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Title: FORWARD MODEL FOR THE SUPERCONDUCTING IMAGING-SURFACE MEG SYSTEM

Author(s): Robert R.H.Kraus, Jr., Andrei Matlachov, Michelle Espy, Biophysics Group (P-21)

Keeran Maharajh, Petr Volegov, University of New Mexico, Albuquerque, NM

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Forward Model for the Superconducting Imaging-Surface MEG System

Kraus, Jr., R.H.[1], Matlachov, A.[1], Volegov, P.[2], Espy, M.[1], and Marahjh, K.[2]

Los Alamos National Laboratory, Los Alamos, NM USA; University of New Mexico, Albuquerque, NM, USA

We have recently completed a novel whole-head MEG system based on the Superconducting Imaging-Surface (SIS) concept originally proposed by van Hulsteyn, et al.[1]. The SIS concept is generally described as a source near a superconducting surface. The source field induces Meissner currents in the superconductor equivalent to a source image 'behind' the surface. A sensor (SQUIDs in our system) placed on the source-side of the SIS will measure the superposed fields from the real and image sources. A second consequence of the Meissner effect is to shield the SQUIDs sensors near the SIS from external or background fields. The shape of the SIS used in our MEG system is a hemisphere with two cut-outs at the nominal ear-locations. A brim is added around the entire periphery with a smooth 0.5 cm radius transition between brim and hemisphere.

Benefits of the SIS concept over existing systems include significantly enhanced signal-to-noise as a consequence of the SIS shielding and inherently generating pseudo-first order gradient fields at the sensors. One of the most significant challenges in realizing this system has been to accurately describe how the SIS system impacts the forward physics of any source model. Two approaches have been examined. The first is a hybrid analytical and empirical model using the analytic formalism to describe the hemisphere[1] and a correction matrix derived from empirical measurements to correct for edge effects. This approach proved overly complex and difficult in practice to obtain sufficient empirical data to derive a well-conditioned correction matrix.

The second approach, reported here, was to develop a boundary element model (BEM) description of the SIS using the exact as-built geometry. Each element is described by a uniform magnetization arising from a distribution of Meissner currents in the superconductor such that $B_{\perp}=0$ at the surface. $\mathbf{B}_i$ at each element is a superposition of the source field and the fields resulting from currents in all other elements. The field normal component field at the i^{th} element in mesh j is given by:

$$\mathbf{B}_i(\mathbf{r})\cdot\hat{n}_i=\left\{\left(\sum_j\sum_{m=1}^{3}\frac{\mu_0}{4\pi}[\mathbf{r}_{jm}^{(1)}\times\mathbf{r}_{jm}^{(2)}]\frac{(\mathrm{r}_{jm}^{(1)}+\mathrm{r}_{jm}^{(2)})}{\mathrm{r}_{jm}^{(1)}\mathrm{r}_{jm}^{(2)}(\mathrm{r}_{jm}^{(1)}\mathrm{r}_{jm}^{(2)}+(\mathbf{r}_{jm}^{(1)}\cdot\mathbf{r}_{jm}^{(2)}))}\right)\cdot\hat{n}_i\right\}\mathrm{I}_j$$

$$\mathbf{r}_{jm}^{(k)}=\mathbf{r}_i-\mathbf{v}_{jm}^{(k)};\ \ \mathrm{k}=1,2;\ \ \mathrm{m}=1,2,3(\mathrm{m}^{th}\mathrm{segment});\ \ \mathrm{j}=1:\#\text{of cells in mesh}$$

$\mathbf{n}_i$ is the unit vector normal to the SIS at the i^{th} cell, $r_j^{(1)}$ and $r_j^{(2)}$ are the position of the 1st and the 2nd endpoint at line segment j. This can be rewritten as,

$$B_i=\sum_j A_{ij}I_j;\quad and\quad A_{ij}=\left(\sum_j\sum_{m=1}^{3}\frac{\mu_0}{4\pi}[\mathbf{r}_{jm}^{(1)}\times\mathbf{r}_{jm}^{(2)}]\frac{(\mathrm{r}_{jm}^{(1)}+\mathrm{r}_{jm}^{(2)})}{\mathrm{r}_{jm}^{(1)}\mathrm{r}_{jm}^{(2)}(\mathrm{r}_{jm}^{(1)}\mathrm{r}_{jm}^{(2)}+(\mathbf{r}_{jm}^{(1)}\cdot\mathbf{r}_{jm}^{(2)}))}\right)\cdot\hat{n}_i$$

For properly conditioned A_{ij}, I_i may be solved by simple matrix inversion, i.e. $\mathbf{A}^{-1}\mathbf{B}=\mathbf{I}$.

A precision phantom was developed to test the model. Modeled and measured magnetic field distributions agreed with typically less than 1% (<0.1% in most cases) discrepancy at all SQUID sensors for more than 60 phantom coil positions. The attached figure shows modeled and measured magnetic field distributions for 25 such phantom coils.

[1] van Hulsteyn, D.B., Petschek, A.G., Flynn, E. R., and Overton, W.C., Superconducting Imaging Surface magnetometry, **Rev. Sci. Instr.** 66, 3777-3784 (1995)

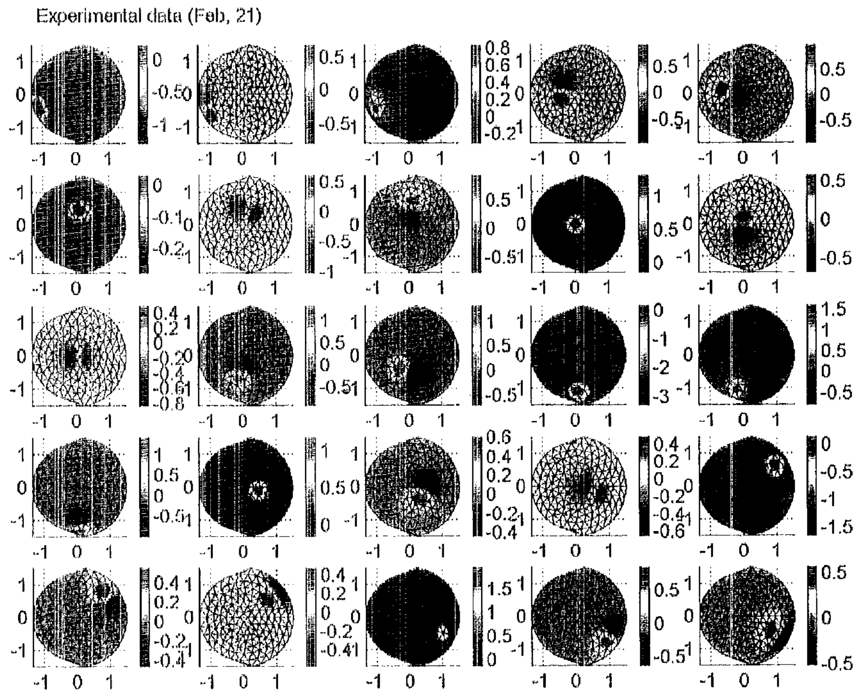

Figure 1a: Whole-Head SIS system measured magnetic field data for 25 phantom positions showing broad distribution of phantom positions and orientations used.

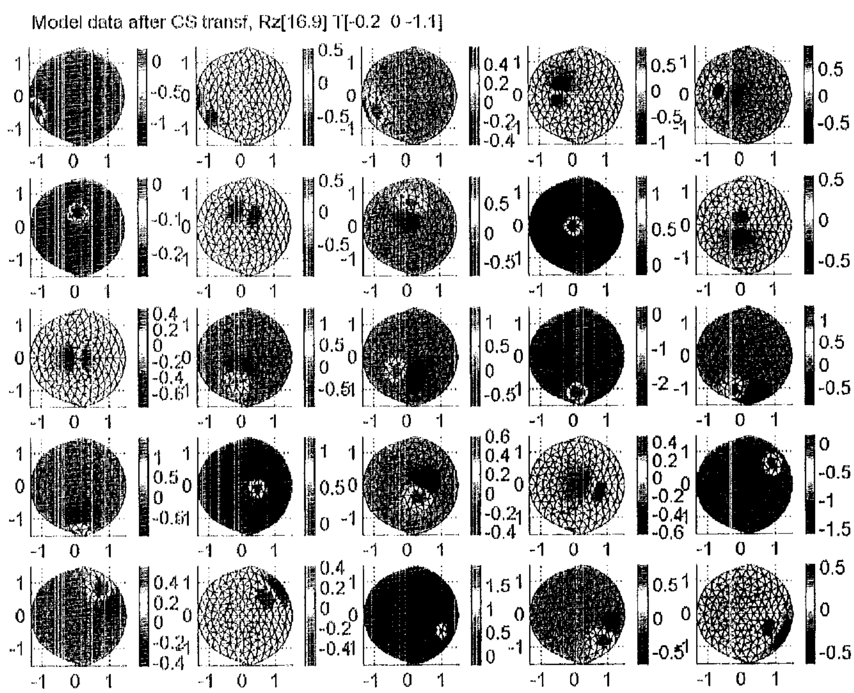

Figure 1b: Whole-Head SIS system calculated magnetic field distributions for 25 phantom positions showing good reproduction of measured data for all phantom positions and orientations.