Automatic off-resonance correction with piecewise linear autofocus

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Introduction: Off-resonance causes image blurring with spiral and radial trajectories. These trajectories are frequently used in fine-resolution or dynamic imaging where it is often impractical to acquire high-fidelity field maps for subsequent deblurring. Standard automatic off-resonance correction (autofocus) methods, which do not require a field map, are based in whole [1-3] or in part [4] on optimizing an objective function [1,5] but suffer from problems related to inaccurate minimization and unreliable focus metrics. We introduce a new autofocus method that does not use optimization metrics. It performs piecewise linear off-resonance estimation and correction [6] by dividing the image into blocks and deblurring each block with local linear processing. The proposed method has been more reliable than conventional autofocus methods, and is noise robust which is important for fast and/or fine-resolution acquisitions. We discuss its use with spiral imaging, but extension to radial is straightforward.

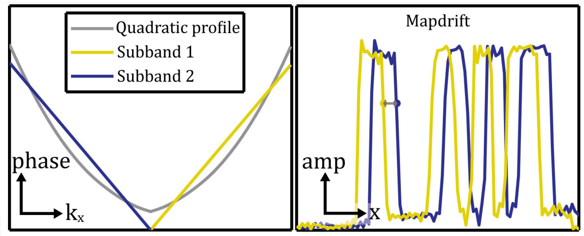

Fig 1: The mapdrift principle. The $e^{-j2\pi f_c t}$ phase error (left) is mostly quadratic and can be estimated from the relative shift between the two subband signals (right).

Theory: Here, we motivate the linear estimation/correction algorithm used to process each block. A linear field map f_o (**Eq. 1**) induces a phase modulation and time-varying k-space trajectory shift in the received signal s_o (**Eq. 2**), as compared to an idealized signal s having no off resonance error. Linear coefficients (f_x,f_y): At echo time $t=T_E$ the k-space trajectory crosses the DC location (**Eq. 3**), and the local coefficients can be estimated from the spectral peak location—so long as the peak occurs at the echo [4]. Constant coefficient (f_c): Because the time map in spiral imaging is roughly quadratic in |k|, the f_c term causes a quadratic phase error which we estimate using mapdrift [7]. The two half-spectrum subbands have opposite linear phase modulations and thus opposite spatial shifts in the image domain (**Fig. 1**). We measure this shift, which is proportional to f_c, by correlating the two signals and finding the lag corresponding to the peak.

Eq 1: $f_o(x,y) = f_c + f_x x + f_y y$

Eq 2: $s_o(k_x,k_y) = e^{-j2\pi f_c t}\, s(k_x+f_x t, k_y+f_y t)$

Eq 3: $s(0,0) = e^{+j2\pi f_c T_E}\, s_o(-f_x T_E, -f_y T_E)$

Methods and Results: In each block, we estimate the local (f_c,f_x,f_y) coefficients and apply linear correction (**Fig. 2**). Before correction, we perform regularized smoothing of the estimated field map to minimize discontinuities along block borders. Example results with 0.7 mm resolution imaging of the right coronary artery (RCA) at 3 Tesla (**Fig. 3**) suggest our method can be superior to conventional autofocus [1,5] and comparable to field map-based frequency segmented correction [8].

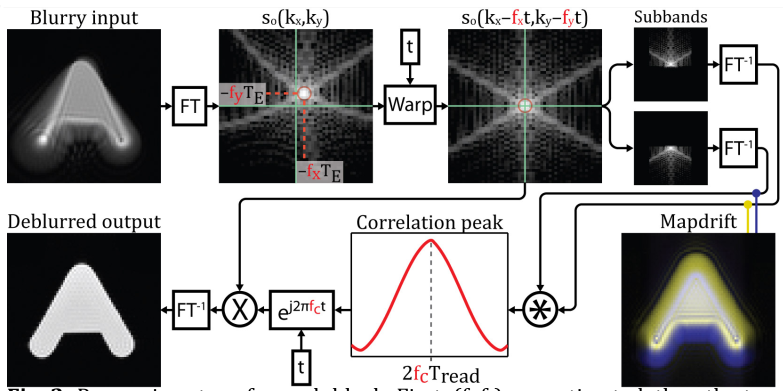

Fig. 2: Processing steps for each block. First, (f_x,f_y) are estimated, then the trajectory shift is corrected. Finally, mapdrift autofocus is applied to estimate and remove f_c. (Note: $t = t(k_x,k_y)$ = trajectory time map and FT = Fourier transform.)

Discussion: The block-based approach is noise robust (examples not shown due to lack of space), which comes from using the echo to estimate (f_x,f_y) and from the inherent averaging inside the correlation operation during f_c estimation. Estimates of f_c will be nearly zero in featureless regions, which is usually acceptable because off-resonance blurring is not apparent in these regions. The proposed method does not require access to the raw data; only the image (after gridding and inverse Fourier transformation) and a time map are needed. Furthermore, it can be used as an alternative to global linear correction [2,3] by processing the entire image as one block, and it can be applied in conjunction with other deblurring algorithms. Block size: Smaller blocks provide better spatial localization and avoid attenuation of rapid off-resonance variations. Larger blocks, however, provide better frequency resolution for estimating (f_x,f_y) and more image features to correlate during f_c estimation. We have achieved good results with blocks that are 2-3x larger than the smallest resolvable features of interest.

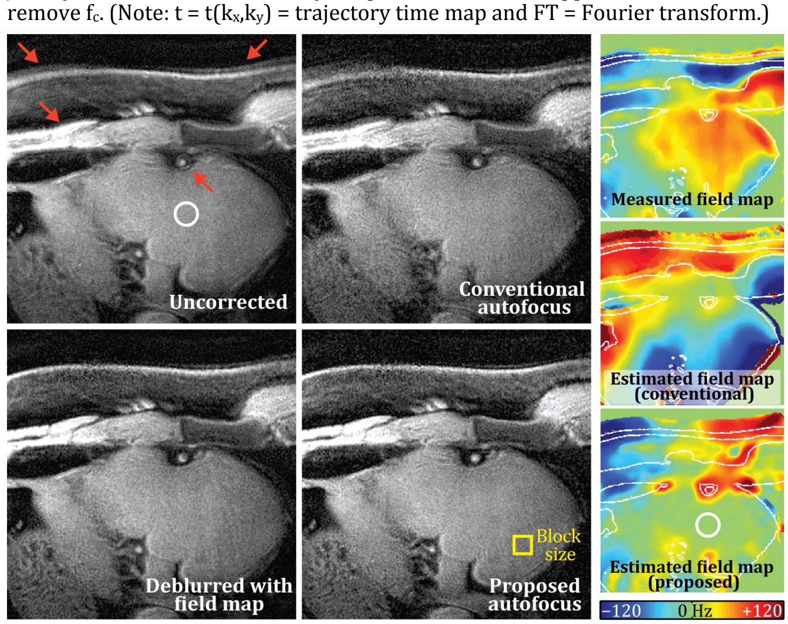

Fig. 3: Fine-resolution image deblurring. As seen near the skin, chest wall, RCA (red arrows) and other places, the proposed method removes more off-resonance artifacts than conventional autofocus and produces images comparable to field map-based correction. The estimated field map also exhibits better agreement with measurement except in featureless areas (white circle).

References: [1] Noll, MRM, 1992, p319-333. [2] Man, MRM, 1997, p906-913. [3] Chen, MRM, 2006, p457-462. [4] Truong, MRM, 2010, p1121-1127. [5] Lee, ISMRM, 2004, p2678. [6] Smith, ISMRM, 2011, p4579. [7] Mancill, Tri-Service Radar Symp, 1981, p391-400.
[8] Noll, IEEE TMI, 1991, p629-637.