# High-accuracy off-resonance estimation from EPI, with application to volumetric navigators (vNavs) enabling real-time motion and frequency correction

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**Target Audience** Users of EPI-based sequences, or sequences with EPI-based navigators, who are interested in tracking the resonance frequency.

**Purpose** This work demonstrates a no-cost modification to EPI with an "external" phase navigator (in our case, the vNav navigator sub-sequence) and a novel fitting algorithm that together allow for very high-accuracy, high-speed estimates of changes in resonance frequency. Sequences with high gradient duty cycles, particularly EPI or those with EPI-based navigators, can produce heating that leads to a gradual drift in the resonance frequency. Fluctuations in the resonance frequency can also be caused by subject respiration and motion, especially at higher field strengths. These frequency drifts can reduce the efficacy of saturation pulses, and also impact the localization of EPI sequences. The latter effect is particularly important in vNavs, because uncorrected frequency drifts will cause errors in the subsequent motion track.

We previously demonstrated volumetric navigators (vNavs) based on 3D-encoded EPI for tracking subject motion when embedded in 3D-encoded morphometry scans [1,2]. We have also shown how paired vNavs with shifted TEs can be used for dynamic shim correction, at the cost of doubling navigator acquisition time [3]. We now present a modification to the vNav sequence paired with a novel fitting algorithm that allows the shift in resonance frequency (*i.e.,* the spatially constant term of the shim correction from [3]) to be measured reliably from a single vNav without expending any additional time. Our method is related to the previous dynamic off-resonance in k-space (DORK) method [4]. However, where DORK uses the center of k-space as acquired in the initial phase navigator lines and compares it to the center of k-space as acquired during the EPI readout, our method uses what was previously dead time in the vNav to acquire a longer phase navigator and compares substantially more points along it. We additionally use the spatial encoding and oversampling in the readout direction of the phase navigator to ensure that the frequency estimate is made only over the FOV, where DORK's fit would include tissues outside the FOV. This method has been integrated into our motion-corrected vNav multiecho-MPRAGE (MEMPRAGE), and our experiment shows our novel method offers more stable results compared to DORK.

**Method** Our vNav sequence is 3D-encoded EPI with a $32^3$ matrix, but is acquired with ¾ partial Fourier encoding in the partition direction and so has 25 excitation pulses. However, while the last 24 pulses are followed by 32 EPI readout lines to form a single partition and fill almost all the available time between excitation pulses, the first pulse was previously followed by only three readout lines, repeated with alternating polarity and without phase blips, and then a TR gap. To enable accurate frequency estimation, we modified our vNav sub-sequence to increase the number of alternating, blip-less readouts after the first pulse from 3 to 32. This fills the previous dead time after the first pulse without modifying any of the other timing parameters of the vNav acquisition, without adding extra excitation pulses, and without adding any time to the vNav.

Similar to DORK, we use the raw complex k-space data of the phase correction lines acquired in our first TR as a reference. In each subsequent TR, we then calculate the off-resonance relative to this first TR. We do this by:

1. Performing a readout-direction inverse Fourier transform, clipping off the oversampled data, and then performing a Fourier transform to ensure our frequency-domain data represents only the FOV selected by the user. Normally this FOV is chosen to include just the brain and excluding non-rigid regions for enhanced motion tracking, with a head-foot readout direction and 2× oversampling to remove anatomy that would wrap into the FOV (*e.g.,* jaw).
2. Sample-wise multiplying the phase correction lines of the new TR with the conjugate of the reference TR. This cancels the effects of eddy-currents and other systematic sources of phase variation that are consistent across TRs.
3. Sample-wise multiplying the output of step 2 with a second copy that has been shifted two lines in the "blip" direction and conjugated. The result is an array whose phases are the difference each sample and its subsequent repetition with the same readout polarity. These phase differences are an estimate of the phase offset due to frequency drift since the original reference scan.
4. Complex average across all 31 lines and across all channels. This performs a weighted average, where the signal amplitudes have been squared in steps 1 and 2 so that only the most reliable signals have much impact on the complex average. The phase of this final average value is then divided by the 2× the echo spacing in order to arrive at the shift in resonance frequency since the reference TR, expressed in Hz.

A water phantom was measured using a 6.5 minute MEMPRAGE with vNavs. Initially the phantom was shimmed and the reference resonance frequency adjusted using the automatic system on a 1.5 T Avanto (Siemens Healthcare, Erlangen, Germany) with the 12-channel head coil. The scanner cooled for two hours before scanning commenced, to ensure maximum opportunity for drift during the MEMPRAGE.

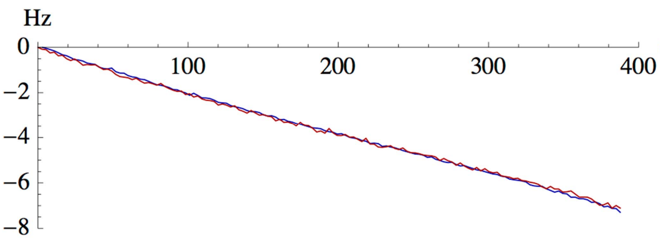


**Fig 1**. Estimated off-resonance during MEMPRAGE using DORK (red) and novel method (blue).

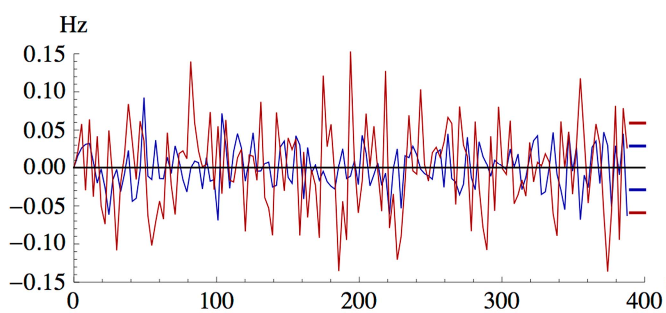


**Fig 2**. Residual estimated off-resonance during MEMPRAGE using DORK (red) and novel method (blue), after removing quartic "trend". Standard deviation of the residuals is plotted on the right.

**Results** Fig. 1 shows the estimated off-resonance using both vNavs and our own offline re-implementation of DORK. Fig. 2 shows the same data, after subtracting a quartic polynomial fit to each time series (the lowest-order function that removed the major trends) so variability is visible. The standard deviations of the estimates after de-trending were 0.059 (DORK) and 0.029 (novel algorithm).

**Conclusions** We have demonstrated how vNavs can be modified to provide high-quality real-time resonance frequency estimates in addition to real-time motion estimates. A gradually shifting resonance frequency can induce an artificial motion in the phase-encode direction of the vNavs, confounding motion estimates. By updating the reference frequency we improve the accuracy of our motion estimates over long scans. This method could also be applied to other EPI sequences with a similar "external" phase navigator TR, where the extra data can similarly be acquired without time penalty. We have also shown a novel algorithm that can take advantage of the additional data being acquired, and provide a more stable estimate of the resonance frequency.

**References** [1] Tisdall et al. "MPRAGE Using EPI Navigators for Prospective Motion Correction" ISMRM 2009, 4656 [2] Tisdall et al. "Volumetric Navigators (vNavs) for Prospective Motion Correction and Selective Reacquisition in Neuroanatomical MRI" MRM 2012 [3] Hess et al. "Real-time Motion and B0 corrected single voxel spectroscopy using volumetric navigators" MRM 2011, 66(2):314-323 [4] J. Pfeuffer et al. "Correction of physiologically induced global off-resonance effects in dynamic echo-planar and spiral functional imaging" MRM 2002, 47(2):344-53

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