An Introduction to Beamforming in MEG and EEG

IBB
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Outline

- Introduction to EEG/MEG source analysis
- Basic idea of a Vector Beamformer
- Data Model
- Filter Design
- Results
- Correlated sources
- Beamformer Types

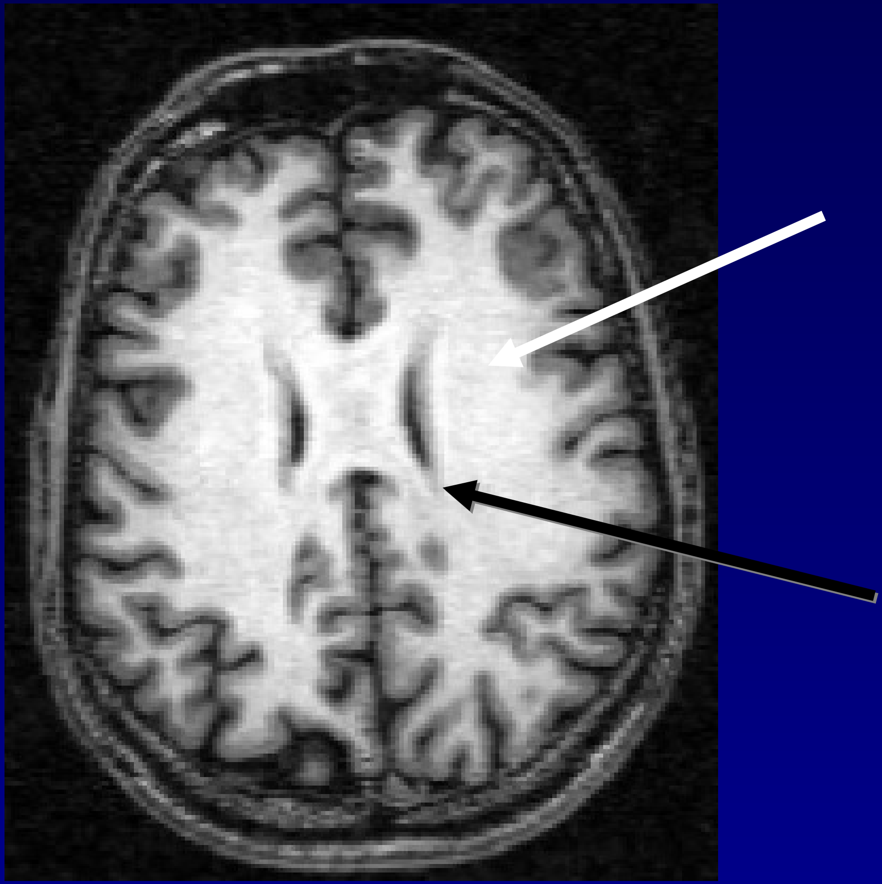
Introduction to EEG/MEG source analysis

- **What is Electro- (EEG) and Magneto-encephalography (MEG)?**

- **275 channel axial gradiometer whole-cortex MEG**
- **128 channel EEG**

Introduction to EEG/MEG source analysis

Gray and White Matter



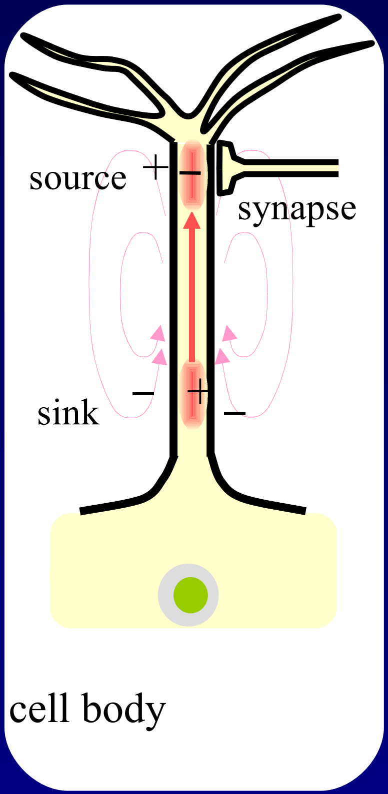
Gray matter

White matter (WM)

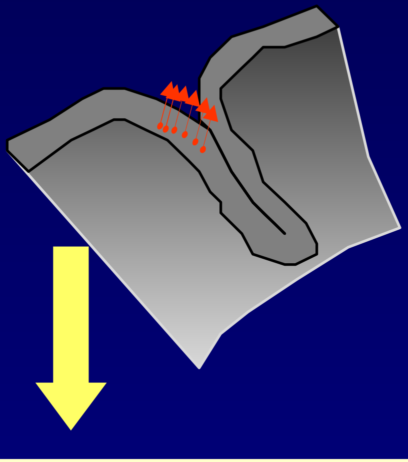
T1 weighted Magnetic Resonance Image (T1-MRI)

Introduction to EEG/MEG source analysis

Source Model:



Microscopic current flow ($\sim 5\times10^{-5}$ nAm)



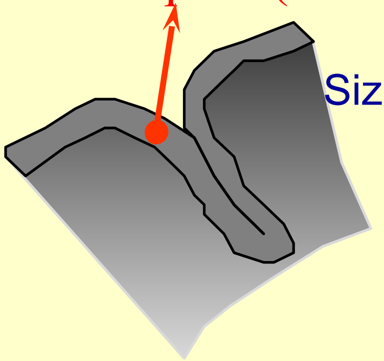
Cortex

Equivalent Current Dipole (Primary current) ($\sim$50 nAm)

Parameters:

position : x_0

moment : M



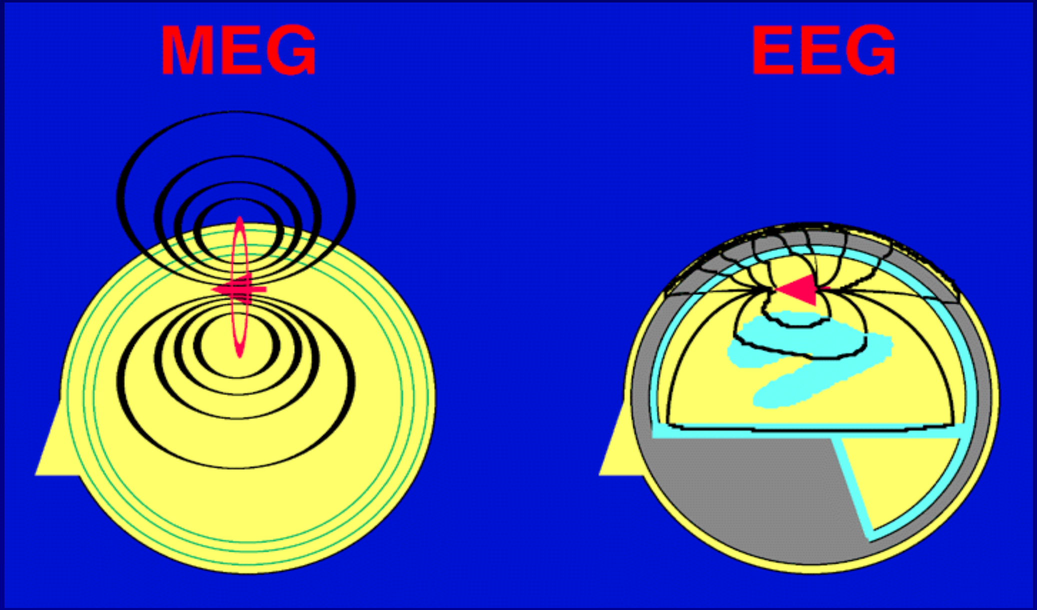
Size of Macroscopic Neural Activity

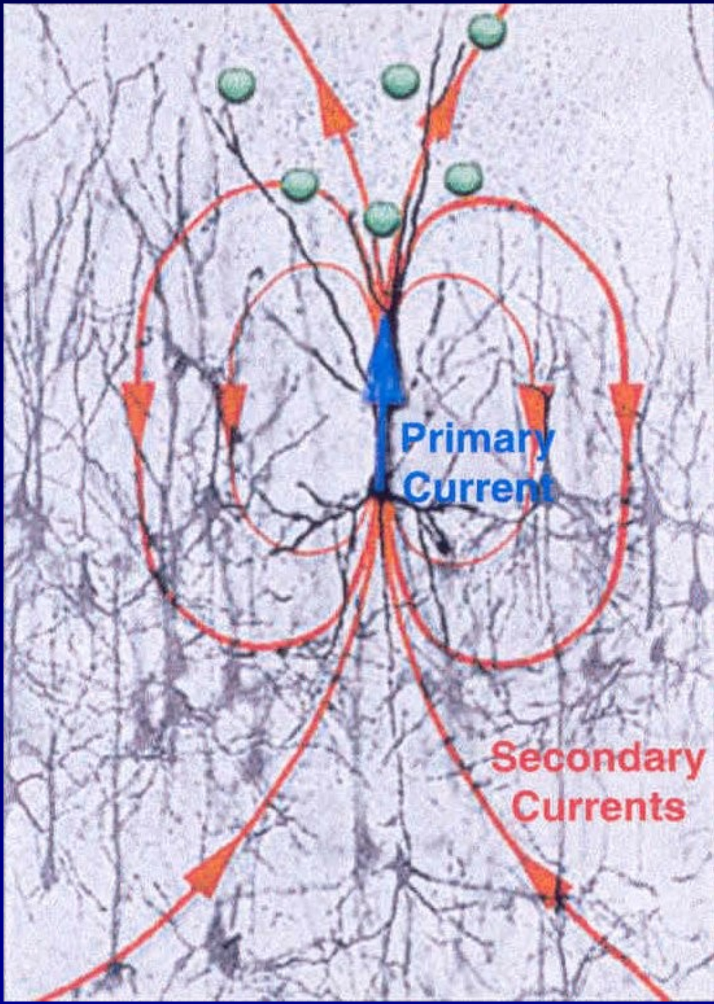
$\sim 30\ \text{mm}^2 = \mathbf{5.5\times5.5\ mm^2}$

Introduction to EEG/MEG source analysis

Source Localization:

- **MEG:** measurement of the magnetic field generated by the primary (main contribution) and secondary currents
- **EEG:** measurement of the electric scalp potential generated by the secondary currents



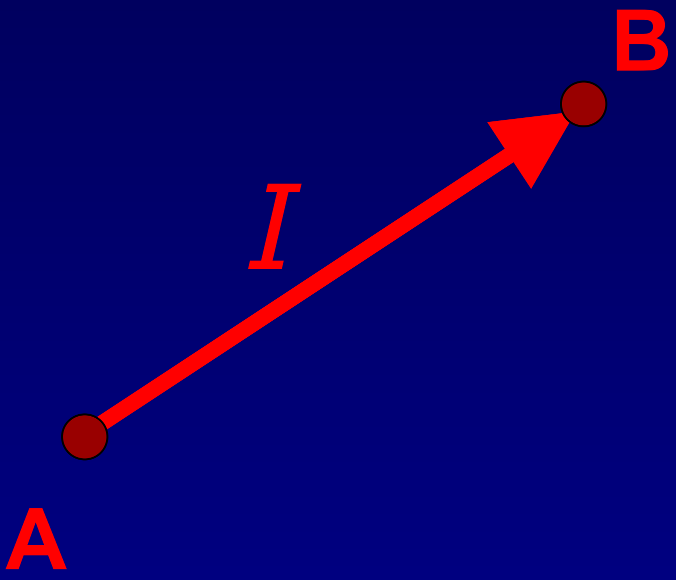


Introduction to EEG/MEG source analysis

Equivalent Current Dipole (ECD)

Definition:

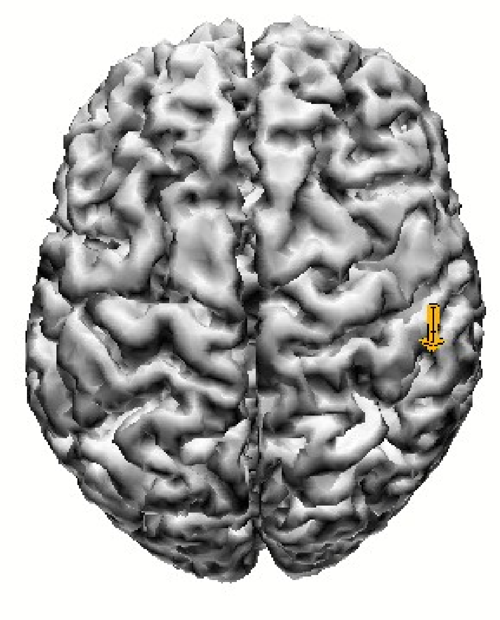
- Current I flowing from a source A (+) to a sink B (-)
  - $Q = I * \mathrm{AB}$ [Unit: *Am*]
- Distance between A and B infinitesimal small (current infinite high): *Point dipole.*
  - $dq = I * dr = j * dV$



Introduction to EEG/MEG source analysis

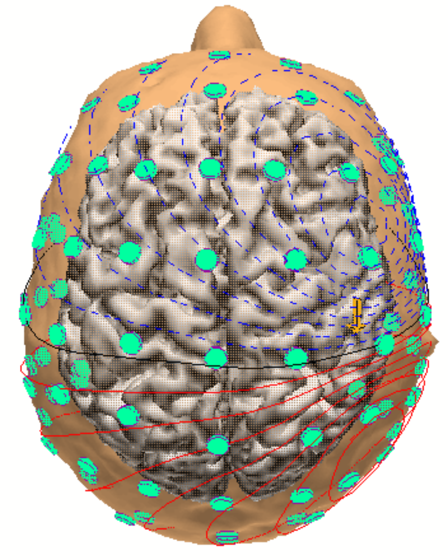
The EEG/MEG Forward Problem:

Place a dipole

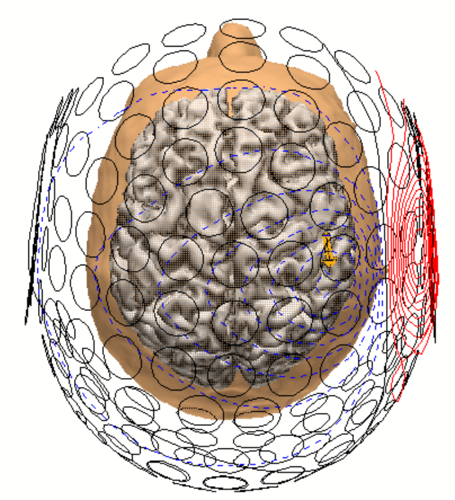


Simulate quasistatic maxwell equasions

Compute EEG



Compute MEG



Introduction to EEG/MEG source analysis

Source Localization:

- **Given:** EEG/MEG measurement of the potential induced by a stimulus
- **Wanted:** the equivalent current dipole described by:
  - Position
  - Strength
  - Direction

Introduction to EEG/MEG source analysis

Source localization is difficult.

- The mathematical problem (inverse problem) is difficult: *ill-posed*.
  - well-posed:
    1. A solution exists.
    2. The solution depends continuously on the data.
    3. The solution is unique.

Introduction to EEG/MEG source analysis

Source localization is difficult.

- Numerical instabilities due to errors (finite precision of the method, noise, …). Small errors in the measured data lead to much larger errors in the source localization (*ill-conditioned*).

- The forward problem (modelling the head as a volume conductor) is difficult:
  - Sphere models
  - BEM models
  - FEM models

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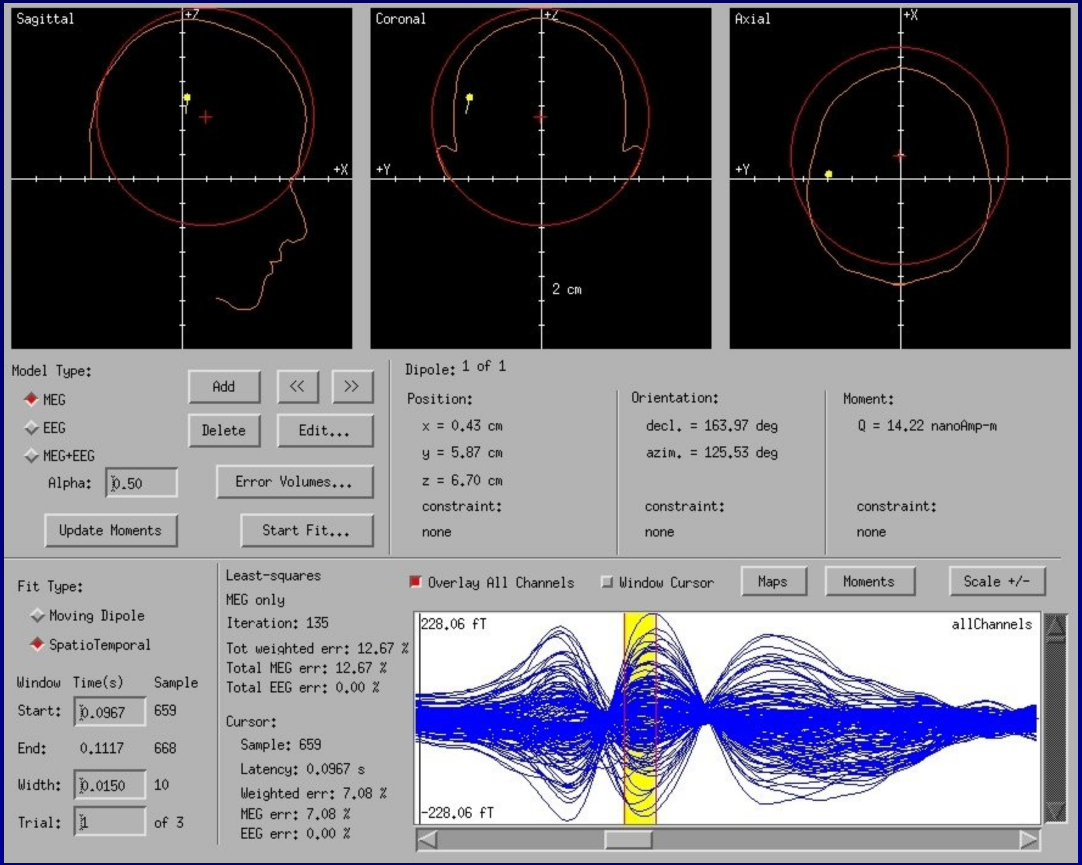
Dipole Fit

Find the dipole position that matches the measured field in the best possible way



Model Type:
◆ MEG
◇ EEG
◇ MEG+EEG
Alpha: 0.50

Dipole: 1 of 1

Position:
x = 0.43 cm
y = 5.87 cm
z = 6.70 cm
constraint:
none

Orientation:
decl. = 163.97 deg
azim. = 125.53 deg
constraint:
none

Moment:
Q = 14.22 nanoAmp-m
constraint:
none

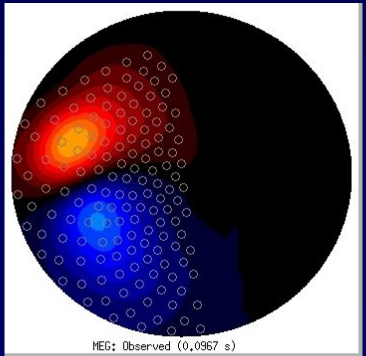
Fit Type:
◇ Moving Dipole
◆ SpatioTemporal

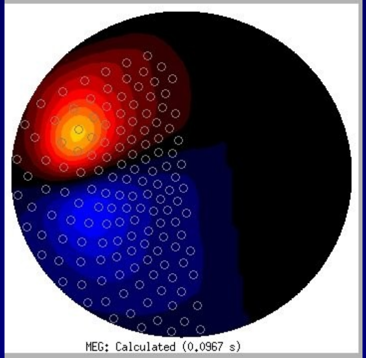
Window	Time(s)	Sample
Start:	0.0967	659
End:	0.1117	668
Width:	0.0150	10
Trial:	1	of 3

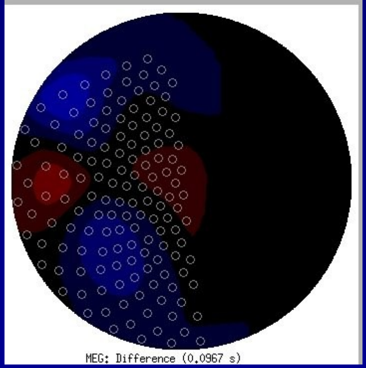
Least-squares
MEG only
Iteration: 135
Tot weighted err: 12.67 %
Total MEG err: 12.67 %
Total EEG err: 0.00 %

Cursor:
Sample: 659
Latency: 0.0967 s
Weighted err: 7.08 %
MEG err: 7.08 %
EEG err: 0.00 %

☒ Overlay All Channels ☐ Window Cursor


MEG: Observed (0.0967 s)


MEG: Calculated (0.0967 s)


MEG: Difference (0.0967 s)

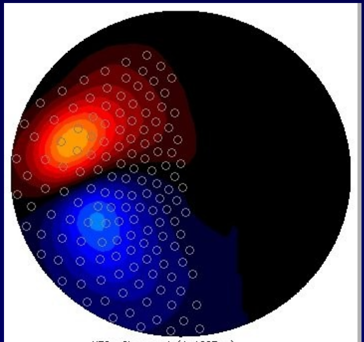
Introduction to EEG/MEG source analysis

Dipole Fit

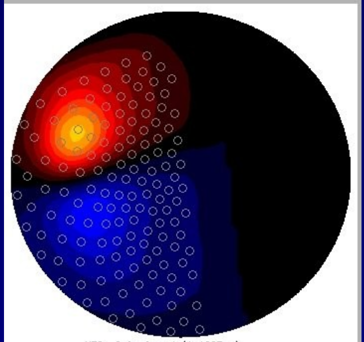
Problems:

- The number of sources must be known in advance.
- Applicable only for a small number of source.

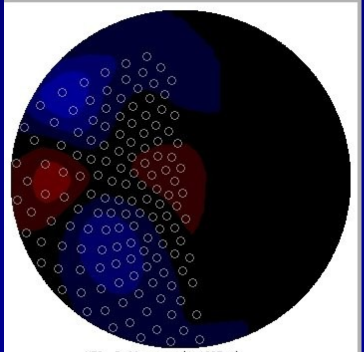
The restriction to a very limited number of possible sources leads to an unique solution.



MEG: Observed (0.0967 s)



MEG: Calculated (0.0967 s)



MEG: Difference (0.0967 s)

Introduction to EEG/MEG source analysis

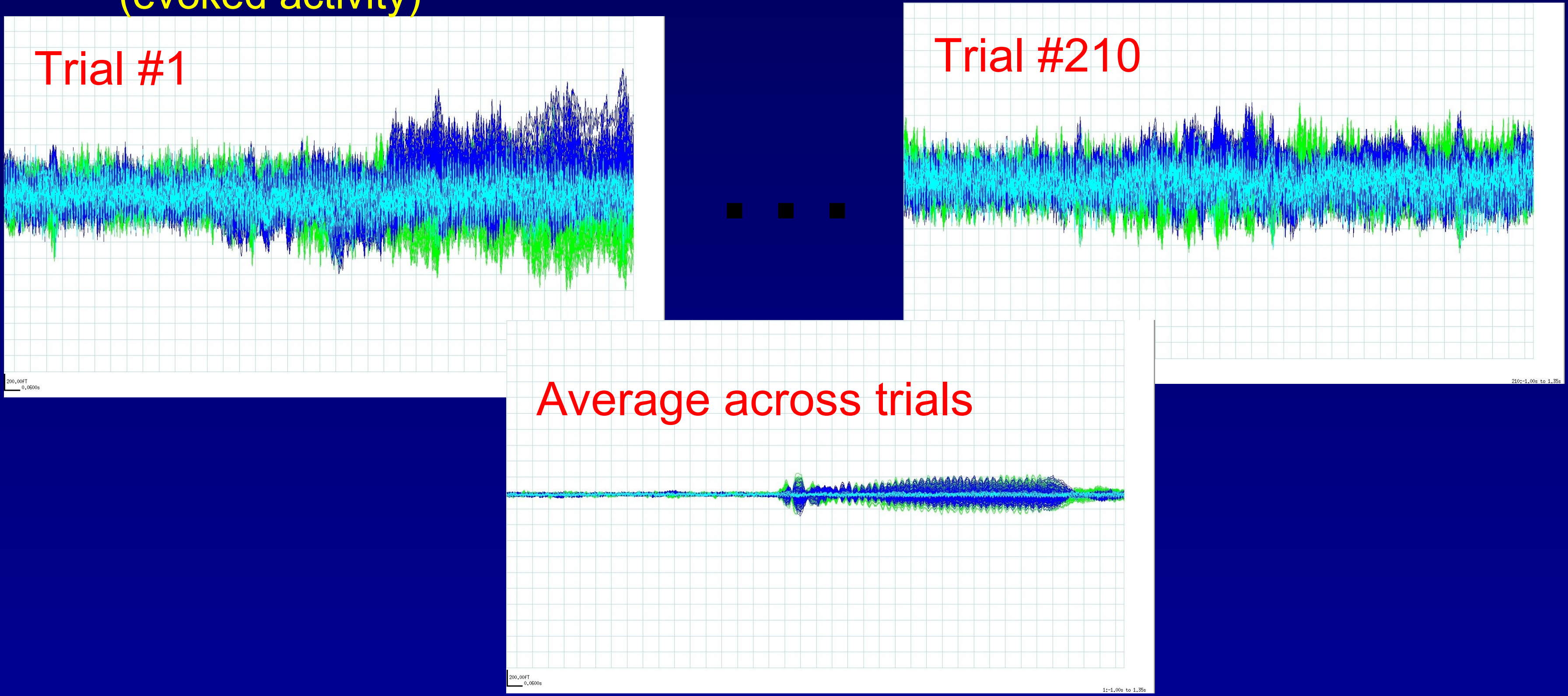
Averaging:

Advantages:

- Increased signal-to-noise ratio
- Reduced brain-noise
- Small number of remaining sources (evoked activity)

Disadvantages:

- Only induced activity can be seen (activity time and phase locked to the stimulus)

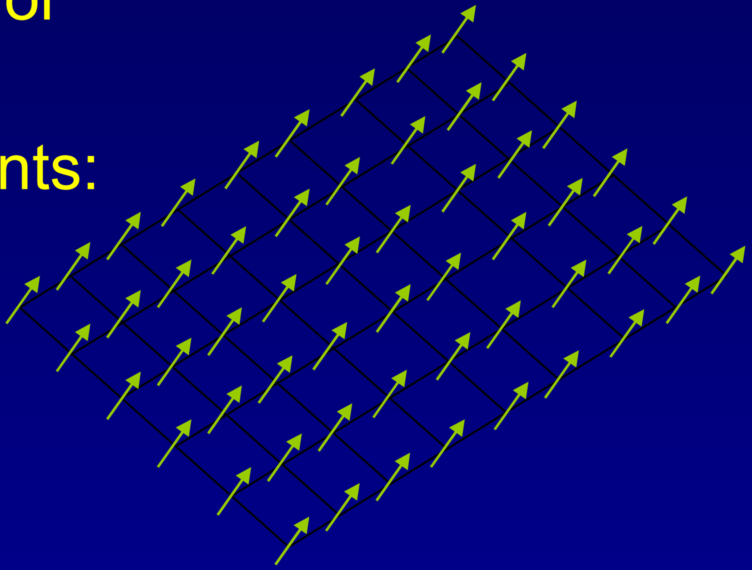


Introduction to EEG/MEG source analysis

Current Density Methods

(e.g. sLORETA)

- 3D grid of fixed dipoles. Typically three dipoles (x , y , z direction) for each grid point.
- Optimization of the dipole moments:
    - Minimal difference to the measured field
    - Minimal energy



The ‘minimal energy’ condition leads to an unique solution.

Introduction to EEG/MEG source analysis

Current Density Methods

(e.g. sLORETA)

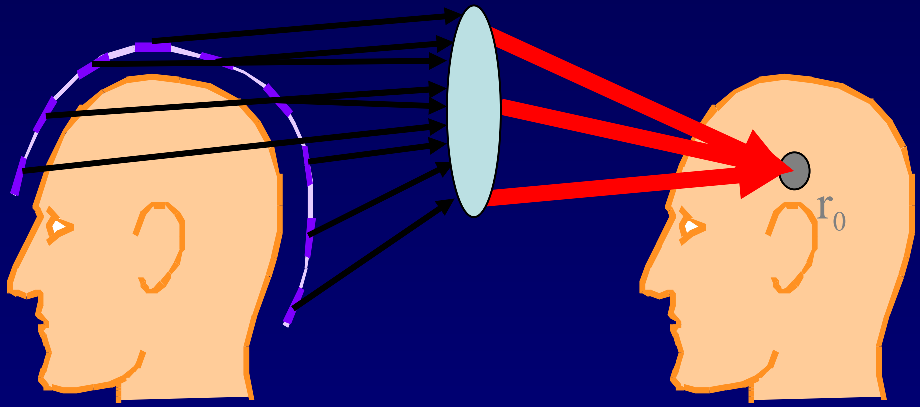
Problems:

- The ‘minimal energy’ condition leads to broad activation patterns.
- For a sufficient signal-to-noise ratio current density methods typically operates on averaged data sets (evoked activity).

Introduction to EEG/MEG source analysis

Beamformer Methods

(e.g. SAM)



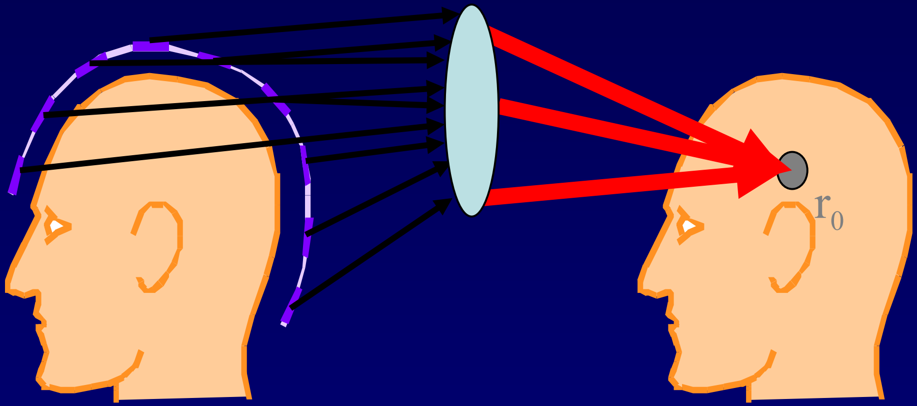
Beamformer methods are different:

- Beamformers do not try to explain the complete measured field. Instead the contribution of a single brain position to the measure field is estimated.
- Beamformers are based on the variance of the source, not directly on its strength.

Introduction to EEG/MEG source analysis

Beamformer Methods

(e.g. SAM)

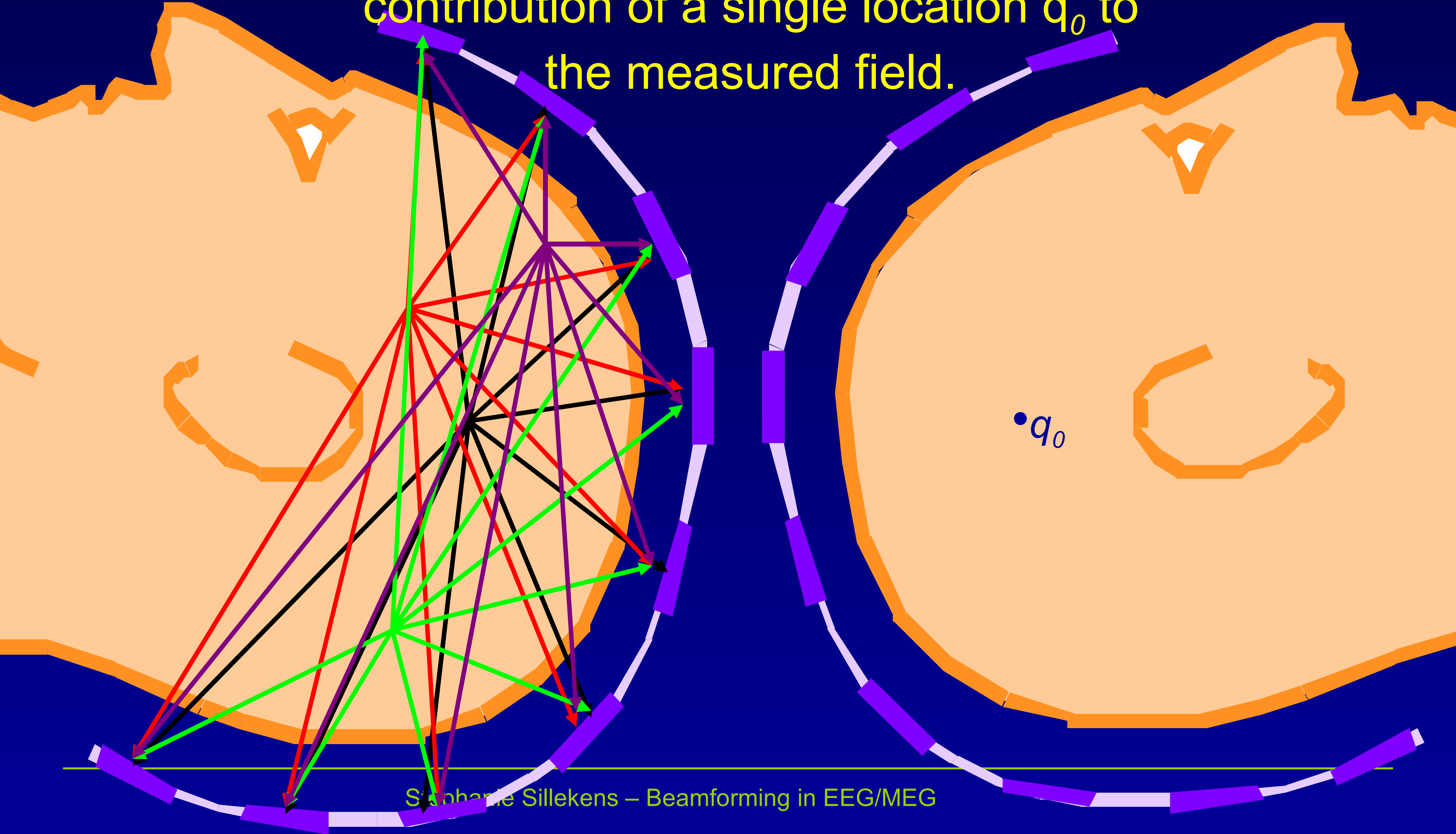


Beamformer methods are different:

- They operate on raw data sets (instead of averaged data sets).
- They can be used to analyse induced brain activity.
- They do not need a-priori specification of the number of active sources.
- They are blind for time correlated neural activity.

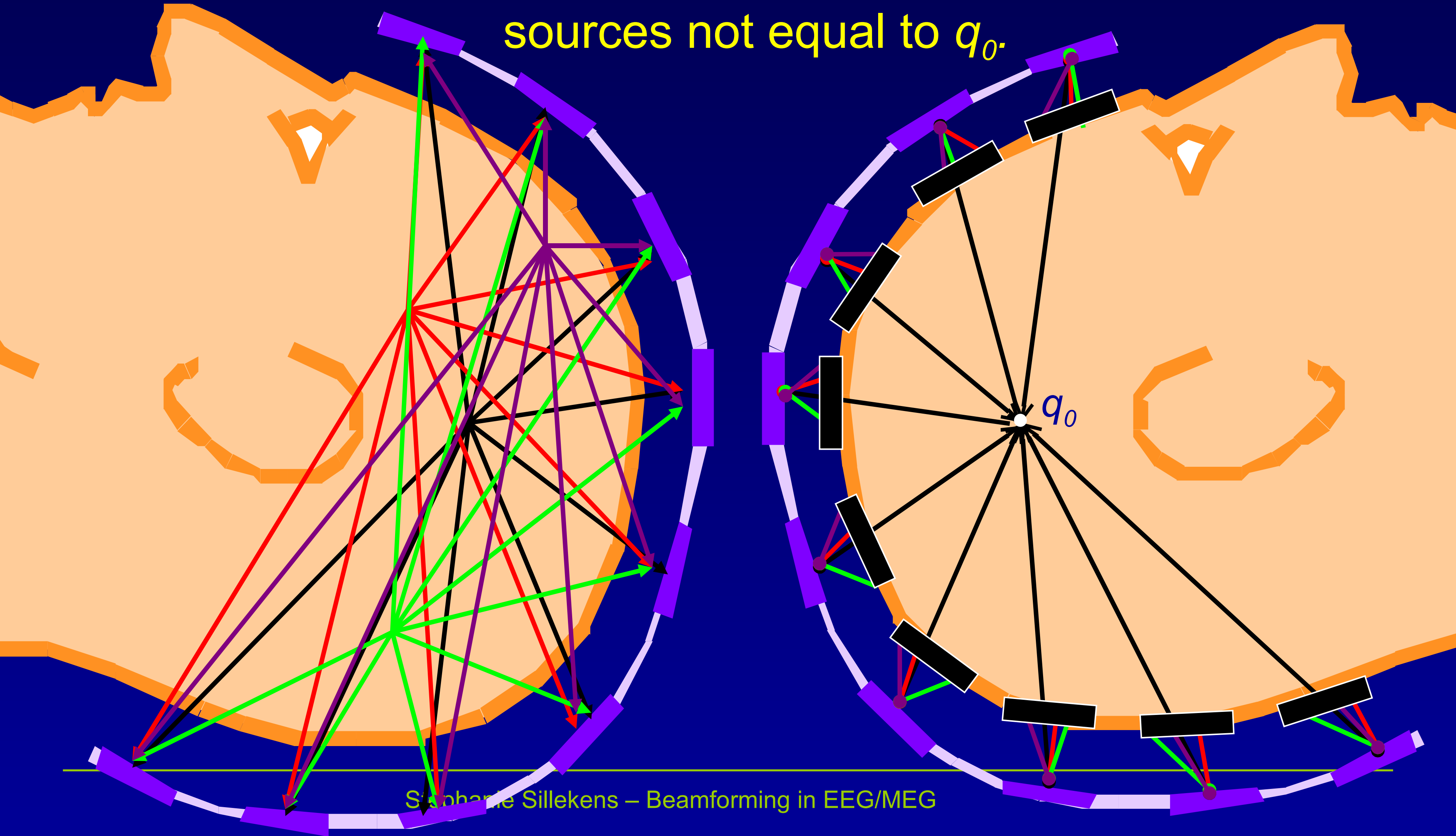
Basic idea of a Vector Beamformer

A beamformer tries to reconstruct the contribution of a single location q_0 to the measured field.



Basic idea of a Vector Beamformer

Beamforming means constructing a spatial filter that blocks the contributions of all sources not equal to q_0.



Data Model

- Datavector x: N×1 vector representing potentials measured at N electrode sites

$$x = \begin{pmatrix} x_1 \\ \vdots \\ x_N \end{pmatrix}$$

- Source Position q: 3×1 vector composed of the x-,y-,z-coordinates

$$q = \begin{pmatrix} q_x \\ q_y \\ q_z \end{pmatrix}$$

- Dipole moment m(q): 3×1 vector composed of the x-,y- and z-components of the dipole moment

$$m(q) = \begin{pmatrix} m_x \\ m_y \\ m_z \end{pmatrix}$$

Data Model

- Transfermatrix H(q): N×3 matrix representing the solutions to the forward problem given unity dipoles in x-,y-,z-direction at position q

$$H(q)=\begin{pmatrix} h_{1x} & h_{1y} & h_{1z} \\ h_{2x} & h_{2y} & h_{2z} \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ h_{Nx} & h_{Ny} & h_{Nz} \end{pmatrix}$$

→ in a linear medium the potential at the scalp is the superposition of the potentials from many active neurons:

$$x=\sum_{i=1}^{L} H(q_i)m(q_i)+\underset{\substack{\uparrow \\ \text{Measurement noise}}}{n}$$

Data Model

Electrical activity of an individual neuron is assumed to be a random process influenced by external inputs.

→ Model the diple moment as a random quantity and describe its behaviour in terms of mean and covariance

- Moment mean vector:

$$\overline{m}(q_i) = E\{m(q_i)\}$$

- Moment covariance matrix:

$$C(q_i) = E\{[m(q_i) - \overline{m}(q_i)] * [m(q_i) - \overline{m}(q_i)]^T\}$$

- The variance associated with a source is a measure of strength of the source. It is defined as the sum of the variance of the dipole moment components:

$$\mathrm{Var}(q) = \mathrm{tr}\{C(q)\}$$

Data Model

Assuming that

- The noise is zero mean $\left(E\{n\}=0\right)$
- the noise covariace matrix is denoted to as Q
- The moments associated with different dipoles are uncorrelated

we have

$$\overline{m}(x)=E\{x\}=\sum_{i=1}^{L}H(q_i)\overline{m}(q_i)$$

$$C(x)=E\left\{\left[x-\overline{m}(x)\right]*\left[x-\overline{m}(x)\right]^T\right\}=\sum_{i=1}^{L}H(q_i)C(q_i)H^T(q_i)+Q$$

Filter Design

- Define the spatial filter for volume element Q_0 centered on location q_0 as an N×3 matrix $W(q_0)$

- The three component filter output is $y = W^T(q_0)x$ ("contribution in x, y and z direction")

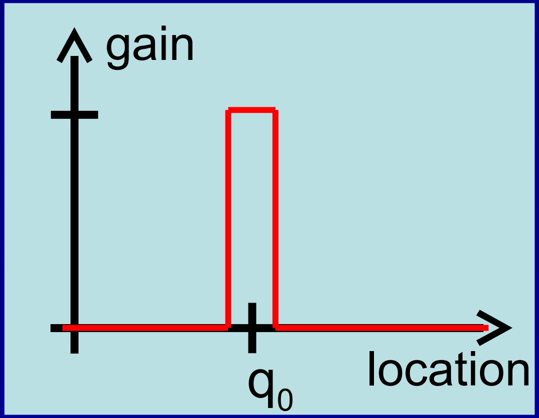
- An ideal filter satisfies

$$W^T(q_0)H(q_0) = \begin{cases} I & \text{for } q = q_0 \\ 0 & \text{for } q \neq q_0 \end{cases} \quad \text{for} \quad q \in \Omega$$

where Ω represents the brain volume.

Passband: $q = q_0$

Stopband: $q \neq q_0$



Filter Design

! In the absence of noise this implies $y=m(q_0)$, the dipole moment at the location of interest.

- Unit response in the pass band is insured by requiring

$$\boxed{W^T(q_0)H(q_0) = I}$$

- Zero response at any point q_s in the stopband implies $W(q_0)$ must also satisfy

$$\boxed{W^T(q_0)H(q_s) = 0}$$

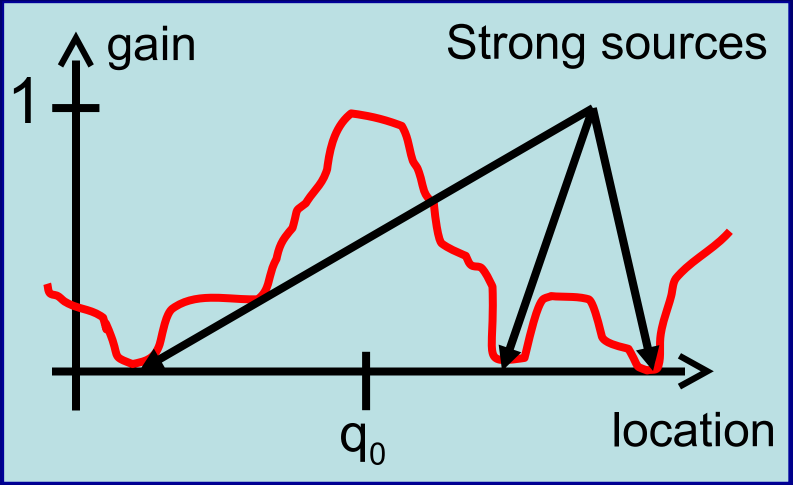
Problem:

At most *N/3-1 sources* (*N* number of sensors) can be completely stopped.

Filter Design

Solution: Use an adaptive Beamformer!

Optimal use of the limited stopband capacity: Contributions of unwanted sources are not fully stopped but reduced. Strong source are more reduced than weak sources.



Filter Design

- **Optimization:** Among all possible spatial filters (filters with gain 1 at q_0) select the filter with the smallest beamformer output (minimal variance).

Why is minimal variance a good measure?

In 1D: For each valid filter we have

$$\text{filter output} = Var(s(q_0, t) + e(t))$$

$$= \mathrm{Var}(s(q_0,t)) + \mathrm{Var}(e(t))$$

$$> \mathrm{Var}(s(r_0,t))$$

(as long as signal *s* and error *e* are uncorrelated).

Filter Design

The problem is posed mathematically as

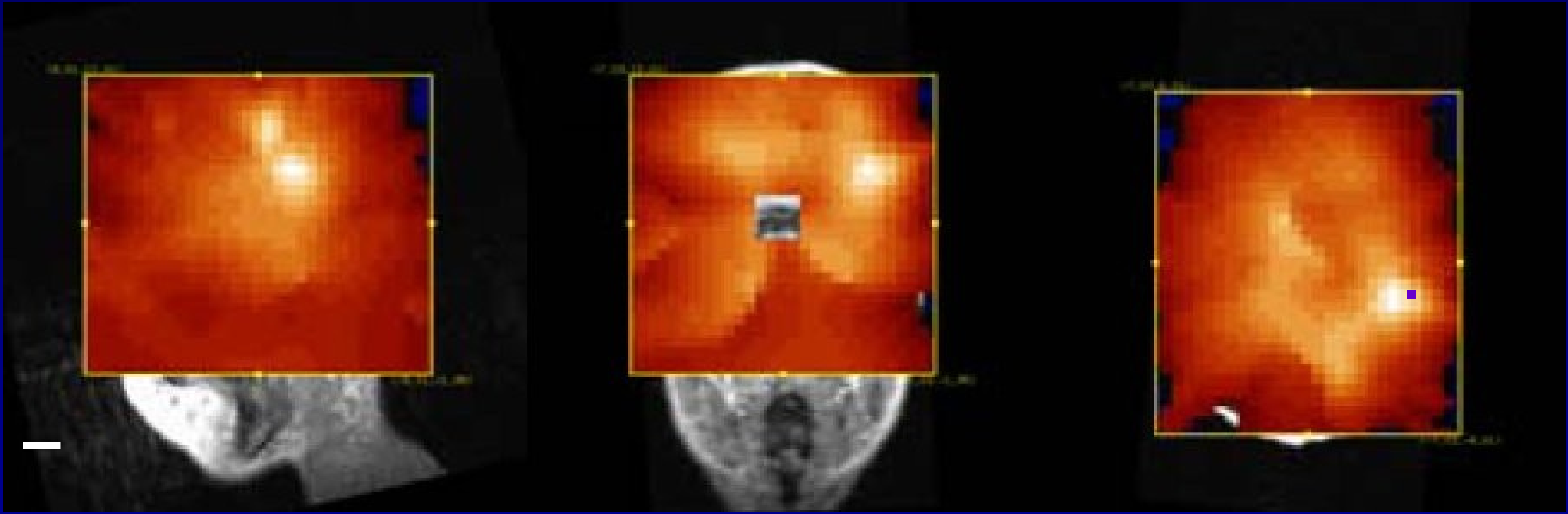
$$\min_{W(q_0)} \operatorname{tr}(Cy) \text{ subject to } W^T(q_0)H(q_0) = I$$

Using Lagrange multipliers we can find the solution:

$$W(q_0) = \left[H^T(q_0)C^{-1}(x)H(q_0)\right]^{-1} H^T(q_0)C^{-1}(x)$$

Beamformer Results

- Calculating the Beamformer output for a 3D grid of head positions leads to a 3D map of brain activity (source variance):

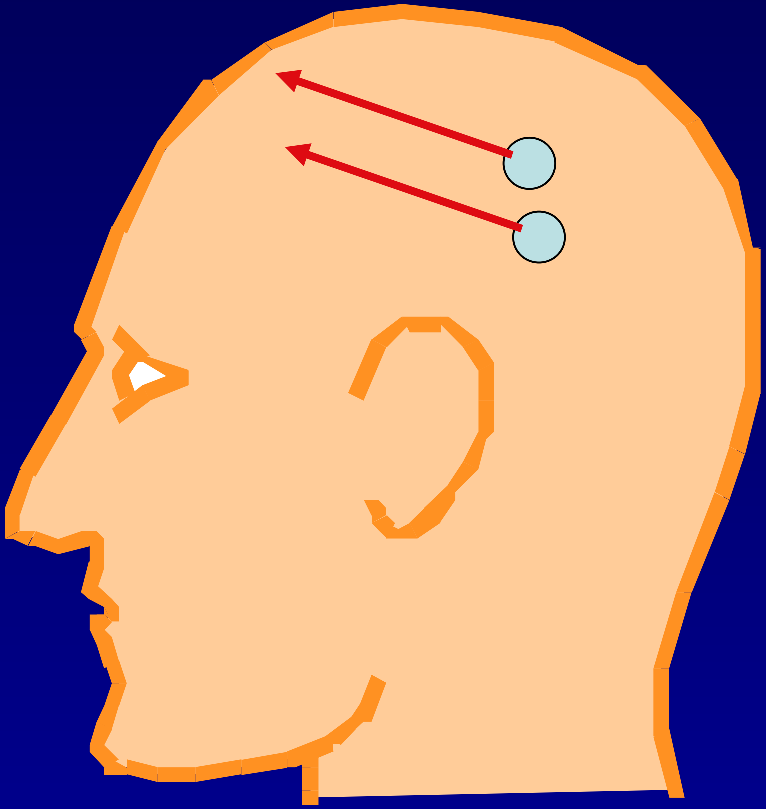


Correlated sources

Fundamental Problem:

Correlated sources:

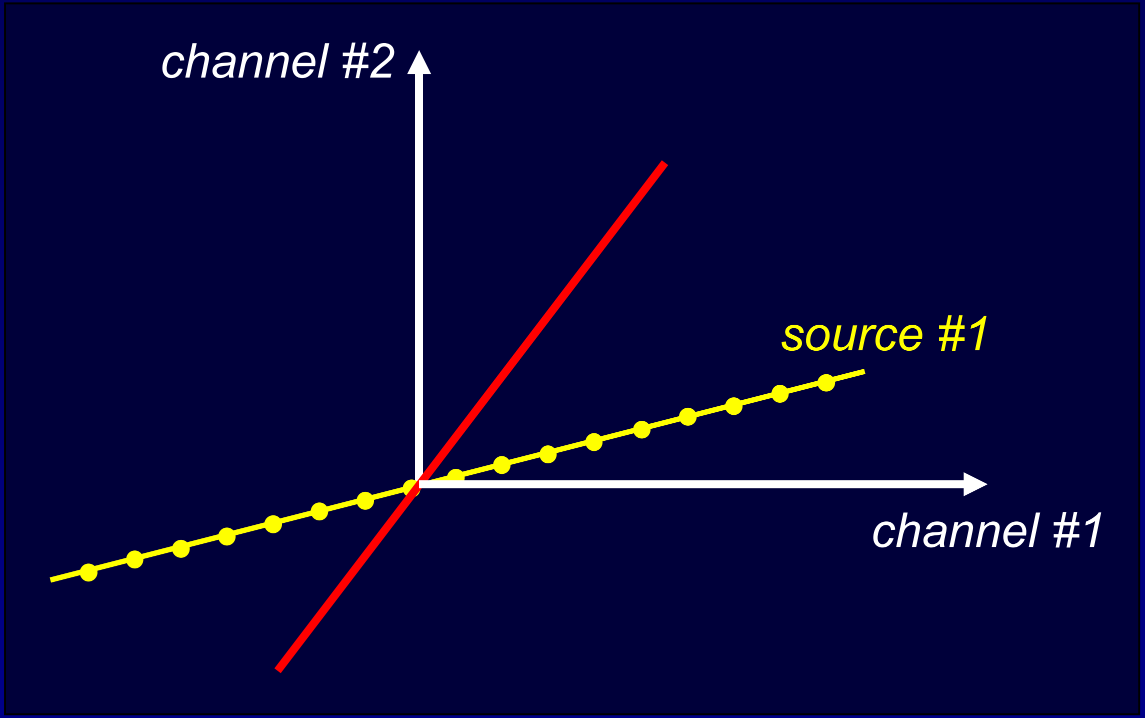
- Correlated sources cancel out each other.
- The amount of cancellation depends on the correlation coefficient.
- Fully correlated sources cannot be seen by a beamformer.



Correlated sources

What’s wrong with correlated sources?

The sensor pattern of a single dipole does not change in time (forms a line in sensorspace).

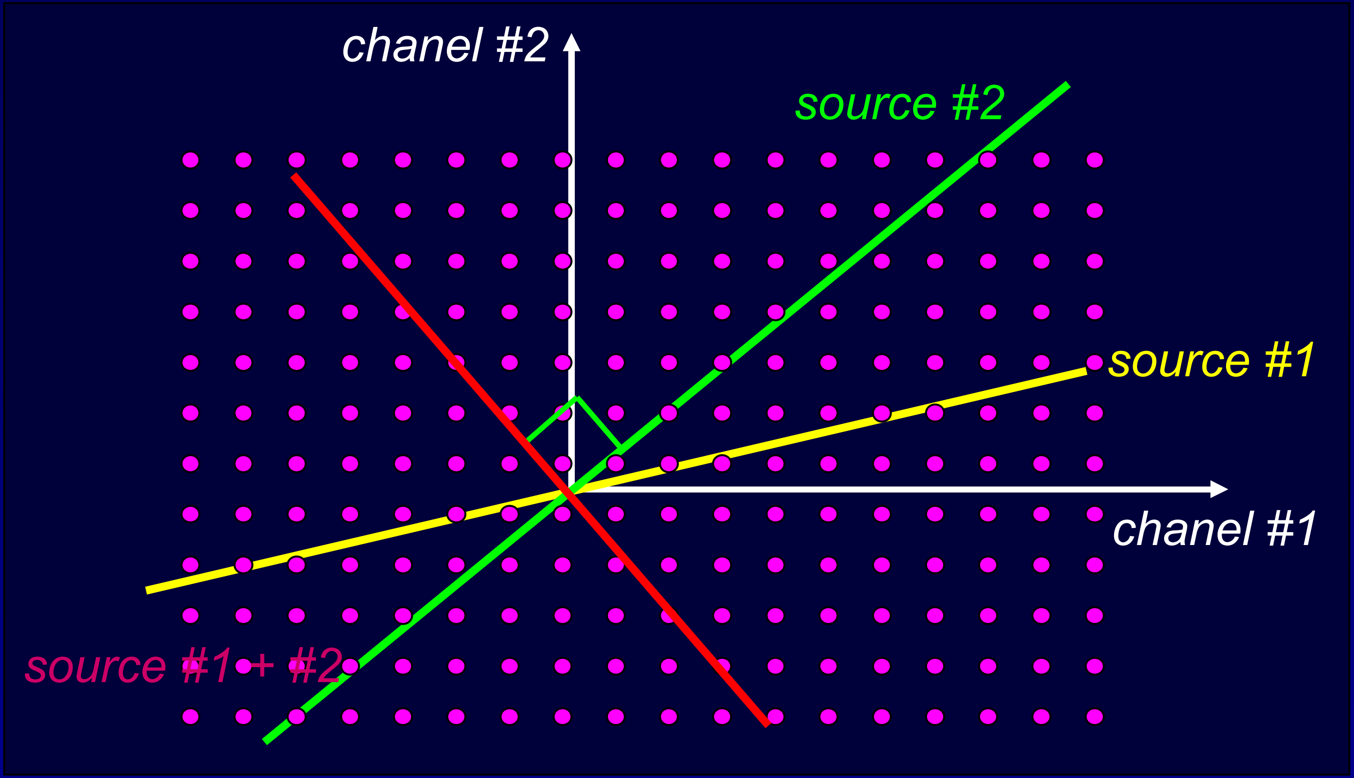


*beamformer, **not** perpendicular to source #1 (within passband)*

Correlated sources

What's wrong with correlated sources?

The sensor pattern of a single dipole does not change in time (forms a line in sensor space).



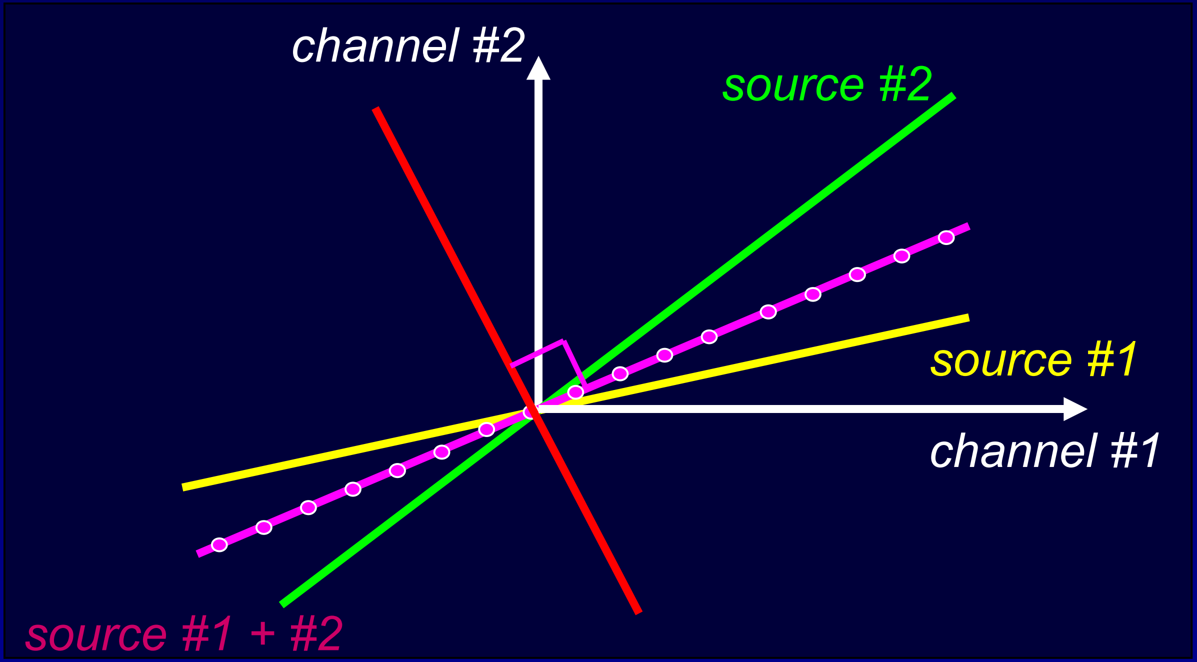
beamformer, perpendicular to source #2 (stopband)

Correlated sources

What's wrong with correlated sources?

The sensor pattern of two fully correlated dipoles is constant in time (line in sensor space).

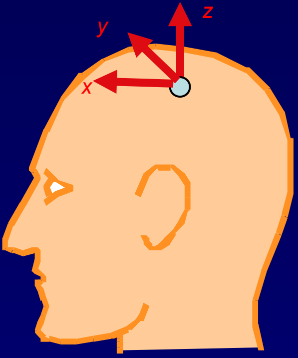
It looks like a single dipole pattern, but obviously, no single brain location can generate this pattern.



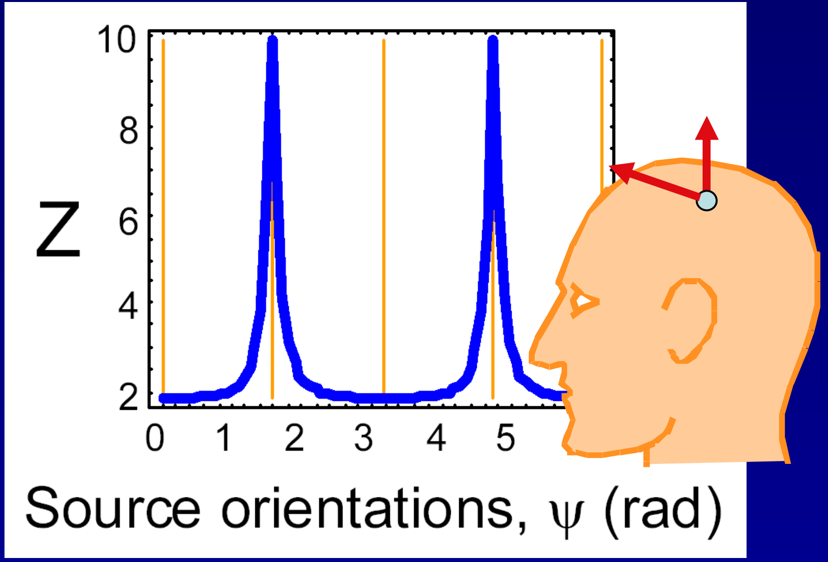
beamformer, perpendicular to source #1 + #2 (stopband)

Beamformer Types

- **Vector Beamformer**
  - Calculation of three beamformer results for each brain location along the x-, y-, and z-direction.
  - Result: $m_x(q_0) + m_y(q_0) + m_z(q_0)$.



- **Synthetic Aperture Magnetometry (SAM)**
  - Estimation of the dipole direction (direction with maximum beamformer result).
  - Result: $m_{estimated\text{-}direction}(q_0)$.
  - More stable than vector beamformer (as long as the dipole direction could successfully be estimated).



Thanks

Special Thanks to Dr. Carsten Wolters and Dr. Olaf Steinsträter for providing some of the material used in this presentation.

Thanks

Thanks for your attention.