Generalized Non-Linear SENSE Shimming

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Introduction: With the SENSE Shimming (SSH) approach (1) a method was introduced recently that allows for estimating B0 field inhomogeneities based on a reference image and a series of points on a single free induction decay (FID). The temporal evolution of the FID data is explained by field inhomogeneities, starting from the reference image, making use of the encoding properties of the different sensitivities of a coil array. The original approach takes into account the slope of the FID data only at the echo time of the reference image (TE). As a consequence it cannot distinguish between effects caused by relaxation and those caused by inhomogeneities. It can therefore only be used for estimating inhomogeneity variations, relative to a baseline measurement. We here present an extension to the method,

which takes into account a larger range of the FID in order to explain not only B0 inhomogeneities but relaxation as well. Since the signal equation is non-linear, the linear fitting of the original approach has to be replaced by a non-linear optimization.

Methods: The SSH method as presented in (1) assumes the slope of FID data on a sufficiently small time scale to depend only on the B0 field inhomogeneities; relaxation is assumed to be negligible. The signal of an FID seen by coil n at time t is described by

$$\Psi_n(t) = \int_V m_n(\vec{r}) e^{z(\vec{r})t} d\vec{r} \, , \qquad (1)$$

where m_n denotes the apparent magnetization seen by coil n; z is assumed to be purely imaginary. For small time frames the equation can then be linearized and thus solved with the conventional least-squares approach. However, it has become evident that relaxation effects cannot be neglected for absolute quantification. Therefore, along with the inhomogeneities (the imaginary part of z), the relaxation (negative real part) has to be included into the model. Both need to be represented by a suitable set of basis functions. Unfortunately coil sensitivites alone do not provide enough information for determining such a high number of degrees of freedom. We therefore suggest to use a larger temporal evolution of the FID. Of course, in such a case the signal cannot be approximated by a linear equation anymore and the problem has to be solved by a non-linear optimization.

The basis functions to be fitted have to be chosen with great care in order to obtain a numerically stable solution. The best results could be obtained in our experiments by splitting a thresholded image mask into a number of less than ten submasks based on the histogram, for the real part. For the inhomogeneities it was found that the representations of six solid harmonics in the transversal plane provided stable results.

The phase of a complex reconstruction of the reference image was used as an additional basis function. It was assumed to consist of the sum of some residual B1 part, and B0. The B1 part was assumed to be describable by less parameters than B0 (at 3T). After phase unwrapping (2), the phase map and the solid harmonics were concatenated and the so obtained basis functions were orthonormalized on the thresholded mask used before, using a singular value decomposition (SVD). The linear SSH method was used for obtaining an initial scaling of the phase map basis function. This initial estimate was then expressed by the orthonormal basis functions and the coefficients were used as a starting point for the iterative optimization.

In vivo measurements were performed in a healthy volunteer, acquiring axial slices through the brain, positioned in the iso-center. A modified spoiled gradient echo sequence was used on a 3T TIM Trio (Siemens Healthcare, Erlangen, Germany), which allowed for seamless acquisition of a reference image with $TE = TE_1$, followed by a second image with $TE = TE_1 + \Delta TE$ and a set of FID acquisitions. From the two images reference field maps were calculated which were used as a gold standard for assessing the results of the SSH method. As coil array a twelve channel head array was used. Imaging parameters: resolution=128x128, 2x2x2mm³, TE=4.92ms, ΔTE=2.46ms, dwell time=10µs, FID length=20ms, TR=40ms, no fat saturation and no subject-specific shimming. A series of eleven data sets was acquired, with the X²-Y² shim component modified in equidistant steps from -40µT/m² to +40µT/m².

Results & Discussion: Figure 1 shows the motivation for the iterative approach: FID simulations based on field maps obtained from the two images do not describe correctly the slope of the measured data. Assuming a global relaxation constant improves fitting dramatically, showing that relaxation can indeed influence the slope significantly. Figure 2 depicts the assembly of the real and imaginary basis functions (the orthonormalization of the imaginary part is not shown). Figure 3 compares visually the field maps obtained in the first (-40µT/m²) and the last (+40µT/m²) data set. A high agreement with the gold standard can be observed for the proposed method. Quantitative results are shown in Figure 4, where the obtained values for five in plane shim coefficients are given (Z0, X, Y, XY and X²-Y²).

As can be seen the results are very encouraging: based on a reference image and a single FID a very accurate field map estimate can be obtained, even in vivo. It has to be pointed out that the obtained values are not relative to a baseline but absolute quantities and that no subject specific shimming was performed. The method should therefore be suitable for fast shimming at low cost, without the need of obtaining full field maps. While Z2 has been ignored here due to the poor support in the iso-center, a 3D version should lead to improvements. Furthermore one might think of more sophisticated segmentation algorithms for choosing the real basis functions, possibly including a priori knowledge.

References: [1] Splitthoff and Zaitsev, MRM 62, 1319-1325, 2009. [2] Zhou et al., MRM 62, 1085-1090, 2009.
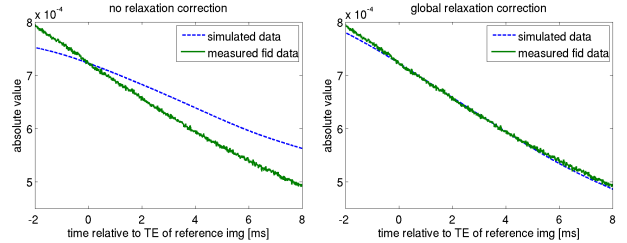
Figure 1: Comparison of measured FID data and simulations based on field maps (in vivo data). Although acquired under the same conditions, the field map alone cannot explain the FID curve at full (left). Making a rough guess on a global relaxation constant (T2*=55ms) shows that relaxation cannot be neglected (right).
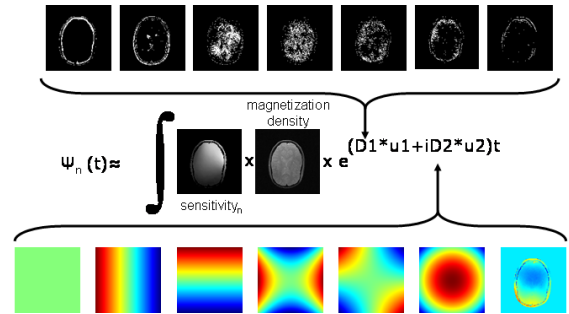

Figure 2: Depiction of how the real (D1) and imaginary (D2) basis functions are put together. This model is then used in an iterative non-linear fit.
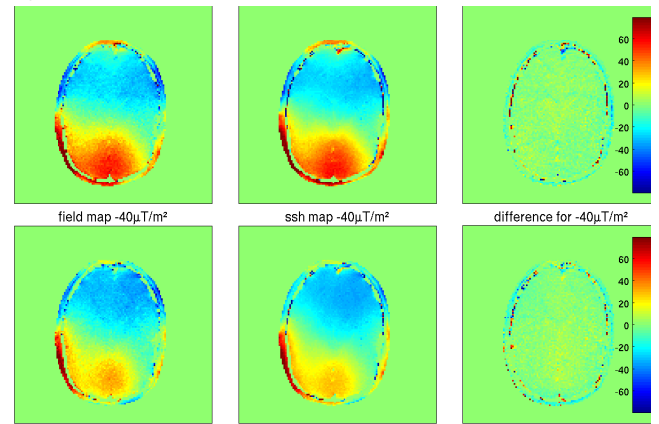

Figure 3: Visual comparison of the results of field maps obtained from the two acquired images and those computed with one image and one FID, as suggested. Difference images are shown on the right hand side. Values are given in Hz.
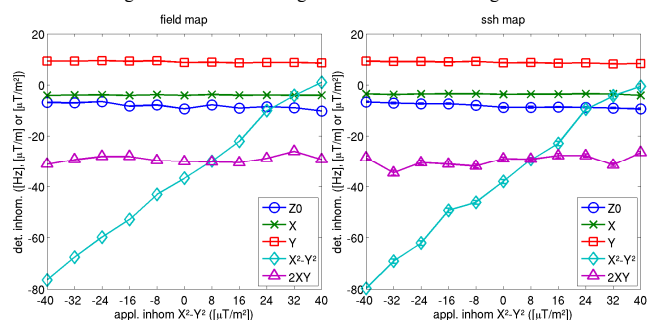

Figure 4: Quantitative comparison of the results. Shown are the detected shim coefficients obtained from field maps (left) and ssh maps (right). For the ssh maps ±σ bars are given based on 50 FID lines. Due to the poor support of Z2 in an axial plane through the iso-centre only Z0, X, Y, X²-Y² and 2XY were taken into account.