**Aalborg University**
*Department of Health Science & Technology*

# "Seizure Onset Detection based on Space Time Frequency Energy Distribution map"

**4th semester on the Master's degree programme,**
Biomedical Engineering and Informatics

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# Abstract

The aim of this project is to investigate a visualization methods effects on detecting epilepsy seizure and its spreading. The visualization method, Space-Time-Frequency Energy Distribution map(STFED map), can presents energy's distribution in 4 dimension. In STFED map, the starting and spreading of the seizure is in a cone shape. With thresholding and mathematical morphology, seizure is classified from normal EEG signals and artifacts.
Totally 10 patients and 53 seizures are participated in the study. The proposed method performance is compared to Support Vector Machine(SVM). The proposed method has slightly weaker performance but it is patient non-specific.

**Lin Wang**

# Preface

The project is completed by group 1075 at 4th semester master of Biomedical Engineering and Informatics at Aalborg University with the main supervisor José Biurrun Manresa.
To guide the reader through the project, part I (Problem Analysis) contains background information on Epilepsy and EEG (1), state of the art(2), problem formulation (3) and aim(4). Part II (Problem Solution) describes the methods(5) applied on the data and the results(6). Part III (Synthesis) includes the Discussion (7) of the results and the final Conclusion (8).


### Thanks

I would like to thank Jianhang Jiao who give me a lot of help in this study.
The project use EEG data from pediatric subjects with intractable seizures by Children's Hospital Boston[1].

# Contents

# Part I

# Problem analysis

# Chapter 1

# Background

## 1.1 Epilepsy

Epilepsy is a common syndrome, a group of neurological disorders characterized by epileptic seizures. [2][3]. Epilepsy is a symptom than to be a disease[4]. The patient is classified as epilepsy patient after a recurrent seizure. Seizure with specific cause are not considered as epilepsy[4]. Its virulence factor are diversified and most of those factor are not understood. The known factor includes brain injury, congenital malformation, oxygen deficiency, brain tumors, strokes both ischemic and hemorrhagic, poison or alcoholism, other known conditions e.g. meningitis. Physical and psychological stress and sleep deprivation can trigger seizure. But the threshold of seizure is different from preson to person. The epilepsy patients has a low threshold and recurrent seizures accur with low presure[3].

According to the World Health Organization, epilepsy, one of the most common neurological syndromes with 1% prevalence, is affecting around 50 million people worldwide[5]. 80% of the patient accur in developing conutries[6]. The incidence of epilepsy is estimated as 68.8 new patients per 100,000 person-years, from the data collected from 1977 to 2002 in Denmark [7]. Because of the improvement of diagnostic system, the incidence increases and then stay constant on 83.3 new cases per 100,000 person-years at risk[7]. Epilepsy incidence is age and gender specific[7]. In Denmark, patients is free of charge for the treatment.[7]

Some of the seizures can be short and go unnoticed, some can cause loss of consciousness and some can cause a long time of spasm. Epilepsy patient desire a normal life in the comunity. However, their recurrent seizure embarrassing them, and isolate them from the outside world. The other people could look down to the patient because lack of knowledge of their condition[6]. The patients who has suffer from epilepsy could lead to a negative attitude[8].

Anti-Epileptic Drug Treatment(AEDs) is the most common treatment. It can control 70% of the seizure[9]. For the others, surgical treatment and neu-

rostimulation could be a option. Because surgical can damage the brain funtion, the seizure focus cannot local at an improtant part ogf the brain[8].The vagus nerve stimulation (VNS) has been proven to able to prevent the epileptic seizures and to reduce the severity[8].

### 1.1.1 Epileptic Seizure Types

Epilepsy can be clssiflied by its symptoms, cause, seizure focus and the size of seizure. The categorization is important because the type of seizure determines treatment. It also helps the international communication.

The standards used in today is "International Classification of Epileptic seizures" which count both symptoms and localization. Accronding to that, epileptic seizures can devided into "partial(focal)" and "generalized"[10].

#### Generalized Seizure

Both hemispheres are involved inthe same time in generalized seizure. Seizures start at the center of brain. Then spread to the other part, shown in figure 1.2 on the facing page. In EEGplot, spike appear at the same timeshown in figure 1.2 on the next page.

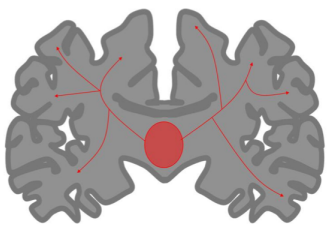

Figure 1.1: Generalized seizures starts in the central part of the brain and then spreads to the rest.[11]

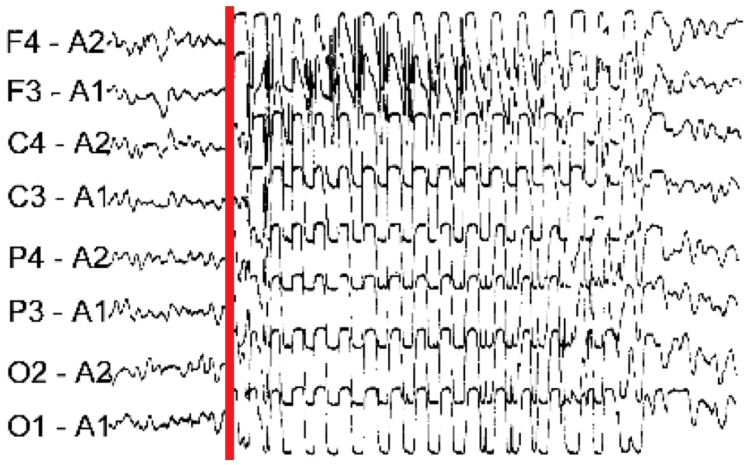


Figure 1.2: EEG of a generalized absence seizure. Seizure starts in all channels at the same time indicated by the red line[10]

Generalized seizure can be devided into some subcategories. The most prominent types of seizures are:
• Tonic/clonic seizures
• Absence seizures
• Myoclonic Seizures

**Tonic/clonic Seizures** is the most common and well known by normal people of the generalized epileptic seizures. Sudden tonic contractions of the muscles accur when seizure happens. Patients scream or cry because shrink of breathing muscles. The patient falls to the ground and might get injuried, follows with the clonic seizures of jerky spasm. The tonic contractions inhibits the respiration and the head turns blue until the breathing restarts. Patient can possibly bite in his or her tongue or the cheek. A stick was used to be preventing these bites but it bring more problem than goods and no longer being used.
The seizure normally last for 1-2 min. After that, most patiens will fall into deep sleep. patient will suffer of loss the memory, a headache and feels tender due to the amount of movements. Tonic/clonic seizures can happen at all times of the day but some specific times of the day it happen more often. If it is inherited then seizure will most likely happen shortly after waking up. If it happens as a complication from complex partial seizures, then it often happen during sleep[10].

**Absence Seizures** typically seen in child epilepsy. It starts with no warning and last for only a few seconds. The patient is unconscious during the seizure.

But because of the tonus of the muscles is preserved and short period of seizure time, the patient will not fall down. The tonus of the head can disappear if the seizure last longer. head will drop first then the body will fall but it is rare. Normally the patient will continue what he is doing without aware of the occurrence of the seizures, which mean the seizure is hard to be noticed This type of seizure happen very frequently, up to several hundred in a day. But it still cause problem to the patient, such as following a lecture.[10].

**Myoclonic Seizures** During myoclonic seizures, the whole body or located to one muscle group will have a sudden contraction. It can be a single contraction or rapidly repetition of contractions. Before going to sleep and after awakening in the morning is the most common seizure hour, due to fatigue and unrefreshing sleep[12].

**Partial Seizure**

Seizures start at surface of the brain, then spread to a bigger area. Sometime it spread to rest of brain and developes as generalized seizure, which is called secondary generalized seizure. In EEGplot, spike start to appear on channels at different time.

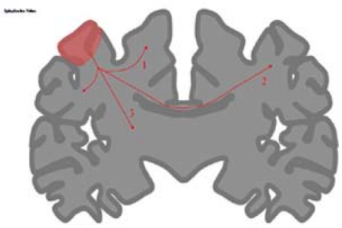

Figure 1.3: Partial seizures starts in the surface of the brain and then start spreadsing.[11]

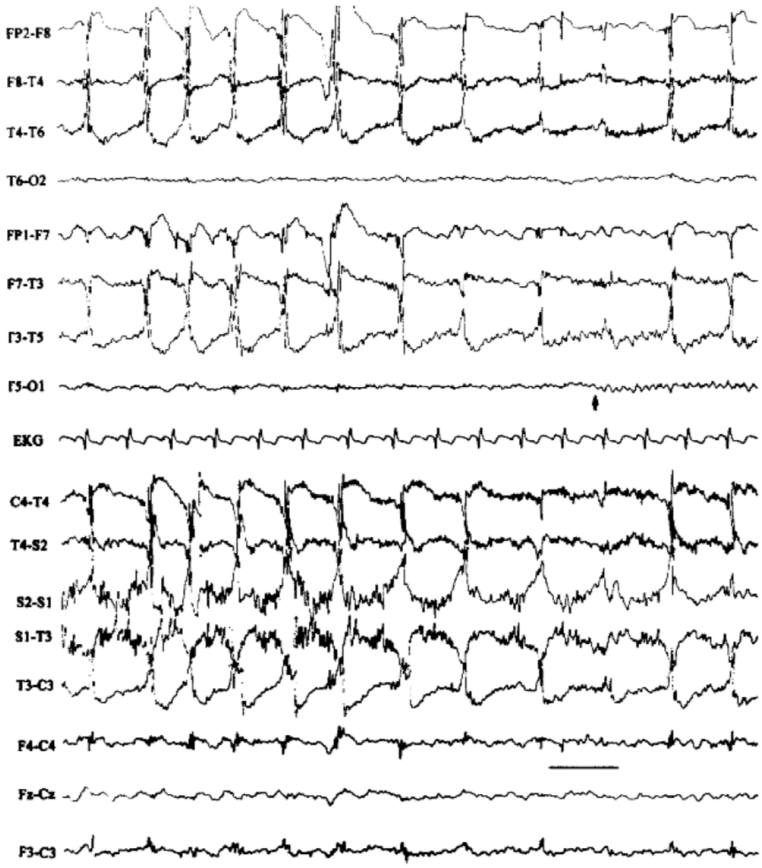


Figure 1.4: EEG of a complex partial seizure. Seizure localized to a specific part of the brain[10]

The symptoms of partial seizure depend on the focus location and and if they stay localized or not.
partial seizure can be devided into some subcategories,simple and complex seizures.

**Simple Seizures** are defined as "the localized abnormal impulses without loss of consciousness".
The patient will normally feel the sign when the seizures starts in a localized part of the cerebral cortex. The sign is the same for the same patient but different form others. That is because it always starts at the same place.
Simple partial seizures can develop into complex partial seizures if the abnormal impulses spread out to the rest of the brain with a loss of consciousness[12].

**Complex Seizures** can start from simple partial seizures, or start with a loss of consciousness. Localized abnormal impulses in the cerebral cortex will

causes loss of consciousness. The seizures normally occur in the temporal lobe. During the seizure, patient often makes automatic actions and can become more complicated if the seizure last a longer time. Complex seizures can develop to a second generalized seizure when the seizure will end with spasms and loss of consciousness[12].

### 1.1.2 Diagnosis of epilepsy

The clinical history will be asked form the patient and some who is close to the patient. The patient may not remember the seizure. It is important to determine the type of epilepsy because that affects the treatment. The Golden Standard of seizures location is ECoG recordings. Although it is invasive [13]. But the most common tool as neurological assessment for epilepsy is EEG[10]. Neurological assessment is used to check if there is any sign of neurological disease that can cause seizure.

### 1.1.3 Treatment of epilepsy

Epilepsy cannot usually be cured. But AEDs can control 70% of the seizure[9]. 80% of people with generalized seizure and only 50% of people with focal seizures can be well controlled[14]. Not all cases of epilepsy are lifelong. A large amount of people's condition is improving to medication is no longer needed. For the other who AEDs coludn't help, surgical treatment, neurostimulation and dietary changes is the other option.

#### Surgical Treatment

The patient first has to be a candidates that comply with the criterias[12]. The type of seizure is important. A generalized seizure patient is not suitable for a surgical treatment, since the seizure occurs throughout most of the brain. But A partial seizure patient is suitable because it is localized. The goal is to have total control of seizures and in 60–70% of cases can be achieved. Cutting out the hippocampus via an anterior temporal lobe resection, removal of tumors, and removing parts of the neocortex are some common procedures[15][16].

## 1.2 EEG

This section provides a overview of electroencephalography (EEG) and some topics that related to the project.

### 1.2.1 Definition

The definition of Electroencephalography(EEG) is the recording of electrical activity on the surface of the scalp. Compare to EEG, recordings at the cortical surface is electrocorticographic(ECoG), or within the brain is

electrogram(EG)[17], show in figure 1.10 on page 13. A deeper location mean it is closer to the neurons and will privide higher spatial resolution, but also make it invasive. Synchronous action of brain cells generates extracellular field potentials. And electrical activity of the brain is the time course of extracellular field. In conclusion, EEG is a graphic representation of Differential electric signals of the brain in time.
For a normal subject, the EEG amplitude recorded on scalp in awake state is 10-100$\mu$V. But in epilepsy seizure, the EEG amplitudes may increase by an order of magnitude (500-1500$\mu$V). The frequency of EEG is from 0.5 Hz to up to 45 Hz and more than 100 Hz for ECoG [18] [19].
There four basic characteristics of EEG make it as a important diagnostic and research tool:[19]

1. High time resolution.
2. Non invasiveness.
3. Simple and inexpensive.
4. Patient can move freely during the recording, unlike MEG or fMRI.

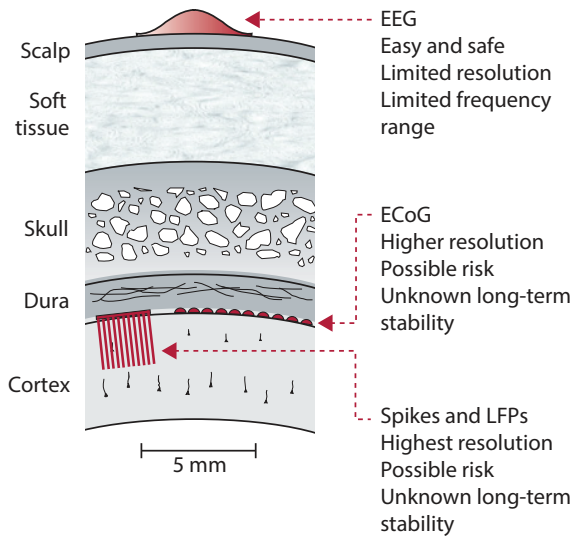


Figure 1.5: Electrical activity record location[17]

### 1.2.2 EEG rhythms

It is the most common ways to classify EEG waveforms is by its frequency. Other ways including classifcation by the shape and the amplitude. The folowing rhythms(frequency band) can be recognized in EEG while in specific activities. With frequency filter, these rhythms can be visible.

- Delta (0.5-4Hz)
- Theta (4-8 Hz)
- Alpha (8-13 Hz)
- Beta (13-30Hz)
- Gamma (> 30 Hz)

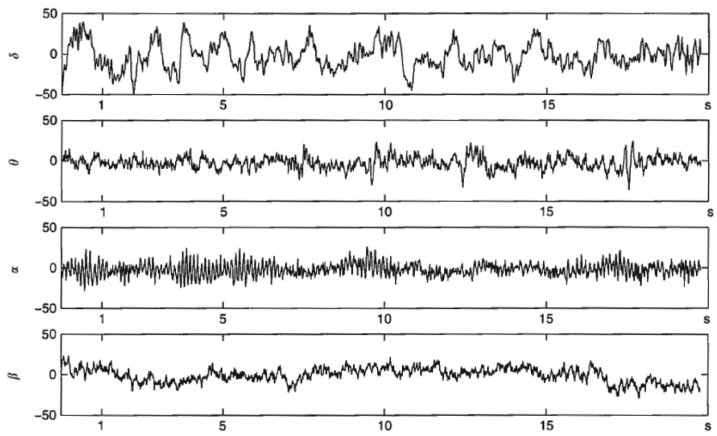


Figure 1.6: EEG frequency bands[18]

### 1.2.3 EEG recording system

EEG recording sytem cosists electrodes, amplifer, A/D convertor and the recod device.

#### Electrodes

Electrodes can be attached to the scalp with adhesive or a EEG recording cap. There is also needle electrode for invasive recording. Multiple electrodes can creat multichannel recording. The impedance of each connection should be less than 5 $k\Omega$ while attaching. brushing the skin to remove dead skin cells, cleaning the recording site and applying conductive paste to each electrode can improve the conection[20].

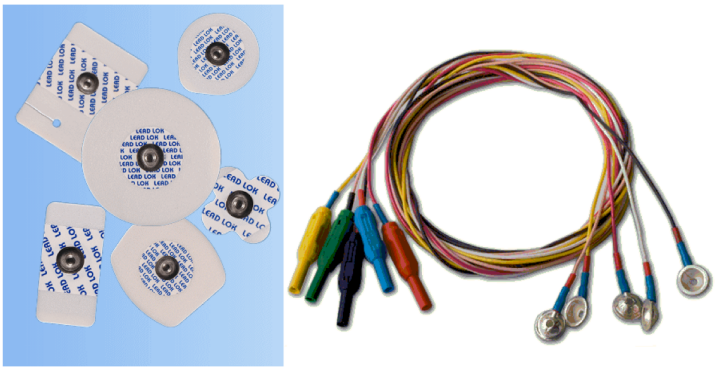

Figure 1.7: EEG disposable electrode(left)[21] and EEG reusable electrode(left)[22]

### 10-20 electrodes placement system

In order to standardize the placement and designation of electrodes , "10-20 electrode placement system" was proposed in 1958. important skull landmarks, nasion(where the frontal bone and two nasal bones intersect), inion (important projection of the occipital bone) and preauricular points (point on the ears) was used to divide the head by distance. Totally 19 EEG electrodes on the scalp and 2 electrodes on the earlobes is stated. The name 10-20 comes form the interial of distance. Electrodes are labelled with the adjacent brain areas and number. brain areas include :F(frontal), C (central), T (temporal), P (posterior) and O (occipital), and number include: odd numbers for left side, even numbers for right side and "z" or "0" in the center.[18][20]

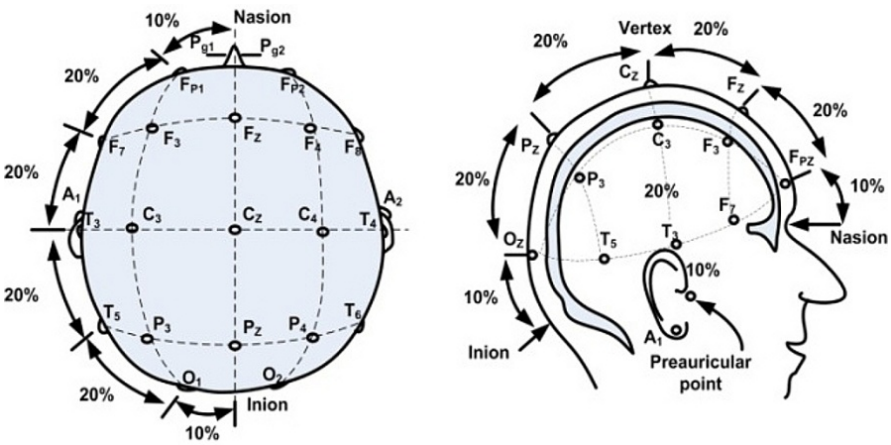


Figure 1.8: 10-20 electrodes placement system[23]

Since EEG is a differential signal, which is the difference of two potential from

two electrodes, the selection of these two electrodes can be:

### Unipolar

Unipolar can be devided into Referential and reference free:
• Referential: using some electrode(normally that is the earlobe or scalp center) as reference electrode, and other electrodes will be measured relative to reference electrode
• Reference free: Using the mean potential from all electrodes as the common reference.

### Bipolar Montage

A pattern is set up to connect electrodes as electrodes pair. One electrode is reference for another.

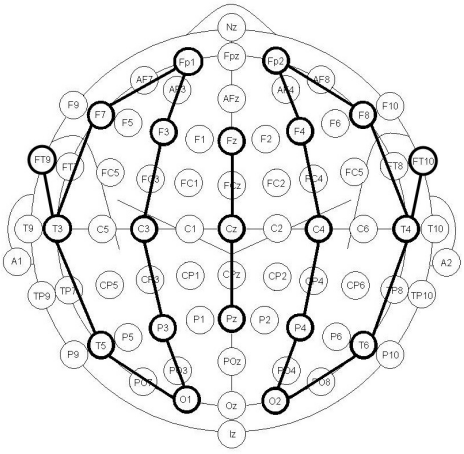


Figure 1.9: The bipolar montage[24]

When an electrode is close to its reference, its amplitude is tend to be lower[20].

### Differential Amplifier

Differential amplifier are device that amplify a differential signal[25], while robust to common-mode signal(noise):

$$V_{out} = A_d(V_{in}^{+} - V_{in}^{-}) + A_c \frac{V_{in}^{+} + V_{in}^{-}}{2} \tag{1.1}$$

$$CMRR = 10\log_{10}\left(\frac{A_d}{A_c}\right)^2 = 20\log_{10}\left(\frac{A_d}{|A_c|}\right) \tag{1.2}$$

1. Differential signal is the differences($V_{\text{in}}^{+} - V_{\text{in}}^{-}$) in electrical potentials between two inputs. A large differential-mode gain($A_d$) can increase the amplitude of signal.

2. Common-mode signal is the common part in electrical potentials($V_{in}^{+} + V_{in}^{-}2$) between two inputs.

A large common-mode rejection ratio(CMRR) can enlarge the Differential signal but suppress common-mode signal in order to actuate the analog to digital converter. From another perspective, it use one input as the refference, and enlarge another input.

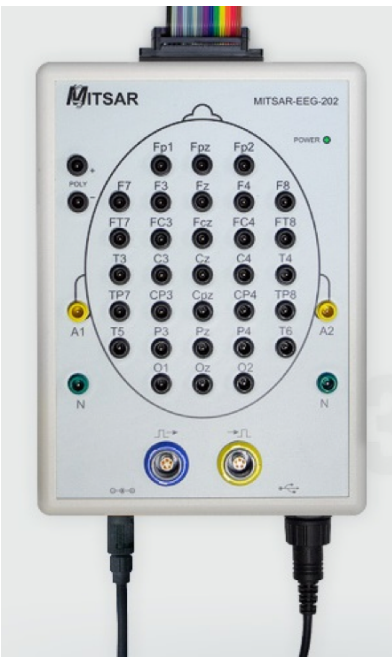


Figure 1.10: An EEG 31 channel amplifier and A/D convertor[26]

### A/D Conversion

Computor can only recognize digital signal, so the analog signal must be coverted by a analog to digital convertor(ADC). ADC is a divice that transform a continues physical signal to a series of discrete values that separated by equal time intervals. Here are three major attributes of ADC[25]:

1. Sampling rate is relate to the time intervals. It determine the resolution in time. According to Nyquist theorem, the frequency of reconstructed digital signal is not bigger than half of sampling rate.

2. Resolution of digital signal determines the number of discriminable amplitude levels(specified by bits).

3. Range of input signal should be correspond to the amplifier.

**Spatial Resolution**

EEG can be used to create brain map. Brain map is a spatial distribution of a specific variable, for instance the power or amplitude of a potential.
A sufficiently large number of scalp electrodes (¿ 64) can improved the limited sampling in space.
EEG has high time resolution. Meanwhile fMRI(functional magnetic resonance imaging) has high spatial resolution and information about absorption of substances in structures, and PET(positron emission tomography) has information about metabolism rate. A coregistration could bring better understanding between electrical activity and hemodynamics. Eventually, our understanding of neurocognitive processes and their disturbances can be improved.
Distortion accur on potential field while it is transfered from cortical surface to the scalp can be corrected by some spatial deblurring methods. A parametric model which simulates the head as a conductor comprised of many compartments(brain, skull, skin) with a different conductivity, Then the activated synapses as current dipoles embedded in that conductor. In analysis of transient EEG phenomena that localised in a certain brain area, the method has been proven useful[**?** ].

### 1.2.4 Artifacts

Artifacts are the signal that is not originate from cerebral activity in the EEG record. Compared to the cortical signals, artifact could have a large amplitudes that corrupt the data.
Although artifacts can be identify by their characteristic shape and distribution, in most case that is only possible for experts. Identify and remove the artifacts is nessary. Whenever artifacts occur, the recordings and patient has to be checked.
Here are two rules of spatial analysis that can recognize the artifact in many case:
• Medium or high amplitude potentials but only occur at single electrode usually are not cerebral activity.
• Repetitive or irregular waveforms that appear simultaneously in unrelated head regions are usually not cerebral activity.
Based on the origin, the artifacts can be divided into two categories, physiological Artifacts and non-physiological Artifacts.

**Physiological Artifacts**

These artifacts originated from patients' body activities::

1. Blinking and other eye movements. These movement can causes frontal electrodes recieving a potential changes.
2. Muscle artifacts. Movement of face muscles and scalp can causes artifacts in the frontal and temporal regions. These artifact can be reduced by relaxing the muscle.
3. Movement artifacts. Blood is pushed into the head while chewing, breathing, or repetitive head movements. The artifacts are rhythmical in tremor.
4. Electrocardiogram. Heart generated potential changes was pick up by the electrodes mainly with wide interelectrode distances.
5. Pulse wave artifact. These artifact when the electrode is above a pulsating vessel, especially in the frontal and temporal areas. It can be recognized by the usually regular recurrence.
6. Skin potential. Sweat, or poor electrode connection with the skin can cause impedance alteration.
7. Dental restorations with dissimilar metals. Connection of dissimilar metals for dental restorations can cause spike-like artifacts, for example in speaking.

**Non-physiological Artifacts**

These artifacts originated from:

1. Interference: Mainly from power lines and equidment, typically as a 50Hz interference waveform. It is hard to avoid when alternating current is used. These artifacts are likely to appear on all channel.
2. Recording electrodes and equipment: Faulty contact between the electrode and the scalp or improperly functioning instrument can cause waveforms that is very different from cerebral activity.

### 1.2.5 Summary

EEG is an important diagnostic tool in clinical neurology, which helps investigate cerebral activity. As a totally non-invasive and low-cost medical technique, EEG provides information about the relationship between cortical sites and evolution of brain processes in time. Artifacts can corrupt the data, reduce the value of diagnosis. It is also a useful technique for processing epilepsy seizure which is the main interest of our project.

# Chapter 2

# State of the Art

Epilepsy is one of the most common neurological diseases with a prevalence of 1%, which affects around 50 million people worldwide[5]. Epilepsy patients have the desire to have a normal life. But the seizure can embarrass them, makes them feel isolated[27]. Seizures are abnormal discharge of brain cells which can be caused by many different brain diseases or traumas. A typical single partial seizure starts in a small pathological area then spreads out to a larger region[28].

Seizures could be controlled by Anti-Epileptic Drug (AEDs) in around 70% of epileptic patients[9]. However, there is still a large number of patients with epilepsy do not response well to the AEDs[29]. For these patients with refractory epilepsy, the potential treatment could be surgical remove seizure onset zone (SOZ) or using neurostimulation as a adjunctive treatment[30].

The seizure focus resection could be performed only when the SOZ are well defined[29]. Preoperative examination is conducted restrictedly to recruit the potential candidates. The endeavor should be made to minimize the region of resection without sacrificing the efficacy of seizure control and the serious loss of brain function. The intraoperative electrocorticography (ECoG) and preoperative EEG monitoring are commonly involved to delineate the SOZ[30]. It is difficult and time-consuming to precisely predict the SOZ in many case since the seizure may reoccur with a long interval. Besides surgical treatment, the neuromodulation for seizure control is another option for refractory epilepsy patients. Currently both the open-loop stimulation and close-loop stimulation are available where the later has been drawn more attention since the less battery consuming and less chance of nerve injury and fatigue[31]. In this case of close-loop stimulation, the stimulation was trigged by the seizures by a feedback EEG signal[31]. EEG plays an important role on epileptic seizures prediction and diagnosis. Typically the EEG is used for prediction the ongoing seizure, however it is easy influenced by the eye-blink and chewing which make the prediction of seizure become imprecise[32]. Therefore, the need to precisely predicate the seizures and locate the SOZ is urgent.

# Chapter 3

# Problem Formulation

There are 30% of epilepsy patiens do not response to AEDs and need other treatment suah as removed seizure onset zone and neurostimulation. Surgery require a well defined SOZ and lot of reading of EEG and ECoG, looking for spike and all kind of waveform, Which are time consuming. Frequency-time anlysis gives another perspective to the data, but also makes the data in a higher dimension. There are MRI and PET which have high spatial resolution but they are expensive. The proposed visualizaion tool, STFED map, can help doctor to read EEG and ECoG, and find the SOZ.[33]
Neurostimulation can suppress the seizure. A open-loop simulator cost more battery and also do some damage to the brain. [31]. Close-loop stimulator can only send the stimulation when the seizure start. This willl require a detection of seizure. The rapid initiation is very important, while some false alarm is allowed. The chance of stoping a seizure is decrease after the seizure's onset. [34] [32] Normally this is perform by a machine learning. But the visualization tool gives another idea.

# Chapter 4

# Aim

The aim of this project is bulid a visulizaion tool to help doctor to read EEG and high dimension data from frequency-time analysis. And bulid a seizure onset detection tool base on the visulizaion tool, apply computer vision on that to recognize the seizure.

# Part II

# Problem Solution

# Chapter 5

# Method

## 5.1 Subjects

The data is collected at the Children's Hospital Boston. Subject is withdrawal of anti-seizure medication up to several days.
23 cases were collected from 22 patient(5 males, ages 3-22; and 17 females, ages 1.5-19). Case 21 has the same patient as case 1, but just after 1.5 years later [32].

Some of patients are excluded becaused it is corupt by a vagal nerve stimulus (VNS) signal. And some patient's recording are abandented becaused they are record in others electrodes placement system. There are totally 10 patients and 53 seizures used in this study.

## 5.2 Experimental protocol

A data set including 664 records and 129 of them contain one or more seizures. Totally 198 seizures is recorded.

Most of the records is one hours long. there is a gap between these record in the same case, typically 10 seconds or less. EEG signal is record as 23 channel with vertical bipolar. Signals samples rate is 256 per second and resolution is 16-bit [32].

## 5.3 Workflow

The workflow is show as figure 5.1 on the next page. The propose method, seizure onset detection based on STFED(Space Time Frequency Energy Distribution) map, is proformed and compare to a common SVM methods.

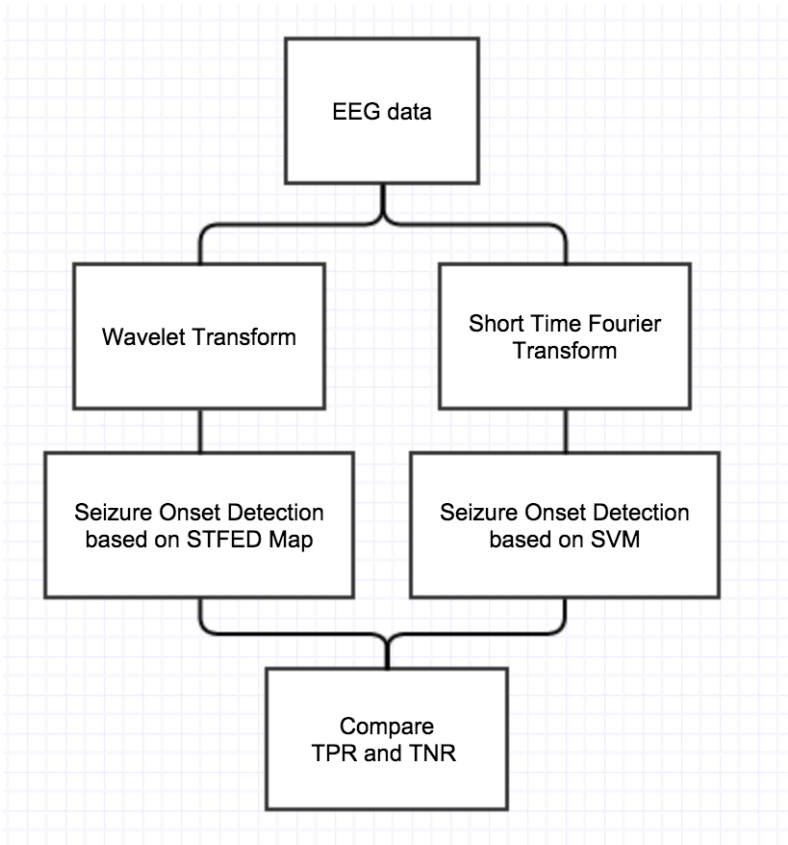


Figure 5.1: The flow chart of the study.

## 5.4 Wavelet Transform

A time domain signal can be transform into time-frequency information. Morlet wavelet is chosen in the study.

Scale is calculate by pseudo frequency of every 1 Hz, from 1 to 10 Hz.

$$F_a = \frac{F_c}{a \cdot \Delta} \tag{5.1}$$

Finally, coefficient of wavelet is converted into energy by square them.

$$E = C^2 \tag{5.2}$$

After performing wavelet transform to all channels, a martix which contains Energy in channels, frequency and time is obtarined. This matrix has 3 dimension.

## 5.5 STFED Map

STFED map is a visualization tool that can present the energy distribution in different position on scalp, frequency and time. It interplates the result from wavelet transform, the 3 dimension martix, from channel to space and obtaine a 4 dimension matrix. The interplation is using the same method as Topographic map.
With the technique of volume rendering, the 4 dimension matrix can be visualized. But that is not required for seizure onset detection. The dtail of how that is performed is discribe in Appendix C on page 59.
Some of the examples and explanation will be presented in the results. That include simulated data, seizure, chewing, blink and normal EEG signals.

## 5.6 Seizure Onset Detection base on STFED Map

The strategies of seaching for seizure are:

1. Look for high energy that distributed in a narrow frequency band;
2. Look for a group of energy that meet the The first strategy. There are no big gap between energy in the group and the group last long enough.

A major cyclic component is tend to be contained in EEG signals during the seizure. [35] In STFED map, that mean a voxel has a high lighness and saturation. In this study, it is quantify by the product of saturation and lightness:

$$A = S * L = \frac{max(r,g,b) - min(r,g,b)}{2} \tag{5.3}$$

With a thresholding, all voxel that meet the first strategy are marked as 1, otherwise 0;
And the second strategy is perfomed with some technique from mathematical morphology. The operation of closing can connecting objects that are close to each others. And the operation of opening can remove objects that are not big enough. These 2 operations are only performed on the dimension of time. Finnally, the position on time dimension of all the voxel that are marked as 1 is output as seizure being detected. This result is compared to the database for quantify. Sensitivity and specificity is calculated.

## 5.7 Seizure Onset Detection base on SVM

The method is purposed from the database. It used The short-time Fourier transform(STFT) for the time-frequency analysis. The energy of differernt channel, time and frequency are calculated. All the energy is rearrange as a

feature vector. 18 channels is uesd. 8 spectral energies from 0 to 24 Hz is extracted. The window is 2 seconds long, and 3 energy is used. There are totally $18 * 8 * 3 = 432$ fearures in a feature vector.[32] Feature vectors from seizure and non-seizure is then used for training and testing. In this study, the linear kernel is used with the value of the box constraint C for the soft margin as 1. The data is divided into 2 part, half for training and half for testing. After the first testing, the training data and test data exchange for the second training and testing.

## 5.8 Quantification

The proposed method, seizure onset detection base on STFED map, is compared to the seizure onset detection base on SVM method. The data for testing include 10 patients and totally 53 seizures. Not the entire recording is used but only during the seizure, before and after the seizure. And the period that just before and after are also not being used for quantification.


Figure 5.2: The recordings that marked as Seizures are uesd as class 1. There are two one minute recording that is one minute before and after seizre are used as class 0.

The seizure onset detection base on STFED map is tuned on 6 seizure from patient 1. And the parameter is not changed for the other patients. The output detections result with the resolution as 0.1 second is compare the class 1 and 0 for calculating the sensitivity and specificity.
The seizure onset detection base on SVM is trained and tested with every patients. The output detections result with the resolution as 1 second is compare the class 1 and 0 for calculating the sensitivity and specificity.
Finally, the sensitivity and specificity from 2 methods are compared.
And the computation time from two method are compare. Both methods is separated into two part:time-frequency analysis and detection. The time-frequency analysis will be perform on a one hour recording and detection will be perform on a 180 seconds recording that including a seizure.

# Chapter 6

# Results

## 6.1 Example of STFED map

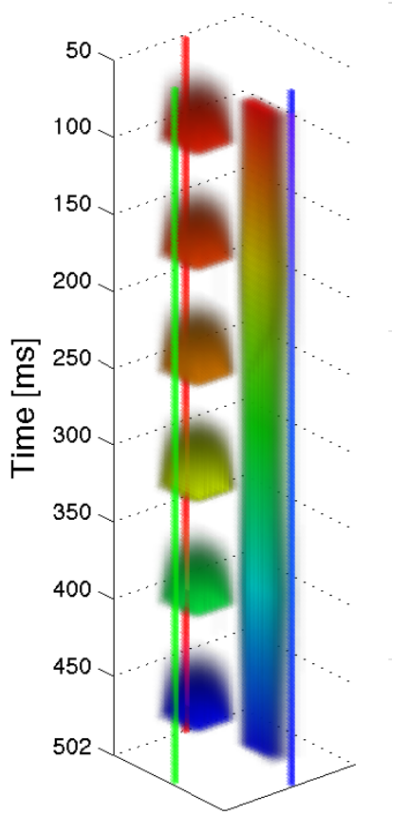


Figure 6.1: An example of STFED map of simulated data. On the right part of the figure, a long cuboid shows constant energy level but frequency increasing. On the left part of the figure, six small cuboids shows increasing energy level but frequency remain constant. The front of the scalp is marked by the green line, and the left and right are marked by blue and red.

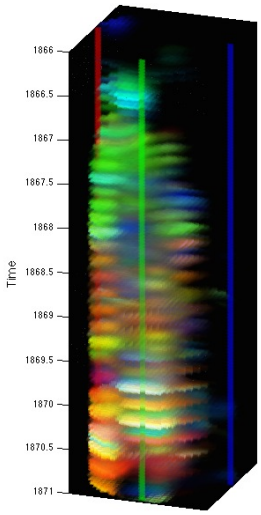


Figure 6.2: An example of STFED map of first 5 seconds in the begining of a seizure. The figure shows how the seizure starts in a point on the right part of the of the scalp and spreads to entire right half of the scalp. The color from green and cyan to orange and red shows the frequency is decreasing.

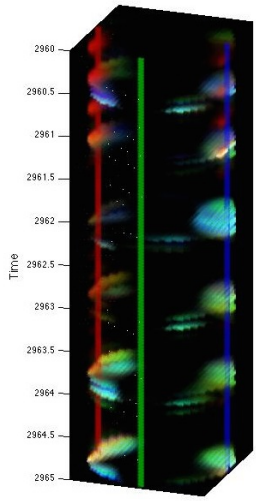


Figure 6.3: An example of STFED map of 5 seconds during chewing. The figure shows the energy is main distributed on periphery of the scalp because that is where the muscle being used are locate. There are 6 rings which mean the patient chewed 6 times in 5 seconds. There are 2 rings in the middle are unbalance which suggests that he use more muscle on his left.

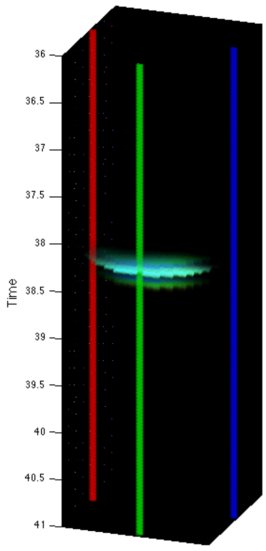


Figure 6.4: An example of STFED map of 5 seconds including a blink. The figure shows the energy is main distributed on front of the scalp because that is where the muscle being used are locate.

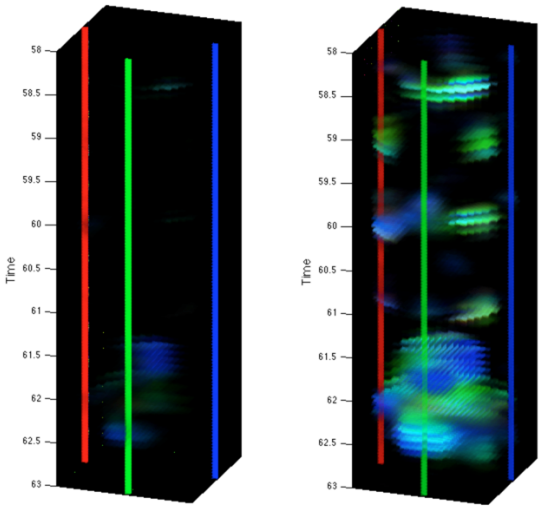


Figure 6.5: An example of STFED map of 5 seconds with normal EEG signals. The left dark figure shows there is very low energy on the scalp. With 5 times the sensitivity as normal, more detail is showed as the right figure

## 6.2 Results of Seizure Onset Detection

10 patients and totally 53 seizures has been involved in the testing. The result of the sensitivity and specificity are showed as the table below:

| Seizure Onset Detection based on | | STFED map | | SVM | |
|---|---|---|---|---|---|
| patient | amount of seizures | Sensitivity | Specificity | Sensitivity | Specificity |
| 1 | 6 | 97.97 | 93.6 | 98.41 | 100 |
| 2 | 3 | 98.23 | 74.42 | 95.16 | 88.39 |
| 3 | 7 | 94.18 | 93.18 | 98.65 | 85.53 |
| 4 | 4 | 69.14 | 100 | 80.95 | 89.96 |
| 5 | 3 | 63.32 | 48.89 | 86.70 | 89.73 |
| 6 | 5 | 94.68 | 74.03 | 90 | 76.56 |
| 7 | 3 | 96.76 | 100 | 98.26 | 99.11 |
| 8 | 12 | 32.09 | 94.13 | 66.21 | 68.38 |
| 9 | 7 | 49.52 | 93.17 | 89.85 | 98.44 |
| 10 | 3 | 97.63 | 91.89 | 94.45 | 87.50 |
| Average | | 79.352 | 86.331 | 89.864 | 88.36 |
| | | Patient Non-Specific | | Patient Specific | |

The computation time comparison:

| | STFED map | SVM |
|---|---|---|
| Frequency-time Analysis of 1 hour recording | 89s | 15s |
| Detection of 180 seconds recording | 17.45s | 0.374s |

# Part III

# Synthesis

# Chapter 7

# Discussion

Instead of rearranging the energy in channel, frequency and time as features vectors in SVM, STFED map interplates them into space, frequency and time, totally 4 dimensions. Then this 'feature matrix' can be seen as an image. It is basically the same information as feature vector but much easy to understand. It can tell about where the energy is, when it is and what frequency it is.

The Seizure has high energy and a major cyclic component, which lead to bright and high saturation image. Normal EEG are relatively weak signal, which are dark and can be separated by the strategy 1:

1. Look for high energy that distributed in a narrow frequency band.

Chewing and blinking has similar spectrum to seizure, see figure 7.1 on the next page, which could be a problem to distinguish for SVM. The spectral features are similar, if the spatial and time features are also similar, SVM will be unable to distinguish them. But the partten in STFEED are very different from seizure, see figure 6.2, 6.3 and 6.4. The partten allow them to be separated by the strategy 2:

2. There are no big gap between energy in the group and the group last long enough.

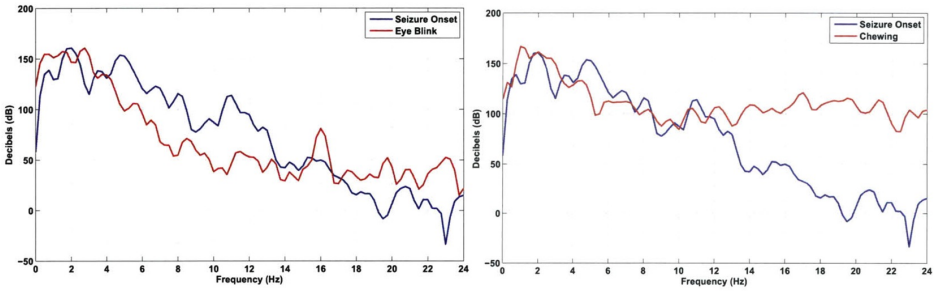


Figure 7.1: spectrum of blink and chewing compared to seizure. Their spectrum are similar to seizure. Figure copied from article[32]

The performance, the sensitivity and specificity, of seizure onset detection based on STFED map is not as good as the performance of seizure onset detection based on SVM. That is 79.352% and 86.331% compare to 89.864% and 88.36%. But it is close in most of the patients(patents 1,2,3,6,7,10). It has lower sensitivity but higher specificity in patients 4 and 8. And lower performance in patients 5 and 9. Overall, The performance is comparable. But the seizure onset detection based on SVM is patient specific. It need a training process. Meanwhile, seizure onset detection based on STFED map is patient non-specific.

Other study report using statistical classifier methods, a sensitivity 98% and specificity 86.8% for patient-specific method and a sensitivity 81% and specificity 71% for patient-specific method.[36]

The computation time of seizure onset detection based on STFED map are much slower than the seizure onset detection based on SVM. After the analysis of the program, Some redundance computation has been found. Which mean that can be improved. It take 89 seconds for wavelet transform every time points(1/256 second) of 1 hour recording. But it only requires to calculate every 0.1 second recording.

And it take 17.45 seconds to detect a 180 seconds recording. Most of the time(11.9 seconds) has been spent on interpolation. It is necessary for visulization but not necessary for detection. If that is being removed. The program can be much faster, although it will be still slower than the seizure onset detection based on SVM.

# Chapter 8

# Conclusion

This project proposes a technique to visualize EEG data. It can present information on 4 dimenssion in space, time and frequency. It can present the spreading of seizure area and help to locate the seizure onset zone. Based on this technique, a new seizure onset detection is proposed. It is patient non-specific and has a comparable performance to the traditional patient non-specific methods. The sensitivity is slight lower than a patient specific methods. This method take a lot computation time but can be improved.

# Part IV

# Appendices & listings

# Appendix A

# Color Space

A color can be described with a color model and a group of values(normally three). Using thesevalues as coodinate, all the points compose a color space. Color space is a combination of color.

Color space is normally three dimensional because human eye has three kind of color receptor. Therefore it can have different dimension for other animal or achromatopsia patients. Three wavelength of light waves are choosen to be the primary colors, because they are the most sesitive wavelength for the color receptor. Primary colors is not a physical concept, but rather a biological concept.

A color space can be bulid up with primary colors. Primary colors can combined and present diffenent color. All these color build up a space. The primary colors become the basis and the ratio of primary colors can be the coordinate of a color. RGB, CMYK and HSL is this kind of color space. But because the limit of the hardware or standard, some of the color that can be seen by human is out of the color space. Those color require a negitive value which is unachievable.

The CIE 1931 color spaces is a common reference standard to difine other color space. Instead of primary colors, they connect power spectrum and color. It is more precise and including all color that can be seen by human. But it is too complicated for daily use. Gamut is the sum of capable of generating color form a technical system. Gamut of different color space is alway be compared with CIE 1931 color space.

## A.1 CIE 1931 color space

CIE 1931 color space is the first color space that connect electromagnetic visible spectrum and color that physiologically perceived in human vision. It is the first color space defined quantitatively by the International Commission on Illumination (CIE) in 1931[37]

### A.1.1 Tristimulus values

There are three kind of color receptors(cone cell) which can sense lightwaves, for short wavelength(S, 420-440nm), middle wavelength(M, 530-540nm) and long wavelength(L, 560-580nm). They work on medium and high-brightness conditions(In low brightness condition, rod cell will take over and creates monochromatic vision). These three stimulus level of the three types of cone cells, can describe any color. They compose the LMS color space. It is a three dimensional space and that make most of the color space in three dimension.

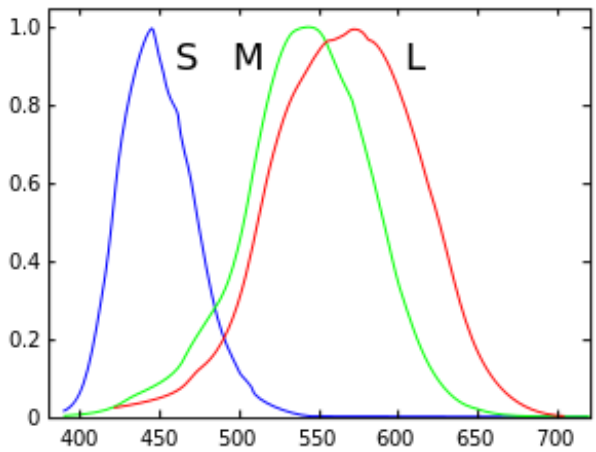


Figure A.1: The normalized spectral sensitivity of three color receptors[38].

### A.1.2 CIE standard observer

The distribution of cones is different on the retinal. The field of view can change the tristimulus values. Therefore CIE defined the standard observer which is in 2° arc of the fovea. That represents an average human's chromatic response. The three color matching functions is then obtained in the experiment.

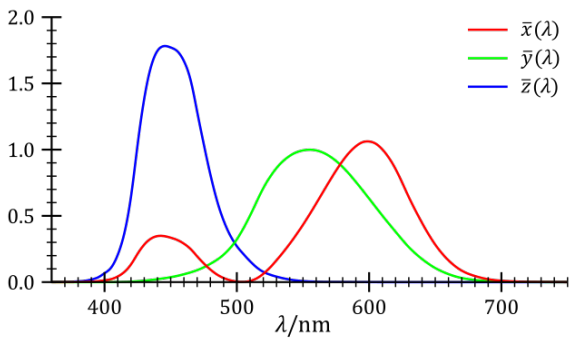


Figure A.2: The three color matching functions[38]

The tristimulus values can be calculated with the spectral power distribution $I(\lambda)$,

$$X = \int_{380}^{780} I(\lambda)\,\overline{x}(\lambda)\,d\lambda \tag{A.1}$$

$$Y = \int_{380}^{780} I(\lambda)\,\overline{y}(\lambda)\,d\lambda \tag{A.2}$$

$$Z = \int_{380}^{780} I(\lambda)\,\overline{z}(\lambda)\,d\lambda \tag{A.3}$$

Other observers can be used to create others color space such as the CIE RGB space.

The tristimulus values is a three dimension space. But the lighness can be devided. Then a two dimension chromaticity is obtained. The Y parameter was a measure of the brightness or luminance of a color because of the special design. Two parameters x and y will describe the chromaticity:

$$x = \frac{X}{X+Y+Z} \tag{A.4}$$

$$y = \frac{Y}{X+Y+Z} \tag{A.5}$$

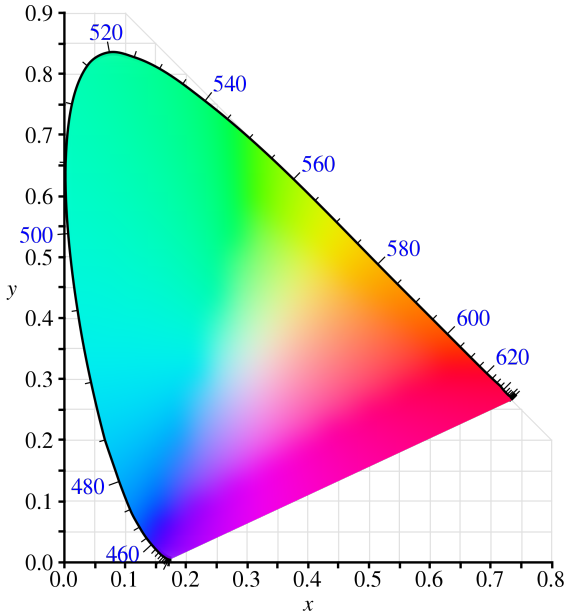


Figure A.3: The CIE 1931 color space chromaticity diagram. With the brigness, the CIE 1731 color space include all possible that human eye can see and every possible spectrum in visible range. The outside edge of the presenting monochromatic light in different wavelength in nanometers. Inside of the shape presenting polychromatic light. Some area of the color space cannot display correctly. That depend on the hardware and standard. It just pretend to be displaied[38].

The tristimulus values can be recover from value x,y and Y:

$$X = \frac{Y}{y}x \tag{A.6}$$

$$Z = \frac{Y}{y}(1 - x - y) \tag{A.7}$$

### A.1.3 Some interesting properties

1. The region in the CIE 1931 color space chromaticity diagram is called the gamut of human vision.

2. Monochromatic lights is mapped to the curve edge(called the spectral locus).

3. The other area is mapped for Polychromatic lights.

4. Less saturated colors is mapped to the middle area.

5. a flat power spectrum in terms of wavelength local at (x,y) = (1/3,1/3). It is call white point.

6. x and y is alway positive because no negitive stimulation exist.

7. No concave is in the shape of gamut.

8. Mixing two colors in the CIE 1931 color space chromaticity diagram can obtained all the color in the between straight line of these two points.

9. Three real sourse can cover a triangel area. But they cannot cover all of the gumat.

## A.2 RGB color space

RGB color space refer to red green and blue. Mixture of these three color can represent different color. It is widly using in electronic equipment, which including monitor and camera. It is device-dependent, where different devices detect or represent a given RGB value differently.

Human beings have three types of cones are sensitive to different wavelength. Yellow-green, blue-green and purple (or violet) is the most sensitive light (wavelength of 420 nanometers and 564,534, respectively). But red green and blue can stimulate those cone cell more indipendently.They can imitate most of the possible color that can be seen. Therfore red green and blue is choosen to be the primary colors. RGB is design for human eye. For other animal more or less primary colors is required.

RGB is additive. It start from black and becomes brighter. A pixel on the screen has smaller structure called "subpixel". The hue and saturation of a subpixel is fixed. But it's lightness can be control.

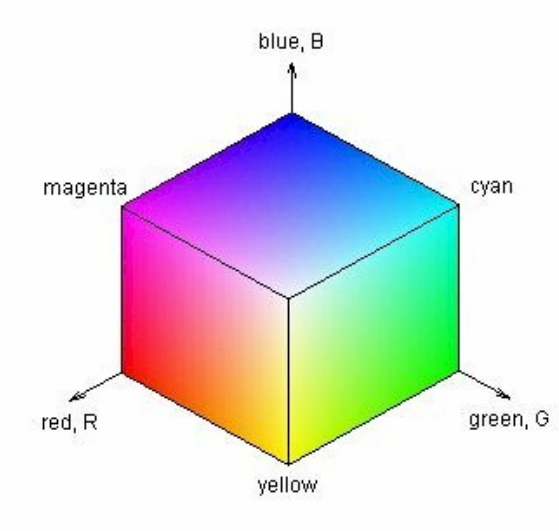


Figure A.4: RGB color space. Mixture of these three primary colors can represent different color[39].

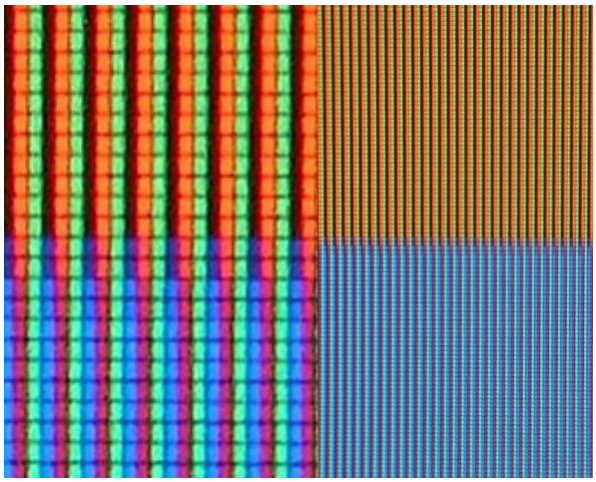

Figure A.5: RGB sub-pixels structure on LCD. A RGB value lights up the subpixel(left).From a further distance, they will be mixed together(right)[40].

## A.3 HSL color space

HSL stands for hue, saturation and lightness. HSL space are transformations of RGB space. It is in cylindrical coordinate system. It is more intuitive and perceptually relevant than RGB which is in Cartesian coordinate system.

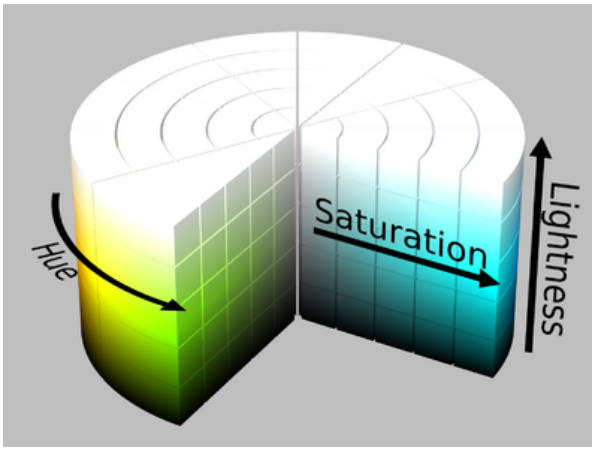


Figure A.6: HSL color space[41].

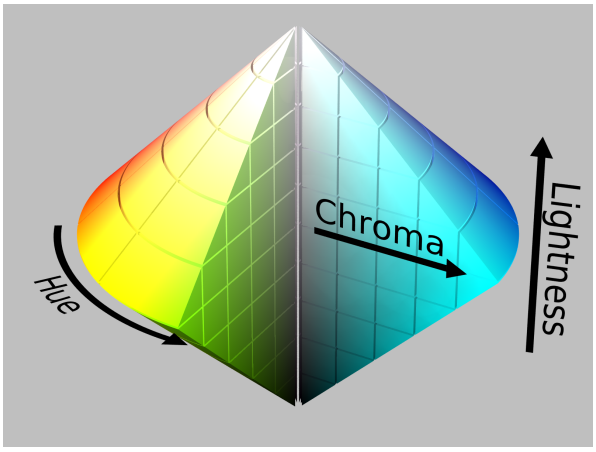


Figure A.7: A bicone HSL color space. In this case, chroma replaces saturation[41].

Hue is main properties of a color. It is feeling of different wave length of lights. It is defined as "The degree to which a stimulus can be described as similar to or different from stimuli that aredescribed as red, green, blue, and yellow"[42]. Hue composes the color wheel which conects the high frequency and low frequency. In color science, hue is related to dominant wavelength and complementary wavelength. A color can be presented by the sum of a flat spectrum white light and a monochromatic light of dominant wavelength, or the difference of a flat spectrum white light color and a monochromatic light of complementary wavelength.

Dominant wavelength and complementary wavelength can be obtained by drawing a straight line between the white point and the a given color in CIE 1931 color space,. The straight line will intersects the edge of the space in two points. Then the dominant wavelength and complementary wavelength is obtained. The intersection point that in the same side of the given color reveals the dominant wavelength. And the intersection point that in the other side of the given color reveals the complementary wavelength. For some color, only one of these wavelength can be obtained, since the bottom edge of the houseshoe shape does contain monochromatic light.

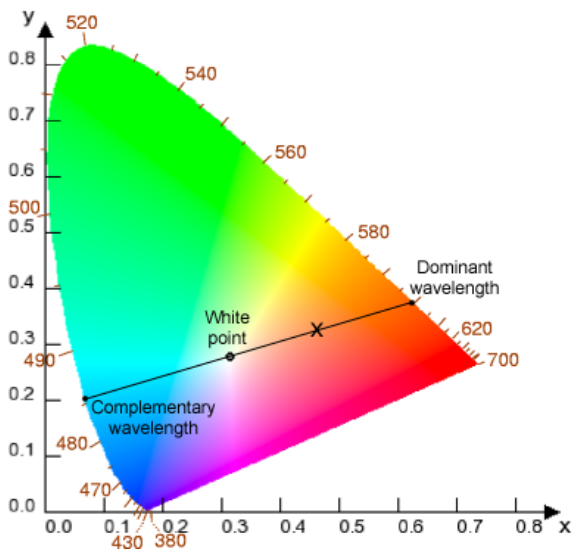


Figure A.8: Dominant wavelength and complementary wavelength of a choosen color. Connect the white point and the choosen color in The CIE 1931 color space chromaticity diagram. The extension line intersect the edge at two points. The intersection point that in the same side of the given color reveals the dominant wavelength. And the intersection point that in the other side of the given color reveals the complementary wavelength. But in some case, only one of those wavelength exists[38].

Saturation is related to colorfulness or chroma. Saturation is the colorfulness of a color relative to its own brightness[42]. A saturation 0 will lead to gray and 1 will lead to maximun colorfulness.
Lightness is the brightness or power of the lights.
Color in HSL can be converts to RGB color. When H between 0° and 360°, H between 0 to 1, and L between 0 to 1,

$$C = (1 - |2L - 1|) * S \tag{A.8}$$

$$X = C * (1 - |(H/60^\circ) mod 2 - 1|) \tag{A.9}$$

$$m = L - C/2 \tag{A.10}$$

$$(R', G', B') = \begin{cases} (C,X,0), 0^\circ \leq H < 60^\circ \\ (X,C,0), 60^\circ \leq H < 120^\circ \\ (0,C,X), 120^\circ \leq H < 180^\circ \\ (0,X,C), 180^\circ \leq H < 240^\circ \\ (X,0,C), 240^\circ \leq H < 300^\circ \\ (C,0,X), 300^\circ \leq H < 360^\circ \end{cases} \tag{A.11}$$

$$(R,G,B) = (R' + m, G' + m, B' + m) \tag{A.12}$$

Color in RGB can be converts to HSL color. When R,G,B between 0 and 1,

$$C_{max} = max(R,G,B) \tag{A.13}$$

$$C_{min} = min(R,G,B) \tag{A.14}$$

$$\Delta = C_{max} - C_{min} \tag{A.15}$$

$$H = \begin{cases} 60^{\circ} \times \frac{G-B}{\Delta} mod6, & if \quad C_{max} = R \\ 60^{\circ} \times \frac{B-R}{\Delta} + 2, & if \quad C_{max} = G \\ 60^{\circ} \times \frac{R-G}{\Delta} + 4, & if \quad C_{max} = B \end{cases} \tag{A.16}$$

$$L = (C_{max} + C_{min})/2 \tag{A.17}$$

$$S = \frac{\Delta}{1 - |2L - 1|} \tag{A.18}$$

## A.4 CMYK color space

CMYK refers to four inks: cyan, magenta, yellow and key(black). It is widly used in color printing.
CMYK is subtractive. White paper reflecting all energy of ligts. It start from white, then some inks is add on the paper and make it darker. The inks absorb different visible lights and give different color. The ideal three primary colors in CMYK, cyan magenta and yellow, is the complementary color of three primary colors in RGB. Cyan absorbs reds lights, magenta absorbs green lights and yellow absorbs blue. It is similar to RGB color space but have another coordinate system.

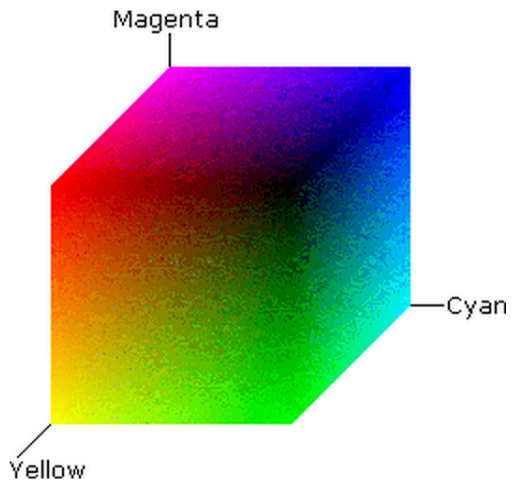


Figure A.9: The ideal CMY color space is basically the same as RGB space but have another coordinate system[43].

The first three ink are not perfectly absorbing all energy in visible lights. Therefore mixture of three primary colors in CMYK is not black but brown.

That is why the forth ink, black, is required. There are also reason for fast printing and economic reason. Black ink is cheaper than the others inks. Therefore, black is not the primary colors but it is necessary. Because the ink is not ideal, the gamut of CMYK is smaller than RGB.
CMYK color can be convert to RGB color:

$$t_{CMYK} = \{C,M,Y,K\} \tag{A.19}$$

$$t_{CMY} = \{C',M',Y'\} = \{C(1-K)+K,M(1-K)+K,Y(1-K)+K\} \tag{A.20}$$

$$t_{RGB} = \{R,G,B\} = \{1-C',1-M',1-Y'\} \tag{A.21}$$

And RGB color can be convert to CMYK color:

$$t_{RGB} = \{R,G,B\} \tag{A.22}$$

$$t_{CMY} = \{C',M',Y'\} = \{1-R,1-G,1-B\} \tag{A.23}$$

$$K = \min\{C',M',Y'\} \tag{A.24}$$

if K=1,

$$t_{CMYK} = \{0,0,0,K\} \tag{A.25}$$

Otherwise

$$t_{CMYK} = \left\{\frac{C'-K}{1-K},\frac{M'-K}{1-K},\frac{Y'-K}{1-K},K\right\} \tag{A.26}$$

# Appendix B

# Volume Rendering

Volume rendering is a wide range of techniques to project a three dimensional discrete data on a two dimension plane[44]. It present detail in a volume but not only detail on the surface. A MRI scan presents the skin, muscles, organs and bones. If only the skin is presents, that is just a picture from camera. Volume rendering is important technique in medical field, geological exploration,Weather analysis and molecular model construction.

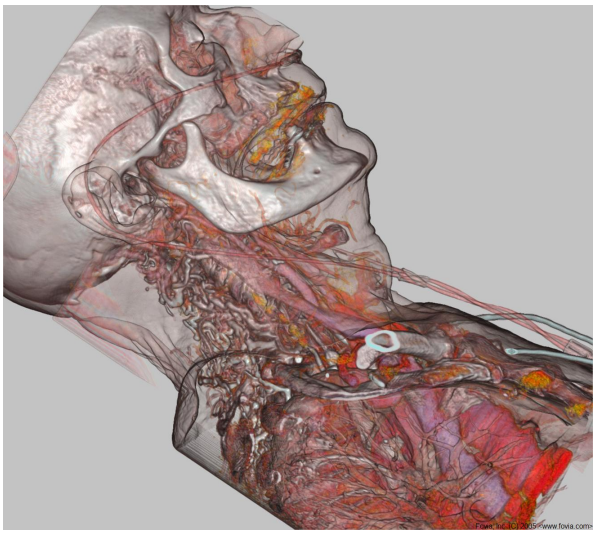

Figure B.1: An example of volume rendering[45].

There are 2 source of volume data:

1. Results of scientific computing, such as: the finite element computation.

2. Measurement data from instrument, such as: CT or MRI scan data.

Usually, there is a grid for the voxel. For example, slices images have the same resolution and distance between the slices are the same. The distance between voxel can be provided from the instruments.
In order to render the projection of data, the camera position or view angle has to be set up. Opacity and color of every voxel has to be defined. Usually a RGBA(red, green, blue, alpha) transfer funtion will be used to define RGBA value for every possible voxel. For example, for MRI, images are in grayscale. A color map(color look-up table) can define the RGB value. A alpha map(alpha look-up table) set up alpha value for every voxel. A different alpha map focus different part of the data set[46].

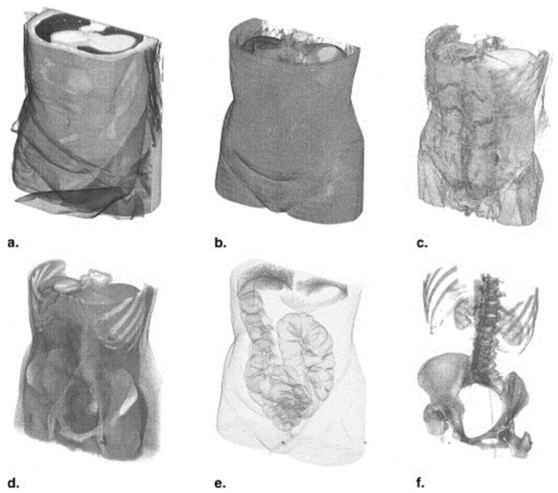


Figure B.2: A different alpha map focus on different part of the data base on its value. A decreasing opacity is set up from a to f[46].

There are several way to perform a direct volume rendering.
A most simple volume rendering algorithm is ray casting. The algorithm is based on ray scanning process which is easy to understand. It can achieve better rendering effect. It can be more easily transplant to the GPU in order to render in real time.
Ray follows a direction that is reverse to the view angle and goes throght the data set. With a optical models, cumulative colors is performed along the path of light, til the ray is out from the data set. The final cumulative color is the color of redering image.
The optical models can be:

1. Absorption only: voxel is cold and dark. They only absorb lights, but no emitting, neither reflection is considered.

2. Emission only: voxel emit light, but do not absorb light.

3. Absorption plus emission: Voxel emit light, and absorb light. But reflection is not considered.

4. Scattering and Shading/shadowing: Voxel may scatter (reflected and refracted) the light from external light source. Becausee of the occlusion between the voxels, the shadow can be generated.

5. Multiple Scattering:Ray can be scattered by multiple voxel.[47]

## B.1 Absorption plus emission model

Absorption plus emission model is the most comon optical model in ray casting. Voxel emit light, and absorb light. But reflection is not considered.

Opacity defines light's ability to penetrate objects. The opacity of the object is $\alpha_2$, and the color of object is $C_2$. Then the lights emit by the object is $\alpha_2 C_2$. If there are $C_1'$ of light comes from the background, only $(1-\alpha_2)C_1'$ can penetrate through. Then the accumulative light $C_2'$ is:

$$C_2' = \alpha_2 C_2 + (1-\alpha_2)C_1' \tag{B.1}$$

This is called "Alpha Blending"[48]. In order to help understand it, here a semitransparent voxel is replaced by a voxel that part transparent and part opaque in figure B.3.

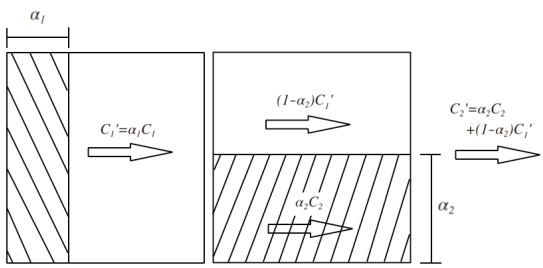


Figure B.3: Two voxel is drawn as blocks. They are part transparent and part opaque(the shaded part). The amount of light is labeled in the figure.

If the object is totally transparent, or $\alpha_2 = 0$, all light from the background can penetrate through. The object cannot be seen, although it has its own color. shown in figure B.4 on the next page.

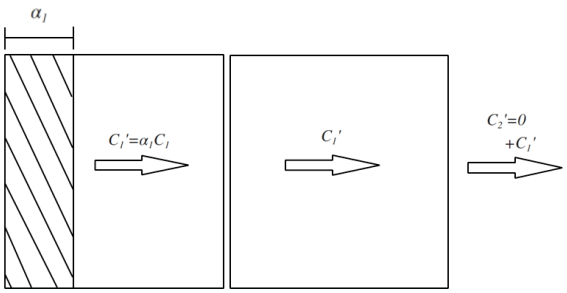


Figure B.4: All light can penetrate through the object if it is totally transparent

If the object is totally untransparent, or $\alpha_2 = 1$, all light from the background is stoped. The background cannot be seen, although it can be very bright. shown in figure B.5.

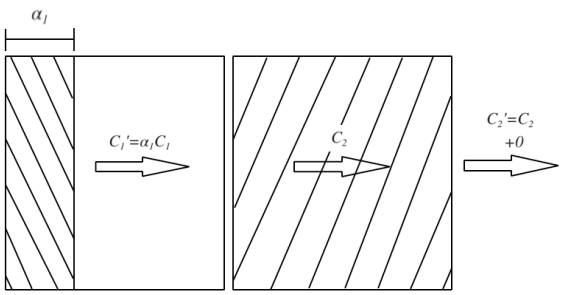


Figure B.5: All light is stoped by the object if it is totally untransparent

The background and first voxel become the new background for the next voxel in the direction. The depth of the voxel is not considered. A voxel is counted, although the ray may just pass through a corner of a voxel.The process is repeated to the final voxel. All the rays will have a final accumulate color $C_n(x,y)$ and these color compose a projection of the three dimenssion data set. This process is shown as figure B.6 on the next page.

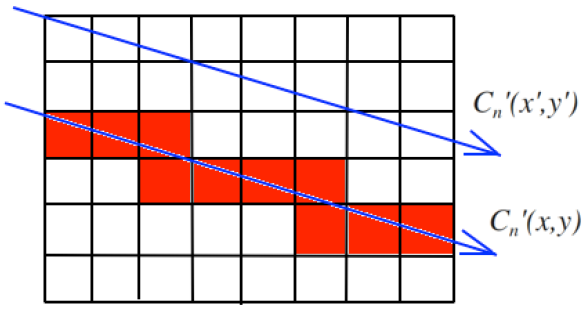


Figure B.6: All red voxel is participated in the computation of the final accumulate color$C_n(x,y)$. The x and y axis is perpendicular to the view angle

In volume rendering, the view angle can be rotated in real time and improves the sense of thrid dimension.
Overall, ray casting is a simple algorithm with high quality renderings. Its Inherently parallel computing allow GPU to accelerate the computation. Light model can be add in. But it is very slow due to lot of rays and sample[48].

# Appendix C

# STFED Map

The workflow is show as figure C.1 on the following page. It can be divided into three parts: time-frequency analysis, interplates form channel to space and STFED map In the time-frequency analysis, wavelet transform is performed, and wavelet coefficient is obtained from the EEG records. Then, wavelet power spectrum is obtained from these coefficient. Wavelet power spectrum can be seen as a spectrum that changing in time. White balance is performed. It is a normalization, redefining what is white. Without the white balance, our method is not sensitive to high frequency, since there is very little energy in high frequency compared to low frequency. In the second part, a spectrum can be map as a color. It is defined in HSL(hue-saturation-lightness) color space and then transformed into RGB(red-green-blue) color space. The color between channels is interpolated. In the third part, self-adapt resolution calculates how much topographic map shoud be created. Alpha value is calculated to make STFED map be translucent and to highlight the high energy. Finally, Volume rendering presenting the stack of modify Topographic map.

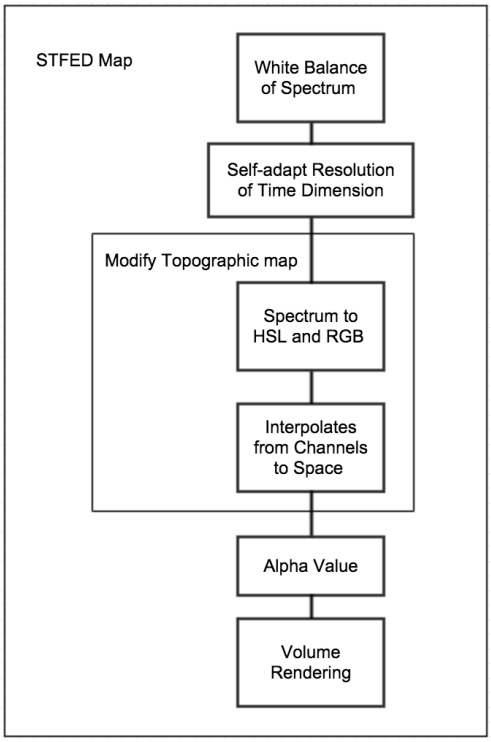


Figure C.1: The flow chart of the STFED map. After time-frequency analysis, information of time and frequency is obtained and normalized. The program will calculate a suitable number of topographic map to creat. Then,hundreds of topographic map is created based on these information and stacked as a volume. After calculate the alpha value, the volume is presented as STFED map with the techique of volume rendering.

## C.1 White Balance

A signal or process which has a spectrum that energy is inversely proportional to its frequency is also called "pink noise"[49]. We can find out that most energy in EEG signal is in the low frequency, show as Figure C.2 on the next page. That will make the modify Topographic map basicly pink. It is very difficult to see the difference in high frequency.

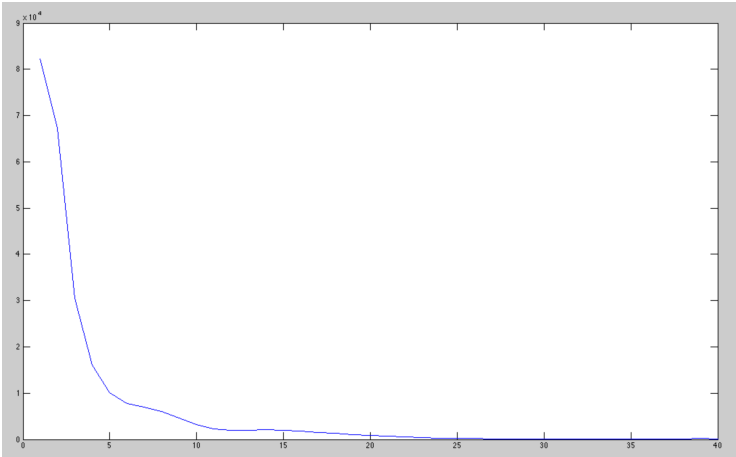


Figure C.2: Averge Energy distribution in frequency, of an entire one hour record with all channel

In photography there is a similar problem. Because of the illumination, the photo can has a color bias. White balance define what is white in the photo and can remove the bias. In order to prevent this problem in this study, a normalization is performed. A gain is given on the high frequency energy which make the energy distribute in frequency basically equal in all recording. This makes the average color of modify Topographic map to white.

The white balance is set up by a recoding, and adapted to others. The recording for setting up the white balance will not be used later for the quantification. It converts absolute value to relative value. These will change the meaning to: Compared to the stanard, how much energy there is in different frequency.

Or the EEG can be simply seen as pink noise and just gain energy with the frequency. This will not require using a record to normalize.

With the white balance, the detail that is in higher frequency can also be present. See figure C.3

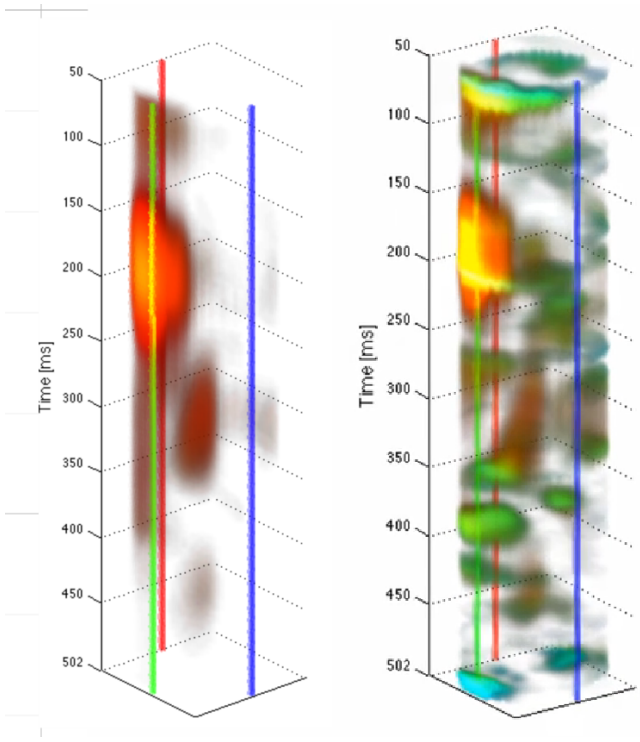


Figure C.3: Left: without white balance; right: with white balance

## C.2 Modify Topographic map

Traditional topographic map show energy distribution in space, of a chosen timing and frequency. It can be improved, showing information of frequency, by using the definition of "color of signal".

Color is the feeling of frequency. And the color of a signal is analogy to power spectrum of visible lights. Similar idea can be found on music theory. Timbre, also known as tone color, make the difference between piano and violin, and any other instruments. In common, lights, sounds, EEG signals, they are all wave. In Physics, spectrogram can be used to describe them objectively.

Instead using color to present energy level, modify Topographic map use brightness. Color is used to present the frequency.

### C.2.1 HSL Color Space

HSL(hue-saturation-lightness) color space is a deformation of RGB color space [50]. RGB is a orthogonal basis for human vision. HSL is another one. Although RGB color space is more convenient in computer graphic, HSL has

more physics meaning. HSL has relation to the mean frequency, deviation of the energy in frequency, energy. They are just another name in another field.

1. Hue: defined as "the degree to which a stimulus can be described as similar to or different from stimuli that are described as red, green, blue, and yellow[42]" Mean frequency.

2. Saturation, related to deviation of the energy in frequency. The higher the saturation, the lower the deviation. If the saturation is one, all the energy is locate on a narrow frequency, like a sin wave.

3. Lightness: energy of the lights.

Using HSL color space means that the colormap is three dimension, different from topoplot. It present energy distribution in a position of modify Topographic map or STFED map.

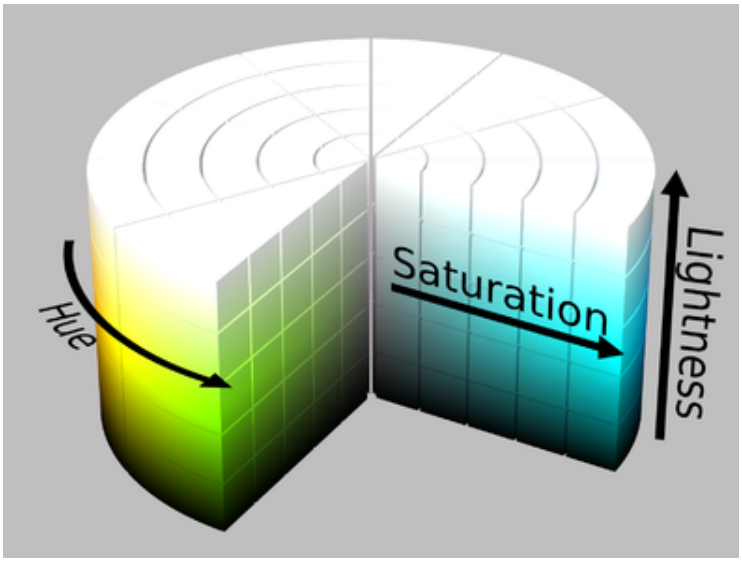


Figure C.4: This figure shows HSL color space. It also is the the colormap of modify Topographic map and STFED map[41]

### C.2.2 Convert HSL into RGB

HSL color space has more Physics meaning. But computer can only recognize RGB mode. There is a formula to convert HSL to RGB value[50, 51]:
When H between 0° and 360°, H between 0 to 1, and L between 0 to 1,

$$C = (1 - |2L - 1|) * S \tag{C.1}$$

$$X = C * (1 - |(H/60°)mod2 - 1|) \tag{C.2}$$

$$m = L - C/2 \tag{C.3}$$

$$(R', G', B') = \begin{cases} (C,X,0),0^{\circ} \leq H < 60^{\circ} \\ (X,C,0),60^{\circ} \leq H < 120^{\circ} \\ (0,C,X),120^{\circ} \leq H < 180^{\circ} \\ (0,X,C),180^{\circ} \leq H < 240^{\circ} \\ (X,0,C),240^{\circ} \leq H < 300^{\circ} \\ (C,0,X),300^{\circ} \leq H < 360^{\circ} \end{cases} \tag{C.4}$$

$$(R,G,B) = (R' + m,G' + m,B' + m) \tag{C.5}$$

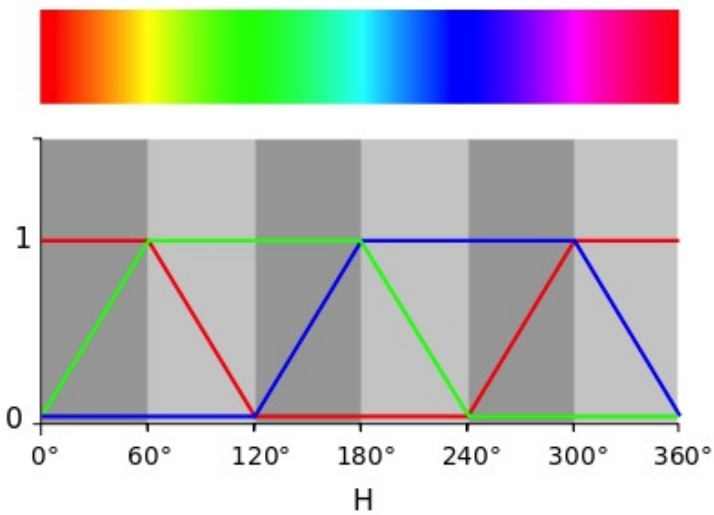


Figure C.5: This figure shows the color and RGB value when H change, and S=1,L=0.5[41]

Firstly, what we want to present is a small unit of lightwave in a specific frequency, or monochromatic light. Therefore, saturation is equal to 1, and lightness is 0.5. When hue change from 0° to 360°, the point will draw a circle on HSL color space's surface. That also simplfy the fomular to:

$$X = 1 - |(H/60^\circ) mod 2 - 1| \tag{C.6}$$

$$(R,G,B) = \begin{cases} (1,X,0), 0^\circ \leq H < 60^\circ \\ (X,1,0), 60^\circ \leq H < 120^\circ \\ (0,1,X), 120^\circ \leq H < 180^\circ \\ (0,X,1), 180^\circ \leq H < 240^\circ \\ (X,0,1), 240^\circ \leq H < 300^\circ \\ (1,0,X), 300^\circ \leq H < 360^\circ \end{cases} \tag{C.7}$$

And there is a problem when H from 240 to 360. In the HSL color space that is magenta. But that is not include in monochromatic light. We make a small change, break the circle into a line. These computation can be summarized as a table that show as Figure C.6.

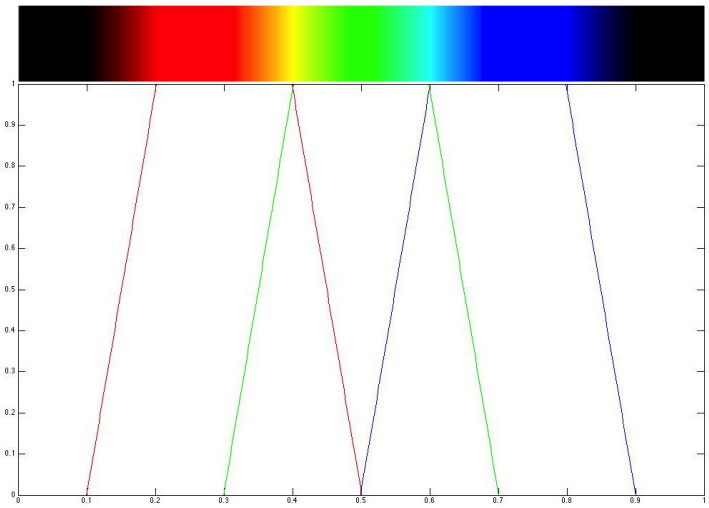

Figure C.6: RGB value compare to frequency of monochromatic light

Finally, Polychromatic light is just sum of multiple monochromatic lights. The RGB value can be simplly sum up.

### C.2.3 Position of Bipolar

Just like topoplot, the coodinate of every channel has to be defined. The position of bipolar is the center of two electrodes. The position is measure from the 10-20 system.

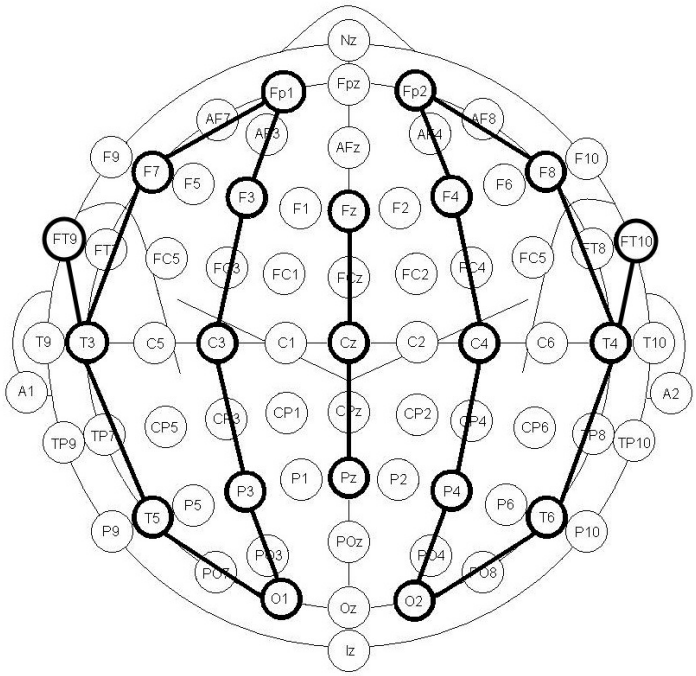


Figure C.7: The Bipolar (double banana) montage using in the database. The thick black line connect pair of electrodes. Every pair of electrode generates a differential signal and will be record in a channel. The signal is the potential difference between two electrodes. Figure edited from website[24]

### C.2.4 Implement of modify Topographic map

Compare to topographic map which maps energy on the traditional , modify Topographic map maps power spectrum. For a short time period, an modify Topographic map is made with these follow step:

1. chosen a the lowest visible frequency and the highest visible frequency. That determine frequency range which is the researcher interesting in. Outside of the visible frequency range will not be visible. The visible frequency range is 1 to 10 in our study.

$$LVF = 1 \tag{C.8}$$

$$HVF = 10 \tag{C.9}$$

2. the wavelet power coefitient E is spectrum changing in time t. Let's call the curve in figure C.8 on the next page R(f), G(f) and B(f). Notice that the power coeficient has been normalized. Calculate the luminous rgb value, Lr Lg and Lb, use the Equition C.10 on the facing page:

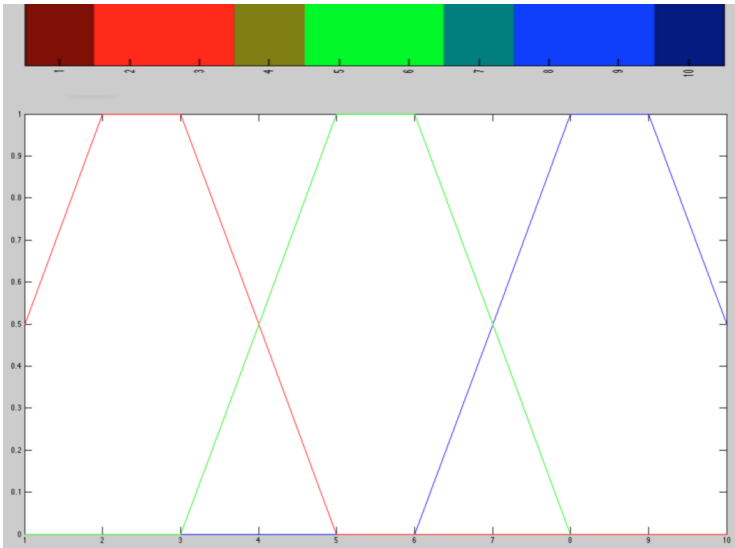

Figure C.8: The x axis is frequency. Red green and blue line are the curve of R(f) G(f) and B(f). There are several difference to figure C.6 on page 65 because the low resolution.

$$Lr(t) = \int_{LVF}^{HVF} E(f,t)R(f)df \tag{C.10}$$

$$Lg(t) = \int_{LVF}^{HVF} E(f,t)G(f)df \tag{C.11}$$

$$Lb(t) = \int_{LVF}^{HVF} E(f,t)B(f)df \tag{C.12}$$

3. On the modify Topographic map, every position of a channel get the luminous rgb value of that channel. Interpolate the luminous rgb value between channel's position.

4. The calculate luminous rgb value can be much bigger then 1. Divide it by a "Expose time", expt, and if that is still bigger than 1, limite that to 1. We can call this RGB value for the output as "Image RGB" value ,Ir Ig and Ib.

$$Ir(t) = \begin{cases} \frac{Ir(t)}{expt} \\ 1(if \frac{Ir(t)}{expt} > 1) \end{cases} \tag{C.13}$$

$$Ig(t) = \begin{cases} \frac{Ig(t)}{expt} \\ 1(if \frac{Ig(t)}{expt} > 1) \end{cases} \tag{C.14}$$

$$Ib(t) = \begin{cases} \frac{Ib(t)}{expt} \\ 1(if \frac{Ib(t)}{expt} > 1) \end{cases} \tag{C.15}$$

5. In order to make the topographic to a circle, cut the corner by setting the Image RGB value to 0. Label the front, left ear and right ear. Here we do it by change the color respectively to green, blue and red.

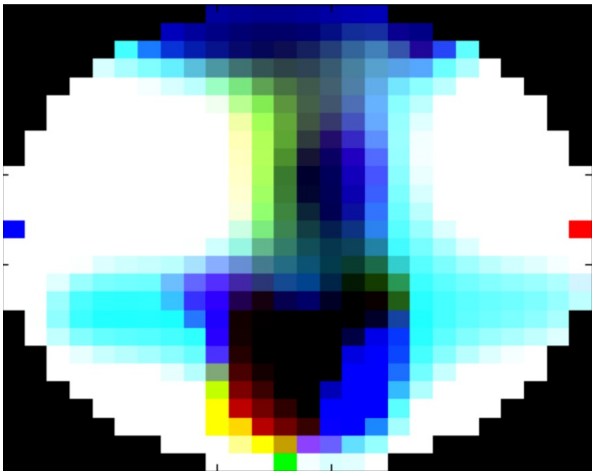

Figure C.9: A sample of modify Topographic map. In the figure, left is labeled with a blue spot, right is labeled with red and the front(below) is green. White show high energy in all visible frequency. Blue shows high energy in high visible frequency and so on.

## C.3 Space-Time-Frequency Energy Distribution Map(STFED Map)

For every short time period, an modify Topographic map is made. In the modify Topographic map, color presenting the frequency information. All of these topographic map stack together and become a volume that can be display by using volume rendering. The first two dimension present the space information, and the third dimension present the time information.

In total, the volume presenting energy distributed in space, time and frequency. That is the reason it is called as Space-Time-Frequency Energy Distribution map(STFED map).

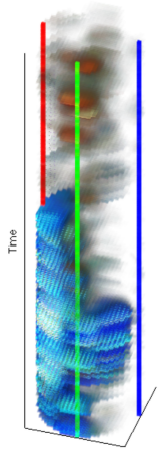


Figure C.10: A sample of STFED map. In the figure, left is labeled with a blue line, right is labeled with red and the front is green. White show high energy in all visible frequency. Blue shows high energy in high visible frequency and so on.

### C.3.1 Self-adapt Resolution

STFED map is a stack of modify Topographic maps. A modify Topographic map presenting information of a short period of time.
We faced a problem on how many modify Topographic map should be created, and how long is the short period of time. It can be up to 256 modify Topographic map per second, which is the same as the sample rate.
In a case, in order to create a STFED map of 10 seconds record, up to 2560 modify Topographic map can be made. The problem is for every modify Topographic map, three interpolation has to be operated. That cost a lot of computation. On a typical screen, the resolution is 2560*1600, any higer resolution of STFED map is not that useful.
We make a small script to set up the resolution. For example, there are 2560 time points in a 10 second record.

1. If the records time period is very short, just create a modify Topographic map for every sample time point. In our study, that is 5 seconds.

2. Otherwise, a suggest resolution, SR, of time dimension in STFED map is given to computer. In our study, that is 600.

$$f_s = 256$$

$$SR = 600$$

In an example, $t = 10s$

3. The computer try to separate all the time points to the resolution. In most case, that cannot be simply done. they will be seperate into group. Every group has n sample points and m sample points are left. In the example

$$\frac{t * f_s}{SR} = n \cdots m$$

In the example

$$\frac{2560}{600} = 4 \cdots 160$$

4. The quotient n will be used to group up the sample point. The number of group will be the real resolution(RR) in time dimension. The last $N_{discard}$ sample points mill be discard.

$$\frac{t * f_s}{n} = RR \cdots N_{discard}$$

In the example, every 4 sample point will be used to create an modify Topographic map.

$$\frac{2560}{4} = 640 \cdots 0$$

Then there will be 640 modify Topographic map.

5. In the short period of time, energy will be average and then used to create the modify Topographic map.

With the self-adapt resolution, a long record can also be presented in STFED map, costing not too much computation time. It removes the ability to zoom. Therefore instead of zooming, the user have to create a new figure with the new range. But that reduces the computation time of interpolation from hours to 10 seconds.

### C.3.2 Alpha Value

In 3D computer graphic, there is an alpha value, or opacity, has to be defined for every voxel(pixel that in 3 dimension) . A voxel that has alpha as 1 cannot be see through. And a voxel that has alpha as 0 cannot be see because it is completely transparent.
In our study, the alpha value is compute by its RGB value for every voxel as:

$$\alpha = 0.64 \times I^2 \tag{C.16}$$

$$= (0.8 \times \frac{R+G+B}{3})^2 \tag{C.17}$$

Where the I is the intensity when a RGB color convert to grayscale. The order is the level to suppress the low intensity voxel that the low energy is locate, make it more transparent.

## C.4 Video of EEG Activity

STFED map is a stack of modify Topographic map. These topoplot can be displaied one by one. A small delay will be between two modify Topographic map. That is a video record of EEG activity, just like capture by a camera that can capture EEG signals.
Because there is no voxel overlapping, the video has advantage on local. It gives higher accuracy on potion and timing. It is also easier to read the frequency and energy information on the colormap. Meanwhile, the STFED map gives understanding of the entire data.

# List of Figures

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