Analysis of Measurement Precision in Continuous Magnetic Field Monitoring

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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 [1,2,3]. A recently proposed method based on time interleaved acquisition of sets of fast relaxing NMR probes allows for scanner independent dynamic magnetic field monitoring even under strong gradients and over arbitrary periods [4,5,6]. Such continuous gradient field monitoring alleviates the limitation on k-space range, acquisition duration and duty cycle of the approaches that use single coherences. The present work aims to assess the precision of this method with regard to geometric probe configuration, gradient strength, alternation pattern, and re-excitation spacing. Several effects are expected to contribute to the total measurement uncertainty: violation of the assumption that the field probes behave like point sources, echo formation upon short repetition times, interpolation errors, higher order and concomitant fields, and thermal noise.

Methods: The field camera head consisted of 16 H_2O based NMR field probes doped with $GdCl_3.6H_2O$, such that $T_2 \approx T_2^* \approx T_1 \approx 136\,\mu s$. The probes were built from a (2.2 mm inner diameter, 30 mm length) glass capillary mounted on a holder made from Polytetrafluoroethylene (PTFE). Six-turn solenoids (202 µm copper wire with PTFE coating) around the capillaries served as transmit/receive coils. The sensors were arranged on two PTFE mounting plates as shown in Fig. 1.a. The plates allowed the probes to be moved in radial direction and the distance between the plates could be adjusted with thread bars to change the size of the setup. Proton containing materials were strictly avoided in the sensitive area of the probes. Field probe signals were acquired using custom built stand-alone receive and excitation chains as well as a spectrometer based on 14 Bit, 250 MHz analogue to digital converters and FPGA based I-Q-demodulation and down-sampling to 2 MHz. The excitation chains allowed the probes to be excited in different time interleaved set configurations of 4 probes each (Fig 1.b). In the single-set configuration the same 4 probes were re-excited after just one probe set alternation period (T_{set}). In the 2-set configuration the same probes were re-excited after $2\,T_{set}$ and the second set of 4 probes is excited in between. The same principle was applied to the 3-set and 4-set configurations with 2 and 3 sets, respectively, in between. The sets were always selected such that the probes of each set were arranged on the corners of a tetrahedron (see color dots on probes in Fig. 1.a). In this way the configurations allowed for well-conditioned measurement of zero and first order fields. Measurements of 1 sec duration were acquired under constant gradients for different T_{set}, gradient strengths, set configurations, and setup diameters. The gradient fields of each direction were calculated for each set and the re-excitation gap ($T_{gap} = 12.5\,\mu s$) was interpolated under the assumption that the gradient fields are band-limited $\left(BW_{field} = \frac{\lfloor T_{set} T_{dwell}/T_{gap} \rfloor}{(2 T_{set} T_{dwell})} \approx 40\,kHz\right)$. Finally the total standard deviation in the resulting field time course was taken as the measure of precision. All measurements were performed on a Philips Achieva 7T system (Philips Healthcare, Cleveland, USA).

Fig. 1.a

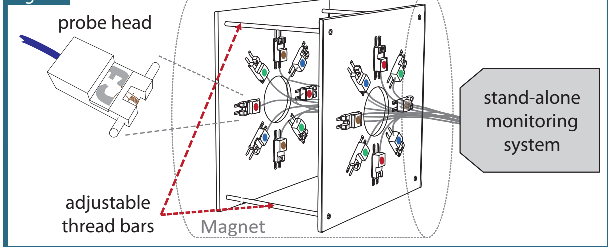


Fig. 1.b

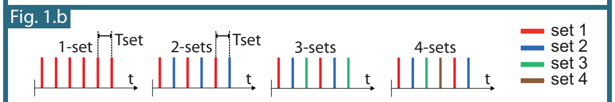


Fig. 2

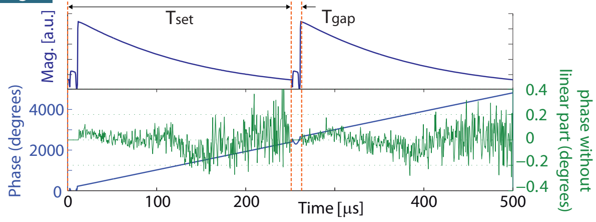


Fig. 3.a G = 40 mT/m, Ø = 29.8 cm

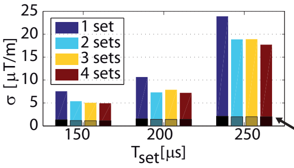
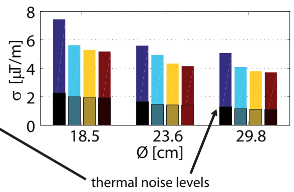


Fig. 3.b Tset = 150 µs , G = 30 mT/m



thermal noise levels

Fig. 3.c Tset = 150 µs, Ø = 29.8 cm

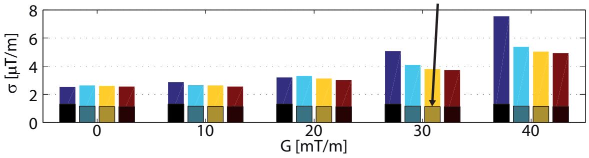
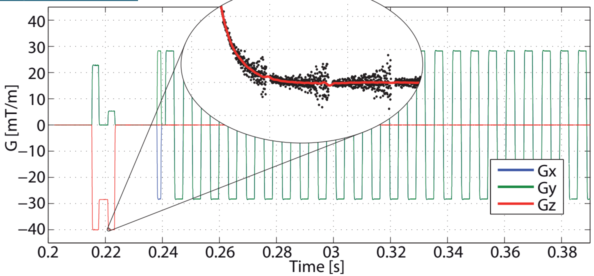


Fig. 4 DW EPI



Results/Discussion: The initial SNR of the FIDs at an acquisition bandwidth of 2 MHz was 4040 in amplitude terms. Figure 2 shows a signal interval of one probe from a measurement with a 1-set configuration and a constant gradient of 20 mT/m. The same probe is re-excited after a T_{set} of 250 µs. The lower part of Fig. 2 shows the signal phase and the non-linear phase residual in the order of 0.1-0.2 degrees. Figure 3.a shows the standard deviation of the constant field under a gradient strength of 40 mT/m and a setup diameter of 29.8 cm for different set alternation periods and set configurations. The shorter (slightly darker) bars represent thermal noise contributions on the final field measurement, calculated with the measured SNR, T_2 and T_1. The achieved sensitivity lies in the range of 5 µT/m which leads to 1-2 µT field measurement error in a typical imaging volume. It can be seen that signal decay for long T_{set} and gradient induced de-phasing have more severe effects than spurious echo formation from fast re-excitation. Errors due to echo formation corrupt the measurements only if de-phasing by strong gradients is involved and can be reduced by means of set alternation, as can be seen in Fig. 3.c. Figure 3.b shows the dependence on the field camera diameter. As expected, the sensitivity increases with diameter. One might expect to see effects of concomitant fields with larger setup diameters and the use of more than one set due to the fact that each set actually measures the field at different positions, but this mechanism seems to be masked by other errors. Based on these findings favorable parameters were selected for the diffusion weighted EPI sequence shown in Fig. 4 ($T_{set} = 150\,\mu s$, 2-set configuration). The zoomed inset shows the field data at 2 MHz bandwidth in black and the interpolated z-gradient with no gaps filtered to a bandwidth of 40 kHz in red.

Conclusions: Continuous monitoring delivers gradient field measurements with $\mu T/m$ precision at a bandwidth of 40 kHz. In the current setup thermal noise is not the major source of error. The measurements suggest that error contributions due to point source violation and hence interpolation inconsistency outweigh the thermal noise. Overall it can be concluded that larger diameters, shorter T_{set}, and set alternation lead to higher sensitivities.

[1] Pound et al, Review of Scientific Instruments, AIP 21:219-225 1950, [2] Barmet et al, MRM 60:187-197 2008, [3] Barmet al. MRM 62(1):269-76 2009, [4] Han et al JMR 201:212-217 2009, [5] Sipilä et al ISMRM 2009 p782, [6] Dietrich et al. ISMRM 2011 p1842