

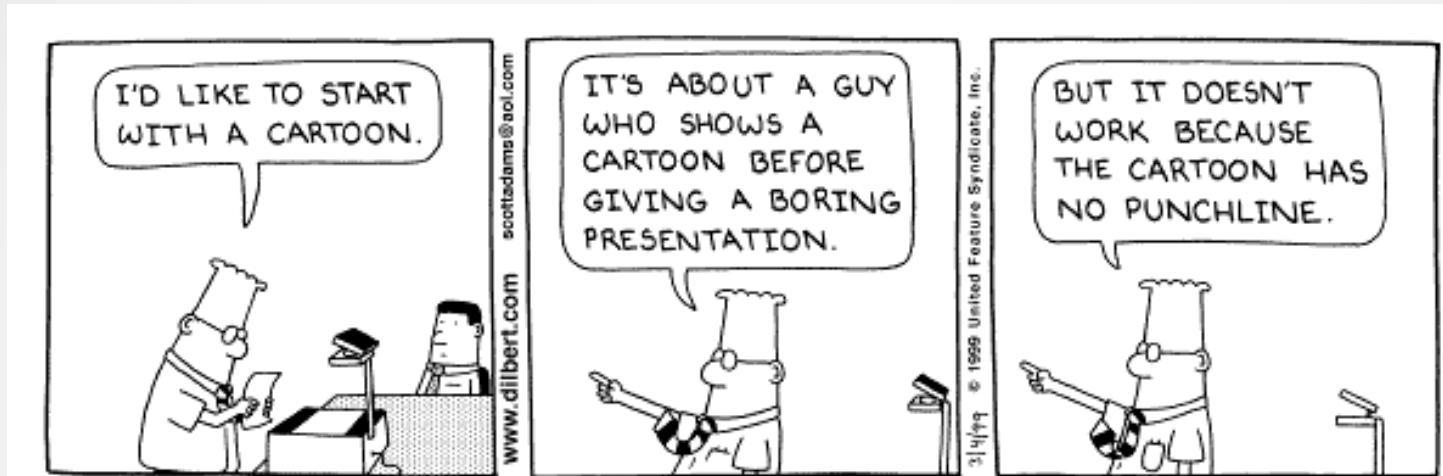
Introduction to Synthetic Aperture Magnetometry (SAM)

Dr. Tom Holroyd
NIMH MEG Core Facility

MEG Short Course

August 6, 2018

Introduction to Synthetic Aperture Magnetometry (SAM)

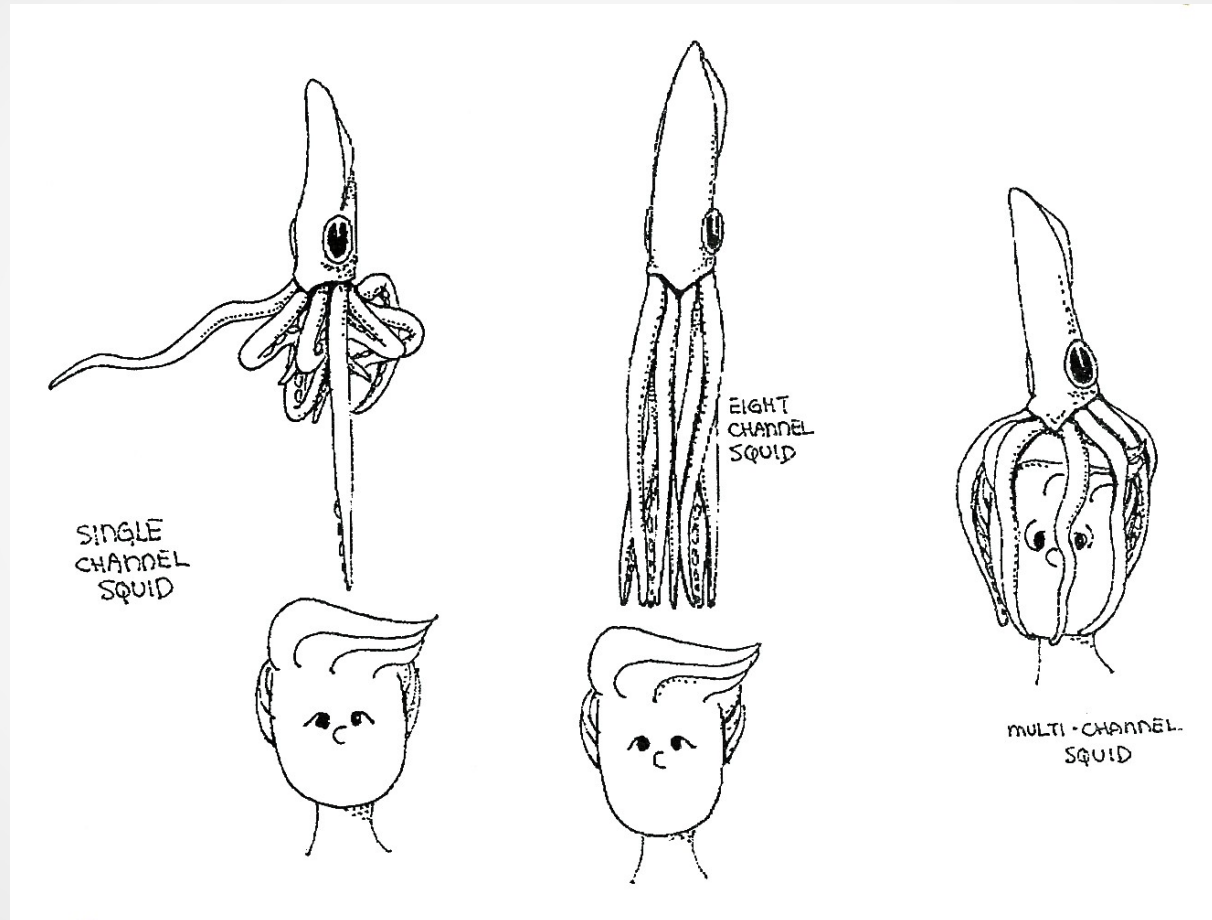


Copyright © 1999 United Feature Syndicate, Inc.
Redistribution in whole or in part prohibited

Introduction

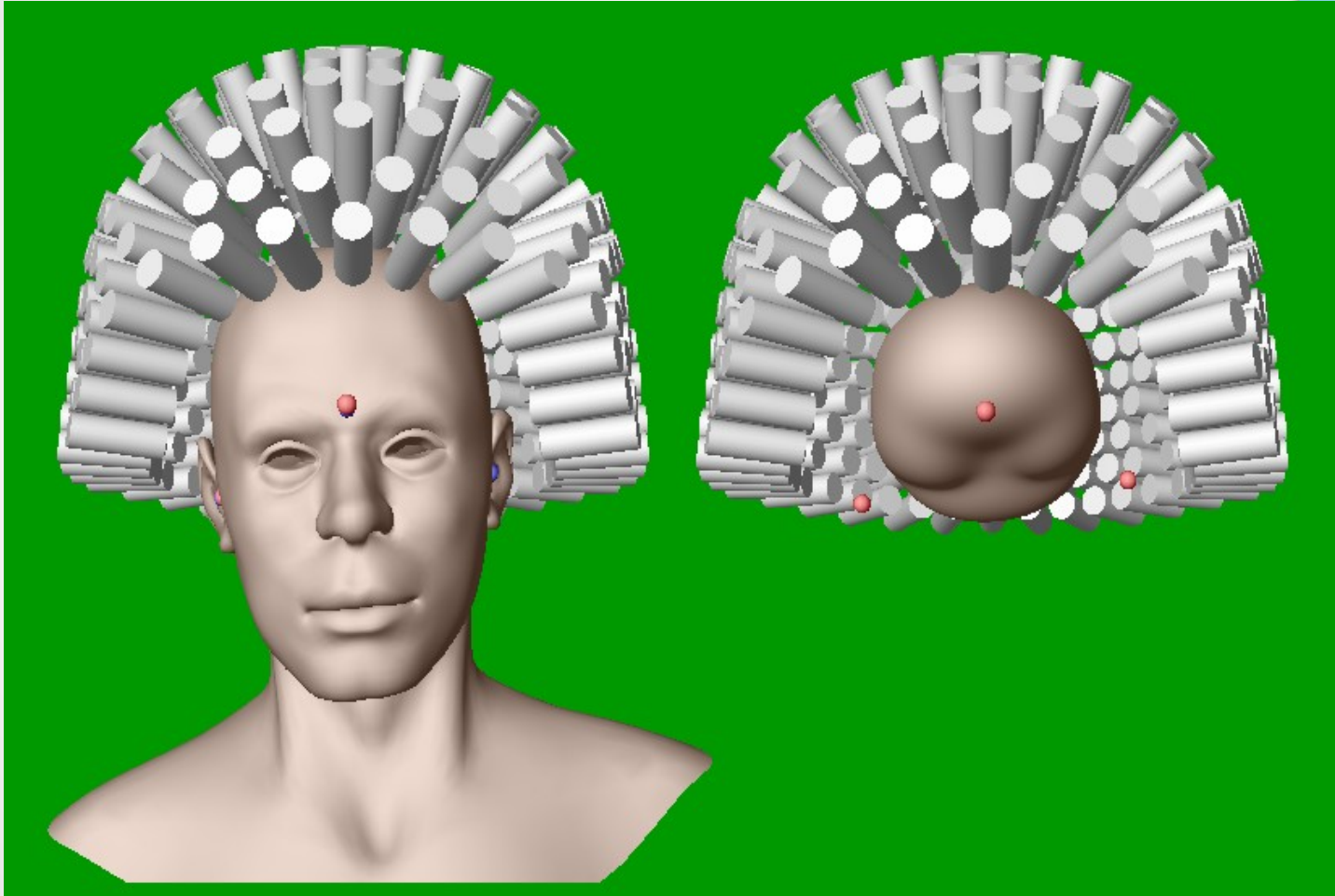
- Magnetoencephalography (MEG)
 - Dipoles, Evoked Fields, and all that
- SAM: Synthetic Aperture Magnetometry (Robinson, et al.)
 - LCMV: Linearly Constrained Minimum Variance Beamformer
- Multivariate Data and Virtual Channels
- Covariance
- The Forward Model
- Computing the Beamformer
- Source Imaging

MEG Sensors



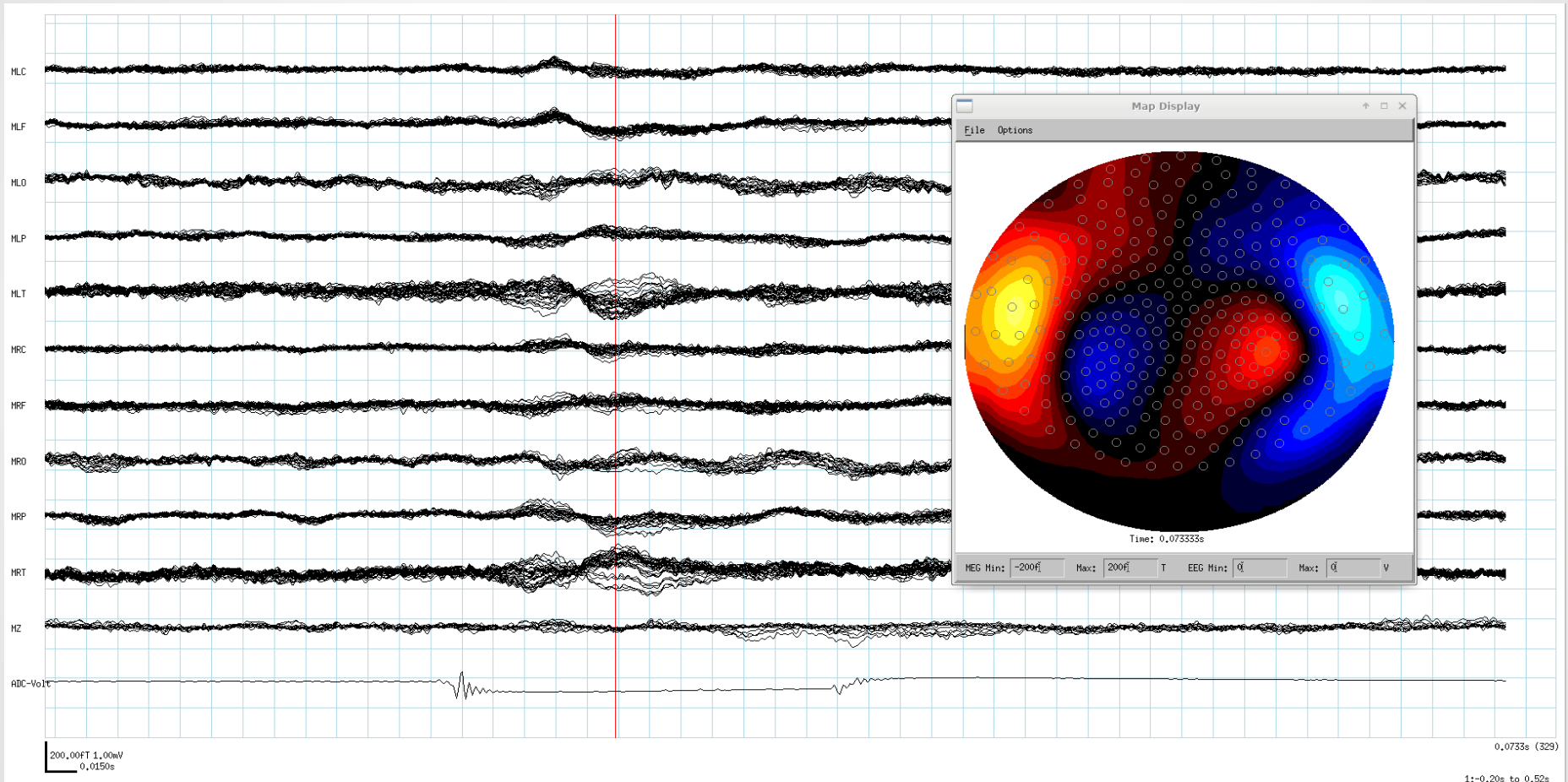
There are various types of MEG sensors.

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

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

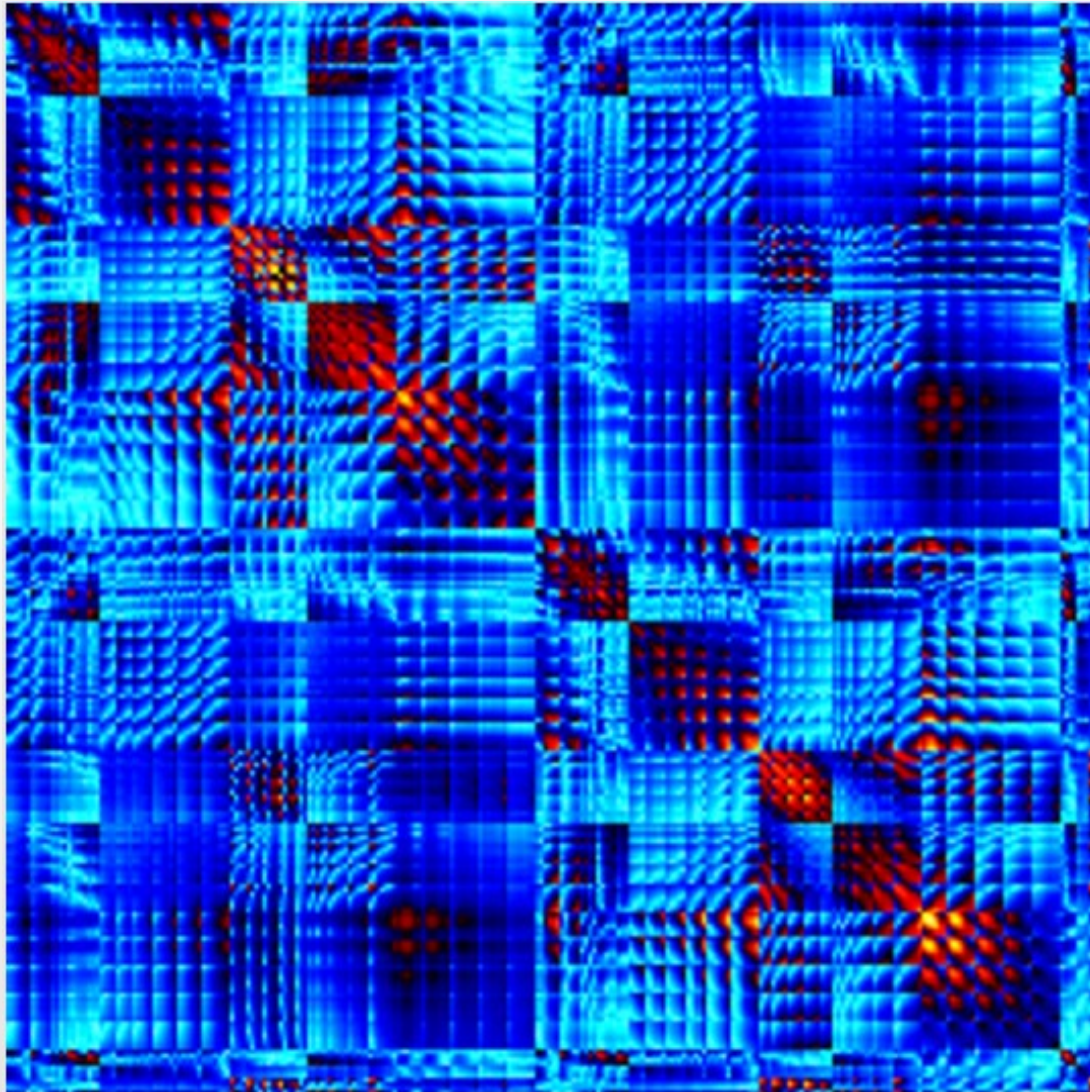
$$\begin{aligned} (\mathbf{H}_{\theta}^T \mathbf{X})^2 &= (\mathbf{H}_{\theta}^T \mathbf{X}) (\mathbf{H}_{\theta}^T \mathbf{X})^T \\ &= (\mathbf{H}_{\theta}^T \mathbf{X}) (\mathbf{X}^T \mathbf{H}_{\theta}) \\ &= \mathbf{H}_{\theta}^T (\mathbf{X} \mathbf{X}^T) \mathbf{H}_{\theta} \\ &= \mathbf{H}_{\theta}^T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

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

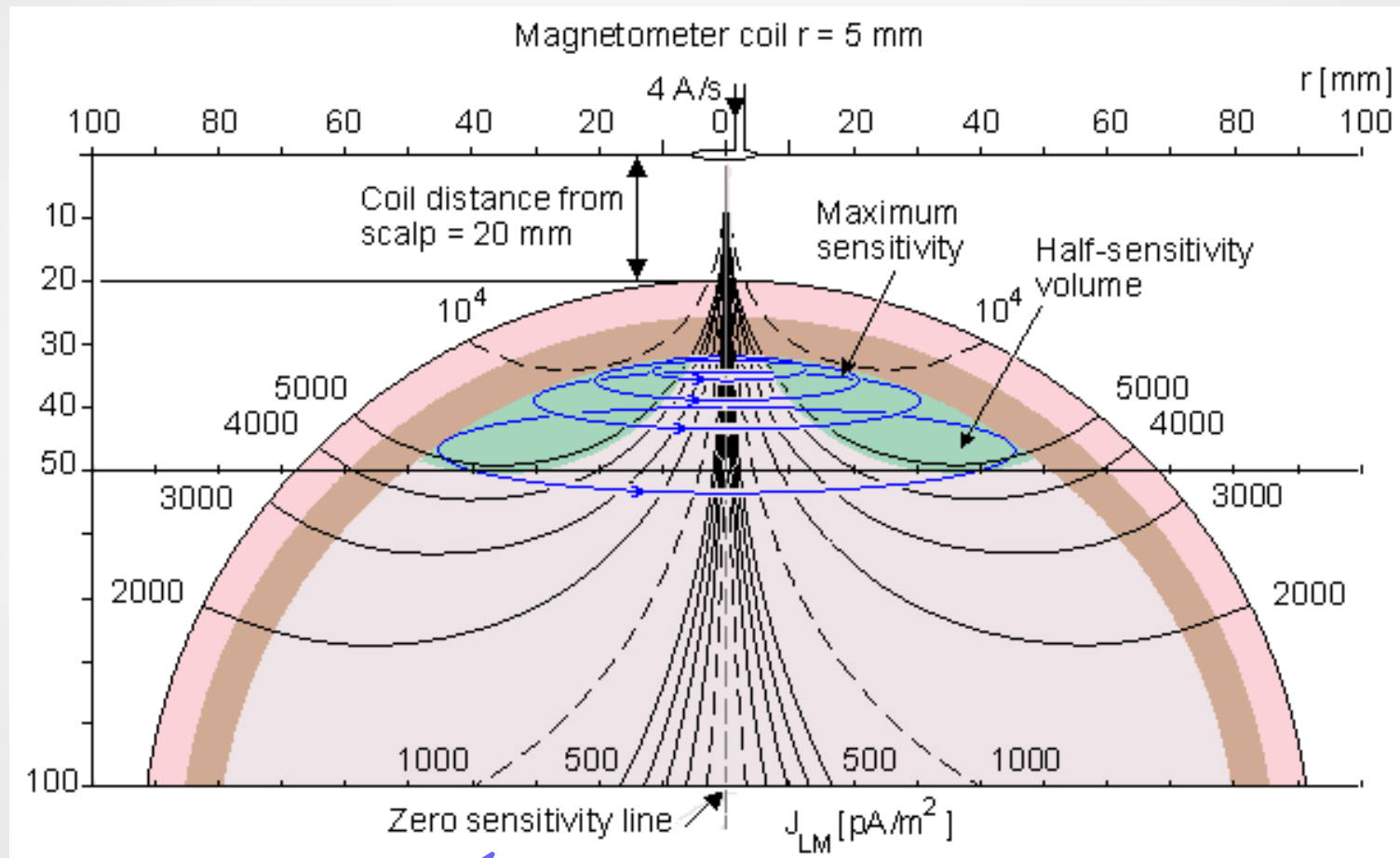
We would like to *minimize* the power in the computed virtual channel, subject to the constraint that the target source have a fixed amplitude. That is, all *other* sources should be minimized, while the target is not.

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

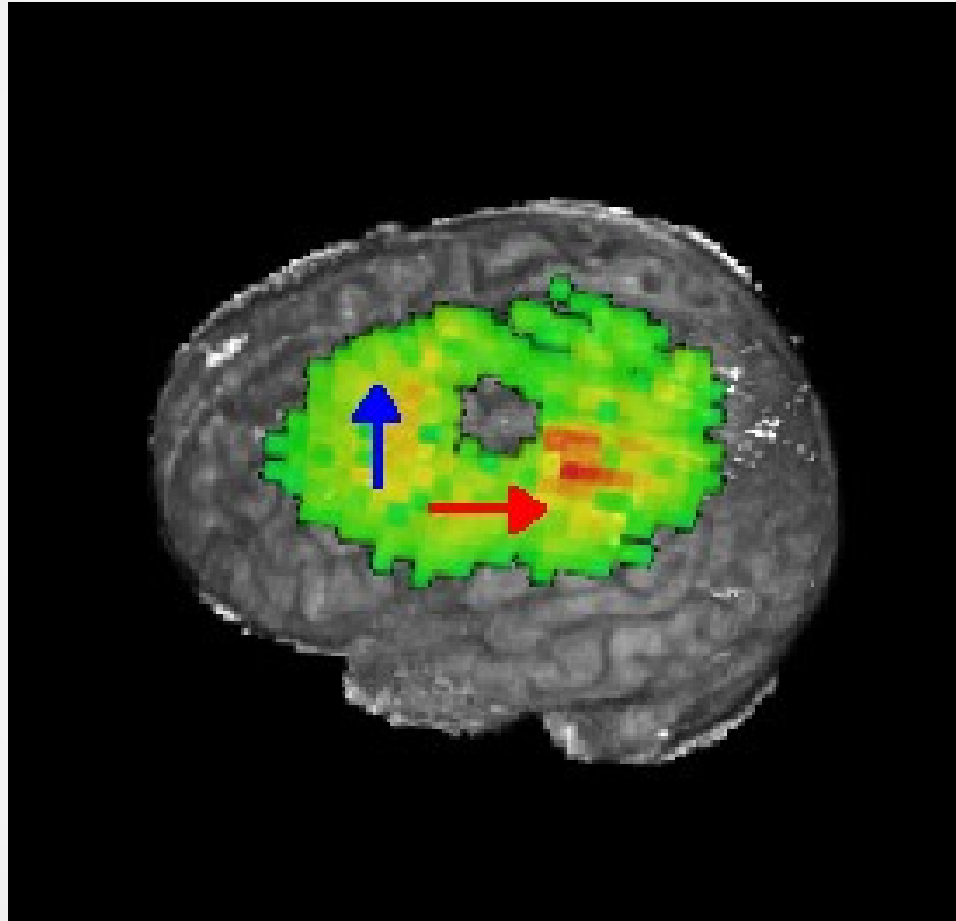
$$\mathbf{H}_\theta^T \mathbf{G}_\theta = 1$$

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?



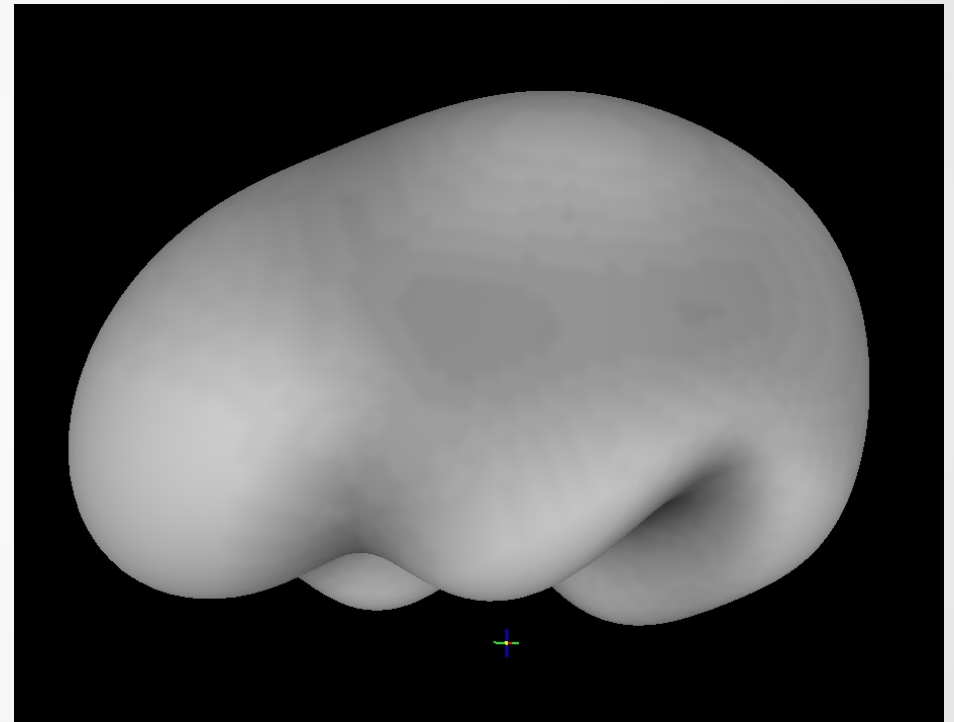
Sensitivity Volume for a Single Sensor



Forward Model—Skull Stripping (AFNI)

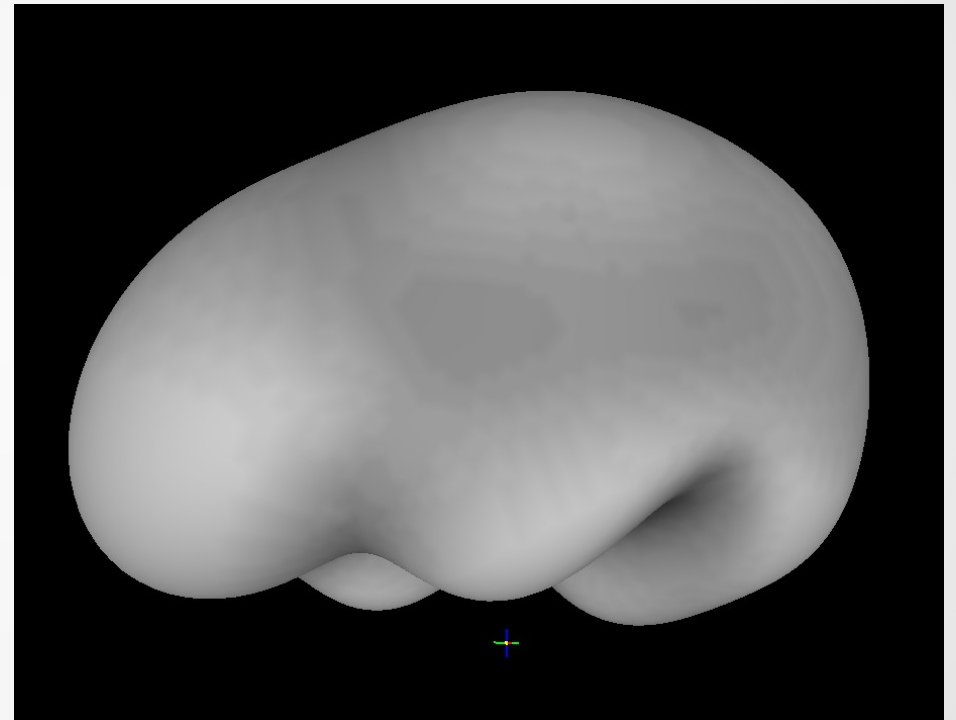
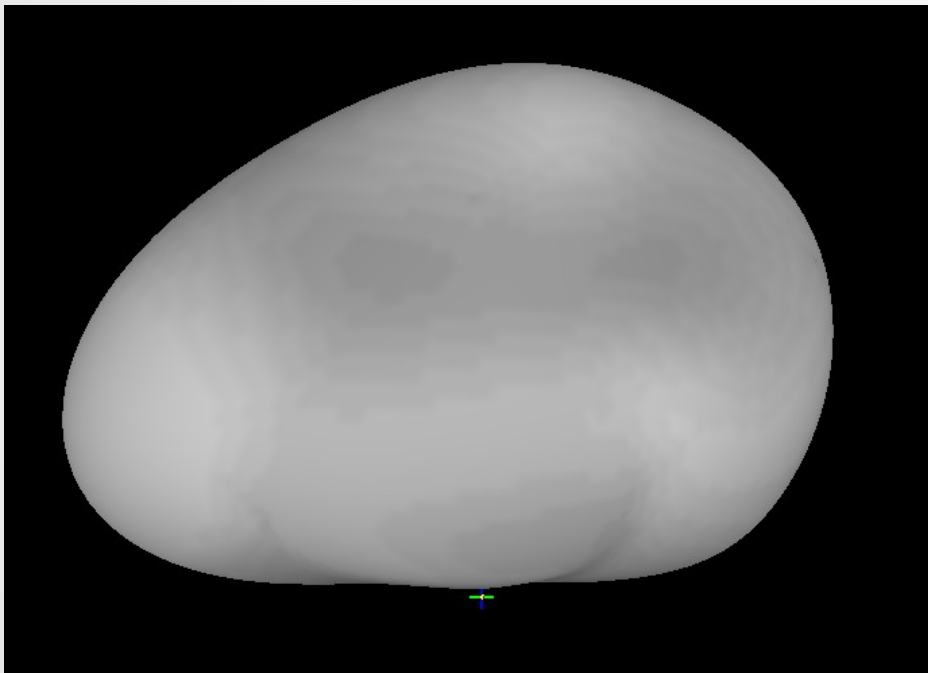


Forward Model—Conductivity Volume



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).

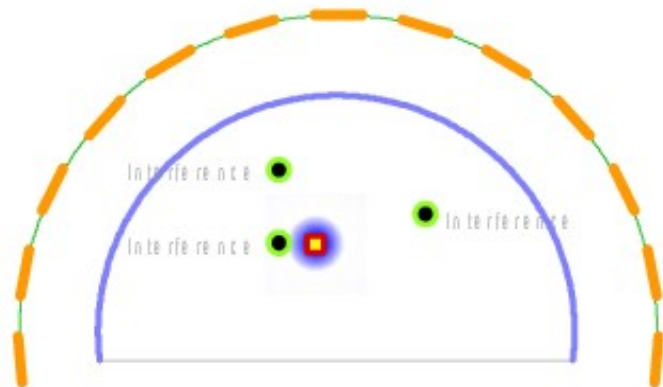
Beamformer Response

- ● ● Unwanted sources
- Target voxel

Sensitivity Patterns

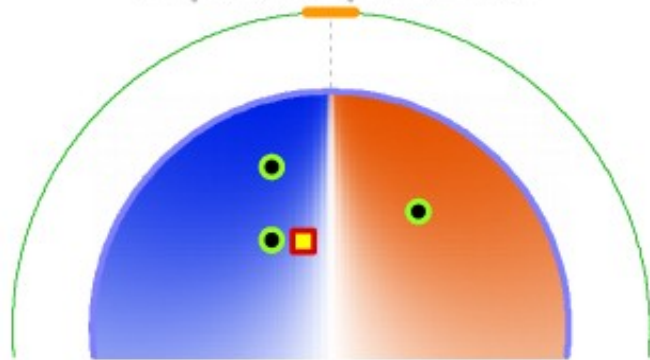
All dipoles perpendicular to the plane of the picture

100 radial gradiometer sensors

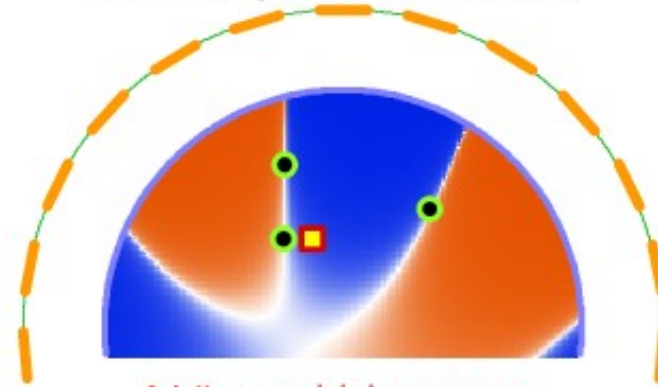


What we would like ... but cannot have

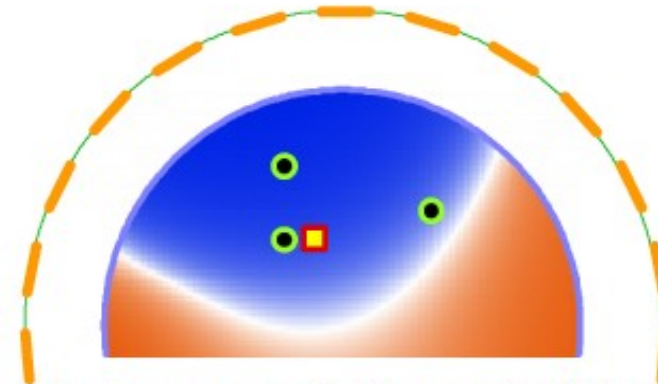
Single radial gradiometer



Radial sensor sensitivity pattern



SAM sensitivity pattern

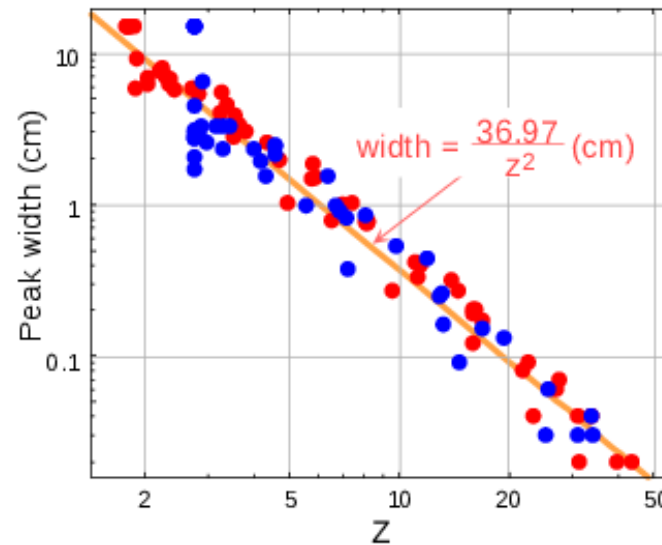
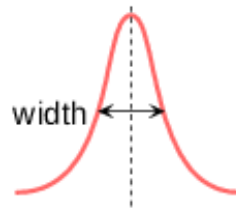


Signal space projection spatial filter

Beamformer Response

SAM Spatial Selectivity Improves With Increasing SNR

$$z^2 = \frac{S_{\theta}^2}{\sigma_{\theta}^2}$$



- ● ● Instrumental noise (shielded)
- ● ● Brain noise (unshielded)

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

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`.

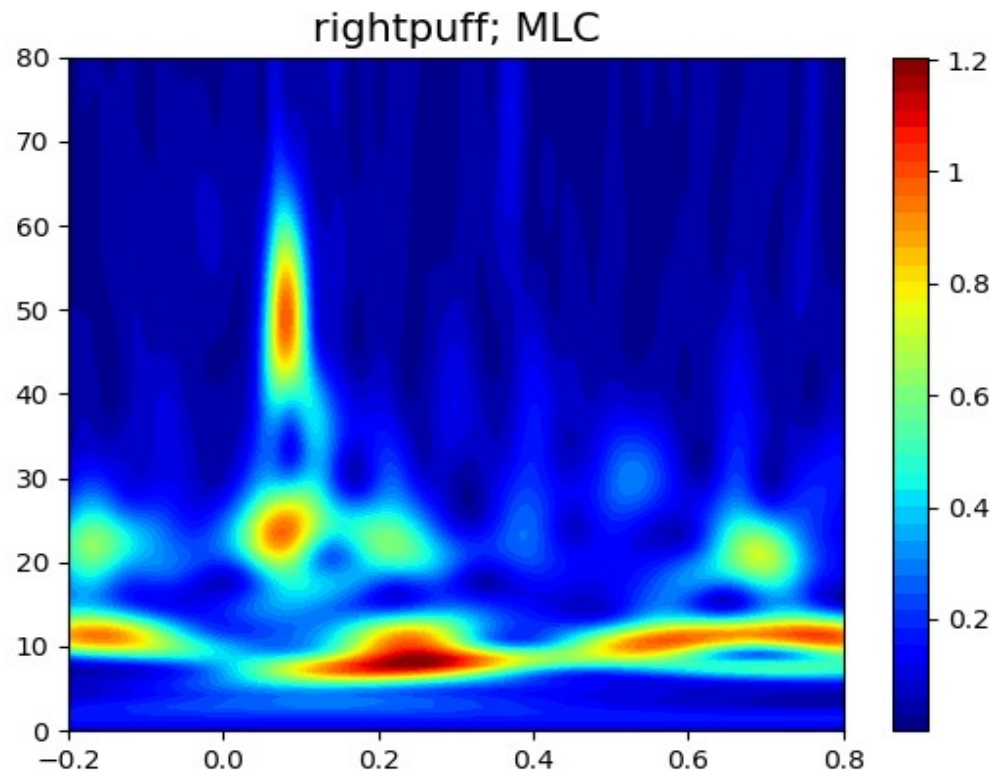
- `sam_4d`

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)

The image displays the AFNI (Analysis of Functional NeuroImages) software interface. It consists of several windows and panels:

- Control Panels (Top Left and Top Right):** These panels allow users to define the view (Original, AC-PC Aligned, Talairach), set Xhairs (Multi, X+), Color (green), Gap (5), and Index (35). They also include buttons for 'Define Overlay', 'Define Datamode', 'DataDir', 'Switch', 'Read', 'UnderLay', 'EditEnv', 'OverLay', 'NIML+PO', and 'Control Surface'. The bottom left panel has 'New', 'Etc->', 'BHHelp', and 'done' buttons.
- Central Panel:** Shows a vertical color scale for overlay #35, ranging from 0 to 1.000. It includes 'Clusterize' and 'Setup ICORR' buttons, and a 'Thresh' (Thr) of 12.39174. A 'See TT Atlas Regions' checkbox is also present.
- Brain Slices (Bottom Left):** Three brain slices are shown in Axial, Sagittal, and Coronal views. The Axial slice is labeled 109, Sagittal 42, and Coronal 99. Each slice has a 'Colr' (Color) and 'Swap' control.
- Time-Series Plot (Bottom Right):** A grid of time-series plots for various voxels. The plot for voxel #35 is highlighted with a yellow box, showing a red peak. The plot title is 'indx=35 val=12.44723 @t=0.05'. The status bar at the bottom right shows: 'I: 14 Fading', 'J: 12 Grid: 20', 'K: 13 Num 0:99', 'Scale: 4 pix/datum', 'Base: global', 'Mean: 8.456705', 'Sigma: 2.660238', 'Tran On = gamma', 'Tran 1: FIM Opt'.
- Bottom Left Panel:** A text box titled 'Atlas TT_Daemon: Talairach-Tournoux Atlas' providing anatomical information:
 - Focus point: Left Postcentral Gyrus
 - AND- Left Brodmann area 3
 - Within 1 mm: Left Brodmann area 4
 - Within 2 mm: Left Precentral Gyrus
 - Within 5 mm: Left Brodmann area 2

sam_ers — AFNI View (15-30 Hz)

[A]u AFNI: scripts/sefimage/TT_N27+tlrc & EYZQADGL.bet...htpuff-leftpuff,ENVdERS_at.nii+tlrc (umiushi.nimh.nih.gov) -

[order: PRI]
x = -19.000 mm [P]
y = 42.000 mm [L]
z = 48.000 mm [S]
Xhairs Multi X+
Color green
Gap 5 Wrap
Index 36
Axial Image Graph
Sagittal Image Graph
Coronal Image Graph
New Etc->
BHelp done

Original View
AC-PC Aligned
Talairach View
Define OverLay ->
See OverLay
Define Datamode ->
DataDir Switch Read
UnderLay EditEnv
OverLay NIML+PO
Control Surface
AFNI Tips

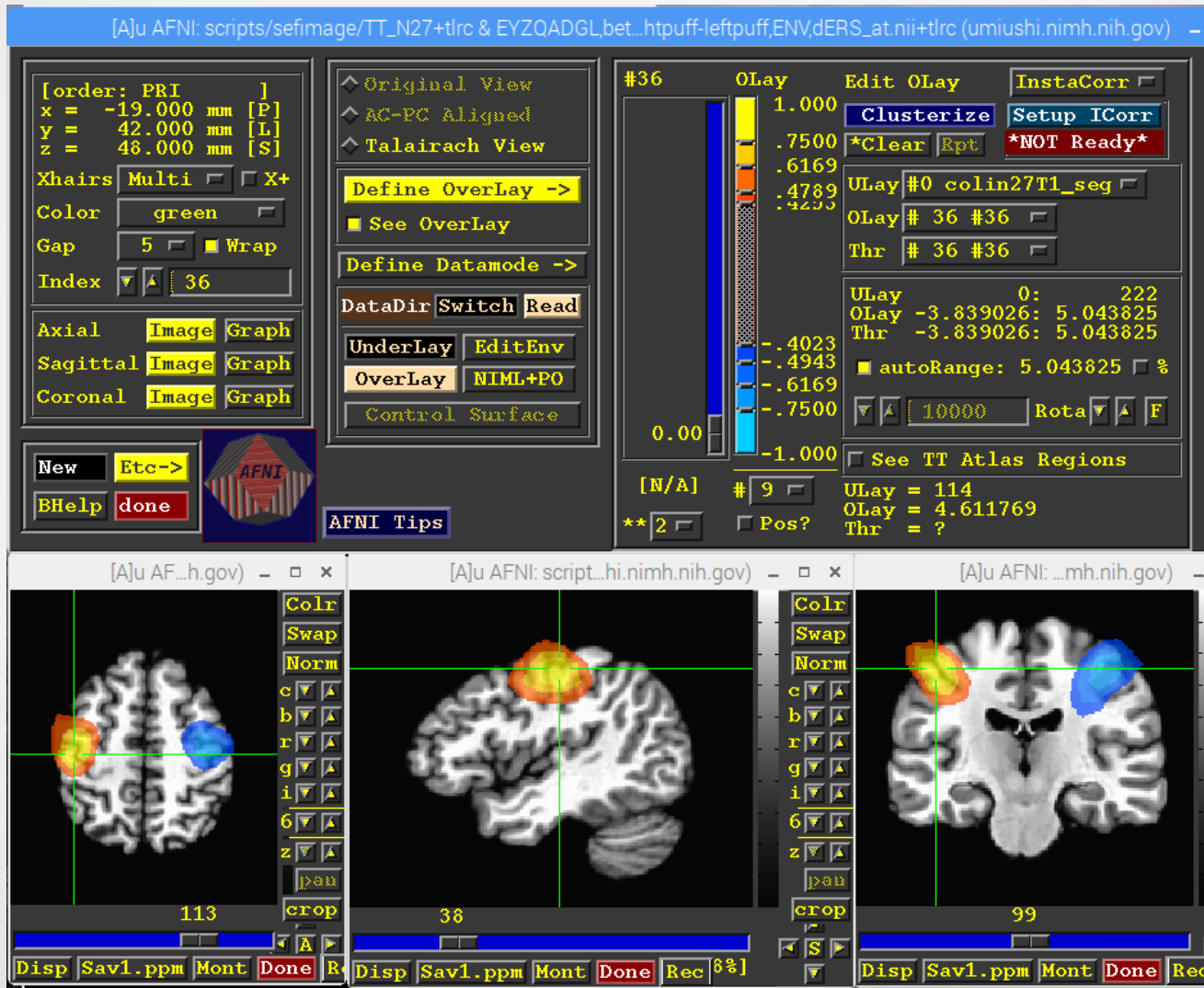
#36 Olay Edit Olay InstaCorr
1.000 Clusterize Setup ICorr
.7500 *Clear Rpt *NOT Ready*
.6169 Ulay #0 colin27T1_seg
.4789 Olay # 36 #36
.4233 Thr # 36 #36
Ulay 0: 222
Olay -3.839026: 5.043825
Thr -3.839026: 5.043825
autoRange: 5.043825 %
10000 Rota F
See TT Atlas Regions
[N/A] # 9 Ulay = 114
** 2 Pos? Olay = 4.611769
Thr = ?

[A]u AF...h.gov) - □ × [A]u AFNI: script...hi.nimh.nih.gov) - □ × [A]u AFNI: ...mh.nih.gov) -

Colr Swap Norm
c
b
r
g
i
6
z
crop
Disp Sav1.ppm Mont Done Rec

113 38
Disp Sav1.ppm Mont Done Rec β%

Colr Swap Norm
c
b
r
g
i
6
z
crop
Disp Sav1.ppm Mont Done Rec



Thanks!

Thank You!