Relative B1+ mapping directly from k-space for rapid Multi-Transmit calibration

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Introduction - The vast majority of B_1+ mapping methods generate field maps by processing a set of images in which the desired flip angle information has been encoded. This approach places a limit on the minimum data that must be acquired – each image has to sufficiently resolve the anatomy being scanned. This abstract presents a method of obtaining relative field maps from much less data by exploiting the fact that B_1+ maps can be compactly represented in k-space. The proposed method circumvents resolving the object and produces relative field maps free of corruption by noise or anatomy. By combining the technique with a standard single channel B_1+ map, it is possible to perform full multi-transmit field mapping in a fast and efficient manner.

Theory - The method utilises the formulation and insights gained from the SPIRIT parallel imaging method [1]. The SPIRIT formulation states that any point in k-space can be synthesised by taking a weighted sum of measurements in its neighbourhood (of size r x r), both locally and from additional receive coils. This is expressed by equation 1, where $d_c(\underline{k})$ is measured k-space intensity at position $\underline{k}$ of the c^{th} coil, $g_{c,c'}(r)$ are appropriate weights, and C is the number of coils. The number of weights is r^2C - 1 per coil, and they can be found by performing a least-squares fit using data from a fully sampled calibration region of k-space of size s x s. By insisting that the least-squares matrix inversion is over-determined, the size of calibration region can be shown to be as given in equation 2. The number of required samples is a function of C and the chosen kernel size.

(1) $$d_c(\underline{k}) = \sum_{c'=1}^{C} g_{c,c'}(r) \otimes d_{c'}(\underline{k})$$ (2) $$s = r - 1 + \sqrt{r^2 C - 1}$$ (3) $$\underline{I}(x,y) = G_I(x,y)\underline{I}(x,y)$$

Equation 1 can be considered in the image domain in a pixel-by-pixel manner as in equation 3 [2], where $\underline{I}(x,y)$ is a C x 1 vector of image intensities at location (x,y), and $G_I(x,y)$ is a C x C matrix containing the values in each voxel of the zero-filled FTs of the fitted SPIRIT kernels. Equation 3 is an eigenvalue equation where the solution has eigenvalue λ=1. By noting that each image is the product of the underlying magnetisation and the receive sensitivities, it can be shown that the principal (λ=1) eigenvectors (EV) of the G_I matrix are directly proportional receive coil sensitivity maps, allowing relative sensitivities to be determined [2].

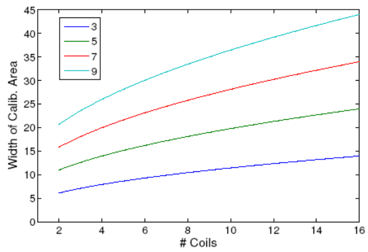

Figure 1 – Required width of calibration area vs. # coils, for several kernel sizes (lines)

This method can be applied for mapping multi-channel transmit fields provided data is acquired with an imaging method in which the transmit field appears in the sequence signal equation in a purely multiplicative manner. A low-flip angle SPGR sequence was chosen, since the measured signal for each transmit configuration simplifies to $I_t = M_0.\theta_t$, where M_0 is the underlying object-dependent signal, and θ_t is the flip-angle distribution in the object. This sequence is then performed C times, once for each transmit configuration, only collecting the number of samples required to perform the fit (equation 2 and figure 1). This approach is highly efficient for B_1+ mapping, since once the frequency content of the field maps is chosen, only the data which is required to estimate those frequencies is measured.

Methods – Both simulated and in-vivo tests were performed. A test dataset was created from a FDTD simulation of the Visible Human [NLM, 1996] in an eight-channel PTx body coil [3]. The expected k-space SPGR signals from the brain (FOV = 44x44) were calculated for a single receive channel when the transmitters were pulsed in eight inverted-phase linear combinations [4]. Noise was added at the same level as measured in the in-vivo dataset (SNR = 27). The process outlined above was performed for kernel sizes 3x3, 5x5 and 7x7 using a calibration region of size 26 x 26 (corresponding to the required number of measurements for a 7x7 kernel). Each λ=1 EV was then divided by the first, producing relative B_1+ maps. These were then multiplied by the gold standard B_1+ map of the first coil to produce estimated B_1+ maps, which were compared to the known simulated fields.

In-vivo brain data was also acquired on a 3T Philips Achieva with an eight channel transmit body coil and six channel receiver coil. Eight 3D SPGR sequences were performed (θ = 1°, TR/TE = 4.4/2ms, FOV = 223x250x180cm, resolution = 2.47x2.5x2.5mm) with alternating transmit configurations, and a central transverse slice was extracted from the datasets for processing (matrix = 88x92). After performing the proposed methodology using the centre 20x20 region of k-space (size corresponds to a 5x5 kernel, see Results), relative B_1+ maps were compared to those measured by modified slice-selective AFI [5,6,7] (TR1/TR2/TE = 30/150/4.6ms, θ = 80°, Δz = 10mm) and from the image-domain low-lip angle SPGR method [8], using both the full SPGR data and using only the 20x20 centre.

Results – The reconstructed field maps of the simulated dataset show agreement with the directly simulated maps for all kernel sizes. The average error in B_1+ magnitude across all relative coil maps for all pixels were [2.1%, 1.3%, 1.3%] for kernel sizes [3, 5, 7]. The average phase errors were [1.34°, 0.68°, 0.65°]. The higher error for both amplitude and phase when using the 3x3 kernel reflects its inability to capture variation in the coil sensitivities corresponding to the higher spatial frequencies. Therefore a 5x5 kernel was used for the in-vivo data.

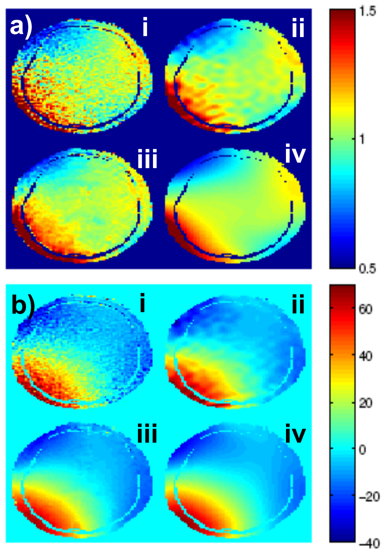

Figure 2 – Relative a) magnitude and b) phase of third coil B_1 maps w.r.t first coil B_1 map. i) SPGR, ii) Low Res SPGR, iii) AFI, and iv) proposed method.

Example in-vivo relative B_1+ maps (third coil compared to the first) are shown in figure 2. The SPGR images have low SNR due to the low flip angle used, which are amplified in the relative map (i). The AFI map (iii) contains corruption from noise and anatomy. The EV approach (iv) match the profiles from the other methods, but without the corruption inherent to those techniques. The low-resolution SPGR ratio (ii) suffers from significant ringing artifact. The acquisition time for determination of full 3D relative coil maps in this using the kernel approach would be 14 seconds.

Discussion – The proposed relative B_1+ mapping technique displays many favourable properties. By directly estimating the spatial frequencies of the transmit field, the method mitigates the anatomical corruption, noise and ringing present in standard approaches. The short TR and low flip-angle makes the approach fast and low SAR. The method is maximally efficient by design, only acquiring the required data to estimate the desired order of spatial frequency in the transmit maps. Only a single absolute B_1+ map is then required to complete a full transmit calibration. If the data for the relative B_1+ field mapping is received on an array coil, the processing can be applied to the individual channels to determine the receive profiles as well. In this case full transmit and receive calibration would be achieved in 14 seconds + the time to acquire a single full B_1+ map.

Acknowledgements – We would like to thank Philips Healthcare for ongoing support with our Multi-Transmit project **References** – [1] Lustig, M. (‘10) MRM 64:457 [2] Lai, P. (‘11) ISMRM 345, [3] Vernickel, P. (‘07) MRM 58:381, [4] Brunner, D. O. (‘09) MRM 61:1480, [5] Yarnyck, V. L., (‘07) MRM 57:192, [6] Nehkre, K. (‘09) MRM 61:84, [7] Malik, S. J. (‘11) MRM 65:1393], [8] Van De Moortele, P. F. (‘07) ISMRM 1676