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Theoretical and Practical Issues in the Proper Use of Beamformers

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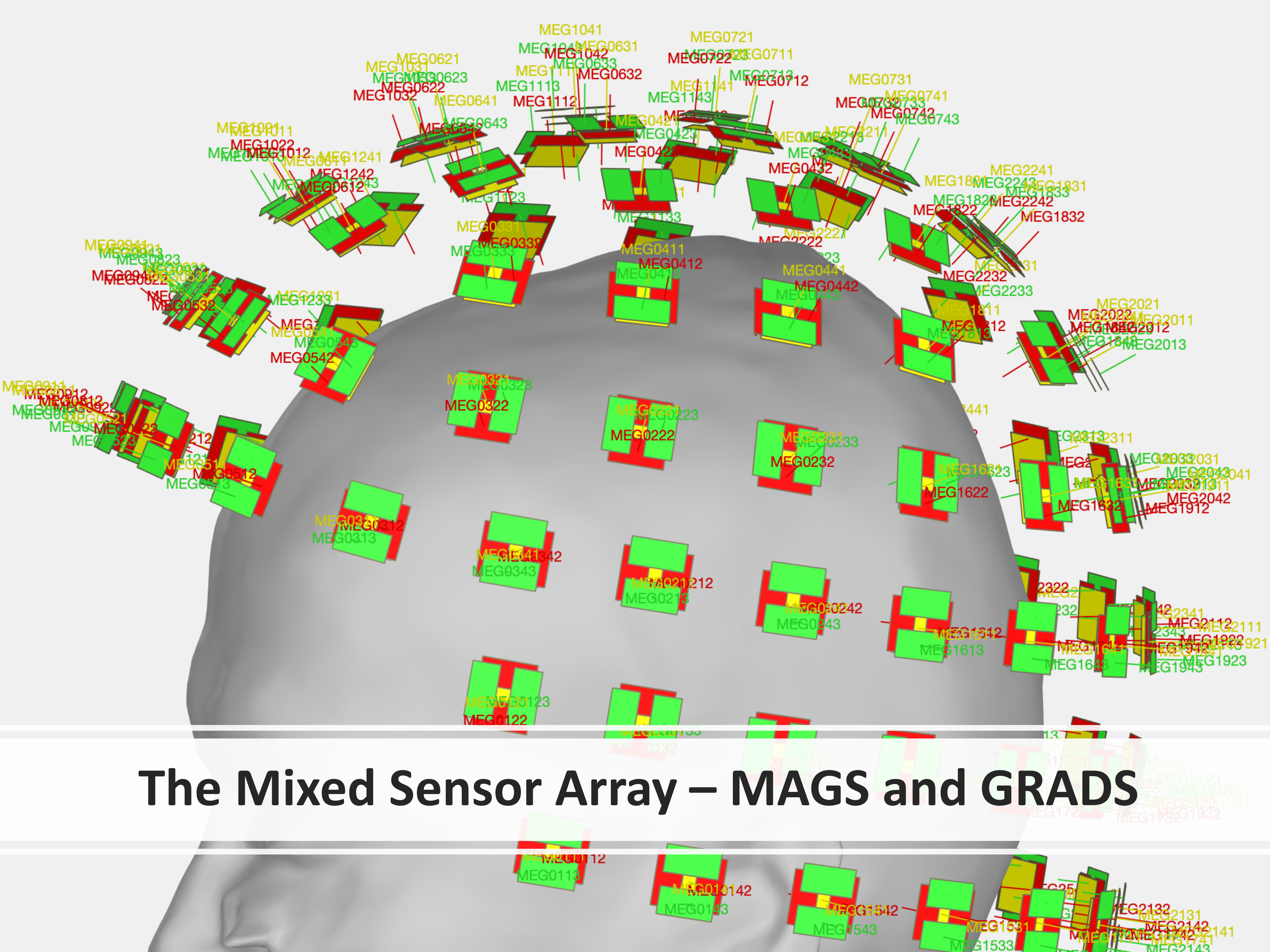
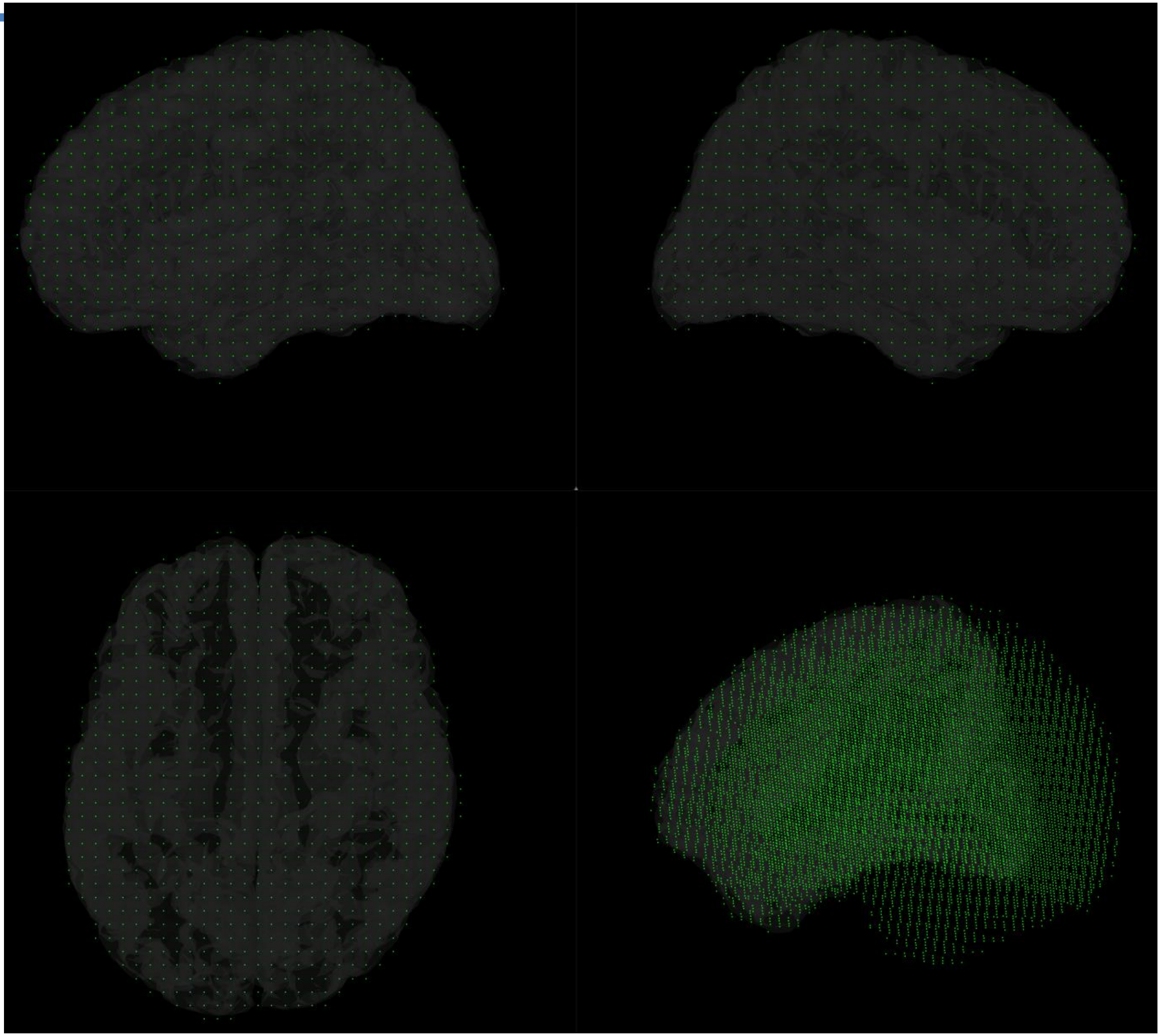


The Mixed Sensor Array – MAGS and GRADS

Grid the Brain Volume with Dipolar Sources



Tutorial Overview

IEEE Signal Processing Magazine, Nov 2001

Baillet, Mosher, Leahy

See also web site at University of Southern California: neuroimage.usc.edu.

Electromagnetic Brain Mapping

Sylvain Baillet, John C. Mosher, and Richard M. Leahy

The past 15 years have seen tremendous advances in our ability to produce images of human brain function. Applications of functional brain imaging extend from improving our understanding of the basic mechanisms of cognitive processes to better characterization of pathologies that impair normal function. Magnetoencephalography (MEG) and electroencephalography (EEG) (MEG/EEG) localize neural electrical activity using noninvasive measurements of external electromagnetic signals. Among the available functional imaging techniques, MEG and EEG uniquely have temporal resolutions below 100 ms. This temporal precision allows us to explore the timing of basic neural processes at the level of cell assemblies. MEG/EEG source localization draws on a wide range of signal processing techniques including digital filtering, three-dimensional image

'HOTODISC, INC. AND 1989–97 TECH POOL STUDIOS, INC.

Types of Source Modeling - “Imaging” (“Imagining”)

Given this discrete grid of source dipoles throughout the brain:

- **Dipolar modeling** finds which single dipole (grid point) best fits the data (multiple dipoles not considered here)
  - SECD, dipole scanning, xfit, etc
- **Minimum Norm Imaging** simultaneously fits all dipoles while minimizing the energy of the image
  - MNE-Python, LORETA, LAURA, etc
- **Beamforming** fits a focal source while minimizing all other energy in the “beam”
  - LCMV, SAM, beamformer

Beamformer Signal Processing Reference

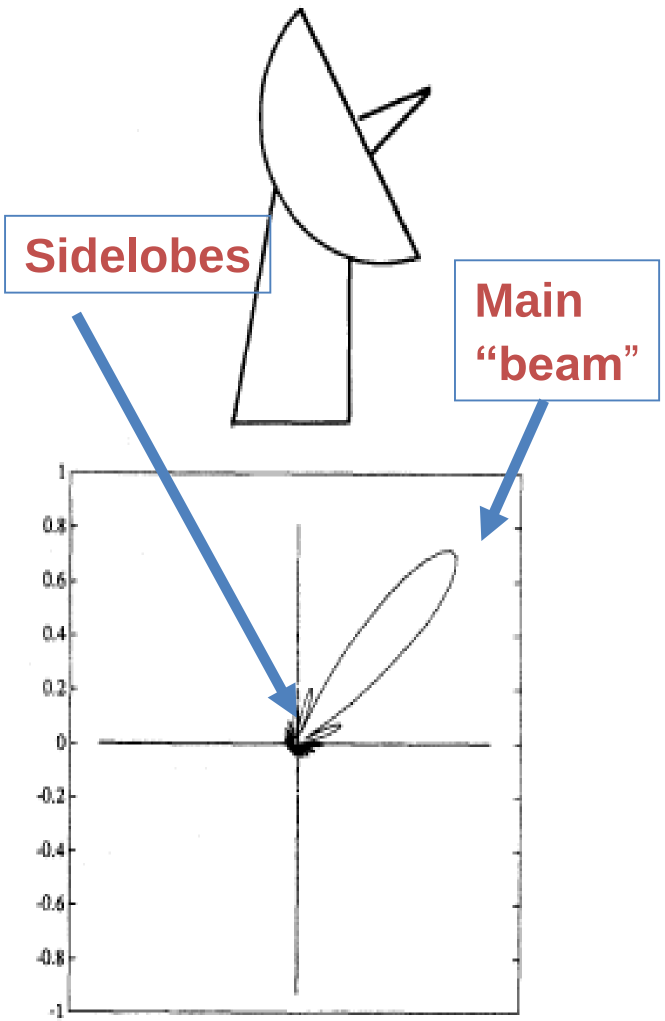
- IEEE ASSP Magazine 1988
- Algorithmic details and references

Beamforming: A Versatile Approach to Spatial Filtering

Barry D. Van Veen and Kevin M. Buckley

- In particular, MEG "beamformer" is more precisely the LCMV

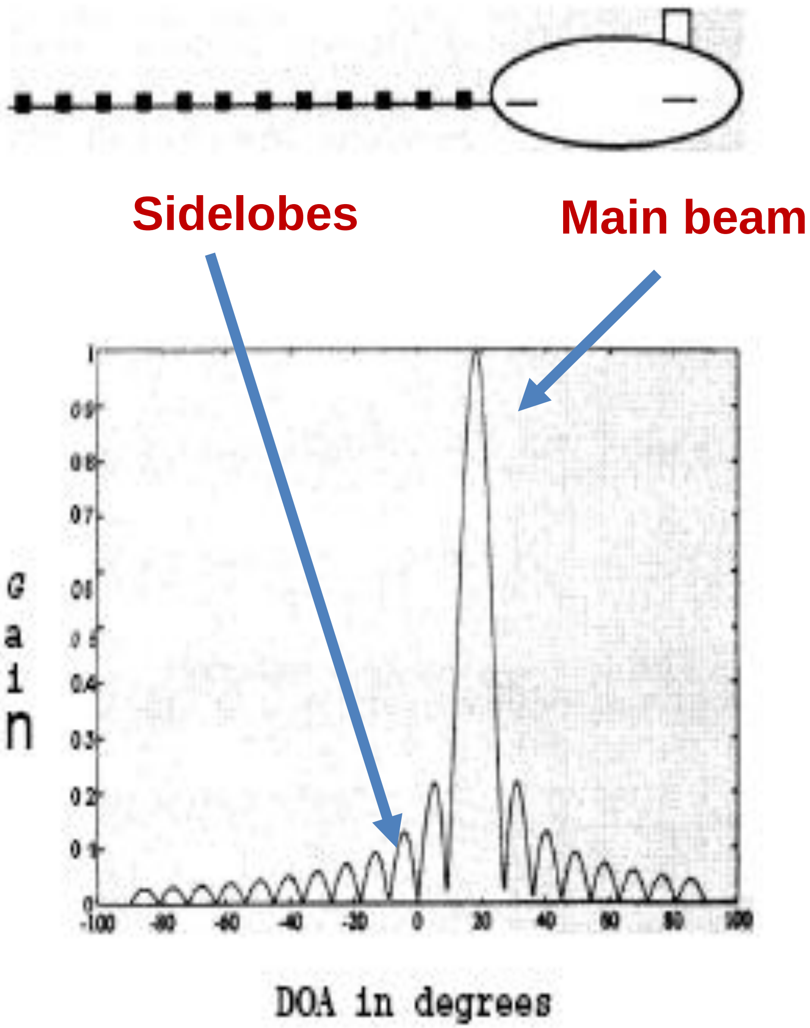
What is a “beamformer”?



van Veen and Buckley 88

- Microwave antenna example
- The size of the dish is the “spatial aperture” or “spatial extent” of the receiver
  - Bigger is better
- The primary reception is along the direction of the main “beam”
- Note the presence of smaller “sidelobes” of the receiver

Beamformer from Arrays of Sensors



van Veen and Buckley 88

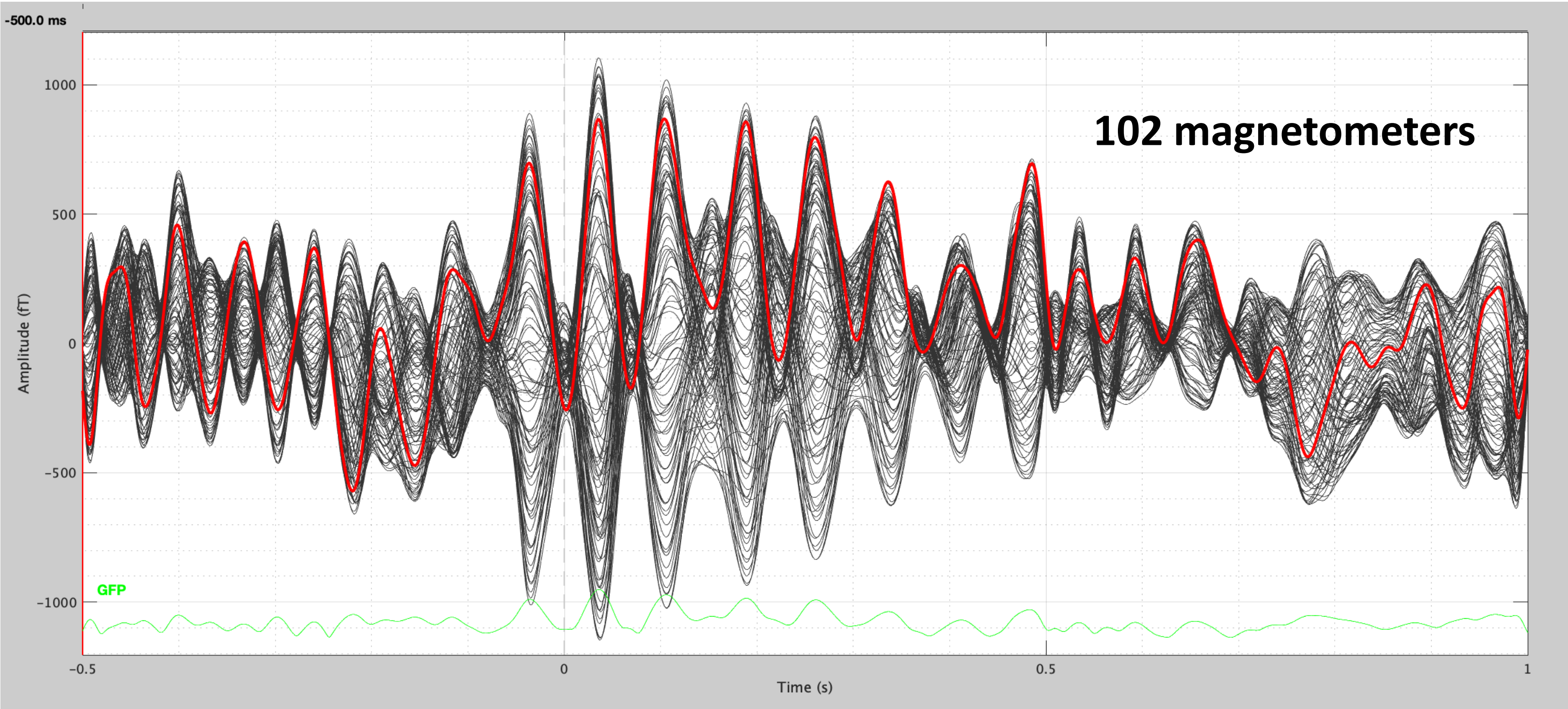
- Sonar towed array example
- Each of the hydrophones is isotropic and identical to the others
- The output of each hydrophone is weighted and delayed relative to the others, then all are summed together into a single output
- The result is high sensitivity to a “direction of arrival” (e.g. 20 degrees here) to the array, and diminished sensitivity to the other directions
- Again, note “sidelobes”

Aston Beamformer Workshop

- January 2019 - Aston Brain Centre, Birmingham, England
- Developers from **SPM12** (Litvak), **Fieldtrip** (Oostenveld), **MNE-Python** (Gramfort), **Nutmeg** (Witte), and **Brainstorm** (Mosher) were locked in a room for four days to hack the issues of the beamformer
  - Actually, Dr. Caroline Witton was a fantastic host
- Simulated data, experimental phantom data, and human data were used as common benchmarks
- Here, we'll use the phantom data to illustrate the beamformer issues

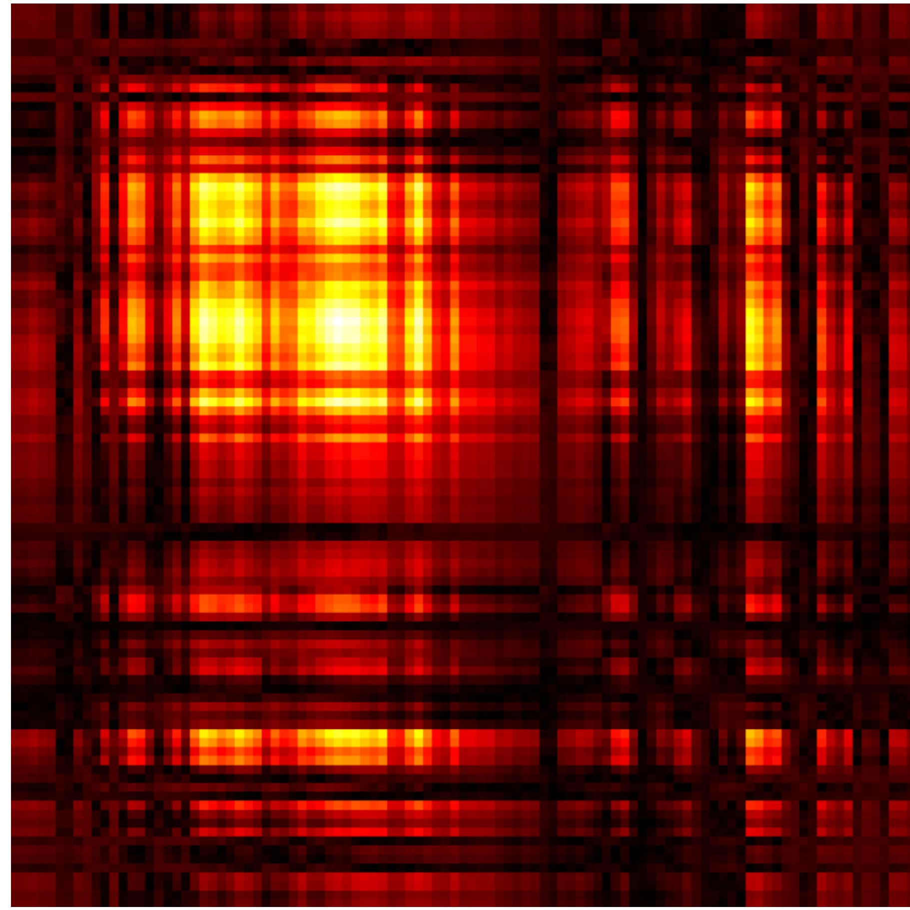
Phantom Data Example – 20 nA-m averaged 100 times

- Experimentally acquired with real environmental noise
- No “brain noise” removing a confound for now
- Source model well-known, but realistically imprecise
- Known separation between “background” and “data”



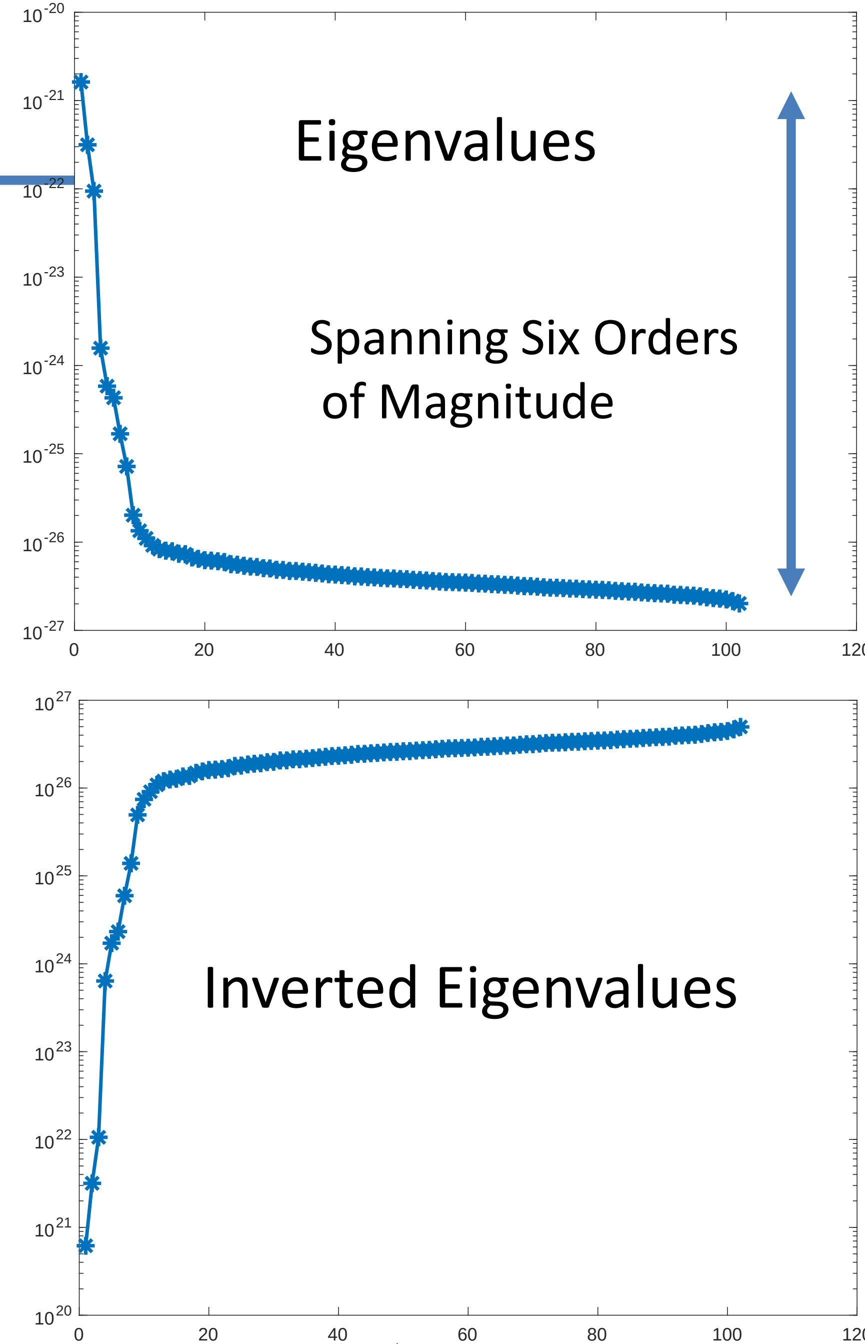
The Covariance Matrix

- Let's look at the pre-stim period, the "noise" or "baseline" data.
- We can calculate the variance of each channel
- We can also calculate the cross-covariance between each pairs of channels
- If we calculate all possible pairs of auto and cross covariances, we arrange these in the "Covariance Matrix"
- **All forms of estimation require inversion of this matrix**



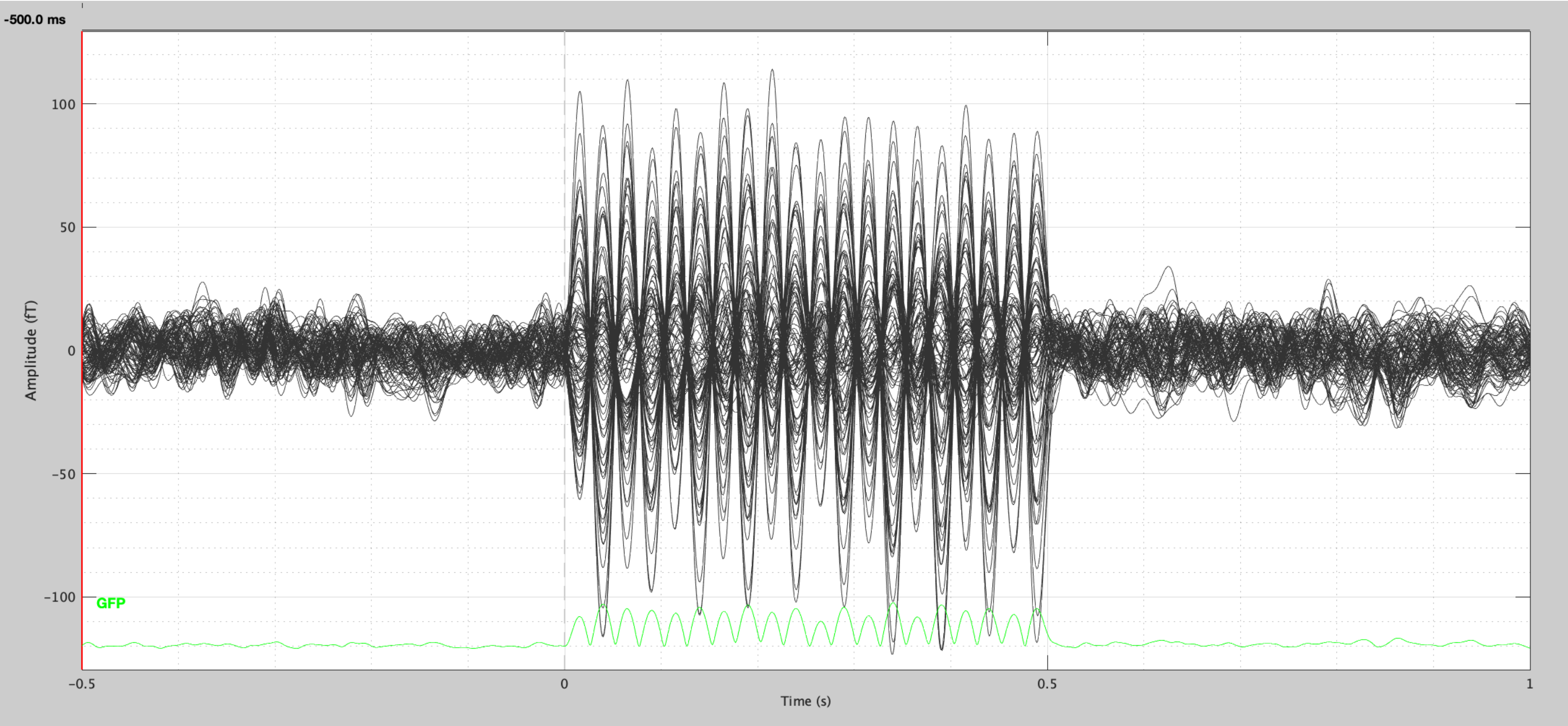
The Eigenspectrum

- The eigenvalues from a PCA or SVD or eigen-analysis of the covariance matrix.
- The inverse of this matrix is easily found by inverting these values.
- Crucial for examination of the strengths and weaknesses of the matrix, prior to inversion.



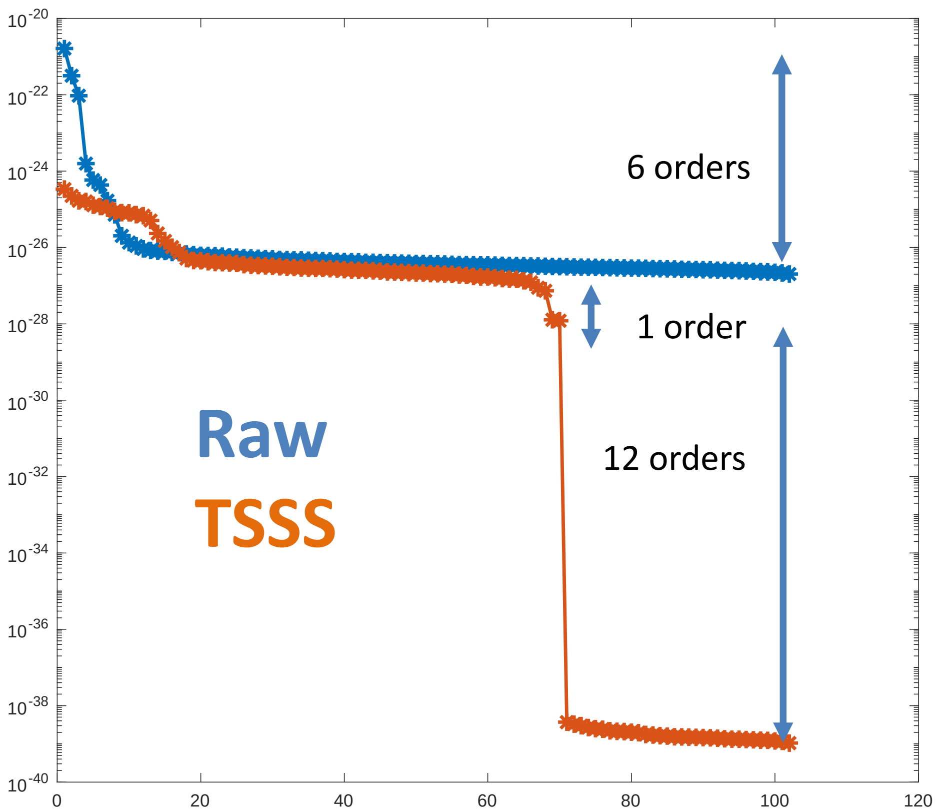
TSSS Filtering

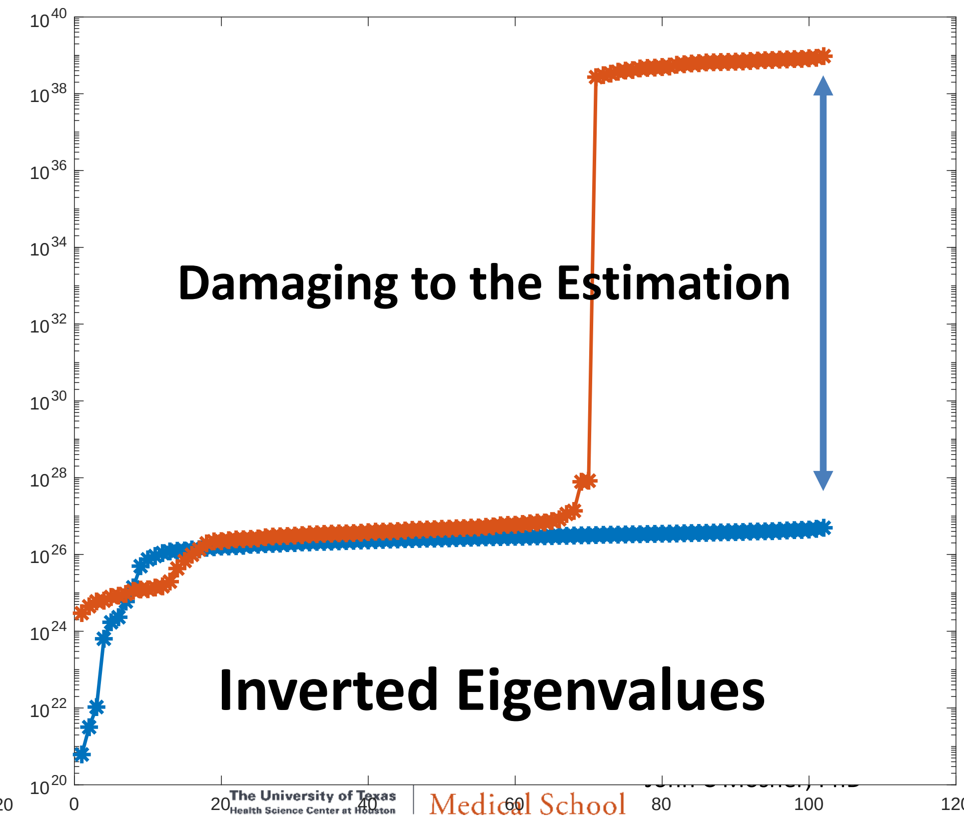
- The phantom data is now easily seen, hence the attraction of this preprocessing.
  - Indeed, TSSS is a highly dimensional beamformer, adapting to the noise statistics.



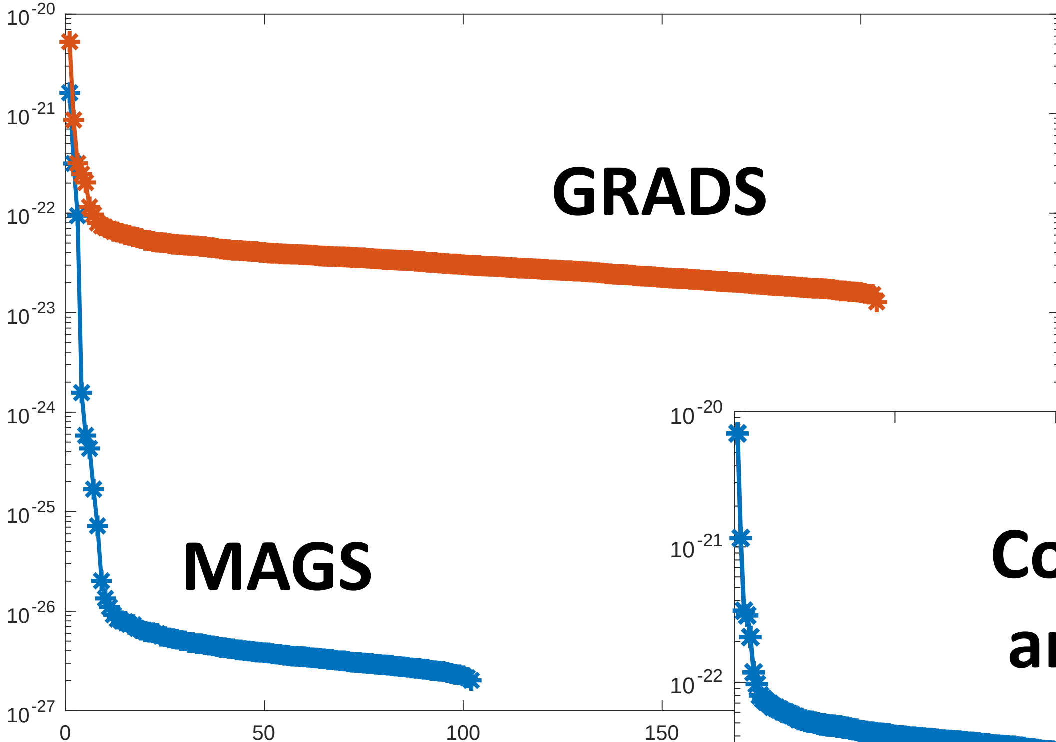
Deficient Eigenspectrum!

- TSSS dramatically alters the eigenspectrum!
- Acquisition, filtering, post-processing can also cause similar deficiencies
- “Regularization” is the art of fixing this deficiency prior to inversion

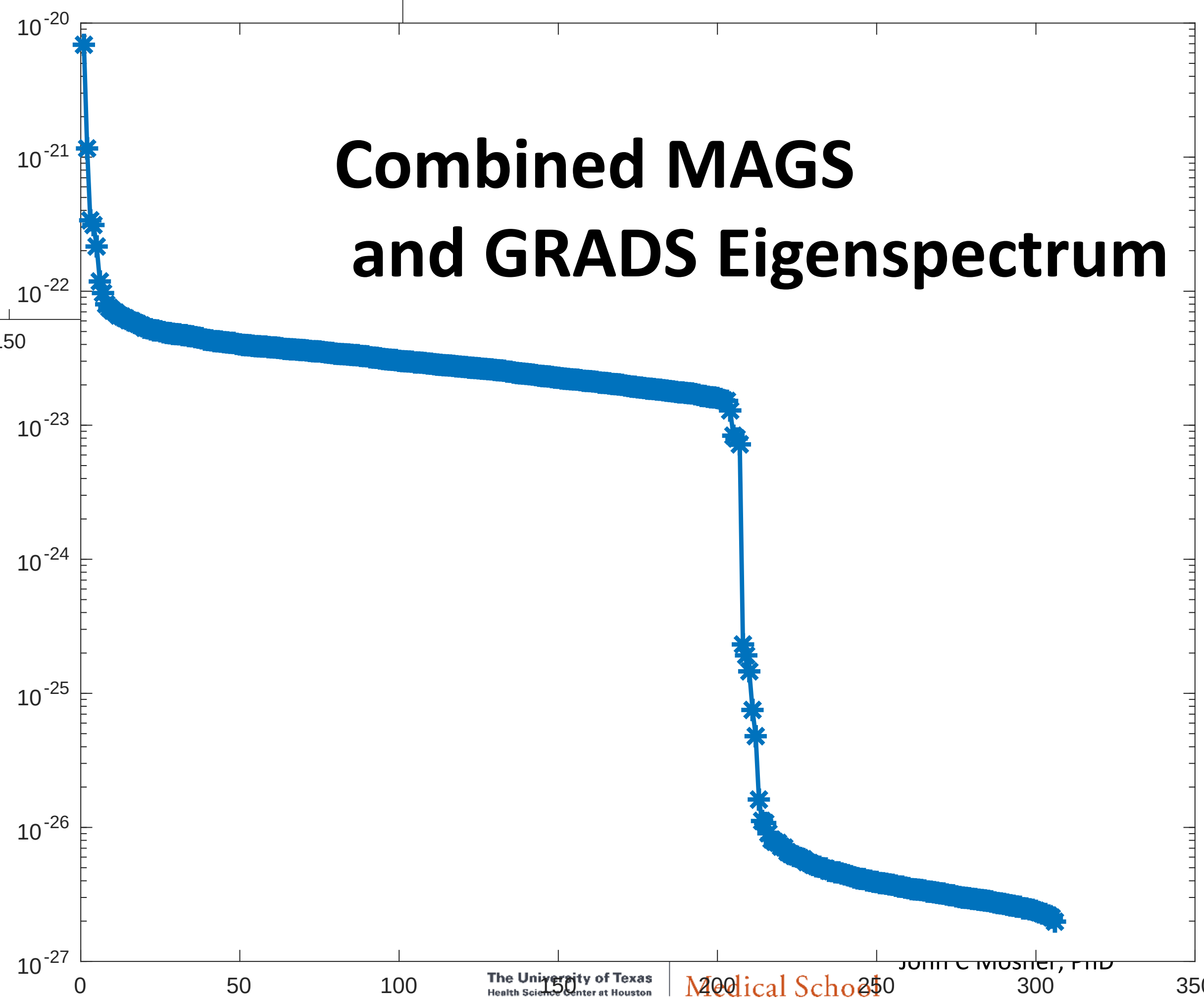




Combined Mags and Grads



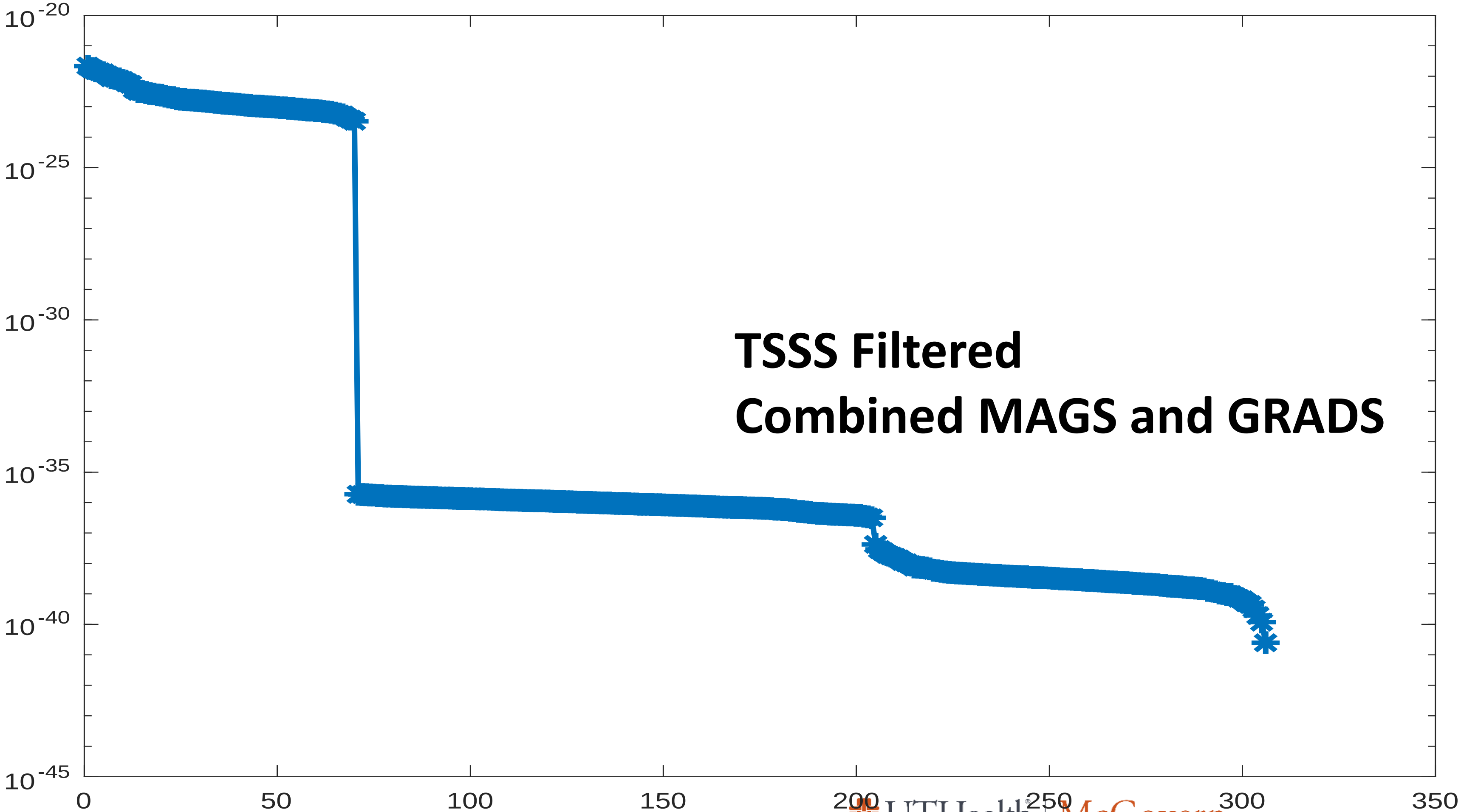
Raw unprocessed data



- Nothing is deficient here!
- ”Small” does NOT mean “deficient”!
- It’s simply the dynamic range of two different sensor types.

Combined Mags and Grads with Deficiencies

- No simple determination here of what is **deficient** and what is **small**



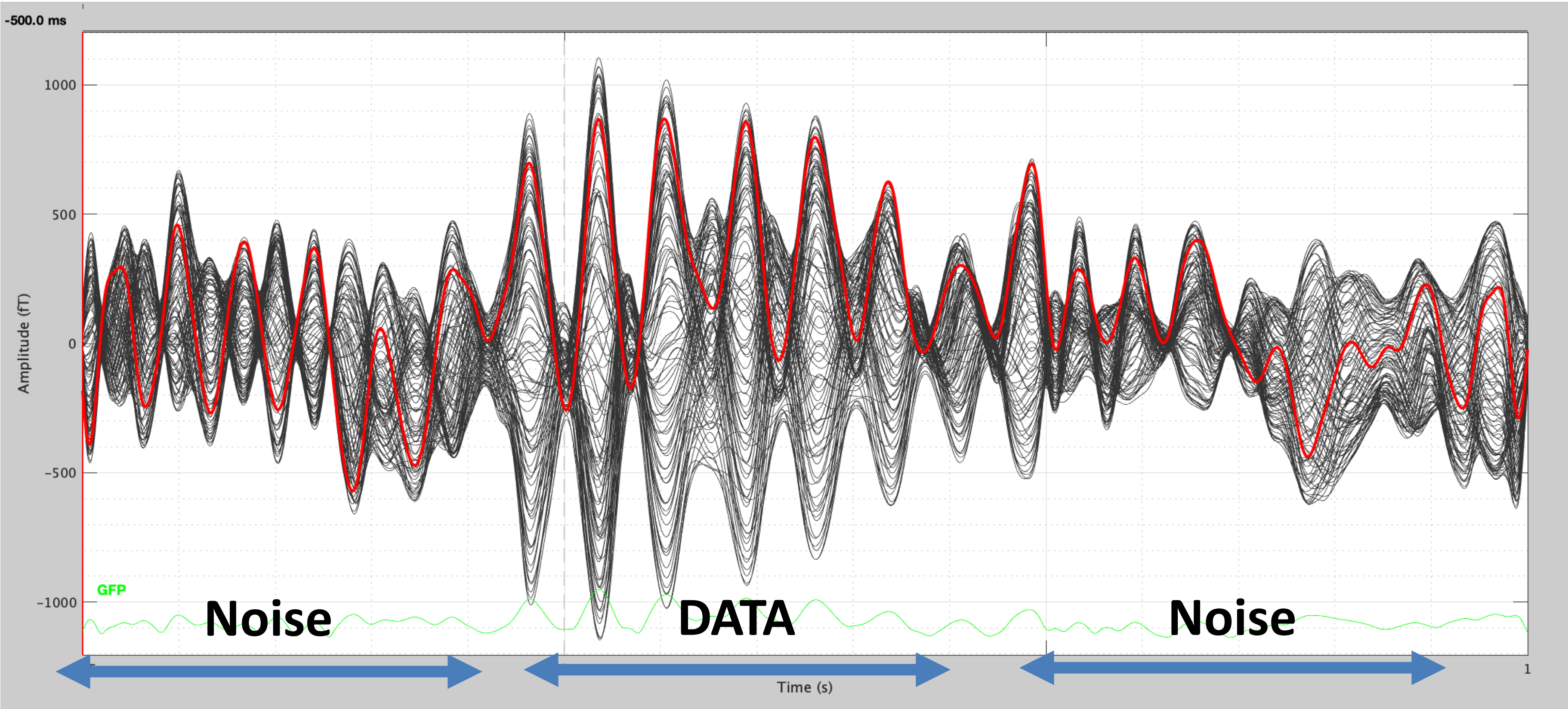
How to Fix?

- **Truncate** the bad eigenvalues.
- **Replace or Augment** the bad eigenvalues
- Treat each array separately, then combine
  - Ignore the cross terms between modalities
  - Recalculate the cross terms between regularized modalities
- Ignore one of the arrays
- Run each array separately and compare results

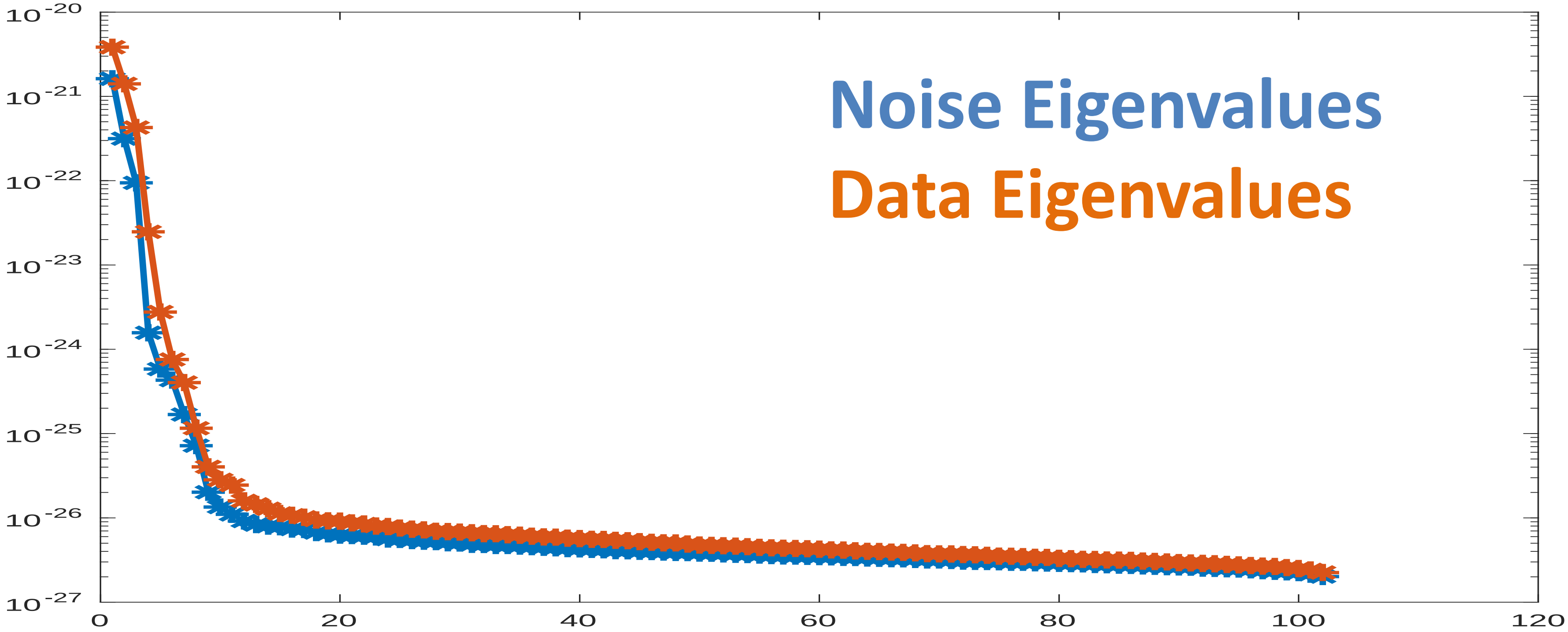
Under active discussion by the working group

The Data Covariance

- Gather as much **data** as possible representing the signal of interest, but avoid “diluting” by adding too much **noise** or non-signal regions.



The Data Covariance



- Eigenspectrum now has both strong noise and weaker signal components.
- Now eliminating or regularizing small eigenvalues may be the very signal parts you were interested in!
- "Pre-whitening" by the noise covariance is a method by which we can disambiguate this issue, but requires more input by the user.

Orientation of the Source

- Recall we have a grid of points throughout the brain.
- For each point, we need to find the **best** orientation of the source (don’t use cortical constraints).
- Differences are:
  - (1) **best** for **power**,
  - (2) **best** for **depth**, or
  - (3) **best** for **significance**,

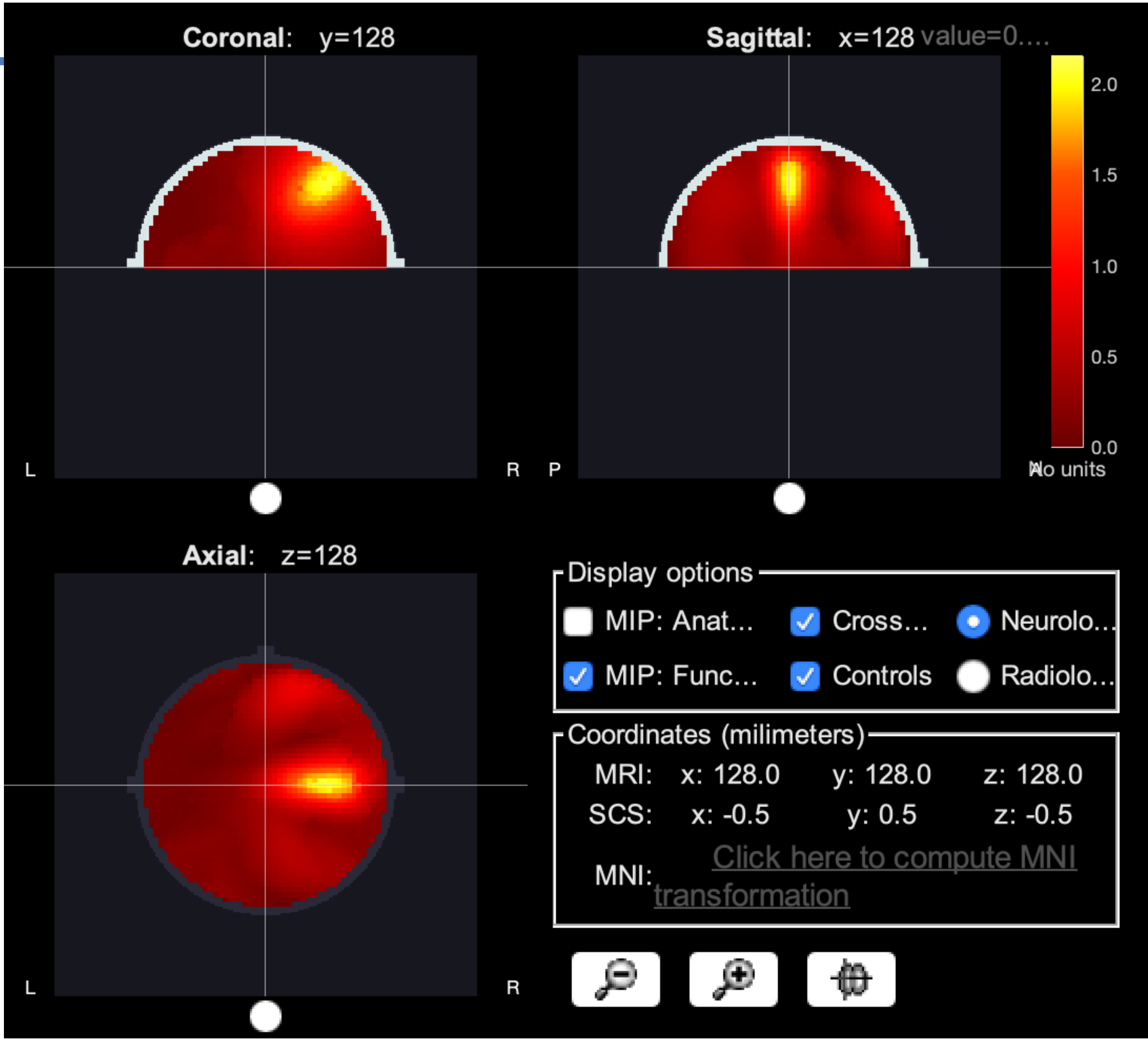
  each leading to possibly different results.

Neural Activity Index and Variations

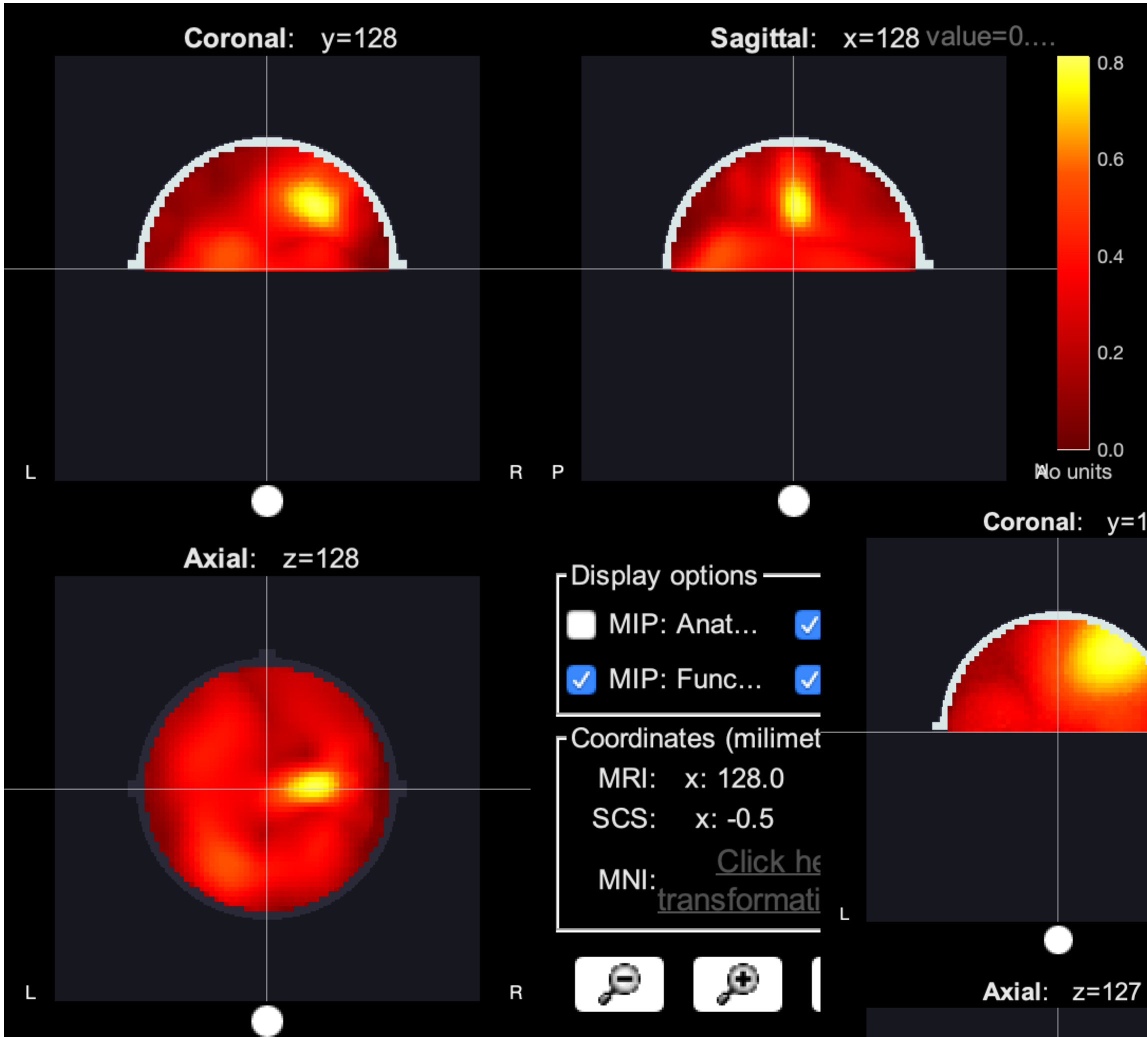
- Under active discussion and comparison, but my strong suggestion is for optimizing orientation best for **significance**
- Analogous to minimum norm community, which used to argue endlessly about “depth weighting” until Dale (2000 Neuron) introduced “dSPM” which is essentially z-scoring for significance relative to noise (related: sLORETA).
- The Neural Activity Index (NAI) of van Veen (1997) is a close variation of z-scoring. SAM algorithm calls this “pseudo-z”.
- So the user must specify both a noise covariance and a data covariance, but this is a good thing, in my opinion!

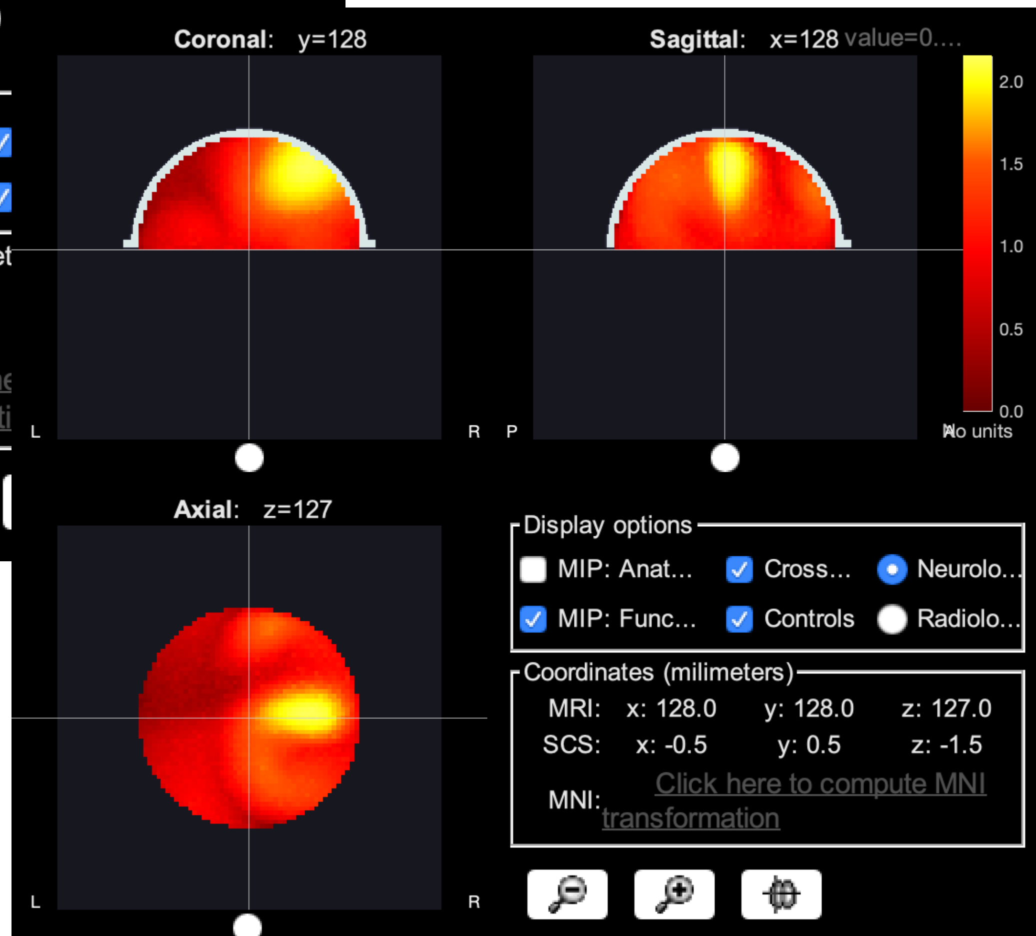
Phantom Beamformer Example

- Z-scoring of the beamformer output of the MAGS



dSPM and Dipole Comparison



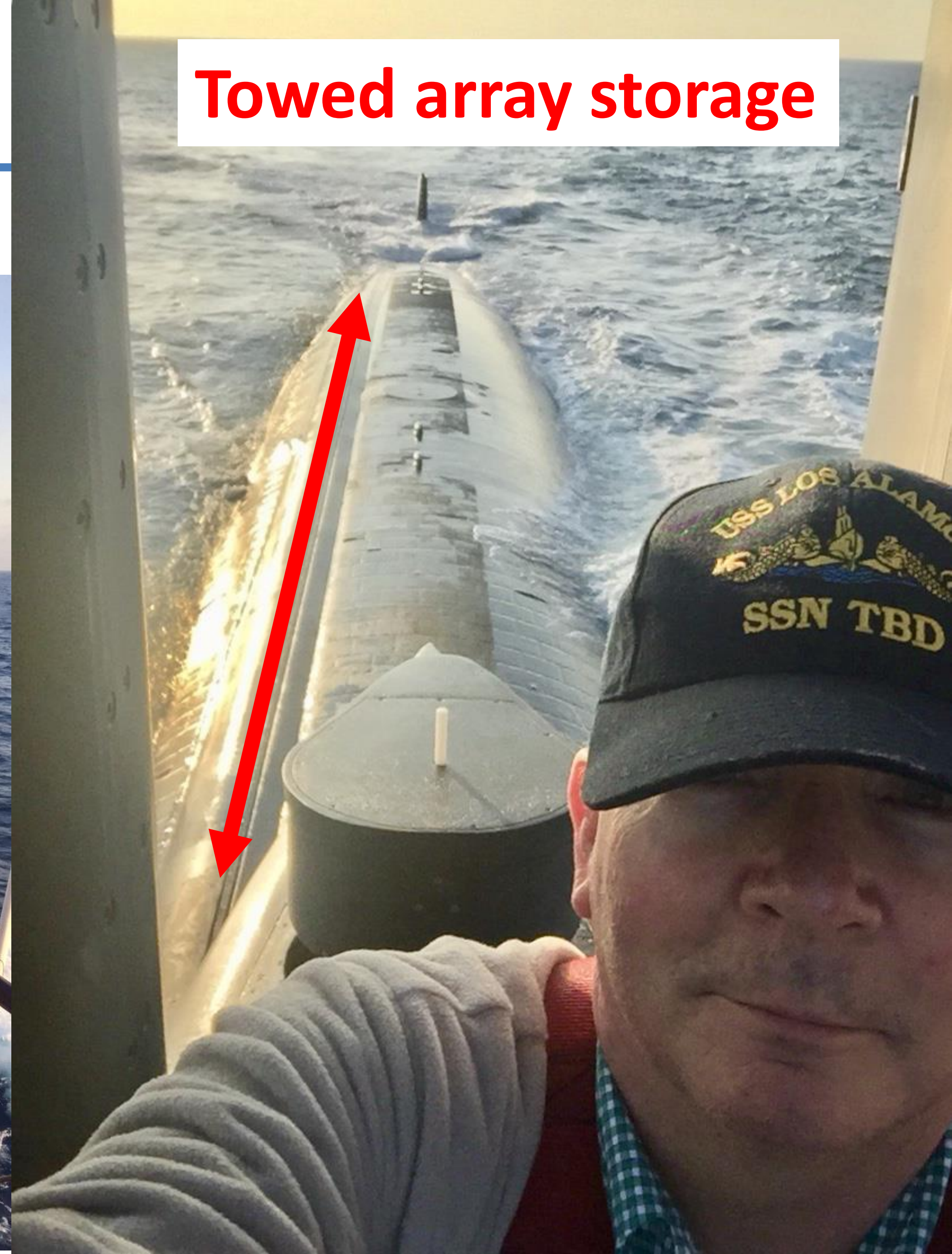


- Using noise covariance matrix
- Similar z-scoring
- Very similar results!

Issues

- To calculate the data covariance, you must select a window of time containing the signal of interest
- Too short of a time window gives a bad estimation in need of a lot of regularization
- Too long of a time window, then you average out the signal you wanted
- You assume that the dipole does not spatially move during this time
- You assume that no other sources during this time are temporally correlated with the source of interest
- Head model must be accurate (EEG a problem)

Beamforming in Action



Sonar Room (from web)

Summary

- The beamformer model is structurally identical to single dipole modeling – the difference is the use of the data covariance, instead of the noise covariance.
- Accurate **estimation** of the data covariance requires a lot of data, not always possible with transient events.
- **Regularization** of the data covariance generally requires the noise covariance, not always easily defined (resting studies).
- In practice, beamforming and dipole modeling become intermixed as users select “too much” data and over-regularize it.
- Orientation optimization and imaging presentations can be different among packages.
- **Watch for papers from the Aston Beamformer group**