Westfälische Wilhelms-Universität Münster

Hierarchical Bayesian Models for EEG Inversion: Depth Localization and Source Separation for Focal Sources in Realistic FE Head Models

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Background of the Talk

- Felix Lucka.
  Hierarchical Bayesian Approaches to the Inverse Problem of EEG/MEG Current Density Reconstruction.
  Diploma thesis in mathematics, University of Münster, March 2011

- Felix Lucka., Sampsa Pursiainen, Martin Burger,Carsten H. Wolters.
  Hierarchical Bayesian Inference for the EEG Inverse Problem using Realistic FE Head Models: Depth Localization and Source Separation for Focal Primary Currents.
  NeuroImage, submitted.

Tasks and Problems for EEG/MEG in Presurgical Epilepsy Diagnosis

EEG/MEG in epileptic focus localization:

- *Focal epilepsy* is believed to originate from networks of focal sources.
- Active in inter-ictal spikes.
- Task 1: Determine number of focal sources (*multi focal epilepsy*?).
- Task 2: Determine location and extend of sources.

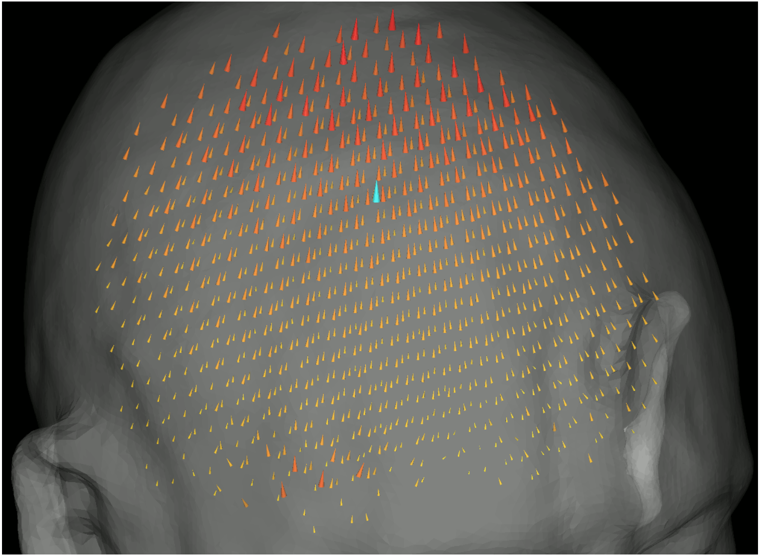
Unknown number and spatial extend of sources?
$\longrightarrow$ Current density reconstruction (CDR).

Problems of established CDR methods:

- Depth-Bias: Reconstruction of deeper sources too close to the surface.
- Masking: Near-surface sources “mask“ deep-lying ones.

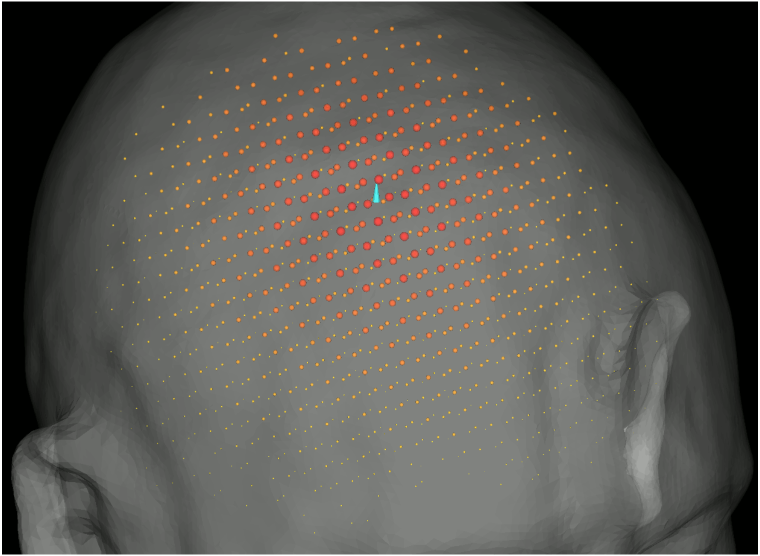
Depth Bias: Illustration

One deep-lying reference source (blue cone) and minimum norm estimate (MNE, Hämäläinen and Ilmoniemi, 1994).



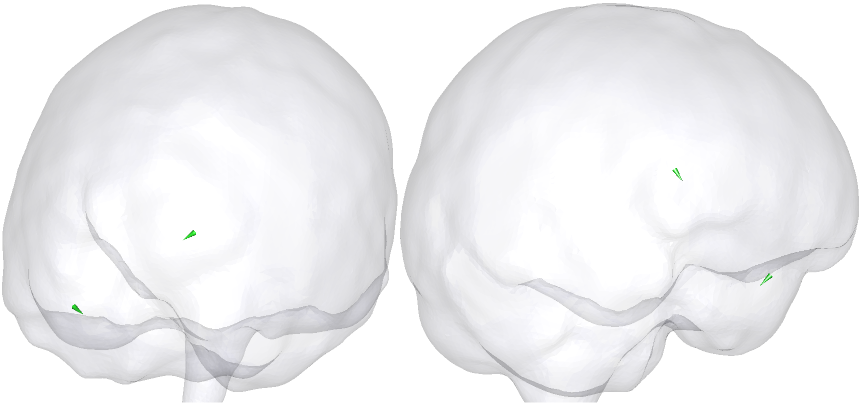
Depth Bias: Illustration

One deep-lying reference source (blue cone) and sLORETA result (Pascual-Marqui, 2002).



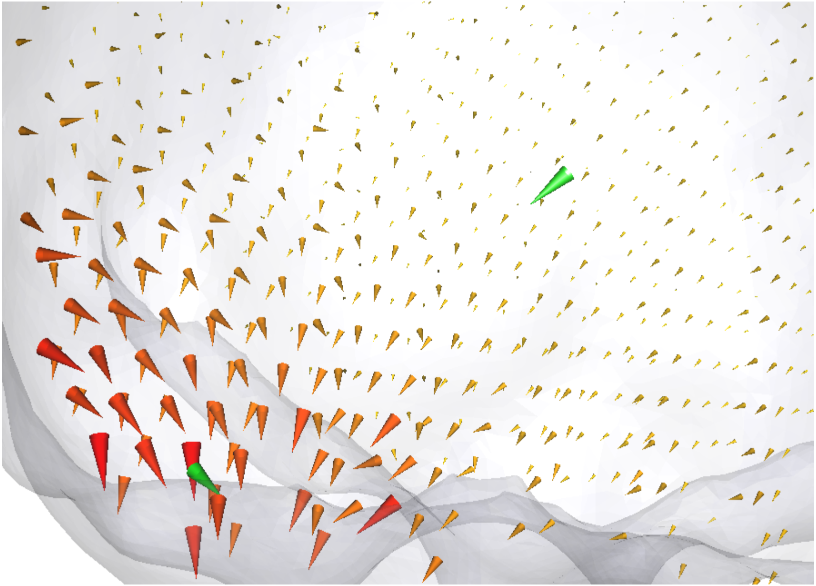
Masking: Illustration

Reference sources.



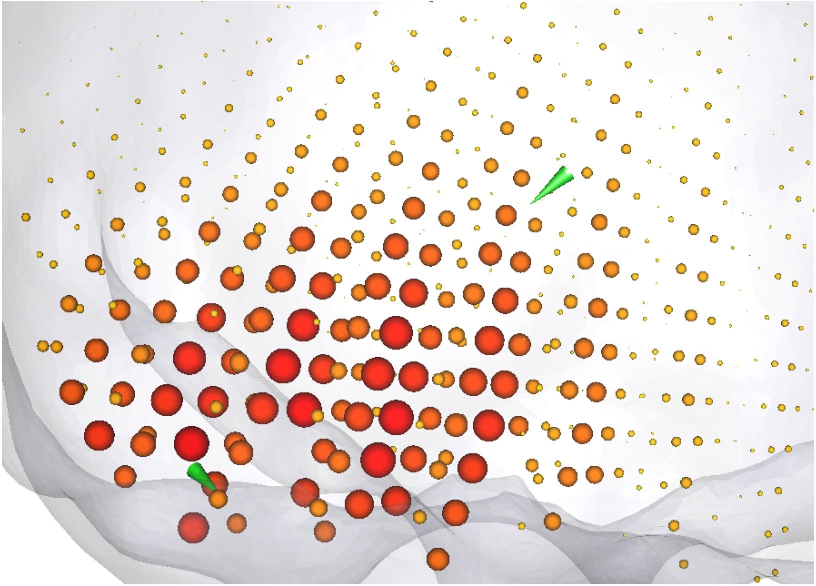
Masking: Illustration

MNE result and reference sources (green cones).



Masking: Illustration

sLORETA result and reference sources (green cones).



Hierarchical Bayesian Modeling (HBM) for CDR

David Wipf and Srikantan Nagarajan.
A unified Bayesian framework for MEG/EEG source imaging.
Neuroimage, 44(3):947-66, February 2009

Key features (proper introduction is behind the scope of this talk...):

- Further development of weighted minimum norm schemes.
- Flexible framework for embedding qualitative and quantitative a-priori information.
- Automatic selection of important features.
- Comprises former methods like MNE, WMNE, LORETA, sLORETA, FOCUSS, MCE,...
- New ways of inference: Full-MAP, Full-CM, γ-MAP, S-MAP, VB

Key Question

Starting point:

- A specific HBM aims to recover source configurations consisting of few, focal sources (introduced in Sato et al., 2004; further examined in Nummenmaa et al., 2007; Wipf and Nagarajan, 2009; Calvetti et al., 2009)
- Calvetti et al., 2009 found promising first results with Full-MAP and Full-CM estimation for deep-lying sources and separation of multiple (focal) sources.

Limitations of Calvetti et al., 2009 :

- Full-MAP results were not convincing; reason unclear.
- No systematic examination; only two source scenarios.
- Head models insufficient.

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Key question

Can Full-MAP and Full-CM for HBM overcome the limitations (depth-bias, masking) of established CDR methods and become a valuable tool for presurgical epilepsy diagnosis?

Own Contributions/Work

Key question

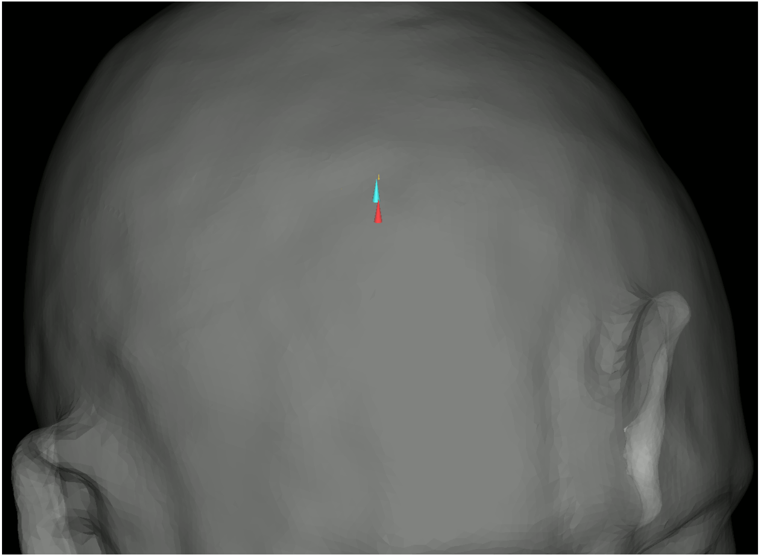
Can Full-MAP and Full-CM for HBM overcome the limitations (depth-bias, masking) of established CDR methods and become a valuable tool for presurgical epilepsy diagnosis?

Work program:

- Implementation of Full-MAP and Full-CM inference for HBM with realistic, high resolution Finite Element (FE) head models.
- Propose own algorithms for Full-MAP estimation.
- Introduction of suitable performance measures for validation of simulation studies.
- Systematic examination of performance concerning depth-bias and masking.

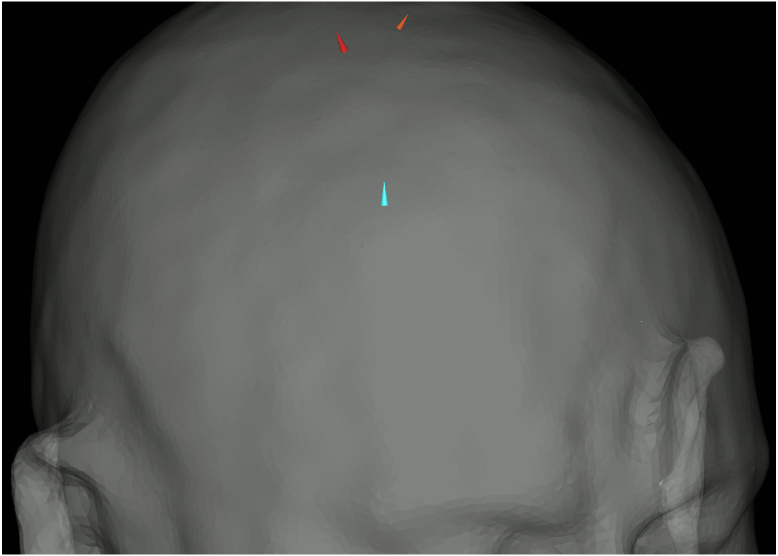
Results Depth Bias: Illustration

One deep-lying reference source (blue cone) and Full-CM result.



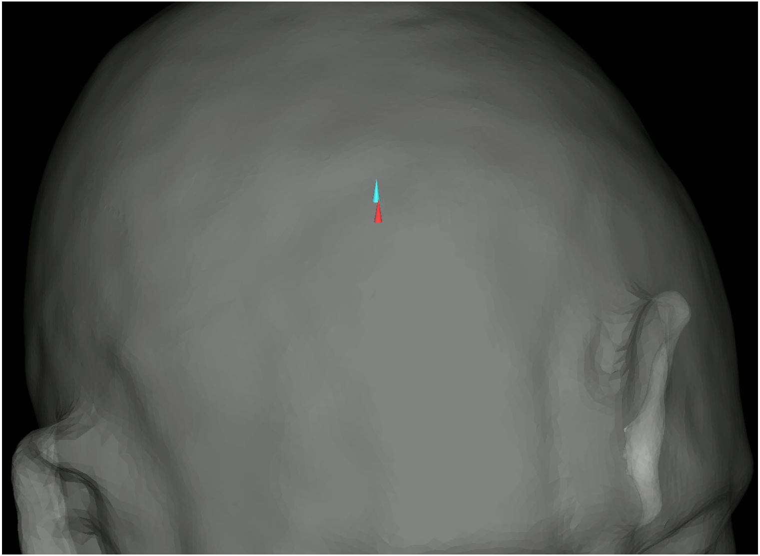
Results Depth Bias: Illustration

One deep-lying reference source (blue cone) and Full-MAP result proposed by Calvetti et al., 2009.



Results Depth Bias: Illustration

One deep-lying reference source (blue cone) and Full-MAP result proposed by us.

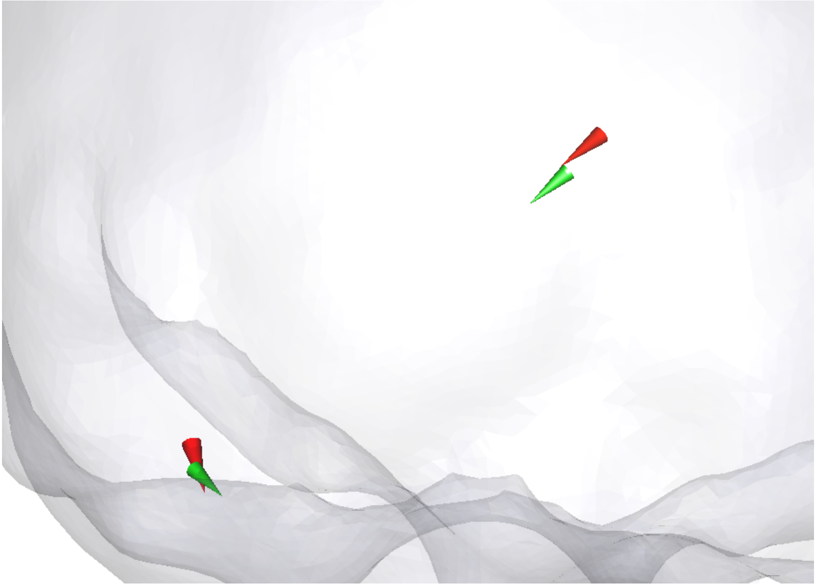


Results Masking: Illustration

Full-CM result and reference sources (green cones).

Results Masking: Illustration

Full-MAP result (by our algorithm) and reference sources (green cones).



Systematic Studies: Summary

Study 1 (depth-bias):

- Reconstruction of single 1000 dipoles; random location and orientation.
- Reconstructions were compared using different performance measures.
- Specific examination of depth bias.

Study 2 (masking):

- Reconstruction of 1000 source configurations consisting of one near-surface and one deep-lying dipole.
- Reconstructions were compared using a new performance measure based on *optimal transport* (called *earth mover's distance*, a *Wasserstein metric*).

Systematic Studies: Summary

Results for Full-MAP and Full-CM estimation:

- Good performance in all validation measures.
- No depth bias.
- Good results w.r.t. orientation, amplitude and spatial extend.
- Full-MAP estimate (by our algorithm): Best results in every aspect examined.

$\Longrightarrow$ Full results: Paper in NeuroImage (submitted), diploma thesis $\Longleftarrow$

Conclusions

Key question

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Results

- Hierarchical Bayesian modeling used with realistic head modeling is a promising framework for EEG/MEG CDR.
- Promising results for deep sources (no depth bias).
- Promising results for challenging multiple source scenarios (no masking).

★ A promising tool for presurgical epilepsy diagnosis. ★

Main References

David Wipf and Srikantan Nagarajan.
A unified Bayesian framework for MEG/EEG source imaging.
Neuroimage, 44(3):947-66, February 2009

Daniela Calvetti, Harri Hakula, Sampsa Pursiainen, and Erkki Somersalo.
Conditionally Gaussian hypermodels for cerebral source localization.
SIAM J. Imaging Sci., 2(3):879-909, 2009

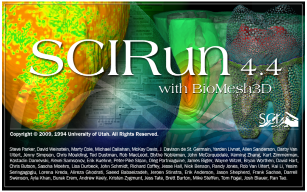
Felix Lucka.
Hierarchical Bayesian Approaches to the Inverse Problem of EEG/MEG Current Density Reconstruction.
Diploma thesis in mathematics, University of Münster, March 2011

Felix Lucka., Sampsa Pursiainen, Martin Burger,Carsten H. Wolters.
Hierarchical Bayesian Inference for the EEG Inverse Problem using Realistic FE Head Models: Depth Localization and Source Separation for Focal Primary Currents.
NeuroImage, submitted.

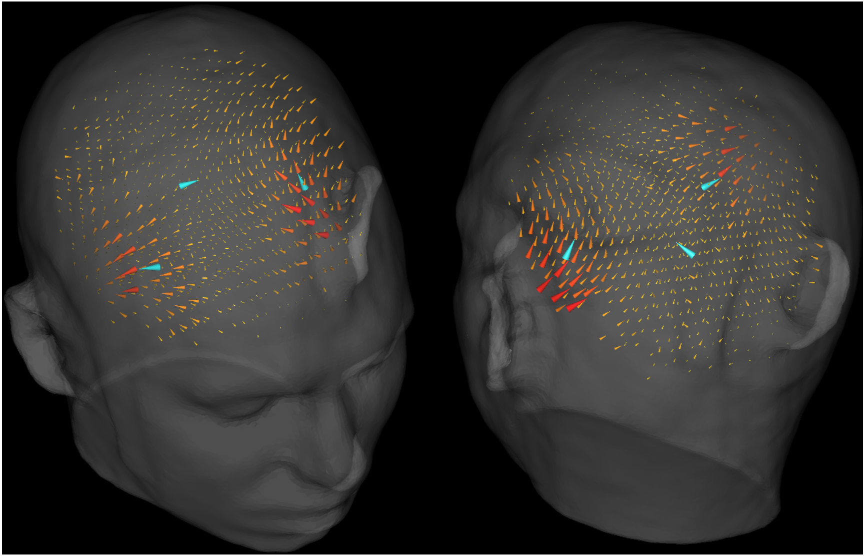
Thank you for your attention!

Software used:

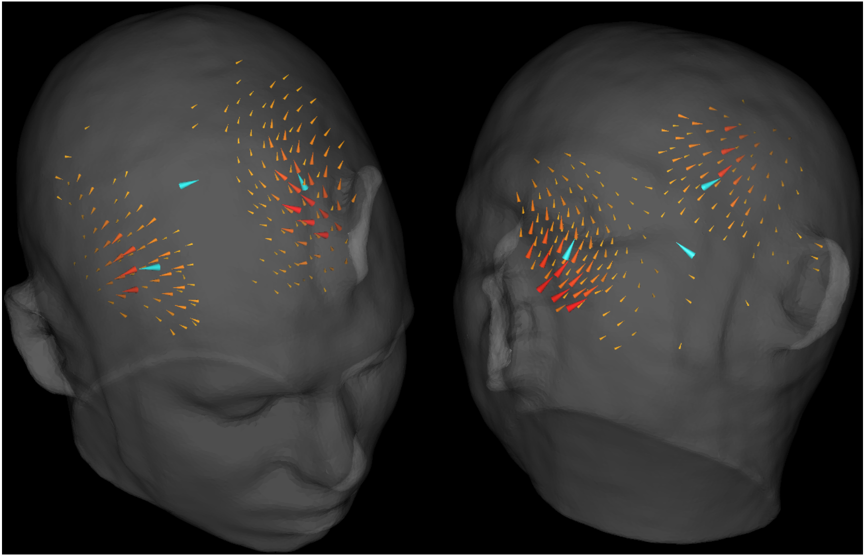
- Model generation: FSL, CURRY, Tetgen.
- Forward simulation: SimBio.
- Inverse computation: Matlab.
- Visualization: SCIRun.



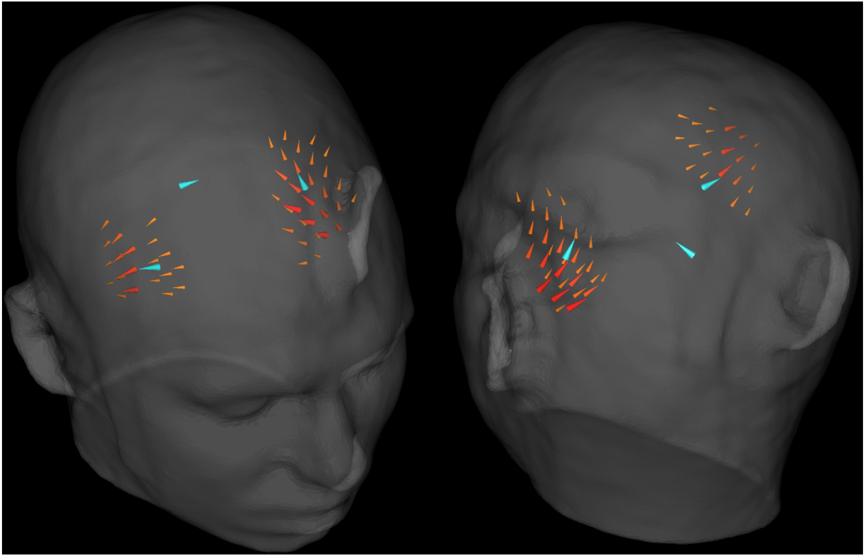
Three Dipoles: MNE



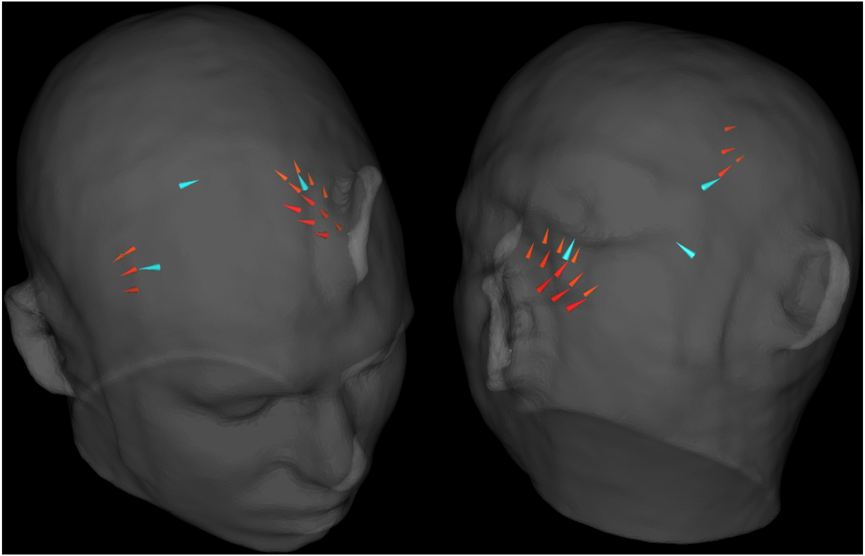
Three Dipoles: MNE, threshold = 30%



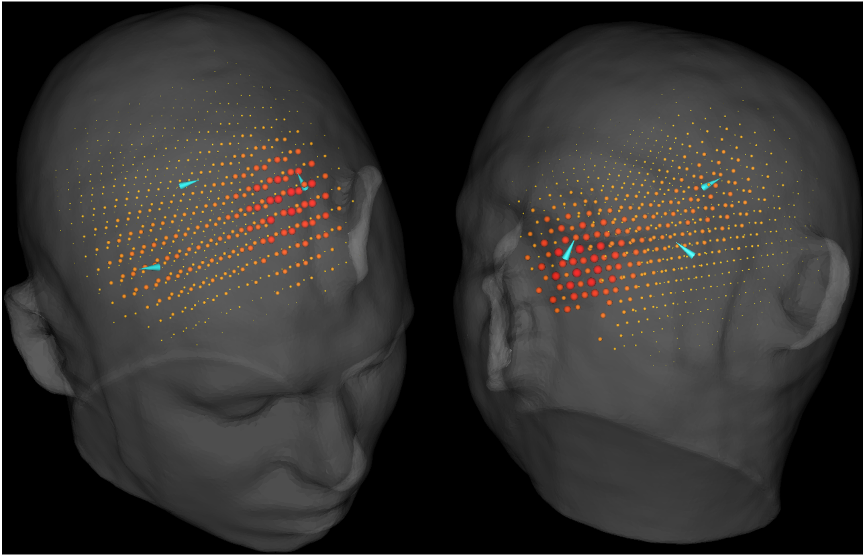
Three Dipoles: MNE, threshold = 50%



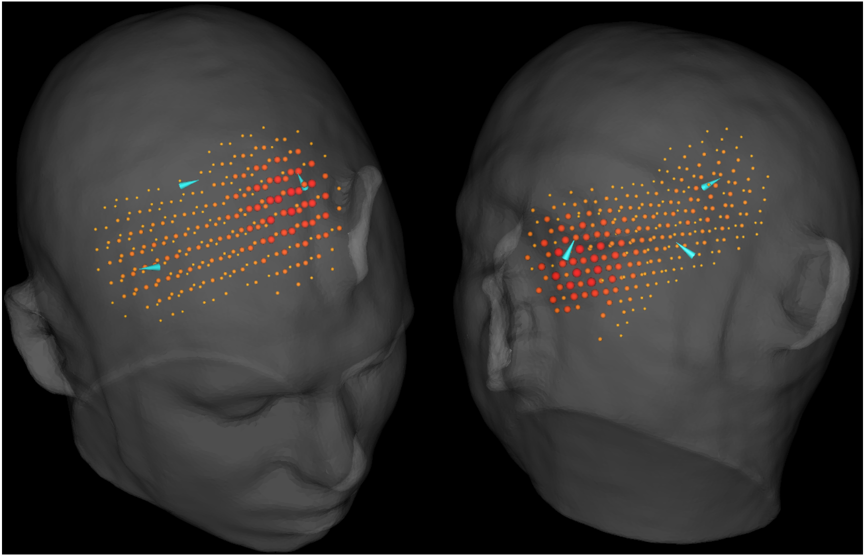
Three Dipoles: MNE, threshold = 70%



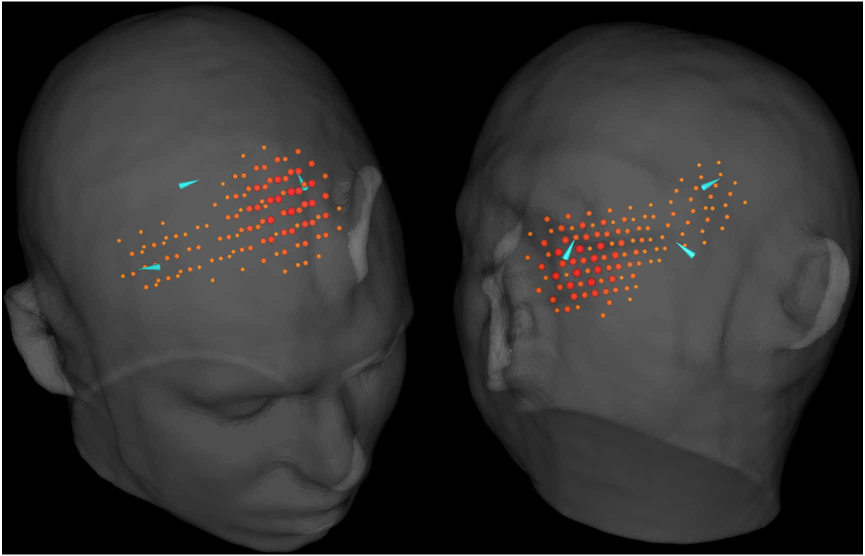
Three Dipoles: sLORETA



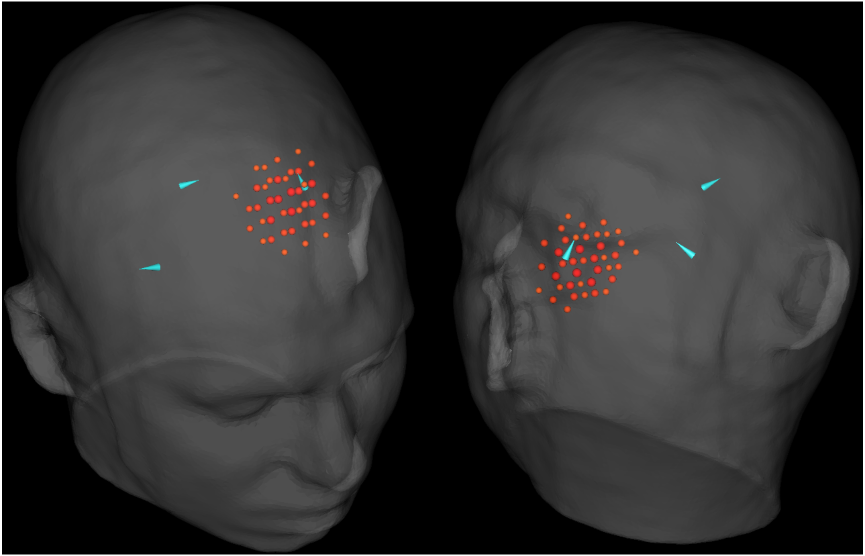
Three Dipoles: sLORETA, threshold = 30%



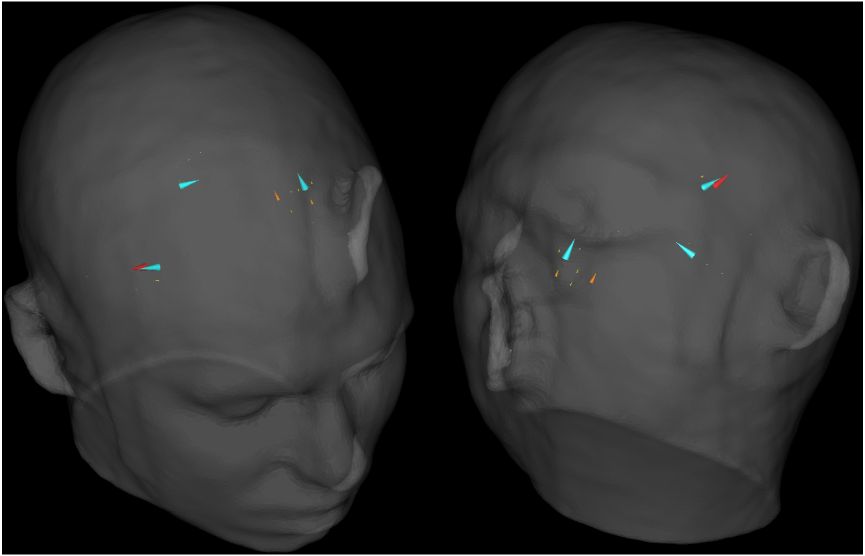
Three Dipoles: sLORETA, threshold = 50%



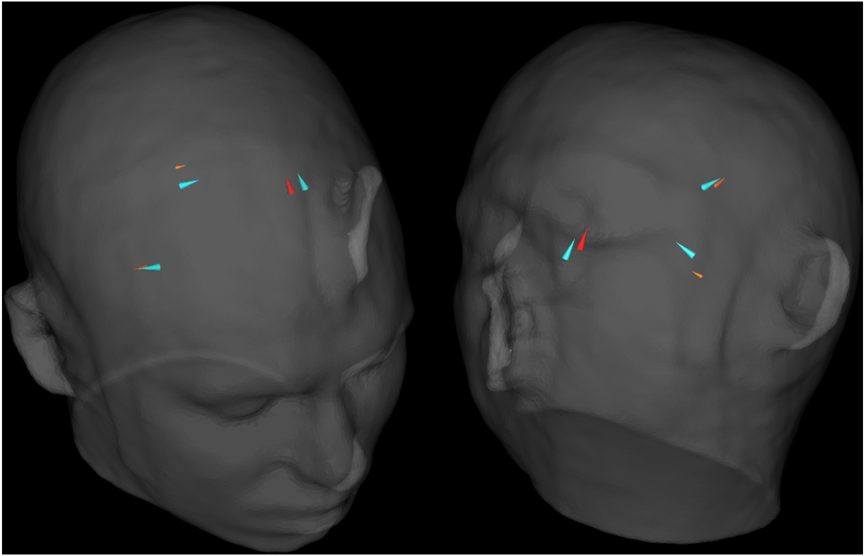
Three Dipoles: sLORETA, threshold = 70%



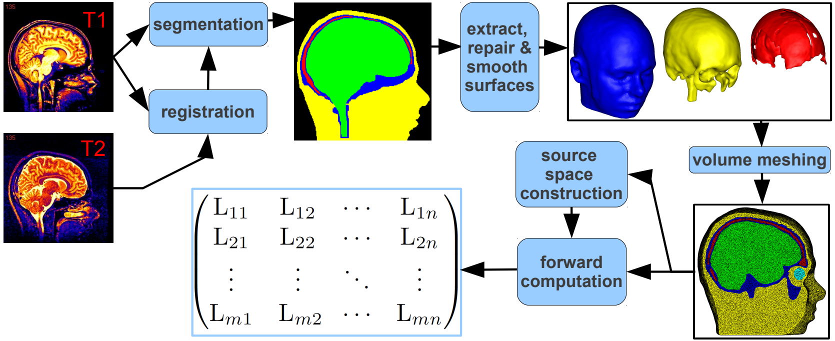
Three Dipoles: Full-CM



Three Dipoles: Full-MAP

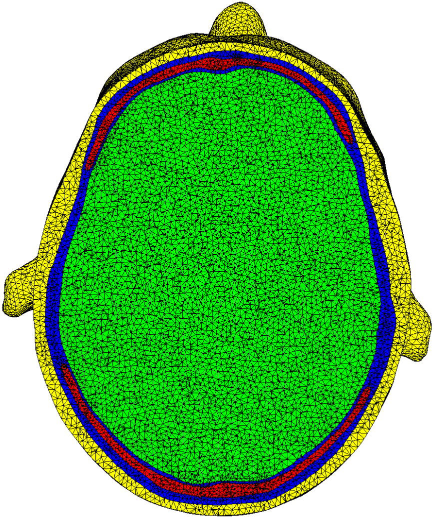
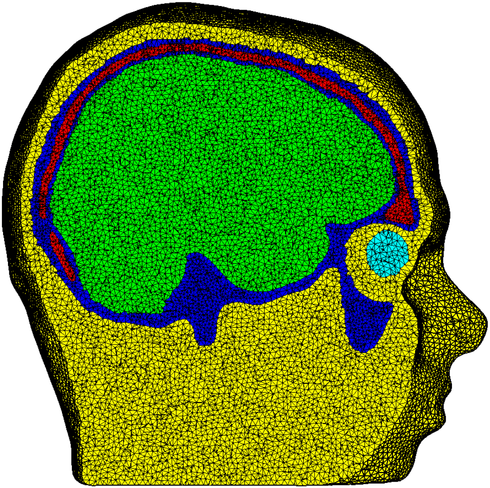


Head Model Generation Pipeline



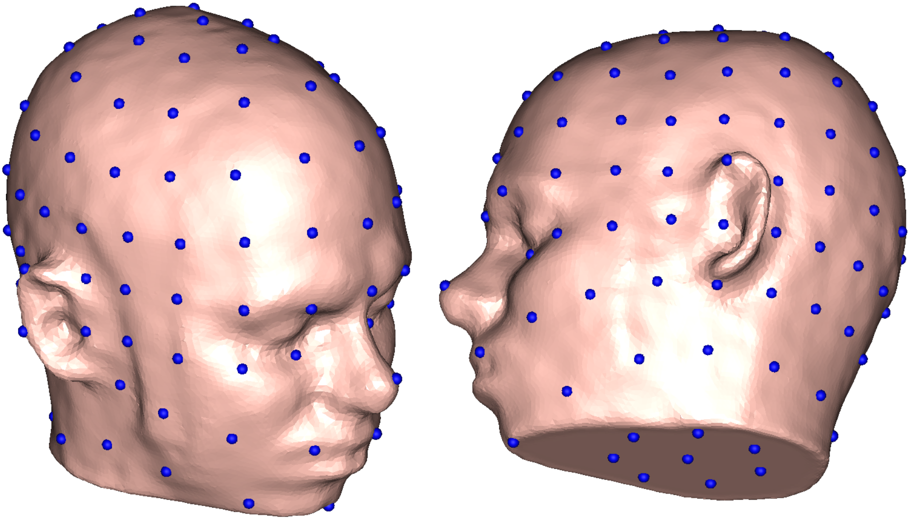
Realistic Tetrahedron Head Model

- Compartments: Skin, eyes, skull compacta and skull spongiosa, inner brain.
- 512 394 FEM nodes and 3 176 162 tetrahedra

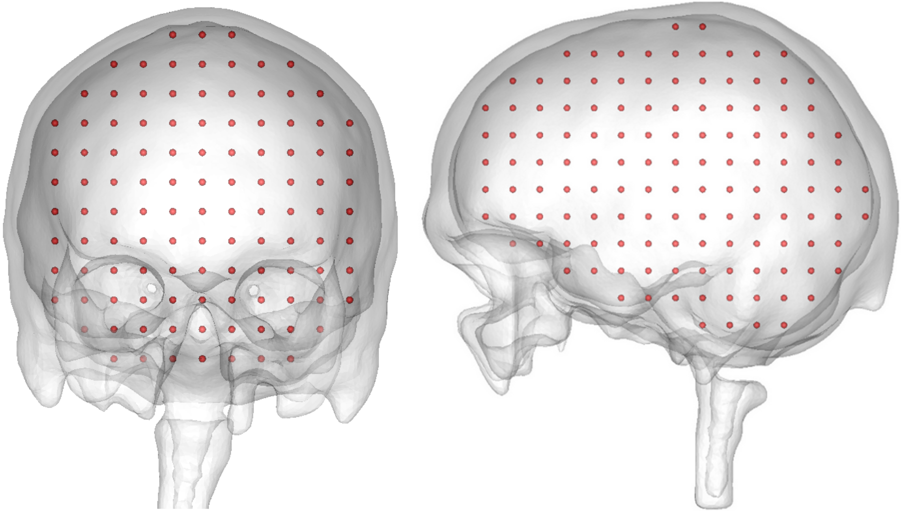
Artificial Sensor Configuration

Artificial full-coverage EEG sensor cap (134 sensors).
Reason: Exclude effect of insufficient sensor coverage.



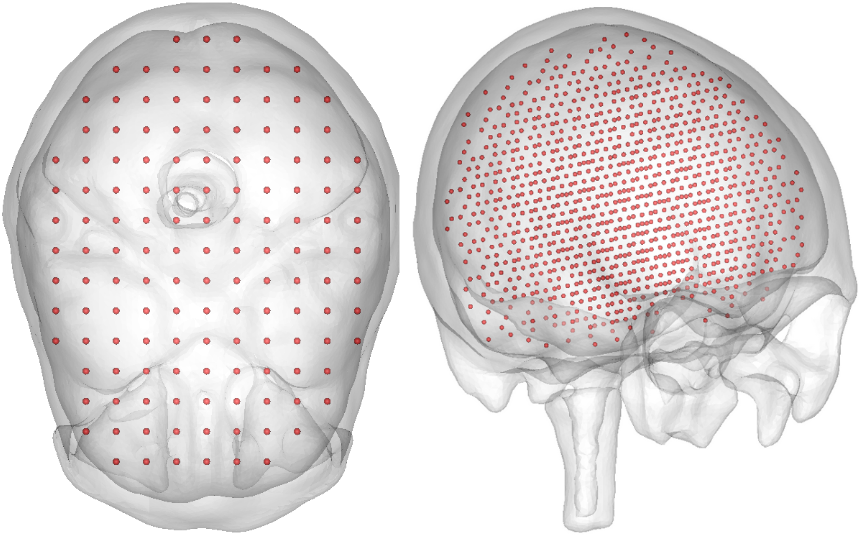
Source Space Grid

1000 source space nodes based on a regular grid.



Studies: Source Space Grid

1000 source space nodes based on a regular grid.



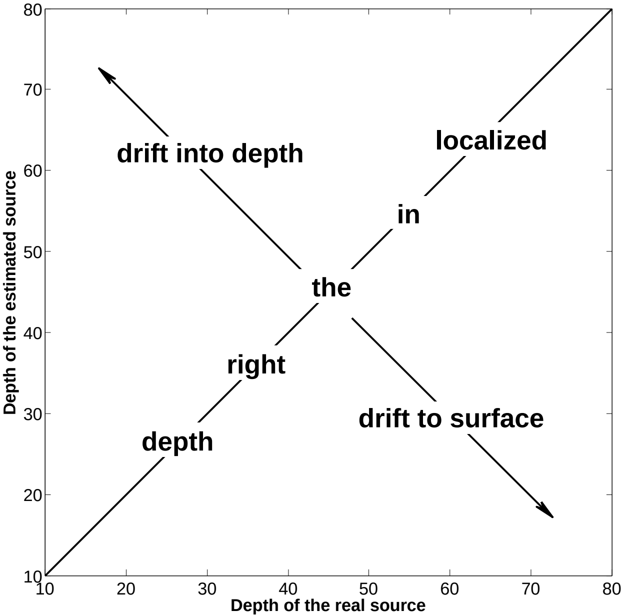
Depth Bias Study: Average Results (considered in this talk)

- 1000 dipoles; random location and orientation.
- Noise level 5%.
- Mean distance from reference source to next source space node: 5.27 mm.

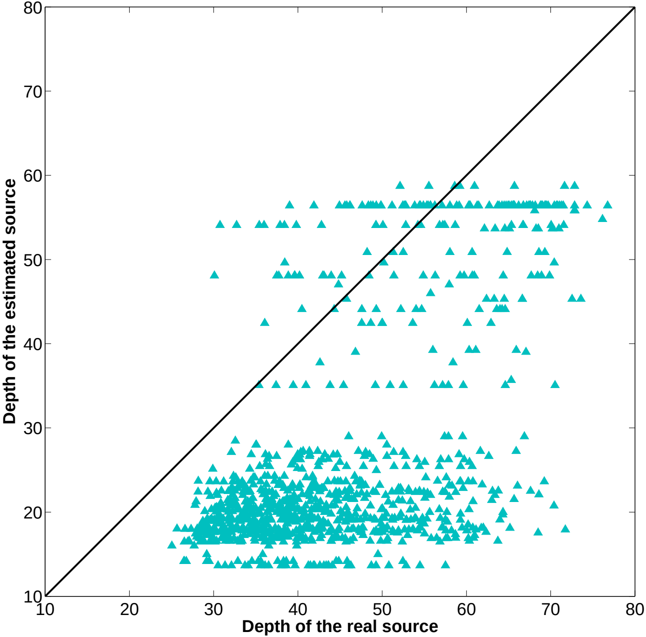
Method	**EMD**	**DLE**
MNE	53.20 mm	29.46 mm
sLORETA	40.58 mm	6.10 mm
CM	7.26 mm	6.21 mm
MAP1	28.18 mm	27.00 mm
MAP2	5.83 mm	5.78 mm

- EMD: *Earth mover's distance*; performance measure based on *optimal transport* (a *Wasserstein metric*).
- DLE: *Dipole localization error*; Distance from reference source to source space node with maximal amplitude (standard performance measure).

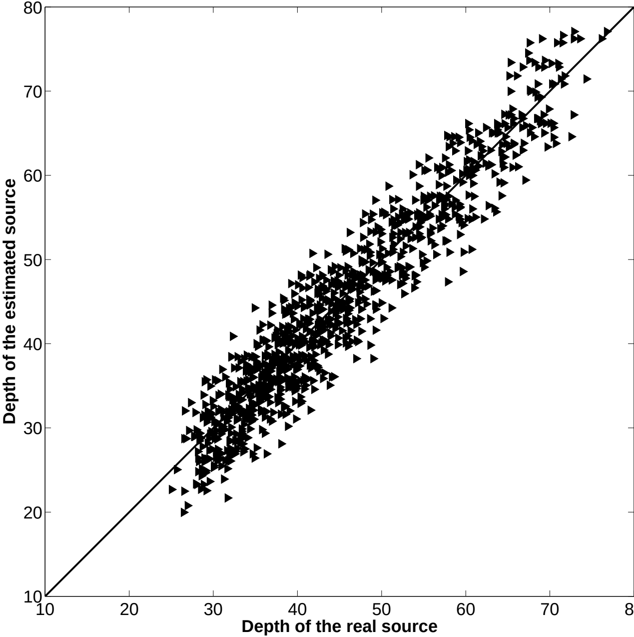
Depth Bias Study: Scatter Plots, Explanation



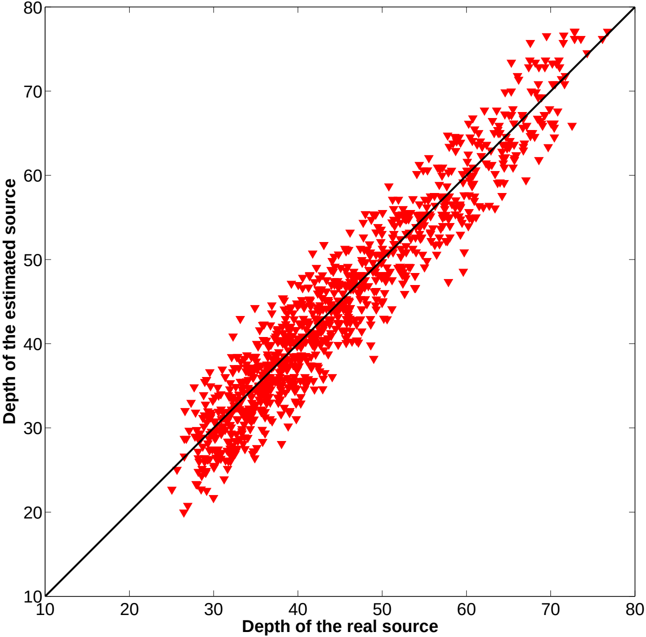
Depth Bias Study: Scatter Plots, MNE



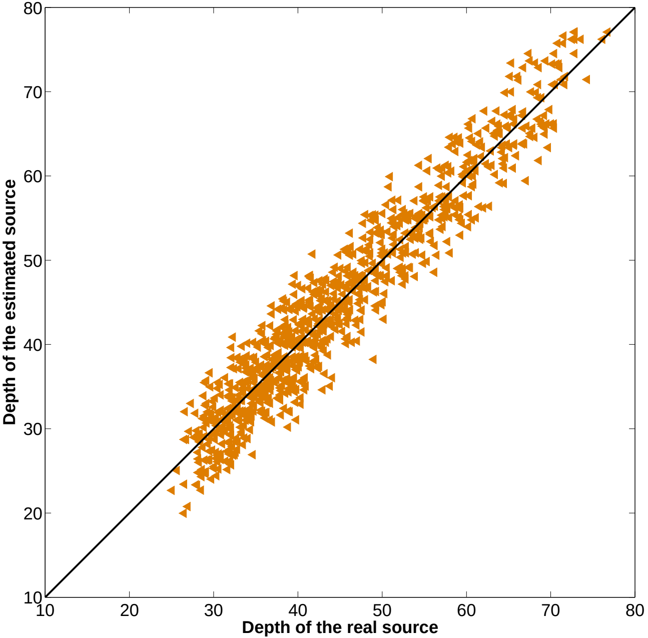
Depth Bias Study: Scatter Plots, sLORETA



Depth Bias Study: Scatter Plots, Full-CM



Depth Bias Study: Scatter Plots, Full-MAP



Averaged Results

- 1000 source configurations consisting of one near-surface and one deep-lying dipole..
- Noise at a noise level of 5%.

Method	EMD
MNE	44.63 mm
WMNE-ℓ_2	43.75 mm
WMNE-reg-ℓ_∞	41.79 mm
sLORETA	36.38 mm
CM	14.57 mm
MAP1	42.10 mm
MAP2	12.41 mm