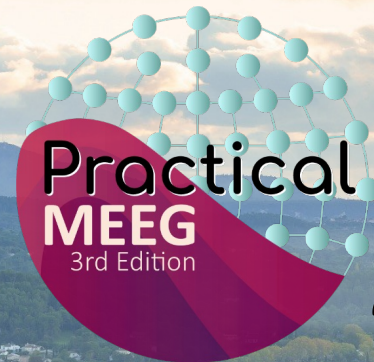


SOURCE LEVEL ANALYSIS I



*October 2025,
Aix-en-Provence*

John C. Mosher
Professor, Department of Neurology
McGovern Medical School
UTHealth Houston, Texas, USA

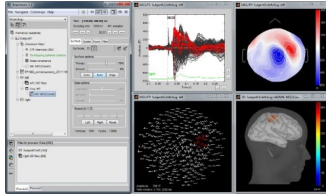
Outline

All models are wrong, but some are useful. -George Box

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Software Tools for MEG/EEG Source Analysis

Brainstorm



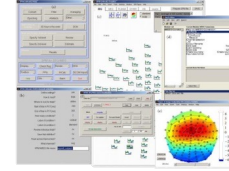
<http://neuroimage.usc.edu/brainstorm/>

MNE & MNE python



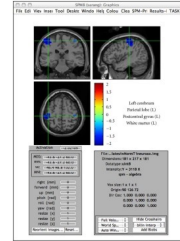
<http://martinos.org/mne/stable/index.html>

SPM



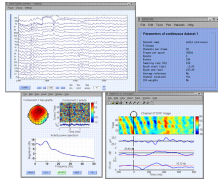
<http://www.fil.ion.ucl.ac.uk/spm/software/>

NutMEG



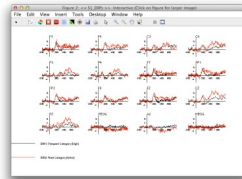
<http://nutmeg.berkeley.edu/>

EEGLAB



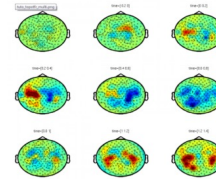
<http://sccn.ucsd.edu/eeelab/>

ERPLAB



<http://erpinfo.org/erplab/>

Fieldtrip



<http://www.fieldtriptoolbox.org/>

rtMEG: Real time MEG software interface

BCILAB: Open source Matlab toolbox for brain-computer interfaces

NFT: Neuroelectromagnetic forward head modeling

OpenMEEG: Neuroelectromagnetic BEM forward head modeling

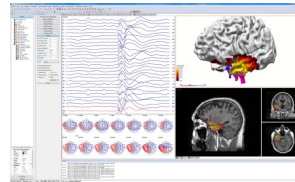
DUNEuro: Neuroelectromagnetic FEM forward head modeling

Commercial Products

Vendor software

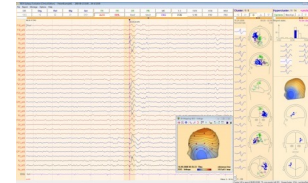
Elekta Neuromag
CTFMEG
EGI: Net Station 5
BioSemi

Curry



<http://compumedicsneuroscan.com/>

BESA



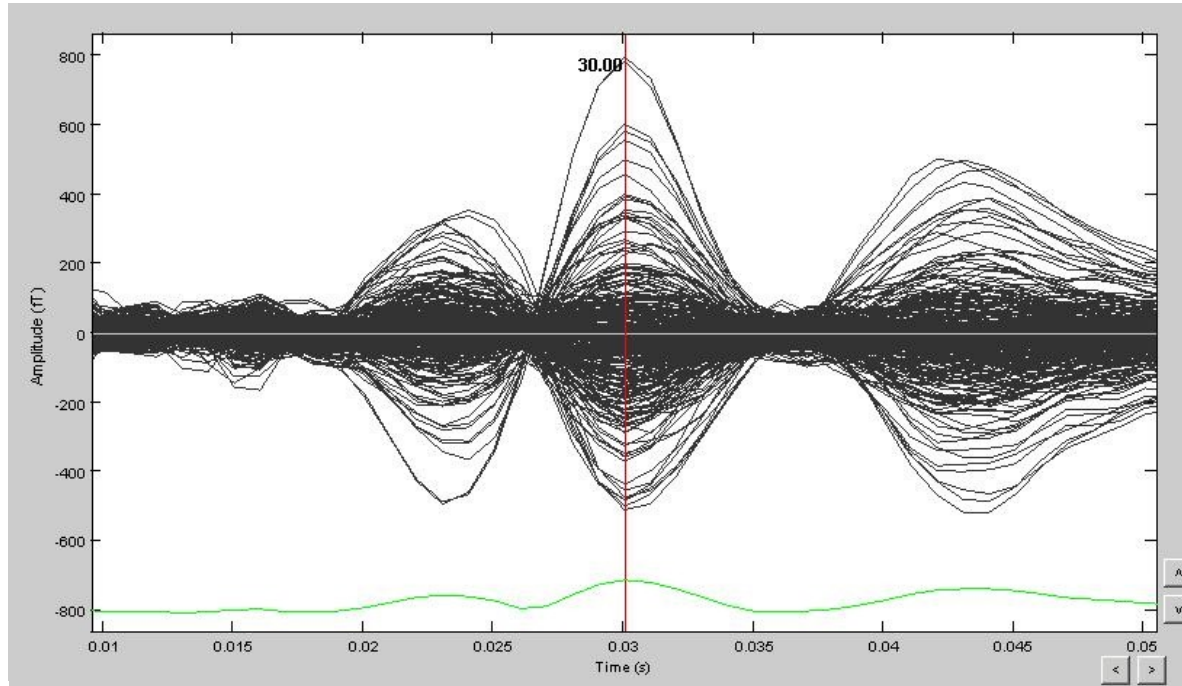
<http://www.besa.de/>

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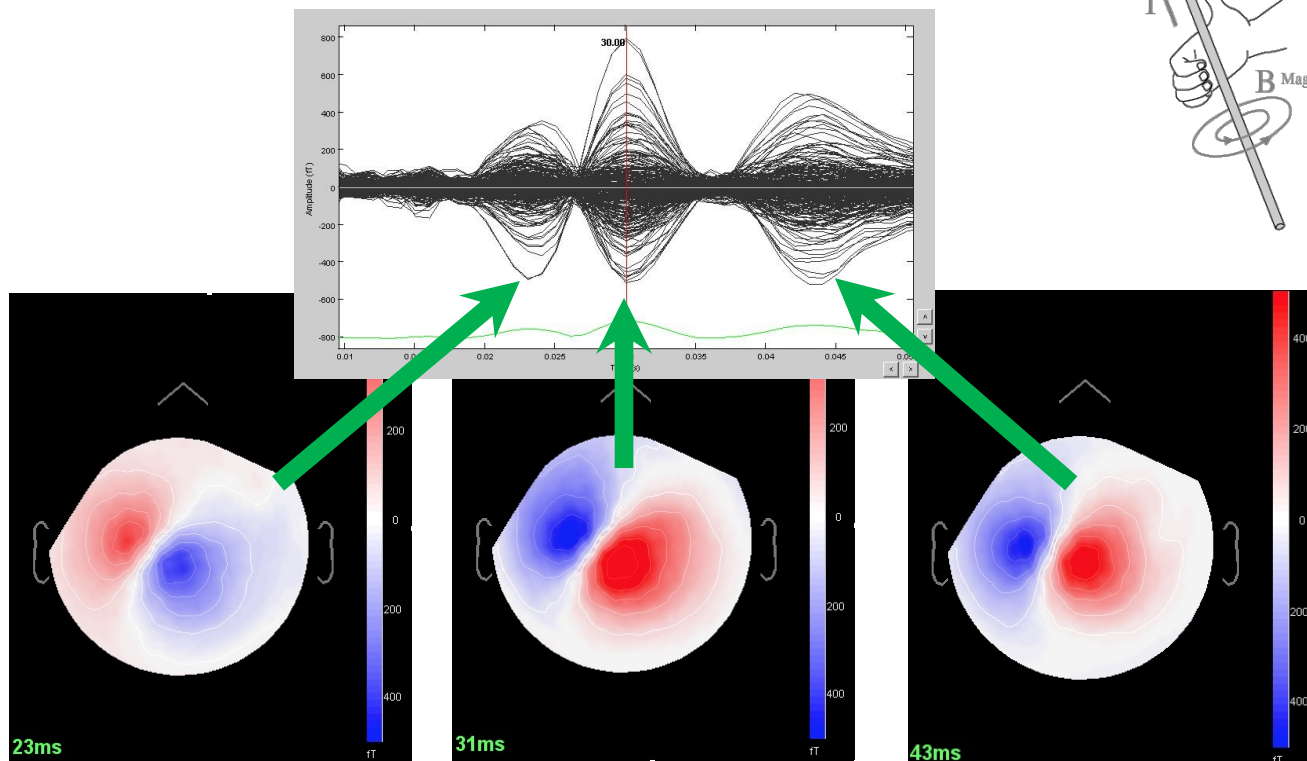
Example: Median Nerve Response



(Dr Klaas, Brainstorm database, CCF MEG Data)

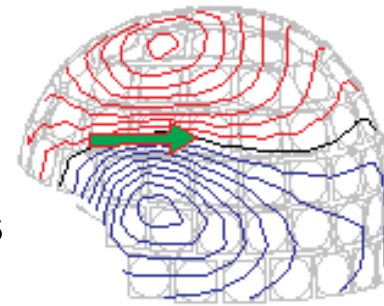
- A “butterfly” diagram representing 204 planar gradiometers

Phase Reversals of Dipolar Orientation

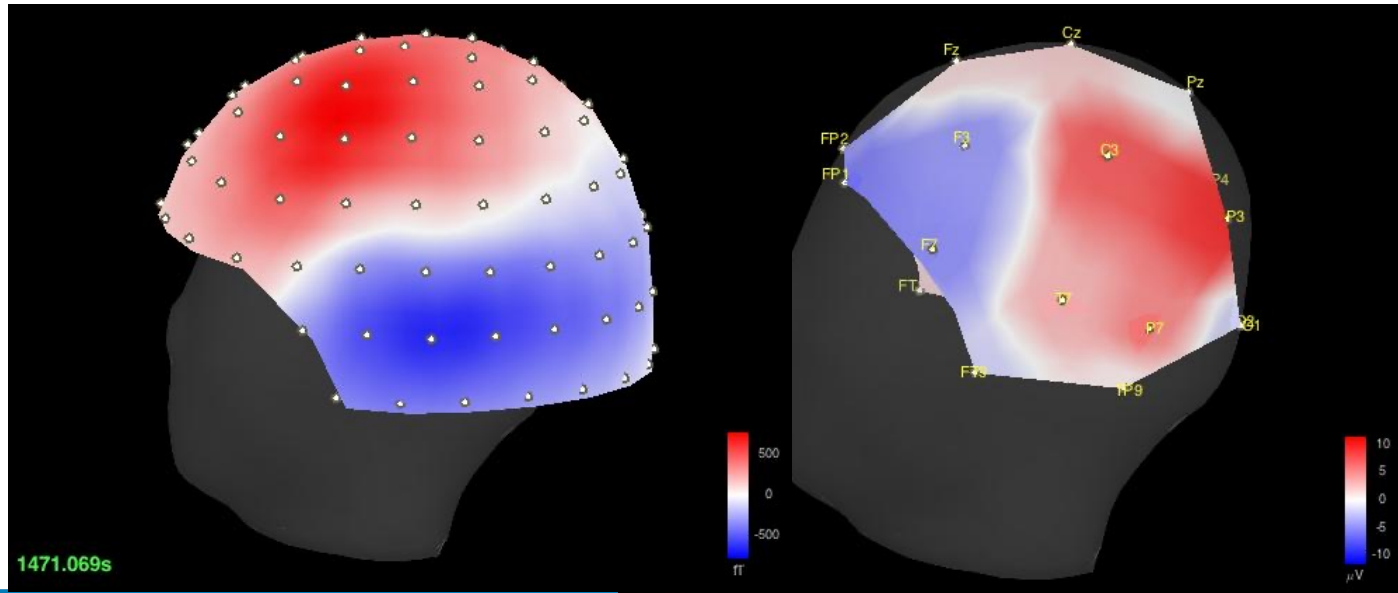


- Anterior, Posterior, Posterior facing dipolar pattern

Topographies of a Dipole



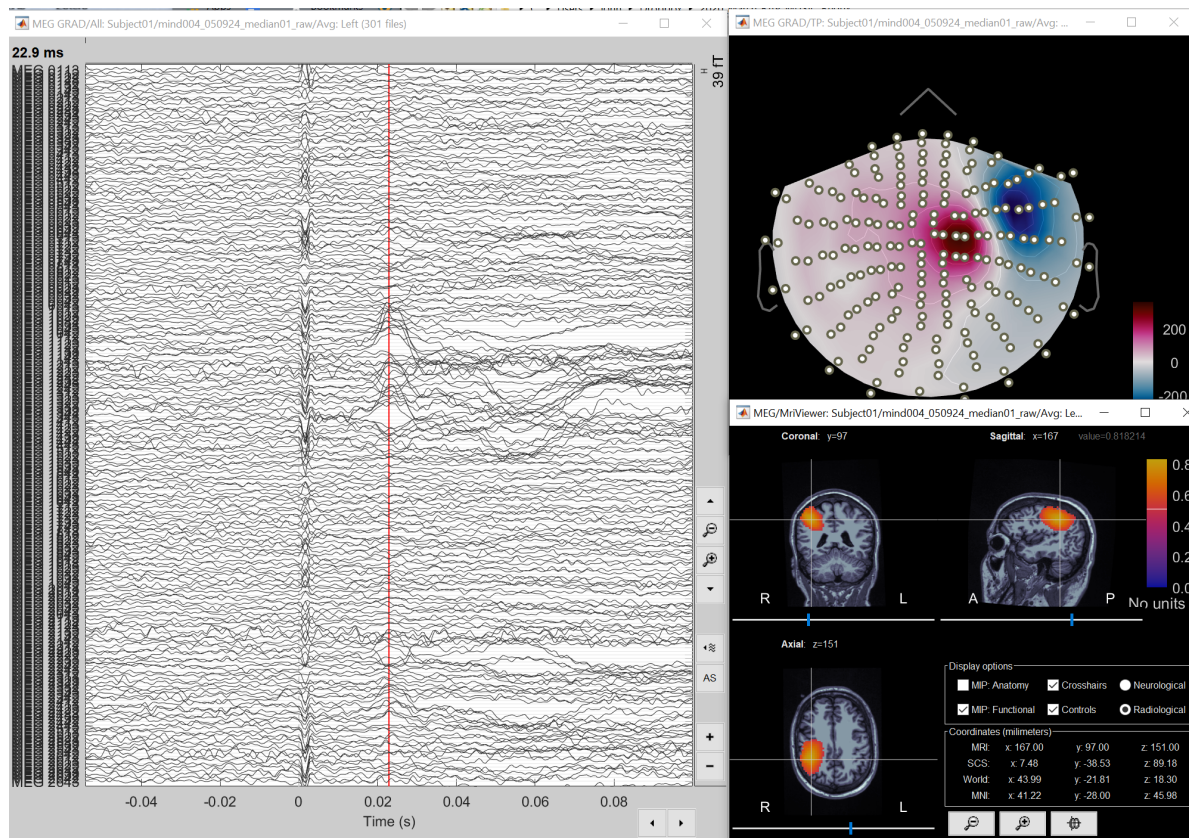
- MEG (306) vs. EEG (23) spatial patterns
- Complementary Directions



From Sensor to Map to Source Image

How do we go from

- sensor data, to
- channel mapping images, to
- source modeling?



Outline

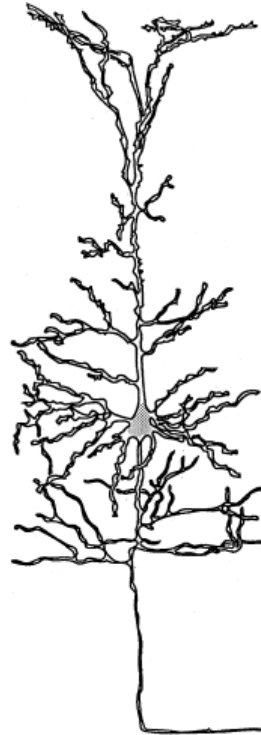
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The Cortical Model: Primary Neural Sources

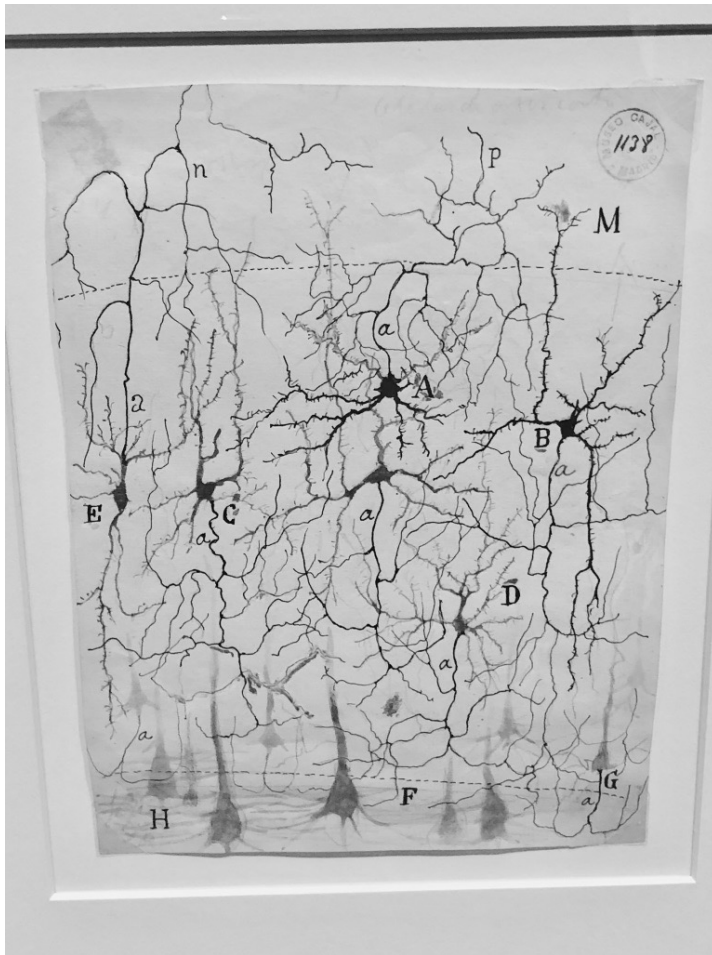


Ramon y Cajal 1888 from Hamalainen
et al. 1993 Reviews of Modern Physics



- Primary currents are produced by current flow in apical dendrites in **cortical pyramidal neurons**.
- These Post Synaptic Potentials (PSPs) are summed over **millions of neurons** and tens of milliseconds
- **Equivalent Current Dipole** modeling is a “Macro-cellular” and not a “microcellular” model.

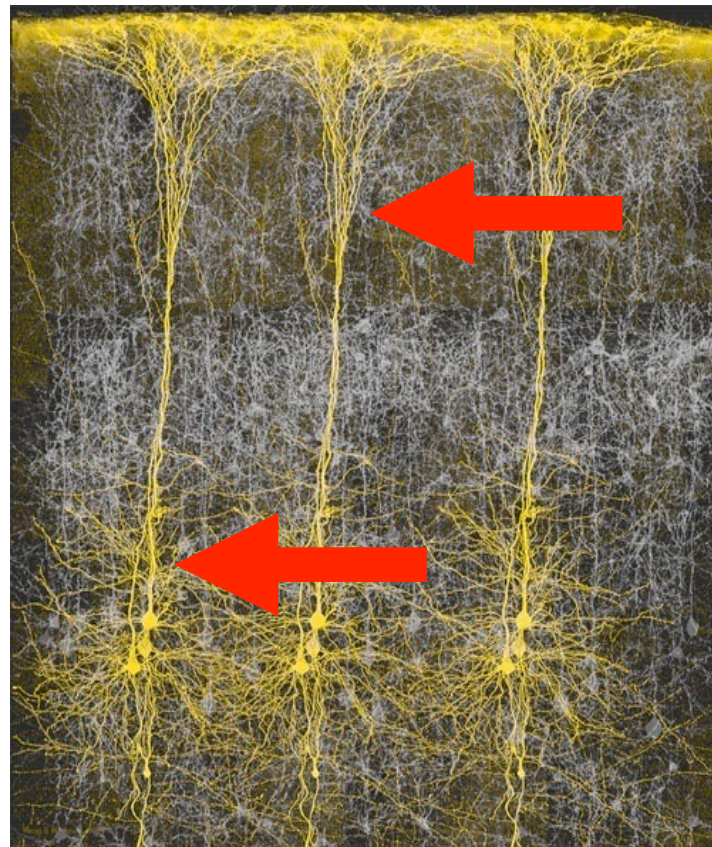
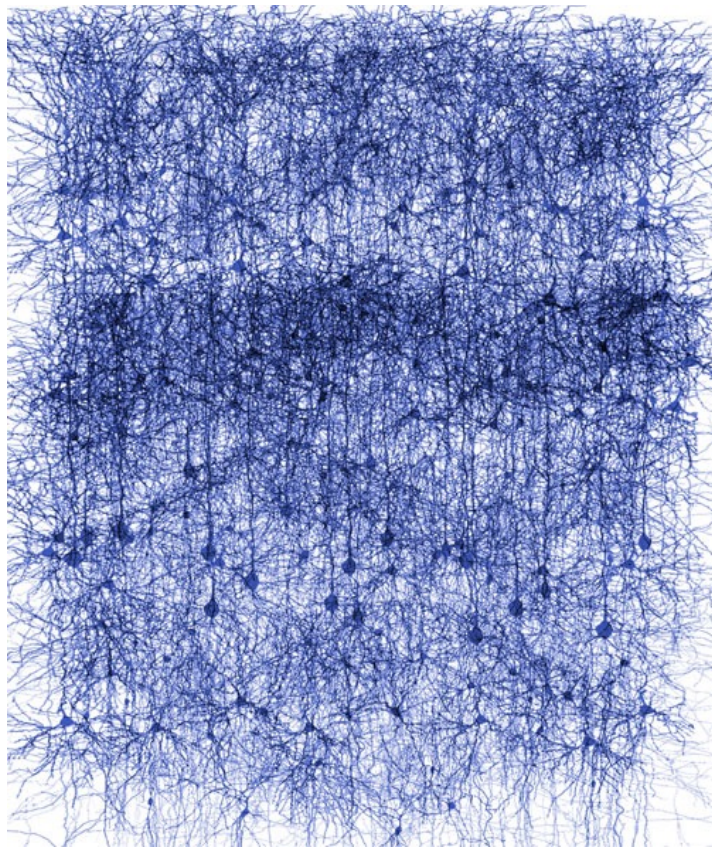
The MIT Museum in Cambridge showcased drawings by Ramon y Cajal from the 1890s.



Dimitrios Pantazis

Matti Hamalainen

A Forest of Neurons in Gray Matter



Excitatory vs Inhibitory PSP

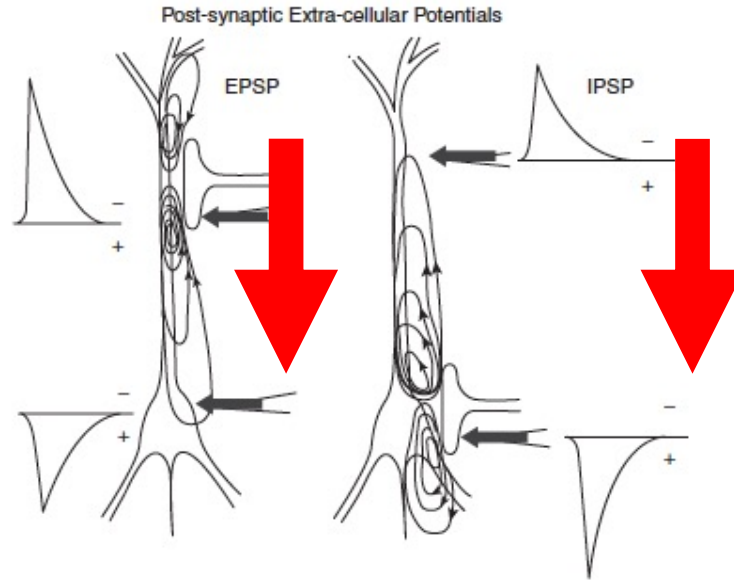
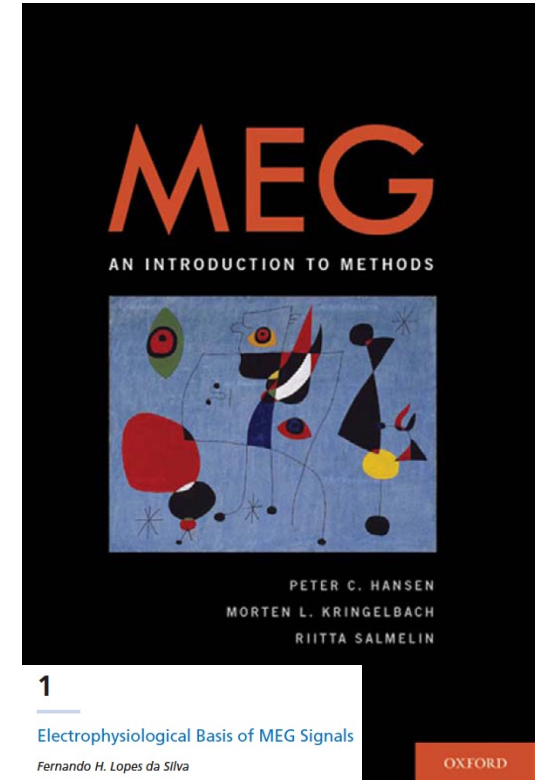
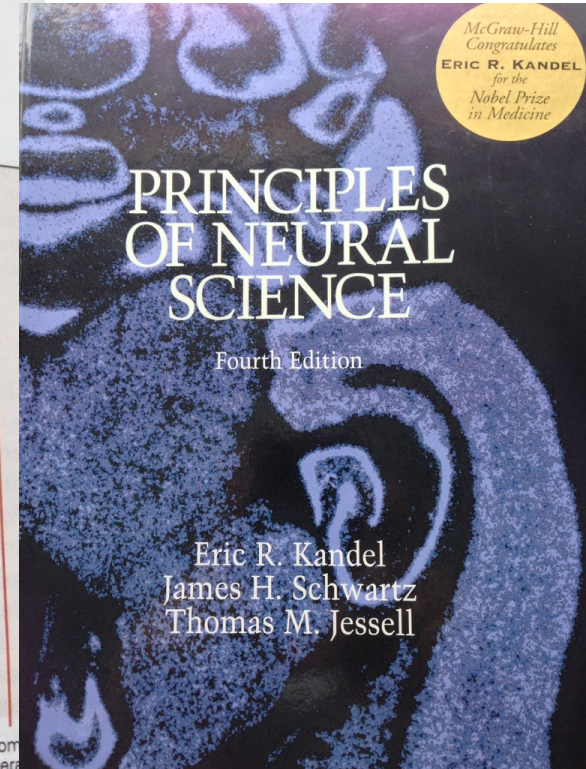
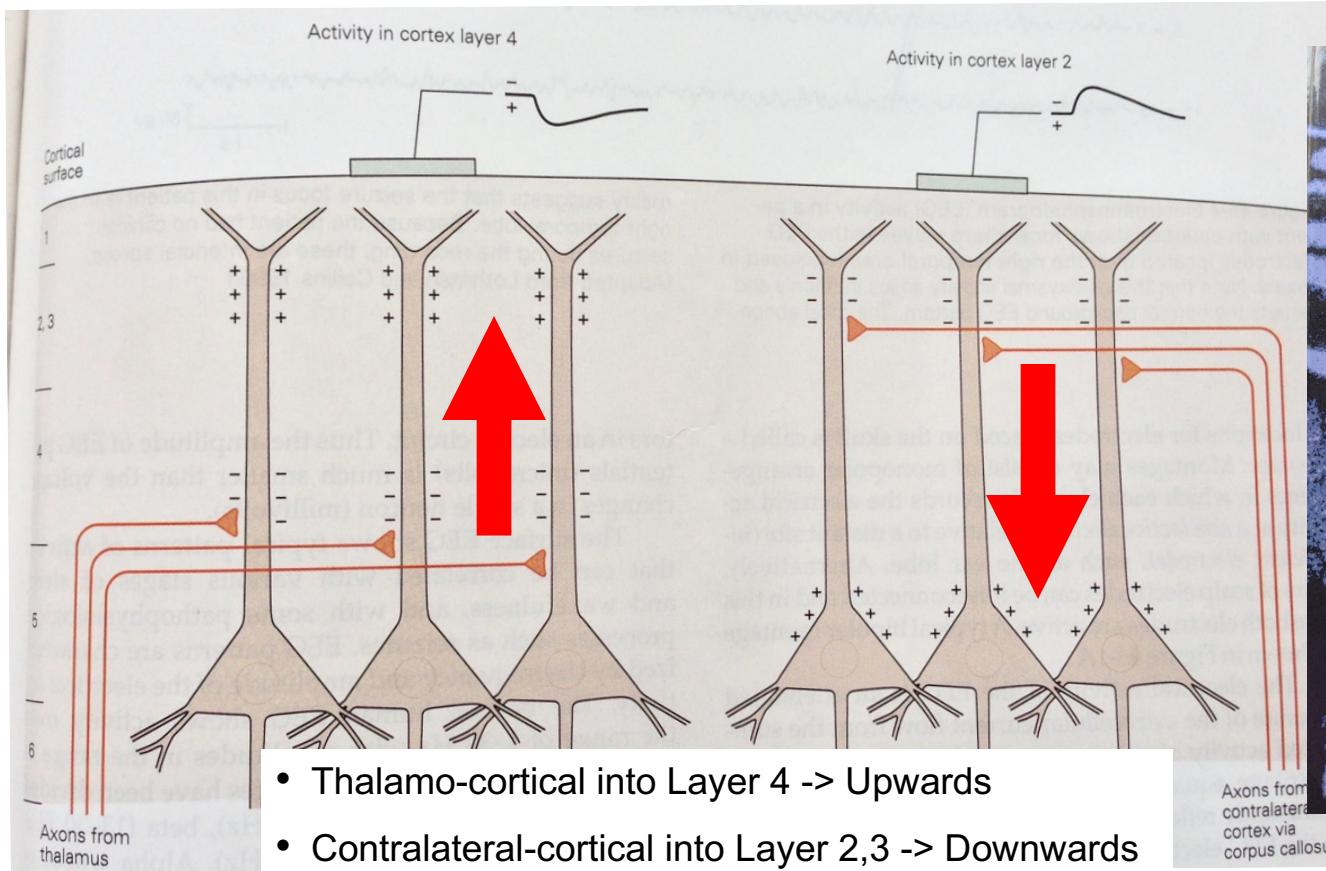


Figure 1-1. Intra- and extracellular current flow in an idealized pyramidal neuron due to different types of synaptic activation. EPSP: excitatory

- Ambiguous whether excitatory in upper layers or inhibitory in lower layers.

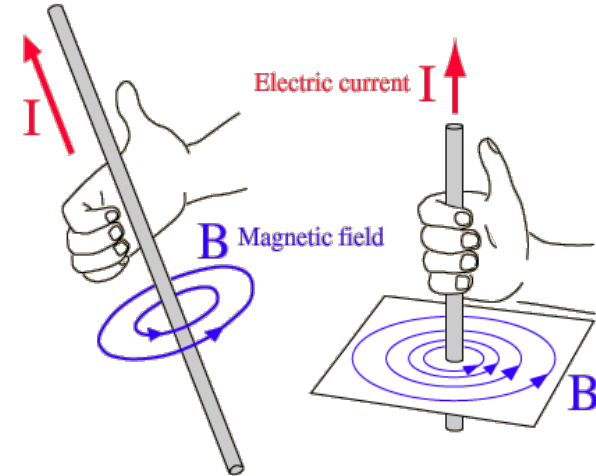
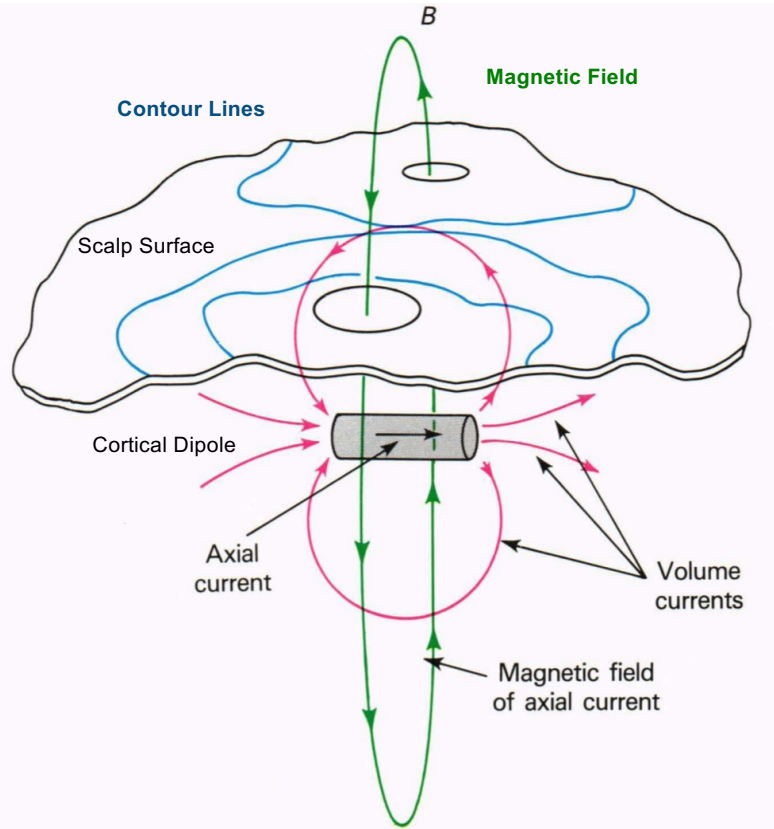


EPSP Distal vs Proximal



Cortical Current Elemental Model

- The same current dipole element produces potentials on the surface (EEG) as well as external magnetic fields (MEG).



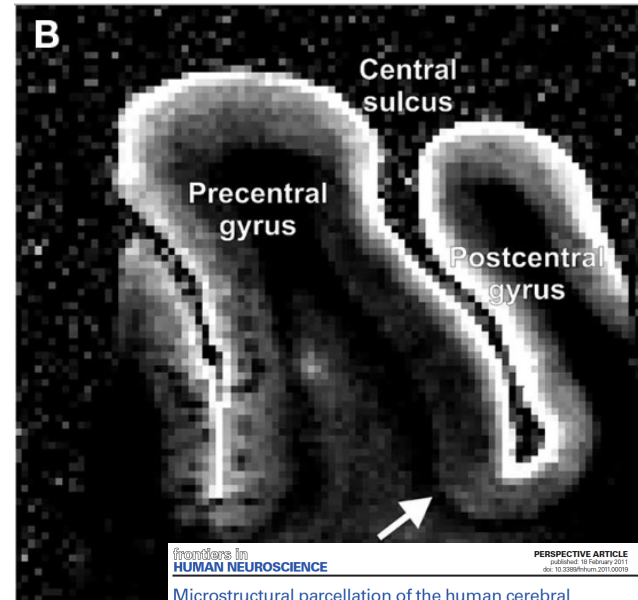
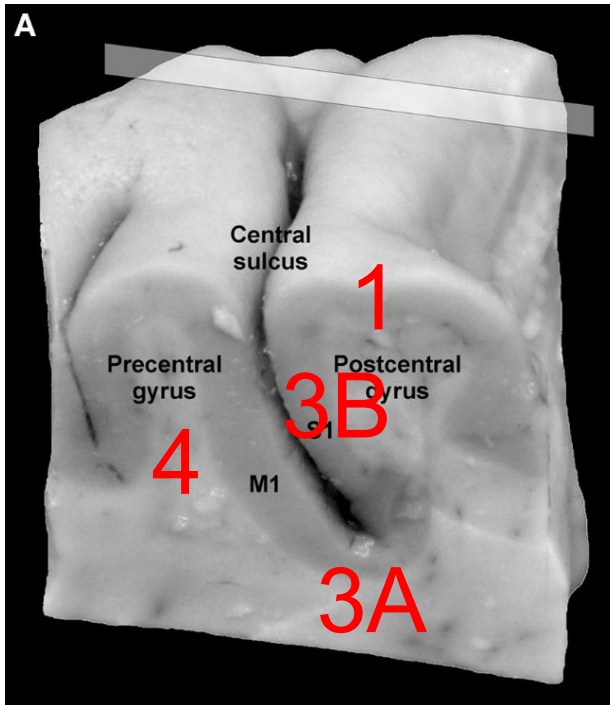
Ko, Skura, Eaton, "A new method for MEG", Johns Hopkins APL Tech Digest, V9 N3, 1988.

Outline

All models are wrong, but some are useful. -George Box

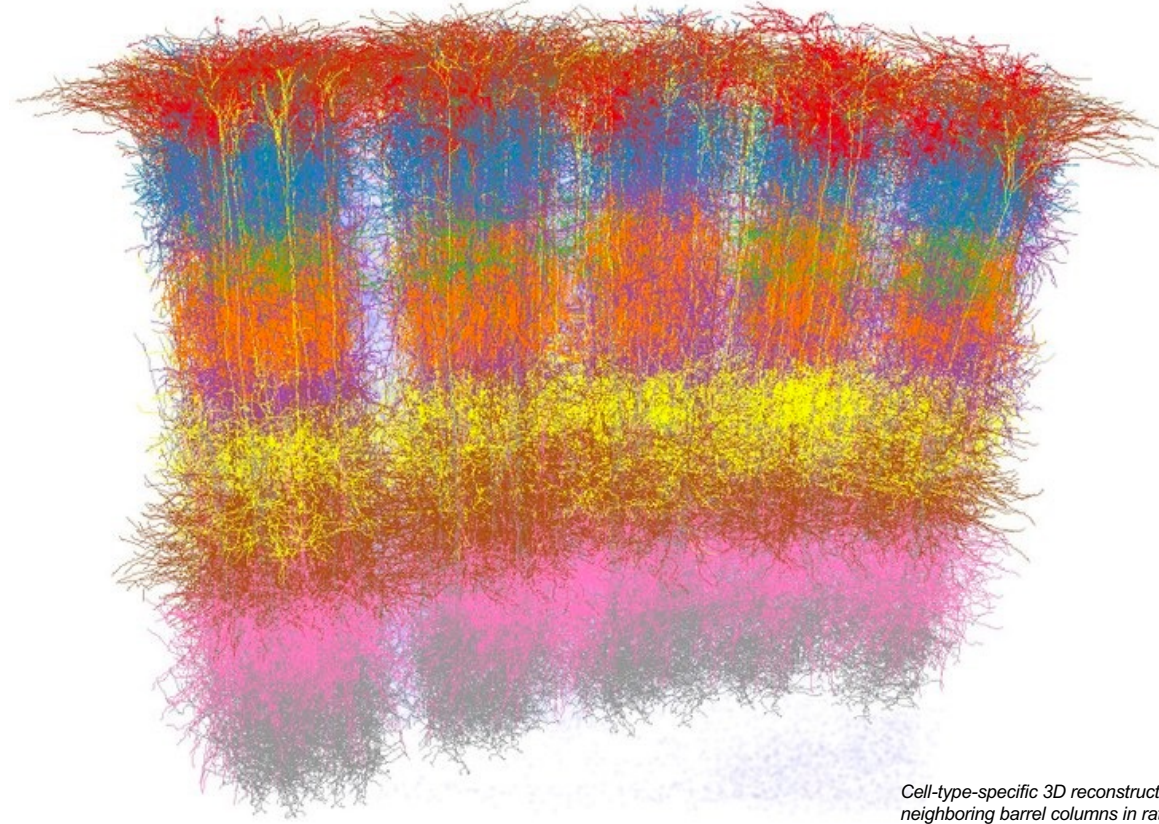
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Brodmann Areas at 7T - Postmortem



- M1 - Brodmann 4 - Anterior Central Sulcus - Precentral Gyrus
- S1 - Brodmann 3A, 3B, 1 - Posterior Central Sulcus - Postcentral Gyrus

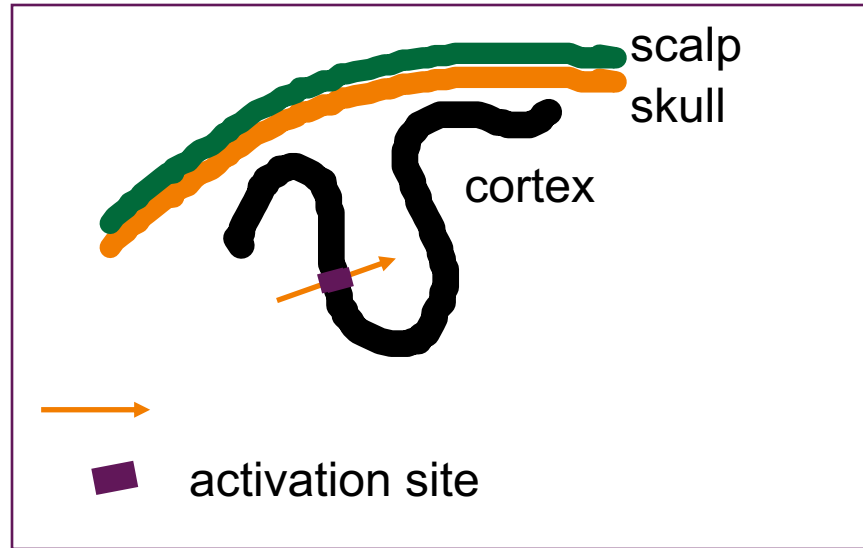
“Cortical Columns”



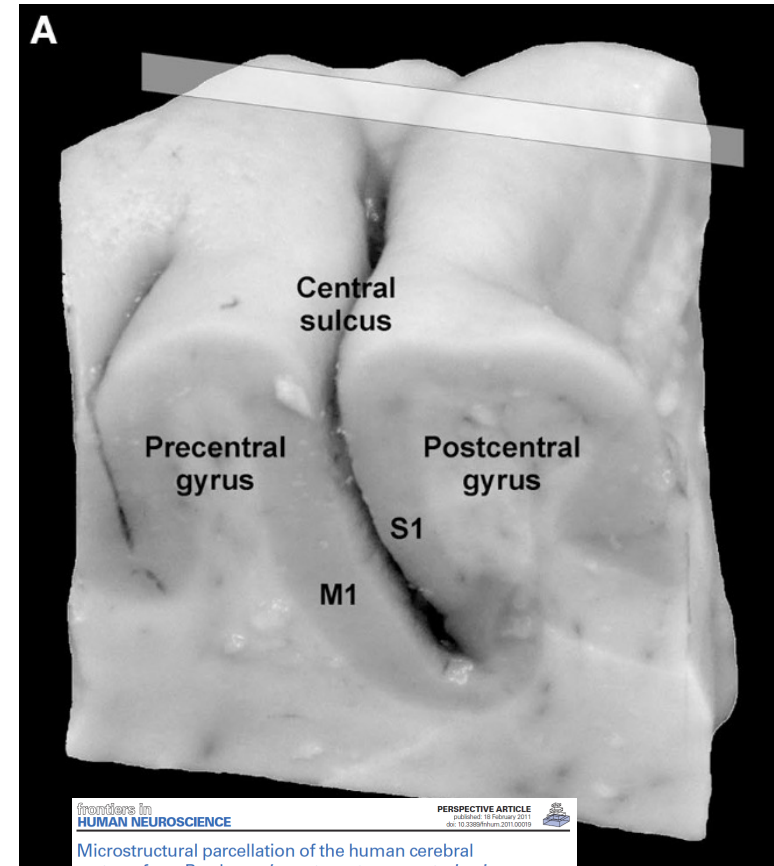
- Model the 3D multilayer cortex as columns.
- Emphasize the 2D cortical surface in units of square mm
- “Wrong” – but useful!

Cell-type-specific 3D reconstruction of five neighboring barrel columns in rat vibrissa cortex (credit: Marcel Oberlaender et al.)

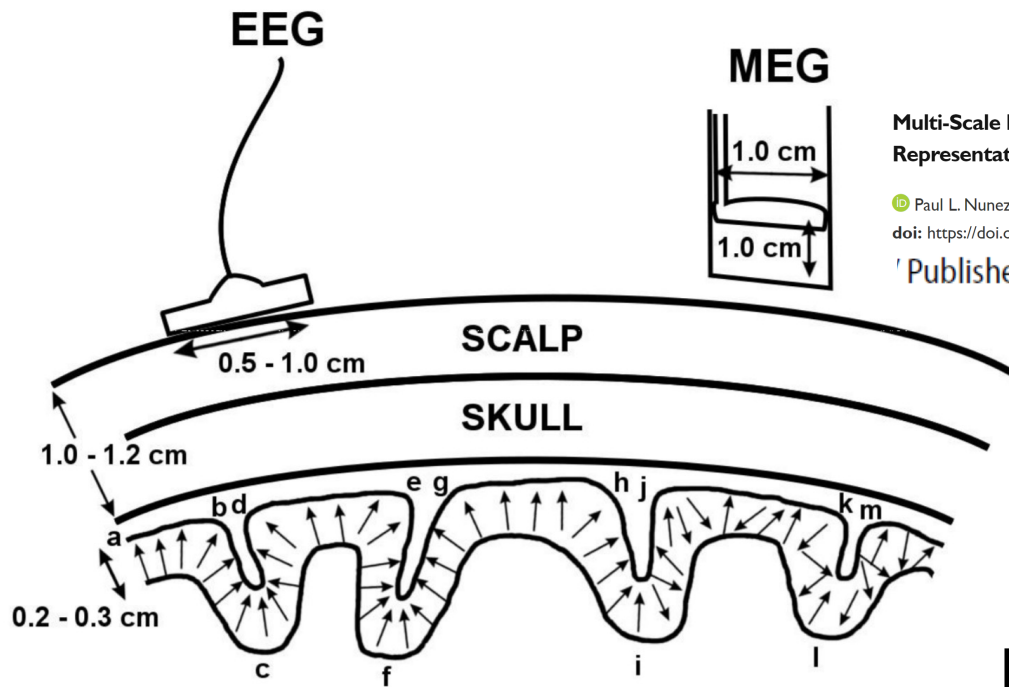
Basic Source Model – The 2D Cortical Mantle



- We can think in terms of the 2D surface area, rather than the true 3D thickness of the cortical mantle.



Not all cortex has a columnar structure!



Multi-Scale Neural Sources of EEG: Genuine, Equivalent, and Representative. A Tutorial Review

Paul L. Nunez, Michael D. Nunez, Ramesh Srinivasan

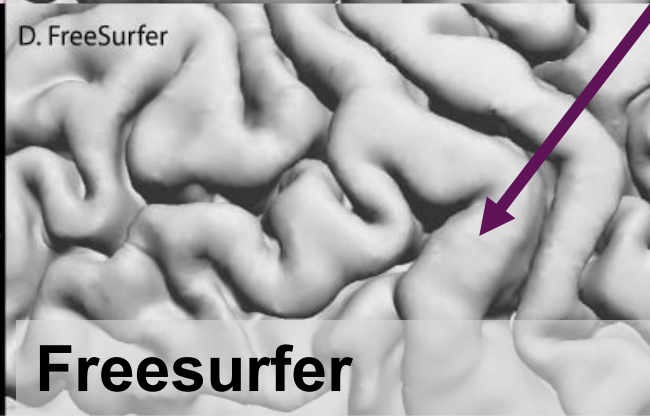
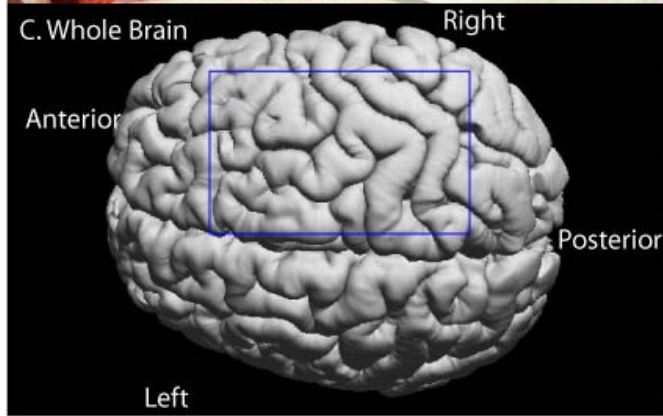
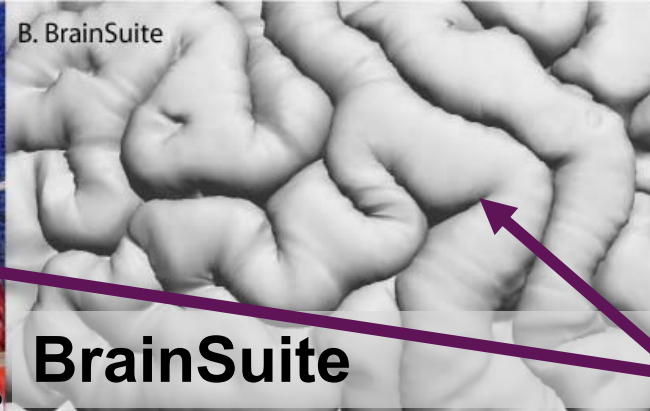
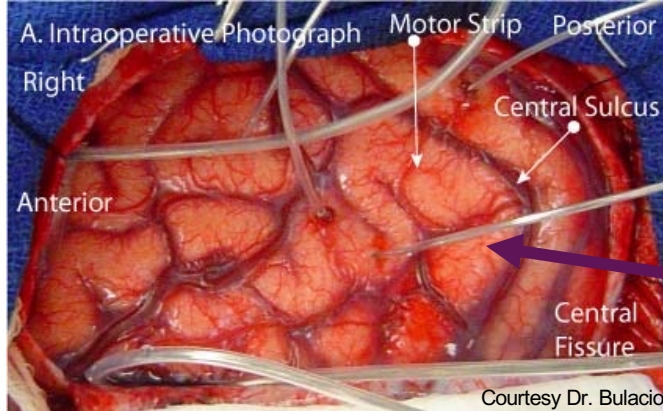
doi: <https://doi.org/10.1101/391318>

Published online: 25 January 2019

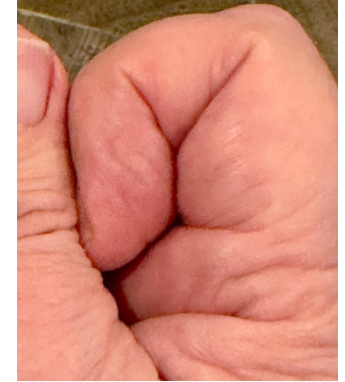
Nunez 2019

Figure 4. Cortical dipole layers. The arrows represent a snapshot of the macro source function $\mathbf{P}(\mathbf{r}, t)$, which is here assumed to be synchronous and directed perpendicular to the local cortical surface over the extended region a-i. In contrast, $\mathbf{P}(\mathbf{r}, t)$ has random directions in regions i-m.

Surface Extraction Algorithms



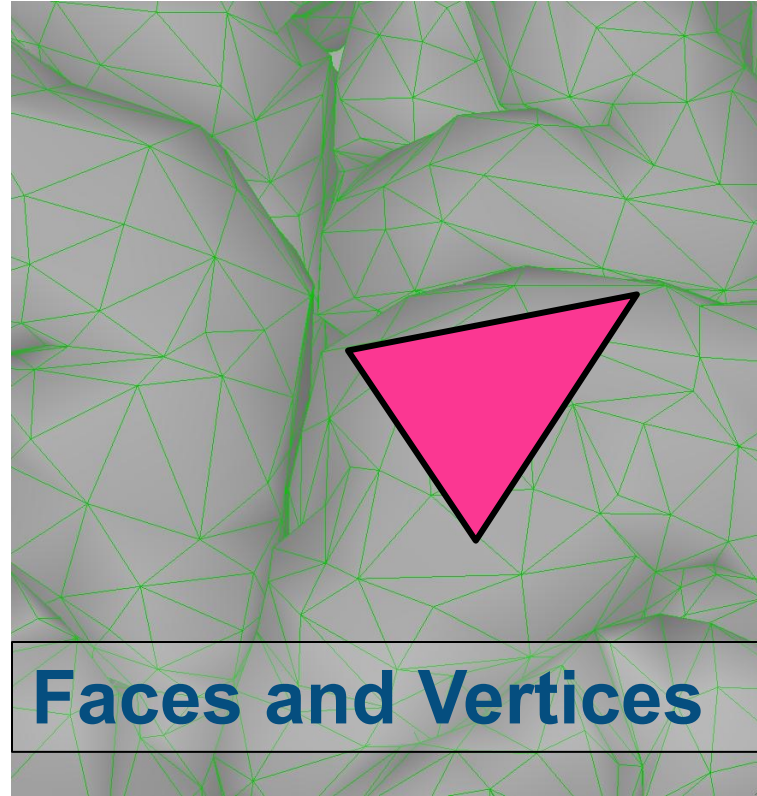
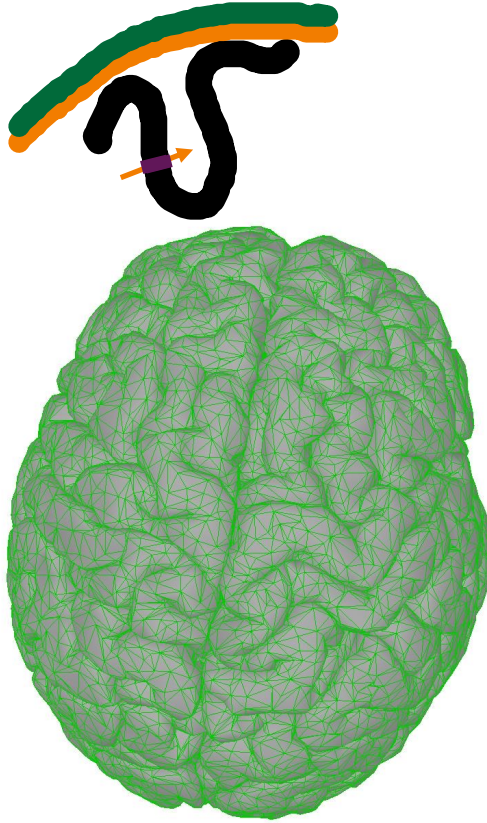
Motor Strip



The “knuckle”
or
The “Omega”

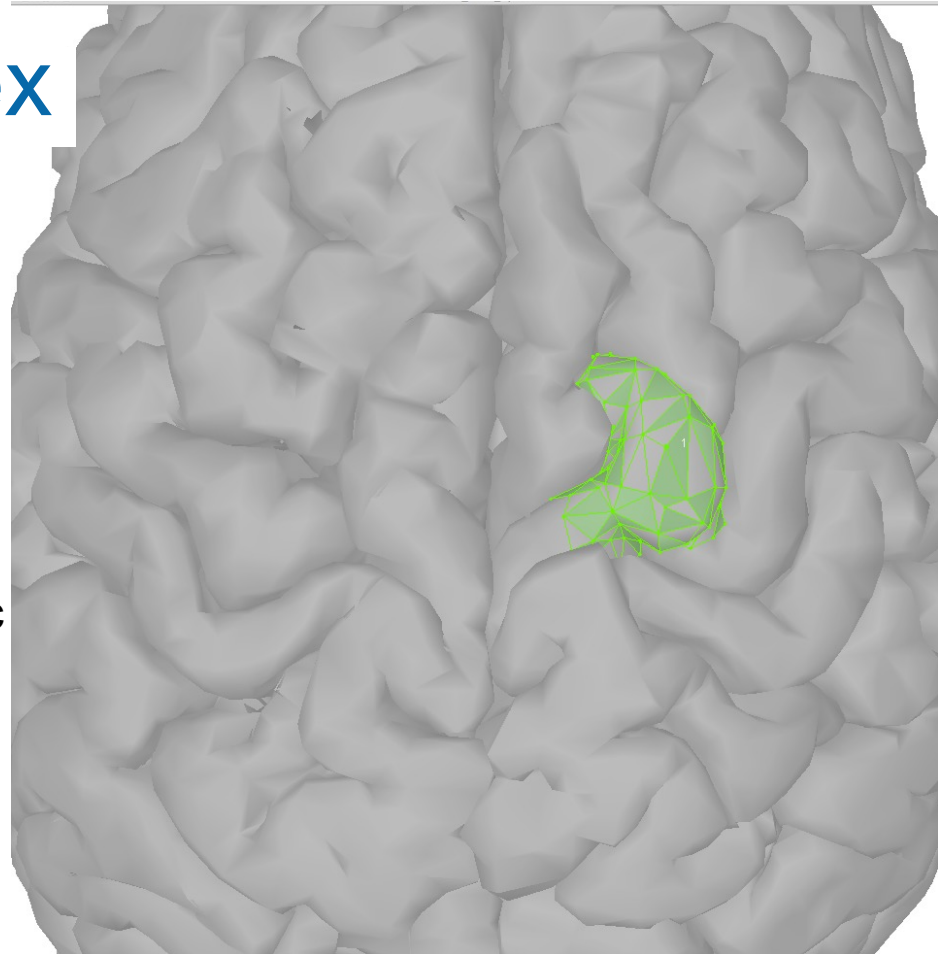
Ω

Cortical Modeling of Sources – Thousands of Triangles

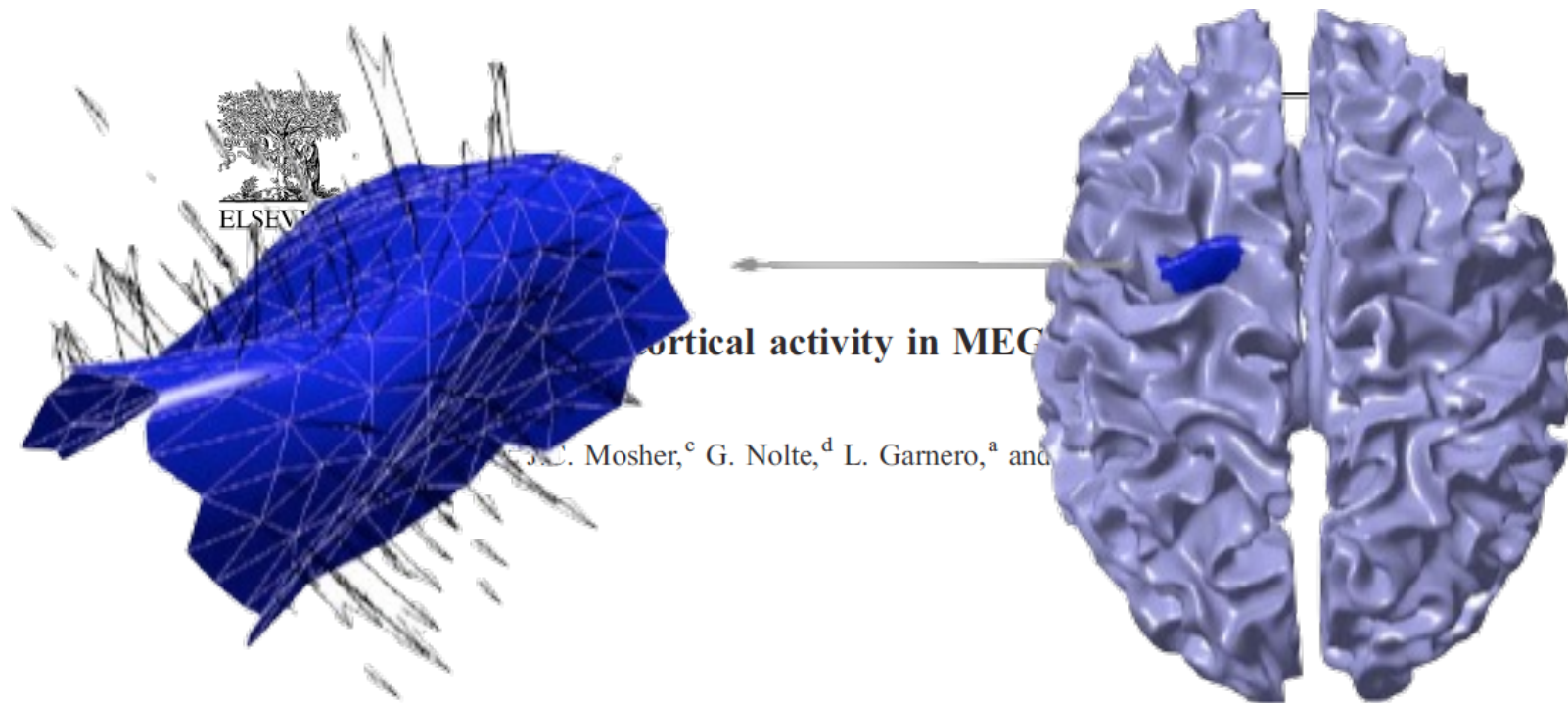


Patches on the Cortex

- Each **Vertex** is a cortical column, representing the cortical surface of the **Faces** connected to it.
- **Patch** models are a collection of Vertices, connected by their Faces.
- Incorporates the intuitive and physiologic concept of a **distributed source**.



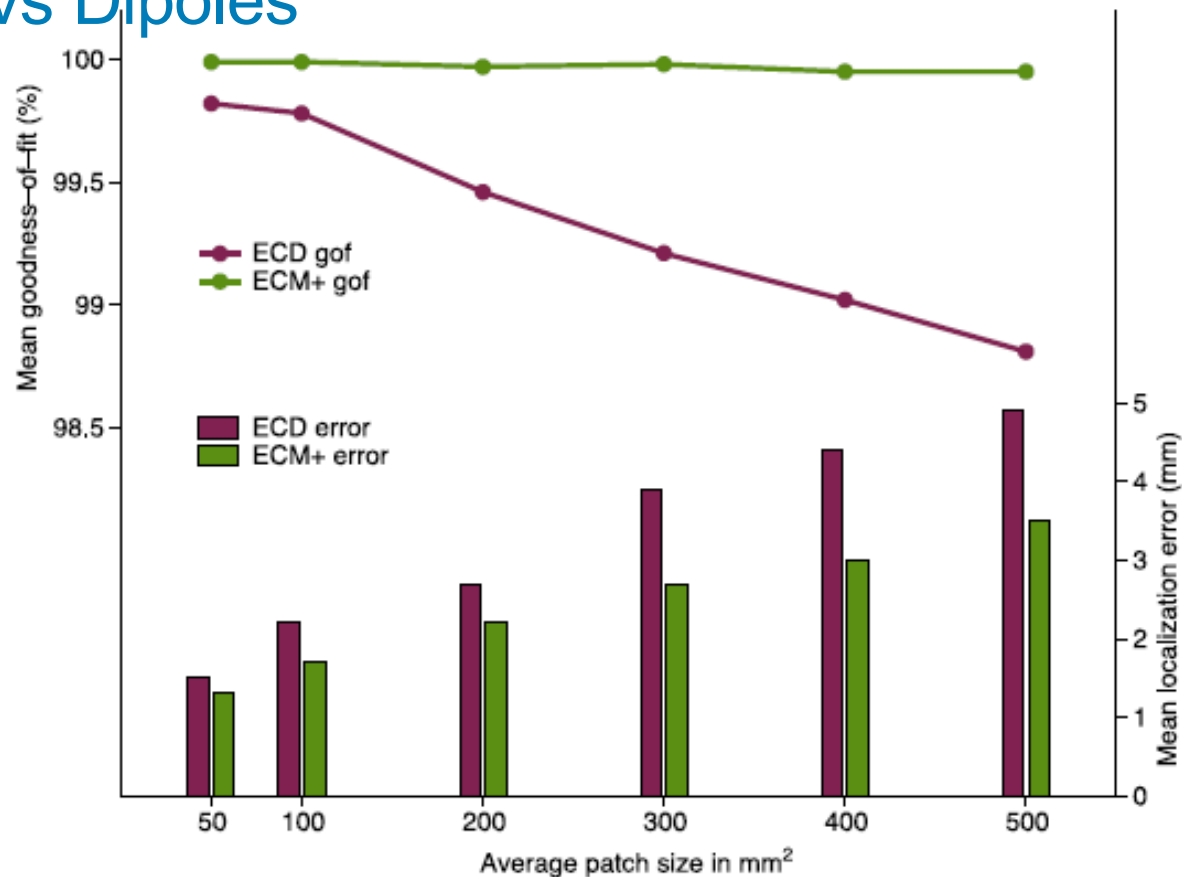
Instead of ECD, Try Realistic Cortical Patches



- Generated tens of thousands of patches from 50 mm² to 500 mm², following the cortical folds
- Fit these extended patches as both equivalent current dipoles and simple “multipoles”

Fitting Multipoles vs Dipoles

- For high quality data, GOF slipped from near 100% to 98.5% when using only a dipole for a 500 mm² patch, with an improvement of about 1.5 mm in localization error.



Patch Modeling Conclusion

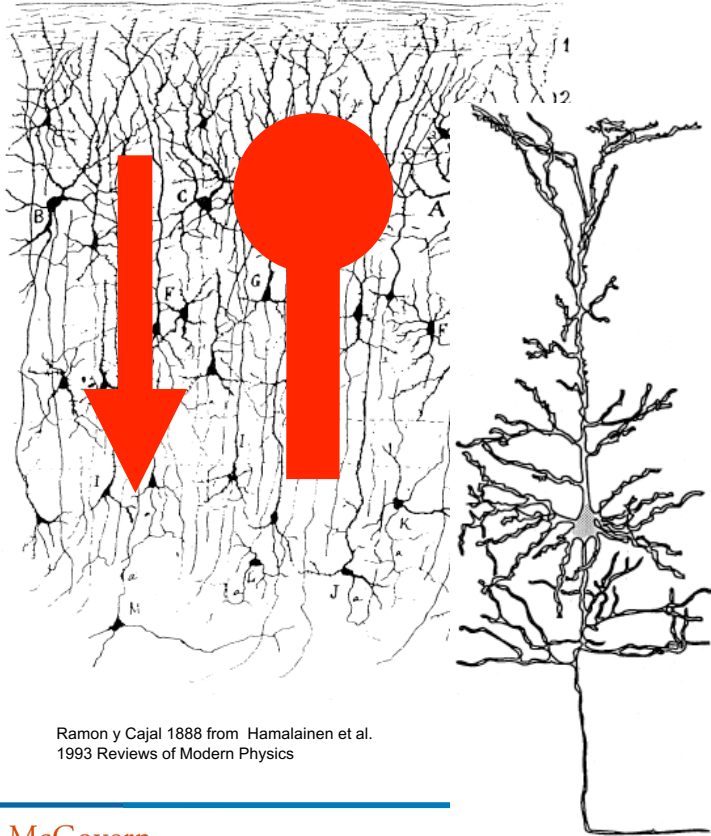
- Clinically: Stay with dipolar models for now
 - Higher-order moments (“parameters”) of patches not easily estimated without concurrently better head modeling and noise estimation

**Model Patches as
Equivalent Current
Dipoles!**

How to interpret the Current Dipole

- We can model -- very well -- a patch of cortex as an equivalent current dipole.
 - (with the correct statistical controls, of course).
- In evoked and averaged studies, it is typical to see ECDs with an amplitude of **20 nA-m**
- In modeling of interictal spikes, **200 nA-m**
- **What can we infer about these amplitudes?**

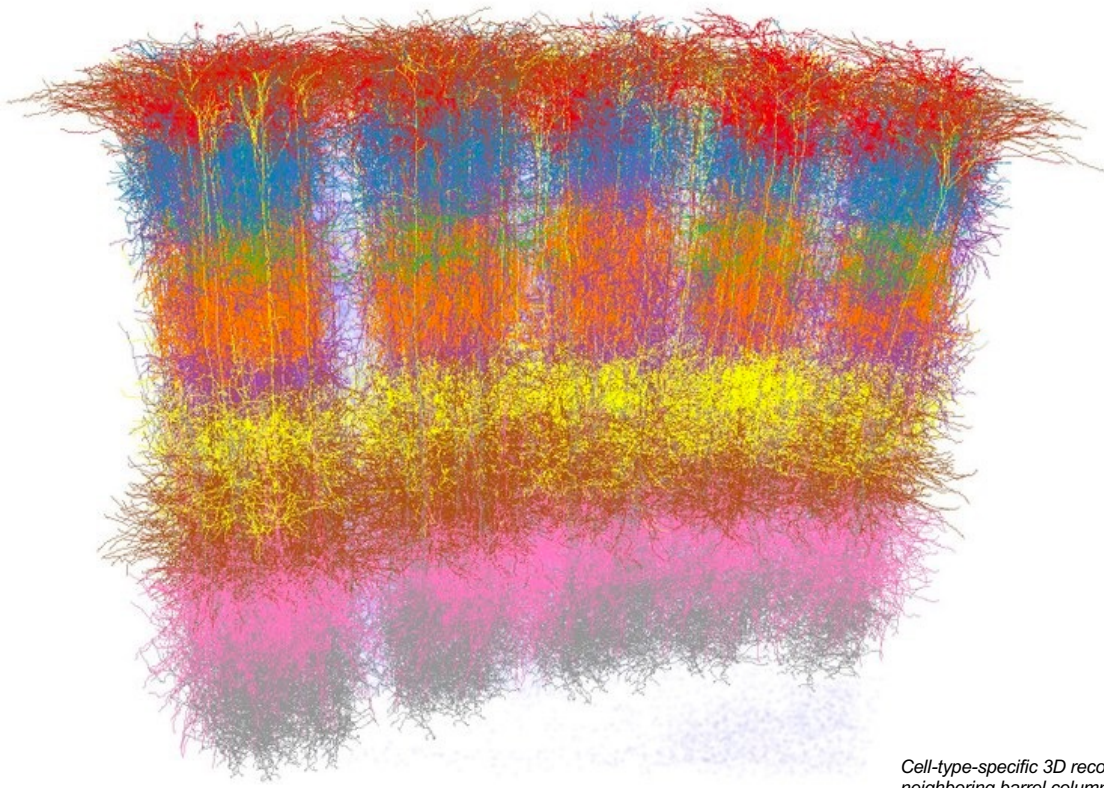
Current Dipole Moment of Neurons



Ramon y Cajal 1888 from Hamalainen et al.
1993 Reviews of Modern Physics

- Post-synaptic Potentials along the length of the pyramidal cells, effective conductor length of about **2mm** (very arguable)
- Each pyramidal cell generates about
 $20 \text{ fA-m} = 20 \text{ pA-mm}$
or **10 pA flowing along 2 mm.**
- Therefore, **one million** cells is
 $20 \text{ nA-m} = 20 \mu\text{A-mm}$,
about that of an evoked response.
- Epilepsy Spike is about
 $200 \text{ nA-m} = 200 \mu\text{A-mm}$
- Compare functional stimulation:
 $4\text{mA bipolar into } 5\text{mm contact separation}$
 $= 20 \text{ mA-mm}$
 $\rightarrow 20,000 \text{ nA-m!}$

“Cortical Columns”



- Ask the modeling question:

How much current
can one square mm
generate?

*Cell-type-specific 3D reconstruction of five
neighboring barrel columns in rat vibrissa cortex
(credit: Marcel Oberlaender et al.)*

“Okada Constant” for Current Density

NeuroImage 111 (2015) 49–58



Contents lists available at [ScienceDirect](#)

NeuroImage

journal homepage: www.elsevier.com/locate/ynimg

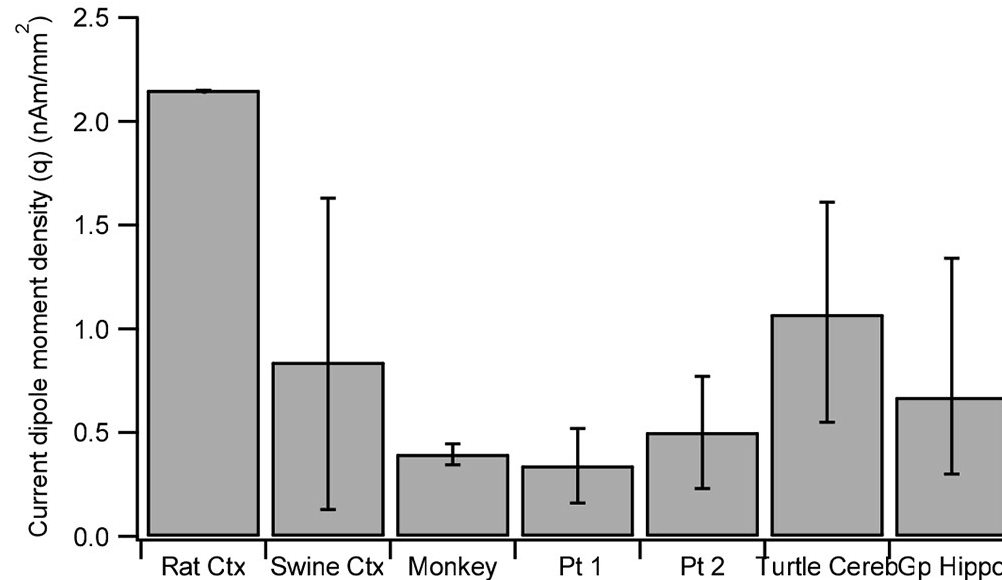
Invariance in current dipole moment density across brain structures and species: Physiological constraint for neuroimaging

Shingo Murakami ^a, Yoshio Okada ^{b,*}

2015 Neuroimage, Vol 111, 49-58

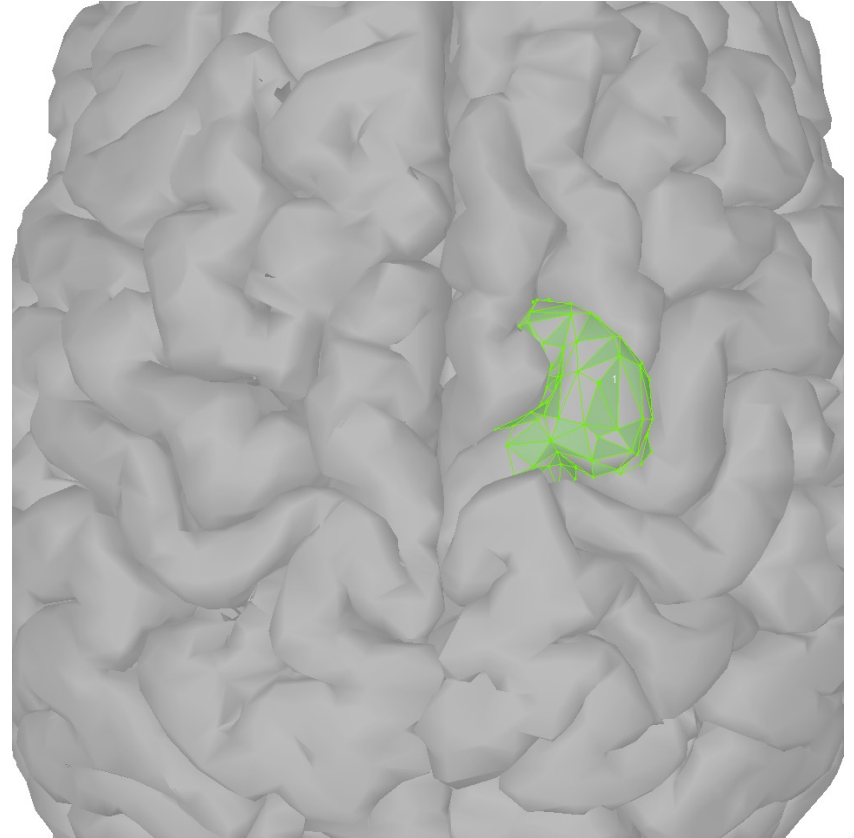
Invariance Across Species - About 1 nA-m / mm²

- Units of nA-m per square mm
- Convenient for immediately scaling cortical area



The Equivalent Current Dipole Models a Patch on the Cortex

- Using “Okada Constant”:
 - 20 nA-m is a **minimum** of 20 mm² of activated cortex
 - 200 nA-m is **minimum** of 200 mm²
- Simply varying the current density over the range of 0.1 to 1 nA-m/mm² easily changes these extents by a **factor of 10**.



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Co-Registration

INVITED REVIEW

Towards Best Practices in Clinical Magnetoencephalography: Patient Preparation and Data Acquisition

John C. Mosher* and Michael E. Funke†

Departments of *Neurology and †Pediatrics, McGovern Medical School, University of Texas Health Science Center, Houston, Texas, U.S.A.

Journal of Clinical Neurophysiology Volume 37, Number 6, November 2020

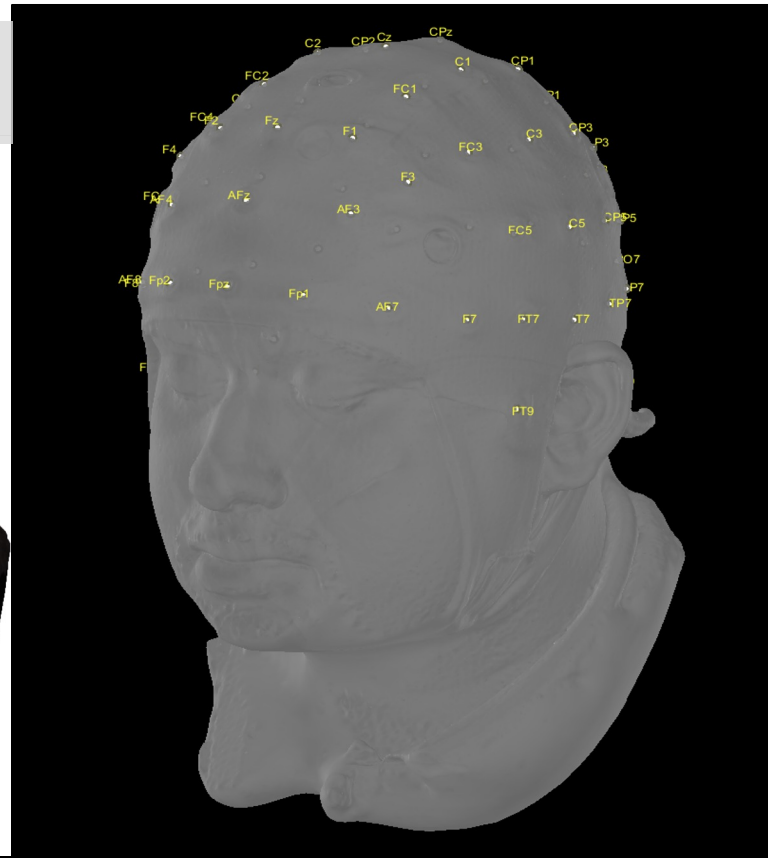


3D Scanning!



3D Scanning for Registration

- In development in Brainstorm
- Extended from FieldTrip Routines

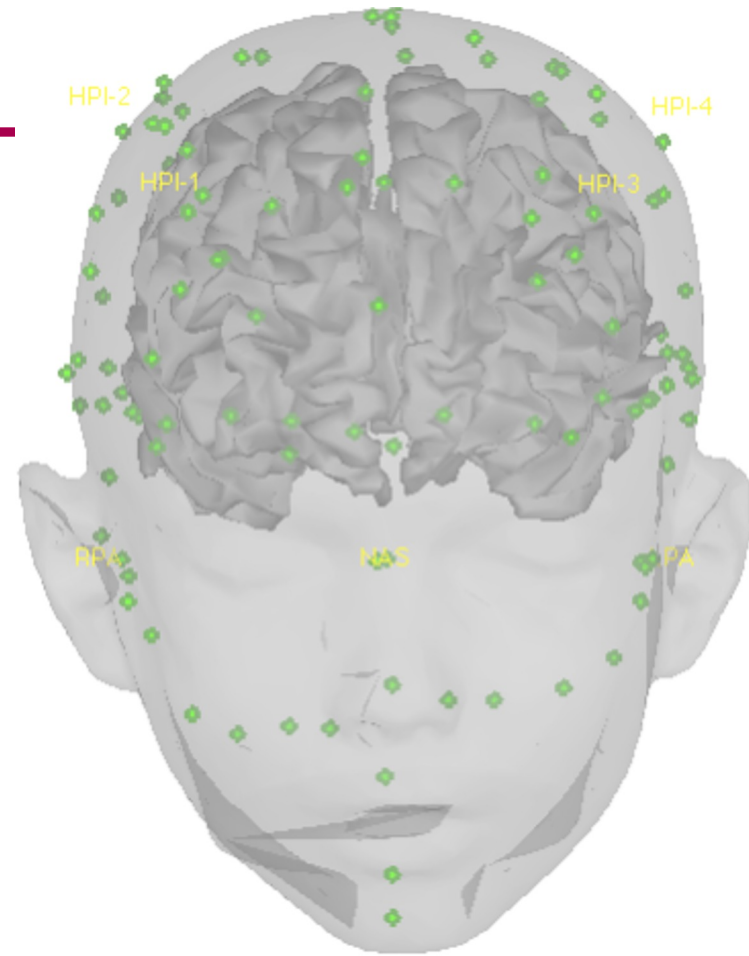
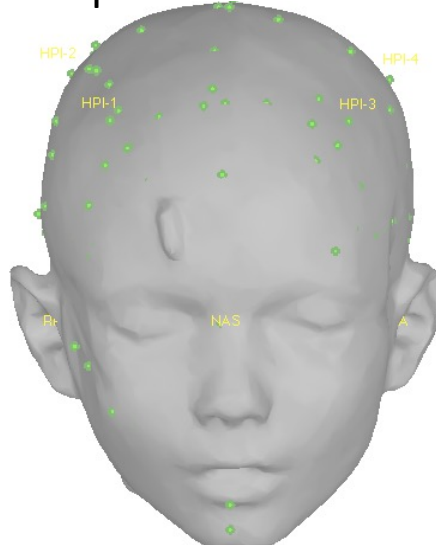


(RMS Error) Mean Difference Between Isotrak and 3D Scanner Points:

2.5 mm

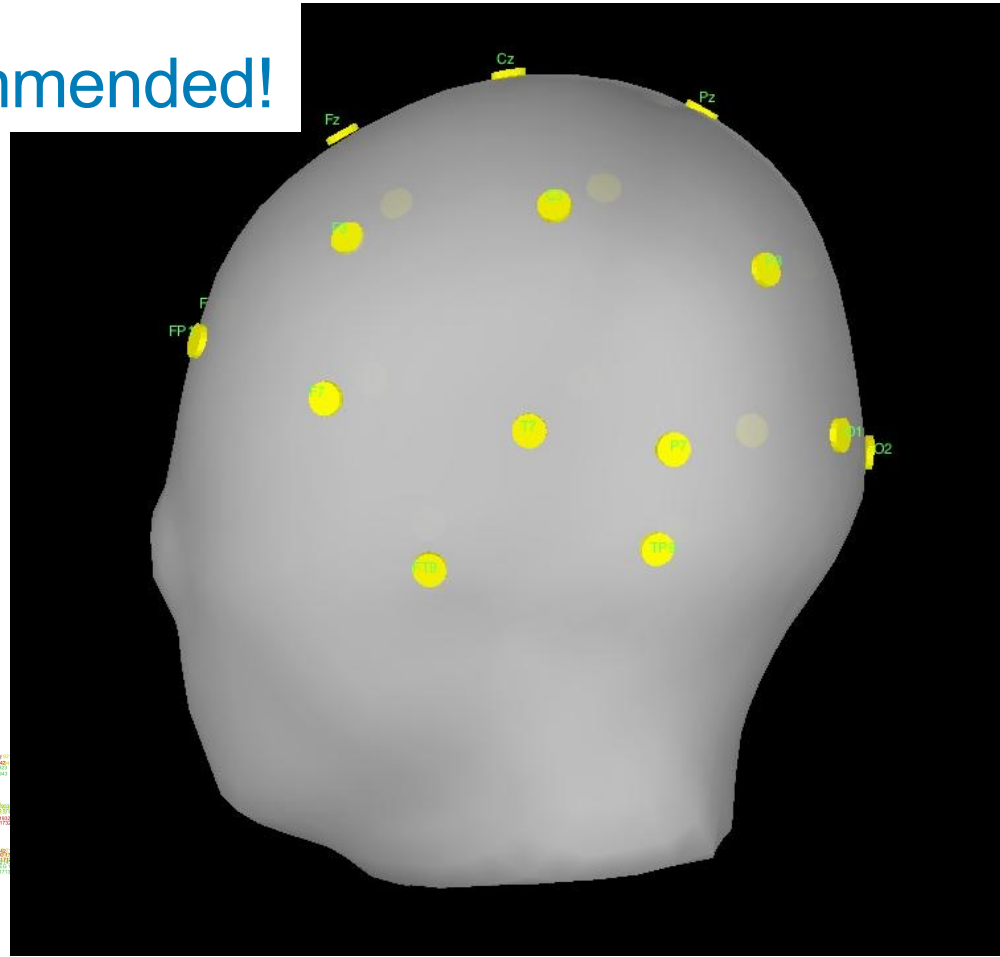
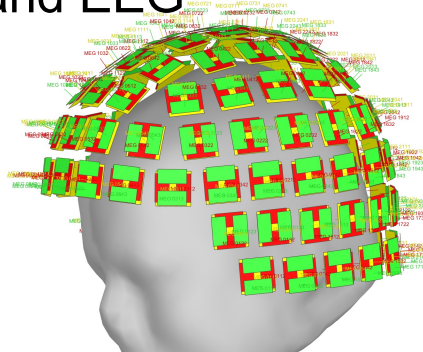
Collect 100 Landmark Points

- Landmarks and HPI Coils are aligned with Scalp Surface extracted from MRI
- Research software can mathematically fit the points to the scalp, or the points can be manually aligned.



EEG Array – Highly Recommended!

- At UTHealth and elsewhere, we simultaneously capture the standard 10-20 configuration of sensors (or a denser arrangement).
- Exploits the complementary patterns of MEG and EEG



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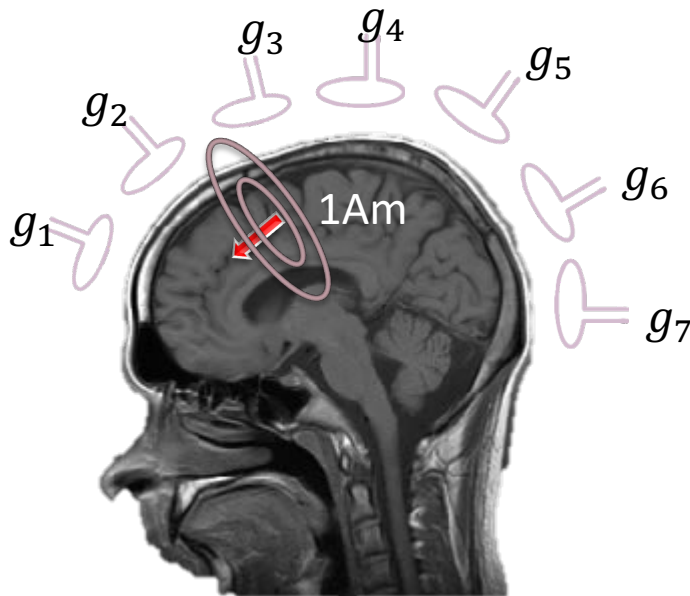
Dipolar (Primary) vs. Secondary Currents



- Picture **primary current** as a small battery inside the brain.
- **Secondary or volume currents** are the gradient currents to “complete the circuit.”
- Primary = NOT Secondary
- All current fields must contain a primary component, but not necessarily a gradient component (e.g., loop).
- Boundaries shape the volume currents.
- **Technically difficult, but each current dipole yields a unique EEG and MEG sensor solution.**

Forward Model

Biot-Savart Law

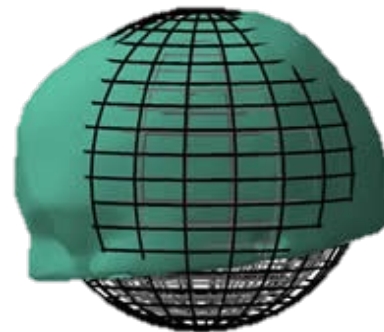


Given a dipole with source strength 1Am, orientation $\vec{e}$ and location $\vec{r}$, what is the produced MEG field $\vec{g}$?

$$B(r) = \frac{\mu_0}{4\pi} \int J(r') \frac{r - r'}{\|r - r'\|^3} dv'$$

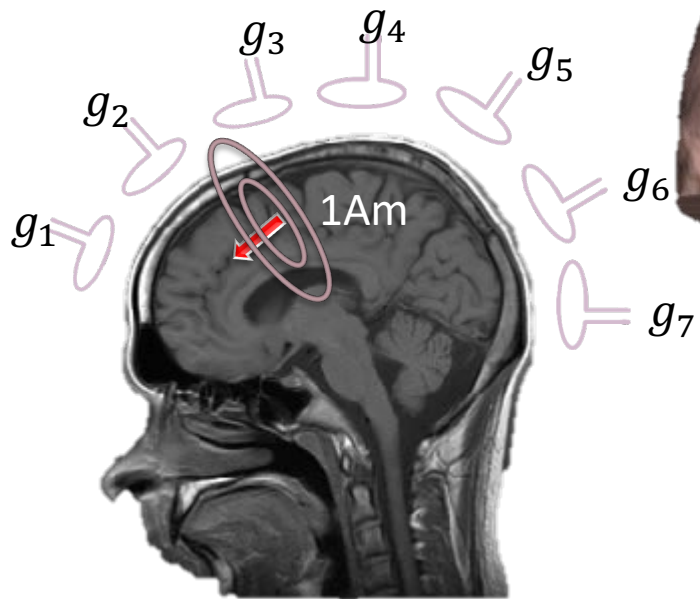
- ❑ Use quasistatic EM model to map from current source to measured fields
- ❑ Interested in '**primary**' rather than '**volume**' currents

Spherical Head Model



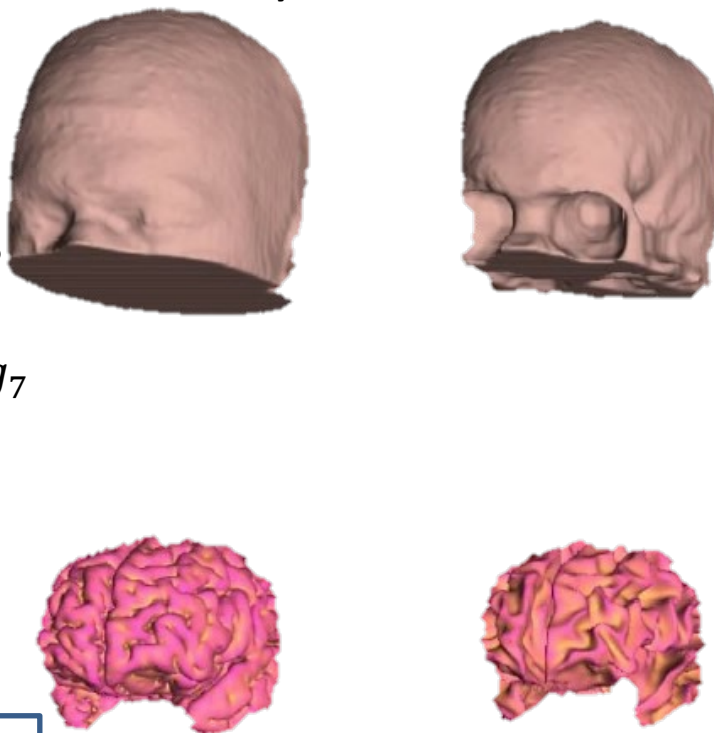
- ❑ Spherical head: closed form for primary dipole

Forward Model

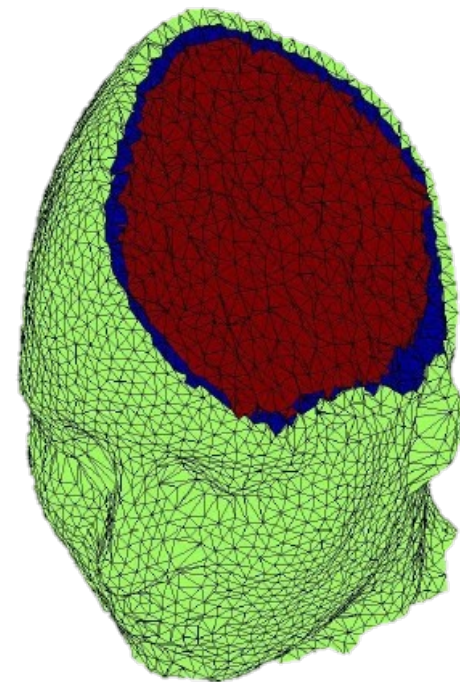


Given a dipole with source strength 1Am, orientation $\vec{e}$ and location $\vec{r}$, what is the produced MEG field $\mathbf{g}$?

Boundary Element Method



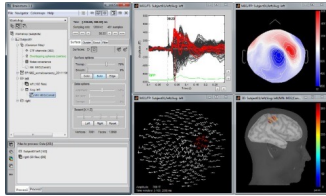
Finite Element Method



Quasi-static: $\nabla \cdot (\sigma \nabla \phi) = \nabla \cdot \mathbf{J}_p$
Solve on all elements

Software Tools for MEG/EEG

Brainstorm



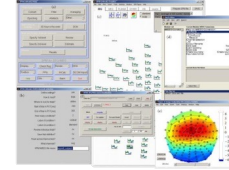
<http://neuroimage.usc.edu/brainstorm/>

MNE & MNE python



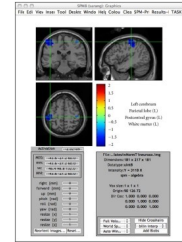
<http://martinos.org/mne/stable/index.html>

SPM



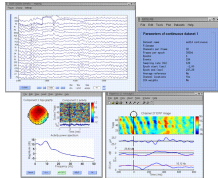
<http://www.fil.ion.ucl.ac.uk/spm/software/>

NutMEG



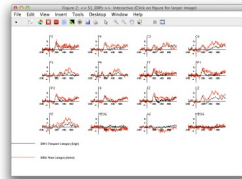
<http://nutmeg.berkeley.edu/>

EEGLAB



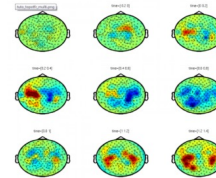
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ERPLAB



<http://erpinfo.org/erplab/>

Fieldtrip



<http://www.fieldtriptoolbox.org/>

rtMEG: Real time MEG software interface

BCILAB: Open source Matlab toolbox for brain-computer interfaces

NFT: Neuroelectromagnetic forward head modeling

OpenMEEG: Neuroelectromagnetic BEM forward head modeling

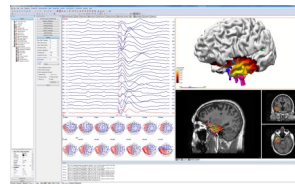
DUNEuro: Neuroelectromagnetic FEM forward head modeling

Commercial Products

Vendor software

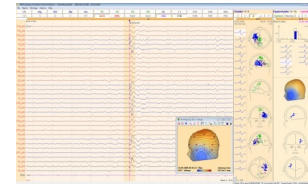
Elekta Neuromag
CTFMEG
EGI: Net Station 5
BioSemi

Curry



<http://compumedicsneuroscan.com/>

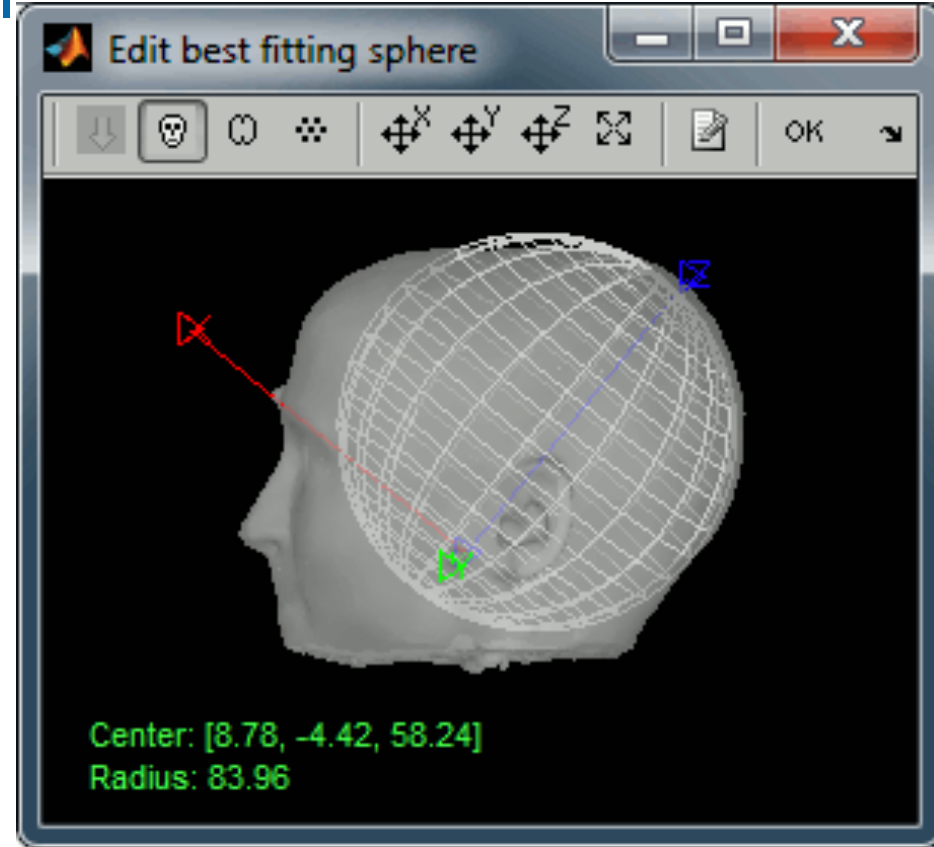
BESA



<http://www.besa.de/>

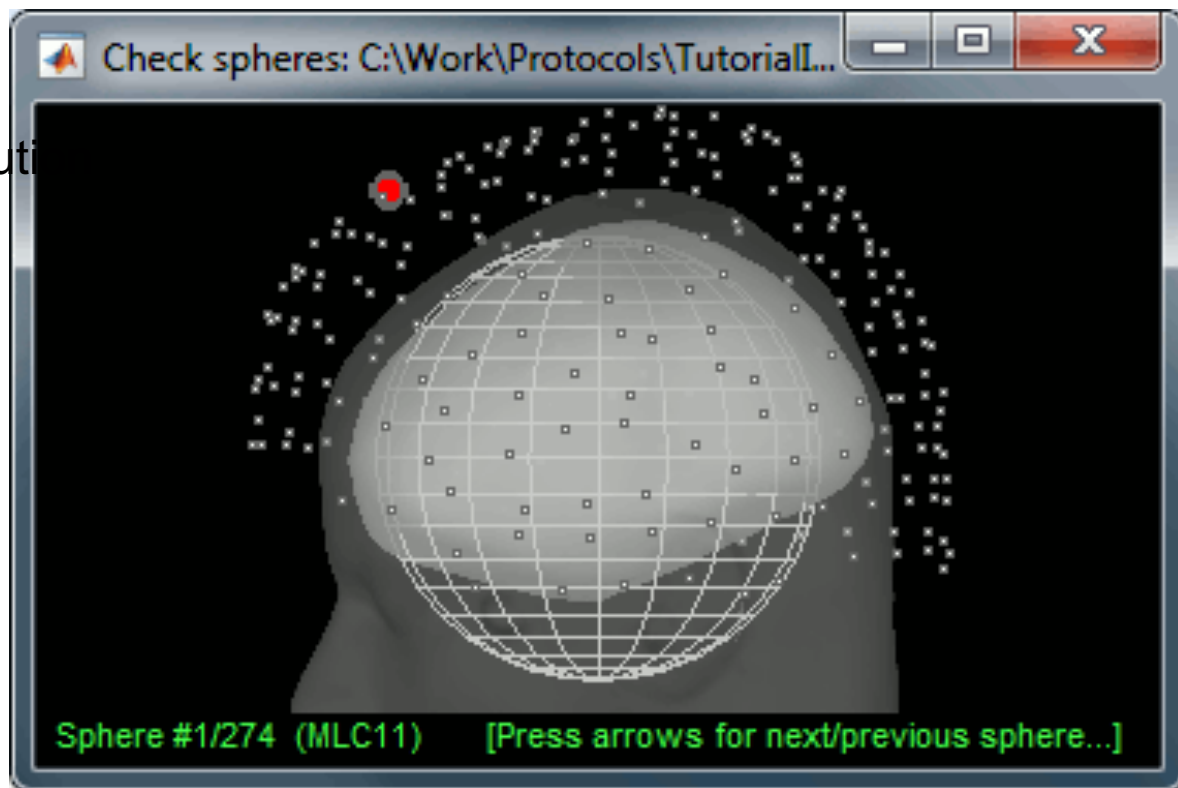
Brainstorm Forward Model

- Spherical head model, (EEG)
 - Analytical solution
 - Quick but not realistic solution



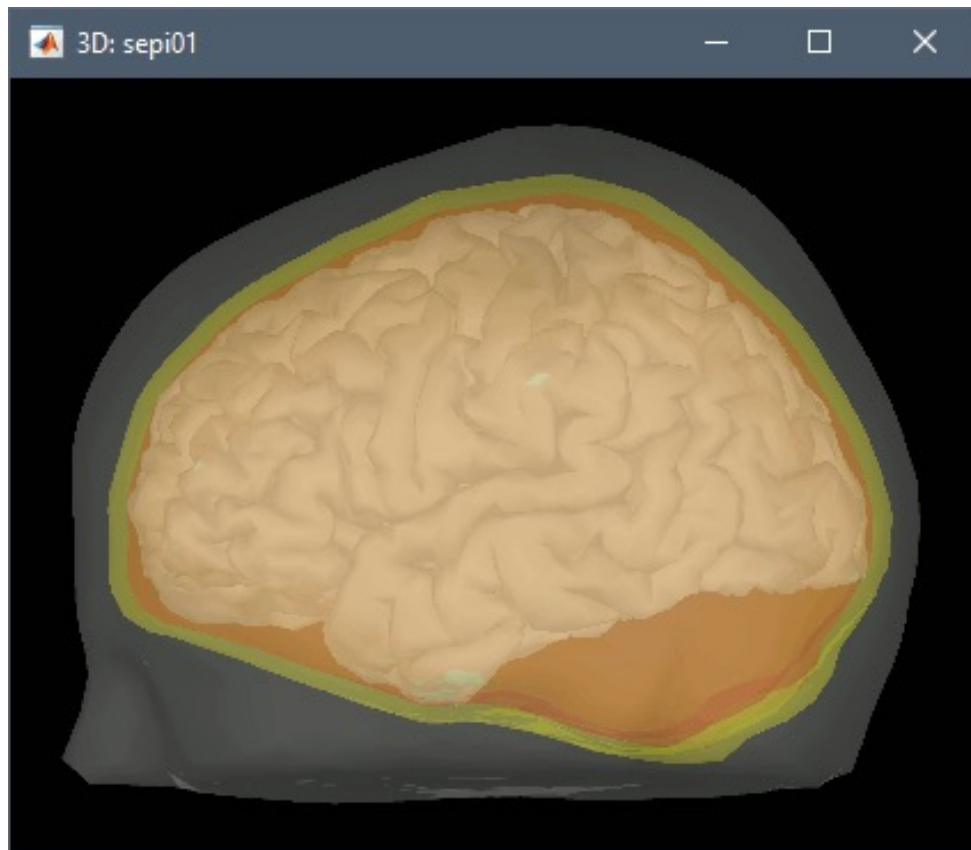
Brainstorm Forward Model

- **Spherical head model, (EEG)**
 - Analytical solution
 - Quick but not realistic solution
- **Overlapping sphere, (MEG)**
 - Analytical solution
 - Maybe sufficient !



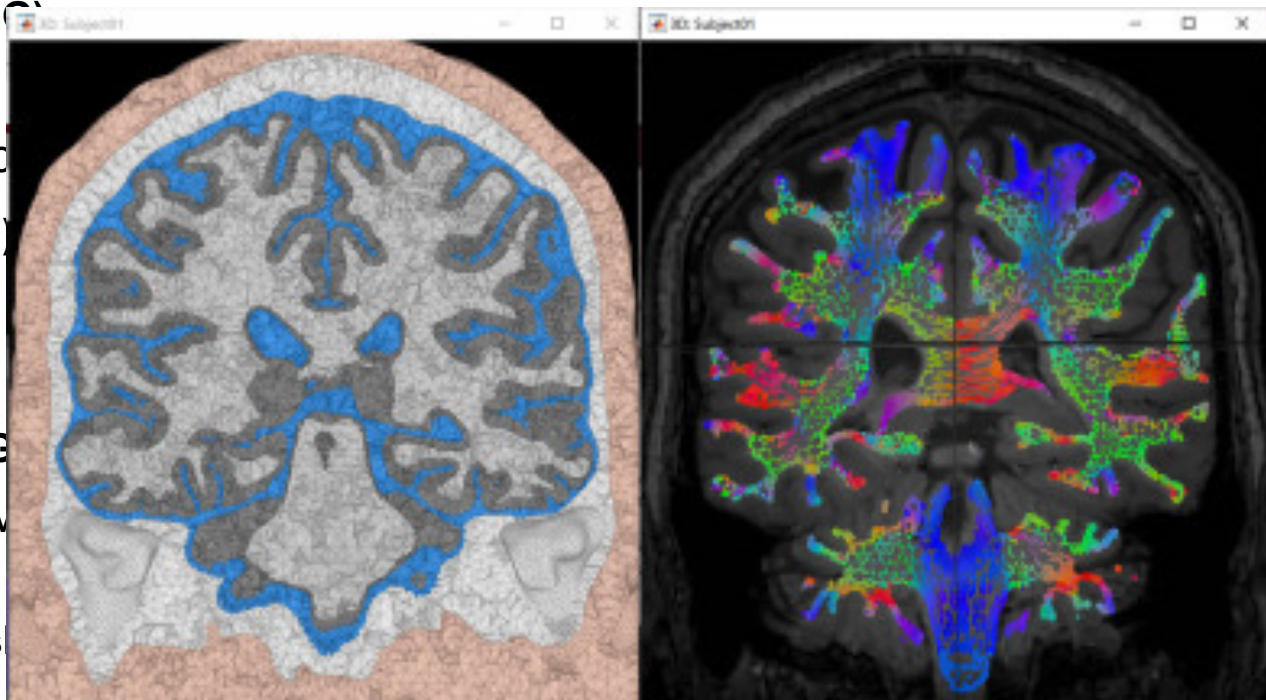
Brainstorm Forward Model

- **Spherical head model, (EEG)**
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- **Realistic model, (EEG/MEG)**
 - Surface mesh=> BEM
 - Isotropic conductivity
 - Up to 3 layers (brain, skull and scalp)

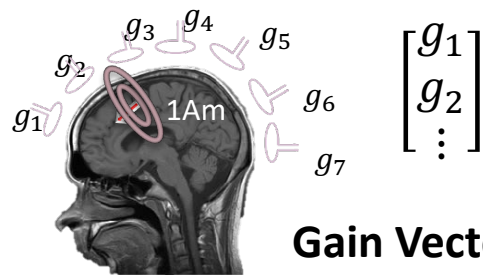


Brainstorm Forward Model

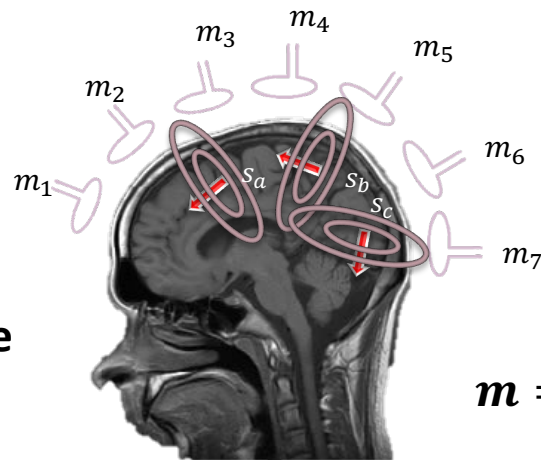
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 - Maybe sufficient !
- **Realistic model, (EEG/MEG)**
 - Surface mesh=> BEM
 - Isotropic conductivity
 - Up to 3 layers (brain, skull, scalp)
- **Volume mesh => FEM**
 - More realistic (derived from MRI)
 - Anisotropic (derived from DWI/DTI)



EM Superposition



Gain Vector One Dipole



Measurement
Multiple Dipoles

$$\mathbf{m} = \mathbf{g}_a \mathbf{s}_a + \mathbf{g}_b \mathbf{s}_b + \dots$$

$$\mathbf{M} = \mathbf{G}\mathbf{S} + \mathbf{N} = \sum_{p=1}^P \mathbf{g}_{(r_p, e_p)} \mathbf{s}_p^T + \mathbf{N}$$

MEG recordings

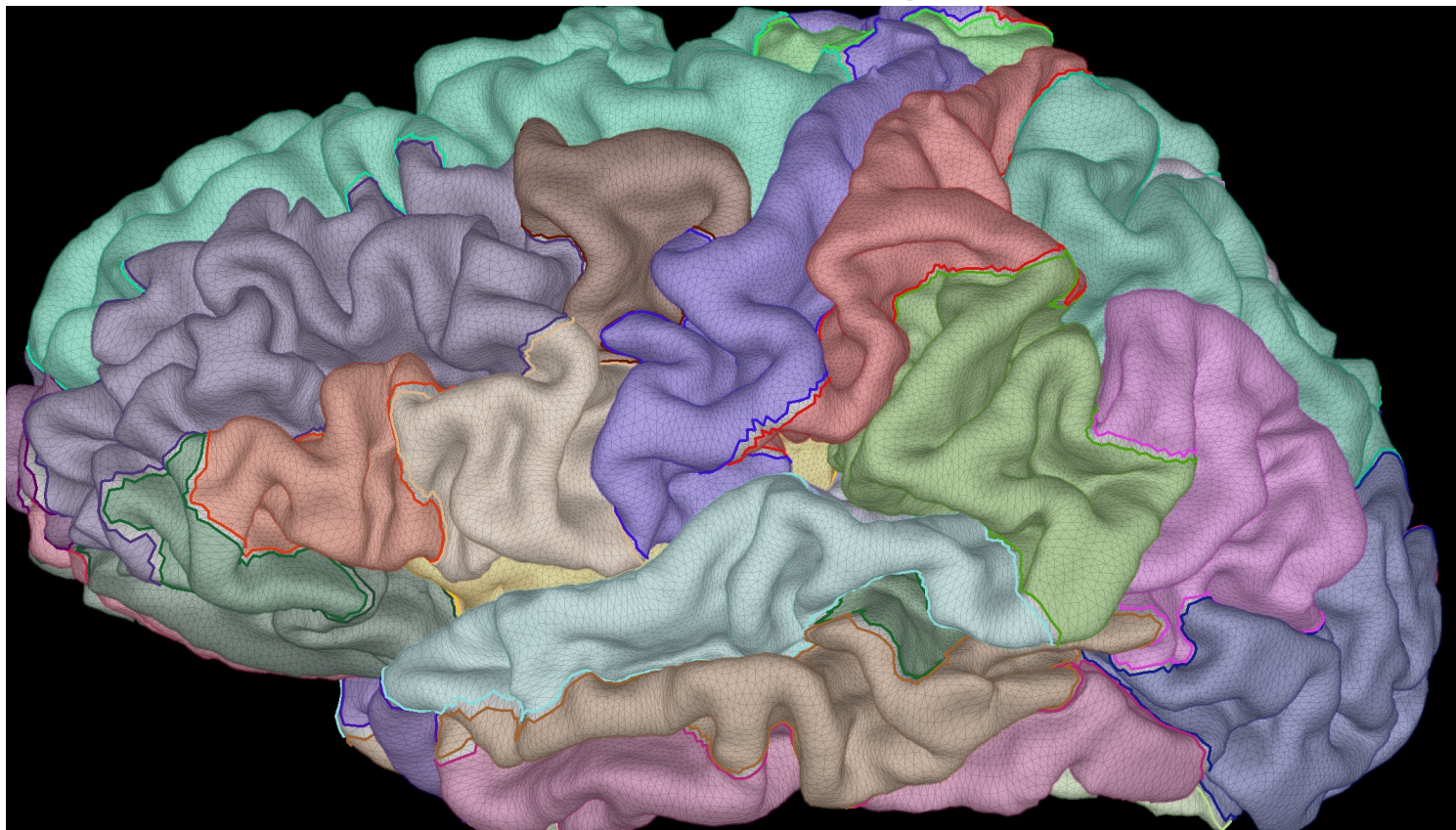
Sum all dipoles

Unit dipole field at a given location / orientation

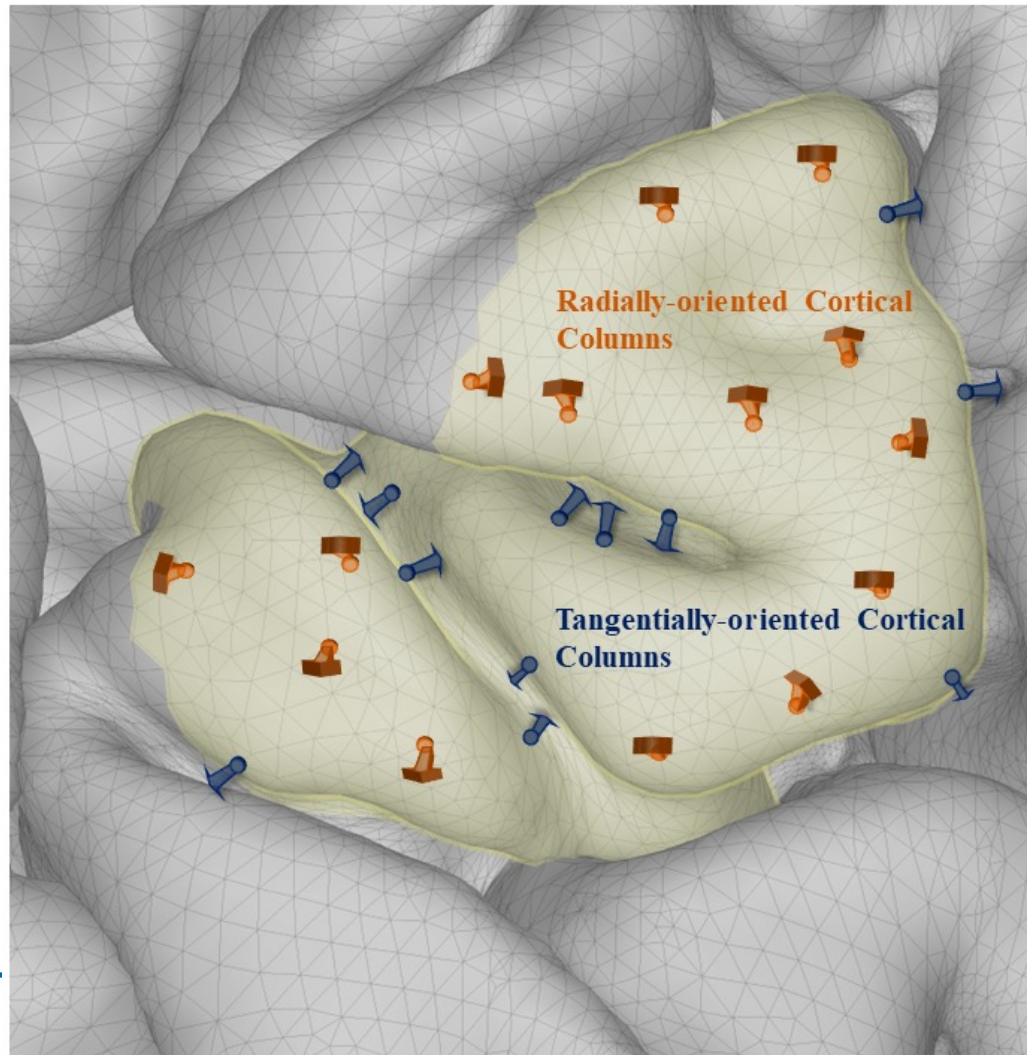
Dipole strength

Noise

252,224 labeled vertices spanning 192,152 square mm



- Each vertex represents about ~1 square mm Cortical Column
- We can restrict our dipole model normal to this rich cortical surface



Lead Field Analyses

- In this example, the cortical surface comprises ~270,000 vertices, and let's assume we have ~250 sensors (channels).
- For each of the vertices, we calculate the forward model to all contacts.
 - OpenMEEG or DuneNEURO
 - Forward model calculated in x, y, and z directions.
 - Gain Matrix** is 250 x 3 for each vertex.
- The result is a **Lead Field Matrix** of size 250 x 810,000.
 - Only a few GB at single precision.
- Each three COLUMNS of the matrix is the **Gain Matrix** for a single dipole.
- By reciprocity, each ROW of this matrix represents samples of the **Lead Field** for that channel.

Outline

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- Validation: phantoms and what the errors actually are
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Full Imaging Model and the Inverse Problem

- In this massive model, the measured data are modeled as

$$\mathbf{m}(t) = \mathbf{L}\mathbf{j}(t) + \mathbf{n}(t)$$

where $\mathbf{L} \equiv [\mathbf{G}_1, \mathbf{G}_2, \dots, \mathbf{G}_{270,000}]$ is the **lead field matrix** for 270,000 **dipole matrices**, and $\mathbf{j} \equiv [\mathbf{q}_1; \mathbf{q}_2; \vdots; \mathbf{q}_{270,000}]$ is the **source vector** of 270,000 **vector dipole moments**, with additive “noise”.

- Two main approaches for solving for the source vector $\mathbf{j}(t)$:
 - **Dipole modeling**: which of the **few** columns of $\mathbf{L}$ fit the measurements
 - **Source imaging**: what collection of patches over **all** columns of $\mathbf{L}$ fit the measurements

Source Covariance and Constrained Orientation

- **Constrained Orientation** for simplicity today
 - Set $L \equiv [g_1, g_2, \dots, g_{270,000}]$ is the **lead field matrix** for 270,000 dipole model **vectors, constrained in orientation normal to cortex**, and $j \equiv [q_1; q_2; \vdots; q_{270,000}]$ is the source vector of 270,000 **scalar** dipole amplitudes.
 - Orientation as a “free” parameter is removed from today’s discussion.
- We **design** a source covariance,
$$C_j = \text{Expected}\{j j^T\}$$
- Typically designed as diagonal, with elements inverse to depth
 - Other variations exist, not discussed today.

Noise or Baseline Covariance

- Before we can tackle the source estimate, we must describe this noise or baseline vector $\mathbf{n}$.
- We assume for convenience that the mean has been removed
 - Note, you need to do this to your data: Remove the mean!
- The inverse methods discussed today rely on L_2 statistics, so we must specify / estimate the **covariance** of $\mathbf{n}$,
$$\mathbf{C}_n = \text{Expected}\{\mathbf{n} \mathbf{n}^T\}$$
- We typically estimate this from **empty room** or **baseline brain activity**.
 - Some period of brain activity **void** of the signal of interest.

Source Imaging – Minimum Norm Estimate

- The linear minimum mean square estimate (LMMSE) answers the question:

What estimate $\hat{\mathbf{j}}$ minimizes its squared error, $(\mathbf{j} - \hat{\mathbf{j}})^T(\mathbf{j} - \hat{\mathbf{j}})$, given the **estimator is linear**:

$$\hat{\mathbf{j}} = \mathbf{C}_j \mathbf{L}^T (\mathbf{L} \mathbf{C}_j \mathbf{L}^T + \mathbf{C}_n)^{-1} \mathbf{m}$$

- Also known as the **weighted, regularized, minimum norm estimate**, or simply **MNE**, or the **Wiener Filter**

Dipole Modeling - Regularized

- We can hold the assumptions identical to the LMMSE, but now we let $A = [\{\mathbf{g}_i\}]$, i = a small set of fixed orientation dipoles.
- The model is now expressed as $\mathbf{m} = A\mathbf{x} + \mathbf{n}$, for our unknown small set of dipoles, with unknown scalar amplitudes now gathered in $\mathbf{x}$, with corresponding design source covariance subset $\mathbf{C}_x$.
- The answer remains the same for the LMMSE,

$$\hat{\mathbf{x}}_{WF} = \mathbf{C}_x \mathbf{A}^T (\mathbf{A} \mathbf{C}_x \mathbf{A}^T + \mathbf{C}_n)^{-1} \mathbf{m}$$

- By the matrix inversion lemma, we may identically express as

$$\hat{\mathbf{x}}_{WF} = (\mathbf{A}^T \mathbf{C}_n^{-1} \mathbf{A} + \mathbf{C}_x^{-1})^{-1} \mathbf{A}^T \mathbf{C}_n^{-1} \mathbf{m}$$

Dipole Modeling – Best Linear Unbiased Estimate

- Because the model A is “tall” (only a few dipoles), then we can let the design source covariance “go to infinity” yielding

$$(A^T C_n^{-1} A + C_x^{-1})^{-1} \rightarrow (A^T C_n^{-1} A)^{-1}$$

- This estimate answers the question, what linear estimate best approximates the data, yielding the BLUE

$$\hat{x}_{\text{blue}} = (A^T C_n^{-1} A)^{-1} A^T C_n^{-1} m$$

- The advantage is the BLUE requires no source prior, but the disadvantages are
 - We often need the prior as a regularizer anyway
 - We have to identify the small set of dipoles, aka “dipole fitting”

Z-Scoring: dSPM, sLORETA

- The i th dipole in these estimates can be expressed as the linear weight $\mathbf{w}_i$ applied to the data,

$$\hat{q}_i = \mathbf{w}_i^T \mathbf{m}$$

- We generate an estimate of the **estimator noise** as

$$\sigma_n(i) = (\mathbf{w}_i^T \mathbf{C}_n \mathbf{w}_i)^{1/2}$$

- The dSPM-weighted score is therefore

$$\hat{q}_{idSPM} = \mathbf{w}_i^T \mathbf{m} / \sigma_n(i)$$

- sLORETA uses a different estimate, but same scaling

$$\sigma_d(i) = (\mathbf{w}_i^T (\mathbf{L} \mathbf{C}_j \mathbf{L}^T + \mathbf{C}_n) \mathbf{w}_i)^{1/2}$$

Beamformers

- Returning to the BLUE, recall it comprises a “few” dipoles in unknown locations,

$$\hat{\mathbf{x}}_{\text{blue}} = (\mathbf{A}^T \mathbf{C}_n^{-1} \mathbf{A})^{-1} \mathbf{A}^T \mathbf{C}_n^{-1} \mathbf{m}$$

- If we have an **estimate** of the data covariance, $\mathbf{C}_m$, estimated from the data, then we may scan for the few dipoles using the single vector dipole model and **replace the noise covariance with the data covariance**, to yield

$$\hat{\mathbf{q}}_{i\text{CAP}} = (\mathbf{g}_i^T \mathbf{C}_m^{-1} \mathbf{g}_i)^{-1} \mathbf{g}_i^T \mathbf{C}_m^{-1} \mathbf{m}$$

- Also known the the LCMV and MVDR, or simply, the beamformer estimate, we denote it here as “CAP” in honor of the widely recognized original contribution by Capon 1969.
- When scanned or imaged over all the dipoles, under the right conditions it peaks at the right locations of the small set of dipoles.
- An analogous z-score version for this estimate is the Neural Activity Index (NAI).

Beamformer “Competition”



NeuroImage
Volume 216, 1 August 2020, 116797



Comparison of beamformer implementations for MEG source localization

Amit Jaiswal ^{a b} ✉, Jukka Nenonen ^a, Matti Stenroos ^b, Alexandre Gramfort ^c, Sarang S. Dalal ^d, Britta U. Westner ^d, Vladimir Litvak ^e, John C. Mosher ^f, Jan-Mathijs Schoffelen ^g, Caroline Witton ⁱ, Robert Oostenveld ^{g h}, Lauri Parkkonen ^{a b j}

MNE-Python, FieldTrip, DAiSS (SPM12), and Brainstorm

- Different beamformer implementations are reported to sometimes yield differing source estimates for the same MEG data.
- We compared beamformers in four major open-source MEG analysis toolboxes.
- All toolboxes provide consistent and accurate results with 3–15-dB input SNR.
- However, localization errors are high at very high input SNR for the tested scalar beamformers.
- We discuss the critical differences between the implementations.

Beamformer Unified View



NeuroImage
Volume 246, 1 February 2022, 118789



A unified view on beamformers for M/EEG source reconstruction

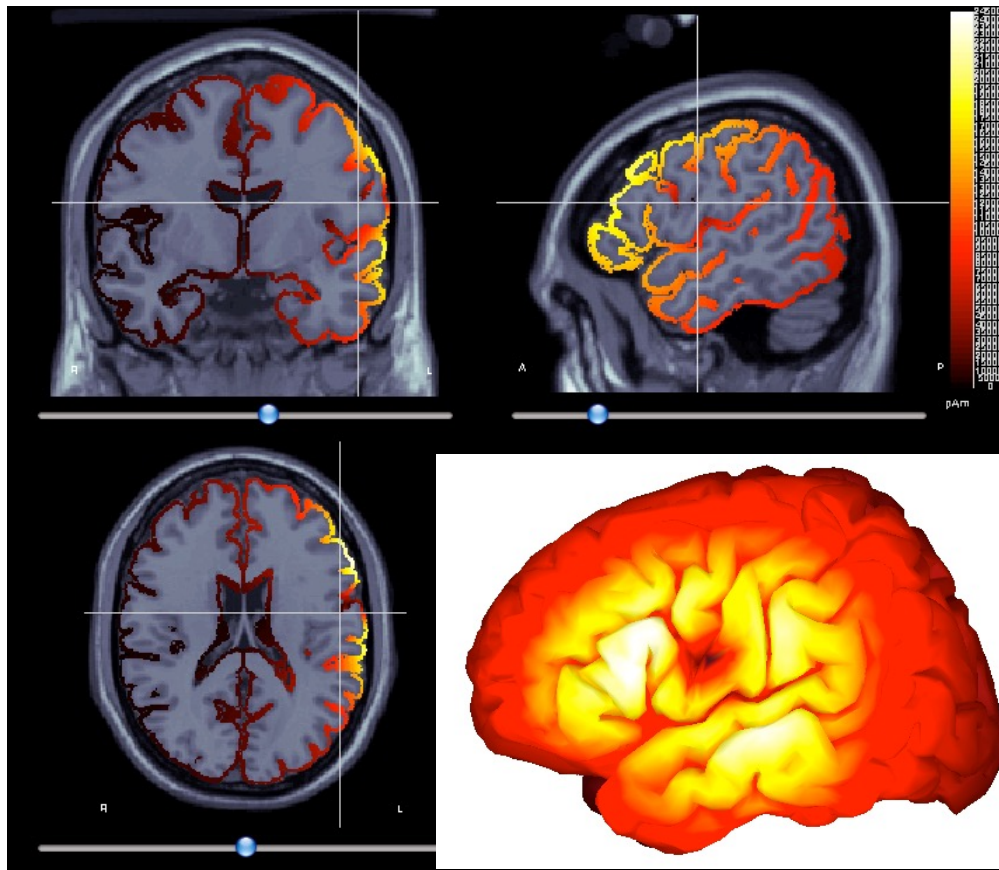
Britta U. Westner^{a b}  , Sarang S. Dalal^b, Alexandre Gramfort^c, Vladimir Litvak^d, John C. Mosher^e, Robert Oostenveld^{a f}, Jan-Mathijs Schoffelen^a

- Concise overview and explanation of beamformers for M/EEG data analysis.
- Practical considerations and best practices for beamforming analyses.
- Unification of terminology across popular open source software packages.
- Comparison of implementations and user interfaces between software packages.

Other Variations not Discussed

- These estimators can be derived from many different viewpoints.
- We glossed over in the math the orientation constraint, for simplicity, which yields scalar moments rather than vector dipole moments.
- Many variations of source covariance design have been published that are not necessarily diagonal.
- The MUSIC method does not require inverting the data covariance, but rather, uses its signal subspace.
 - Brainstorm’s “dipole scan” is actually a MUSIC implementation

Minimum Norm Imaging on Volume vs Cortex



- Basic idea is to restrict the lead field imaging through the volume to just the cortical surface.

Source Solutions

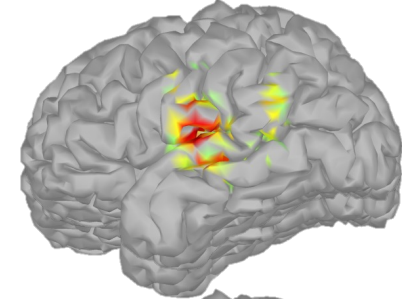
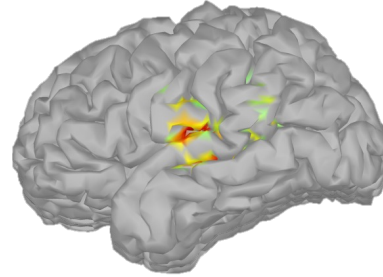
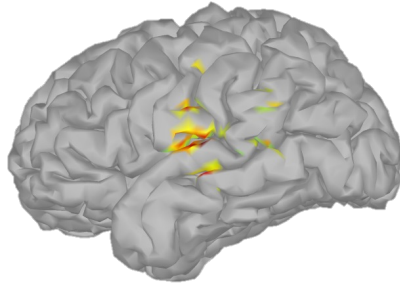
Binaural auditory stimulation, MEG
Maps thresholded at 50% of maximum

MNE

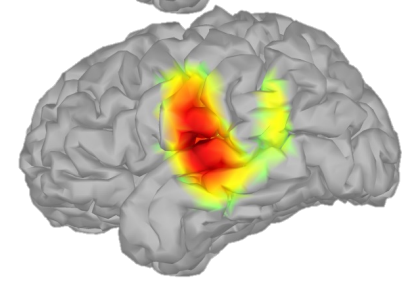
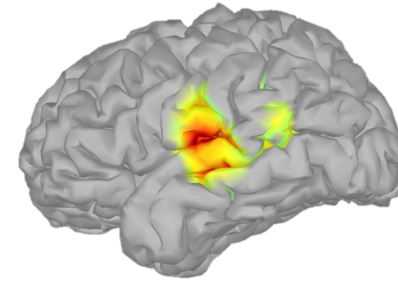
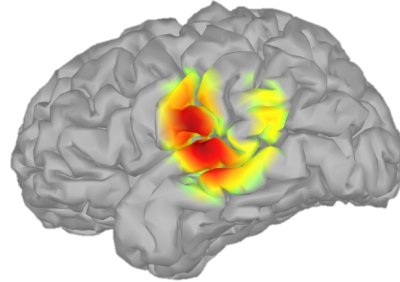
dSPM

sLORETA

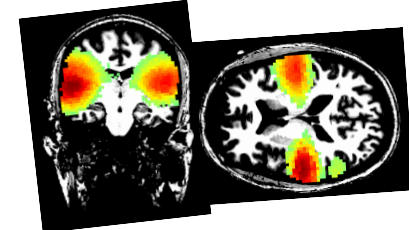
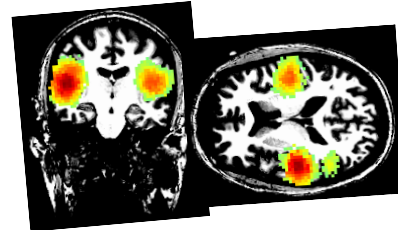
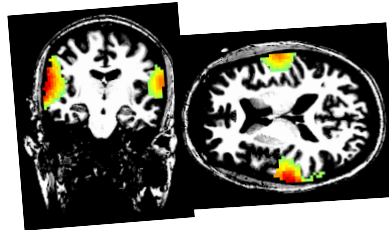
Orientation
Constrained



Orientation
Unconstrained



Volume
Unconstrained

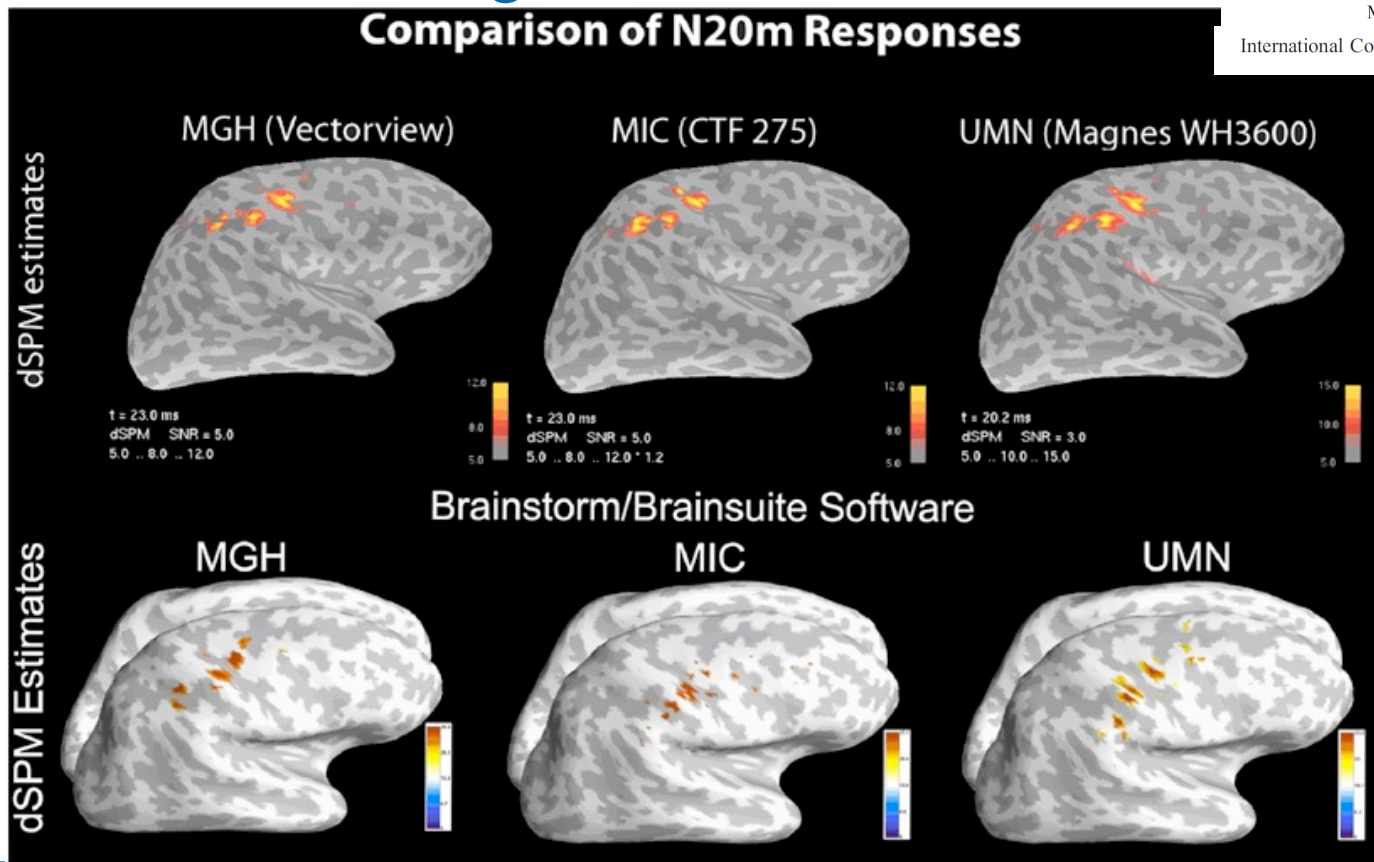


Cross-site Pooling of MEG Data

Paving the way for cross-site pooling of
magnetoencephalography (MEG) data

M.P. Weisend^{a,b,*}, F.M. Hanlon^a, R. Montaña^b, S.P. Ahlfors^c,
A.C. Leuthold^d, D. Pantazis^c, J.C. Mosher^f, A.P. Georgopoulos^d,
M.S. Hämäläinen^c, C.J. Aine^b

International Congress Series 1300 (2007) 615–618



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Experimental Confirmations

The human condition is complex: heads aren't spheres, sources aren't single dipoles.

How do you confirm some of these basics experimentally?

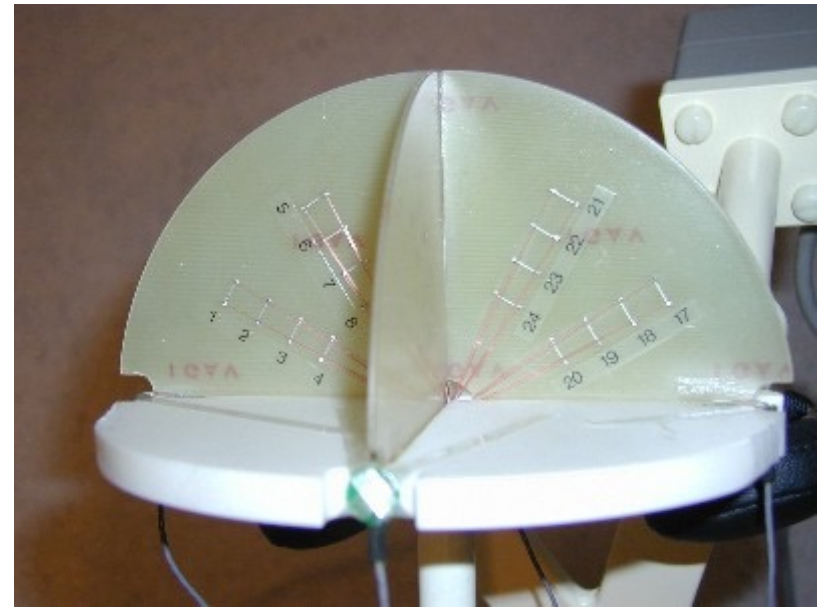
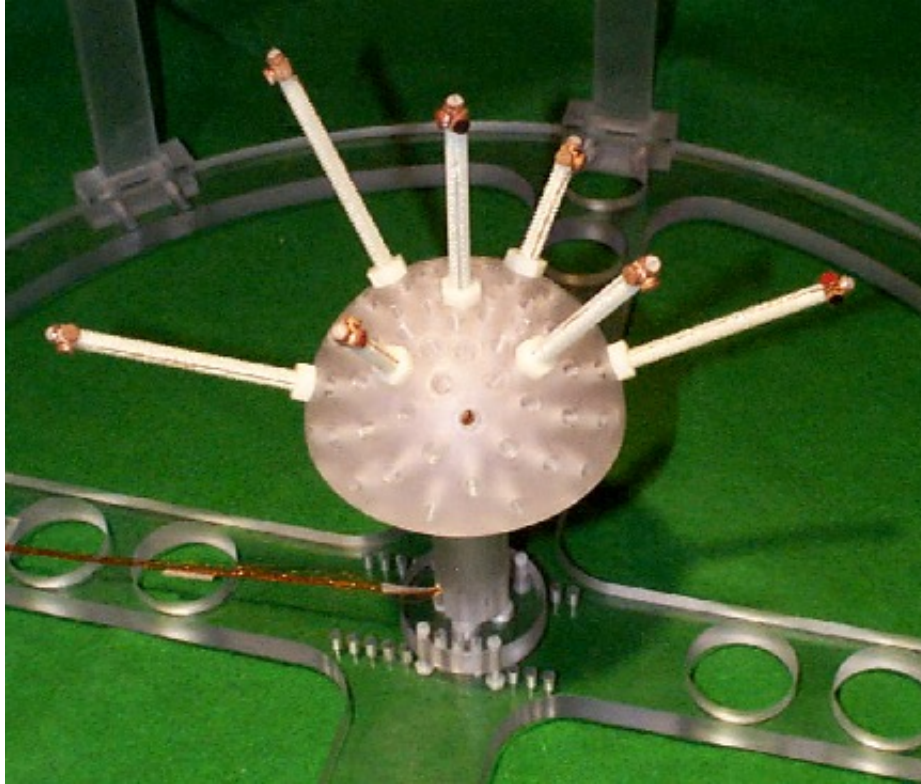
- => Phantoms

“Wet” Phantom



Wet phantom, dipolar source, sphere, saline.

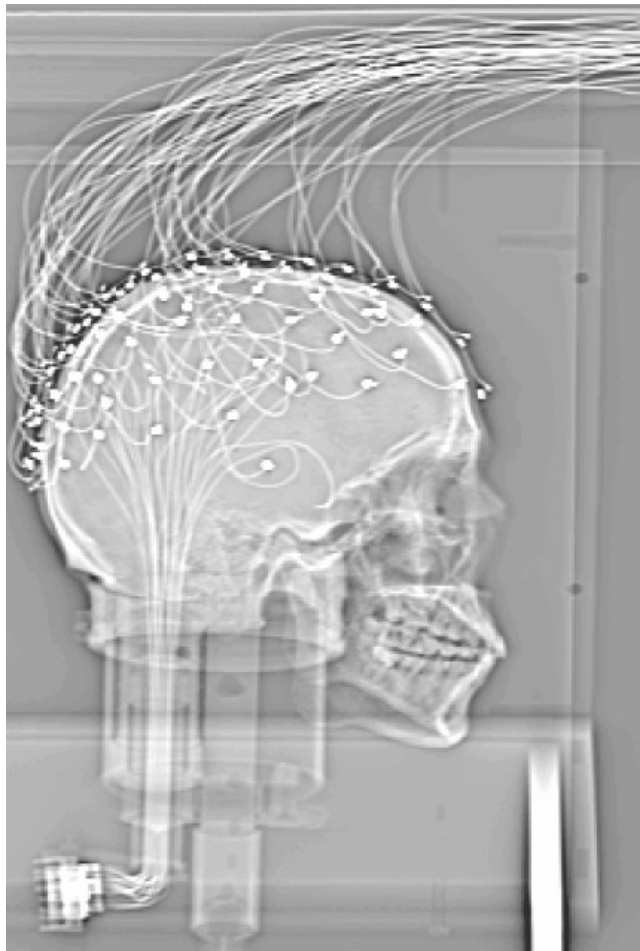
“Dry” Calibration Phantoms



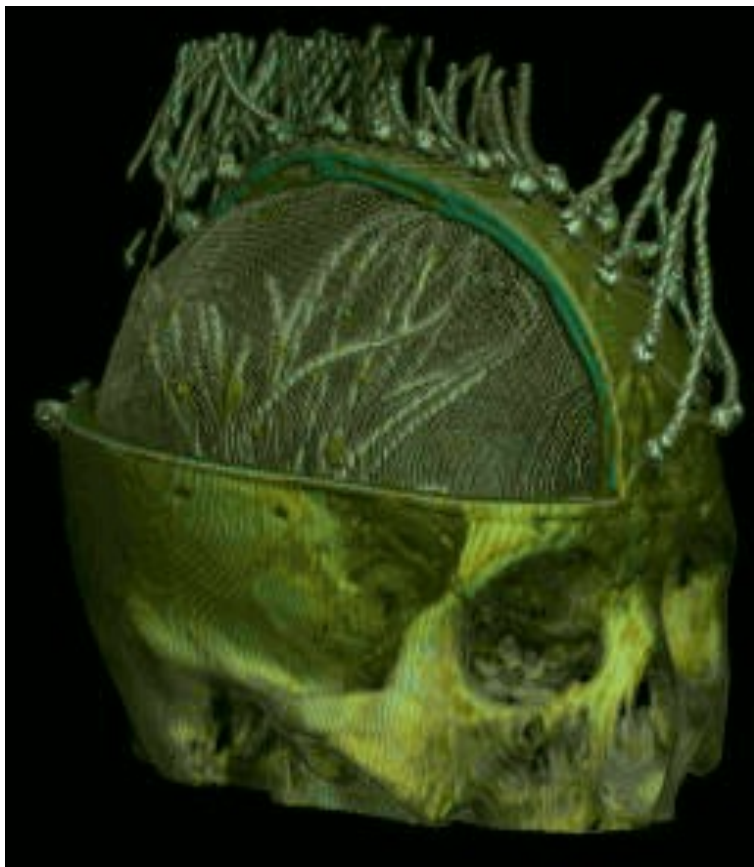
- At LANL, three-axis circular magnetic dipoles.
- From Neuromag, triangular-shaped magnetic dipoles.
- Sub mm accuracy typically achievable.

Human Skull Phantom

32 coaxial optically-isolated
current dipole sources



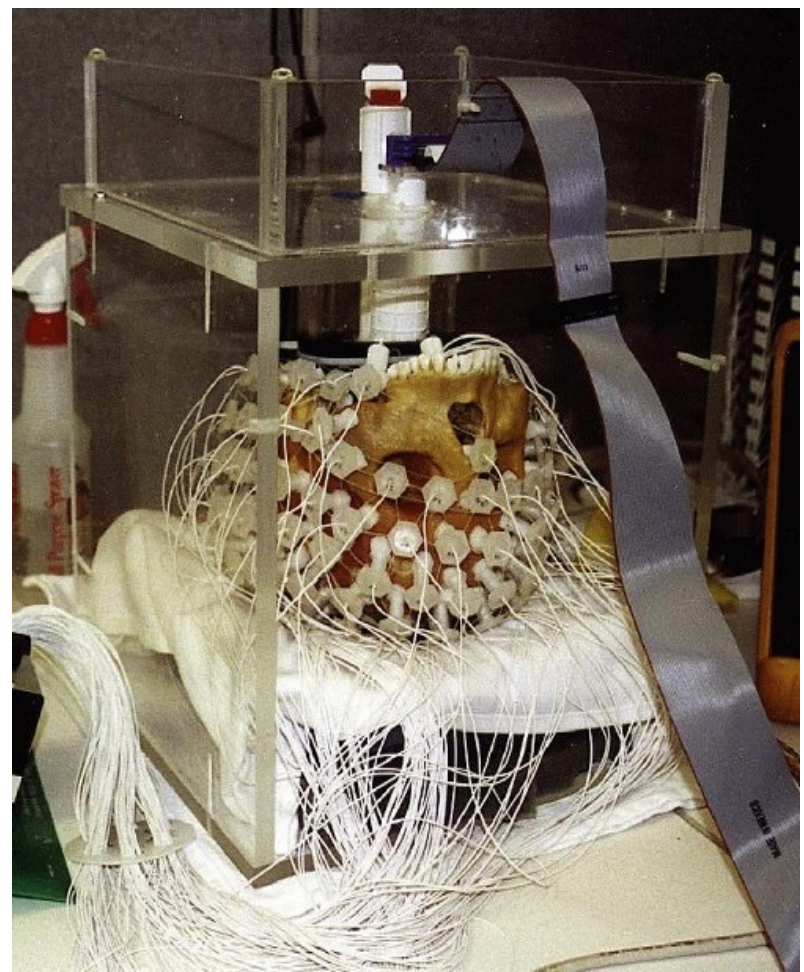
EEG and MEG Compatible



Ground truth from CT scan

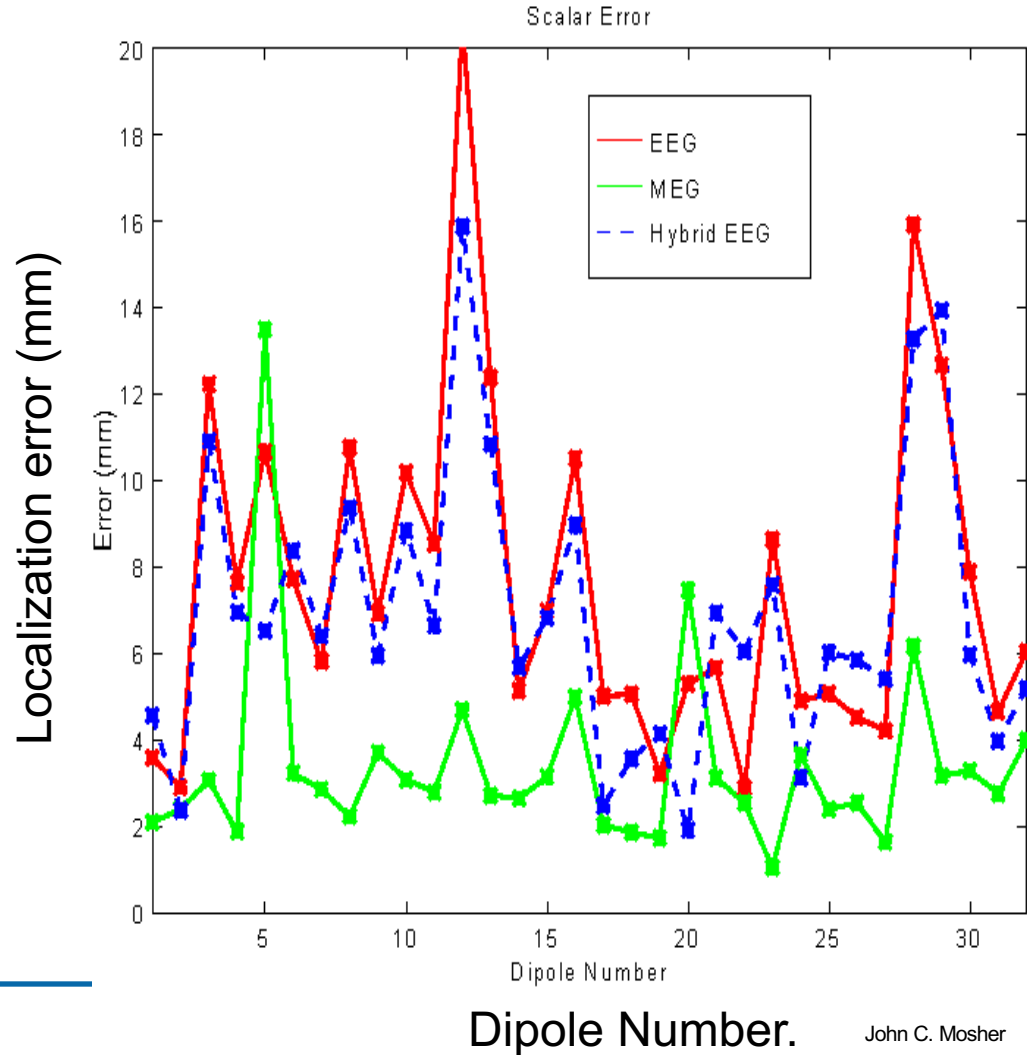
EEG Phantom Studies

- Colleagues at EGI, Incorporated, Eugene, OR.
- 128 channel EEG array, placed simultaneously like a hairnet.
- USC Human skull phantom tested on EGI machines.



Phantom Localization Errors

- Sources fit using R-MUSIC, spherical and realistic BEM forward models
- Average error for 32 dipoles using spherical head model: 4.1mm
- Average error for 32 dipoles using BEM head model: 3.4mm
- EEG: 2x greater error



EEG Limitation: Uncertain Skull Model

- Simulated differences in noise, array coverage, array density.
- Experimental errors larger than theory for EEG.
- Supposition is the imprecision in modeling the diploic space.



Electroencephalography and clinical Neurophysiology 107 (1998) 159–173



A study of dipole localization accuracy for MEG and EEG
using a human skull phantom

R.M. Leahy^{a,*}, J.C. Mosher^b, M.E. Spencer^c, M.X. Huang^d, J.D. Lewine^e

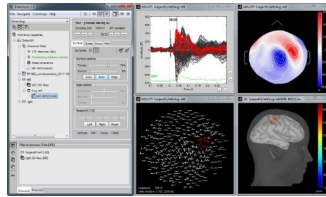
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Software Tools for MEG/EEG

Brainstorm



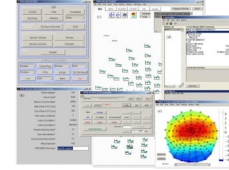
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MNE & MNE python



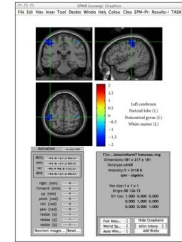
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SPM



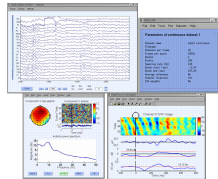
<http://www.fil.ion.ucl.ac.uk/spm/software/>

NutMEG



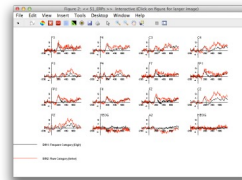
<http://nutmeg.berkeley.edu/>

EEGLAB



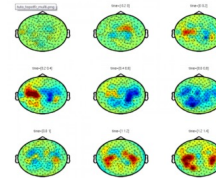
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BCILAB: Open source Matlab toolbox for brain-computer interfaces

NFT: Neuroelectromagnetic forward head modeling

OpenMEEG: Neuroelectromagnetic BEM forward head modeling

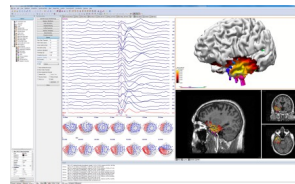
DUNEuro: Neuroelectromagnetic FEM forward head modeling

Commercial Products

Vendor software

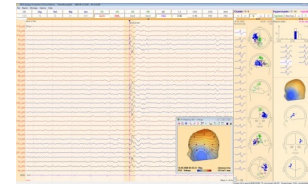
Elekta Neuromag
CTFMEG
EGI: Net Station 5
BioSemi

Curry



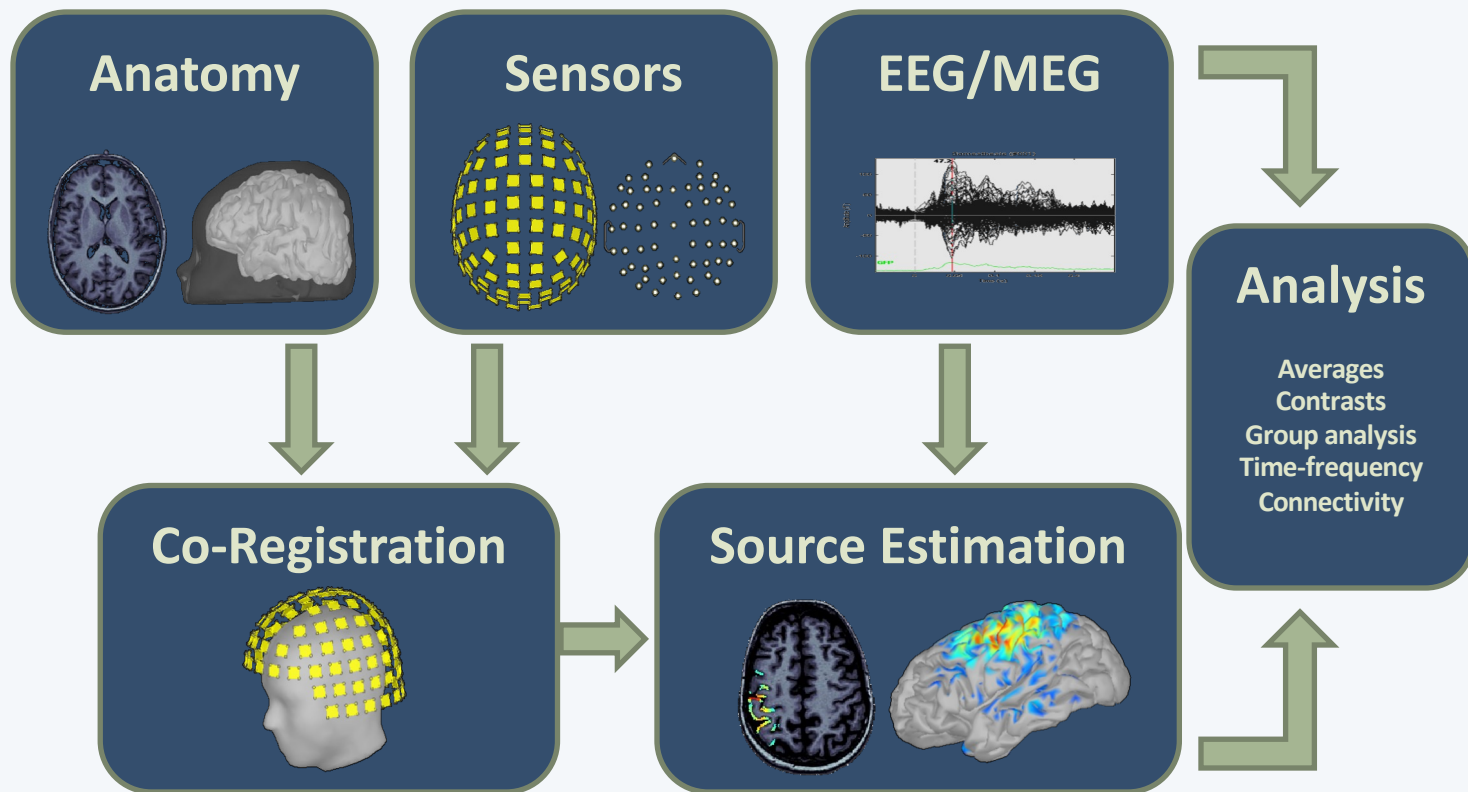
<http://compumedicsneuroscan.com/>

BESA



<http://www.besa.de/>

Summarizing the Workflow



Summary (1)

- Source space rests on a simple quasi-static model: $\mathbf{m}(t) = \mathbf{L}\mathbf{j}(t) + \mathbf{n}(t)$
- Everything downstream depends on a
 - credible lead field model $\mathbf{L}$
 - a sane noise covariance $\mathbf{C}_n$.
- Biophysics sets intuition:
 - the equivalent current dipole is a macro model of cortical patches;
 - evoked responses scale around tens of nA·m, epileptic spikes higher.
 - The Okada constant lets you back-of-the-envelope area from moment.
- Cortex modeling matters:
 - realistic surfaces and orientation constraints convert a huge volume search into a 2D mantle problem that matches physiology.

Summary (2)

- Coregistration is non-negotiable:
 - small pose errors bias dipole fits and degrade beamformers. Verify residuals visually and numerically before any inverse.
- Forward models are a design choice:
 - spheres are fast and often fine for MEG;
 - BEM improves realism;
 - FEM handles anisotropy when you need it.
- Inverse methods in practice:
 - Dipole fit/scan for focal, high-SNR events.
 - MNE+dSPM/sLORETA for distributed activity with variance-normalized interpretability.
 - LCMV for spatial filtering, with care on covariance, windows, and regularization.
- Phantom results show
 - MEG spheres can be acceptable, BEM reduces errors,
 - EEG is typically about 2x worse because of skull uncertainty.