# Removing SSFP Banding Artifacts from DESPOT2 Images Using the Geometric Solution


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**Introduction**: Driven-Equilibrium Single-Pulse Observation of $T_1$ (DESPOT1) is a widely used time-efficient alternative to Inversion Recovery measurements of longitudinal relaxation[1]. The equivalent method for transverse relaxation, DESPOT2[2], is less common due to off-resonance banding artifacts in the balanced Steady-State Free Precession (bSSFP) sequence that become problematic at a field-strength of 3T and above. A previous method to correct these artifacts, DESPOT2-FM[3], requires a complicated algorithm that can take over 48 hours to process a human brain at 1 mm isotropic voxel size on a single-core CPU. Recently a Geometric Solution was presented to remove band artifacts[4]. We integrate this method with DESPOT2 to create $T_2$ maps in seconds, at the expense of further scan time as 4 phase-cycles are required, compared to 2 for DESPOT2-FM.

**Theory**: Xiang and Hoff showed that the elliptical bSSFP signal equation has an interesting property – any pair of lines joining points measured with opposing phase-cycling patterns will cross at the same point[4], called the Geometric Solution (GS). The signal equation describing the GS is:

$$M_E = G\frac{1-ae^{-i(\omega+\phi)}}{1-b\cos(\omega+\phi)}, G = \frac{-M_0\sin\alpha\,(1-E_1)\sqrt{E_2}e^{i\omega/2}}{1-E_1E_2^2-(E_1-E_2^2)\cos\alpha}, a=E_2, b=\frac{E_2(1-E_1)(1+\cos\alpha)}{1-E_1E_2^2-(E_1-E_2^2)\cos\alpha}$$

where $M_E$ is the magnetization at the echo time $T_E$, $M_0$ the equilibrium magnetization, $G$ the Geometric Solution, $\omega$ the off-resonance frequency, $\Phi$ the phase-cycling angle, $\alpha$ the flip-angle, and $E_1=\exp(-T_R/T_1)$, $E_2=\exp(-T_R/T_2)$. This can be linearized over two or more flip-angles[1], and $T_2$ and $M_0$ extracted using least-squares fitting (where $m$ is the slope and $c$ the intercept). $\omega$ can also be calculated from the GS:

$$\frac{G_i}{\sin\alpha_i} = \frac{E_1-E_2^2}{1-E_1E_2^2}\frac{G_i}{\tan\alpha_i} + M_0\sqrt{E_2}\frac{1-E_1}{1-E_1E_2^2} \therefore T_2 = \frac{2T_R}{\ln\left(\frac{mE_1-1}{m-E_1}\right)}, M_0 = c\frac{1-E_1E_2^2}{\sqrt{E_2}\,(1-E_1)}, \omega = \frac{\angle G_i}{\pi T_R}$$

The precision of the GS method was compared to DESPOT2-FM with both two (FM2) and four (FM4) phase-cycling patterns using Monte-Carlo simulations across a range of $T_2$ values, but using only a pair of flip-angles optimised for measuring $T_2$=100 ms[2].

**Experiments**: A doped water phantom and single adult male volunteer were scanned on a 3T GE Discovery MR750 system (General Electric, USA), using a protocol consisting of: SPGR scans with $T_R$=8.3 ms, flip-angles 4&18°; bSSFP scans with $T_R$=4.9 ms, flip-angles 15&70° and phase-cycling of 45,135,225&315°; and an IR-SPGR image for B1 mapping[3]. The SPGR and bSSFP images had 1 mm isotropic voxel sizes and lasted 6.5 and 13 minutes respectively. A $T_1$ map was created from the SPGR data and used to calculate $T_2$ maps using both the GS, FM2 & FM4 methods (FM2 used only the 45&215° phase-cycled images). During the phantom scan banding artifacts were deliberately induced by mis-setting the shim in the z-direction. Inter-scan motion was corrected by rigidly aligning all images to the first SPGR image using ANTs[5].

**Results**: Figure 1 shows that GS has comparable precision to FM2 but worse than FM4 at long $T_2$ values. Figure 2 shows the results of the scans. GS shows markedly improved band removal, particularly compared to FM2. Processing times were 90 ms, 164 ms and 20 µs per voxel for FM2, FM4 and GS respectively on an Intel Xeon 2.4 GHz CPU.

**Conclusion**: DESPOT2-GS decreases the required processing time by 4 orders of magnitude, exhibits improved robustness against banding artifacts and comparable quality compared to DESPOT2-FM. However it required an additional 50% scan time in our protocol (total time 22 minutes), which may be impractical in clinical situations.

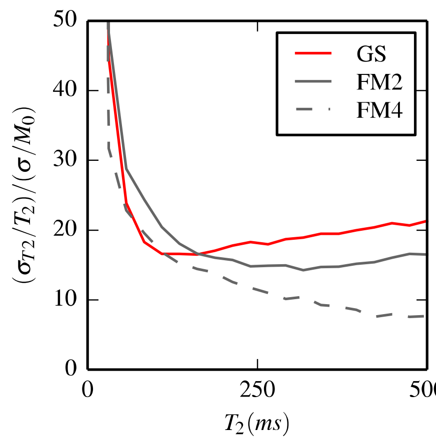


Figure 1: Simulated relative precision of GS, FM2 & FM4 across a range of T2 values


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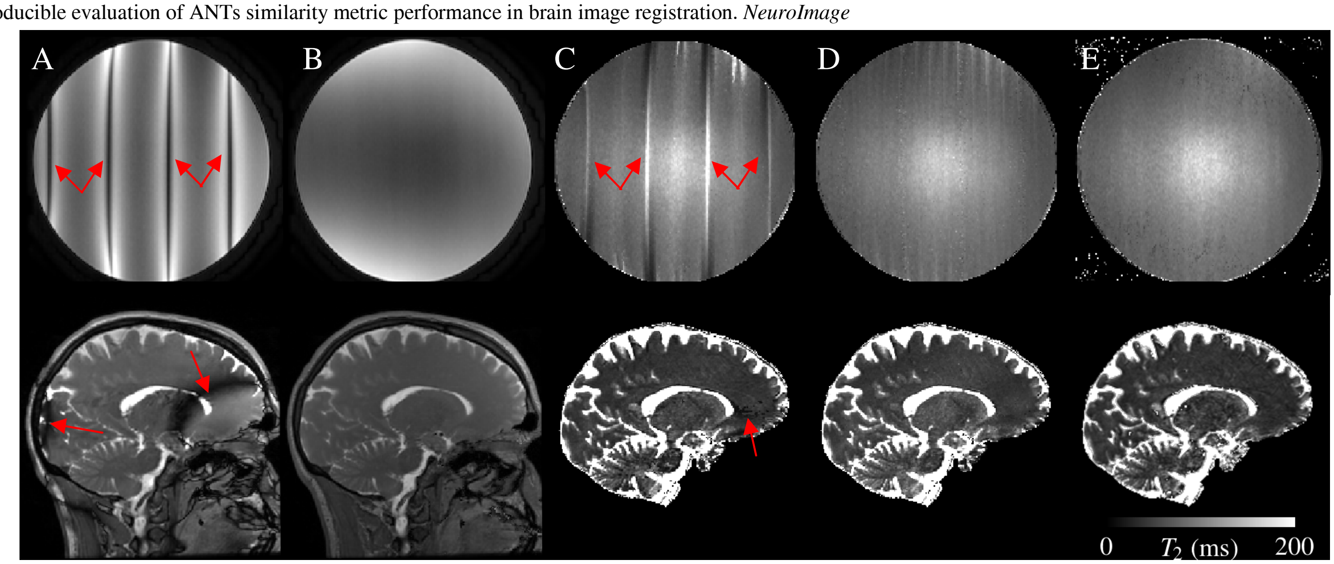


Figure 2: Results of the phantom (top) and volunteer (bottom) scans. A – Raw SSFP image exhibiting banding artifacts (highlighted with red arrows). B – GS image with no bands. C – $T_2$ from FM2 showing residual artifacts (red arrows) D – $T_2$ from FM4 E – $T_2$ from GS. The GS maps exhibit greater robustness against banding artifacts and comparable quality to the FM maps.