

# Transmit field fitting at 9.4 T using analytical solutions to Maxwell's equations

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**Target Audience** Researchers using parallel transmit arrays at UHF.

**Purpose** We aim to reliably produce accurate complex maps of the transmit fields of a parallel transceiver array at 9.4 T. These maps are used for  $B_1^+$  static shimming, kt-points homogenised excitation<sup>1</sup> and are intended for spokes homogeneous slice selective excitation and full parallel transmit RF pulse design. We investigate a recently proposed method for modelling complex RF fields using low order analytical solutions to the Helmholtz wave equations in a homogeneous sphere in a spherical polar coordinate system.

**Methods** Following the method proposed by Sbrizzi et al., we produce spherical Bessel functions of low order that are analytical solution to the magnetic Helmholtz wave equation<sup>1</sup>;  $\nabla^2 \mathbf{B} + \zeta^2 \mathbf{B} = 0$  where  $\zeta^2 = \epsilon \mu \omega^2 - i \sigma \mu \omega$ . We then use these basis functions to fit relative  $B_1^+$  maps (RB1)<sup>2</sup> of an 8-channel transceiver array at 9.4 T in a 180 mm diameter spherical 50 mM phosphate buffered saline (PBS) phantom and also *in vivo*. In all cases, five orders of spherical bessel functions were used with  $\omega/2\pi = 400$  MHz. Relative permittivity,  $\epsilon_r$ , and conductivity,  $\sigma$ , were allowed to vary and chosen to minimise the fit error to the measured data. These fitted transmit maps (Maxwell) were qualitatively compared to absolute  $B_1^+$  maps acquired using DREAM<sup>3</sup> and the AFI<sup>4</sup>. Static shimming (CP mode at the centre) and kt-points<sup>5</sup> were performed using DREAM and the resulting RF pulses were used to predict the excitation using the RB1, AFI, Maxwell and DREAM transmit maps. The CP mode was predicted *in vivo* using RB1, AFI, Maxwell and DREAM transmit maps. The accuracy of the DREAM prediction was previously validated using measured AFI and FLASH data to remove the receive weighting from kt-points and CP mode excited FLASH data.

**Results** Figure 1 shows the fit errors as a function of  $(\sigma, \epsilon_r)$  with the optimal values:  $(0.55 \pm 0.5$  S/m,  $\epsilon = 78 \pm 5)$  and  $(0.33 \pm 0.5$  S/m,  $\epsilon = 60 \pm 5)$  for the PBS phantom and brain respectively.

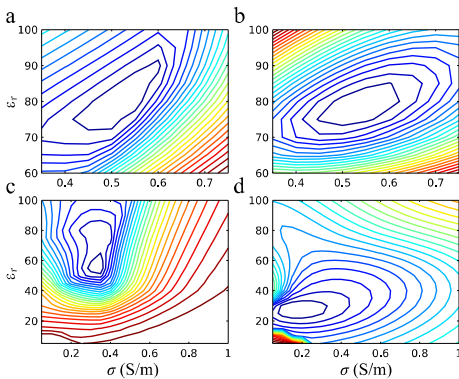


Figure 1.  $L^2$ -norm of the  $B_1^+$  fit error for the spherical PBS phantom, a-b, and *in vivo*, c-d. The error between the RB1 and Maxwell maps, a & c, and between the AFI and Maxwell maps, b & d, are shown.

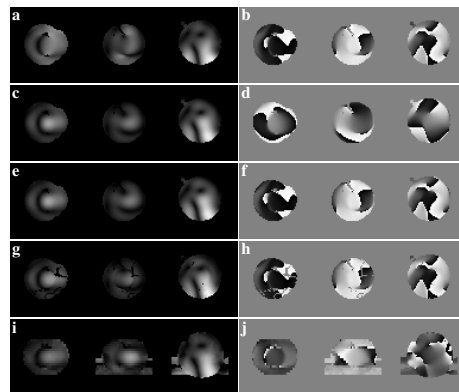


Figure 2. Phantom  $B_1^+$  maps of channel 1 using RB1, a-b, Maxwell, c-d, relative phase Maxwell, e-f, AFI, g-h, and DREAM, i-j. Mid-sagittal, coronal and axial slices are shown. Magnitude, left, and phase, right, are shown.

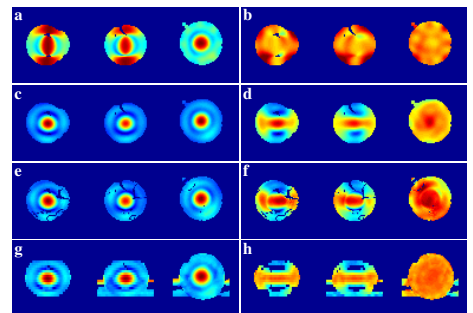


Figure 3. Predicted excitations in a phantom using CP mode at the centre (left) and kt-points over a slab (right).  $B_1^+$  maps used were RB1, a-b, Maxwell, c-d, AFI, e-f, and DREAM, g-h. Mid-sagittal, coronal and axial slices are shown.

**Discussion** The fit error in the spherical PBS phantom was well behaved and provided a clear minimum that was coincidental for the error between the RB1 and Maxwell, and the AFI and Maxwell fields (see Fig. 1). The literature<sup>6</sup> gives  $(\sigma, \epsilon_r)$  values of (0.74, 57), (0.44, 42), and (2.25, 71) for grey matter, white matter and CSF respectively. The *in vivo* fit error minimising values of  $\epsilon_r$  are reasonable, but  $\sigma$  appears to be low. Comparing *in vivo* Maxwell with AFI fields failed, probably due to poor quality AFI data (Figs. 1d and 4c). Figures 4b and 4d qualitatively compare well.

Maxwell fields predict the CP mode excitation with sufficient accuracy (Fig. 3c). Some radial weighting is evident in the kt-points excitation prediction (Fig. 3d); this may be due to an incorrect estimate of  $\epsilon_r$  or  $\sigma$ .

This method also reveals the receive fields and the unmixed transmit and receive phases. The absolute transmit phase (Fig. 2d) was made relative to channel 8 (Fig. 2f) for the comparison to the RB1 phase (Fig. 2b). No study was made of the receive maps, but this might be done by using them in SENSE reconstruction of artificially undersampled data and comparison with fully sampled data.

**Conclusion** A method of forcing the relative  $B_1$  maps to obey Maxwell's equations was used to obtain more correctly scaled transmit maps. Although a flip angle calibration measurement is still required. The minimum fit error is proposed to find  $\epsilon_r$  or  $\sigma$ , which appears to work well in phantom and less well *in vivo*. More investigation is needed so this method can be used routinely *in vivo* at 9.4 T.

**References** <sup>1</sup>A Sbrizzi et al., *MRM* (2013) in press, <sup>2</sup>A Sbrizzi et al., *MRM* (2013) in press, <sup>3</sup>K Nehrke and P Börnert, *MRM* (2012) **68** p1517, <sup>4</sup>V L Yarmykh, *MRM* (2007) **57** p192, <sup>5</sup>M A Cloos et al., *MRM* (2012) **67** p72, <sup>6</sup>S Gabriel et al., *Phys Med Biol* (1996) **41** p2271.

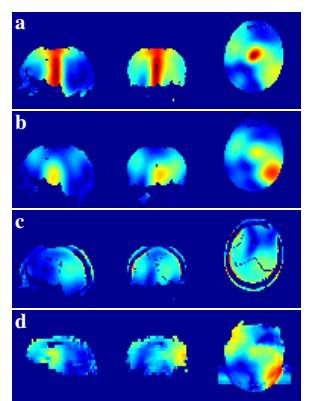


Figure 4. Predicted CP mode *in vivo*.  $B_1^+$  maps used were RB1 mapping, a, Maxwell, b, AFI, c, and DREAM, d. Mid-sagittal, coronal and axial slices are shown.