# An Efficient Method to Correct Signal Drop-Out in EPI

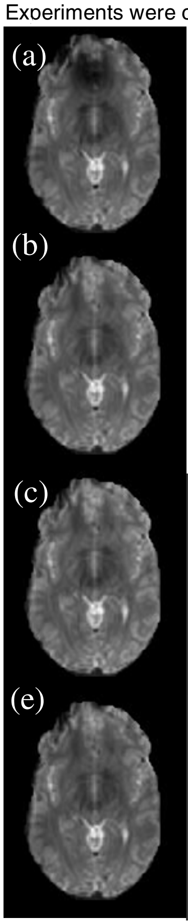
H. Marshall[1], D. J. Larkman[1], J. V. Hajnal[1]

[1]Robert Steiner MRI Unit, Imaging Sciences Department, MRC Clinical Sciences Centre, Hammersmith Hospital, Imperial College London, London, United Kingdom

**INTRODUCTION:** Echo planar imaging (EPI) suffers from signal loss due to through-slice magnetic field ($B_0$) inhomogeneity, which can be corrected using the z-shim[1] method. Z-shim approximates local $B_0$ variations as linear and recovers signal by applying an opposite refocusing gradient. However, the required gradient is spatially varying and unknown, and each refocused image requires a separate acquisition. Multiple z-shims are required for full correction, making the method inefficient. Methods have been developed to increase the speed of z-shim acquisition[2,3] and minimise the number of z-shims required by appropriate choice of refocusing values[4,5]. For a rectangular slice profile, Ordidge et al[4] used a series expansion in k-space and showed that 4 z-shim measurements are sufficient to recover 90-97% of signal for most pixels in the brain, and Wild et al[5] reduced this to 3 z-shims. In this study we demonstrate that 2 z-shim values can produce equivalent results and propose an efficient procedure to select suitable values.

**BACKGROUND AND THEORY:** Viewed in k-space, full signal in a given pixel in a slice selected image is achieved when the k = 0 point of the Fourier transform of the slice profile is measured. Where change in $B_0$ through the slice is linear, the result is a shift of the Fourier transform of the slice profile away from the centre of k-space so the measured signal comes from a point $k \neq 0$, the signal is dephased through-slice in image space. The shape of the k-space profile is not changed providing the $B_0$ variation is linear (a gradient field). Applying a gradient in the slice direction shifts the slice profile back so that a correctly chosen z-shim allows full signal to be recovered. Ordidge observed that if the k-space slice profile is known, then signal recovery can be achieved from a suitable set of measurements with different z-shims applied. For a rectangular slice, the k-space profile is a sinc function with zero crossings every $\Delta k$, where $\Delta k = 2\pi$ / slice thickness. If signals are measured with z-shims that shift in steps of $\Delta k$, the sum of squares (SOS) of these approximate to the full signal. For a sinc slice profile, 3 such points provide a good approximation as long as the main lobe of the profile is between two of the points (Wild et al[5]). In practice the actual slice profile is usually not a pure sinc. We have observed that at 3T the main lobe of the slice profile is well conserved, but side lobes are highly variable in shape where through-slice gradients exist. This suggests that data sampled from the main lobe are likely to provide the most robust contributions to such corrections, and perhaps are all that is required. Given that limited points are desired for correction, it is important to find the mean k-space location $k_0$ for which the available range of shifts from $k_0 - \Delta k/2$ to $k_0 + \Delta k/2$ allows the maximum number of pixels in the images to be corrected (where $\Delta k$ is now generalised to be half the width between zero crossings of the main lobe of the true slice profile). This requires the distribution of shifts to be determined, which can be done using a large number of measurements with different z-shims applied, or more efficiently by fitting the known k-space slice profile shape to a sparse set of measurements[6].

**METHODS:** The SOS method was simulated in MATLAB using two points on a sinc function at a variable separation in k over a shift range of $\Delta k$. Experiments were conducted using a Philips 3T Intera system and processing was performed in IDL. A single-shot dynamic EPI sequence was modified to acquire 50 z-shimmed images per slice, to finely sample the k-space slice profile for use as a gold standard dataset. The whole brain was imaged with slice thicknesses of 3, 4 and 5mm. The optimal spacing predicted by the simulation was tested by sub-sampling this gold standard dataset in the same way as the simulation. The central lobe of the RF pulse was used as a model for the k-space slice profile. To test the proposed sparse calibration method the gold standard dataset was subsampled to find the smallest number of points which, when fitted pixel by pixel with the model slice profile, produced a robust estimate of the histogram of shifts from the full dataset. The fitting procedure first identified the sampled z-shim that produced the largest signal and then used this and the neighbour with the next largest signal to determine the predicted full signal amplitude and the required shift. The fits were then tested against the full data set to identify errors. Once a robust histogram of shifts had been estimated, this was used to find the optimal value of $k_0$ for the SOS correction methods, both on a slice by slice and a whole brain basis. Results were compared with the gold standard. Tests were performed on 7 datasets from 2 subjects.



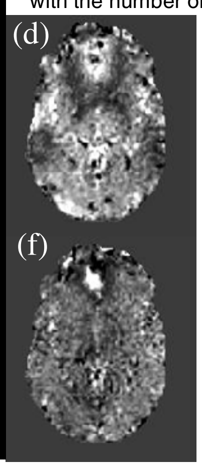




Figure 2: (a) the uncorrected image, (b) gold standard correction, (c) 3 pt SOS spaced by $\Delta k$, (d) gold – 3 pt SOS, (e) 2 pt SOS spaced by $0.9\Delta k$ and (f) gold – 2 pt SOS

**RESULTS:** For a sinc function the simulation predicted an optimum spacing of $0.9\Delta k$ for 2 z-shim values combined by SOS (figure 1a). Over this range of shifts, 2 z-shims spaced optimally perform better than 3 points spaced at $\Delta k$ (the sinc series expansion requires 11 terms to achieve the same level of accuracy). This was confirmed by experimental data, with $0.88\Delta k$ being the measured optimal spacing. Robust histogram estimation was achieved with measurements spaced by $0.9\Delta k$, with the number of points required increasing as slice thickness increased ($\Delta k$ decreased relative to the shift range). In these experiments the number of points required was $\Delta x + 1$, where $\Delta x$ is the slice thickness in mm. Image reconstruction results for a slice-optimised choice of $k_0$ from the histogram (figure 1b, red lines $k_0 \pm \Delta k/2$) are shown in figure 2: (a) is a conventional 3mm slice above the frontal sinus showing through-slice signal loss, (b) is the gold standard correction from the whole 50 z-shim dataset, (c) the 3 z-shim SOS correction with $\Delta k$ spacing and (e) the 2 z-shim correction with $0.9\Delta k$ spacing, while (d) and (f) show the difference gold - 3 point SOS and gold - 2pt SOS respectively. Note that over most of the slice (and for 95% of all pixels in the brain) the 2 z-shim SOS correction is closer to the optimum, however, in the few pixels where it failed, the failure is more extreme than in the 3 z-shim case. Choosing $k_0$ on the basis of a whole brain histogram (figure 1b, blue lines $k_0 \pm \Delta k/2$) rather than the slice specific histogram, reduces the correction fraction by 1% over the whole brain for a 3mm slice thickness.

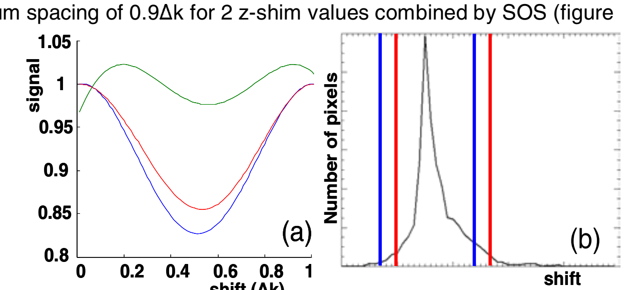



Figure 1: (a) Predicted correction over $\Delta k$ shift range for 3 z-shim SOS $\Delta k$ spacing (red), 2 z-shim SOS $\Delta k$ spacing (blue) and 2 z-shim SOS $0.9\Delta k$ spacing (green), (b) shift histogram for displayed slice

**DISCUSSION:** The SOS combination of only 2 z-shims at optimal spacing gives accurate correction for most pixels in the brain at 3T. In combination with a shift histogram estimation method using k-space slice profile fitting, the approach is efficient in both set up and operation. Techniques such as fMRI, which benefits greatly from z-shim but requires large amounts of data, are particularly suitable applications and the method can easily be combined with parallel imaging for even greater efficiency.

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**REFERENCES:** (1) J. Frahm et al. MRM 6:4, 1988; (2) K.Heberlein et al. MRM 51:1, 2004; (3) Q.Yang et al. MRM 52:6, 2004; (4) R. Ordidge et al. MRM 32:3, 1994; (5) J. Wild et al. MRM 48:5, 2002; (6) H. Marshall et al. Proc BCISMRM, 2005