Forward and Inverse EEG Source Modeling

using

NFT – The Neuroelectromagnetic Forward Head Modeling Toolbox

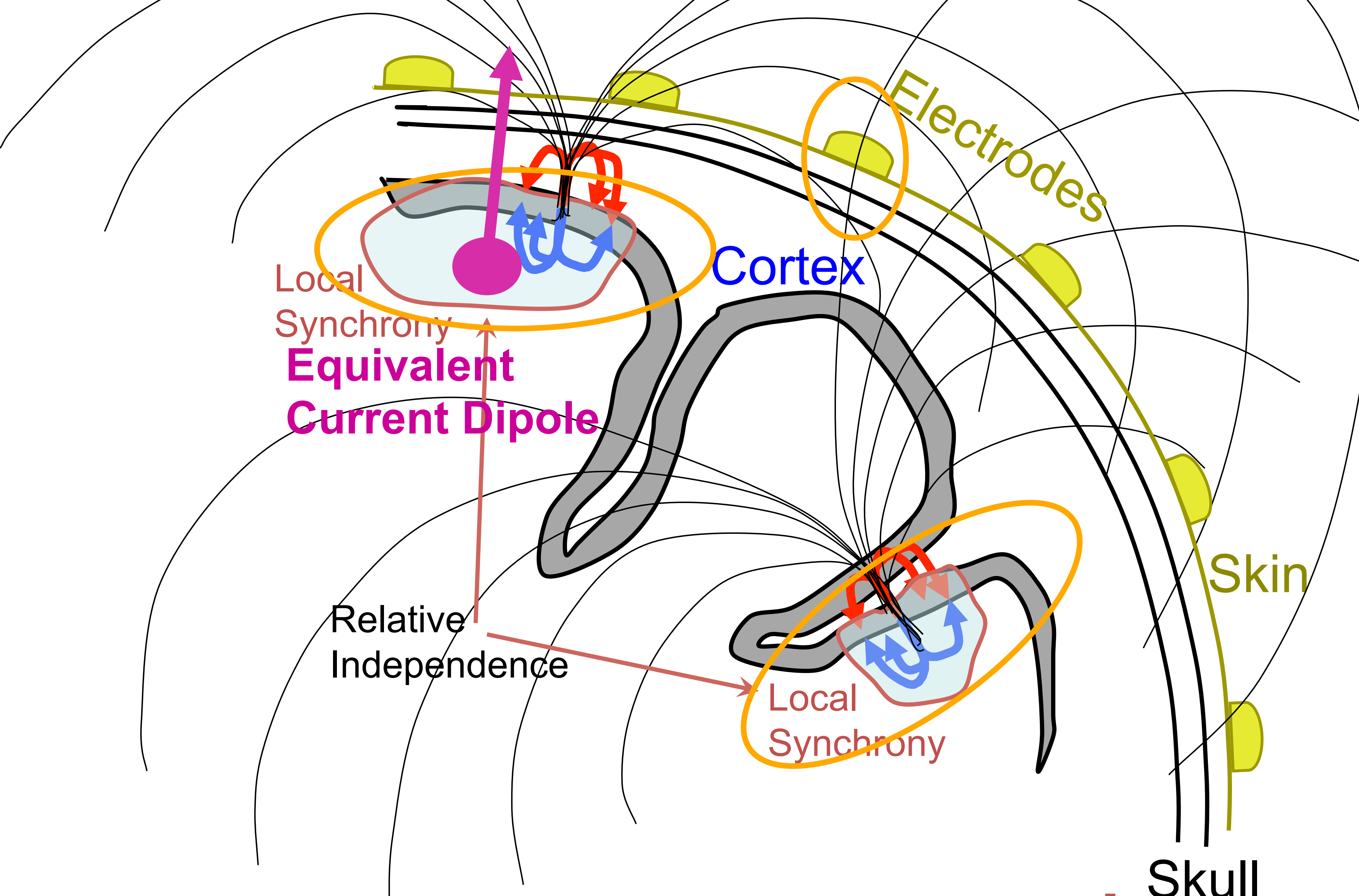
Swartz Center for Computational Neuroscience

Scott Makeig & Zeynep Akalin Acar

Institute for Neural Computation

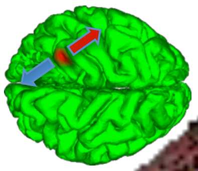
UCSD, La Jolla CA

EEGLAB Workshop, Aspet, France – June, 2013

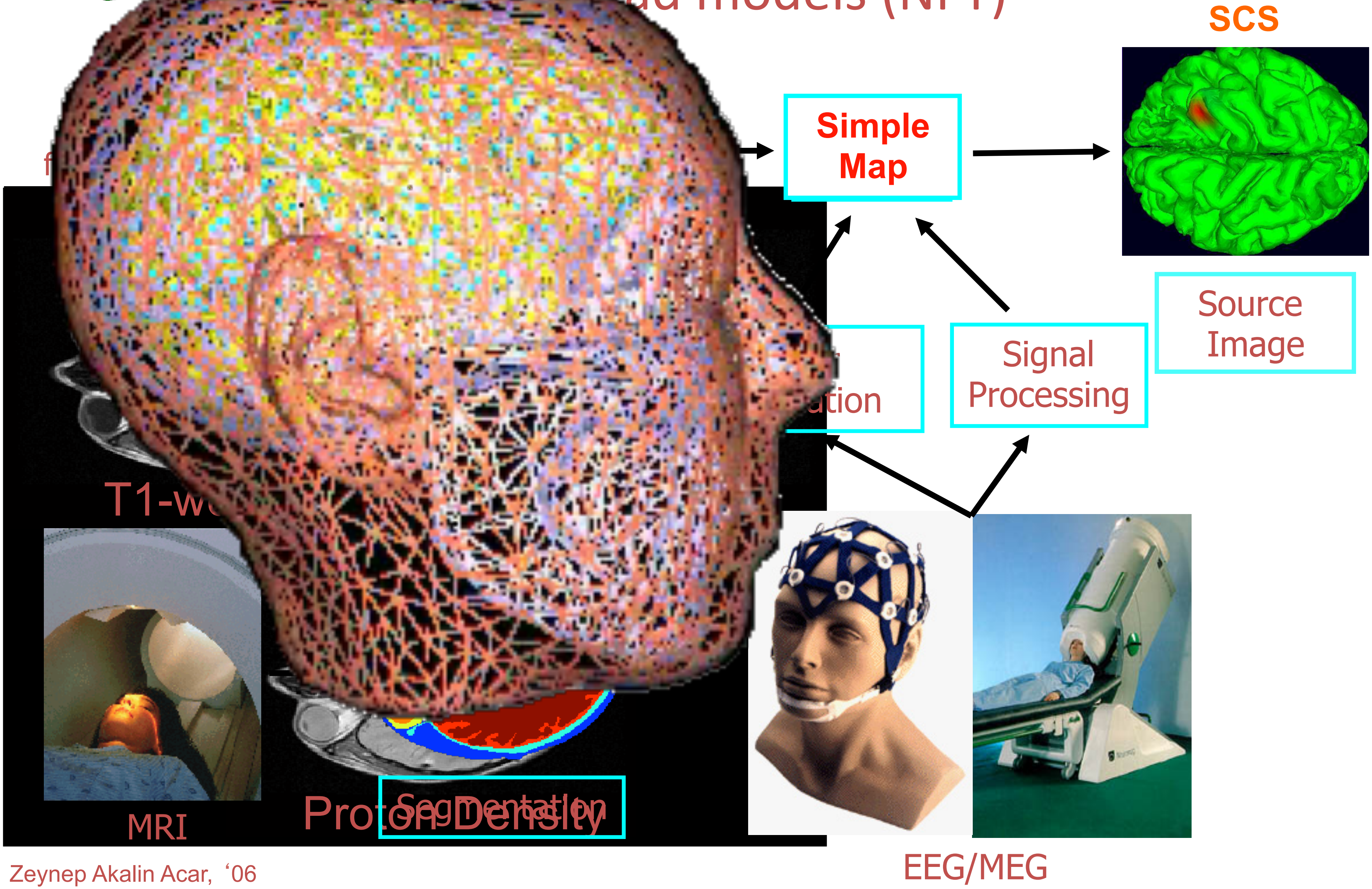


Scalp dynamics ≠ Source dynamics !

S. Makeig 2007



Electromagnetic source localization using realistic ead models (NFT)



Zeynep Akalin Acar, '06

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Neuroelectromagnetic Forward Head Modeling Toolbox☆

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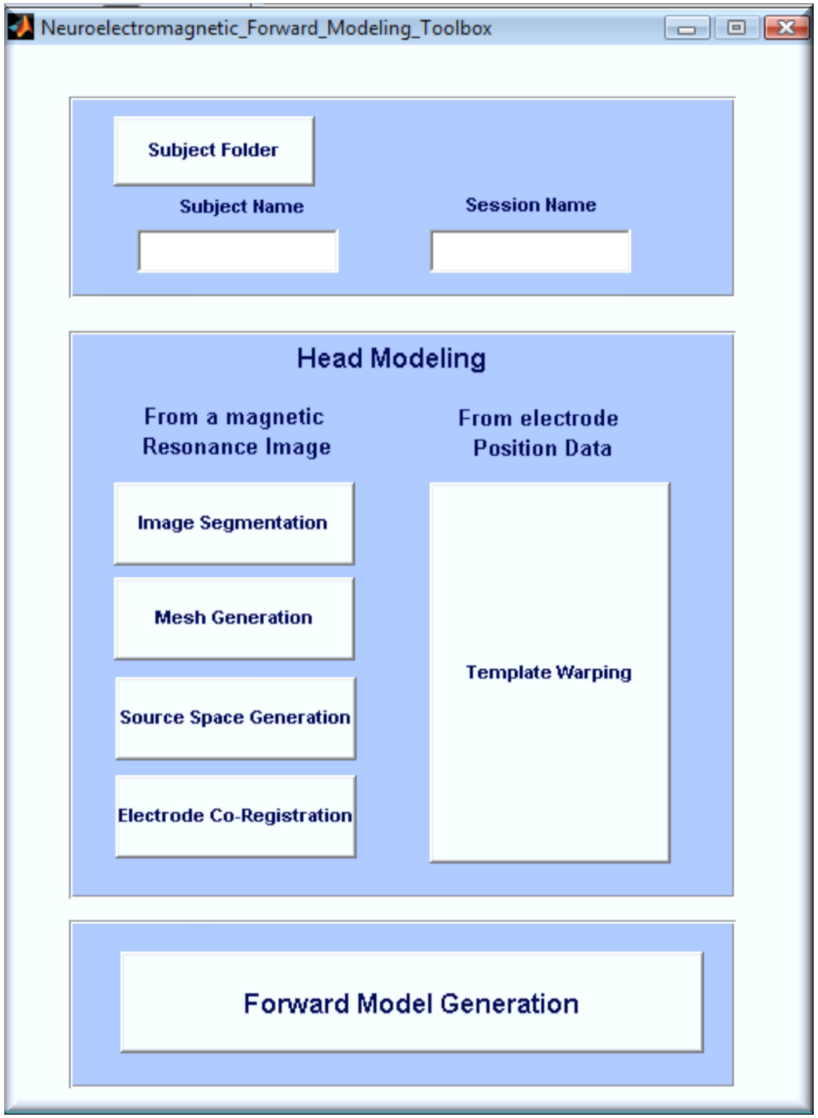
ABSTRACT

This paper introduces a Neuroelectromagnetic Forward Head Modeling Toolbox (NFT) running under MATLAB (The Mathworks, Inc.) for generating realistic head models from available data (MRI and/or electrode locations) and for computing numerical solutions for the forward problem of electromagnetic source imaging. The NFT includes tools for segmenting scalp, skull, cerebrospinal fluid (CSF) and brain tissues from T1-weighted magnetic resonance (MR) images. The Boundary Element Method (BEM) is used for the numerical solution of the forward problem. After extracting segmented tissue volumes, surface

NFT: Introduction

- ***A MATLAB toolbox for realistic head modeling and forward problem solving.***
- **Can use available subject information:**
  - T1-weighted 3-D MR images ***and/or***
  - Digitized sensor (electrode) locations
- **Implements all head modeling steps:**
  - Segmentation of MR images
  - Mesh generation
  - Warping a template head model to the sensor positions
  - Sensor/head image co-registration
  - Lead field matrix: Source space → Sensors

NFT Main Menu

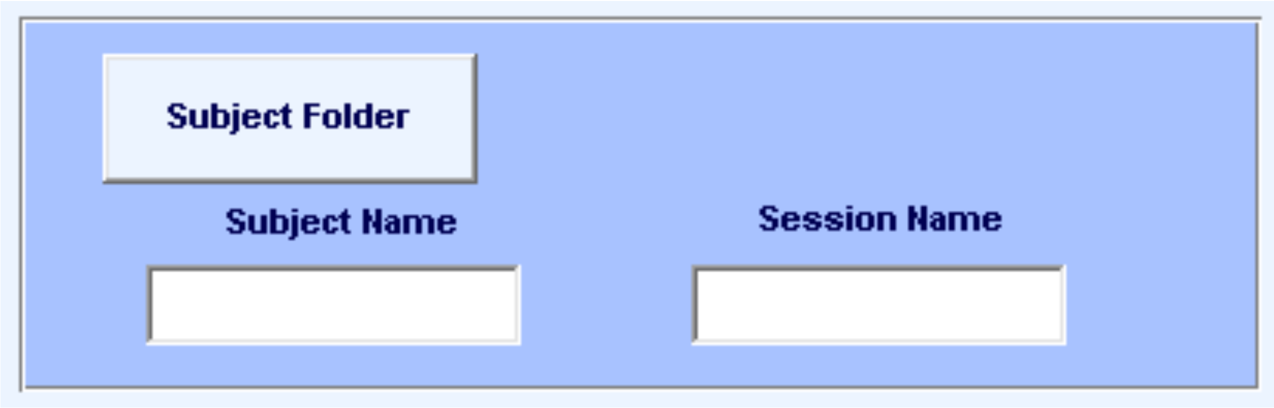


Subject Selection

Head Modeling

Forward Modeling

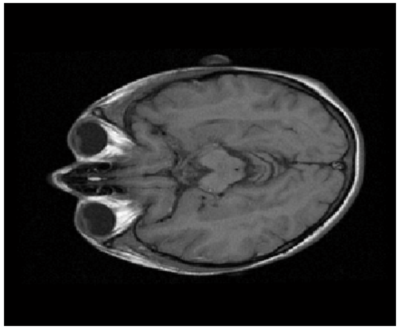
Subject Selection



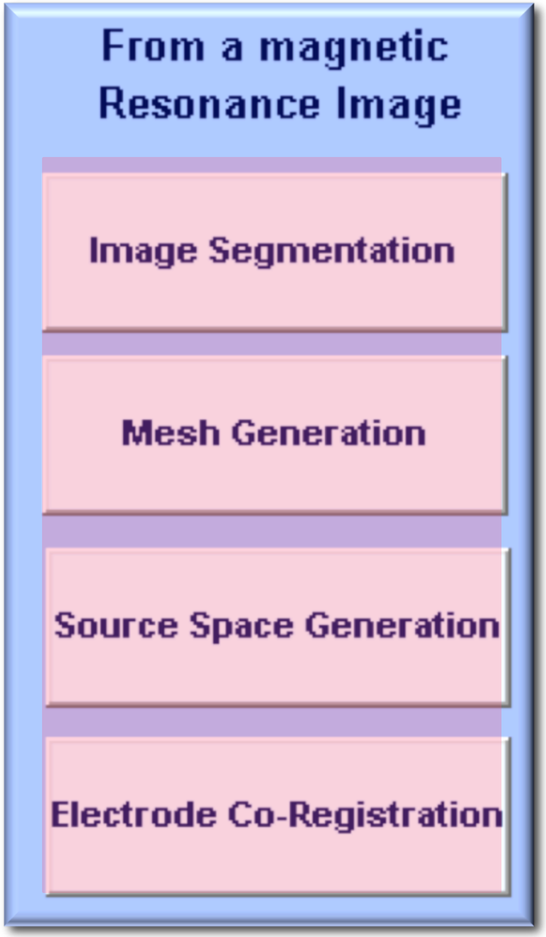
- Select subject folder name
- Specify subject code
- Specify session name

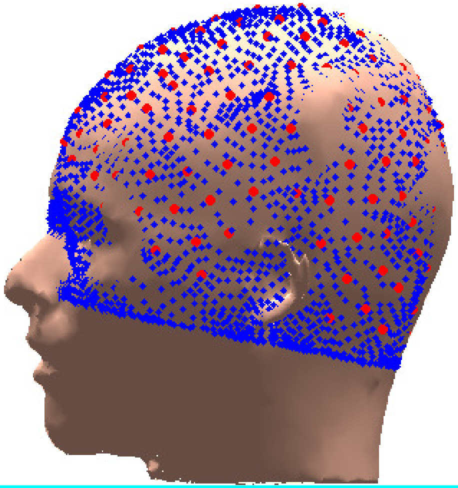
Head modeling from an MR head image

MR image

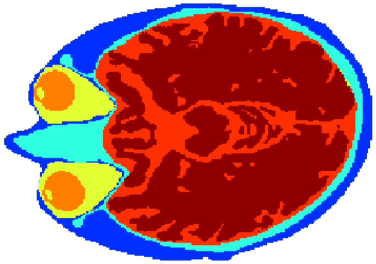


T1-weighted

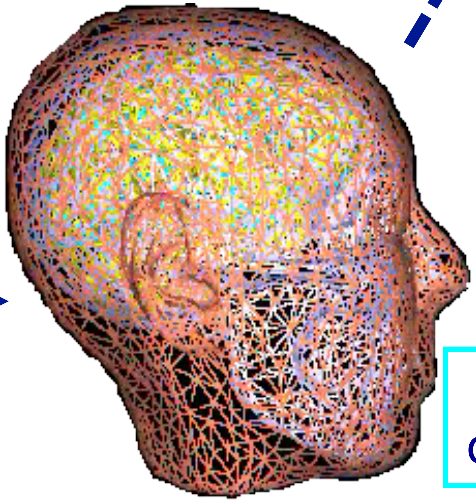




Electrode Registration



Tissue Segmentation



BEM mesh construction

Preparing the MR image for segmentation

Use FREESURFER to

- Perform inhomogeneity correction
- Convert to 1x1x1 pixels
- Arrange direction of the image
- Save in Analyze format

Image Segmentation

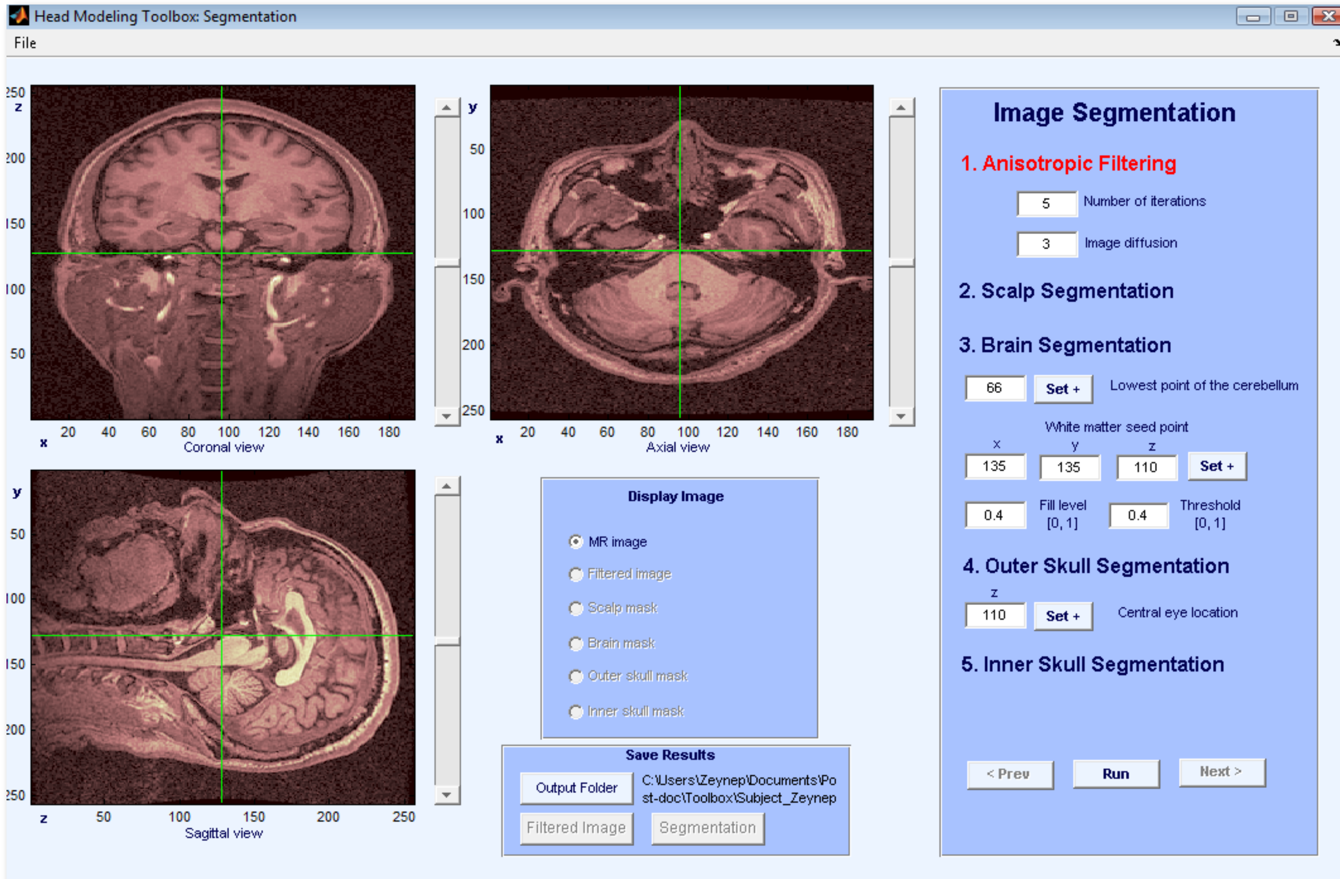
From a magnetic Resonance Image

Image Segmentation

Mesh Generation

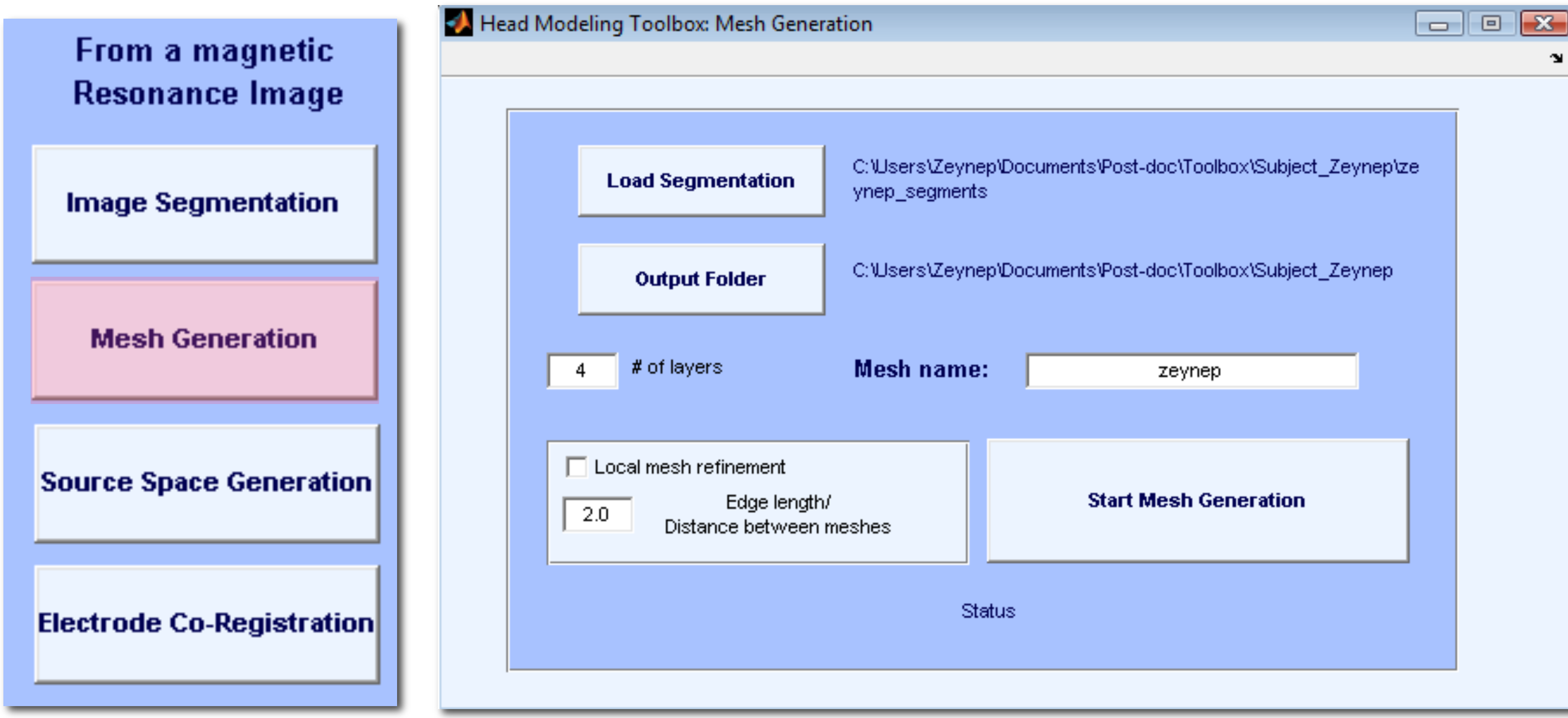
Source Space Generation

Electrode Co-Registration



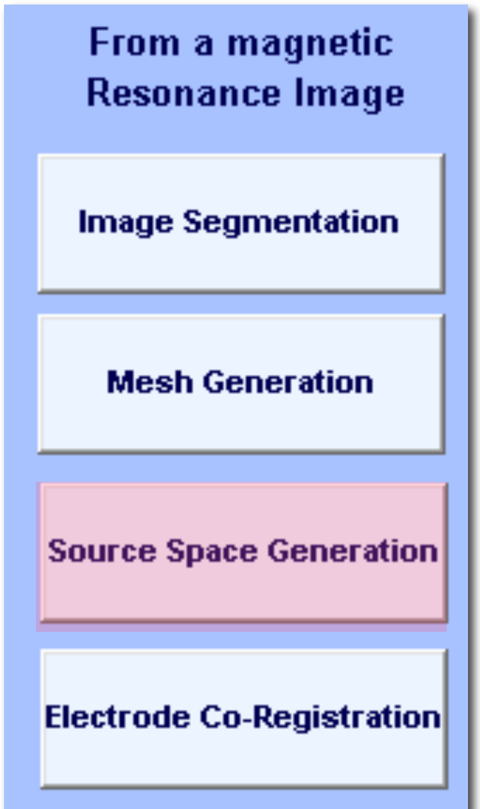
- Interface for Segmenting the MR image

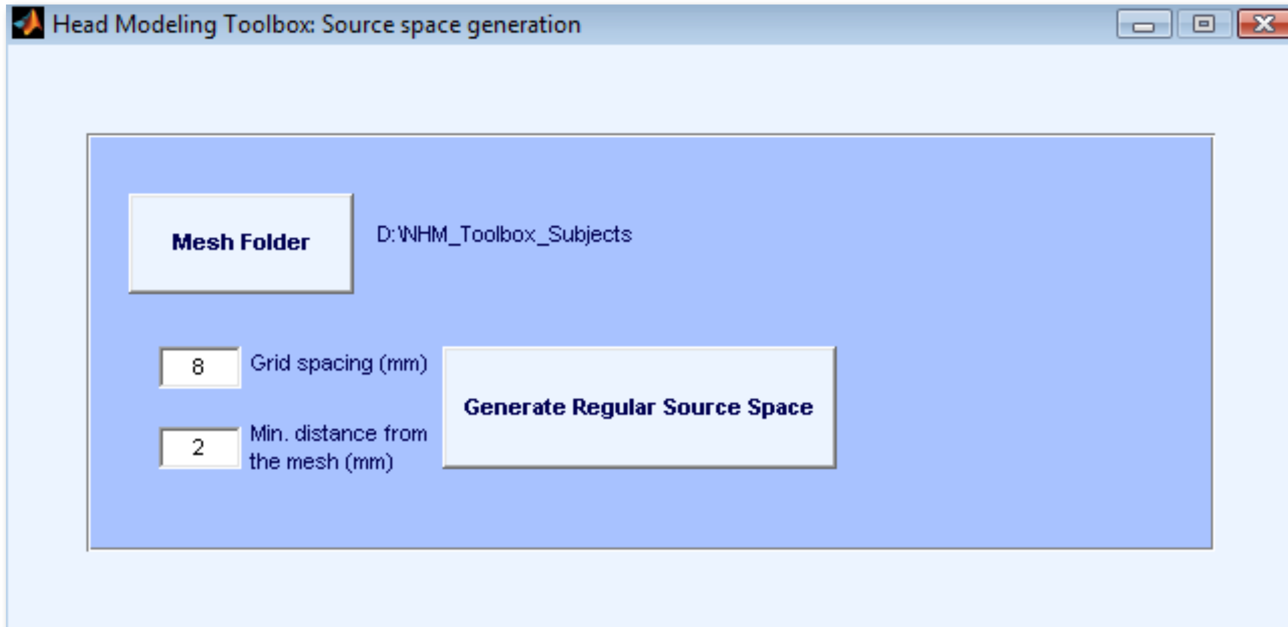
Mesh Generation



- Generate a mesh for a 3- or 4-layer BEM head model
  - (triangulation, correction, coarsening, refinement)

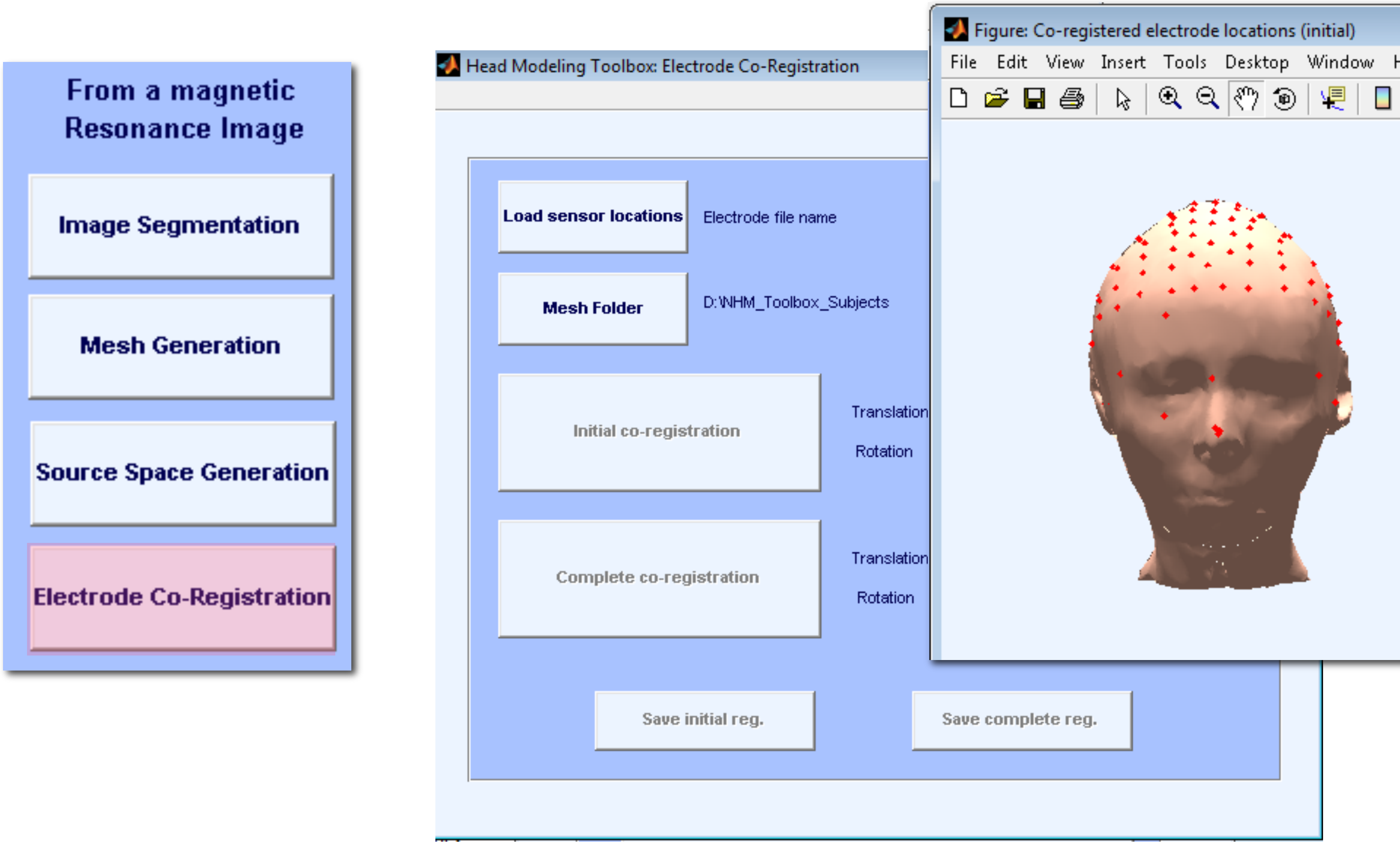
Source Space Generation



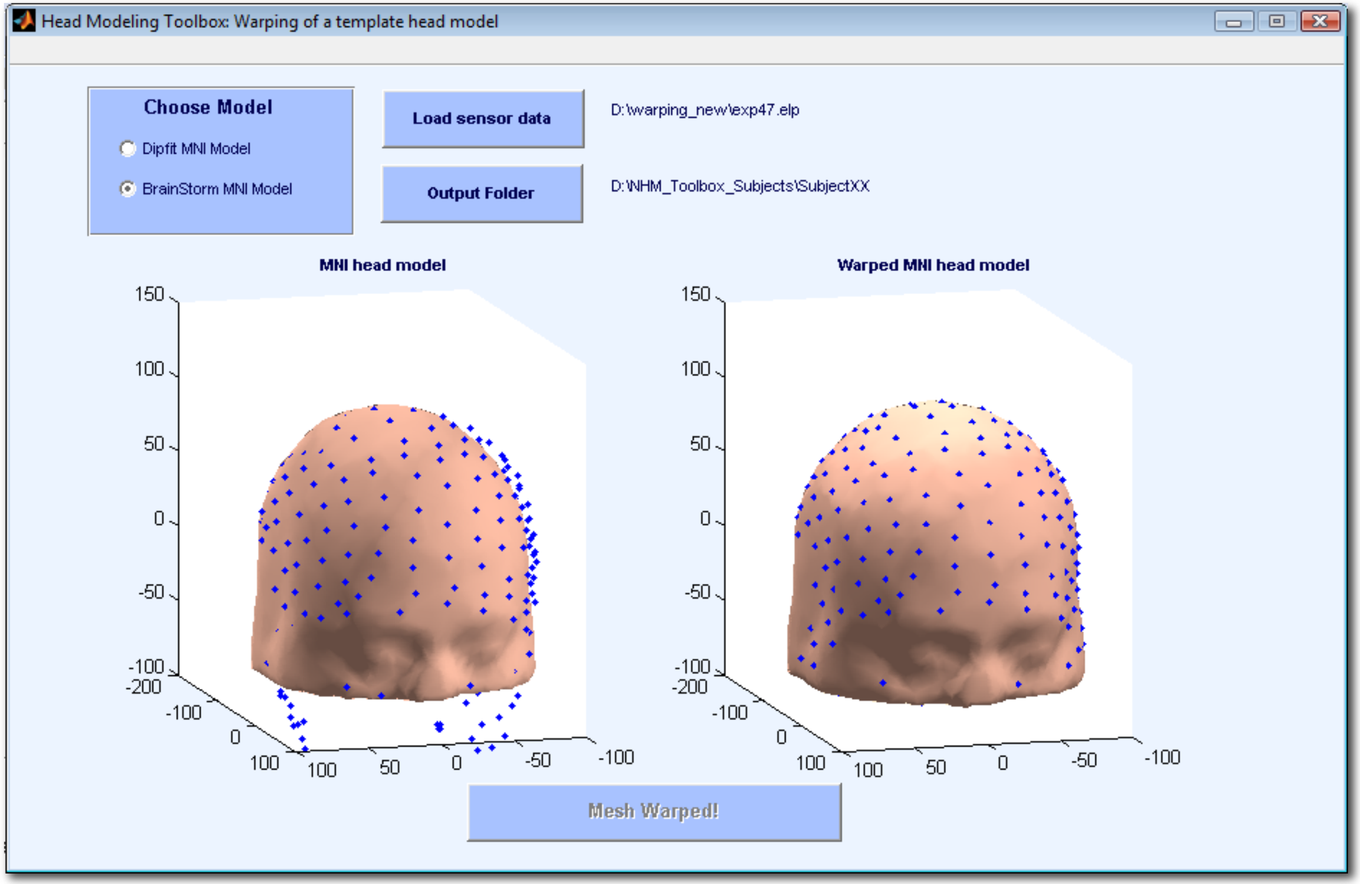


- Here, generate a simple source space:
  - A regular grid within the brain space
    - with a given spacing & min. dist. to the mesh

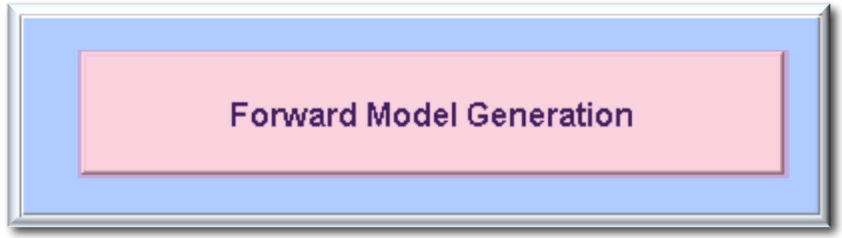
Electrode Co-Registration



Electrode Position-Based Template Head Warping



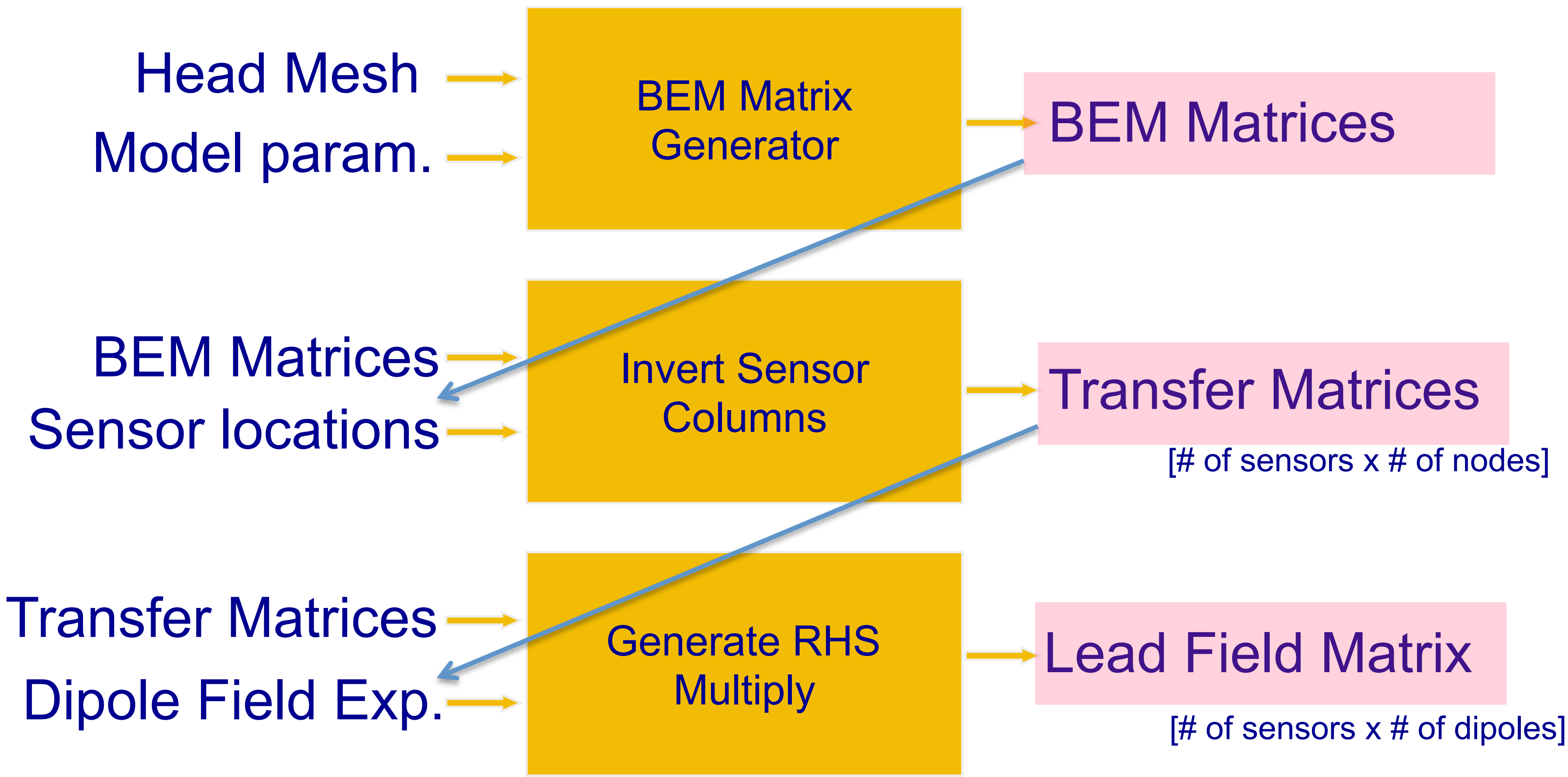
Forward Model Generation



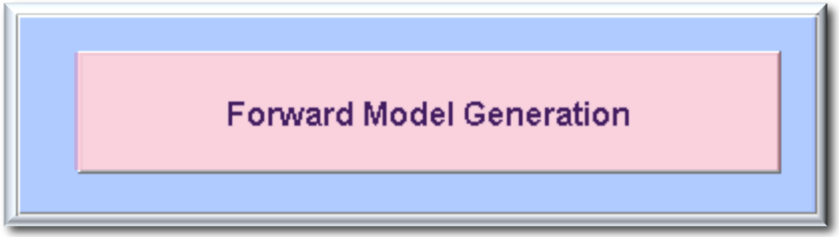
- Generates the Forward Model from meshes
  - BEM or FEM

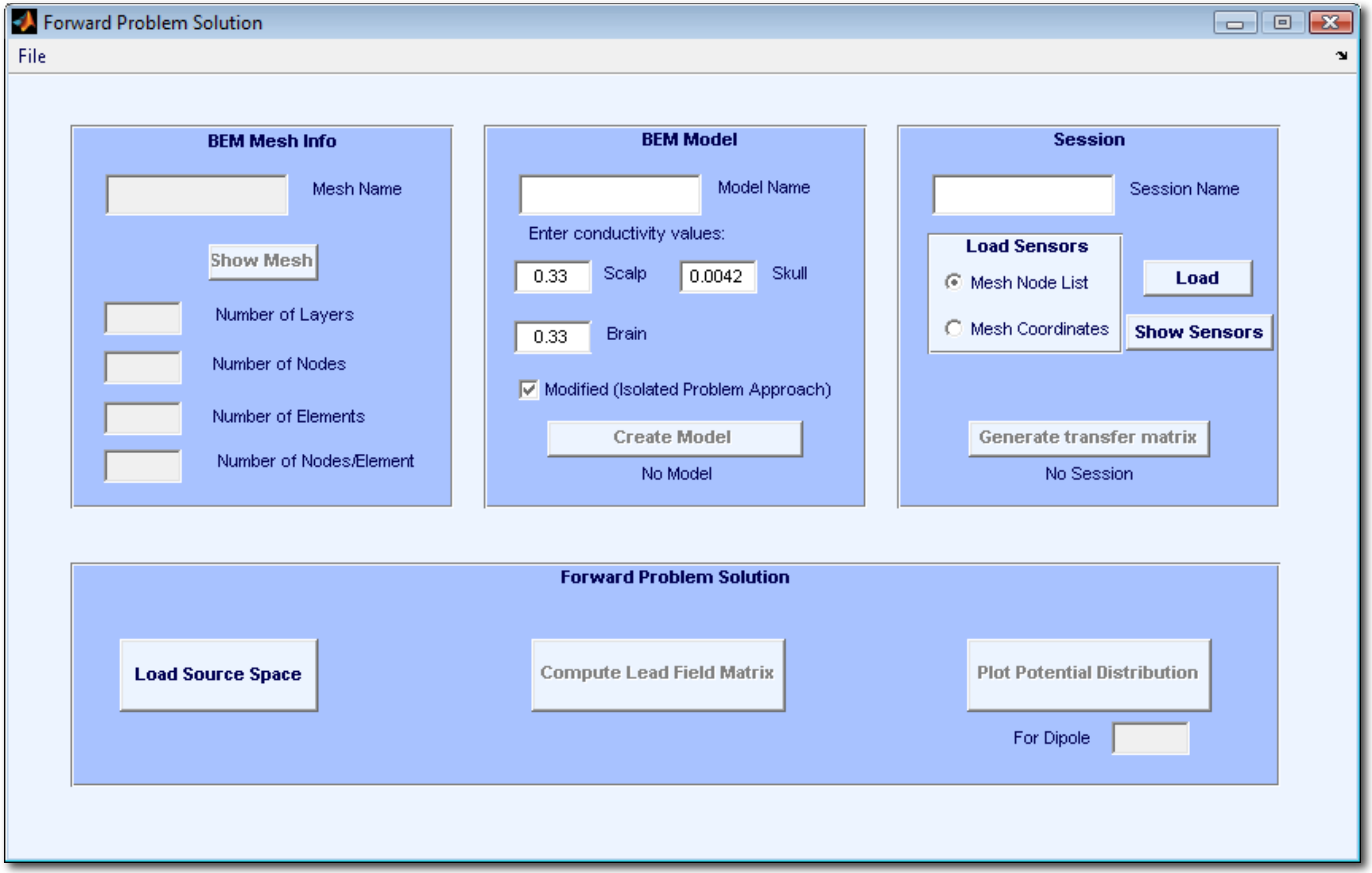
- Generates three structures:
  - Mesh
  - Model (Mesh + Electrical Properties)
  - Session (Model + Sensors)

Forward Problem Solution

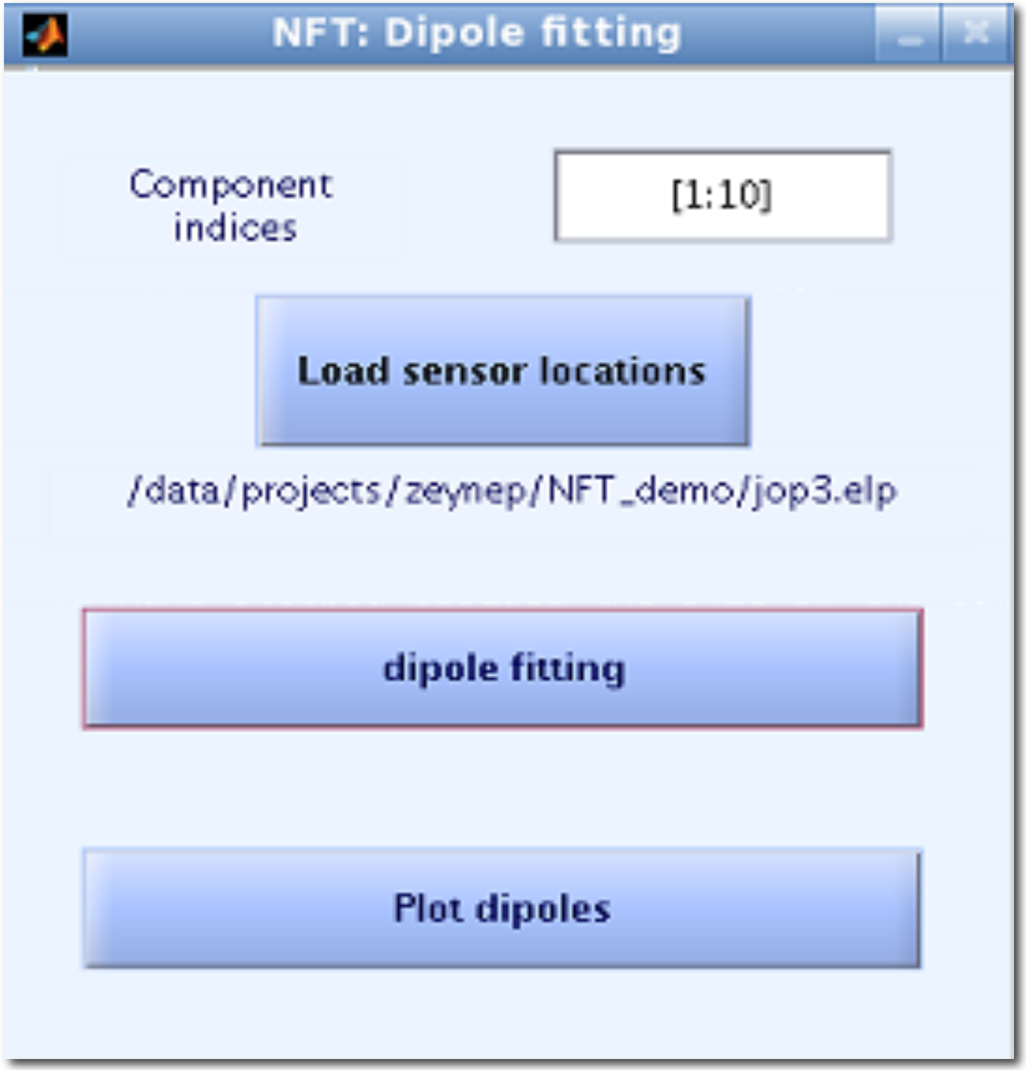


Forward Problem Solution

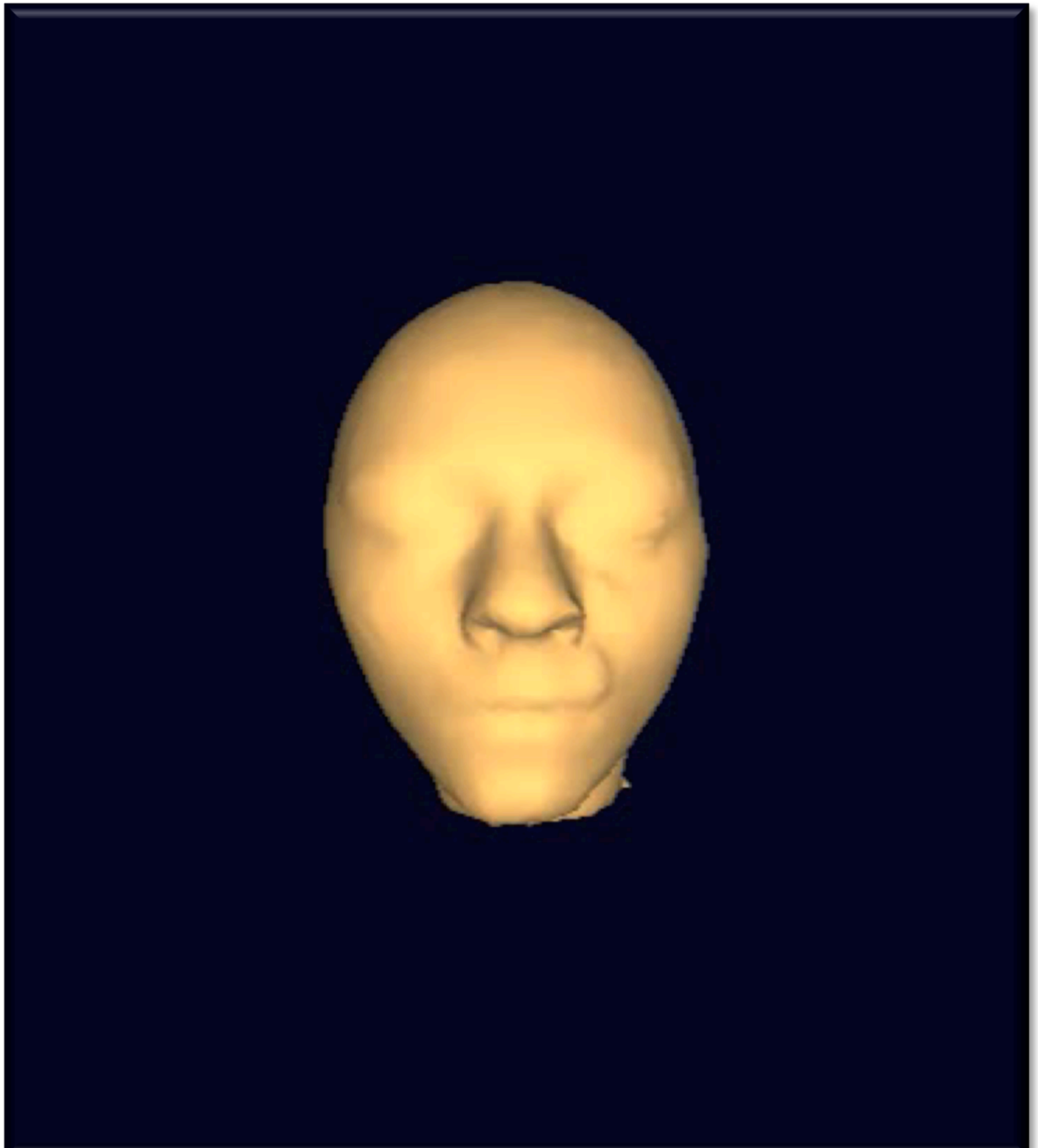




Solving inverse problems → NIST



A Four-Layer BEM Head Model



Neuroelectromagnetic
Forward head modeling
Toolbox (**NFT**)

# of elements

Scalp:	6,900
Skull:	6,800
CSF:	9,000
Brain:	8,800
Total	31,500

Z. Akalin Acar, 2010

Source localization error comparisons

BEM Head Models:

- **4-layer MR-based realistic BEM head model**
- 3-layer MR-based realistic BEM head model
- MNI template head model
- Electrode-warped MNI template head model
- Spherical BEM head model

Brain Topogr
DOI 10.1007/s10548-012-0274-6

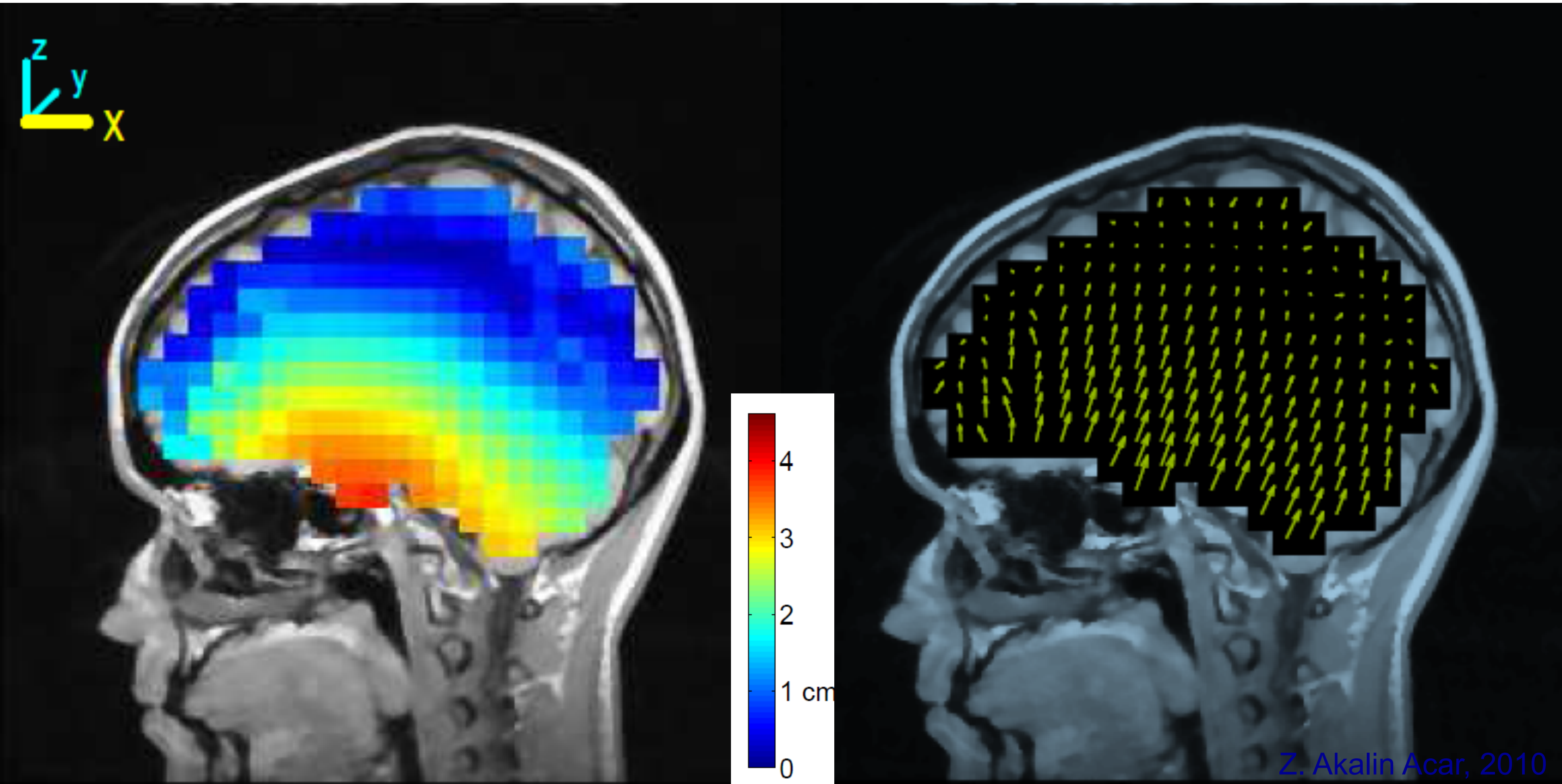
ORIGINAL PAPER

Effects of Forward Model Errors on EEG Source Localization

Zeynep Akalin Acar · Scott Makeig

Source Localization Error

- Using a simple **3-layer spherical** head model
- Instead of a good 4-layer **realistic BEM** head model…



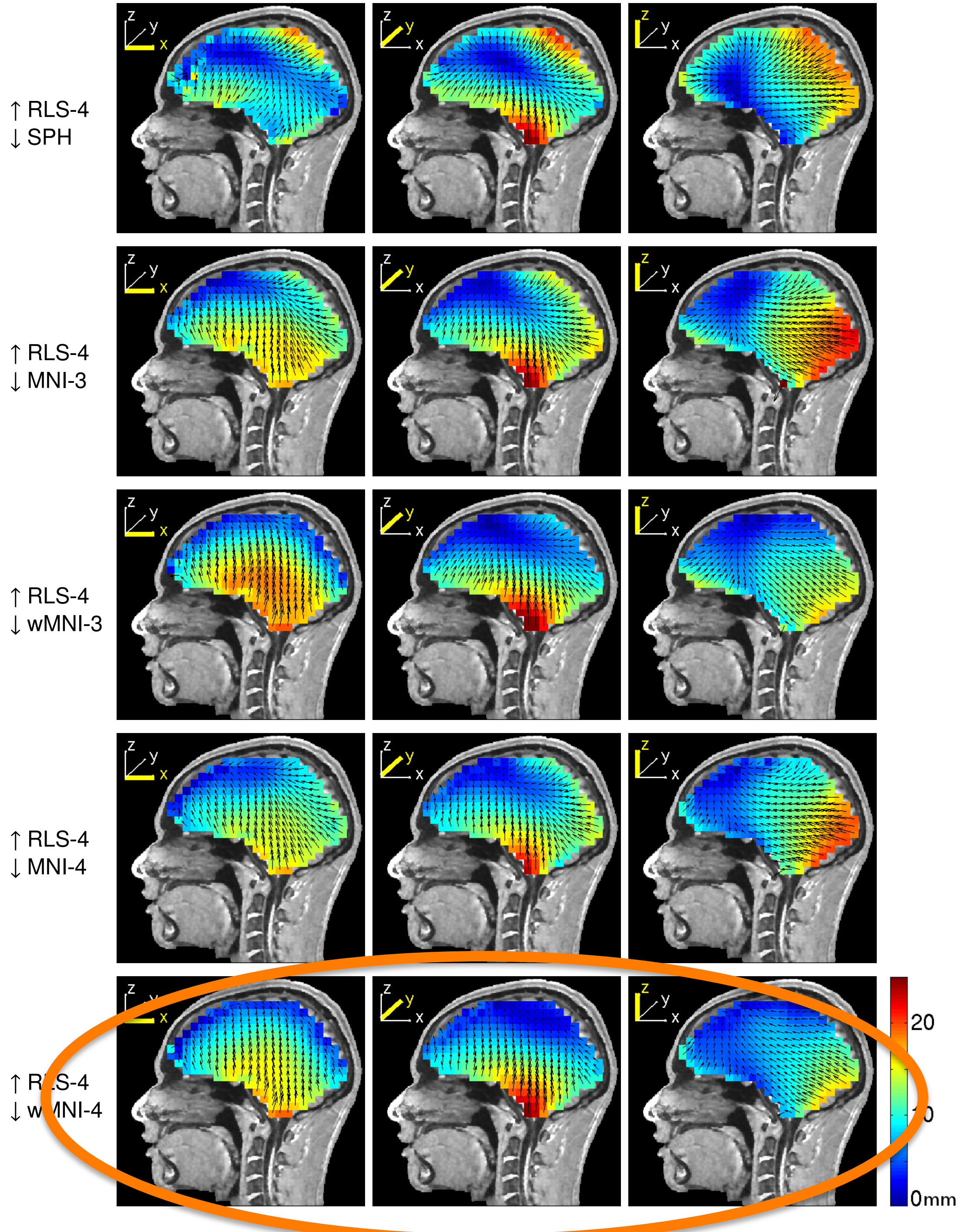


Fig. 4
Subject S1

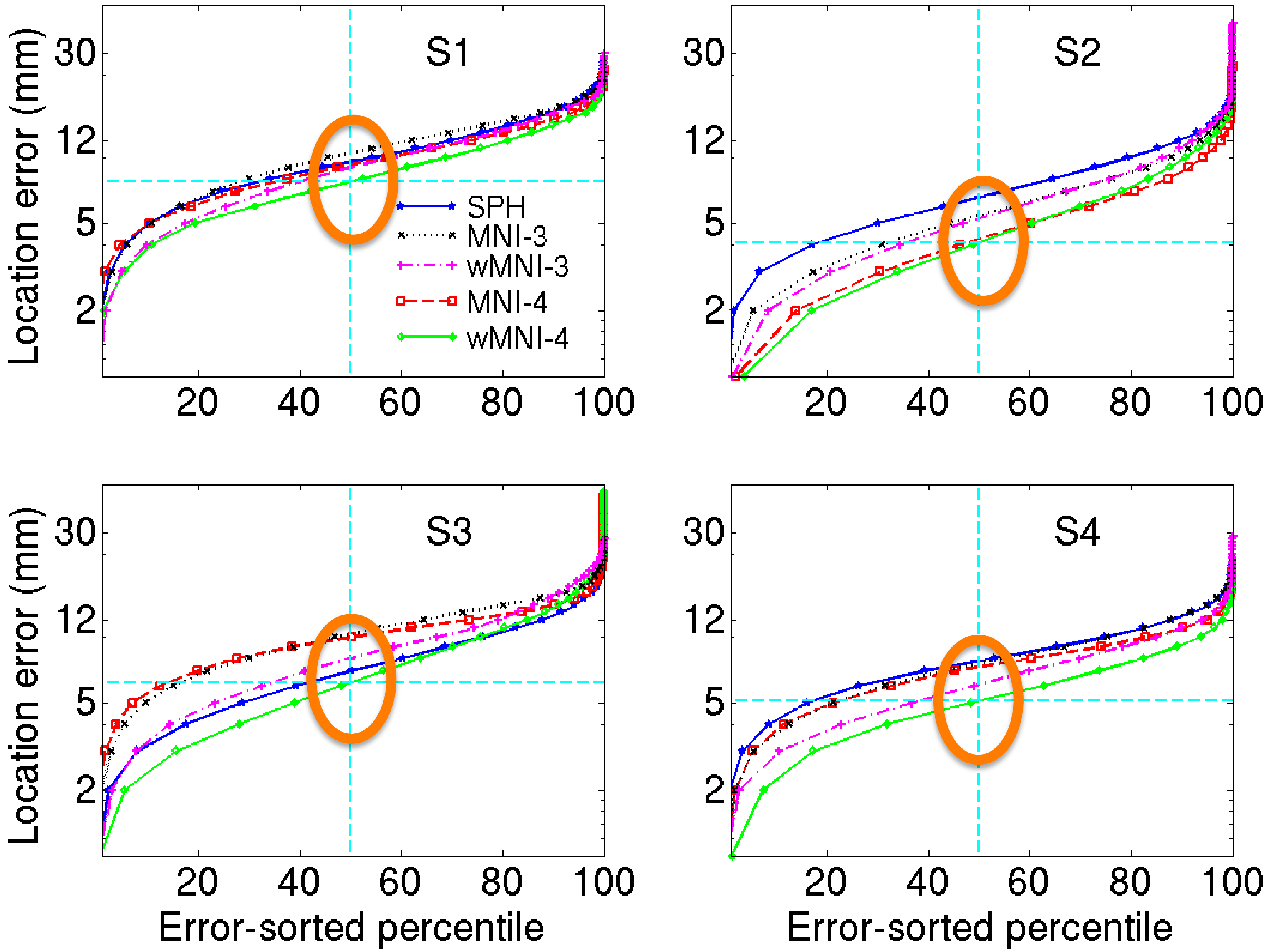
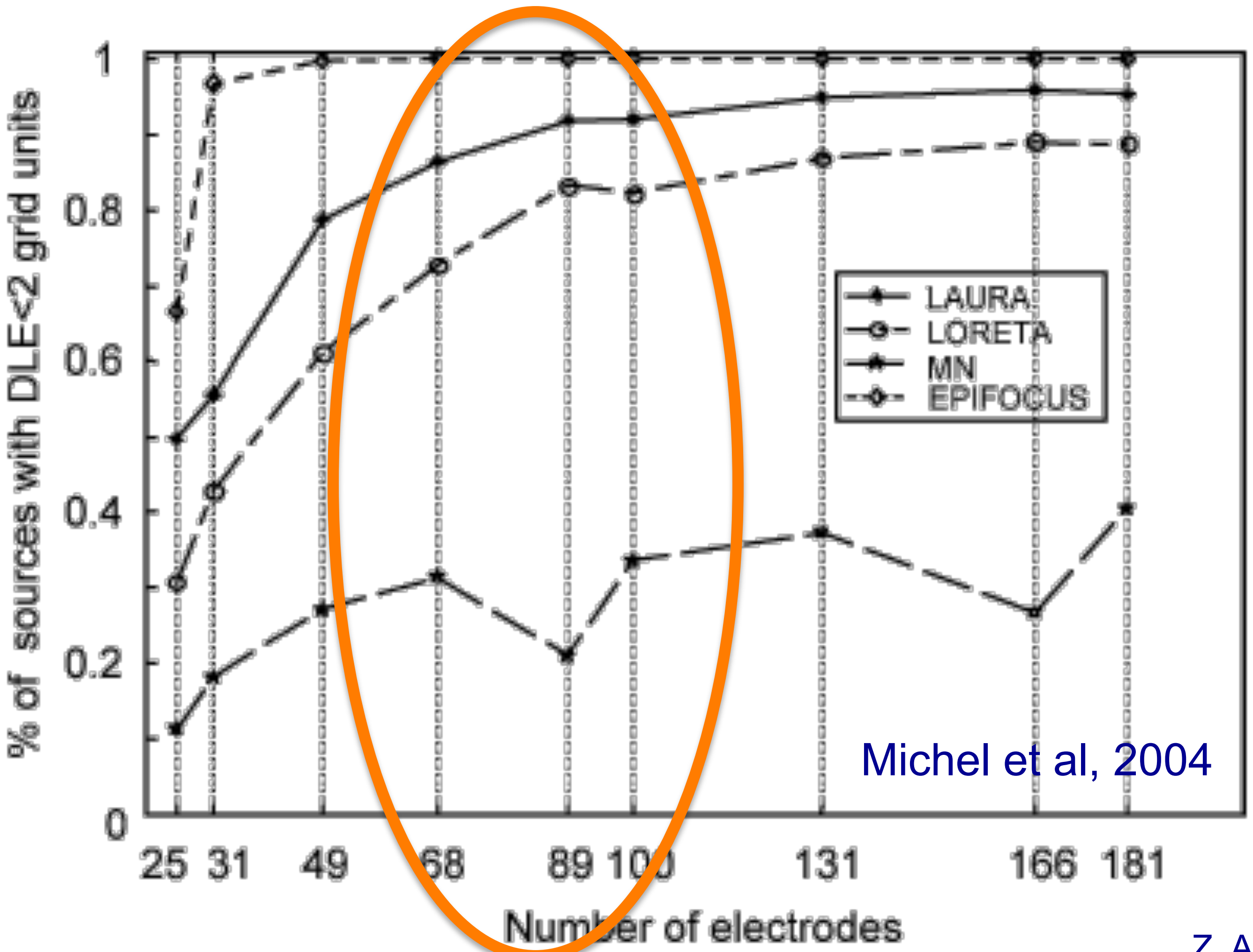

S1
S2
S3
S4
SPH
MNI-3
wMNI-3
MNI-4
wMNI-4
Location error (mm)
Error-sorted percentile
30
12
5
2
20
40
60
80
100

Fig. 7

Effect of Number of Electrodes

- Single dipole source
- 3-layer spherical head model
- 1152 solution points



Z. Akalin Acar, 2010

Effect of Number of Electrodes

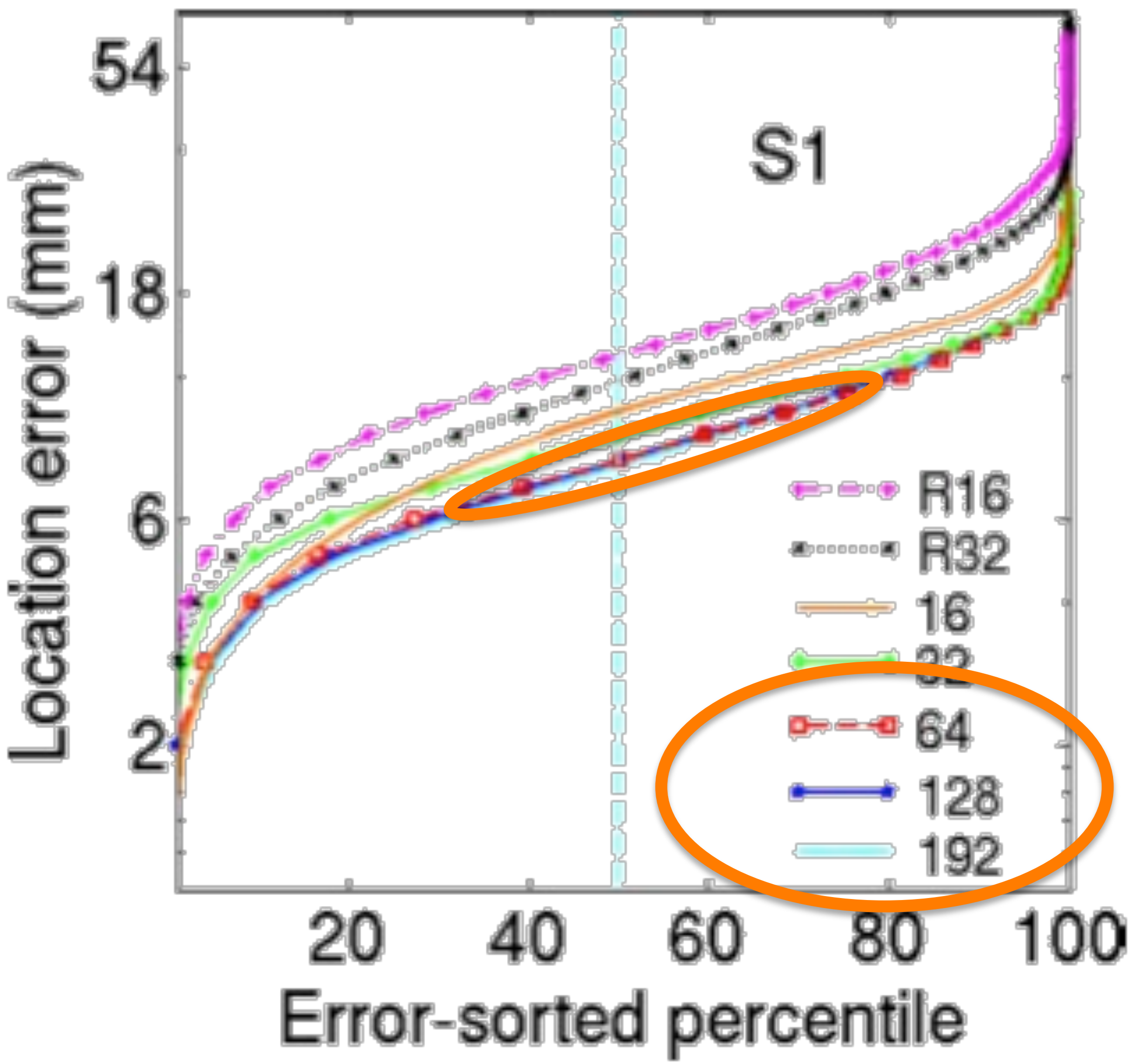


Fig. 16
Channel number

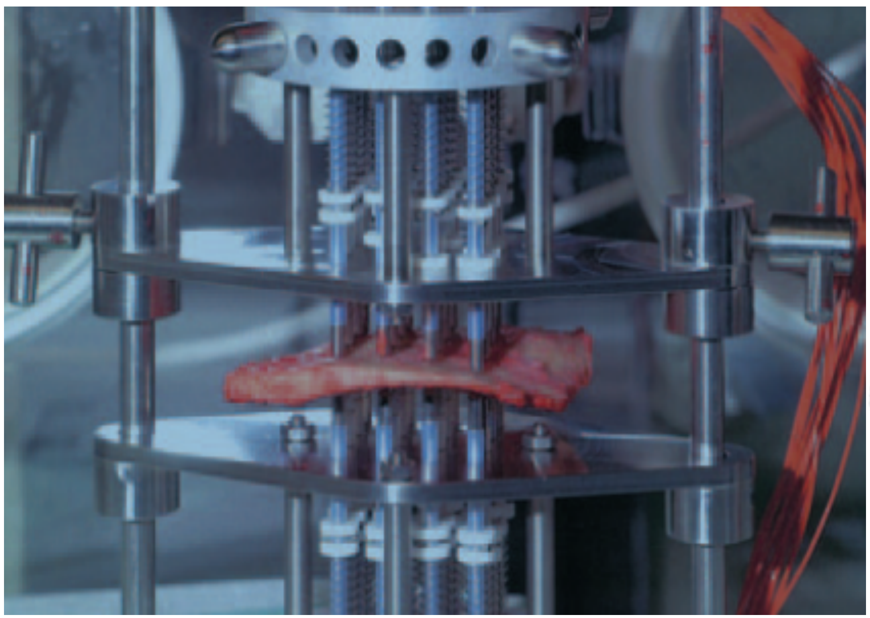
Effects of Skull Conductivity Estimation

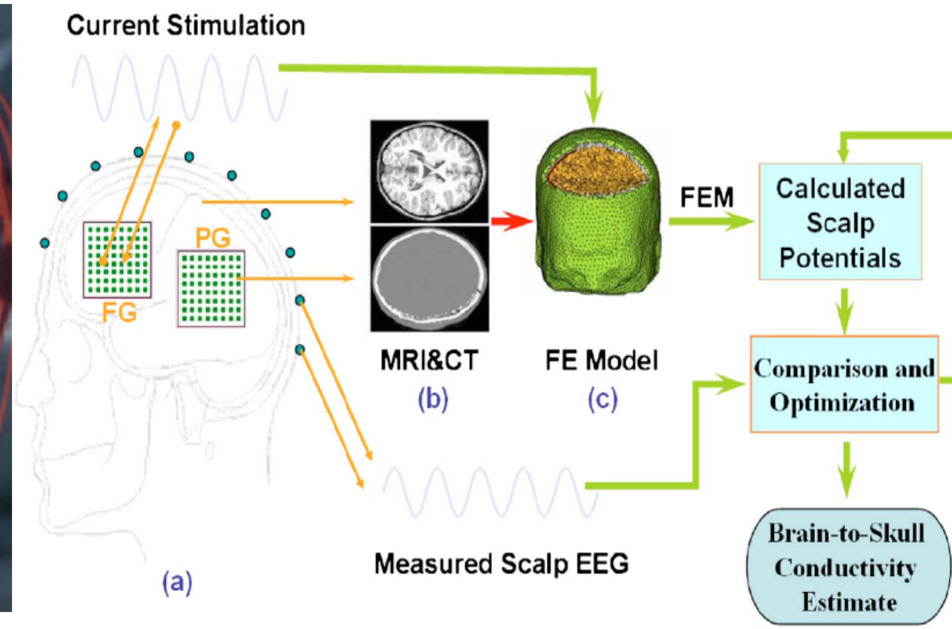
Measurements of skull conductivity:

- MR-EIT
- Magnetic stimulation
- Current injection

In vivo

In vitro





Hoekama et al, 2003

He et al, 2005

Z. Akalin Acar, 2010

Skull Conductivity Measurements

Brain to skull ratio		
Rush and Driscoll	1968	80
Cohen and Cuffin	1983	80
Oostendorp et al	2000	15
Lai et al	2005	25

Measurement	Age	σ (mS/m)	Sd (mS/m)
Agar-agar phantom	–	43.6	3.1
Patient 1	11	80.1	5.5
Patient 2	25	71.2	8.3
Patient 3	36	53.7	4.3
Patient 4	46	34.4	2.3
Patient 5	50	32.0	4.5
Post mortem skull	68	21.4	1.3

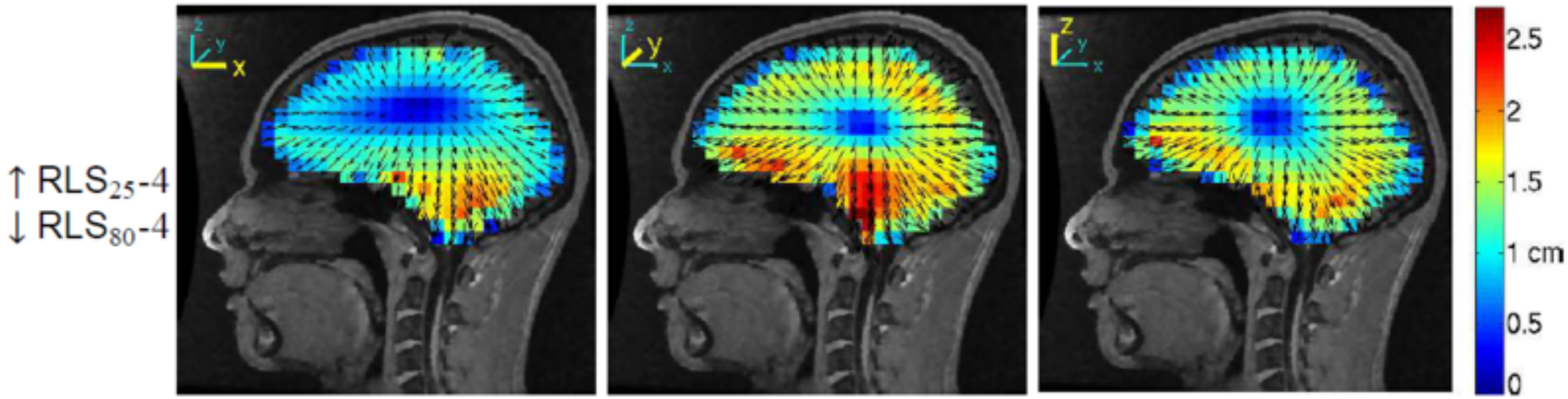
Skull conductivity by age

Hoekama et al, 2003

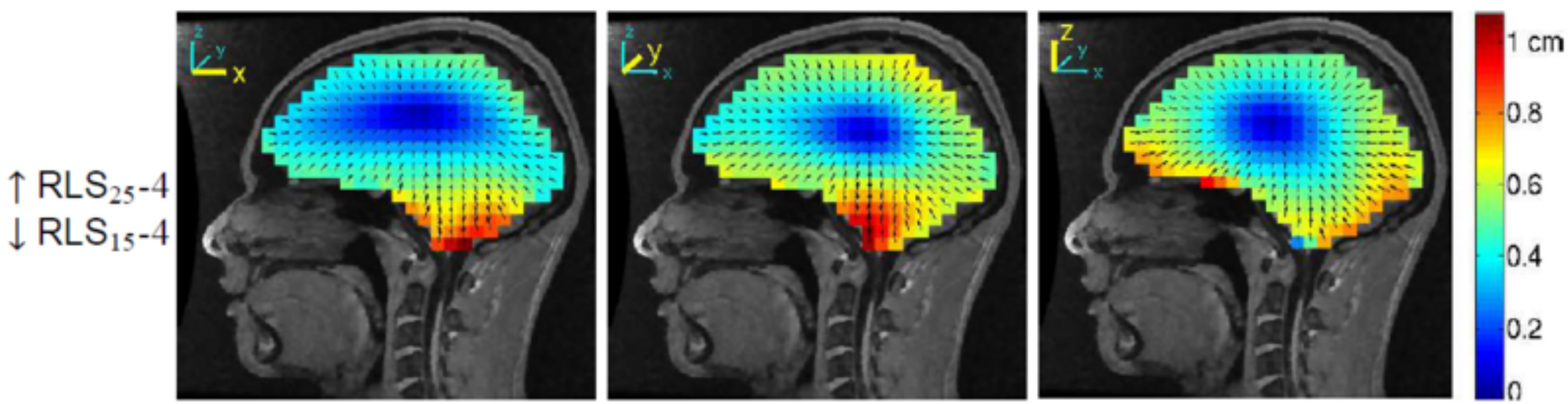
Z. Akalin Acar, 2010

Source Localization Errors

- Forward model (individual BEM) – brain/skull cond. 25
- Inverse model (individual BEM) – brain/skull cond. 80



- Forward model (individual BEM) – brain/skull cond. 25
- Inverse model (individual BEM) – brain/skull cond. 15



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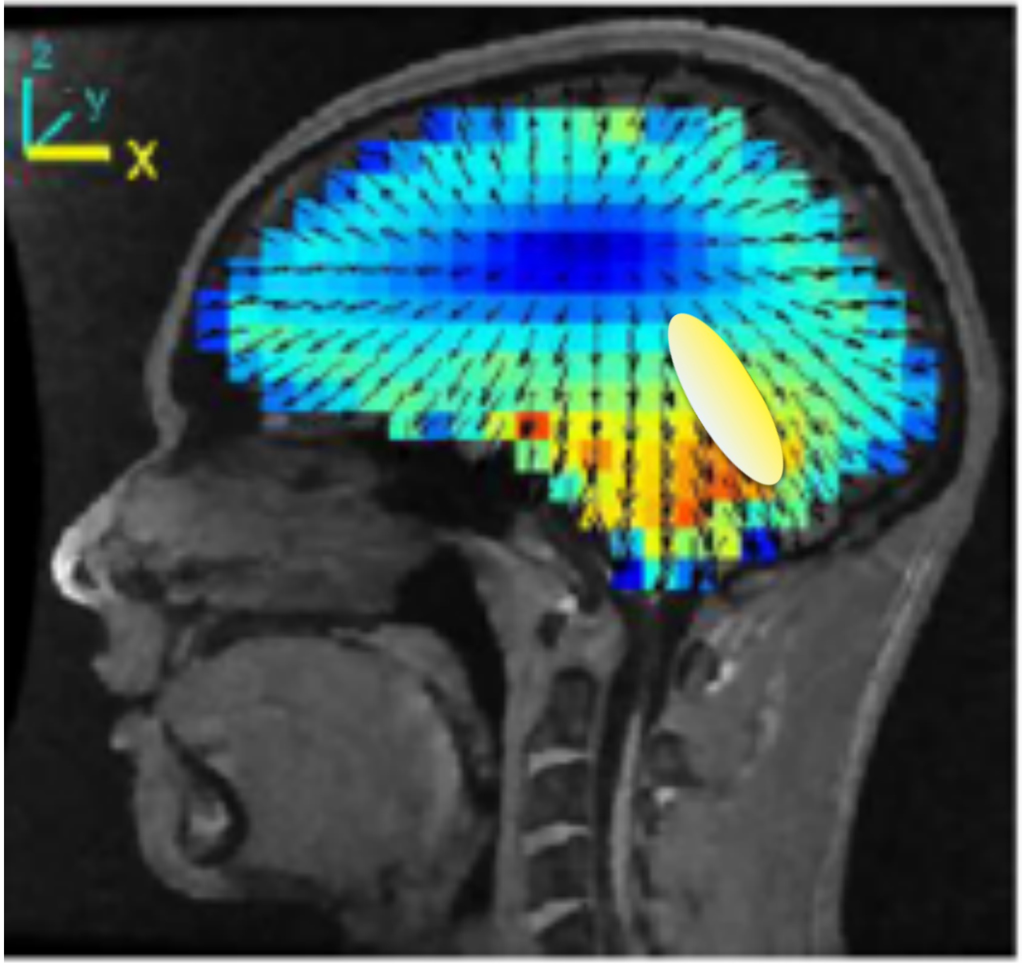
Source Localization Errors



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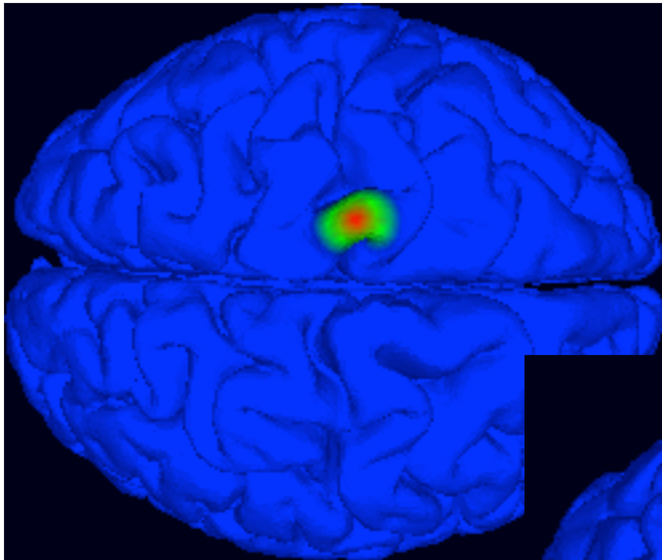
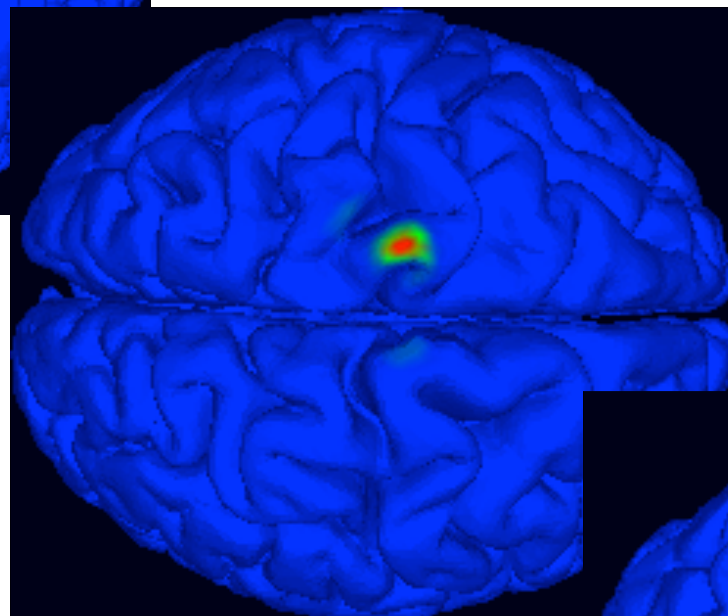
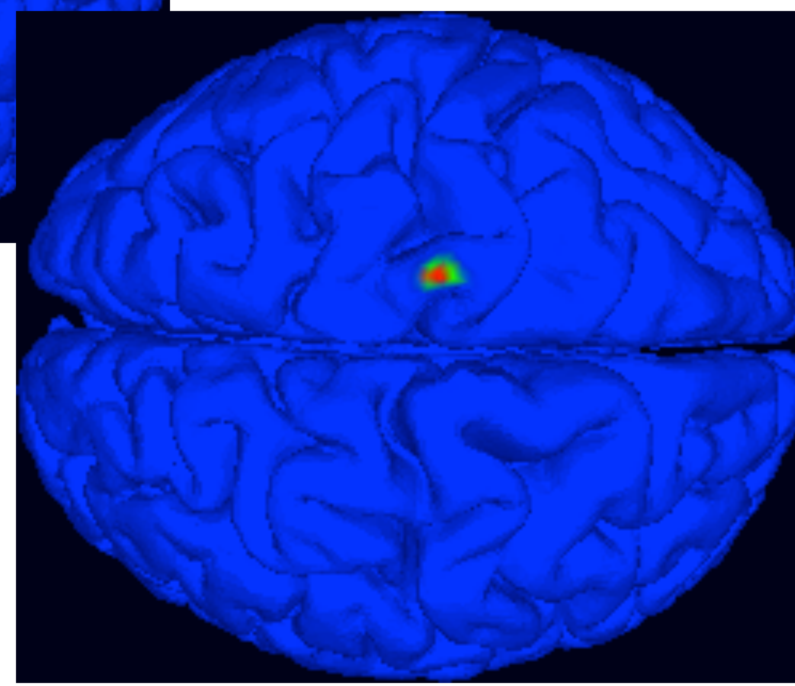
Conformal cortical patch source dictionary



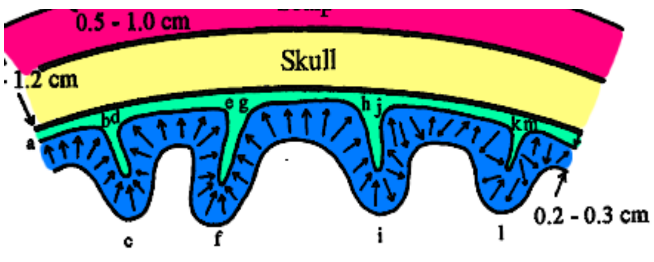




Zeynep Akalin Acar,, S. Makeig, G. Worrell, ‘09

Conformal cortical patch basis model

→ Model a source as a sum of overlapping patches

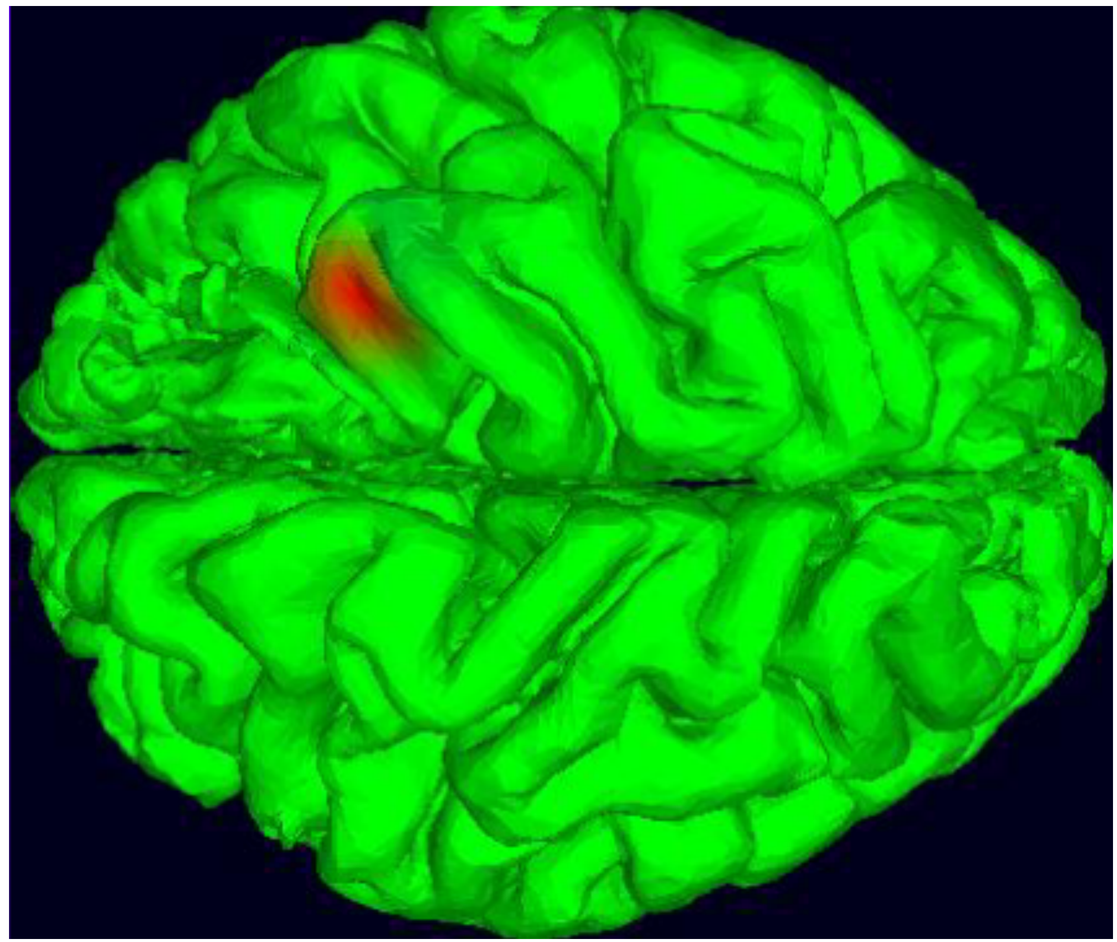


Sparse

Compact

Smooth

- Cheng Cao 2011



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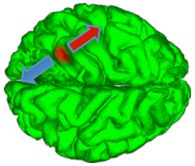
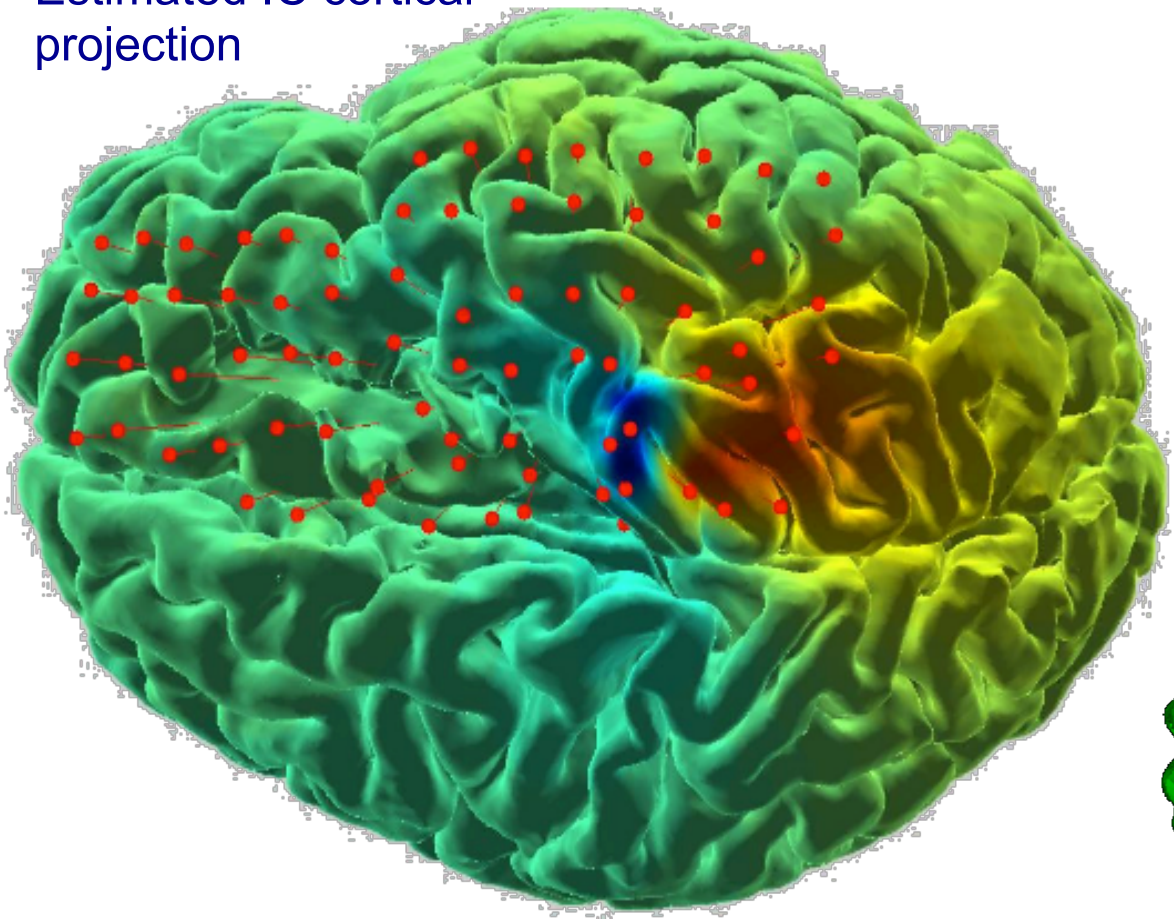


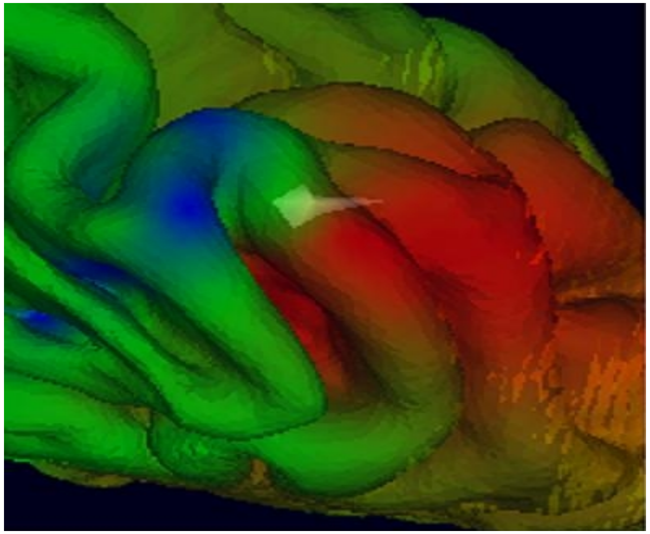
Source models

of an IC from an intracranial data set

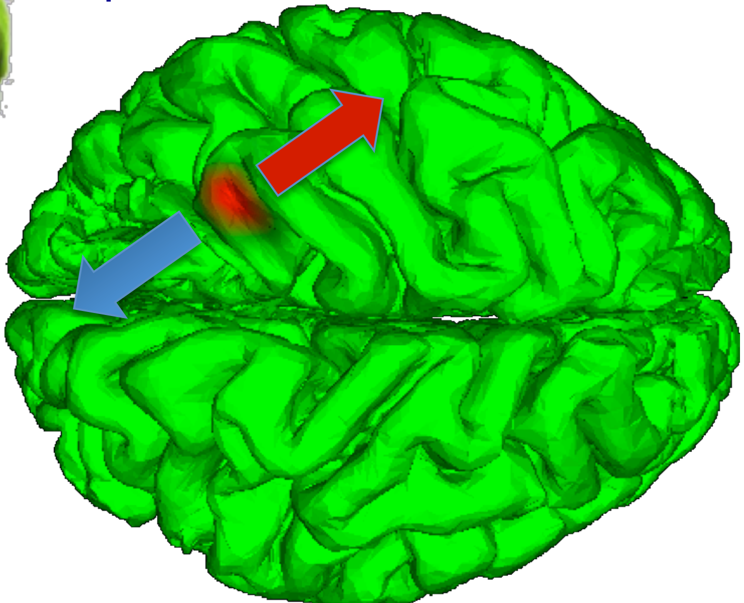
Estimated IC cortical projection



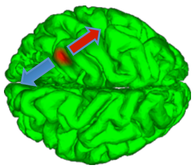
Equivalent Current Dipole Model



Sparse Patch Basis Model



Z. Akalin Acar, 2010



Summary I

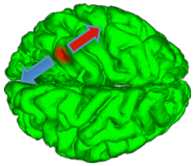
- **Forward modeling**

  is required to interpret the scalp topographies
- Interpreting scalp topographies means

  inverse modelling or "**source estimation**"
- Mathematical techniques are available

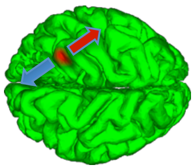
  to aid in interpreting scalp topographies

  → These are **inverse source models**



Summary II

- **Inverse modeling**
  - Model assumptions for the (volume conductor) head
  - Model assumptions for source (equiv. dipole source)
  - Additional assumptions on source location/orientation
- **Single point-like sources**
- **Multiple point-like sources**
- **Distributed sources**
  - Different mathematical solutions
    - Dipole fitting (linear and nonlinear)
    - Linear estimation (regularized)
- **For EEG inverse modeling, conductivity is key!**

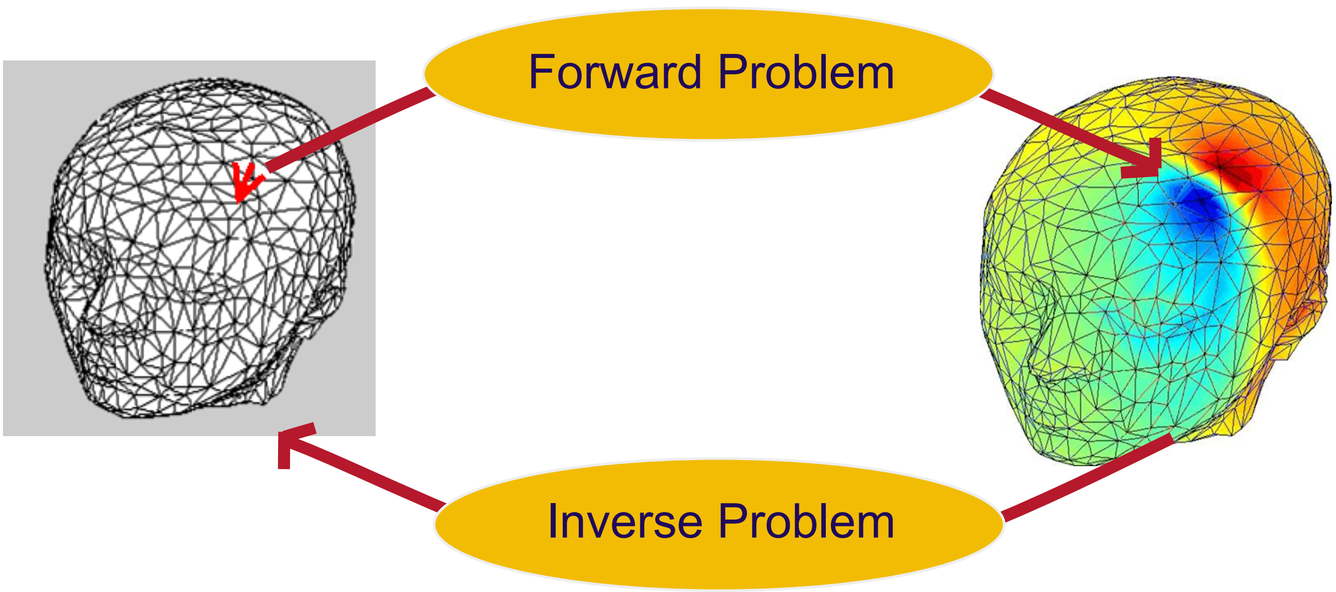


Source modeling

forward problem →

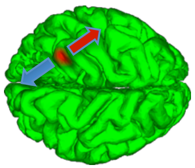
physiological source electrical current	body tissue volume conductor	observed potential or field

← inverse problem



EEG or MEG

R. Oostenveld, Z. Akalin Acar & S. Makeig, 2010



Source Localization Requirements

- Selected/processed EEG signal
  → **Simple single-source scalp map** !
- Number/positions of electrodes on the head surface
- Numerical head model
- Co-registration of EEG electrodes with head model
- Evidence/assumptions about the source space
- Choice of inverse model
- Choice of numerical method

Swartz
Center for
Computational
Neuroscience

NFT

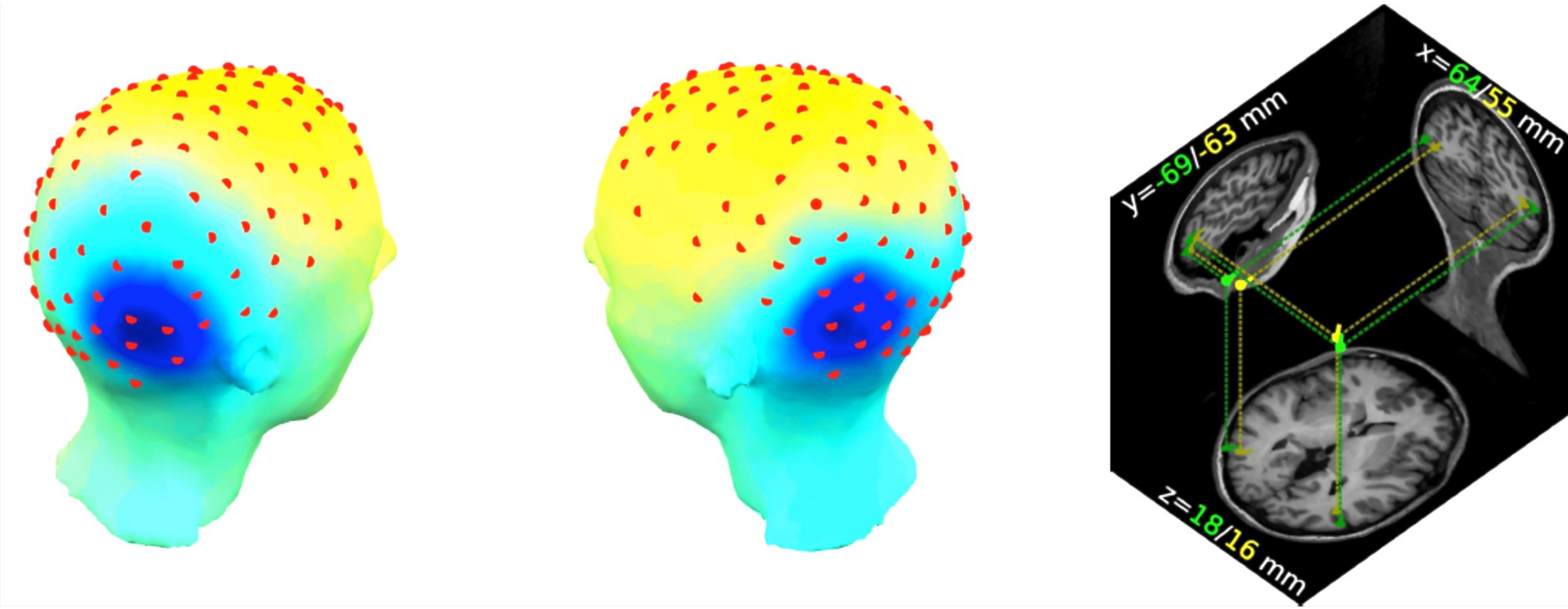
Neuroelectromagnetic

Forward Head Modeling Toolbox

Zeynep Akalin Acar

May 25, 2010

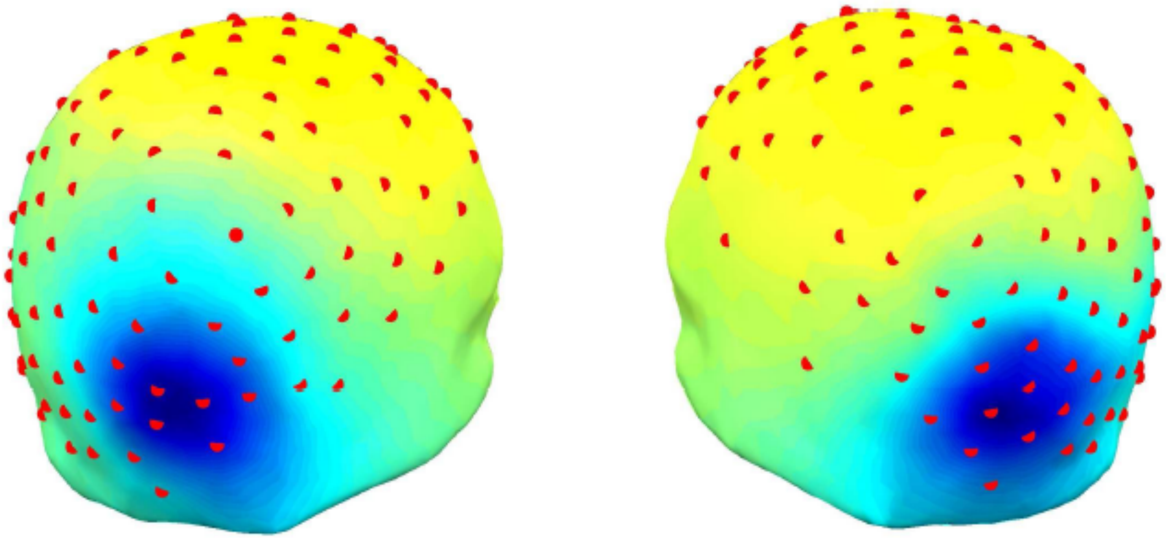
3- and 4-layer MR-based realistic head model

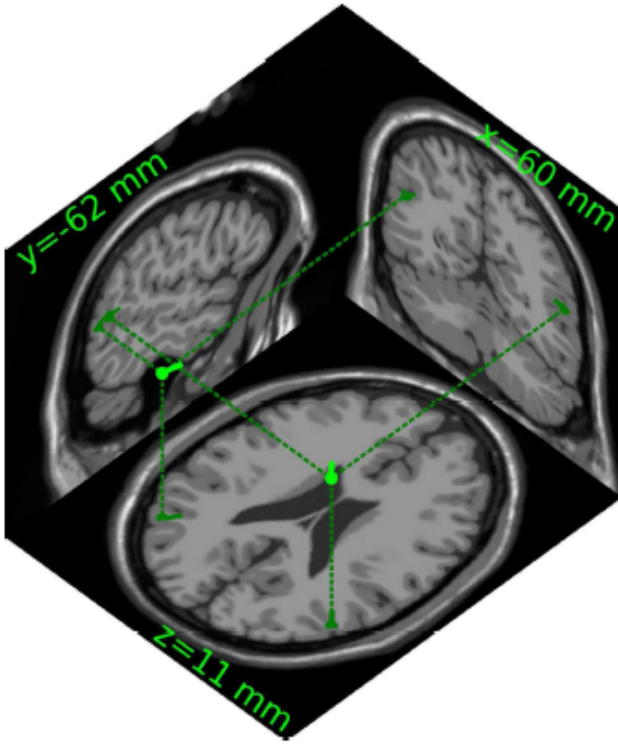


Scalp maps of 2 components

Sources of 2 components
green dipoles - 4-layer
yellow dipoles - 3-layer

MNI template head model

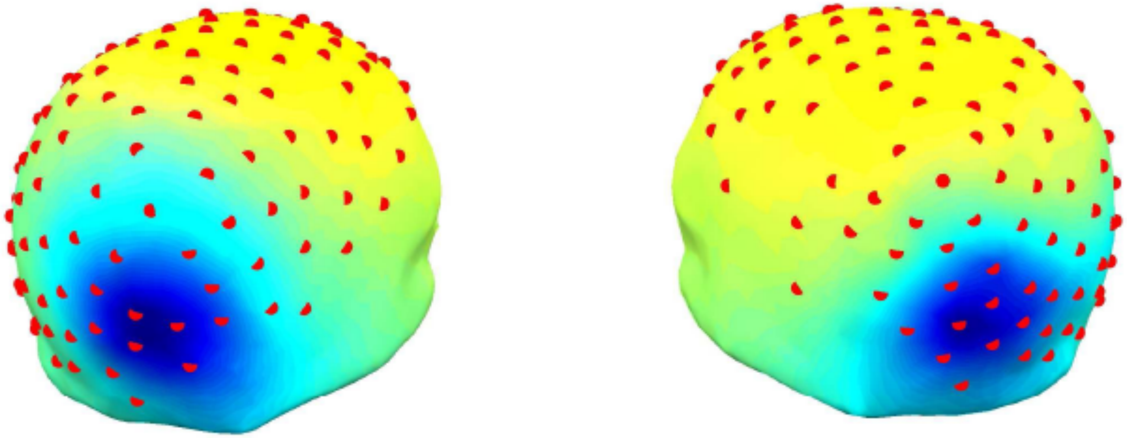




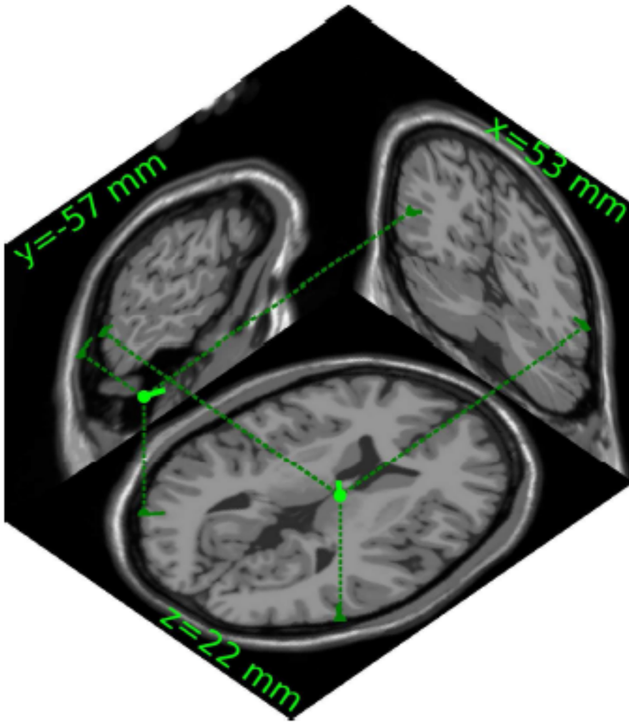
Scalp maps of 2 components

Sources of 2 components

Electrode-position warped MNI template head model

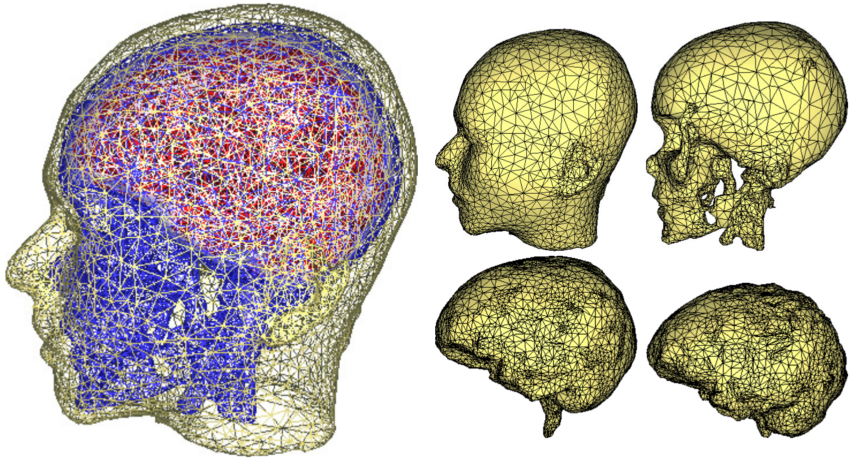


Scalp maps of 2 components

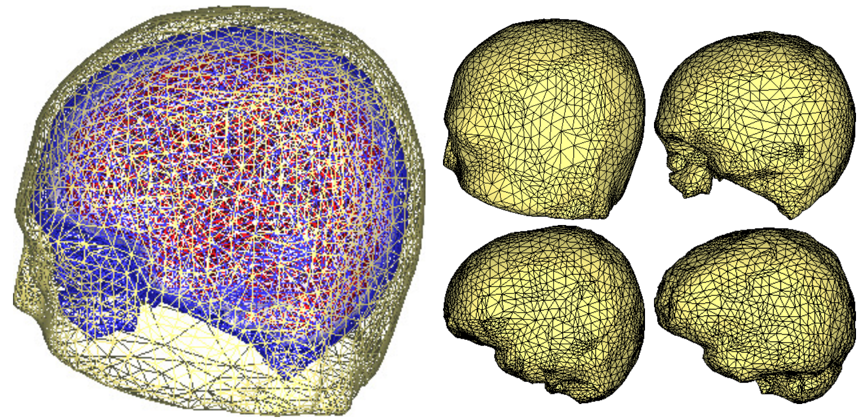


Sources of 2 components

Four-layer individual BEM head model



Four-layer MNI template BEM head model



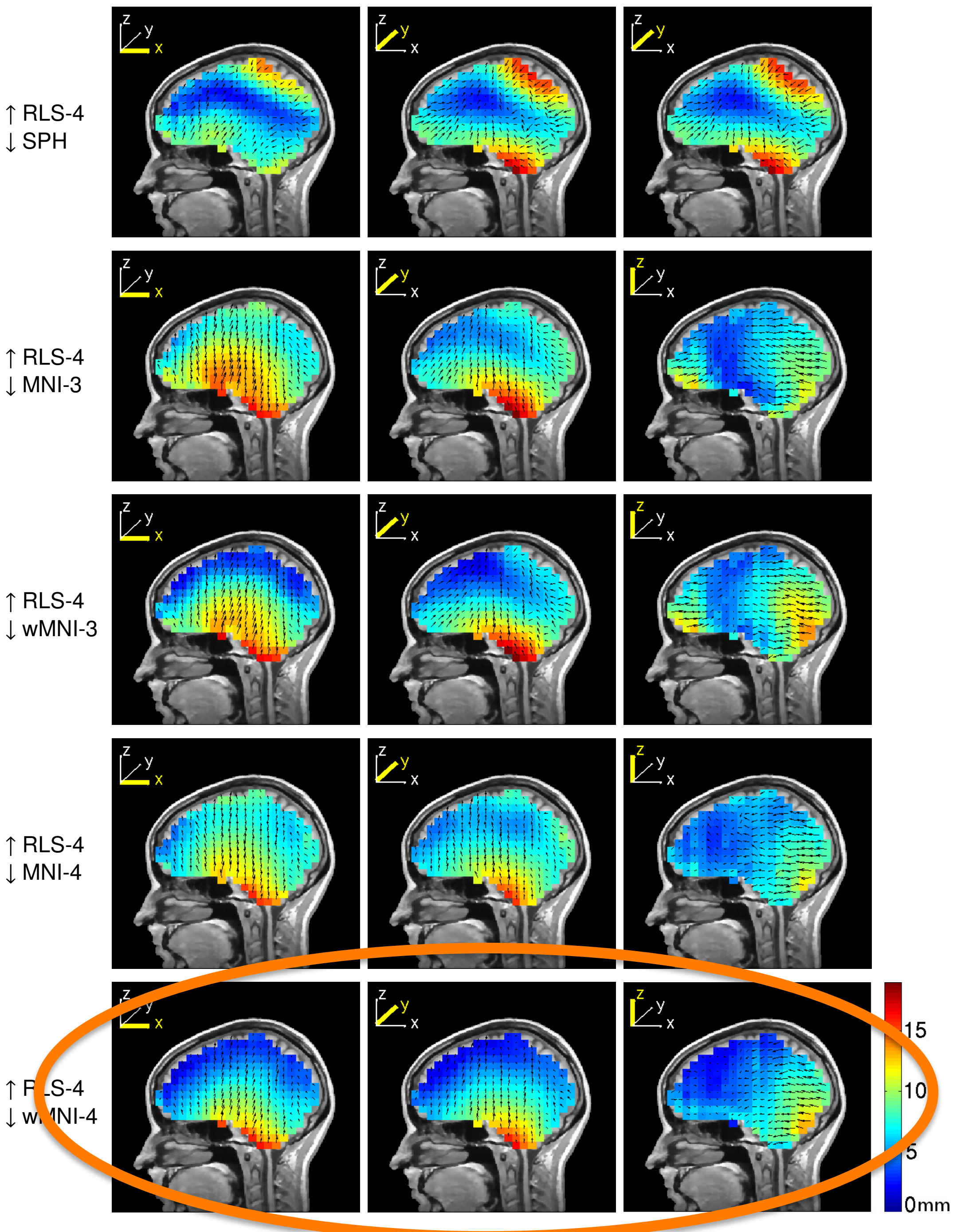


Fig. 9
Mean of 4 Ss

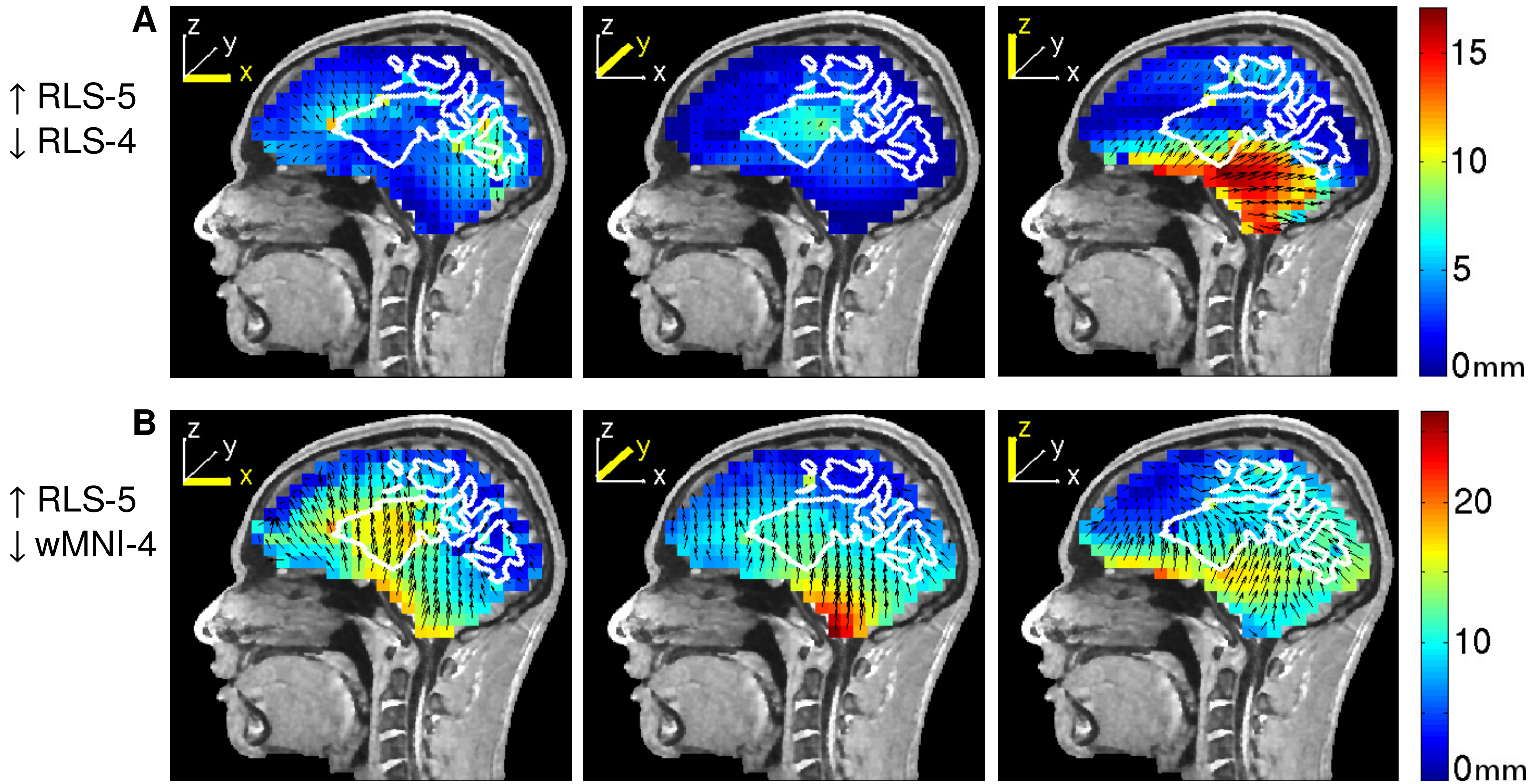


Fig. 11
5 → 4-layer

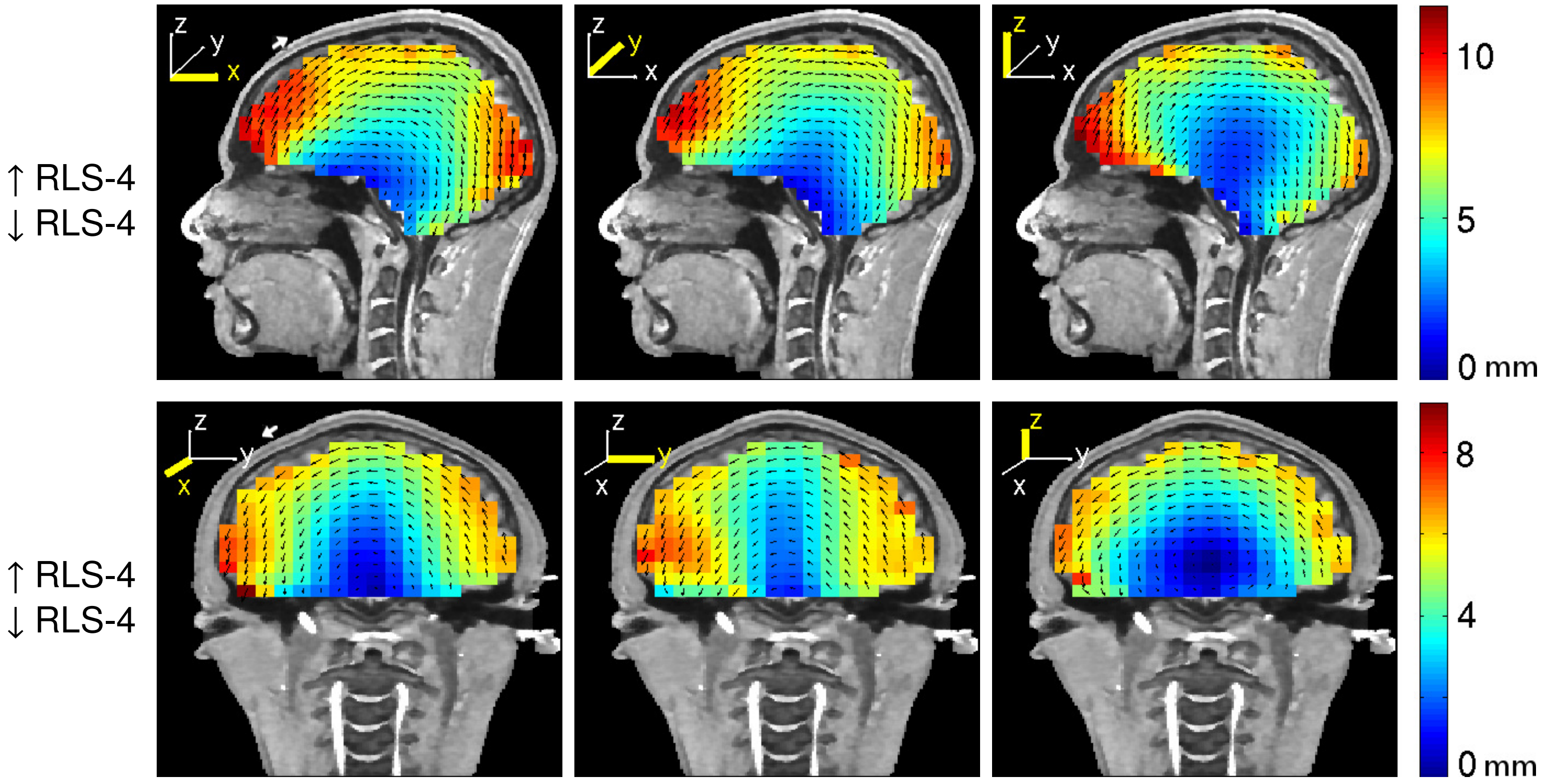


Fig. 12
Cap shifts

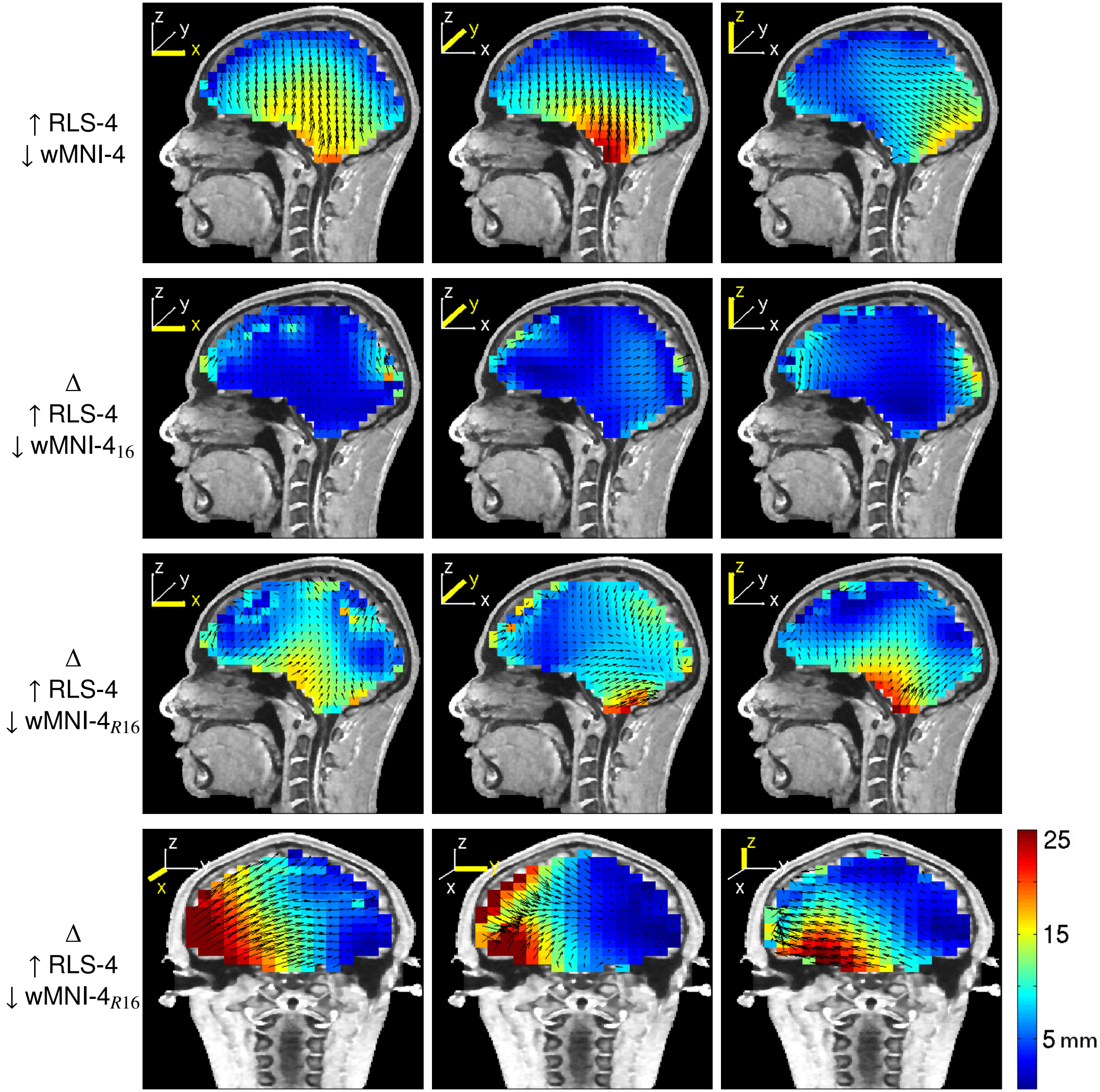
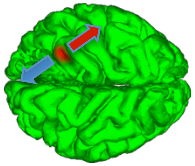


Fig. 15
Montage



Effect of reference electrode

"The choice of a particular reference electrode … does not change in any way the biophysical information contained in the potential distribution. It does not in any way change the relation between source and potential, except for an additive constant of no physical significance."

- Geselowitz, 1998

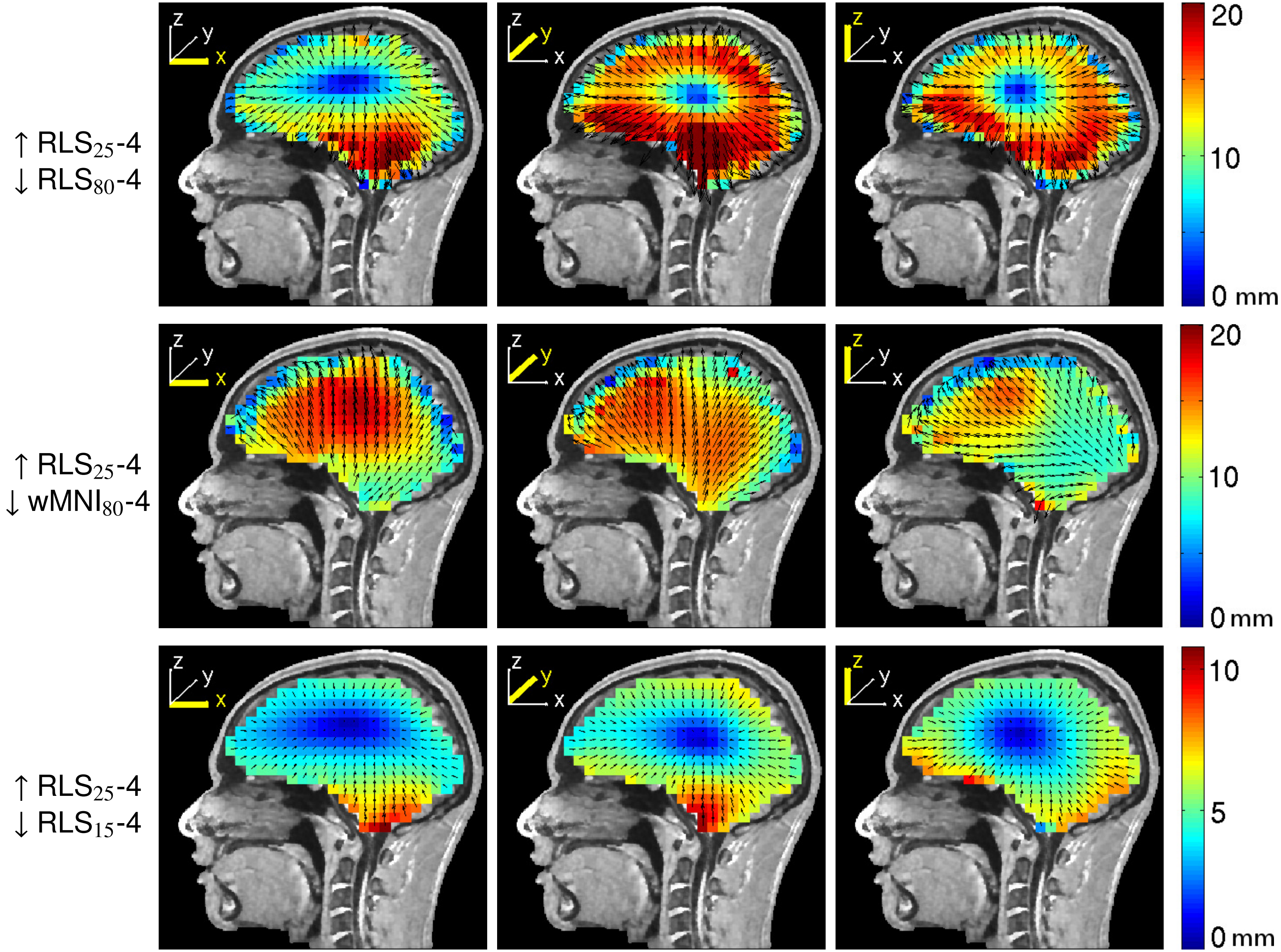


Fig. 13
Skull conductivity

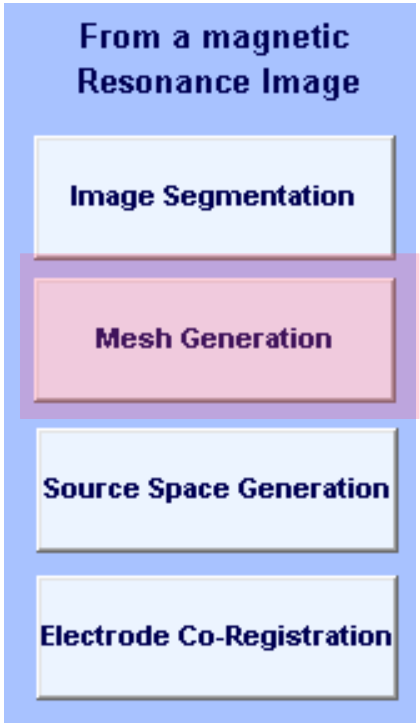
NFT External Program Code Incorporated

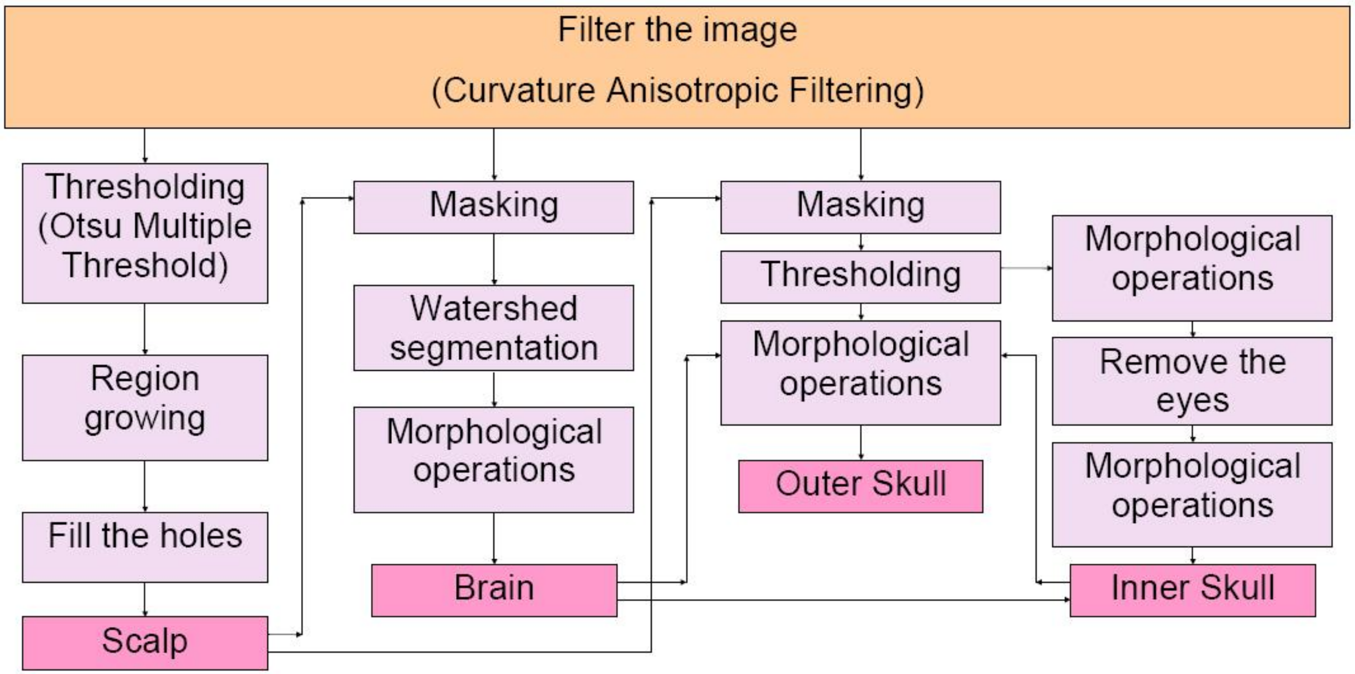
- 3rd Party Tools and Libraries:
  - ASC: High quality triangulation
  - Qslim: Mesh Coarsening
  - MATITK
    - MATLAB interface to ITK image processing toolkit
  - METU-BEM
    - Boundary Element Method (BEM) Solver
- Source code is available for all these components.

NFT: Operation

- **T1 MR Images**
  - Choose subject
  - Generate subject head model
  - Segmentation
    - Mesh generation
  - Register sensors to mesh
    - Sensor set = session
  - Generate forward model
  - Generate Lead Field Matrix
- **Template Mesh**
  - Choose subject
  - Select sensors
  - Warp Template to sensors
  - Generate forward model
  - Generate LFM for sensors

Image Segmentation Flowchart





- Classifies four tissues from T1-weighted images
  - (Scalp, Skull, CSF and Brain)

Forward Problem Solver

- MATLAB interface to numerical solvers
- Boundary Element Method
  - No MEG (yet)
  - Supports IPA and Accelerated BEM
  - Interfaces to the Matrix generator written in C++
- Other computations in MATLAB
- Generated matrices are stored on disk for future use.
- Other solvers:

  Finite Element Method (FEM)