TECHNISCHE UNIVERSITÄT ILMENAU

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Institut für Biomedizinische Technik und Informatik

Electromagnetic inverse problems in biomedical engineering

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Overview

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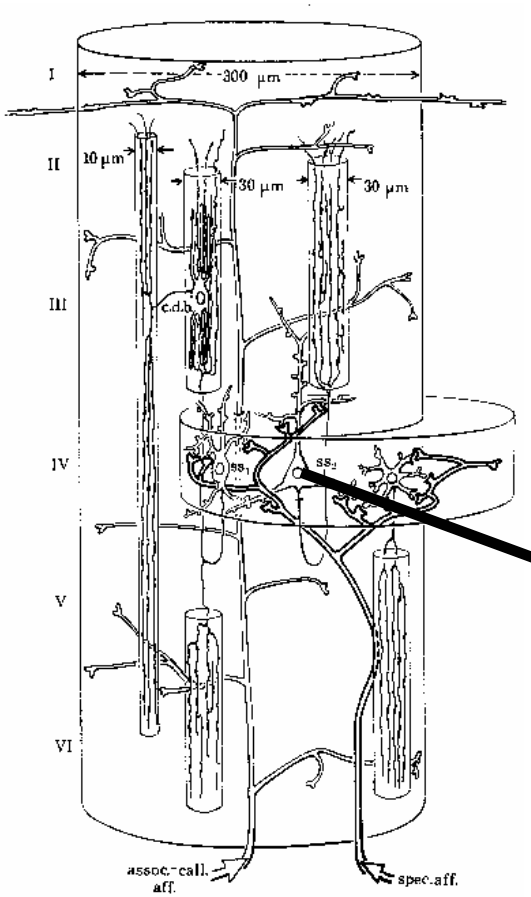
1. Introduction
2. Localization of magnetic markers in the alimentary tract
3. The influence of forward model conductivities on EEG/MEG source reconstruction
4. Optimization of magnetic sensor arrays for magnetocardiography
5. Validation of source reconstruction procedures

Introduction

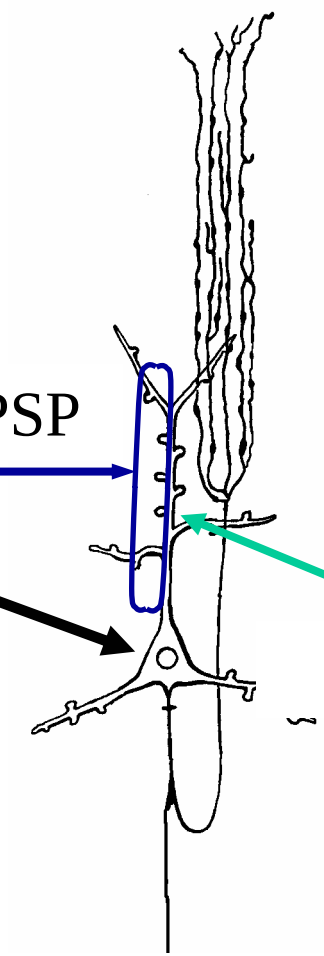
Genesis of bioelectromagnetic fields and potentials

Cortical column

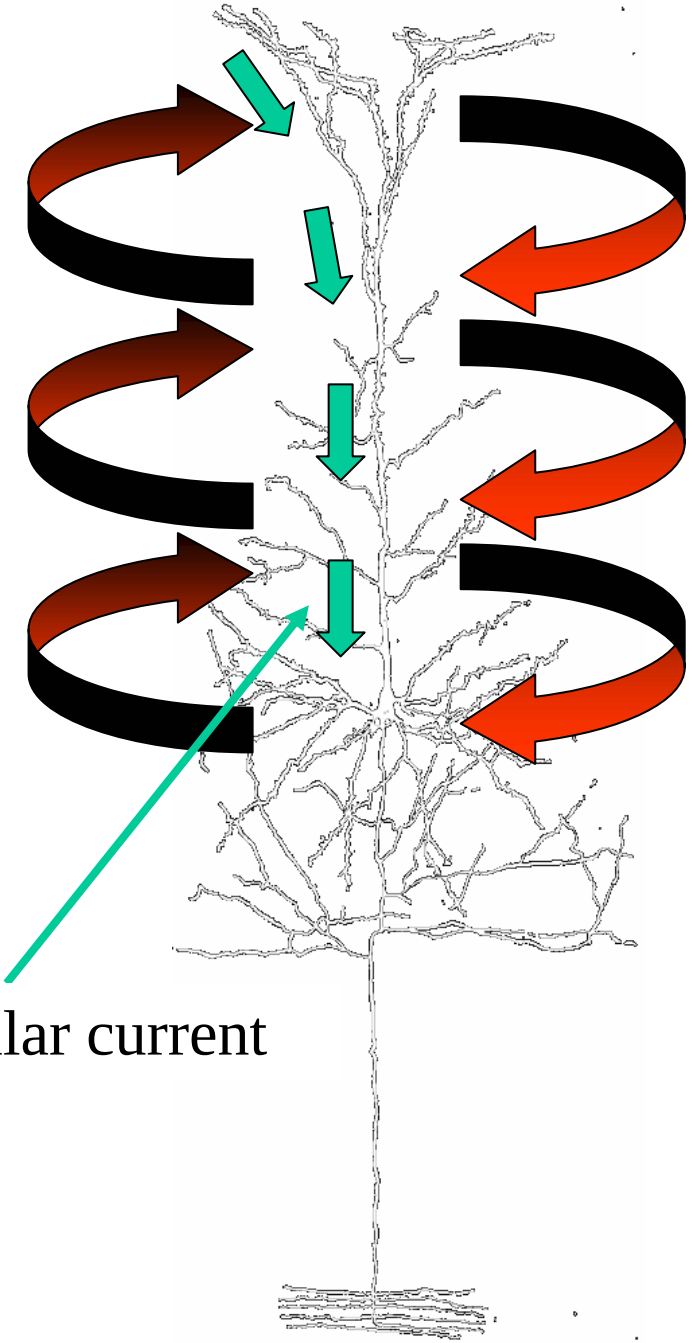
Pyramidal cell

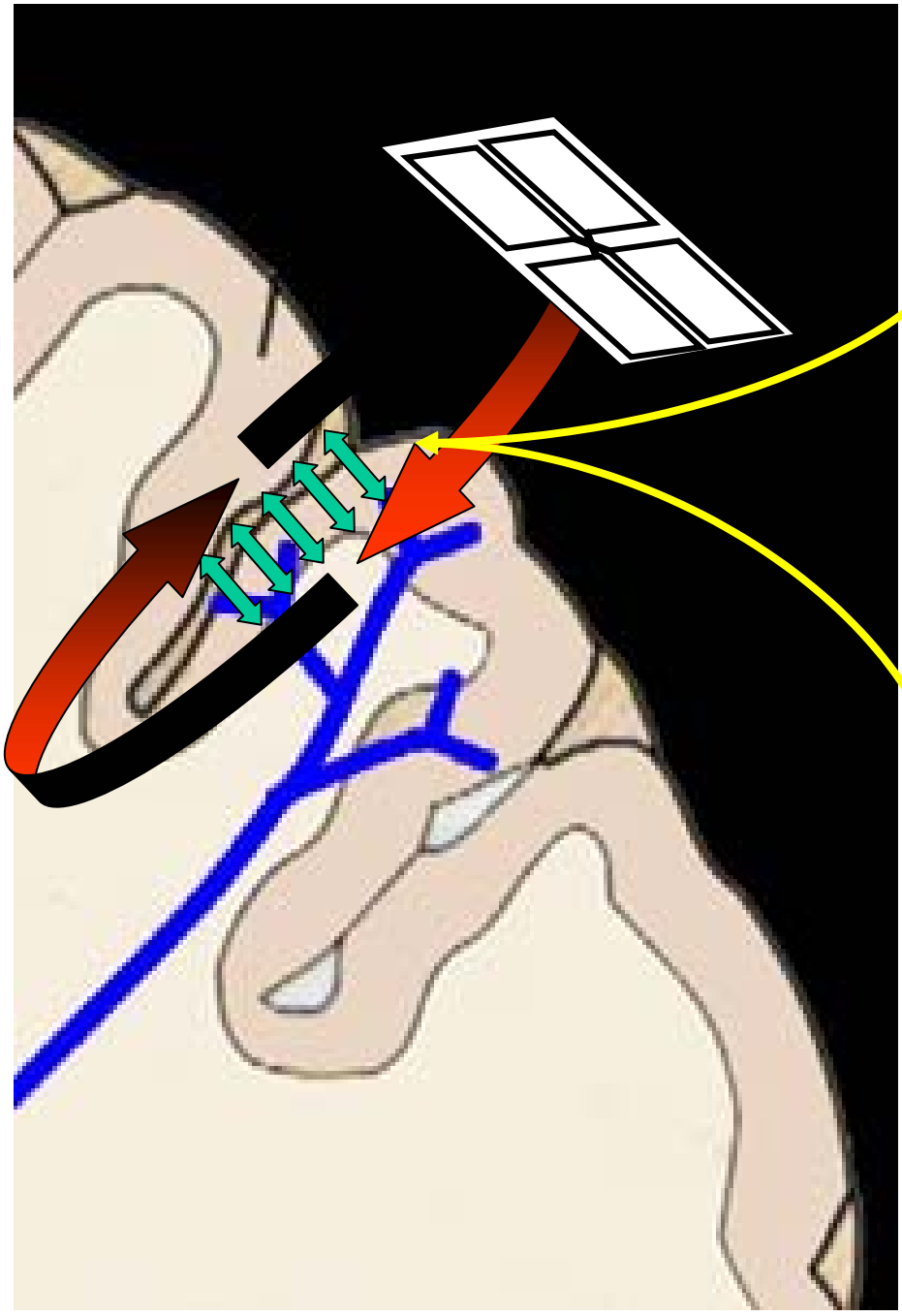


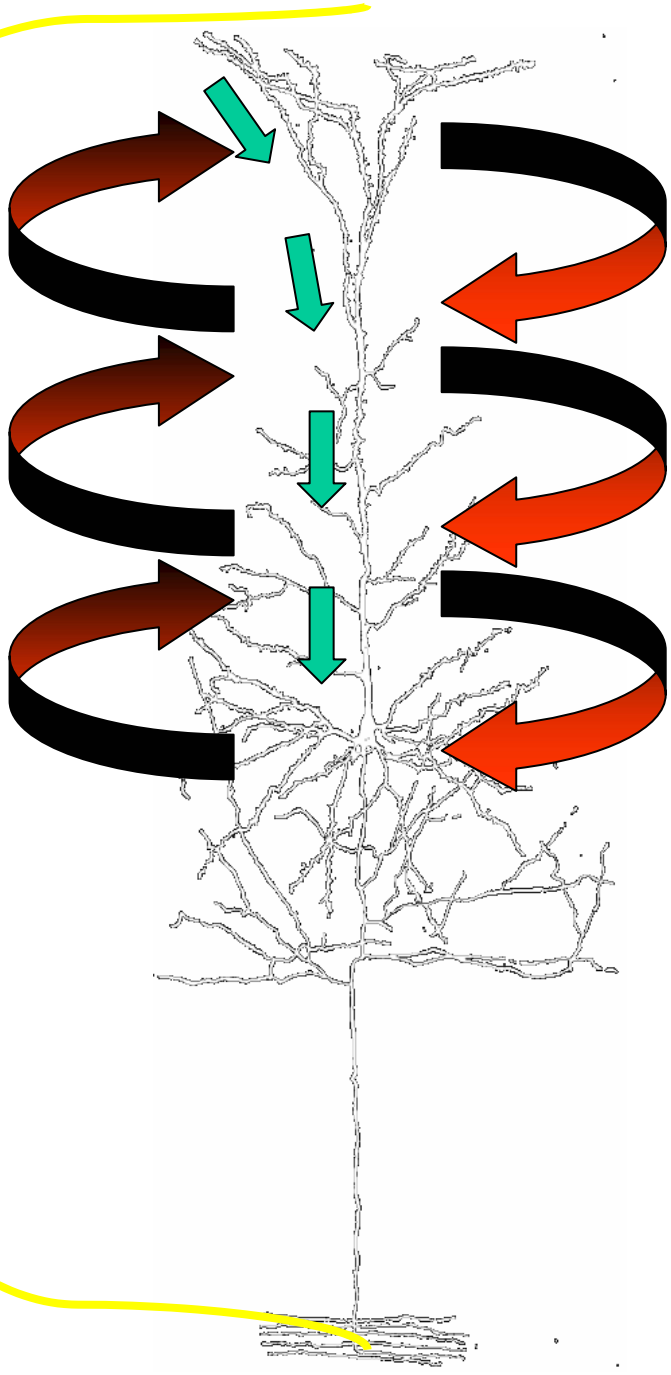
EPSP



intracellular current



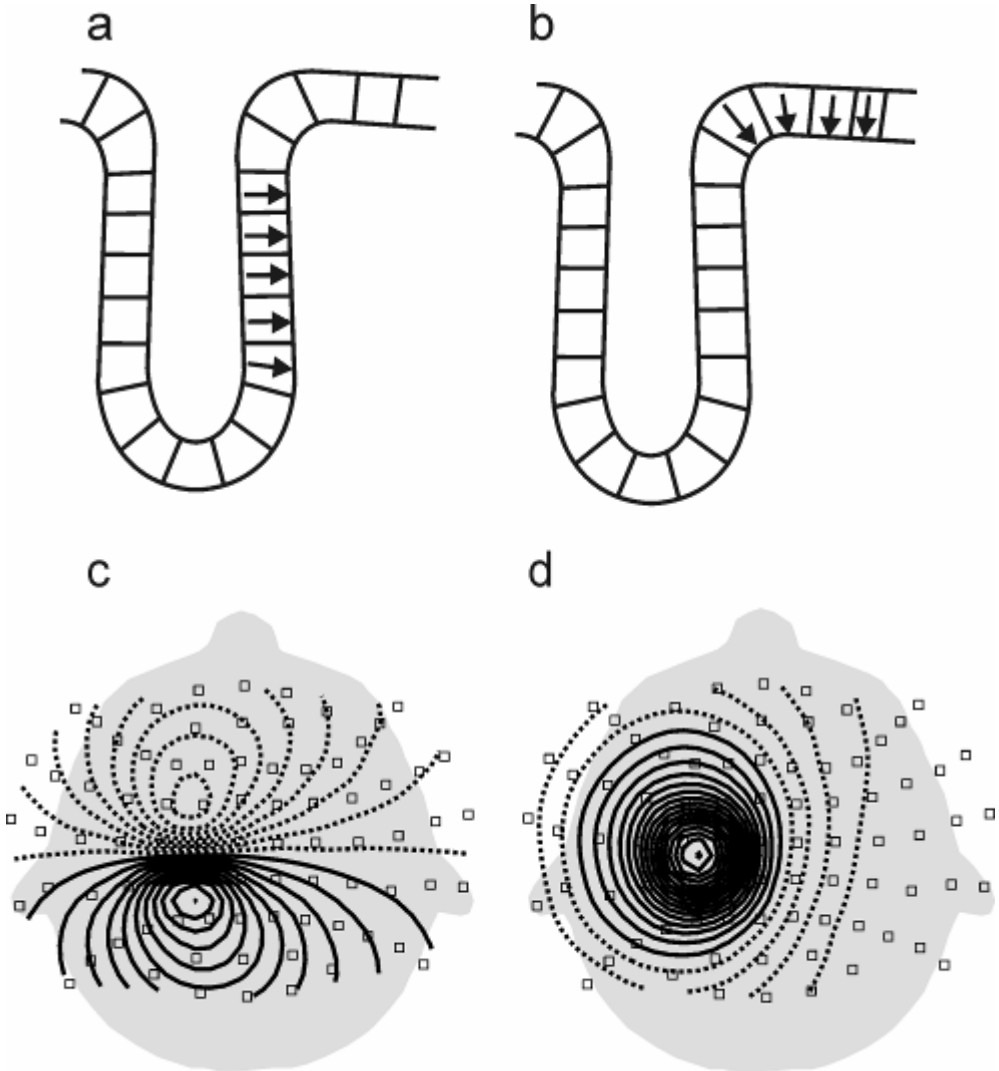




Genesis of bioelectromagnetic fields and potentials

(a) and (c): tangential direction

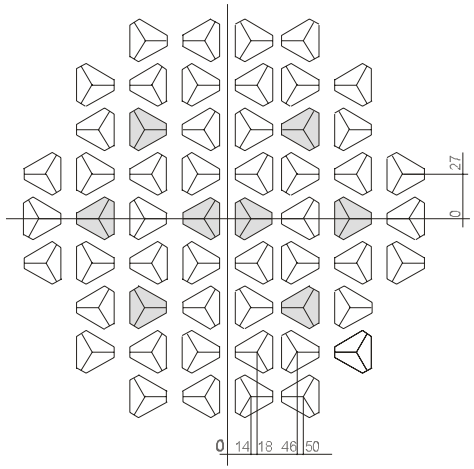
(b) and (d): radial direction



Measurement of biomagnetic fields

Argos 200

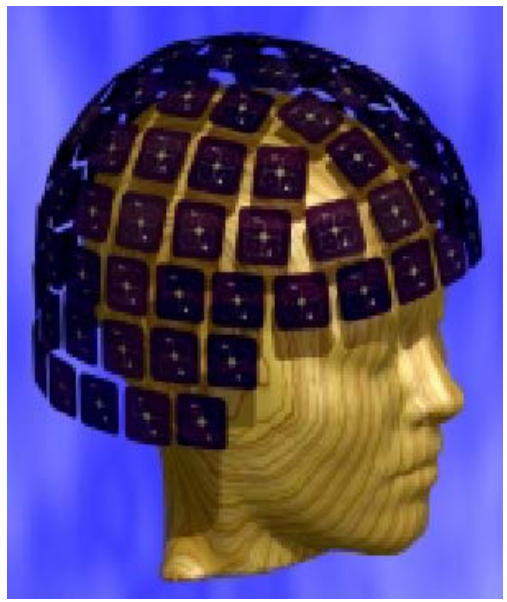
ATB (Chieti, Italy)



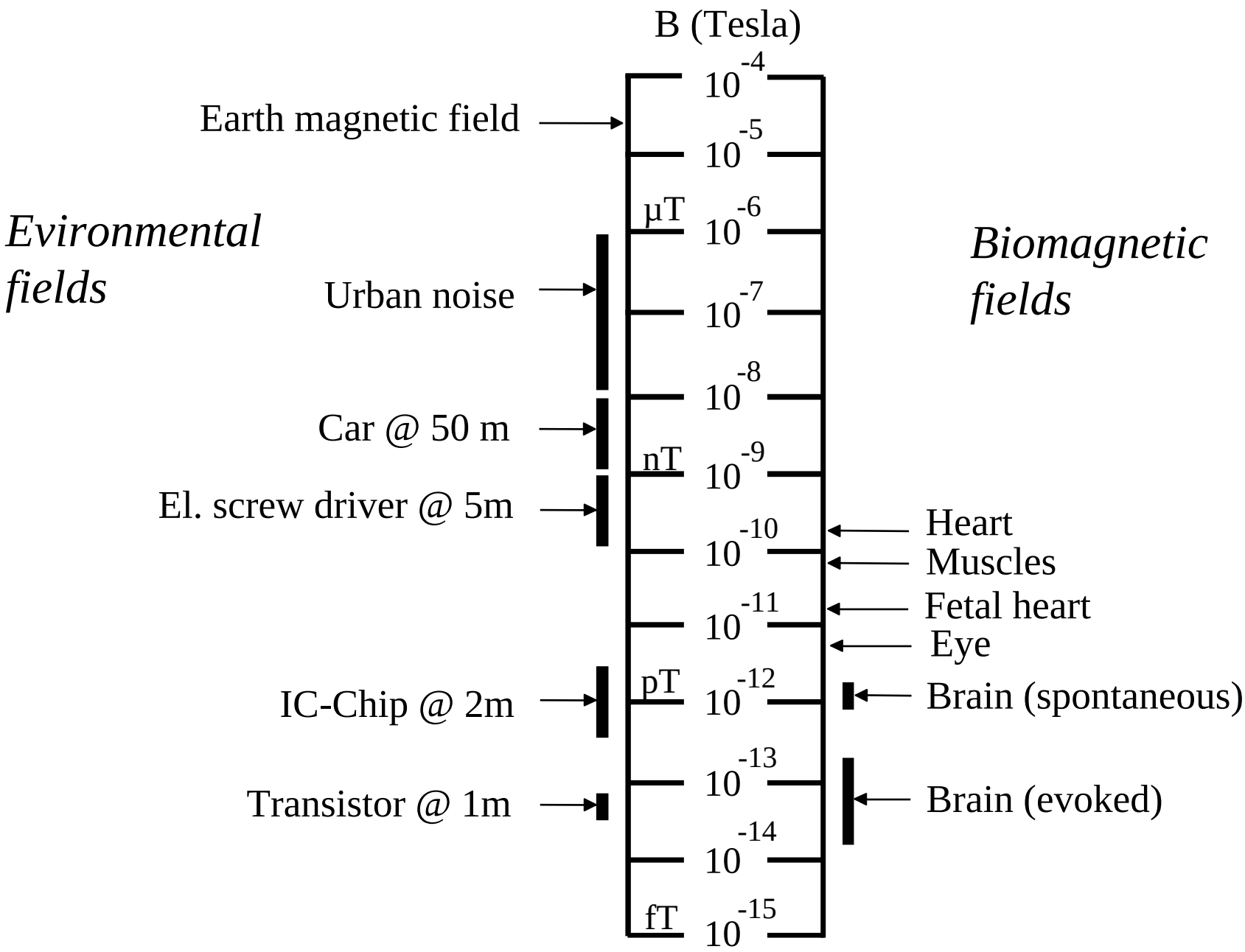
Vectorview

Neuromag

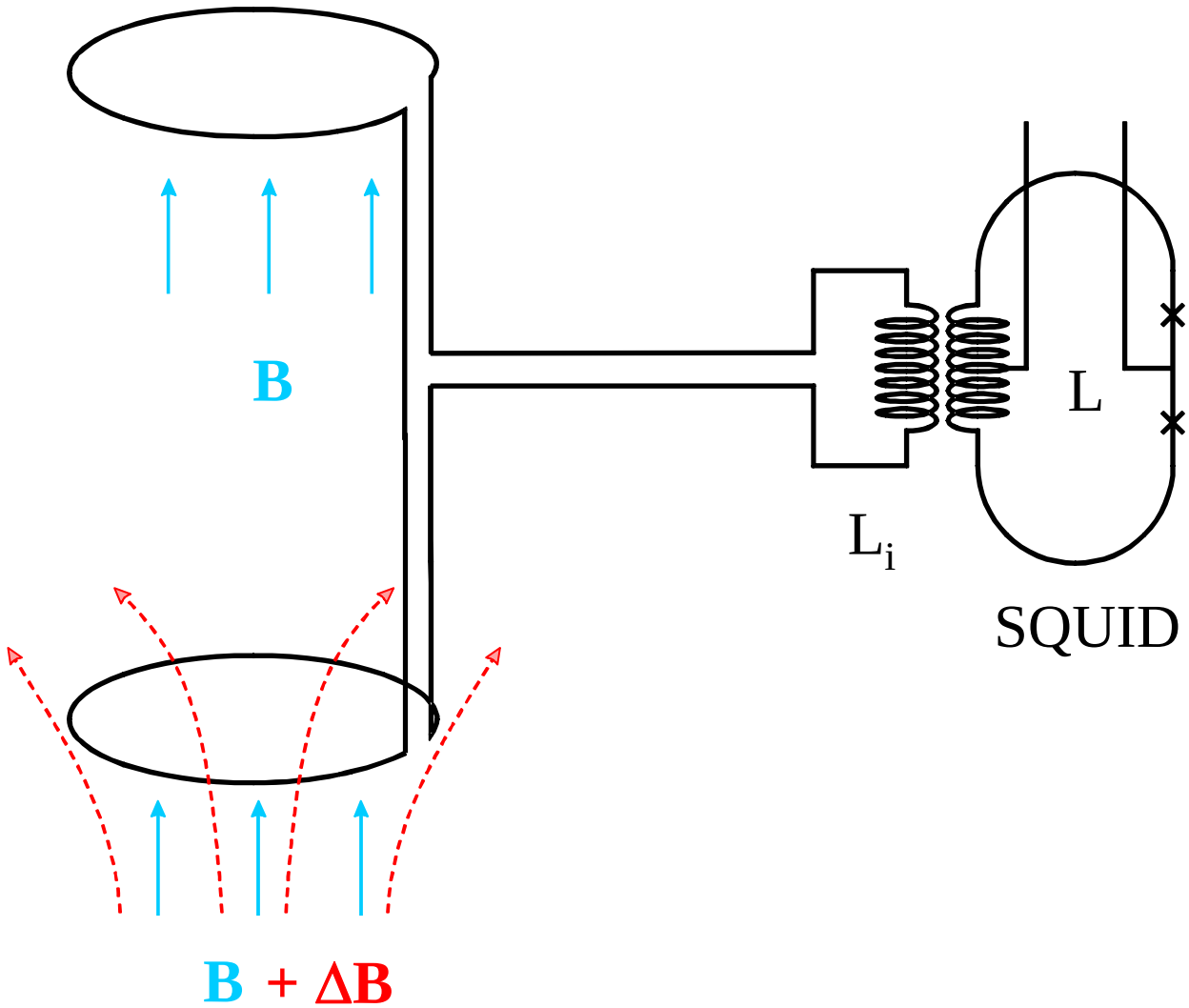
(Helsinki, Finland)



Comparison of typical amplitudes of the magnetic induction B



Magnetometer and Gradiometer

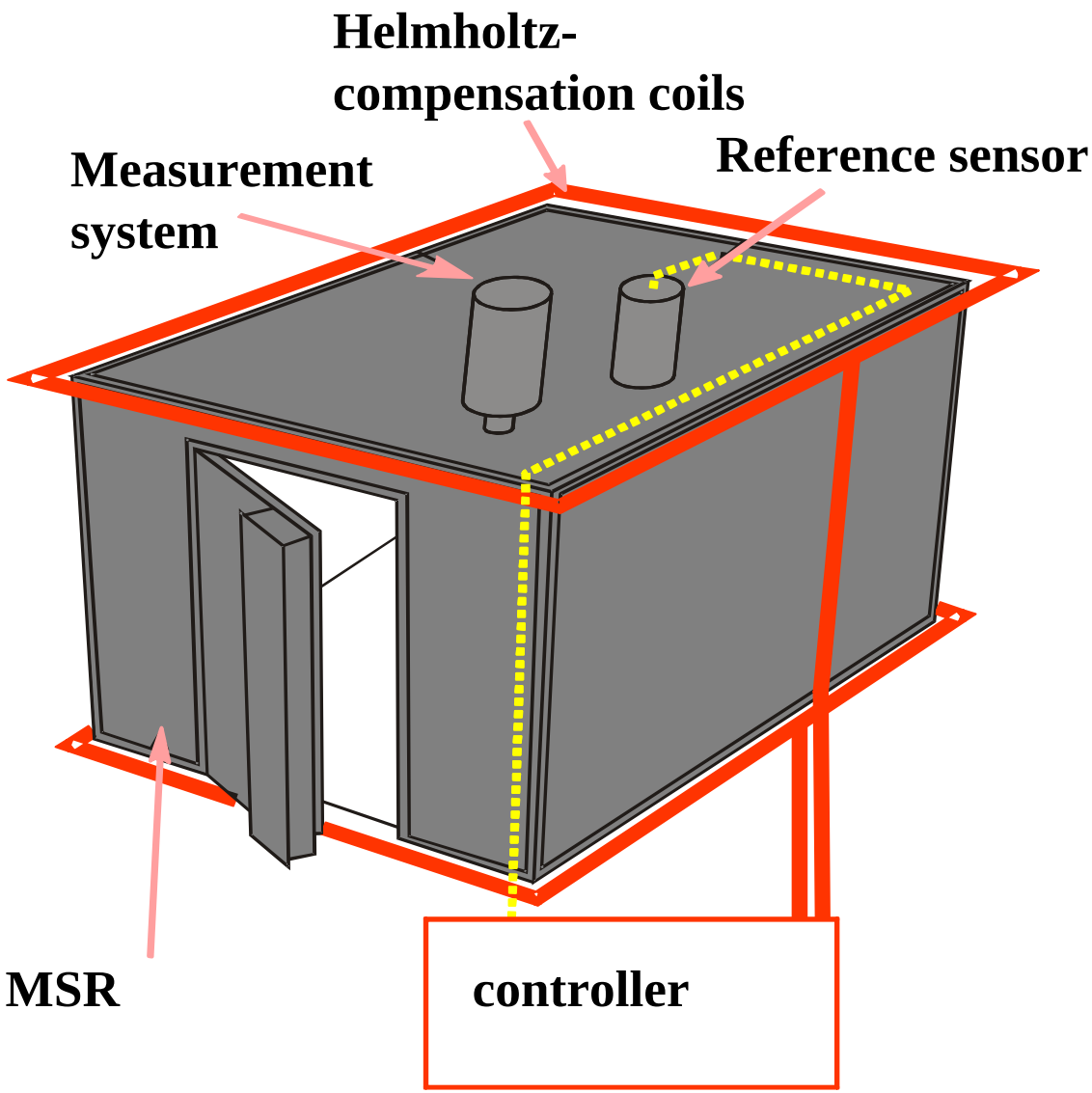


Magnetic shielding

Goal:
Shielding against external disturbances

Design criteria:
Compromise between costs and shielding

Realization:
Passive
Active



Source reconstruction overview

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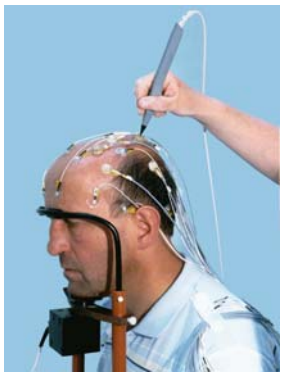
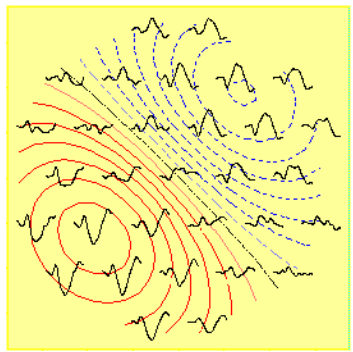
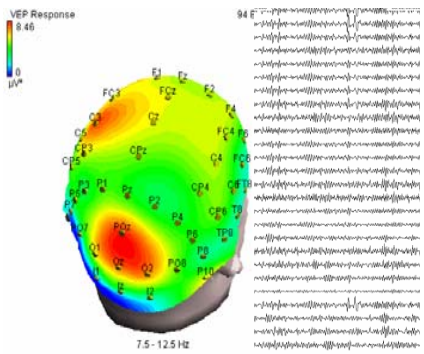
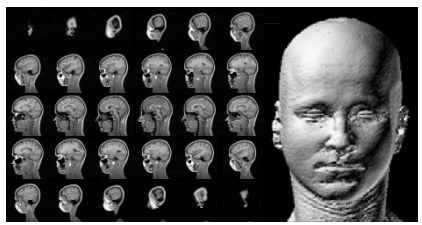
Measurements



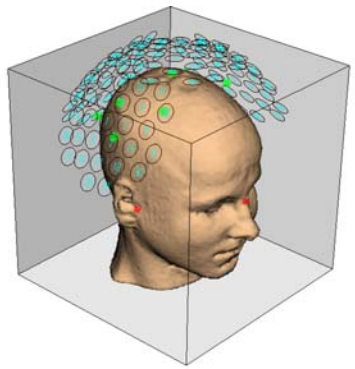
Data

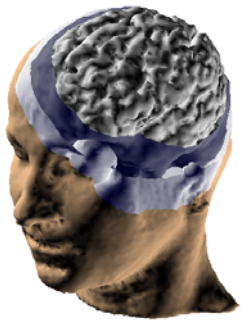




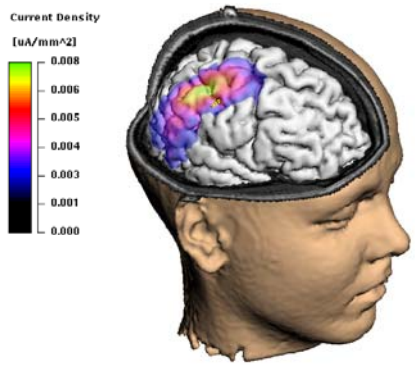


Models





Results and Interpretation



Solution of the inverse problem

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Problem

Measurement data

Forward problem

Inverse problem

Sources

Overview

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1. Introduction
2. Localization of magnetic markers in the alimentary tract
    1. Multipole method
    2. Simulations
    3. Phantom measurements
    4. Clinical study
3. The influence of forward model conductivities on EEG/MEG source reconstruction
4. Optimization of magnetic sensor arrays for magnetocardiography
5. Validation of source reconstruction procedures

Localization of magnetic markers in the alimentary tract

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- **Motivation:**
  - **Analysis of tract motion (peristalsis)**
  - **Passage / throughput times**
  - **targeted disposal of drugs**
- **Methods:**
  - **Magnetically marked capsules**
  - **Fast and robust method for (online) localization**
- **Problem:**
  - **Interferences**
- **Solution:**
  - **Multipole approach for simultaneous localization and external noise compensation**

State of the art

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- **Noise suppression with various methods**
- **Marker localization with non-linear search methods (Simplex, Levenberg-Marquardt, Gauss-Newton)**

Multipole method

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- **Multipole expansion of the measured magnetic field with inner and outer components (multipoles)**
- **Comparison of coefficients of the Taylor series expansion of the magnetic dipole field with inner multipoles yields a system of equations for the determination of the dipole location and moment from the inner multipole of 1st and 2nd order**
- **Noise cancelation by elimination of outer components**
- **Iterative usage in time series analysis**

Hilgenfeld & Haueisen, Biomagnetic Research and Technology, 2004

Inner components

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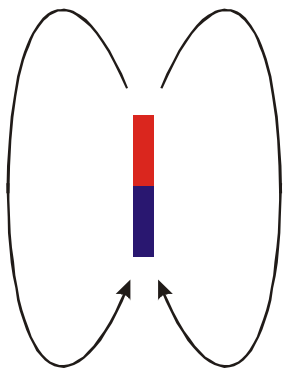
Dipole
First order tensor

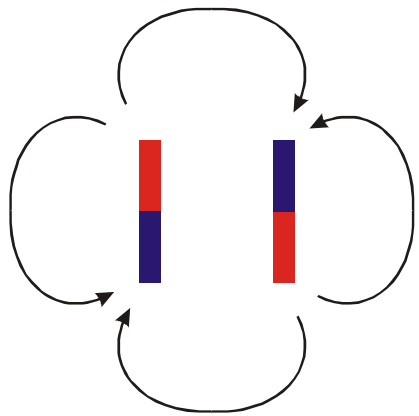
3 linearly independent components

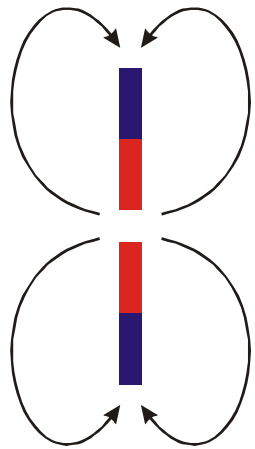


Quadrupole
Second order tensor

symmetric

5 linearly independent components





Outer components

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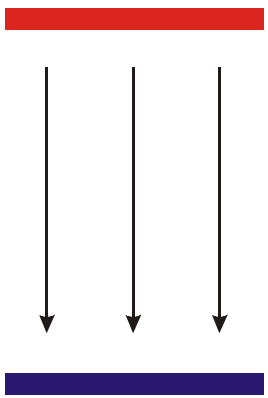
First order tensor

3 linearly independent components

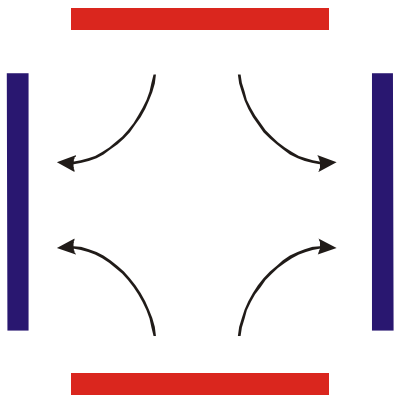


homogeneous disturbing field of 0th order

Second order tensor

symmetric

5 linearly independent components

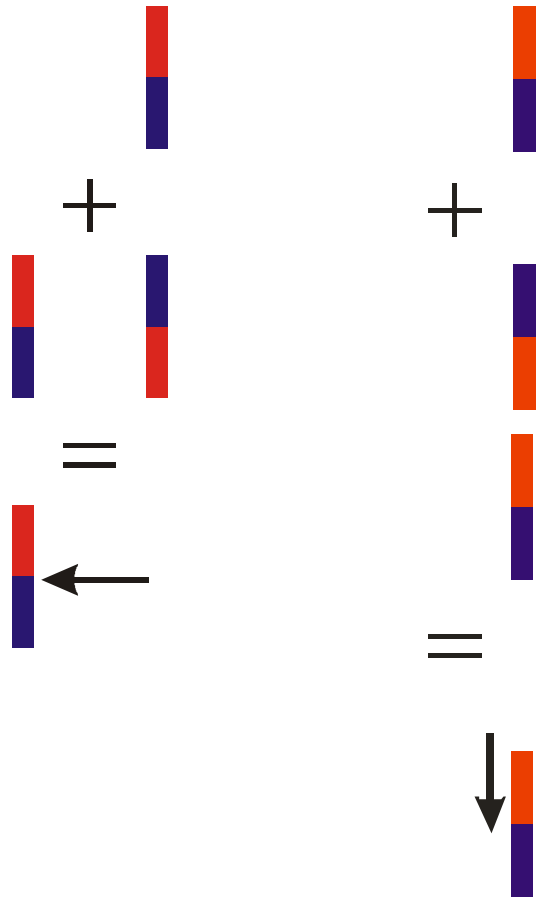


gradient disturbing field of 1st order

Localization and noise separation

Inner components

location and place of the marker are reconstructed from the dipole und quadrupole at coordinate center



Separation of outer components as noise.

Multipole expansion

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Multipole expansion for the field of a magnetic marker close to (0,0,0):

$$\vec{B}_{\mathrm{m}}(\vec{r}) = \frac{\mu_0}{4\pi}\sum_{j=1}^{3}\left(F_{\mathrm{m}}^{i,j}(\vec{r})\right)_{i=1}^{3} c_j^{\mathrm{m}} + \frac{\mu_0}{4\pi}\sum_{k=1}^{3}\sum_{j=1}^{3}\left(F_{\mathrm{m}}^{i,j,k}(\vec{r})\right)_{i=1}^{3} c_{j,k}^{\mathrm{m}} + \frac{\mu_0}{4\pi}\sum_{l=1}^{3}\sum_{k=1}^{3}\sum_{j=1}^{3}\left(F_{\mathrm{m}}^{i,j,k,l}(\vec{r})\right)_{i=1}^{3} c_{j,k,l}^{\mathrm{m}} + \dots$$

Form functions F can be treated as Taylor series expansion:

$$F_{\mathrm{m}}^{i} = \frac{x_i}{r^3}, \qquad F_{\mathrm{m}}^{i,j} = -\frac{\partial F_{\mathrm{m}}^{j}}{\partial x_i},$$

$$F_{\mathrm{m}}^{i,j,k} = -\frac{\partial F_{\mathrm{m}}^{j,k}}{\partial x_i}, \qquad F_{\mathrm{m}}^{i,j,k,l} = -\frac{\partial F_{\mathrm{m}}^{j,k,l}}{\partial x_i}.$$

Multipole expansion

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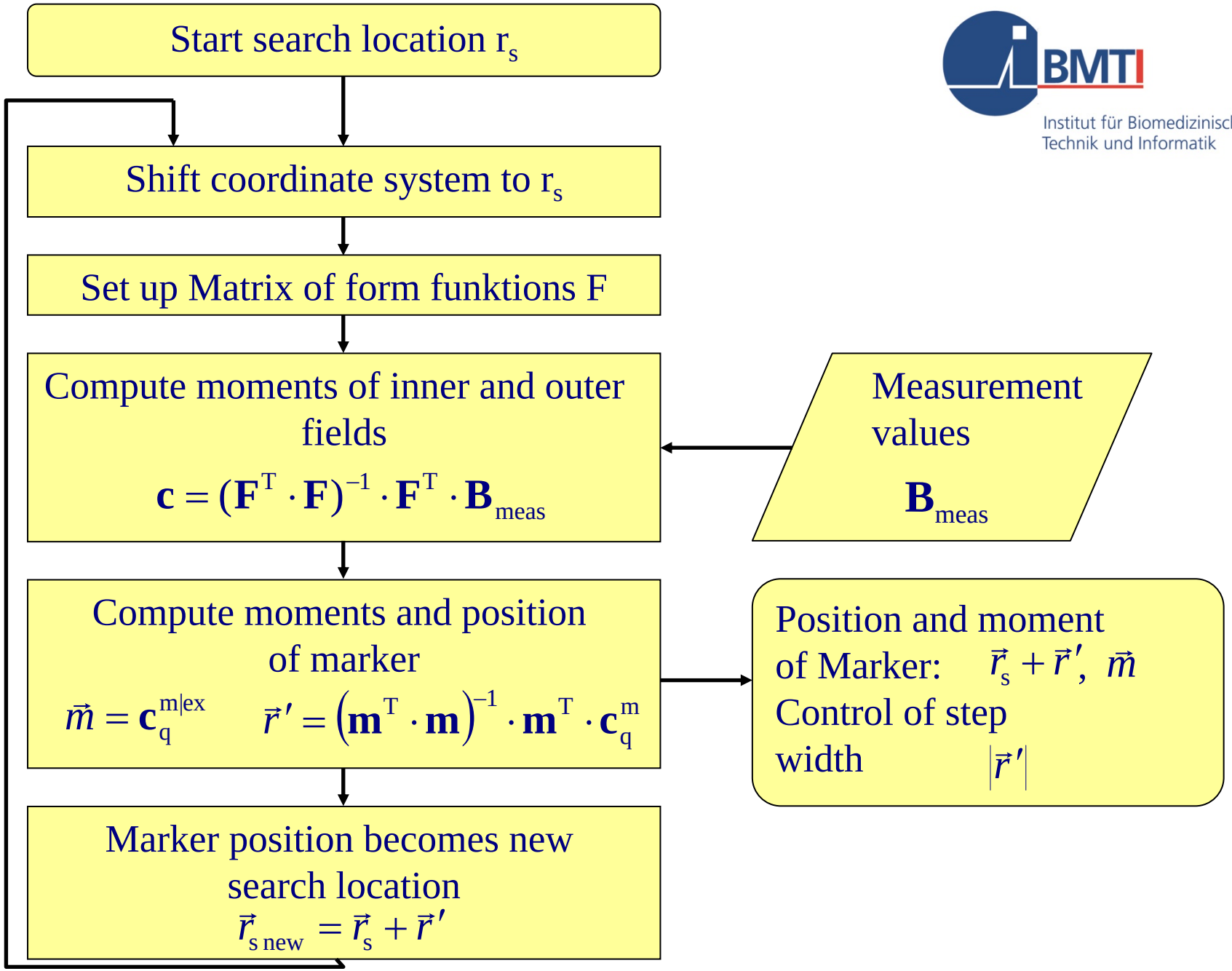
Multipole expansion for the field of distant external noise sources:

$$\vec{B}_{\mathrm{ex}}(\vec{r}) = \frac{\mu_0}{4\pi}\sum_{j=1}^{3}\left(F_{\mathrm{ex}}^{i,j}(\vec{r})\right)_{i=1}^{3} c_j^{\mathrm{ex}} + \frac{\mu_0}{4\pi}\sum_{k=1}^{3}\sum_{j=1}^{3}\left(F_{\mathrm{ex}}^{i,j,k}(\vec{r})\right)_{i=1}^{3} c_{j,k}^{\mathrm{ex}} + \frac{\mu_0}{4\pi}\sum_{l=1}^{3}\sum_{k=1}^{3}\sum_{j=1}^{3}\left(F_{\mathrm{ex}}^{i,j,k,l}(\vec{r})\right)_{i=1}^{3} c_{j,k,l}^{\mathrm{ex}} + \ldots$$

Form functions for external sources derived from the inner sources:

$$F_{\mathrm{ex}}^{i,j} = \frac{\partial\left(F_{\mathrm{m}}^{j} r^3\right)}{\partial x_i}, \quad F_{\mathrm{ex}}^{i,j,k} = \frac{\partial\left(F_{\mathrm{m}}^{j,k} r^5\right)}{\partial x_i}, \quad F_{\mathrm{ex}}^{i,j,k,l} = \frac{\partial\left(F_{\mathrm{m}}^{j,k,l} r^7\right)}{\partial x_i}$$



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Simulation setup

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Aims:

- Localization error as a function of noise
- Localization error after one step, as function of starting distance
- Convergence distance depending on noise level

Set up:

- Dipole with 20µAm^2, 300mm below sensor level
- Gaussian noise
- Variation of multipole expansion order

Simulation setup

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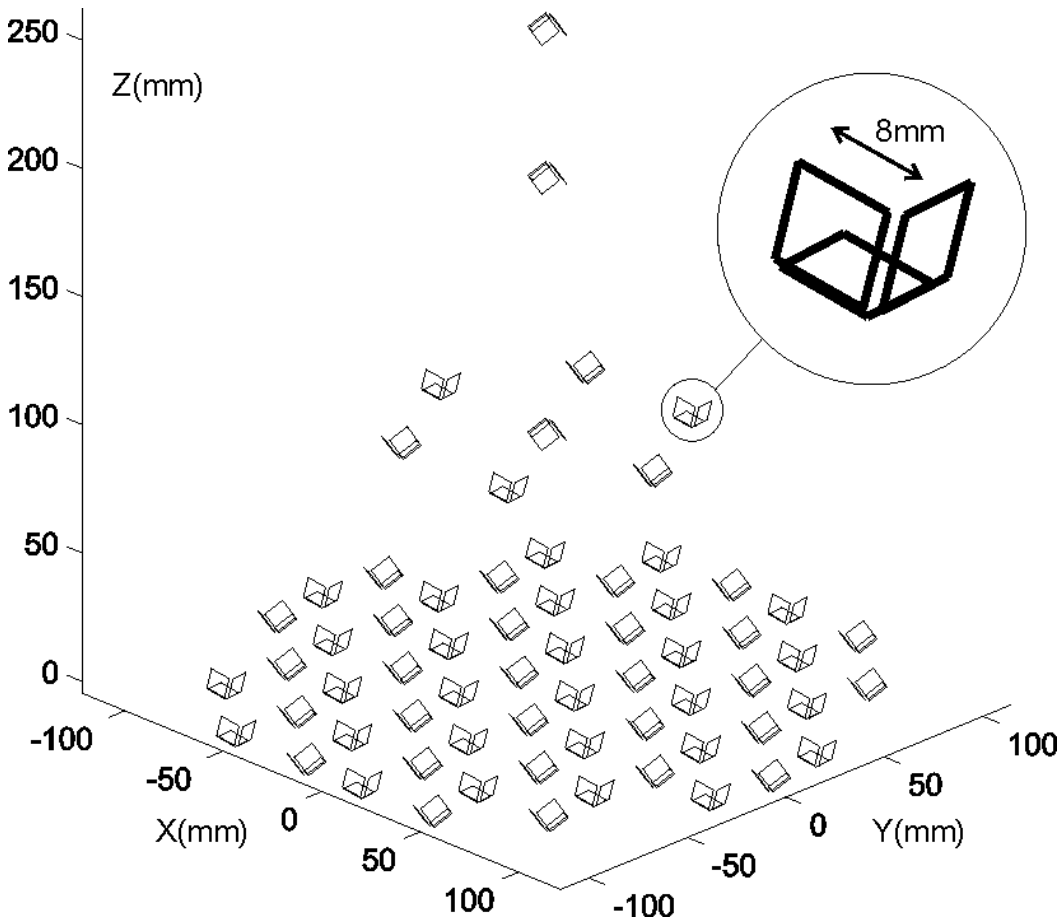
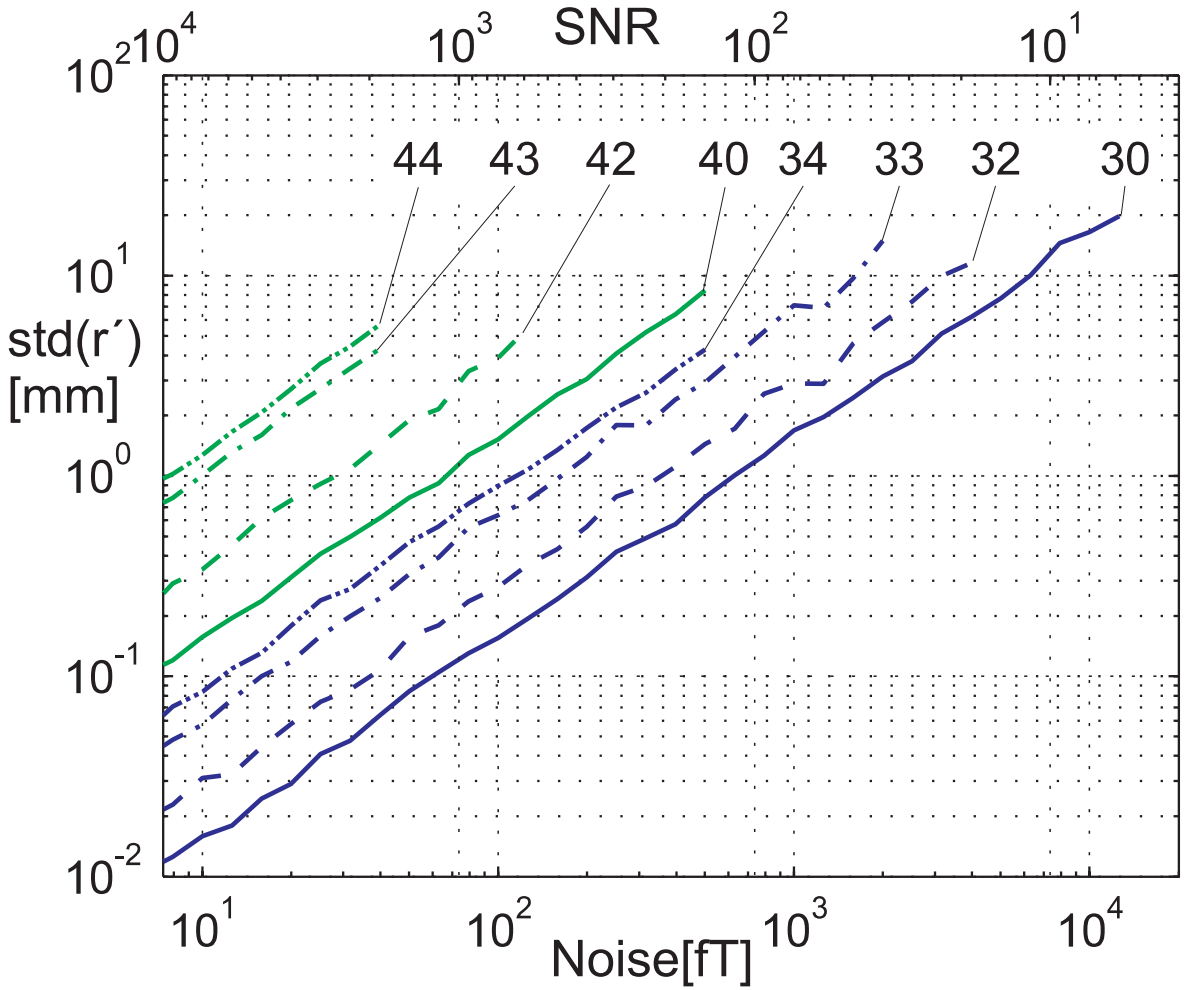


Simulations

Localization error as a function of noise



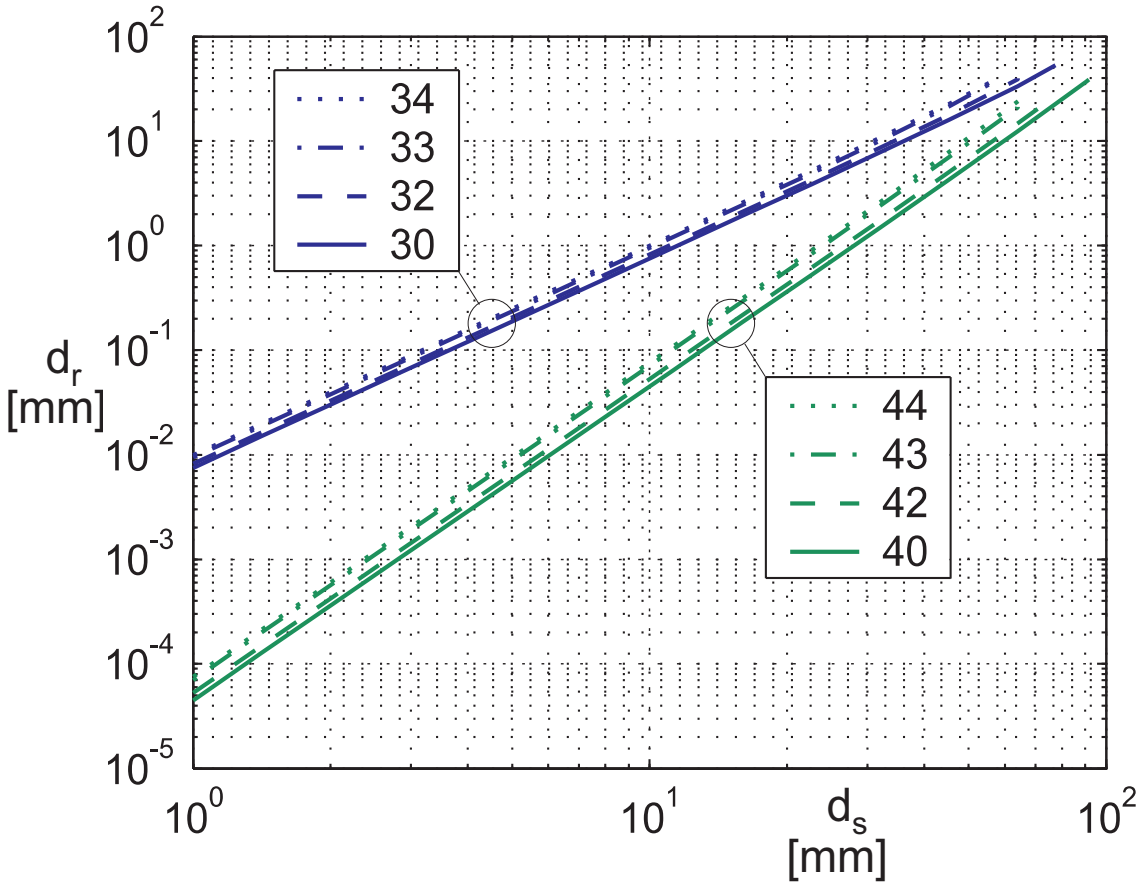
Marker strength 20µAm^2
Marker pos z = -300mm

100 repeated runs per data point

2 ... Dipole, 3 ... Dipole and Quadrupole,
4 ... Dipole, Quadrupole und Octupole
1st number: inner
2nd number: outer multipole

Simulations

Localization error depending on the starting point distance d_s for one iteration



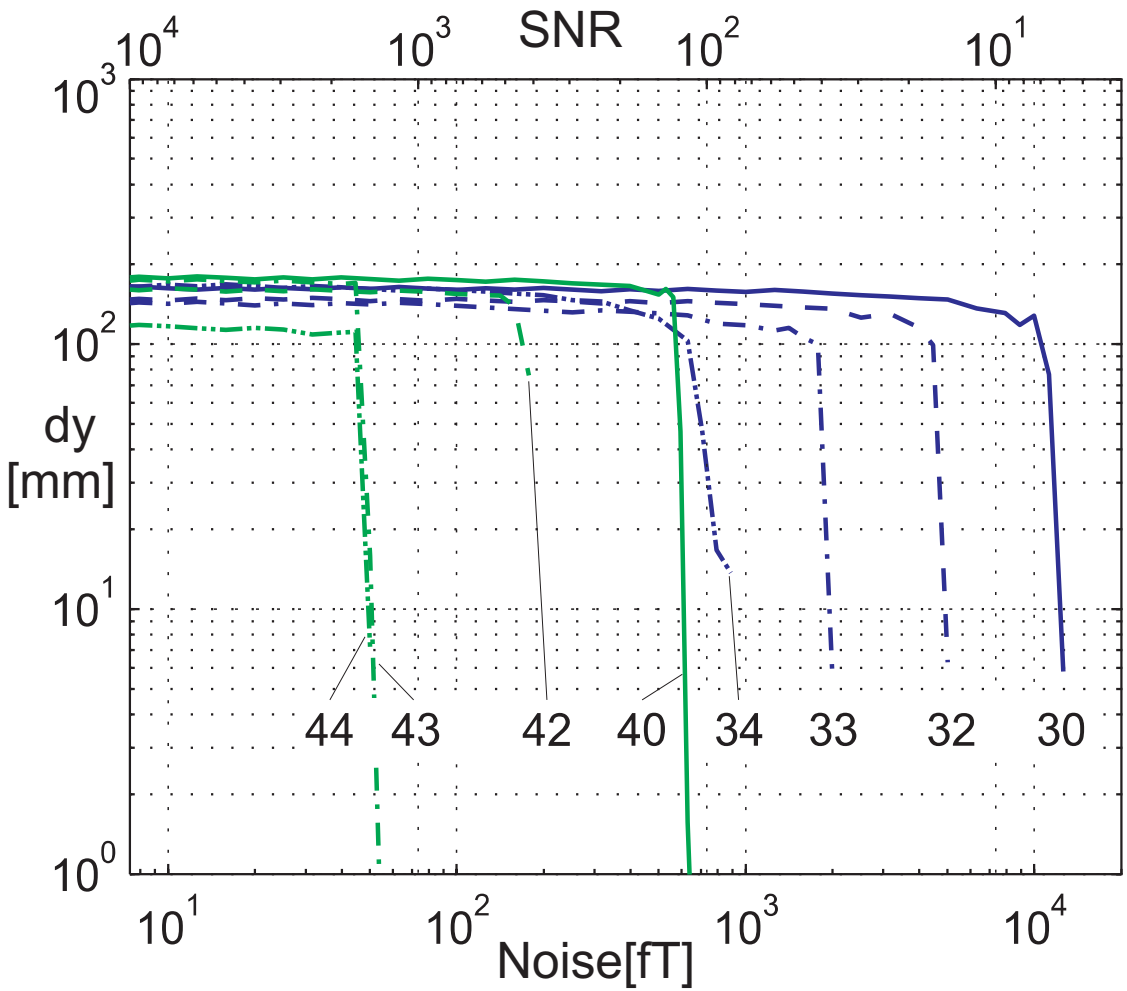
Marker strength 20µAm^2
Marker pos z = -300mm

100 repeated runs per data point

2 ... Dipole, 3 ... Dipole and Quadrupole,
4 ... Dipole, Quadrupole und Octupole
1st number: inner
2nd number: outer multipole

Simulations

Convergence distance depending on noise level



Marker strength 20µAm^2
Marker pos z = -300mm

100 repeated runs per data point

2 ... Dipole, 3 ... Dipole and Quadrupole,
4 ... Dipole, Quadrupole und Octupole
1st number: inner
2nd number: outer multipole

Measurement with glass phantom

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Marker in fluid (sucrose) under measurement system

Measurement with glass phantom

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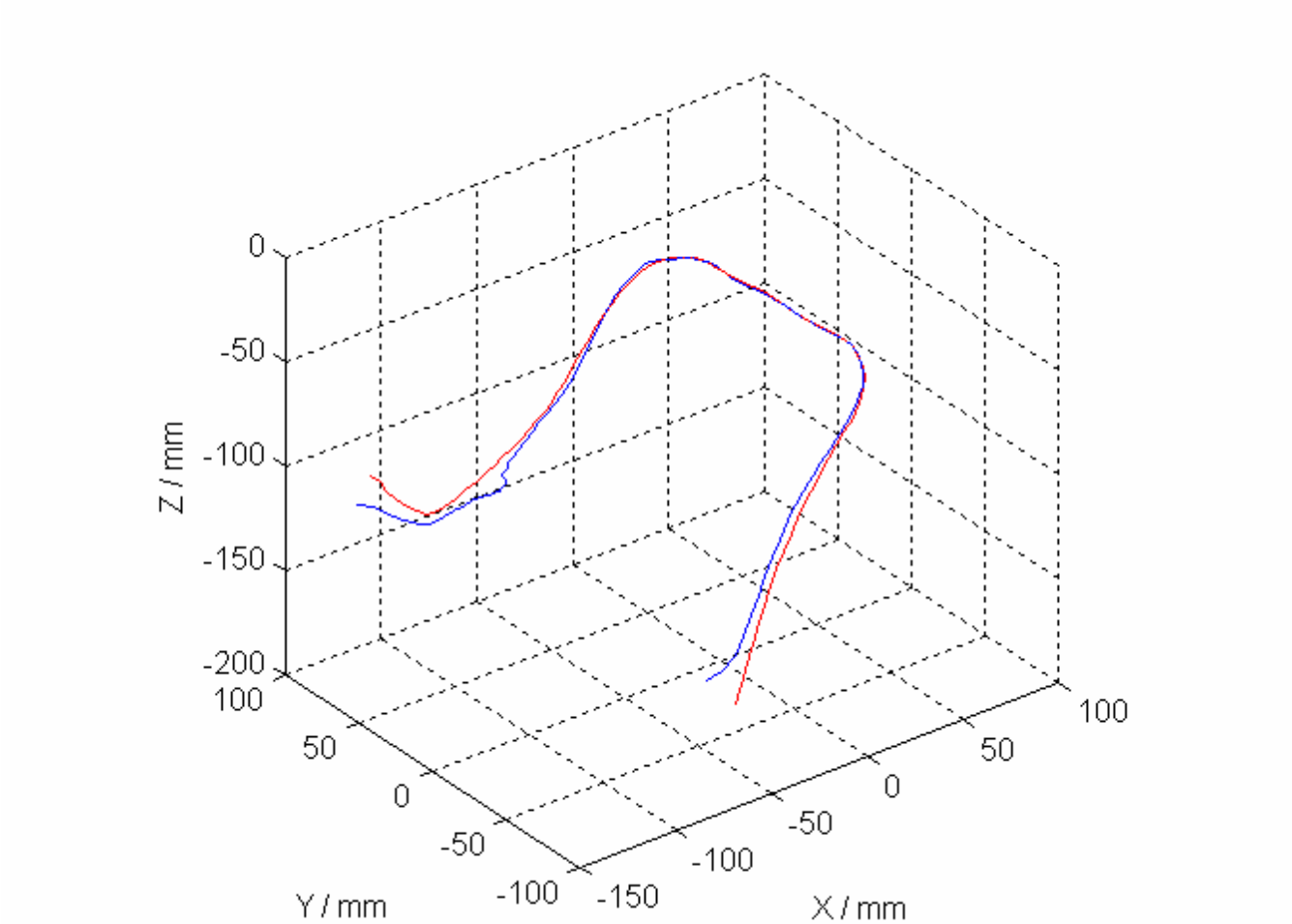


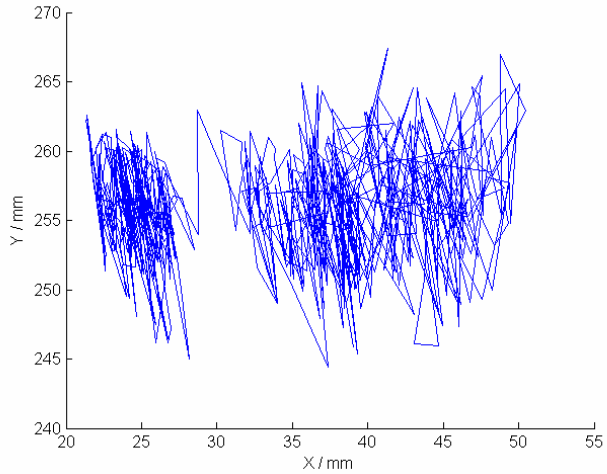
Clinical study with magnetically marked tablets

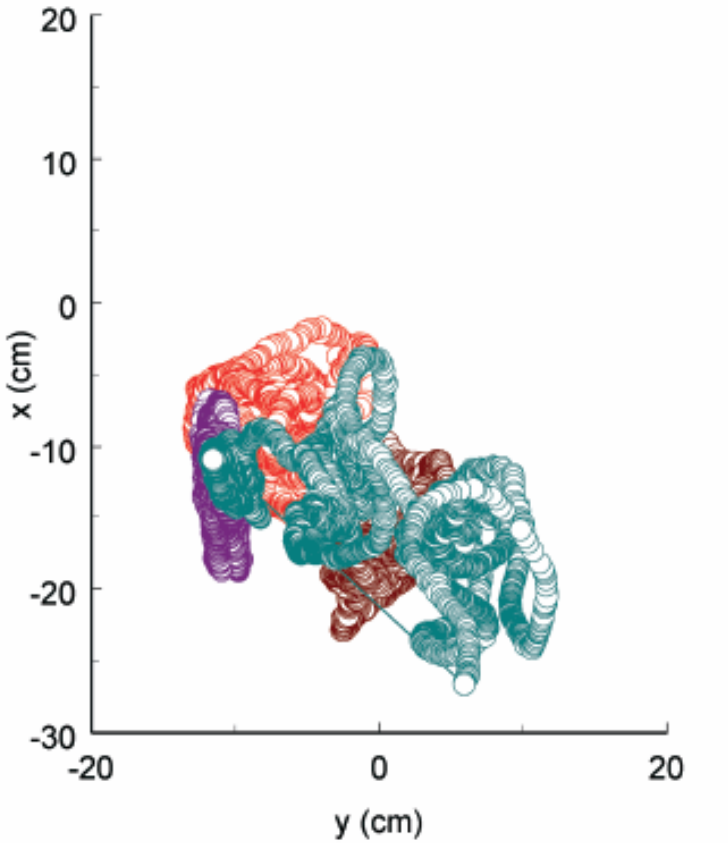
Clinical study with magnetically marked tablets

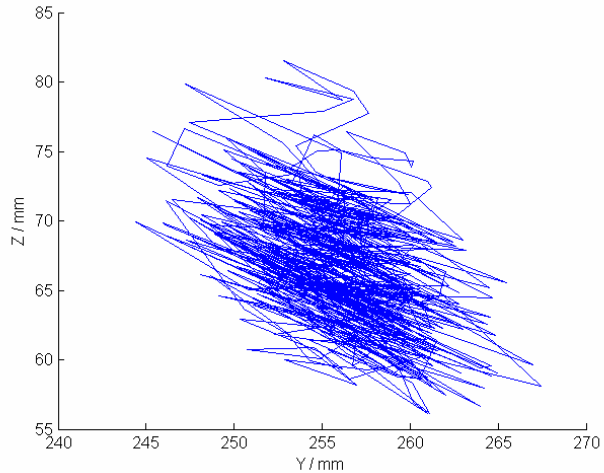
- Determination of drug disposal in the intestine
- Test- and reference tablets
- Two sets of measurement on 12 probands
- 10-min for single measurement, 30 min inter-measurement time, total time about 12 hours
- 2 probands per day, blood control every 30 min

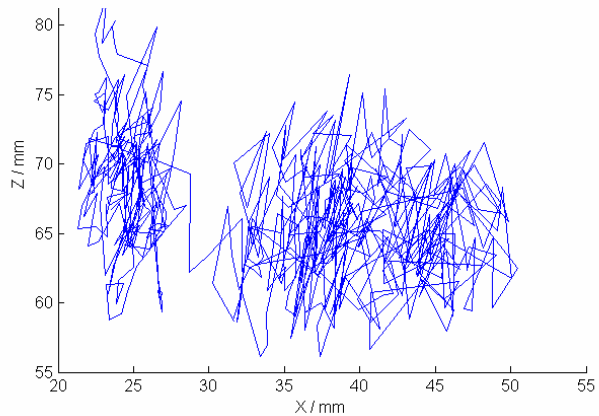
Localization results

- one measurement,1S/s
- Respiratory movements
- larger movement in the colon









Marker moment for one series

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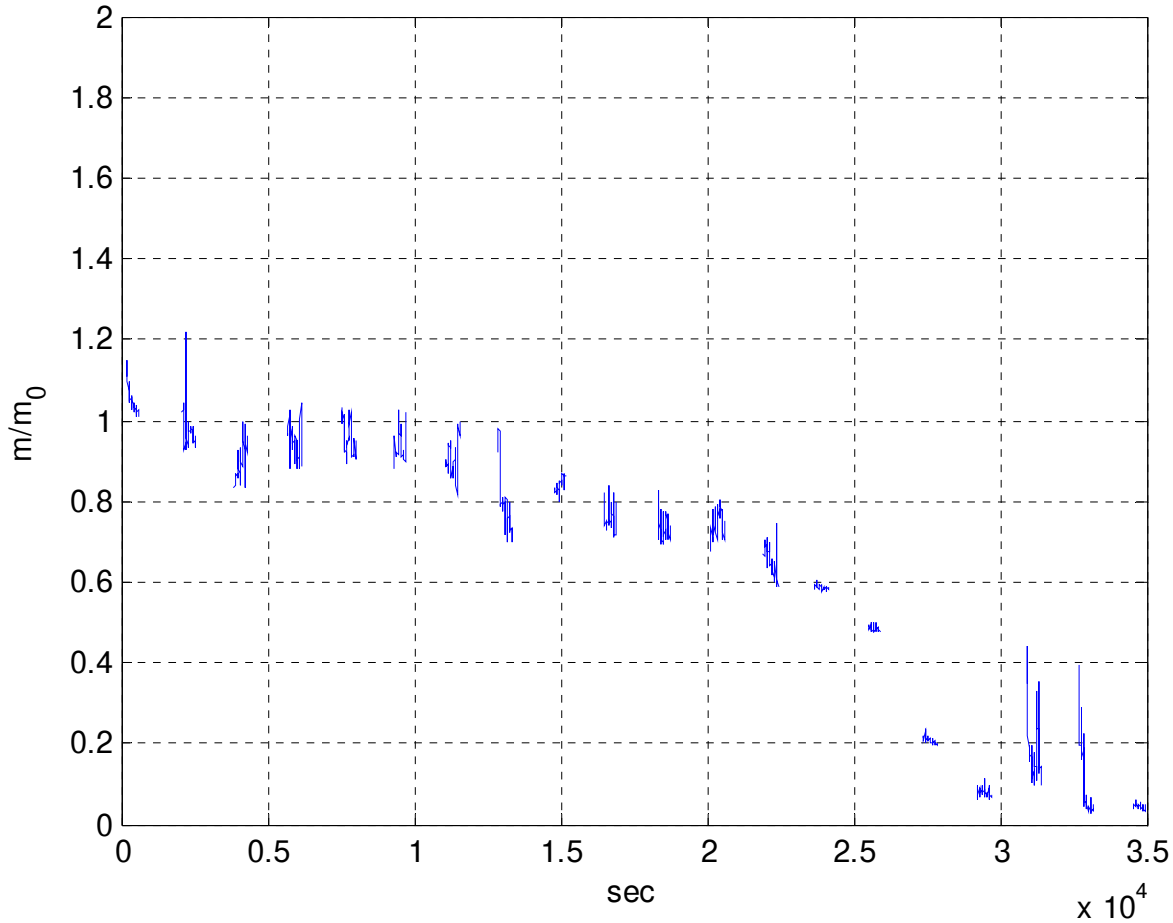

Summary

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- Fast online method: max. 3 iterations for each localization
- SNR better 100 is recommended
- Inner oktupole not used because of high sensitivity to noise
- Starting point within about 10 cm of true location

Hilgenfeld & Haueisen, Biomagnetic Research and Technology, 2004

Overview

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1. Introduction
2. Localization of magnetic markers in the alimentary tract
3. The influence of forward model conductivities on EEG/MEG source reconstruction
    1. Finite Element Modeling
    2. Animal sensitivity analysis
    3. Human sensitivity analysis
4. Optimization of magnetic sensor arrays for magnetocardiography
5. Validation of source reconstruction procedures

Introduction

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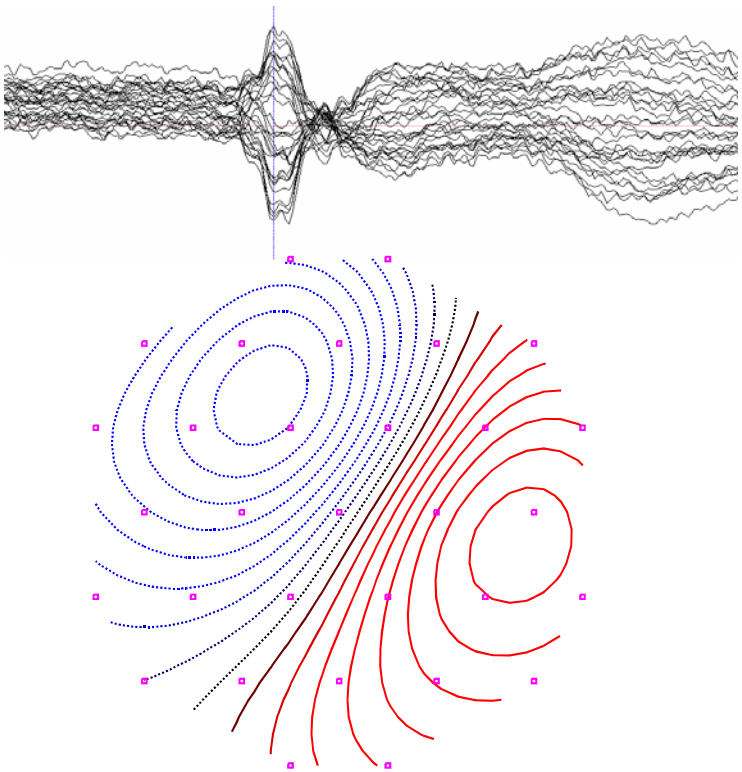

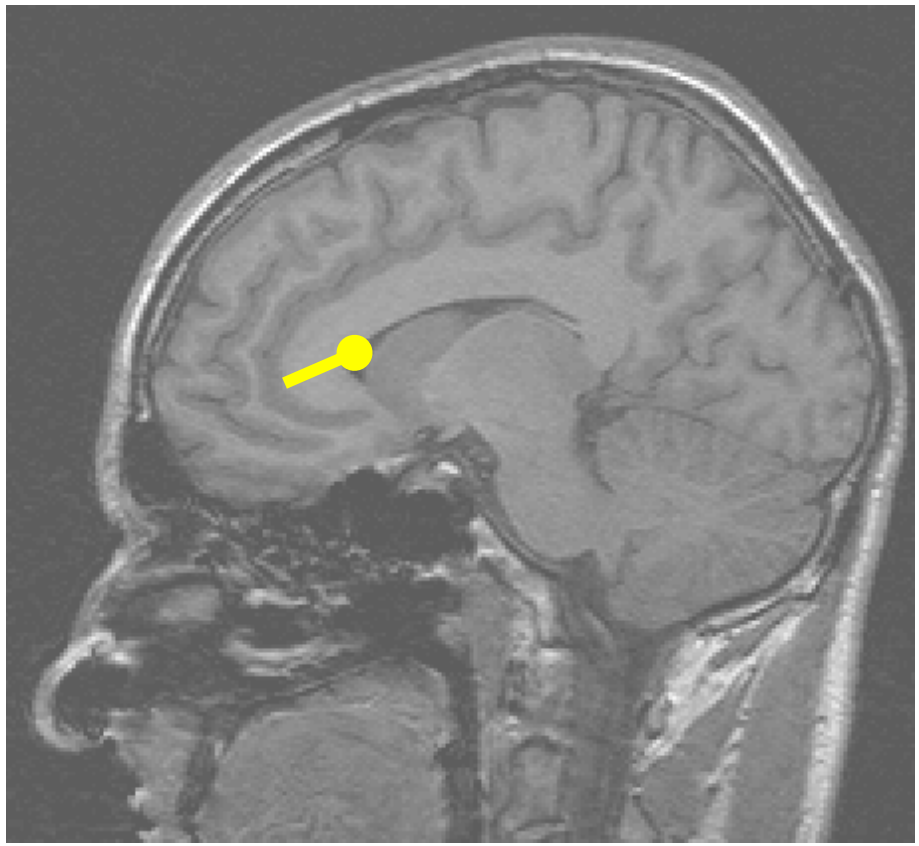

- How does volume conduction influence source estimation?
- How does anisotropy influence source estimation?

SimBio and NeuroFEM

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Image Registration (T1, T2, PD)

↓

Segmentation

↓

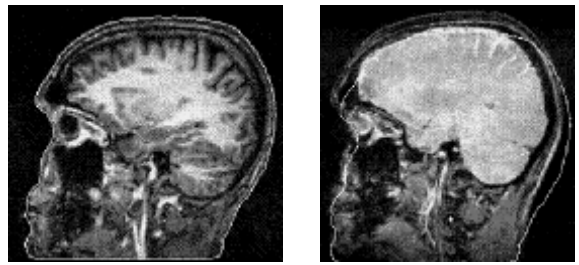
Mesh Generation BEM/FEM

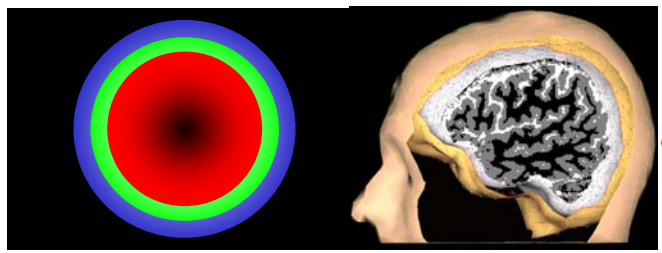
↓

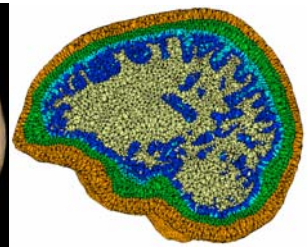
Forward toolbox
Inverse toolbox

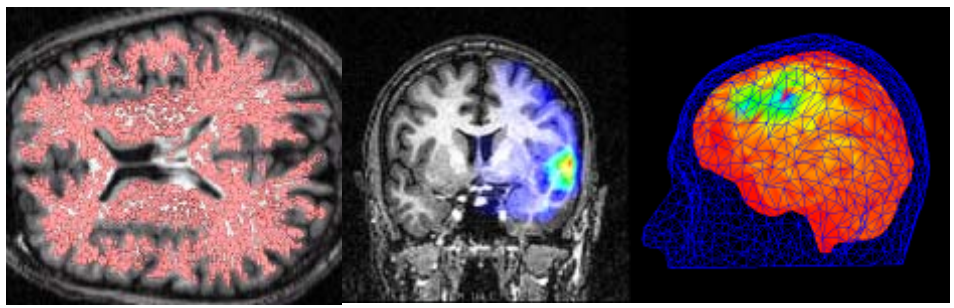
↓

Visualisation









Galerwin

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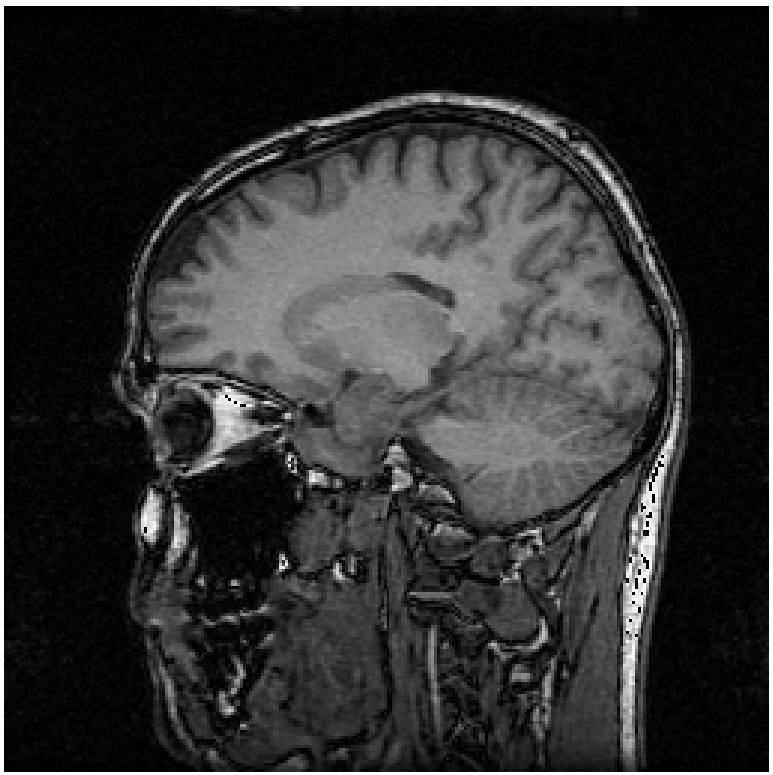
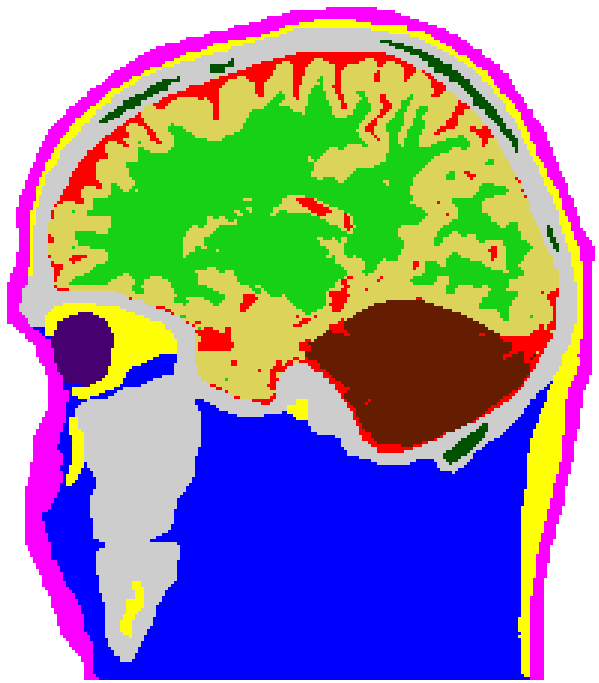
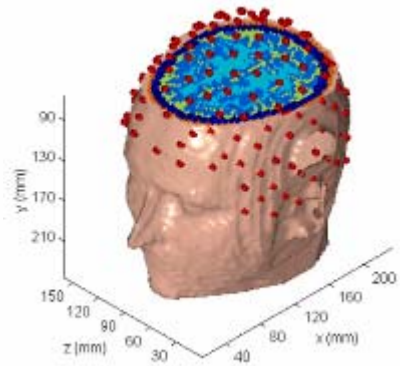
T1 weighted MR data:
- 1.6 mm slice thickness,
- 102 slices,
- 1 mm x 1 mm pixel size

FEM model cross section:
- resolution of 1 mm x 1 mm x 3.2 mm,
- 1,456,069 hexahedral elements (voxels)
- adaptive JCG solver







Schimpf, Haueisen et al., Parallel Computing, 1998

Conductivity and anisotropy data

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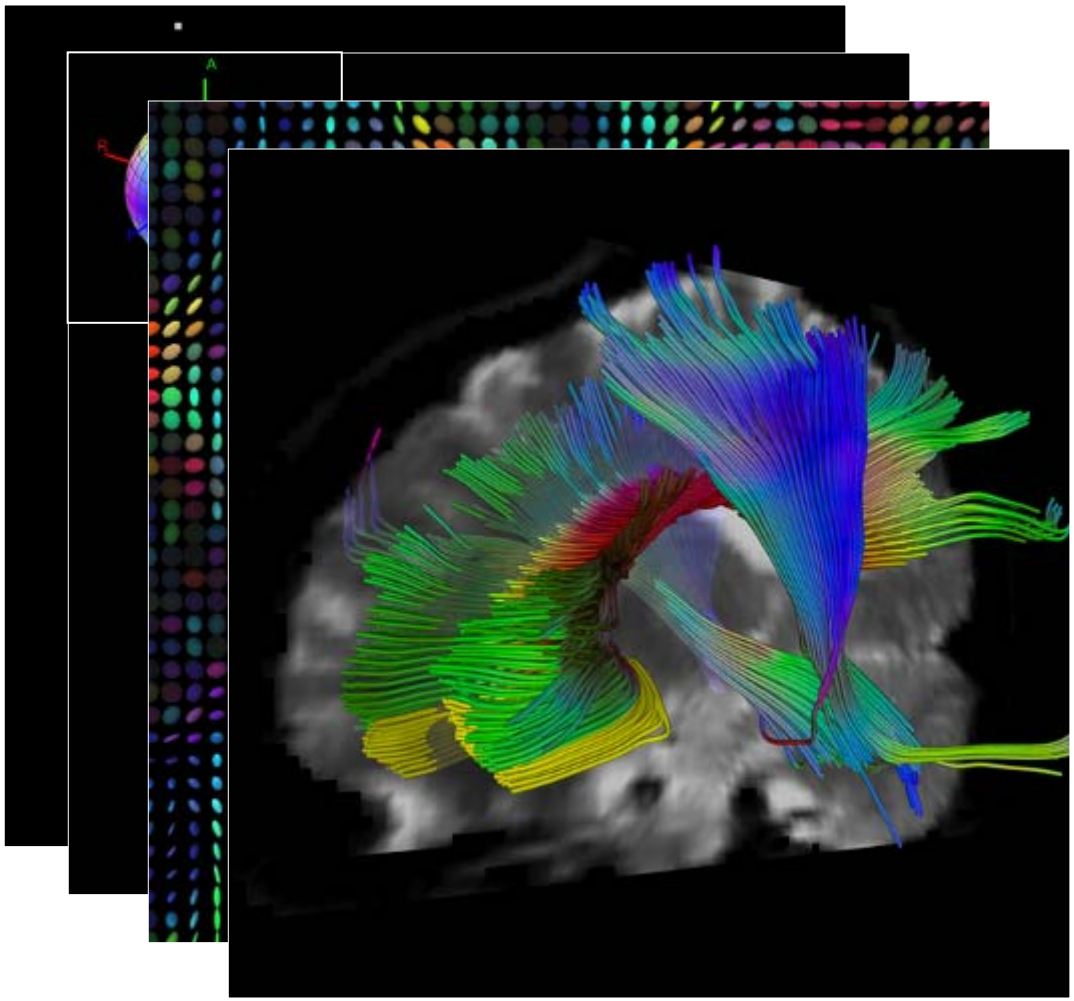
Human Diffusion Tensor Imaging



Anisotropy map (FA)

Anisotropy map color coded

Diffusion tensor as ellipsoid

Fiber tracking (main direction of strong anisotropic tensors)

Böhr, Güllmar, Knab, Reichenbach, Witte, Haueisen: Brain Res, 2007

Conductivity and anisotropy data

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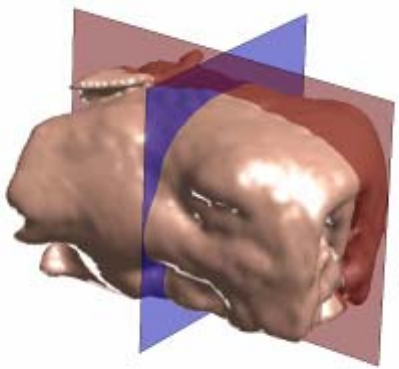
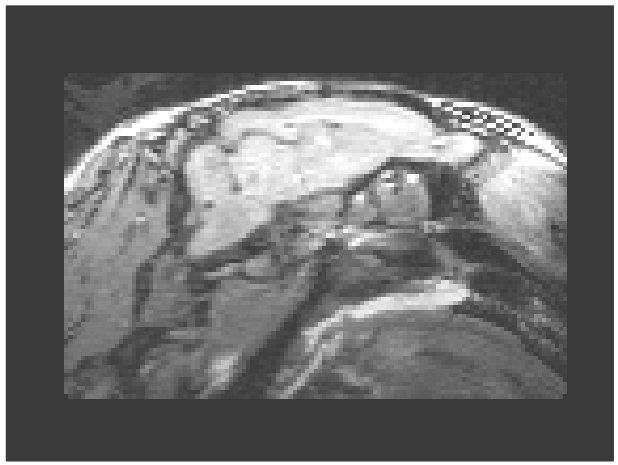
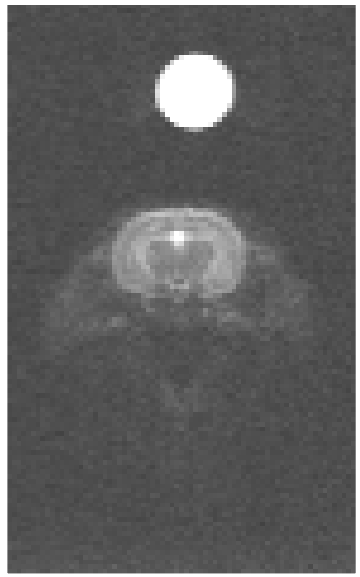
Technik und Informatik

Rabbit imaging

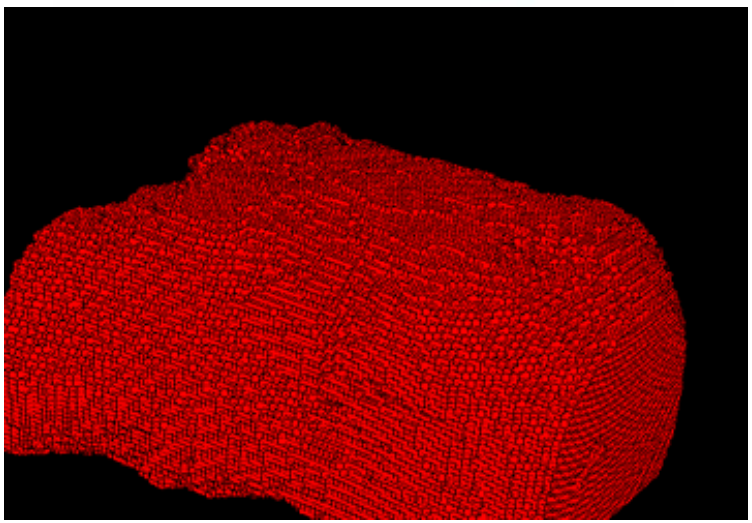




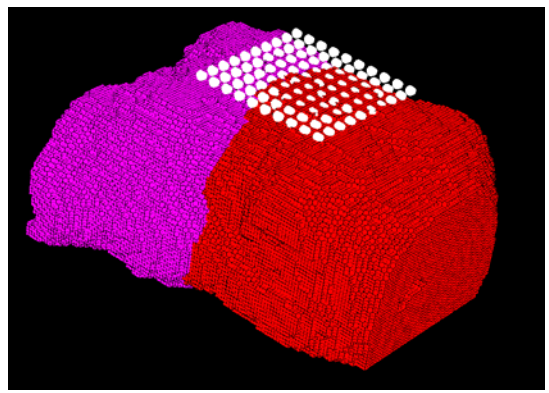
Flash3D T1
(isotropic resolution 0.625 mm)



TSteam - DTI



633172 cubic
elements (0.6mm)



Animal sensitivity analysis

Simulations with a block of white matter

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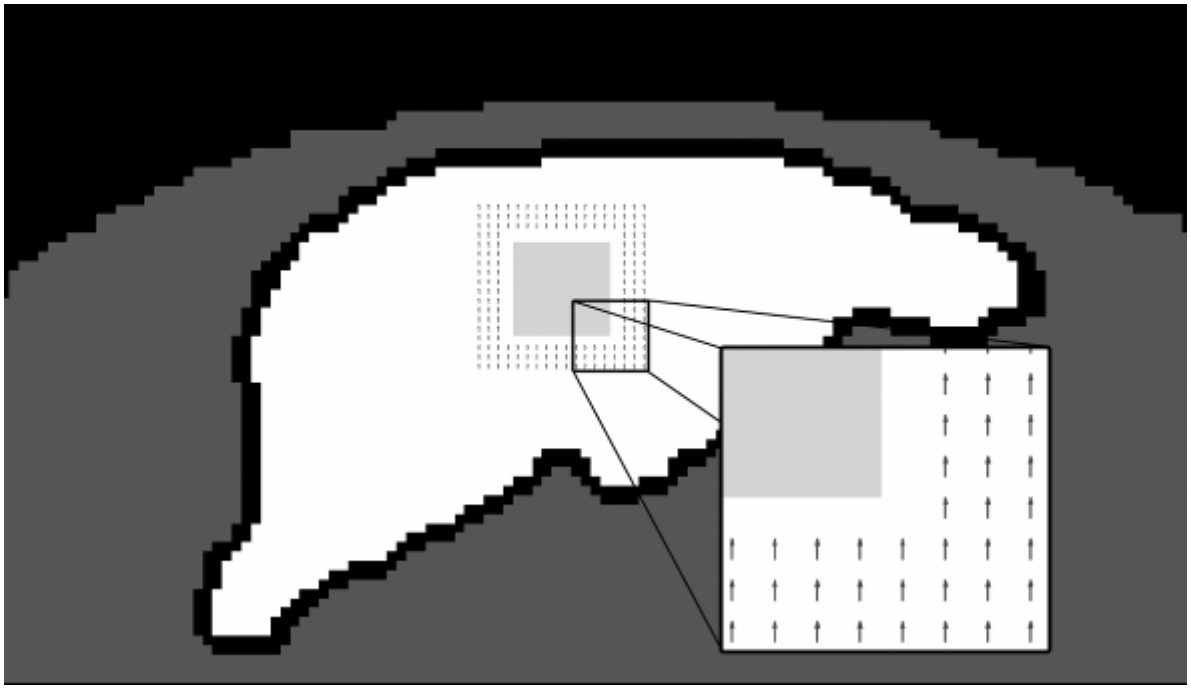

Sagittal slice with 4 tissue types:

- skin
- skull
- gray matter
- artificial white matter block

- source space with 3 layers of dipoles around the anisotropic block
- dipole orientation left/right, rostral/caudal, and inferior/superior
- anisotropic conductivity of 1:10 in caudal-rostral orientation

Animal sensitivity analysis

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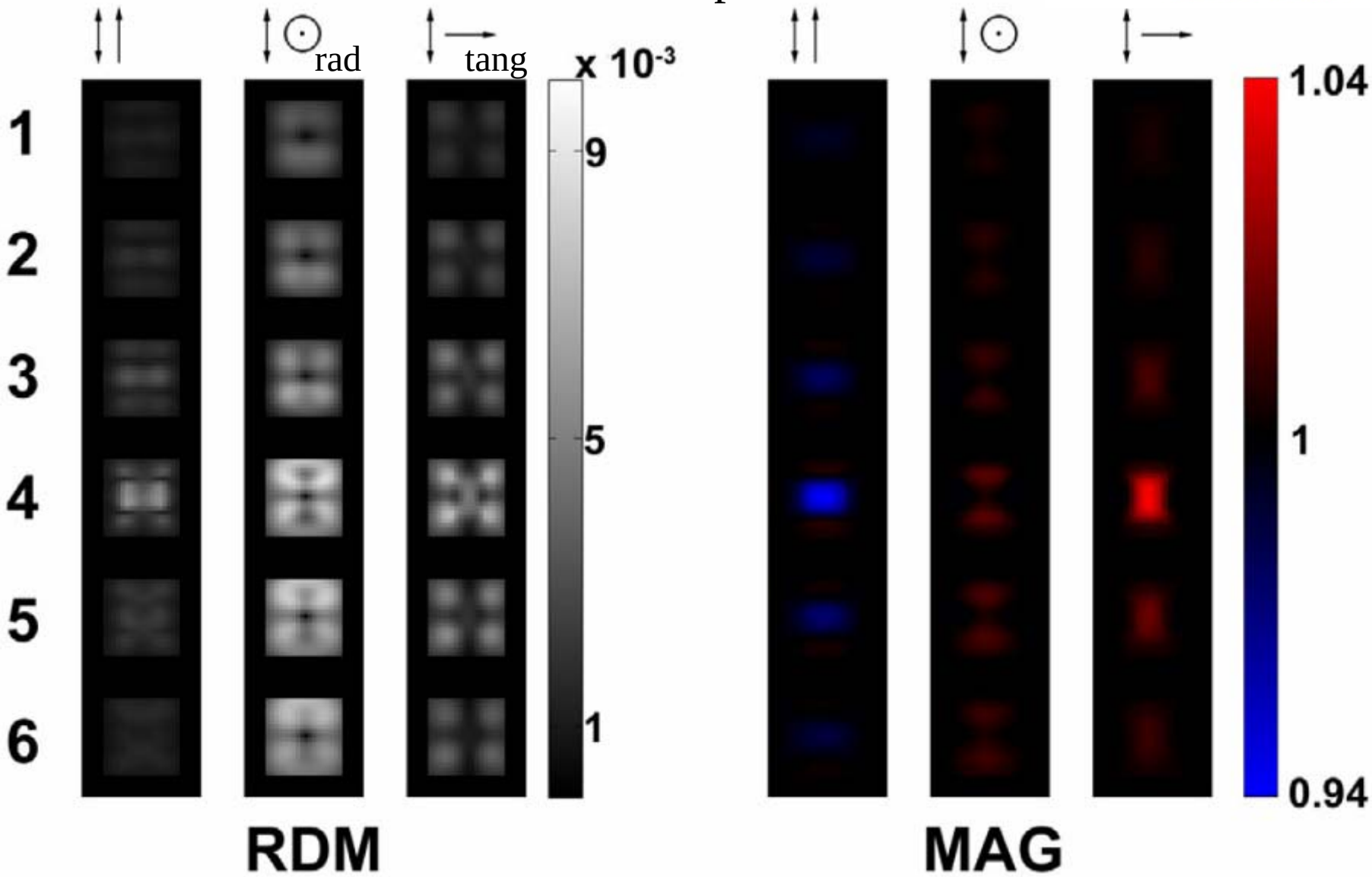
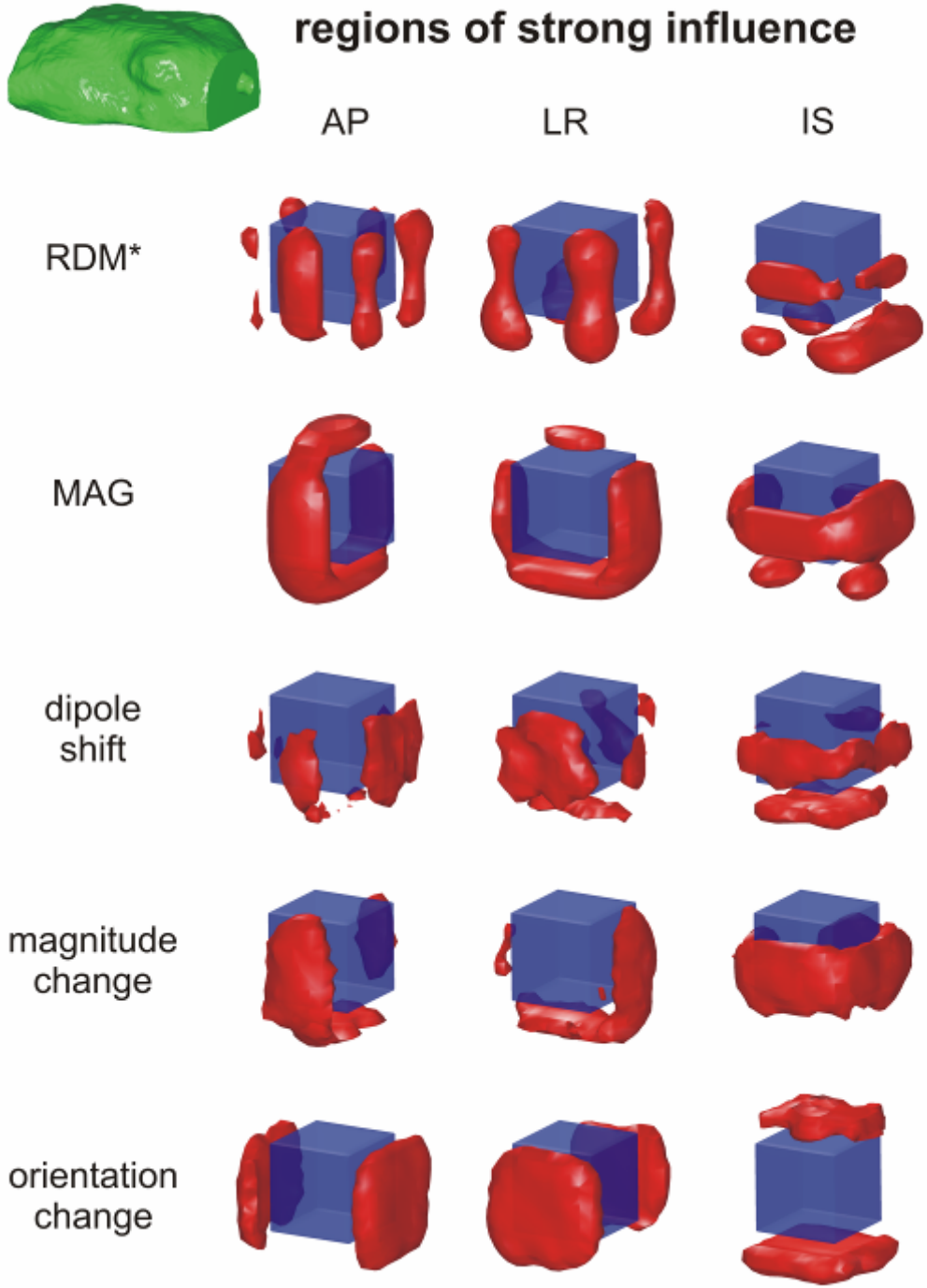
Differences in the forward computations



Simulations with a block of white matter

Values above the 0.8 percentile for RDM*, MAG, dipole shift, magnitude change and orientation change are visualized by red surfaces.



Güllmar, Haueisen et al.
IEEE TBME 2006

Experimental validation

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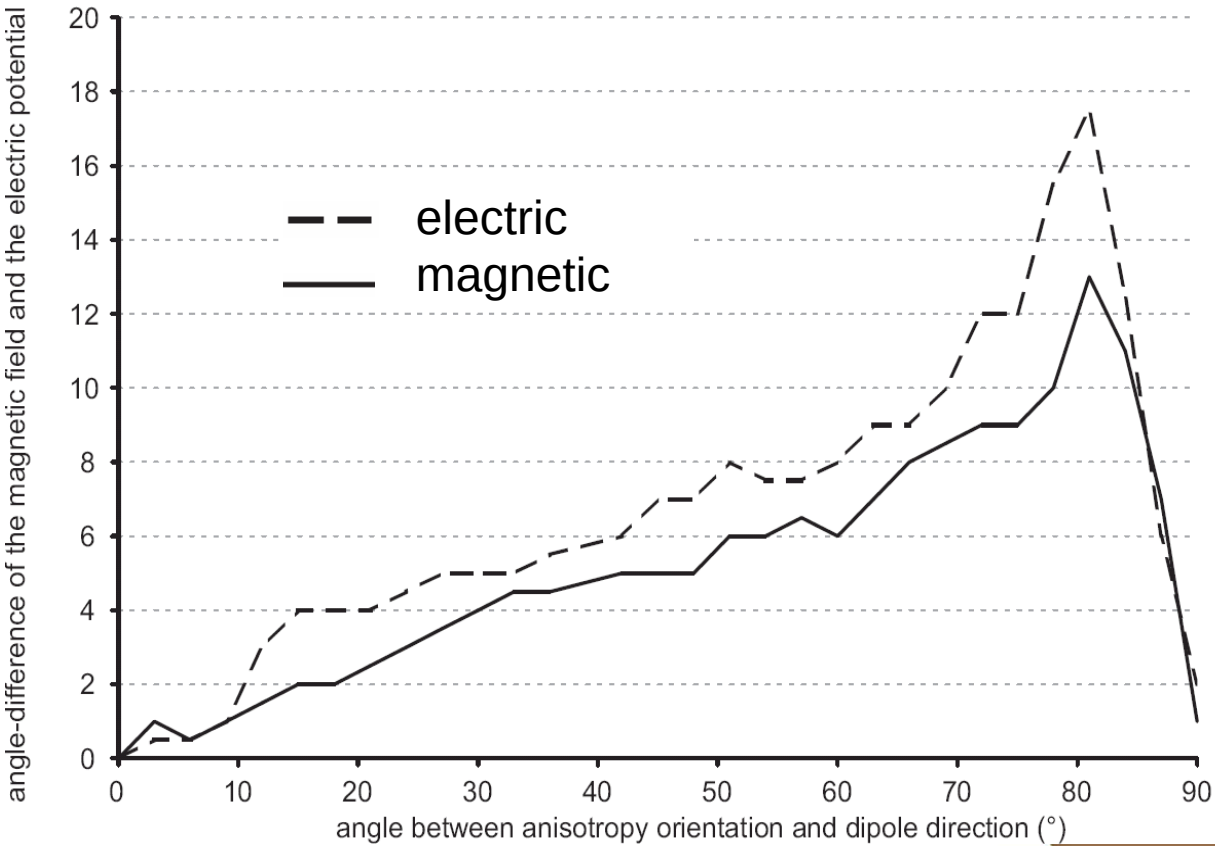
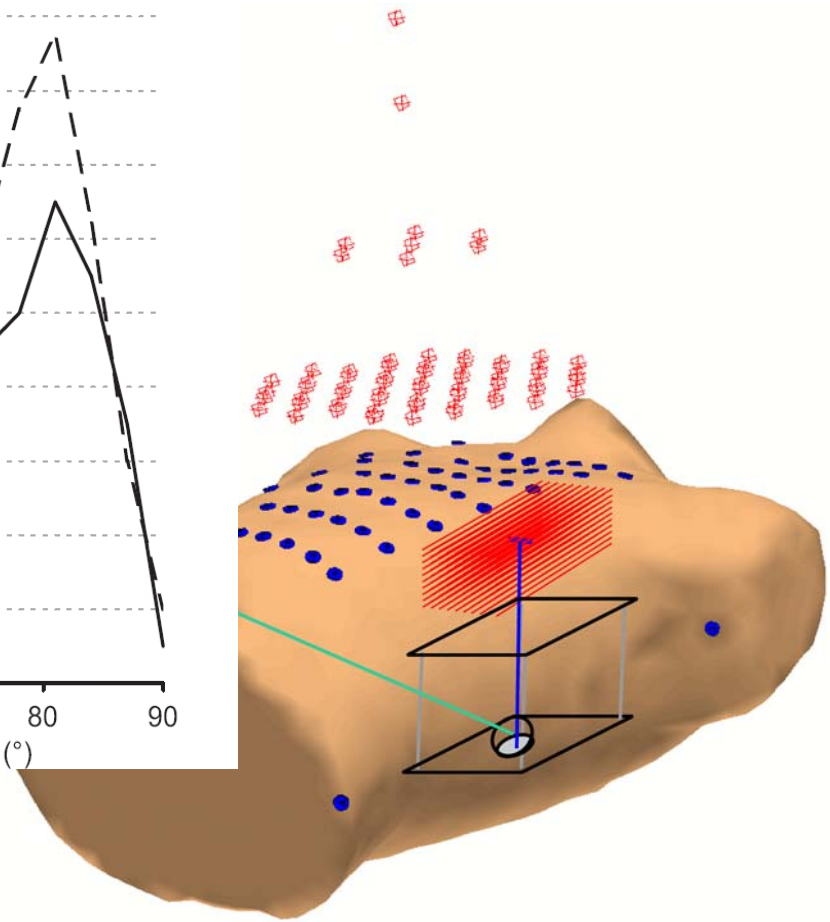


Anisotropic block in a torso phantom



Liehr, Haueisen: Phys Med Biol, 2008

Experimental validation

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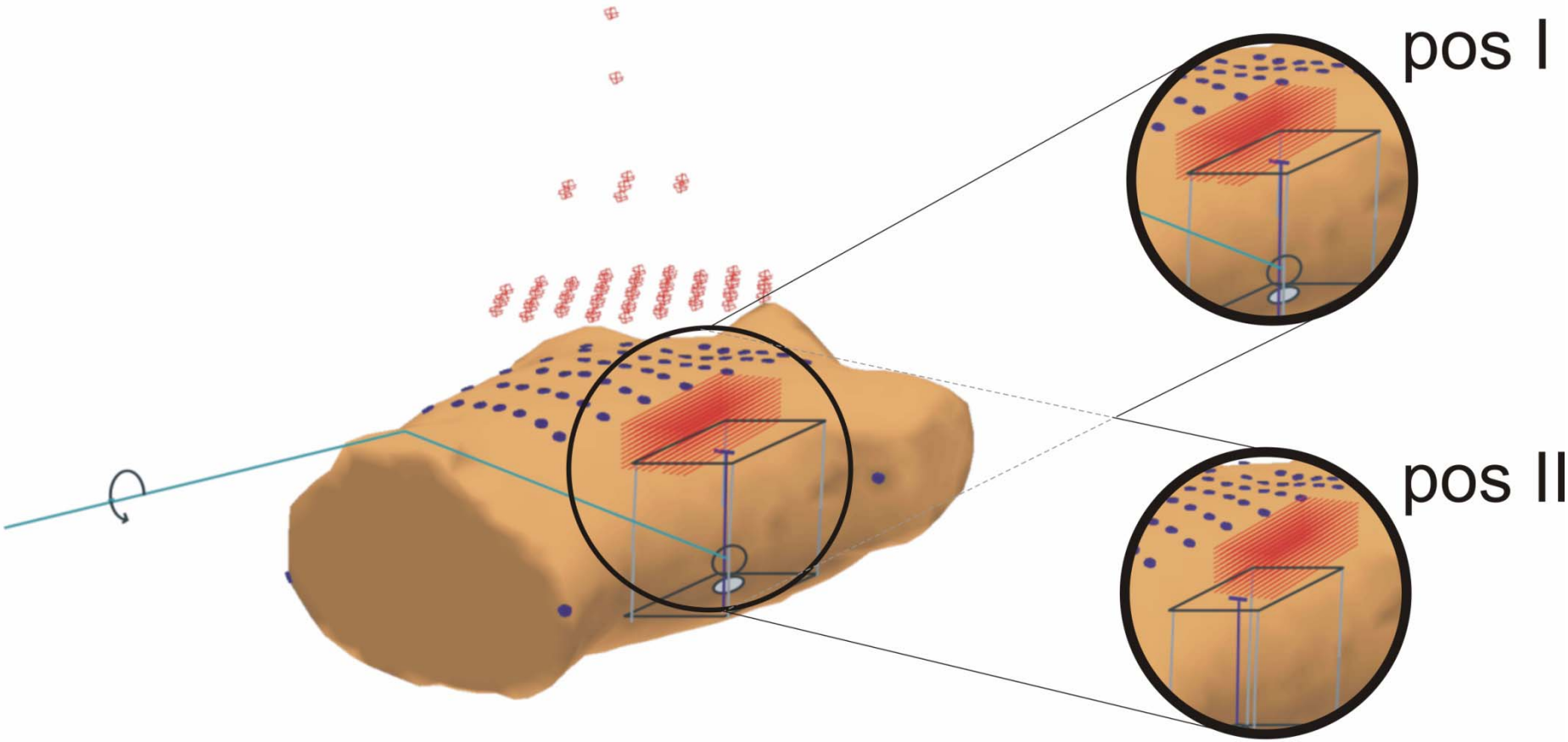
Anisotropic block in a torso phantom



Sengül, Haueisen et al. submitted, 2008

Experimental validation

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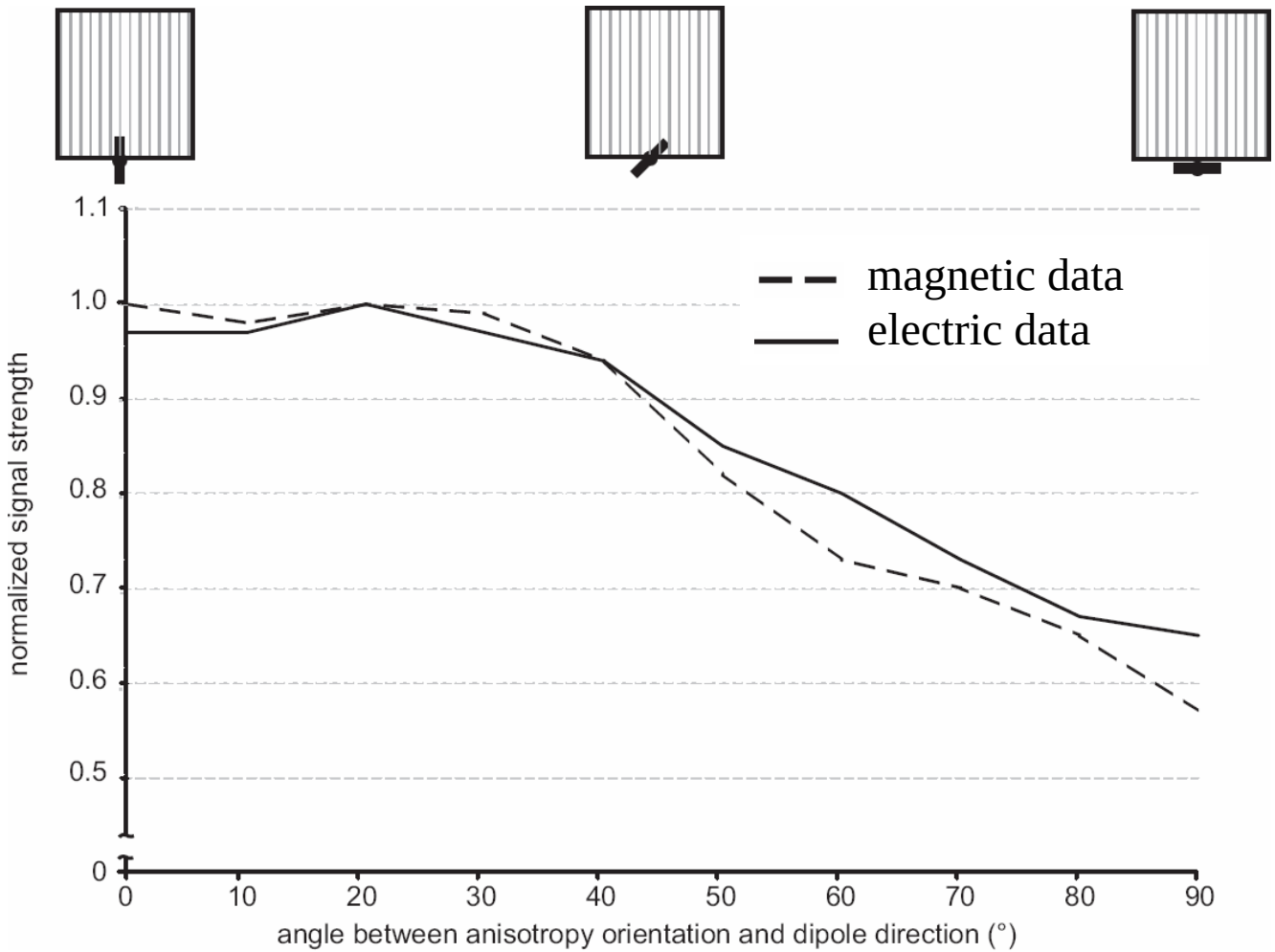


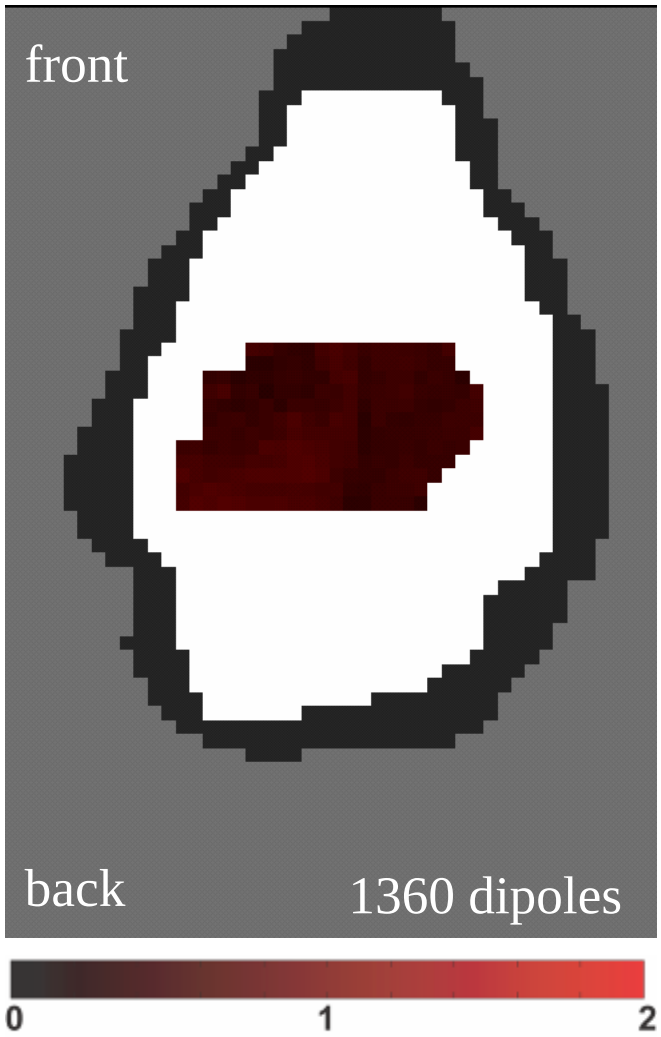
Anisotropic block in a torso phantom

Sengül, Haueisen et al. submitted, 2008

Animal sensitivity analysis

Simulations with measured conductivity tensors

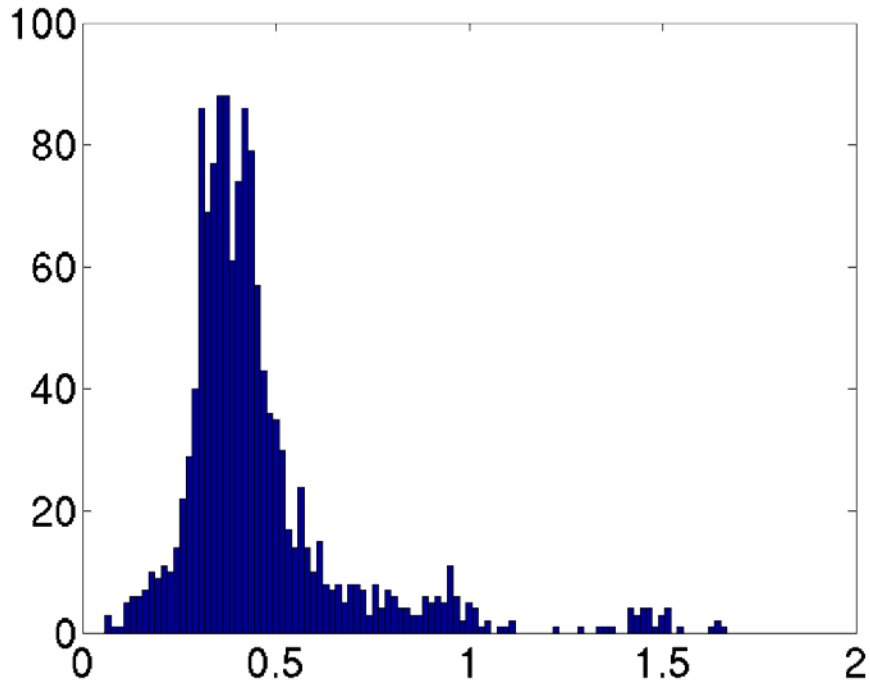
Institut für Biomedizinische Technik und Informatik



Dipole shift in mm

Source localization error

Forward computation:
anisotropic model
Inverse: isotropic model



Histogram of the dipole shift

Animal sensitivity analysis

Simulations with measured conductivity tensors

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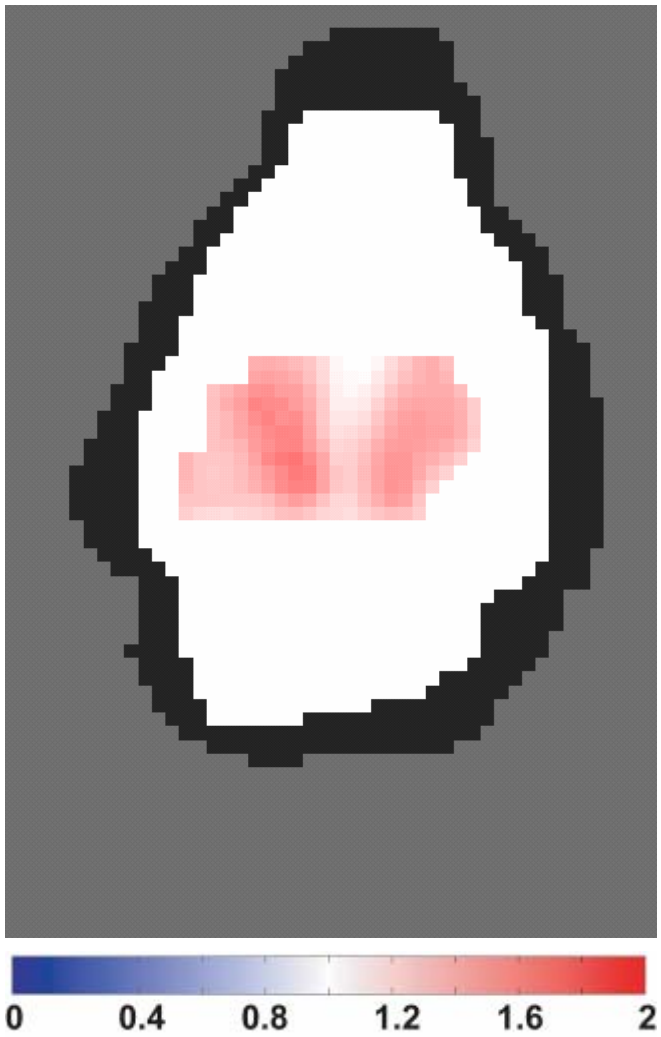
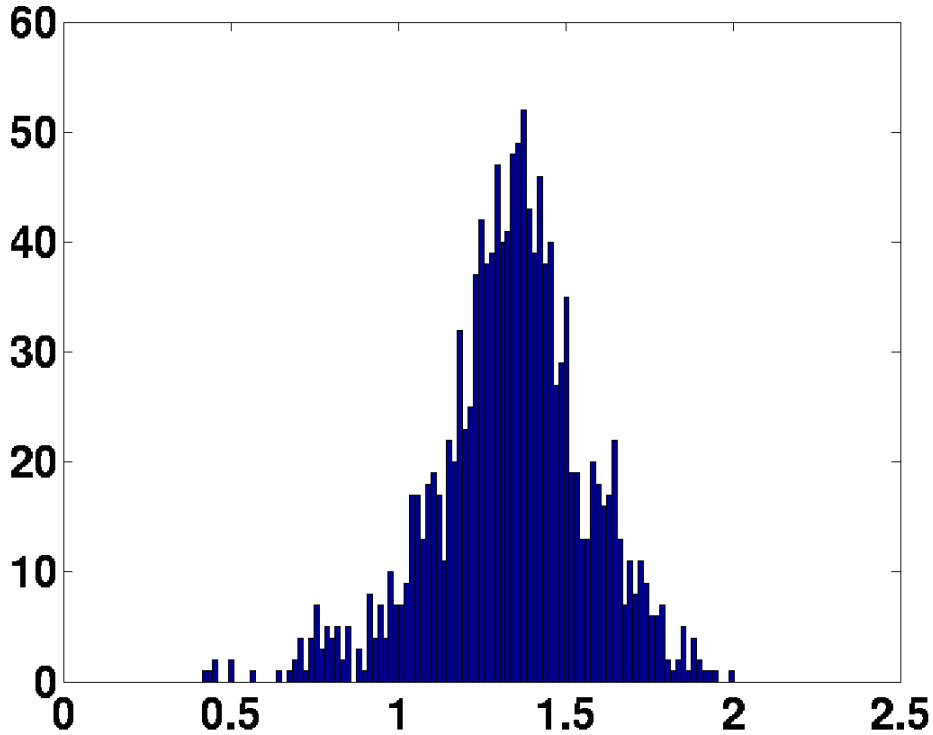


Magnitude change (relative to 1)

Dipole magnitude estimation error



Histogram of the dipole magnitude errors

Animal sensitivity analysis

Simulations with measured conductivity tensors

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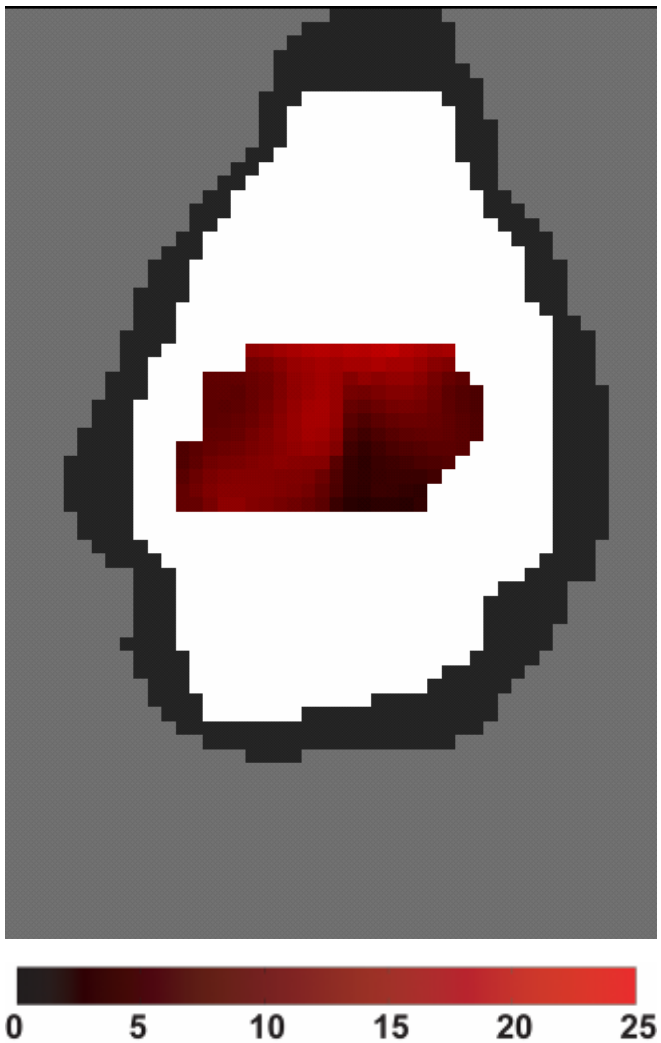
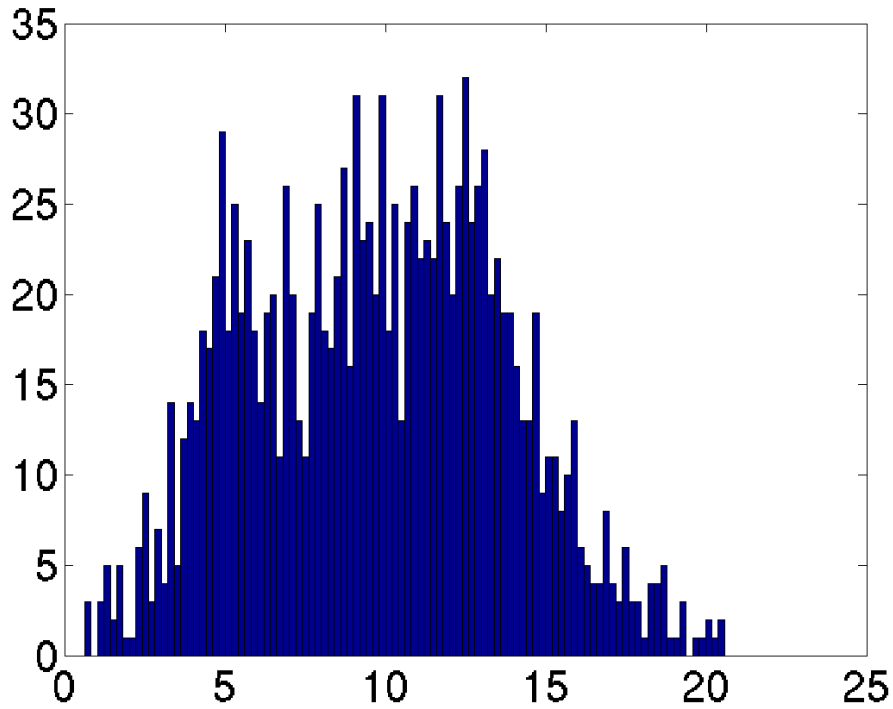


Orientation change in deg

Dipole orientation estimation error



Histogram of the dipole orientation errors

Sensitivity analysis

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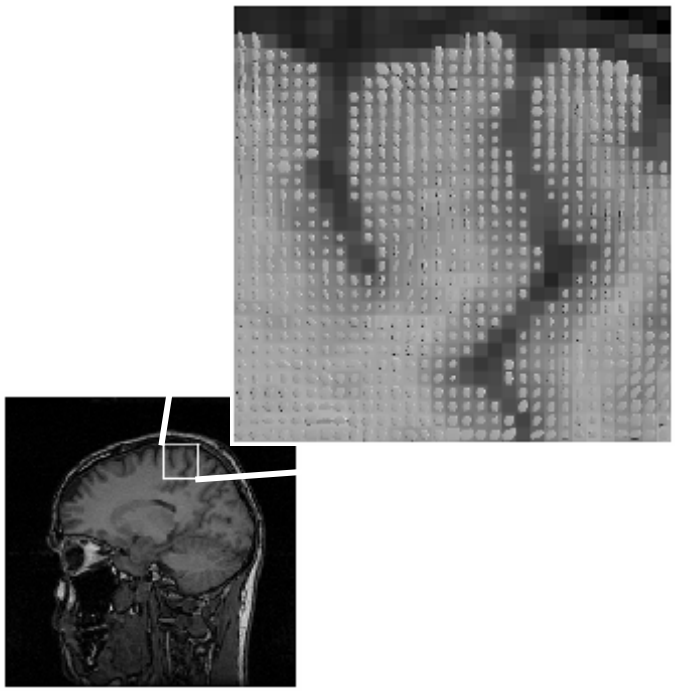
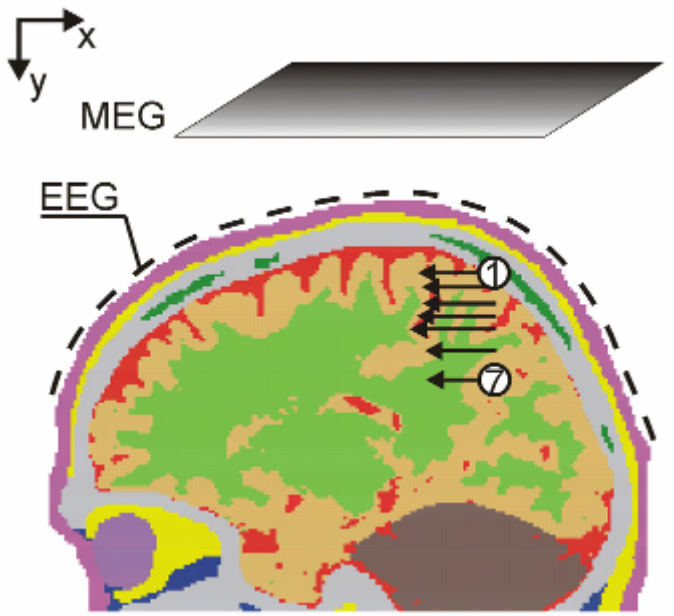
Forward simulations with isotropic and anisotropic human head models





Results:

Correlation:
above 0.98

Magnitude:
more than 50% change

Tissue anisotropy seems to have a minor influence on source localization but a major influence on dipole strength estimation.

Haueisen et al., The influence of brain tissue anisotropy on human EEG and MEG. Neuroimage 15:159-166, 2002

Sensitivity analysis

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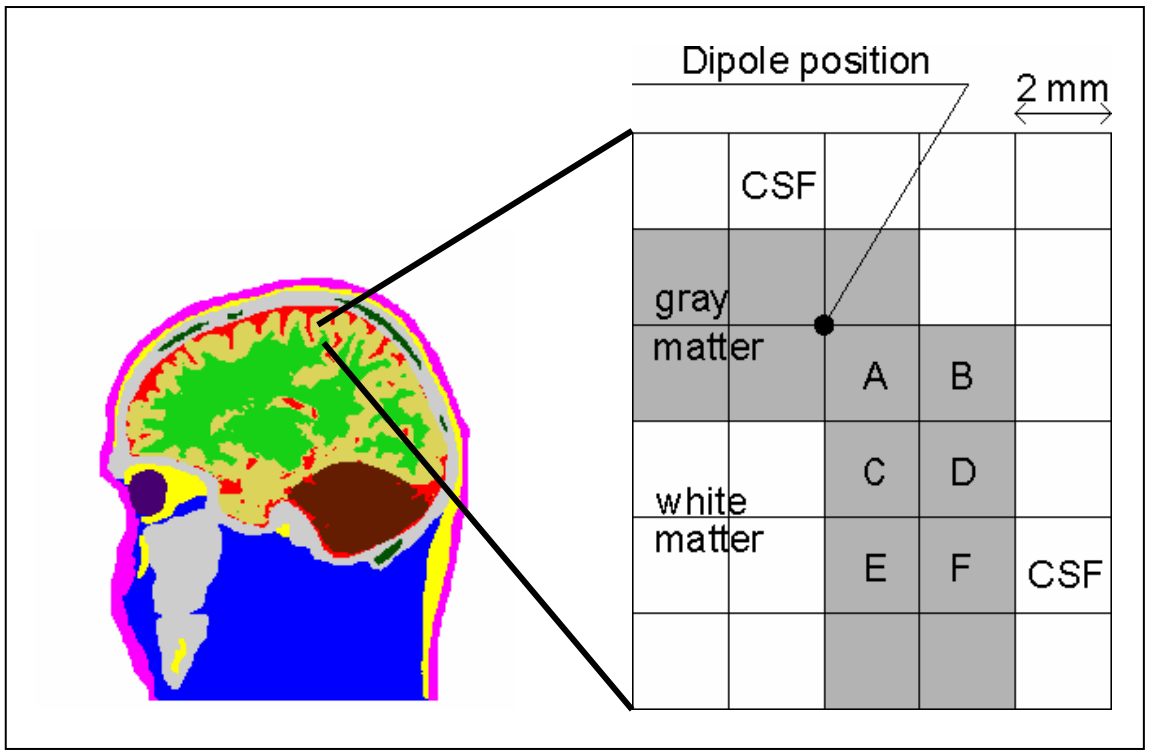
Simulations with conductivity changes of single voxels



Results:

Correlation:

Change in A: 0.98

Change B-F: >0.999

Magnitude:

Change in A: 2 - 60%

Change B-F: < 1%

Conductivity changes in the vicinity of the dipole influence source estimation.

Haueisen et al., The influence of local conductivity changes on MEG and EEG. Biomed. Tech. 45 (7-8), 211 – 214, 2000

Human sensitivity analysis

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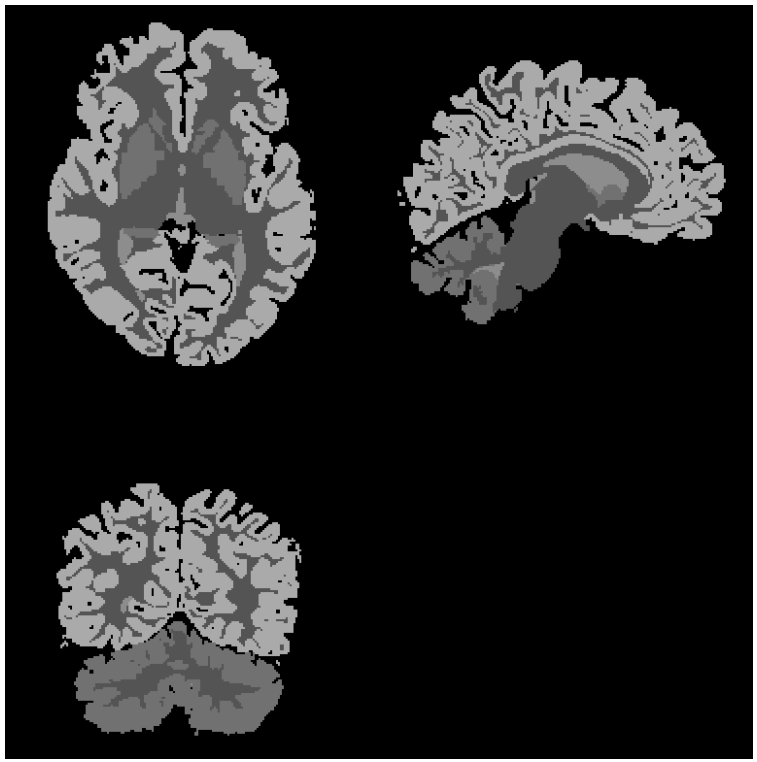

- 5 tissue types
- 3.2 million cubic elements (1mm)
- 130 electrodes
- 25,000 dipoles perpendicular to cortical surface
- anisotropies of 1:2, 1:5, 1:10 and 1:100

Comparison of isotropic and anisotropic model output by RDM and MAG mapped to each dipole position

Human sensitivity analysis

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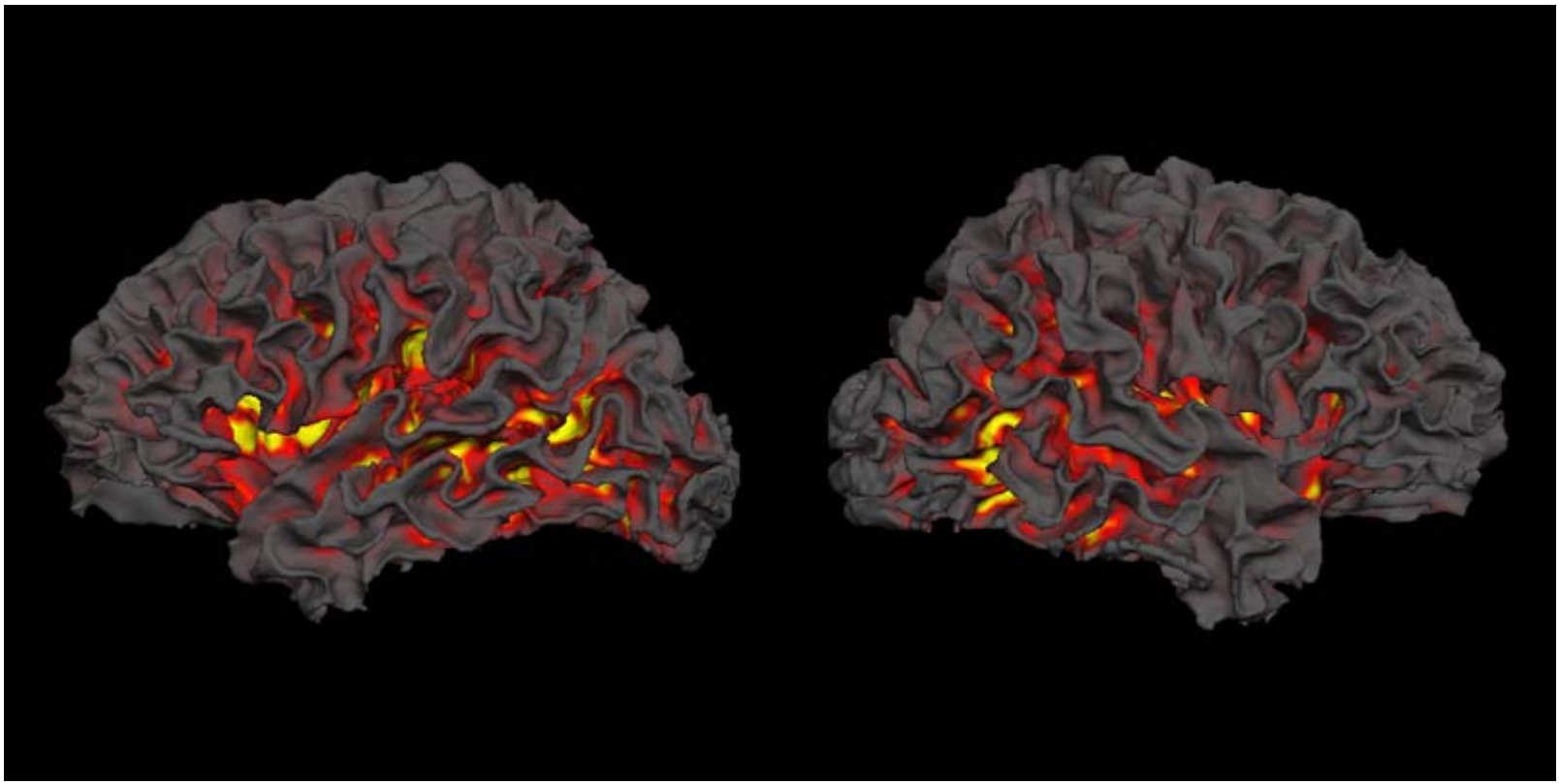

right hemisphere left hemisphere

Relative Difference Measure – outside view

Human sensitivity analysis

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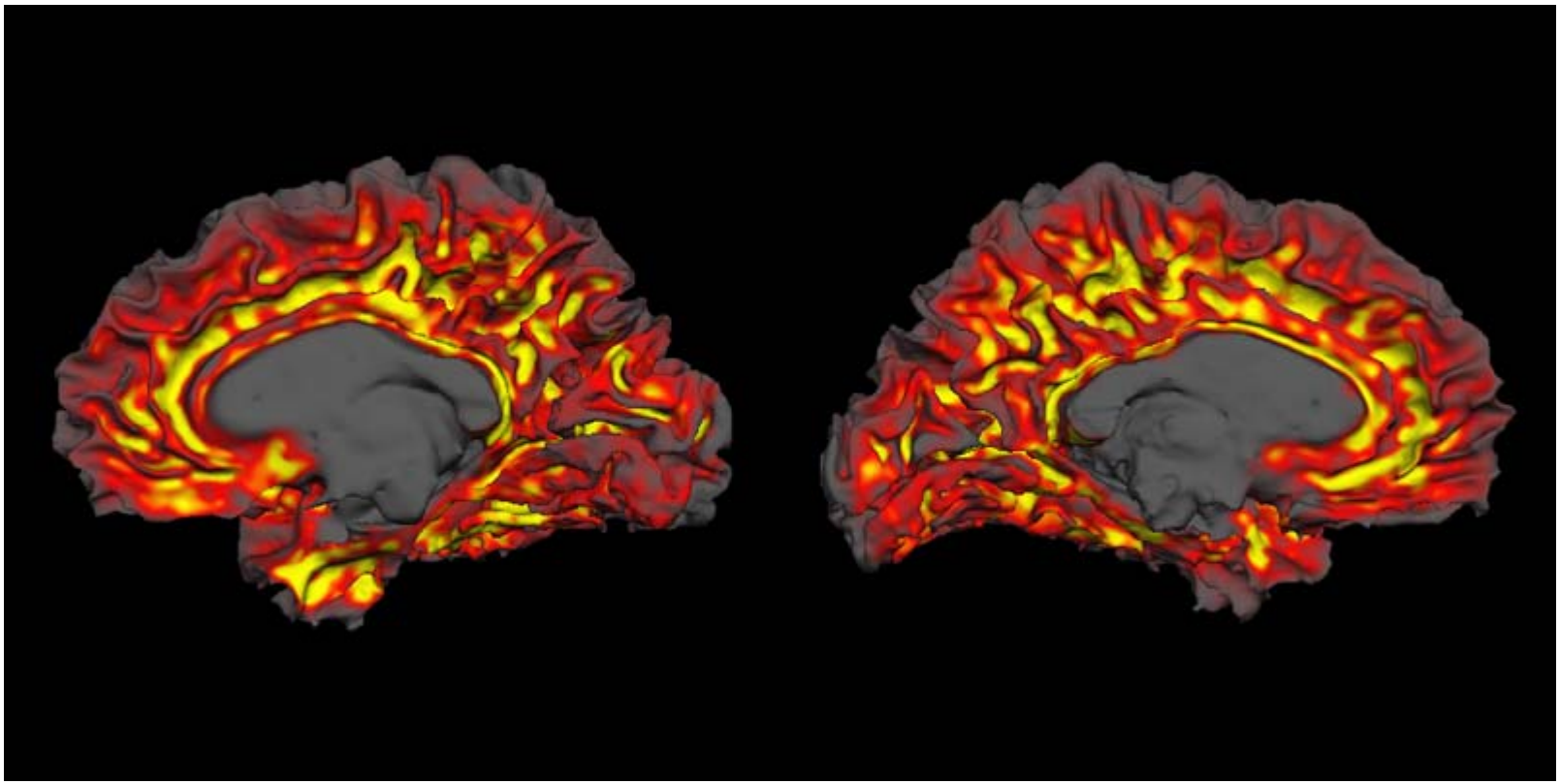

right hemisphere left hemisphere

Relative Difference Measure – inside view

Conclusions

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- Anisotropic volume conduction influences source strength and source orientation estimation more than source location estimation.
- Local conductivity properties in the vicinity of the source crucially influence source estimation.
- Model errors both on a local and a global scale are not Gaussian.