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Temporal Difference as Signal Feature Extractor

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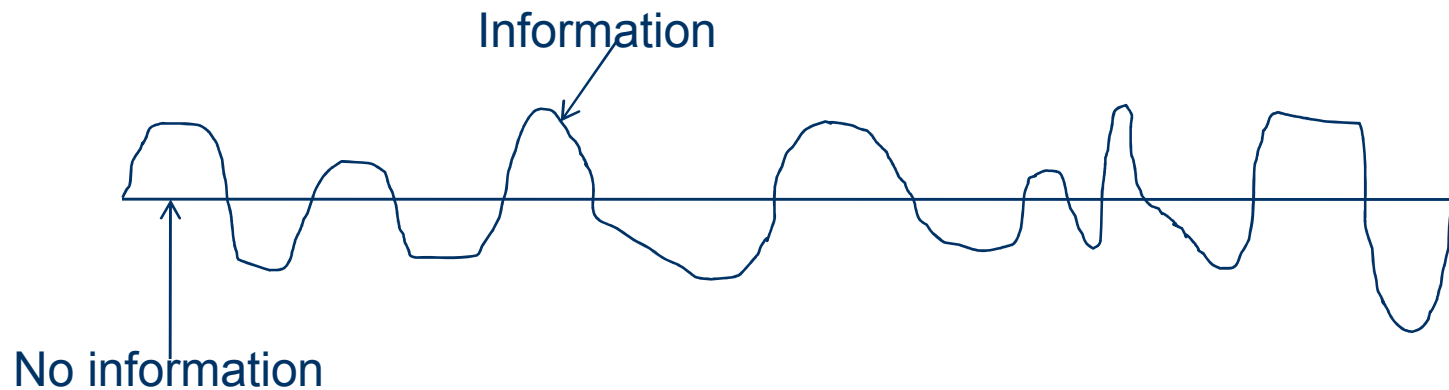
What is a signal?

- A piecewise continuous function $s : \{0\} \cup \mathbb{R}^+ \rightarrow \mathbb{R}$.
- Bounded.
- Square integrable.
- Smoothly traceable, that is, if A is a subset of any compact set, such that $s'(t)$ does not exist for any t in A , then A must be finite.

The last condition is necessary, because otherwise analog EEG or ECG cannot be recorded on a piece of paper.

Information Modeling in a Signal

$\frac{d^2 s(t)}{dt^2} ds(t)$ is the amount of work done to embed information in the signal = the information content of the signal at t .



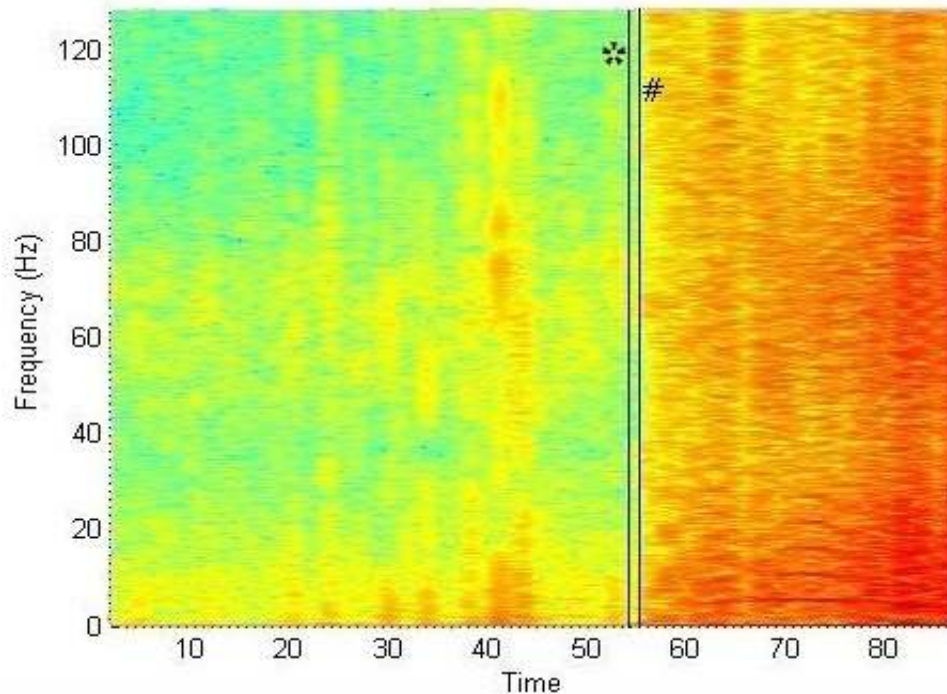
Communication Signals vs. Biomedical Signals

- Communication signals are generated, modulated, propagated, detected/estimated, demodulated, denoised, amplified etc.
- Biomedical signals are detected/estimated, denoised, amplified, visually examined (visual inspection is the gold standard), etc.
- Any automated system for biomedical signal processing must emphasize on geometric pattern recognition.

Seizure Detection

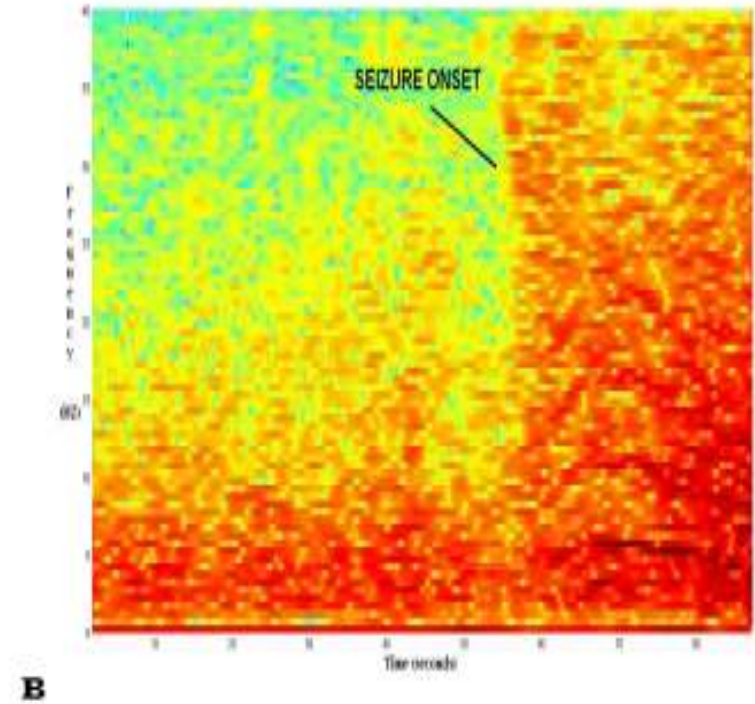
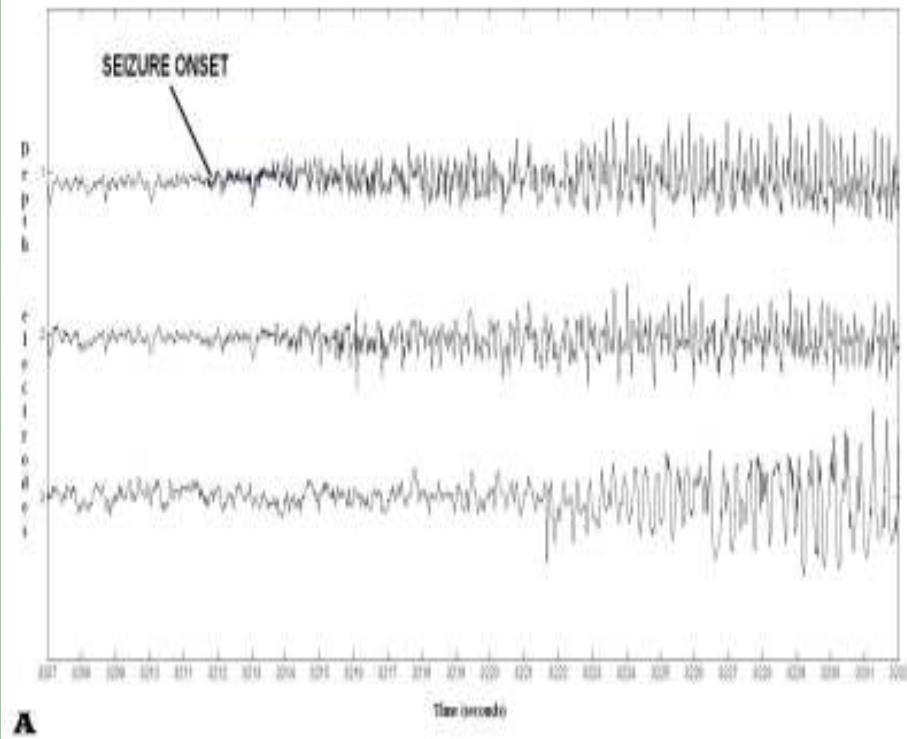
$$E_S(s(t)) = \frac{d}{dt} \left(\frac{d^2 s(t)}{dt^2} s(t) \right)$$

Majumdar, 2013



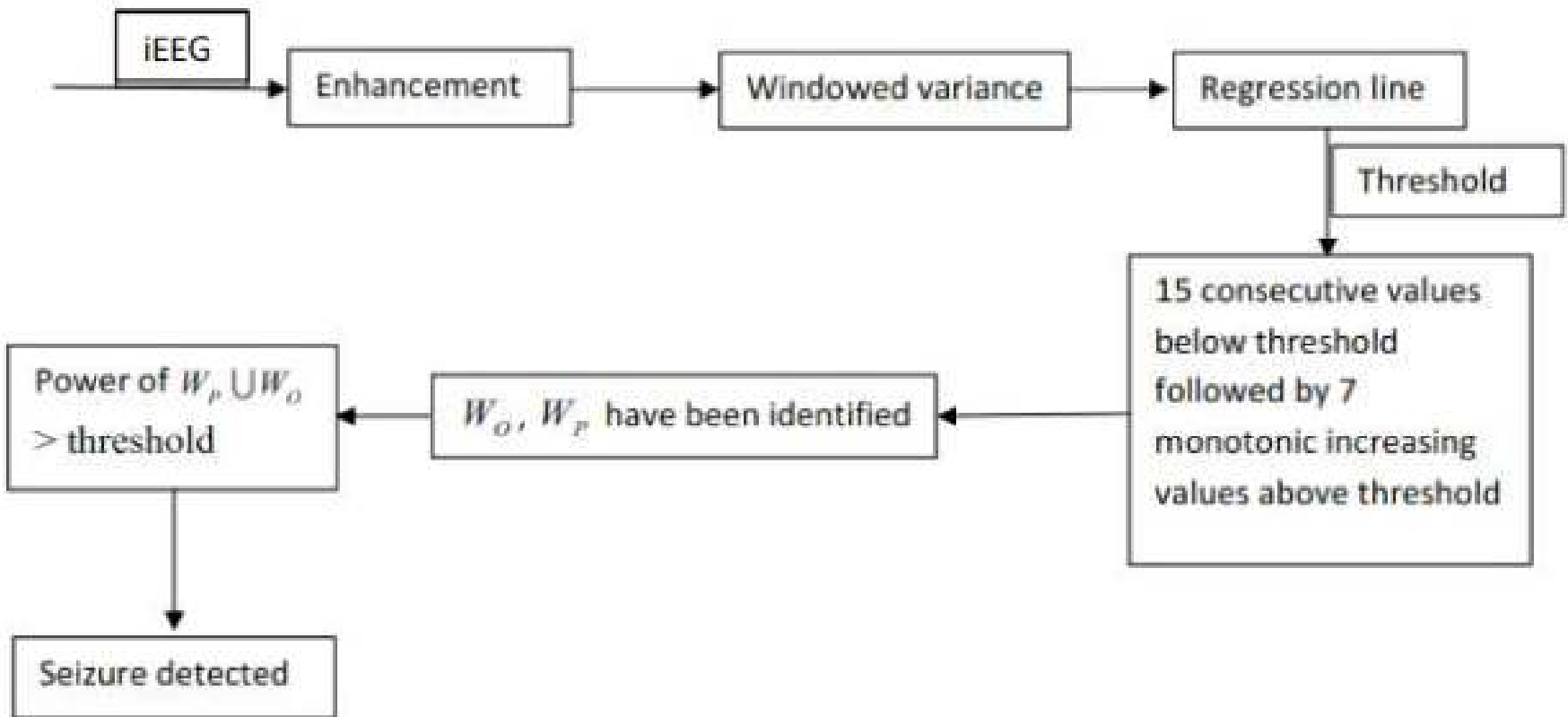
Power spectrum after applying the operator E_S on the raw ECoG signal. * indicates epileptologist identified seizure onset. # indicates automatically detected onset. Malali et al. 2014

Power Spectrum on Raw ECoG



Malali et al. 2014.

Onset Detection Algorithm



Motivation for E_s

$$E_s(s(t)) = \frac{d}{dt} \left(\frac{d^2 s(t)}{dt^2} s(t) \right) = \frac{d}{dt} (Fs)$$

When F does not depend on s , the rightmost expression gives the 'information power' of the signal s .

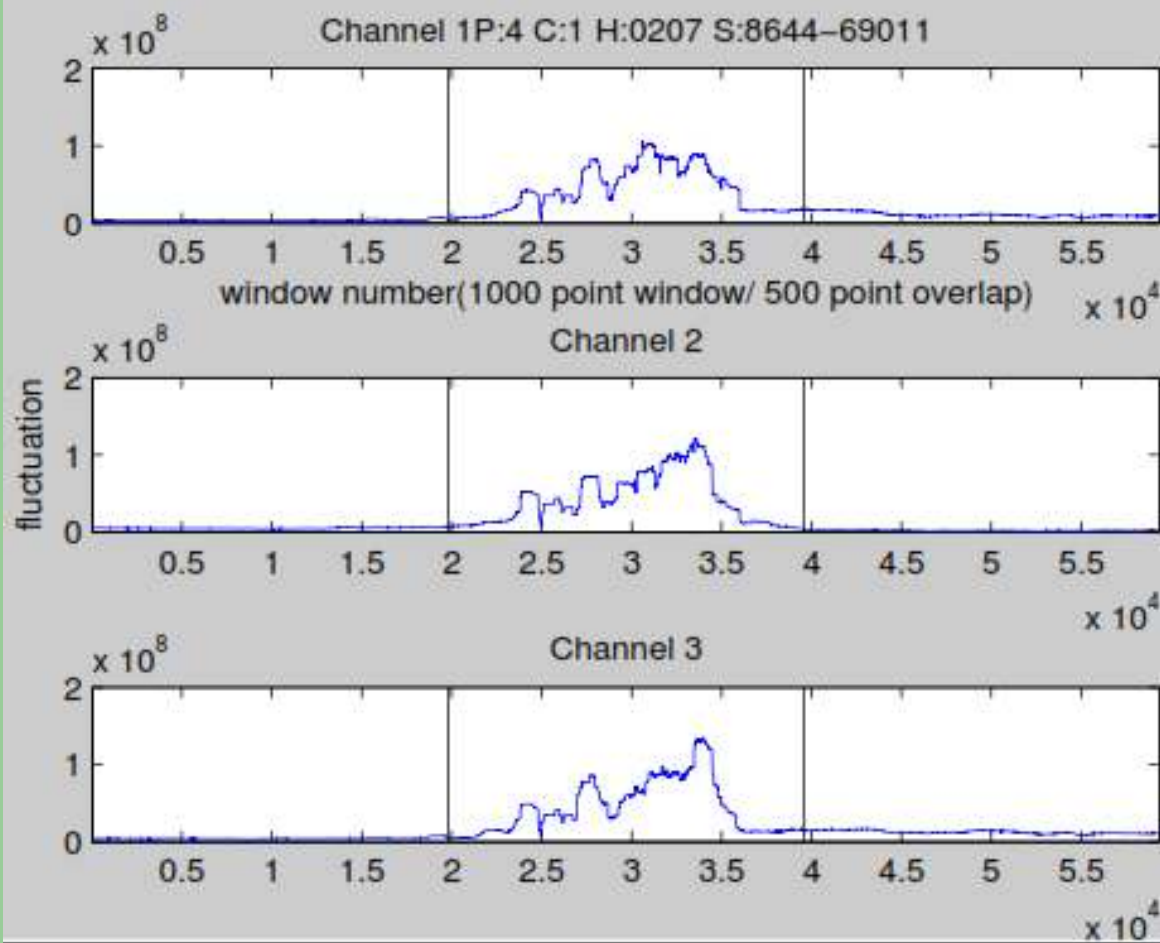
For electrophysiological signals s is to be replaced by voltage V

$$\frac{d}{dt} \left(\frac{d^2 V(t)}{dt^2} V(t) \right) = \frac{d}{dt} (FV)$$

The electromotive force F responsible for generating V is independent of V , which is not possible by Hodgkin-Huxley model.

For epileptic seizure ECoG this means the ligand-gated ion channels may play an important role in seizure.

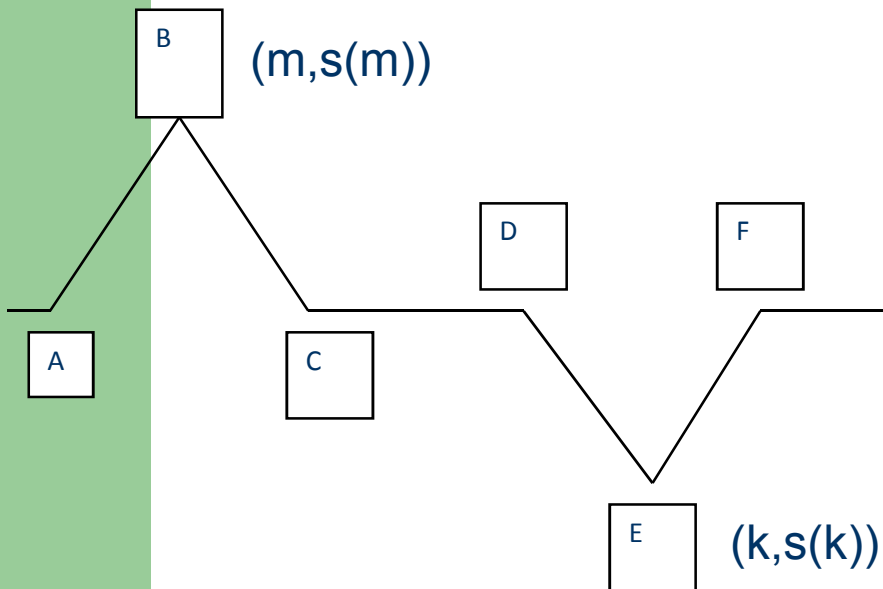
Fluctuation Operator E_v on Focal Seizure ECoG



Plot generated by Abhishek Malali. Black vertical lines indicate seizure onset and offset.

Enhancement of seizure ECoG happens due to higher order derivatives in E_v , but role of ligand-gated ion channels cannot be ruled out.

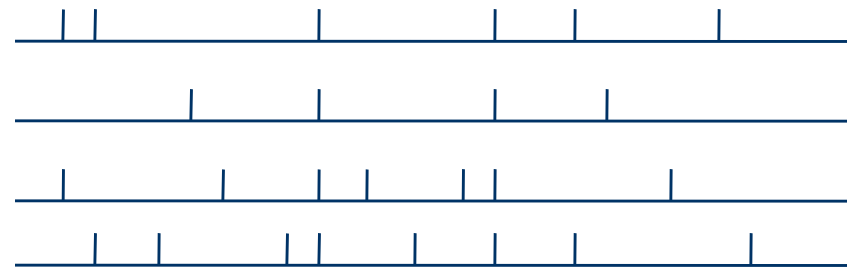
Multichannel Simultaneous Peaks and Troughs Detection



$$P(m-) < 0 \ \& \ P(m+) > 0 \ \& \ s''(m) < 0$$

$$P(k-) < 0 \ \& \ P(k+) > 0 \ \& \ s''(k) > 0$$

$$P(s) = \frac{d^2 s}{dt^2} \frac{ds}{dt}$$

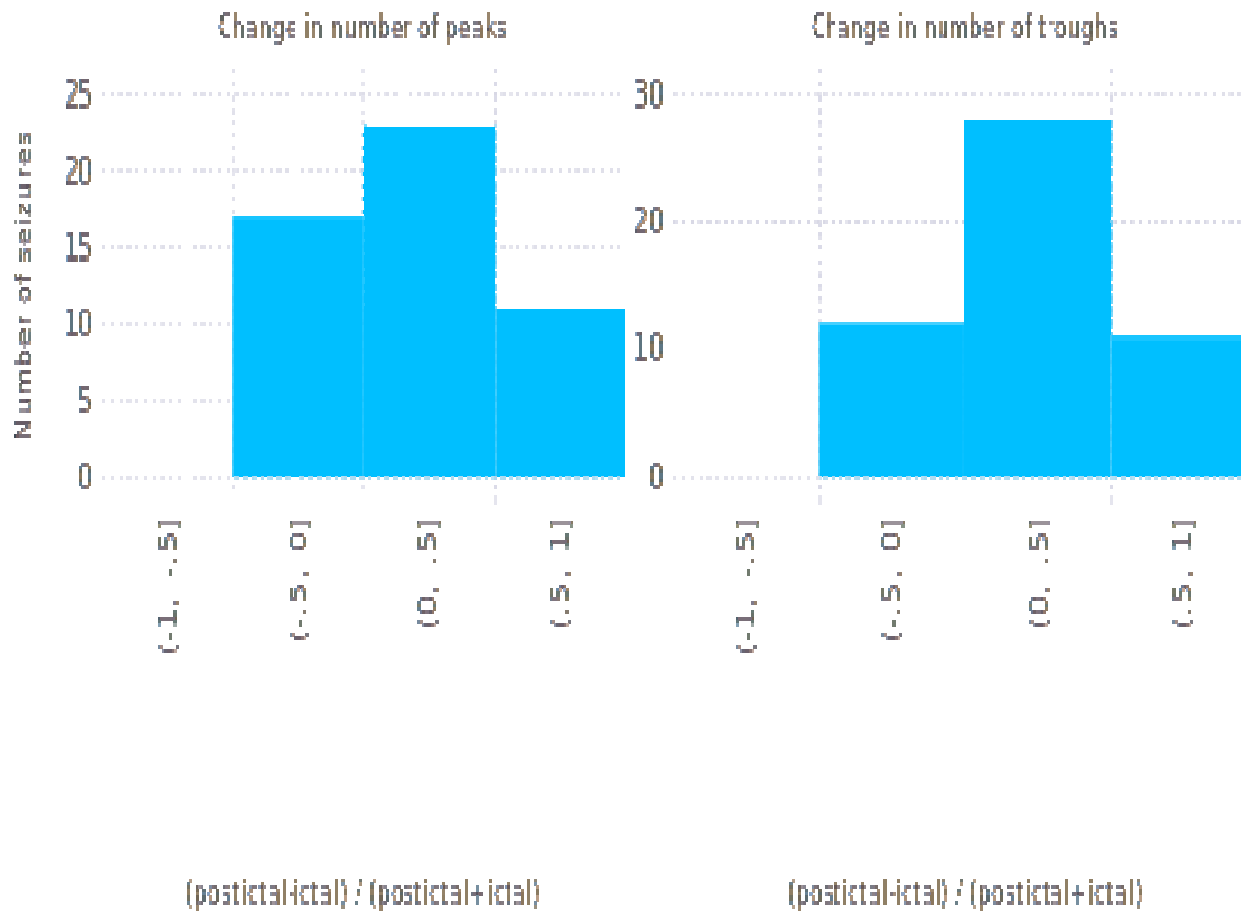


Majumdar et al. 2014

Seizure Termination

- Simultaneous peaks and troughs across the focal ECoG channels are more after the offset than during the seizure, where the duration after the offset has been taken to be equal to the seizure duration.
- Does it have anything to do with seizure termination?

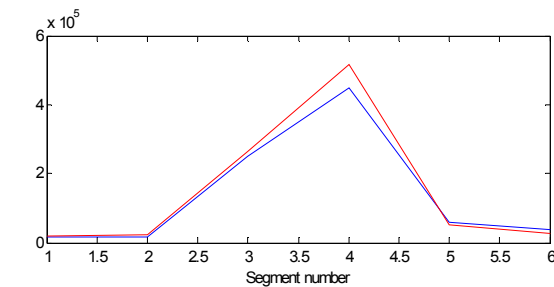
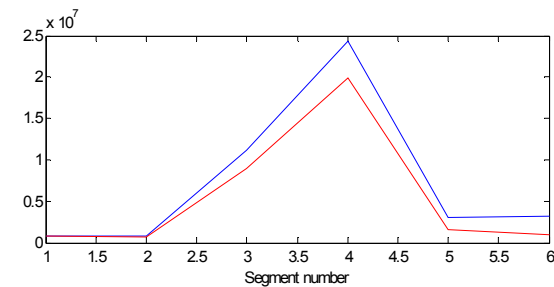
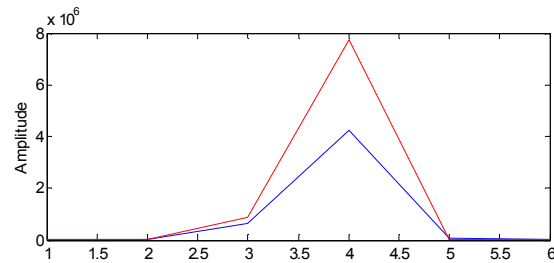
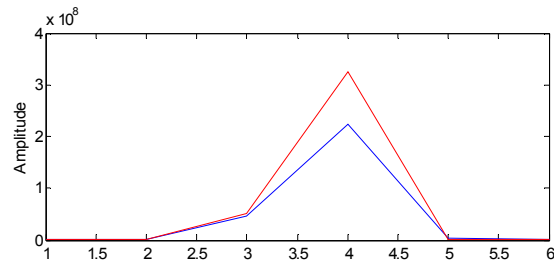
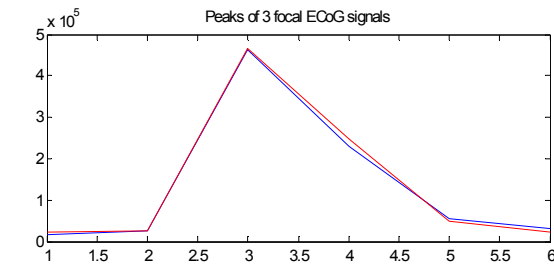
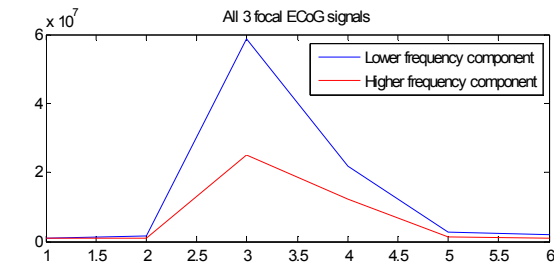
Simultaneous Peaks and Troughs Across Focal Channels More after Offset than During the Seizure



Generated by
Shashi Gowda

$$\frac{\text{postictal} - \text{ictal}}{\text{postictal} + \text{ictal}}$$

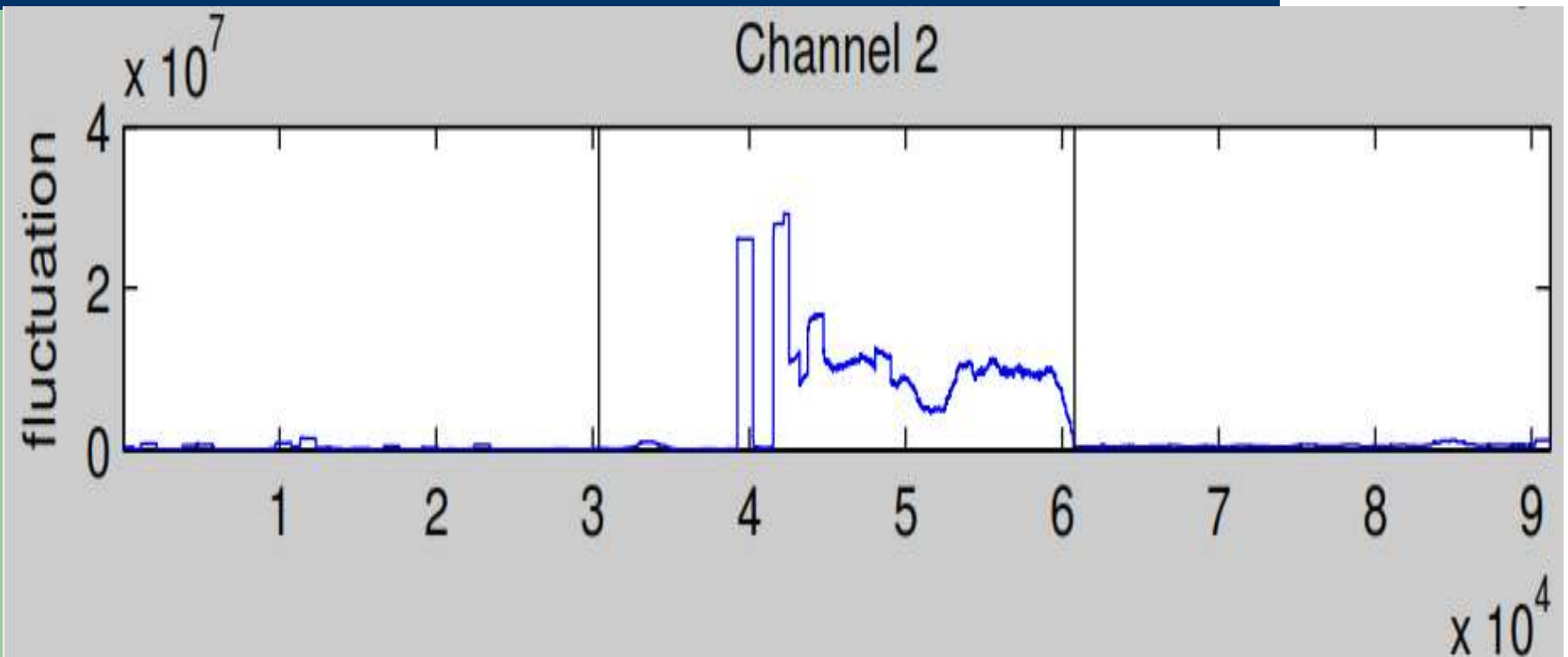
Peaks Are Generated by Higher Frequency Components



Peaks and Troughs in Signals

1. Band-pass filtered between 8 and 42 Hz, because power spectrum is strongest in this band.
2. During seizure 26 – 42 Hz dominates in the 'peak alone' signals whereas 8 – 25 Hz dominates in the whole signals.
3. After the offset both the bands get almost equal and very low amplitude.
4. For 2 or 3 signals can have high number of peaks and troughs.

Tiny Ripples after Offset



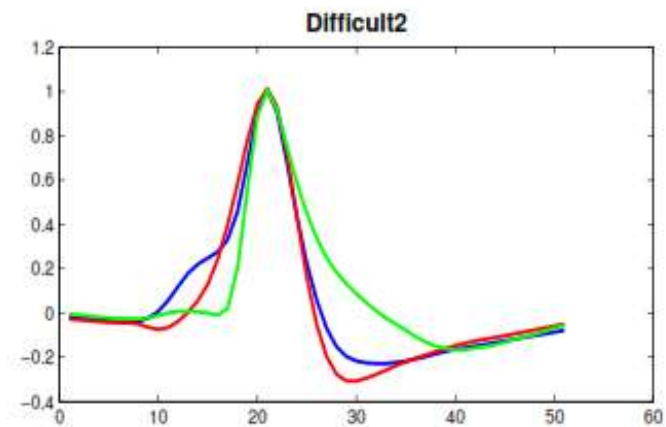
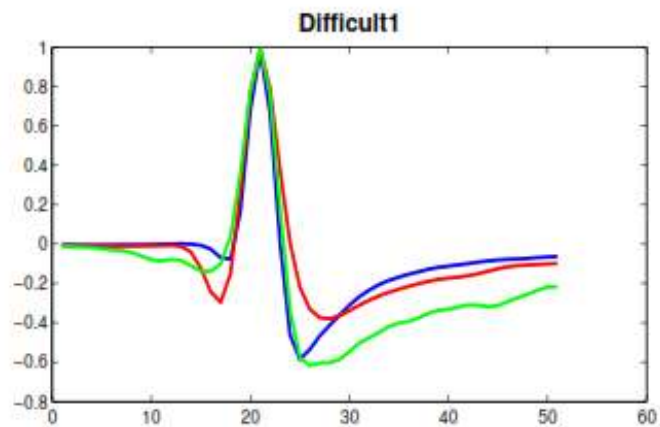
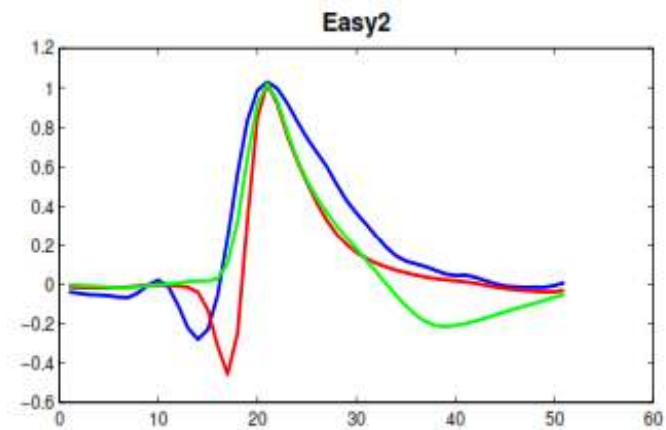
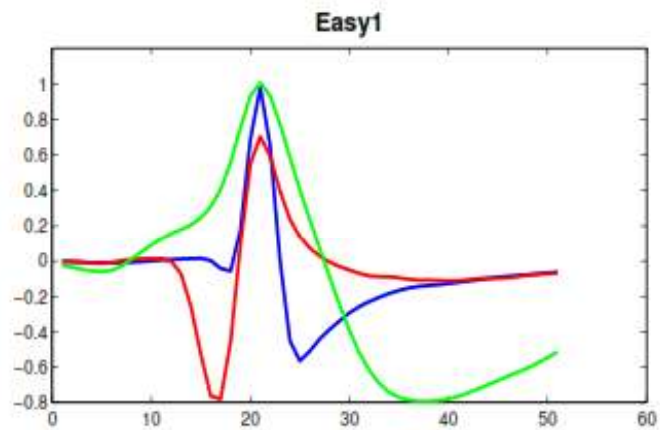
$E_S(s(t)) = \frac{d}{dt} \left(\frac{d^2 s(t)}{dt^2} s(t) \right)$ has been termed as fluctuation.

Ripples Are Due to Ligand Gated Ion Channels

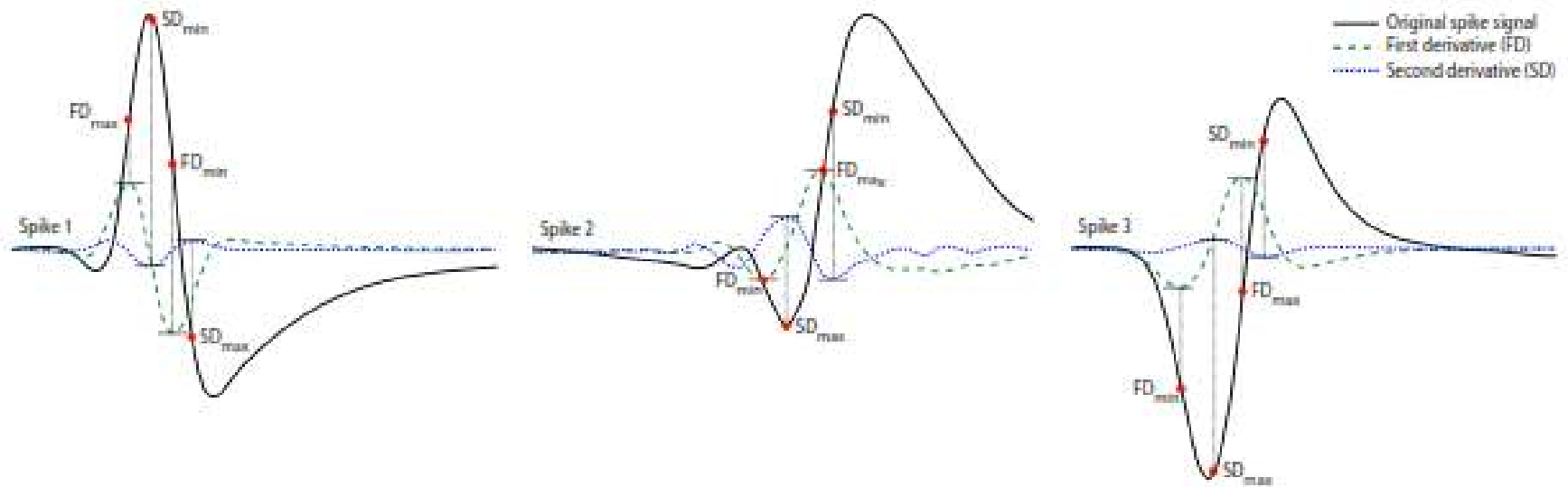
$$\text{var} \left(E_S(s(t)) - \frac{d^2 s(t)}{dt^2} \frac{ds(t)}{dt} \right) \approx 0$$

If the above expression holds in the focal ECoG signals after the seizure offset then the tiny ripples after the offset are indeed due to ligand gated ion channels, which means the seizure network excitability has been suppressed by GABA.

Spike Sorting



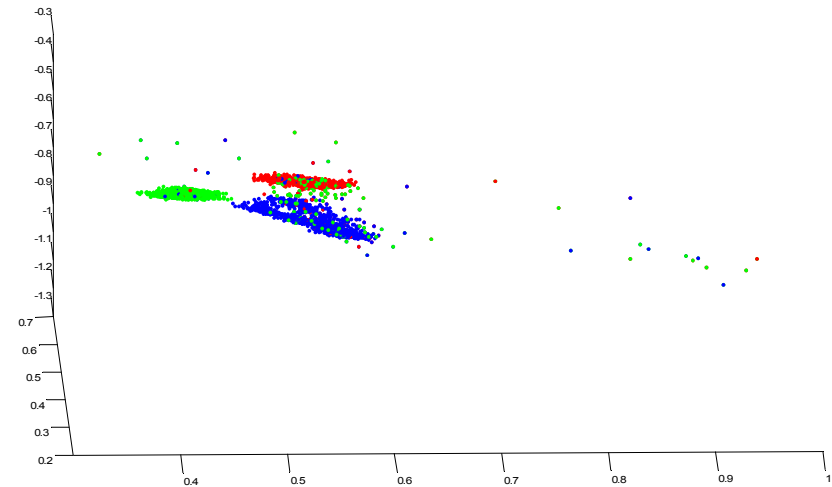
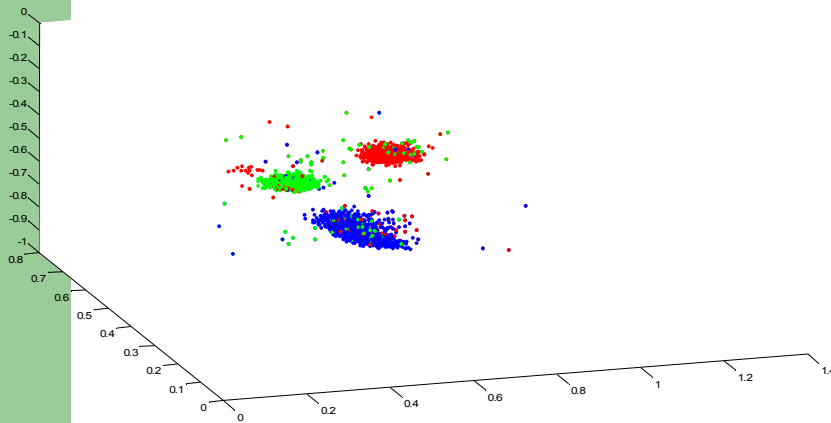
First and Second Derivative



Maximum and minimum of the first derivative, and maximum of the second derivative are the three features, which give a very high degree of sorting efficiency for extracellular spikes.

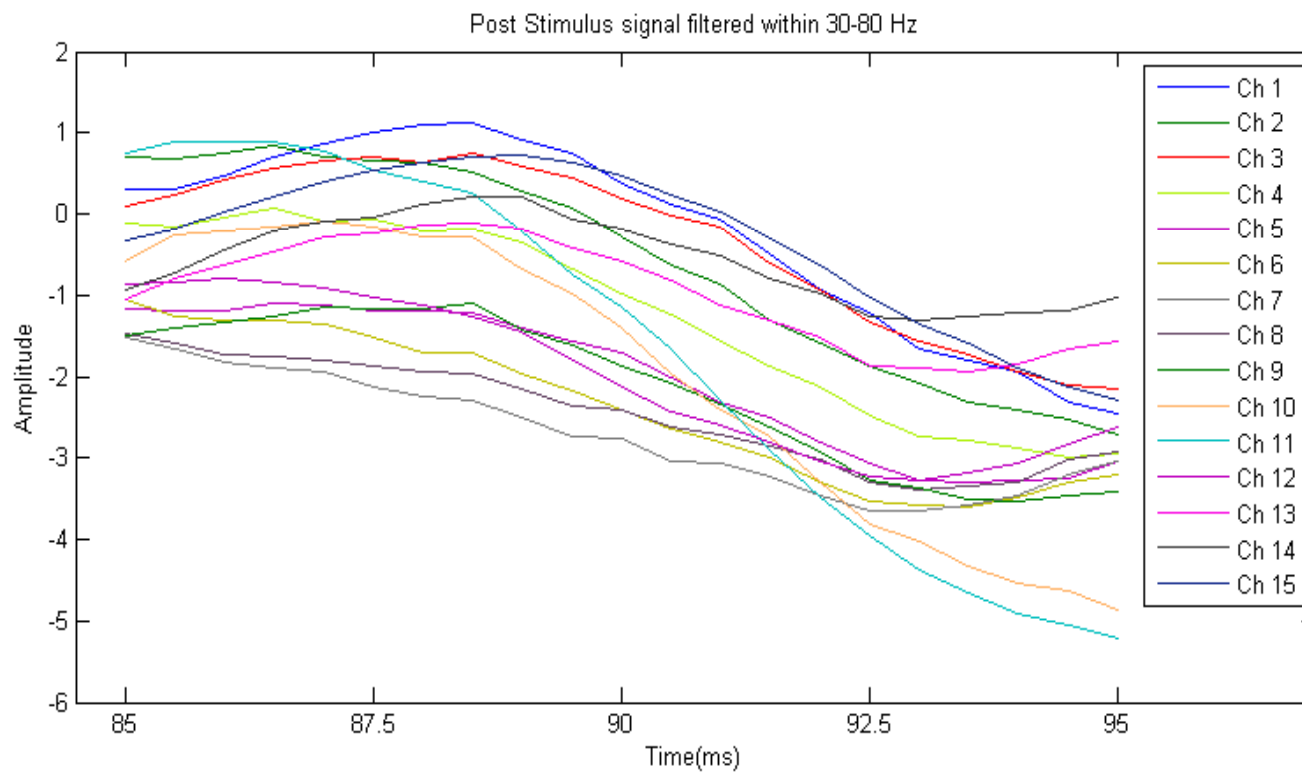
Efficient Feature Extraction

Clusters for Easy1 spikes corrupted with noise (SNR = 100/5).



Clusters for Difficult1 spikes corrupted with noise (SNR = 100/15).

Neuronal Spike Signals from Monkey Brain



Binarization of Spike Trains

0	0	0	0	0	1	0	1	0	0	1	0	0	1	0	1	0	0	0	0
0	0	0	0	1	0	0	1	0	0	1	0	1	0	1	0	1	0	0	0
0	0	0	1	0	0	0	1	0	0	1	0	1	0	0	1	0	0	1	0
0	1	0	0	0	0	0	0	0	1	0	0	1	0	0	1	0	0	0	0
0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0
0	1	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
0	0	1	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0
0	1	0	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0
0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	1	0	0
0	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1	0	0
0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	0	0	1	0	0	1	0	0	1	0	0	0	0	0
0	0	0	0	0	0	1	0	1	0	1	0	1	0	0	0	0	0	0	0
0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0

Algebraic Operations for an Error Correcting Code for BCI

3	1	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	
	1	1	1	0	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	
	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	1	0	1	1	1	1	
	1	1	1	1	0	0	1	1	1	1	0	0	1	0	1	1	1	0	0	0	1	0	0
4	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1	
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	
	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
	1	1	1	0	1	1	0	1	1	1	1	0	1	1	0	1	0	0	0	0	1	0	0
5	1	1	1	1	1	1	0	1	0	1	1	0	1	1	1	1	1	1	0	1	1	1	
	1	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	0	1	0	1	
	1	1	1	0	1	1	1	0	0	1	1	1	1	1	1	1	0	1	1	1	0	1	
	0	1	1	1	1	1	0	1	0	1	0	1	1	1	1	0	0	0	1	0	1	0	1
6	1	1	1	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	
	0	0	1	0	0	1	1	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	
	1	1	0	0	0	0	0	0	0	0	1	0	1	0	1	0	1	0	0	0	1	0	1
	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	

(3), (4), (5) are collapsed code for three trials by elementwise Boolean addition across collection of columns and elementwise Boolean product across collection of rows. (6) Common pattern present in 9 trials after collapsing of code in each of them.

References

- K. Majumdar, Analysis of brain oscillations by temporal derivatives, *Society for Neuroscience abstract no.197.10*, San Diego, Nov 8 – 13, 2013.
- A. Malali, G. Chaitanya, S. Gowda and K. Majumdar, Analysis of cortical rhythms in intracranial EEG by temporal difference operators during epileptic seizures, 2014 (under preparation).

References (cont)

- K. Majumdar, P. D. Prasad and S. Varma, Synchronization implies seizure or seizure implies synchronization? *Brain Topography* **27(1)**: 112 – 122, 2014.
- S. Shekhar and K. K. Majumdar, An area based extracellular neural spike detection and two dimensional feature extraction algorithm, 2014 (under review in *Biomedical Signal Processing and Control*).