Westfälische
Wilhelms-Universität
Münster

Hierarchical Bayesian Models for Focal EEG/MEG Inversion

"Innovative Verarbeitung bioelektrischer und biomagnetischer Signale" - bbs2012

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Background of the Talk

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, accepted.

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

Depth Bias and Masking in EEG/MEG

Recovery of brain networks involving

- multiple,
- focal,
- possibly deep-lying

sources.

Very important for the analysis of neurophysiological data and in clinical applications.

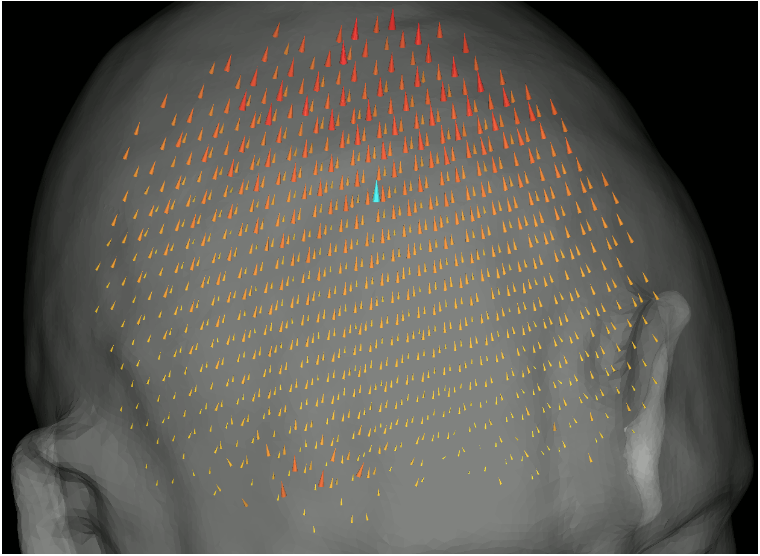
Unknown number and spatial extend of sources?
$\longrightarrow$ Current density reconstruction (CDR).

Problems of established CDR methods:

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

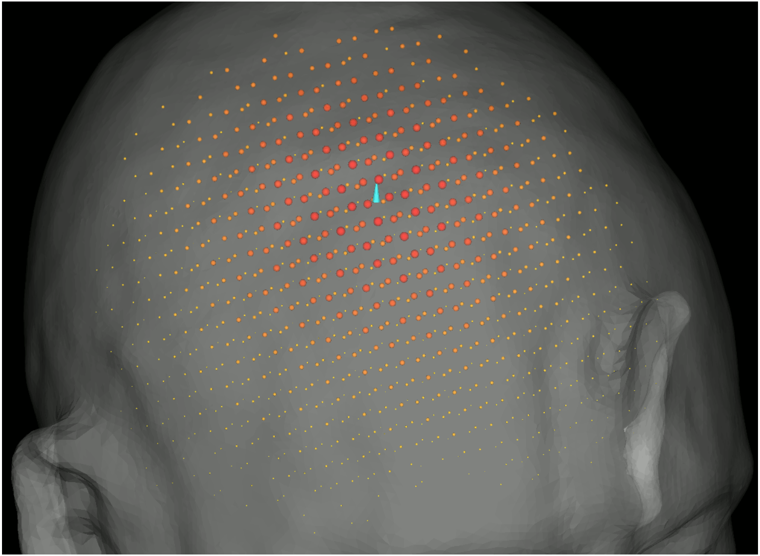
Depth Bias: Illustration

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



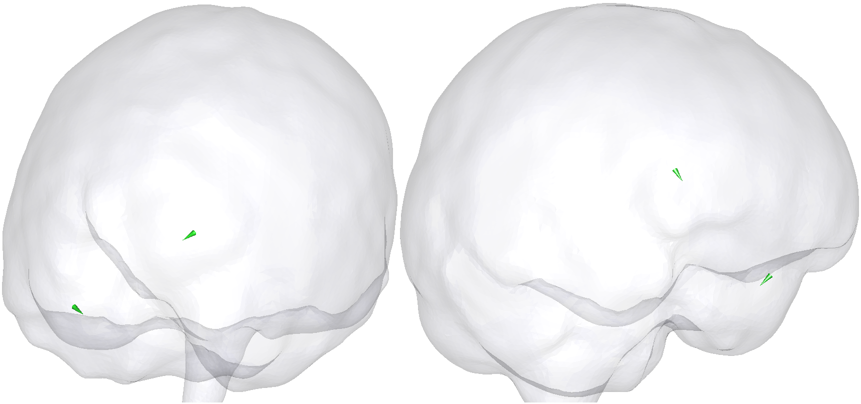
Depth Bias: Illustration

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



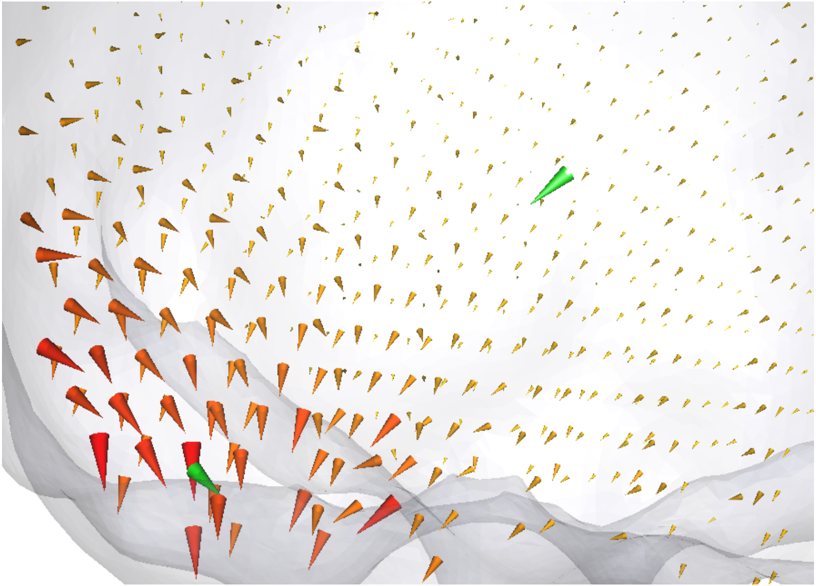
Masking: Illustration

Reference sources.



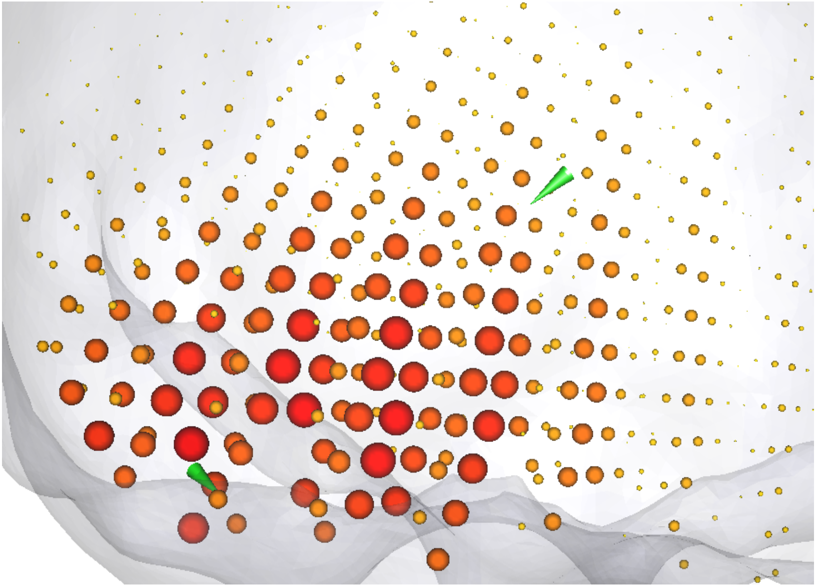
Masking: Illustration

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.

Key Question

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Key question

Can Full-MAP and Full-CM for HBM overcome the limitations (depth-bias, masking) of established CDR methods?

Own Contributions/Work

Key question

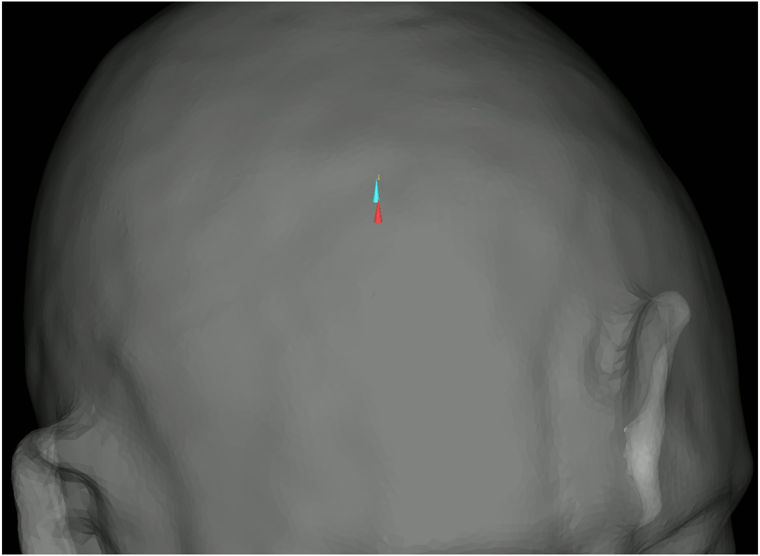
Can Full-MAP and Full-CM for HBM overcome the limitations (depth-bias, masking) of established CDR methods?

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 in simulation studies.

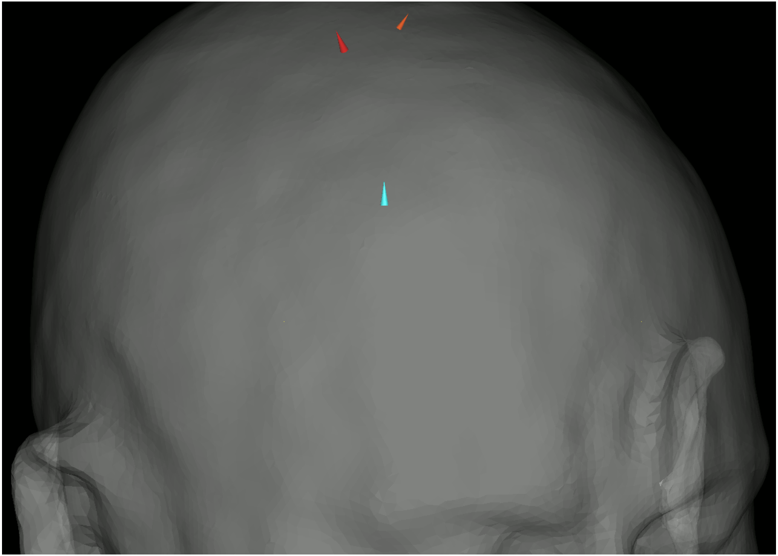
Results Depth Bias: Illustration

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



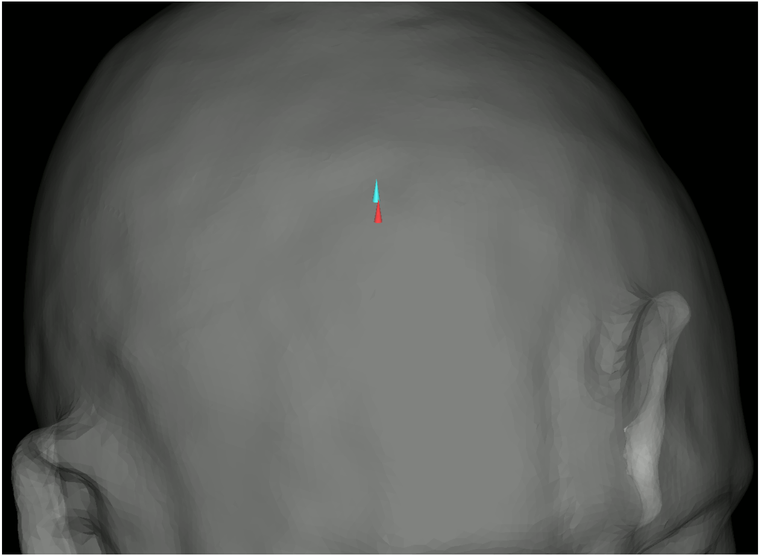
Results Depth Bias: Illustration

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.

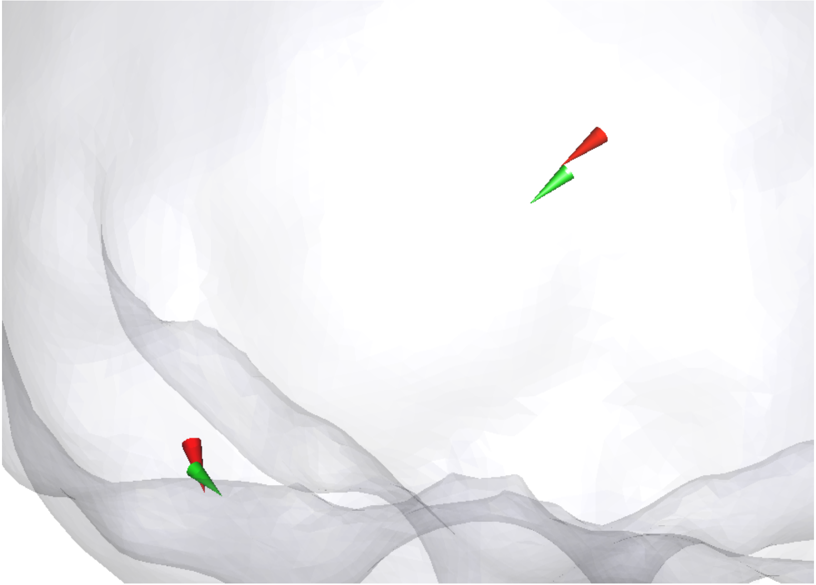


Results Masking: Illustration

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:

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, accepted.

Conclusions

Key question

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Can Full-MAP and Full-CM for HBM overcome the limitations (depth-bias, masking) of established CDR methods?

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 the analysis of neurophysiological data. ★

Work in Progress and Outlook

- Analysis of real data, e.g., tonotopy & auditory pathway reconstruction
- Temporal extension
- Extension to extended source scenarios
- Comparison to other HBM-based methods
- Interplay of HBM and more realistic head modeling
- Multimodal integration: EEG, MEG, PET, SPECT, fMRI, DW-MRI...

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

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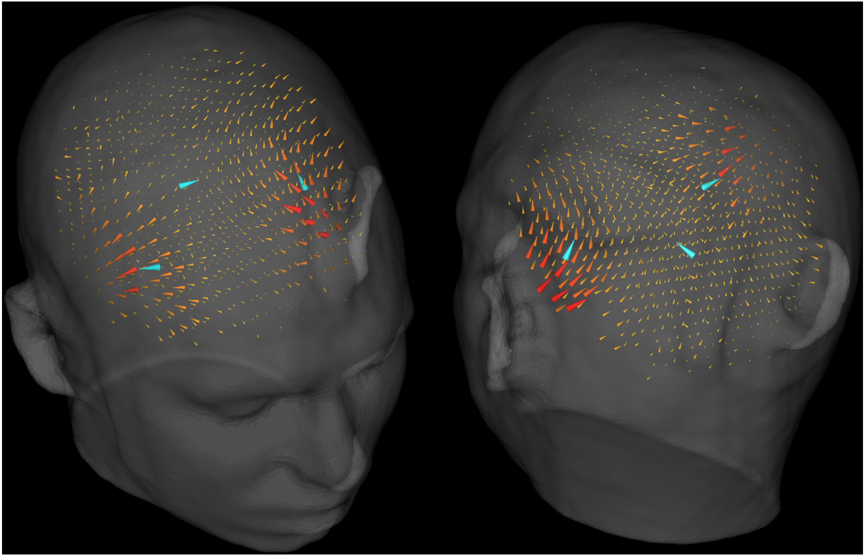
Hierarchical Bayesian Inference for the EEG Inverse Problem using Realistic FE Head Models: Depth Localization and Source Separation for Focal Primary Currents.
Neuroimage, accepted.

Thank you for your attention!

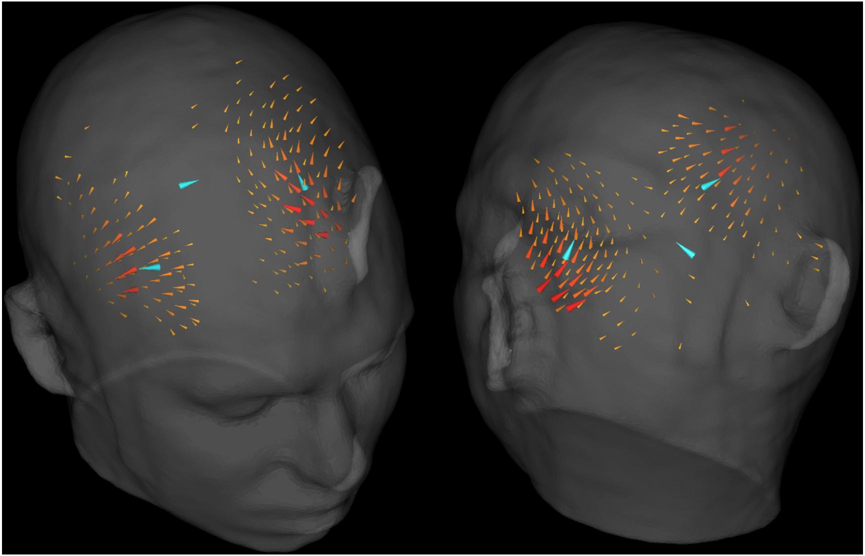
Software used by our group:

- Registration: FSL,FAIR;
- Segmentation: FSL, CURRY;
- FEM Meshing: Tetgen, vgrid, iso2mesh;
- FEM Computation: SimBio;
- Data Preprocessing: CURRY, BESA;
- Inverse computation: Matlab;
- Volume Visualization: SCIRun;
- Everything else & software integration: Matlab;

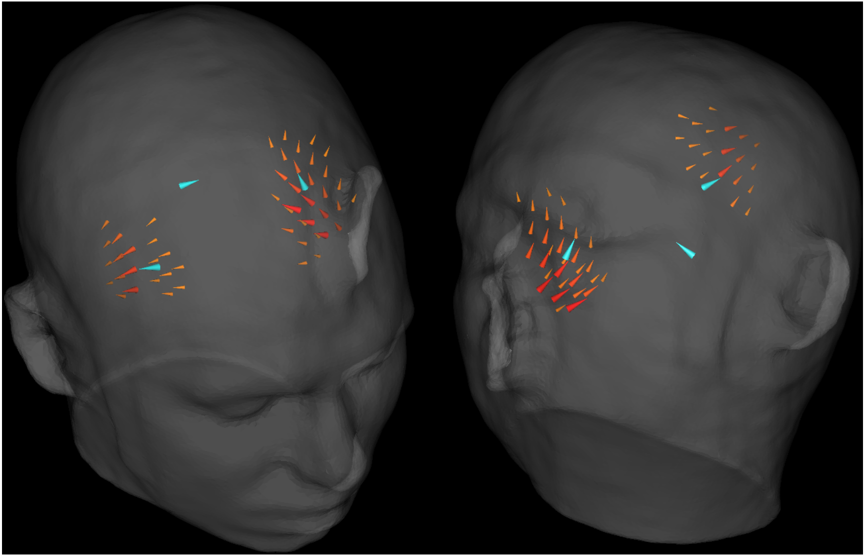
Three Dipoles: MNE



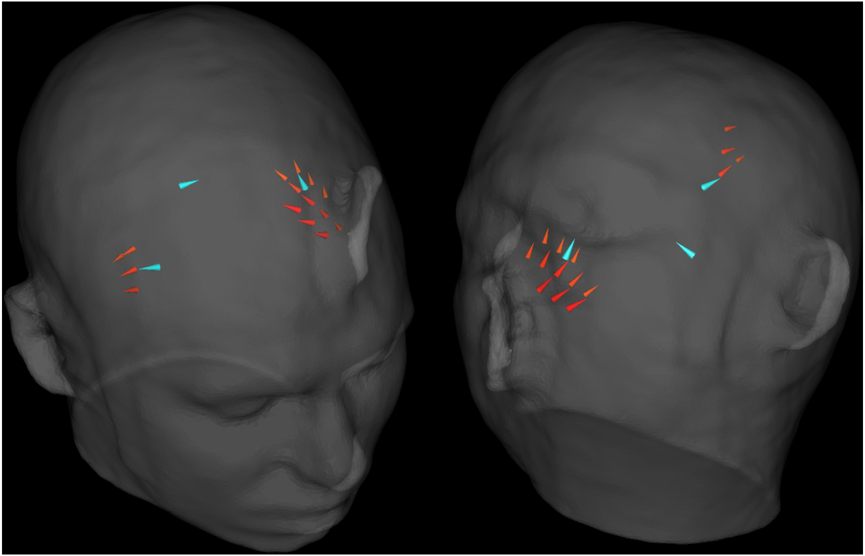
Three Dipoles: MNE, threshold = 30%



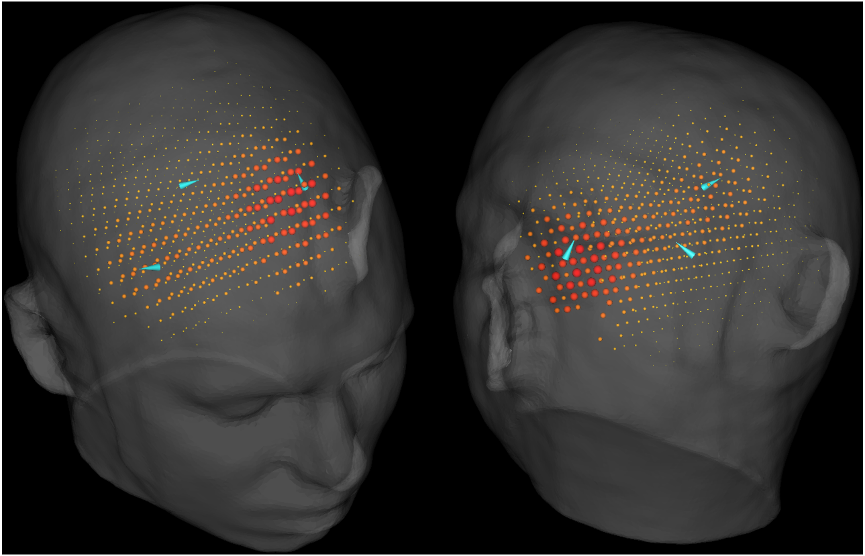
Three Dipoles: MNE, threshold = 50%



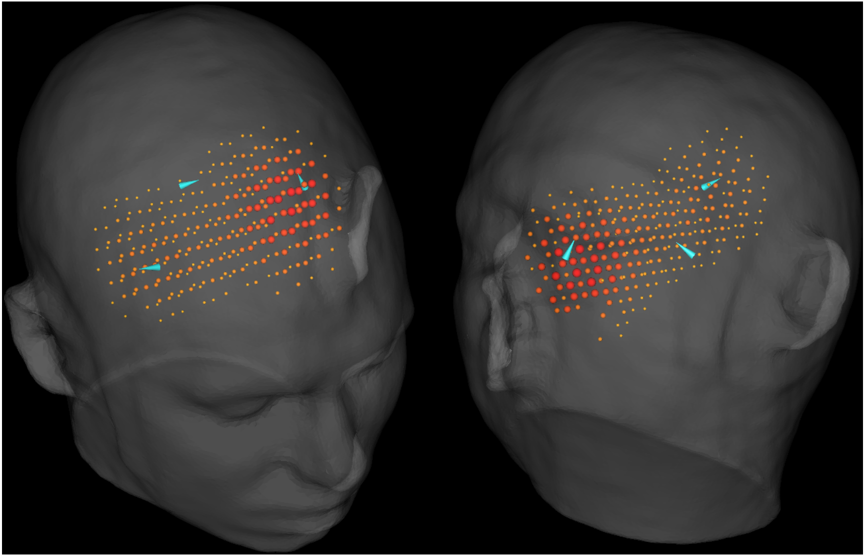
Three Dipoles: MNE, threshold = 70%



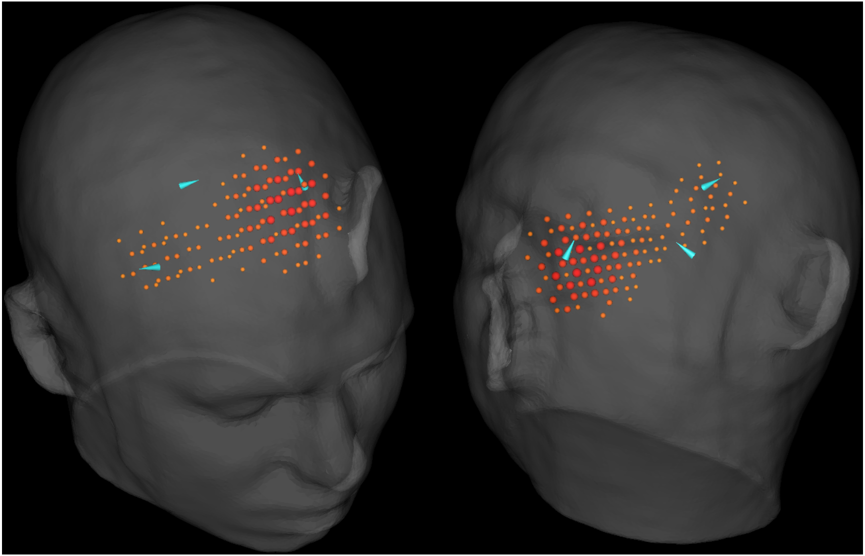
Three Dipoles: sLORETA



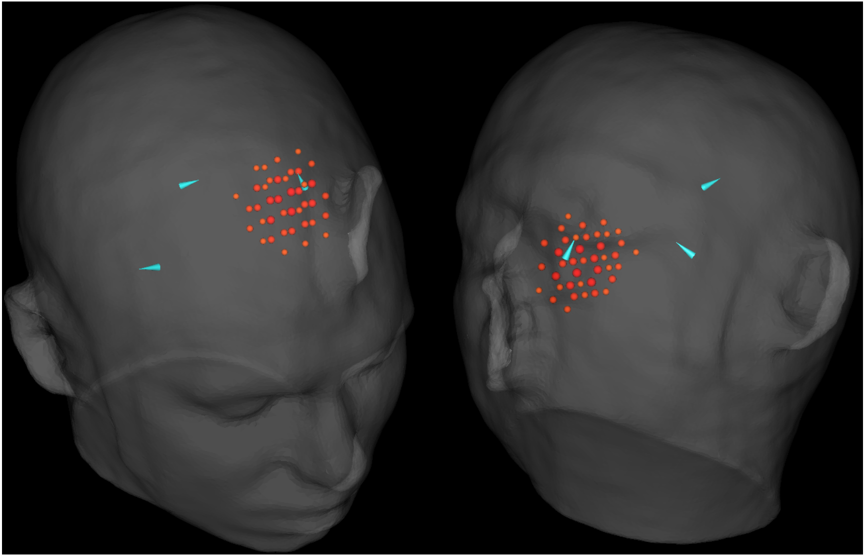
Three Dipoles: sLORETA, threshold = 30%



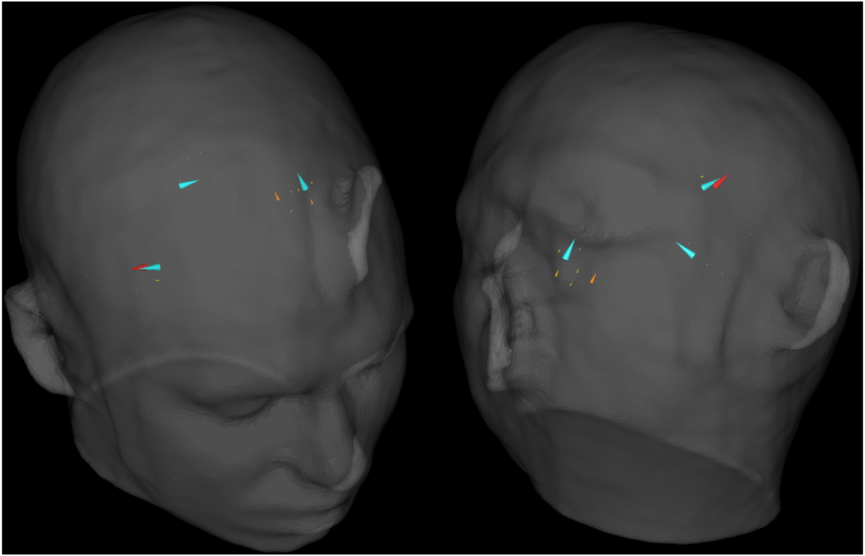
Three Dipoles: sLORETA, threshold = 50%



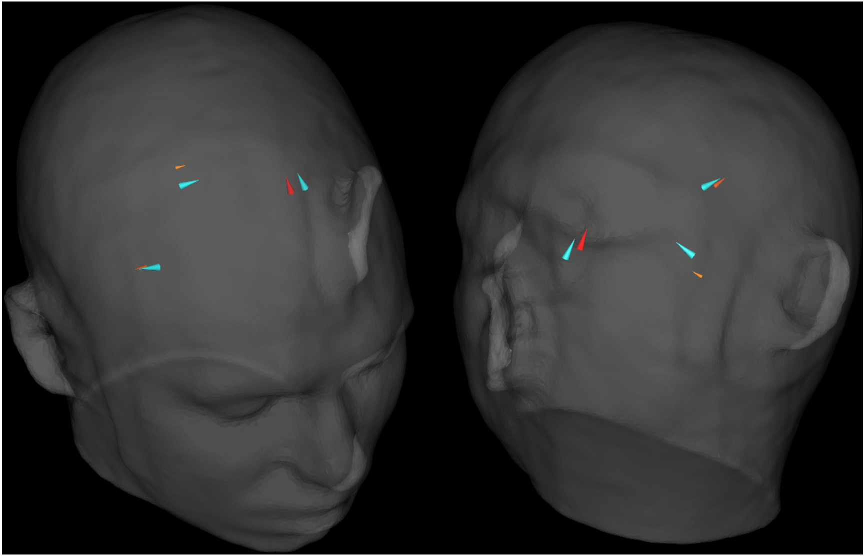
Three Dipoles: sLORETA, threshold = 70%



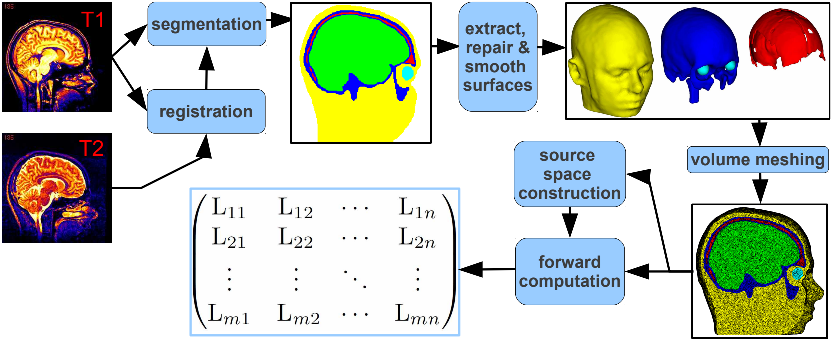
Three Dipoles: Full-CM



Three Dipoles: Full-MAP

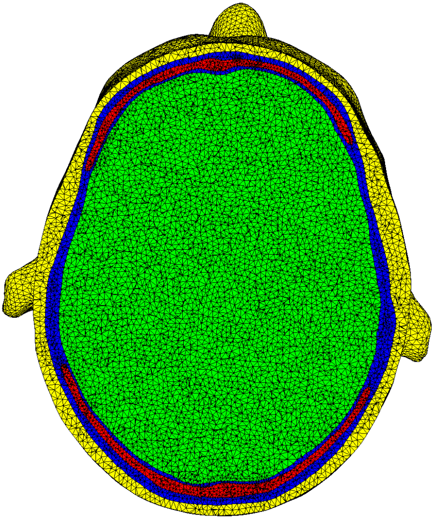


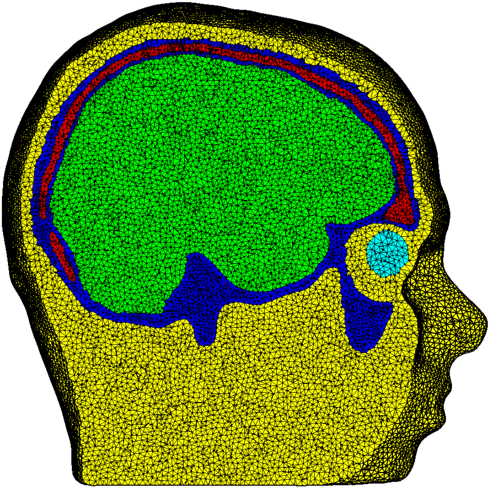
Head Model Generation Pipeline



Realistic Tetrahedron Head Model

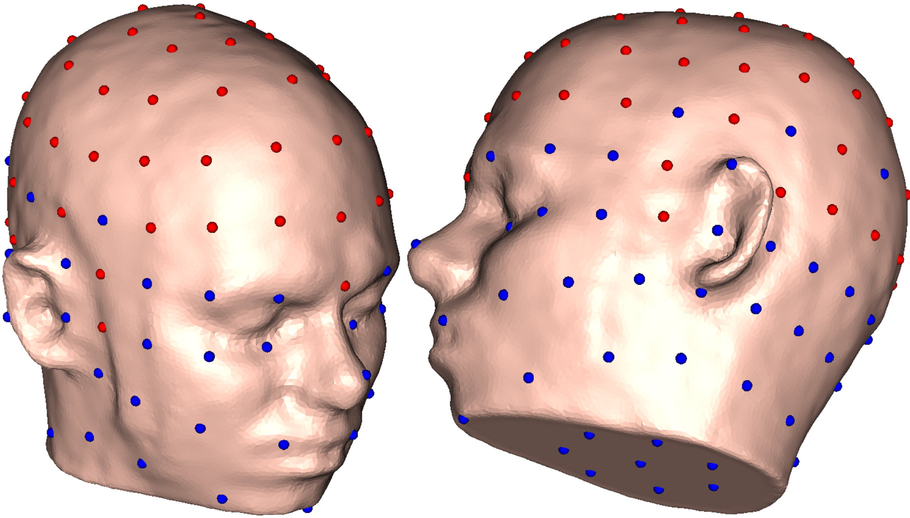
- Compartments: Skin, eyes, skull compacta and skull spongiosa, inner brain.
- 512 394 FEM nodes and 3 176 162 tetrahedra





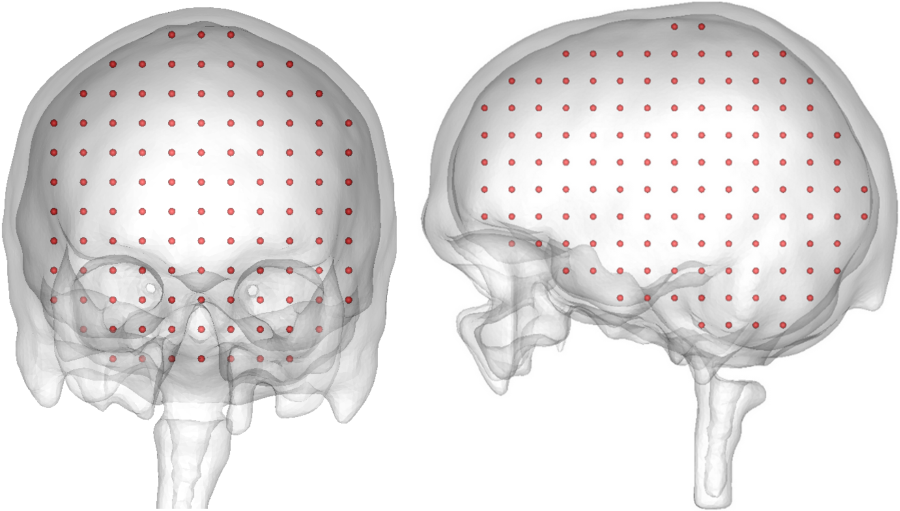
Realistic and Artificial Sensor Configurations

Red spheres: Realistic sensor configuration (63 electrodes); Red and blue spheres: Artificial sensor configuration (134 electrodes).



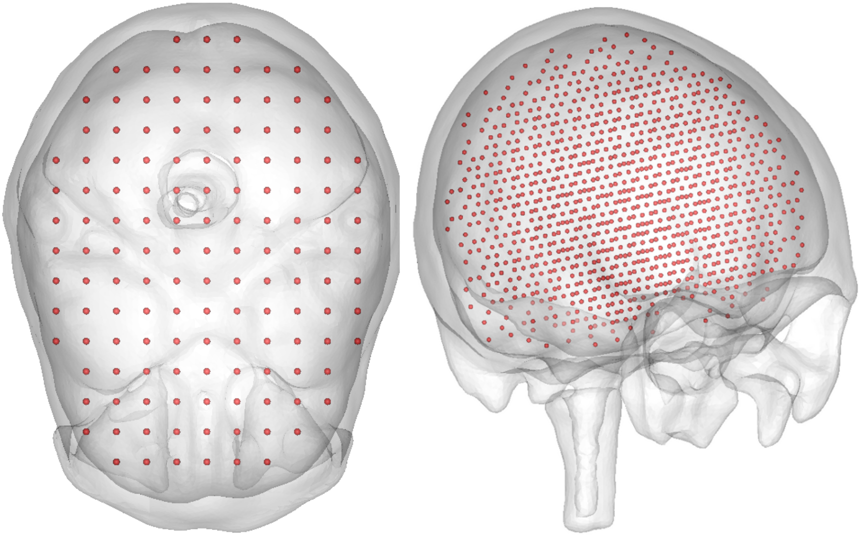
Source Space Grid

1000 source space nodes based on a regular grid.



Studies: Source Space Grid

1000 source space nodes based on a regular grid.



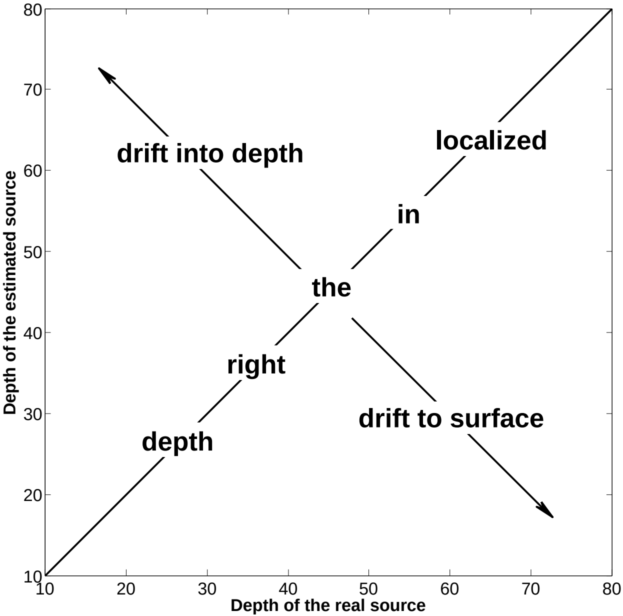
Depth Bias Study: Average Results (considered in this talk)

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

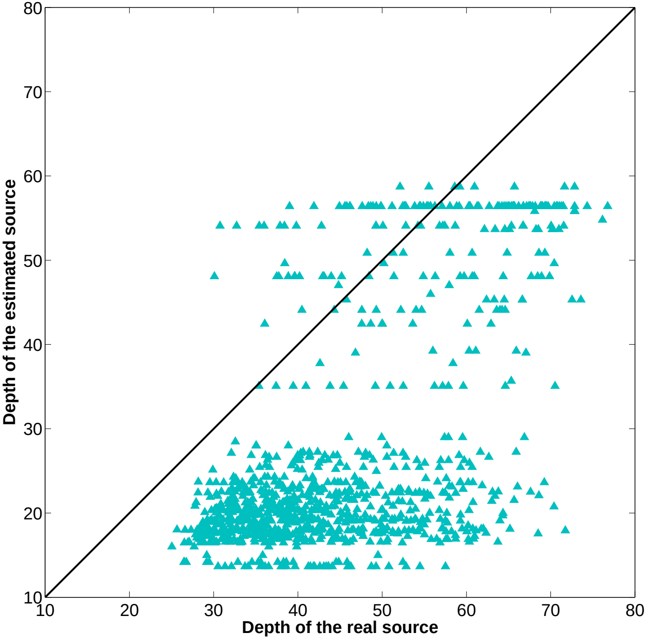
Method	EMD	DLE
MNE	53.20 / 54.90 mm	29.46 / 33.07 mm
sLORETA	40.58 / 43.43 mm	6.10 / 6.60 mm
CM	7.26 / 8.85 mm	6.21 / 6.94 mm
MAP1	28.18 / 32.77 mm	27.00 / 33.76 mm
MAP2	5.83 / 6.15 mm	5.78 / 6.14 mm

- 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).

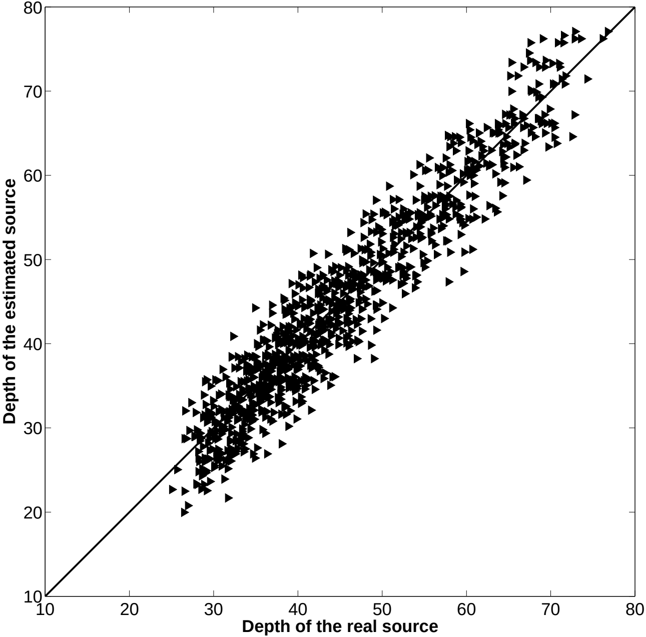
Depth Bias Study: Scatter Plots, Explanation



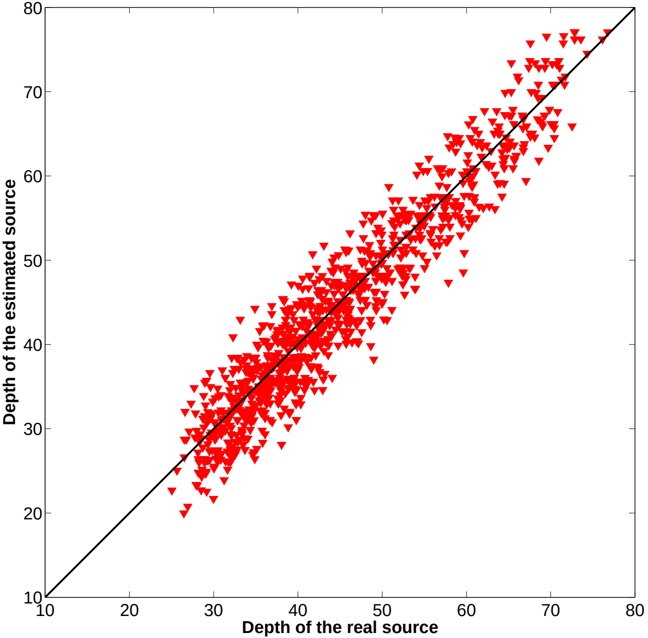
Depth Bias Study: Scatter Plots, MNE, artificial cap



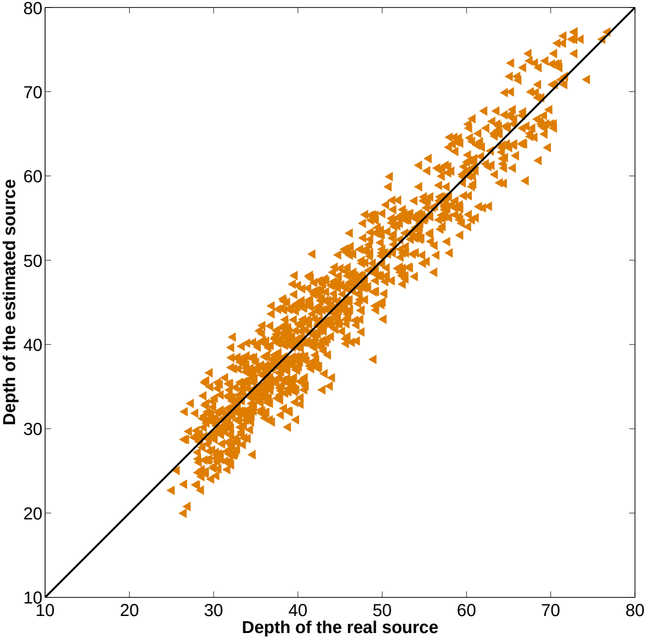
Depth Bias Study: Scatter Plots, sLORETA, artificial cap



Depth Bias Study: Scatter Plots, Full-CM, artificial cap



Depth Bias Study: Scatter Plots, Full-MAP, artificial cap



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 / 45.75 mm
WMNE-ℓ_2	43.75 / 44.62 mm
WMNE-reg-ℓ_∞	41.79 / 42.78 mm
sLORETA	36.38 / 38.07 mm
CM	14.57 / 18.21 mm
MAP1	42.10 / 47.97 mm
MAP2	12.41 / 15.83 mm