An Algebraic Solution for Banding Artifact Removal in bSSFP Imaging

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Introduction Balanced steady state free precession (bSSFP) sequences in MRI efficiently generate high signal images. While bSSFP exhibits excellent refocussing of spins dephased by B_0 magnetic field inhomogeneity, excessive interpulse phase evolution θ yields signal nulls (bands) in images. Typically, successive RF pulses in the bSSFP pulse train are phase cycled by an angle Δθ in order to spatially shift the bands. Band attentuation is then achieved through some form of image combination [1,2].

Previously, we presented a geometric cross-solution (GS) which employs four phase cycled images to eliminate banding artifacts [3]; an image was formed from the cross-point of lines connecting alternating data points in the complex plane. An alternative approach is to demodulate the system using algebra: here a θ-independent magnetization expression is derived from the bSSFP magnetization formulae of four phase cycled images. The performance of GS, the new algebraic solution (AS), and a standard complex sum (CS) are compared.

Theory Eq(1) represents a convenient formulation of the complex bSSFP magnetization [4,5]. α is the flip angle, and T1 and T2 relaxation terms are given by $E_1 = e^{-TR/T_1}$ and $E_2 = e^{-TR/T_2}$. Signal in the four phase cycled images (for k = 1→4, $\Delta\theta_k$ = 0°, 90°, 180°, 270° respectively) is represented by four unique I_k expressions dependent on four parameters M, E_2, b and θ. AS is found by solving for the θ-independent magnetization M — see Eq(2). GS is given in Eq(3) [3].

$$I_k = M\frac{1-E_2e^{i(\theta+\Delta\theta_k)}}{1-b\cos(\theta+\Delta\theta_k)} \qquad M=\frac{M_0(1-E_1)\sin\alpha}{1-E_1\cos\alpha-E_2^2(E_1-\cos\alpha)} \qquad b=\frac{E_2(1-E_1)(1+\cos\alpha)}{1-E_1\cos\alpha-E_2^2(E_1-\cos\alpha)} \quad (1)$$

$$\textbf{AS} \qquad M=\frac{I_1I_3(I_2-I_4)(1+i)+I_2I_4(I_1-I_3)(1-i)}{I_1I_2-I_3I_4+i(I_2I_3-I_1I_4)} \quad (2)$$

$$\textbf{GS} \qquad M=\frac{(x_1y_3-x_3y_1)(I_2-I_4)-(x_2y_4-x_4y_2)(I_1-I_3)}{(x_1-x_3)(y_2-y_4)+(x_2-x_4)(y_3-y_1)} \quad (3)$$

Methods Both AS and GS were applied to simulated and MR phantom images. Data was simulated using Eq(1) with α = 41° and TR = 5ms. Tissue has T1 = 200ms→3000ms, and T2 = 40ms→3000ms. Accordingly, E_2 = [0.88, 0.92, 0.97, 0.99] was set horizontally, and b = [0.2, 0.4, 0.6, 0.75] was set vertically, yielding a matrix of 16 E_2/b combinations. For each combination, θ values were varied from –π to π (Fig.1A). Phantom data was generated using a 3D TrueFISP (bSSFP) sequence on a 1.5T Siemens Avanto scanner. The imaged water bottle held a Zimmer™ (Warsaw, IN) Co-Cr-Mo alloy hip prosthesis to provide field inhomogeneity. The four datasets were acquired with 52x3mm slices, α = 70°, and TE/TR = 1.9ms/3.8ms (Fig.2A). Data was processed pixel-by-pixel: complex signal values I_k, their real parts x_k, and imaginary parts y_k were input into Eq(2) and Eq(3) to calculate AS and GS. Additionally, CS and a 2nd pass AS for improved SNR [6] were computed. SNR was calculated regionally by dividing the mean signal by its standard deviation.

Results Fig.1 depicts one of the four simulated images, and the corresponding CS, GS, and AS — all with and without noise. Both GS and AS eliminate bands. Fig. 2 shows the four phantom images, CS, GS, AS, and an SNR-improved 2nd pass AS. The SNR values in red on images with noise show that GS consistently has the highest SNR, and CS and AS have relatively similar SNR. Fig.2D & E illustrate that the lack of coherent ripple artifacts in AS permits regional processing to elevate SNR. AS becomes unstable if the real and imaginary parts of the input images are swapped, whereas GS is unaffected by data swapping (not shown).

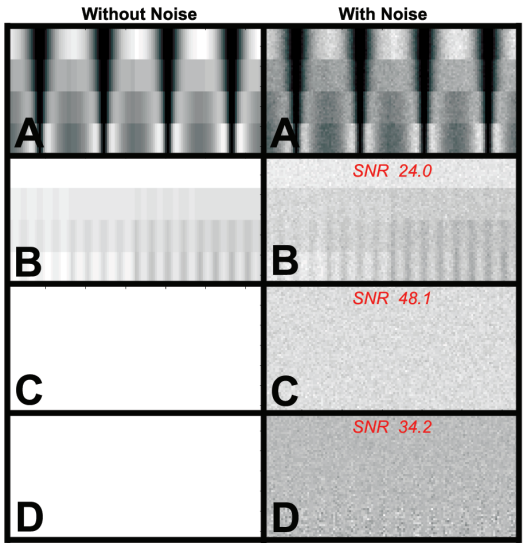

Fig.1: Simulated images without (left) and with (right) noise. A: One of four original datasets. B: Complex sum. C: Geometric solution. D: Algebraic solution.

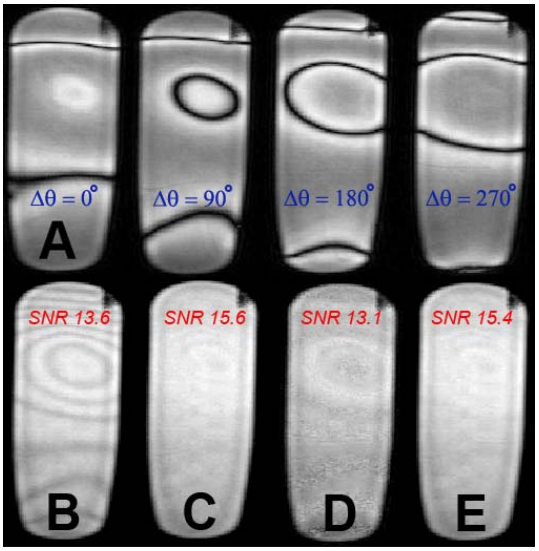

Fig.2: MR phantom images. A. Four phase cycled originals. B: Complex sum. C: Geometric solution. D: Algebraic solution (AS). E: SNR-enhanced AS.

Discussion An algebraic solution to the bSSFP banding problem is formulated and compared with the recently introduced geometric solution. GS and AS have fundamental differences: unlike GS, AS requires absolute definition of its real and imaginary parts, coinciding with the sign of the "i"s in Eq(2). GS is more robust in noise, thanks to the cross-point's resilience to data variability. Both solutions remove banding and yield incoherent, non-ripple artifacts which permit regional SNR enhancement. This work inspires further optimization and investigation into bSSFP signal demodulation.

References [1] Zur *et al*., MRM, 16:444-459, 1990. [2] Bangerter *et al.*, MRM, 51:1038-1047, 2004. [3] Xiang & Hoff, Proc. ISMRM, 18:74, 2010. [4] Ernst & Anderson, Rev Sci Instrum, 37:93-102, 1966. [5] Lauzon & Frayne, Conc Mag Res, 34A(3):133-143, 2009. [6] Xiang & An, JMRI, 7:1002-1015, 1997