k-t-Calibration improves continuous field monitoring for image reconstruction

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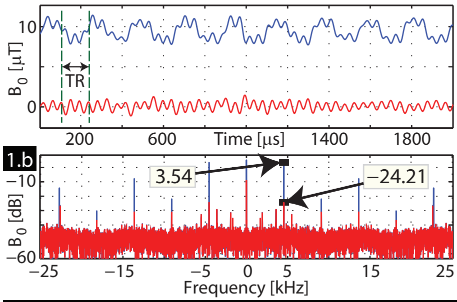
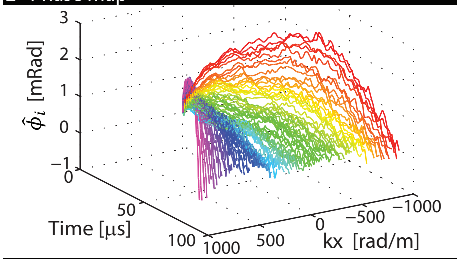
Introduction: Dynamic magnetic field monitoring with NMR probes enables the observation of the spatio-temporal magnetic field evolution during MR experiments [1-4]. A recently proposed method based on time interleaved acquisition of sets of fast relaxing NMR probes allows for sequence independent dynamic magnetic field monitoring [5-6]. As compared to field monitoring relying on single coherence probe acquisitions, this approach removes the limitations in terms of coverable k-space range, acquisition duration and duty cycle. However, internally and externally induced B_0 field inhomogeneities inside the probes, non-uniform probe excitation and detection sensitivities, spectral impurities of the NMR active material, and inhomogeneous relaxations in the NMR active material result in minimal, systematic, phase errors in the range of mrads during the coherence life-time. When concatenating the train of resulting field evolutions (typical TR is in the range of ~100-200 µs) to achieve a continuous temporal coverage, these distortions form the dominant source of error. The error may be further amplified since the remaining short probe re-excitation gaps (≈14 µs) are interpolated (assuming band limitation of the field evolution), to retrieve a fully continuous field time course. Typically these systematic errors result in interpolation inconsistencies (jumps) between readouts and probe sets (Fig. 1.a, blue). Consequently, in the spectrum of a constant field, peaks with a frequency of 1/TR and multiples thereof appear (Fig. 1.b, blue). If k-space trajectories are integrated from the obtained continuous field evolution, these systematic errors accumulate over time, preventing image reconstruction for long readouts. The present work aims to remove this limitation by means of probe calibration in the joint k-space and time domain.

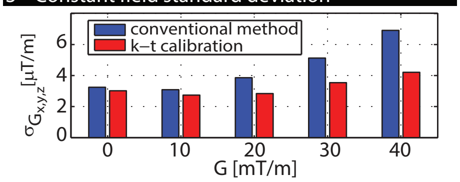
1.a Field evolution, TR = 110 µs, 2-probe-sets



2 Phase map

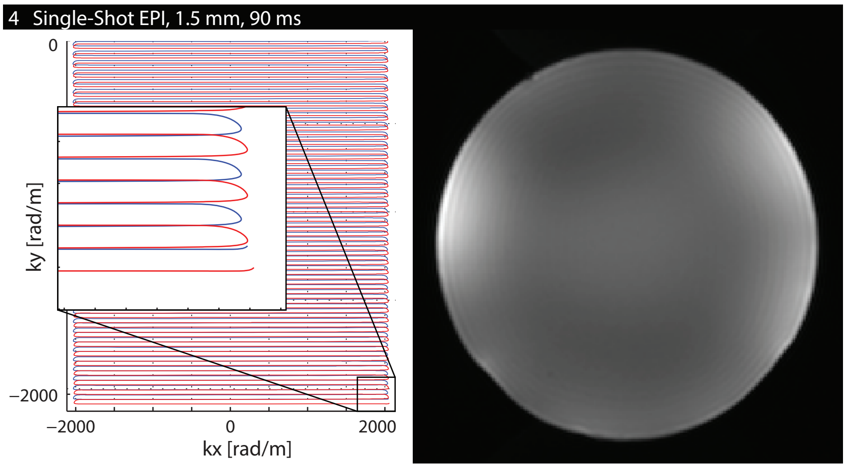


3 Constant field standard deviation



Methods: Ideally the probes sample the spatial phase function $\phi(\boldsymbol{r_0}, t) = \gamma \int_{t_0}^{t} |\boldsymbol{B}(\boldsymbol{r_0}, \tau)| d\tau$, since the last probe excitation t_0, at sufficiently many places $\boldsymbol{r_0}$ surrounding the imaging volume. The k-space trajectory $\boldsymbol{k}$ can then be retrieved by solving the inverse problem $\boldsymbol{\phi}_p(t) = \boldsymbol{Pk}(t) + \boldsymbol{\omega}_{ref,P} t$, where $\boldsymbol{\phi}_p(t)$ is the phase evolution of all probes and $\boldsymbol{P}$ is the so called probing matrix, reflecting the way in which the probes sample the spatial basis functions, which is typically calculated by measuring the probe positions under constant reference fields [1,7]. Taking the non-uniform field distributions inside a probe into account, the probe phase can be modeled as $\phi_i = \measuredangle \int_V M(\boldsymbol{r})\, e^{-i\gamma \int_{t_0}^{t} |\boldsymbol{B}(\boldsymbol{r},\tau)| d\tau} d^3 r$, where M denotes the probe magnetization and V the probe volume. In terms of k-space notation the phase can be written as $\phi_i(t, \boldsymbol{k}) = k_0(t) + \hat{\phi}_i(t - t_0, \boldsymbol{k})$, with k_0 being the 0-order, or B_0 term, which is only time dependent, and $\hat{\phi}_i$ denoting the probe's k-t-dependent phase evolution. The probe-dependent k-t-phase-evolutions $\hat{\phi}_i$ are constant and can hence be calibrated in a scan where the k-space trajectory is known with high fidelity such as in a center out acquisition with static and settled gradient fields with varying strengths. Knowing $\hat{\phi}_i$ for each probe, allows the actual field evolution to be interpolated into the sufficiently densely sampled k-t calibration data set by means of a non-linear least squares fit. The stand-alone continuous field monitoring system [5-6] was equipped with 16 H_2O based NMR field probes, doped with $GdCl_3.6H_2O$ such that $T_2 \approx 65\,\mu s$ was used. The probes were arranged in 2 sets of 8 probes each, placed on the edges of 2 nested cubes, such that the positions were well conditioned to measure first order spherical harmonic field evolutions. The phase maps $\hat{\phi}_i(t, \boldsymbol{k})$ were measured under different constant gradient strength and directions ($\boldsymbol{k} = \gamma\, \boldsymbol{G}_{const}\, t$). In this work 40 directions distributed on a sphere, and 2 mT/m strength steps from -40 mT/m to +40 mT/m were used, resulting in a total of 1640 strength-direction combinations. The actual measurements were delayed with respect to the gradient ramp-up by 130 ms to avoid eddy currents, and averaged over 30 measurements to reduce the noise. The phase maps $\hat{\phi}_i$ were interpolated using distance-weighted linear interpolation, and the Matlab lsqnonlin solver with the Levenberg-Marquardt algorithm (The MathWorks, Inc., Natick, Massachusetts, United States) was used to solve the non-linear least-squares problem. The method was tested for field monitoring of a single-shot EPI acquisition (res=1.5mm, readout duration=90 ms, max. gradient strength: 40 mT/m) as well as for field monitoring of constant gradient fields of different strengths and directions, to assess the precision of the resulting field data. All measurements were performed on a Philips Achieva 7T system (Philips Healthcare, Cleveland, USA).

4 Single-Shot EPI, 1.5 mm, 90 ms



Results/Discussion: Fig. 2 shows the distortion (non-linear part) of a k-t-phase map for one probe and one k-space dimension. The apparent smoothness justifies the interpolation scheme of the calibration data and its monotonicity due to the large linear components (not shown in Fig. 2) ensures a unique solution. Fig. 1.a shows the first few samples of the B_0 term during a constant 40 mT/m gradient with the reference method [1] in blue and the k-t-calibration method in red. Fig. 1.b shows the spectrum of the same signal calculated over the whole 100 ms readout. The frequency peaks caused by the systematic phase errors $1/(n\,TR)$ are reduced by more than 20 dB. Fig. 3 shows the standard deviation of constant field gradients of different strength, with and without k-t-calibration at a field-bandwidth of 30 kHz. As expected, the improvements due to k-t-calibration are larger under strong gradients, due to the increase in field inhomogeneity inside the probes. Fig 4 shows the measured, single-shot EPI trajectory with (red) and without (blue) k-t-calibration, and the corresponding phantom image, reconstructed with the k-t-calibrated trajectory. The zoomed part shows how the calibration affects the trajectory.

Conclusions: The presented field probe calibration method strongly reduces systematic errors in continuous field monitoring and renders it applicable to image reconstruction as demonstrated in a demanding single-shot EPI example. The calibration approach thus removes the pre-existing limitations of monitoring-based reconstruction to moderate resolutions and acquisition durations.

(1) Barmet C et al. MRM 2008;60(1):187-197, (2) Han H et al. J. Magn. Reson. 2009 201(2):212-217, (3) Sipilä P et al. ISMRM 2009 p. 782, (4) Zanche ND et al. MRM 2008 60(1):176-186, (5) Dietrich BE et al. ISMRM 2011 p. 1842, (6) Dietrich BE et al. ISMRM 2013 p. 2716, (7) Wilm BJ et al. MRM 2011 65:1690-1701