# Simple Cross-Solution for Banding Artifact Removal in bSSFP Imaging

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**Introduction** Fast imaging methods using Balanced Steady-State Free-Precession (bSSFP), such as TrueFISP or FIESTA, are finding broad clinical applications owing to their high efficiency in data acquisition and desirable contrast. Unfortunately, banding artifacts are often seen in bSSFP imaging as signal modulation due to $B_0$ inhomogeneity. Several images can be acquired in which these bands are spatially shifted by RF phase-cycling, and combined into an image with reduced banding artifacts. Various algorithms for image combination have been used [1-3], including Maximum Intensity Projection (MIP), Sum of Squares (SOS), Nonlinear Averaging (NLA), and Complex Sum (CS). However, none of the above removes banding completely when a finite number of phase cycles are employed. In this work, based upon a novel elliptical model of the signal, a simple analytical solution to the problem is presented which is able to remove banding artifacts completely.

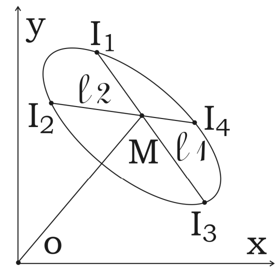


Fig.1 Elliptical model of bSSFP signal

$$I = M \frac{1 - a e^{i\theta}}{1 - b \cos\theta} \qquad (1)$$

**Methods** Theory The signal from bSSFP can be described by Eq. (1) [4, 5], where M is the complex magnetization, “a” and “b” are real functions of $T_1$, $T_2$, and flip angle, and angle θ is the spin phase evolution per TR which depends on $B_0$ field inhomogeneity. With RF phase-cycling, a number of such equations can be obtained in which the angle θ has known increments Δθ. Eq.(1) resembles equations in water-fat imaging [6], which suggests the possibility of finding all parameters by solving these equations simultaneously. It has been discovered that when four complex images $I_1$, $I_2$, $I_3$ and $I_4$ are acquired with Δθ = 0, π/2, π, and 3π/2 respectively, M can be solved analytically to yield Eq.(2), where $(x_j, y_j)$ are the real and imaginary parts of the $j^{th}$ complex image. This solution has the following geometric interpretation: Eq.(1) is in fact a parametric equation that traces out an ellipse in the complex plane as θ changes continuously from 0 to 2π. When N phase-cycled acquisitions are used, each pixel is represented by N points along the ellipse. The situation for N = 4 is shown in Fig.1. Two straight lines $\ell_1$ and $\ell_2$ can be constructed by connecting the two “diagonal pairs” ($I_1$, $I_3$) and ($I_2$, $I_4$). The solution M in Eq.(2) is nothing but the intersection of $\ell_1$ and $\ell_2$, and is thus termed a “Cross-Solution (XS)”. This solution is totally independent of θ, and represents the completely demodulated magnetization M. In contrast, one of the other most effective algorithms, CS [3], only finds the “centre of mass” of the 4 points on the ellipse. This still has θ dependence, suggesting an incomplete demodulation of the magnetization. Eq. (2) can either give a direct solution pixel-by-pixel, or guide a second path solution for improved SNR, similar to that for water-fat imaging [6].

$$M = \frac{(x_1 y_3 - x_3 y_1)(I_2 - I_4) - (x_2 y_4 - x_4 y_2)(I_1 - I_3)}{x_1 y_2 + x_2 y_3 + x_3 y_4 + x_4 y_1 - x_1 y_4 - x_4 y_3 - x_3 y_2 - x_2 y_1} \qquad (2)$$

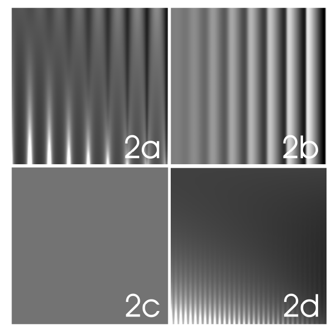


Fig.2 Simulated bSSFP banding in magnitude (a), and phase (b), removed by XS (c), still remaining after CS (d)

Simulation and Experiment Equation (1) was used to generate a set of 4 phase-cycled images, in which M remains a constant but “a” and “b” change from 0 to 1 along vertical and horizontal directions respectively, to cover all possible scenarios of signal modulation [5]. The angle θ changes in the horizontal direction from 0 to 16π, creating 8 cycles of banding. Four such data sets are generated by adding Δθ = 0, π/2, π, and 3π/2 to θ, simulating phase-cycling. The magnitude and phase of one of the 4 images are shown in Figs. 2(a) and (b). Phantom experiments were performed on a 1.5T scanner (Siemens Magnetom Avanto, Erlangen, Germany) using a TrueFISP sequence with TR/TE = 4.2/2.1ms. Four phase-cycled images with Δθ = 0, π/2, π, and 3π/2 were acquired; the magnitude of one of them is shown in Fig. 3(a). The artifactual dark lines were induced by metal implants near the imaging plane, which contained water and sponge.

**Results** The “Cross-Solution” (XS) given in Eq.(2) was used to obtain the demodulated magnetization M for both simulated and experimental data; results are shown in Fig. 2(c) and Fig. 3(b), respectively. For comparison, CS was used to generate Fig. 2(d) and Fig.3(c). Clearly, the banding artifact has been completely eliminated by XS as shown in Figs. 2(c) and 3(b), but still remains in Figs.2(d) and 3(c) after CS, demonstrating the effectiveness of the proposed XS algorithm for all possible combinations of parameters “a” and “b”.

**Discussion** A novel elliptical signal model is presented, which not only allows intuitive visualization and understanding of bSSFP signal, but also suggests a simple analytical “Cross-Solution (XS)” for signal demodulation, leading to complete banding artifact removal in both simulated and experimental data. Natural extensions of this work include an SNR study, and generalization of XS for other sampling intervals along the ellipse.

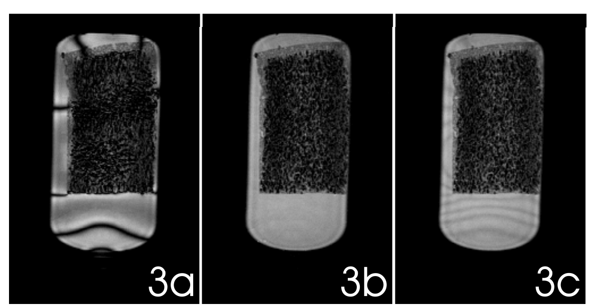


Fig.3 Banding in original bSSFP image (a), removed by XS (b), still remaining after CS (c)

**References**

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