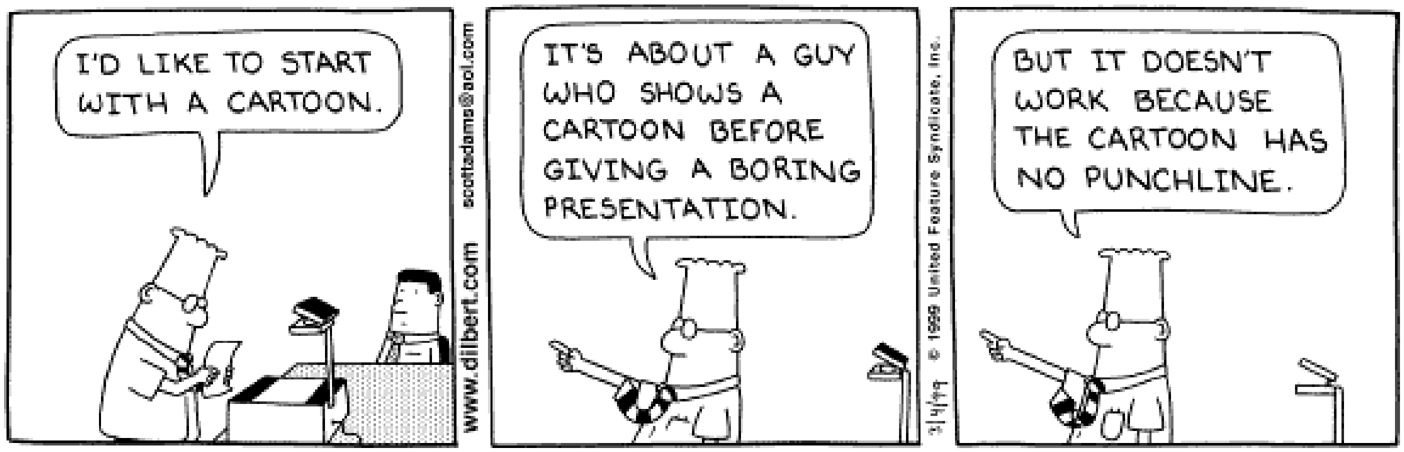
Introduction to Synthetic Aperture Magnetometry (SAM)

Dr. Tom Holroyd
NIMH MEG Core Facility

MEG Short Course

August 6, 2018

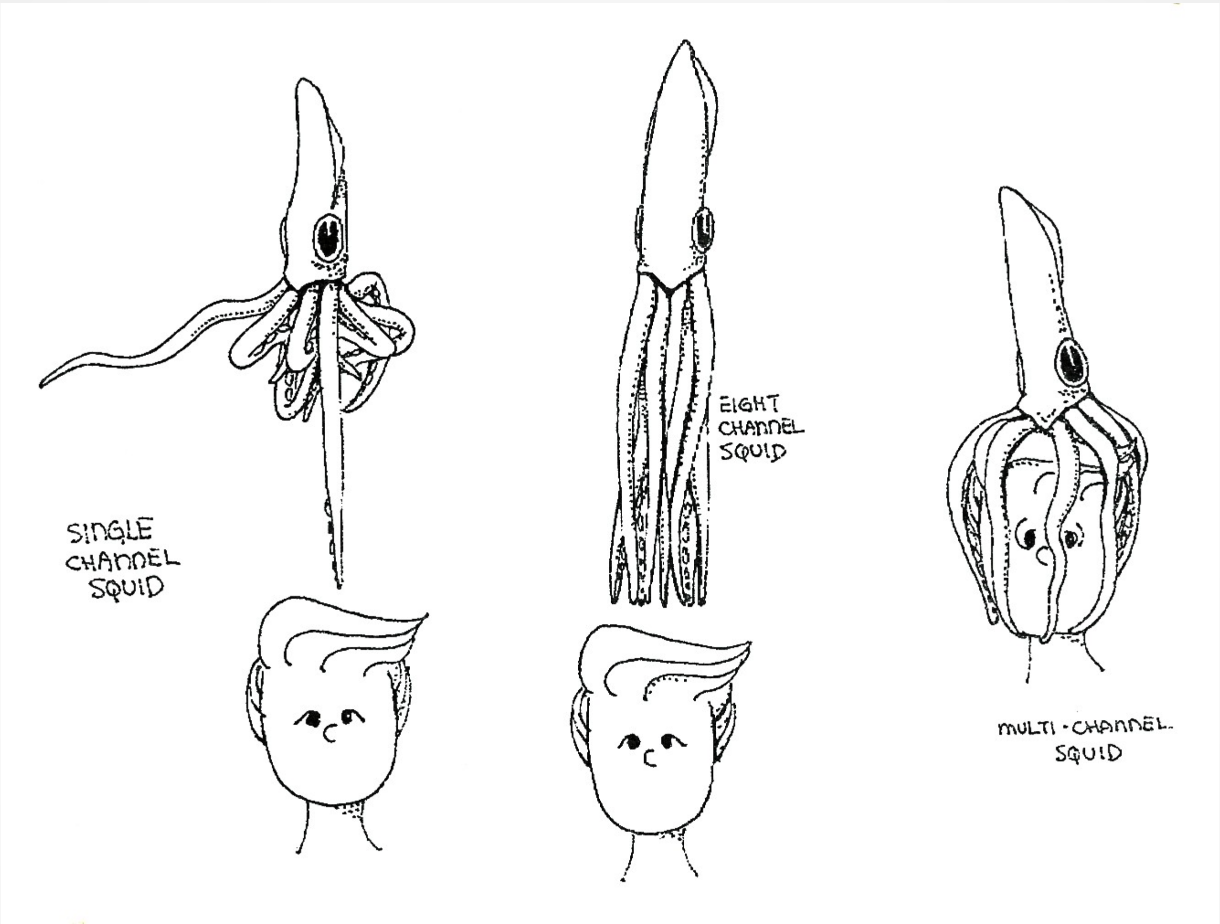
Introduction to Synthetic Aperture Magnetometry (SAM)



Introduction

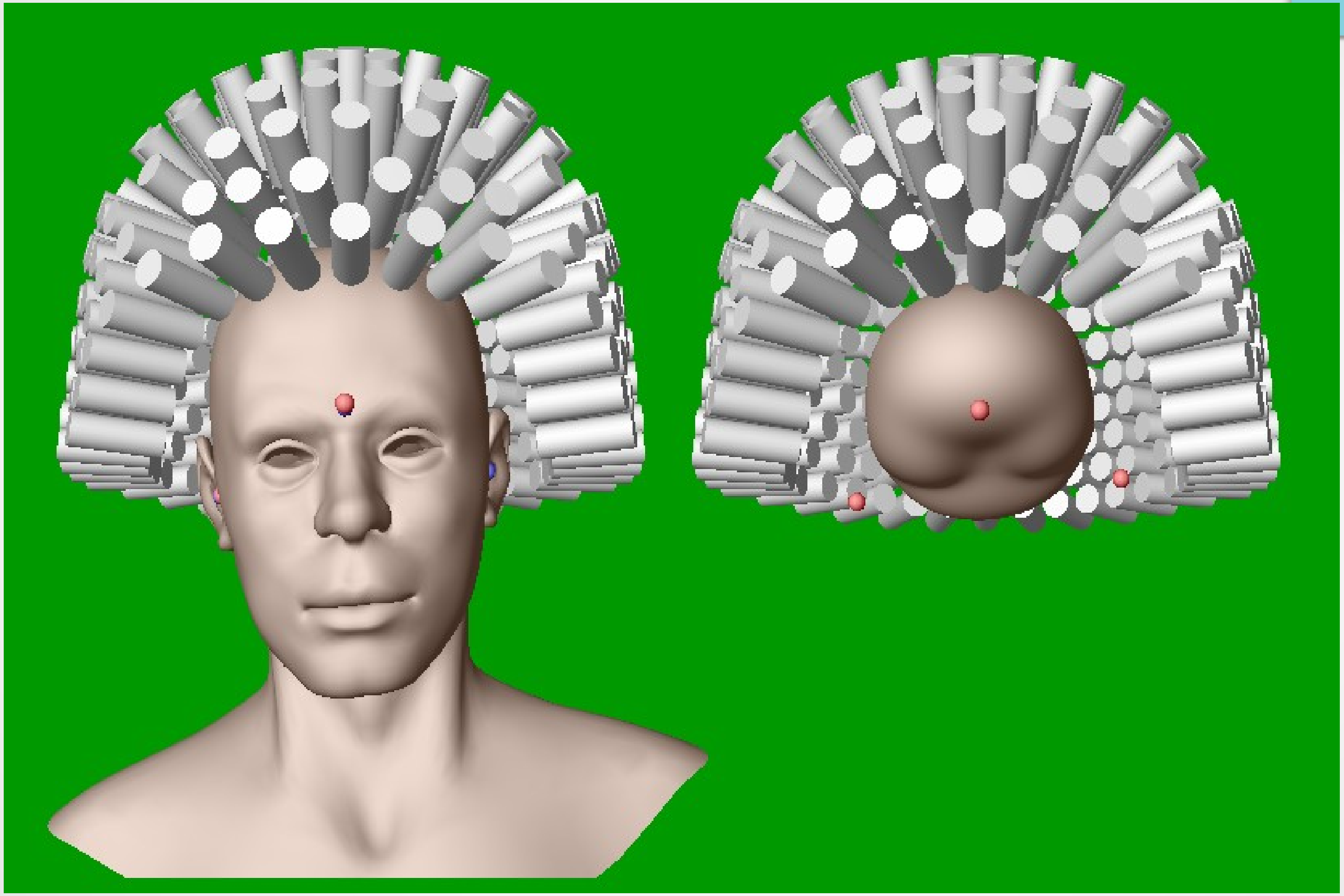
- Magnetoencephalography (MEG)
  - Dipoles, Evoked Fields, and all that
- SAM: Synthetic Aperture Magnetometry (Robinson, et al.)
  - LCMV: Linearly Constrained Minimum Variance Beamformer
- Multivariate Data and Virtual Channels
- Covariance
- The Forward Model
- Computing the Beamformer
- Source Imaging

MEG Sensors



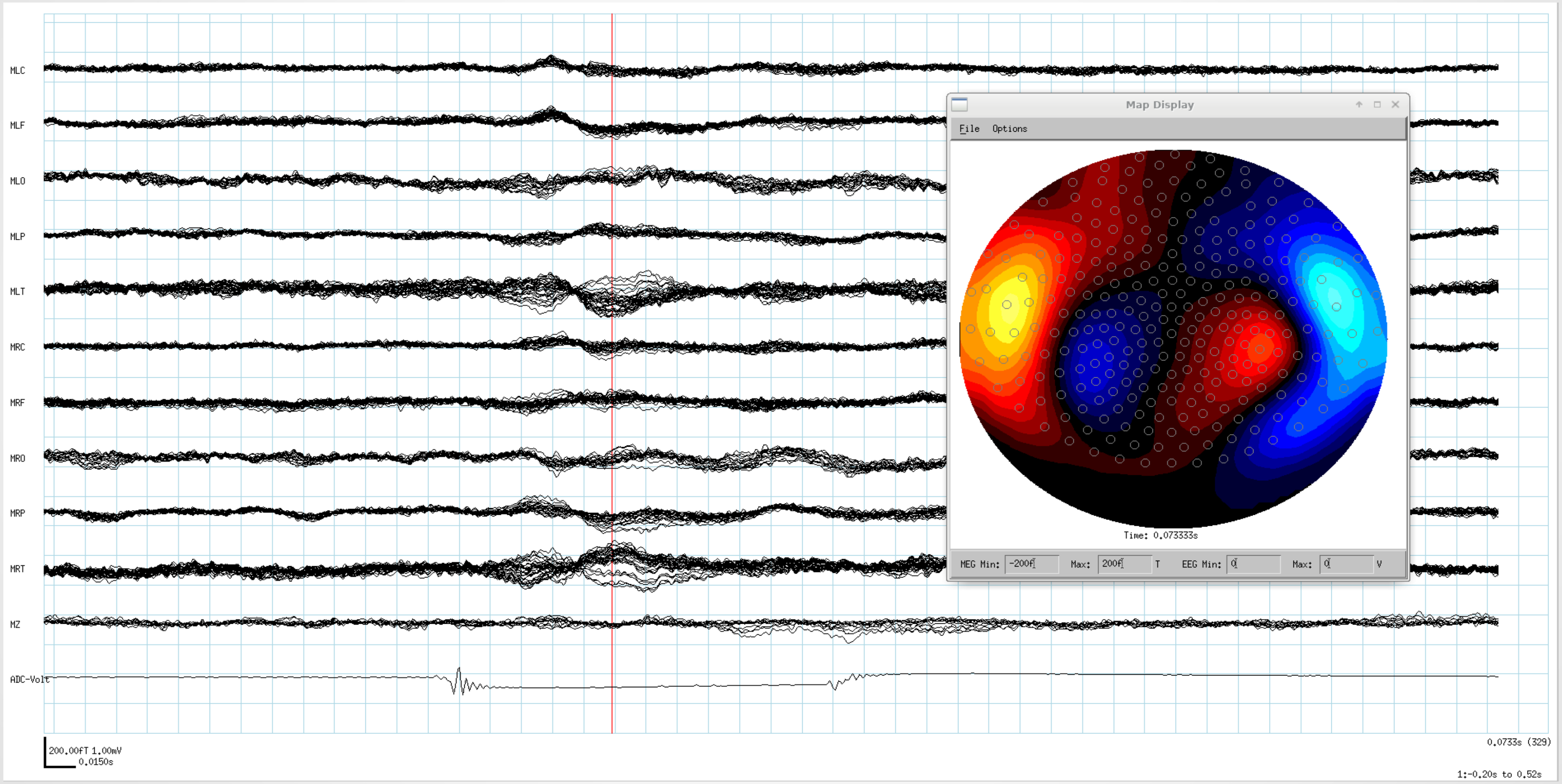
There are various types of MEG sensors.

The MEG Sensor Array



MEG sensor data are collected from an array of sensors (called gradiometers) located around the head.

Magnetic Sources in the Brain



Auditory Evoked Field - a pair of dipoles (bilateral activation of primary auditory cortex, superior temporal lobe).

Multivariate Data

$$\mathbf{X} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1T} \\ x_{21} & x_{22} & \cdots & x_{2T} \\ \vdots & \vdots & \ddots & \vdots \\ x_{N1} & x_{N2} & \cdots & x_{NT} \end{bmatrix}$$

MEG data for a time window are represented by the matrix $\mathbf{X}$. The rows of $\mathbf{X}$ are the raw data for each of the N channels, and the columns are the sensor values for each point in time.

In practice, MEG sensors have an unknown offset, so the mean over time is removed from each channel.

Virtual Channels

$$\mathbf{H}_\theta^T \mathbf{X} = [\hat{x}_{H1}\ \hat{x}_{H2}\ \cdots\ \hat{x}_{HT}]$$

The data are projected (multiplied) by the *beamformer* $\mathbf{H}$ to create a virtual channel. There is one beamformer for each target location in the brain, specified here by θ. The virtual channel is an estimate of the source activity for that location.

Often, we are interested in the amount of source *power*, that is, the power in the virtual channel, which is equal to its variance.

Covariance

$$S_\theta^2 \approx \left(\mathbf{H}_\theta^T \mathbf{X}\right)^2 = \sum_t \hat{x}_{Ht}^2$$

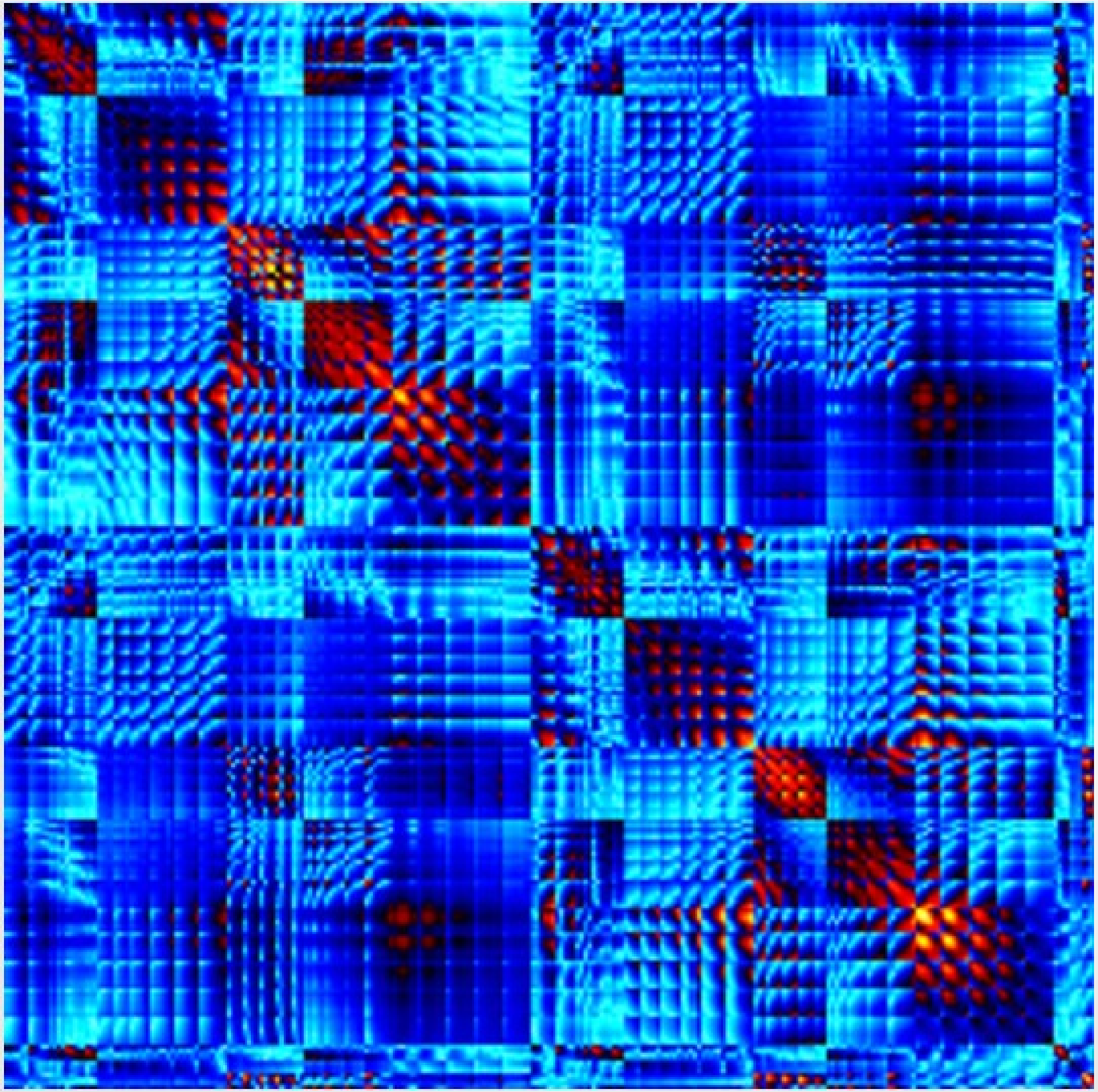
$$\begin{aligned}\left(\mathbf{H}_\theta^T \mathbf{X}\right)^2 &= \left(\mathbf{H}_\theta^T \mathbf{X}\right)\left(\mathbf{H}_\theta^T \mathbf{X}\right)^T \\ &= \left(\mathbf{H}_\theta^T \mathbf{X}\right)\left(\mathbf{X}^T \mathbf{H}_\theta\right) \\ &= \mathbf{H}_\theta^T \left(\mathbf{X}\mathbf{X}^T\right) \mathbf{H}_\theta \\ &= \mathbf{H}_\theta^T \mathbf{C} \mathbf{H}_\theta\end{aligned}$$

The sum of squares of the virtual channel equals the variance*, and is an estimate of the *power*, S^2.

A quick matrix calculation shows that power is a function of the data covariance matrix $\mathbf{C}$ and the beamformer $\mathbf{H}$ for that source.

* because we removed the mean from each channel

Covariance Matrix (15–30 Hz)



Using a Prior to Construct a Beamformer

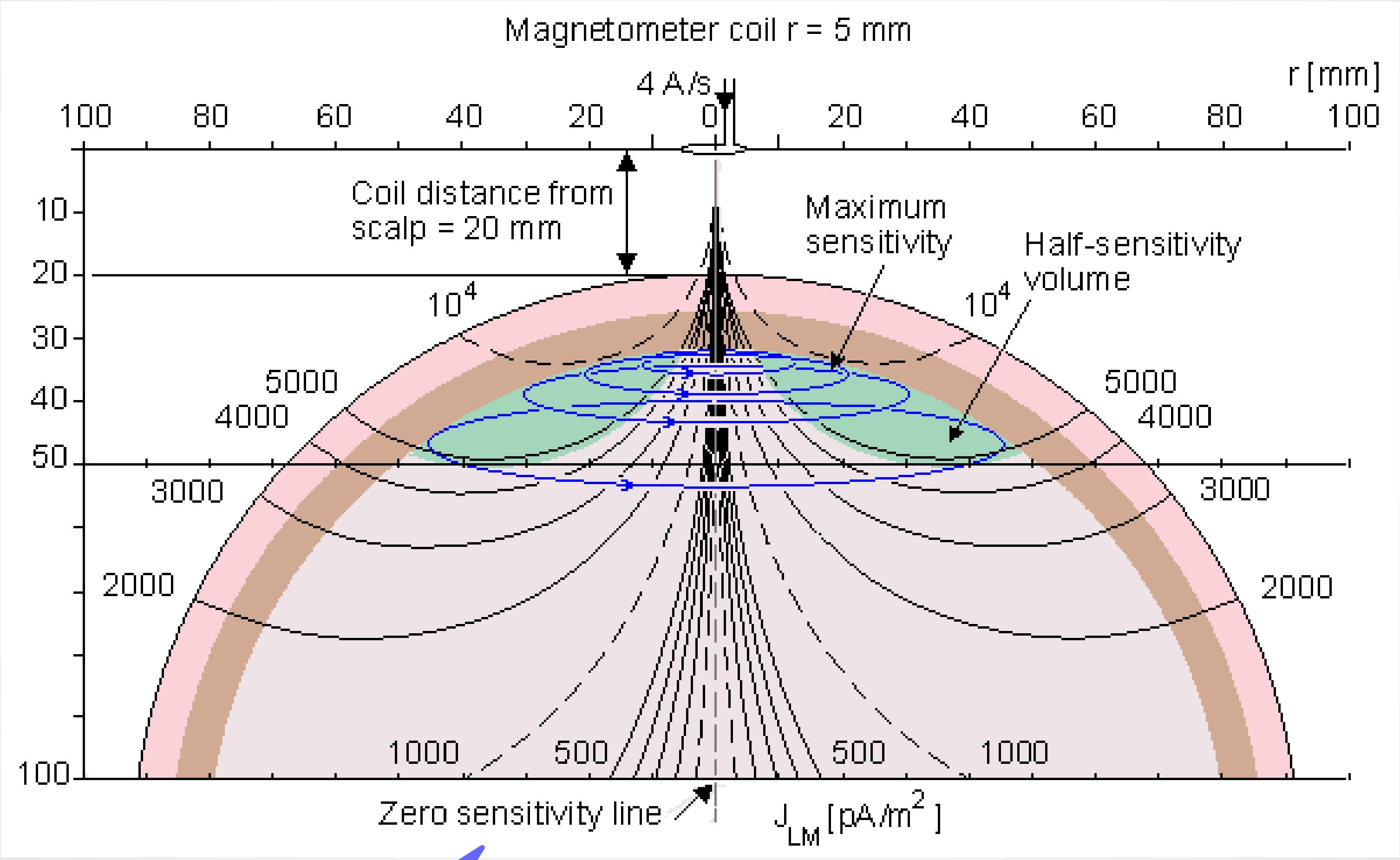
We would like to *minimize* the power in the computed virtual channel, subject to the constraint that the target source have a fixed amplitude. That is, all *other* sources should be minimized, while the target is not.

If $\mathbf{G}$ is the theoretical response from a source at location θ:

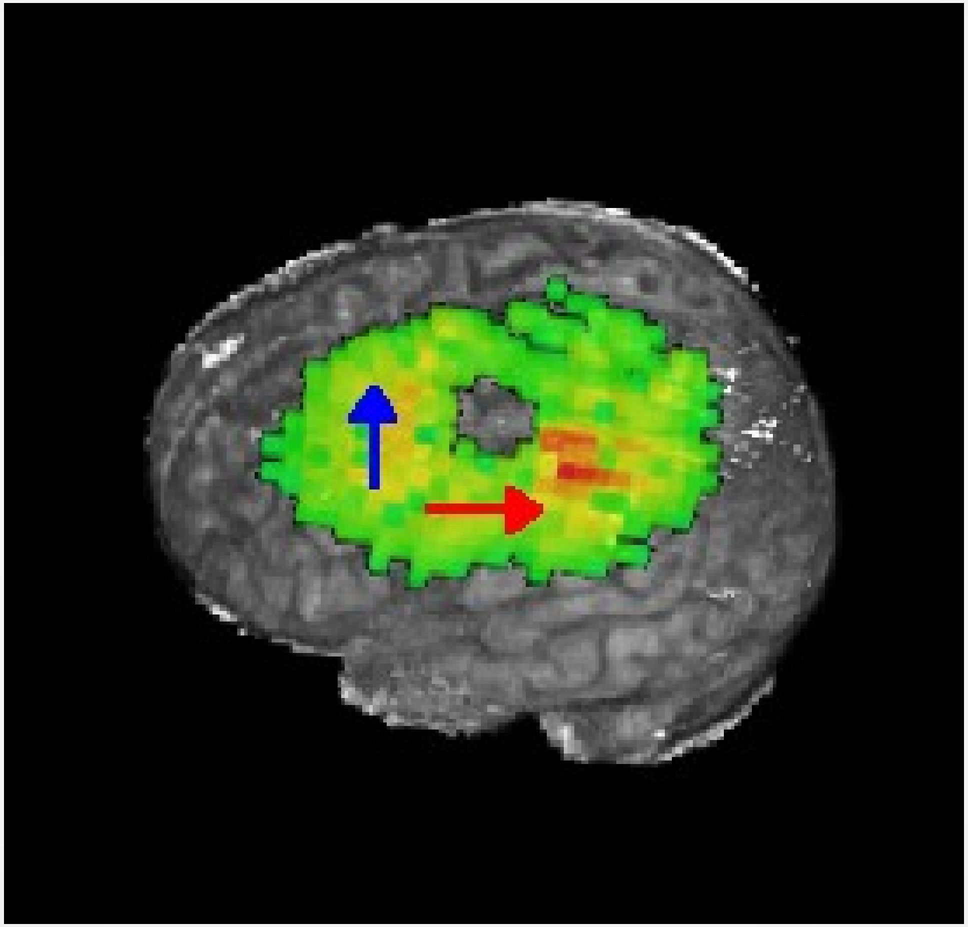
$$\mathbf{H}_\theta^T \mathbf{G}_\theta = 1$$

We would like the beamformer $\mathbf{H}$, when multiplied by the field theoretically produced from the target source, to yield unit amplitude, while minimizing all other signals.

The Forward Model—What is Measured?

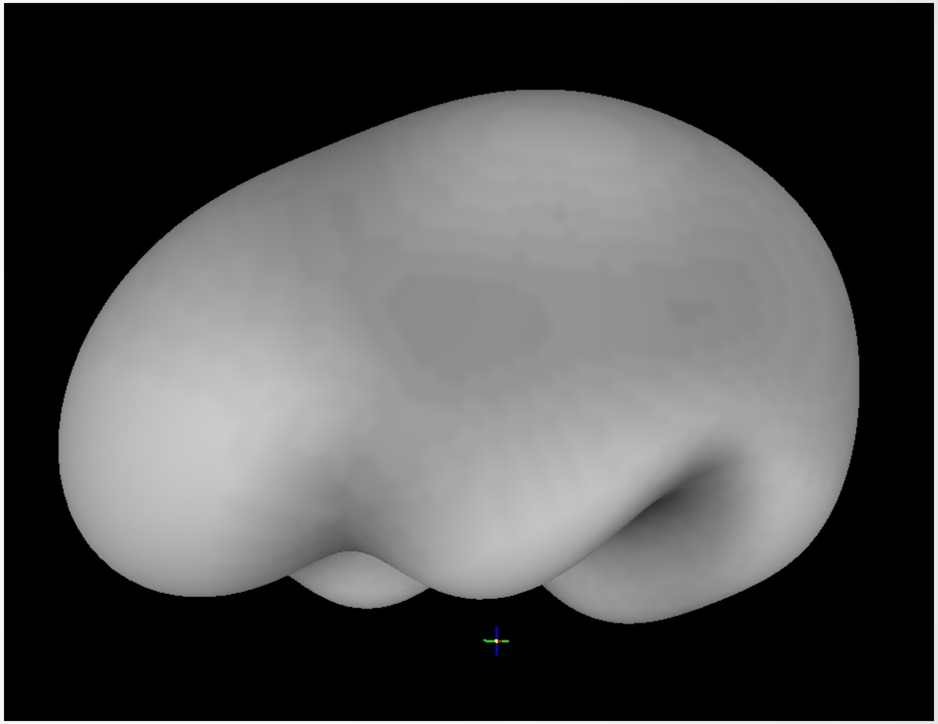


Sensitivity Volume for a Single Sensor



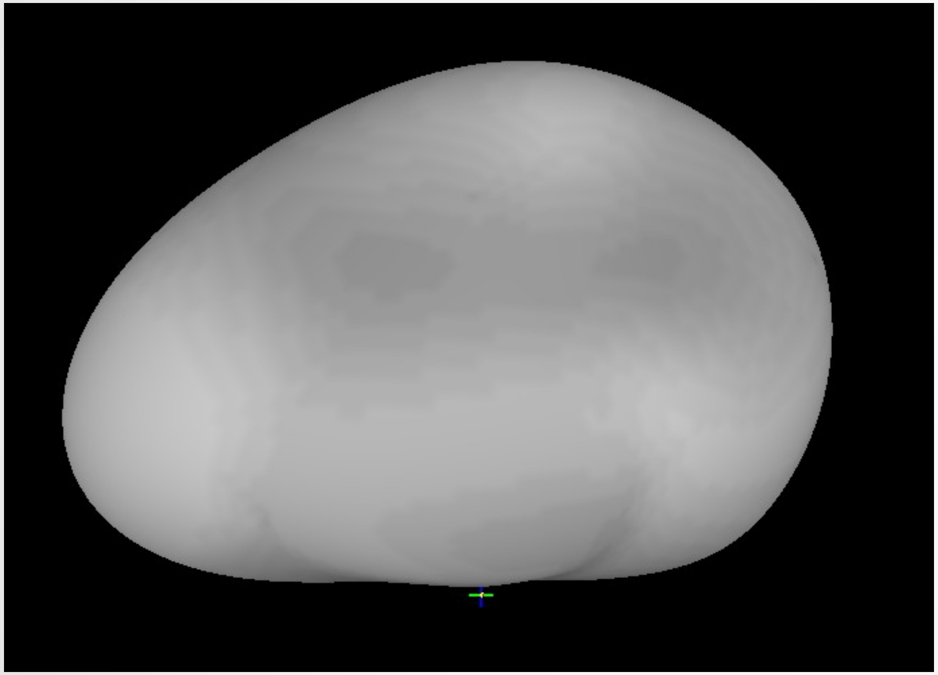
Forward Model—Skull Stripping (AFNI)

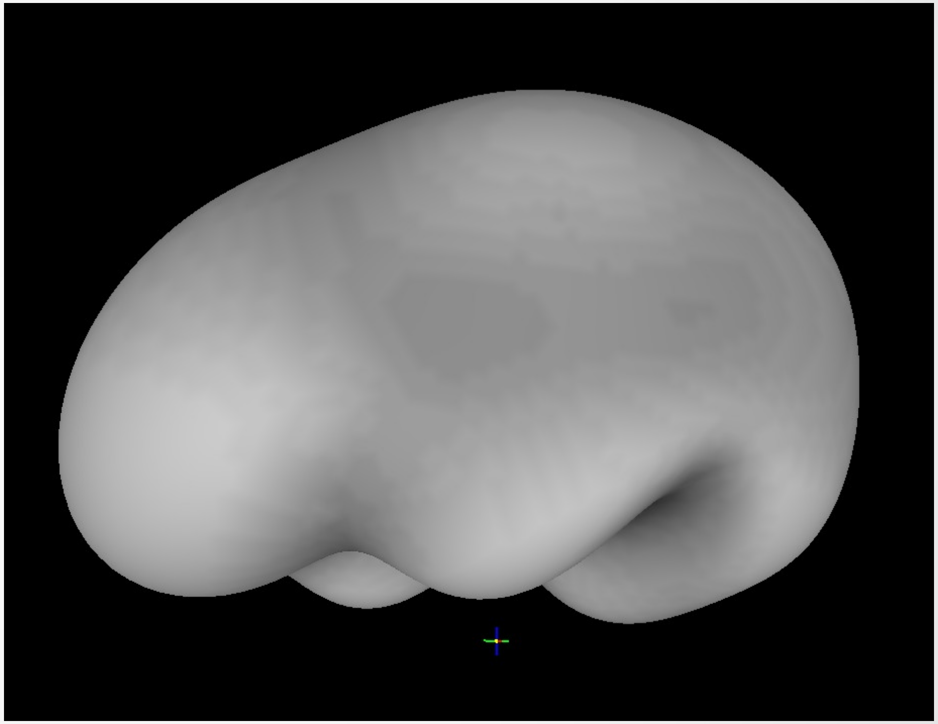
Forward Model—Conductivity Volume



Extracted brain shapes.

The Forward Model





Usually, just the general shape of the conducting volume is necessary, although more anatomically correct models can be used.

The Beamformer

$$\mathbf{H}_\theta = \frac{\mathbf{C}^{-1}\mathbf{G}_\theta}{\mathbf{G}_\theta^T\mathbf{C}^{-1}\mathbf{G}_\theta}$$

The Backus-Gilbert inverse was originally developed in the field of seismology, where it is used to determine subsurface features from arrays of acoustic sensors receiving explosion data. Synthetic Aperture Radar is another example.

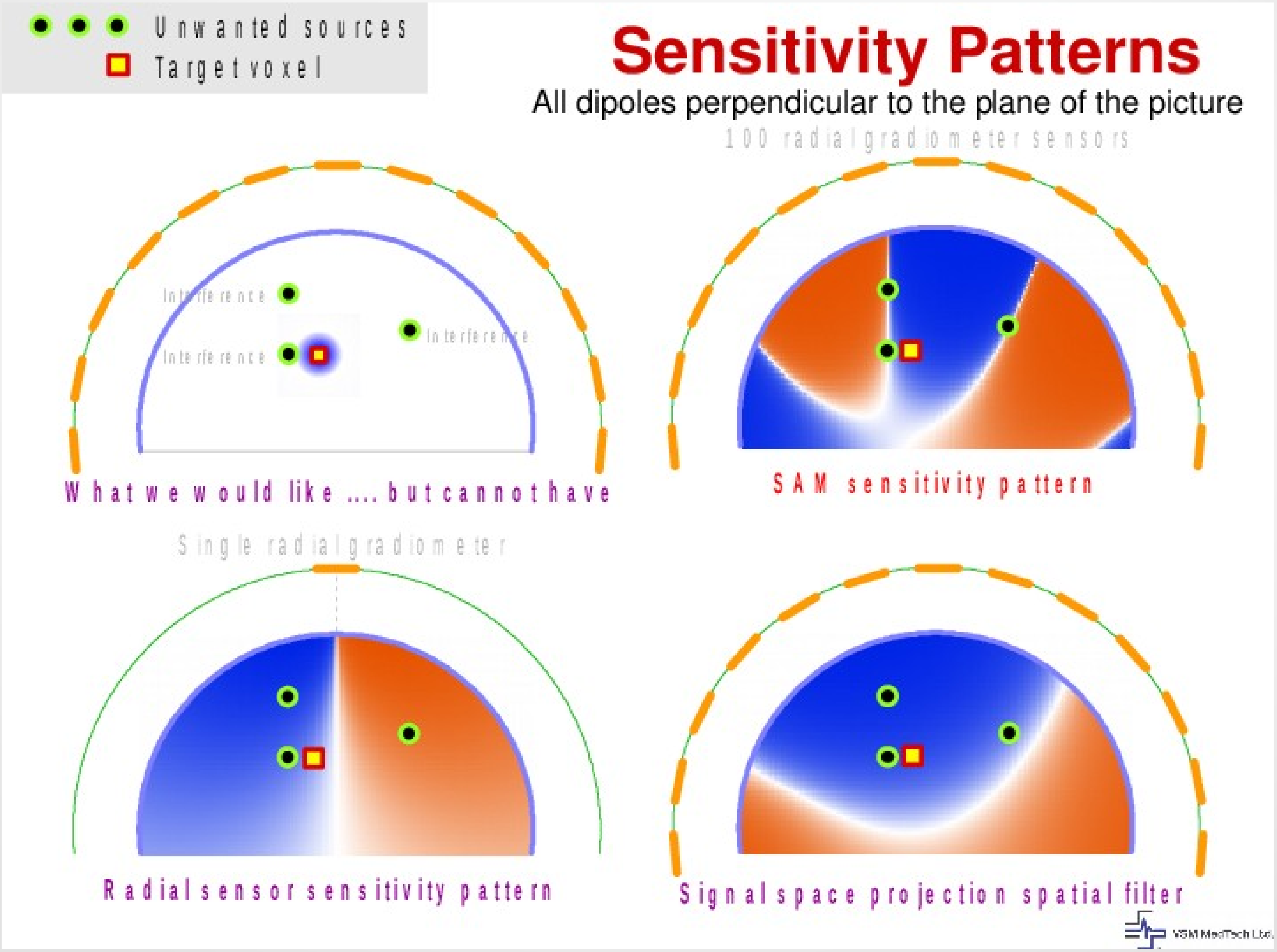
The data statistics (2nd order) are combined with the prior forward solution to determine an optimal beamformer that is selective only for the given source location.

The Beamformer

Because there are a relatively small number of MEG channels, and a much larger number of active sources in the brain, it is impossible to find a beamformer $\mathbf{H}$ that eliminates all the unwanted power. This problem is reduced by band-pass filtering the data to reduce the number of visible sources, and by computing the covariance across many trials.

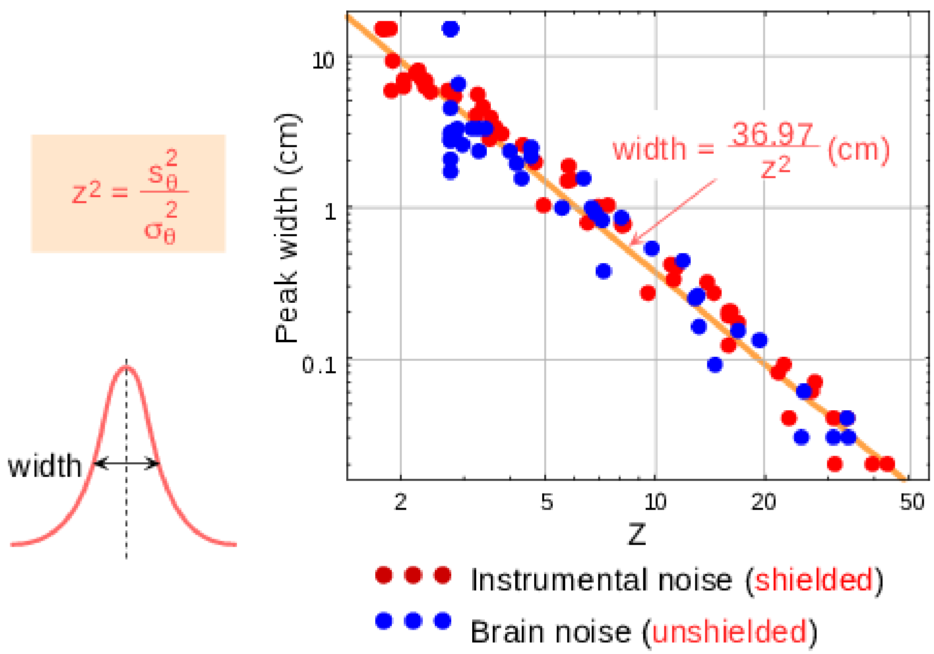
Usually, covariance is accumulated over many short time windows fixed relative to a given event (such as a button press response or a stimulus presentation).

Beamformer Response



Beamformer Response

SAM Spatial Selectivity Improves With Increasing SNR



Dipole moments: 1, 2, 5, 10, 20, 50, 100 nA· m

Distances from the center: -2, -1, 1, 2, 3, 4, 5, 6, 7, 8, 9 cm

Noise collected with: 143 and 151 radial gradiometer based systems

VSM MedTech Ltd.

Source Imaging

- `sam_cov`

  Compute covariance matrices for a given time-frequency window, relative to some specified dataset markers.

- `sam_wts`

  Compute beamformers, also known as *weights*. They can be computed over a 3d grid covering the brain*, or for individually specified targets.

  * stored as NIFTI images

- `sam_3d`

  Compute a 3d NIFTI image of source power or entropy using the weights computed by `sam_wts`.

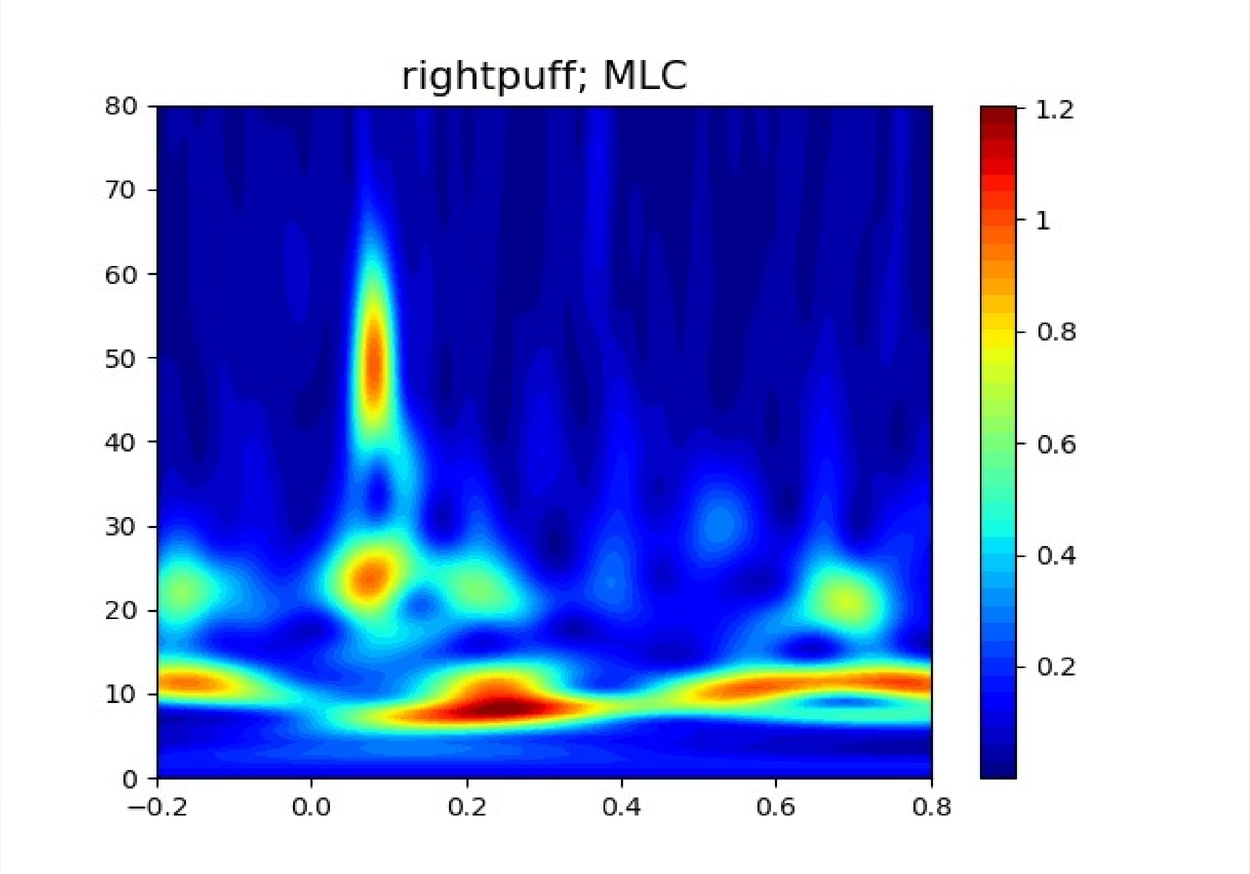
- `sam_4d`

  Compute a 3d+time image of signal, power, or entropy, with smoothing.

- `sam_ers`

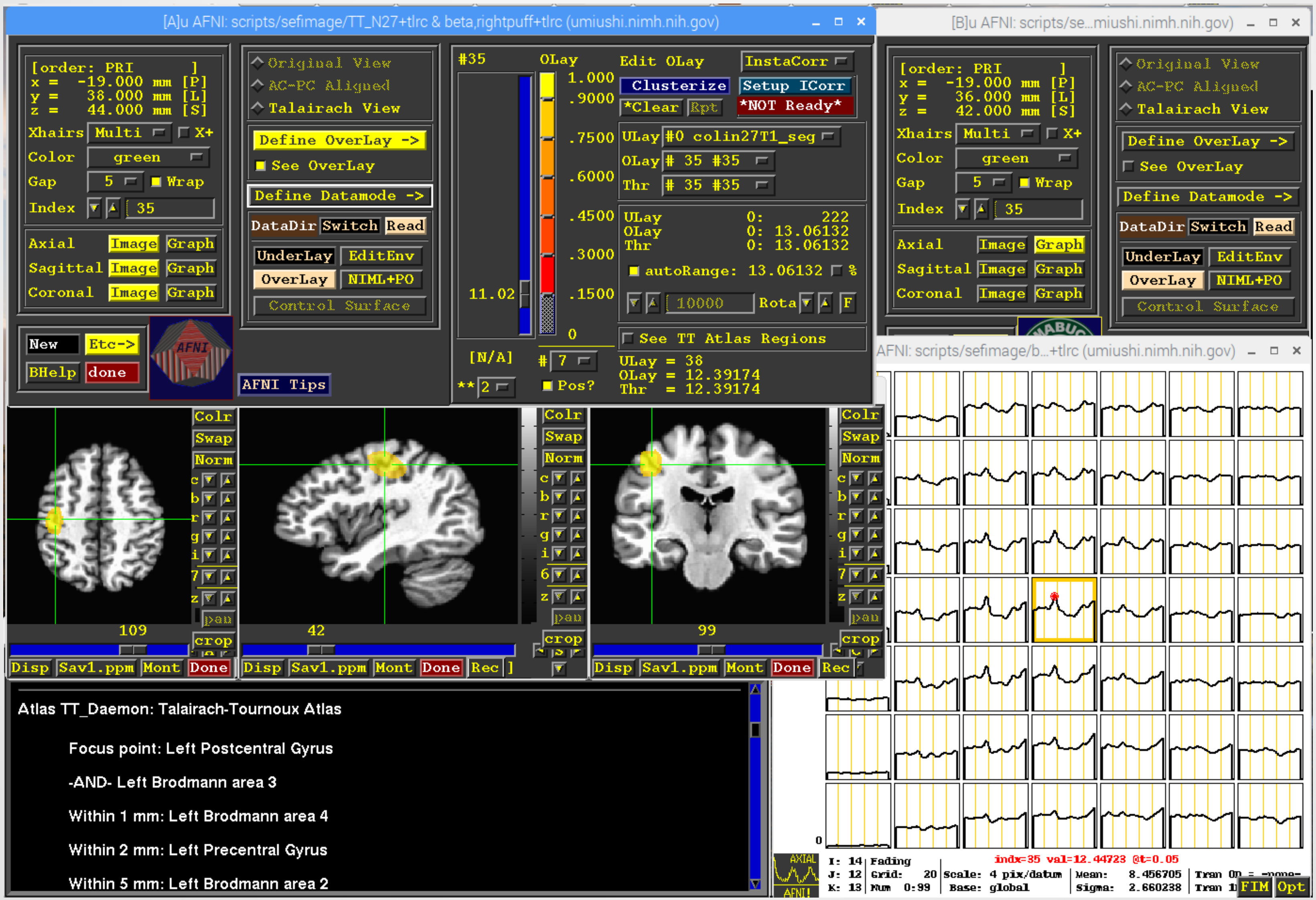
  Event related source imaging computes baseline adjusted differential 3d+time images.

Where to Look?

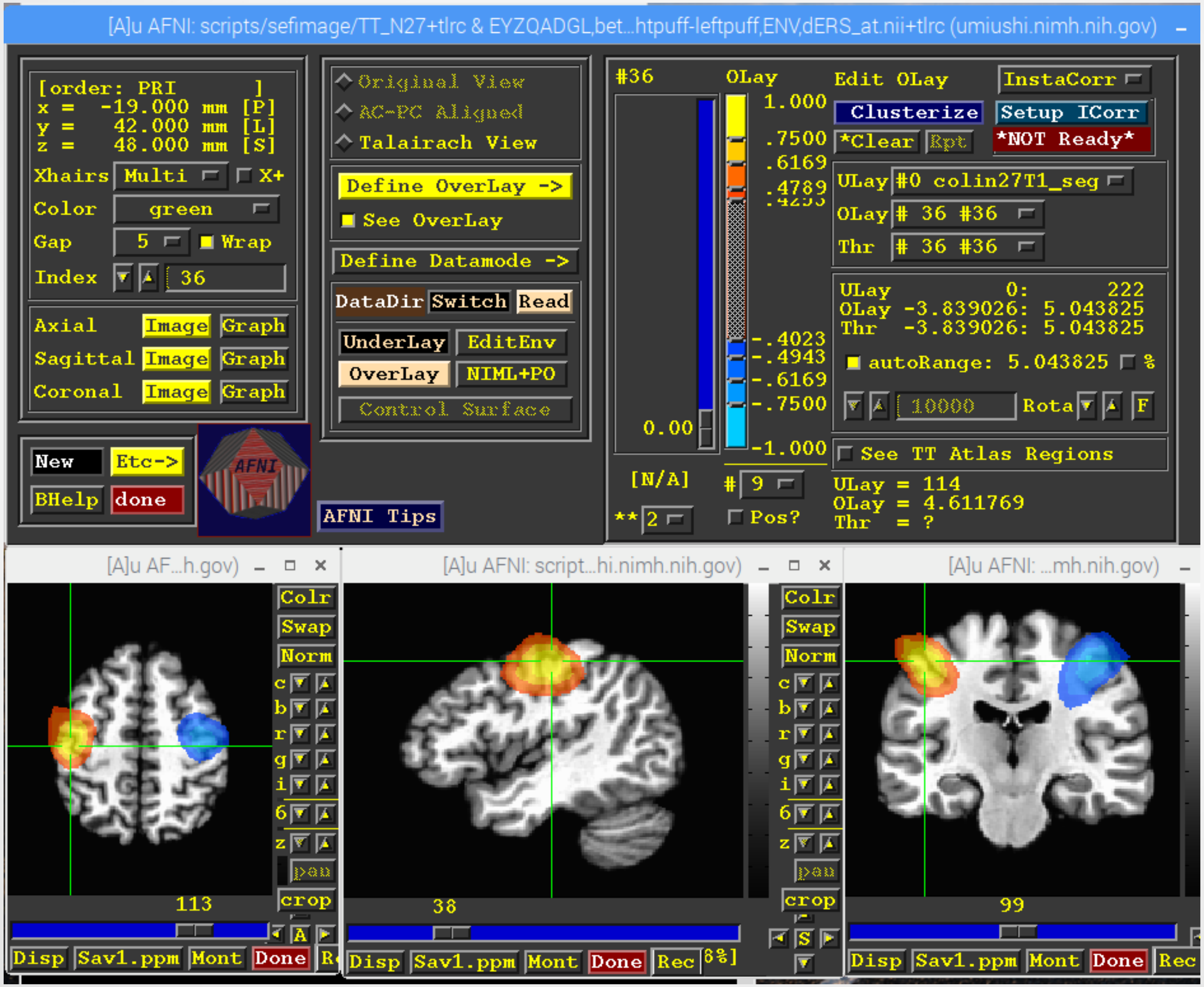


Time-Frequency plot of average power for a right index-finger airpuff over left-central MEG channels.

sam_4d — AFNI View (15-30 Hz)



sam_ers — AFNI View (15-30 Hz)



Thanks!

Thank You!