University of Oxford
Institute of Biomedical Engineering

A Fast Solution to a Robust Minimum Variance Beamformer and its Application to Simultaneous MEG and Local Field Potential Data

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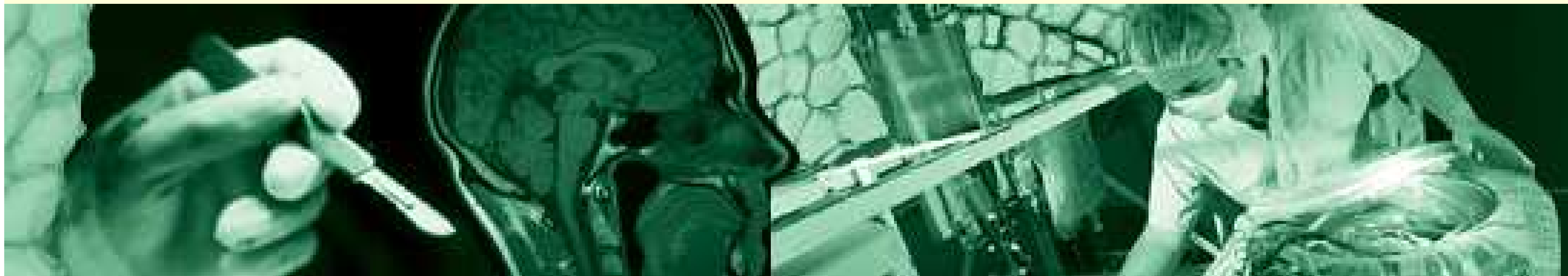

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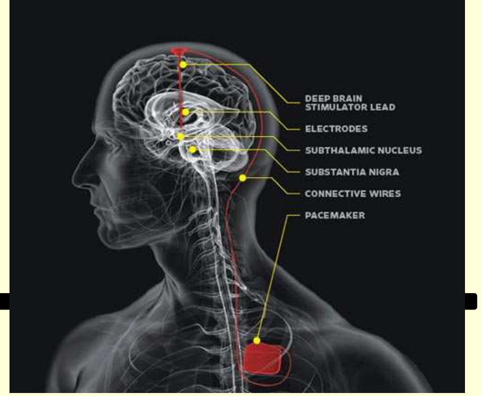
MEG and DBS



DBS (Deep brain stimulation):

Electrodes implanted into brain and stimulated with a.c. electrical signal. Used in treatment of disorders of nervous system, eg pain, Parkinson's disease, Multiple sclerosis

MEG (Magnetoencephalography):

Forms image of brain electrical, magnetic sources from external magnetometers through beamforming

Difficulties from DBS:

Very small signals (deep sources)

Interference from the burr hole in the skull :

introduce a null here in beamformer

Paper Contributions

(i) Novel beamformer:

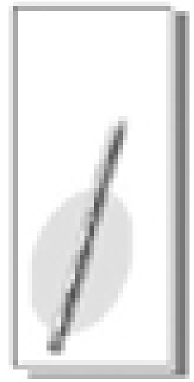
- (i) Exploits correlation while stimulation is 'ON' to improve beamforming parameters
- (ii) Stimulation ON: Signal at frequency between 50 and 130Hz at electrode locations, detect correlated signal in MEG sensors

- Show in simulation that this reduces errors when stimulation is off

- Demonstrate using clinical data from a pain patient with DBS electrodes in the hypothalmus

Techniques

- Assume LFP data recorded from small elliptical volume around each implanted electrode



- Include null at the skull burr hole
- Use robust minimum variance beamformer (RMVB) to optimise source field estimation from magnetometer measurements (Lorenz et al, 2005)

Forward model

For MEG measurement y(t) and recorded LFP data s(t) (from electrodes)

$$\mathbf{y}(t) = \int_{\mathbf{a}_s \in \Omega} \mathbf{a}_s \mathbf{s}(t-\tau) + \mathbf{A}_n \mathbf{S}_n(t)^T + \mathbf{n}(t)$$

- a_s : lead-field vector corresponding to the location of LFP
- A_n : matrix containing the leadfield vector of interference l(burr hole) locations
- Ω : small elliptical volume over which the LFP data is recorded
- τ : delay between LFP and MEG data
- n(t): random additive noise

$$\mathbf{y}(t) = \int_{\mathbf{a}_s \in \Omega} \mathbf{a}_s \mathbf{s}(t-\tau) + \mathbf{A}_n \mathbf{S}_n(t)^T + \mathbf{n}(t)$$

Problem Formulation

- Objective: to find a linear filter **w** which will estimate the LFP signals from MEG data in the ‘on’ condition.

$$s(t-\tau) = w^T y(t)$$

To find best **w** use optimisation: Penalty factor

$$\underset{\mathbf{w},\tau}{\operatorname{argmin}}\ E\{\|\mathbf{w}^T\mathbf{y}(t) - \alpha\mathbf{s}(t-\tau)\|\}$$

$$s.t.\ \mathbf{w}^T\mathbf{a}_s = 1,\ \forall \mathbf{a}_s \in \Omega,\ \mathbf{w}^T\mathbf{A}_n = \mathbf{0}$$

Source vector (LFP)

Burr hole

And $$\underset{\mathbf{w},\tau}{\operatorname{argmin}}\ E\{\|\mathbf{w}^T\mathbf{y}(t) - \alpha\mathbf{s}(t-\tau)\|\}$$

$$= \underset{\mathbf{w}}{\operatorname{argmax}}\ \mathbf{w}^T\mathbf{R}_y\mathbf{w} - 2\alpha\mathbf{w}^T\mathbf{r}_{ys}$$

R_y : covariance matrix of y

r_{ys} : cross correlatation between y and s.

Lagrange Multiplier Solution of the Problem

- The solution of w given by:

$$\mathbf{w} = (\mathbf{R}_y + \lambda \mathbf{Q})^{-1}(\alpha \mathbf{r}_{ys} - \lambda \mathbf{e} - \frac{1}{2}\mathbf{A}_n \boldsymbol{\mu})$$

- In which:

$$\boldsymbol{\mu} = 2\left(\mathbf{A}_n^T(\mathbf{R}_y + \lambda \mathbf{Q})^{-1}\mathbf{A}_n\right)^{-1}\mathbf{A}_n^T(\mathbf{R}_y + \lambda \mathbf{Q})^{-1}(\alpha \mathbf{r}_{ys} - \lambda \mathbf{e})$$

- Diagonalise using the secular equation

$$\sum\left(\frac{\bar{\kappa}_i \gamma_i^{\frac{1}{2}} + \breve{e}_i}{1 + \lambda \gamma_i}\right)^2 = 1 + \breve{\mathbf{e}}^T \breve{\mathbf{e}}$$

- Where e is the dimension of the LFP ellipse,λ is the largest eignevalue and $\bar{\boldsymbol{\kappa}} = \mathbf{V}^T \mathbf{R}_y^{-\frac{1}{2}} \boldsymbol{\kappa}$, $\bar{\mathrm{e}} = \mathbf{V}^T \mathbf{R}_y^{-\frac{1}{2}} \mathbf{e}$ and $\breve{e} = \mathbf{Q}^{-\frac{1}{2}} \mathbf{e}$.

- Note this is a simpler solution than in other literature for ellipsoidal source.

Algorithm for implementation of the method

Algorithm 1 Solution of $\mathbf{w}$ for problem stated in (4)

set $\mathbf{Q} = \mathbf{E}\mathbf{E}^T - \mathbf{e}\mathbf{e}^T$
compute SVD of $\mathbf{R} \rightarrow \mathbf{S}\mathbf{V}\mathbf{S}^T$
set $\mathbf{R}^{-\frac{1}{2}} = \mathbf{S}\mathbf{V}^{-\frac{1}{2}}$
compute SVD of $\mathbf{R}^{-\frac{1}{2}}\mathbf{Q}(\mathbf{R}^{-\frac{1}{2}})^T \rightarrow \mathbf{V}\mathbf{\Gamma}\mathbf{V}^T$
initialise λ such that $\lambda > -\frac{1}{\gamma_N}$
while λ is not converged **do**
  update $\bar{\boldsymbol{\kappa}} = \mathbf{V}^T\mathbf{R}_y^{-\frac{1}{2}}(\alpha\mathbf{r}_{ys} - \frac{1}{2}\mathbf{A}_n\boldsymbol{\mu})$
  update λ using Newton technique based on (12)
  update $\boldsymbol{\mu}$ using equation (7)
end while
calculate the optimal value of $\mathbf{w}$ using (6).

Validation: Simulation

Spherical head model:

One deep source, one at 'burr hole'

Gaussian white noise added.

The time courses of source: sine wave in 'off'

cosine wave in 'on'

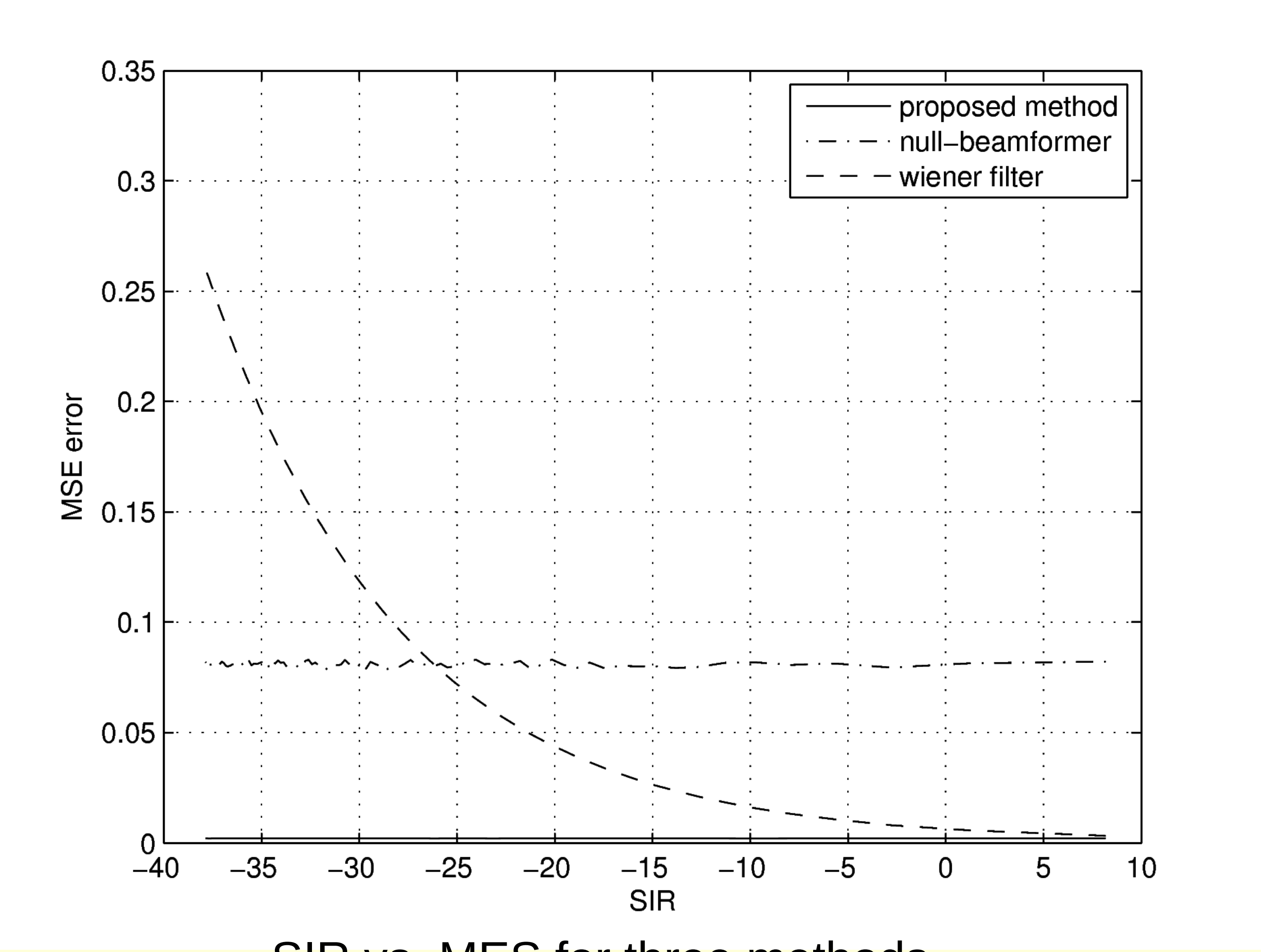
Compare new beamformer with

(i) Wiener filter: $\mathbf{w} = \mathbf{R}_y^{-1}\mathbf{r}_{ys}$

(ii) Filter with burr hole null but no correlation term:

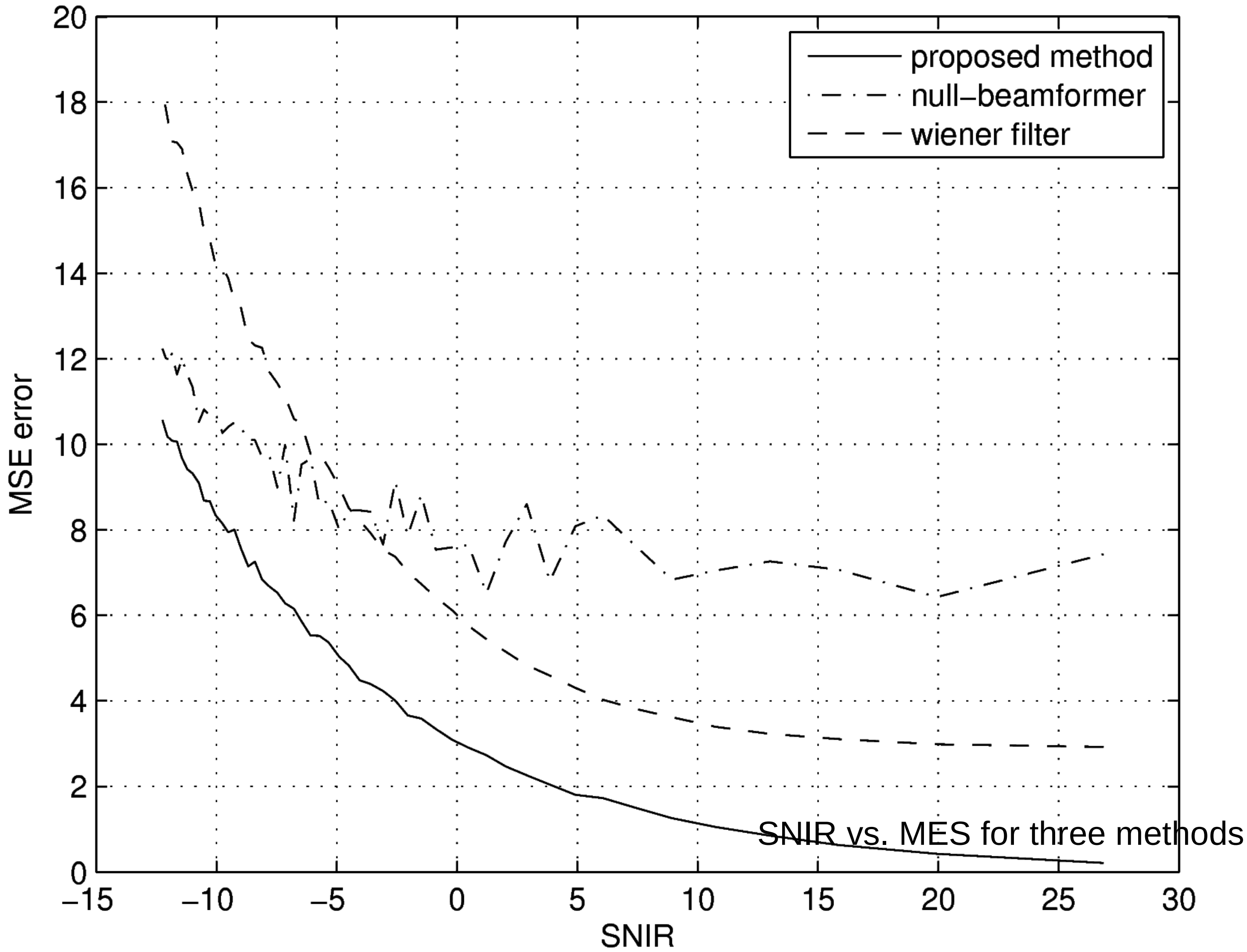
$\mathbf{w} = \mathbf{R}_y^{-1}\tilde{\mathbf{A}}(\tilde{\mathbf{A}}^T\mathbf{R}_y^{-1}\tilde{\mathbf{A}})^{-1}\mathbf{c}$ where $\tilde{\mathbf{A}} = [\mathbf{a}_s \ \mathbf{A}_n]$ and $\mathbf{c} = [1 \ 0]$.

Simulation Results



SIR vs. MES for three methods

Simulation Results



SNIR vs. MES for three methods

Clinical data

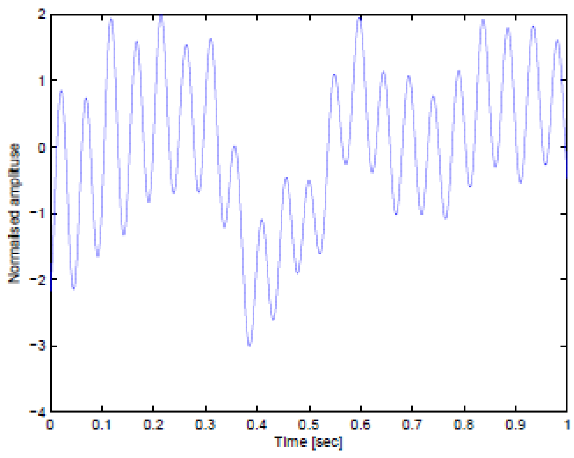
Patient: 40 year old female with chronic whole body pain. Stimulated at 50Hz and 5V in periaqueductal area (PAG) – provided pain relief

Platinum-irradium surfaces on electrodes, 1.27mm diameter, contact separation of 2mm

MR scan prior to DBS electrodes inserted.

Registered to MEG image using Polhemus Fastrack using left and right ear nasion positions

- (a) Recorded LFP data in ‘off’ condition



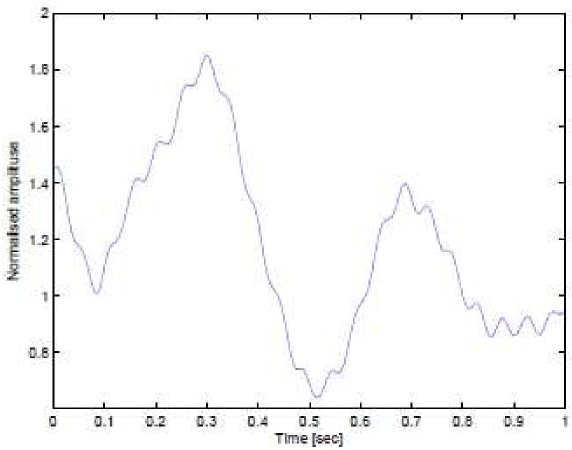
(a)

Reconstructed data

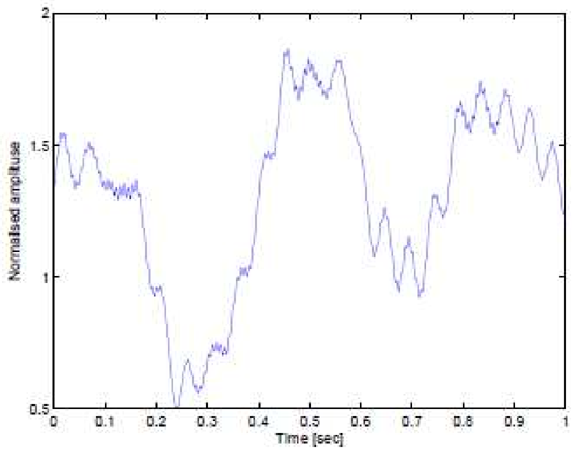
(b) Wiener filter

(c) Nulled for burr hole

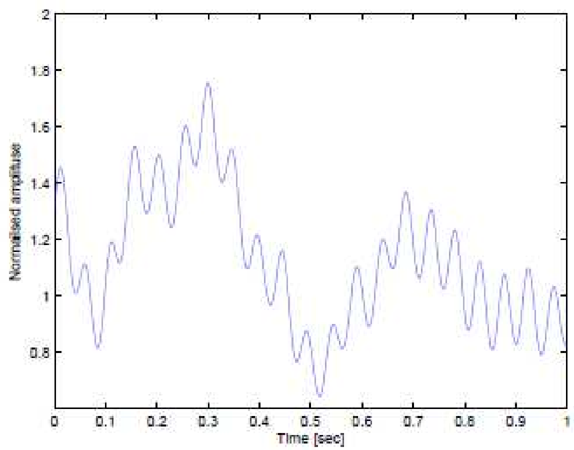
(d) with null and using ‘ON’ correlation information.



(b)



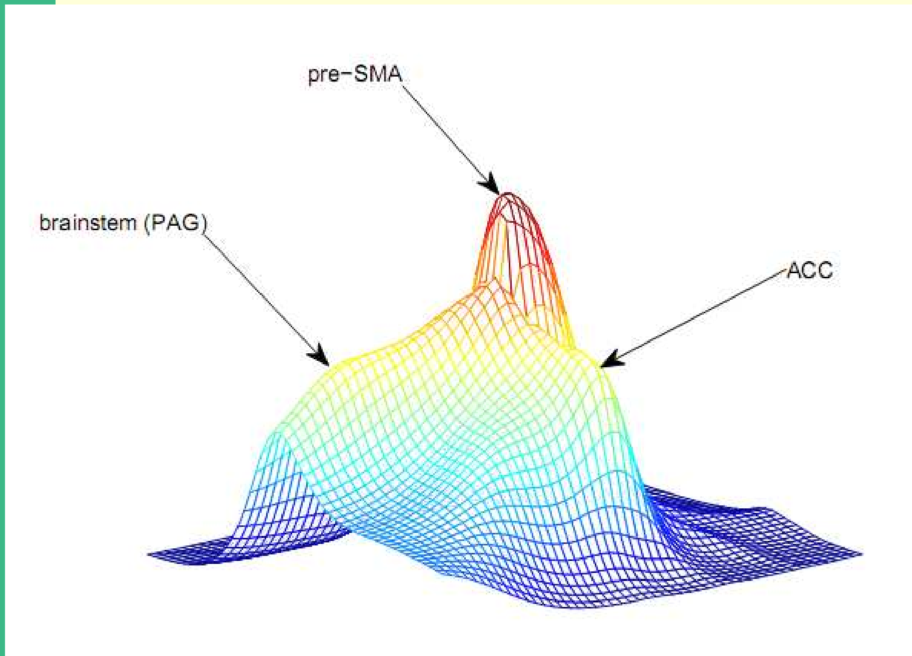
(c)



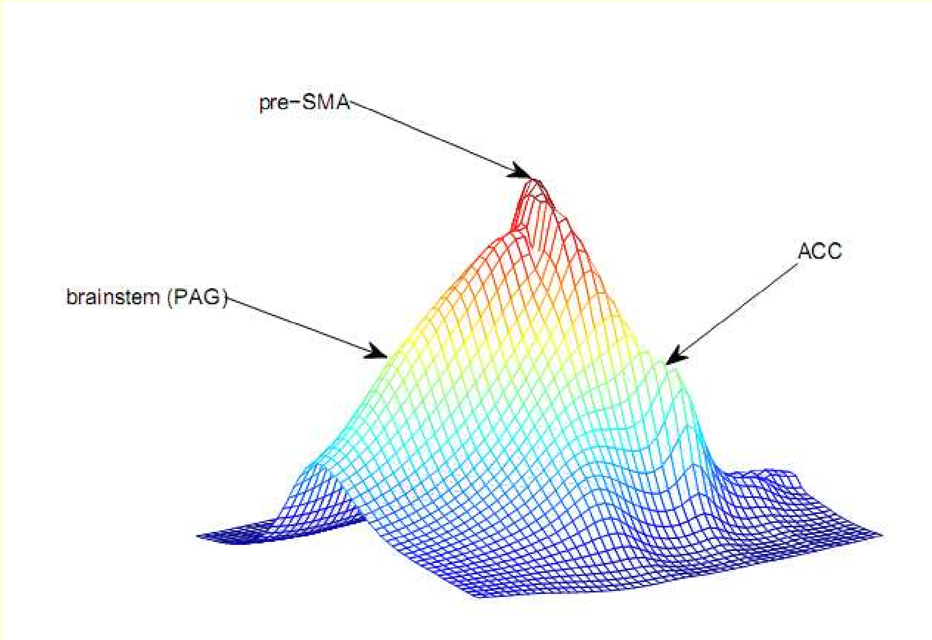
(d)

Sources in brain

'OFF' condition



'ON' condition



CONCLUSIONS

- Improved results from using correlation.
- Estimating the LFP signal from an elliptical volume rather than a point also offered more accurate estimation.
- Demonstrated on simulation and clinical data from DBS patient.