A Novel Wavelet Based Technique for Detection and De-Noising of Ocular Artifact in Normal and Epileptic Electroencephalogram

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***Abstract*—The Electroencephalogram (EEG) is a biological signal that represents the electrical activity of the brain. Typical EEG instrumentation settings used are low pass filtering at 75Hz and paper recording at 100V/cm and 30mm/s for 10-20 minutes over 8-16 simultaneous channels. A commonly encountered problem in clinical practice during EEG recording is the 'blanking' of the EEG signal due to blinking of the user's eyes. Eye-blinks and movements of the eyeballs produce electrical signals that are collectively known as Ocular Artifacts and these are 10-100 times stronger than the EEG Signal which is being recorded. The effective filtering of these ocular artifacts is extremely difficult owing to the fact that their frequency spread (1Hz - 50Hz) is observed to be overlapping with that of the EEG. Another major drawback of the existing frequency based de-noising techniques is that they require continuous recording of the Electrooculargram (EOG) signals as well. Recently, Stationary Wavelet Transform (SWT) of the corrupted EEG signal has been used to de-noise it. This paper presents a novel and simple technique for the detection and subsequent de-noising of these ocular artifacts using Haar wavelets of high orders. A comprehensive error analysis has been carried out, both in the time domain based artifact detection as well as the frequency domain based SWT de-noising of EEG. This procedure is also highly artifact selective and so we have applied it to detect and de-noise Epileptic EEG signals.**

Keywords: Electroencephalogram (EEG) Signal, Electrooculargram (EOG) Signal, Epilepsy Detection, Ocular Artifacts, Wavelet Transform.

I. INTRODUCTION

Electroencephalogram (EEG) serves as an extremely valuable tool for clinicians and researchers to study the activity of the Brain in a non-invasive manner. The frequency content of the EEG is between DC and 75Hz and its amplitude is generally in the order of 10-45μV. Extracting the EEG in an environment where the Signal-to-Noise Ratio (SNR) can be as low as 10dB forces us to ensure that the artifacts caused by sources internal to the human body like EOG and neck muscle movements are detected and filtered out accurately. The Cornea-Retinal Potential (CRP) developed as a result of the movement of the eyeballs also causes 'blanking' of the EEG Signal due to the spikes that occur. This along with the blink related artifacts are often dominant over other electrophysiological contaminating signals like the ECG and movement of body muscles. The ocular artifacts are around 10-100 times stronger than the EEG and thus cause sharp spikes as shown in *Figure-1.*

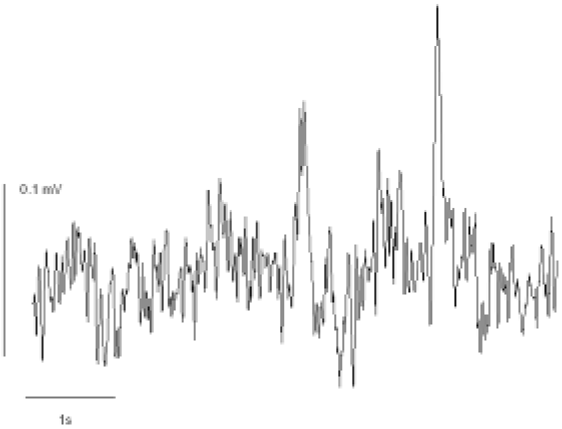


Fig. 1. EEG signal showing the sharp spikes caused due to Ocular Artifacts.

The existing de-noising techniques that are based on frequency selective filtering lead to a substantial loss of the EEG data. Prohibiting the subjects from blinking or moving their eyeballs is not a plausible solution and in-fact the effort of the subject in ensuring that he does not do the aforementioned actions can have a significant impact on the recorded EEG. Due to these factors, frequency selective filtering methods for removal of ocular artifacts from EEG recordings has been and continues to be a major challenge today. Wavelet based filtering is an attractive alternative owing to its ability to study the time-frequency maps simultaneously. Stationary Wavelet Transform (SWT) has recently been used to de-noise the EEG data, but owing to the Ocular Artifacts being significantly uncorrelated with the recorded EEG data, the reconstructed signal is often not a very good approximation of the original EEG. So basically the problem lies in the fact that no existing method is able to detect the moment the eye-blink occurs accurately. In this paper we have used Haar wavelets of high orders to detect and de-noise these ocular artifacts.

II. HAAR WAVELET BASED DETECTION OF CHANGE IN THE STATE OF THE EYES

The need to continuously monitor the EOG while recording the EEG Signal and its corruption due to concentration on the part of the user so as not to move or blink his eyes forces us to device an alternate method for detecting and removing the Ocular Artifacts. The EEG Signal which is picked up by non-invasive methods over the scalp of the subject is corrupted by a multitude of artifacts of which those caused by the EOG cause maximum distortion. In this section we give a brief description of the effect that the Ocular Artifacts have in the amplitude and frequency spectrum of the EEG data that is recorded. We also describe a novel and elegant technique using the sharply varying Haar Wavelets to accurately detect changes in the state of the eye and this shall be extended in the subsequent section to detect eye-blinks and eyeball movements.

A. EEG amplitude dependence on the state of the eye

It has been known for quite some time now that the Alpha Rhythm of the EEG, which is the principal resting rhythm of the brain in adults while they are awake, is directly influenced by visual stimuli. Auditory and mental arithmetic tasks with the eyes closed leads to strong alpha waves, which are suppressed when the eyes are opened. This property of the EEG has been used, ineffectively, for a long period of time to detect eye blinks and movements. The slow response of thresholding, failure to detect fast eye blinks and the lack of an effective de-noising technique forced researchers to study the frequency characteristics of the EEG as well.

B. EEG recorded during change in state of the eye

Successful de-noising of the recorded EEG Signal is directly dependent upon the precise detection of change in state of the eye from the open state to the closed state and vice-versa. For this we require a continuous recording of the EEG Signal regardless of change in the state of the eye. Such a continuously recorded EEG Signal is shown in *Figure-2* and from the abrupt increase in its amplitude at t = 5s, we can easily guess that the eye is open for the first 5s and closed for the next 5s. This immediate increase (or decrease) of the amplitude of the EEG Signal when the eyes are closed (or opened) was known to Medical Scientists for quite some time, but using this difference in amplitude levels to control external devices by thresholding had gone unnoticed for over 30 years and it was not until 1998 that a team of scientists at the University of Technology, Sydney, Australia noticed this fact and made what is known today, as the ’Mind Switch’. But amplitude thresholding, though useful for Bio-Control cannot be used to effectively detect the eye blinks that occur quite rapidly. So the focus of research on detection and de-noising of these Ocular Artifacts in EEG, shifted from the time domain to the frequency domain.

C. Detection of change in state of the eyes: Need for a wavelet based approach

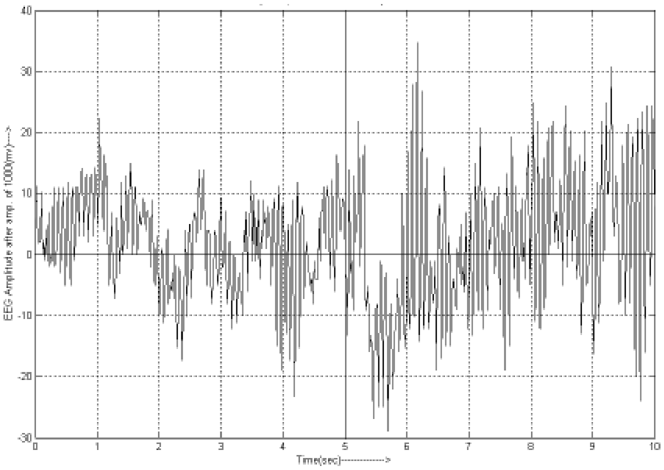


Fig. 2. EEG Signal showing change in state of eye at t = 5s

On analysis of the frequency spread of the EEG data that contained the Ocular Artifacts, researchers found that the difference in the frequency of the Spikes caused due to Rapid Eye Blink (REB) and the EEG signal could be used along with a simultaneous recording of the EOG to detect and remove these artifacts. But correlation of the EEG and EOG is futile, especially because of the inherent corruption of EEG data by the restraint on the users eye movements and blinks. The failure of accurate detection of these artifacts by singular observation of the time or frequency domains forces us to use wavelets to study time-frequency maps. In this section, we have used the Haar wavelet of high orders to decompose the recorded EEG Signal to detect the exact moment when the state of the eye changes and on subsequent de-noising we arrive at extremely good reconstructions of original EEG data. This technique has been extended in the subsequent section to detect eye-blinks and movement of the eyeballs as well.

1) Haar wavelet based detection - Closing of the eyes: In order to detect closing of the eyes, we have used the EEG data samples like the one shown in *Figure-3.* Here the subject’s eye is open for the first 5s and is then closed at t = 5s after which it remains closed.

On decomposing this EEG data sample with the discontinuous Haar Wavelet of order 8, we obtain 8 successive approximations. The final stage of approximation yields a Step Function, whose falling edge accurately detects the moment when the user’s eye goes from the Open State to the Closed State. This can be seen clearly from *Figure-4* where at t = 5s and Sample Index(n) = 256, the Haar Wavelet decomposition yields the falling edge of the Step Function. We have extensively tested this technique on various EEG data samples acquired from a spectrum of sources and even under extremely noisy conditions with multiple artifacts, we are able to successfully detect the closing of the subject’s eye. The resulting time measurement is accurate to ±18ms as we shall see in the next section.

2) Haar wavelet based detection - Opening of the eyes: In order to detect opening of the eyes, let us consider as an example, the EEG data shown in *Figure-5.* Here the subject’s eyes are closed for the first 2.5s and are then opened at t =

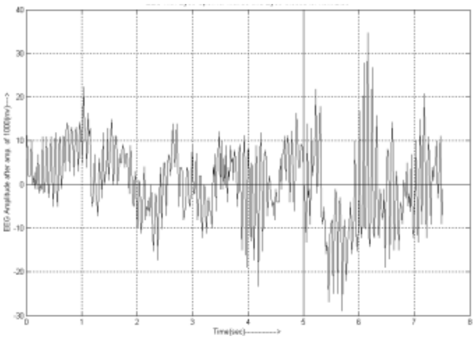


Fig. 3. EEG Signal with eyes closed at t = 5s.

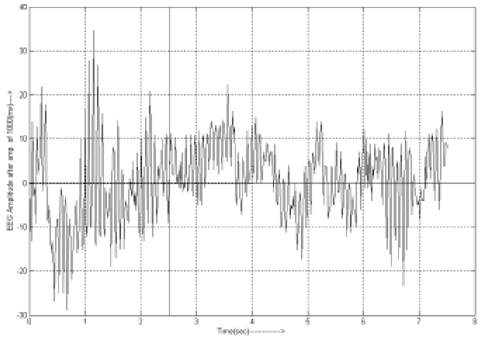


Fig. 5. EEG Signal with eyes opened at t = 2.5s.

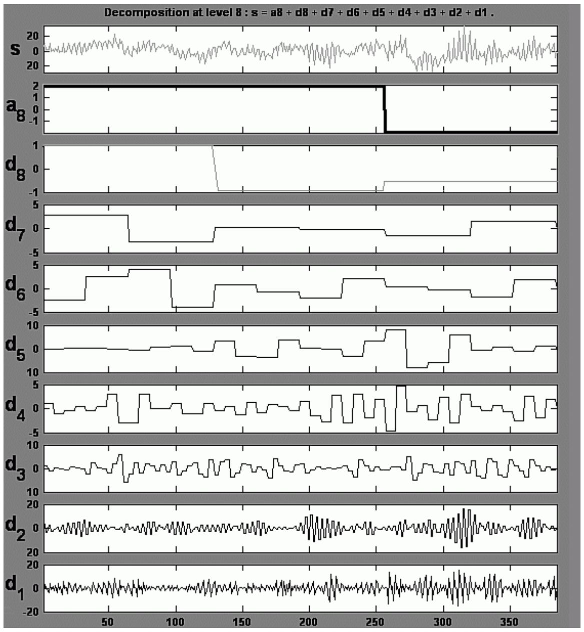


Fig. 4. Decomposition with Haar wavelet of 8th Order.

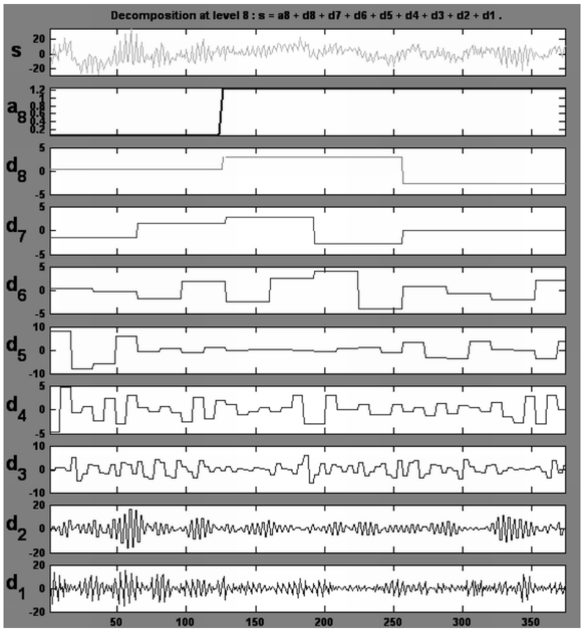


Fig. 6. Decomposition with Haar wavelet of 8th Order.

2.5s after which they remain open.

Once again, the final stage of approximation yields a Step Function, whose raising edge accurately detects the moment when the user's eye goes from the closed ctate to the open state. This is depicted in *Figure-6* where at t = 2.5s and Sample Index(n) = 128, the Haar Wavelet decomposition yields the raising edge of the Step Function. As concluded previously, we are able to successfully detect the opening of the Subject's eyes under a multitude of conditions, some of them with SNR as low as 10dB. The resulting time is accurate to ±12ms as we shall see in the next section.

III. EXTENSION OF THE HAAR WAVELET BASED ANALYSIS TO DETECT AND FILTER EYE BLINKS

As we had seen in the previous section, on decomposing the EEG data with the Haar wavelets of high orders we obtain a step function with a falling edge for a change in the state of the eyes from open to closed and a step function with a rising edge for a change in state of the eyes from closed to open. In this section we shall extend the same technique to detect eye-blinks accurately. For this we shall consider as an example, the EEG data shown in *Figure-7,* where there is a blink artifact between 0.3s and 0.5s. On decomposing this with a Haar Wavelet of degree 7, the final approximation yielded the Step function with the falling edge at 0.28s and the rising edge at 0.5s as shown in *Figure-8.*

The reconstruction of the EEG Signal at the output of the Haar Wavelet and subsequent filter yields us the signal as shown in *Figure-9.* The main advantage of this technique over existing wavelet based EEG de-noising methods is the precise detection of the moments when the state of the eye changes which ensures the absence of remnant Ocular Artifact and the perfect reconstruction of the EEG data. The standard deviation, mean absolute deviation and the median absolute deviation that are calculated for the re-constructed EEG signals at the output of the Haar Wavelet Filter are shown in *Figure-9.* 157 normal EEG samples and 104 Epileptic EEG samples were analyzed and the timing errors involved in their detection are shown in *figure-10* where the frequency of occurance of different time deviations is plotted as a function of the aberrant times in

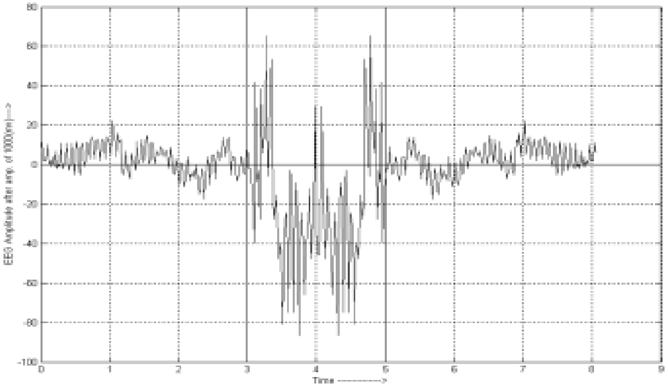


Fig. 7. EEG Signal with Eye-blink Artifact clearly recorded.

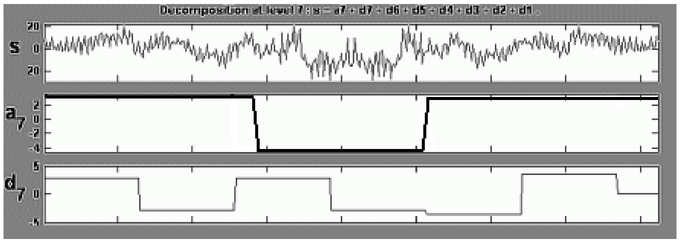


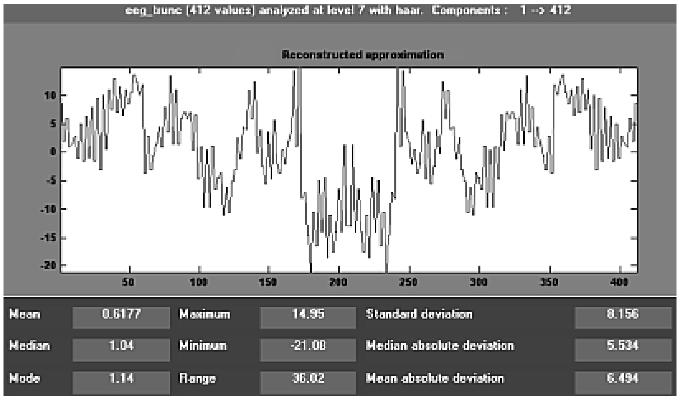
Fig. 8. Detection of Eye-blink with Haar wavelet of 7th Order.

milliseconds.

The values of minimum, maximum and mean deviations in detection times for the 157 normal EEG samples and the 114 Epileptic EEG samples recorded are summarized in *Table-1* and *Table-2* respectively.

IV. Results and Discussions

The effectiveness of the de-noising of Ocular artifacts from EEG is dependent to a large extent on their accurate detection. Our experiments have shown conclusively that using discontinuous wavelets like Haar of High orders is the simplest way to determine the instant when Ocular Artifacts occur and as we have seen in the previous section, this leads to very accurate reconstruction of the EEG signal. The validity of the technique has also been verified with the EEG data samples obtained by invasive methods using the correlated output of multiple needle electrodes. In situations where the EEG Signal strength is in the order of 50 dB or more, we are able to detect the Ocular Artifacts with an average accuracy of ±0.92ms for opening of the Eyes, ±3.01ms for the closing of the eyes and ±3.87ms for eye-blinks. For movements of the eyeballs in the horizontal and vertical directions the detection accuracy is found to be around ±7ms on an average. In case of Epileptic EEG, where the seizure spikes and artifacts create a situation with SNR<10Db, the detection accuracy decreases by about ±1ms to ±6ms on an average and these are certainly satisfactory. We are presently researching on the extremely artifact selective nature of our Haar Wavelet filters as this could aid in the accurate detection of Epilepsy while eliminating the need for EOG recording and obtaining a very good reconstruction of the EEG signal as well. From the reconstructed approximation at the output of the Wavelet filters and subsequent correlation with EEG obtained from invasive methods we can confidently declare that the use of discontinuous Wavelets of high orders is a very viable solution to the problem of detection and de-noising of Ocular Artifacts in Electroencephalogram.



Mean 0.6177
Median 1.04
Mode 1.14
Maximum 14.95
Minimum -21.08
Range 36.02
Standard deviation 8.156
Median absolute deviation 5.534
Mean absolute deviation 6.494

Fig. 9. Re-constructed EEG at output of Haar Wavelet

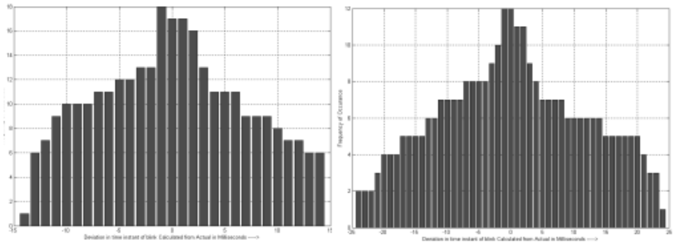


Fig. 10. Error in time detection : (a.) Eye Blink in Normal EEG and (b.) Blink in Epileptic EEG

TABLE I

Normal EEG: Deviation of detection times from Actual

Action Done	Min.(ms)	Max.(ms)	Mean(ms)
Eyes Opened	0	12	0.92
Eyes Closed	0	18	3.01
Eyes Blink	0	19	3.87
Eyes Movement(Vertical)	2	24	7.11
Eyes Movement(Horizontal)	3	20	7.14

TABLE II

Epileptic EEG: Deviation of detection times from Actual

Action Done	Min.(ms)	Max.(ms)	Mean(ms)
Eyes Opened	0	28	3.73
Eyes Closed	1	32	4.07
Eyes Blink	4	35	6.70
Eyes Movement(Vertical)	6	43	13.00
Eyes Movement(Horizontal)	6	40	12.89

V. CONCLUSION

The use of frequency based Ocular artifact removal methods require continuous monitoring of the EOG Signal as well as the EEG Signal and there is remnant EOG in the recorded EEG Signal even after the filtering process. Expecting the subject not to blink his eyes or move his Iris is not an acceptable solution and this exercise of restraint on the part of the user may itself lead to corruption of the EEG that is being recorded. Amplitude based thresholding methods can be used only in absolutely artifact free situations or while devising control systems for patients with extreme paralysis. The separation of the ocular artifacts based on amplitude is not a viable solution leading to the relatively slow response of thresholding compared to the fast rate of eye blinks. Existing methods based on wavelet analysis for removal of ocular artifacts from EEG leads to loss of the data and there is still remnant artifact in the collected samples and this is easily verified by comparing this with data obtained by invasive methods. The main cause is the incorrect detection of the artifacts and not the process of their filtering. The existing methods cope up with this defect by having over 8-16 simultaneous channels and the correlated data obtained is then applied to the Wavelet filters that remove the Ocular Artifacts. This paper presents a novel and efficient method for accurate detection and subsequent de-noising of these artifacts caused by eye blinks and eyeball movements, both of which generate signals that are 10-100 times stronger than the EEG that is being recorded. By making use of the sharply discontinuous Haar wavelets of high orders we are able to make precise detection of these Ocular Artifacts and this leads to their complete removal and accurate reconstruction of the EEG signal. The analysis on the error involved in our technique has produced encouraging results with the maximum deviations being as low as 18ms for normal EEG and 24ms for epileptic EEG. Another significant result, which we are presently doing further research on, is the extremely artifact-selective nature of these discontinuous wavelets that can be designed to remove just the ocular artifacts while permitting the seizure spikes caused due to disorders like epilepsy to appear in the observed EEG Signal. In other words, this method can be used to remove the ocular artifacts, or a combination of such artifacts, while ensuring detection of disorders like epilepsy. This is impossible with mere frequency based filtering which will filter out both the epileptic seizures,the artifacts and even a substantial part of the EEG signal. Hence, our efforts are directed towards researching and designing Haar and other similar discontinuous Wavelets for highly artifact selective detection and de-noising.

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