Sharif University of Technology
Electrical Engineering School

Advanced Neuroscience HW4

INVESTIGATION OF CORTICAL TRAVELING WAVES IN ARRAY DATASET

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Part.1 - Pre-Processing of Data

We keep the clean trials which the dataset has given us their numbers.

Part.1.1 - Removing Pink Noise

We know that all raw biological signals have a 1/f spectrum on their power spectrum which is called pink noise. Pink noise should be removed because it makes lower frequencies to have high powers and because of that, information in higher frequencies will be lost. In order to remove the pink noise, at the first, I've calculated the power spectrum for each trial of each channel. power spectrum is power of two of single side band amplitude spectrum. Then we fit a line to the log-log power spectrum of each signal. Be careful that the fitted line's slope should be forced to -1 since 1/f in log-log scale has a slope of -1. Here's the result of the fitted line to a log-log scale of a trial of an electrode:

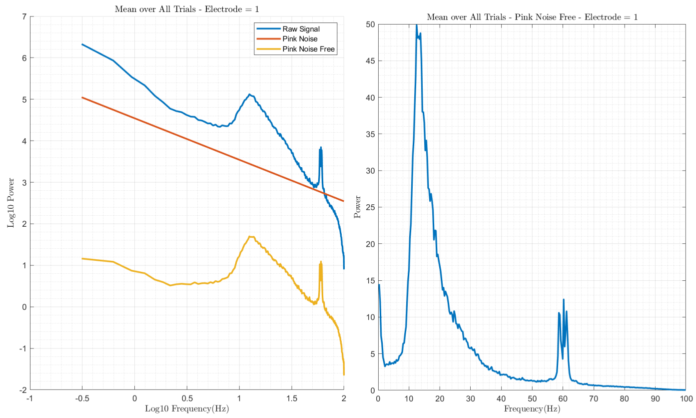

Figure 1: Raw Signal - Fitted Pink Noise - Removed Pink Noise Signal

As you can see in the left log-log plot, a line with scope of -1 is fitted to our raw data and then removed from the raw signal. In the right plot, you can see the power spectrum which its showing that this electrode has a dominant frequency of around 11-12 Hz.
Before calculating the dominant frequencies of electrodes, to prove that we have removed the pink noise correctly, we plot the power spectrum averaged over all trials of all electrodes:

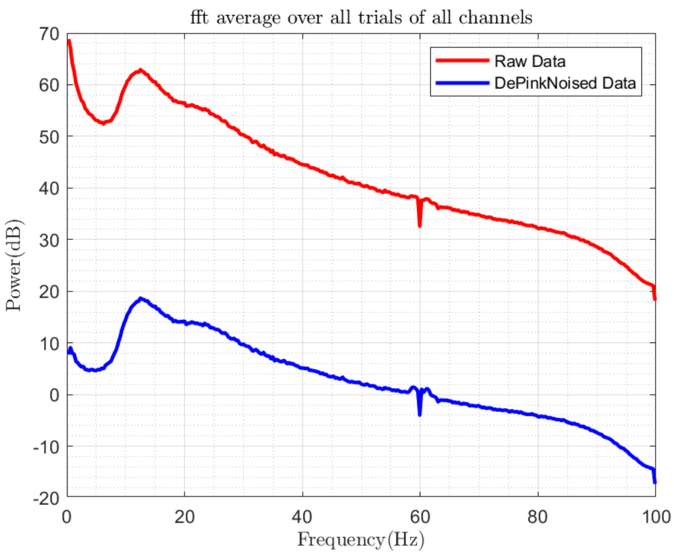

Figure 2: Raw Signal - Removed Pink Noise Signal - Averaged Over All Trials of All Electrodes

As you can see, in Fig.2, power of low frequencies are lowered and it seems to have a mean frequency dominant of around 12 Hz.
Now to find the most dominant frequency of each electrode, we find the frequency which the ,averaged over all trials of that electrode power spectrum, is maximum. Here's the result:

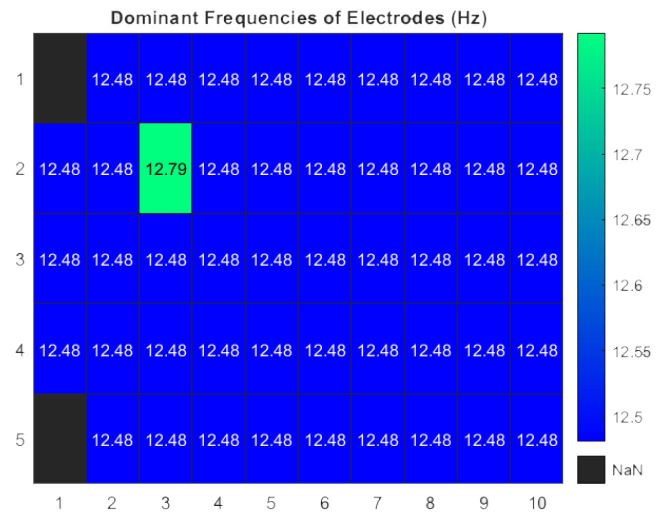

Figure 3: Raw Signal - Removed Pink Noise Signal - Averaged Over All Trials of All Electrodes

Part.1.2 - Electrodes Clustering

As you saw in Fig.3, all of the electrodes' frequency dominants were 12.48 Hz but one electrode which is 12.79 Hz. This is a very good result since we can put all electrodes in one cluster and it makes our spatial distribution more continuous.

Part.1.3 - Time Frequency Analysis

Using short time Fourier transform (STFT), at first, we calculate power vs time and frequency for each trial of each electrode. Then like part.1.1, we removed pink noise in the frequency dimension by fitting by a line with scope 1. Here‘s the result for both raw and de-noised signal averaged over all trials of all electrodes:

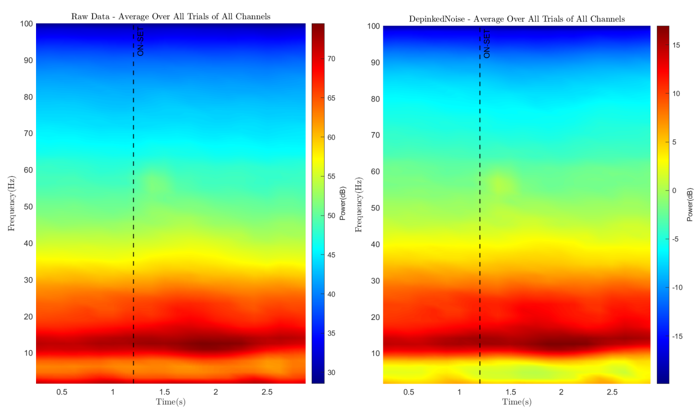

Figure 4: Power vs Time & Frequency for Raw and De-Noised Signal

Part.1.4 - Analysing Part.1.3 result

As you can see in Fig.4, after removing pink noise, we have very low frequency components and it seems that the dominant frequencies are around High theta(theta = [8 12]Hz) and low Beta(Beta = [13 30]Hz). It seems that after the on-set, we have more power in our frequency band of interest which is around 12 Hz. But also we have high powers in that frequency band before the on-set which is logical since the task involve a high activity of working memory too. Comparing to Hatsopoulos et.al 2006, we have almost the same high power frequencies, Both from 10 to 20 Hz:

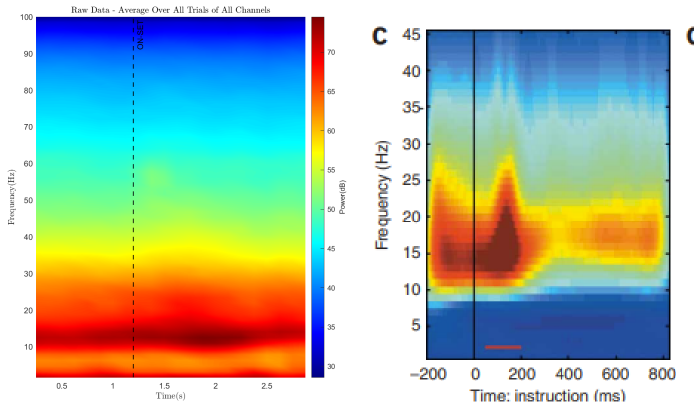

Figure 5: Power vs Time & Frequency for De-Noised Signal Comparing to Hatsopoulos et.al 2006

Part.2 - Analysis of Traveling Wave (Phase Propagation)

Now by results that we get from pre-processing parts, we are going to analyze traveling wave on our data.

Part.2.1 - Band Passing the Data

As we saw in, part.1.1 and .1.2, all of our electrodes have a dominant frequency of around 12.5 Hz. So in order to bandpass the data, we design a second order Butterworth filter with fc of 12.5 Hz and bandwidth of 1.5 Hz. So we band pass the signals from 11 to 13 Hz and analyze the wave in this frequency. Here‘s the designed filter and filtered signal:

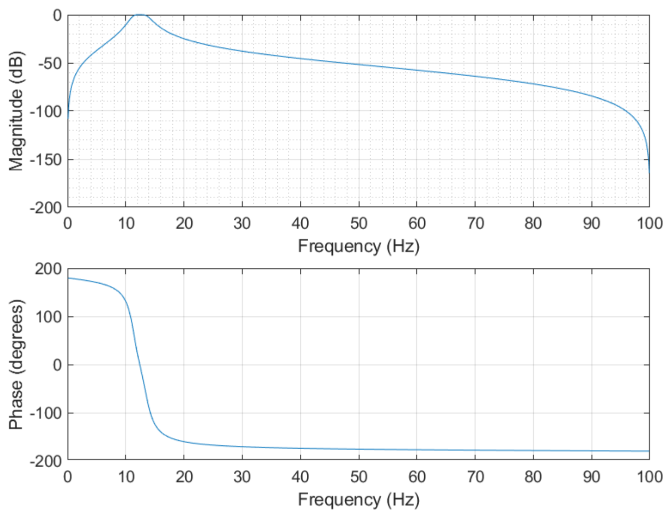

Figure 6: Second Order Butterworth Designed Filter

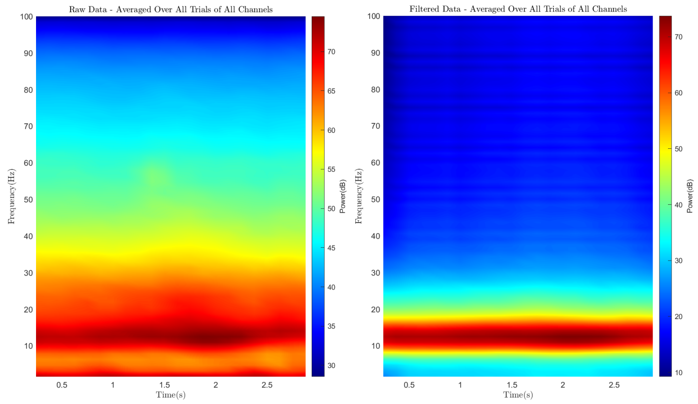

Figure 7: Power vs Time & Frequency for Raw Signal and Band Passed Signal

Part.2.2 - Instantaneous Phase of Filtered Signal

Now that we have our data ready, we first have to calculate the first principle parameter in traveling wave which is the instantaneous phase for all trials of all electrodes. At last we would have a 4-D matrix ([5 10 490 641]) which 5*10 is the size of the electrode array, 490 is the number of trials and 641 is the time samples. How do we calculate the instantaneous phase?
Using Hilbert transform of the each signal, we create the analytic signal for each trial of each electrode and extract the phase:

$$\begin{aligned} S_{\mathrm{a}}(f) &\triangleq \begin{cases} 2S(f), & \text{for } f>0, \\ S(f), & \text{for } f=0, \\ 0, & \text{for } f<0 \end{cases} \\ &= \underbrace{2\,\mathrm{u}(f)}_{1+\mathrm{sgn}(f)} S(f) = S(f) + \mathrm{sgn}(f)S(f), \end{aligned}$$

Figure 8: Fourier Transform of Analytic Signal

$$\begin{aligned} s_{\mathrm{a}}(t) &\triangleq \mathcal{F}^{-1}[S_{\mathrm{a}}(f)] \\ &= \mathcal{F}^{-1}[S(f) + \mathrm{sgn}(f)\cdot S(f)] \\ &= \underbrace{\mathcal{F}^{-1}\{S(f)\}}_{s(t)} + \overbrace{\underbrace{\mathcal{F}^{-1}\{\mathrm{sgn}(f)\}}_{j\frac{1}{\pi t}} * \underbrace{\mathcal{F}^{-1}\{S(f)\}}_{s(t)}}^{\text{convolution}} \\ &= s(t) + j\underbrace{\left[\frac{1}{\pi t} * s(t)\right]}_{\mathcal{H}[s(t)]} \\ &= s(t) + j\hat{s}(t), \end{aligned}$$

Figure 9: Analytic Signal

$$\phi(t) \triangleq \arg[s_{\mathrm{a}}(t)]$$

Figure 10: Instantaneous Phase

Part.2.3 - Wave (cos(phi))

By taking the cosine of the instantaneous phase of each electrode of a selected trial (here for trial 259), we plot the calculated cosine over time. Here are some snapshots to show the wave that we see: (recorded demo can be found on the uploaded zip)

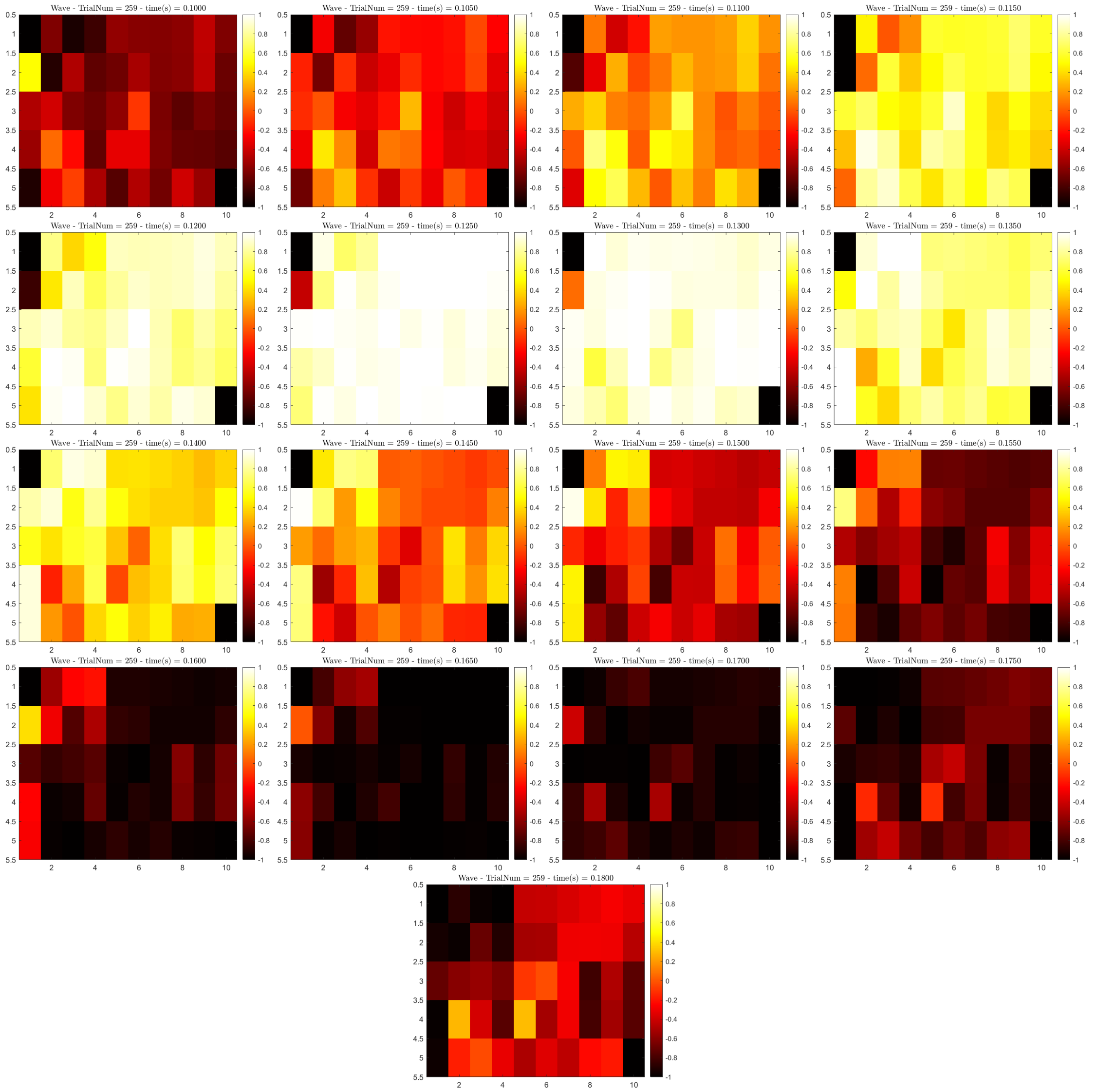

Figure 11: cos(phi) - One Period of a Wave in Trial 259

As you can see in Fig.11, a period of wave (except the last one which is the start of the new wave) propagates the array in 0.0750 seconds. Seems that the wave starts from a little up right, to the a little bottom left (20 to -170 deg). By clicking HERE , you can see the demo.

Part.2.4 - Measuring the Wave

We observed a wave in previous part but in order to make certain that is a wave or that is good wave, we have to some measurings. We plot gradient Vectors and Contour of Phase, Gradient Vectors Direction Histogram, Average Gradient Vectors , Phase Gradient Directionality (PGD) and Speed of the wave.

0.1 Part.2.4.1 - Gradient Directionality and Contour

Here we plot contour of instantaneous phase and gradients calculated for each of the electrodes in time for trial 259. Here are some snopshots in the same time interval of the Fig.11 which we showed the wave:

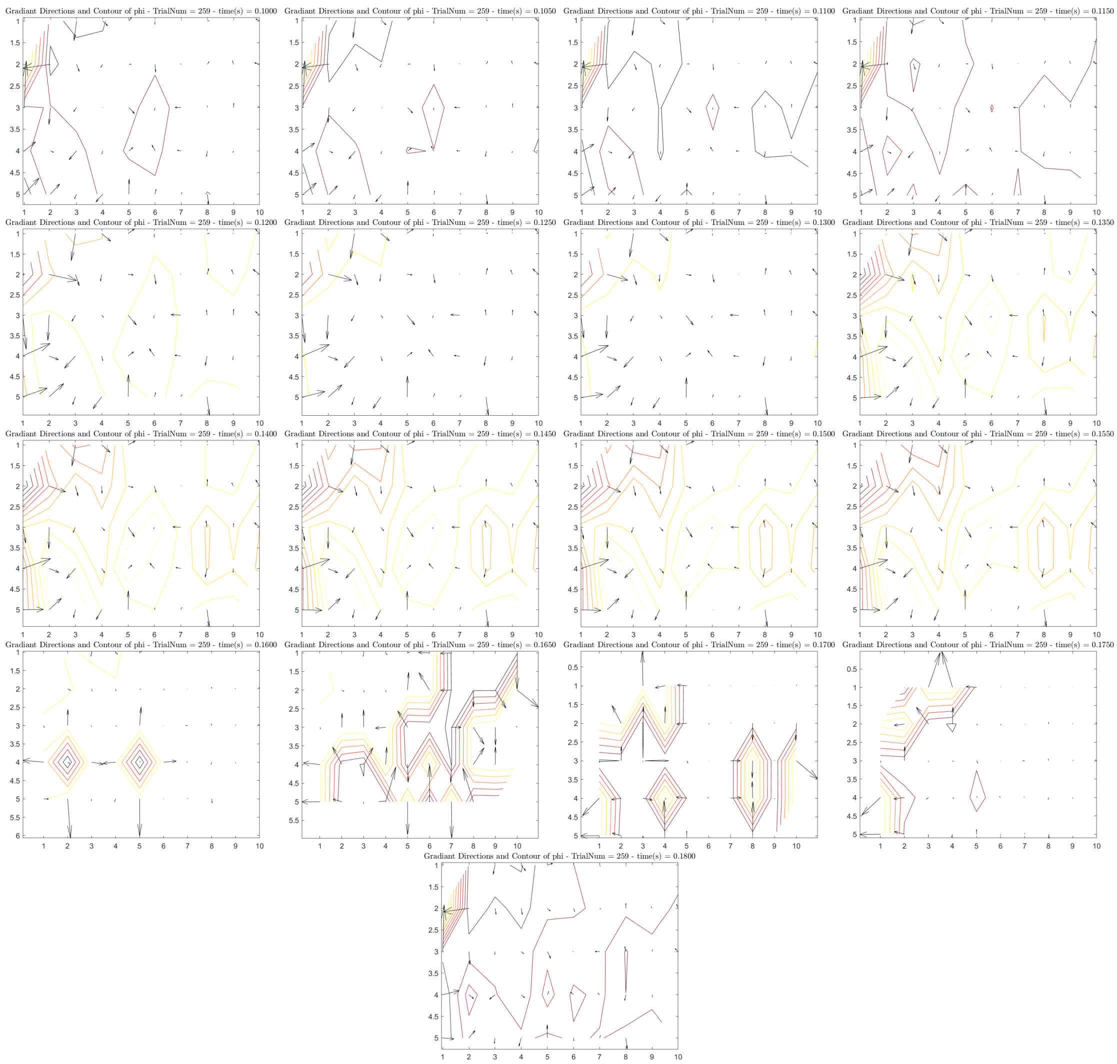

Figure 12: Contour of Phase and Gradient Vectors - One Period of a Wave in Trial 259

As you can see in Fig.12, in most of the samples, the biggest vectors have a direction of right or left ([0 20]deg or [180 200]deg) or it seems that the mean of the gradient vectors have this directions, just as we observed with the cosine of phase demo in previous part. At the end, it‘s better to plot the gradient vectors direction histogram to confirm the direction of the wave that we saw in the first part (cosine of phase).
You can see the demo of this part either attached in the zip file or by clicking HERE

0.2 Part.2.4.2 - Gradient Directionality Histogram

To make sure about the direction of the gradients which leads us to the direction of the wave (direction of the wave is +180deg of the direction of the averaged gradient vector), we here plot the histogram of the gradient vectors by taking atan2 of them for trial 259. Here‘s the result in the same time interval of the previous parts:

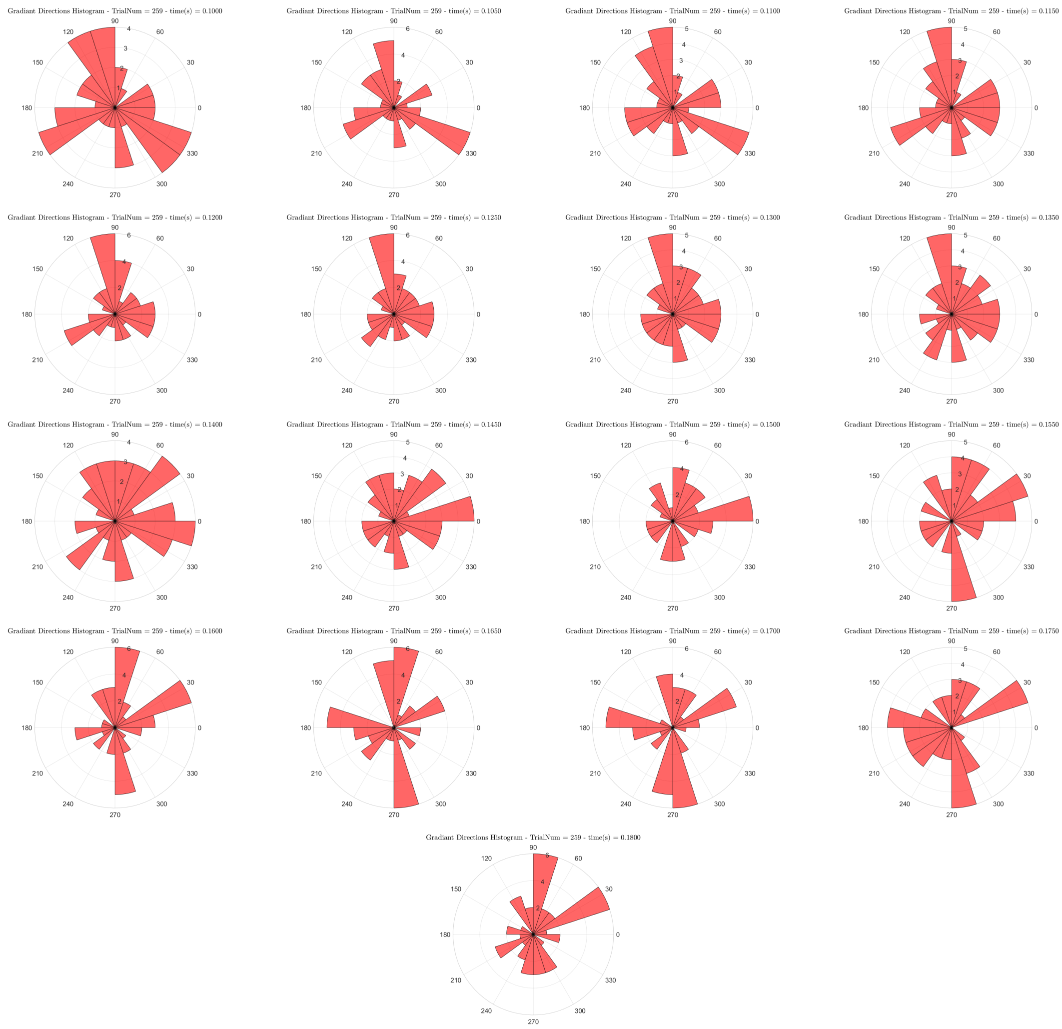

Figure 13: Gradient Directionality Histogram for - One Period of a Wave in Trial 259

As you can see, it seems that the average of this directions are again around 0 to 20 deg or 180 to 200 deg which confirm previous results. To see the demo, check out the zip file or click HERE.

0.3 Part.2.4.3 - Average Gradient Directionality

In the end, nothing is better than to plot the averaged gradient vector over all electrodes in each sample time. Here are some snapshots in the time interval like previous parts:

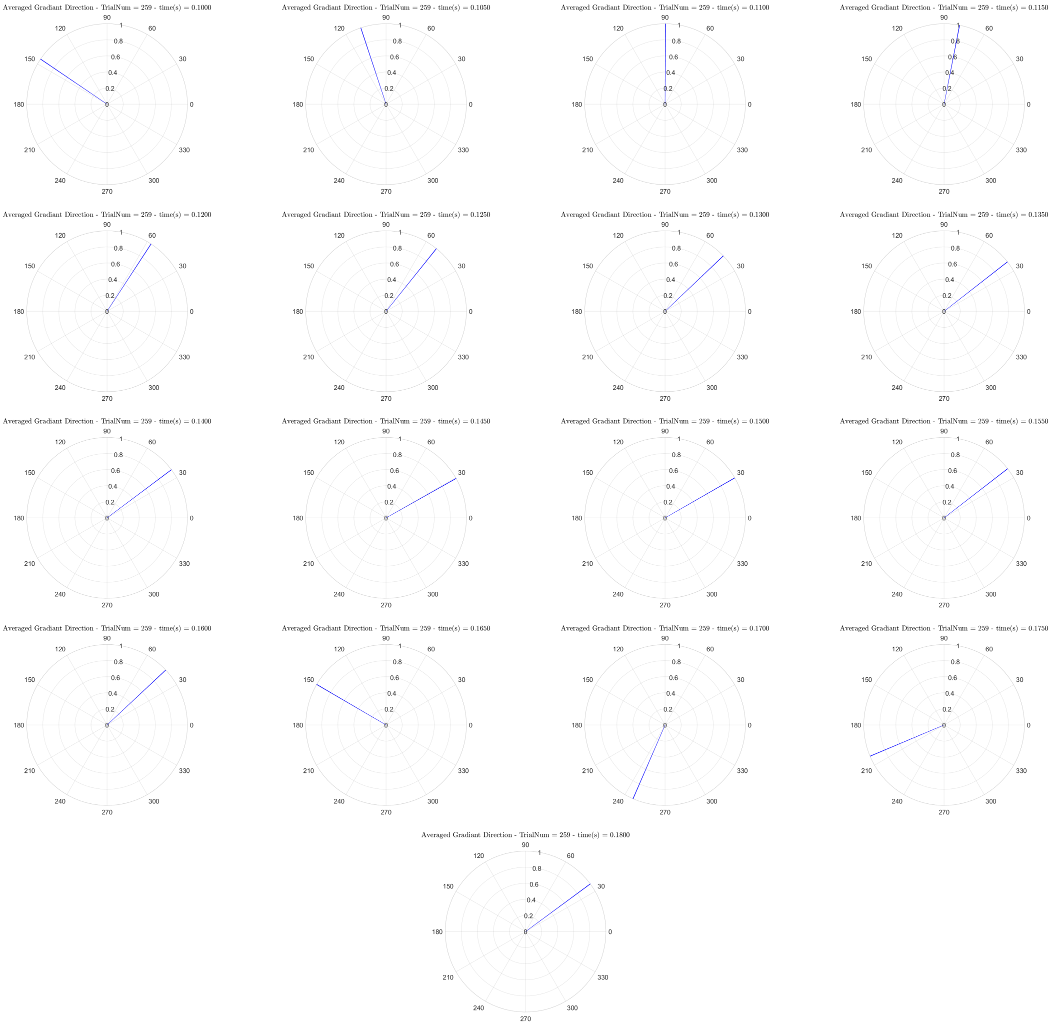

Figure 14: Average Gradient Directionality - One Period of a Wave in Trial 259

As you can see, at most of the time samples, the averaged direction is around our estimate ([0 20]deg or [180 200]deg). To see the demo, check out the zip file or click HERE. The reason of existence of the directions that are not in ([0 20]deg or [180 200]deg) is maybe that our signal in that time doesn't have enough power and so this jumps in phase will be created.

At the end of HW, we plot the histogram of all trials of all electrodes and it confirm all of our guesses with more accurate result.

0.4 Part.2.4.4 - Phase Gradient Directionality (PGD)

So let's talk about how consistent and how good our wave (if is there any!) is. In order to measure and quantify our wave we calculate PGD over time for our selected trial which is 259 and here's the result in the previous time interval:

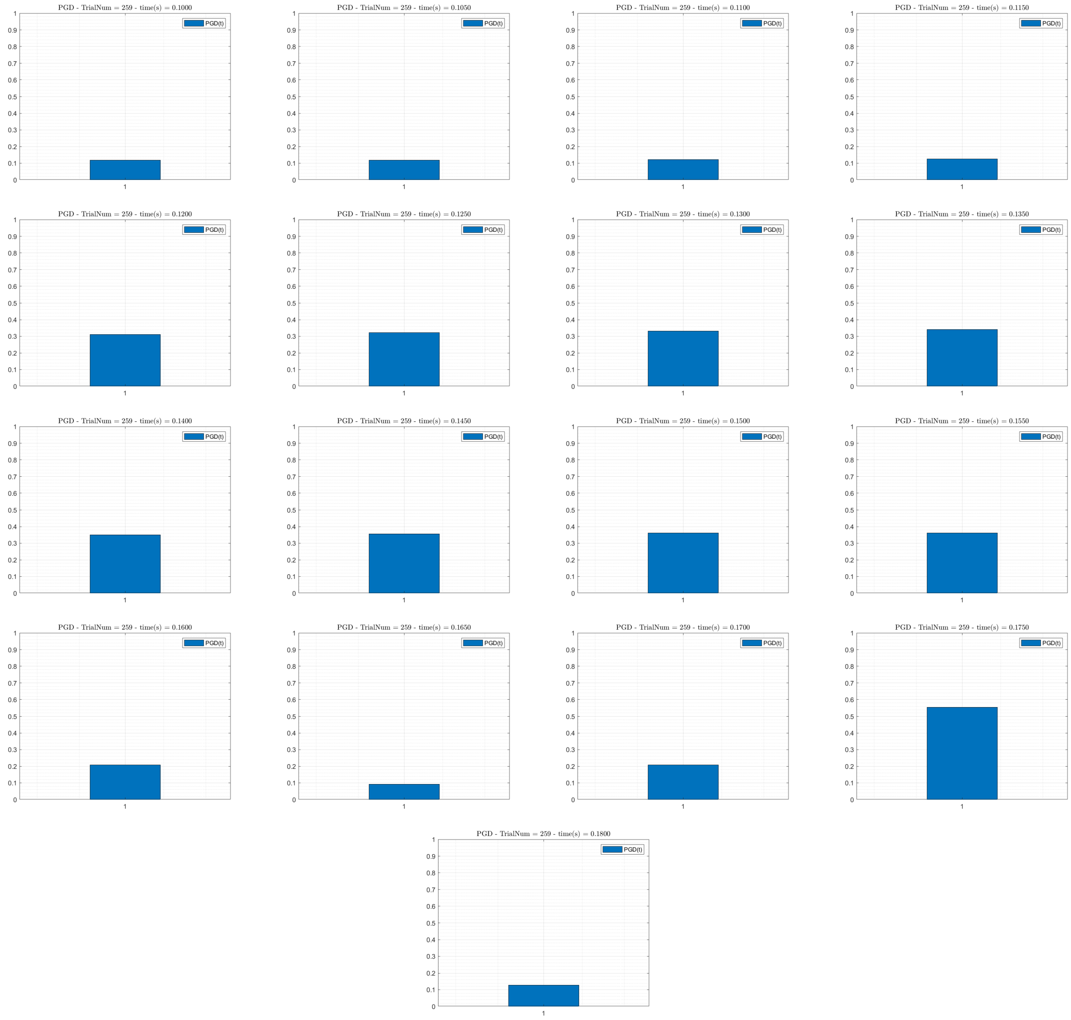

Figure 15: PGD - One Period of a Wave in Trial 259

As we can see, we have relativly high PGDs but in order to have a better feeling, let's plot the histogram of PGDs of this trial over all time, too. Before showing the histogram, you can checkout the demo, check out the zip file or click HERE. Since the task involves working memory too, we don't except to have higher PGDs after onset for sure. It could be less or higher and we can have good waves before onset too. For example in this trial (259), the average PGD after onset is less then the average PGD before onset: (check out the demo!)

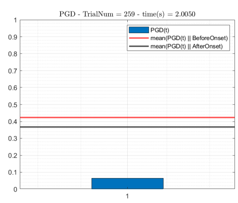

Figure 16: Averaged PGDs and the Last Time Sample PGD - Trial 259

So let's plot the histogram that I said earlier:

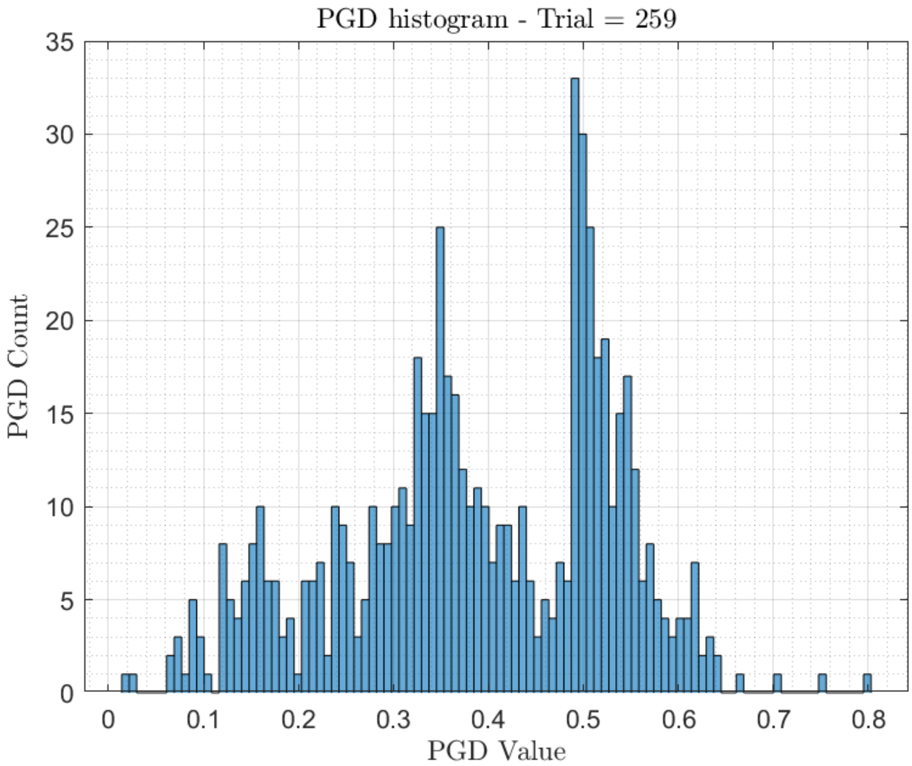

Figure 17: Histogram of PGDs for all times - Trial 259

As you can see, we have high values of PGD indicating the existence of good waves. At the end of the HW, I will plot the PGDs histogram over all trials for a better result.

0.5 Part.2.4.5 - Speed

We can plot speed of the time interval we had in previous parts but it makes sense, so I just put the demo HERE to watch. Let's plot the histogram of speed for trial 259 too:

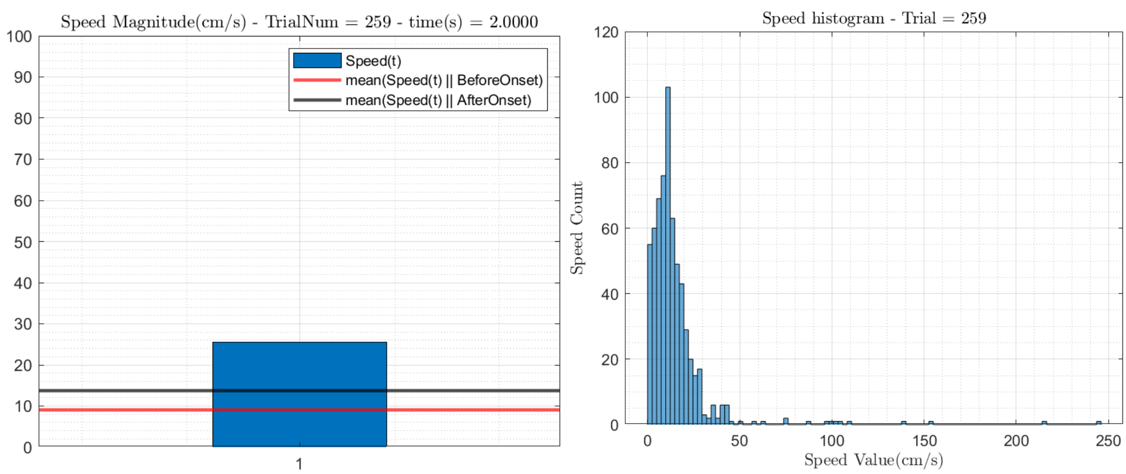

Figure 18: Averaged Speeds and the Last Time Sample Speed and Histogram of Speeds for all times - Trial 259

At the end of the HW, I will plot the speeds histogram over all trials for a better result. But Fig.19 is showing mostly the speeds around 10 to 80 cm/s which is logical according to the literatures.

0.6 Part.2.4.5 - Demo of All Calculated Wave Properties

Now we plot all the properties in one figure.HERE's the demo:

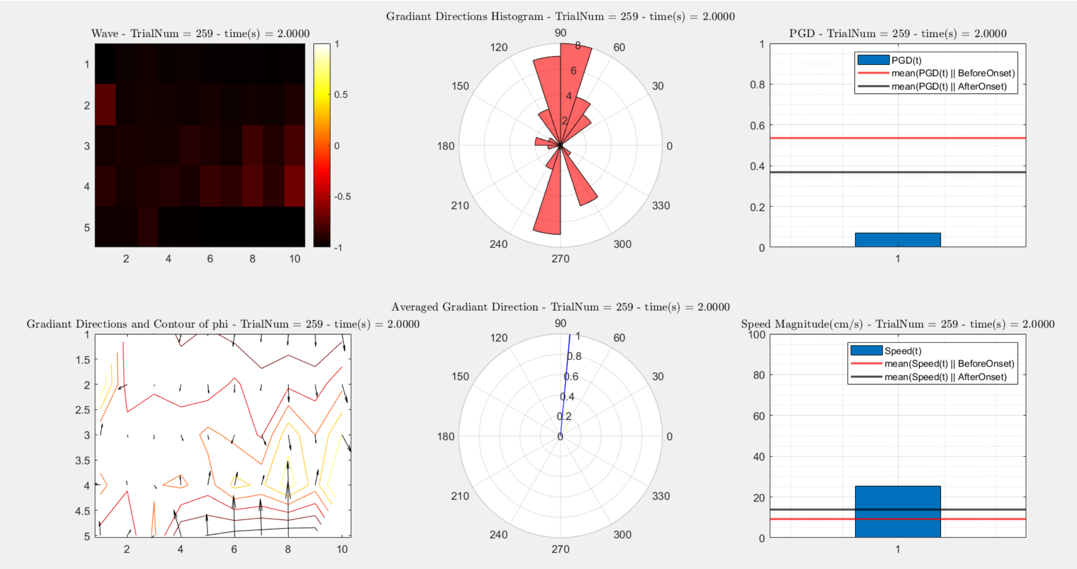

Figure 19: All Wave Properties Last Time Sample - Trial 259

Part.2.6- Preferred Direction of the Wave

As we said in previous parts, it seems that the wave direction is around [+10 -170]deg but here we want to make sure if there is any preferred direction, what it is. To do so, I plot the histogram of the mean of the direction of 48 electrode directions over all trials of all times with PGD more than 0.5 and here's the result:

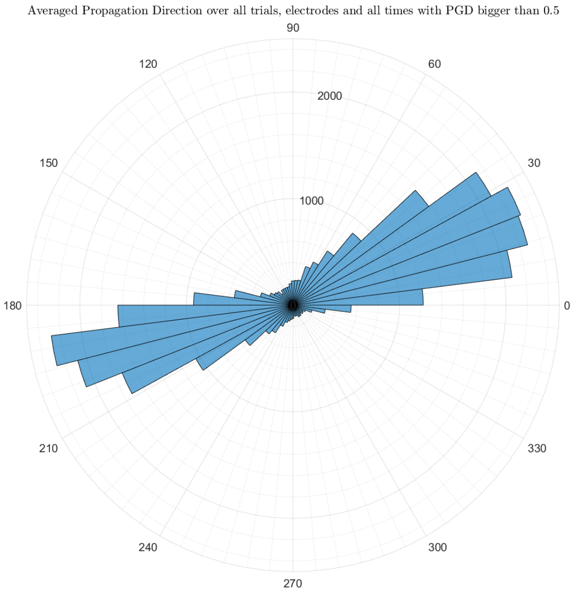

Figure 20: Averaged Gradient Direction Over All Trials of All Times with PGD >= 0.5

As you can see, the propagation direction is what we estimated. It's from top right to bottom left or the inverse.

Part.2.7- Averaged Phase Propagation Speed

As we said in previous parts, it seems that the wave speed is around [10 80]cm/s. Now I plot the histogram of the speed over all trials of all times with PGD more than 0.5 and here‘s the result:

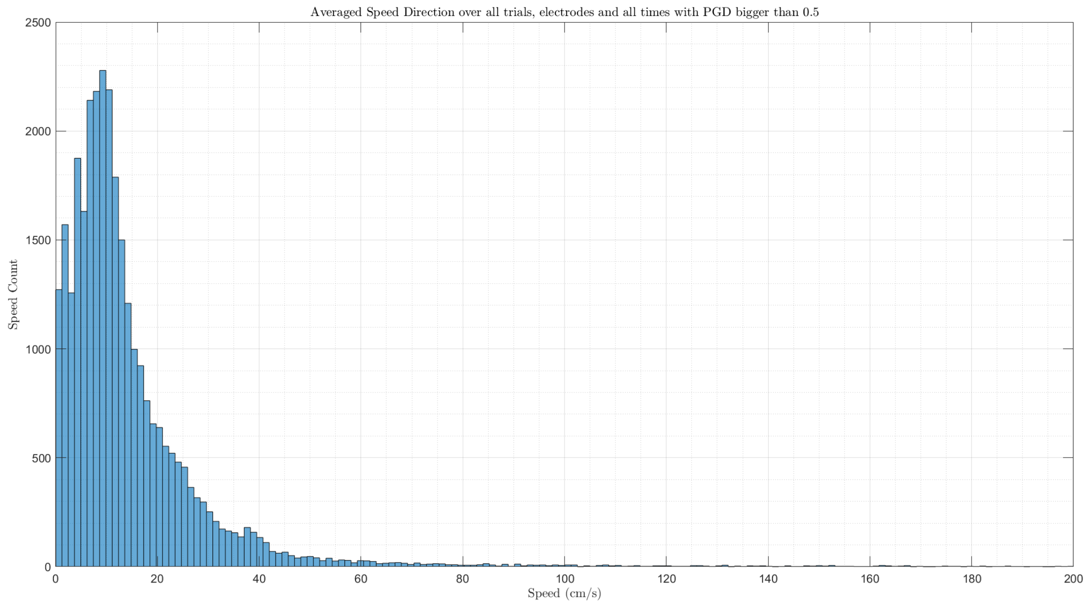

Figure 21: Averaged Gradient Direction Over All Trials of All Times with PGD >= 0.5

Part.2.8- Averaged Phase Gradient Directionality (PGD)

Histogram of PGD over all times of all trials:

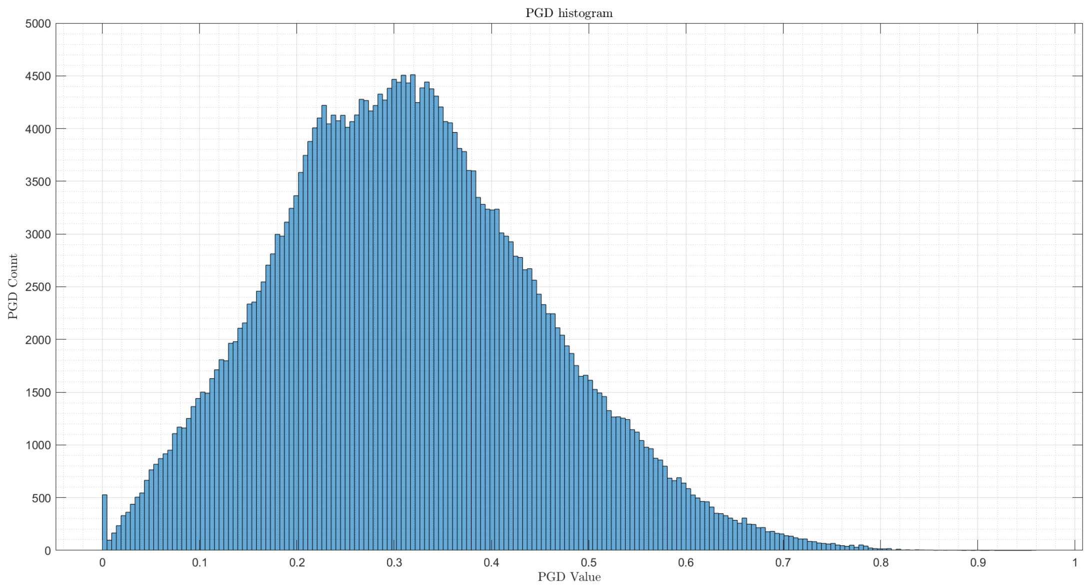

Figure 22: Histogram of All PGDs over trials and times

As we can see, we have both high and low PGD values corresponding to good quality waves and fluctuations that are not wave or they‘re not a good wave.

Part.2.9- Measuring the Wave by Fitting a Plane to the Spatial Pattern of the Phases

As we now we can fit a plane to the phases of all electrodes at each time and calculate something like PGD which is called alternate PGD. To fit the plane, I have used regress function of MATLAB and HERE's the demo and one snapshot of the demo:

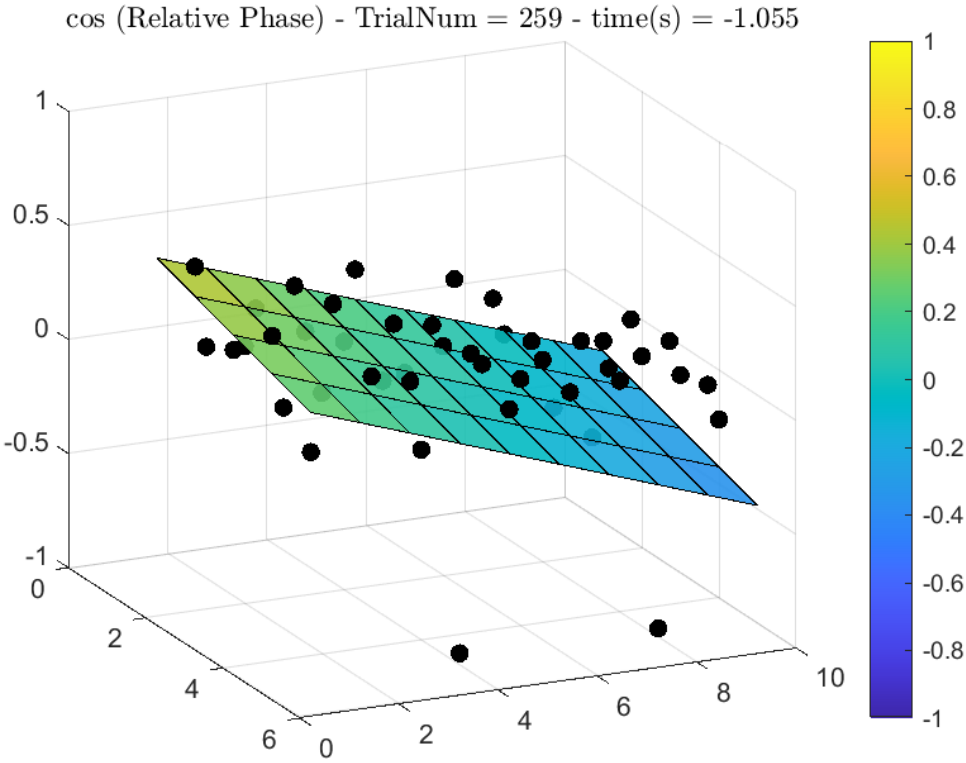

Figure 23: Fitted plane to the Cosine of phase in One Sample Time - Trial = 259

The blacks dot are the residuals.

Part.2.10 - Alternate PGD

To measure the fitted plane and measure the wave, we use these two measures:

$$r = \sqrt{\left[\frac{1}{n}\sum_{i=1}^{n}\cos(\theta_i - \hat{\theta}_i)\right]^2 + \left[\frac{1}{n}\sum_{i=1}^{n}\sin(\theta_i - \hat{\theta}_i)\right]^2}$$

Figure 24: Measure of How Much The Plane Is Fitted Well

$$\rho_{cc} = \frac{\sum_{i=1}^{n}\sin(\theta_i - \bar{\theta})\sin(\hat{\theta}_i - \bar{\hat{\theta}})}{\sqrt{\sum_{i=1}^{n}\sin^2(\theta_i - \bar{\theta})\sum_{i=1}^{n}\sin^2(\hat{\theta}_i - \bar{\hat{\theta}})}}, \quad \text{Circular corrcoef}$$

$$\rho_{adj}^2 = 1 - \frac{(1-\rho_{cc}^2)(n-1)}{n-k-1}$$

ρ_{adj}^2 as *phase gradient directionality* (PGD)

Figure 25: Directional Consistency

By implementing the functions of these two parameters which is attached to my files, HERE's the demo and one snapshot of the demo:

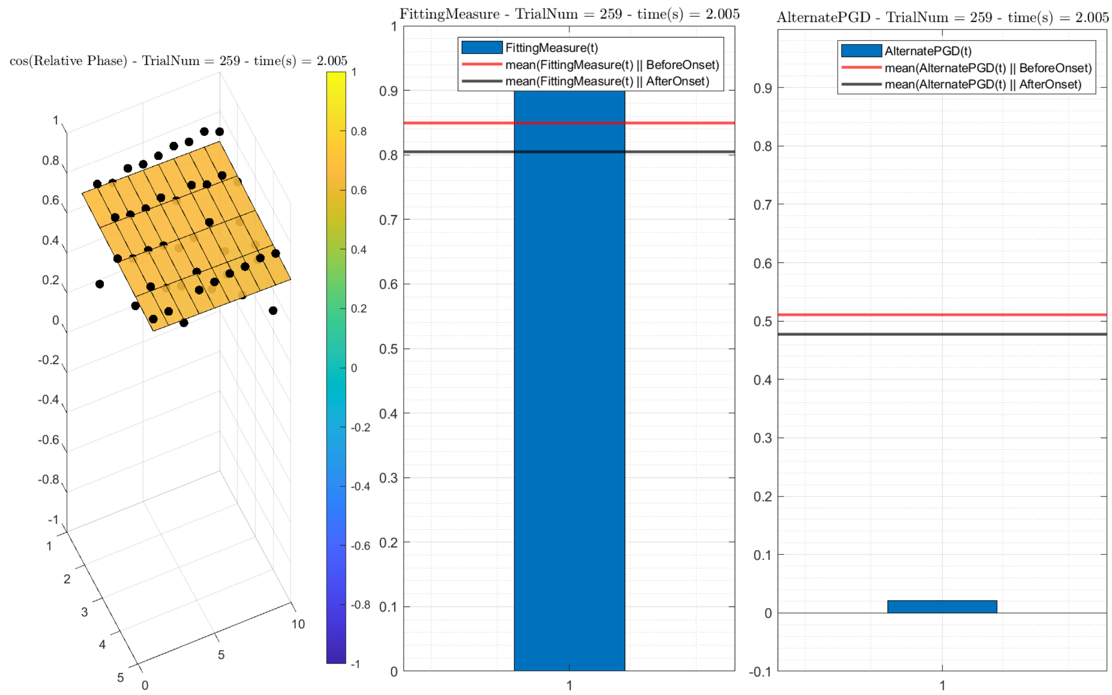

Figure 26: Fitted Plane And the Measure of How Good It's Fitted and Alternate PGD in Last Time Sample - Trial 259

Part.2.11 - Alternate PGD vs Original PGD

Let's check the histogram of these two different measures which come from two different algorithms:

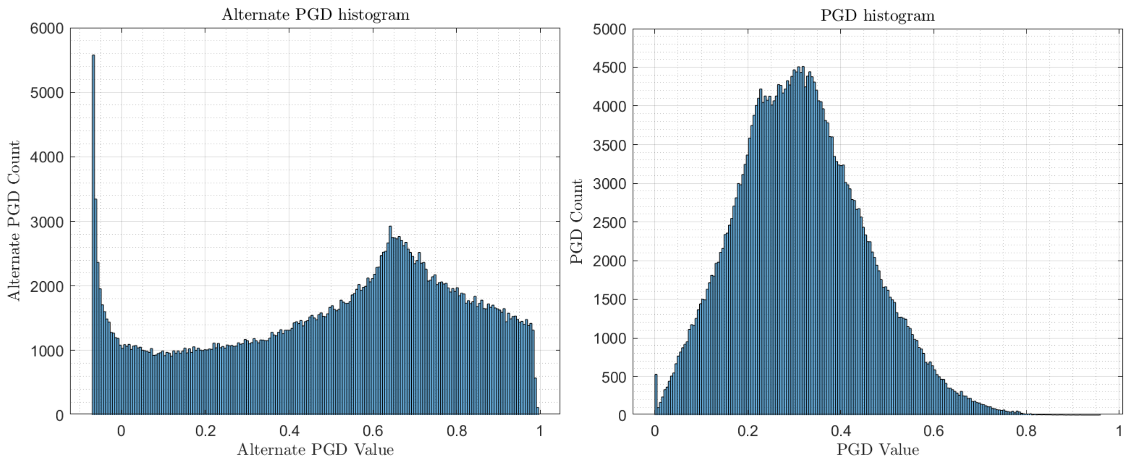

Figure 27: Fitted Plane And the Measure of How Good It's Fitted and Alternate PGD in Last Time Sample - Trial 259

As you see, alternate PGD have higher values too, But in average, it's like the original PGD. Alternate PGD have some negative values too which I don't know why!