into blips and rungs. During blips there is only phase accrual due to the gradients (i.e., zero RF), which leads to the top equation for the pulse's Cayley-Klein parameters (A,B). When multiplied out, that equation yields a straightforward relationship between the blip areas and the final parameters (bottom equation).*

**Results** Figure 2 shows SE water and fat excitation patterns, which were obtained via division of short-TE GRE images from SE images acquired with each pulse. Excitation patterns for the shimmed pulses contain strong inhomogeneities at the phantom's periphery. The EV pulses designed using the small-tip optimal gradients reduced the inhomogeneity at some of these locations, but increased inhomogeneities elsewhere, resulting in little overall gain in homogeneity compared to shimming. In contrast, the large-tip-optimal set excited significantly more homogeneous patterns than the other two sets, at both frequencies (2.4x and 3.2x less variance than small-tip optimal water and fat, respectively).

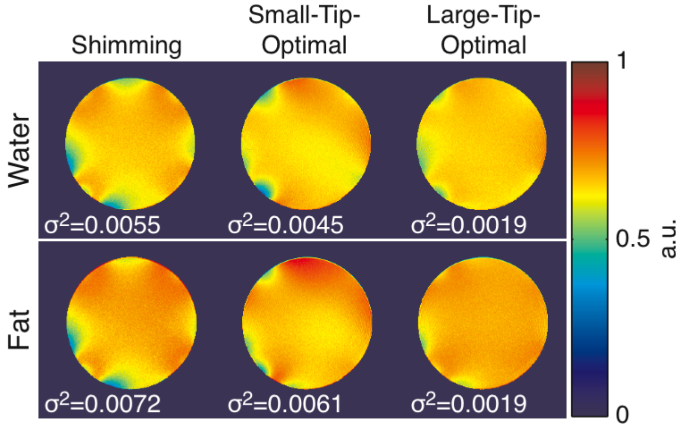


***Figure 2: Experimental Results.** The proposed joint RF and gradient optimization technique results in a significant improvement in homogeneity of the spin echo excitation pattern, in terms of signal magnitude variance within the phantom.*

**Conclusion** We have introduced a new framework for optimizing phase encoding locations of large-tip-angle pulses, and demonstrated that a gradient descent optimization based on this framework results in improved homogeneity in a dual-band spin echo $B_1$+ shimming experiment. No additional Bloch simulations are required compared to large-tip RF design alone, so this benefit comes at a negligible cost in compute time. We have also applied optimization transfer principles [4] to this problem, which results in an efficient, parameter-free phase encode optimization algorithm (results not shown).

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**References** [1] CY Yip et al, MRM, 58:598-604, 2007. [2] A Zelinski et al, IEEE TMI, 27:1213-29, 2008. [3] JM Pauly et al. IEEE TMI, 10:53–65, 1991. [4] AK Funai et al. IEEE TMI, 27:1484-94, 2008. [5] PP Stang et al, ISMRM 2008, p. 145. [6] WA Grissom et al, IEEE TMI, 28:1548-59, 2009.