Using Spatio-Temporal Field Monitoring for Iterative Higher Order DSU Pre-Emphasis Calibration

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Introduction: The transition to ultra-high field promises a range of major advantages for functional MRI and MRSI, including higher SNR, stronger BOLD-effects and higher spectral resolution. However these advantages come at the expense of B_1 and B_0 inhomogeneity, among others. To adress the latter higher order shimming with slice-wise or regional dynamic shim updates (DSU) [1] is a particularly promising approach.

Dynamic shimming involves fast switching of magnetic fields and thus induces eddy currents in the shim coils themselves and in surrounding conductive structures. These lead to time-dependent higher-order field distortions, which can last for up to a few seconds and may be larger than underlying static distortions. To be useful in practice, DSU hence needs active eddy-current compensation by pre-emphasis, requiring suitable hardware and calibration.

This work presents the implementation of 3rd-order DSU on a 7T human MR system, using fast iterative pre-emphasis calibration with a 3rd-order field camera [2,3]. Compared to FASTERMAP [4,5], this approach offers higher time resolution and is significantly faster, because it observes and disambiguates all spherical-harmonic field components simultaneously and in real time.

Materials and Methods: All measurements were performed on a 7T Philips Achieva whole-body system (Philips Healthcare, Cleveland, USA), equipped with a full set of 3rd-order shim coils, shim amplifiers and a digital DSU unit (Resonance Research Inc, Billerica, USA). The field camera was based on 16 NMR probes equally distributed on a sphere with a diameter of 20 cm, as described in [3]. Re-exciting the probes at regular intervals, this setup permits observing the temporal field evolution at microsecond resolution over several tens of seconds. A linear transform then converts the probe measurements into 16 spherical harmonics that correspond to the fields realized by the shim coils.

While switching currents in each single shim coil separately, the time-dependent field distributions were recorded. The acquired data revealed static cross-terms as well as eddy-current-induced exponential decays, which were fitted by a tri-exponential fit in MATLAB (Mathworks, Natick, USA) to calculate the time constants that were used for initializing the iterative pre-emphasis calibration approach. Once the ranges of the time constants were set by adjusting capacitances in the DSU unit, the time constants and amplitudes of the pre-emphasis currents could be refined via a software interface. The resulting quality of pre-emphasis was then assessed by re-acquiring the field evolution data. By typically 4-7 iterations of this kind, pre-emphasis settings for each shim channel were iteratively optimized.

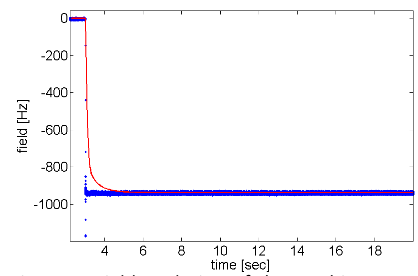

Figure 1: Field evolution of the XY-shim term during and after switching the XY shim to 30% of its maximum value with (blue) and without (red) pre-emphasis.

This approach allowed for calibrating the eddy current compensation in the switched shim coil itself, and also for eddy-current cross terms to Z0. However, cross-terms to 1st-order fields were not addressed because control input to the gradient coils from the shim interface was not available yet. Also some 3rd-order pre-emphasis settings were not fully implemented due to current amplitude limitations.

Echo Planar Imaging (EPI) scans (Fig.(3)) were acquired in vivo with different static and dynamic shim settings, using a standard fMRI protocol. The shim was set 1.3 ms before excitation and 17 ms before acquisition. The shim values were the same for the compared images (b-d), except for the global shim (a).

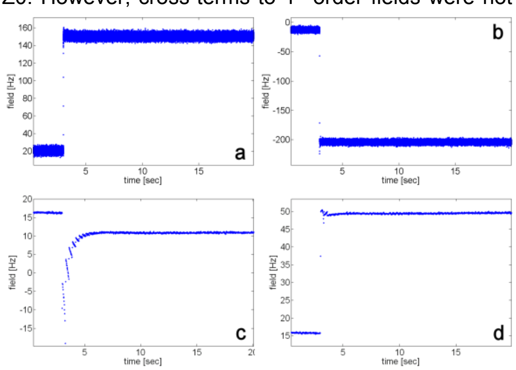

Figure 2: TOP: Temporal field evolution of the unshielded 3rd order Y3-shim term (a) and the shielded 2nd order Z2-shim term (b) with pre-emphasis, during and after switching these shims respectively. BOTTOM: Z0-shim cross contribution, while switching the Y3-shim coil (c) and the Z2-shim coil (d).

Results and Discussion: Figs. (1) and (2) show the time dependence of some shim term contributions of the magnetic field, during and after switching the respective shim coil to 30% of its maximum current. Fig. (1) compares the switching process with (blue) and without (red) pre-emphasis. As shown, the switched shim reaches its final values almost instantly, with optimized pre-emphasis. The difference between the desired and the measured time evolution of the switched shim is < 2% of the shim step within less than 2 ms.

This allows for acquiring data almost immediately after switching the shim without a significant loss of image quality compared to a global shim. Fig. (2) also presents the Z0 cross term contribution, while switching the Y3 (c) and the Z2 (d) shim, respectively. As visible, especially for the 3rd order, the cross term pre-emphasis is not perfect yet. Nevertheless the results show a significant improvement compared to a global shim and demonstrate that the pre-emphasis calibration by using field monitoring is capable of minimizing arising problems of DSU.

Fig. (3) presents a comparison between EPIs acquired with a global 3rd-order shim (a), a static 3rd-order shim of the shown slice (b) and a dynamic 3rd-order shim with (d) and without (c) pre-emphasis. Significant image distortions can be seen in the images acquired without pre-emphasis. Even if the pre-emphasis calibration in this case is not complete, it is possible to gain image quality using DSU with pre-emphasis even over a global shim, and almost reach the quality of a static slice based shim.

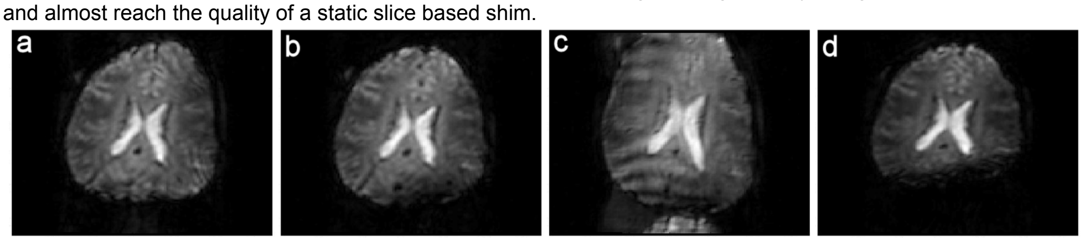

Figure 3: Comparison of EPIs using a global 3rd order shim (a), a static slice based 3rd order shim (b) and a dynamic slice based 3rd order shim without (c) and with (d) pre-emphasis.

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