Breaking the Brain's Secret Code

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and

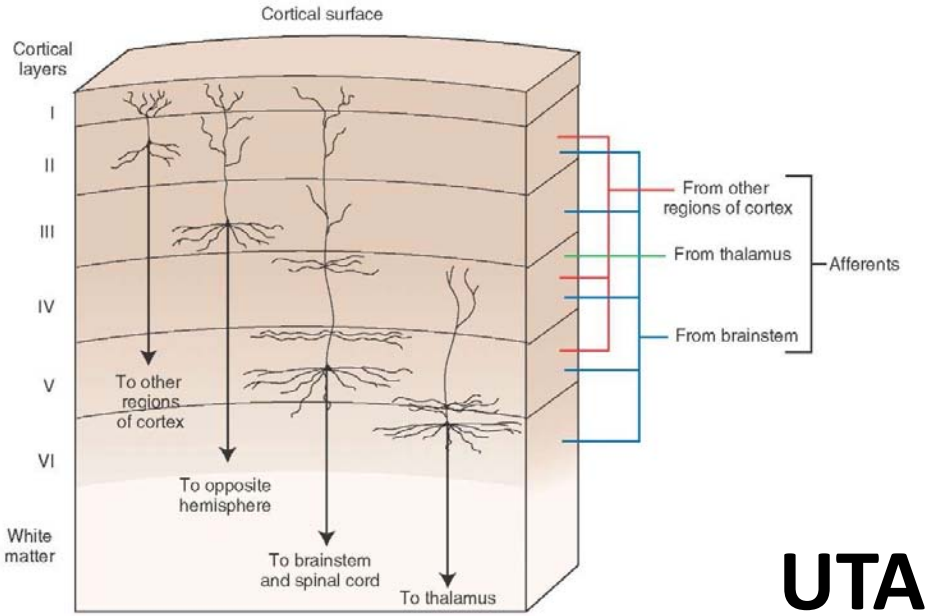
Larry Sorensen, Advisor

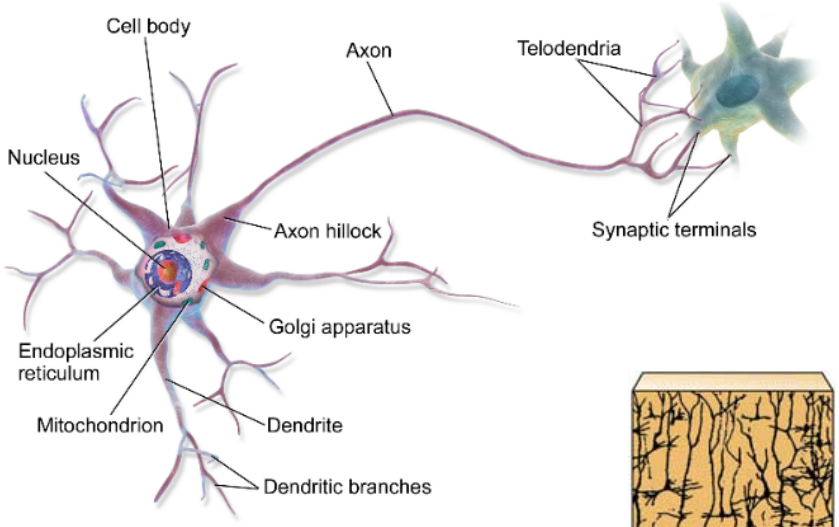
June 07, 2019

The Brain,

The Utah Array,

The Experiment





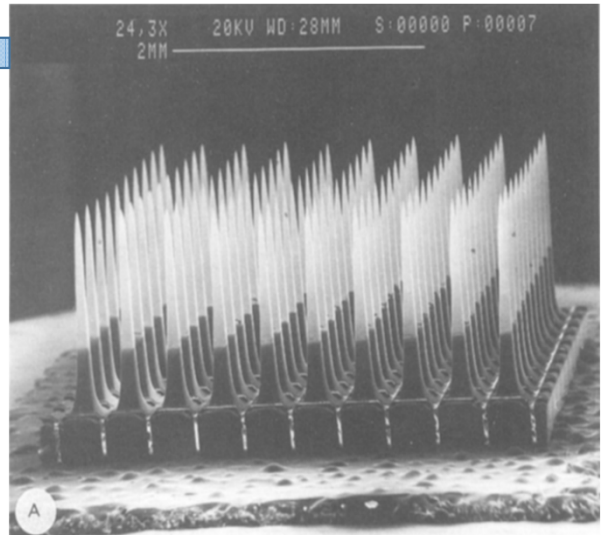
UTAH ARRAY

Electrode Design

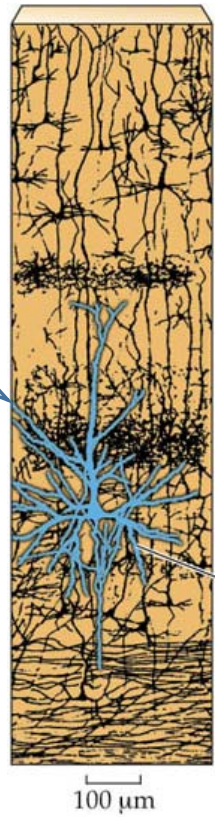
- Length: 1.5-mm
- Diameter: 4.0 µm
- Materials: silicone base, platinum tips

Cortex Design

- Thickness: 3.5-mm
- The Utah Array embeds near the middle layer of the cortex.



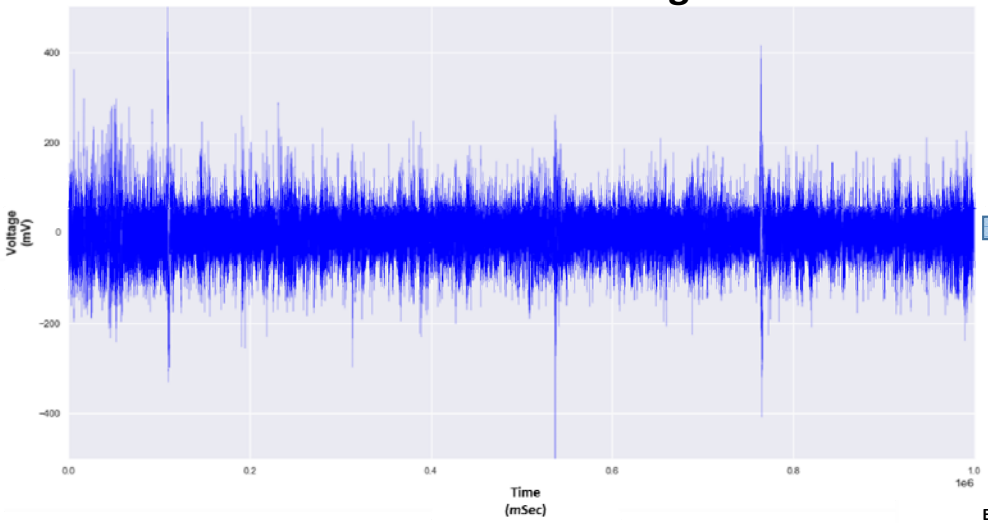
A single pyramidal neuron.



Raw Data in the Time Domain:

81 Electrode Voltages vs. Time

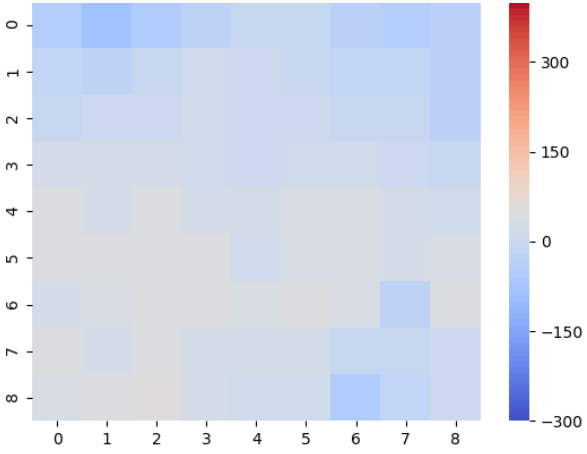
Electrode e01 Voltages



Heatmap Plot of All Electrodes

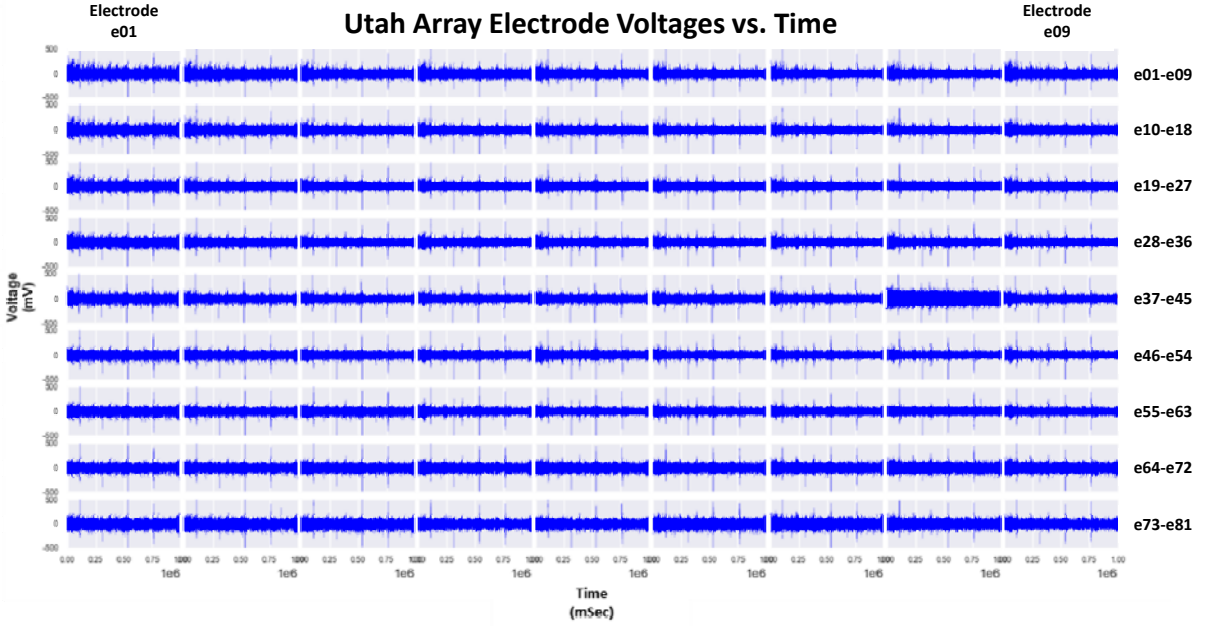
- 9 x 9 grid
- 81 voltages

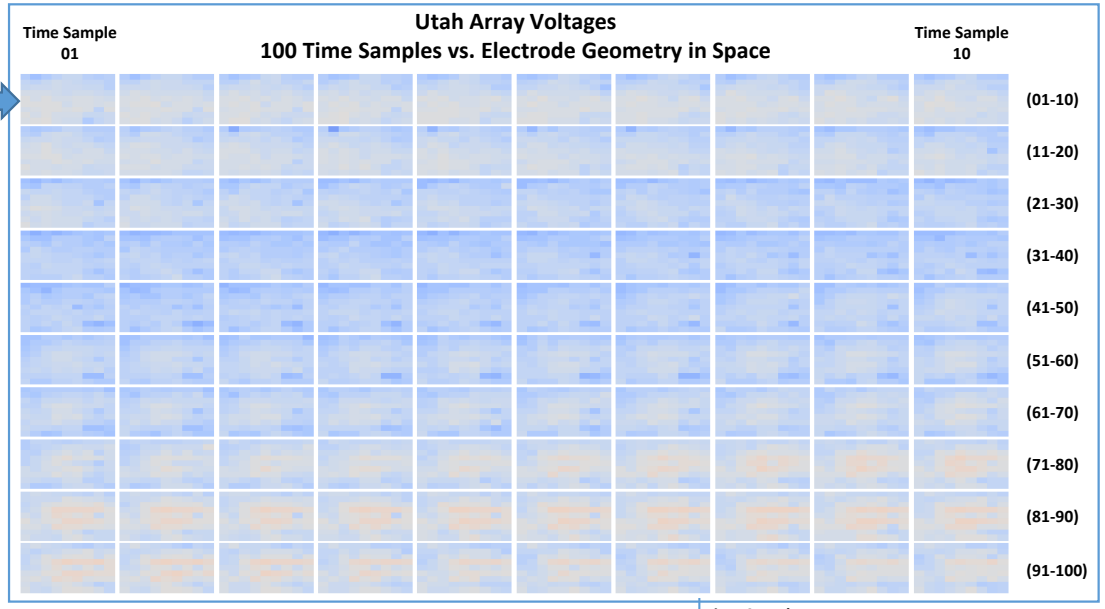
A Single Time Sample of Electrode Voltages vs. Electrode Geometry in Space



0	-47.2	-88.0	-54.6	-24.2	-7.1	-3.5	-32.2	-47.4	-36.6
1	-17.7	-25.8	-5.2	12.3	4.2	-3.2	-14.6	-13.6	-39.7
2	-7.4	8.1	5.9	16.5	8.6	1.5	-0.1	-6.6	-31.1
3	28.7	27.0	28.5	13.1	8.0	16.3	13.5	6.0	-6.3
4	47.7	26.9	42.9	22.3	24.8	32.3	31.2	22.1	10.3
5	41.5	49.5	43.6	45.9	14.8	35.0	31.9	25.2	36.0
6	24.9	34.8	41.4	40.9	39.4	43.2	39.9	-26.1	48.0
7	47.6	26.1	45.7	28.8	24.0	27.5	-6.6	-2.8	5.9
8	34.3	49.5	52.7	23.5	15.8	12.6	-50.1	-11.8	7.2

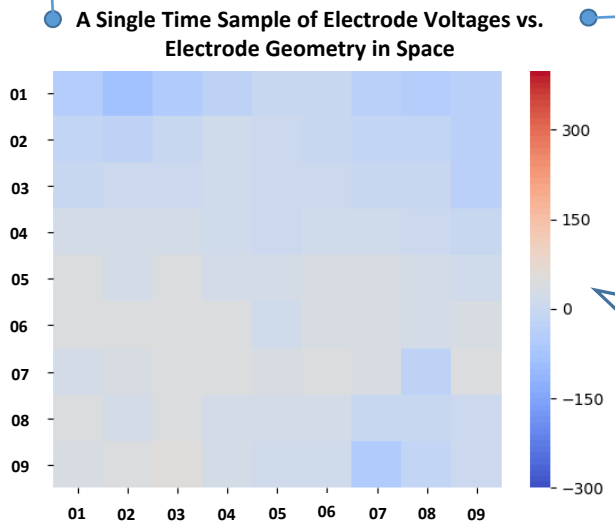
Utah Array Electrode Voltages vs. Time





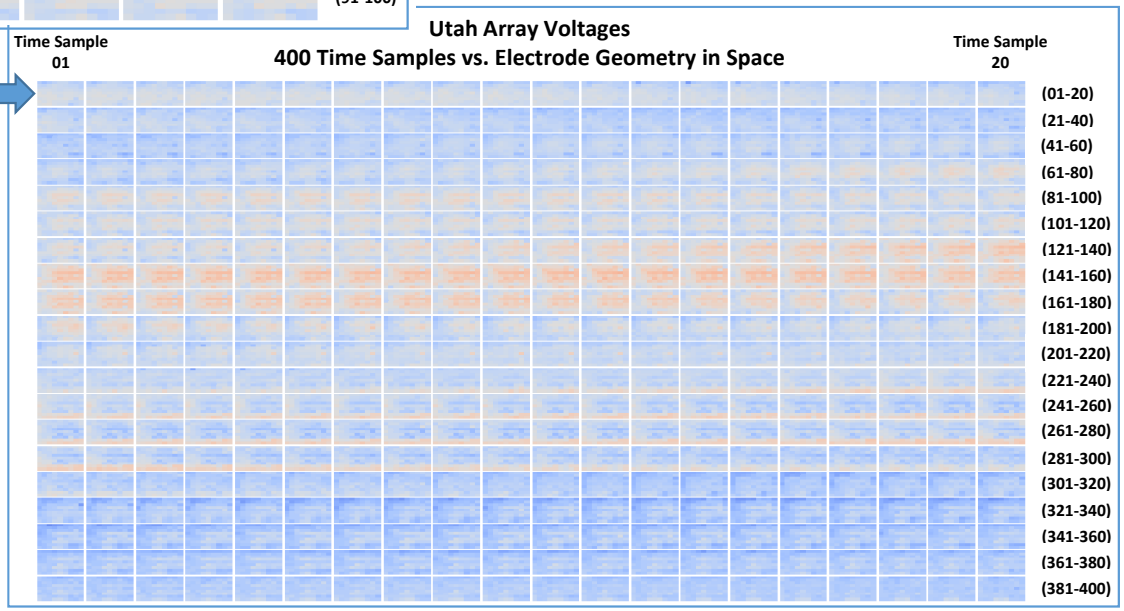
Look Up Table (LUT) Transformation Functions

- How to improve the contrast between matrix elements?
- Here, LUT = $f(x)$.

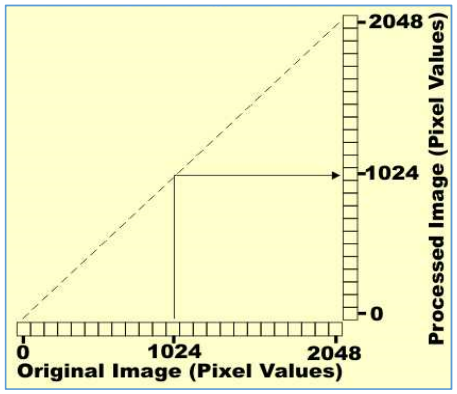


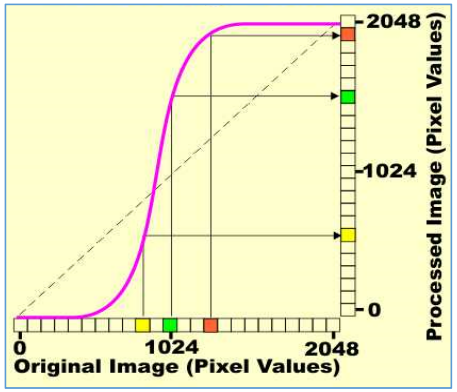
Heatmap Plot of All Electrodes

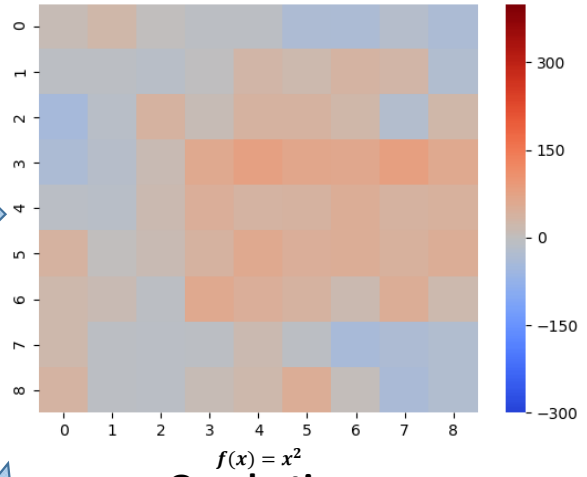
- 9 x 9 grid
- 81 voltages



Various Types of Look-Up Table (LUT) Functions and Results Upon Utah Array Electrodes

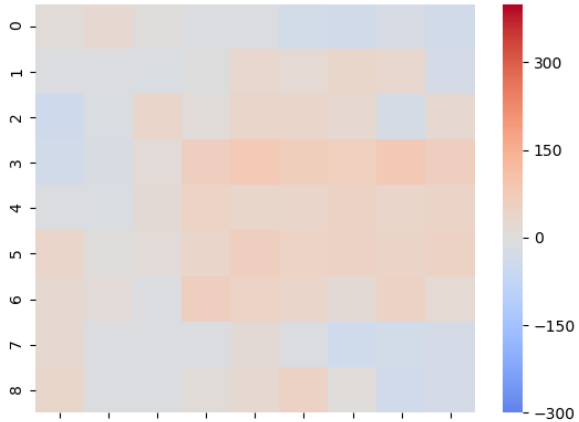






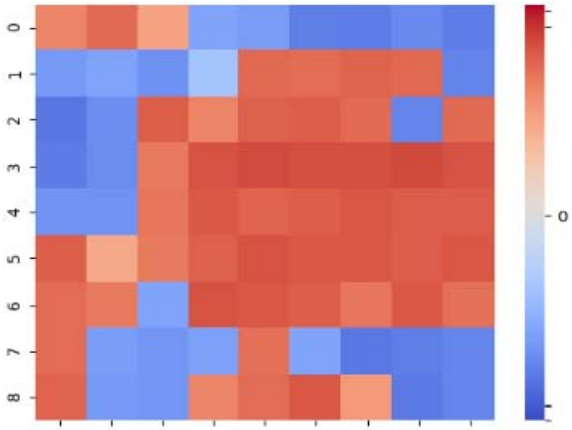
$f(x) = x^2$

Quadratic



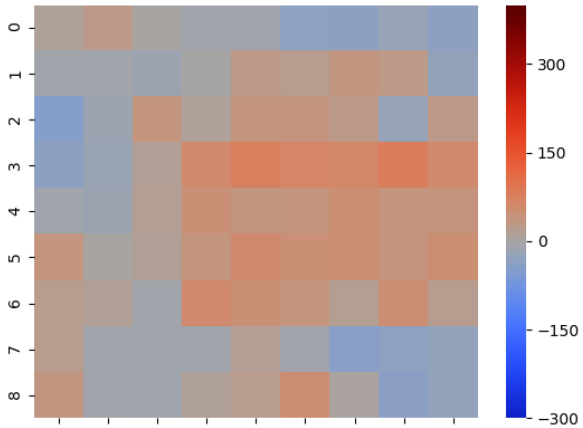
$f(x) = x$

Linear



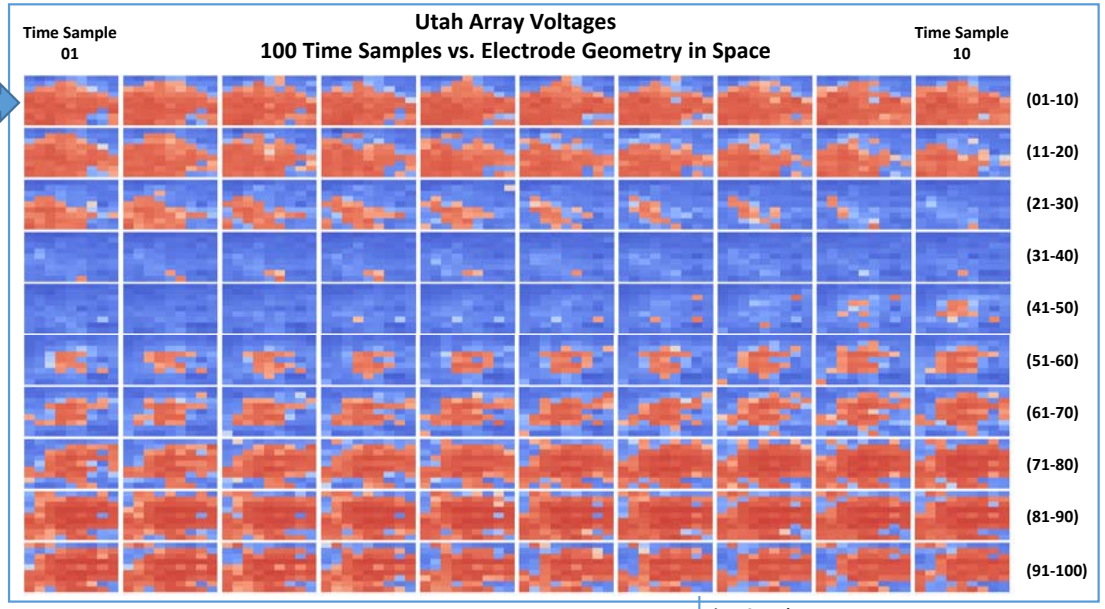
$f(x) = log_{10}(x)$

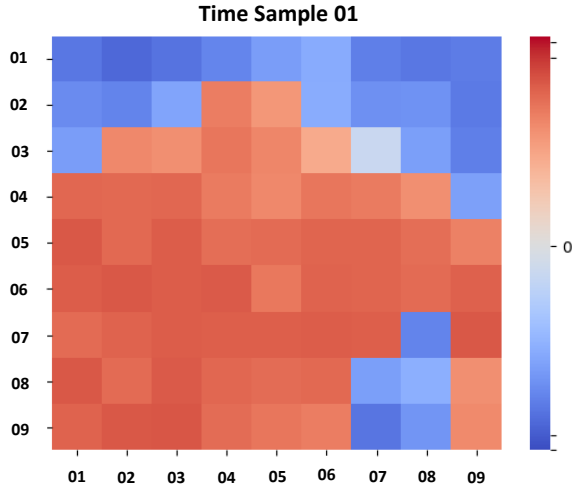
Logarithmic



$f(x) = x^3$

Cubic





Heatmap Plot of All Electrodes

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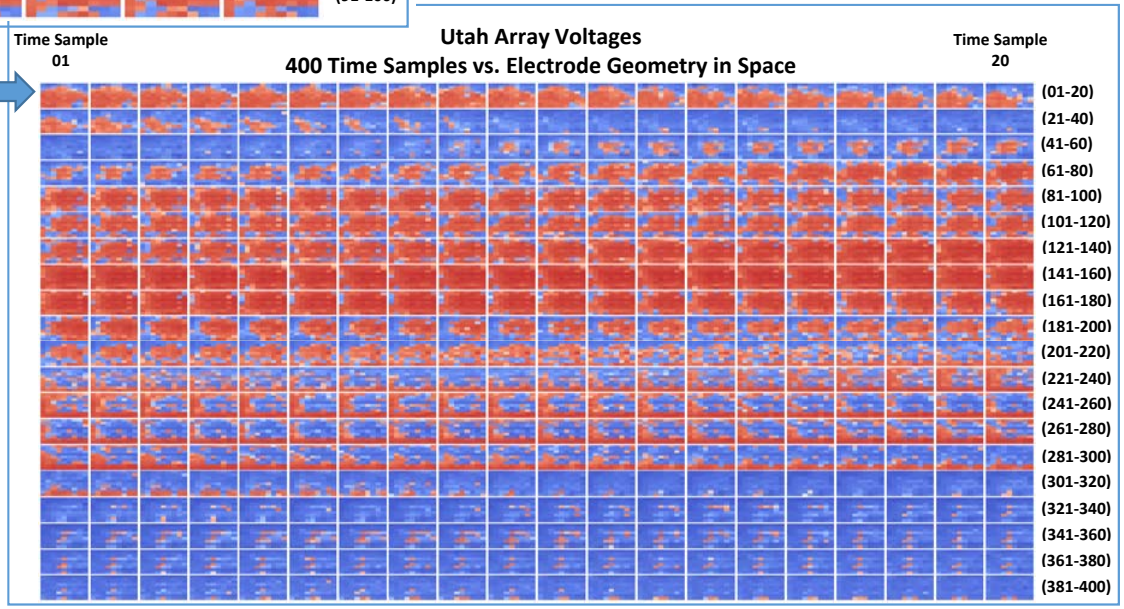
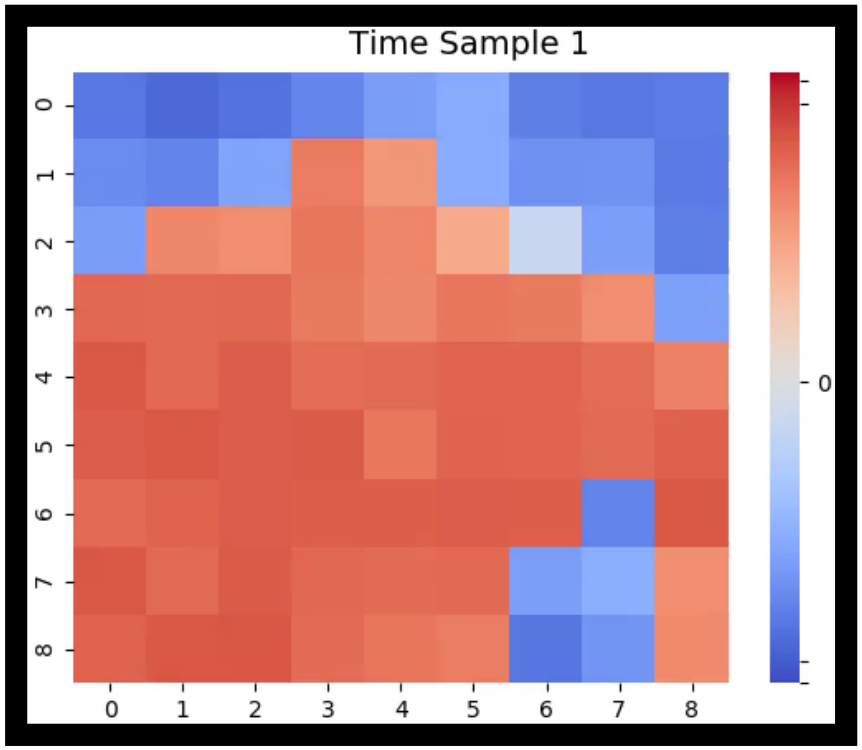
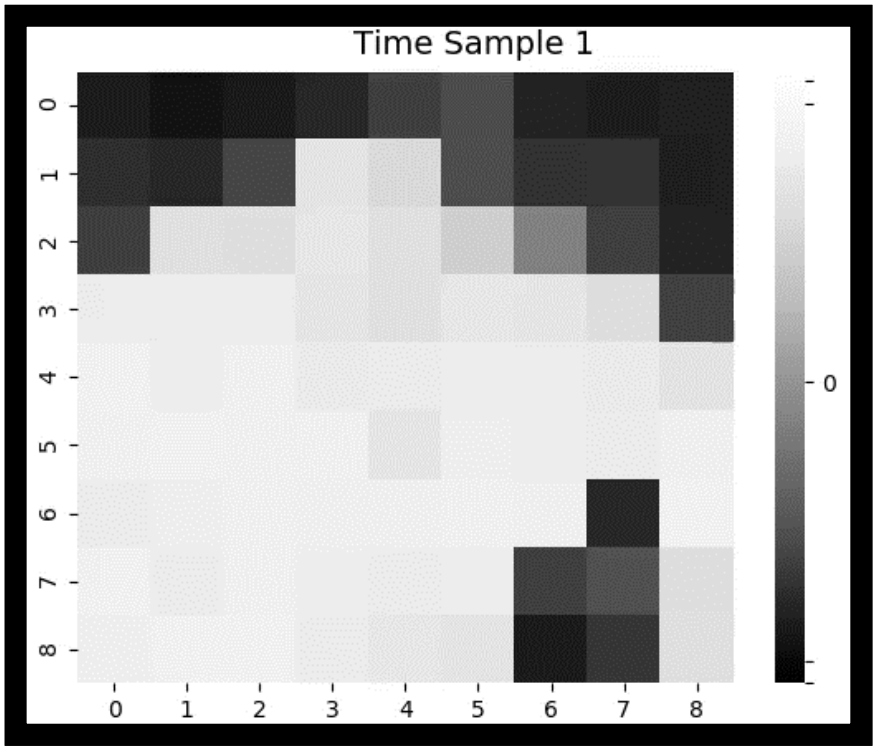


Look Up Table (LUT) Transformation Functions

- Here, LUT = $Log_{10}(x)$.
- This is an improved state of contrast between matrix elements!



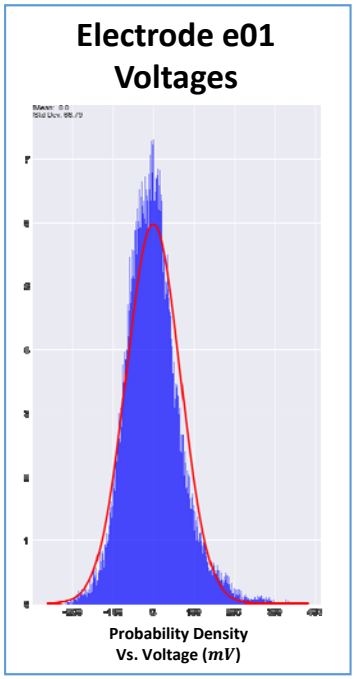
- [Animation] A time series animation of the Utah Array electrode voltages, in false color.

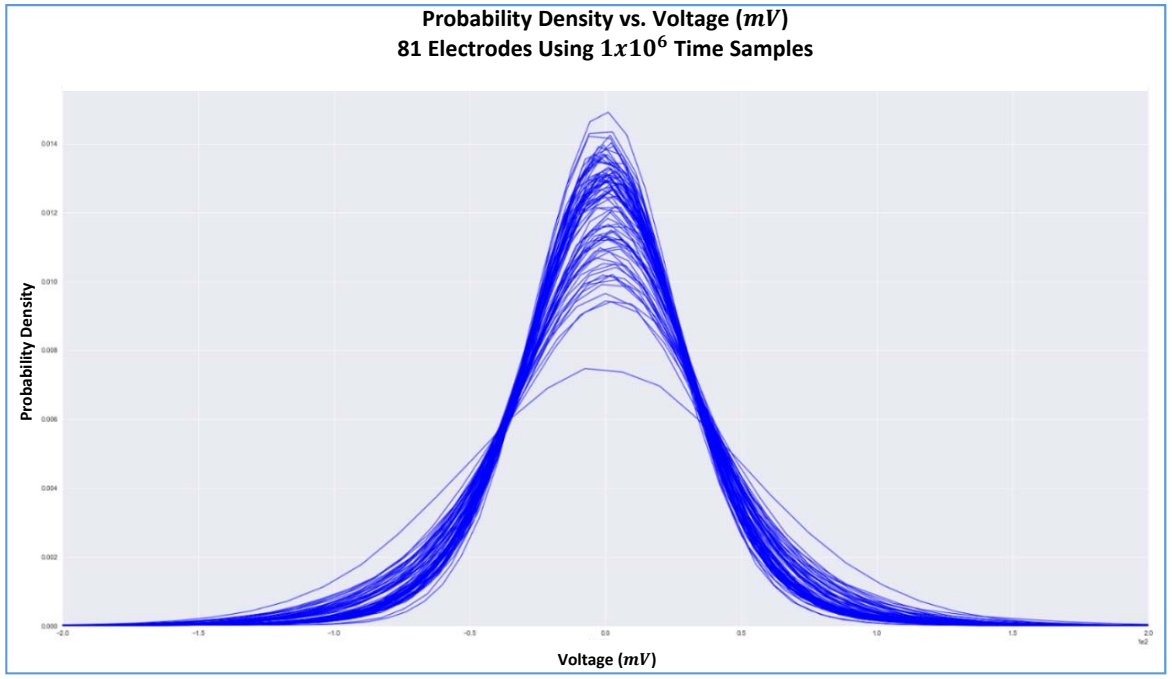


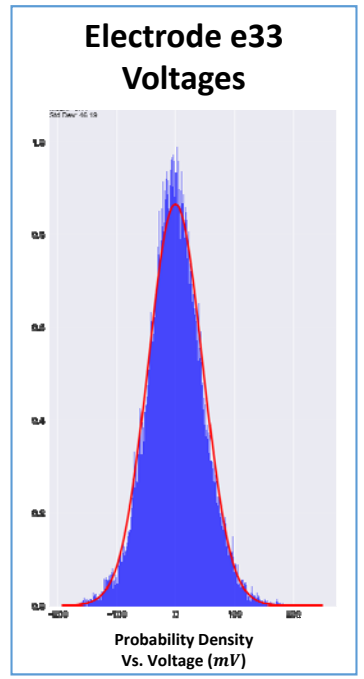
- [Animation] A time series animation of the Utah Array electrode voltages, in gray scale.

Statistical Analysis:

Histograms, Scatter Plots, and Correlation Coefficients





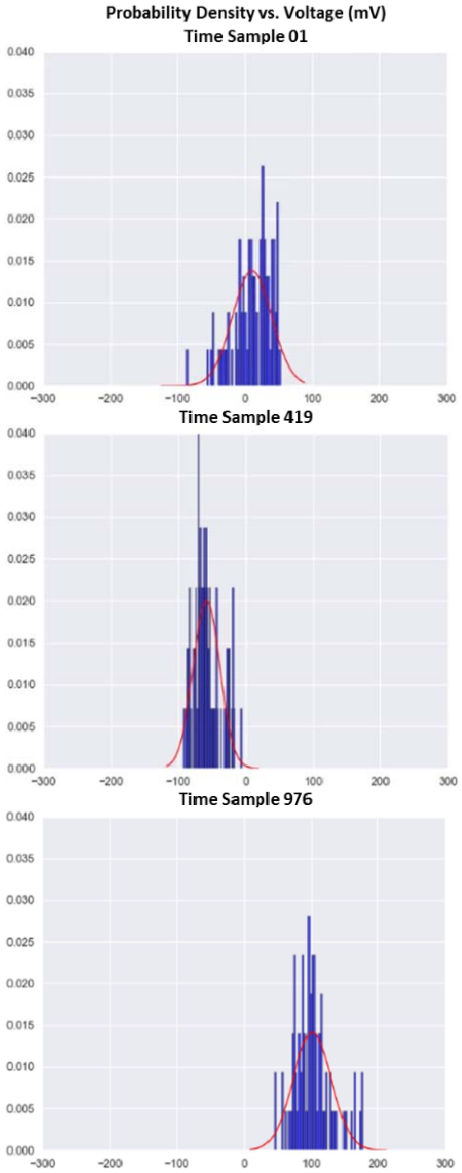


Voltage Histogram Plots

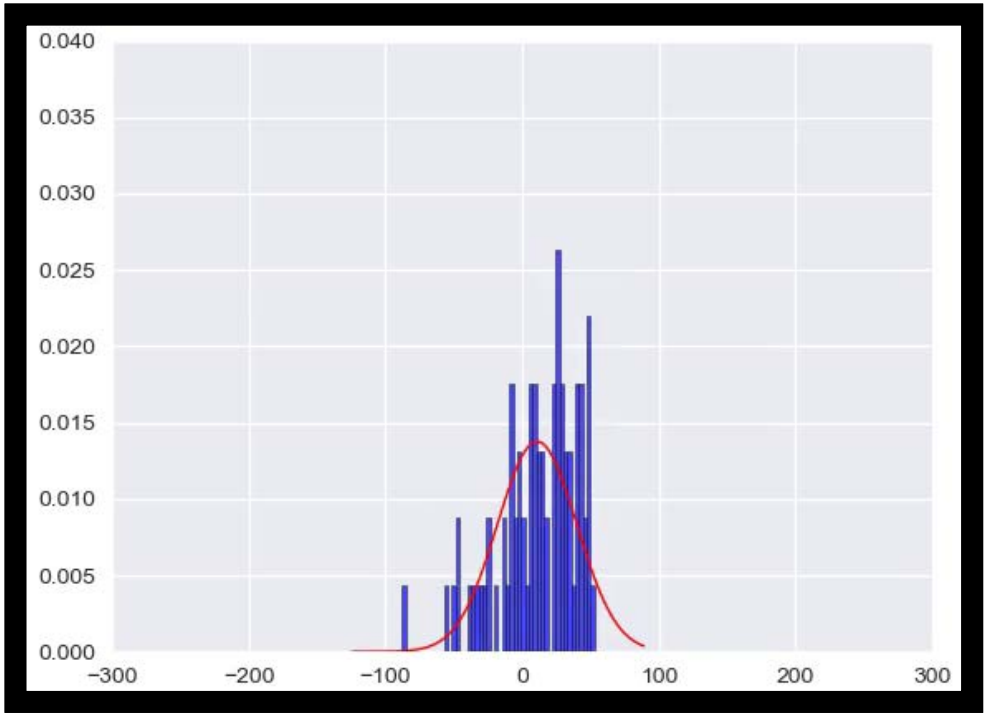
- Histograms are plotted using all 1,000 seconds of available data.
- Mean of 0.0 for electrodes e01 and e33.

Probability Density Curves

- Mean of 0.0 for all 81 electrode probability density curves.
- A Gaussian analysis is therefore permissible.

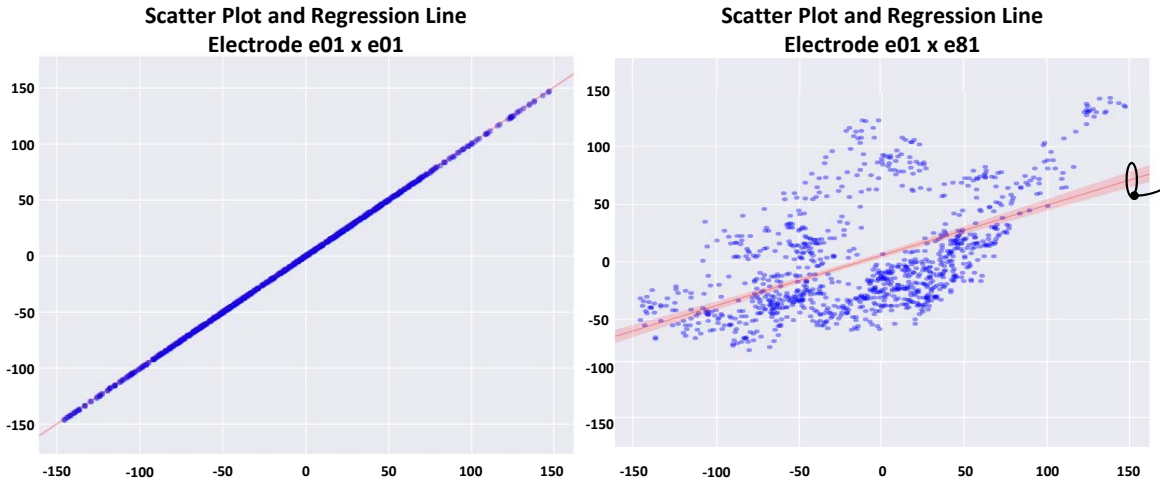


Histograms for all 81 Electrodes vs. Time



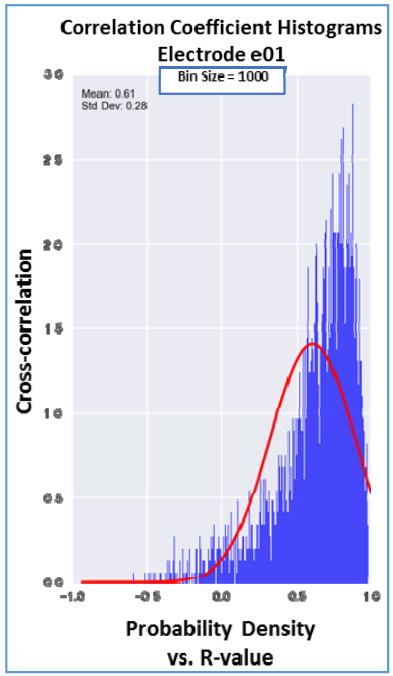
- [Animation] Note the variance in electrode voltages across time.

Scatter Plots



r_{xy}

Correlation Coefficients, r_{xy}



Scatter Plot / Correlation

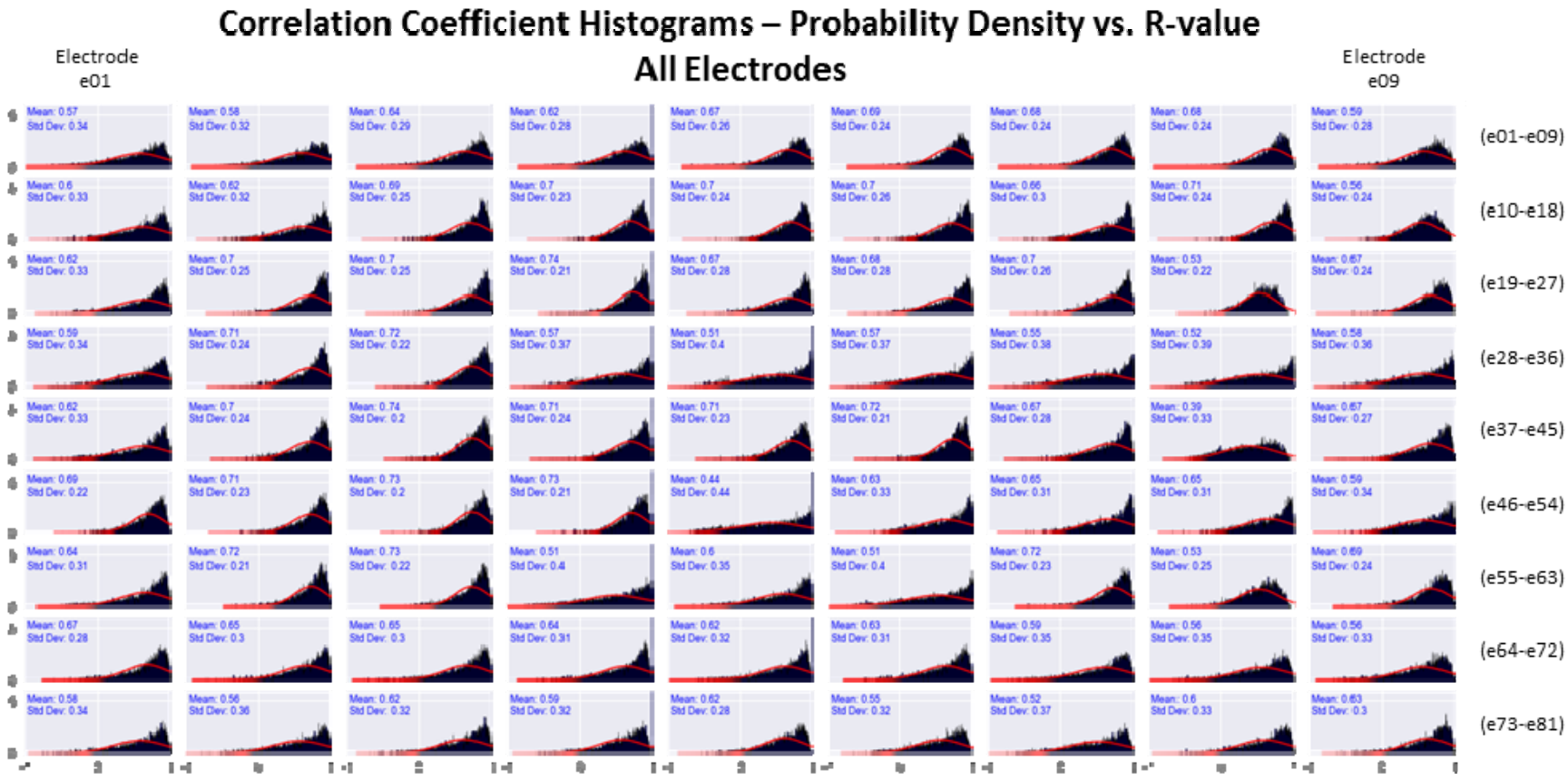
- The variance in X and Y independently.

Correlation Coefficient

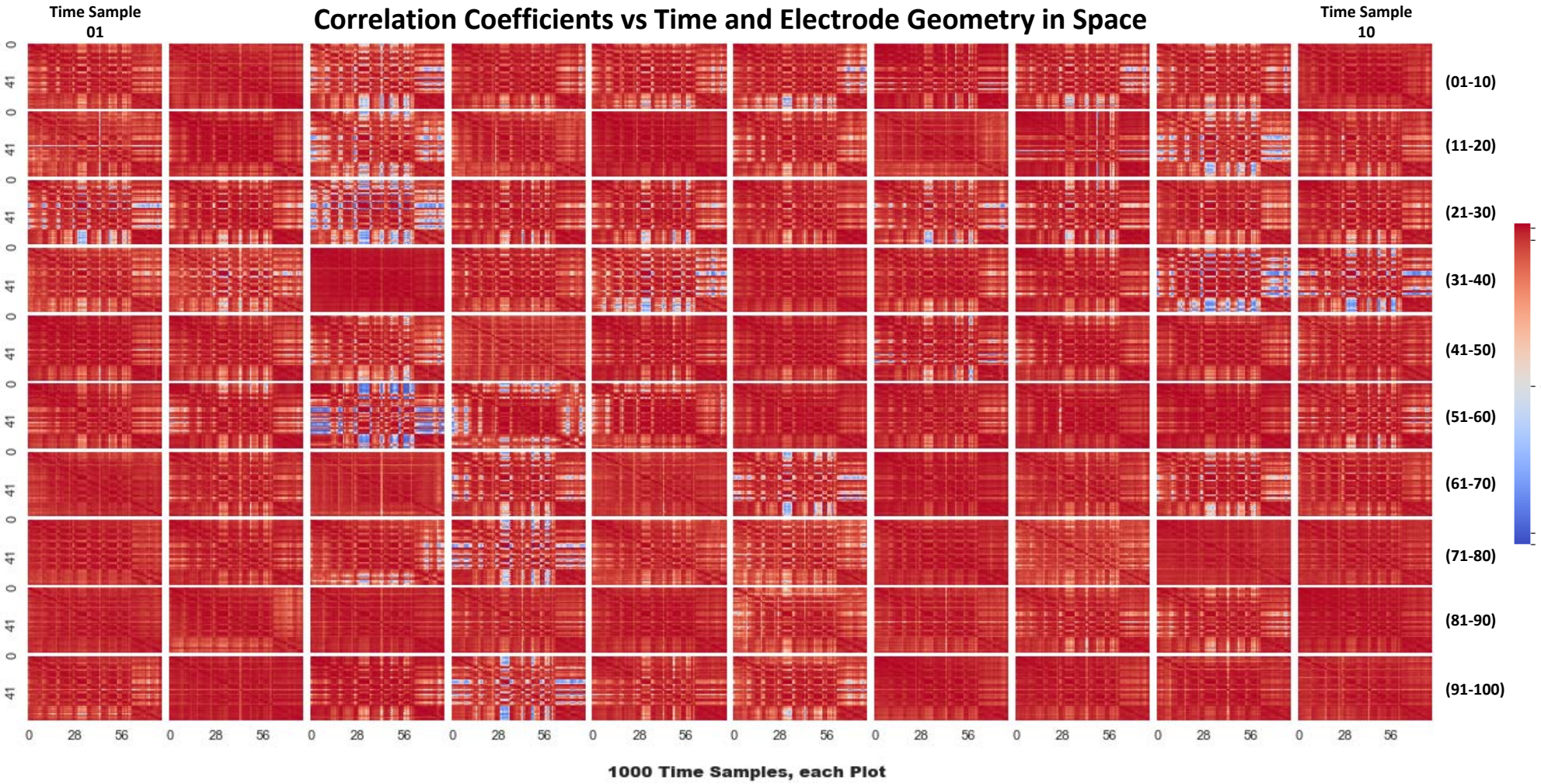
- The correlation coefficient, r, is a random sample estimate of both the direction and strength between variables X and Y.
- A positive coefficient result means that as one variable increases, so does the other, and vice versa for a negative coefficient.

$$r_{xy} = \frac{cov(x,y)}{\sqrt{S_x S_y}} = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 (y_i - \bar{y})^2}}$$

$$= \frac{cov(x,y)}{\sqrt{var(y)\mathrm{var}(y)}}.$$

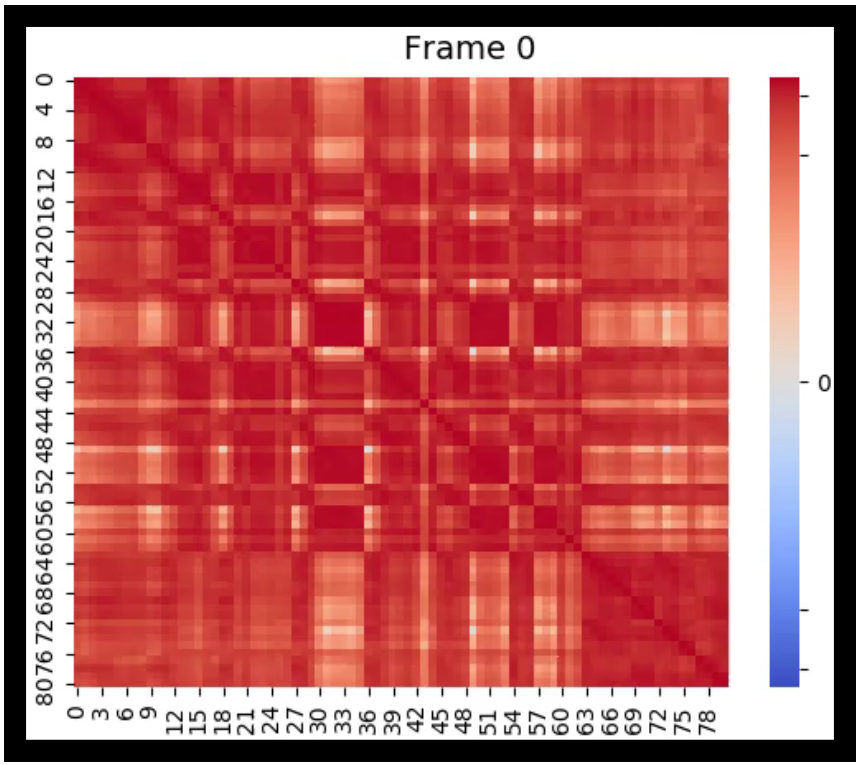


- Histogram plots showing the correlation coefficients of each electrode.
- Note that all electrodes have a positive mean and probability density.

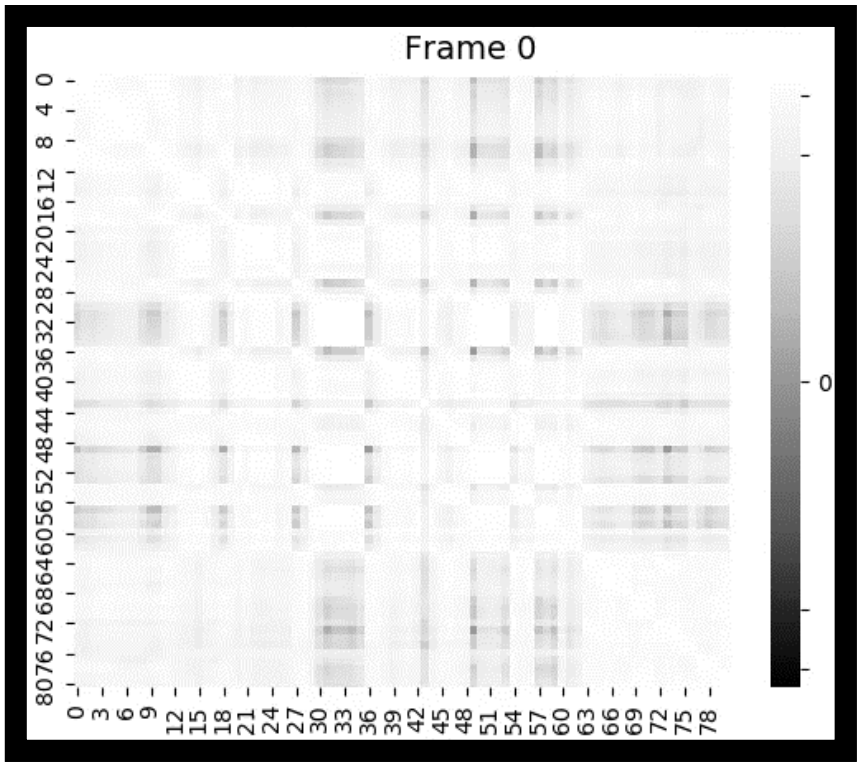


- A time series matrix of correlation coefficient heatmap plots.
- Note the generally positive magnitudes of the coefficients.

Correlation Coefficients Across Time



- [Animation] A time series animation of the Utah Array electrode correlation coefficients, in false color.



- [Animation] A time series animation of the Utah Array electrode correlation coefficients, in gray scale.

From Scatter Plots and Correlation Coefficients

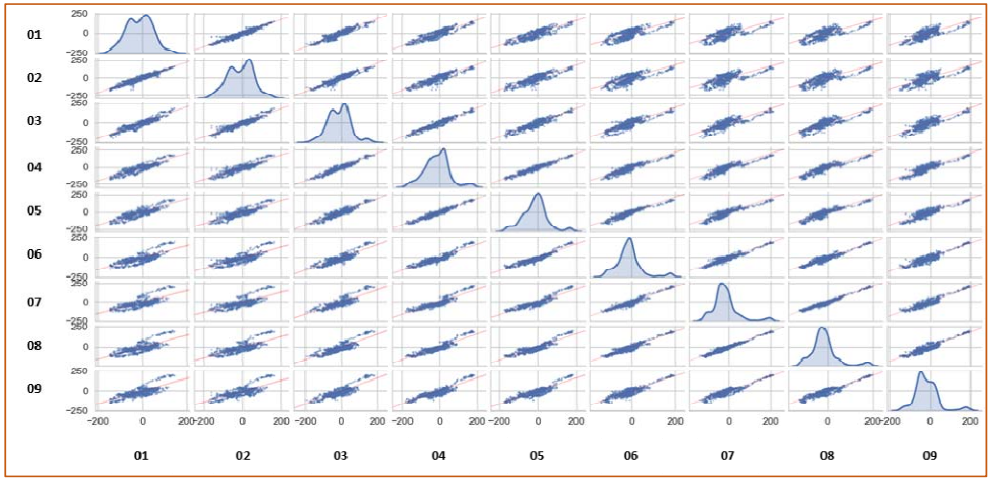
To Time Correlation Functions

And Equivalence Classes

Scatter Plot / Covariance Matrix For Two Cases: Electrodes e01–e09 and e28-e36

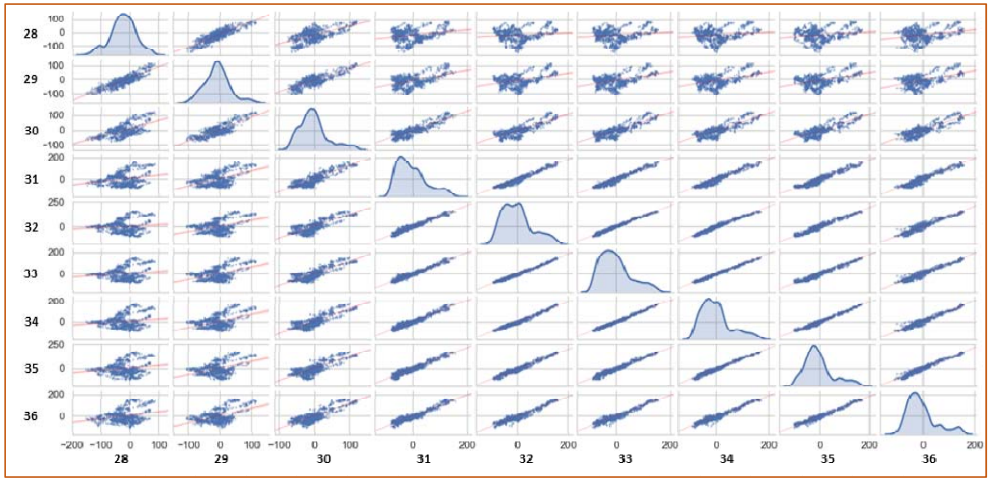
- The variance in X and Y together.
- 2 type of equivalency classifications are shown between the scatter plot figures.

Electrodes e01–e09



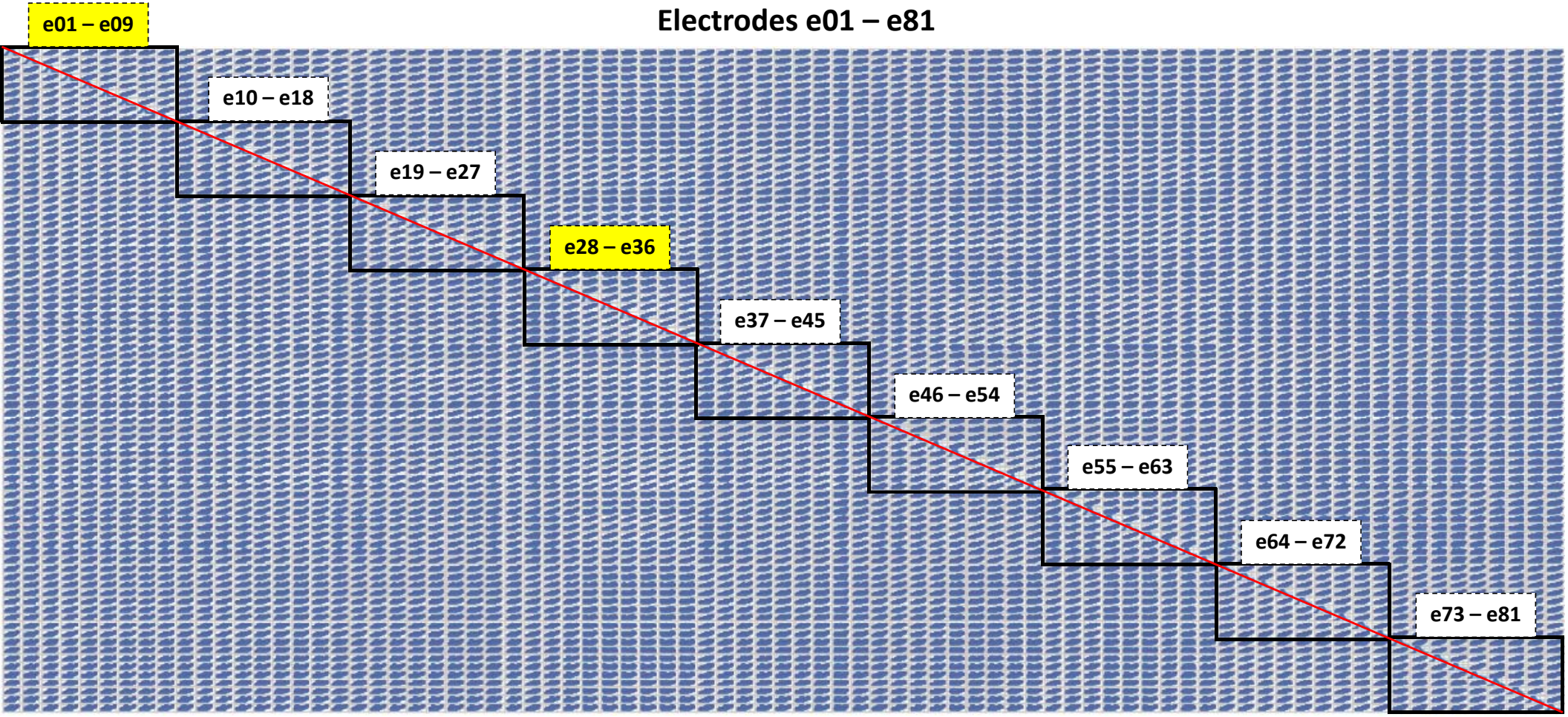
- High correlation in all plots.

Electrodes e28–e36

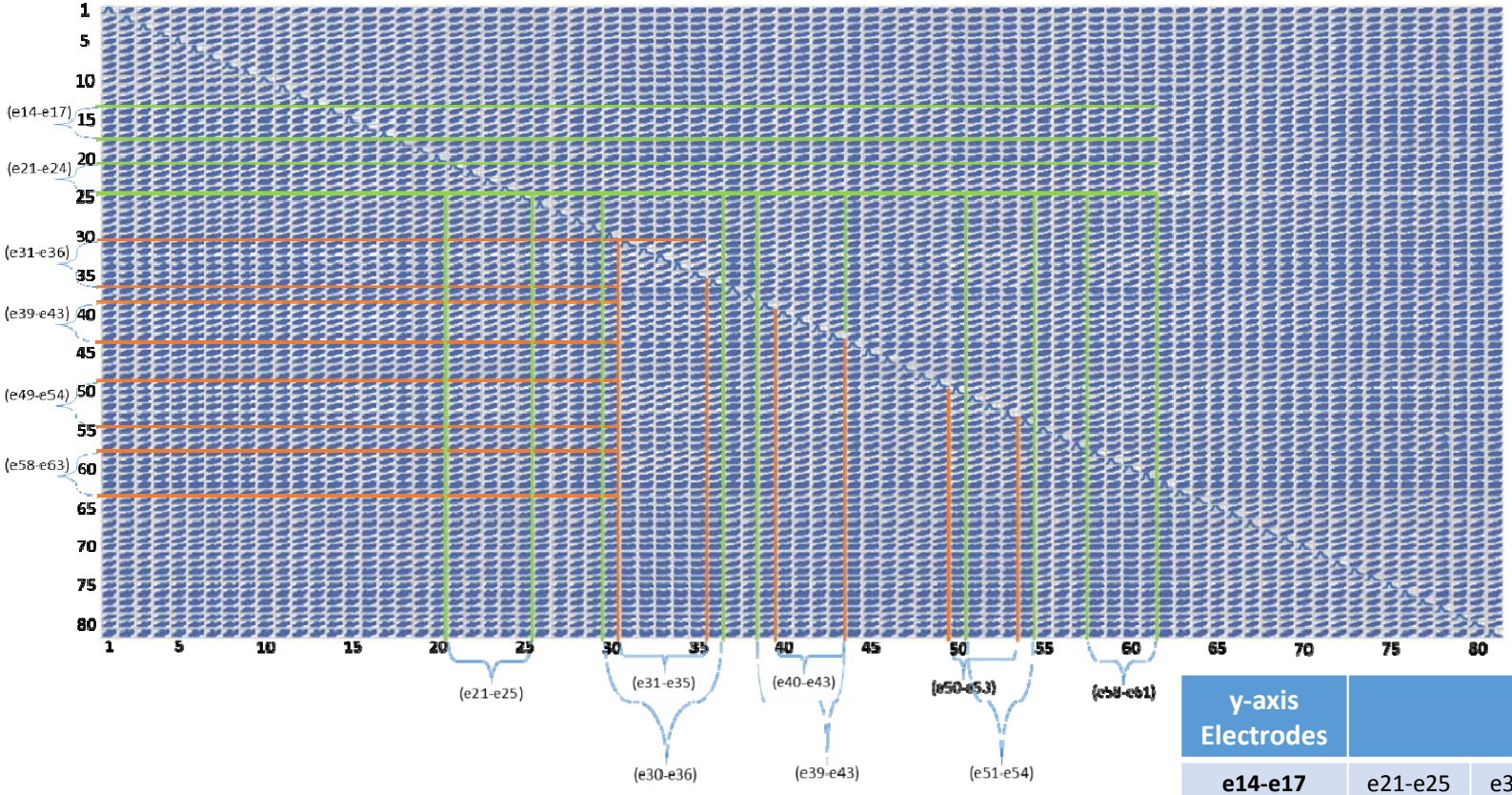


- Both high and low correlations are observed.
- Increased white space is shown for the highly correlated results.

Scatter Plot / Covariance Matrix
Electrodes e01 – e81



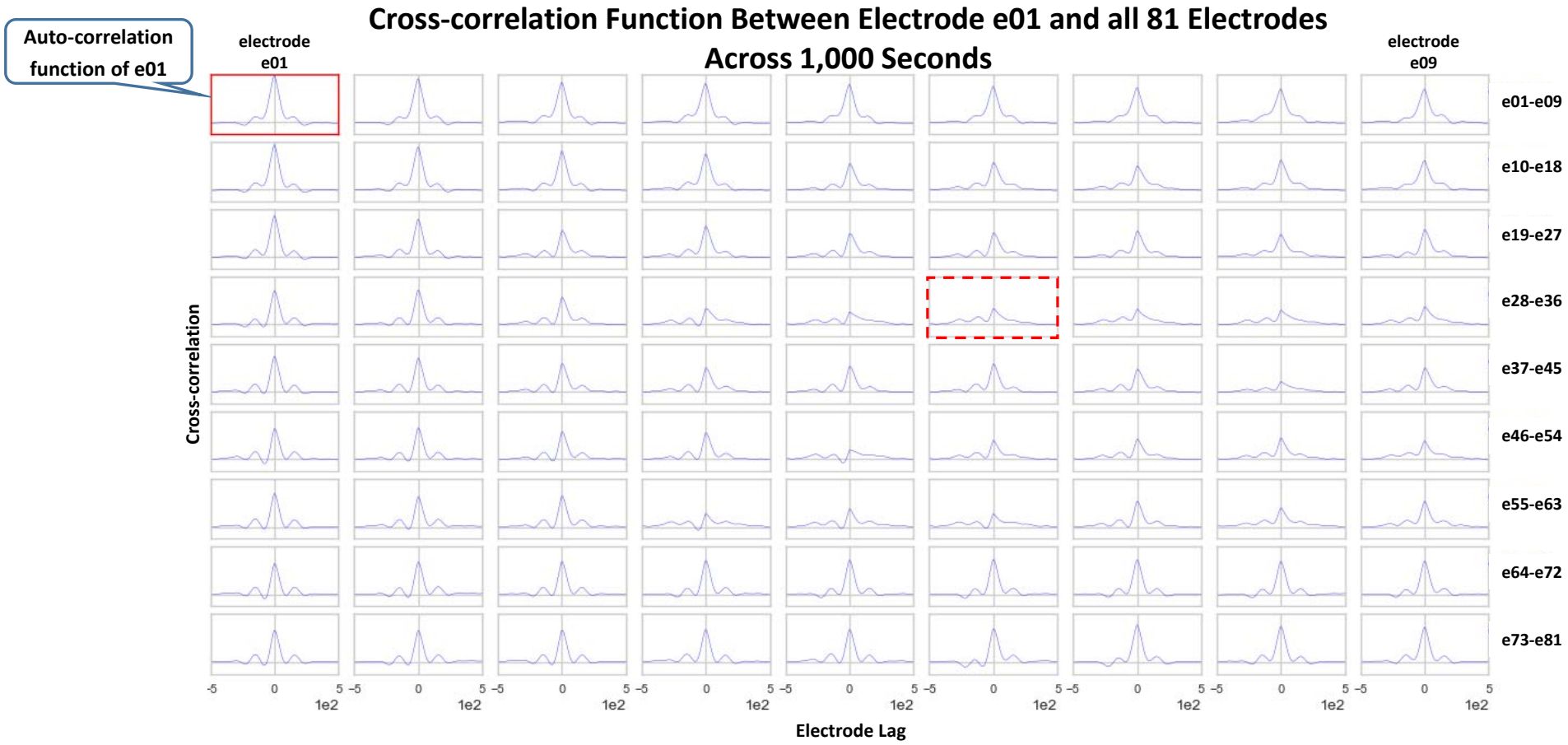
Scatter Plot / Covariance Matrix



y-axis Electrodes	x-axis Electrodes Covariance				
e14-e17	e21-e25	e30-e35	e39-e43	e51-e54	e58-e61
e21-e24	e21-e25	e30-e35	e39-e43	e51-e54	e58-e61
e31-e36	-	e31-e36	-	-	-
e39-e43	-	e31-e36	e40-e43	-	-
e49-e54	-	e31-e36	e40-e43	-	-
e58-e63	-	e31-e36	e40-e43	e50-e53	-

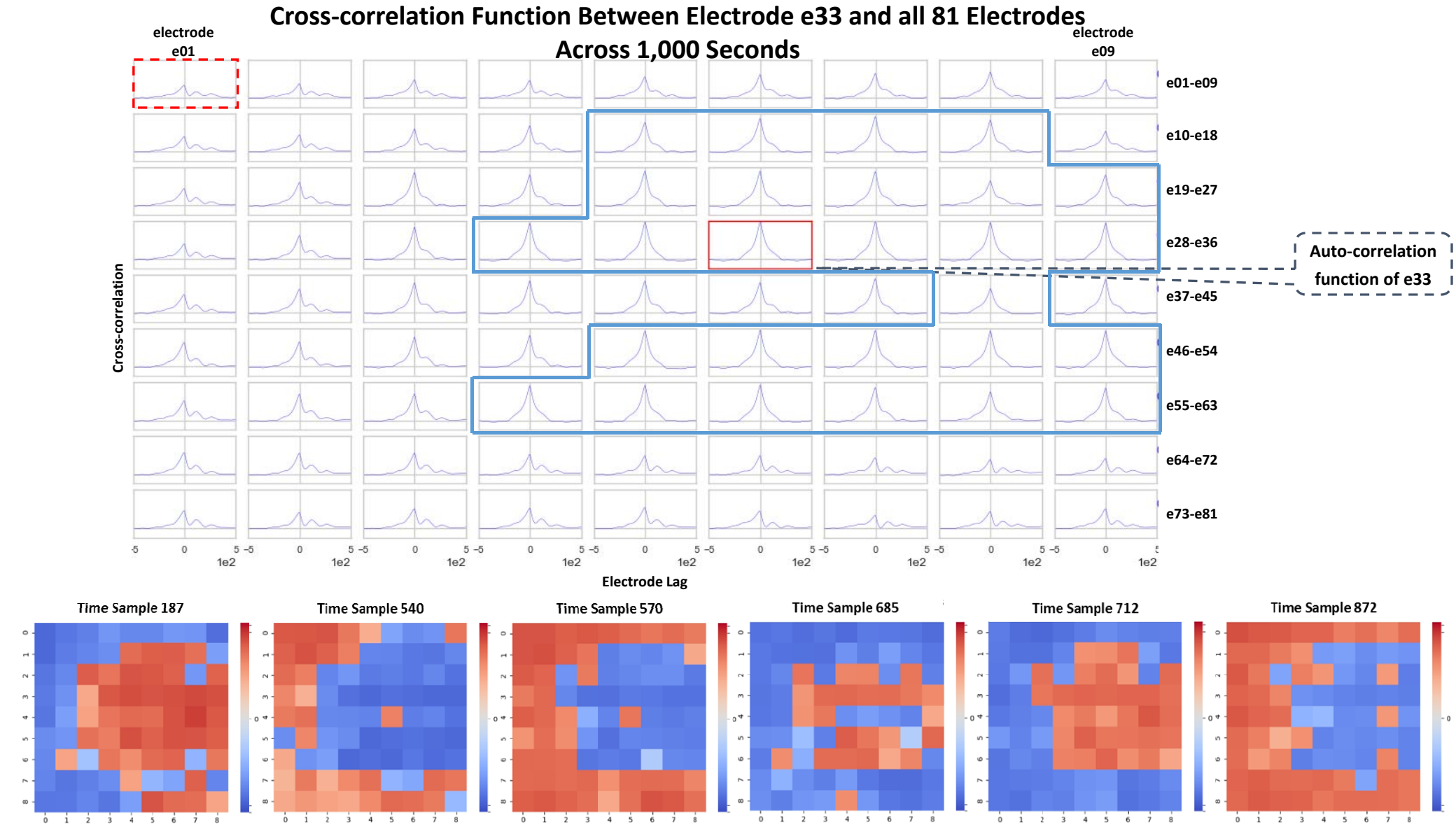
Equivalency Classifications

- Extracting classification groups via the visible variations in pattern densities.

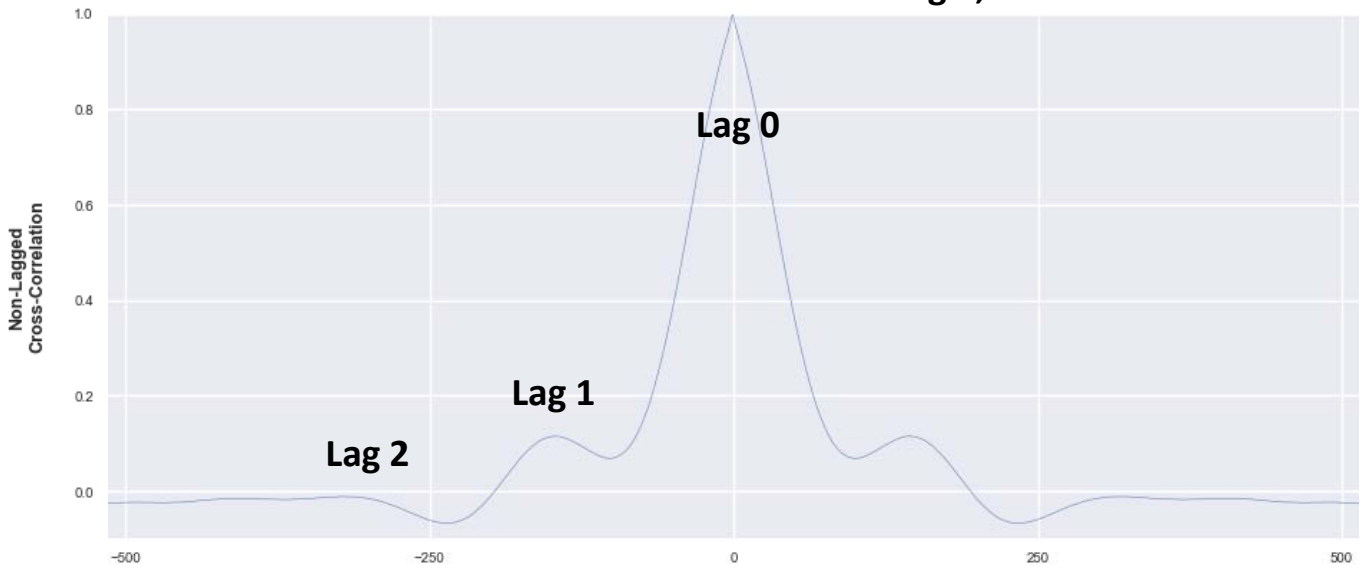


Cross-Correlation Functions

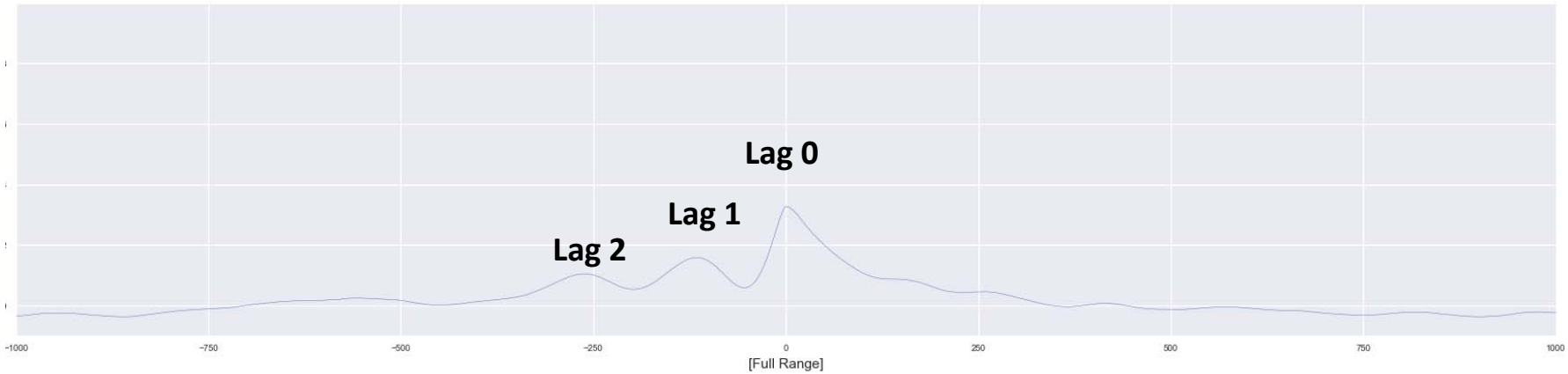
- Observe the asymmetric characteristic of electrode e33 and those similar in shape.
- Observe the remaining electrode classifications that are symmetric and similar in shape to the auto-correlation.


Cross-correlation Function Between Electrode e33 and all 81 Electrodes
Across 1,000 Seconds
electrode
e01
electrode
e09
e01-e09
e10-e18
e19-e27
e28-e36
e37-e45
e46-e54
e55-e63
e64-e72
e73-e81
Auto-correlation
function of e33
Cross-correlation
Electrode Lag
1e2
Time Sample 187
Time Sample 540
Time Sample 570
Time Sample 685
Time Sample 712
Time Sample 872

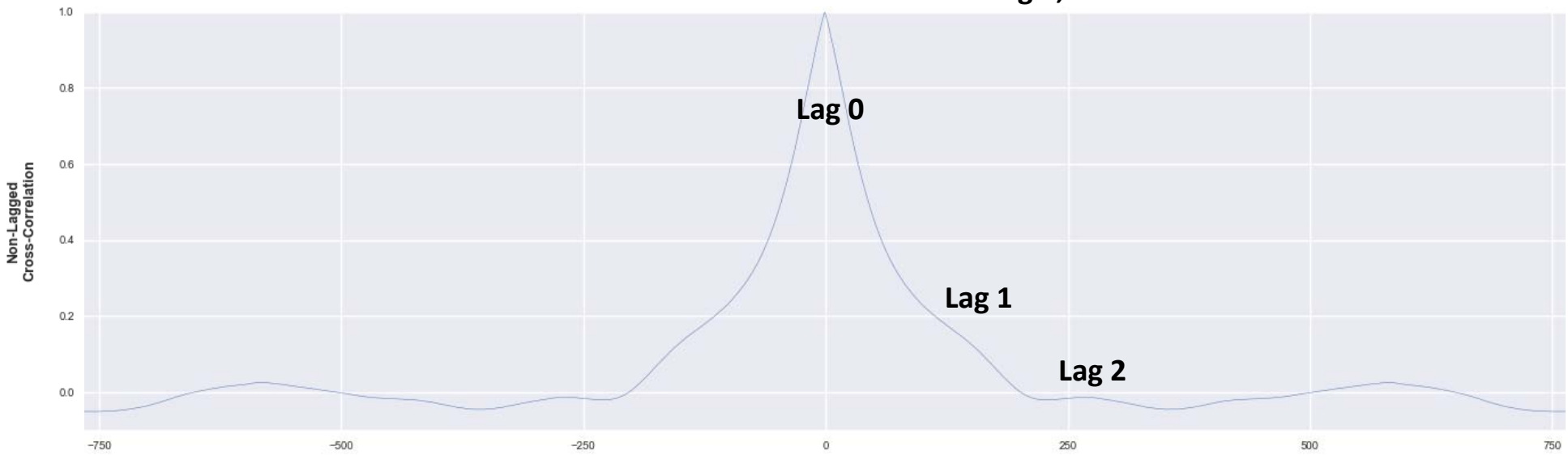
Auto-Correlation Function of Electrode e01 using 1,000 Seconds of Data



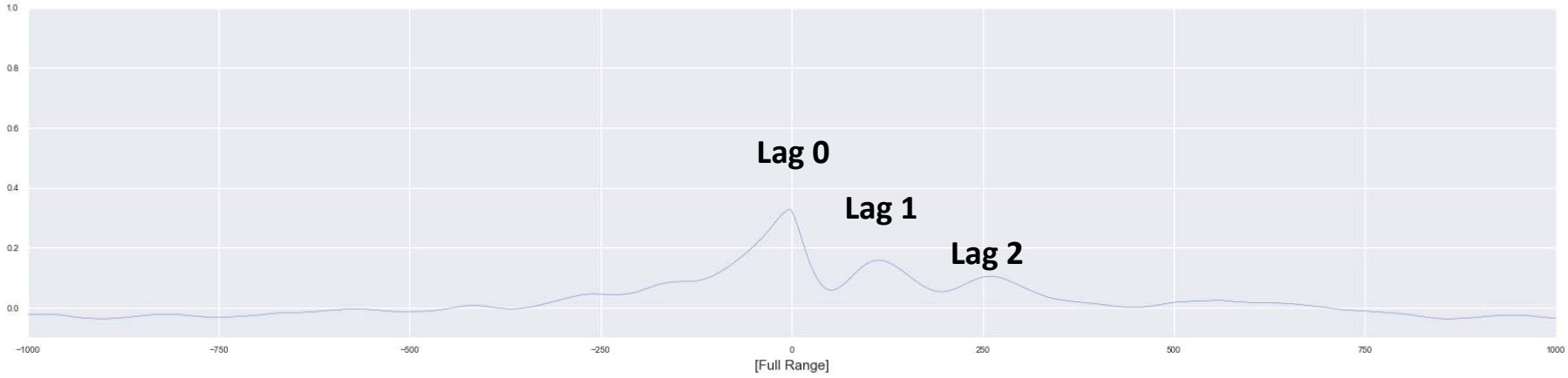
Cross-Correlation Function of Electrodes using 1,000 Seconds of Data
Electrodes e01 vs. e33



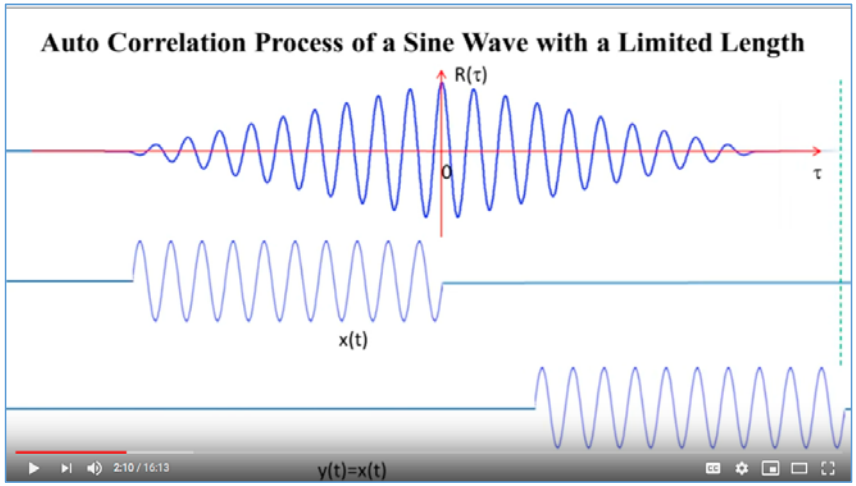
Auto-Correlation Function of Electrode e33 using 1,000 Seconds of Data

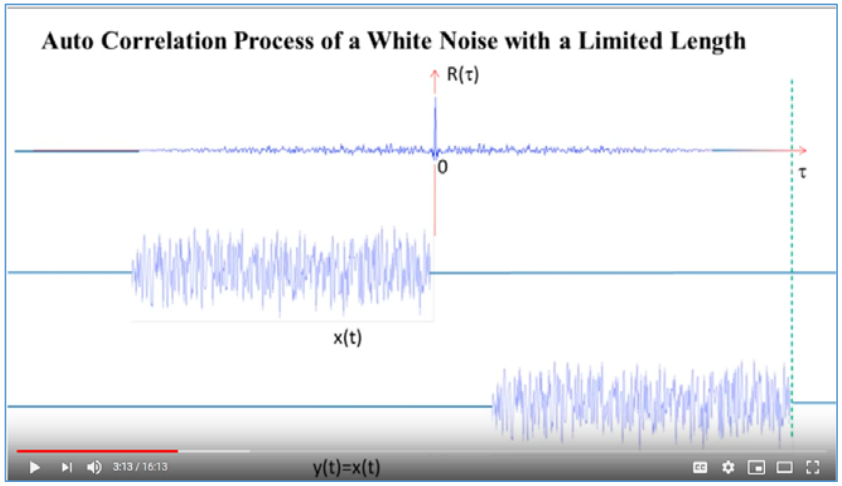


Cross-Correlation Function of Electrodes using 1,000 Seconds of Data
Electrodes e33 vs. e01



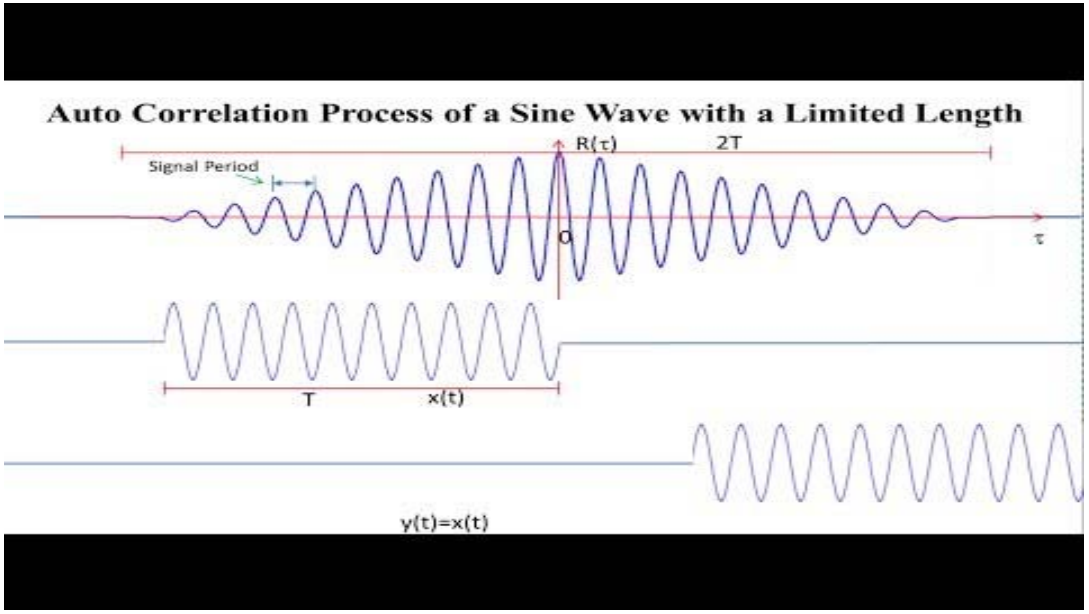
Explanation of Cross-Correlation Function Characteristics





Sine Wave

‘Brain Wave’

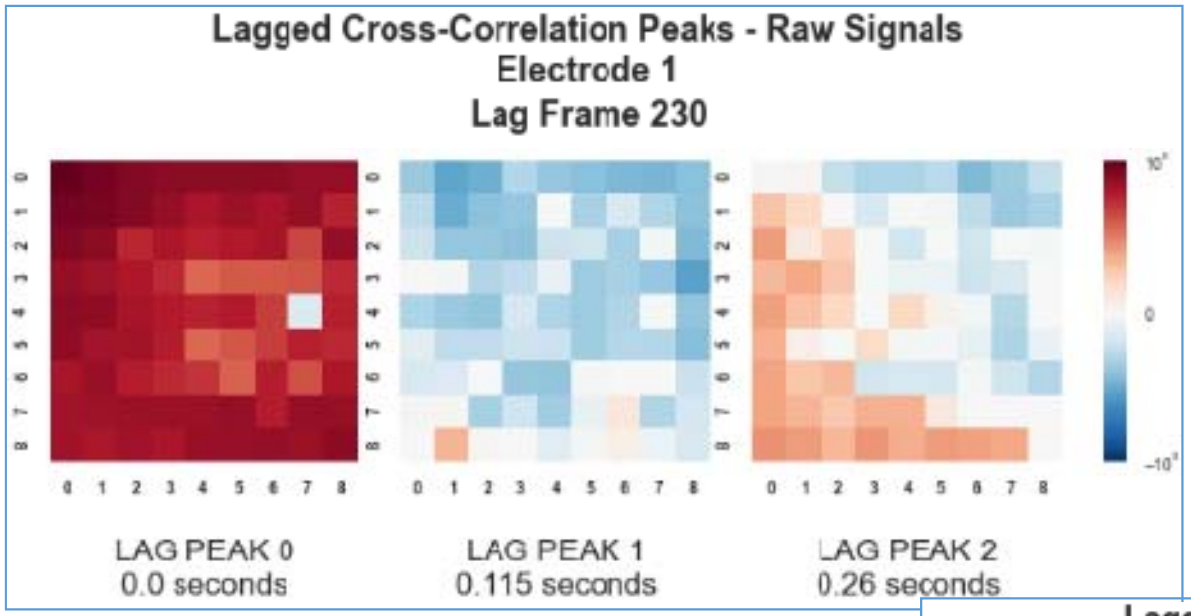


https://youtu.be/L6YJqhbsuFY

Apply ‘Human Intelligence’

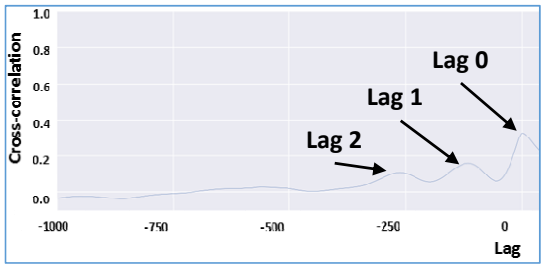
For Pattern Recognition

What Does a Human See?



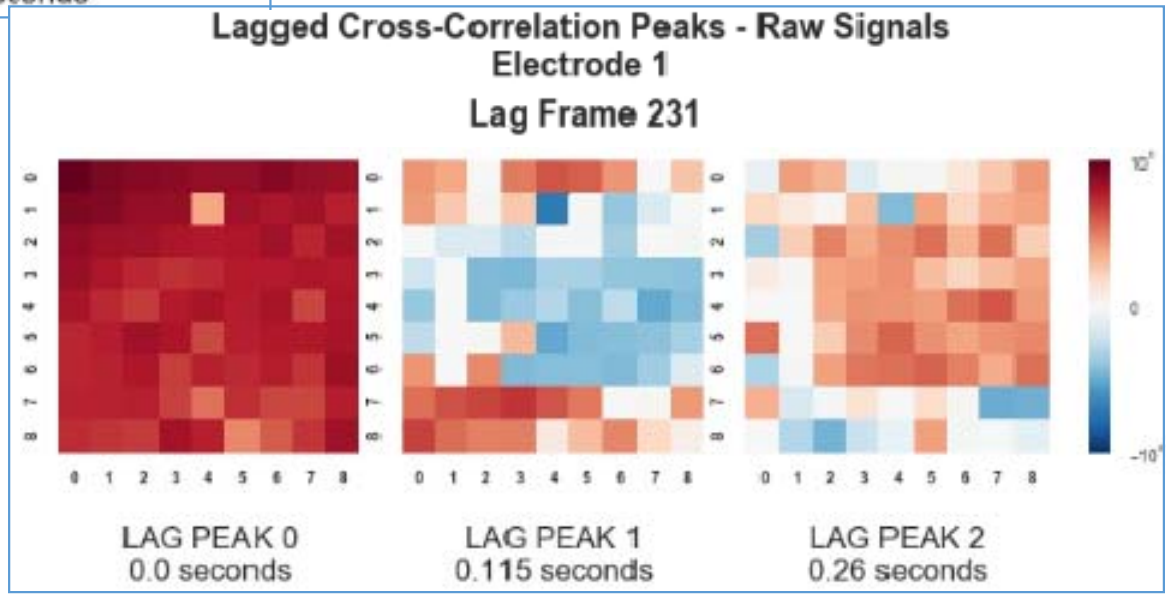
Human Lag Peak Analysis vs. Electrode Geometry in Space

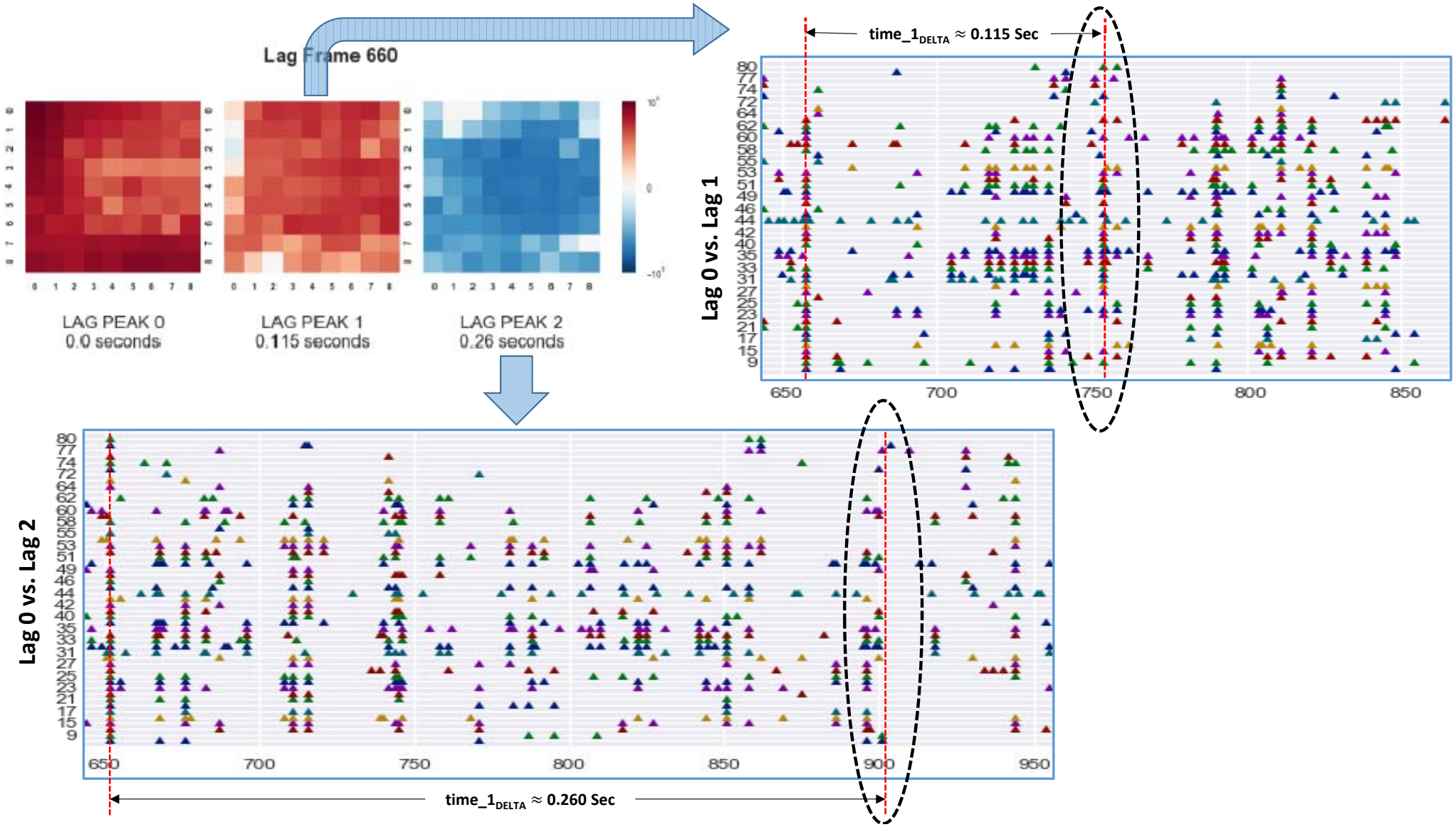
- How are the lag peaks correlated with the main peak and with each other?



<u>Pattern Recognition – Human Observation</u>

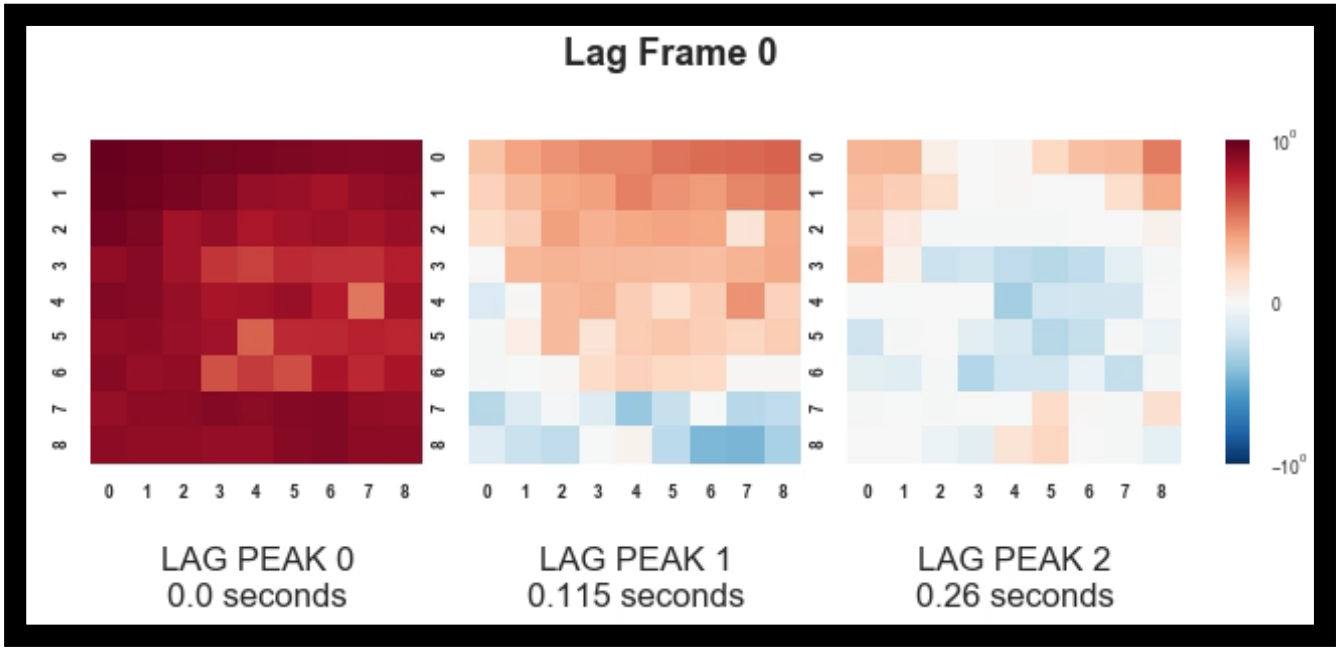
- Determine when 2 or more consecutive frames return nearly identical results.
- Each time step is 1-mSec, making human observable pattern recognition a very challenging method to employ.




Lag Frame 660
LAG PEAK 0
0.0 seconds
LAG PEAK 1
0.115 seconds
LAG PEAK 2
0.26 seconds
time_1DELTA ≈ 0.115 Sec
Lag 0 vs. Lag 1
650
700
750
800
850
Lag 0 vs. Lag 2
650
700
750
800
850
900
950
time_1DELTA ≈ 0.260 Sec

Pattern Recognition

- When specific elements of each of the 3 plots give similar cross-correlation magnitudes, the likelihood of electrode signal identification is increased.
- An even stronger likelihood is achieved when the frame-to-frame visualization is nearly identical for the identified electrode signal(s).



Future Work

What Does a Computer See?

Recommendation:

- Apply Artificial Intelligence and Machine Learning algorithm analysis against the Utah Array dataset.
- Machine Learning is particularly good at finding patterns within large datasets.