B_0 Field Monitoring by Air-Matched Phantoms

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Introduction: Fast magnetic resonance imaging sequences such as gradient echo (GRE) echo planar imaging (EPI) are sensitive to spatial and temporal changes of B_0 arising from susceptibility effects, temperature changes of the shims and motion of the object. This leads to time variant common image artefacts such as distortions and intensity losses. Different correction techniques e. g. field map yield parameters for correction fields to be applied for subsequent measurements. Temporal or spatial changes of B_0 during the scan are typically not taken into account. A possible remedy is the extraction of the field fluctuations from raw data [1-2], shim navigators [3] or by using field sensors which permits to measure field changes during the experiment in real time. In this work spherical phantoms susceptibility-matched to air as proposed in [4] are used to monitor field variations from which applied shim coefficients are estimated. Further the frequency detection accuracy and the number of necessary spheres are estimated.

$$B_z(\vec{r}) = \sum_{n=0}^{\infty}\sum_{m=0}^{n}\left[A_{nm}\cos\left(m\phi\right)+B_{nm}\sin\left(m\phi\right)\right]r^n P_{nm}\left(\cos\left(\vartheta\right)\right) \quad \text{(Eq.1)}$$

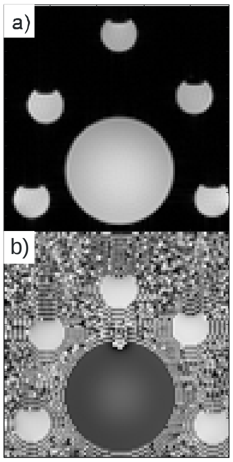

Figure 1: Experimental configuration: a) GRE magnitude. image, back part, b)GRE phase image, frontal part

Methods: The measured inhomogeneity field is typically fitted to a series of field harmonics (Eq. 1) which is a solution of the Laplace equation of the magnetic field in a source-free cavity. Fitting aims at finding the coefficients A_{mn} and B_{mn} of the compensation field for shimming.

Table tennis balls with a diameter of 4cm and filled with an aqueous Ho^{3+} solution matched to air, prepared as described in [1] were used as field sensors. All experiments were performed on a 3T Tim TRIO with a TxRx Head coil (Siemens Medical Solutions, Erlangen, Germany); image reconstruction, field map calculation, masking and robust regression to magnetic field spherical harmonics up to order 2 were performed off-line with MATLAB (The MathWorks, Inc., Natick, MA, USA). The mask of the phantom was created with BET [5]. Fits were performed over the phantom (F1) or over the spheres (F2), subtracted from the result of the last background field fit and compared with the applied field amplitude. Fits F2 were performed with different number of spheres and different sensor volumes in order to estimate the minimal number of probes and sensor volume which are required to achieve successful regressions. The mean value of the volume is calculated and set to the volume centre position.

Frequency adjustments were omitted in order to have the same shim settings for all measurements. A slightly modified product sequence was used for field mapping, allowing ΔTE=0.5ms (sequence parameters: TE1=4.53ms, TR=608ms, 90° flip angle, FOV=240×240mm²). A bottle phantom was surrounded by eight spheres as depicted in Fig. 1. The first measurement was performed with 11 repetitions with fixed shim settings, denoted as Mb_1 … Mb_{11}. The magnitude image of the first echo was used for determining the centre positions of the spheres, no distortion correction was applied. Three measurements with additional magnetic fields were performed, denoted as Ma_1 to Ma_3 in-between each a measurement without additional fields was acquired. In Ma_1 to Ma_3 the amplitude of ΔA00, ΔB11 and ΔA22 were swept as indicated in Tab.1. The resulting coefficients of both regressions F1 and F2 of Ma_i were subtracted from the coefficients of the previous background measurement and compared to the applied field amplitude. Mb_1 to Mb_{11} were used to calculate the standard deviation (abbreviated in the following as 'std') after subtracting field drifts, assumed to be linear over the time period of 15min. The std is an estimate for the accuracy of the fit for the shim coefficients from the fit F2. The std for different number of spheres (1 to 10) and sensor size (1×1×1px³, 3×3×3px³, 5×5×5px³ and 7×7×7px³) were calculated from which the minimal necessary number of spheres and sensor size were determined for the case of a constant frequency offset and three gradients (i) and additionally with the quadratic fields (ii). These were used for the calculation of the field amplitudes for the measurements Ma_i.

Applied field harmonics	Applied value	fit F1	fit F2, 10 spheres, 7×7×7px³	fit F2i 5 spheres, 7×7×7px³
ΔA00 [Hz]	20.00	25.3±0.4	17.7±7.0	19.5±5.4
ΔA00 [Hz]	10.00	11.0±0.4	9.1±7.0	11.1±5.4
ΔA00 [Hz]	5.00	4.7±0.4	2.9±7.0	4.6±5.4
ΔA00 [Hz]	-5.00	-9.1±0.4	-11.7±7.0	-9.8±5.4
ΔB11 [μT/m] (Gy)	-4.13	-4.79±0.07	-7.6±3.9	-4.5±2.7
ΔB11 [μT/m] (Gy)	-2.48	-2.74±0.07	-2.9±3.9	-2.8±2.7
ΔB11 [μT/m] (Gy)	1.65	1.9±0.07	2.0±3.9	2.1±2.7
ΔA22 [μT/m²] (x²-y²)	-51.48	51.4±0.7	-50.6±18.2	0.00
ΔA22 [μT/m²] (x²-y²)	-22.88	24.±0.7	-16.1±18.2	0.00
ΔA22 [μT/m²] (x²-y²)	-11.44	11.9±0.7	-27.3±18.2	0.00
ΔA22 [μT/m²] (x²-y²)	-8.58	8.5±0.7	-11.7±18.2	0.00

Table 1: Applied and resulting coefficients from the fits F1, F2 and F2i

Results: Fig. 2 summarises the dependency of the std for three exemplarily chosen shim coefficients for different sensor volumes against the number of spheres used for fitting. 'Optimal' parameters for (i), fit F2i, seem to be 5 spheres and a volume of 7×7×7px³ because the std values are slowly changing for more spheres. The obtained values are summarized in Tab.1 with the std as the error.

Discussion: The constant blue line in Fig.2 is the std from F1. The std for x²-y² (Fig. 2c) is high and for z² even higher (~50μT/m²) which makes it very difficult to detect small changes of these fields as showed in Tab.1 and extract optimal fit parameters for (ii). The linear field and the constant frequency are in a range where small changes can be detected, as illustrated in Tab.1. The result of the fit F2i is in agreement with the applied values. The robust regression will not give any values for higher orders because not enough points are given to solve the linear equation system as mathematically expected. In the presented experiment the spheres are positioned relatively near to the imaged object. If the spheres would be farther away from the magnetic isocentre their estimated position from the GRE magnitude image would not be correct and therefore also nonlinearities of the encoding gradients and shim correction fields will be detected. The higher standard deviation of the fits F2 can probably be due to not perfectly susceptibility matching of phantoms.

Conclusion: Magnetic field sensors as the presented phantoms can be used to monitor the magnetic field evolution, in the presented case reliably only up to first order with low errors for the case of a sensor volume of 7×7×7px³ and 5 spheres. Further work will include a comparison of the experimental results with simulations. The presented work is a proof of concept for the possibility of using 5 field sensors for real time field tracking up to the first order and demonstrates the difficulty of estimating higher orders, where more than 10 sensors seem to be necessary or prior knowledge of the imaged object is required.

Acknowledgement: This work is a part of the INUMAC project supported by the German Federal Ministry of Education and Research, grant #01EQ0605.

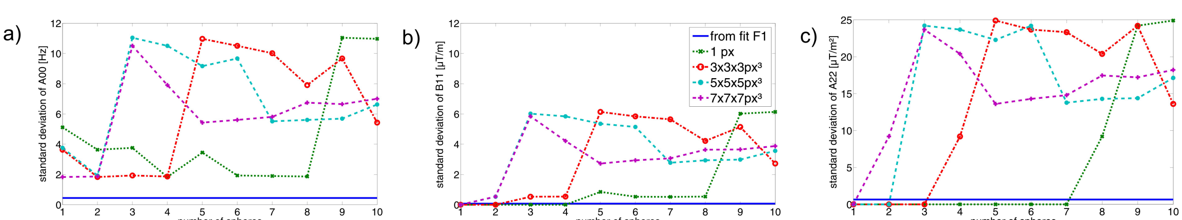

Figure 2: a), b), c) standard deviation for coefficient A00, B11, A22, respectively

Literature:

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