



Radboud University



Denoising MEG and OPM data

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What is noise?

Anything that is not signal

Instrumental noise

sensor noise, electronic interference, cross-axis projection errors

Ambient noise

earth magnetic field, traffic, train, elevator, AC-line noise, mechanical vibrations

Physiological noise

cardiac, ocular, muscle, breathing, movement

Brain noise

stuff from the brain that is not of experimental interest

OPM MEG vs SQUID MEG

OPMs see the DC-field

Environment moves relative to the sensors

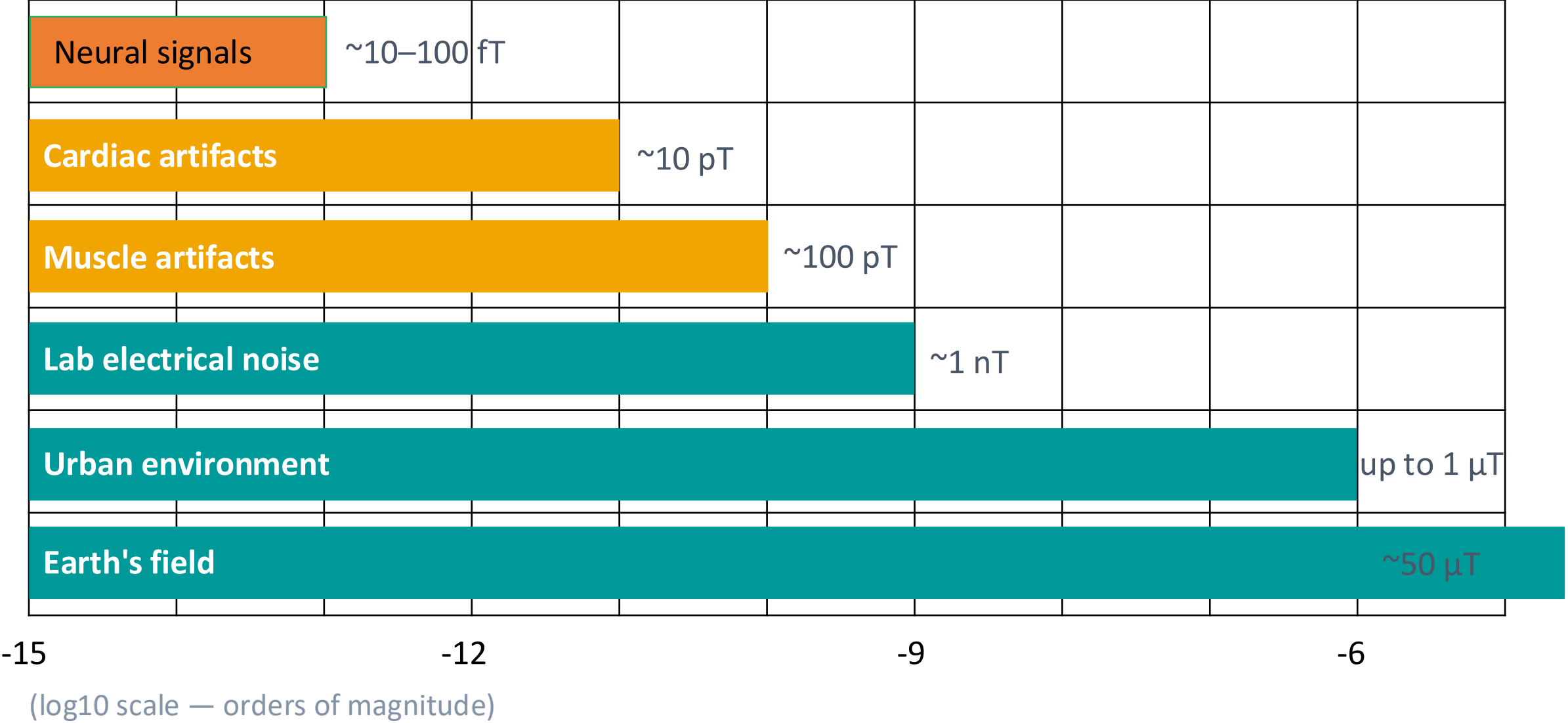
Neural sources don't move relative to the sensors

Sensor noise characteristics:

- higher noise floor, ~2-5 times larger noise OPM vs. SQUID

- lower bandwidth, up to 100 Hz for OPM

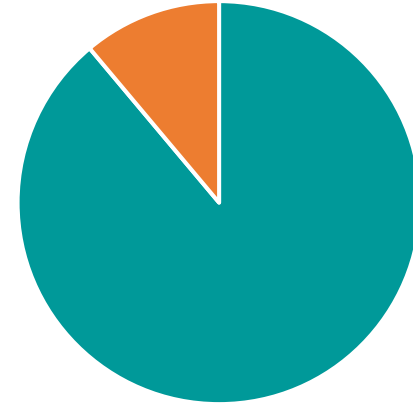
Noise in context



what's a few orders of magnitude?

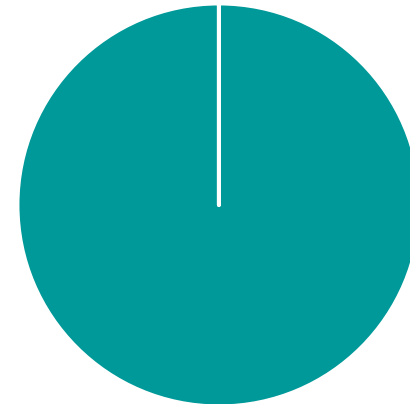


Total signal log10 scale



■ earth magnetic field ■ brain stuff

Total signal



■ earth magnetic field ■ brain stuff

How to address the noise

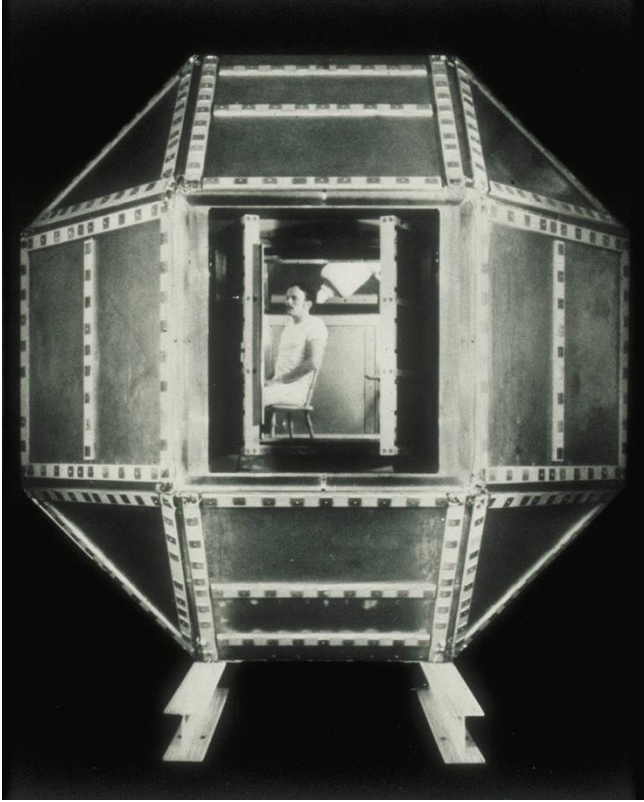
Keep the noise out with a shield

Active shielding

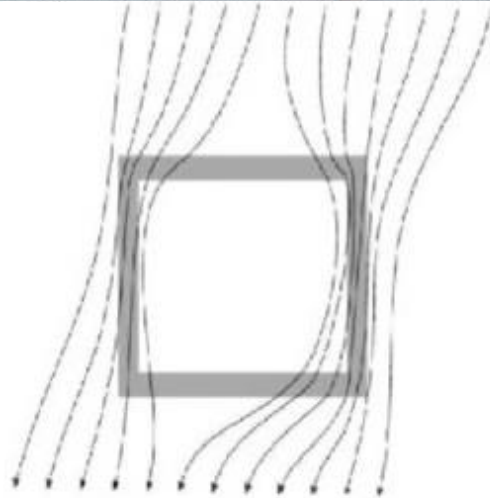
Keep the noise out:

Magnetically shielded room (MSR)

these have to be large for SQUID systems



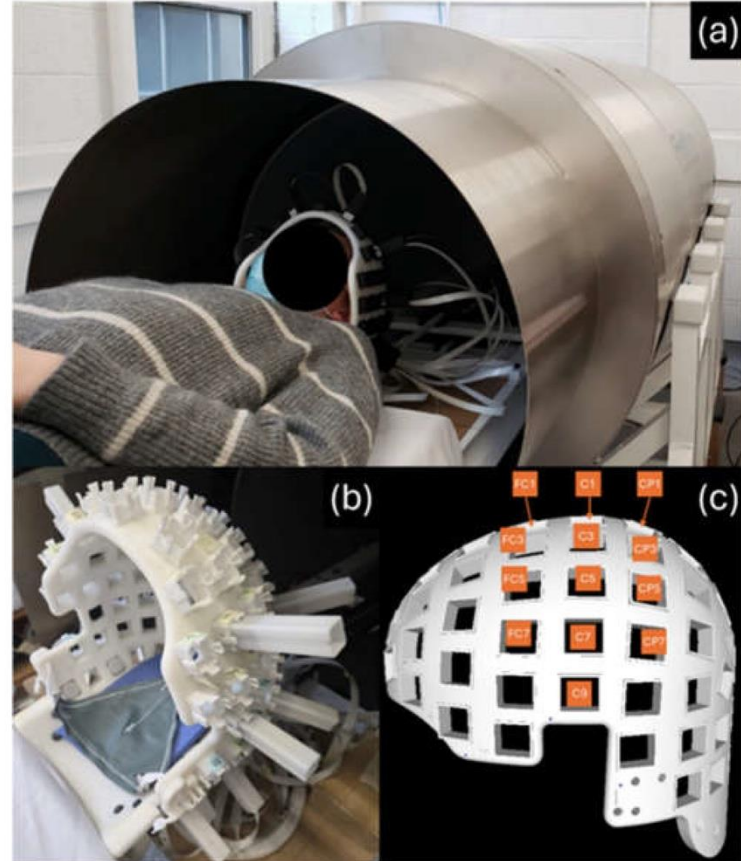
The magnetically shielded room built by David Cohen at MIT's Francis Bitter National Magnet Laboratory in 1969.



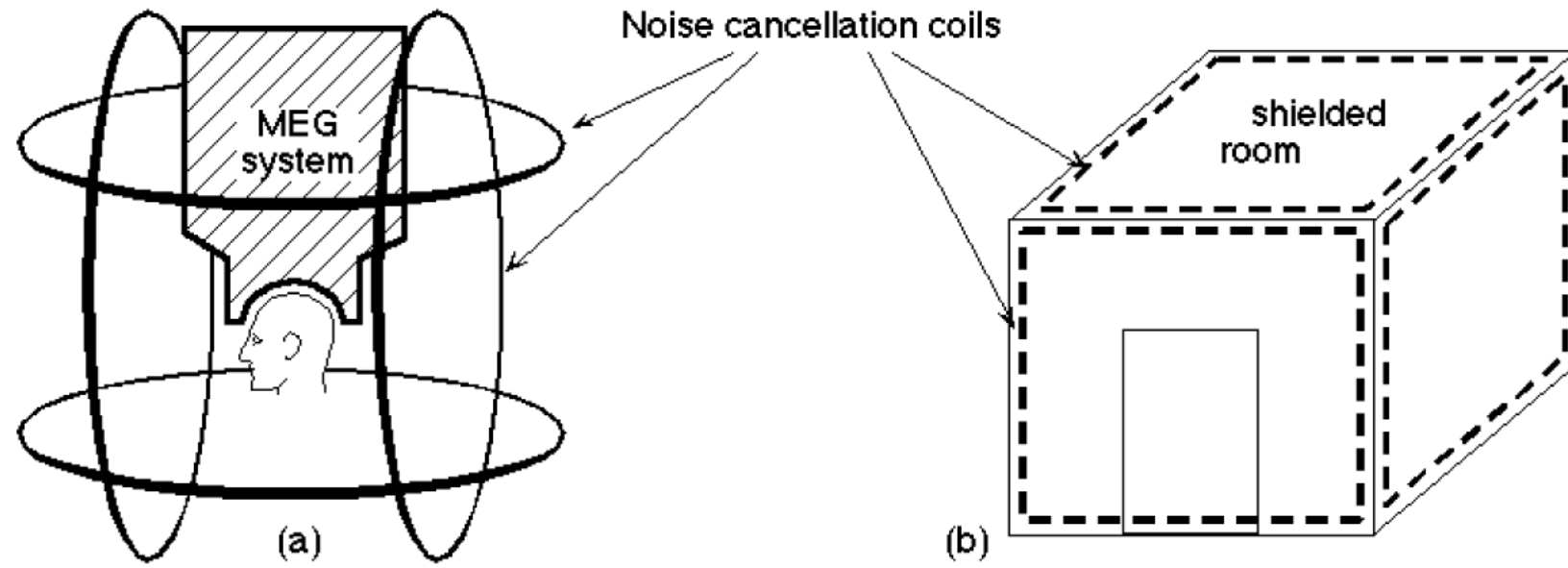
Keep the noise out:

OPMs allow for small person-sized magnetic shields

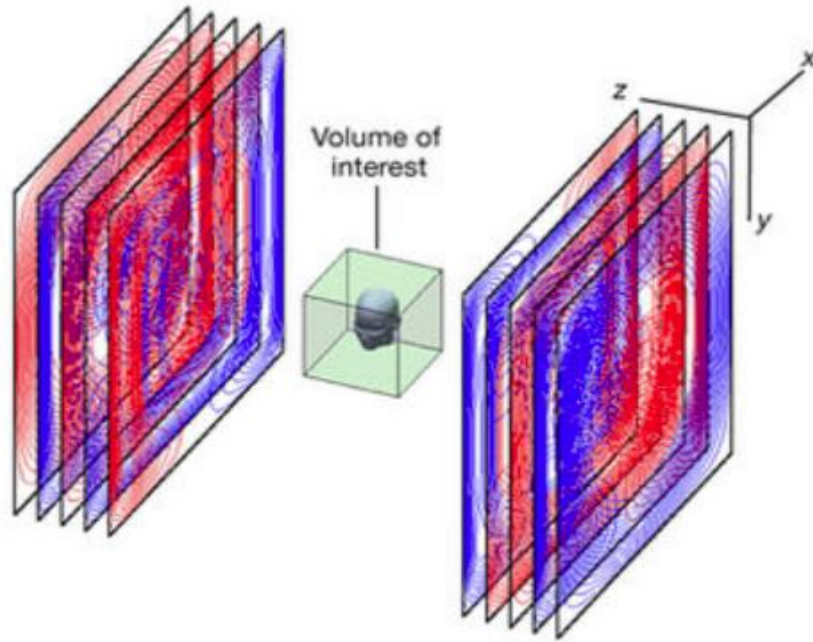
at a fraction of the weight and cost



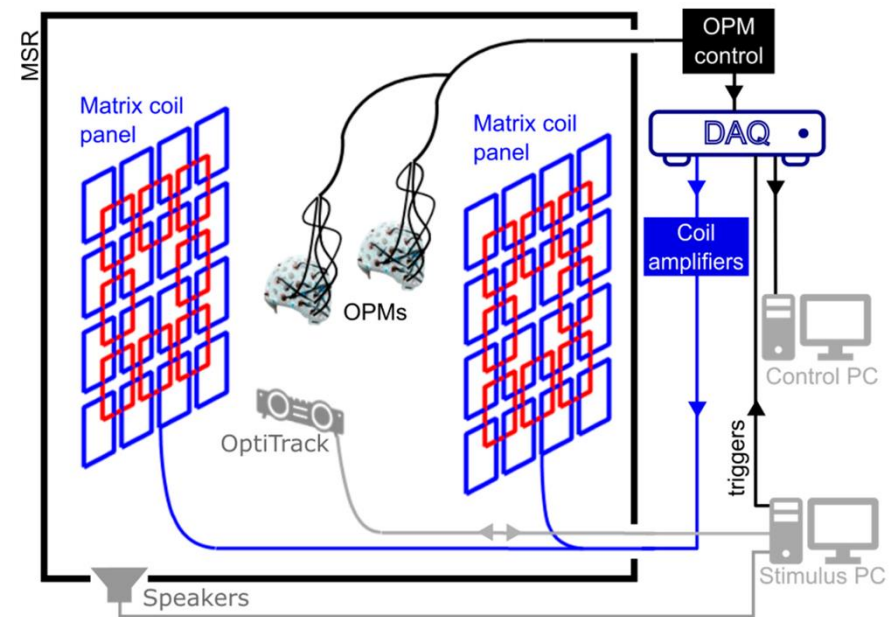
Active shielding



Active shielding



Bi-planar coils



Matrix coils

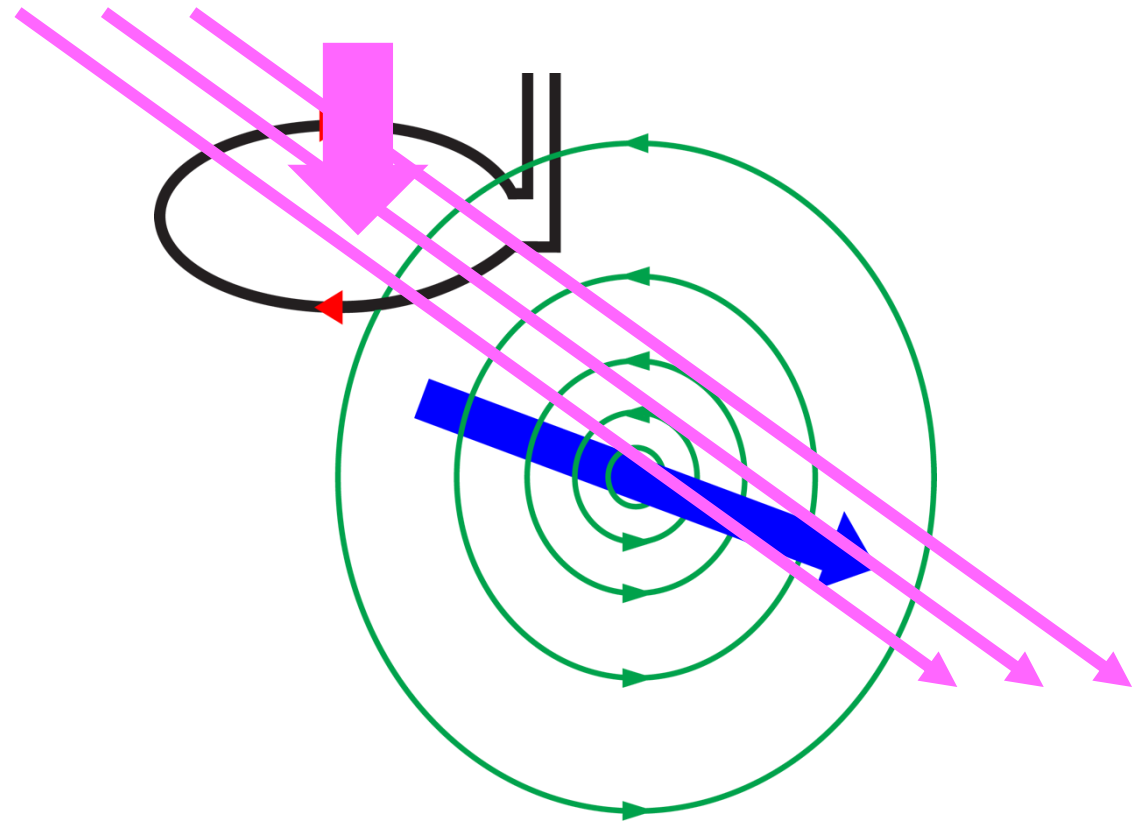
How to address the noise

Keep the noise out with a shield brings down the ambient field into nT-range

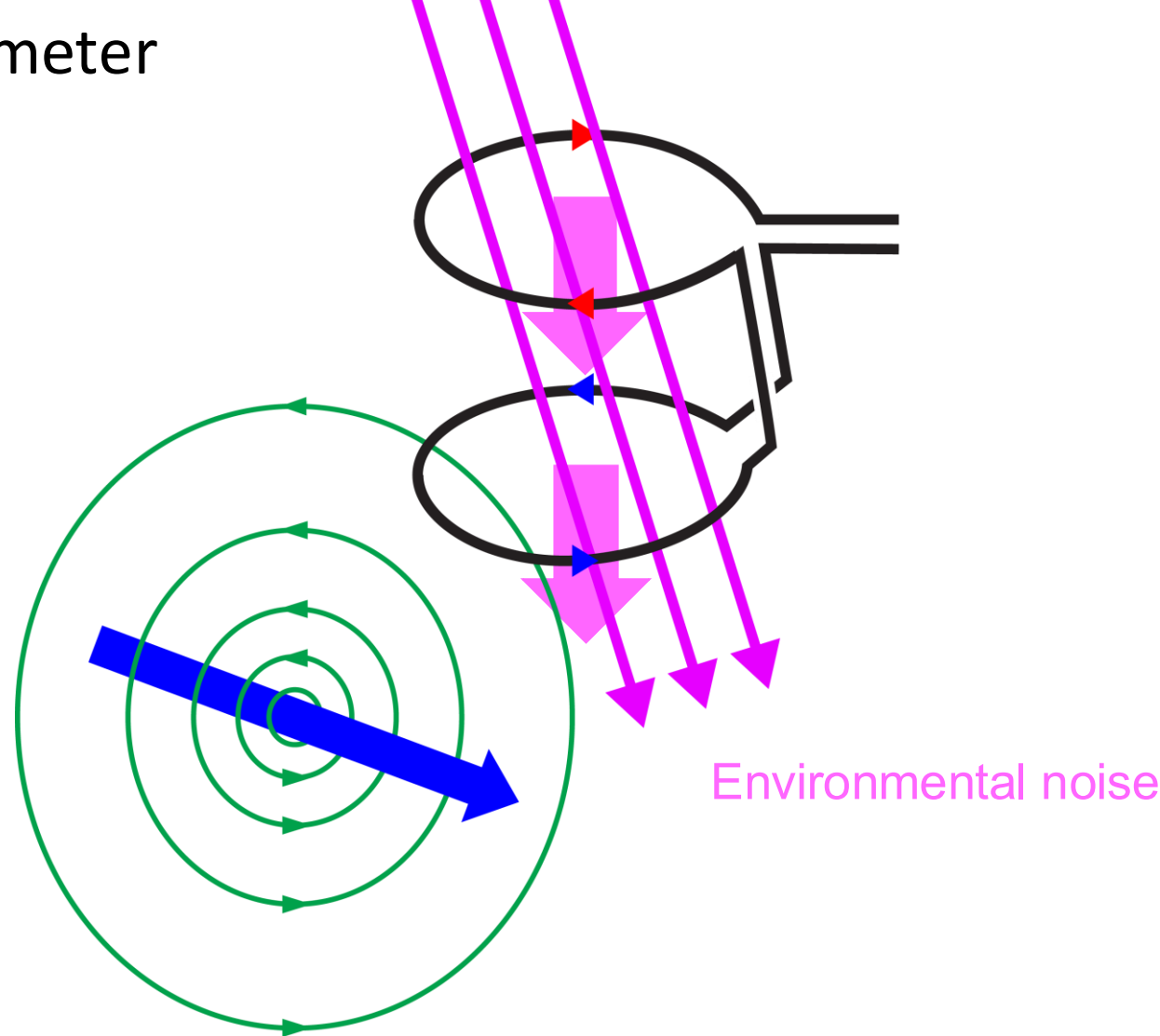
Active shielding may be needed to get OPMs in operational range

Gradiometry

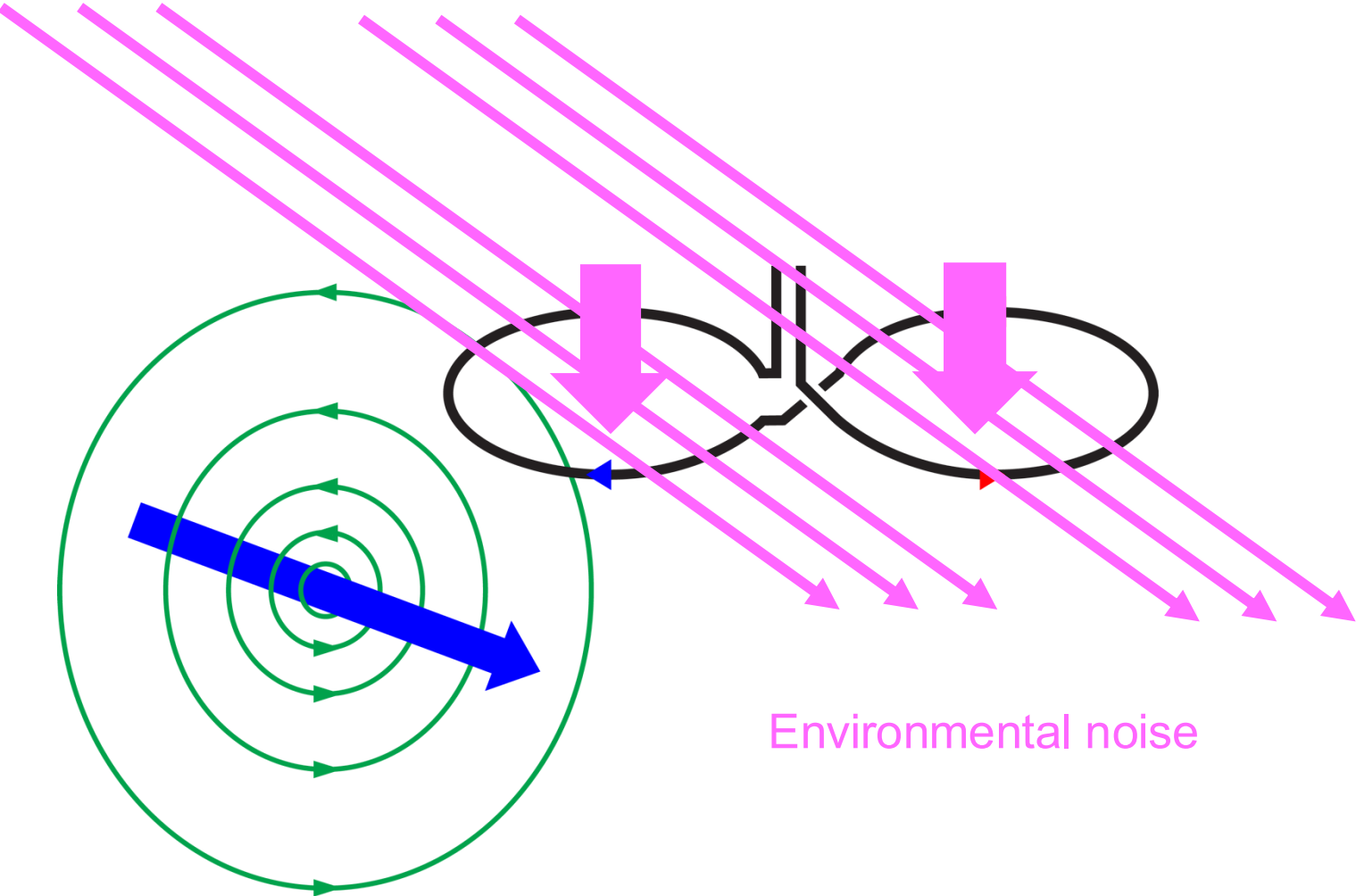
Gradiometry: Magnetometer



Gradiometry: Axial gradiometer



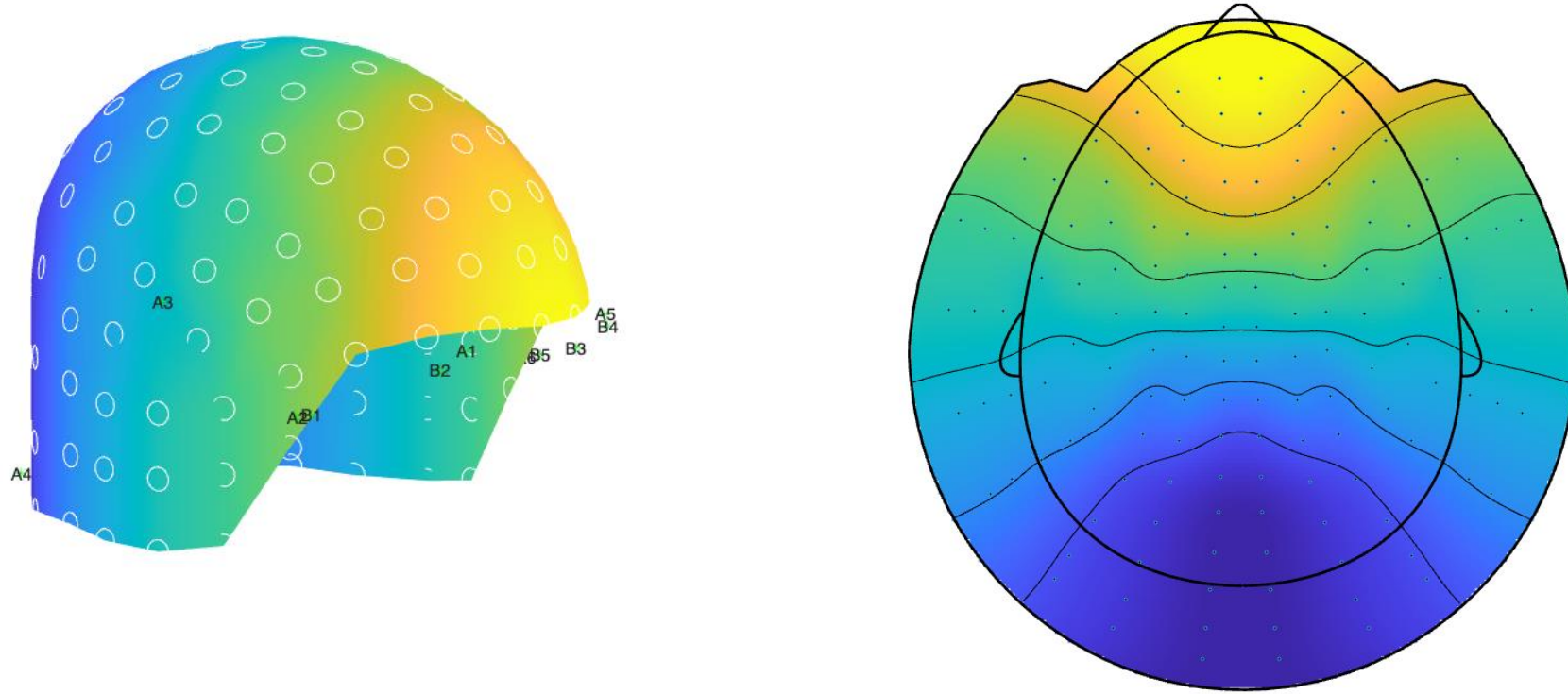
Gradiometry: Planar gradiometer



Gradiometry in OPM systems is somewhat impractical



Excursion, what does a (far away) (noise) source look like?

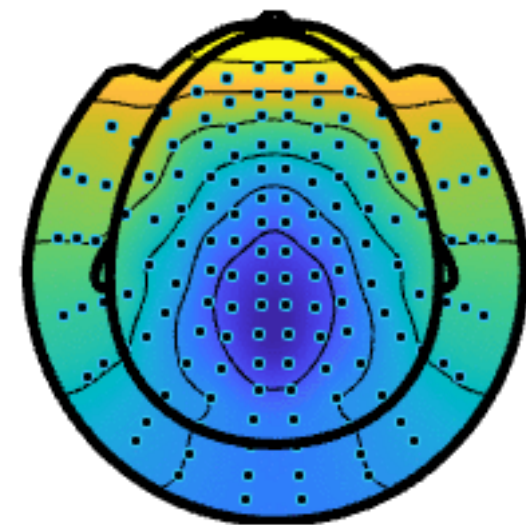
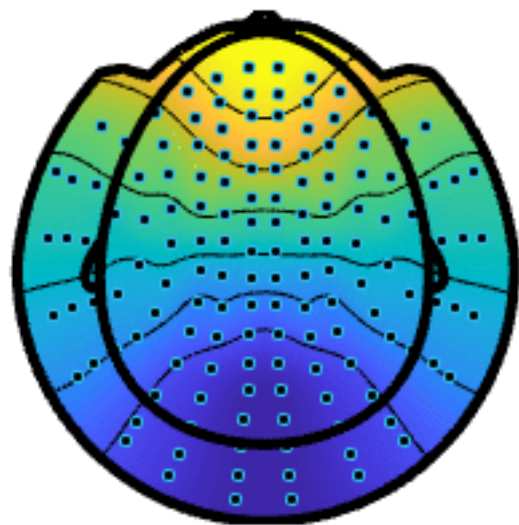
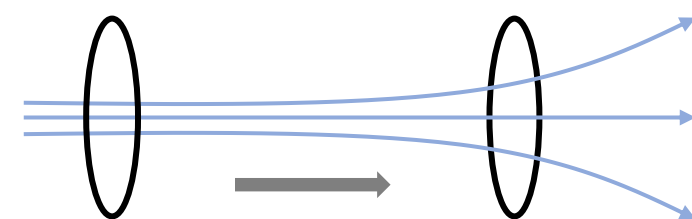
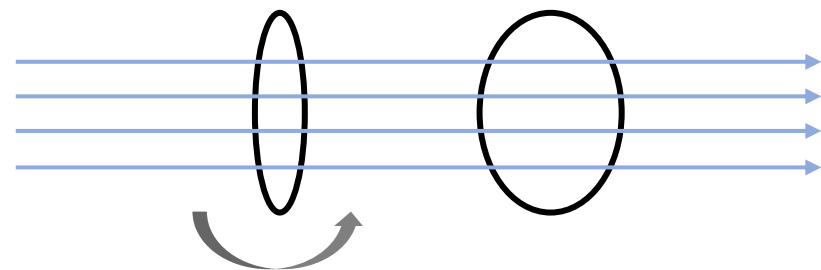


Each source has a specific spatial fingerprint

If the source of the noise moves relative to the sensors, the topography changes

Besides showing up with a certain spatial topography, the noise source strength may fluctuate in amplitude over time

Excursion: moving magnetometers



How to address the noise

Keep the noise out with a shield

Active shielding

Gradiometry

Baseline correction / spectral normalisation / averaging

Regression if noise is known/measured/modelled

Regression/subtraction of noise

$$x_{\text{cleaned}}(t) = x(t) - \beta^T * \text{noise}(t)$$

$$\beta = [\text{noise} * \text{noise}^T]^{-1} * \text{noise} * x^T$$

Examples:

noise = sine/cosine waves @ 50 Hz (e.g. `ft_preproc_<huppeldepup>filter`)

noise = breathing time course

Works well if noise time course is uncorrelated with signals of interest

Noise can be multidimensional:

$$x_{\text{cleaned}}(t) = x(t) - \beta_1^T * \text{noise}_1(t) - \beta_2^T * \text{noise}_2(t) - \dots - \beta_N^T * \text{noise}_N(t)$$

Reference sensors

Use reference signals further away from the brain to measure the ambient noise at the close-to-the-brain sensors, fit a regression model, and subtract:

$$X_{\text{cleaned}} = X_{\text{close-to-the-brain-sensors}} - B * X_{\text{reference-sensors}}$$

B can be estimated adaptively from appropriate data (`ft_denoise_pca` works generically), or

B can be taken as a set of calibrated weights based on the geometry of the coil-array (`ft_denoise_synthetic` CTF-SQUID systems only)

The reference signals are far from the brain and don't pick up meaningful brain signals

Risk of 'overfitting': inject correlated noise into sensors-of-interest

Reference sensors in OPM systems is somewhat impractical



How to address the noise

Keep the noise out with a shield

Active shielding

Gradiometry

Baseline correction / spectral normalisation / averaging

Regression if noise is known/measured/modelled

‘within’ a channel

use external reference sensors

use close-to-the-brain sensors a.k.a. software denoising with spatial filters

Software denoising with spatial filters

Independent Component Analysis

Adaptive Multipole Modelling

Beamforming

Harmonic Field Correction



Signal Space Projection

Dual Signal Space Projection

Signal Space Separation

General recipe and some considerations

$$X_{\text{cleaned}} = X - B * X = (I - B) * X = P * X$$

$B * X$ is a model of the noise

Risk of overfitting (subtracting brain signals)

Reduces 'degrees-of-freedom'

Some methods perform a second temporal filtering step

further regress out the part of the noise that is correlated with the data

The more channels, the better

Multi-axis measurements

Example: SSP

$$X_{SSP} = P * X$$

Typically uses an empty room measurement, but can be the recording itself

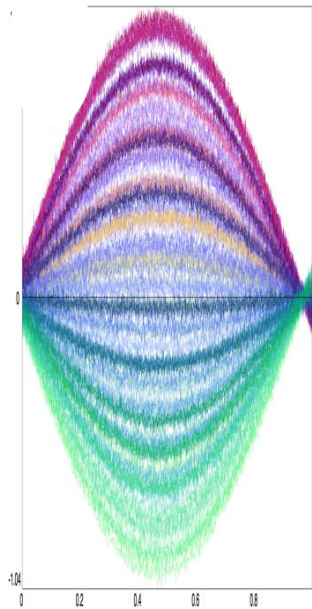
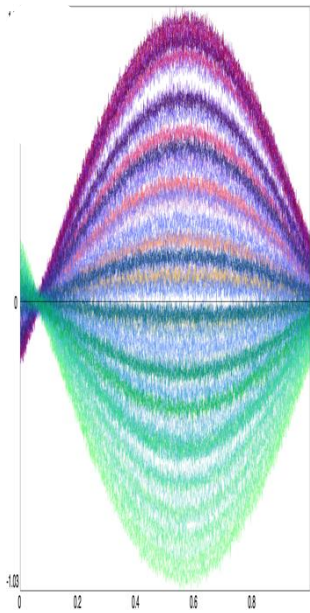
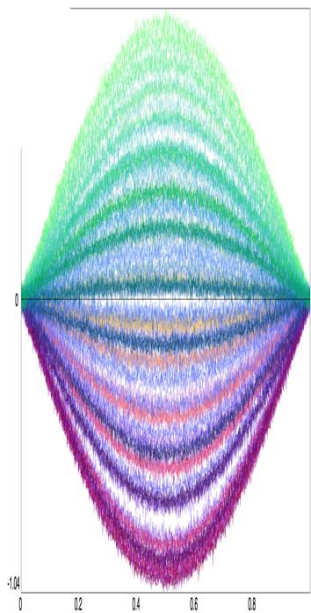
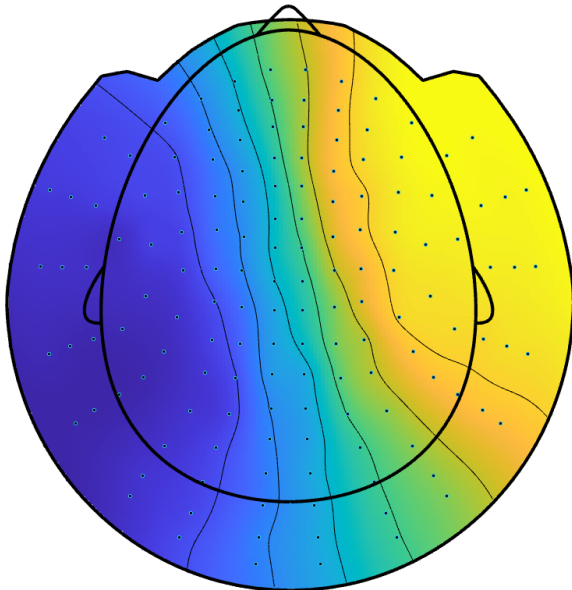
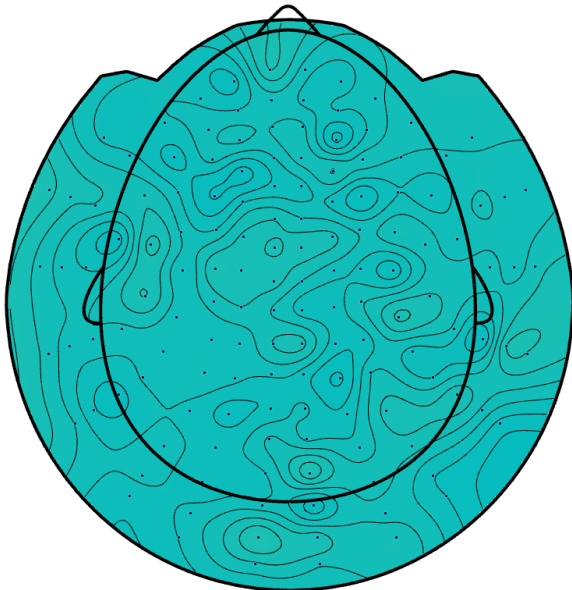
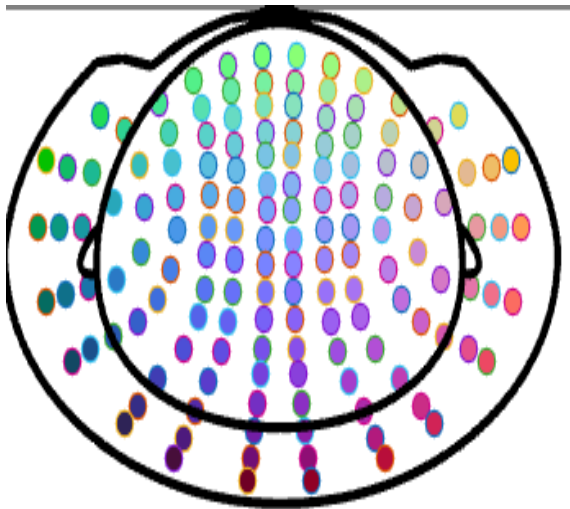
Principal component analysis: $USV^T = X$

The first 'n' components are assumed to capture the noise

$$P = I - [u_1 \dots u_n] * [u_1 \dots u_n]^T$$

No accurate sensor positions required (but need to be constant)

Example: SSP



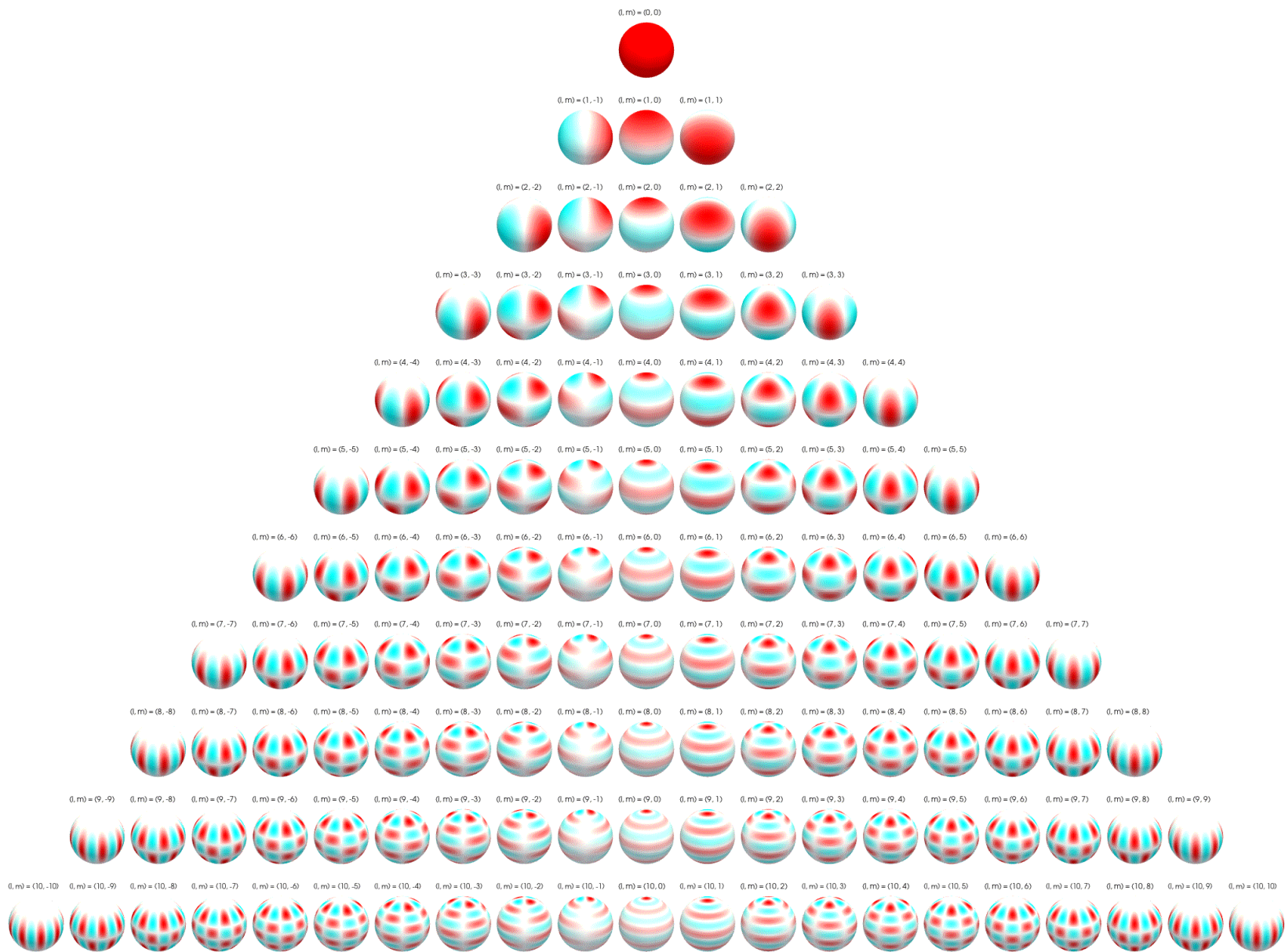
Example: HFC

$$X_{\text{HFC}} = P * X$$

Assumes the spatial structure of the ambient noise to have low spatial frequencies
(i.e. the field changes slowly over space)

Maps the data onto a spherical harmonics basis $Y_{\text{sph}} = Q * X$

Example: HFC



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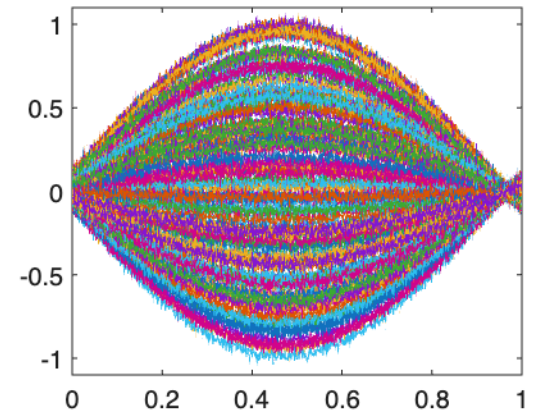
Maps the data onto a spherical harmonics basis $Y_{\text{sph}} = Q * X$

The first 'n' components are assumed to capture the noise

$$P = I - [q_1 \dots q_n] * [q_1 \dots q_n]^T$$

Accurate sensor positions (and orientations) required

Example: HFC



SSS, a.k.a. Maxfiltering

Magic bullet for denoising on Neuromag/Elekta SQUID systems

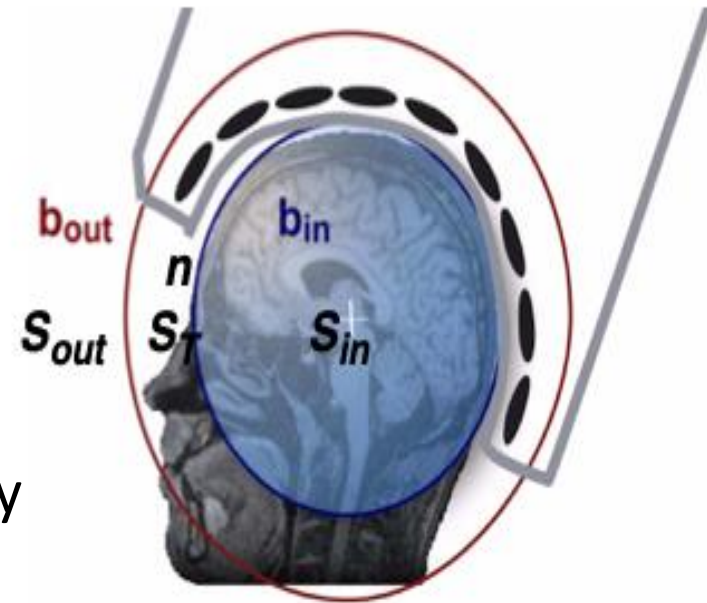
Based on spherical harmonics

Separate sources from inside and outside a sphere

Requires accurate sensor positions
and accurate calibration
and spatial oversampling
and bad channels to be detected a priori

Subsequent regression step to remove temporally
correlated noise

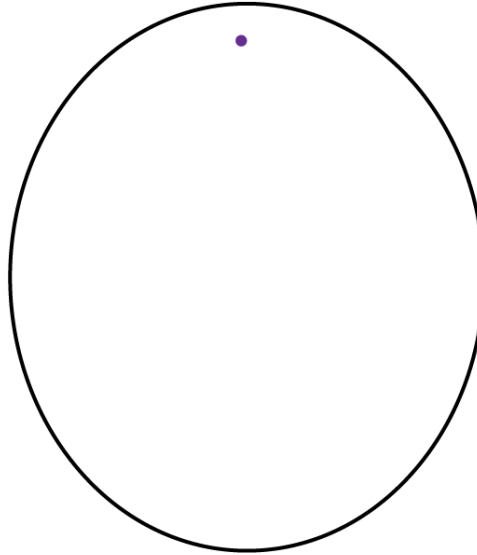
Risk of overfitting



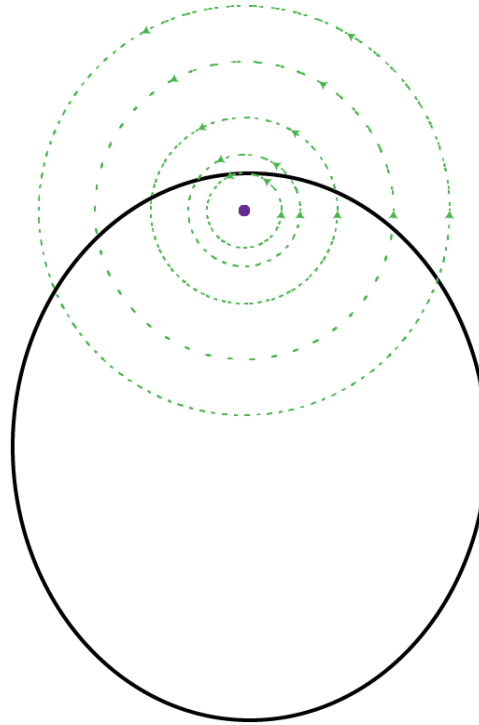
$$b = b_{in} + b_{out} + n$$

Wait: didn't you also mention multi-axis measurements?

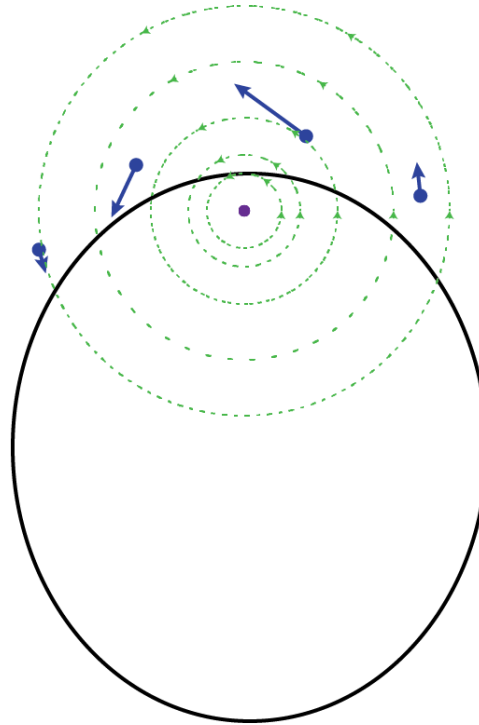
Rausschmeisser: OPMs allow for multi-axis measurements



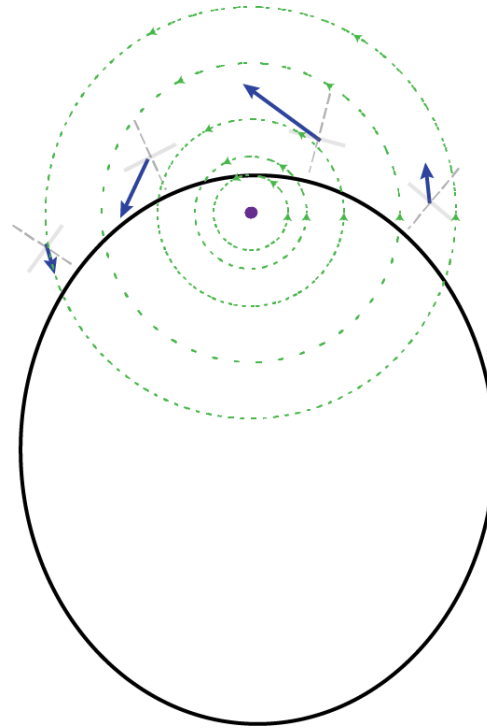
Excursion: OPMs allow for multi-axis measurements



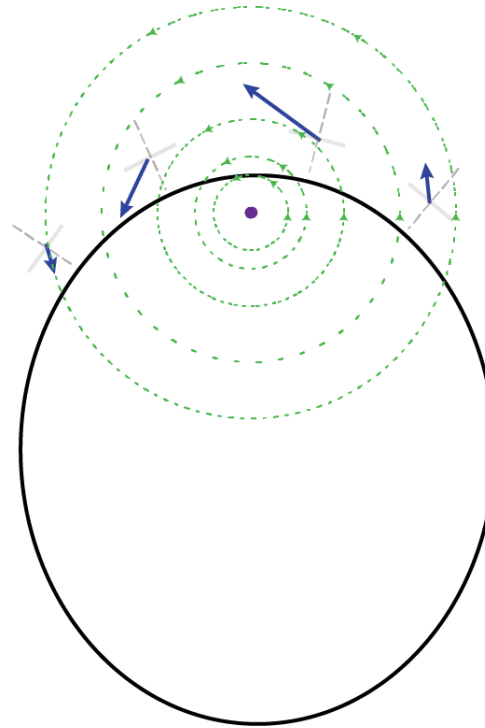
Excursion: OPMs allow for multi-axis measurements



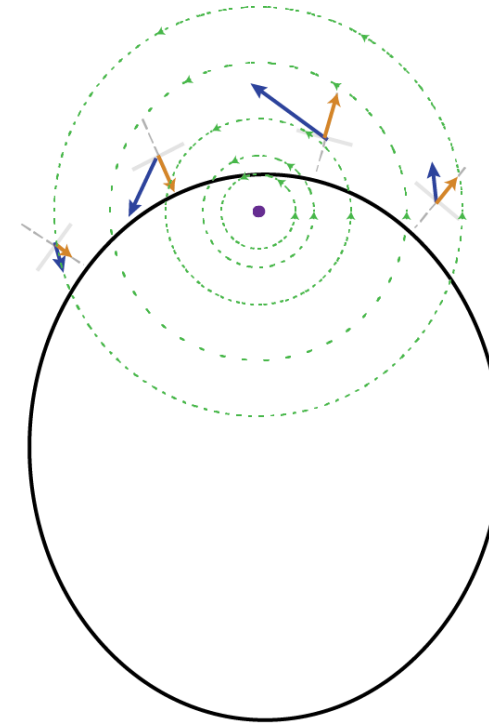
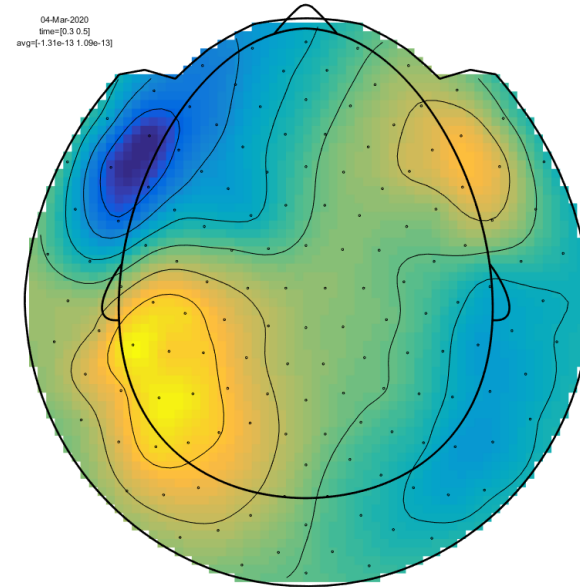
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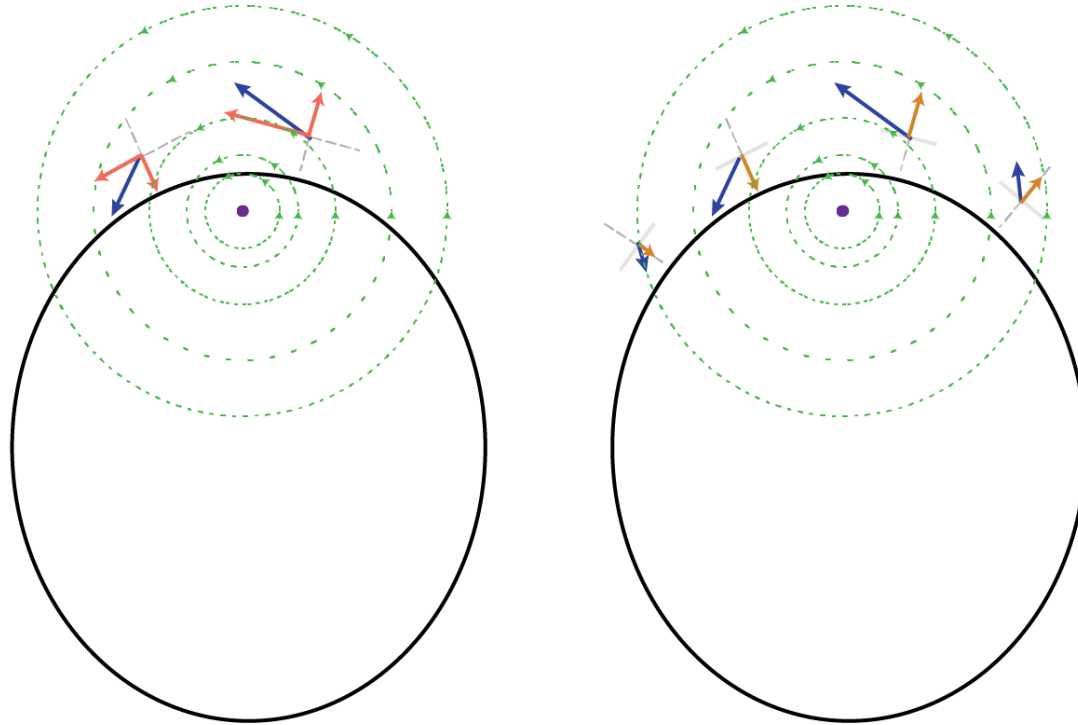
Excursion: OPMs allow for multi-axis measurements



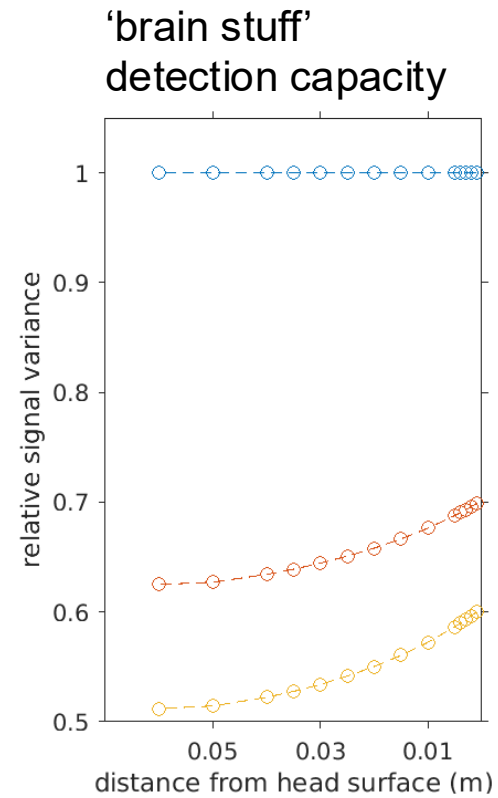
Excursion: OPMs allow for multi-axis measurements



Excursion: OPMs allow for multi-axis measurements



Sensitivity characteristics of 1/2/3 axis systems



Summary

Keep the noise out with a shield

Active shielding

(Gradiometry)

Baseline correction / spectral normalisation / averaging

Regression if noise is known/measured/modelled

‘within’ a channel

(use external reference sensors)

use close-to-the-brain sensors a.k.a. software denoising with spatial filters

The best denoising algorithm may be situation dependent



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