Correcting Phase Errors from B_0 Eddy Currents in Non-Cartesian Imaging

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INTRODUCTION

Overall consistency in image quality from non-Cartesian sequences is typically still not equivalent to that possible with Cartesian methods. One reason for this difference is that non-Cartesian sequences are more sensitive to a variety of errors, including gradient deviations and timing and phase errors. There is an ongoing need to characterize and correct these errors, as described by Pipe in the "Unmet Needs" session at a previous ISMRM meeting (1). B_0 eddy currents are one cause of phase errors that are more problematic in non-Cartesian imaging. Time-varying gradients induce eddy currents in the cryostat which cause the B_0 field strength to vary over time. These field perturbations are manifested as variation in signal frequency across the readout. While scanners actively work to maintain a stable B_0, this compensation is usually limited to longer time constants, so phase errors are still seen during periods of gradient activity.

For a conventional spin-warp Cartesian sequence, phase errors due to B_0 eddy currents are manifested as a linear phase roll across *k*-space, leading to a small and likely unnoticeable bulk shift in image space. For radial imaging, the direction of this shift varies for each projection, leading to blurring. The situation is even more complicated for multi-echo sequences that sample multiple projections in differing directions after each excitation, especially if ramp sampling is used.

We enhance a per-scan calibration that was previously used to measure gradient deviations from linear eddy currents to additionally measure phase errors due to B_0 eddy currents (2). We demonstrate this by measuring and correcting the phase errors with VIPRME, a multi-echo 3DPR acquisition. We see phase variations of up to 45° across a readout, but the effect on image quality is subtle and correction is typically unnecessary.

MATERIALS AND METHODS

Gurney *et al.* (2) demonstrated a method for measuring phase errors resulting from B_0 eddy currents. The technique an extension of Duyn's method for measuring linear eddy currents (3) and requires only a single additional experiment per axis. We integrated this measurement into several research sequences, making measurements at ±2 cm and ±4 cm off isocenter. For 3DPR acquisitions, the B_0 eddy current measurement is made along each axis separately and a correction is applied to each projection by adjusting the phase of the acquired signal using a linear combination of the B_0 eddy current effects on each axis based on the projection angle.

We measured phase errors on GE HealthCare 3.0 T scanners with a large phantom. Several sequences were tested, including a four half-echo SPGR-VIPR acquisition (4) with a bandwidth of ±125 kHz and a 16 cm spherical FOV with 0.6 mm isotropic resolution and a dual half-echo LC-SSFP VIPR acquisition (5) with similar parameters. Measurements from the phantom were also used to improve reconstruction of a human knee scan by linearly combining the orthogonal axis measurements to estimate and correct the phase error at each *k*-space point.

RESULTS AND DISCUSSION

Figure 1 shows the phase error measurements for the four half-echo SPGR-VIPRME scan. Notice the substantially larger phase variations associated with A/P gradients, with the error varying over nearly 45° during the course of the readout. Phase variation on the other axes are substantially smaller, but a prominent phase oscillation of 4° at 62.5 kHz is apparent during periods of S/I gradient ramp. The authors believe this is interference due to gradient amplifier switching. Figure 2 shows the phase error plotted against *k*-space position for a single multi-echo readout. Note that the vast majority of the phase variation is consistent between closely spaced projections, leading to a minimal amount of destructive high-frequency oscillation in the *k*-space data. Figure 3 shows the phase error over time for a dual half-echo LC-SSFP acquisition, with peak phase variations of ±12° on the A/P axis. For each sequence, a subtle improvement in image quality was visible after correcting for the B_0 phase errors.

CONCLUSIONS AND FUTURE WORK

Phase errors due to B_0 eddy current are measurable and do indeed have a small impact on image quality. In practice today, these effects are fairly insignificant and can usually be neglected. As acquisition speeds and resolution are further increased, this effect will become more significant and corrections may become necessary. These phase errors may also be significant when using multi-echo acquisitions with phase-sensitive reconstruction techniques like phase-contrast imaging and water/fat decomposition.

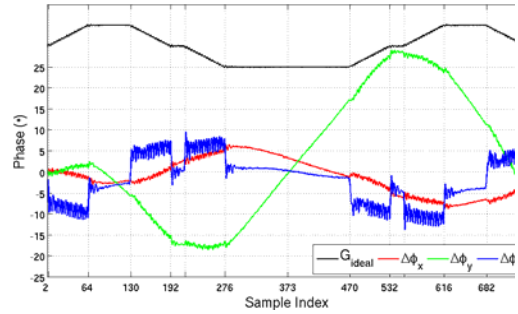

***Figure 1**: B_0 eddy currents lead to phase variations during periods of gradient activity. Note that A/P gradients can cause a phase error varying over nearly 45° during a single echo. The nominal gradient waveform is shown in black.*

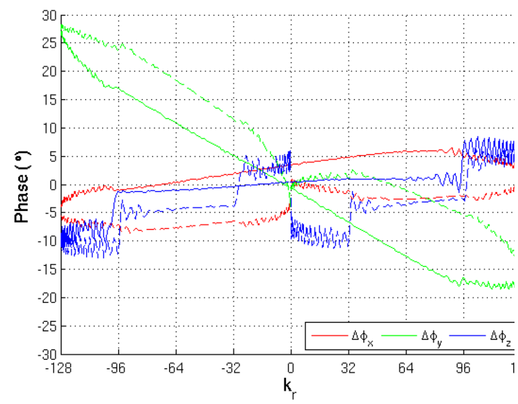

***Figure 2**: The phase error is shown here graphed against k-space position. The first and fourth half-echo are shown with dashed lines, while the central full echo is shown as a solid line. By graphing the phase error against k-space position, it is clear that the variation between closely spaced projections is minimal. Peak differences of 10-15° are seen between adjacent projections, leading negligible signal loss due to high-frequency phase modulation.*

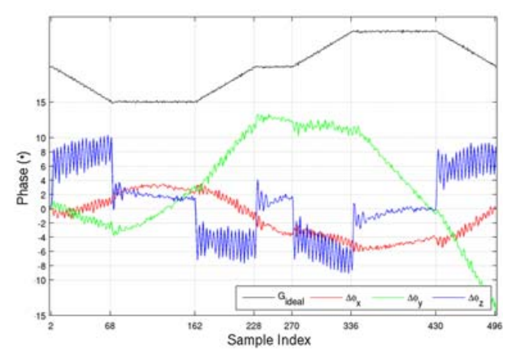

***Figure 3:** The dual-echo LC-SSFP exam exhibits less phase error, likely due to the shorter periods at full gradient strength. Nearly all of the error is consistent between closely spaced projections, with peak differences of only about 7°, leading to a minimal effect on image quality.*

REFERENCES AND ACKNOWLEDGEMENTS

1. Pipe, "Unmet Needs," 15th ISMRM ('07) **2.** Gurney *et al.*, 13th ISMRM, 866 ('05) **3**. Duyn *et al.*, JMR 132:150 ('98) **4.** Brodsky *et al.*, 11th ISMRM, 322 ('03) **5.** Vasanawala *et al.*, MRM 43(1):82 ('00)

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