Electro-Magneto-Encephalography for the three-Shell Model: Numerical Implementation for Distributed Current in Spherical Geometry

A.S.Fokas[1] & V.Michel[2]
[1] *Department of Applied Mathematics and Theoretical Physics*
University of Cambridge
Cambridge, CB3 0WA, UK
[2] *Geomathematics Group, Department of Mathematics*
University of Siegen
57068 Siegen, Germany

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Abstract

The basic inverse problems for the functional imaging techniques of Electroencephalography (EEG) and Magnetoencephalography (MEG) consist of estimating the neuronal current in the brain from the measurement of the electric potential on the scalp and of the magnetic field outside the head. Here we present a rigorous derivation of the relevant formulae for a three-shell spherical model in the case of independent as well as simultaneous MEG and EEG measurements. Furthermore, we introduce an explicit and stable technique for the numerical implementation of these formulae. Numerical examples are presented using the locations and the normal unit vectors of the real 102 sensors of the Electa Neuromag (R) apparatus.

1 Introduction

For the study of real time brain processes, among the most important imaging techniques are electroencephalography (EEG) and magnetoencephalography (MEG). Taking into consideration that the language of mind is electrical signaling, it follows that EEG and MEG allow, in some sense, the recording in real time of "brain conversations". In order to produce images of brain activation using either EEG or MEG it is necessary to solve certain mathematical inverse problems. Indeed, the neuronal current (the so-called primary current) creates an electric potential which can be measured on the scalp, as well as a magnetic field which can be measured outside the head. The relevant inverse problems for EEG and MEG involve the calculation of the neuronal current from the knowledge of the electric potential and the magnetic field respectively. However, as it was already known to Helmholtz since 1853, the solutions of these problems are non-unique.

For MEG, a complete answer to the non-uniqueness question for a homogeneous *spherical* model was presented in [1] and [2] where it was shown that: (a) The only part of a continuously distributed current that can be reconstructed via MEG consists of certain moments of one of the two functions specifying the tangential component of the current (the other function specifying the tangential component, as well as the radial component of the current are "invisible" in the spherical model of MEG). (b) It is possible to reconstruct uniquely the current that minimizes the L^2-norm. Some of these results were extended, from a spherical to a star-shape geometry in [3]. The mathematical notion of complementarity of MEG and EEG for a *spherical* geometry was introduced in [4] where it was shown that the component of a continuously distributed neuronal current which generates the electric potential (and hence measured by EEG) lives in the orthogonal complement of the component of the current which generates the magnetic potential (which is measured by MEG).

A straightforward approach for the solution of the inverse problems associated with simultaneous EEG and MEG measurements was introduced in [5]. This approach yields a complete answer to the non-uniqueness question even in the case of an arbitrary geometry. Furthermore, in the particular cases of spherical and ellipsoidal geometries it yields effective formulae for the "visible" component of the current.

In this paper: (a) We present the *rigorous* solution of the inverse problems associated with the spherical three-shell model in the case of independent as well as simultaneous EEG and MEG measurements. In the case of independent MEG measurements, the formula is identical to the one in [1], [2], but the derivation is much simpler. (b) We introduce an effective numerical implementation of the associated formula for MEG, both for independent as well as simultaneous EEG and MEG measurements.

The spherical three-shell model consists of a sphere Ω_{c} modeling the space occupied by the cerebrum, surrounded by three concentric shells $\Omega_{\mathrm{f}}, \Omega_{\mathrm{b}}, \Omega_{\mathrm{d}}$, modeling the spaces occupied by the cerebrospinal fluid, the skull and the skin. These compartments are distinguished by their different values of electric conductivity, which will be denoted respectively by σ_{c}, σ_{f}, σ_{b}, σ_{d}. The domains $\Omega_{\mathrm{c}}, \Omega_{\mathrm{f}}, \Omega_{\mathrm{b}}, \Omega_{\mathrm{d}}$ are defined as follows:

$$\Omega_{\mathrm{c}} : 0 \leq r < c_1, \Omega_{\mathrm{f}} : c_1 < r < f_1, \Omega_{\mathrm{b}} : f_1 < r < b_1,$$
$$\Omega_{\mathrm{d}} : b_1 < r < d_1.$$

Also, Ω_{e} will denote the space defined by $r > d_1$.

In the following, vectors are denoted by bold-face letters such as $\mathbf{r}$, $\boldsymbol{\tau}$, $\mathbf{Q}$, and $\mathbf{J}$, whereas their Euclidean norms are denoted by their corresponding non-bold-face counterparts, for example, r and τ. Moreover, the associated unit vectors are denoted by $\hat{\mathbf{r}} := r^{-1}\mathbf{r}$, $\hat{\boldsymbol{\tau}} := \tau^{-1}\boldsymbol{\tau}$, etc.

2 A Simple Derivation of the Result of [2] and its EEG Analogue

2.1 MEG

Proposition 2.1 *Let $\mathbf{Q}(\boldsymbol{\tau})$ be the moment of a dipole at the point $\boldsymbol{\tau}$ with $\tau < d_1$. Then, the corresponding magnetic potential $U^{\mathrm{D}}(\mathbf{r}, \boldsymbol{\tau})$ at the exterior Ω_{e} satisfies*

$$4\pi r \frac{\partial U^{\mathrm{D}}}{\partial r} = -(\mathbf{Q}(\boldsymbol{\tau}) \times \boldsymbol{\tau}) \cdot \nabla_{\boldsymbol{\tau}} \frac{1}{|\mathbf{r} - \boldsymbol{\tau}|}, \quad \mathbf{r} \in \Omega_{\mathrm{e}}. \tag{1}$$

Proof. Recall that

$$-\frac{4\pi}{\mu} \mathbf{r} \cdot \mathbf{B}^{\mathrm{D}}(\mathbf{r}) = \mathbf{r} \cdot \left(\mathbf{Q} \times \nabla_{\mathbf{r}} \frac{1}{|\mathbf{r} - \boldsymbol{\tau}|} \right). \tag{2}$$

Since $\tau < d_1$, B^{D} is obviously in $\mathrm{C}^{(\infty)}(\Omega_{\mathrm{e}})$. Using the definition of U^{D} (note that the Maxwell equations imply the existence of U^{D}), i.e.

$$\mathbf{B}^{\mathrm{D}} = \mu \nabla_{\mathbf{r}} U^{\mathrm{D}},$$

as well as the identity

$$\nabla_{\mathbf{r}} \frac{1}{|\mathbf{r} - \boldsymbol{\tau}|} = -\nabla_{\boldsymbol{\tau}} \frac{1}{|\mathbf{r} - \boldsymbol{\tau}|},$$

equation (2) becomes

$$4\pi \mathbf{r} \cdot \nabla_{\mathbf{r}} U^{\mathrm{D}} = \mathbf{r} \cdot \mathbf{Q} \times \nabla_{\boldsymbol{\tau}} \frac{1}{|\mathbf{r} - \boldsymbol{\tau}|}. \tag{3}$$

But the RHS of this equation equals

$$\mathbf{r} \cdot \mathbf{Q} \times \frac{(\mathbf{r} - \boldsymbol{\tau})}{|\mathbf{r} - \boldsymbol{\tau}|^3} = \boldsymbol{\tau} \cdot \mathbf{Q} \times \frac{(\mathbf{r} - \boldsymbol{\tau})}{|\mathbf{r} - \boldsymbol{\tau}|^3} = \boldsymbol{\tau} \cdot \mathbf{Q} \times \nabla_{\boldsymbol{\tau}} \frac{1}{|\mathbf{r} - \boldsymbol{\tau}|},$$

which equals the RHS of equation (1). Also

$$\mathbf{r} \cdot \nabla_{\mathbf{r}} U^{\mathrm{D}} = r \frac{\partial U^{\mathrm{D}}}{\partial r}$$

and hence equation (3) becomes equation (1). ■

Note that, in the following, $\mathbf{J}^{\mathrm{P}}$ denotes the primary current which is derived from the integration of terms including the dipole moment $\mathbf{Q}$. In a sense, it is the continuous analogue of the discrete dipole moment. Correspondingly, whereas U^{D} represents the magnetic potential of a single dipole, we will write U for the continuous version, i.e.

$$U(\mathbf{r}) := \int_{\Omega_{\mathrm{c}}} U^{\mathrm{D}}(\mathbf{r}, \boldsymbol{\tau})\, \mathrm{dV}(\boldsymbol{\tau}).$$

Proposition 2.2 *Let $\mathbf{J}^{\mathrm{P}}(\boldsymbol{\tau})$ be supported in Ω_{c} and assume that it has sufficient smoothness so that Gauss's theorem can be applied. Then*

$$4\pi U(\mathbf{r}) = -\int_{\Omega_{\mathrm{c}}} \left\{ \left[\nabla_{\tau} \cdot (\mathbf{J}^{\mathrm{P}}(\boldsymbol{\tau}) \times \boldsymbol{\tau})\right] \sum_{n=0}^{\infty} \frac{\tau^n}{r^{n+1}(n+1)} P_n(\hat{\mathbf{r}} \cdot \hat{\boldsymbol{\tau}}) \right\} \mathrm{dV}(\boldsymbol{\tau}),\ \mathbf{r} \in \Omega_{\mathrm{e}}. \tag{4}$$

Proof. Using the basic identity

$$\frac{1}{|\mathbf{r} - \boldsymbol{\tau}|} = \sum_{n=0}^{\infty} \frac{\tau^n}{r^{n+1}} P_n(\hat{\mathbf{r}} \cdot \hat{\boldsymbol{\tau}}), \quad r > \tau, \tag{5}$$

in equation (1), dividing the resulting equation by r, integrating the result with respect to r and using the fact that U^{D} vanishes as $r \to \infty$, equation (1) yields

$$4\pi U^{\mathrm{D}}(\mathbf{r}, \boldsymbol{\tau}) = (\mathbf{Q}(\boldsymbol{\tau}) \times \boldsymbol{\tau}) \cdot \nabla_{\boldsymbol{\tau}} \sum_{n=0}^{\infty} \frac{\tau^n}{r^{n+1}(n+1)} P_n(\hat{\mathbf{r}} \cdot \hat{\boldsymbol{\tau}}), \quad \mathbf{r} \in \Omega_{\mathrm{e}}. \tag{6}$$

The above derivation involves interchanging integration with respect to $\mathrm{d}r$ with $\nabla_{\boldsymbol{\tau}} \sum_{n=0}^{\infty}$. This can be justified as follows: We investigate the series

$$\begin{aligned} &\sum_{n=0}^{\infty} \left(\hat{\boldsymbol{\tau}} \frac{\partial}{\partial \tau} + \frac{1}{\tau} \nabla^*_{\hat{\boldsymbol{\tau}}} \right) \frac{\tau^n}{r^{n+2}} P_n(\hat{\mathbf{r}} \cdot \hat{\boldsymbol{\tau}}) \\ = &\sum_{n=1}^{\infty} \left(n \frac{\tau^{n-1}}{r^{n+2}} P_n(\hat{\mathbf{r}} \cdot \hat{\boldsymbol{\tau}}) \hat{\boldsymbol{\tau}} + \frac{\tau^{n-1}}{r^{n+2}} P'_n(\hat{\mathbf{r}} \cdot \hat{\boldsymbol{\tau}}) (\hat{\mathbf{r}} - (\hat{\boldsymbol{\tau}} \cdot \hat{\mathbf{r}}) \hat{\boldsymbol{\tau}}) \right), \end{aligned}$$

where $\nabla_{\boldsymbol{\tau}} = \hat{\boldsymbol{\tau}} \frac{\partial}{\partial \tau} + \frac{1}{\tau} \nabla^*_{\hat{\boldsymbol{\tau}}}$ is the usual decomposition of the gradient operator in its radial and angular parts. The series is, for fixed $\boldsymbol{\tau} \in \Omega_{\mathrm{c}}$, uniformly convergent with respect to $\mathbf{r} \in \Omega_{\mathrm{e}}$, since it is dominated by

$$\sum_{n=1}^{\infty} \left(n \frac{\tau^{n-1}}{r^{n+2}} + \frac{\tau^{n-1}}{r^{n+2}} \frac{n(n+1)}{2} \cdot 2 \right)$$

(see [6], p. 39 for the estimates of P_n and P'_n). Thus,

$$\begin{aligned} &\nabla_{\boldsymbol{\tau}} \sum_{n=0}^{\infty} \frac{\tau^n}{r^{n+2}} P_n(\hat{\mathbf{r}} \cdot \hat{\boldsymbol{\tau}}) \\ = &\sum_{n=1}^{\infty} \left(n \frac{\tau^{n-1}}{r^{n+2}} P_n(\hat{\mathbf{r}} \cdot \hat{\boldsymbol{\tau}}) \hat{\boldsymbol{\tau}} + \frac{\tau^{n-1}}{r^{n+2}} P'_n(\hat{\mathbf{r}} \cdot \hat{\boldsymbol{\tau}}) (\hat{\mathbf{r}} - (\hat{\boldsymbol{\tau}} \cdot \hat{\mathbf{r}}) \hat{\boldsymbol{\tau}}) \right). \end{aligned}$$

Furthermore, for similar reasons the series

$$\sum_{n=1}^{\infty} \int_{\varrho}^{\infty} \left| n \frac{\tau^{n-1}}{r^{n+2}} P_n \left(\hat{\mathbf{r}} \cdot \hat{\boldsymbol{\tau}}\right) \hat{\boldsymbol{\tau}} + \frac{\tau^{n-1}}{r^{n+2}} P_n' \left(\hat{\mathbf{r}} \cdot \hat{\boldsymbol{\tau}}\right) \left(\hat{\mathbf{r}} - \left(\hat{\boldsymbol{\tau}} \cdot \hat{\mathbf{r}}\right) \hat{\boldsymbol{\tau}}\right) \right| \mathrm{d}r \Bigg|_{\varrho = r}$$
$$\leq \sum_{n=1}^{\infty} \left(\frac{n}{n+1} \cdot \frac{\tau^{n-1}}{r^{n+1}} + \frac{\tau^{n-1}}{r^{n+1}} \cdot \frac{1}{n+1} n(n+1) \right) + \mathrm{const}$$

is convergent for all $\mathbf{r} \in \Omega_{\mathrm{e}}$. Consequently, the interchanging of the integration with the gradient operator and the summation is allowed.
Integrating (6) with respect to $\boldsymbol{\tau}$ (which represents the transfer from the discrete case of a single dipole to the continuous case) and using Gauss's theorem yields the following:

$$4\pi U(\mathbf{r}) = \int_{\partial\Omega_{\mathrm{c}}} \mathbf{n} \cdot \left(\mathbf{J}^{\mathrm{P}}(\boldsymbol{\tau}) \times \boldsymbol{\tau}\right) \sum_{n=0}^{\infty} \frac{\tau^n}{r^{n+1}(n+1)} P_n(\hat{\mathbf{r}} \cdot \hat{\boldsymbol{\tau}}) \, \mathrm{dS}(\boldsymbol{\tau})$$
$$- \int_{\Omega_{\mathrm{c}}} \left\{ \left[\nabla_{\tau} \cdot \left(\mathbf{J}^{\mathrm{P}}(\boldsymbol{\tau}) \times \boldsymbol{\tau}\right)\right] \sum_{n=0}^{\infty} \frac{\tau^n}{(n+1) r^{n+1}} P_n(\hat{\mathbf{r}} \cdot \hat{\boldsymbol{\tau}}) \right\} \mathrm{dV}(\boldsymbol{\tau}).$$

But $\mathbf{J}^{\mathrm{P}}(\boldsymbol{\tau})$ vanishes on $\partial\Omega_{\mathrm{c}}$ and thus equation (4) follows. ■

Remark 2.1 *Equation (6) shows that the component of* $\mathbf{J}^{\mathrm{P}}(\boldsymbol{\tau})$ *in the* $\hat{\tau}$ *direction does not contribute to the magnetic field generated by a single dipole. Thus, measurements of* U *yield the two components* $(\mathbf{J}^{\mathrm{P}})^{\theta}$ *and* $(\mathbf{J}^{\mathrm{P}})^{\varphi}$. *On the other hand, equation (4) shows that for a continuously distributed current, the measurement of* U *yields information only about the single function* $\nabla_{\tau} \cdot (\mathbf{J}^{\mathrm{P}}(\boldsymbol{\tau}) \times \boldsymbol{\tau})$. *Hence, we "lose information", i.e. we go from two functions to a single function, as a result of Gauss's theorem!*

Proposition 2.3 *Let* $\hat{\boldsymbol{\tau}}, \hat{\boldsymbol{\theta}}, \hat{\boldsymbol{\varphi}}$ *denote the unit vectors in the spherical directions of the point* $\boldsymbol{\tau}$, *i.e.*

$$\begin{aligned} \hat{\boldsymbol{\tau}} &= (\sin\theta\cos\varphi, \sin\theta\sin\varphi, \cos\theta), \\ \hat{\boldsymbol{\theta}} &= (\cos\theta\cos\varphi, \cos\theta\sin\varphi, -\sin\theta), \\ \hat{\boldsymbol{\varphi}} &= (-\sin\varphi, \cos\varphi, 0). \end{aligned}$$

Let $(J^{\tau}, J^{\theta}, J^{\varphi})$ *be the spherical components of* $\mathbf{J}^{\mathrm{P}}$, *i.e.,*

$$\mathbf{J}^{\mathrm{P}} = J^{\tau} \hat{\boldsymbol{\tau}} + J^{\theta} \hat{\boldsymbol{\theta}} + J^{\varphi} \hat{\boldsymbol{\varphi}}. \tag{7}$$

Then

$$\mathbf{J}^{\mathrm{P}} \times \boldsymbol{\tau} = \tau \left(J^{\varphi} \hat{\boldsymbol{\theta}} - J^{\theta} \hat{\boldsymbol{\varphi}} \right).$$

If J^{θ} *and* J^{φ} *are represented in the form*

$$J^{\theta} = \frac{1}{\tau} \left(G_{\theta} - \frac{1}{\sin\theta} F_{\varphi} \right), \quad J^{\varphi} = \frac{1}{\tau} \left(\frac{1}{\sin\theta} G_{\varphi} + F_{\theta} \right), \tag{8}$$

where $F, G \in \mathrm{C}^{(2)}(\Omega_{\mathrm{c}})$ and the subscripts θ, φ refer to derivatives, then

$$\nabla_\tau \cdot (\mathbf{J}^{\mathrm{P}} \times \boldsymbol{\tau}) = \frac{1}{\tau}\Delta_{\theta,\varphi} F, \quad \Delta_{\theta,\varphi} \doteqdot \frac{1}{\sin\theta}\left[\partial_\theta \sin\theta \partial_\theta + \frac{1}{\sin\theta}\partial_\varphi^2\right]. \tag{9}$$

Proof.

$$\nabla_\tau \cdot (\mathbf{J}^{\mathrm{P}} \times \boldsymbol{\tau}) = \frac{1}{\tau^2 \sin\theta}\left\{\tau(\tau \sin\theta J^\varphi)_\theta + \tau(-\tau J^\theta)_\varphi\right\}$$

$$= \frac{1}{\sin\theta}\left\{(\sin\theta J^\varphi)_\theta - (J^\theta)_\varphi\right\} = \frac{1}{\tau\sin\theta}\left[(\sin\theta F_\theta)_\theta + \frac{1}{\sin\theta}F_{\varphi\varphi}\right].$$

■

Theorem 2.1 *Let $\mathbf{J}^{\mathrm{P}}$ be expanded in the form (7), (8). Then*

$$4\pi U(\mathbf{r}) = -\int_{\Omega_{\mathrm{c}}} \left\{[\Delta_{\theta,\varphi} F(\tau,\theta,\varphi)] \sum_{n=0}^{\infty} \frac{\tau^{n-1}}{r^{n+1}(n+1)} P_n(\hat{\mathbf{r}} \cdot \hat{\boldsymbol{\tau}})\right\} \mathrm{dV}(\boldsymbol{\tau}). \tag{10}$$

Furthermore, if

$$F(\tau,\theta,\varphi) = \sum_{n=0}^{\infty}\sum_{m=-n}^{n} f_n^m(\tau) Y_n^m(\theta,\varphi), \tag{11}$$

where

$$\sum_{n=0}^{\infty}\sum_{m=-n}^{n} |f_n^m(\tau)|\, n^{3+\varepsilon} < +\infty \tag{12}$$

for some $\varepsilon > 0$ and for all $\tau \in [0, c_1]$, then

$$U(\mathbf{r}) = \sum_{n=0}^{\infty}\sum_{m=-n}^{n} \frac{Y_n^m(\Theta,\Phi)}{r^{n+1}} \frac{n}{2n+1} \int_0^{c_1} \tau^{n+1} f_n^m(\tau)\,\mathrm{d}\tau, \quad \mathbf{r} \in \Omega_{\mathrm{e}}, \tag{13}$$

where (r, Θ, Φ) denote the spherical coordinates of $\mathbf{r}$.

Proof. Note that the summability condition (12) implies that

$$\sum_{n=0}^{\infty}\sum_{m=-n}^{n} (f_n^m(\tau))^2\, n^{6+2\varepsilon} < +\infty,$$

which corresponds to the following embedding in Sobolev spaces:

$$F(\tau,\cdot,\cdot) \in \mathcal{H}_{3+\varepsilon}(\Omega) \subset \mathrm{C}^{(2)}(\Omega) \text{ for all } \tau \in [0, c_1],$$

where Ω represents the unit sphere in $\mathbb{R}^3$. For further details we refer to [6], pp. 81. Moreover, due to condition (12) it is allowed to interchange $\Delta_{\theta,\varphi}$ with the limit of the Fourier series since

$$\begin{aligned}\left|\sum_{n=0}^{\infty}\sum_{m=-n}^{n} f_n^m(\tau)\Delta_{\theta,\varphi}Y_n^m(\theta,\varphi)\right| &= \left|\sum_{n=0}^{\infty}\sum_{m=-n}^{n} f_n^m(\tau)[-n(n+1)]Y_n^m(\theta,\varphi)\right| \\ &\leq \sum_{n=0}^{\infty}\sum_{m=-n}^{n} |f_n^m(\tau)|\, n(n+1)\sqrt{\frac{2n+1}{4\pi}}\end{aligned}$$

is uniformly convergent on Ω for every $\tau \in [0, c_1]$.
Furthermore, using $\mathrm{dV} = \tau^2 \sin\theta \,\mathrm{d}\tau\, \mathrm{d}\theta\, \mathrm{d}\varphi$ and

$$\int_0^{2\pi}\int_0^{\pi} Y_n^m(\hat{\boldsymbol{\tau}})P_{n'}(\hat{\boldsymbol{\tau}}\cdot\hat{\mathbf{r}})\sin\theta\,\mathrm{d}\theta\,\mathrm{d}\varphi = \frac{4\pi}{2n+1}\,Y_n^m(\hat{\mathbf{r}})\delta_{nn'} \tag{14}$$

equation (10) immediately becomes equation (13). ∎

Remark 2.2 (Relation between (13) and the result of [2]) *In [2] the problem was first mapped to a harmonic problem. This appears to be an unnecessary complication. In any case, it is straightforward to obtain the analogous result: Equation (1) yields*

$$4\pi U^{\mathrm{D}}(\mathbf{r},\boldsymbol{\tau}) = (\mathbf{Q}(\boldsymbol{\tau})\times\boldsymbol{\tau})\cdot\nabla_{\boldsymbol{\tau}}\left(\frac{1}{\tau}\partial_\tau^{-1}\frac{1}{|\mathbf{r}-\boldsymbol{\tau}|}\right). \tag{15}$$

Indeed,

$$4\pi U^{\mathrm{D}}(\mathbf{r},\boldsymbol{\tau}) = (\mathbf{Q}(\boldsymbol{\tau})\times\boldsymbol{\tau})\cdot\nabla_{\boldsymbol{\tau}}\left(-\partial_r^{-1}\frac{1}{r|\mathbf{r}-\boldsymbol{\tau}|}\right)$$

and it can be verified (using for example equation (5)) that

$$-\partial_r^{-1}\frac{1}{r|\mathbf{r}-\boldsymbol{\tau}|} = \frac{1}{\tau}\partial_\tau^{-1}\frac{1}{|\mathbf{r}-\boldsymbol{\tau}|}.$$

Integrating the RHS of equation (15) w.r.t. $\boldsymbol{\tau}$ *and using Gauss's theorem we find*

$$-\int_0^{2\pi}\int_0^{\pi}\int_0^{c_1}\frac{1}{\tau}(\Delta_{\theta,\varphi}F)\frac{1}{\tau}\partial_\tau^{-1}\frac{1}{|\mathbf{r}-\boldsymbol{\tau}|}\,\tau^2\sin\theta\,\mathrm{d}\tau\,\mathrm{d}\theta\,\mathrm{d}\varphi.$$

Then integrating by parts w.r.t. τ*, we obtain*

$$\begin{aligned}&-\int_0^{2\pi}\int_0^{\pi}\left[\partial_\tau^{-1}\left(\Delta_{\theta,\varphi}F(\tau,\theta,\varphi)\right)\right]\left(\partial_\tau^{-1}\frac{1}{|\mathbf{r}-\boldsymbol{\tau}|}\right)\Bigg|_{\tau=0}^{\tau=c_1}\mathrm{d}\theta\,\mathrm{d}\varphi \\ &+\int_0^{2\pi}\int_0^{\pi}\int_0^{c_1}\left[\partial_\tau^{-1}(\Delta_{\theta,\varphi}F(\tau,\theta,\varphi))\right]\frac{1}{|\mathbf{r}-\boldsymbol{\tau}|}\sin\theta\,\mathrm{d}\tau\,\mathrm{d}\theta\,\mathrm{d}\varphi.\end{aligned}$$

We have

$$\left(\partial_\tau^{-1}\frac{1}{|\mathbf{r}-\boldsymbol{\tau}|}\right)\Bigg|_{\tau=0} = \left(\sum_{n=0}^{\infty}\frac{1}{n+1}\frac{\tau^{n+1}}{r^{n+1}}P_n\left(\hat{\mathbf{r}}\cdot\hat{\boldsymbol{\tau}}\right)\right)\Bigg|_{\tau=0} = 0.$$

Using

$$\partial_\tau^{-1}(\Delta_{\theta,\varphi}F(\tau',\theta,\varphi)) = -\int_\tau^{c_1} \Delta_{\theta,\varphi}F(\tau',\theta,\varphi)\,\mathrm{d}\tau'$$

we get

$$4\pi U(\mathbf{r}) = -\int_{\Omega_c} \frac{1}{|\mathbf{r}-\boldsymbol{\tau}|}\left(\frac{1}{\tau^2}\int_\tau^{c_1}(\Delta_{\theta,\varphi}F)(\tau',\theta,\varphi)\,\mathrm{d}\tau'\right)\mathrm{dV}(\boldsymbol{\tau}). \tag{16}$$

Remark 2.3 (Relation with the minimization of [2]) *Let*

$$U(\mathbf{r}) = \sum_{n=0}^{\infty}\sum_{m=-n}^{n}\frac{c_n^m}{r^{n+1}}Y_n^m(\hat{\mathbf{r}}).$$

In [2], starting with equation (16) it was shown that the constants c_n^m are given by

$$c_n^m = \frac{n}{2n+1}\int_0^{c_1}\tau^{n+1}f_n^m(\tau)\,\mathrm{d}\tau. \tag{17}$$

The derivation of (17) was based on the following: If h is defined by

$$h(\tau,\theta,\varphi) = \frac{1}{\tau^2}\int_\tau^{c_1}\Delta_{\theta,\varphi}F(\tau',\theta,\varphi)\,\mathrm{d}\tau' = \sum_{n=0}^{\infty}\sum_{m=-n}^{n}h_n^m(\tau)\mathrm{Y}_n^m(\theta,\varphi),$$

then

$$h_n^m = -\frac{n(n+1)}{\tau^2}\int_\tau^{c_1}f_n^m(\tau')\,\mathrm{d}\tau'. \tag{18}$$

Furthermore,

$$c_n^m = -\frac{1}{1+2n}\int_0^{c_1}\tau^{n+2}h_n^m(\tau)\,\mathrm{d}\tau. \tag{19}$$

Substituting (18) into (19) and using integration by parts we find equation (17). The advantage of the new derivation is that it yields directly (17) (see equation (13)).

2.2 EEG

Proposition 2.4 *Let $\mathbf{Q}(\boldsymbol{\tau})$ be the moment of a dipole at the point $\boldsymbol{\tau}$. Then, the corresponding electric potential at the scalp is given by*

$$u_\mathrm{s}^\mathrm{D}(\mathbf{r},\boldsymbol{\tau}) = \frac{1}{4\pi}\mathbf{Q}(\boldsymbol{\tau})\cdot\nabla_{\boldsymbol{\tau}}\sum_{n=0}^{\infty}s_n\tau^nP_n(\hat{\boldsymbol{\tau}}\cdot\hat{\mathbf{r}}), \quad r = d_1, \tag{20}$$

where the constant s_n depends on the conductivities and the geometric characteristics.

Proof. See [12]. ■

In analogy to the MEG case, we will write u_s for the continuous analogue of u_s^D.

Theorem 2.2 *Let*

$$\mathbf{J}^{\mathrm{P}}(\boldsymbol{\tau}) = \nabla_{\boldsymbol{\tau}}\Psi(\boldsymbol{\tau}) + \nabla_{\boldsymbol{\tau}} \times \mathbf{A}(\boldsymbol{\tau}), \quad \nabla_{\boldsymbol{\tau}} \cdot \mathbf{A}(\boldsymbol{\tau}) = 0 \tag{21}$$

with $\Psi \in \mathrm{C}^{(2)}(\Omega_{\mathrm{c}}, \mathbb{R}) \cap \mathrm{C}^{(1)}(\overline{\Omega_{\mathrm{c}}}, \mathbb{R})$ *and* $\mathbf{A} \in \mathrm{C}^{(2)}(\Omega_{\mathrm{c}}, \mathbb{R}^3) \cap \mathrm{C}^{(1)}(\overline{\Omega_{\mathrm{c}}}, \mathbb{R}^3)$. *Then the electric potential at the scalp is given by*

$$u_{\mathrm{s}}(\mathbf{r}) = -\frac{1}{4\pi}\int_{\Omega_{\mathrm{c}}} (\Delta\Psi(\boldsymbol{\tau})) \sum_{n=0}^{\infty} s_n \tau^n P_n(\hat{\boldsymbol{\tau}} \cdot \hat{\mathbf{r}})\, \mathrm{dV}(\boldsymbol{\tau}), \quad r = d_1. \tag{22}$$

Furthermore, if Ψ *is expanded in the form*

$$\Psi(\boldsymbol{\tau}) = \sum_{n=1}^{\infty}\sum_{m=-n}^{n} \psi_n^m(\tau) Y_n^m(\hat{\tau}), \tag{23}$$

where $\{\psi_n^m(\tau)\}_{n=1,2,\ldots;\, m=-n,\ldots,n}$ *satisfies the summability condition (12), then*

$$u_{\mathrm{s}}(\mathbf{r}) = -\sum_{n=1}^{\infty}\sum_{m=-n}^{n} \frac{s_n}{2n+1} c_1^{n+1}\left[c_1 \dot{\psi}_n^m(c_1) - n\psi_n^m(c_1)\right] Y_n^m(\hat{\mathbf{r}}), r = d_1. \tag{24}$$

Proof. Integrating (20) with respect to $\mathrm{dV}(\boldsymbol{\tau})$ over Ω_{c}, using Gauss's theorem for the RHS, and noting that

$$\nabla \cdot \mathbf{J}^{\mathrm{P}} = \nabla \cdot (\nabla\Psi + \nabla \times \mathbf{A}) = \Delta\Psi,$$

equation (20) becomes equation (22).
Replacing in (22) Ψ by the RHS of (23) and using the identity

$$\tau^2 \Delta\psi_m^n(\tau) Y_n^m(\hat{\boldsymbol{\tau}}) = \left[\frac{\mathrm{d}}{\mathrm{d}\tau}\left(\tau^2 \frac{\mathrm{d}}{\mathrm{d}\tau}\psi_n^m(\tau)\right) - n(n+1)\psi_n^m(\tau)\right] Y_n^m(\hat{\boldsymbol{\tau}}),$$

as well as the orthogonality relation (14), equation (22) yields

$$u_{\mathrm{s}}(\mathbf{r}) = \tag{25}$$
$$-\sum_{n=1}^{\infty}\sum_{m=-n}^{n} \frac{s_n}{2n+1}\left\{\int_0^{c_1}\left[\frac{\mathrm{d}}{\mathrm{d}\tau}\left(\tau^2\frac{\mathrm{d}}{\mathrm{d}\tau}\psi_n^m(\tau)\right) - n(n+1)\psi_n^n(\tau)\right]\tau^n\,\mathrm{d}\tau\right\} Y_n^m(\hat{\boldsymbol{\tau}}).$$

Note that the application of Δ to (23) was considered here in analogy to the proof of Theorem 2.1. Integration by parts yields

$$\int_0^{c_1}\left[\frac{\mathrm{d}}{\mathrm{d}\tau}\left(\tau^2\frac{\mathrm{d}}{\mathrm{d}\tau}\psi_n^m(\tau)\right)\right]\tau^n\,\mathrm{d}\tau =$$
$$c_1^{n+1}\left[c_1\dot{\psi}_n^m(c_1) - n\psi_n^m(c_1)\right] + n(n+1)\int_0^{c_1}\psi_n^m(\tau)\tau^n\,\mathrm{d}\tau,$$

hence equation (25) becomes equation (24). ∎

Remark 2.4 (Relation with the harmonic kernel) *In the case of the homogeneous sphere, it is straightforward (but again unnecessary) to rewrite equation (23) in terms of the harmonic kernel. Indeed, for the homogeneous case the constant s_n is given by*

$$s_n = \frac{1}{\sigma d_1^{n+1}} \frac{2n+1}{n+1} = \frac{1}{\sigma d_1^{n+1}} \left[2 - \frac{1}{n+1} \right].$$

Thus, the term $s_n \tau^n$ gives the two terms

$$\frac{2}{\sigma} \frac{\tau^n}{d_1^{n+1}}, \qquad -\frac{1}{\sigma} \frac{\tau^n}{d_1^{n+1}(n+1)} \tag{26}$$

and since

$$\sum_{n=0}^{\infty} \frac{\tau^n}{d_1^{n+1}} P_n(\hat{\mathbf{r}} \cdot \hat{\boldsymbol{\tau}}) = \frac{1}{|\mathbf{r} - \boldsymbol{\tau}|} \Big|_{r=d_1},$$

the first of the terms (26) yields immediately the harmonic kernel. Regarding the second term we note that

$$\begin{aligned} \int_0^{c_1} \tau^n (\Delta\Psi(\boldsymbol{\tau})) \tau^2 \frac{\mathrm{d}\tau}{n+1} &= \int_0^{c_1} \frac{\tau^{n+1}}{n+1} (\tau \Delta\Psi(\boldsymbol{\tau}))\, \mathrm{d}\tau \\ &= \int_0^{c_1} \tau^n \left\{ \int_\tau^{c_1} \tau' (\Delta\Psi(\boldsymbol{\tau}'))\, \mathrm{d}\tau' \right\} \mathrm{d}\tau. \end{aligned}$$

Hence, equation (22) can be rewritten in terms of the following harmonic kernel:

$$u_{\mathrm{s}}(\mathbf{r}) = -\frac{1}{4\pi\sigma} \int_{\Omega_{\mathrm{c}}} \left[2(\Delta\Psi)(\tau,\theta,\varphi) - \frac{1}{\tau^2} \int_\tau^{c_1} \tau' (\Delta\Psi)(\tau',\theta,\varphi)\, \mathrm{d}\tau' \right] \frac{\mathrm{dV}(\boldsymbol{\tau})}{|\mathbf{r} - \boldsymbol{\tau}|}, \tag{27}$$

$r = d_1$.

2.3 Simultaneous MEG and EEG Measurements

The case of simultaneous MEG and EEG measurements is analysed in [5]. In this case the basic formulae for EEG are the same, i.e. equations (21), (23) and (24) are still valid. However, for MEG instead of equations (7), (8), (11) and (13), the basic formulae are equations (24) and the following expressions:

$$\frac{4\pi}{\mu} \mathbf{r} \cdot \mathbf{B}(\mathbf{r}) = -\sum_{n=1}^{\infty} \sum_{m=-n}^{n} \frac{c_1^{n+2}}{2n+1} [c_1 \dot{a}_n^m(c_1) - (n-1) a_n^m(c_1)] \frac{Y_n^m(\hat{\mathbf{r}})}{r^{n+1}}, \quad r > d_1, \tag{28}$$

$$A^\tau(\boldsymbol{\tau}) = \sum_{n=1}^{\infty} \sum_{m=-n}^{n} a_n^m(\tau) Y_n^m(\hat{\boldsymbol{\tau}}), \quad 0 < \tau < c_1. \tag{29}$$

The reason for this difference is that now the EEG measurements impose the expansion (24) for the current, thus the expansion (7), (8) is inappropriate.

3 Numerical Implementation

3.1 Description of the Spline Method

In MEG the following data are given

$$b_k = \boldsymbol{\nu}_k \cdot \mathbf{B}(\mathbf{r}_k), \quad k = 1, 2, ..., M, \tag{30}$$

where both $\mathbf{r}_k$ and the unit vector $\boldsymbol{\nu}_k = \boldsymbol{\nu}(\mathbf{r}_k)$ (which is normal to the surface of the device at the point $\mathbf{r}_k$) are known. Our goal is to reconstruct the maximum possible information for the current from the above data. For this purpose, we will use the novel technique of [7, 8] (see also the historical references there), which we now describe. This method (more precisely a version of this method adapted in each case) has already been successfully applied to similar inverse problems in seismic tomography (see [7, 8]) and in inverse gravimetry (see [9, 10]).

The unique determination of either the function $f_n^m(\tau)$ in equation (11) or the function $a_n^m(\tau)$ of (29) requires some a-priori assumption about the current, such as the assumption that $A^\tau(\boldsymbol{\tau})$ is biharmonic. Thus, we will represent either of these functions in the form $\alpha_n^m G_n(\tau)$, where $G_n(\tau)$ is assumed to be known (in the case of the harmonicity assumption G_n is given by τ^n). Hence

$$A^\tau(\boldsymbol{\tau}) = \sum_{n=1}^{\infty} \sum_{j=-n}^{n} \alpha_n^j G_n(\tau) Y_n^j(\hat{\boldsymbol{\tau}}), \quad 0 < \tau < c_1, \tag{31}$$

and similarly for F. This motivates the introduction of the following orthonormal set in $\mathrm{L}^2(\Omega_\mathrm{c})$:

$$H_n^j(\boldsymbol{\tau}) = \gamma_n^{-\frac{1}{2}} G_n(\tau) Y_n^j(\hat{\boldsymbol{\tau}}), \quad \gamma_n = \int_0^{c_1} s^2 G_n^2(s)\, \mathrm{d}s, \quad n \in \mathbb{N}, j = -n, ..., n. \tag{32}$$

The main idea is to expand $A^\tau(\boldsymbol{\tau})$ in terms of appropriate reproducing kernels K [7, 8], instead of spherical harmonics: Let $K(\boldsymbol{\tau}, \mathbf{r})$ be defined by

$$\begin{aligned} K(\boldsymbol{\tau}, \mathbf{r}) &= \sum_{n=1}^{\infty} \sum_{j=-n}^{n} A_n^{-2} H_n^j(\boldsymbol{\tau}) H_n^j(\mathbf{r}) \\ &= \sum_{n=1}^{\infty} \sum_{j=-n}^{n} A_n^{-2} \gamma_n^{-1} G_n(\tau) Y_n^j(\hat{\boldsymbol{\tau}})\, G_n(r) Y_n^j(\hat{\mathbf{r}}), \end{aligned} \tag{33}$$

where the sequence (A_n) has to satisfy a certain summability condition (see [7, 8] for further details).

Let $\mathcal{F}^k$, $k = 1, \ldots, M$, represent the functional which maps A^τ (or F) to the corresponding data $b_k = \boldsymbol{\nu}_k \cdot \mathbf{B}(\mathbf{r}_k)$. In the following we assume that each $\mathcal{F}^k$ is linear and continuous. We use these functionals to construct basis functions for the expansion of A^τ:

$$A^\tau(\boldsymbol{\tau}) = \sum_{k=1}^{M} a_k \mathcal{F}^k_{\mathbf{r}} K(\boldsymbol{\tau}, \mathbf{r}). \tag{34}$$

Here, $\mathcal{F}^k_{\mathbf{r}} K(\boldsymbol{\tau}, \mathbf{r})$ means that $\boldsymbol{\tau}$ is kept fixed and $\mathcal{F}^k$ is applied to the function $\mathbf{r} \mapsto K(\boldsymbol{\tau}, \mathbf{r})$.
In this way we obtain the linear system

$$b_m = \sum_{k=1}^{M} a_k \mathcal{F}^m_{\boldsymbol{\tau}} \mathcal{F}^k_{\mathbf{r}} K(\boldsymbol{\tau}, \mathbf{r}), \tag{35}$$

for the constants a_k, $k = 1, ..., M$.
Mathematical considerations (see [7, 8] and the references therein) show that the reproducing kernel corresponds to a Hilbert space $\mathcal{H}((A_n)) \subset \mathrm{L}^2(\Omega_\mathrm{c})$. This space is equipped with the inner product

$$\langle F, G \rangle_{\mathcal{H}((A_n))} := \sum_{n=1}^{\infty} \sum_{j=-n}^{n} A_n^2 \left\langle F, H_n^j \right\rangle_{\mathrm{L}^2(\Omega_\mathrm{c})} \left\langle G, H_n^j \right\rangle_{\mathrm{L}^2(\Omega_\mathrm{c})}$$

and its induced norm $\| \cdot \|_{\mathcal{H}((A_n))}$. Note that the sequence (A_n^{-1}) is typically chosen to be monotonically decreasing and converging to zero. Thus, this norm provides a kind of non-smoothness measure, since it weights high-degree parts stronglier than low-degree parts. Within this context, the following essential features of the method can be established (see [7, 8] and the references therein for proofs):

- If the used linear and continuous functionals $\mathcal{F}^k$, $k = 1, ..., M$, are linearly independent, then the linear system (35) is uniquely solvable, i.e. the expansion (34) is unique.
- Among all solutions $F \in \mathcal{H}((A_n))$ satisfying $\mathcal{F}^m F = b_m$, $m = 1, ..., M$, the solution of the form (34) uniquely minimizes the norm $\| \cdot \|_{\mathcal{H}((A_n))}$. Hence, it is the "smoothest" interpolant. This result motivates the name "spline".
- Among all functions of the form (34), the solution given by (35) is closest (in the $\| \cdot \|_{\mathcal{H}((A_n))}$-sense) to the unknown function (best approximation property).

Two further features of the spline method are of particular importance for the numerical implementation.

- The linear system (35) can be regularized by adding a positive constant λ to the diagonal of the matrix. The corresponding spline (34) is then the minimizer of
$$\sum_{k=1}^{M} \left(\mathcal{F}^k A^\tau - b_k \right)^2 + \lambda \, \| A^\tau \|^2_{\mathcal{H}((A_n))} \, .$$

An increased value of λ emphasizes the smoothing of the function in relation to the accuracy of the interpolation. Often in practice, a pure interpolation ($\lambda = 0$) is not adequate for a numerical implementation due to the occurence of ill-conditioned matrices.

- The spline (34) can also be represented in terms of a Lagrange basis by

$$A^{\tau}(\boldsymbol{\tau}) = \sum_{k=1}^{M} b_k \, L_k(\boldsymbol{\tau}), \tag{36}$$

where the Lagrange basis

$$L_k(\boldsymbol{\tau}) = \sum_{j=1}^{M} l_j^{(k)} \, \mathcal{F}_{\mathbf{r}}^j K(\boldsymbol{\tau}, \mathbf{r}), \quad k = 1, \ldots, M$$

is obtained from the linear systems

$$\sum_{j=1}^{M} l_j^{(k)} \, \mathcal{F}_{\boldsymbol{\tau}}^m \mathcal{F}_{\mathbf{r}}^j K(\boldsymbol{\tau}, \mathbf{r}) = \delta_{mk}, \quad m = 1, \ldots, M, \, k = 1, \ldots M. \tag{37}$$

Note that (37) consists of M linear systems, which all have the same matrix as (35). Equation (37) requires that $\mathcal{F}^m L_k = \delta_{mk}$ such that in (36) $\mathcal{F}^m A^{\tau} = b_m$, $m = 1, \ldots, M$. This representation in a Lagrange basis is an essential advantage in the case that a time series $\{b_m(t_i)\}_{m=1,\ldots,M, \, i=1,\ldots,N}$ has to be analyzed; indeed, in this case the Lagrange basis is calculated only once and then is stored in the computer. The spline can then be calculated almost in real time after the determination of the data b_m, $m = 1, \ldots, M$.

3.2 Details of the Implementation

The implementation of the above scheme using the real sensor positions and normal vectors of Electro Neuromag (R) is discussed below. In this context, we will focus on the determination of F in (11) in terms of $\mathbf{B}$.

3.3 The Data Situation

In the following, we assume that the measured magnetic field $\mathbf{B}$ and its potential U are represented in terms of (scalar respectively vector) spherical harmonics by

$$\begin{aligned} U(\mathbf{r}) &= \sum_{n=1}^{\infty} \sum_{j=-n}^{n} c_n^j \, r^{-n-1} Y_n^j \left(\hat{\mathbf{r}}\right), \\ \mathbf{B}(\mathbf{r}) &= \mu \sum_{n=1}^{\infty} \sum_{j=-n}^{n} r^{-n-2} \, c_n^j \left[(-n-1) \, \mathbf{y}_n^{j,1} \left(\hat{\mathbf{r}}\right) + \sqrt{n(n+1)} \, \mathbf{y}_n^{j,2} \left(\hat{\mathbf{r}}\right) \right], \end{aligned}$$

$|\mathbf{r}| > 1$, where

$$\begin{aligned} \boldsymbol{y}_n^{j,1}(\hat{\mathbf{r}}) &:= \hat{\mathbf{r}}\, Y_n^j(\hat{\mathbf{r}}), \\ \boldsymbol{y}_n^{j,2}(\hat{\mathbf{r}}) &:= (n(n+1))^{-1/2}\, \nabla_{\hat{\mathbf{r}}}^* Y_n^j(\hat{\mathbf{r}}). \end{aligned}$$

For further details on the vector spherical harmonics $\boldsymbol{y}_n^{j,i}$ we refer to [6], pp. 321. Moreover,

$$F(\boldsymbol{\tau}) = \sum_{n=1}^{\infty} \sum_{j=-n}^{n} F_n^j\, G_n(\tau) Y_n^j(\hat{\boldsymbol{\tau}}). \tag{38}$$

Here, we know due to (13) and (17) that

$$c_n^j = \frac{n}{2n+1} \int_0^{c_1} \tau^{n+1} F_n^j G_n(\tau)\, \mathrm{d}\tau.$$

Based on a priori conditions, we expect to have a known relation

$$F_n^j = \sigma_n c_n^j; \quad n \in \mathbb{N},\, j = -n, ..., n$$

with $\sigma_n \neq 0$ for all $n \in \mathbb{N}$. Note that this is a further restriction to the previous assumptions, since we require invertibility ($\sigma_n \neq 0$ for all n), whereas the isotropy (σ_n is independent of j) already follows from the modelling above. The data (see (30)) can then be represented as

$$\begin{aligned} \left(\mathcal{F}^k F =\right) \boldsymbol{\nu}_k \cdot \mathbf{B}(\mathbf{r}_k) &= \mu \sum_{n=1}^{\infty} \sum_{j=-n}^{n} \sigma_n^{-1} F_n^j\, r_k^{-n-2} \left[(-n-1) \boldsymbol{\nu}_k \cdot \mathbf{y}_n^{j,1}(\hat{\mathbf{r}}_k) \right. \\ &\quad \left. + \sqrt{n(n+1)}\, \boldsymbol{\nu}_k \cdot \mathbf{y}_n^{j,2}(\hat{\mathbf{r}}_k) \right], \end{aligned} \tag{39}$$

where $k = 1, \ldots, 102$.

3.4 Spline Basis

We now investigate the practical calculation of the spline basis functions

$$\boldsymbol{\tau} \mapsto \mathcal{F}_{\mathbf{r}}^k K(\boldsymbol{\tau}, \mathbf{r}), \quad k = 1, ..., 102.$$

The use of (39) requires the knowledge of the expansion coefficients F_n^j in (38) if $F(\mathbf{r}) = K(\boldsymbol{\tau}, \mathbf{r})$ for fixed $\boldsymbol{\tau}$. By comparing (33) and (38) we get $F_n^j =$

$A_n^{-2}\gamma_n^{-1}G_n(\tau)Y_n^j(\hat{\boldsymbol{\tau}})$. Hence,

$$\begin{aligned}
\mathcal{F}_{\mathbf{r}}^k K(\boldsymbol{\tau},\mathbf{r}) &= \mu \sum_{n=1}^{\infty}\sum_{j=-n}^{n} \sigma_n^{-1}A_n^{-2}\gamma_n^{-1}G_n(\tau)Y_n^j\left(\hat{\boldsymbol{\tau}}\right) r_k^{-n-2} \\
&\qquad \times \left[(-n-1)\boldsymbol{\nu}_k\cdot \mathbf{y}_n^{j,1}\left(\hat{\mathbf{r}}_k\right) + \sqrt{n(n+1)}\,\boldsymbol{\nu}_k\cdot \mathbf{y}_n^{j,2}\left(\hat{\mathbf{r}}_k\right)\right] \\
&= \mu \sum_{n=1}^{\infty} \sigma_n^{-1}A_n^{-2}\gamma_n^{-1}G_n(\tau) r_k^{-n-2}\,\frac{2n+1}{4\pi} \\
&\qquad \times \left[(-n-1)\boldsymbol{\nu}_k\cdot\hat{\mathbf{r}}_k P_n\left(\hat{\boldsymbol{\tau}}\cdot\hat{\mathbf{r}}_k\right) + \boldsymbol{\nu}_k\cdot\left(\hat{\boldsymbol{\tau}} - \left(\hat{\boldsymbol{\tau}}\cdot\hat{\mathbf{r}}_k\right)\hat{\mathbf{r}}_k\right)P_n'\left(\hat{\boldsymbol{\tau}}\cdot\hat{\mathbf{r}}_k\right)\right],
\end{aligned}$$

where the last equation follows from the addition theorem for spherical harmonics.

3.5 Matrix Entries

Before the spline coefficients are available, the system of linear equations has to be solved. For this purpose, the matrix with entries of the kind

$$\mathcal{F}_{\boldsymbol{\tau}}^m\mathcal{F}_{\mathbf{r}}^k K(\boldsymbol{\tau},\mathbf{r}), \quad m,k\in\{1,\ldots,102\}$$

has to be computed. They can be calculated as follows:

$$\begin{aligned}
\mathcal{F}_{\boldsymbol{\tau}}^m\mathcal{F}_{\mathbf{r}}^k K(\boldsymbol{\tau},\mathbf{r}) &= \mu^2 \sum_{n=1}^{\infty}\sum_{j=-n}^{n} \sigma_n^{-2}A_n^{-2}\gamma_n^{-1} r_k^{-n-2} r_m^{-n-2} \\
&\times \left[(-n-1)\boldsymbol{\nu}_k\cdot \mathbf{y}_n^{j,1}\left(\hat{\mathbf{r}}_k\right) + \sqrt{n(n+1)}\,\boldsymbol{\nu}_k\cdot \mathbf{y}_n^{j,2}\left(\hat{\mathbf{r}}_k\right)\right] \\
&\times \left[(-n-1)\boldsymbol{\nu}_m\cdot \mathbf{y}_n^{j,1}\left(\hat{\mathbf{r}}_m\right) + \sqrt{n(n+1)}\,\boldsymbol{\nu}_m\cdot \mathbf{y}_n^{j,2}\left(\hat{\mathbf{r}}_m\right)\right] \\
&= \mu^2 \sum_{n=1}^{\infty} \sigma_n^{-2}A_n^{-2}\gamma_n^{-1}\left(r_k r_m\right)^{-n-2}\,\frac{2n+1}{4\pi} \\
&\times \Big[(-n-1)^2\left(\boldsymbol{\nu}_k\cdot\hat{\mathbf{r}}_k\right)\left(\boldsymbol{\nu}_m\cdot\hat{\mathbf{r}}_m\right)P_n\left(\hat{\mathbf{r}}_k\cdot\hat{\mathbf{r}}_m\right) \\
&+(-n-1)\left(\left(\boldsymbol{\nu}_m\cdot\hat{\mathbf{r}}_m\right)\boldsymbol{\nu}_k\cdot\nabla_\xi^* + \left(\boldsymbol{\nu}_k\cdot\hat{\mathbf{r}}_k\right)\boldsymbol{\nu}_m\cdot\nabla_\eta^*\right)P_n(\boldsymbol{\xi}\cdot\boldsymbol{\eta})\big|_{\boldsymbol{\xi}=\hat{\mathbf{r}}_k,\boldsymbol{\eta}=\hat{\mathbf{r}}_m} \\
&+ \boldsymbol{\nu}_k^{\mathrm{T}}\left(\nabla_{\boldsymbol{\xi}}^*\otimes\nabla_{\boldsymbol{\eta}}^* P_n(\boldsymbol{\xi}\cdot\boldsymbol{\eta})\right)\boldsymbol{\nu}_m\big|_{\boldsymbol{\xi}=\hat{\mathbf{r}}_k,\boldsymbol{\eta}=\hat{\mathbf{r}}_m}\Big] \\
&= \mu^2 \sum_{n=1}^{\infty} \sigma_n^{-2}A_n^{-2}\gamma_n^{-1}\left(r_k r_m\right)^{-n-2}\,\frac{2n+1}{4\pi} \\
&\times \big[(-n-1)^2\left(\boldsymbol{\nu}_k\cdot\hat{\mathbf{r}}_k\right)\left(\boldsymbol{\nu}_m\cdot\hat{\mathbf{r}}_m\right)P_n\left(\hat{\mathbf{r}}_k\cdot\hat{\mathbf{r}}_m\right) \\
&+(-n-1)\left(\left(\boldsymbol{\nu}_m\cdot\hat{\mathbf{r}}_m\right)\left(\boldsymbol{\nu}_k\cdot f\left(\hat{\mathbf{r}}_k,\hat{\mathbf{r}}_m\right)\right)\right. \\
&+ \left.\left(\boldsymbol{\nu}_k\cdot\hat{\mathbf{r}}_k\right)\left(\boldsymbol{\nu}_m\cdot f\left(\hat{\mathbf{r}}_m,\hat{\mathbf{r}}_k\right)\right)\right)P_n'\left(\hat{\mathbf{r}}_k\cdot\hat{\mathbf{r}}_m\right)
\end{aligned}$$

$$+ (\boldsymbol{\nu}_k \cdot f(\hat{\mathbf{r}}_k, \hat{\mathbf{r}}_m)) (f(\hat{\mathbf{r}}_m, \hat{\mathbf{r}}_k) \cdot \boldsymbol{\nu}_m) P_n''(\hat{\mathbf{r}}_k \cdot \hat{\mathbf{r}}_m)$$
$$+ \boldsymbol{\nu}_k^{\mathrm{T}} g(\hat{\mathbf{r}}_k, \hat{\mathbf{r}}_m) \boldsymbol{\nu}_m P_n'(\hat{\mathbf{r}}_k \cdot \hat{\mathbf{r}}_m)\big],$$

where $f(\boldsymbol{\xi}, \boldsymbol{\eta}) := \nabla_{\boldsymbol{\xi}}^*(\boldsymbol{\xi} \cdot \boldsymbol{\eta}) = \boldsymbol{\eta} - (\boldsymbol{\xi} \cdot \boldsymbol{\eta})\boldsymbol{\xi}$ for $\boldsymbol{\xi}, \boldsymbol{\eta} \in \Omega$,

$$g(\boldsymbol{\xi}, \boldsymbol{\eta}) := \nabla_{\boldsymbol{\xi}}^* \otimes (\boldsymbol{\xi} - (\boldsymbol{\eta} \cdot \boldsymbol{\xi})\boldsymbol{\eta}) = \mathbb{1} - \boldsymbol{\xi} \otimes \boldsymbol{\xi} - (\boldsymbol{\eta} - (\boldsymbol{\xi} \cdot \boldsymbol{\eta})\boldsymbol{\xi}) \otimes \boldsymbol{\eta},$$

$\mathbb{1}$ is the 3×3 - identity matrix and ∇^* is the surface gradient with respect to Ω. The derived expansion in Legendre polynomials can (in a truncated form) be numerically evaluated by the use of the Clenshaw algorithm (see [11]).

3.6 A Numerical Example

We will study here the case where F is restricted to a spherical shell given by $0 < a \leq \tau \leq 1 < c_1$. Moreover, we assume that the density F has a vanishing zeroth moment (i.e. its zeroth degree coefficient vanishes) and only depends on the angular variables but not on the radial one. For this purpose we can easily derive a spectral relation between U, F, and $\mathbf{B}$ by using the results above.

Theorem 3.1 *Let $0 < a < 1 < c_1$ be a given real number. Furthermore, let $F : \Omega_{\mathrm{c}} \to \mathbb{R}$ be a given function which is square–integrable and satisfies (11), (12) and the following conditions:*

$$\int_\Omega F(\boldsymbol{\tau})\, \mathrm{dS}(\hat{\boldsymbol{\tau}}) = 0 \text{ for all } \tau \in [0, c_1], \tag{40}$$

$$F(\boldsymbol{\tau}) = 0 \text{ if } \tau \notin [a, 1], \tag{41}$$

$$F(\boldsymbol{\tau}) = F(\mathbf{r}) \text{ if } \hat{\boldsymbol{\tau}} = \hat{\mathbf{r}} \text{ and } \tau, r \in [a, 1]. \tag{42}$$

Then the corresponding function $U \in \mathrm{L}^2(\Omega_{\mathrm{e}})$ is given by

$$U(\mathbf{r}) = \sum_{n=1}^{\infty} \sum_{m=-n}^{n} c_n^m r^{-n-1} Y_n^m(\hat{\mathbf{r}}), \quad \mathbf{r} \in \Omega_{\mathrm{e}}. \tag{43}$$

with

$$f_n^m(\tau) = \underbrace{\frac{n+2}{1-a^{n+2}} \frac{2n+1}{n}}_{=\sigma_n} c_n^m, \quad \tau \in [a, 1]$$

The convergence of the series in (43) has to be understood in the sense of $\mathrm{L}^2(\Omega_{\mathrm{c}})$.

Proof. From Theorem 2.1 we know that $F \in \mathrm{L}^2(\Omega_{\mathrm{c}})$ with

$$F(\boldsymbol{\tau}) = \sum_{n=1}^{\infty} \sum_{m=-n}^{n} f_n^m(\tau) Y_n^m(\hat{\boldsymbol{\tau}})$$

and (12) (note that condition (40) implies that the coefficient for $n = 0$ vanishes) is related to U by

$$\int_0^{c_1} \tau^{n+1} f_n^m(\tau) d\tau = \frac{2n+1}{n} c_n^m; \quad n = 1, 2, ...; \ m = -n, ..., n.$$

Due to the assumptions (41) and (42) on F, i.e. $f_n^m(\tau) = F_n^m$ if $\tau \in [a,1]$ and $= 0$ else, we conclude that

$$\begin{aligned} \int_a^1 \tau^{n+1}\,\mathrm{d}\tau\, F_n^m &= \frac{2n+1}{n}\, c_n^m \\ \Leftrightarrow F_n^m &= \frac{n+2}{1-a^{n+2}}\,\frac{2n+1}{n}\, c_n^m \ . \end{aligned}$$

■

Hence, in this particular case we have

$$\begin{aligned} \sigma_n &= \frac{n+2}{1-a^{n+2}}\,\frac{2n+1}{n}, \\ G_n(\tau) &= \chi_{[a,1]}(\tau), \\ \gamma_n &= \int_0^{c_1} s^2 G_n^2(s)\,\mathrm{d}s = \int_a^1 s^2\,\mathrm{d}s = \frac{1}{3}\left(1-a^3\right). \end{aligned}$$

Note that the associated functionals $\mathcal{F}^k$ (see (39)) are obviously linear. Moreover, the norm of F is given by

$$\|F\|^2_{\mathrm{L}^2(\Omega_c)} = \sum_{n=1}^{\infty}\sum_{j=-n}^{n} \left(F_n^j\right)^2 \gamma_n$$

and the triangle inequality as well as the Cauchy–Schwarz inequality yield the following estimate:

$$\begin{aligned} \left|\mathcal{F}^k F\right| &\leq \mu \sum_{n=1}^{\infty}\sum_{j=-n}^{n} \sigma_n^{-1}\left|F_n^j\right| r_k^{-n-2}\left[(n+1)\sqrt{\frac{2n+1}{4\pi}} + \sqrt{n(n+1)}\sqrt{\frac{2n+1}{4\pi}}\right] \\ &\leq \frac{\mu}{\sqrt{4\pi}}\left(\sum_{n=1}^{\infty}\sum_{j=-n}^{n}\left(F_n^j\right)^2\gamma_n\right)^{1/2} \\ &\quad \times \left(\sum_{n=1}^{\infty}\sum_{j=-n}^{n}\gamma_n^{-1}\sigma_n^{-2}r_k^{-2n-4}4(n+1)^2(2n+1)\right)^{1/2} \\ &\leq 2\,\frac{\mu}{\sqrt{\pi}}\,\|F\|_{\mathrm{L}^2(\Omega_c)}\left(\sum_{n=1}^{\infty}\sum_{j=-n}^{n}\gamma_n^{-1}\sigma_n^{-2}r_k^{-2n-4}4(2n+1)^3\right)^{1/2} . \end{aligned}$$

Hence, each functional $\mathcal{F}^k$ is continuous, since the latter series converges (note that $|r_k| > 1$).
In the numerical test, we use the following example: F is the sum of two kernels of the following form:

$$\boldsymbol{\tau} \mapsto \kappa\,\frac{1}{4\pi}\,\frac{1-h^2}{\left(1+h^2-2h\left(\boldsymbol{\eta}\cdot\hat{\boldsymbol{\tau}}\right)\right)^{3/2}} - \frac{1}{4\pi} = \kappa\sum_{l=1}^{\infty}\frac{2l+1}{4\pi}\,h^l P_l\left(\boldsymbol{\eta}\cdot\hat{\boldsymbol{\tau}}\right) \ ,$$

where $\gamma \in \mathbb{R}$, $h \in]-1,1[$, and $\boldsymbol{\eta} \in \Omega$ are fixed. Here, we choose $\kappa_1 = 0.029$, $h_1 = 0.7$, and $\boldsymbol{\eta}^{(1)} = (1,1,1)/\sqrt{3}$ for the first kernel and $\kappa_2 = 0.0047$, $h_2 = 0.8$, and $\boldsymbol{\eta}^{(2)} = (-1,0,1)/\sqrt{2}$ for the second one.
In other words, we have

$$F_n^j = \sum_{i=1}^{2} \kappa_i \, h_i^n \, Y_n^j \left(\boldsymbol{\eta}^{(i)} \right) \tag{44}$$

in (38). Figure 1 shows F on the upper hemisphere.

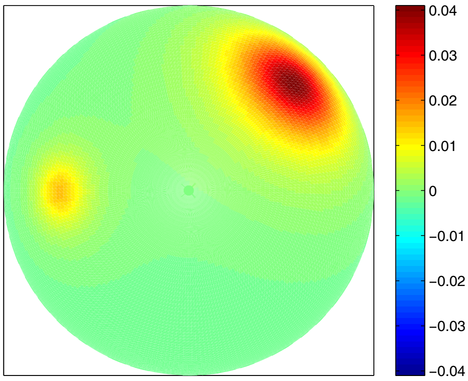

Figure 1: Exact solution F of the numerical test

By inserting (44) in (39) we obtain

$$\begin{aligned}
\boldsymbol{\nu}_k \cdot \mathbf{B}\left(\mathbf{r}_k\right) &= \mu \sum_{i=1}^{2} \kappa_i \sum_{n=1}^{\infty} \sigma_n^{-1} h_i^n r_k^{-n-2} \frac{2n+1}{4\pi} \left[(-n-1) \boldsymbol{\nu}_k \cdot \hat{\mathbf{r}}_k \, P_n \left(\boldsymbol{\eta}^{(i)} \cdot \hat{\mathbf{r}}_k \right) \right. \\
& \left. + \boldsymbol{\nu}_k \cdot \left(\boldsymbol{\eta}^{(i)} - \left(\hat{\mathbf{r}}_k \cdot \boldsymbol{\eta}^{(i)} \right) \hat{\mathbf{r}}_k \right) P_n' \left(\boldsymbol{\eta}^{(i)} \cdot \hat{\mathbf{r}}_k \right) \right]
\end{aligned}$$

Since a closed representation of this series is unknown to us, we truncate the summation at degree 1000 and use this approximation for the given data, where $a = 0.9$. Moreover, we used the real sensor positions $\mathbf{r}_k$ and normal vectors $\boldsymbol{\nu}_k$ of Electa Neuromag (R), where the radii r_k of the sensor positions $\mathbf{r}_k$ range from 1.0635 to 1.4571.
The Lagrange basis (with $A_n = 0.85^{-n/2}$ in the reproducing kernel and truncation of the corresponding series at degree 100) was calculated where the regularization parameter λ was chosen with the aid of the L-curve method as approximately 0.24% of the absolute maximum of the matrix entries. Figure 2

shows the matrix before and after the regularization.

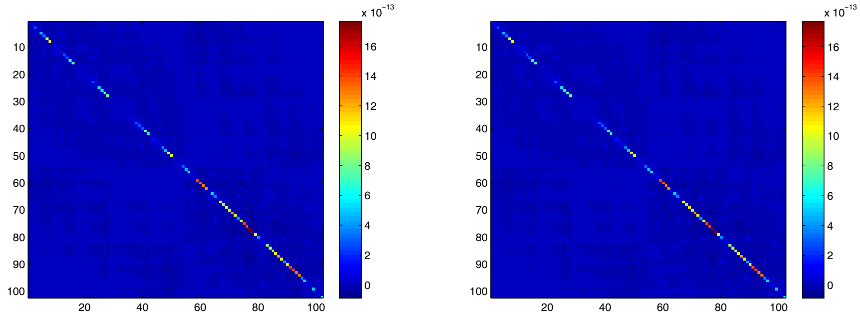

Figure 2: Matrix before (left hand side) and after (right hand side) the regularization

Figure 3 shows the resulting spline and the errors with respect to F for different noise levels. With respect to a point grid $\{\boldsymbol{x}_i\}_{i=1,\ldots,14{,}400}$ on the upper hemisphere (the grid used for the plotting in Figure 3) the RMS error

$$\left(\frac{1}{14,400}\sum_{i=1}^{14{,}400}\left(\sum_{k=1}^{102}\boldsymbol{\nu}_k\cdot\mathbf{B}\left(\mathbf{r}_k\right)\,L_k\left(\boldsymbol{x}_i\right)-F\left(\boldsymbol{x}_i\right)\right)^2\right)^{\frac{1}{2}}$$

is shown in Table 1. Note that $\max_{1\leq i\leq 14{,}400}|F(\boldsymbol{x}_i)|\approx 0.041$. The results show that a close and stable approximation can be obtained via the described numerical method.

Level of noise	RMS error
0	0.00082955
5	0.00087723
10	0.0010343
15	0.00090755
20	0.0014324

Table 1: RMS error with respect to the level of noise

4 Conclusions

The basic inverse problems for the functional imaging techniques of MEG and EEG consist of estimating the neuronal current $\boldsymbol{J}^{\mathrm{P}}(\boldsymbol{\tau}),\boldsymbol{\tau}\in\Omega_{\mathrm{c}}$ in terms of the

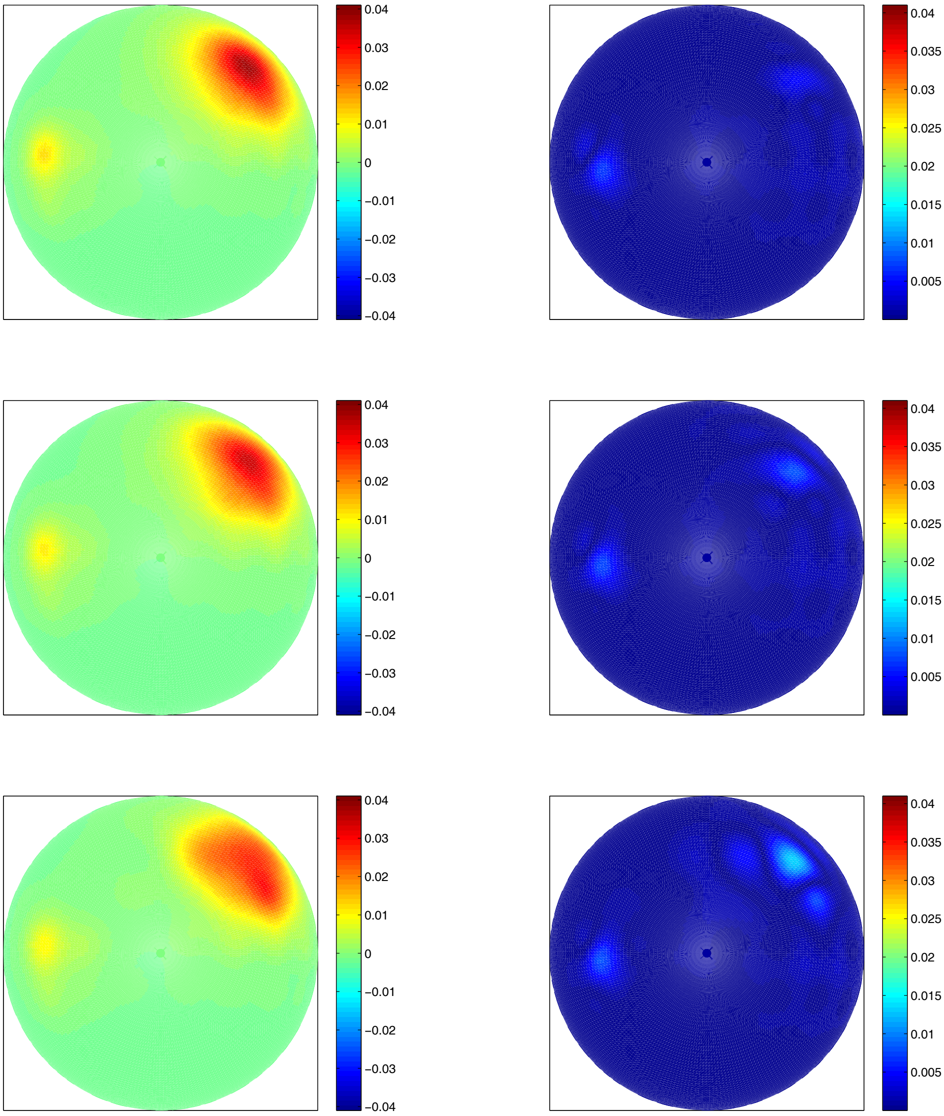

Figure 3: Spline (left hand column) and absolute error (right hand column) for different levels of noise: Each data $\boldsymbol{\nu}_k \cdot \mathbf{B}(\mathbf{r}_k)$ was disturbed by a random number in the range $[-p\%, p\%] \cdot (\boldsymbol{\nu}_k \cdot \mathbf{B}(\mathbf{r}_k))$ for $p = 0$ (1^{st} row), $p = 10$ (2^{nd} row) and $p = 20$ (3^{rd} row).

electric potential $u_{\rm s}(\boldsymbol{r}), \boldsymbol{r} \in \partial\Omega_{\rm d}$, and of the quantity $\boldsymbol{\nu} \cdot \boldsymbol{B}(\boldsymbol{r}), \boldsymbol{r} \in \Omega_{\rm e}$, respectively, where $\Omega_{\rm c}$ denotes the space occupied by the cerebrum, $\partial\Omega_{\rm d}$ denotes the scalp, $\Omega_{\rm e}$ denotes the space exterior to the head, $\boldsymbol{B}(\boldsymbol{r})$ denotes the magnetic field and $\boldsymbol{\nu}$ is a certain unit vector. For the three-shell spherical model, an explicit formula for $\boldsymbol{J}^{\rm P}$ in the case of simultaneous MEG and EEG measurements was derived in [5]. Here, we have presented the rigorous derivation of $\boldsymbol{J}^{\rm P}$ in terms of $u_{\rm s}(\boldsymbol{r})$ and of $\boldsymbol{\nu} \cdot \boldsymbol{B}(\boldsymbol{r})$, for the case of independent as well as simultaneous EEG and MEG measurements. Furthermore, we have presented a novel numerical implementation of the analytical formulae based on the reproducing kernel technique of [8] and [9].

In the case of independent MEG measurements the relevant formula is identical to that derived in [1] and [12], but now the derivation is both rigorous and simpler. The formulae (13) and (24) show that MEG and EEG measurements yield information about two of the three scalar functions specifying the neuronal current. In particular, it is possible to determine the angular parts of these two functions as well as to obtain explicit constraints satisfied by their radial parts. The complete determination of the radial parts of these two functions, as well as the determination of the third scalar function specifying the current, requires some additional *a priori* assumptions about the current. One such assumption is that the current minimises the L^2-norm. In this case for independent MEG and EEG measurements, the radial parts of the functions $f_n^m(\tau)$ and $\psi_n^m(\tau)$ are proportional to τ^{m+1} and τ^n respectively (see [13]). The derivation of the corresponding formulae in the case of simultaneous MEG and EEG data will be presented in [13].

Our plan in the future is to compare our approach with commercial software using anthropomorphic data. We will use independent as well as simultaneous MEG and EEG measurements and also, in order to obtain a unique current, we will use L^2-minimization, as well as other types of constraints.

Regarding other approaches to reconstructing the neuronal current, we note that existing strategies can be divided into two broad categories [14]: those based on dipole models and those based on continuously distributed models. Our approach assumes a continuously distributed current, thus in what follows we discuss only the latter models. The most well known such approach is the minimum norm solution which assumes that the three-dimensional current distributions should have minimum L^2-norm. This approach differs from our approach since we *first* identify the part of the current that can be determined from the measurements, and *then* we minimize the relevant L^2-norm. This yields an *explicit analytic formula*. Similar remarks are valid for the other weighted minimum norm approaches used in the literature, such as FOCUSS [15] and RWMN [16], as well as for the Laplacian weighted minimum norm approach called LORETA [17].

In the case of independent EEG measurements, our approach provides the analytical solution, as well as the numerical implementation, of the so-called ELECTRA model [18]; the advantage of this model is that it can be compared with intracranial recordings.

It appears that the main advantages of our approach are the following: (a) it can

indentify precisely the part of the neuronal current that can be determined from the given measurements; (b) it has the flexibility to be supplemented with any regularization strategy such as L^2-minimization and the minimizations used in FOCUSS, RWMN and LORETA; (c) it can be numerically implemented in an effective, stable way. However, it should be emphasised that until the method is applied to real data and is compared with commercial software, the above advantages are purely speculative.
An important limitation of our approach is the assumption of a *spherical* model. We envision to overcome this limitation as follows: (a) to attempt the numerical implementation of the formulae of [5] associated with the three-shell ellipsoidal model; (b) to implement the overlapping sphere head model, proposed in [19]; (c) to implement the spherical head model with anatomical constraints [20]. Progress in this direction will be reported in future publications.
Finally, we note that Electa Neuromag (R) in addition to measuring $\boldsymbol{\nu}(\boldsymbol{r})\cdot\boldsymbol{B}(\boldsymbol{r})$, it also measures $\nabla_{\hat{\boldsymbol{r}}}(\boldsymbol{\nu}(\boldsymbol{r})\cdot\boldsymbol{B}(\boldsymbol{r}))$. These latter data can also be handled using the numerical technique of section 3. The question of extracting further information for the current from these additional data is under investigation.

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