Fundamentals of Beamforming: Transforming MEG Signals to Source Estimates

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Topics

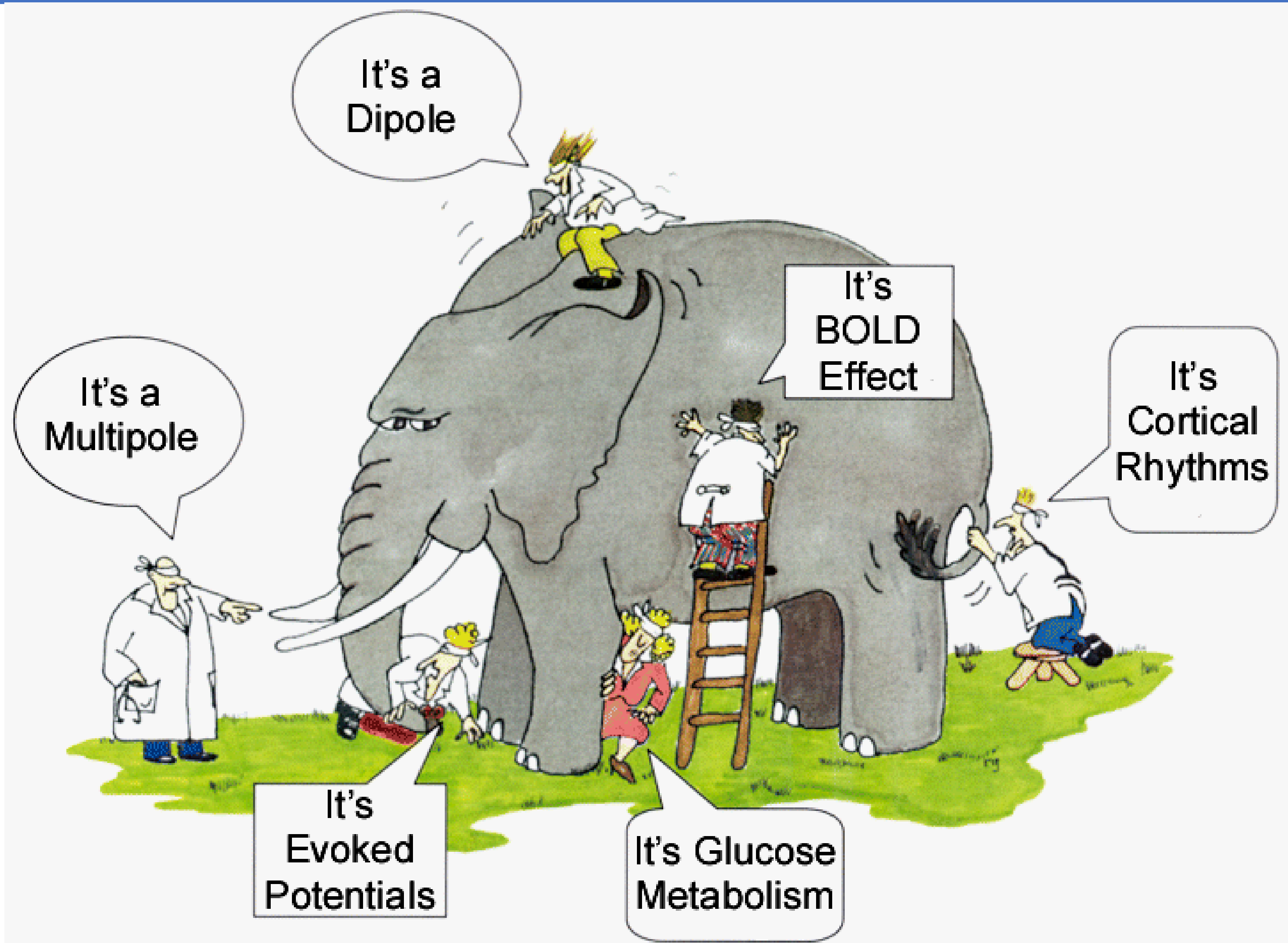
- Models for evaluating brain activity
- Some limitations of MEG source analysis
- The linearly-constrained minimum variance (LCMV) beamformer
- Beamformer computational steps
- Beamformer performance
- The “virtual sensor”
- Correlated source activity
- Extended source activity

Topics (cont'd)

- Incorporating priors
- Real-time beamforming
- Examples of beamformer imaging
- Conclusions

This is not intended as a guide for using SAM analysis software

Models of Cognitive Brain Activity



Which Model is Correct?

- They all are! Models and solutions reduce a very complex system (the brain) to just a few parameters
- All source models and functional imaging solutions are useful descriptors (some more useful than others – depending what is studied)
  - Design your study before selecting an analysis method
- Some models are closer to the "truth"
- None of these models, alone, are sufficient to reveal all the complexity of brain function

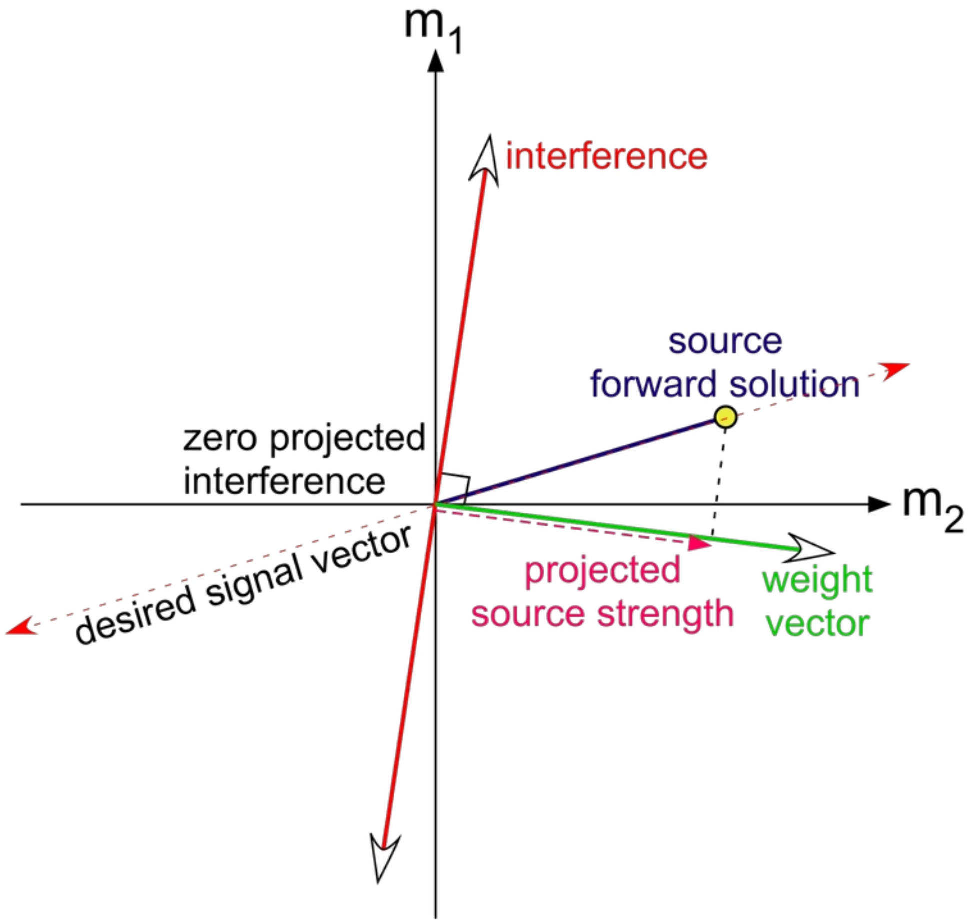
Some Limitations of MEG Source Analysis

- There is no generalized inverse solution for an arbitrary distribution of source activity from either MEG or EEG!
  - This is because there is no combination of potential or fields on the surface or outside the head that can impress a region in the interior where current is greatest
- Inverse solutions can be improved by constraints but are never unique:
  - Confining solutions to a surface and orientation (i.e., cortical layer)
  - Assuming there is only one or few discrete (dipole) sources
- Beamforming <u>is not</u> an inverse solution
- Beamforming <u>estimates</u> source activity by suppressing all signals that are not parallel (in *N*-dimensional signal space) to an *a priori* forward solution

Linearly-Constrained Minimum Variance Beamformer

- SAM is a scalar linearly-constrained minimum-variance (LCMV) beamformer (based upon the method of Gauss, 1821)
- Is *not* a simultaneous solution for all sources – it estimates source activity at a given coordinate, one point at a time
- Estimates the uncorrelated fraction of the source activity – signals from correlated sources are attenuated
- Solution is unique in 3-dimensional source space, whereas inverse solution (without constraints) is not
- Robust against all forms of interference – environmental magnetic noise, brain noise, MCG, muscle artifacts, etc.
- SAM beamformer is *spatially-selective noise reduction*

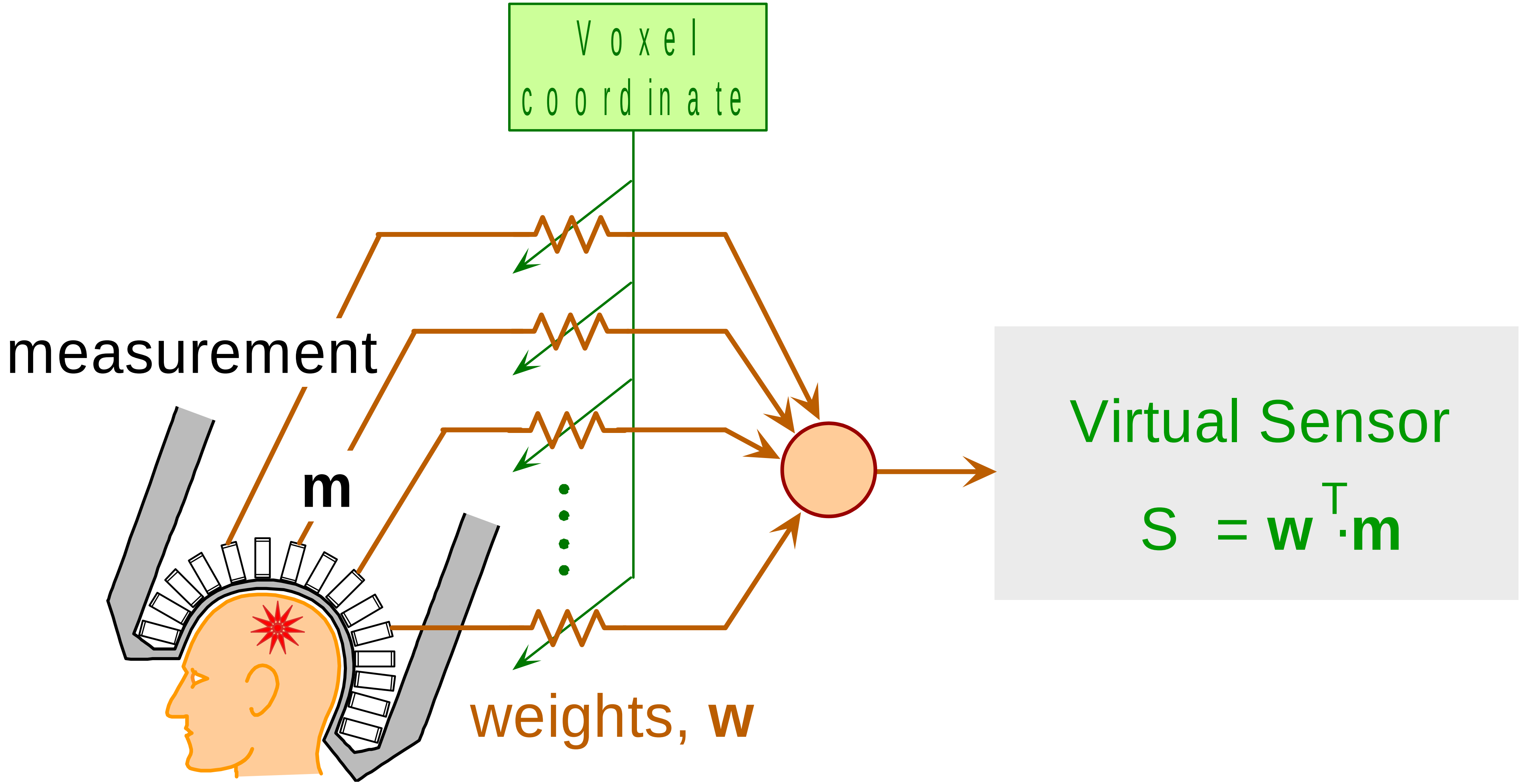
Adaptive Beamforming in a 2-D Signal Space



The MEG signal tells us which directions in signal space to cancel the interference

A forward solution – the predicted field at each sensor – tells us which direction in signal space signal should not be cancelled

Beamforming is the Weighted Linear Combination of Measurements



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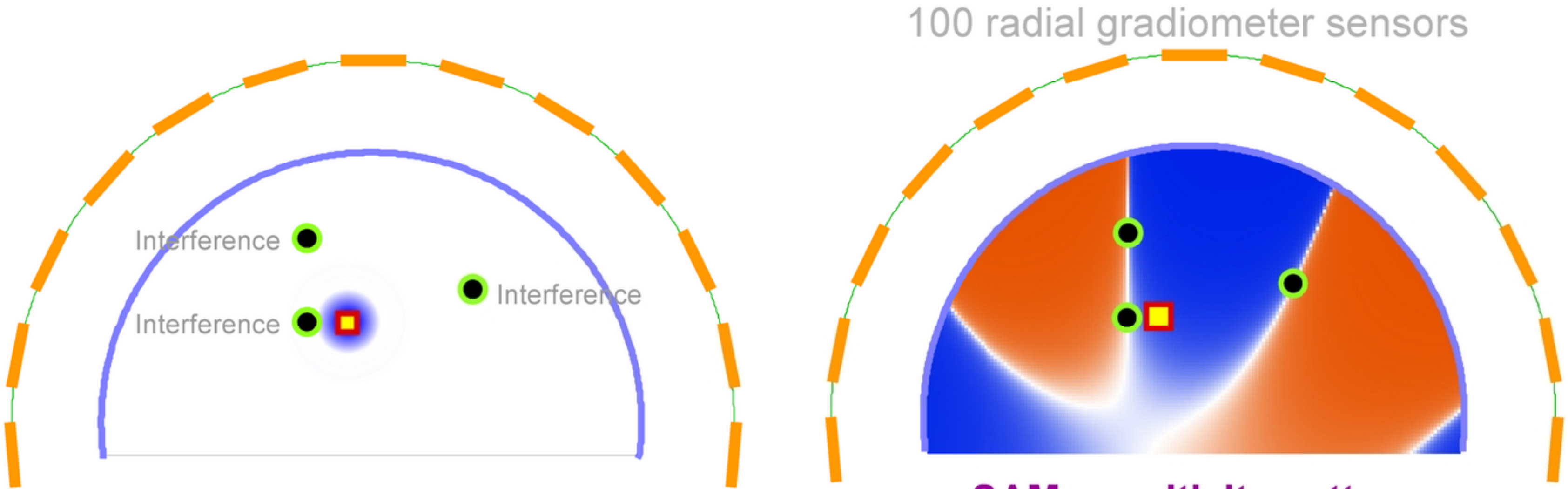
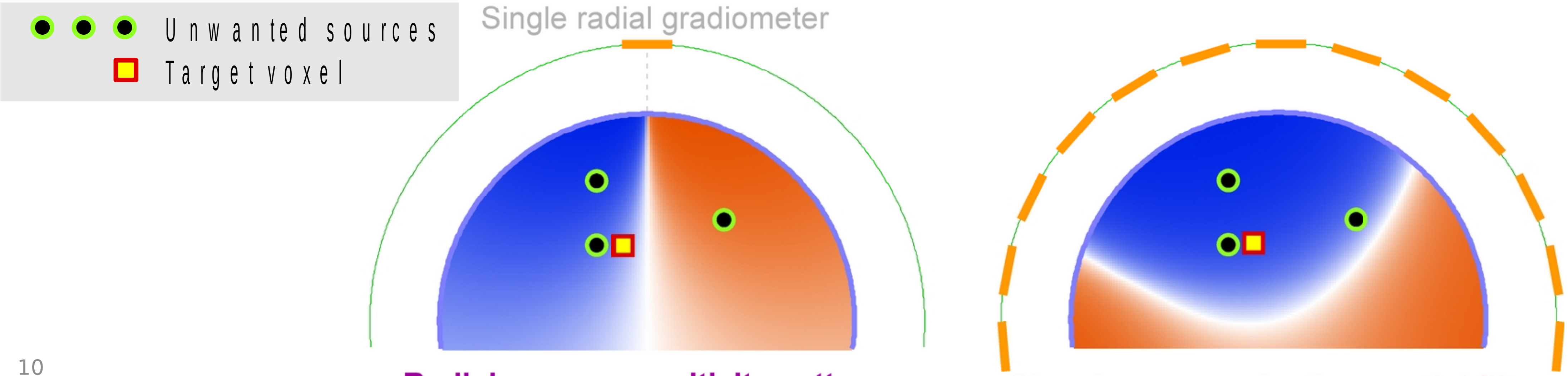
Sensitivity Patterns (dipoles perpendicular to plane)



What we would like .... but cannot have

SAM sensitivity pattern



Radial sensor sensitivity pattern

Signal space projection spatial filter

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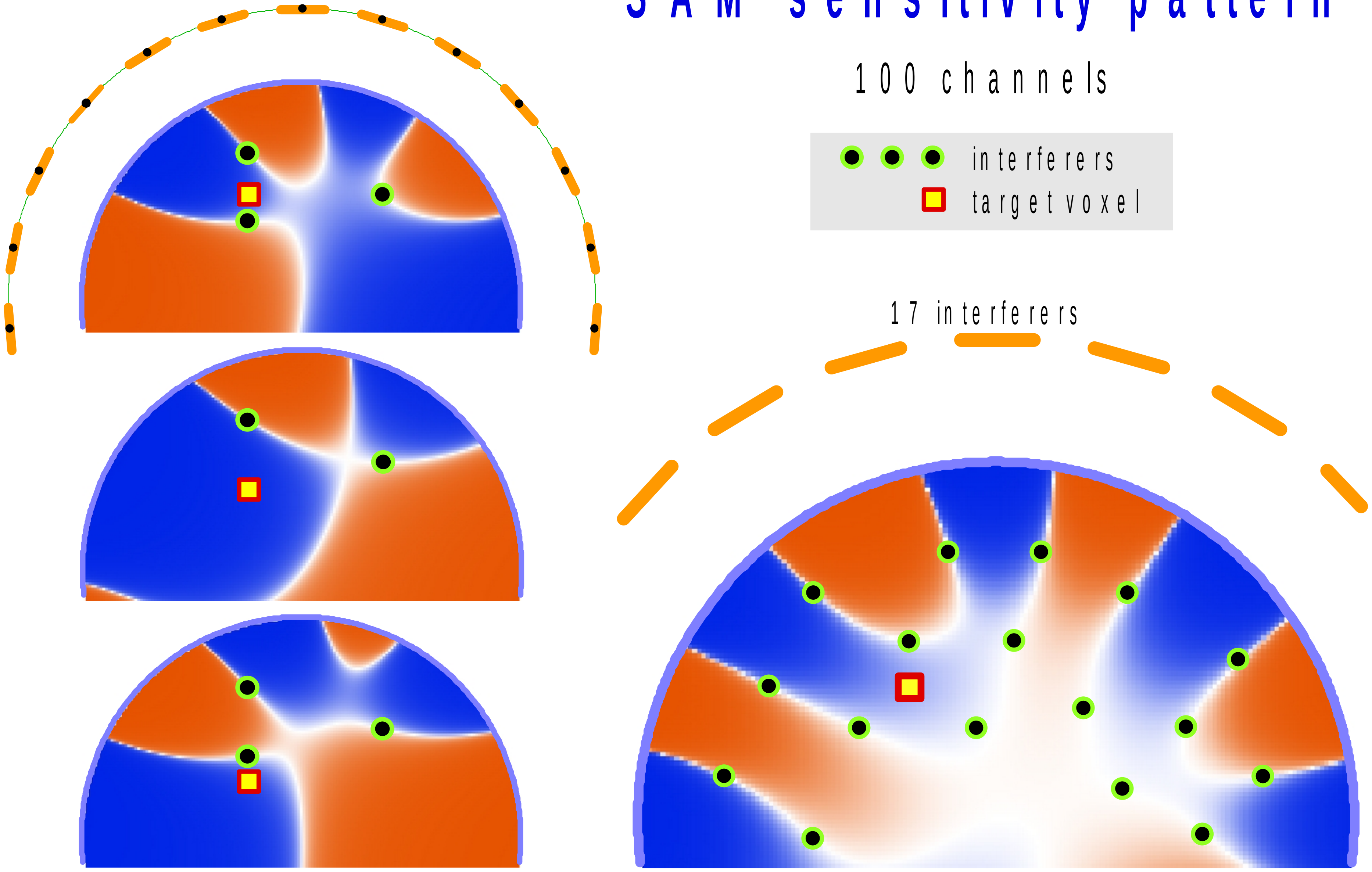
SAM sensitivity pattern

100 channels



Information about the nulls - in the covariance matrix

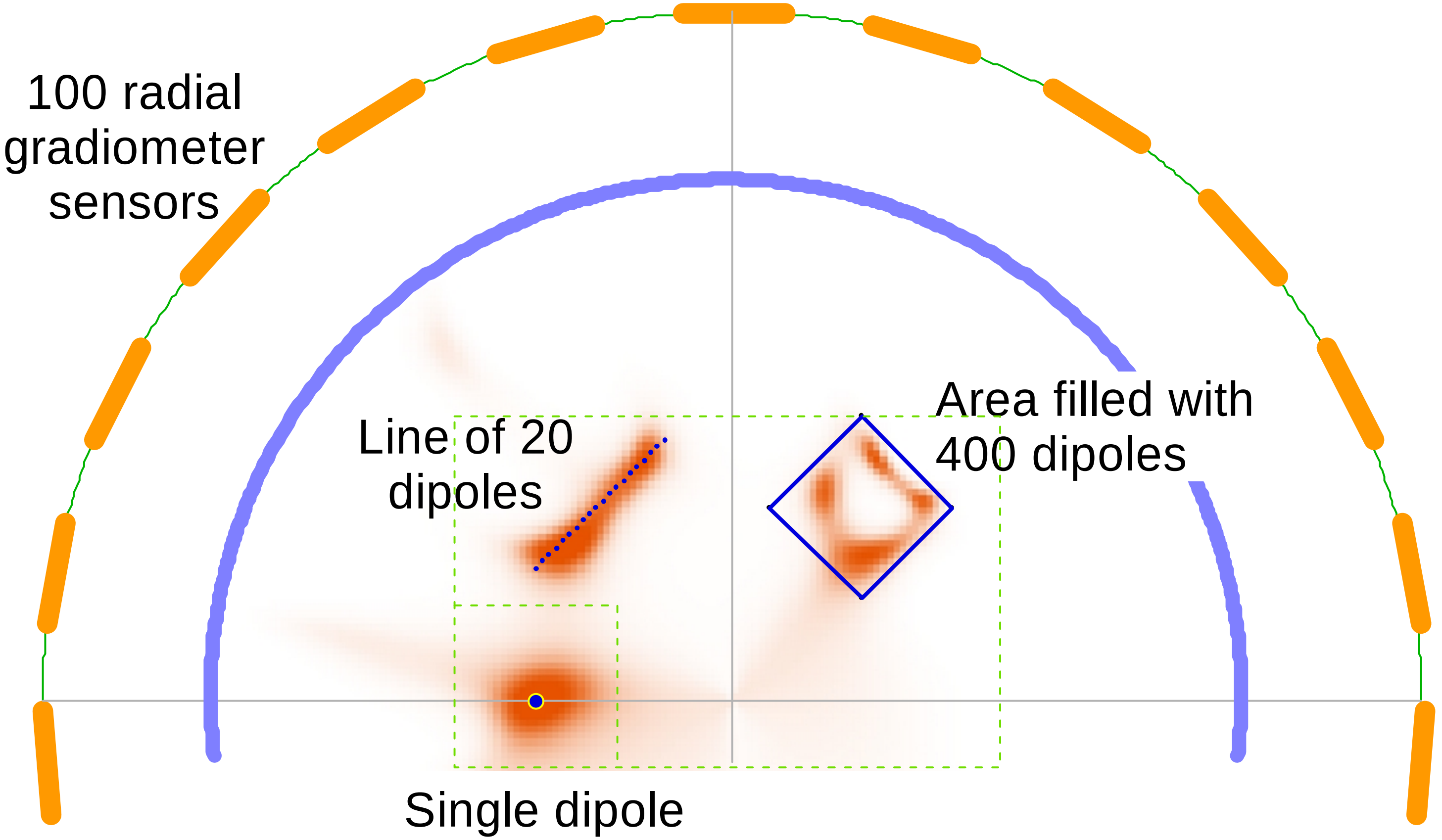
Computational Steps for Scalar LCMV Beamforming

- Given multi-sensor MEG measurements , compute covariance matrix
- For each coordinate **r** in the brain, compute *M* x 3 lead field matrix of forward solutions,
- Solve generalized eigensystem for eigenvector (source orientation) giving maximum signal-to-noise ratio (not needed for vector beamformer):
- Then the forward solution for all sensors is:
- Alternatively, use unit normal vector to the cortical surface:

Computational Steps for LCMV Beamforming (cont'd)

- Solve for beamformer coefficients:
- Estimated source dipole moment is:
- Estimated source power is:
- Projected sensor noise power is: , where is the diagonal matrix of sensor noise
- Beamformer output signal-to-noise is:

Beamformer Imaging of Distributed Sources



Brain noise: 1000 dipoles
Random position and orientation
q = 0.5 to 3 nA.m

White noise: 3 fT rms/√Hz
BW = 15 Hz

Uncorrelated dipoles: Single: 30 nA.m
Line: 15 nA.m
Area: 10 nA.m

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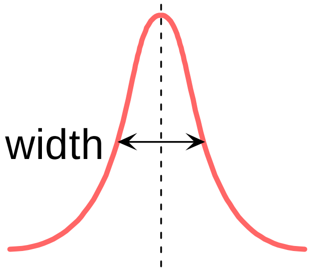
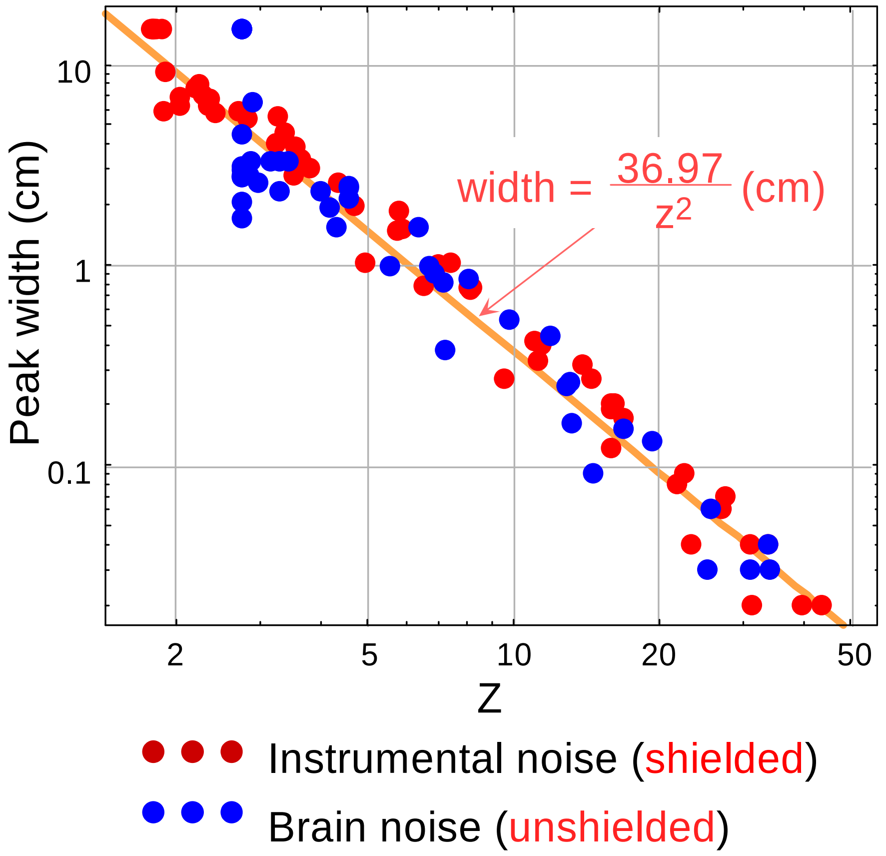
Beamformer Spatial Selectivity Increases with S/N

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





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

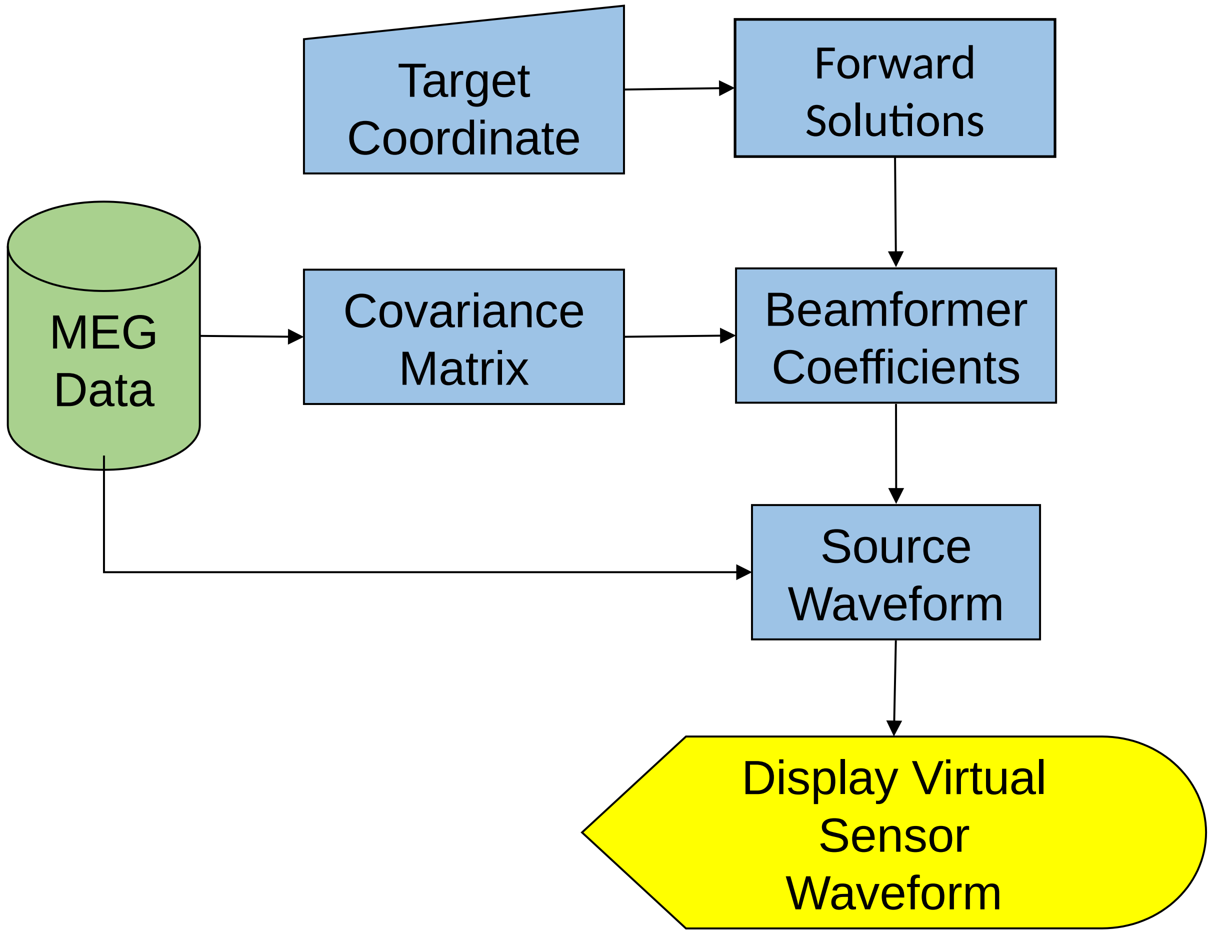
Distances from the center: -2, -1, 1, 2, 3, 4, 5, 6, 7, 8, 9 cm

Noise collected with: 143 and 151 radial gradiometer based systems

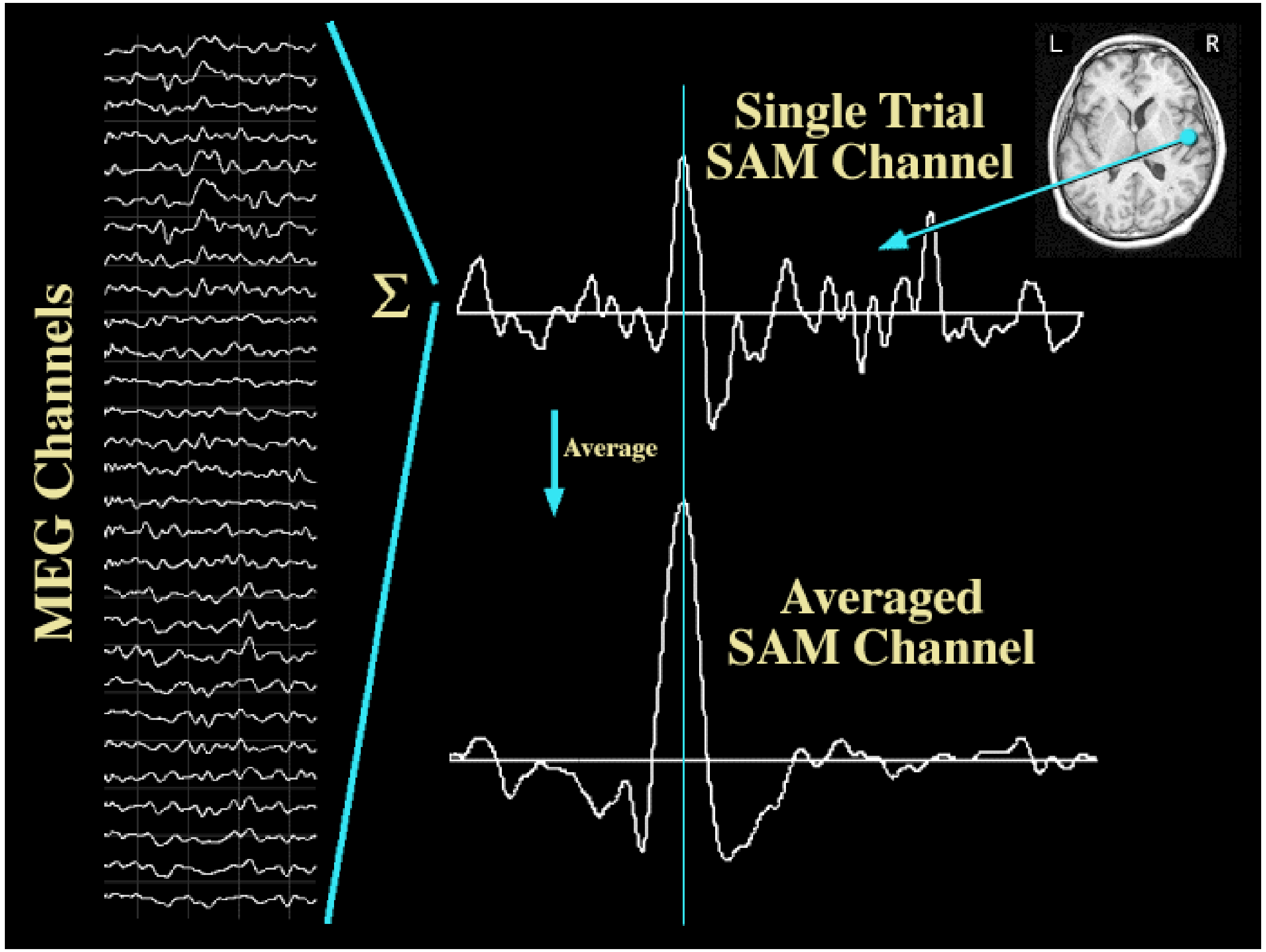
Virtual Sensor Waveforms

- Virtual sensor is a weighted linear combination of all MEG sensor
- Weights are computed by SAM to attenuate all signal subject to dipole source model
- Weights are not dependent upon whether selected source is active
- If source is active: SAM estimates source waveform (dipole moment)
- If source is inactive: only sensor noise and “leakage” appears in source waveform

Beamformer Virtual Sensor Flowchart



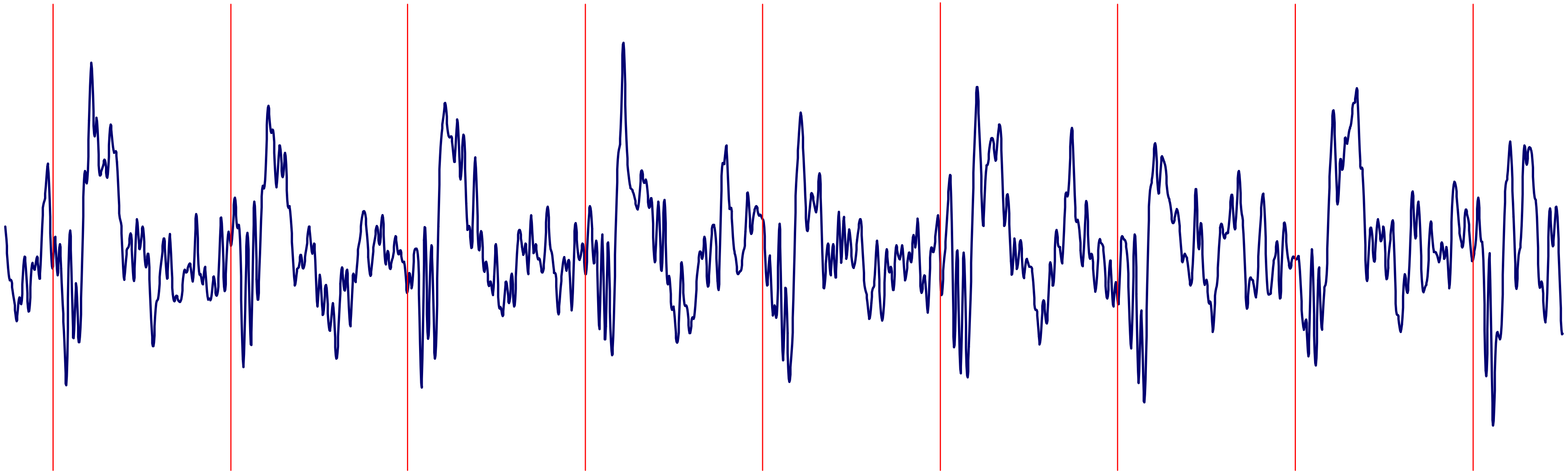
Beamformer Virtual Sensor Improves AEF S/N



By the weighted sum of all channels, the beamformer can achieve a high signal-to-noise "virtual sensor" response for single trial data

Single Trial Somatosensory Evoked Response

Continuous recording during median nerve electrical stimulation



DC – 300 Hz
300 ms ISI

Correlated Sources: A Crucial Limitation of Beamforming

- The single-source LCMV beamformer is ”blind” to the correlated fraction of source activity
- The signal-space vector of correlated sources is not the same as each of its components
- The solution is to solve for the beamformer coefficients for all sources, simultaneously – an *N*-source beamformer
- Think of this as a “null beamformer” where the solution for each source nulls all remaining sources instead of merely minimizing them
- This simultaneous beamformer works well when *N* is small

Do not use this method for generating images!

What About Beamforming Extended Sources?

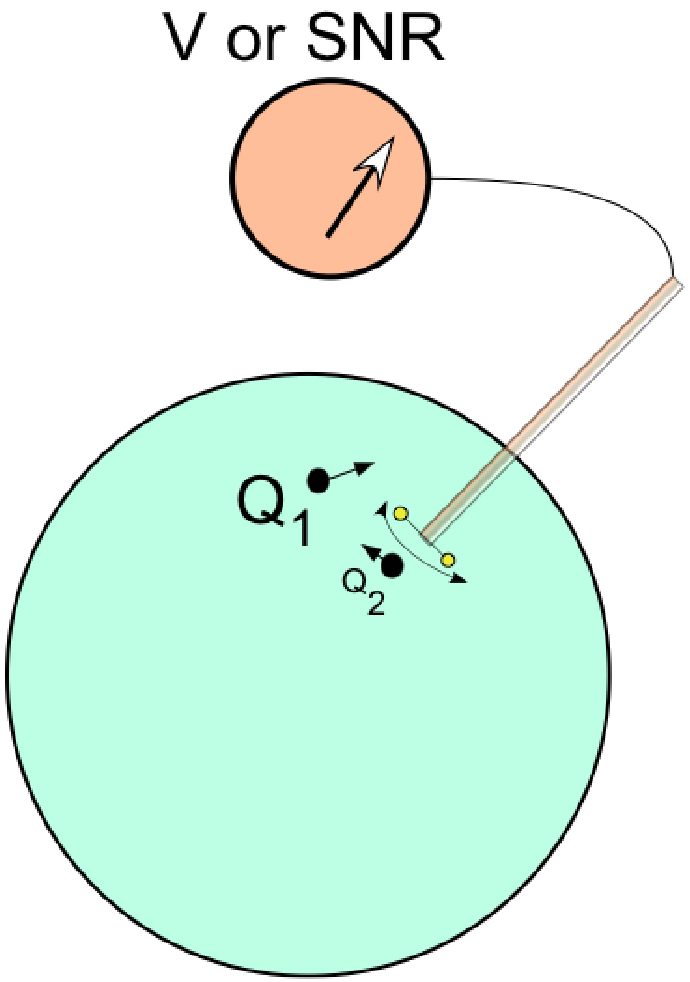
- Beamformer requires an accurate forward solution
- Forward solution for an extended source or “patch” of cortex is not the same as for a point current dipole
- To compute the forward solution for a patch of cortex or ROI
  1. Model the patch as an array of N point current dipoles
  2. Compute the N x M forward solution matrix
  3. Compute the singular value decomposition (SVD) of the solution matrix
  4. Solve for the solution vector accounting for, say, 90% of the predicted fields
  5. The solution vector represents the forward solution for the extended source

Solving for Moment Vector without Priors

EEG analogy to search for optimal moment vector

Rotate electrode pair for maximum voltage or maximum SNR

Search for moment vector of Q_2 may be biased by the presence of stronger dipole Q_1



(See slide 12 for generalized eigensystem solution for moment vector)

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Incorporating Prior Knowledge

- Each current dipole source has a position and moment vector orientation
- Without priors, the moment vector can be estimated by the generalized eigensystem solution
- Unit normal vector to the cortical surface is a surrogate for the current dipole moment vector
- Unit normal vector eliminates polarity ambiguity
- Use the subject's segmented cortical surface (e.g., from Freesurfer) to find the moment vector for any position (surface vertex)

Caution!: This requires highly accurate coregistration!

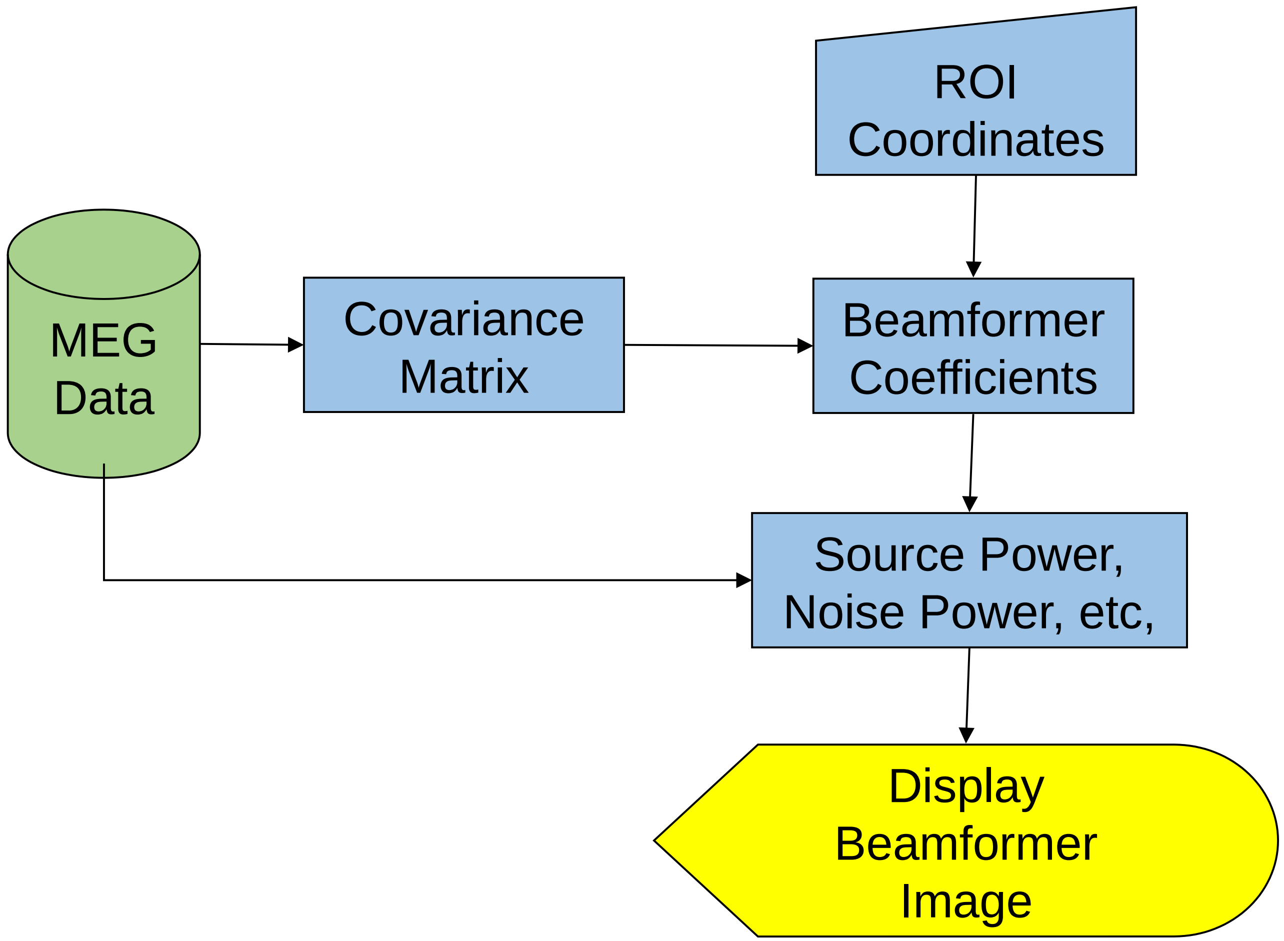
Real-Time Beamforming

- Covariance of MEG is not stationary!
- Sequential regression method computes an [unscaled] inverse correlation matrix as each new sample is acquired
- Beamformer output can be updated sample-by-sample

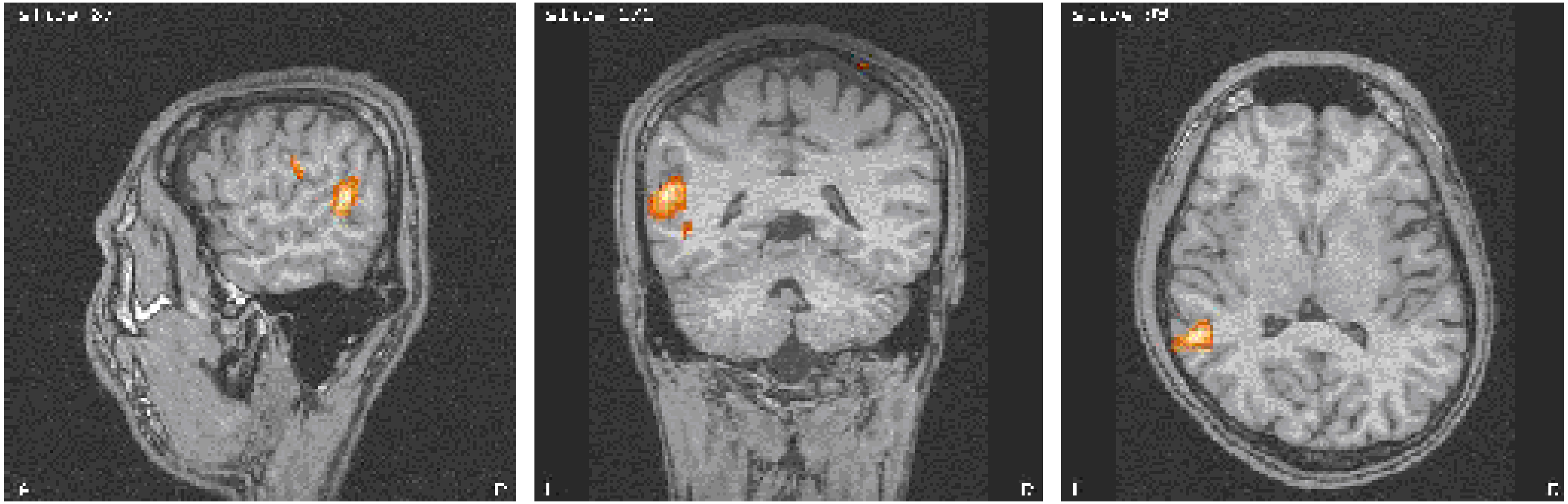
where

- Beamformer coefficients can be computed using for any source current dipole using its forward solution and the real-time inverse covariance for each sample *k*
- Since is an unscaled inverse covariance, the beamformer output will be unscaled
- Beamformer output S/N will be unchanged by the scale factor

Beamformer Imaging Flowchart



Example: Imaging Auditory Hallucinations



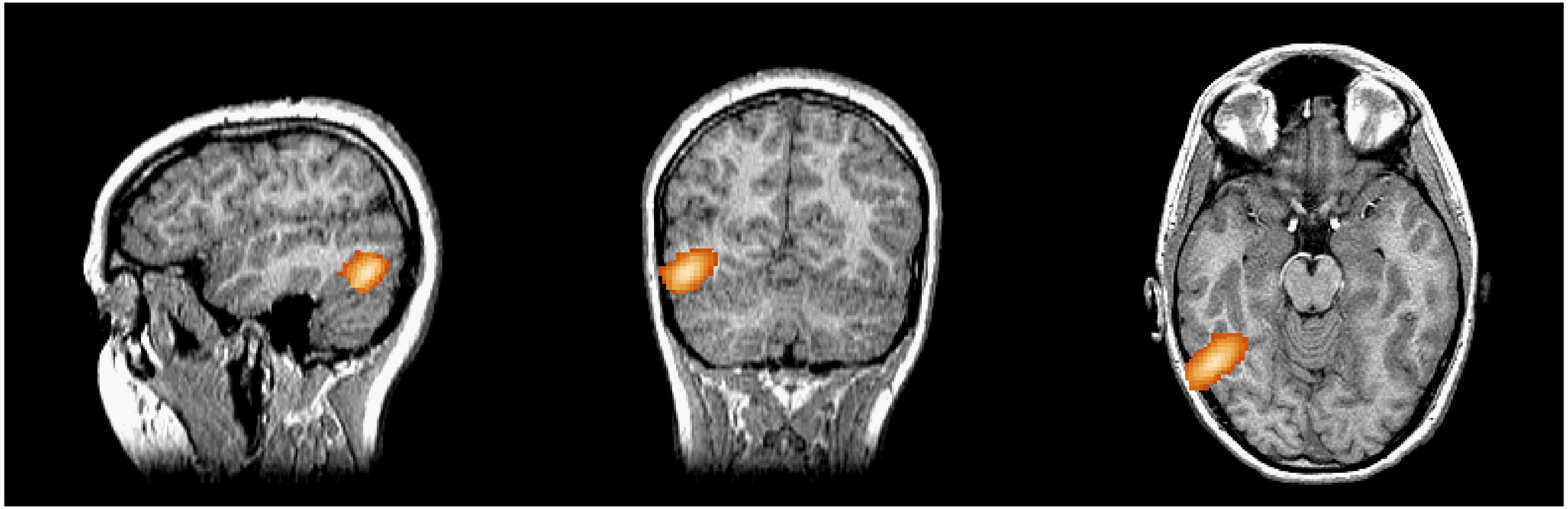
SAM differential statistical image

Bootstrap method (jack-knife)

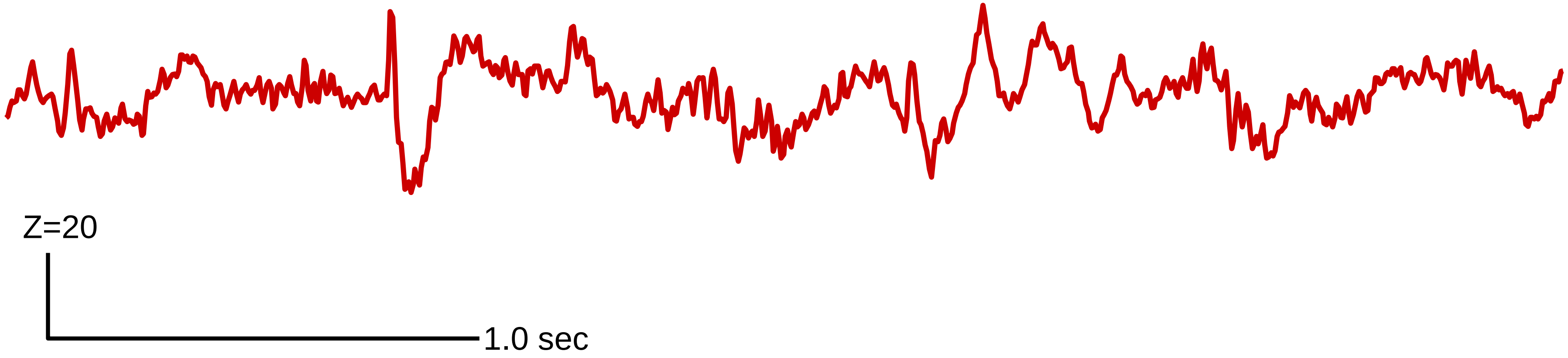
Values $p < 10^{-3}$ shown

Scaled as: $-\log_{10}p$

Example: Imaging Interictal Spikes



Corresponding virtual sensor waveform at local maximum in image:



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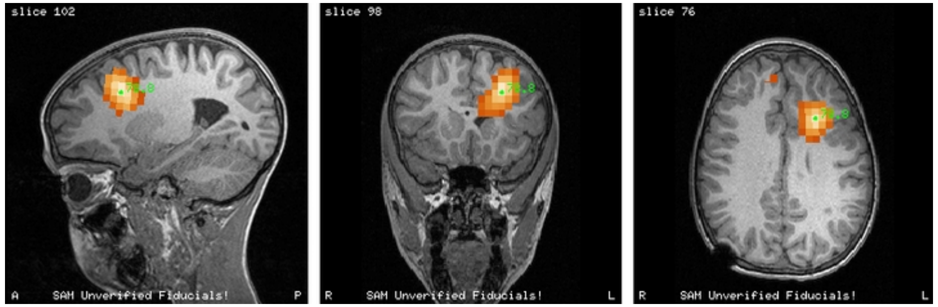
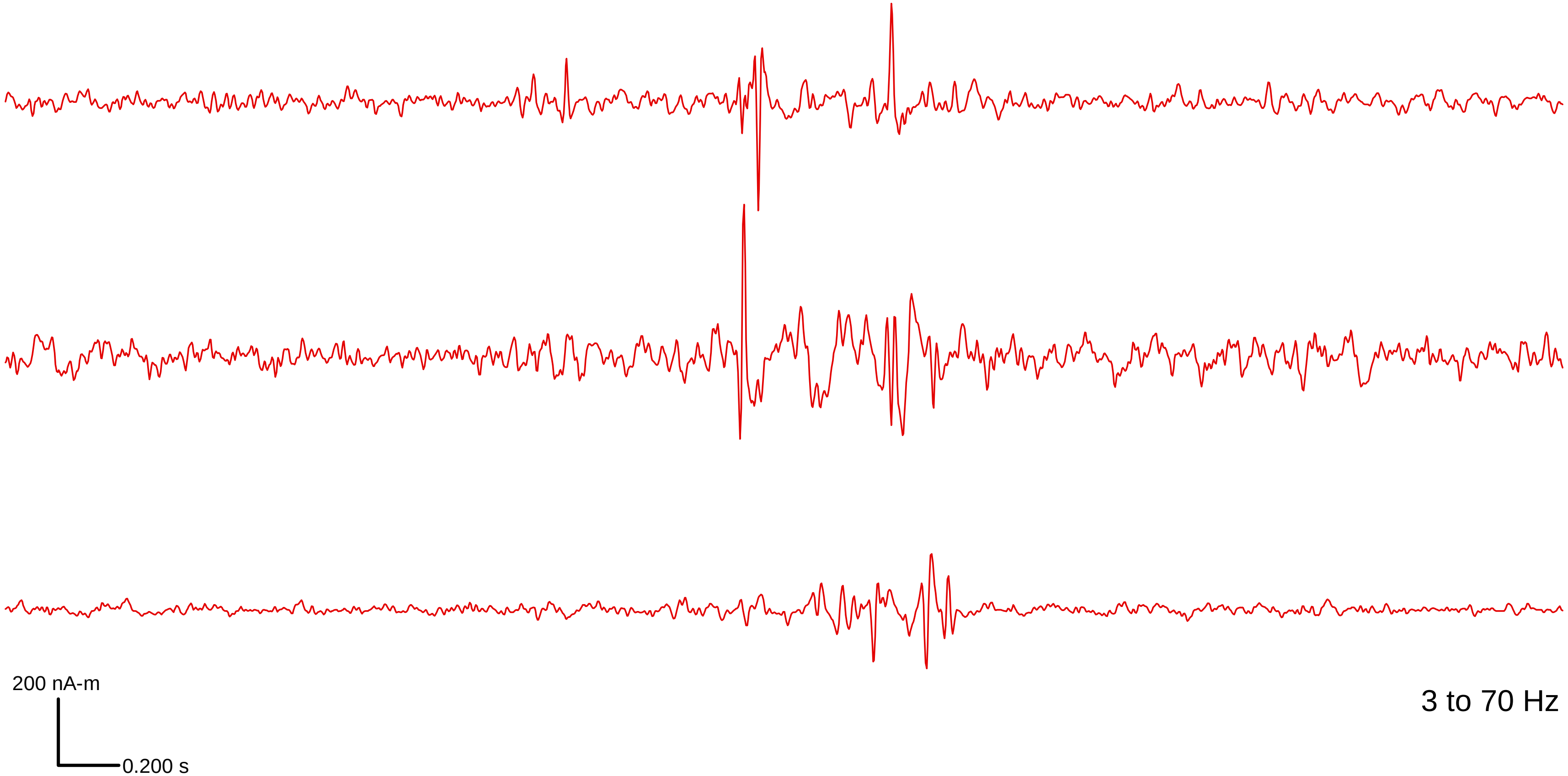
Example: Interictal Spikes with Vagus Nerve Stimulator





Conclusions

- Present LCMV beamformer analysis has proved useful for functional imaging of sensorimotor, cognitive, & pathological (epileptic) brain activity
- Source waveforms and functionally specific images are generated by transforming beamformed virtual sensor time series using mapping functions:
  - Difference in source power, S/N, FFT, excess kurtosis, rank vector entropy, mutual information, symbolic transfer entropy, etc
- The latter, non-linear dynamical transforms, show connectivity
- New SAM analyses will be made available for efficient imaging of spontaneous, phase-locked & time-locked event-related brain activity

Any Questions?