

ANALYSIS OF DC OFFSET IN iOS DEVICES  
FOR USE IN AUDIO FORENSIC EXAMINATIONS

by

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Analysis of DC Offset for iOS Devices for Use in Audio Forensic Examinations

Thesis directed by Professor Catalin Grigoras

## ABSTRACT

Due to the physical properties of electronic components, DC offset will occur to some extent in all audio recordings. DC offset is the effect of direct current on an audio recording, and causes the audio signal to no longer oscillate around the absolute zero quantization level. The mean amplitude of a recording is calculated to determine the global amount of DC offset. Measuring the offset, its change over time, and its standard deviation can be used during forensic examination to aid in determining the authenticity of a recording as well as for exclusionary purposes when multiple recorders could possibly be the source of a recording. The scope of this thesis is to measure the DC offset that occurs in recordings made by Apple mobile devices running on iOS, to quantify the uniqueness of this offset within this family of devices as well as against previously tested audio recording devices, and to see if different hardware and apps affect the offset. To accurately determine this, multiple apps were tested in conjunction with the built-in microphone, the Apple EarPods that come with the iPhone 5, and the Apple Earphones that come with previous iPhone models. Furthermore, all recordings were made in laboratory conditions with a minimum amount of outside noise, only the app making the current recording was open, Auto-Brightness was switched off, and all outside connectivity (wireless, Bluetooth, 3G, 4G, LTE) was turned off.

The form and content of this abstract are approved. I recommend its publication.

Approved: Catalin Grigoras

## DEDICATION

I dedicate this thesis to my family, Tom, Josie and Lauren, and my fiancée, Emily Vinson. This would not have been possible without your love and support. You have provided me with the strength and encouragement needed to bring me to where I am today.

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## **List of Abbreviations**

### **Abbreviation**

ADPCM	Adaptive Differential Pulse-Code Modulation
AES	Audio Engineering Society
CLA	Compression Level Analysis
DC	Direct Current
DSP	Digital Signal Processing
DSS	Digital Speech Standard
ENF	Electric Network Frequency
LTAS	Long-Term Average Spectrum
MP3	MPEG-1/MPEG-2 Audio Layer III
PCM	Pulse-Code Modulation
QL	Quantization Level
SD	Standard Deviation
WMA	Windows Media Audio

## 1. Introduction

In the field of audio forensics, there are numerous tests that may be performed during the authentication of a recording. These include examination of a digital recording's file structure, critical listening, waveform analysis, electric network frequency (ENF) comparison, and a myriad of other forms of analysis. One of the most recent types of examination comes in the form of measuring the affect of the direct current (DC) on the audio signal. This effect is known as DC bias, more often referred to as DC offset, and from this point on only referred to as such. As per Federal Standard 1037C, bias is known as:[1]

- A systematic deviation of a value from a reference value
- The amount by which the average of a set of values departs from a reference value

In the case of DC offset, the effect of the DC current on an audio recording appears as a negative or positive departure of the audio waveform from equal distribution around the x-axis, otherwise known as the absolute zero quantization level (QL).

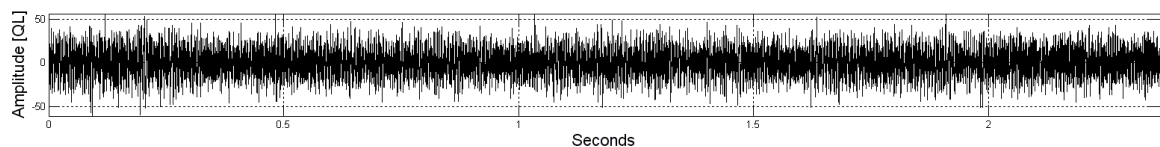
When an audio recording is made, the recording device must use electrical energy. Either an external power supply or an internal battery provides this energy, and it will be present to some extent in the audio recording via the current running through the device. This presence may manifest itself in a number of ways, among which include AC hum, ENF, noise, etc. One form of energy that is always present in a recording is the direct current running through the recording device, and exists in

both analog and digital recordings. The addition of the direct current to the audio signal is referred to as DC offset, and will affect the audio waveform by making it no longer centered around the absolute zero QL. This will result in a positive or negative shift of the waveform from the x-axis, and when the global DC offset, also known as DC offset mean, is calculated, the resulting value will be either positive or negative because of this shift from the x-axis. To calculate the DC offset, we measure the mean amplitude of the audio recording. An ideal audio recording would have a DC offset mean value of zero, but this is technically impossible due to the nature of complex waveforms. We must work with audio recordings in an environment such as MATLAB to accurately calculate the amount of DC offset. For this study, QL values were chosen as the unit of measurement to calculate the DC offset because they are the smallest form of measurement available when measuring the amplitude of digital audio.

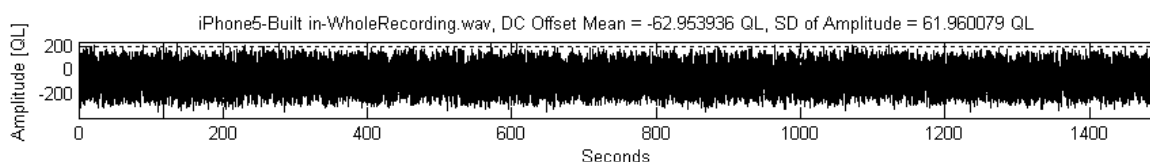
Due to the nature of digital audio, the number of available QLs per sample in a recording is determined by the recording format's bit depth, and the amount of samples per second of audio is determined by the sample rate. For example, CD quality audio is of the WAV PCM (pulse-code modulation) format, and has a bit depth of 16 and sample rate of 44.1 kHz. This means that one second of audio contains 44,100 samples, and each sample has 65,536 possible QL values, with 65,536 being the equivalent of  $2^{16}$ . Because of the compressions and rarefactions in acoustic energy, digital audio waveforms will analogously go between the zero-

crossing (no acoustic energy), the peak (the compression), back through the zero-crossing, the trough (the rarefaction), and repeat until the end of the acoustic energy. Therefore, digital audio must be signed in accordance to the positive and negative aspects of this energy. As such, the QL values will range from -32,768 to 32767 for a 16-bit recording, and confirms that the DC offset can be either a positive or negative QL value. When calculating the mean amplitude, the sum of all the QLs is divided by the amount of samples. It should be noted that DC offset can also be calculated in dB and percent, but for higher accuracy and precision it is best to use QLs.

In Figure 1 and Figure 2, we see an example of an audio signal exhibiting no apparent DC offset followed by an audio signal exhibiting a negative DC offset. We say no apparent DC offset because there will always be some amount of offset for a complex audio waveform even when DC offset correction has been applied to the digital audio. From this point on, a signal that has no apparent offset will be said to have no offset for the sake of simplicity. The signal containing no offset fluctuates around the absolute zero QL, while the audio signal seen in Figure 2 lies below the zero QL. The signal in Figure 2 oscillates in such a way that the signal is centered at approximately -60 QL.



**Figure 1 – Signal without DC Offset – iPhone 5 – Built-In - Camera App**



**Figure 2 –Signal with DC Offset – iPhone 5 – Built-In - SuperNote**

So how does this affect the forensic examination of digital audio recordings?

Because DC offset is quantifiable on a very small and exact scale, it may be useful during the authentication of a recording. There will be high uniformity between any two products of the same type due to the assembly line nature of mass-produced items, which dictates that any differences should be nominal between devices of the same model. As such, there should be some degree of uniqueness in the DC offset that manifests itself in these devices' recordings due to companies using different manufacturing processes and parts between their various audio recording products. In today's digital society, we are deluged with a massive amount of products that incorporate digital audio recording such as digital handheld recorders, tablets, mobile phones and video cameras. This research focuses on a subset of these devices, Apple's line of mobile iDevices. iDevices can be considered any of their products running on the mobile operating system, iOS. These include all iPhones, iPads, iPod Touches, and Apple TVs. This study is not concerned with the Apple TV, as it is not portable, and it is not capable of recording audio.

This particular research study aims to quantify the uniqueness of the DC offset present in these iDevices. iOS comes packaged with the ability to record digital audio via the Voice Memos and Camera apps by using the built-in microphone or an external microphone such as the one present on the EarPods that are included with the iPhone 5. Along with the ability to take photos, the Camera app is capable of capturing video with audio and this research tested for DC offset when using the Camera app's video/audio recorder. There are also many third party apps and microphones that are capable of recording audio, and multiple ones were tested to see if they affect the DC offset. Similar to any number of digital handheld recorders, iDevices can be a source of digital evidence. This research is meant to measure and examine the DC offset that is present in recordings made by various iDevices, to determine the usability of these measurements for the purpose of forensic examination, and if these measurements are at all unique when compared against previously tested digital audio recorders.

Test recordings were made using various apps and three different microphones. The DC offset values measured for these iDevice recordings were also compared against devices tested in previous research. To perform these tests, the DC offset mean and standard deviation (SD) of the amplitude were measured per recording as well as the DC offset and its SD in four different sized windows. Histograms were made of the amplitude per recording and the four DC offset window sizes. The SD of the amplitude was measured in 4 window sizes. In addition, the minimum,

maximum, mean, and SD of the DC offset were calculated for all window sizes. As mentioned before, QL values were chosen as the unit of measure for DC offset values. Likewise, all SD values are measured in QLs.

Once measured, DC offset can be used to for exclusionary purposes. It should only be used as such because the value is only relatively unique, and it is possible that other audio recorders may exhibit similar DC offset values. Therefore, we must be able to distinguish between inter- and intra-variability. For this study, two sets of inter- and intra-variability were examined. In the first set, it was necessary to determine the inter-variability among all tested iDevices, and the intra-variability between recordings made with the same iDevice. In the second set, the inter-variability was examined between recordings made by the iDevices and from devices tested in previous research. Likewise, the intra-variability was examined for recordings made by devices of the same make and model. As the inter-variability increases, it becomes increasingly easier to distinguish between recordings coming from different devices. In the same manner, as intra-variability decreases, it becomes more difficult to distinguish between these recordings. It may also be possible to determine if a recording has been edited by measuring the DC offset at frequent intervals in a recording.

## **2. Prior Research**

DC offset is a relatively unexplored form of measurement when used in forensic analysis, and there have only been a few studies on its effectiveness when used in audio forensics. The primary contributors in this line of research are Bruce Koenig, Doug Lacey, Catalin Grigoras, Jeff Smith, and Suzana Galic Price who have had their research published in the field of audio forensics and DC offset research.[2][3] Furthermore, a poster presentation was given by the Author at the 46<sup>th</sup> Audio Engineering Society (AES) International Conference held in Denver, Colorado in June of 2012.[4] To date, there have been three research studies specific to DC offset in digital audio recordings, two published and one a white paper awaiting publication; all were conducted using handheld digital audio recorders.

### **2.1 Nine Digital Recorders**

The first published research study, *Evaluation of the Average DC Offset Values for Nine Small Digital Audio Recorders*, was conducted by Koenig et al. The nine devices tested were:

- Olympus DS-330
- Olympus SME DM-40
- Olympus VN-3100PC
- Olympus VN-8100PC
- Olympus WS-600S
- Olympus WS-700M
- Philips LFH0642/27

- Sony ICD-PX312
- Sony ICD-UX512

These recorders were given all new batteries, date and time were set, all recording modification features were switched off, microphone sensitivity was turned to the highest setting, and internal memory was chosen to store the recordings. Four input sources were selected for each recorder: the internal microphone, two different external microphones, and no input by using a dummy plug inserted into the microphone jack. Ten tests were conducted using these settings listed in Table 1.

**Table 1 - Ten Microphone Setups**

Test	Microphone(s)	Audio Input	Analyzed Length (sec)
1	None	N/A	60
2	Internal	Live Male Talker	60
3	Sony ME52W	Pre-Recorded Male Talker	60
4	Sony ME515	Pre-Recorded Male Talker	60
5	None	N/A	60
6	Internal	Pre-Recorded Male Talker	60
7	Sony ME52W	Pre-Recorded Male Talker	60
8	Sony ME515	Pre-Recorded Male Talker	60
9	None	N/A	60
10	Internal	FM News Radio	1200

The initial test by Koenig et al. compared the DC offset mean calculated by five programs, and measured in multiple formats. It was found that only MATLAB and a WinHex script designed to analyze audio sample amplitudes were able to provide accurately measured values, and that the offset should be measured in QL values for best accuracy. Further testing revealed that SD values for amplitude of a recording

most likely vary dependent on the audio information being recorded. It was also found that microphone identification would probably not be possible due to very small variations between the average DC offset values when comparing recordings made with the same microphone and with different microphones. Additionally, the SDs of the DC offsets between the nine recorders were inconsistent. It was recommended by the authors that further tests were needed for recordings made in different environments, with longer record times, and using more microphone and recorder pairings.[5]

## **2.2 Audio Compression Algorithms**

The poster presentation by Fuller, *How Audio Compression Algorithms Affect DC Offset in Audio Recordings*, tested the following five handheld digital audio recorders:

- Alesis PalmTrack
- Olympus DM-520
- Olympus WS-700M
- Tascam DR-07
- Zoom H2

This research tested how transcoding from 44.1 kHz/16-bit WAV PCM to the MP3 (MPEG-1/MPEG-2 Audio Layer III) and WMA (Windows Media Audio) formats might affect DC offset. Adobe Audition was used for transcoding, and MATLAB was used to for all calculations and measurements. Three recordings were made using each recorder in a relatively silent environment for a total of 15 recordings.

Audition was then used to remove handling noise from the beginning and end of the recordings, and for transcoding the audio files. The files were transcoded into both constant bit rate (CBR) and variable bit rate (VBR) MP3s and WMAs. The encoding settings were as follows:

**Table 2 - Transcoding Formats**

Encoding Type	Bit Rates	Sample Rates	Bit Depth	Quality Rating
CBR MP3	32-320 kbps	11,025 – 44,100 Hz	N/A	N/A
VBR MP3	N/A	N/A	N/A	10-100
CBR WMA	32-320 kbps	44,100 Hz	16 bit	
VBR WMA	N/A	44,100 Hz	16 bit	10-98

Because MATLAB only works with audio in the WAV format, the recordings had to be transcoded back to 44.1 kHz/16-bit WAV PCM. The average DC offset for each recording was calculated using the three DC offset means of the three original WAV recordings. Next, the DC offset mean was calculated for all transcoded recordings, and the values were plotted for each recorder and encoding type. An example can be seen in Figure 3 showing the three recordings' DC offset means as solid lines, and their subsequent values when transcoded to all CBR MP3 settings. Similarly, the SD of the amplitude was calculated for all transcoded recordings, and it was found transcoding did not affect the waveform amplitude. The SD of the DC offset mean values was calculated per recorder and encoding type to determine the variance around the average DC offset mean. The final calculation took the maximum difference between the DC offset mean for each pairing of recorder and encoding

type. Upon comparison of all measurements and calculations, the following conclusions were presented:[6]

- Waveform amplitude is negligibly affected by audio compression algorithms
- DC offset is slightly affected by audio compression algorithms with the effects increasing as the quality decreases.
- The amount the audio compression algorithms affected the recordings varied between recorders
- The effects on the DC offset by the audio compression algorithms were relatively small with all but one DC offset mean having a difference of less 0.5 QL from the original WAV recordings.
- DC offset should be used for exclusionary purposes in forensic analysis

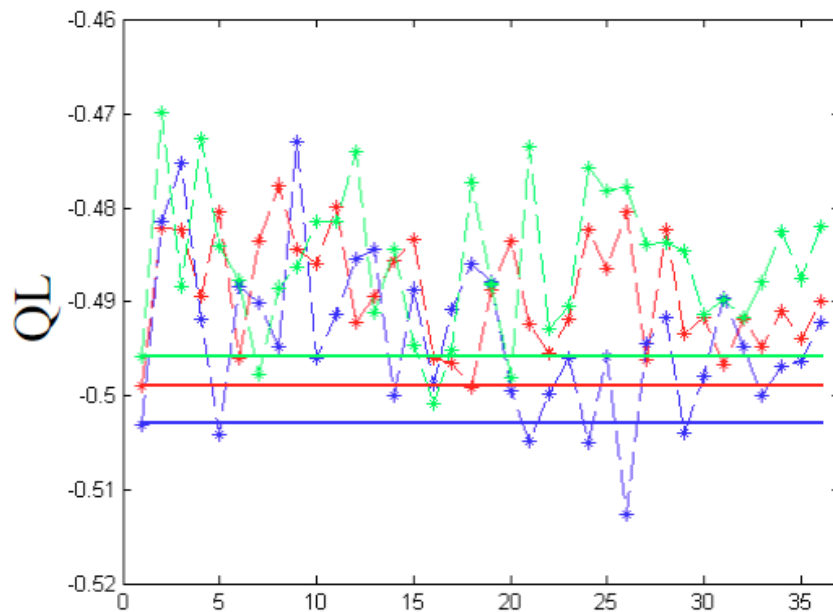


Figure 3 - Alesis PalmTrack - WAV & 35 MP3 CBRs - DC Offset Means

### 2.3 Acoustic Consistency

Koenig and Lacey's most recent study, *The Average DC Offset Values for Small Digital Audio Recorders in an Acoustically-Consistent Environment*, is a follow-up to the

research discussed in **2.1 Nine Digital Recorders**. In this research, the same nine devices were tested, and the following conditions were employed for all recordings:

- 30 minute recordings
- The same acoustic environment
- The same audio information
- Consistent microphone positions

This is an improvement from the prior study, as a known base for comparison is established for all recordings made under these particular conditions. Five audio formats were tested, and the average DC offset mean per recorder and their SDs were taken for 1-, 2-, 3-, 6-, 10-, 15-, and 30-minute segments.

The SD values for all nine recorders as well as for six of the recorders, excluding the three oldest, were combined and averaged, and these values were plotted over time. Figure 4 shows that after approximately 10 minutes the variation in the SD begins to level off. The authors concluded that, among the tested recorders and settings, the majority of the DC offset values had a very limited range of -0.59104 to 0.01604 except for the recorders capable of recording in the DSS (Digital Speech Standard) format. Additionally, differentiating between recordings made using the recorders and settings in this range would be extremely difficult. It was also found that SD decreased as recording length increased, and the SD dropped more than 75% from the 30-second recordings to the 30-minute recordings. Furthermore, variations in the SD by plus or minus 1 QL were typical for approximately 68% of the recordings, and this percentage jumped to 99.7% for variations of plus or minus 3 QLs. Among

the formats tested, only DSS and ADPCM (Adaptive Differential Pulse-Code Modulation) had SD values that remained relatively high compared to the other formats. It was concluded that this is probably due to being older digital audio formats.

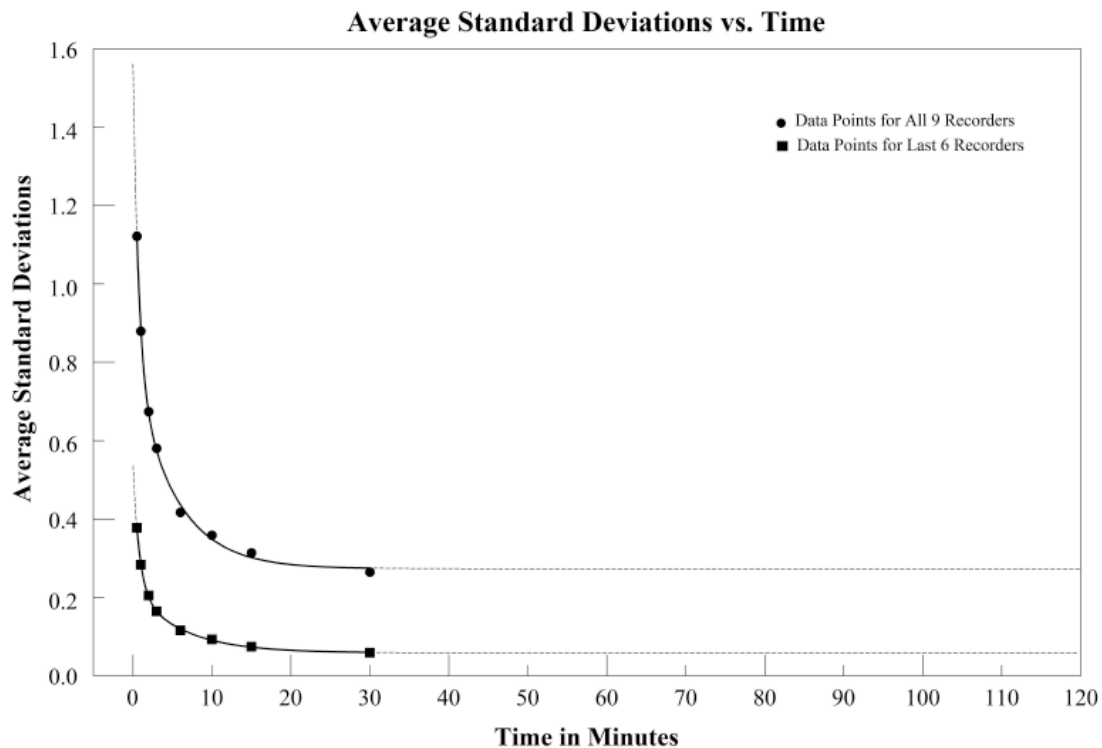


Figure 4 – Average Standard Deviation Versus Time

The final conclusions of this study point to previous mentioned assertions that DC offset should only be used for exclusionary purposes, and that DC offset values should remain consistent if the recording environment and settings for a recorder do not change. It is also noted that duplicating the conditions of a recording when creating an exemplar for forensic examination may be very difficult due to factors such as the environment, speech amplitude, the original recorder, location of sound

sources, etc. The authors recommend that further studies be conducted in different environments, enabling various recording features such as voice activation, using different recorder and microphones, changing the placement of the source and/or recorder, using multiple copies of the same make of recorder.[7]

### **3. Materials and Methodology**

To determine the uniqueness of DC offset among iDevices, multiple models were selected for this research, and multiple input sources and apps were used to make the audio recordings. Three mono input sources and seven apps were chosen to test their possible affect on the DC offset present in seven iDevices. In addition to each iDevice's built-in microphone, the EarPods included with the iPhone 5 and the Apple Earphones, both employing a remote and microphone, were chosen as external microphones. Additionally, a third party electret microphone, the Olympus ME15, was chosen for testing, but could not interface correctly with any of the iDevices, and was excluded from further testing. The seven selected iDevices were as follows:

- iPhone 5
- iPhone 4S
- iPhone 4
- iPhone 3GS
- iPad 2
- iPad 1
- iPod Touch 2<sup>nd</sup> Generation

Along with the iOS included Voice Memos and Camera apps, five third party apps were selected for testing:

- SuperNote by ClearSky Apps
- VoiceRecord by BejBej Apps
- QuickVoice by nFinity Inc
- iTalk by Griffin
- MicPro by 24/7 Apps

These apps were chosen for a number of reasons:

- They were free
- They were relatively popular on the App Store
- They could export recorded audio

The primary reason for multiple apps was to test if any differences in digital signal processing (DSP) might affect the DC offset. It should be noted that certain iDevice models are not capable of running some of these apps due to hardware and software limitations. The iPad 1 and iPod Touch do not contain a built-in camera, so the Camera app does not appear on these models. Both the iPad 1 and iPad 2 do not come with the Voice Memos app, as it is not included in their iOS software bundle. Finally, the iPod Touch is only capable of recording audio by means of an external microphone, as there is no built in microphone in the 2<sup>nd</sup> generation iPod Touches. Table 3 lists the various iOS software versions per iDevice.

**Table 3 - iOS Software Versions**

iDevice	iOS Version
iPhone 5	6.1.2
iPhone 4S	6.1.2
iPhone 4	6.0.1
iPhone 3GS	6.1.2
iPad 2	6.1.2
iPad 1	5.1.1
iPod Touch	4.2.1

Before the bulk of audio was recorded, each app was tested for any possible changes it might make to the DC offset. These tests revealed that both the Voice Memos and Camera app apply DSP at some stage in the recording process that removes the DC offset from recordings. Further testing of the third party apps revealed that only

SuperNote and MicPro did not use DSP to remove the DC offset. Once these results were discovered, the next step was to determine whether or not the DC offset was affected by these two apps. Initial testing revealed that both apps exhibited very similar results when making test recordings in the same environment and for approximately the same length of time. It was concluded that one app, SuperNote, would be selected to perform the rest of the test recordings. The following sections will discuss these results along with all other tests. SuperNote was selected for its ability to easily name and export recordings as well as having smaller file sizes due to a lower sampling rate of 16 kHz. Additionally, the iPod Touch was found to be useless for any further testing, as the version of iOS running on it was not compatible with any of the third party apps, and the iOS apps use DSP to remove the DC offset.

Prior to recording, all iDevices were fully charged to ensure proper power distribution, and all apps were closed save for the one performing the recording. Additionally, Airplane Mode was enabled to ensure no outside connectivity could be made during the recording process, and Auto-Brightness was turned off. An approximately twenty-five minute long recording was made per each iDevice and microphone pairing. This recording length was chosen based on the previously mentioned research study where it was found that fluctuation in the SD reduced as recording length increased, and the SD dropped significantly for recordings over 10 minutes in length.[8] Accordingly, the DC offset mean for longer recordings will be

more consistent than for shorter recordings when acquired from the same recorder, settings, and environment.

The recordings were made in a near-ideal acoustic environment to minimize the possibility of any transients, voices, external noises, etc. being introduced into the recording process. To achieve this, a small room was selected that contained many acoustically absorbent materials, the lights were turned off to avoid florescent hum, and studio-grade acoustic foam was used to surround the various iDevices.

Furthermore, the iDevices were placed as close together as possible, and not moved during the entire recording process. For all recordings made using the iDevices' built-in microphones, recordings were made simultaneously. For recordings made using the external microphones, only three iDevices could be used at a time, as there were only one set of EarPods, and two sets of Earphones available for testing. The recordings made to determine if SuperNote and MicPro affect the DC offset were made using the iPhone 5 and its built-in microphone. These recordings were approximately 2 minutes in length, and recorded in the same conditions. It should be noted that some audio recording apps allow for a recording to be paused and continued ad infinitum, but this function was not tested due to the DC offset possibly being affected by handling noise and DSP.

After the recording process was complete, the recordings were transferred to a Windows workstation running MediaInfo, WinHex, Adobe Audition 3.0.1 and

MATLAB r2010b Version 7.11.0.584. MediaInfo and WinHex were necessary to determine recording format information, Audition was needed to perform minor editing and conversion to WAV, and MATLAB was used for processing the WAV files and performing all scientific calculations. iTunes and iPhoto were capable of transferring the recordings made with Camera and Voice Memos, but were unable to transfer any of the third party apps' recordings. To retrieve these recordings, some of the apps were capable of creating a private network to share their recordings, including SuperNote, and others had to send their recordings by email. Once all test recordings were retrieved, their recording formats were examined in MediaInfo. WinHex and Audition were used to confirm these findings. The results can be seen in Table 4.

**Table 4 - Recording Formats**

App	Format	Sample Rate	Bit Rate	Channels
Camera	MPEG-4, AAC	44.1 kHz	63 kb/s	Mono
Voice Memos	MPEG-4, AAC	44.1 kHz	63 kb/s	Mono
SuperNote	AIFF, ADPCM	16 kHz	64 kb/s	Mono
iTalk	AIFF, PCM	44.1 kHz	705 kb/s	Mono
Voice Record	MPEG-4, AAC	48 kHz	108 kb/s	Mono
MicPro	AIFF, ADPCM	44.1 kHz	352 kb/s	Stereo
QuickVoice	CAF	16 kHz	256 kb/s	Mono

Adobe Audition was then used to truncate any handling noise at the beginning and end of the recordings. To prevent inaccuracies when calculating the DC offset, these edits were performed at or as close to zero-crossings as possible. To make sure the transcoding process did not affect the DC offset, a test recording was analyzed with

Audition. This test recording had the DC offset measured in Audition prior to transcoding, and then measured again once transcoded. Measuring the DC offset in Audition was necessary, as MATLAB does not work with any of the apps' recording formats. However, it should be noted that Audition calculates the offset value as a percentage, and was only used for determining if transcoding adversely affects DC offset. It was then determined that transcoding in Audition would not change the audio files, so all recordings were converted to WAV and brought into MATLAB for measurements and calculations. The edited SuperNote recordings were converted to 16 kHz/16-bit/mono WAV PCM uncompressed files. The MicPro recordings were converted to 44.1 kHz/16-bit/mono WAV PCM uncompressed files, as their native sample rate is 44.1 kHz.

The two main types of calculation performed were mean and SD. The mean is simply calculated by summing all QL values and dividing by the number of samples. SD is calculated as the square root of the variance. Figure 5 shows the formula used to calculate the SD. The variance is found by taking the difference between each sample's QL and the DC offset mean, squaring each value, summing the resultant values, and then averaging the sum. Once calculated, the SD allows us to find the 'normal' range of values for a particular set of values. When calculating the SD of amplitude for a recording made in a silent environment, values that fall outside of this range would be loud transient sounds such as claps, door slams, coughs, etc.

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \mu)^2}$$

Figure 5 - Formula for Standard Deviation

A script was written in MATLAB that calculated the following information:

- Plot of the waveform
- The DC offset
- The SD of the amplitude
- The minimum and maximum amplitude
- Plots of the DC offset values for four window sizes
  - 5-seconds
  - 10-seconds
  - 30-seconds
  - 1-minute
- The mean for these four sets of DC offset values
- The SD for these four sets of DC offset values
- The minimum and maximum of these 4 sets of DC offset values
- Histogram plots of the amplitude and 4 sets of DC offset values
- Plots of the SD of the amplitude in four window sizes
  - 5-seconds
  - 10-seconds
  - 30-seconds
  - 1-minute

All this information can be seen in the plots found in **Appendix: Plots and**

**Measurements.** The following sections analyze the results of these tests, and make in depth comparisons between the various iDevices as well as the results found in previous studies of digital audio recorders.

## 4. Results

### 4.1 SuperNote Versus MicPro

To begin with, it was necessary to make comparisons between recordings made by SuperNote and MicPro to determine whether or not the apps would have any effect on the DC offset introduced onto a recording. Two recordings were made per recorder, approximately two minutes in length, and all truncations and transcoding were performed as previously mentioned in **3 Materials and Methodology**.

MATLAB was then used to calculate the DC offset and SDs, and the resulting values can be referenced below in Figure 6 and Figure 7. It should be noted that the recordings made with SuperNote were slightly shorter than those made by MicPro, and after truncating handling noise, the length of the second SuperNote recording dropped below two minutes. This resulted in the inability to calculate an SD value for the DC offset in 1-minute window because there was only one full window, and can be seen in Figure 7. **Appendix: Plots and Measurements** can be referenced for visual comparison between the plots for these four recordings. Based on the results of the calculations performed, it was found that there were no significant differences between the recordings to necessitate making further recordings with both devices. All subsequent recordings were made using SuperNote.

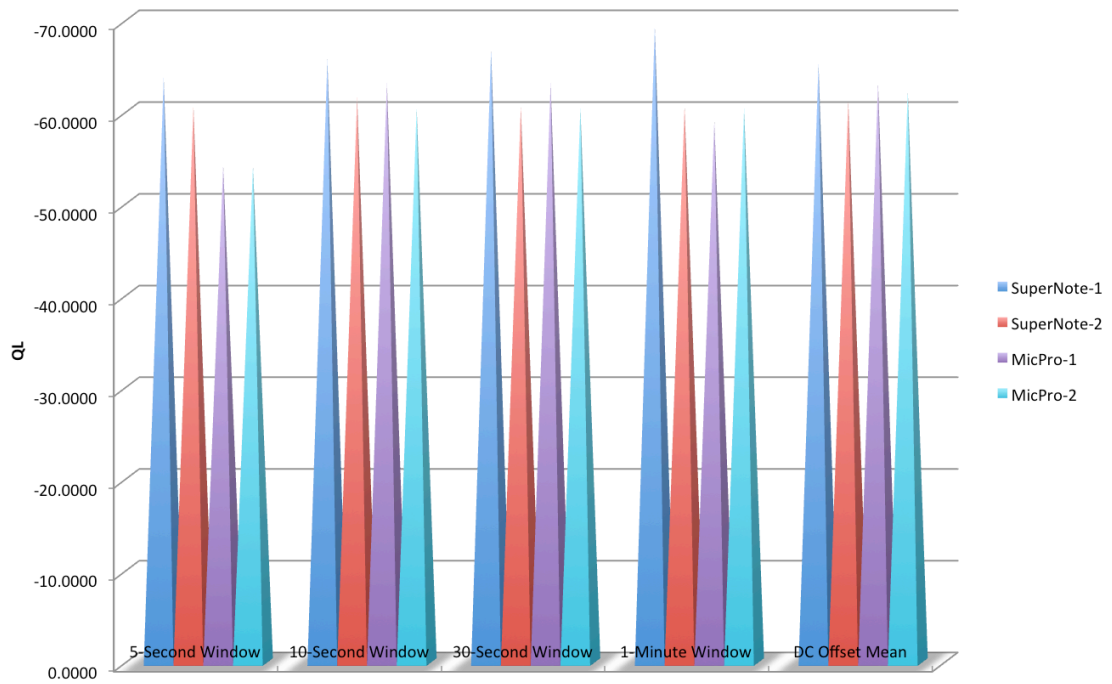


Figure 6 - DC Offset Mean and in Windows - SuperNote vs. MicPro

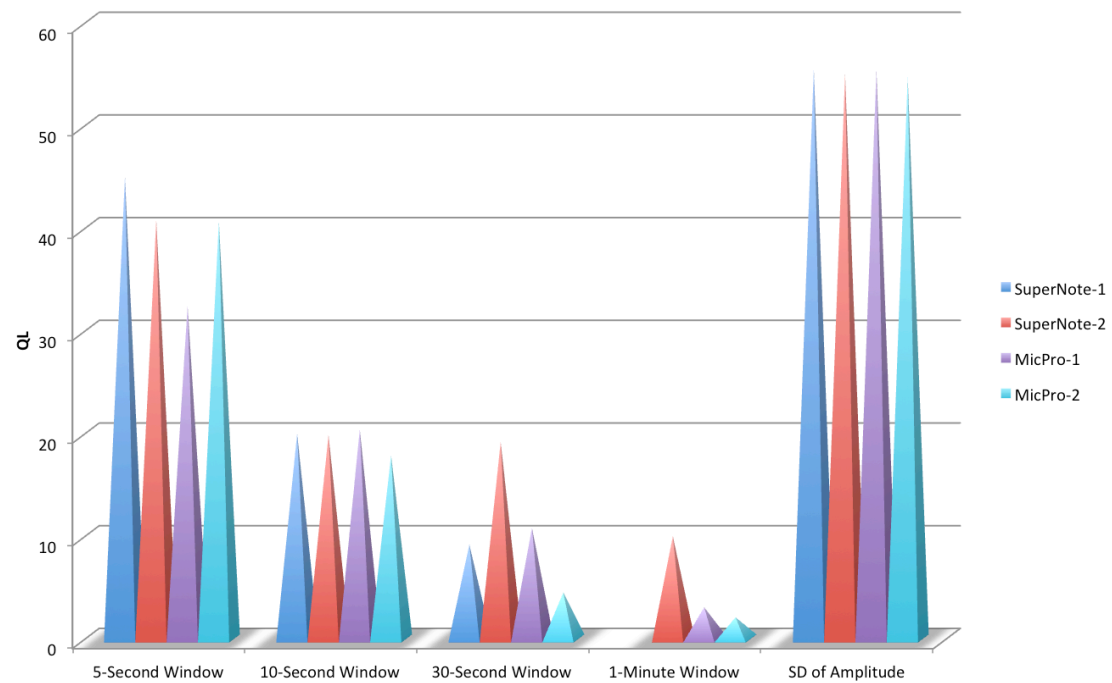


Figure 7 - SD of DC Offset Windows and QL - SuperNote vs MicPro

## 4.2 DC Offset and Standard Deviation

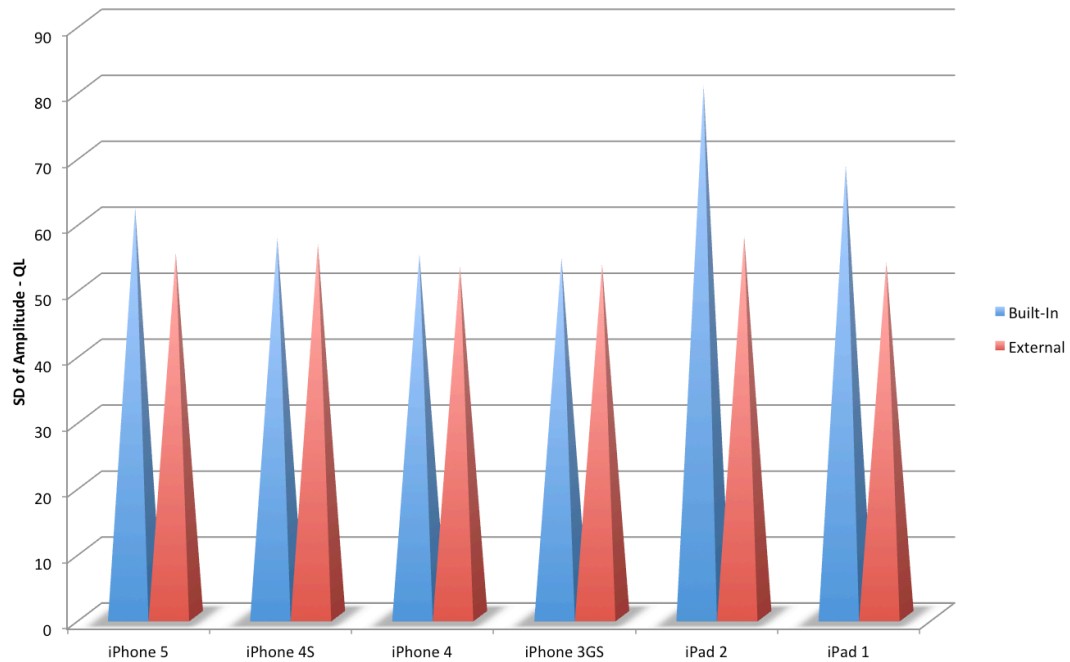


Figure 8 - DC Offset Mean - Built-In vs External Microphones

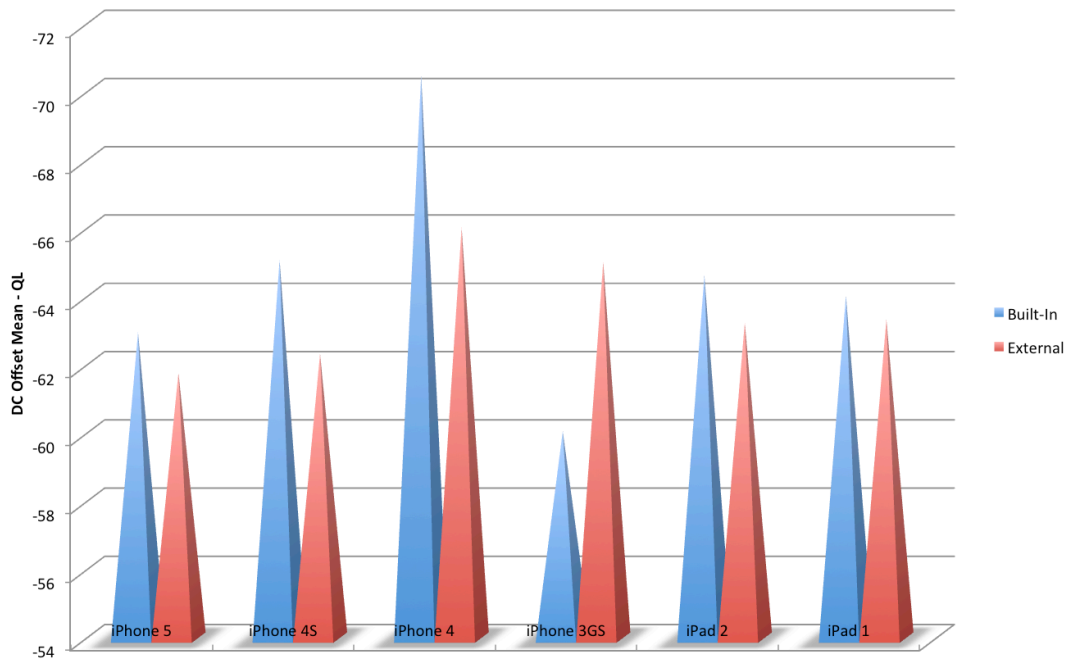


Figure 9 - SD of Amplitude - Built-In vs External Microphones

Figure 8 and Figure 9 graph the DC offset mean and SD of the amplitude, and can be used for comparisons between the recordings made with the built-in microphones

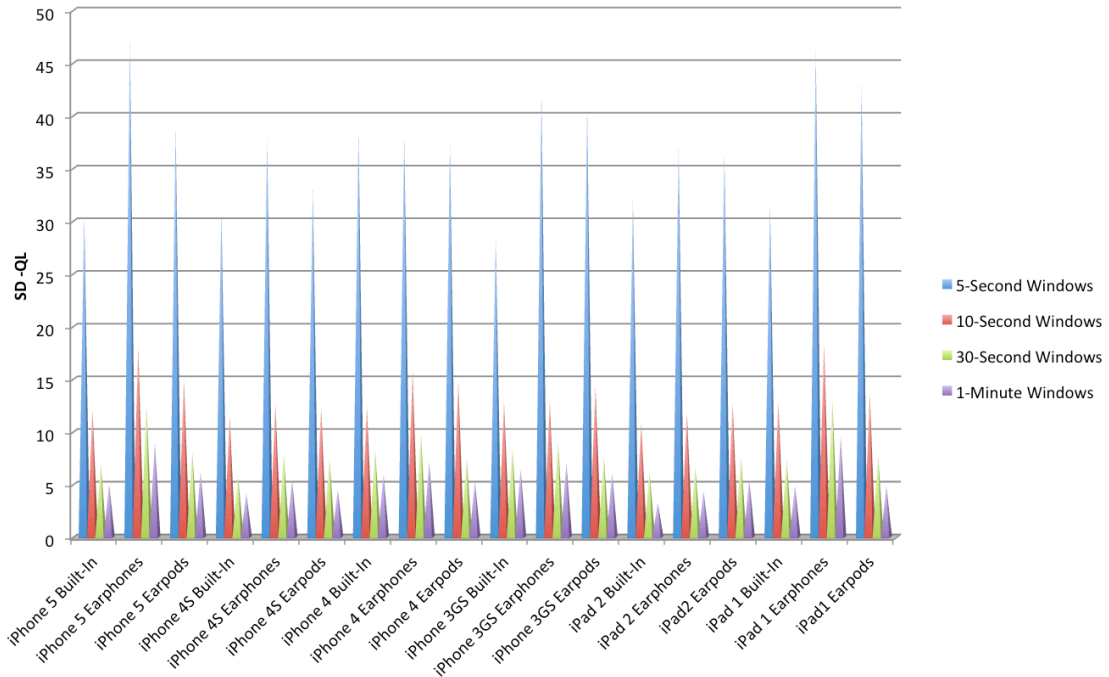
and external microphones. When reading Figure 8, make sure to note that the y-axis is flipped for easier comprehension. We separate the values for the internal microphone from the external microphones because the external microphones may induce their own effects onto the recorded audio signal. When looking at these two figures, we see that the DC offset mean is higher for all recorders using the built-in microphone except for the iPhone 3GS, which is approximately 5 QL higher, and all SD values are lower for the external microphones. All SD values are relatively close except for the recordings made with two iPads when using their built-in microphones. This is most likely attributed to slightly higher overall amplitudes in these two recordings.

#### **4.3 Calculations Based on Window Sizes**

In addition to measuring the DC offset and SD over an entire recording, it is important to look at how these values change over time, and how the accuracy of these measurements change depending on the size of the data measured. For this study, calculations were made using 5-, 10-, 30-, and 60-second DC offset mean window sizes, whose plots can be seen in **Appendix: Plots and Measurements**. Additionally, the SD, mean, minimum, and maximum values were calculated per window size. Initial results found that as the window size increased, the SD significantly dropped, and can be seen in Figure 10. This drop in the SD indicates that increased window sizes can provide more accurate results. Furthermore, we

can see that the SD dropped uniformly for all the iDevice and microphone pairings.

When averaged, the SD of the DC offset in 1-minute windows came to 5.8148 QL.



**Figure 10 - SD of DC Offset Windows**

Accordingly, the minimum and maximum values for the DC offset per window size decreased as the window size increased. In addition, the mean of the DC offsets per window size stayed very close to the DC offset mean value per recording except for the 5-second window values. Figure 11 shows of these results with the x-axis going from lowest to highest DC offset mean. This tells us that measuring the DC offset in windows will result in relatively consistent values independent of window size.

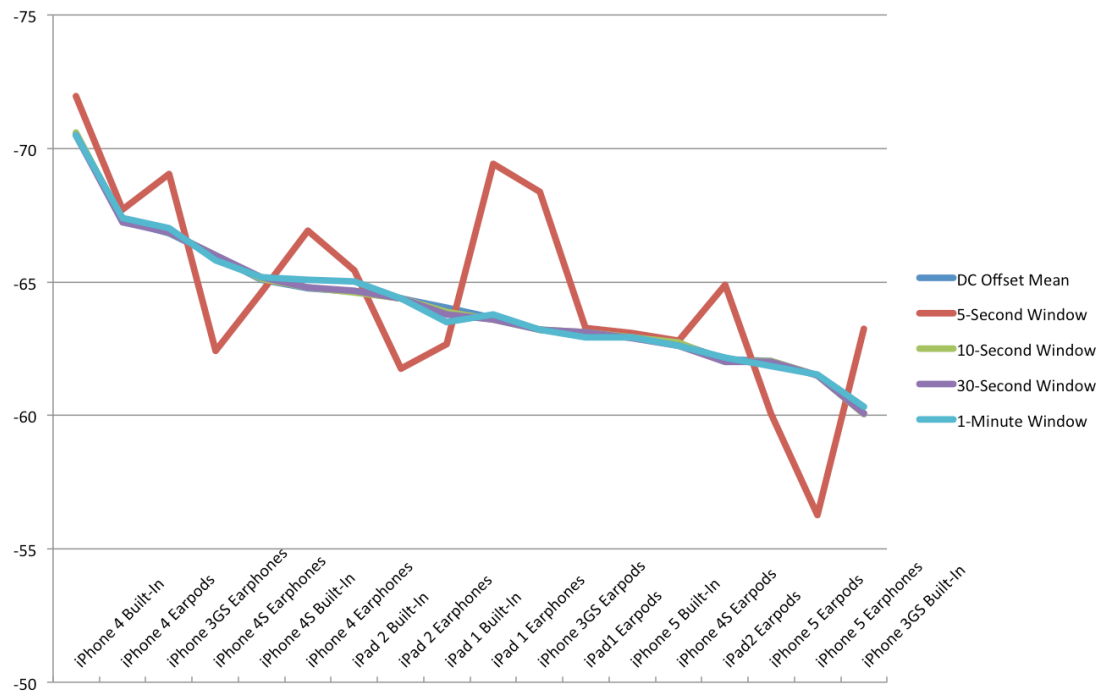


Figure 11 - DC Offset Mean and for Windows

The SD of the amplitude for these recordings stayed relatively consistent, as can be seen in Figure 12, where the SD fluctuates around the average SD value of 54.8000 QL by a few QLs when measured in 1-minute windows. Analogous results were found for the majority of the recordings, and only the recording made using the iPad 2 and built-in microphone had much larger fluctuations, as seen in Figure 13. This may be attributed to the amplitude of the audio signal slightly decreasing over time. Further examples for all recordings, including 5-, 10-, 30-, and 60-second window plots, can be observed in **Appendix: Plots and Measurements**.

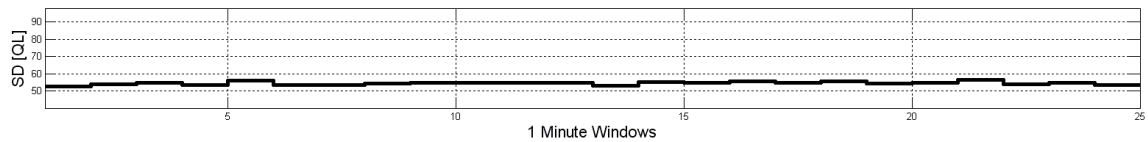


Figure 12 - SD at 1-Minute Intervals - iPhone 5 - EarPods

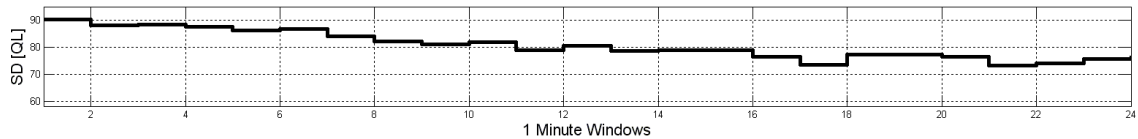


Figure 13 - SD at 1-Minute Intervals - iPad 2 - Built-In

## 4.4 Histograms

Histograms were made for the amplitude and for the DC offset mean per window size. Correlations can be made between the minimum and maximum QL values for these sets of data, by comparing the histograms seen in Figure 16 against the values found in Figure 18 for the iPhone 5. Furthermore, the minimum and maximum QL values of each recording are included with the histogram of the amplitude, and correlate to the plot of the waveform as seen in Figure 14. Like results can be seen when comparing the plots indexed in **Appendix: Plots and Measurements**.



Figure 14 - iPhone 5 - EarPods - Waveform

When viewing the waveform seen above in Figure 14, we can observe that it does not oscillate uniformly. A more obvious example can be seen in Figure 15 of a shorter recording made by the iPhone 5 using the built-in microphone, where there appears to be two main QL distributions. The histogram plot of the waveform, as seen in Figure 16, verifies this irregular fluctuation, and shows us two primary peaks. Depending on the iDevice and microphone pairing, the histogram plot of the amplitude changes between the various recordings. The recordings made using the built-in microphone all exhibited a histogram with a wide distribution rather than a strong peak, as seen in Figure 17. Only recordings made with the external microphones exhibited a histogram containing two peaks, and not all iDevices revealed these results. Both the iPhone 4S and iPad 2 had wide histograms for all three microphone pairings. These results can be further observed in **Appendix: Plots and Measurements**. It should be noted that test recordings were made to examine if these irregular fluctuations in the waveform oscillation remain in recordings where higher amplitude information is being recorded, but it could not be determined due to the density of the waveform.

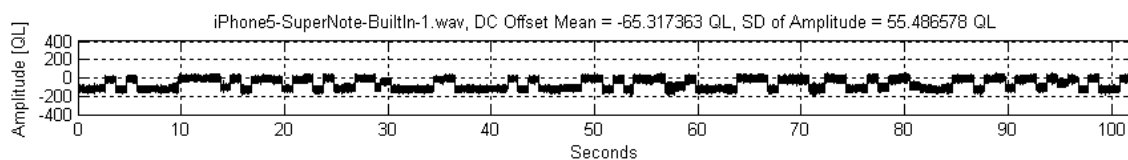


Figure 15 - iPhone 5 - Built-In - Waveform

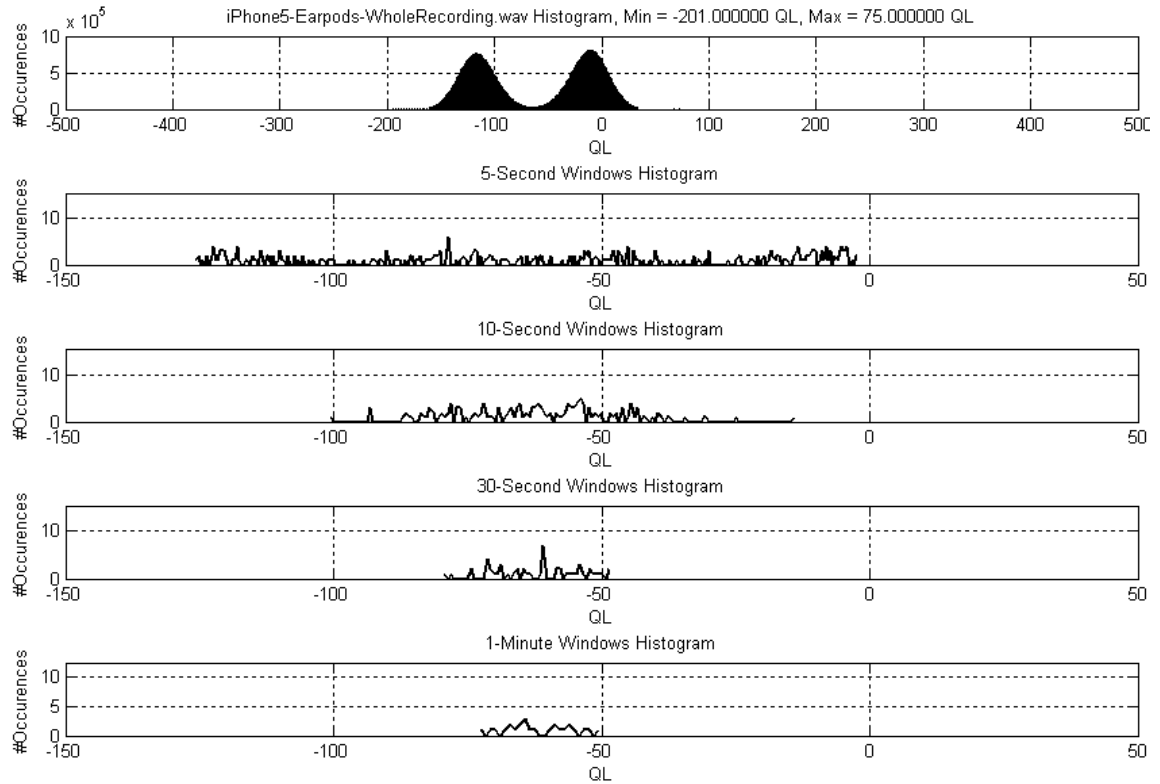


Figure 16 - Histograms - iPhone 5 - EarPods

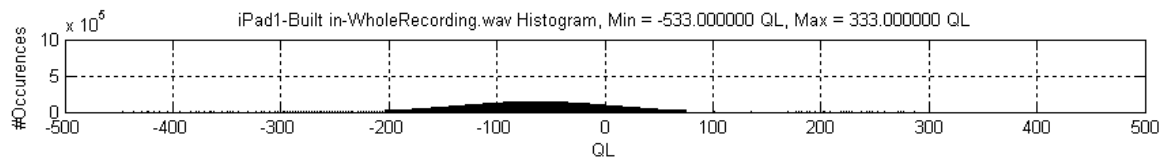


Figure 17 - Histogram - iPad 1 - Built-In Mic

## 5. Comparisons and Conclusions

For the following sections, refer to **Appendix: Plots and Measurements** for easier comparison between the recordings' plots.

### 5.1 DC Offset

The most apparent similarity between the DC offset mean values is that they all occur between -70.4947 and -60.0564 QL, and as mentioned before tend to be higher for the built-in microphones. In the studies described in **2 Prior Research**, DC offset mean values were measured for a total of 14 recorders, with values ranging from approximately -64.538 QL to 23.444 QL between them.[9][10][11] This establishes a baseline for comparison, and lets us know that there can be overlap between various types of digital audio recorders. However, while this range technically encompasses multiple devices, it is actually the result of multiple test recordings made using an Olympus DS-330 in the DSS format.[12] This particular recorder, as well as the DSS format, exhibits an extremely wide range of offset values between its various recording settings, while other devices tested in these different studies were much more consistent and actually comprised a much smaller range. Excluding the DS-330 and Olympus SME DM-40 recorders' DC offset means when using the DSS format, the range dropped between -10.2495 and 11.30 QLs for all other recorders tested in these studies. The following two tables show the results of this previous research found by Koenig et al. for these two recorders using

the DSS format with the results outside the non-DSS range highlighted in red.[13][14] The majority of the DC offset mean values for these devices varied even less, and fell within a range of less than 5 QL values of 0 QL.[15][16][17]

**Table 5 - DS-330 DC Offset Mean – Inconsistent Environment**

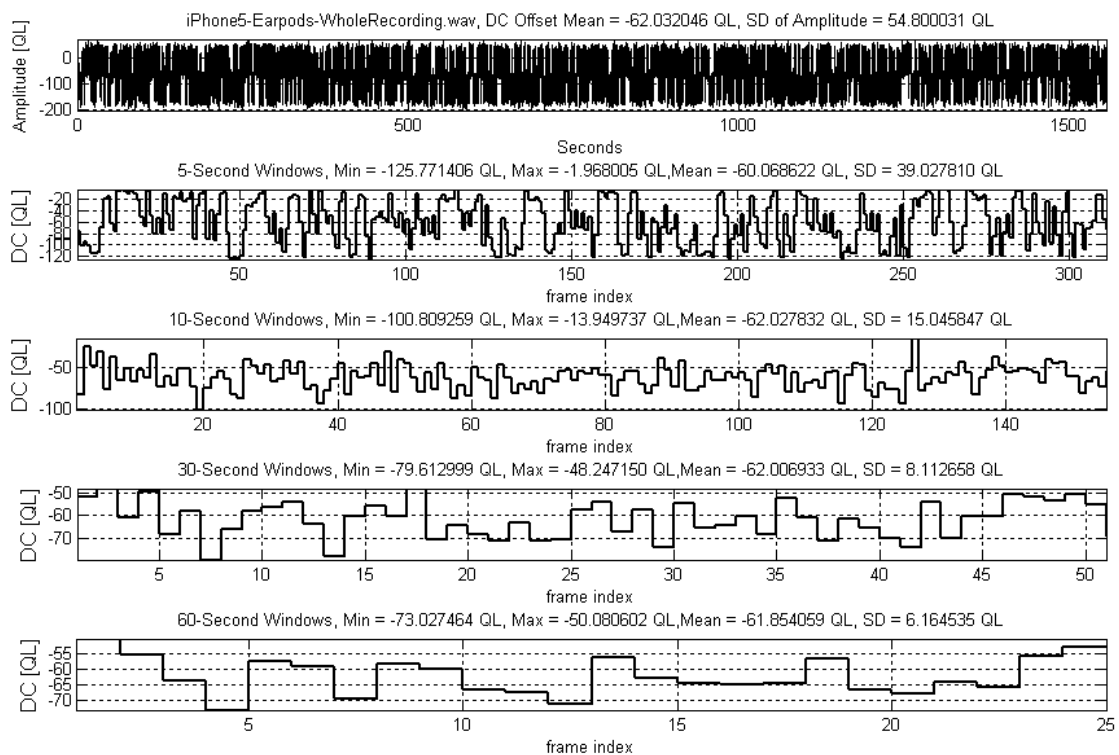
Test/Mode/Mic	DC Offset Mean
T1/DSS-SP/NoMic	-5.575
T1/DSS-LP/NoMic	-1.292
T2/DSS-SP/IntMic	15.787
T2/DSS-LP/IntMic	-64.538
T3/DSS-SP/ME52WMic	16.062
T3/DSS-LP/ME52WMic	-20.591
T4/DSS-SP/ME51SMic	22.307
T4/DSS-LP/ME51SMic	-37.458
T5/DSS-SP/NoMic	-5.535
T5/DSS-LP/NoMic	-1.260
T6/DSS-SP/IntMic	12.914
T6/DSS-LP/IntMic	4.201
T7/DSS-SP/ME52WMic	6.932
T7/DSS-LP/ME52WMic	23.444
T8/DSS-SP/ME51SMic	6.662
T8/DSS-LP/ME51SMic	0.054
T9/DSS-SP/NoMic	-5.516
T9/DSS-LP/NoMic	-1.256
T10/DSS-SP/IntMic	-5.601
T10/DSS-LP/IntMic	-10.919

**Table 6 - DS-330 and SME DM-40 DC Offset Mean - Consistent Environment**

Recorder	Mode	DC Offset Mean
DS-330	SP	4.21283
	LP	-34.28392
SME DM-40	SP	5.78800
	LP	-36.38407

Along with the average DC offset for the entire length of the recording, we must look at it over shorter periods of time, as it is possible that a recording coming in for forensic examination may be closer to one minute rather than twenty or more.

Figure 18 shows how the DC offset varies between the four different window sizes. Upon inspection of these plots, as well as the other plots found in **Appendix: Plots and Measurements**, it becomes apparent that there is variation in the DC offset over time despite the relative consistency in the amplitude of the audio waveform.



**Figure 18 - iPhone 5 - EarPods - DC Offset Plots**

When observing the amount of fluctuation between these windows in Figure 18, we see offset values ranging between -125.8323 QL and -2.9099 QL for the 5-second windows, and the range is reduced between -69.3397 QL to -46.8481 QL for 1-

minute windows. Despite this wide fluctuation, the different windows' mean values remains relatively consistent between the various iDevice and microphone pairings when compared to the corresponding DC offset mean of the recordings' amplitude. This can be confirmed by the graph seen in Figure 11.

This points us towards the observation that larger windows provide stronger results. However, there is most likely an ideal window size. When comparing the DC offset mean values for all recordings against the mean for their correlating window sizes we find that there is very little variation among the values. The largest difference found was approximately 6 QL between the DC offset mean of the iPad 1 and Earphones pairing and the 5-second window mean value. Two other differences were found of approximately 5 QL, and occurred between the DC offset mean of the iPhone 5 and Earphones pairing, and the DC offset mean of the iPhone 3GS and EarPods pairing when compared against their respective 5-second window mean values. This can be confirmed in Figure 11 as the line graph of the 5-second window mean values significantly deviates from the other four lines. With this in mind, it becomes apparent that we should use window sizes greater than five seconds. When looking at the difference between the DC offset mean and the other three window sizes, we observe a much smaller difference with the largest value being 0.5338 QL when comparing the DC offset mean of the iPad 1 built-in microphone recording against the 1-minute window mean value.

## 5.2 Standard Deviation

In addition to measuring the DC offset for a recording, it is also very important to measure the SD of this offset as it changes over time and the SD of the amplitude. Calculating the SD of the DC offset over time allows us to observe the amount of intra-variability that occurs in the DC offset of the recording, and lets us determine the usefulness of the DC offset value for forensic examination. If intra-variability is low, then the DC offset will remain relatively consistent throughout a recording. This allows the DC offset mean value to be useful in forensic examination as the value should be consistent for all recordings made by a particular recorder and microphone combination. DC offset may not be useful for a recording that exhibits high intra-variability throughout a recording, as the DC offset amount may irregularly fluctuate within a wide range of values. The SD of the amplitude was calculated to corroborate that the recordings were all made under the same laboratory conditions. Therefore the range of the recordings' amplitudes should all be relatively close, and their SDs should be very similar in value. It is recommended that SD of the amplitude be excluded from forensic examination due to its dependence on the recorded audio signal.

In **4.3 Calculations Based on Window Sizes**, it was observed that the SDs of the four DC offset window sizes decreased as the window size increased, and this was consistent for all iDevices. It was found that the average SD of the 1-minute DC offset windows came to 5.8148 QL, and the range of these values was spread

between 3.2788 and 9.5896 QL. This consistency indicates that the intra-variability of each iDevice's DC offset should remain relatively low, and as such makes the DC offset mean useful in forensic examination. In correlation with the values measured for the DC offset mean and average per window size, as seen Figure 11, it appears that the 1-minute window size may be the most valuable in forensic examination, and that the 5-second window size is too small to provide useful results. It was also observed that the SD values when using the Earphones were higher for all recordings except for the iPad 2. This indicates that the Earphones may have the most adverse effect of the DC offset independent of the recording device.

In previous studies, the largest SD of the DC offset mean values was found to be 19.49 QL for the Olympus DS-330.[18] This indicates that the DC offset in iDevices is significantly different than that found in these previously tested digital audio recorders. Furthermore, all other SDs found in these previous studies were much lower than those found for the Olympus DS-330. Unfortunately, these values were calculated in a different manner than in this study, and as such cannot be directly compared to the results found here.

### **5.3 Histograms**

In **Appendix: Plots and Measurements**, we can observe and compare histogram plots from all the recordings. These histograms provide visual correlation between the DC offset, and the SD. All amplitude and DC offset window histograms have the

same respective X and Y scale so they may be viewed and compared with greater ease and in equal proportion. The histograms that contain two peaks correlate with the waveforms that appear to have two main QL distributions such as that seen in Figure 16. As mentioned before, the histograms that do not have two peaks have a wide distribution rather than a strong peak.

The most apparent observation that can be drawn from the DC offset window histograms is the relatively wide dispersion of the values. For all window sizes, there are no particularly strong reoccurring values. However, as the window size increases these values become less spread out, and tighten around the DC offset mean value. Correlation can be seen between this trend and the corresponding plots of the DC offset windows and their minimum, maximum, mean, and SD values. Furthermore, the amplitude histograms, which contain two peaks, are relatively equally spread around the DC offset mean value. These histograms containing two peaks correlate with the waveforms that have two strong QL distributions, and examples can be seen when comparing the plots for the iPhone 5, 4, and 3GS and iPad 1 when using the external microphones.

## **5.4 Conclusions**

The measurements and comparisons conducted in this research point to a few main conclusions regarding the use of DC offset in forensic examination, and whether or

not iDevices exhibit any unique traits when compared with other digital audio recorders. With respect to previous findings that DC offset traits can be similar across multiple recording devices, it is still recommended that any measurements be only used for exclusionary purposes. Furthermore, when used in the forensic examination of audio, these tests should only comprise a part of the analysis, and many other forms of inquiry should be performed such as spectral analysis, waveform analysis, ENF analysis, long-term average spectrum (LTAS), compression level analysis (CLA), etc.[19]

For all tested iDevices, it was found that the DC offset mean remained relatively consistent between the various iDevice and microphone pairings. Similarly, the SD of the amplitude for these recordings fell within a comparably small range, save for the iPad 2 when using the built-in microphone, which indicates that all recordings had very similar recorded audio signal amplitudes. When measured in 1-minute windows, it was found that the SD of the DC offset had very minor variations among the tested iDevices. These findings lead to the conclusion that there should be relatively low intra-variability of the DC offset values between recordings made by the tested iDevices. When compared with measurements taken from previous research, we can conclude that these iDevices are relatively unique as there is nearly zero overlap when comparing DC offset and SD values. It can also be said that while having a relatively low intra-variability between iDevices, there is a high inter-variability when compared to other devices. Furthermore, the low intra-variability

of the DC offset mean and SD values will likely increase as the recording length becomes shorter. Finally, it should be noted that certain iDevice and microphone pairings might be more identifiable when analyzing the histogram of their QLs.

## **5.5 Additional Notes & Future Research**

While many of the apps tested in this research used DSP to perform DC offset removal, they still exhibit an extremely small amount of offset due to the complexity of the resulting recorded waveform. There may also be other visible effects of the recording process when viewing the waveform. For example, a video recording made with the Camera app will result with an audio waveform that does not actually begin at the first sample. In effect this means that the waveform remains at a constant 0 QL until the app starts feeding audio information into the video recording. Such manifestations may be useful when trying to identify a particular recording, and further research needs to be conducted on this issue.

As with any research, there is always the need to conduct more studies. This is especially true for DC offset, as it is a relatively unexplored form of measurement when used in the forensic examination of digital audio recordings. One of the most important parts of the research of DC offset is making test recordings with as many devices as possible, and there are a plethora of devices that have yet to be tested. This is compounded by the possibility of numerous recording settings and formats

per recording device. Since a large portion of the population owns mobile phones and other devices capable of recording audio, it is important to test devices that are not typical handheld digital audio recorders. In addition to the iDevices tested in this research, there are still many more that are capable of recording audio as well as a numerous other smart phones.

Along with the need to test new devices, real world examples need to be taken into account. Ideal conditions will not be the norm when digital audio evidence is being tested in a forensic lab, and research must be conducted that addresses this issue. One such study has been performed, but concluded that a wide variety of tests still need to be performed in a variety of environments, with longer recording lengths, and with a larger variety of recorders and microphones.[20] This thesis expands on these ideas by testing a number of new recording devices, and making recordings at longer lengths. However, research still needs to be done with recordings that mimic real world conditions that include room noise, handling noise, start and stops, etc. It may also be beneficial to test how the energy going into a recorder may affect the DC offset. The type of battery, the charge of a battery, and if the recorder is powered by an AC power supply all might impose their own effects on a recorder.

In addition to testing new devices and in different environments, future research should incorporate a wider range of calculations such as those used in this study. The use of histograms can help analyze the range of DC offset values, and better

visualize the waveform for comparison. Measuring the DC offset and SD in windows can let an examiner see how much fluctuation occurs throughout a recordings, and can be useful in comparisons between other recorders and recordings. Along with incorporating more calculations, the results of DC offset research should be aggregated for easier use in forensic audio examination.

## **Appendix: Plots and Measurements**

This section provides plots of the waveform, DC offset in windows, histograms of the amplitude and DC offset in windows, and SD of the amplitude in windows for all recordings. Along with these plots, various calculated values are included per recording. Among these are, the values for the DC offset mean, SD of the amplitude, the mean of the DC offset values for the various window sizes, the SD of these offset values, and minimum and maximum values for the amplitude and the DC offset values in windows.

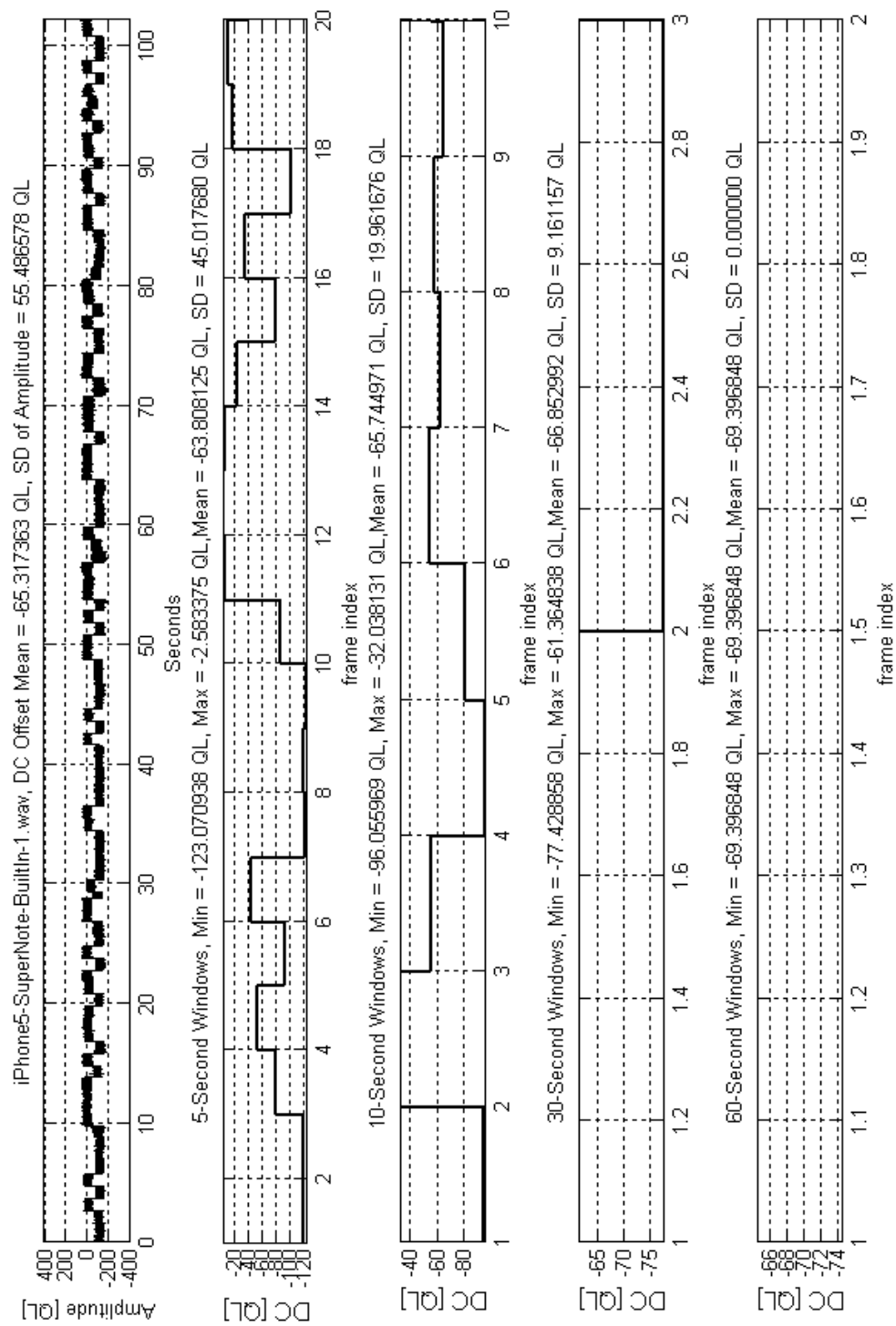


Figure 19 - SuperNote - Test 1 - DC Offset Plots

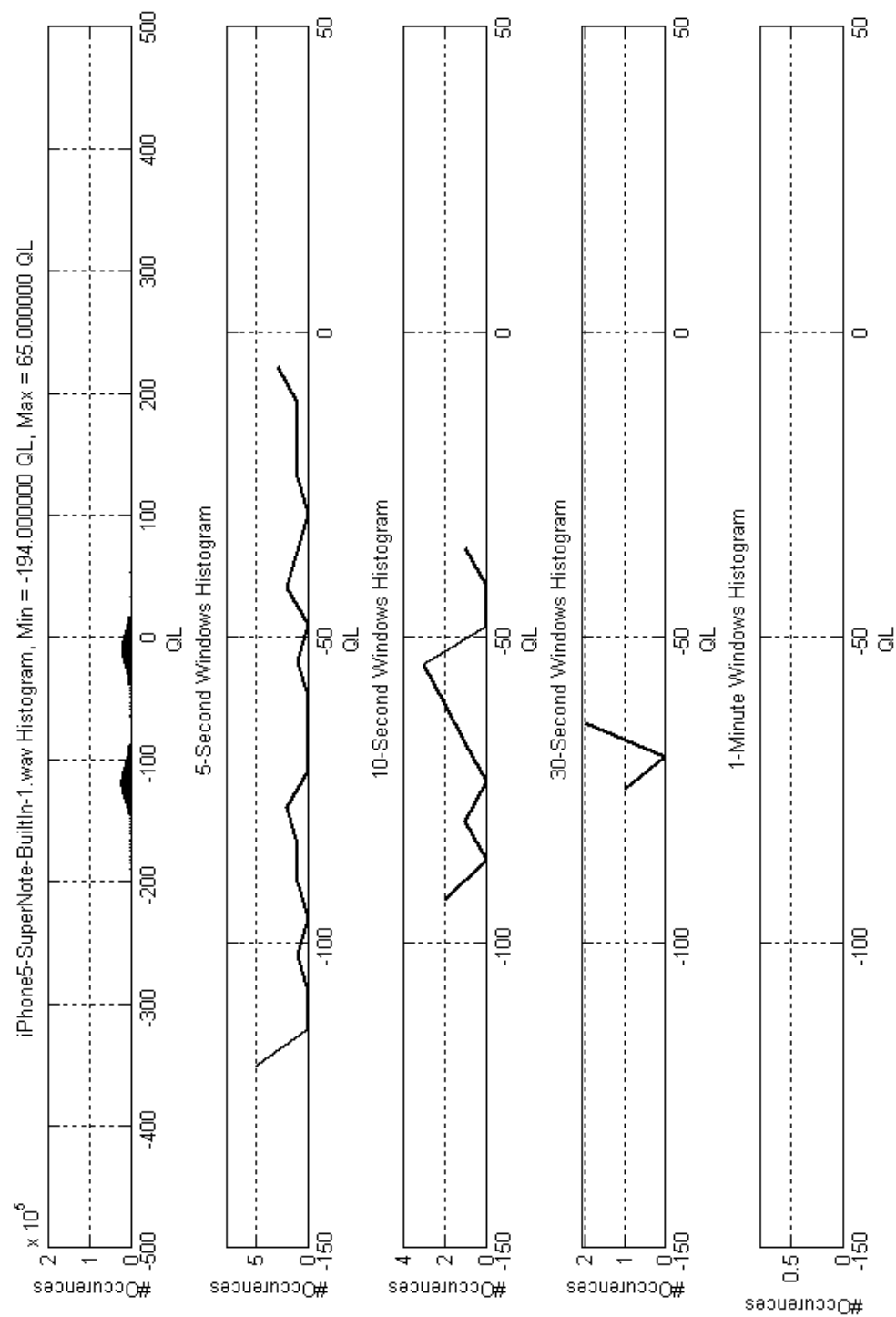


Figure 20 - SuperNote - Test 1 - Histograms

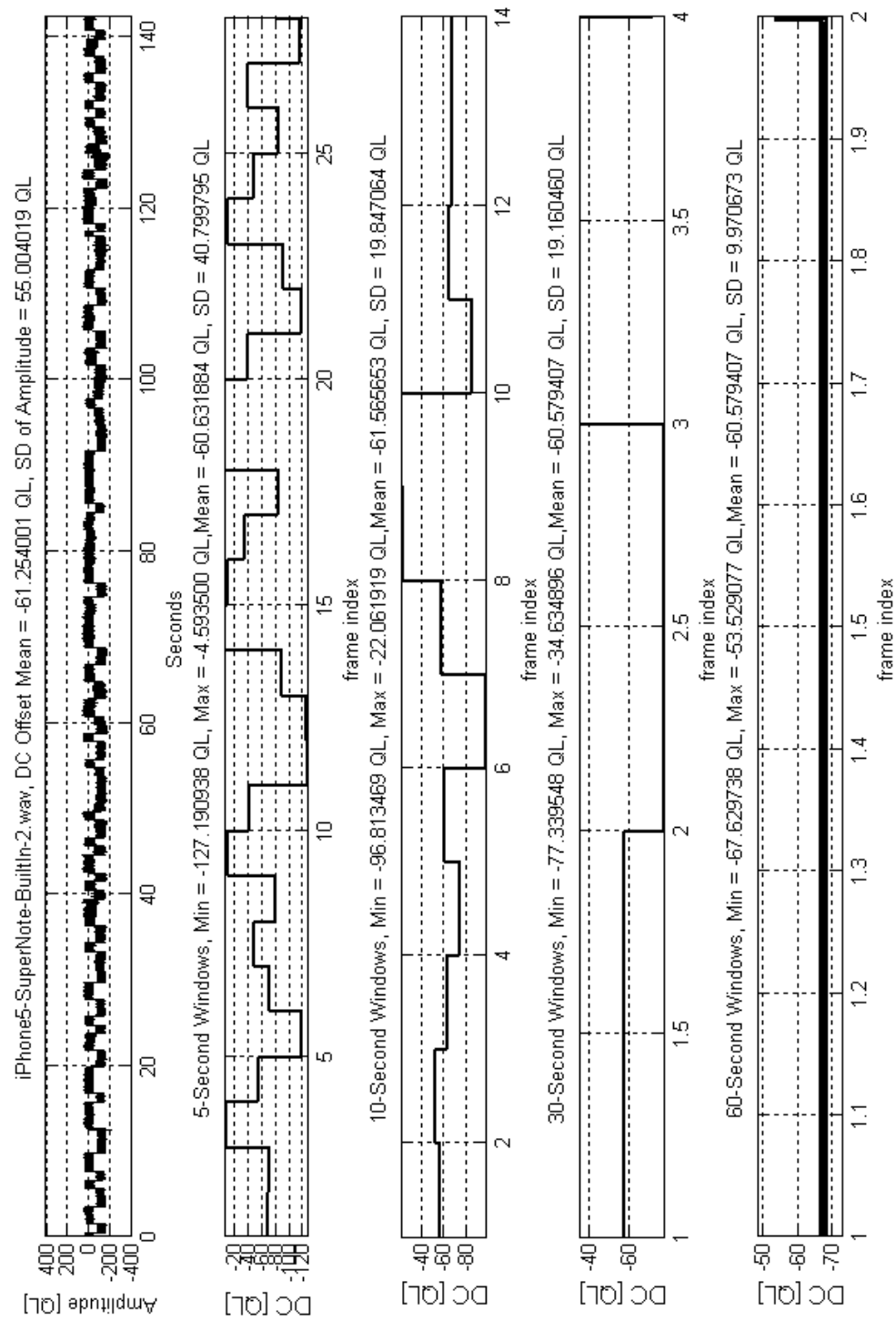


Figure 21 - SuperNote - Test 2 - DC Offset Plots

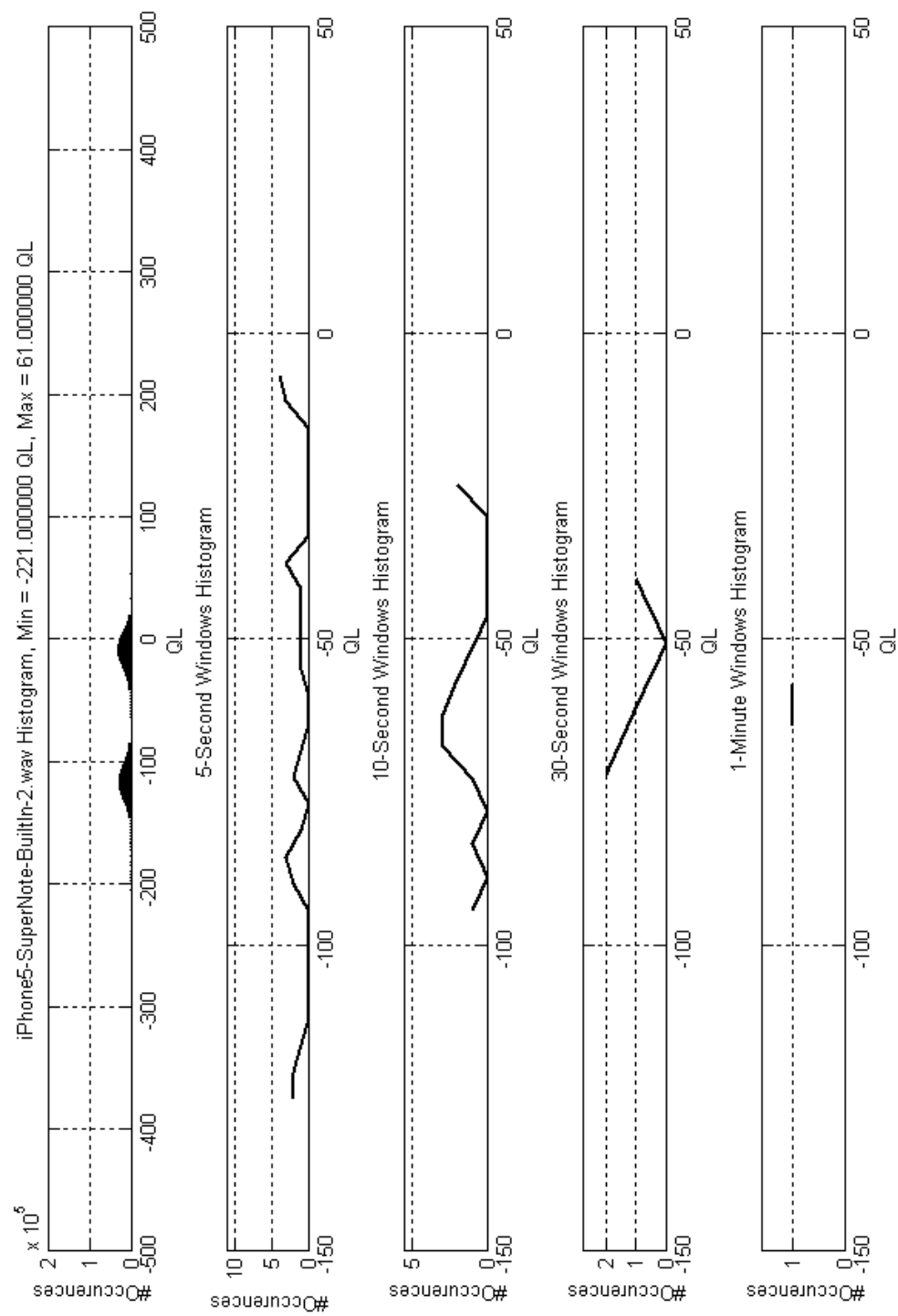


Figure 22 - SuperNote - Test 2 - Histograms

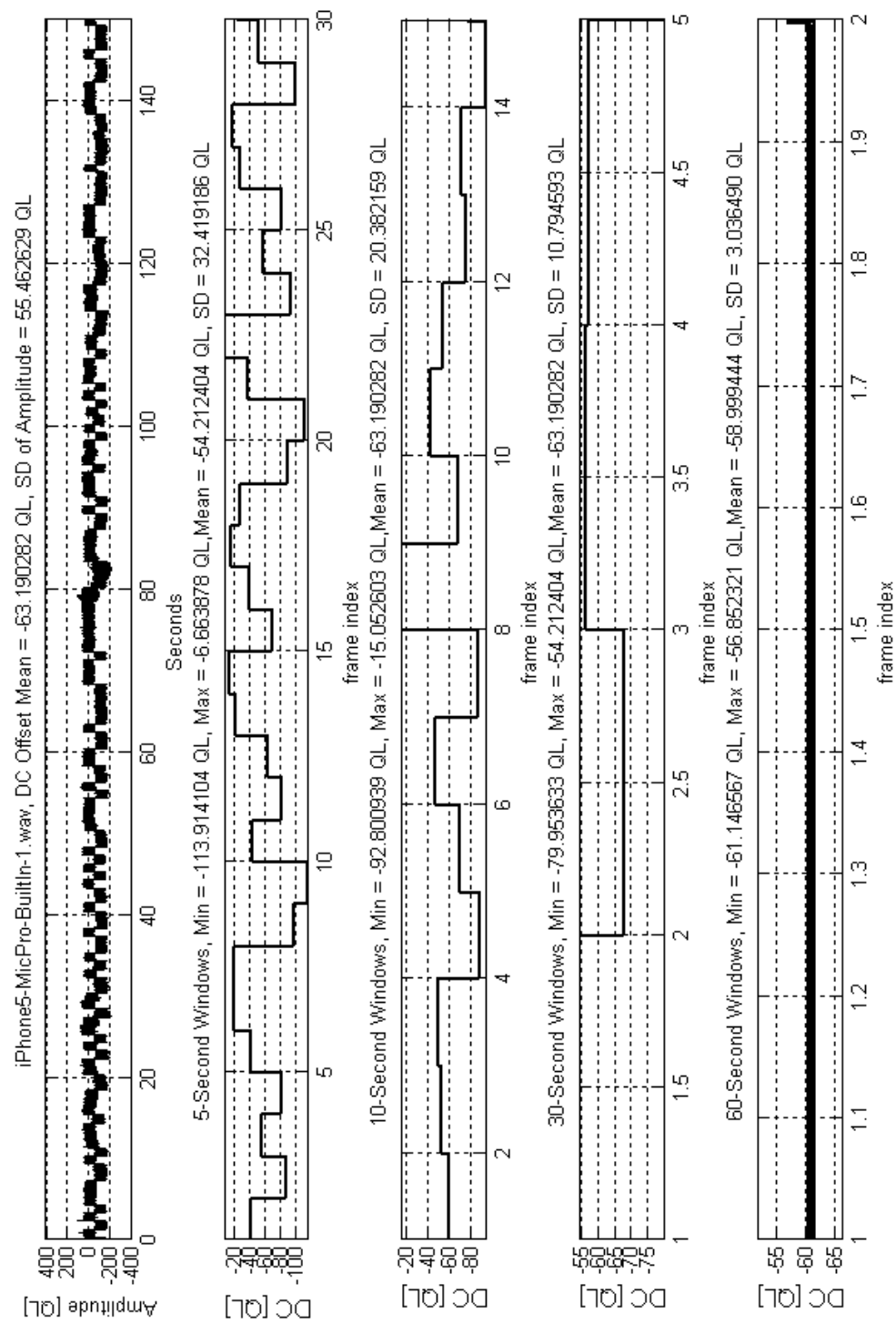


Figure 23 - MicPro - Test 1 - DC Offset Plots

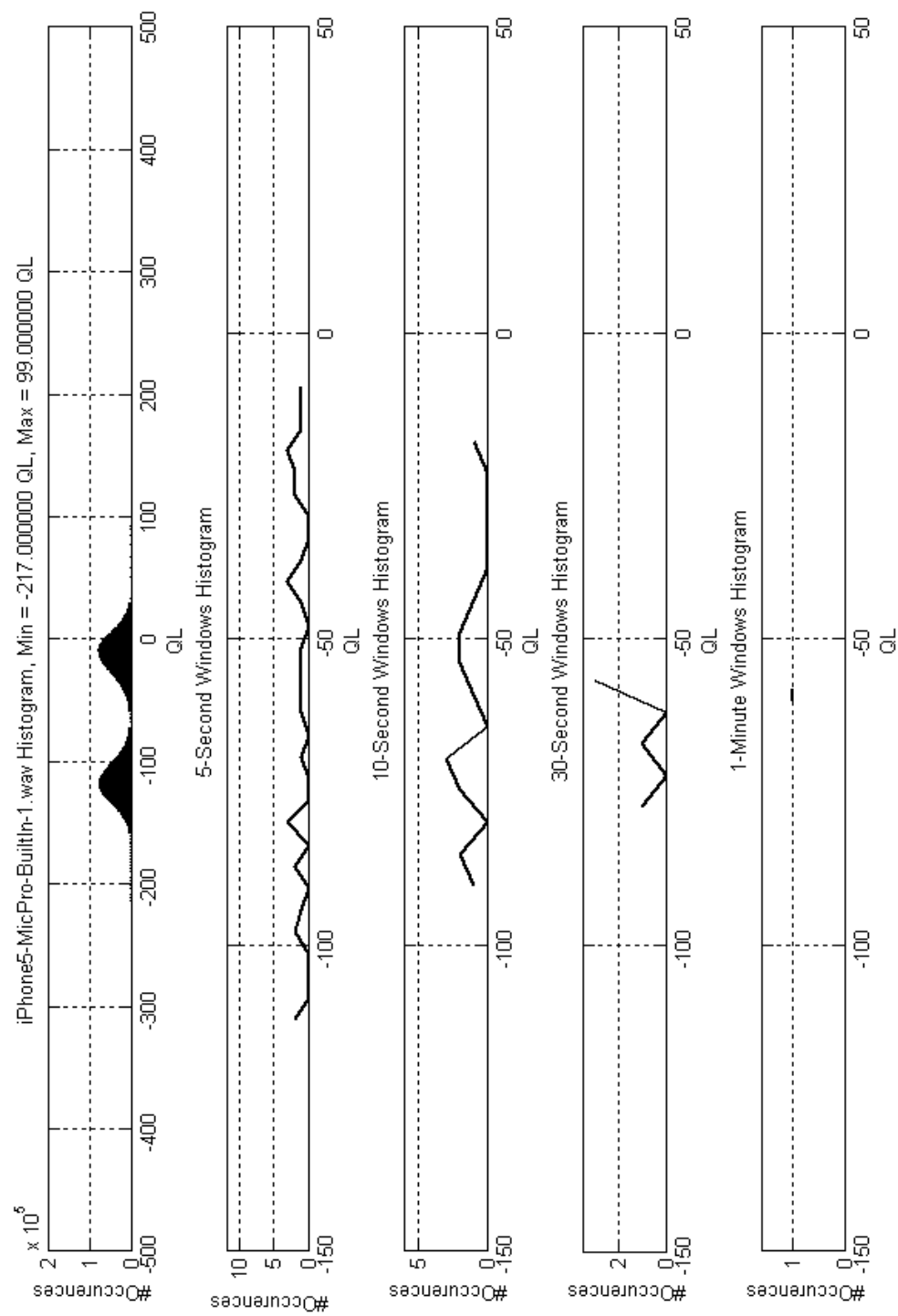


Figure 24 - MicPro - Test 1 - Histograms

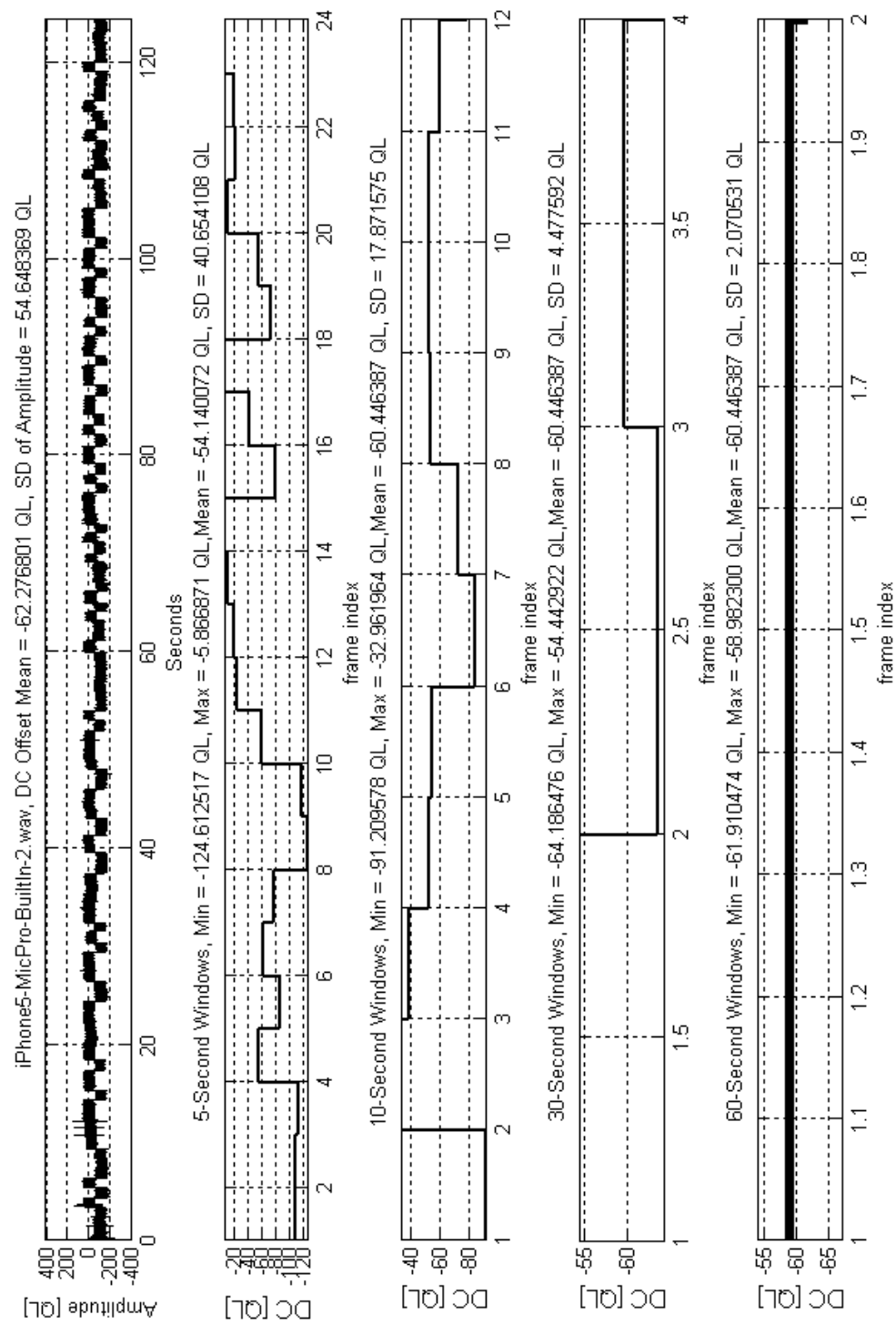


Figure 25 - MicPro - Test 2 - DC Offset Plots

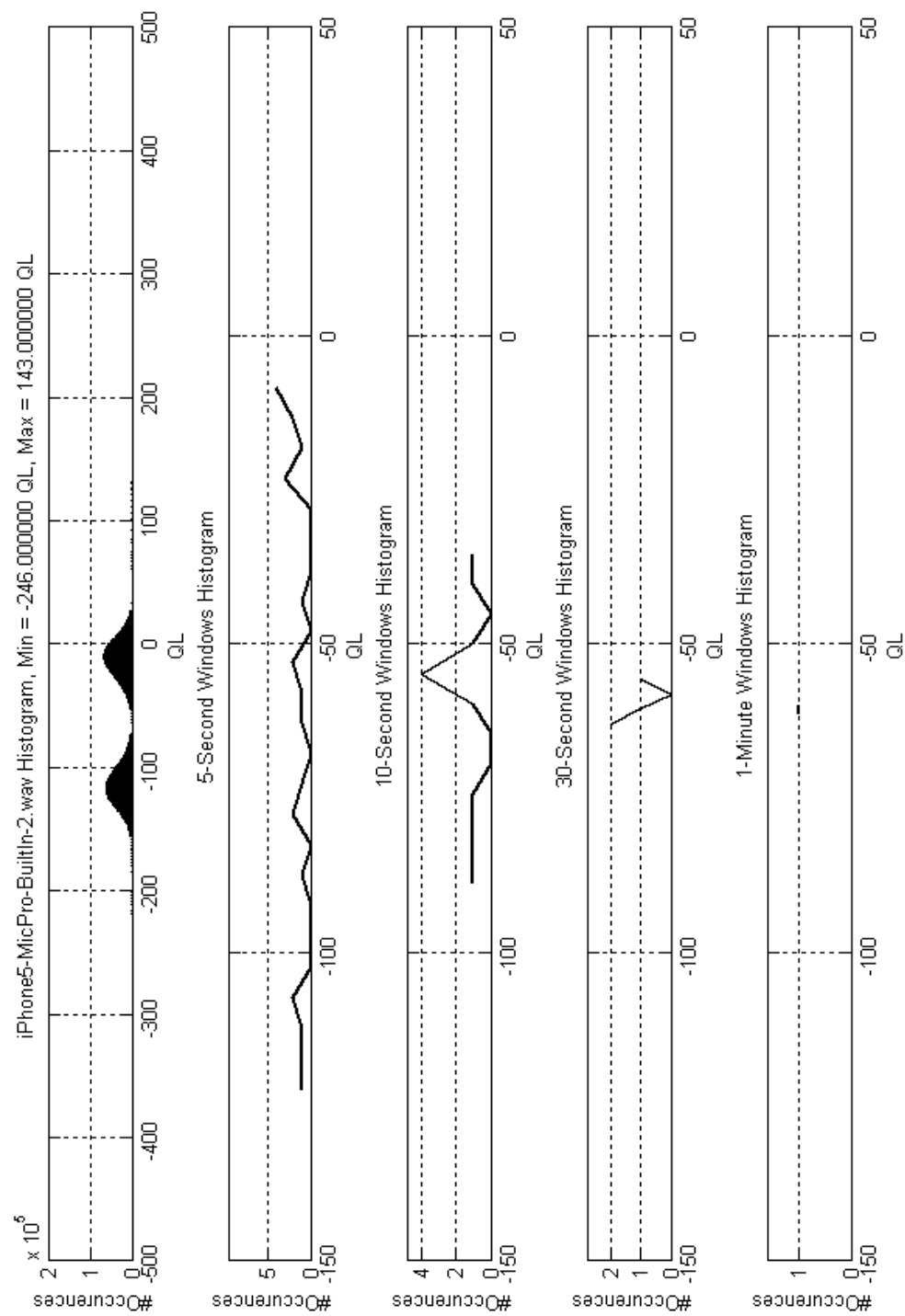


Figure 26 - MicPro - Test 2 - Histograms

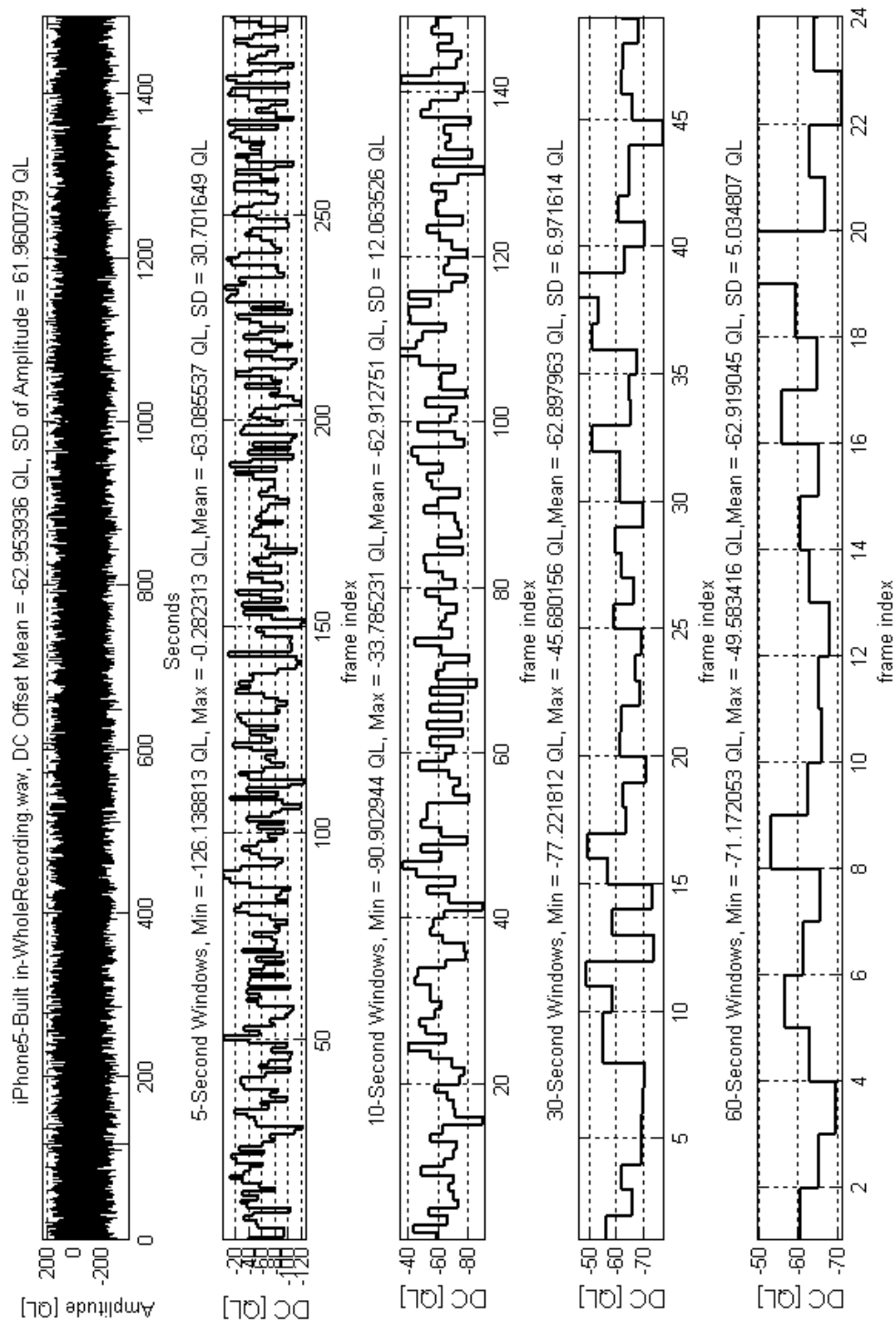


Figure 27 - iPhone 5 - Built-In - DC Offset Plots

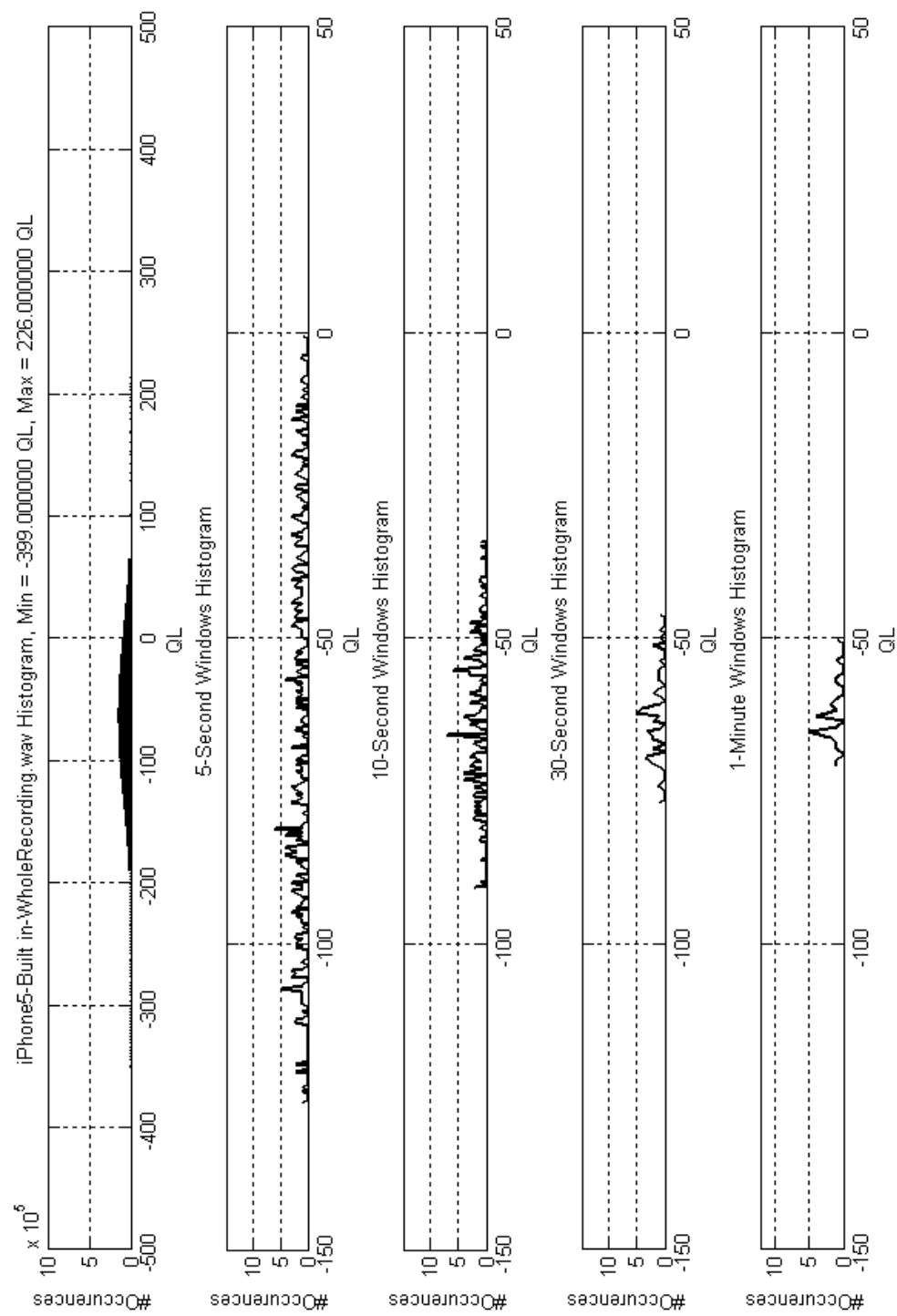


Figure 28 - iPhone 5 - Built-In - Histograms

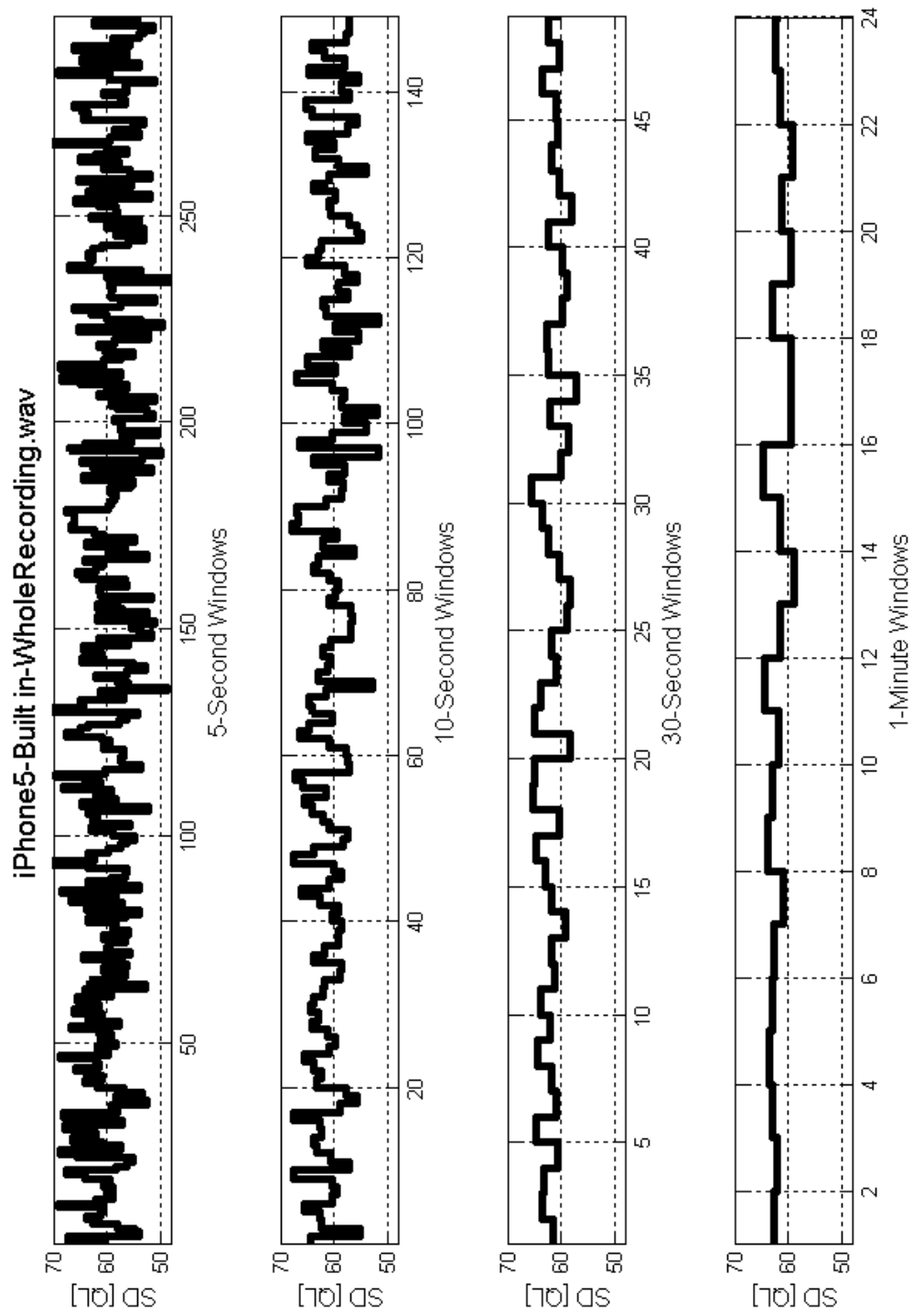


Figure 29 - iPhone 5 - Built-In - SD Windows

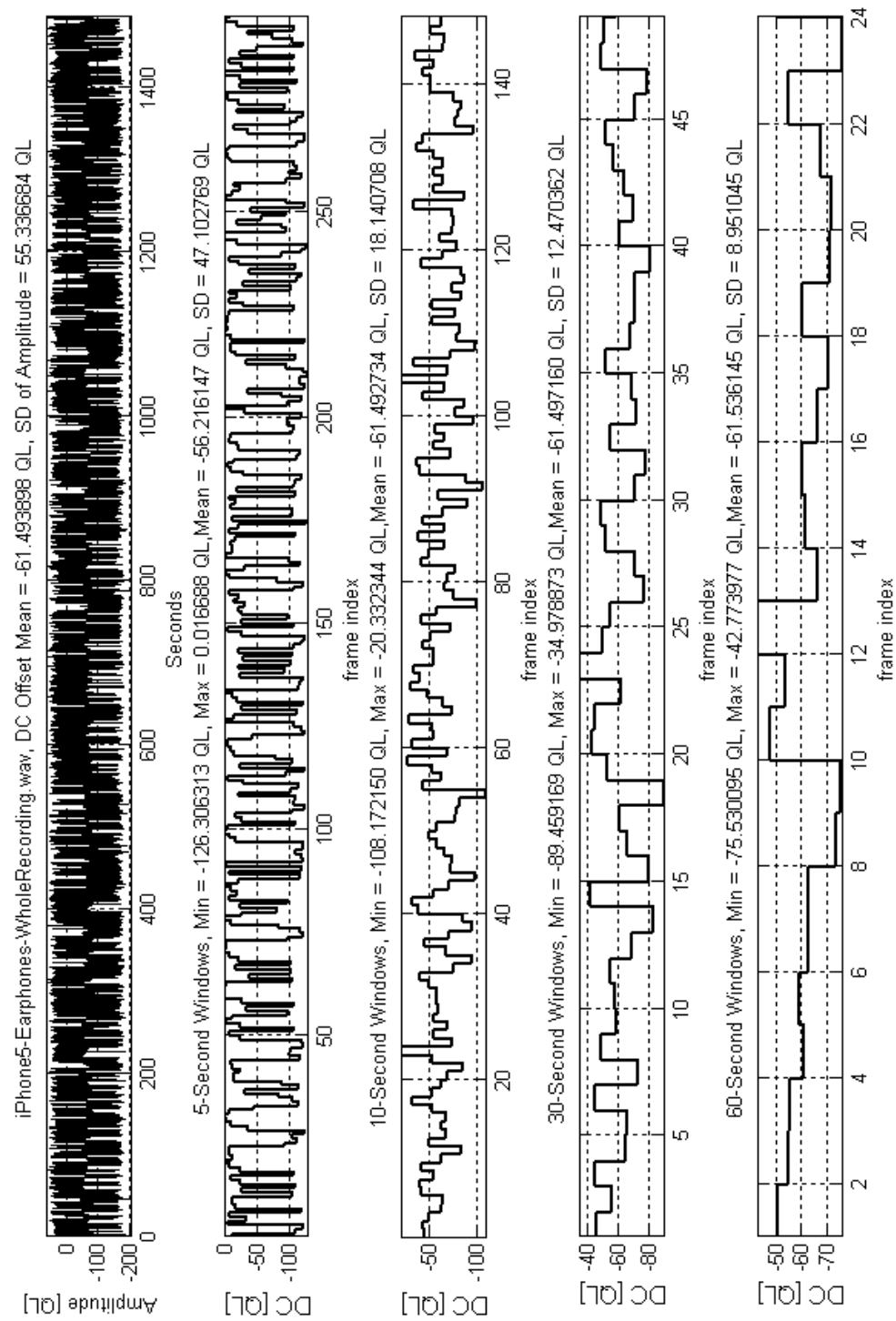


Figure 30 - iPhone 5 - Earphones - DC Offset Plots

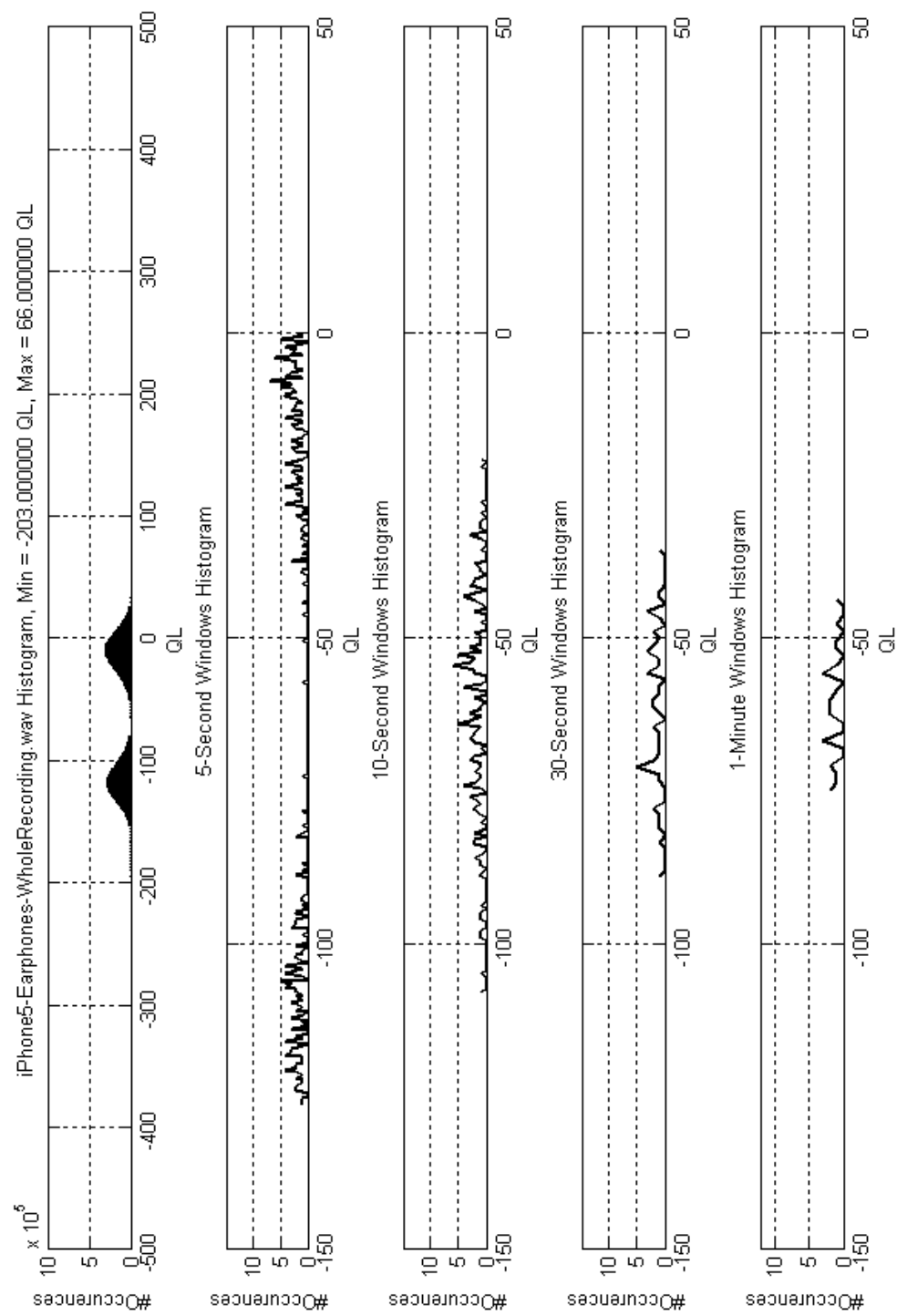


Figure 31 - iPhone 5 - Earphones - Histograms

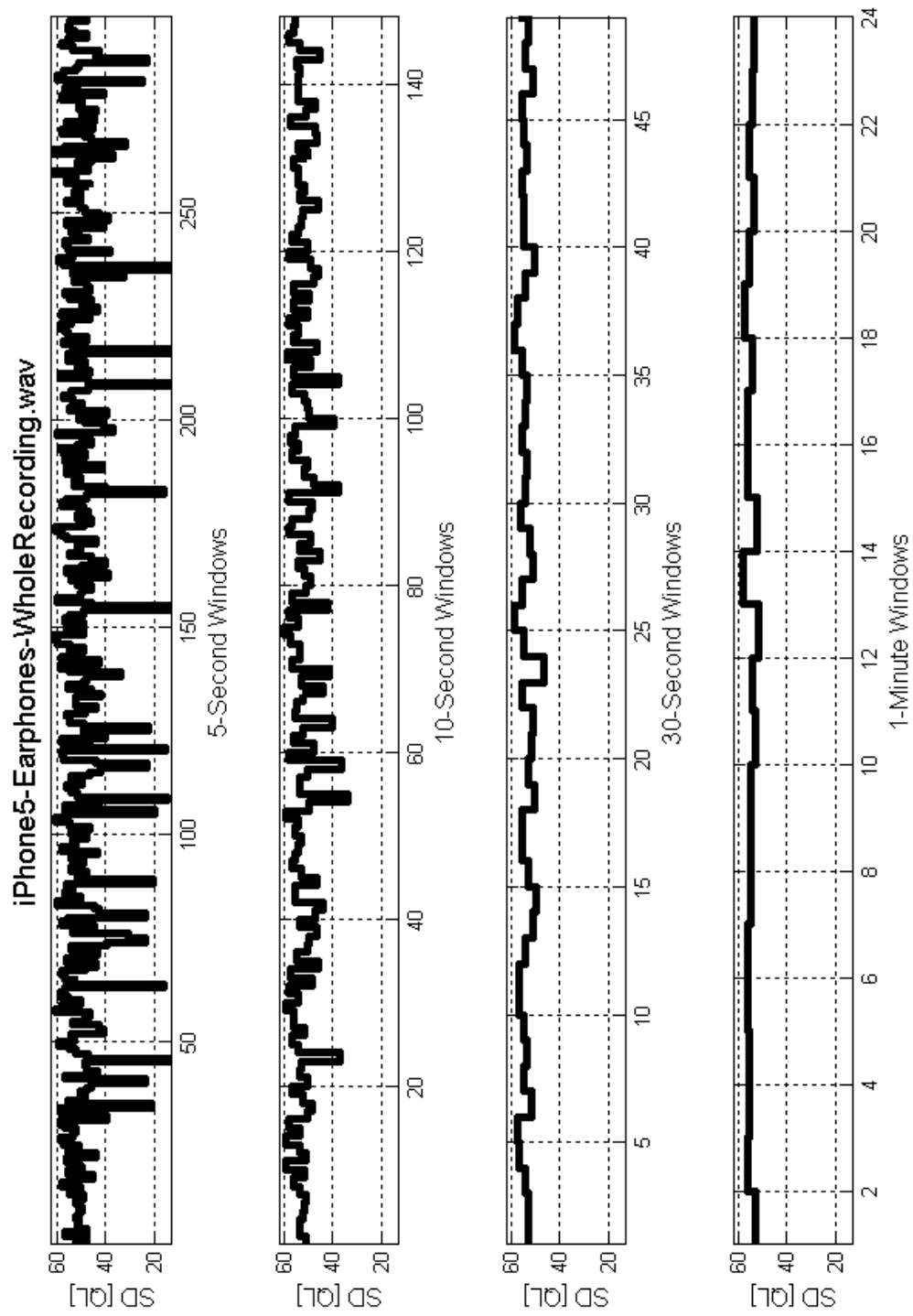


Figure 32 - iPhone 5 - Earphones - SD Windows

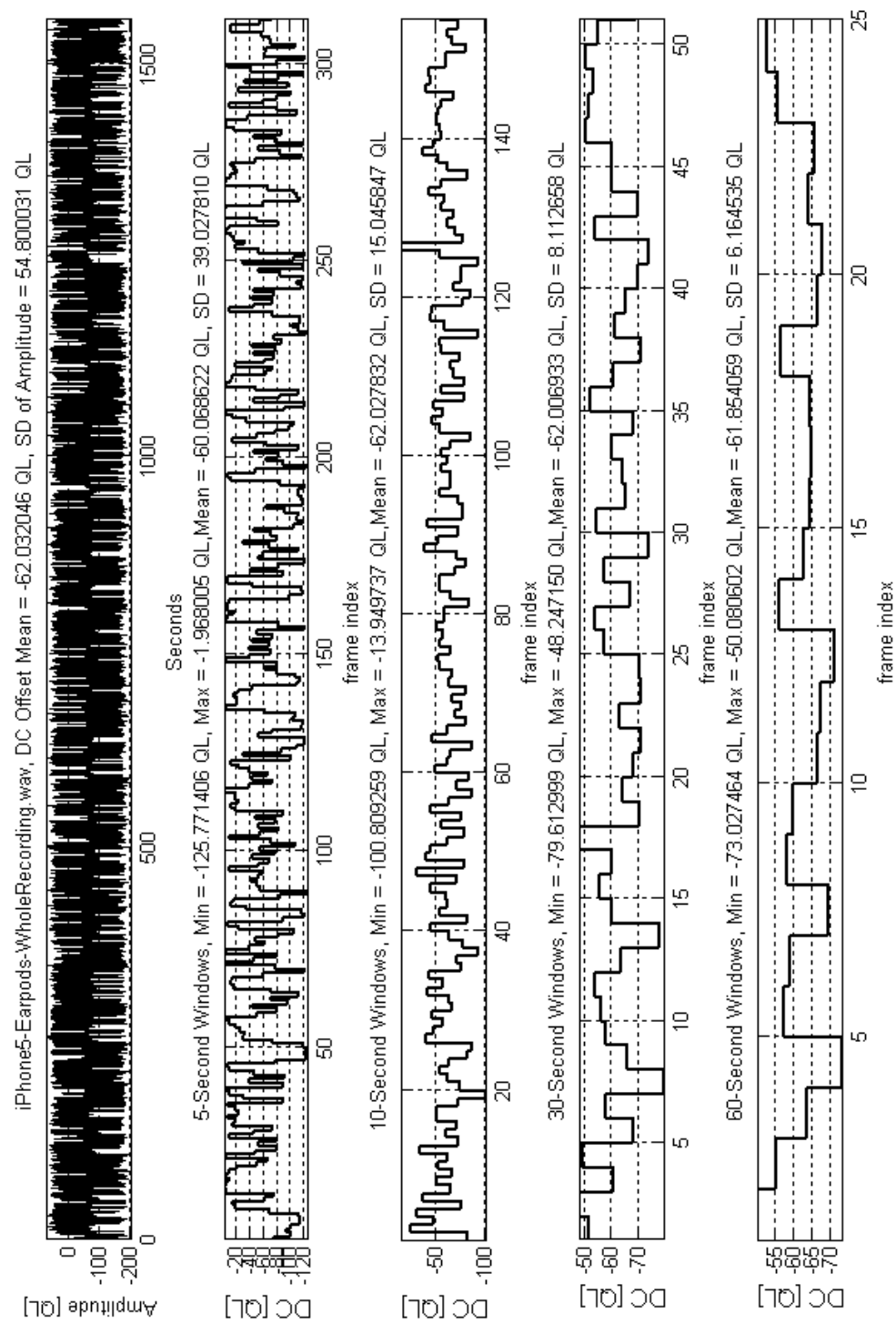


Figure 33 - iPhone 5 - EarPods - DC Offset Plots

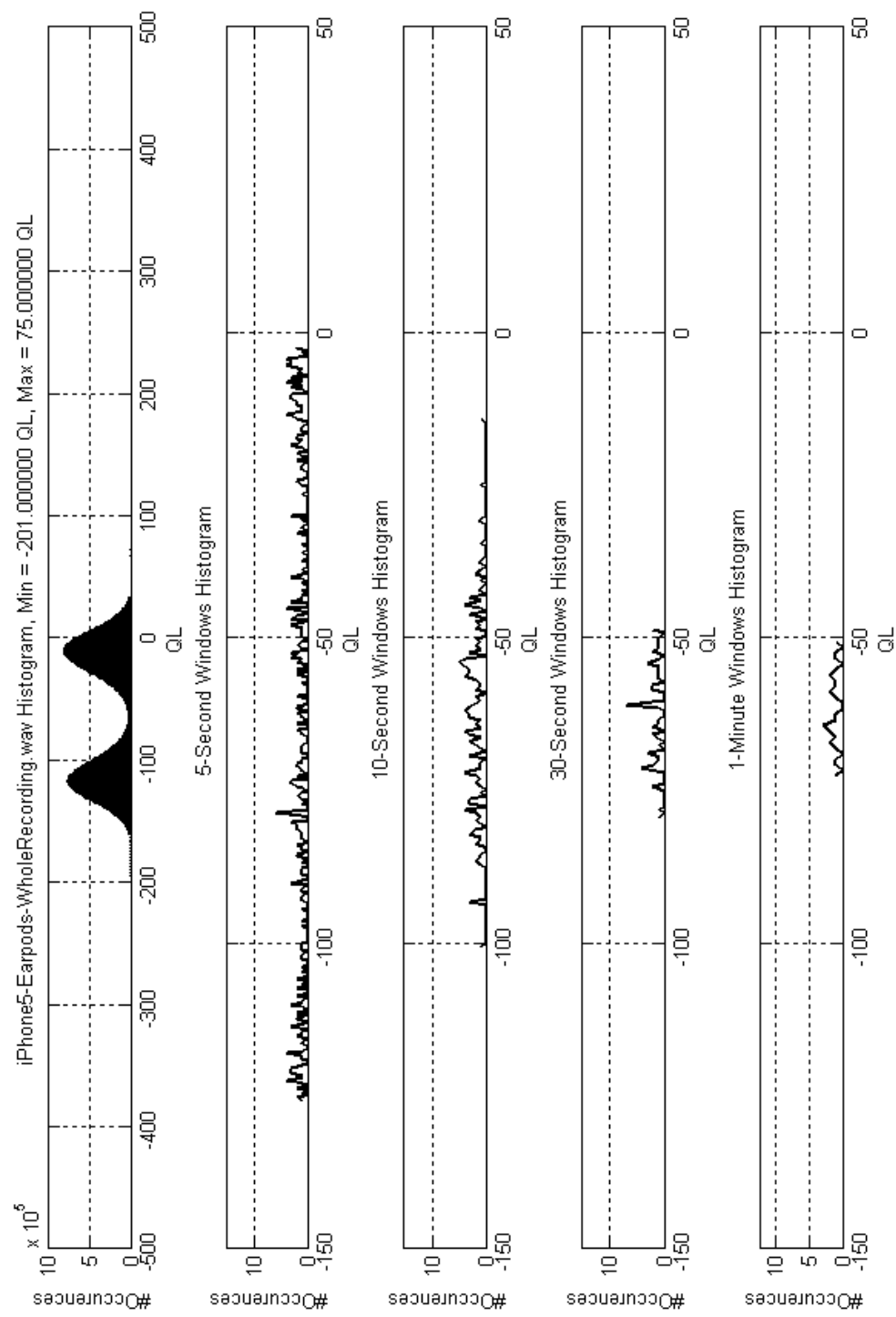


Figure 34 - iPhone 5 - Earpods - Histograms

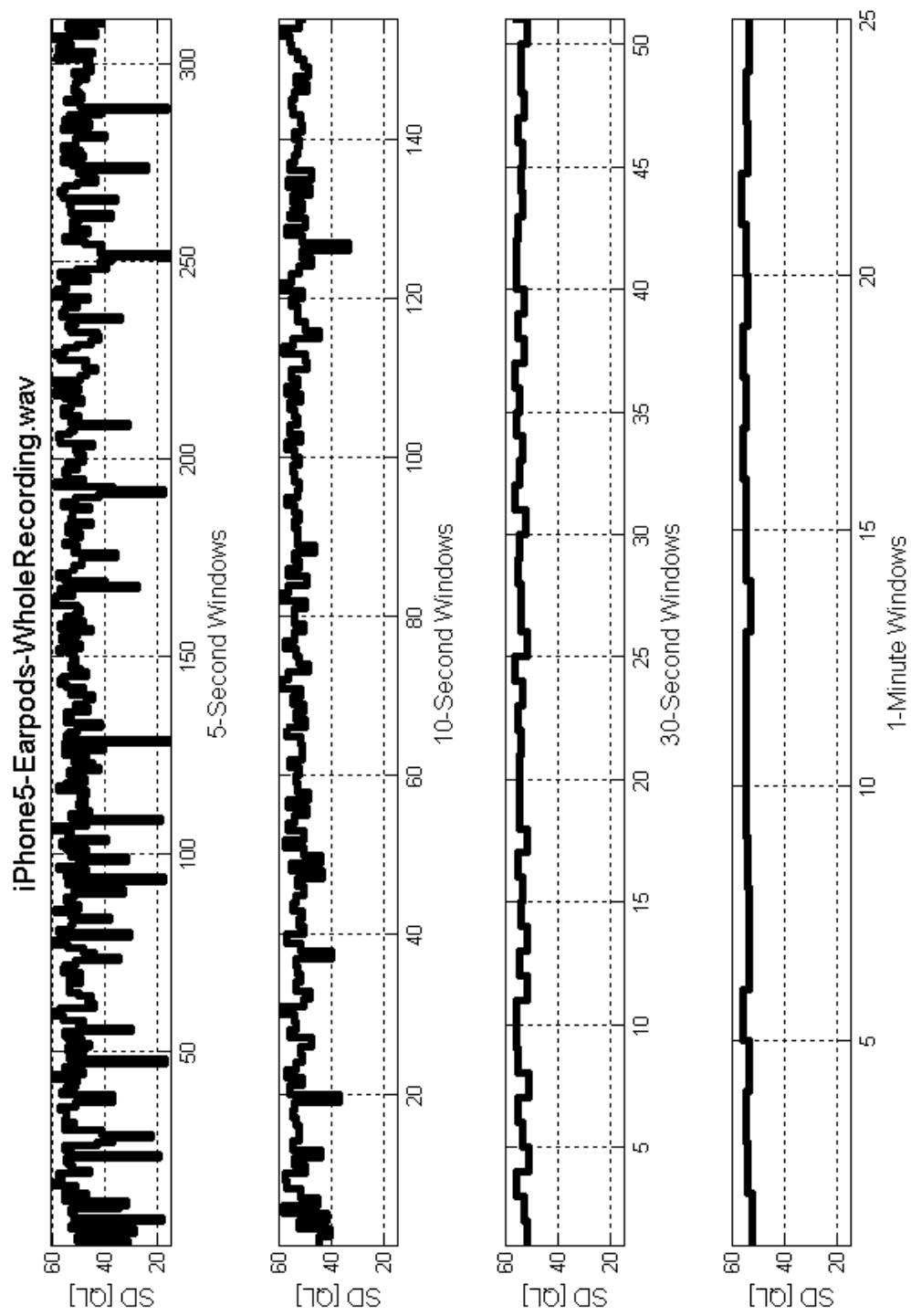


Figure 35 - iPhone 5 - EarPods - SD Windows

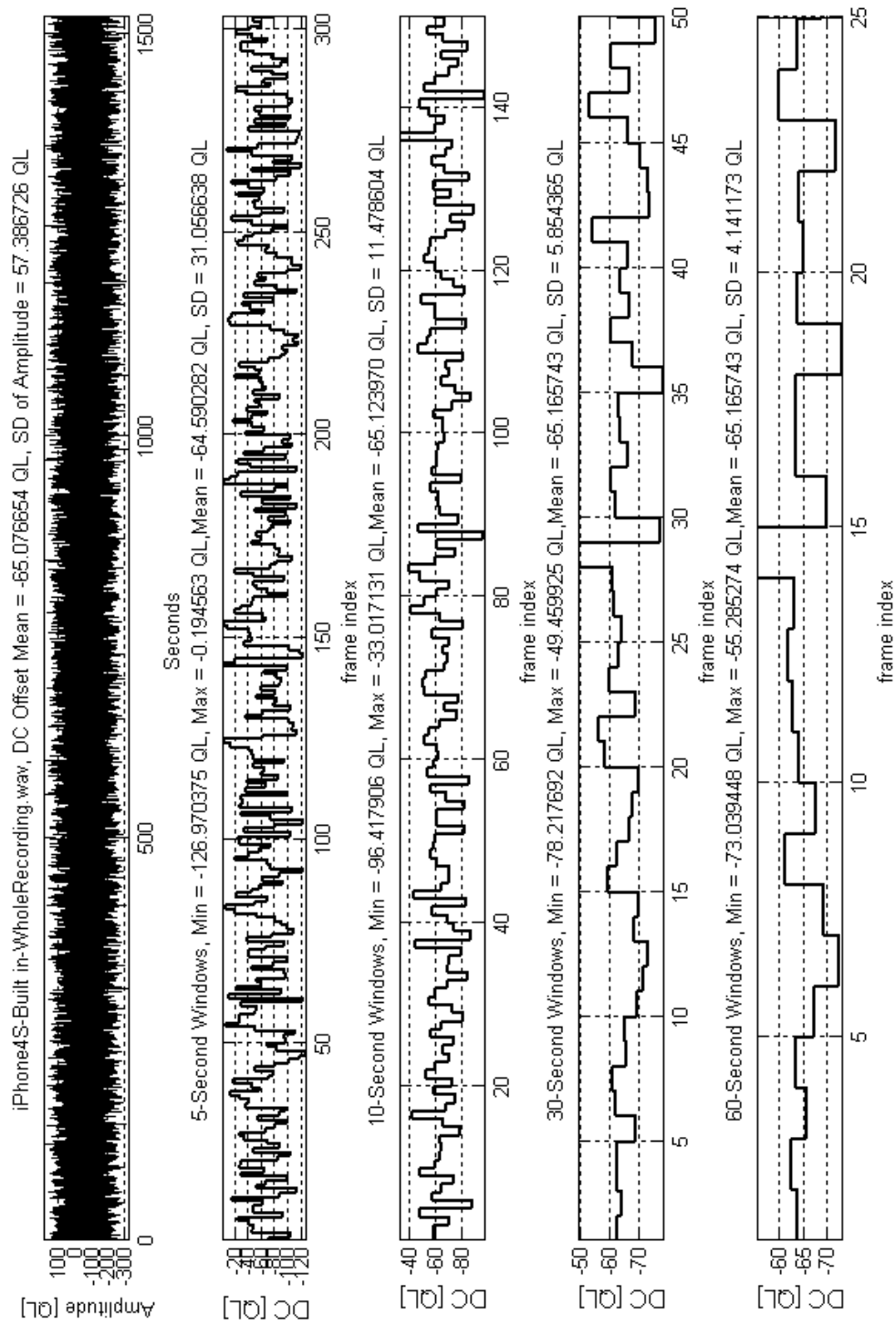


Figure 36 - iPhone 4S - Built-In - DC Offset Plots

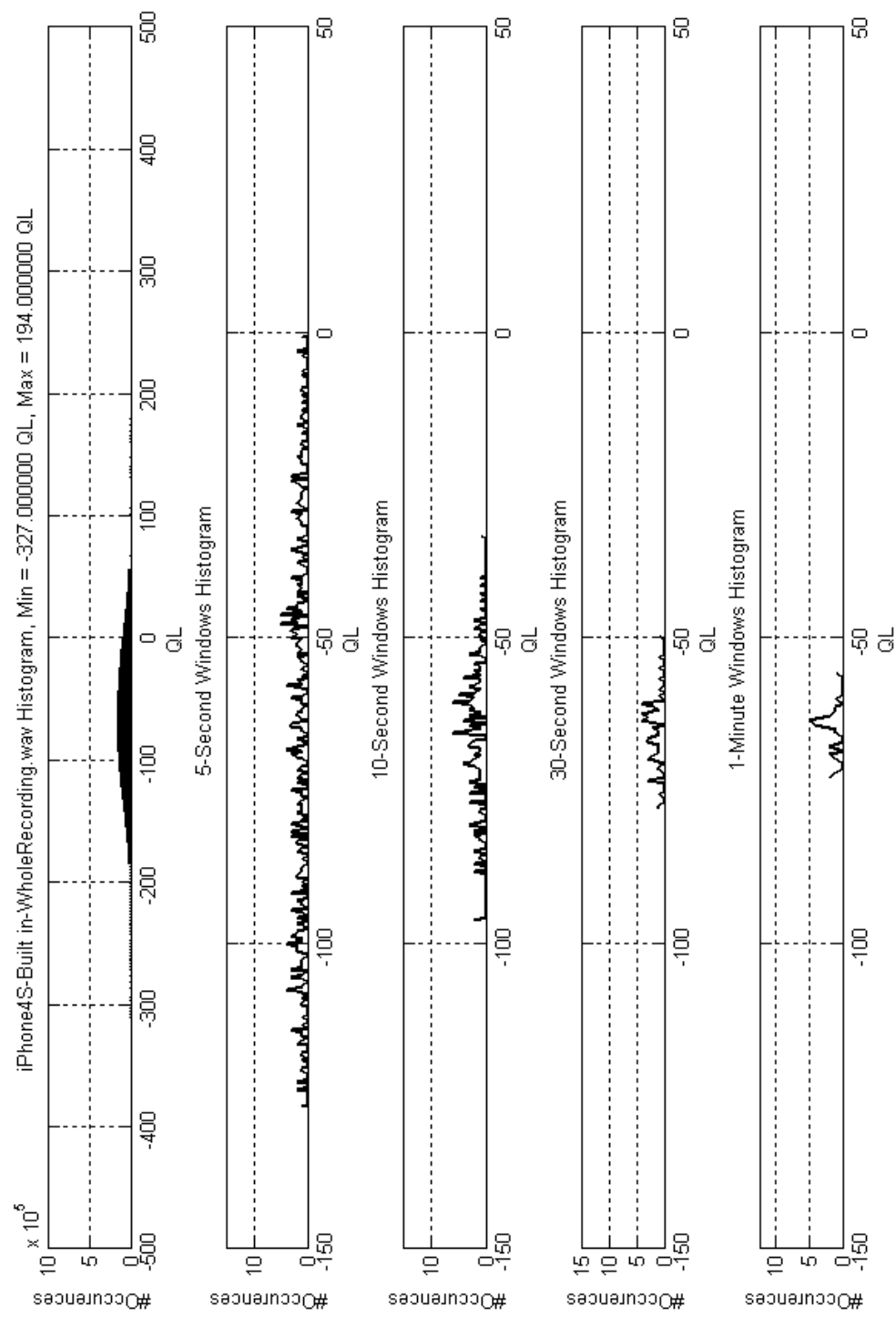


Figure 37 - iPhone 4S - Built-In - Histograms

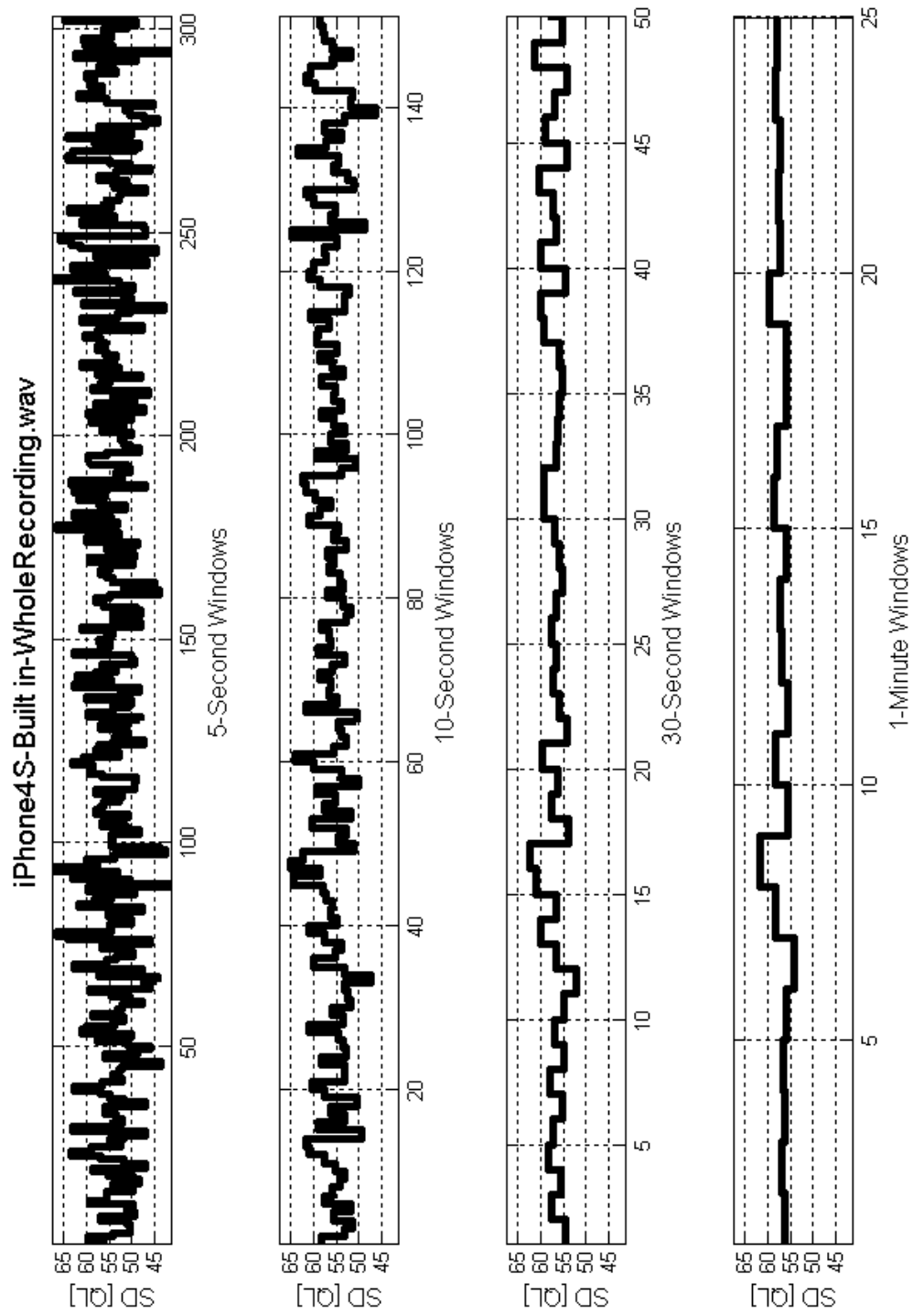


Figure 38 - iPhone 4S - Built-In - SD Windows

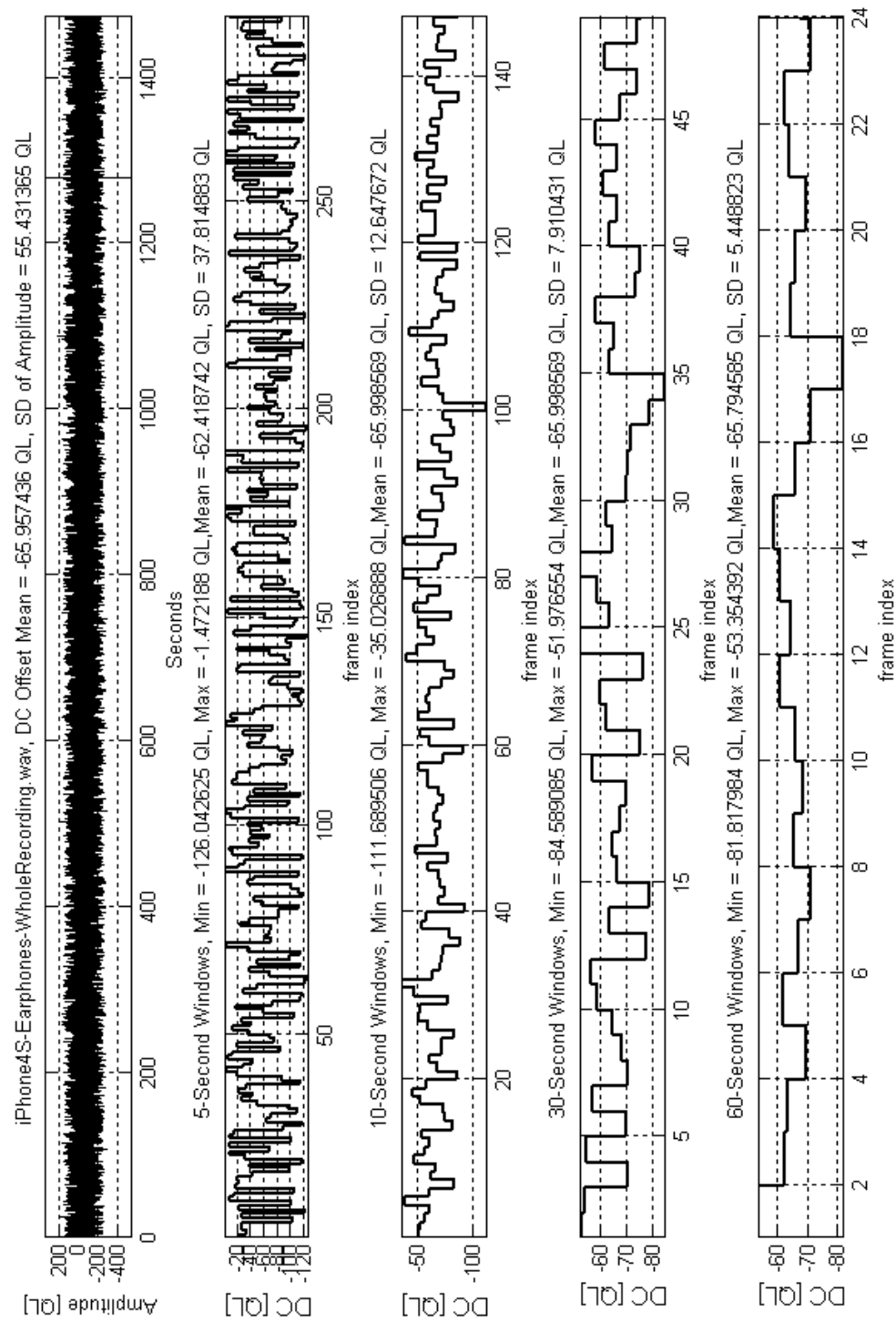


Figure 39 - iPhone 4S - Earphones - DC Offset Plots

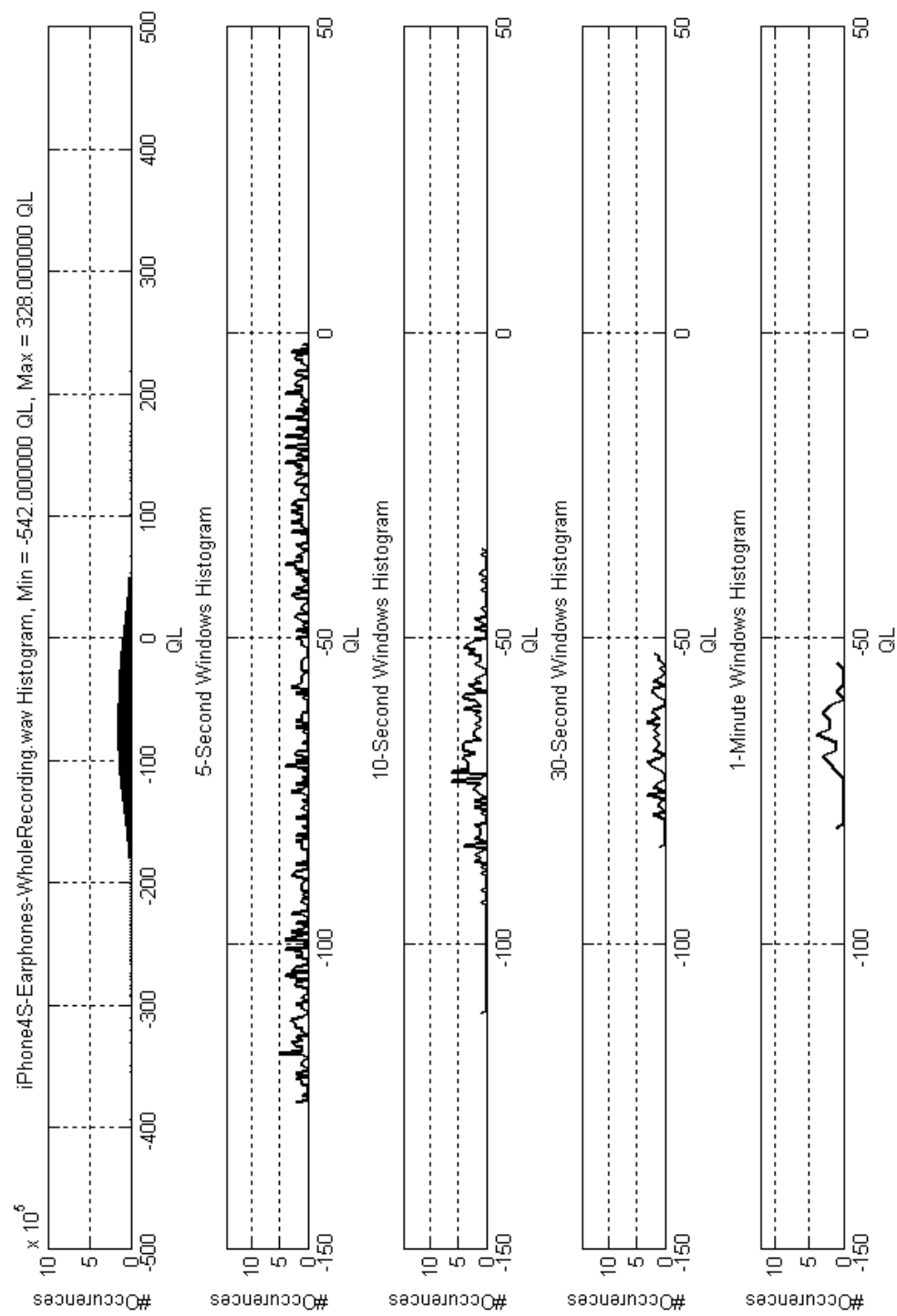


Figure 40 - iPhone 4S - Earphones - Histograms

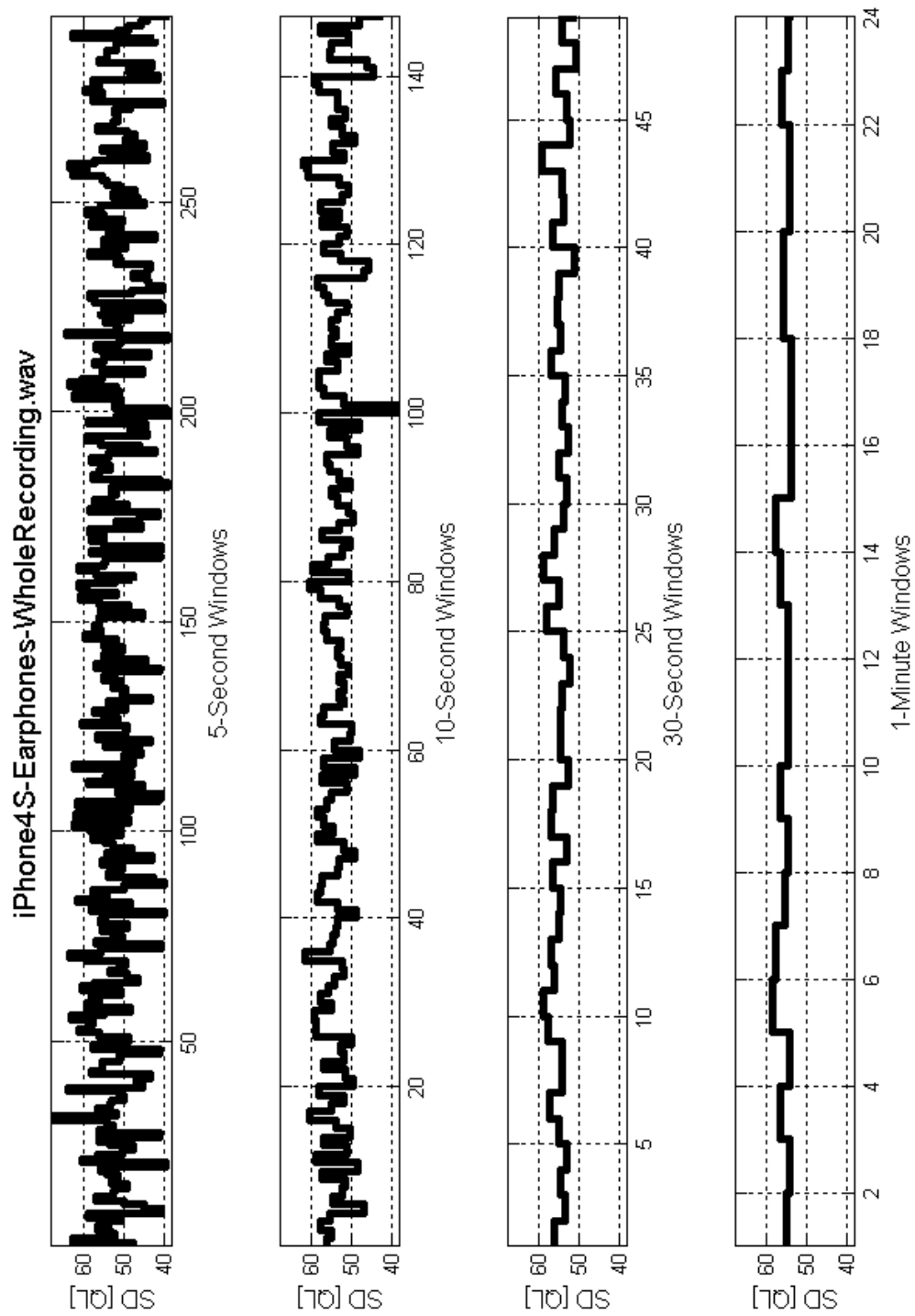


Figure 41 - iPhone 4S - Earphones - SD Windows

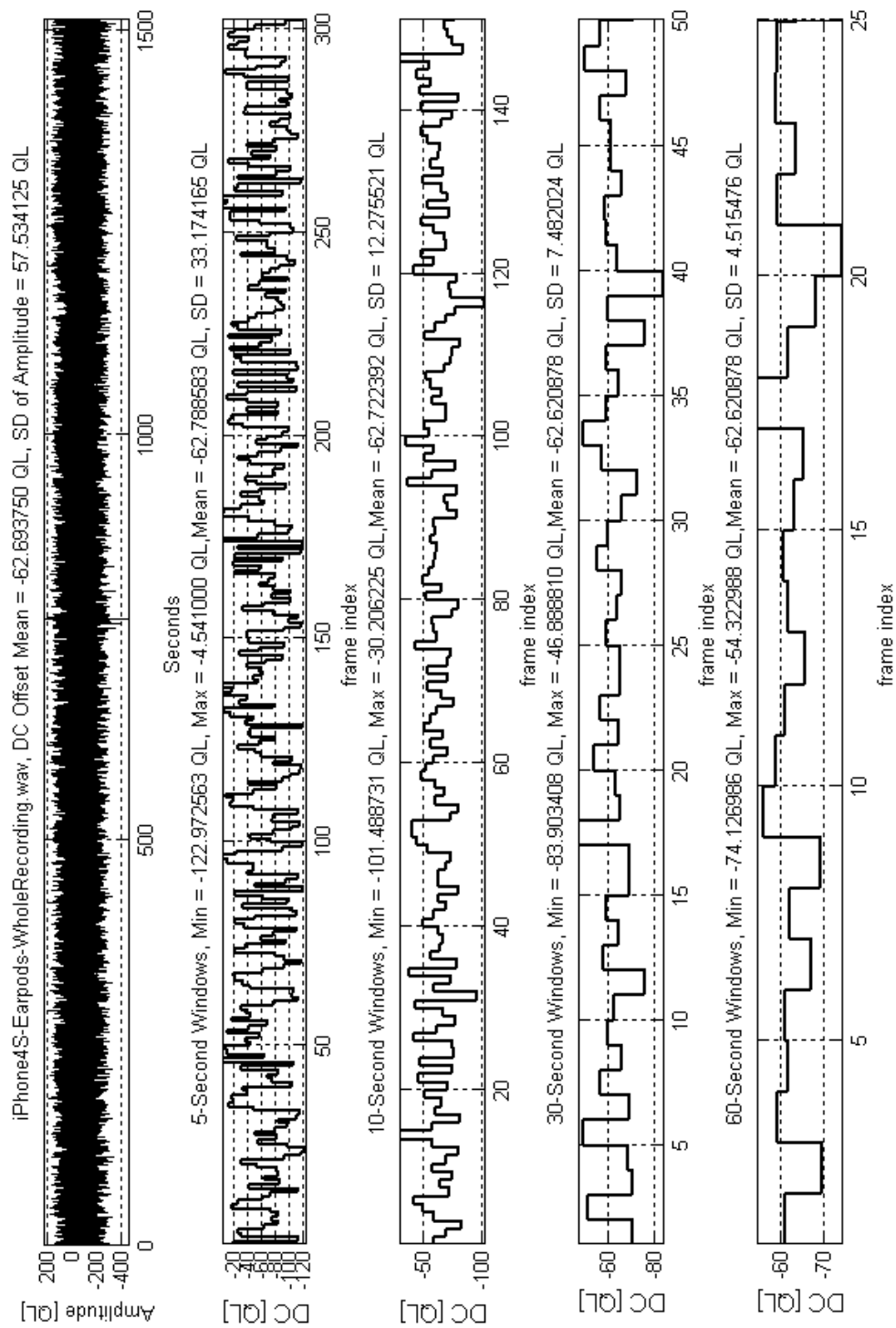


Figure 42 - iPhone 4S - EarPods - DC Offset Plots

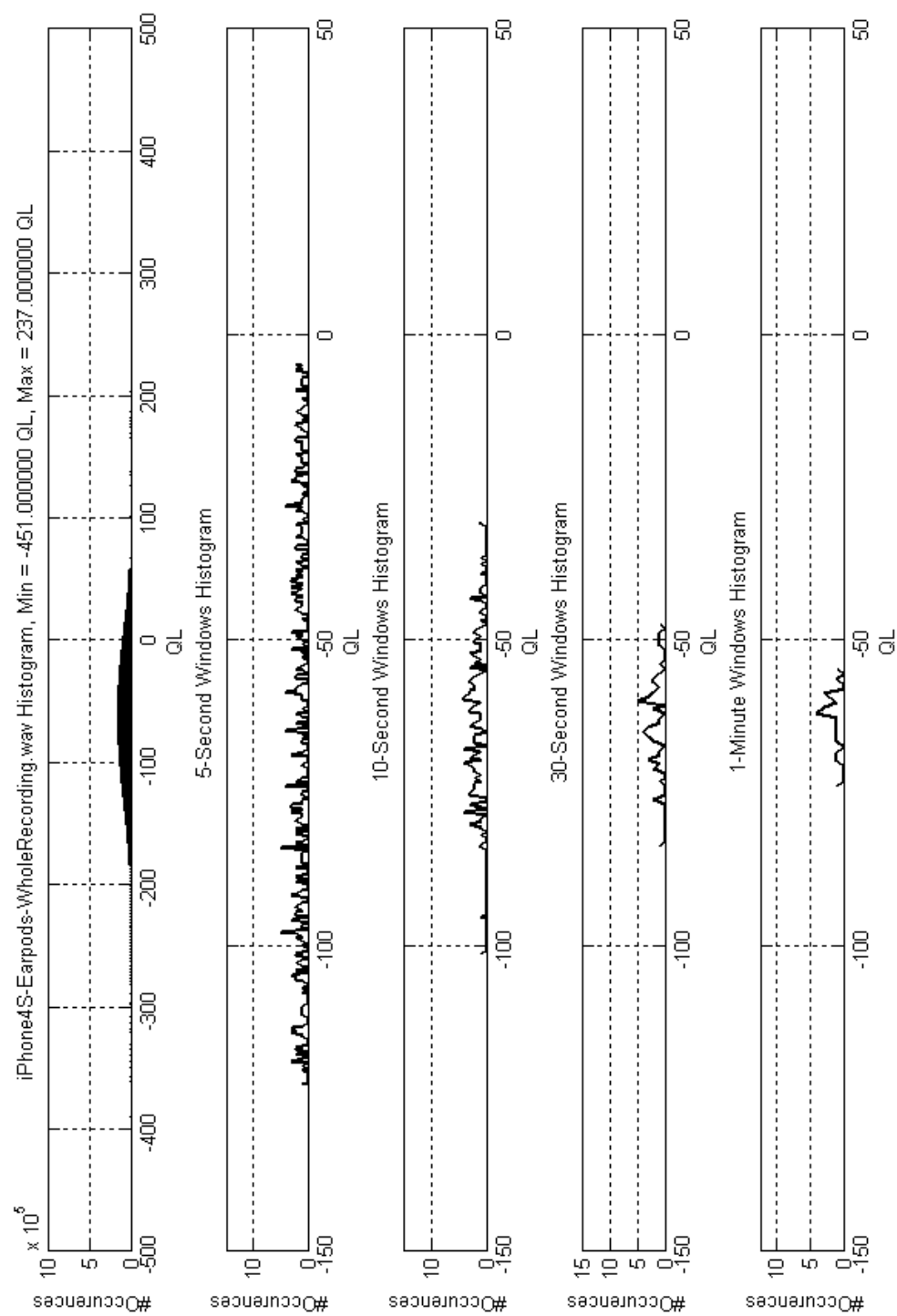


Figure 43 - iPhone 4S - EarPods - Histograms

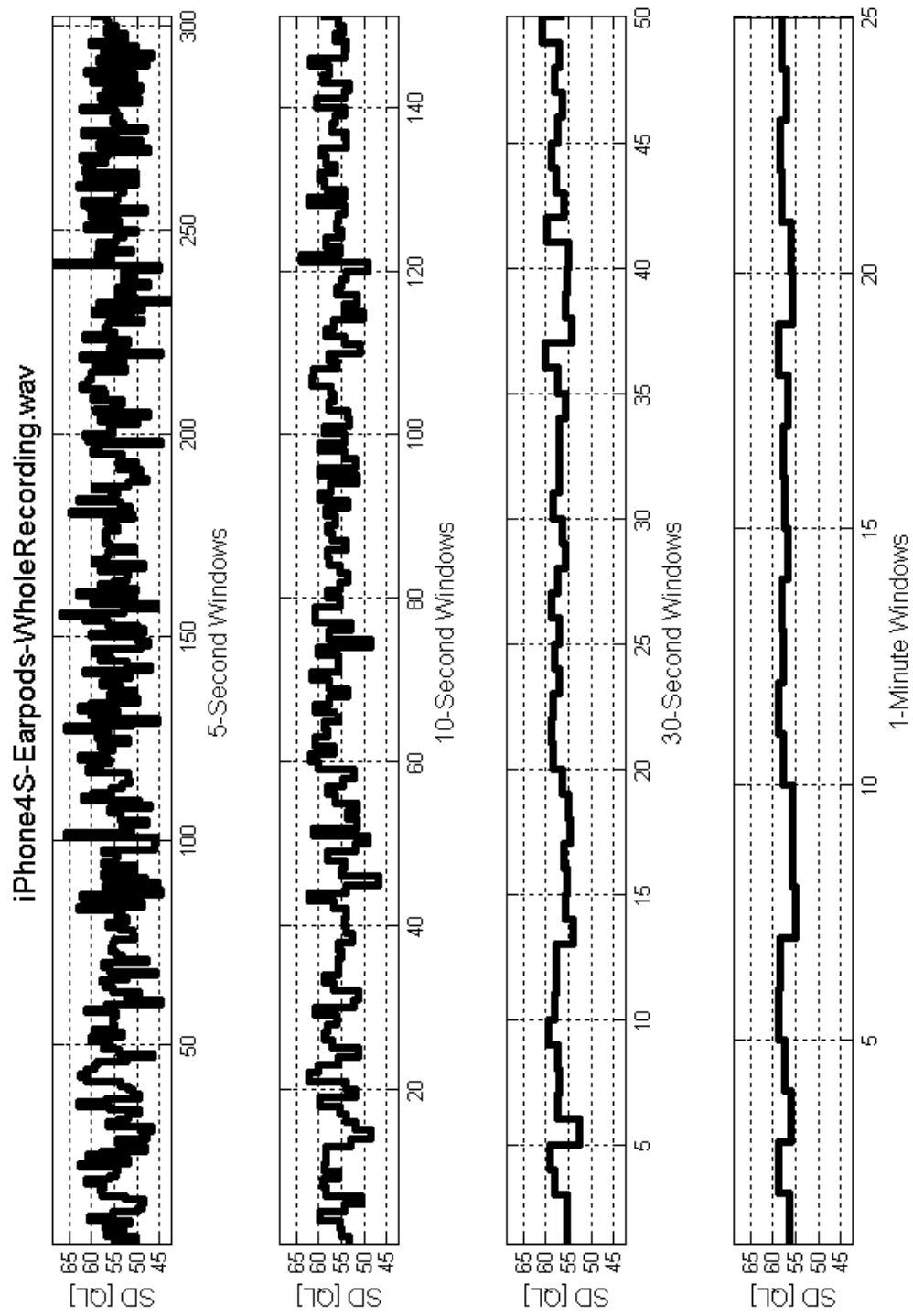


Figure 44 - iPhone 4S - EarPods - SD Windows

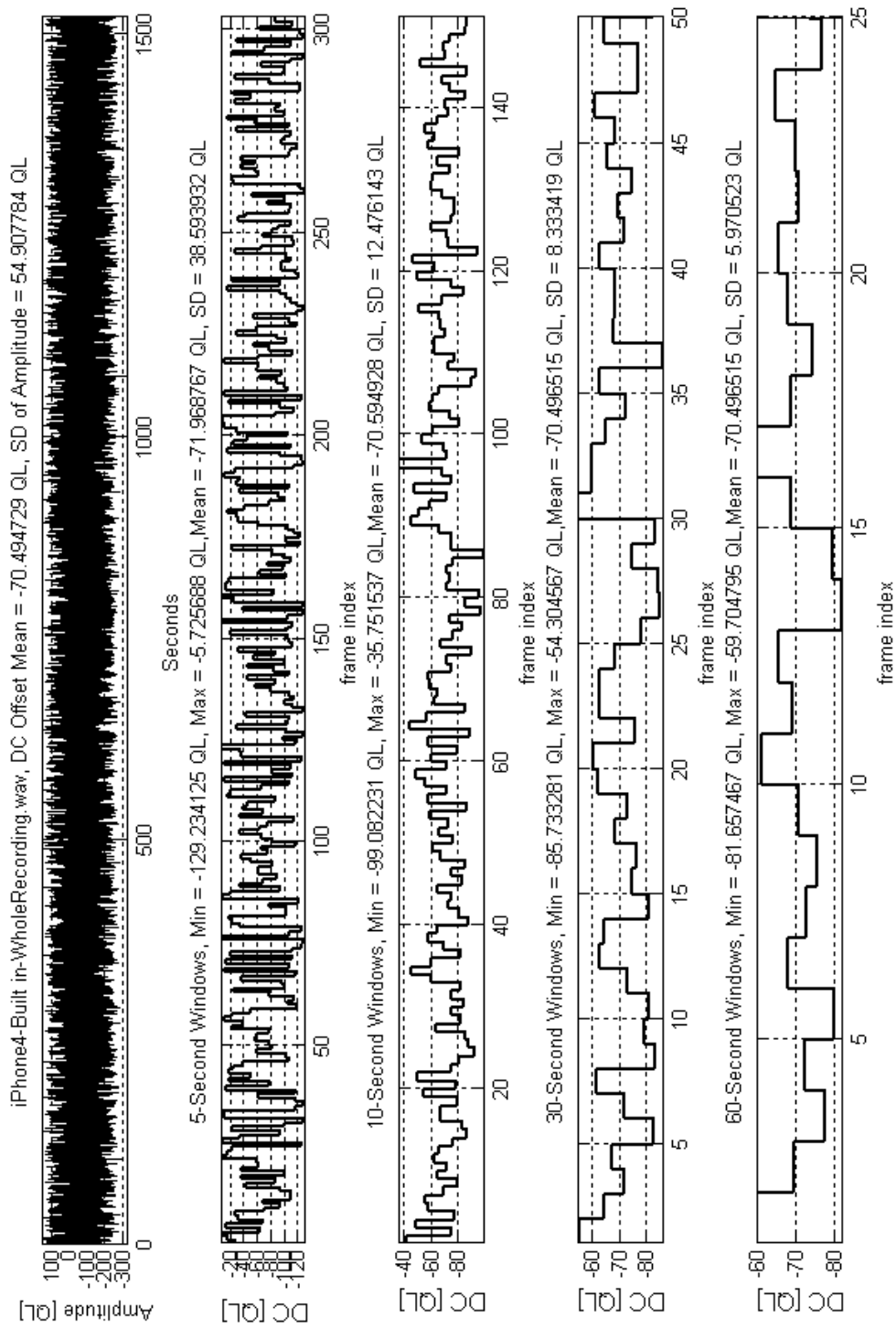


Figure 45 - iPhone 4 - Built-In - DC Offset Plots

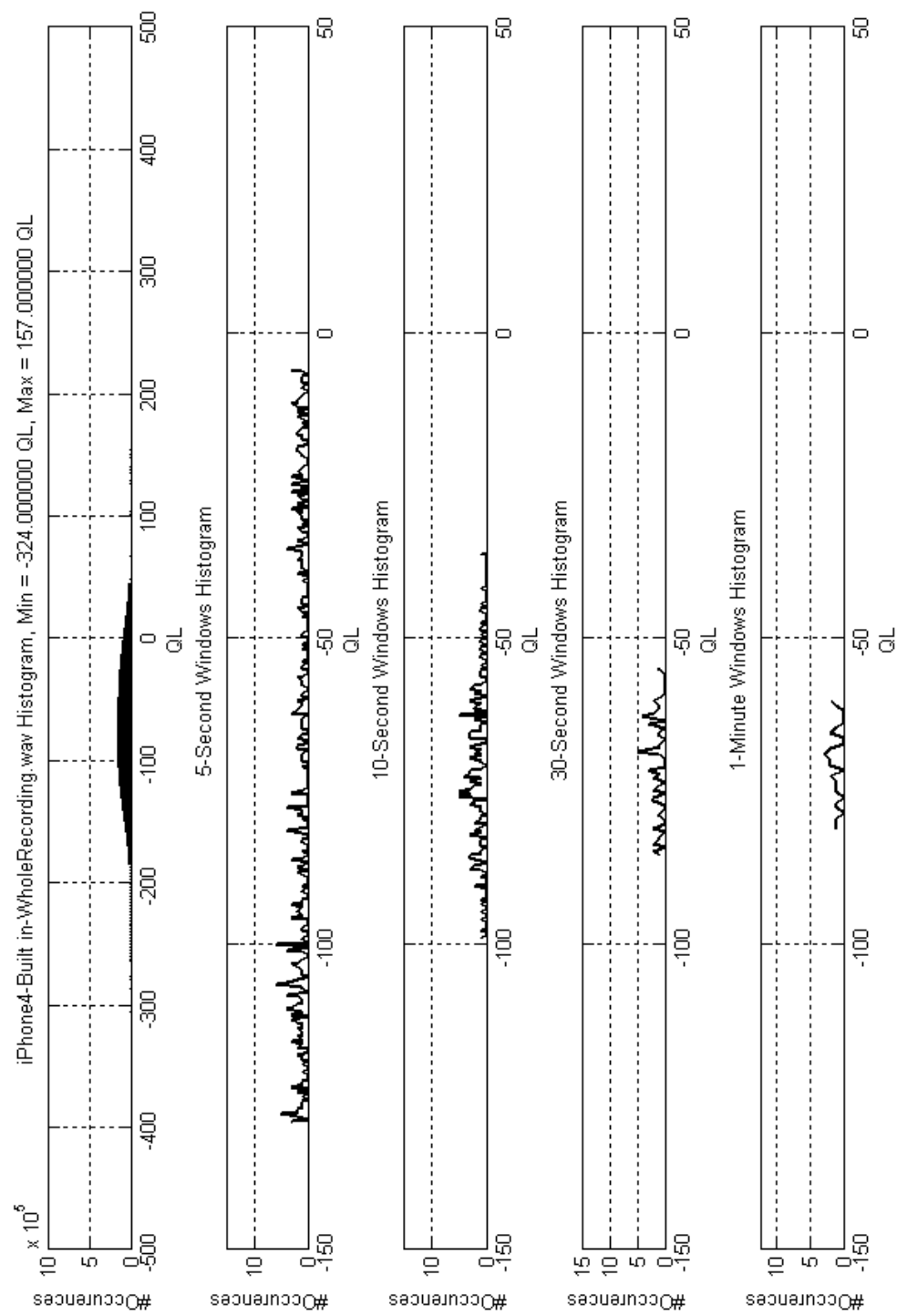


Figure 46 - iPhone 4 - Built-In - Histograms

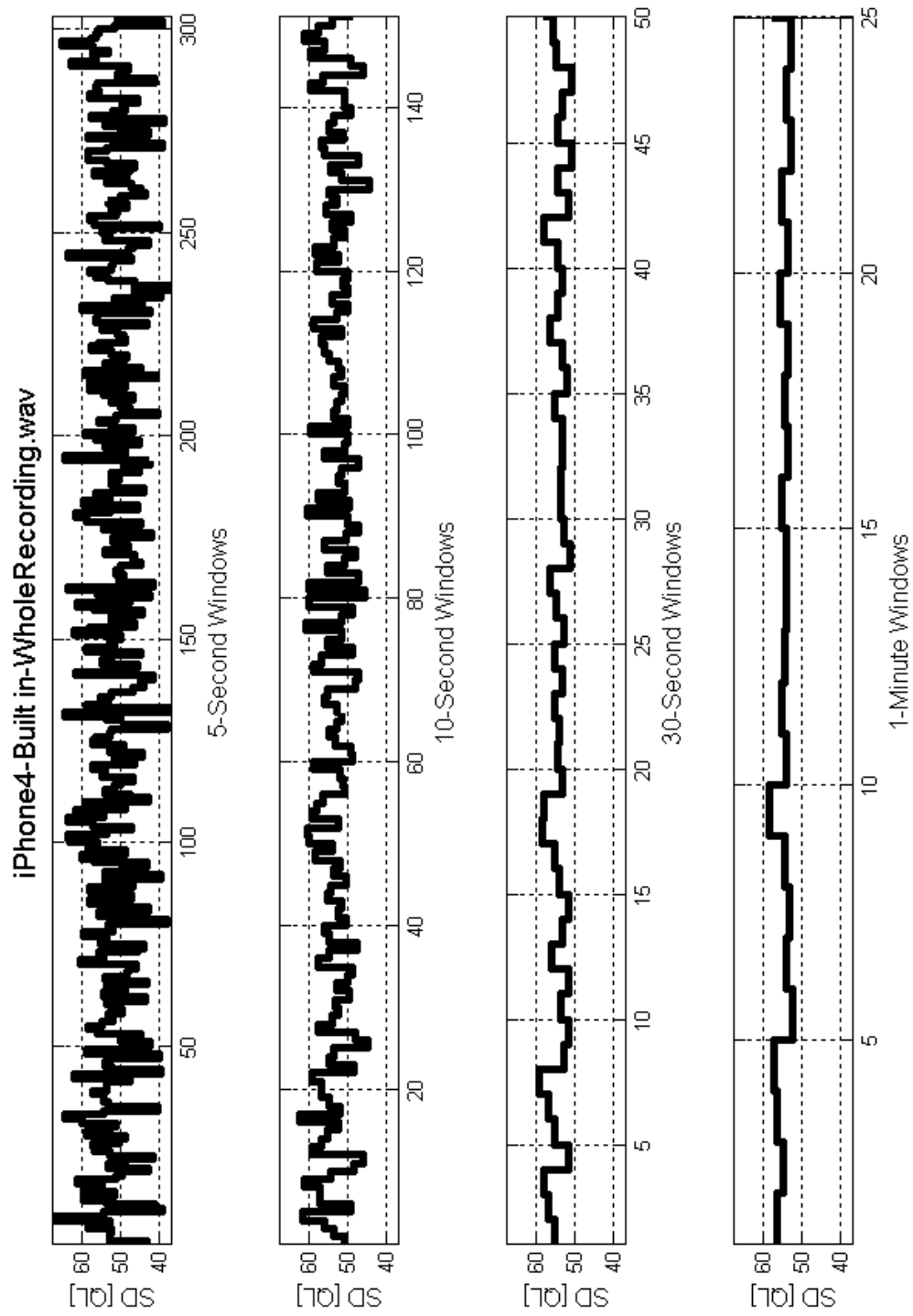


Figure 47 - iPhone 4 - Built-In - SD Windows

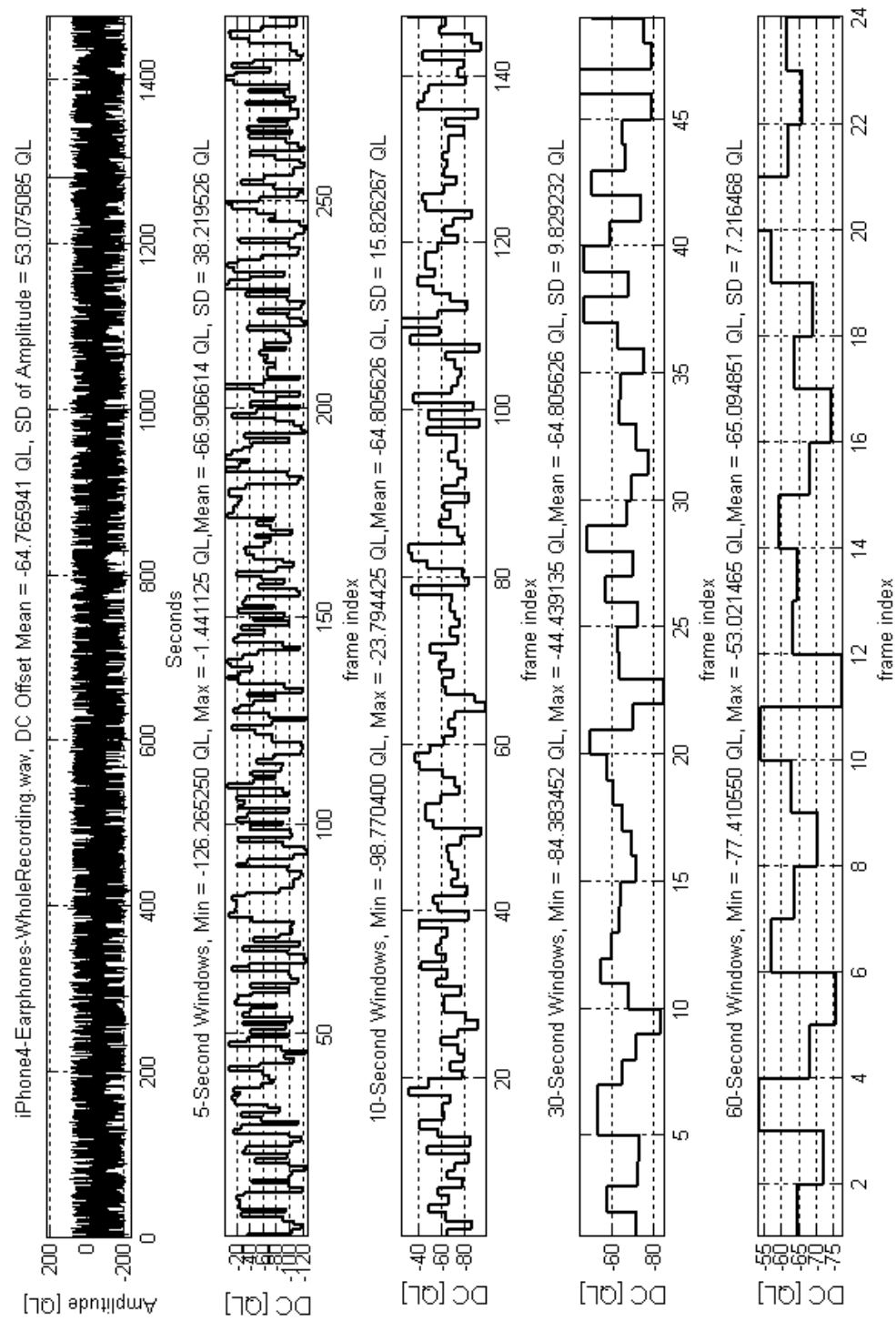


Figure 48 - iPhone 4 - Earphones - DC Offset Plots

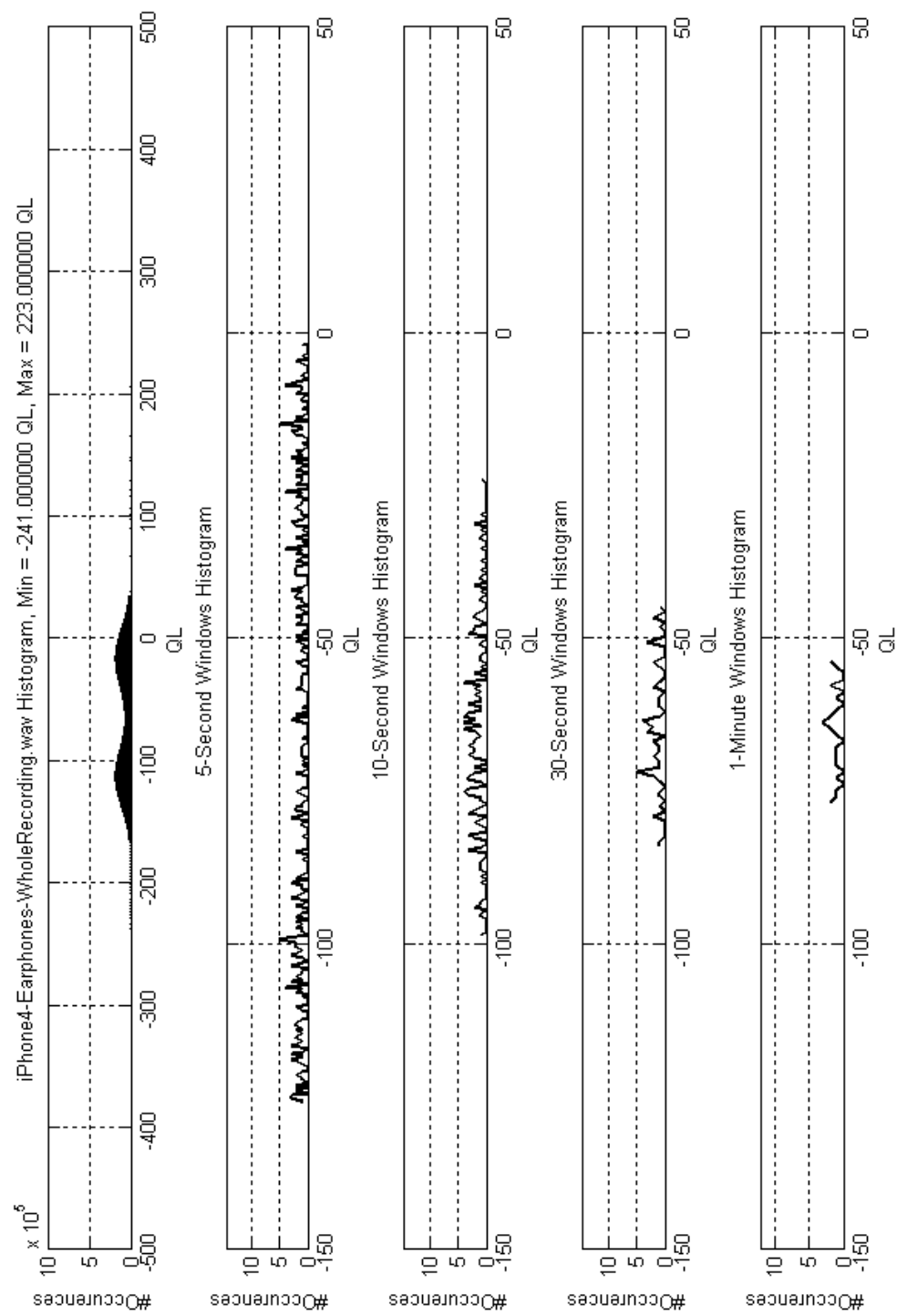


Figure 49 - iPhone 4 - Earphones - Histograms

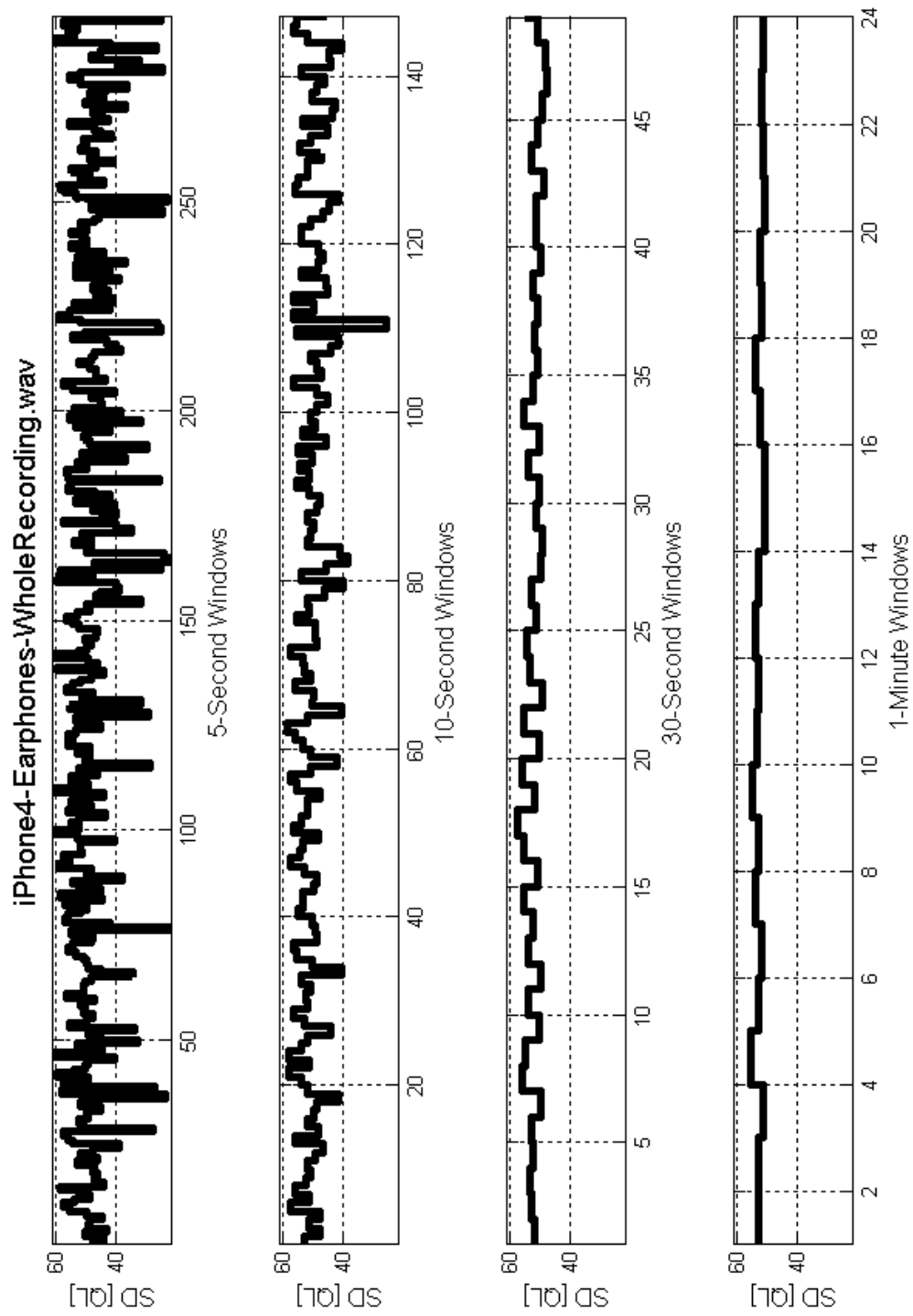


Figure 50 - iPhone 4 - Earphones - SD Windows

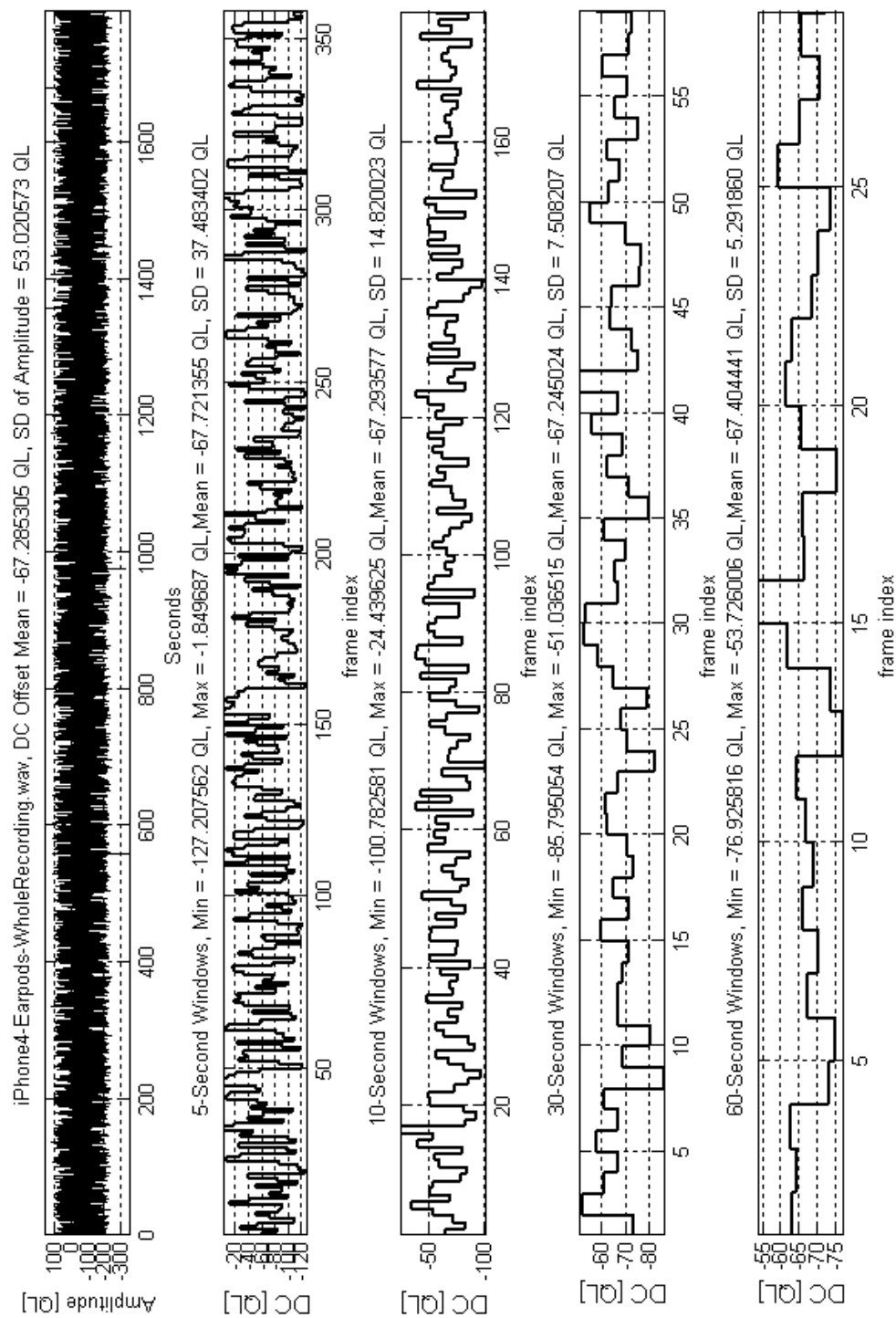


Figure 51 - iPhone 4 - EarPods - DC Offset Plots

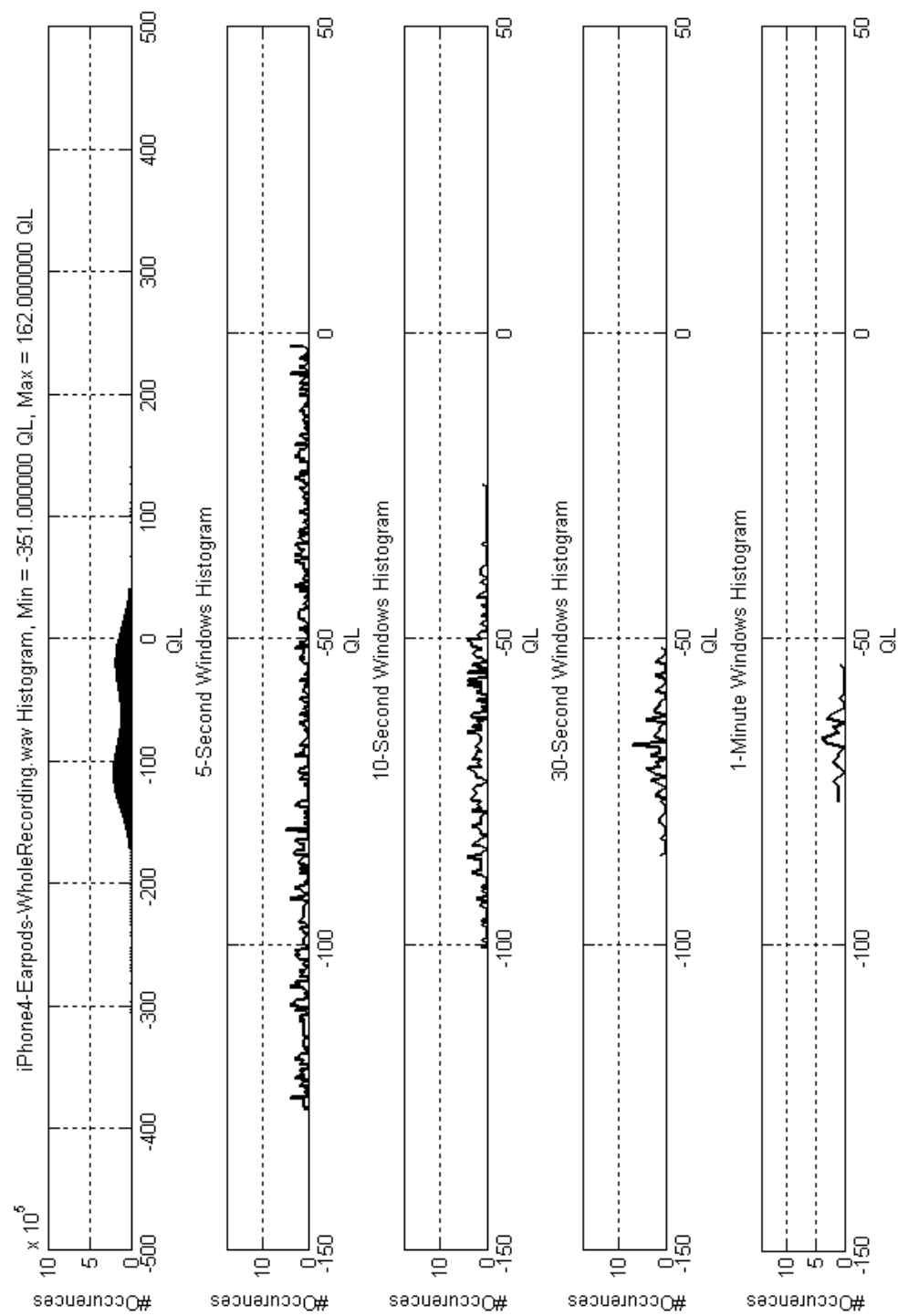


Figure 52 - iPhone 4 - EarPods - Histograms

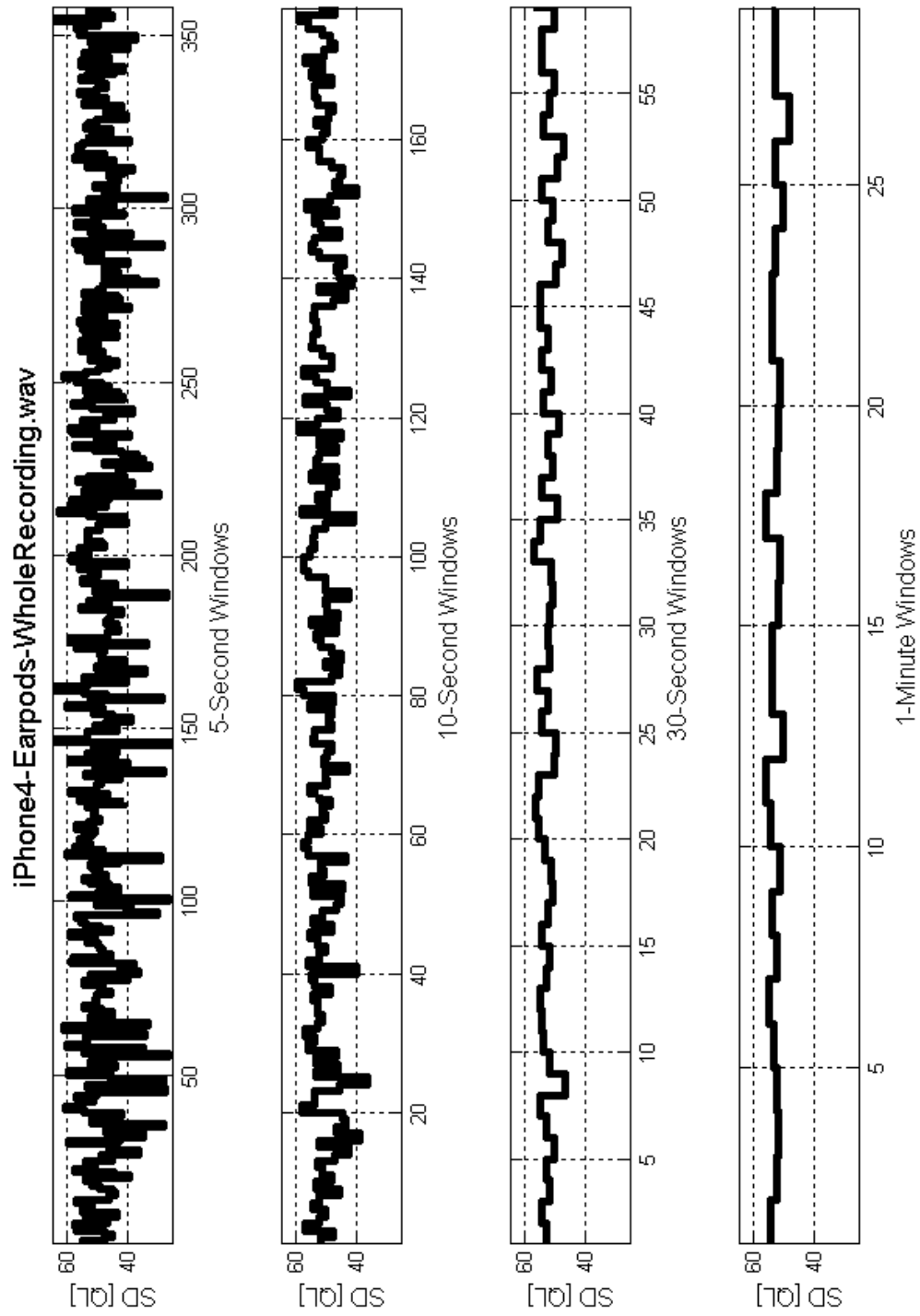


Figure 53 - iPhone 4 - EarPods - SD Windows

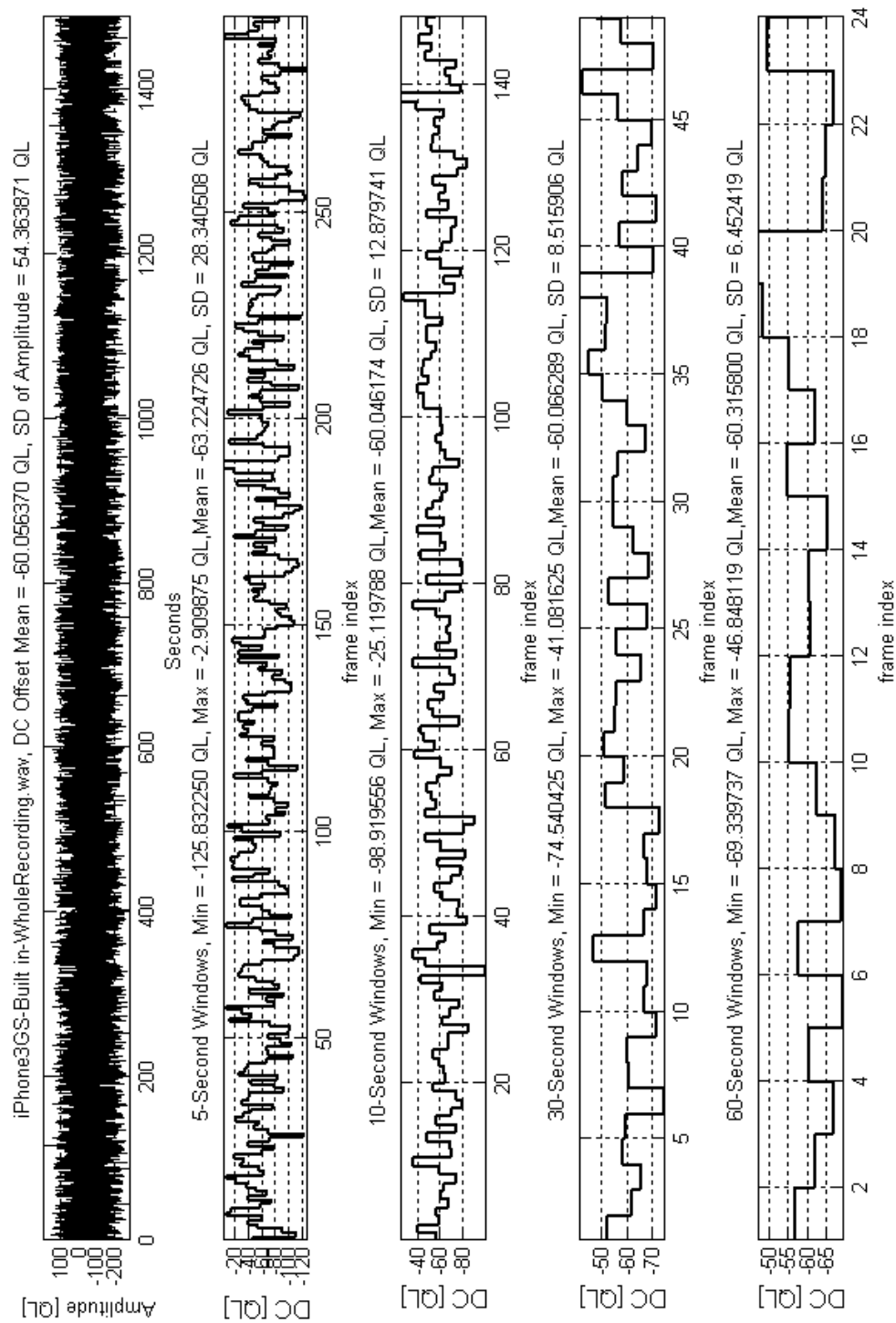


Figure 54 - iPhone 3GS - Built-In - DC Offset Plots

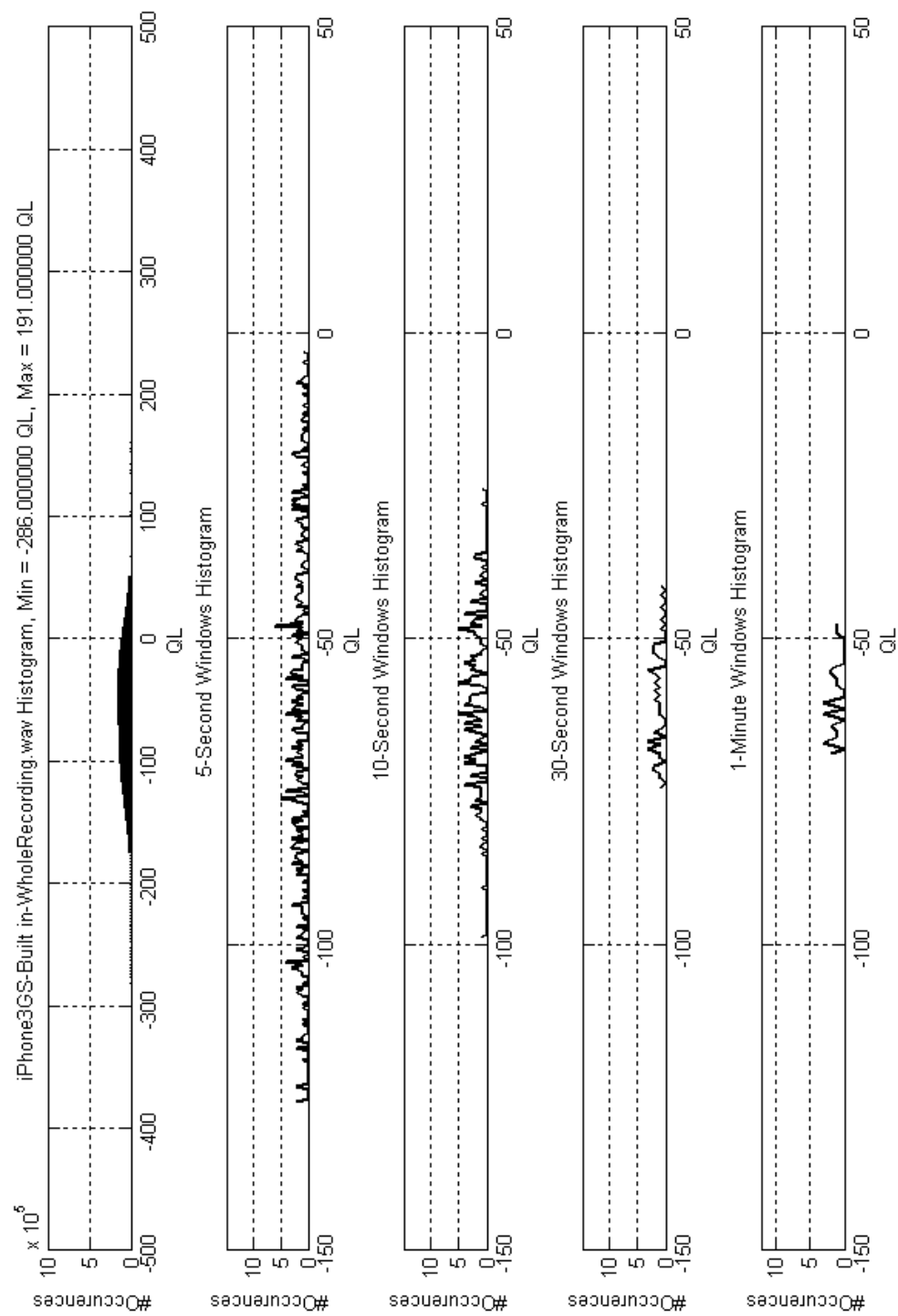


Figure 55 - iPhone 3GS - Built-In - Histograms

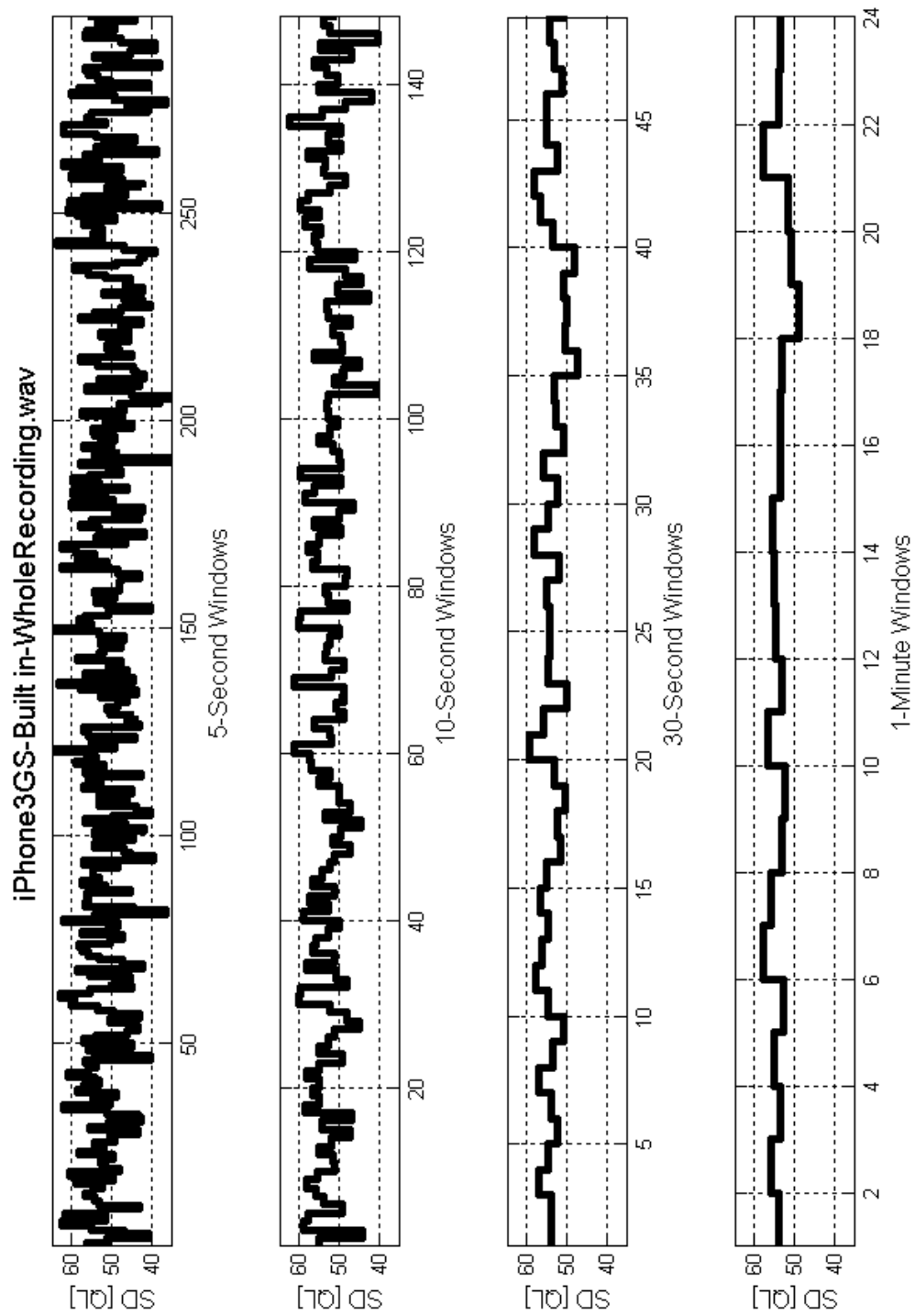


Figure 56 - iPhone 3GS - Built-In - SD Windows

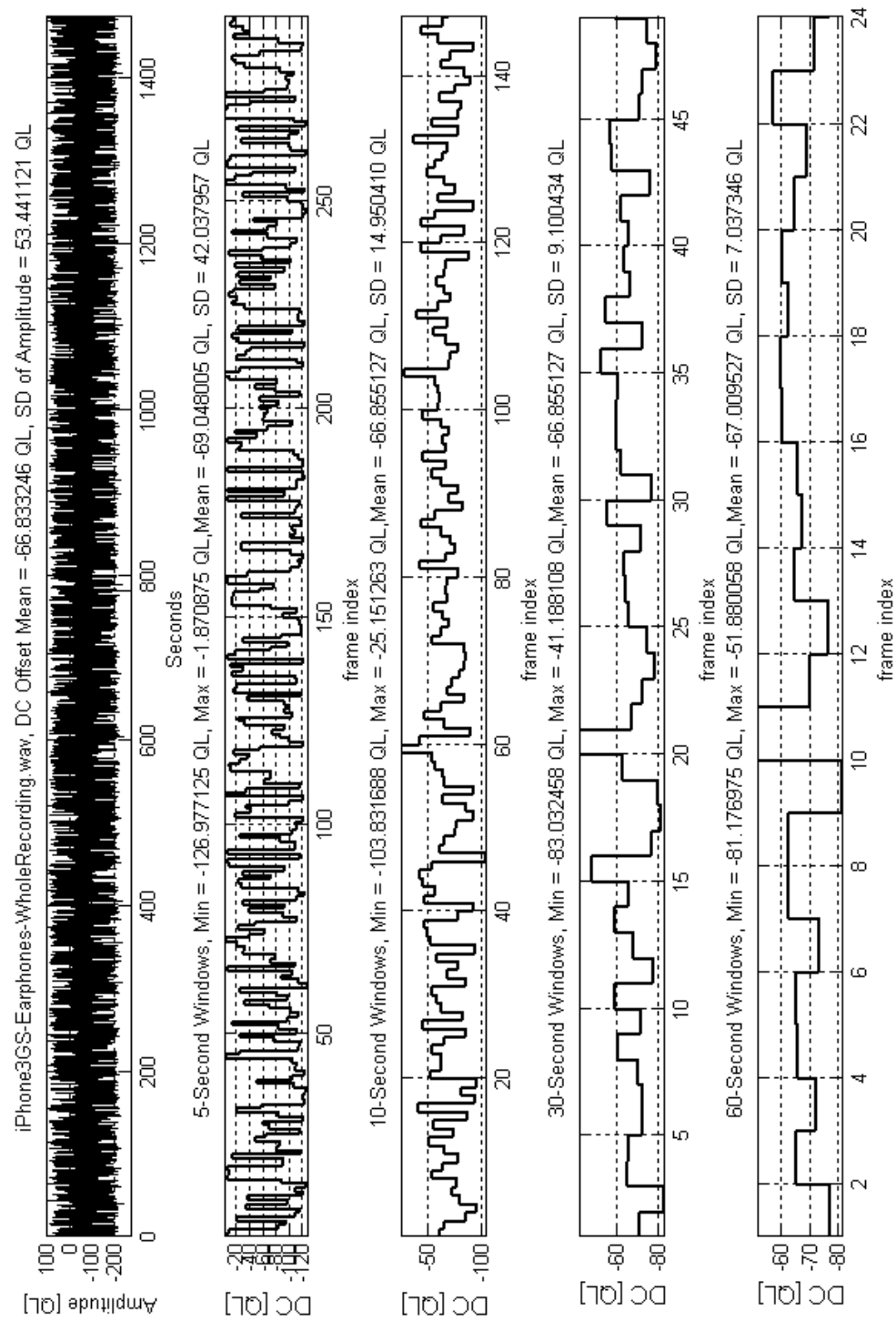


Figure 57 - iPhone 3GS - Earphones - DC Offset Plots

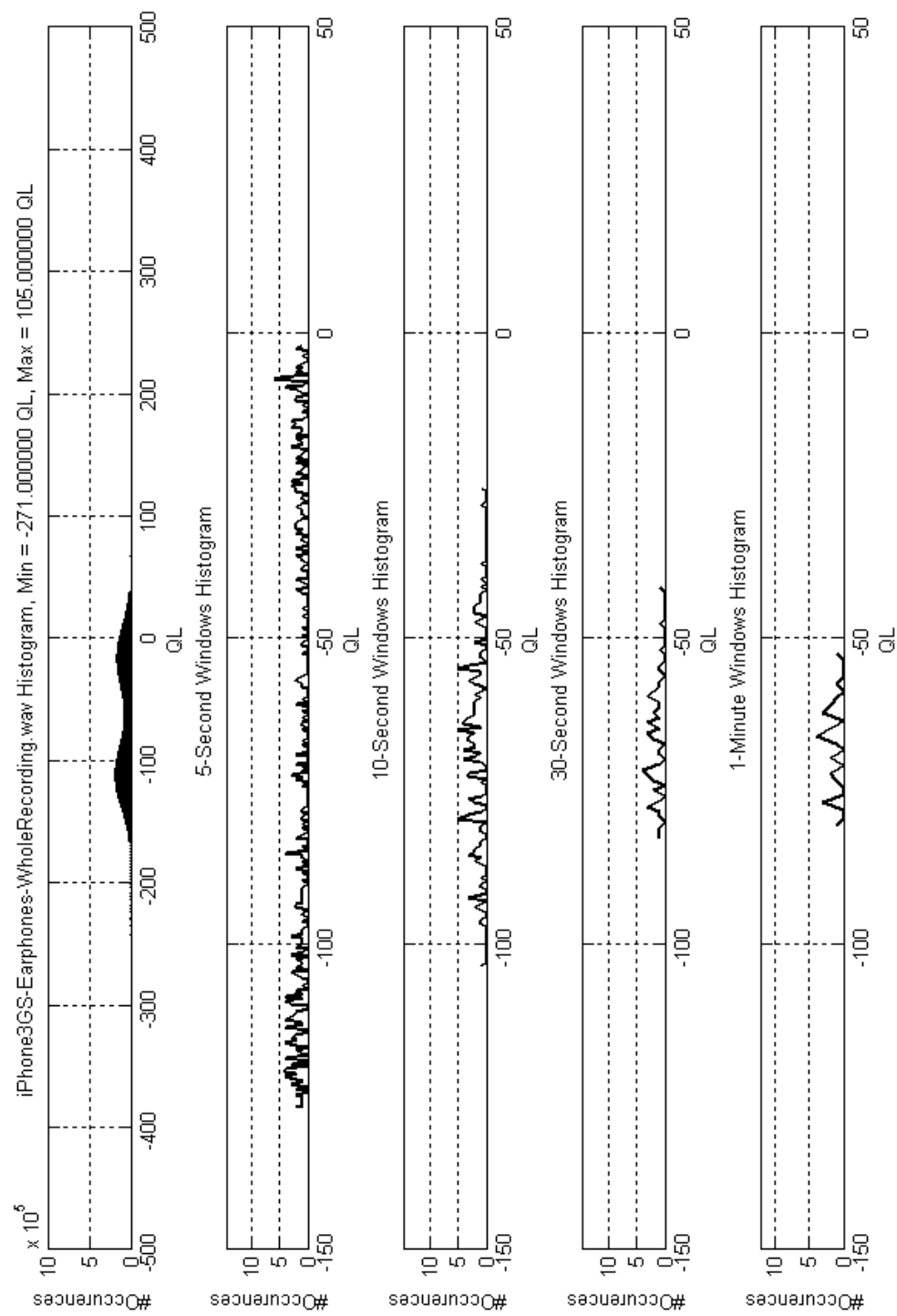


Figure 58 - iPhone 3GS - Earphones - Histograms

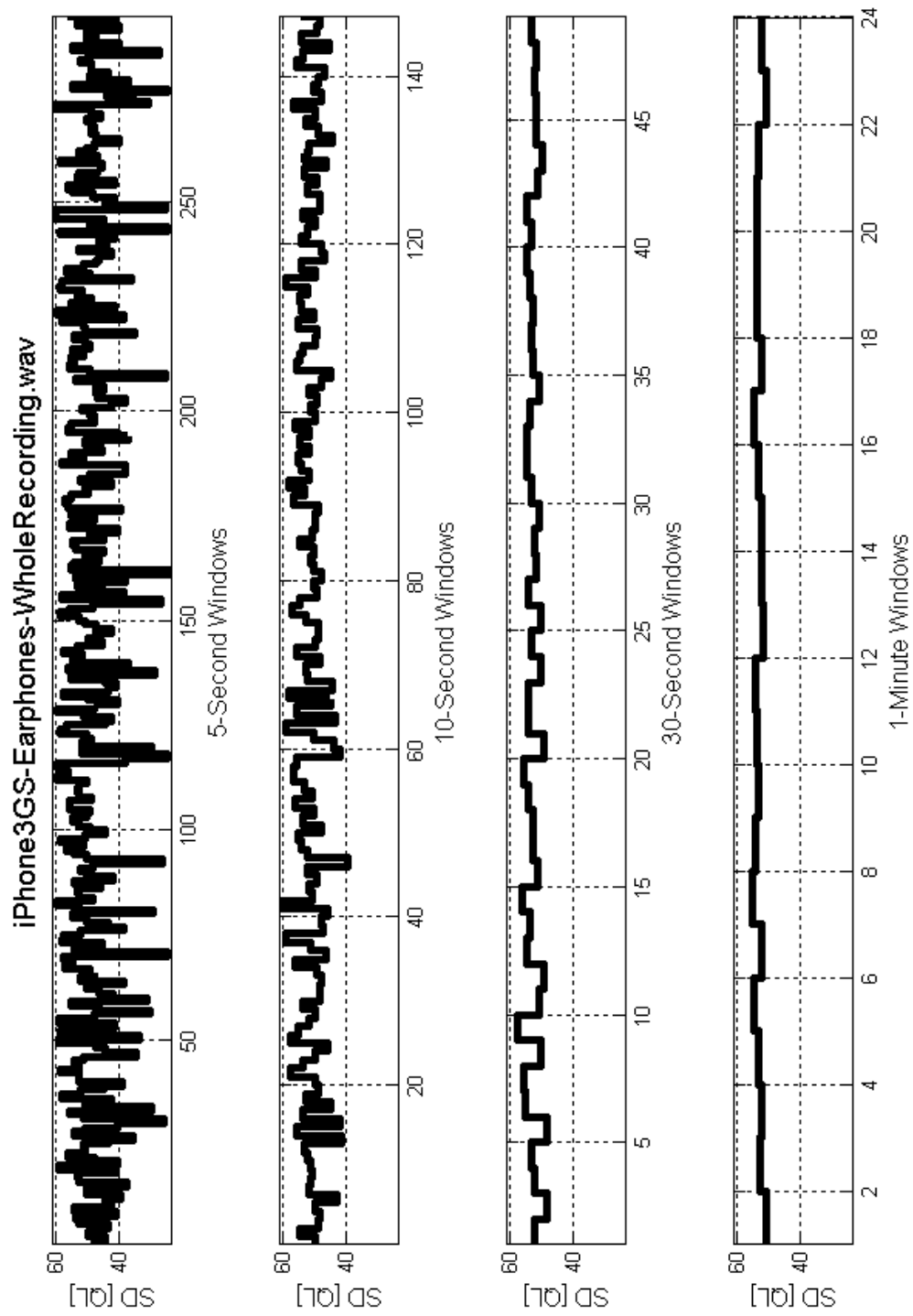


Figure 59 - iPhone 3GS - Earphones - SD Windows

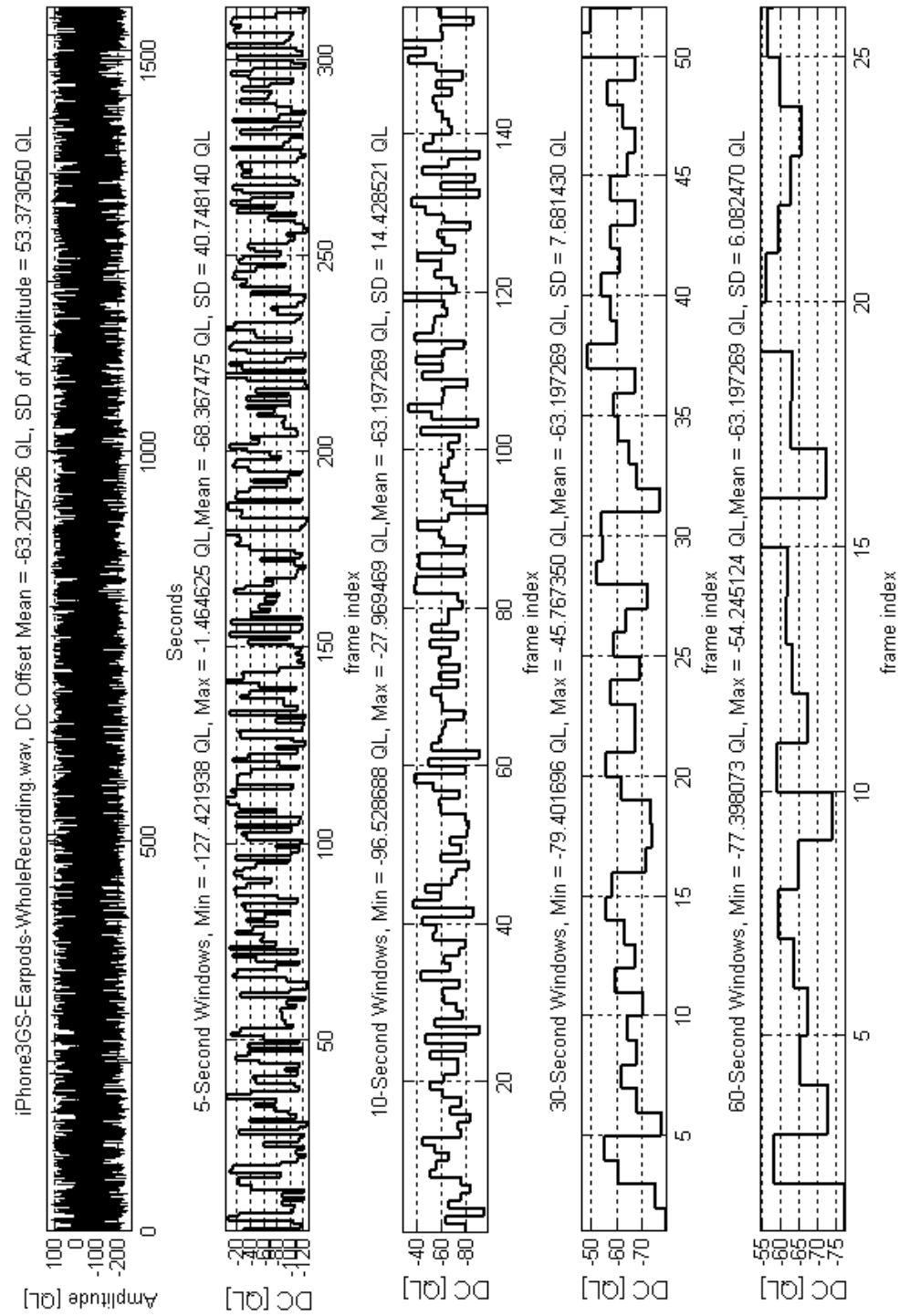


Figure 60 - iPhone 3GS - EarPods - DC Offset Plots

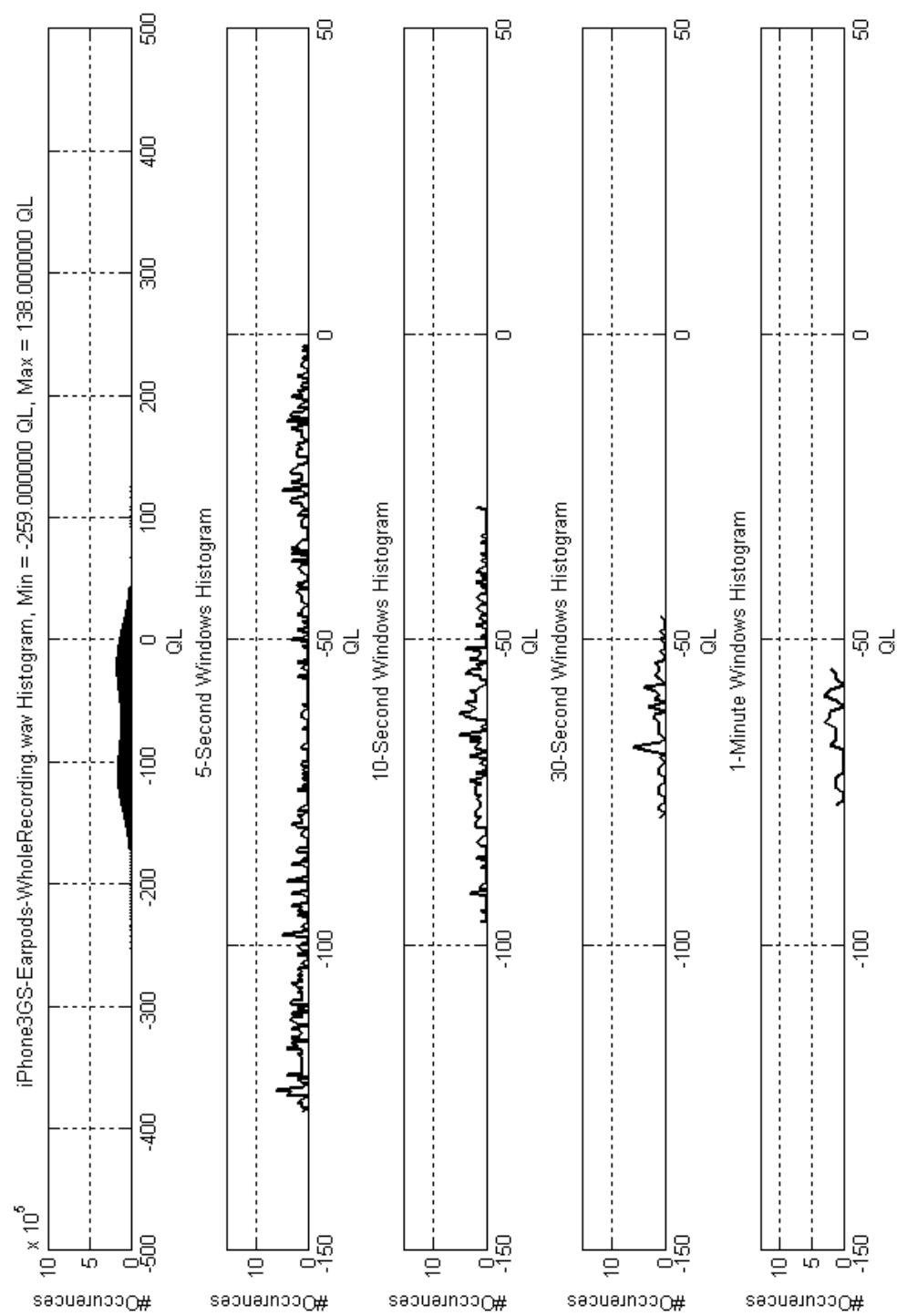


Figure 61 - iPhone 3GS - EarPods - Histograms

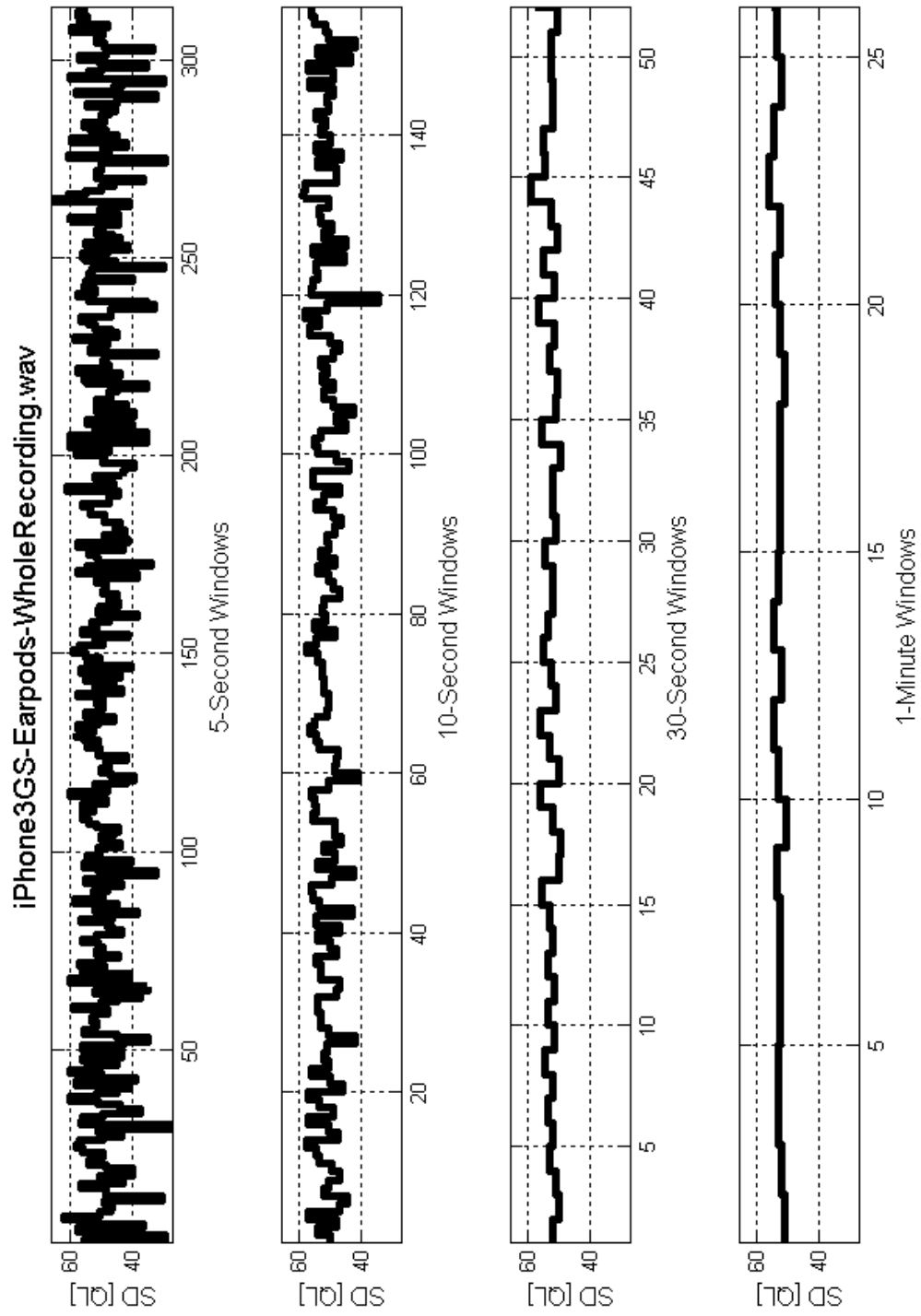


Figure 62 - iPhone 3GS - EarPods - SD Windows

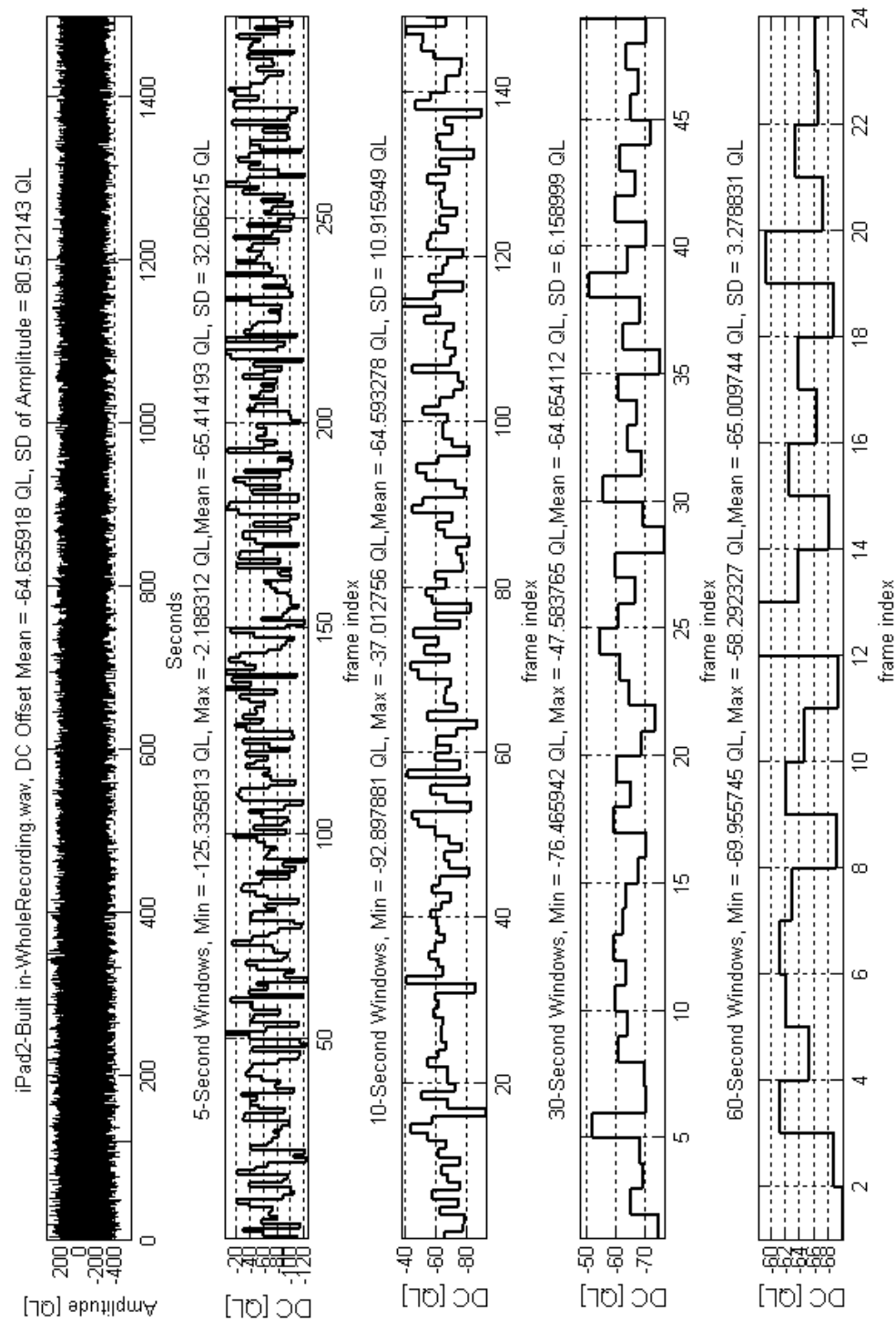


Figure 63 - iPad 2 - Built-In - DC Plots

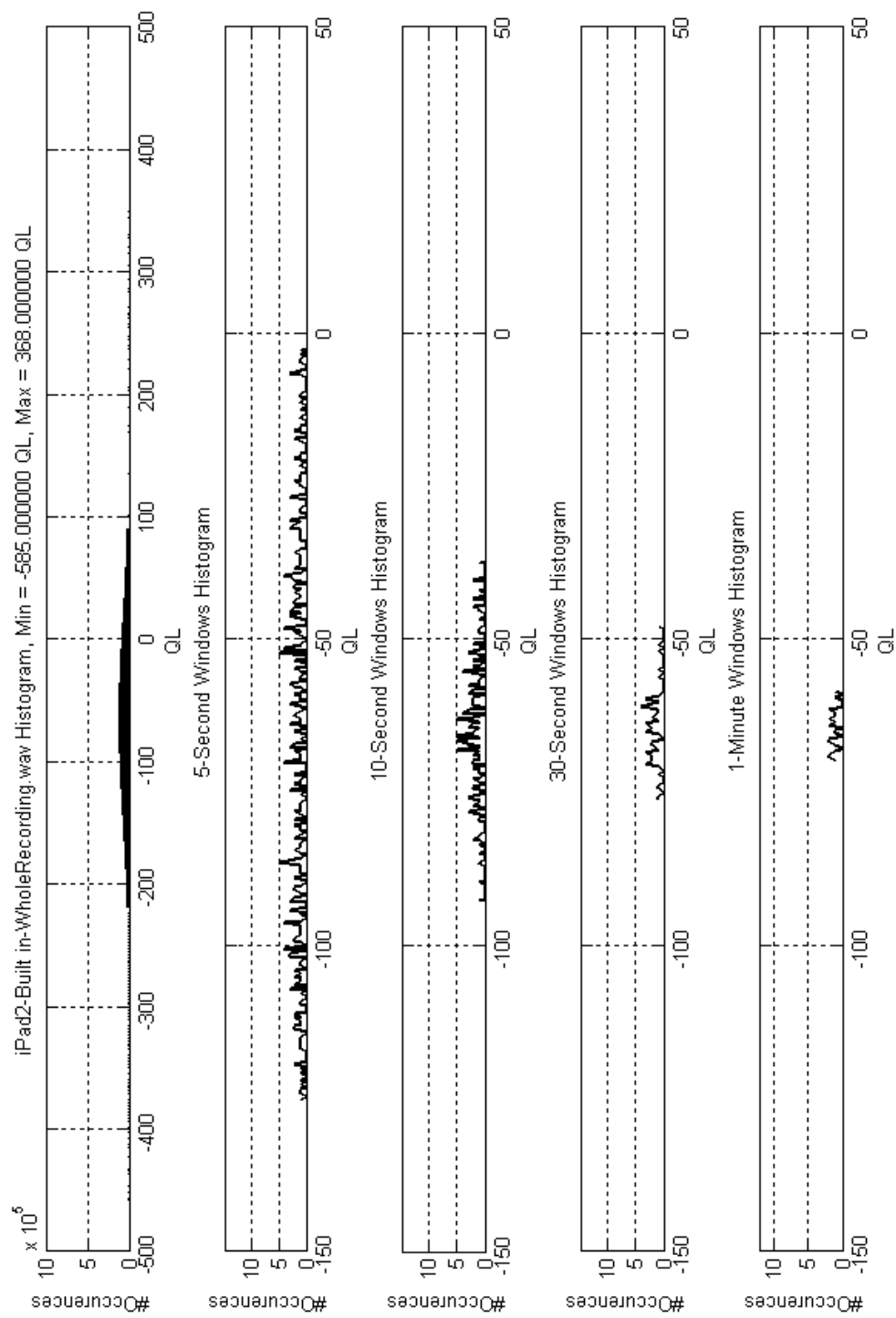


Figure 64 - iPad 2 - Built-In - Histograms

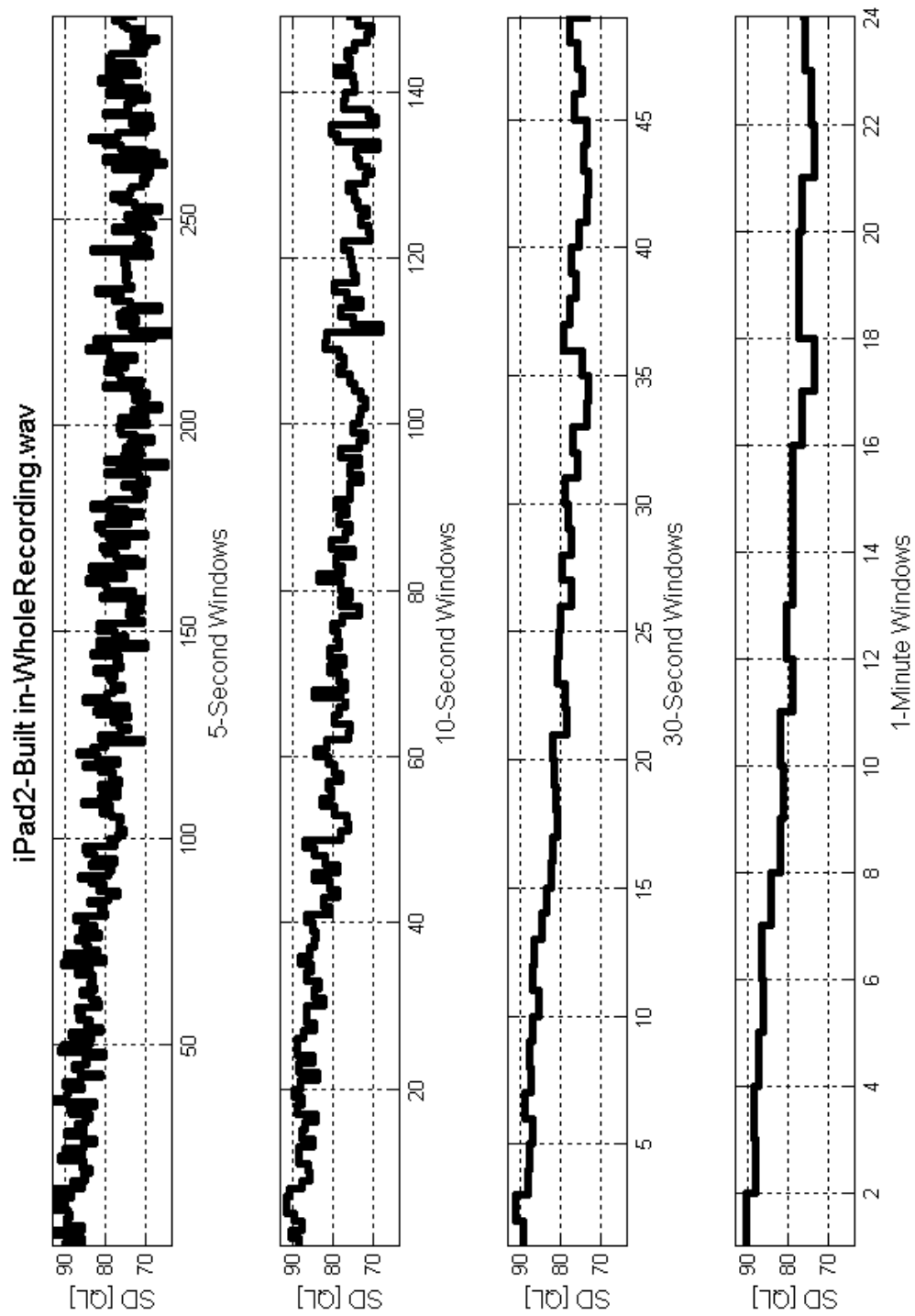


Figure 65 - iPad 2 - Built-In - SD Windows

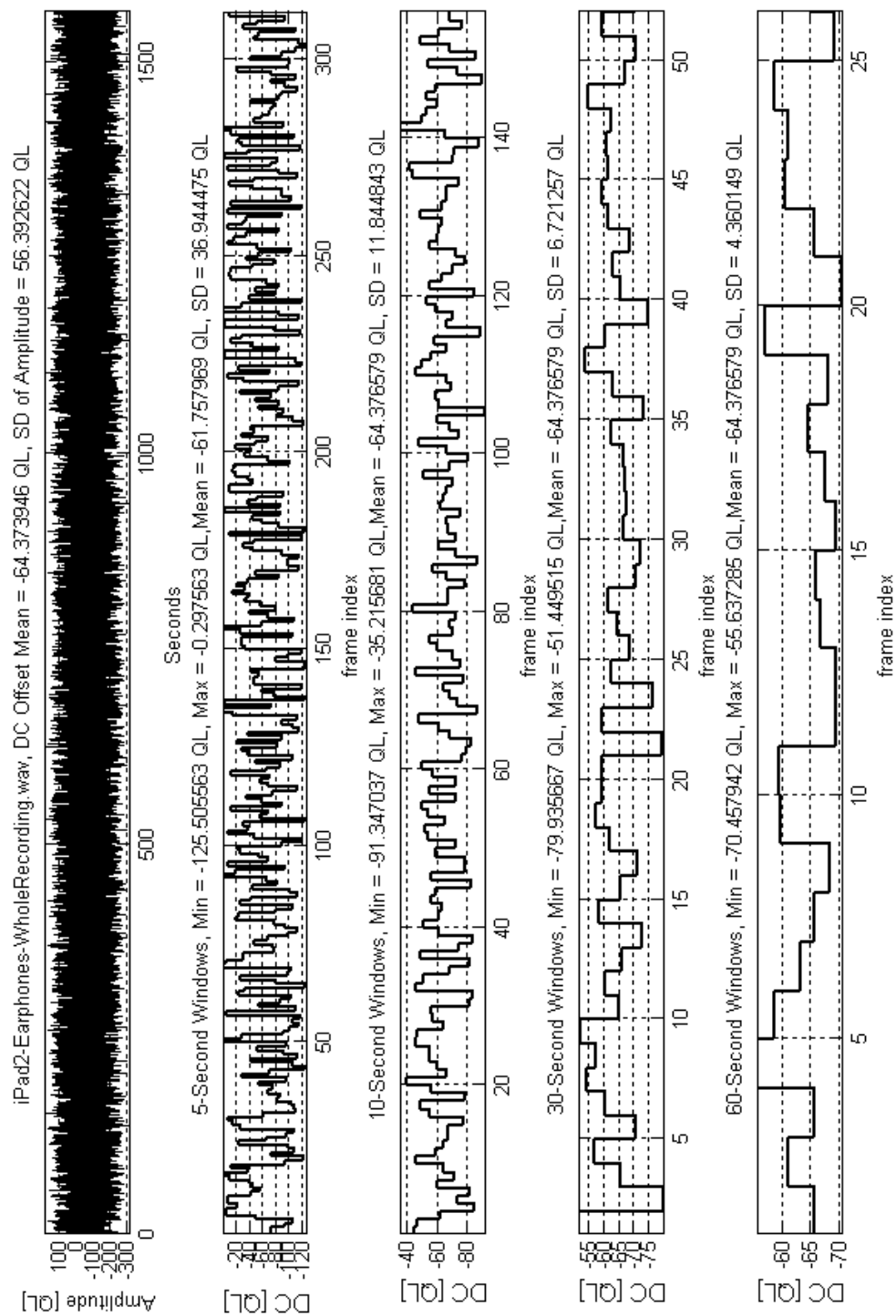


Figure 66 - iPad 2 - Earphones - DC Offset Plots

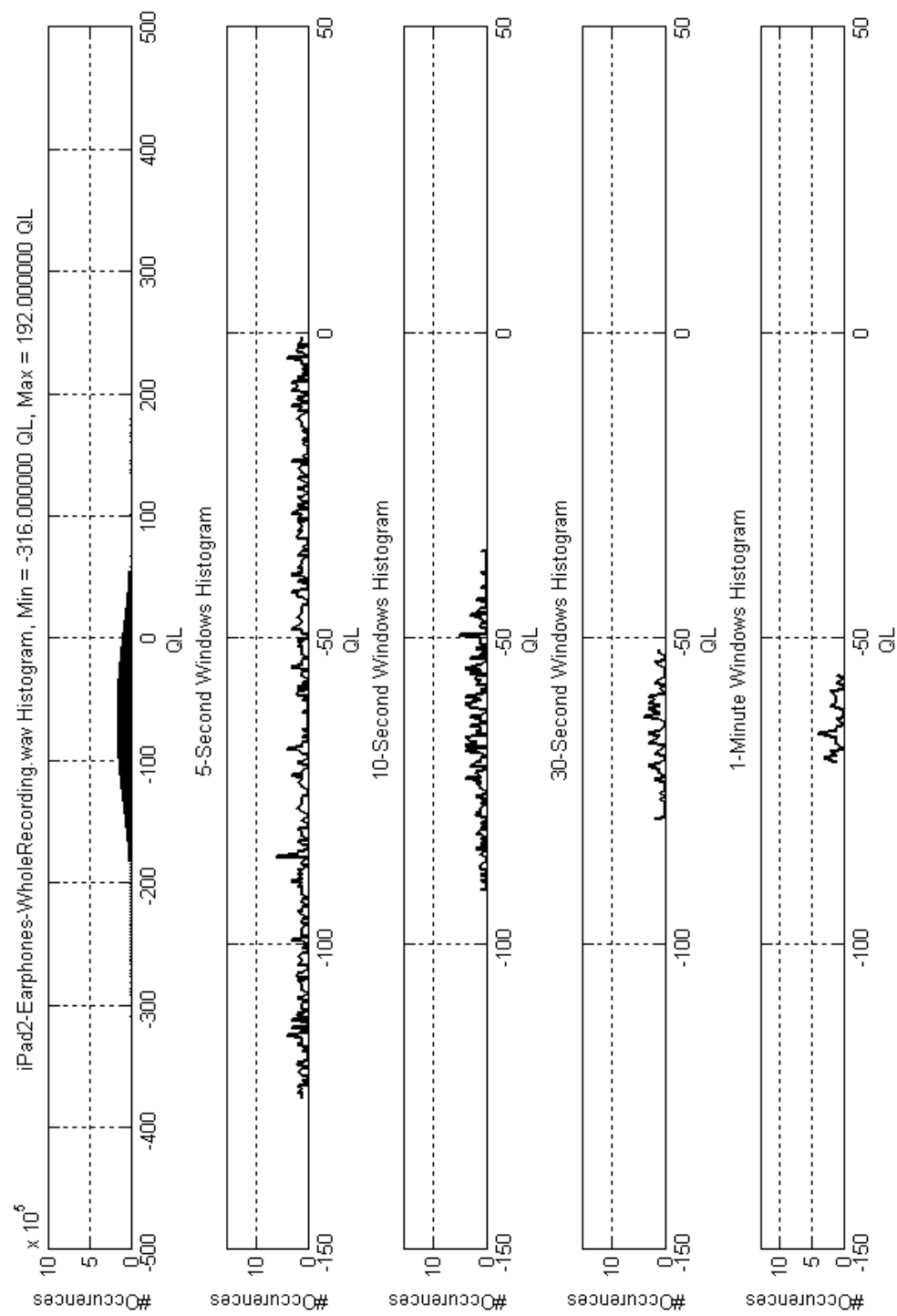


Figure 67 - iPad 2 - Earphones - Histograms

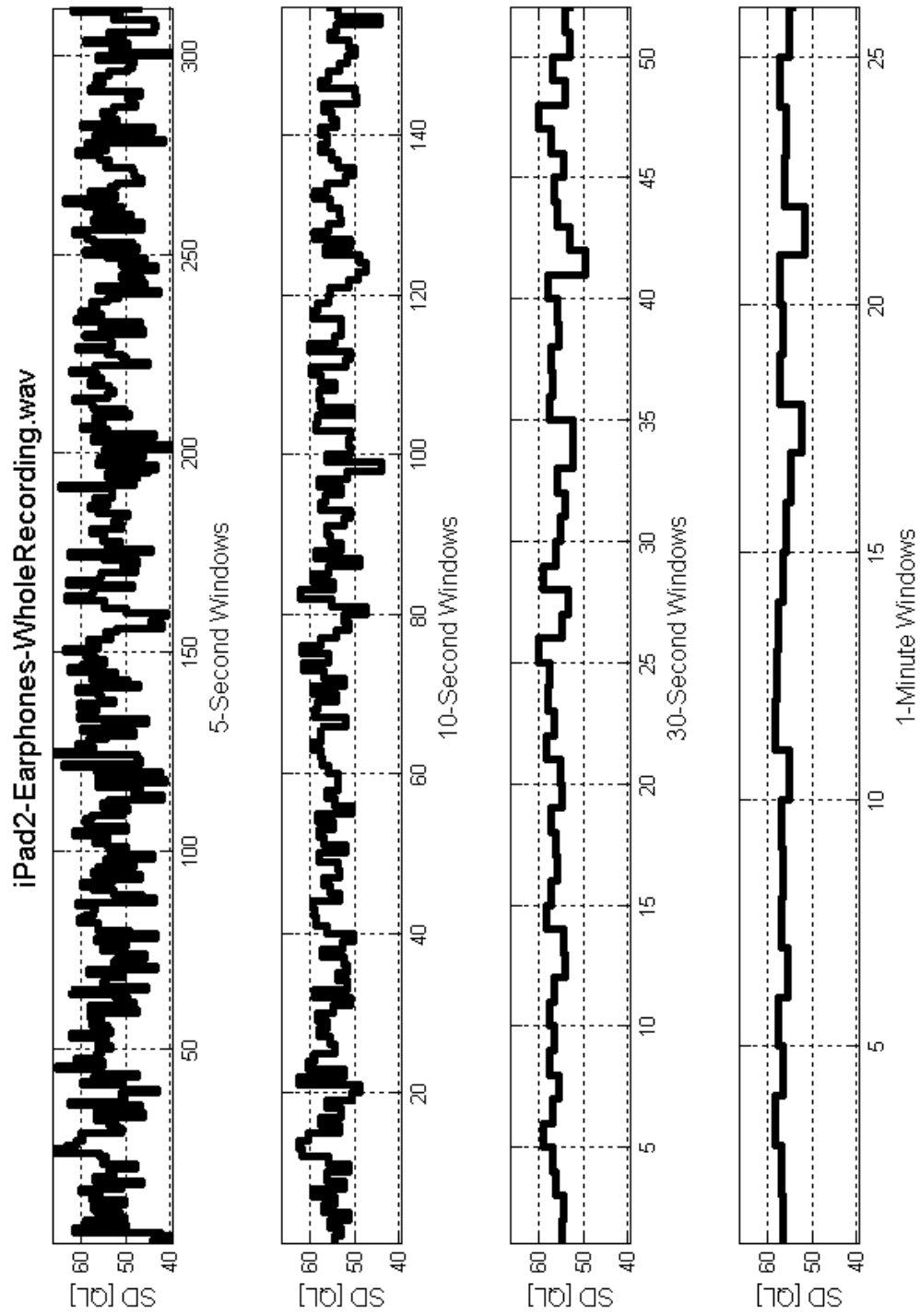


Figure 68 - iPad 2 - Earphones - SD Windows

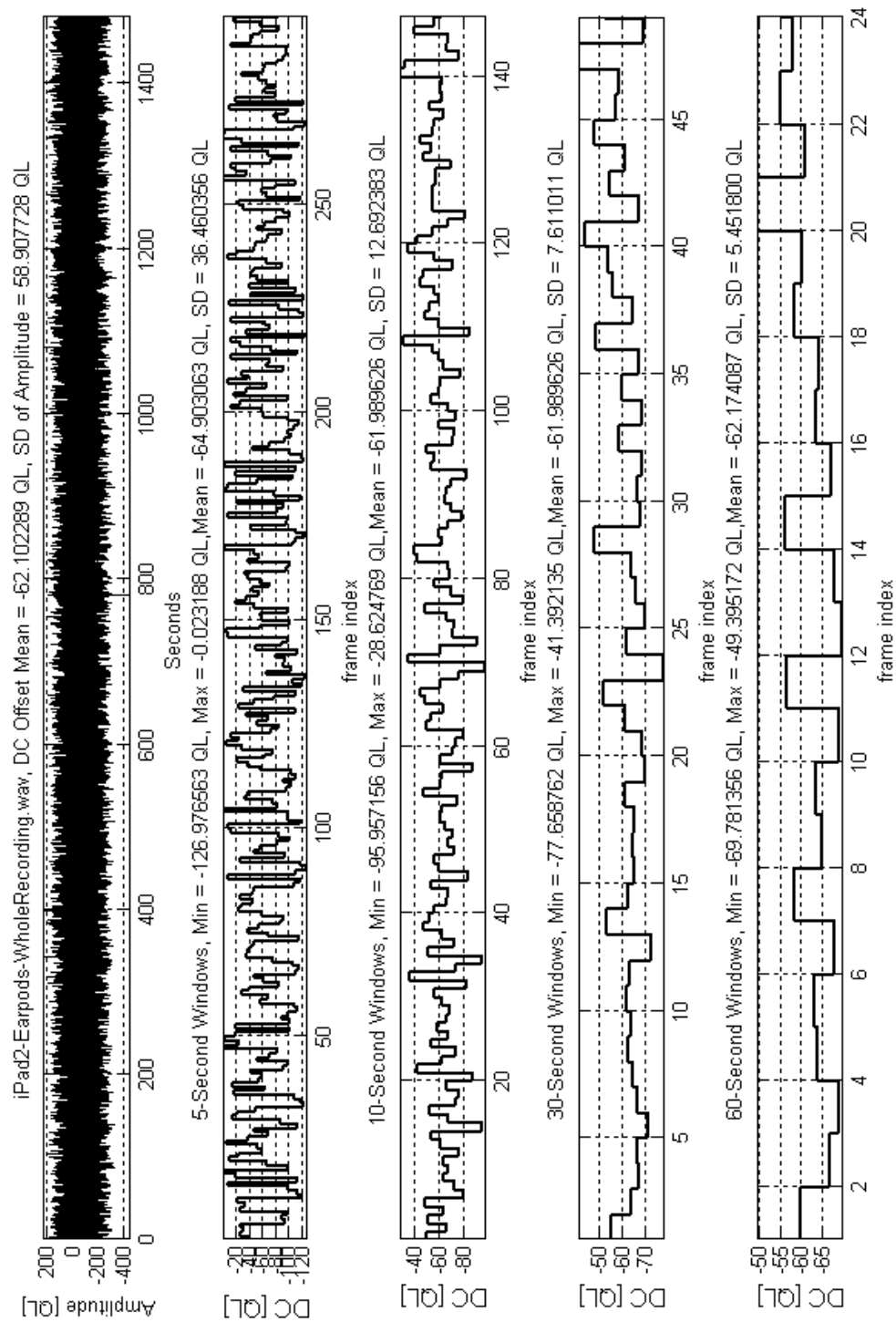


Figure 69 - iPad 2 - EarPods - DC Offset Plots

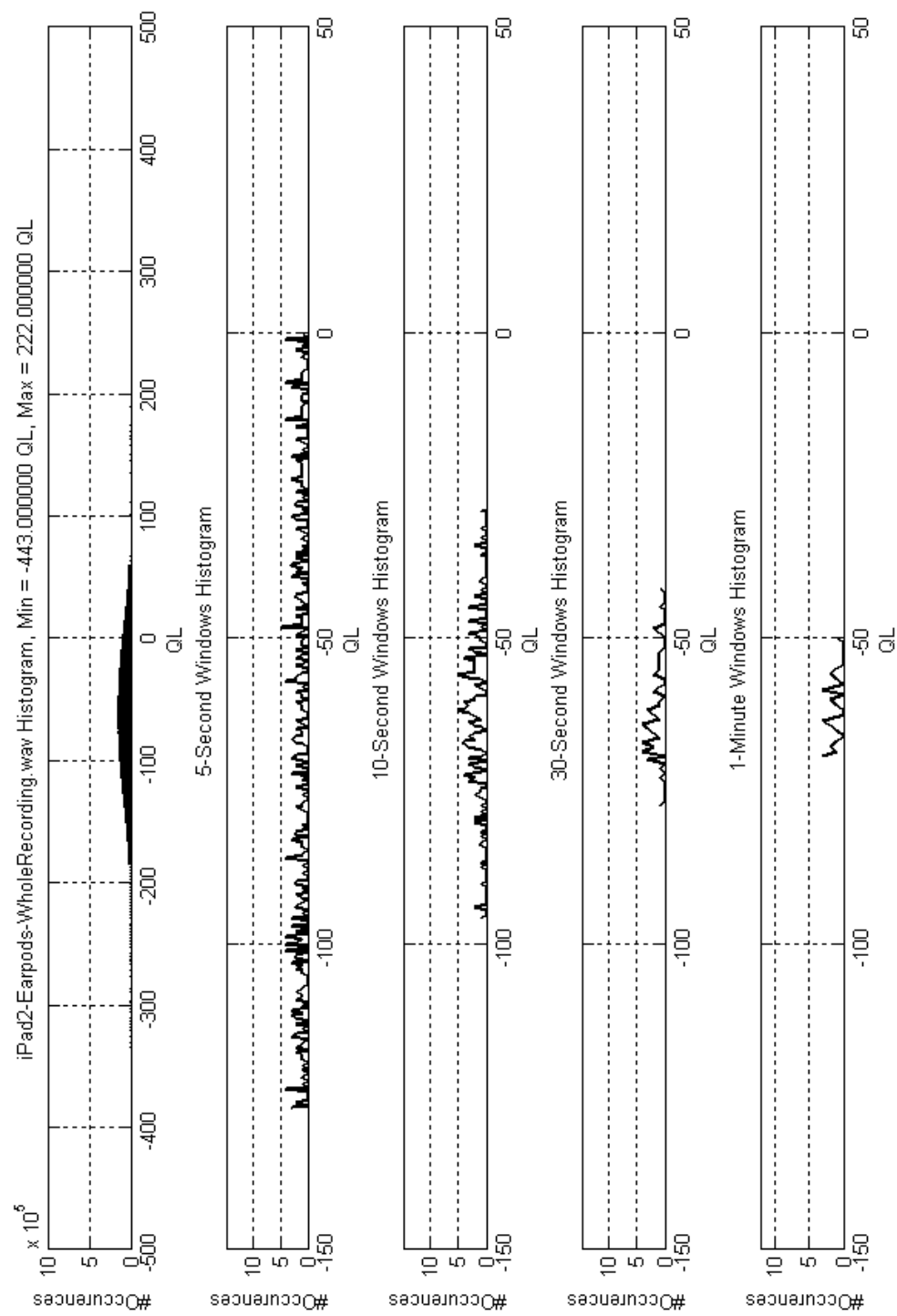


Figure 70 - iPad 2 - EarPods - Histograms

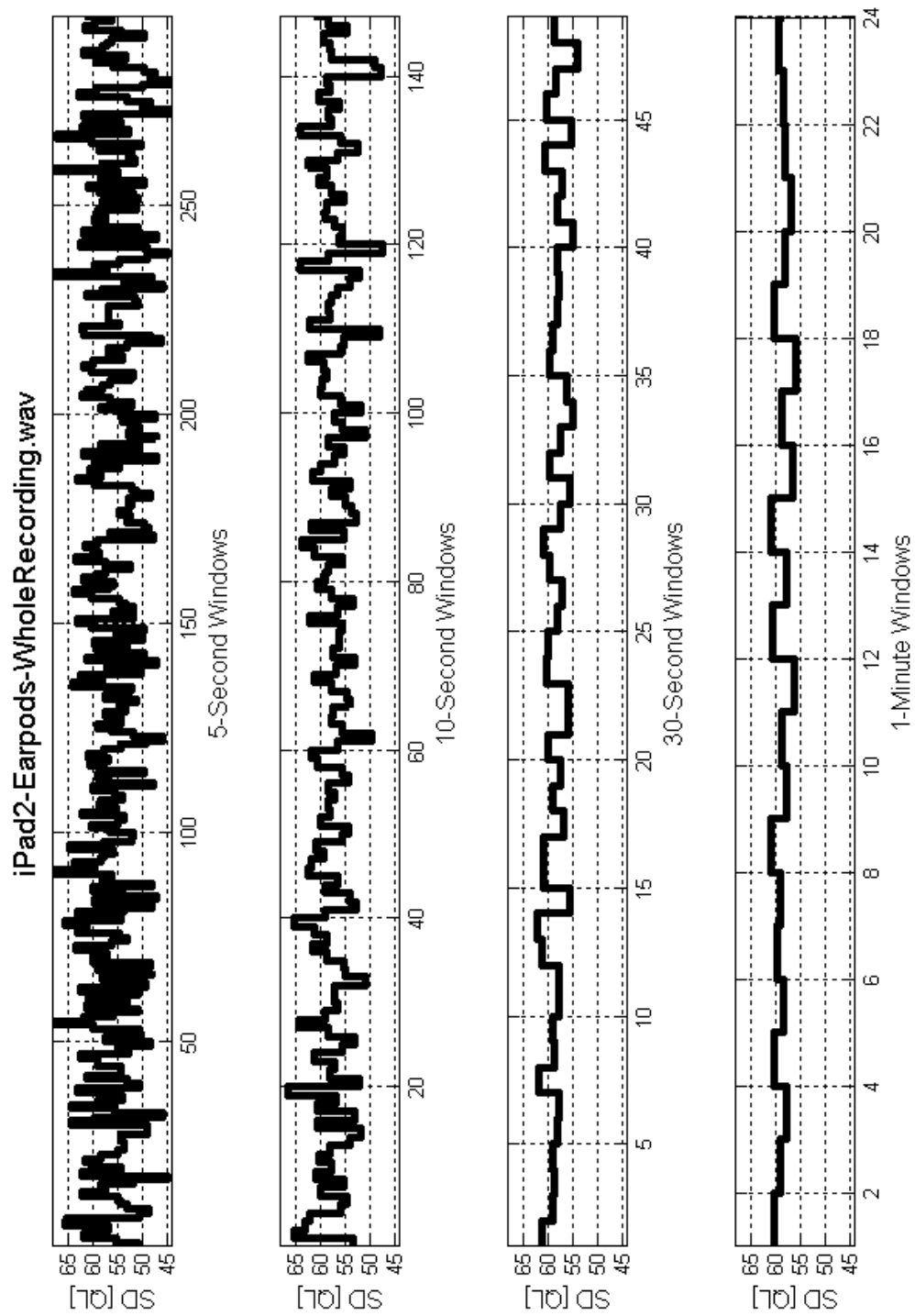


Figure 71 - iPad 2 - EarPods - SD Windows

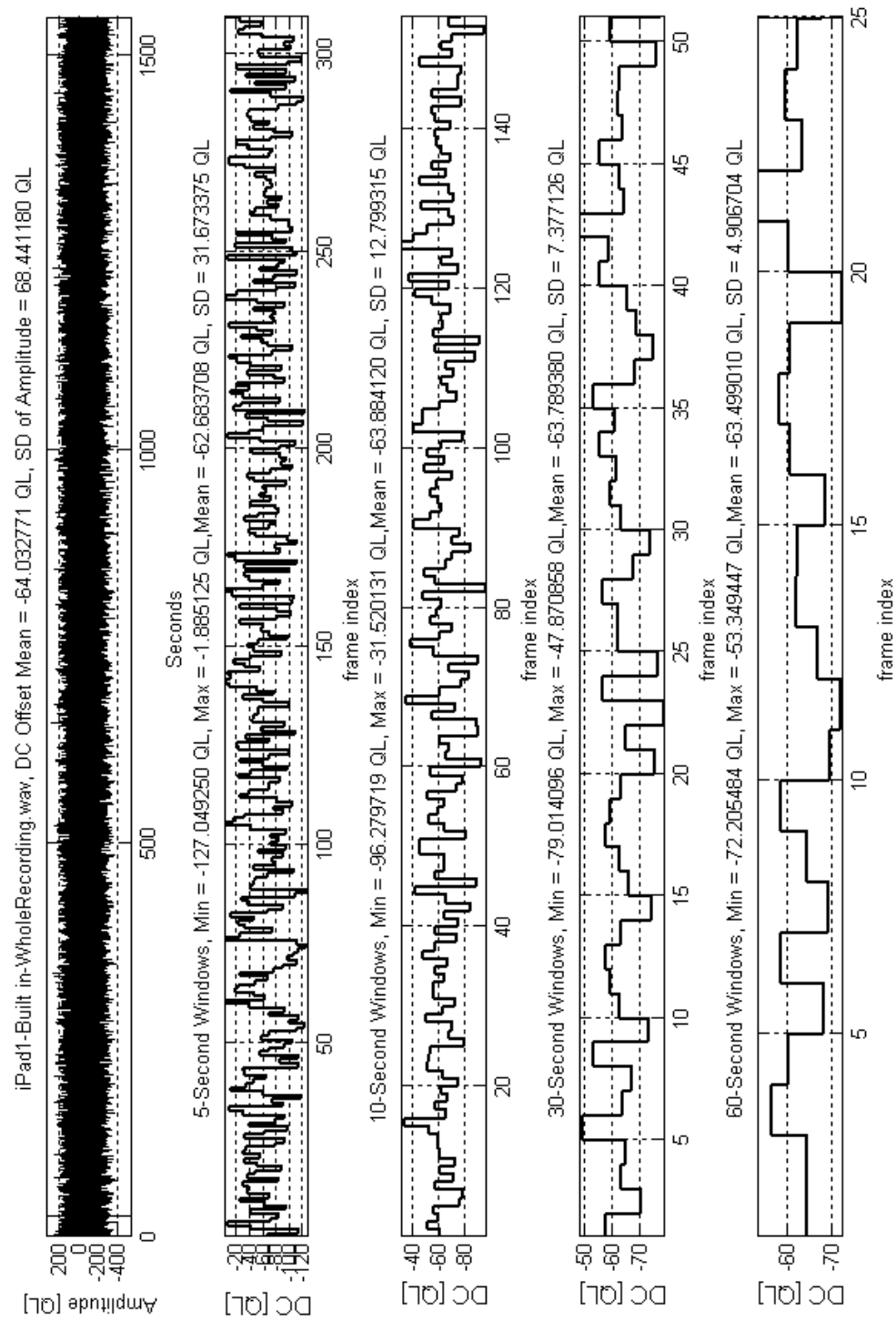


Figure 72 - iPad 1 - Built-In - DC Offset Plots

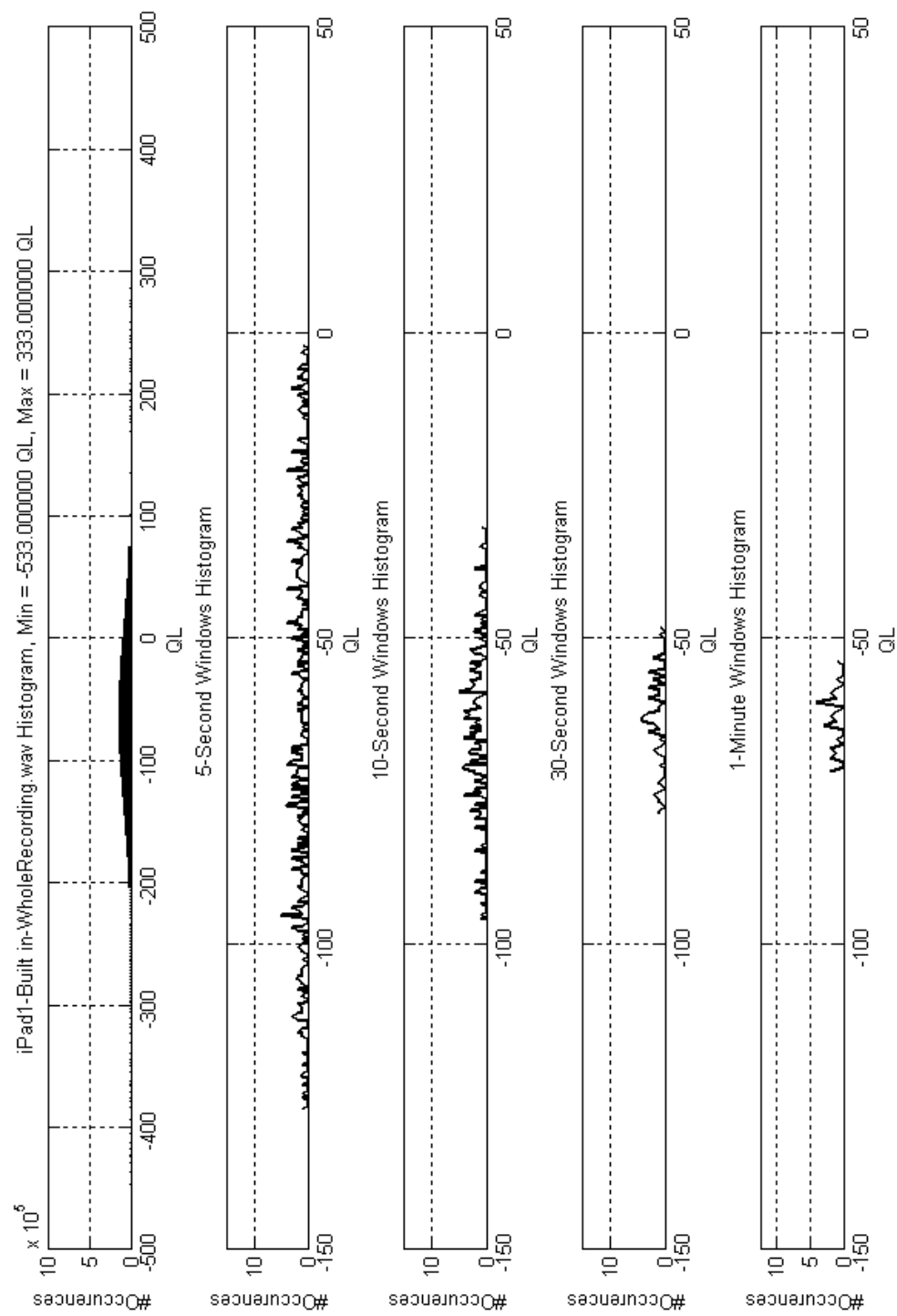


Figure 73 - iPad 2 - Built-In - Histograms

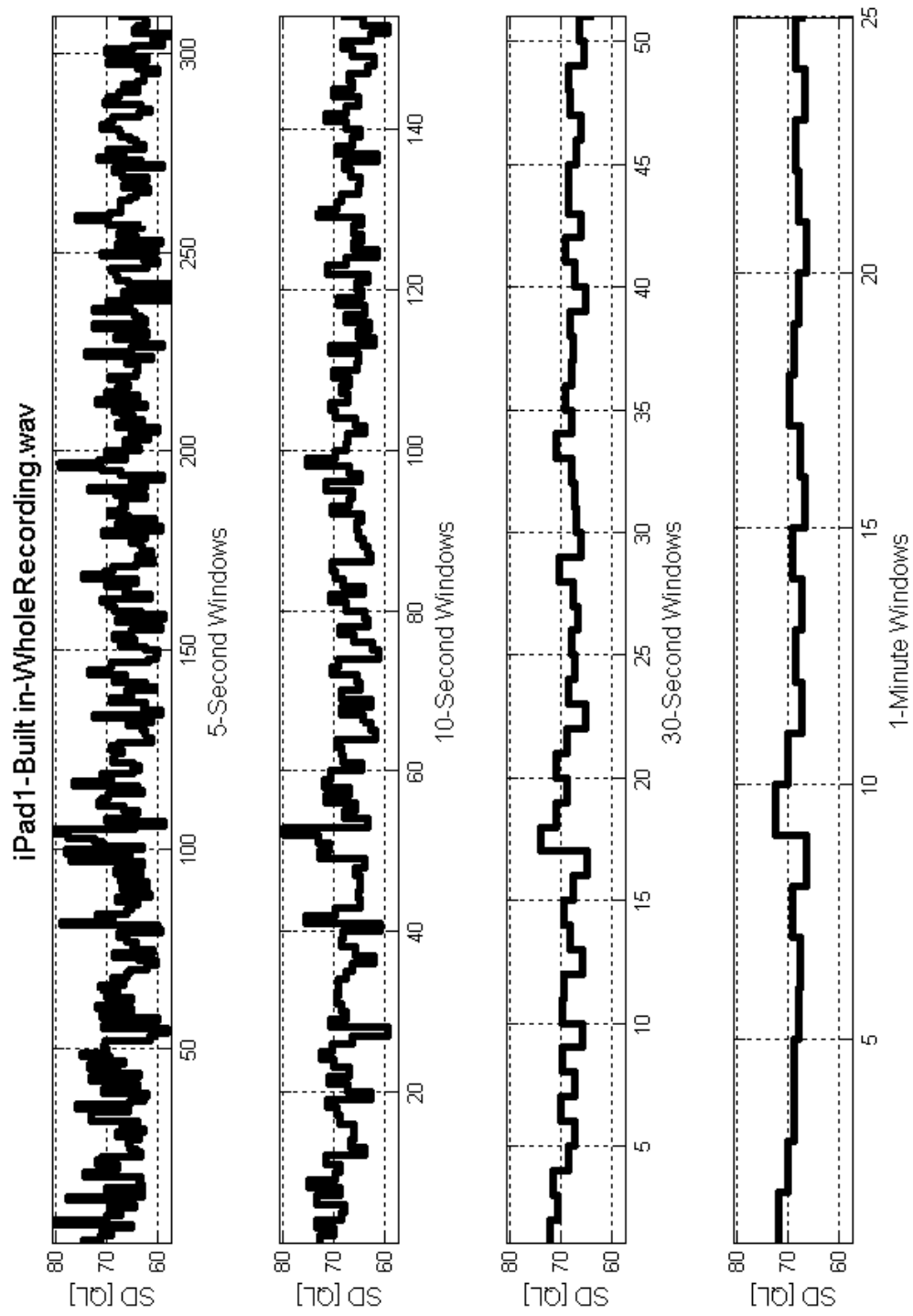


Figure 74 - iPad 2 - Built-In - SD Windows

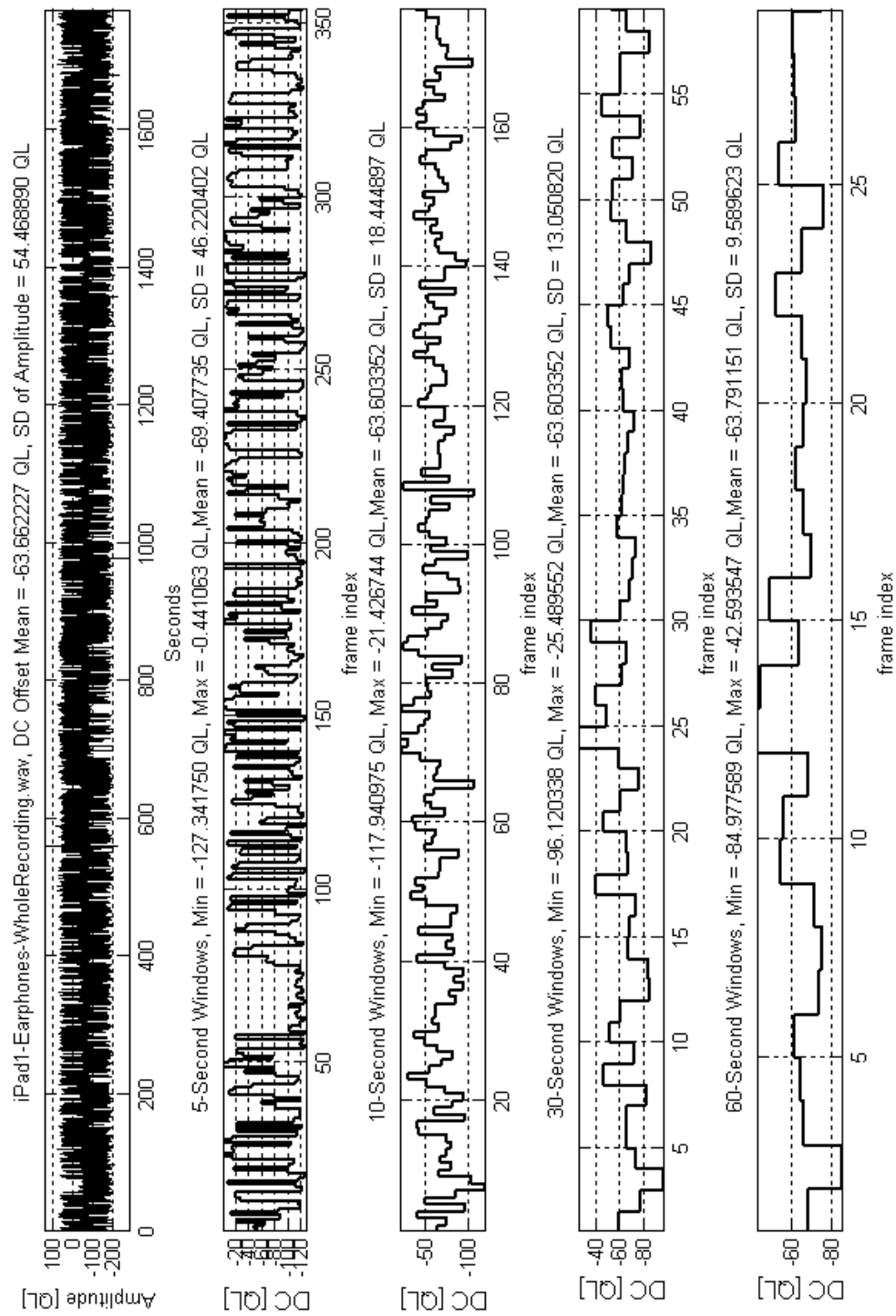


Figure 75 - iPad 2 - Earphones - DC Offset Plots

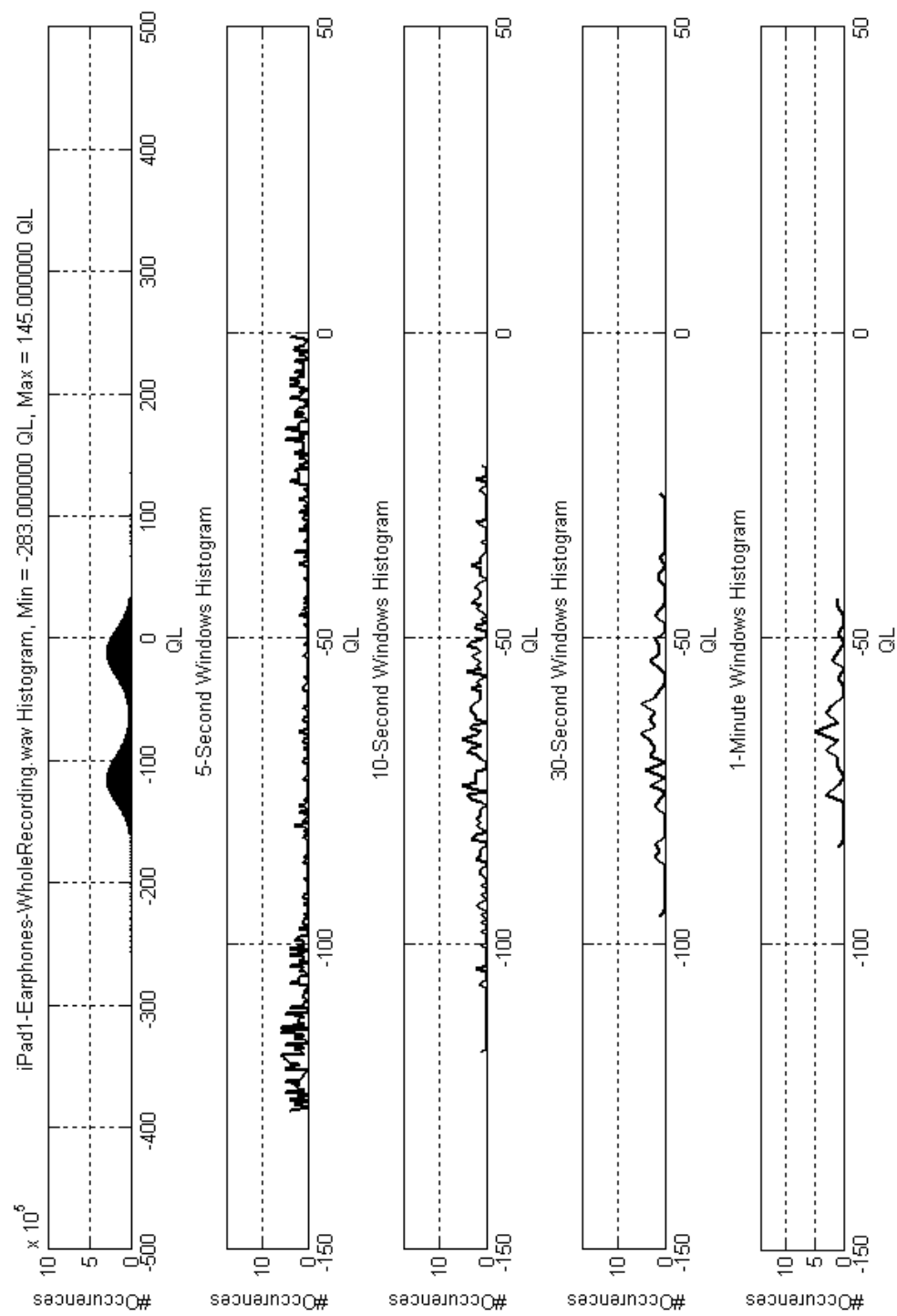


Figure 76 - iPad 2 - Earphones - Histograms

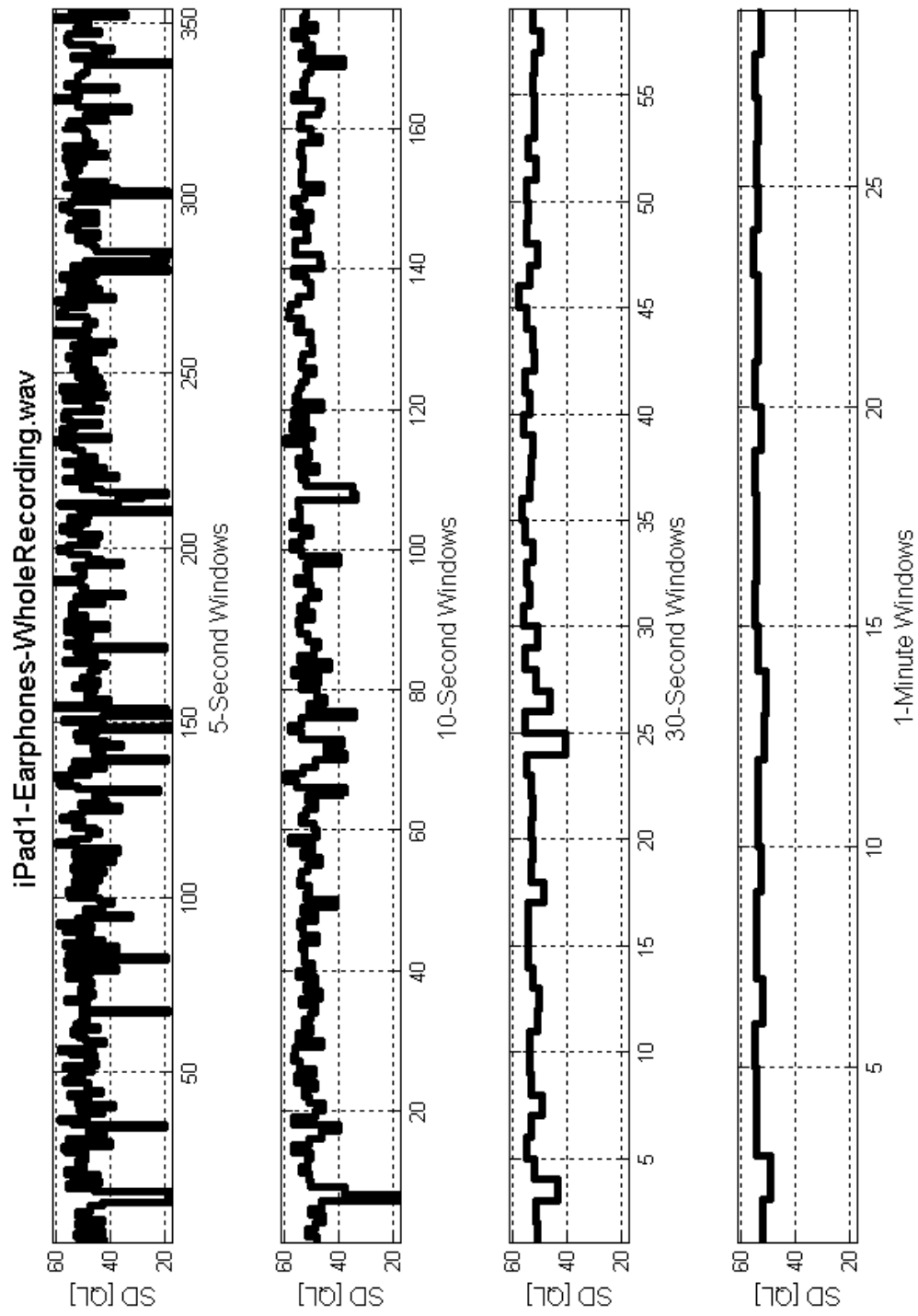


Figure 77 - iPad 2 - Earphones - SD Windows

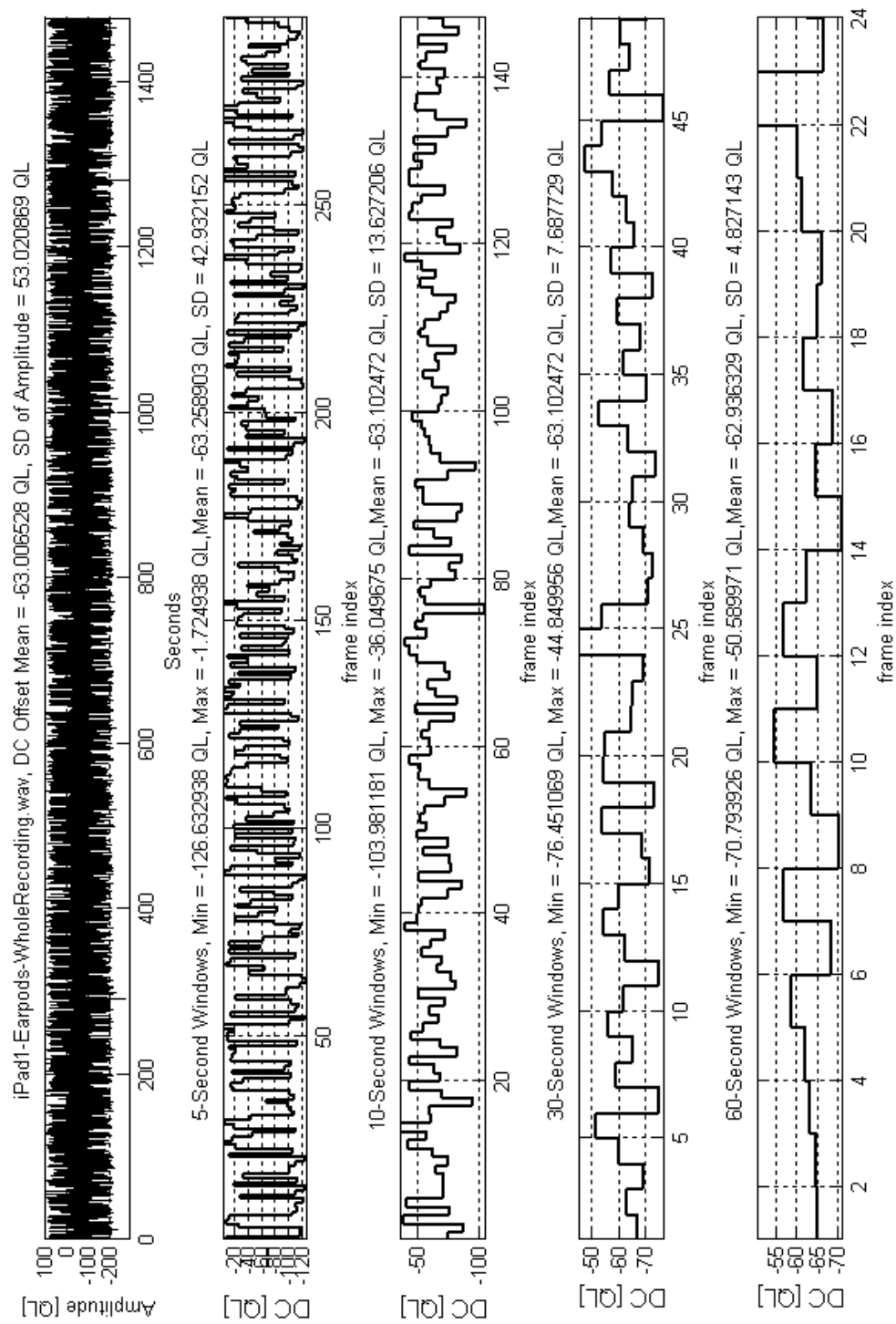


Figure 78 - iPad 2 - EarPods - DC Offset Plots

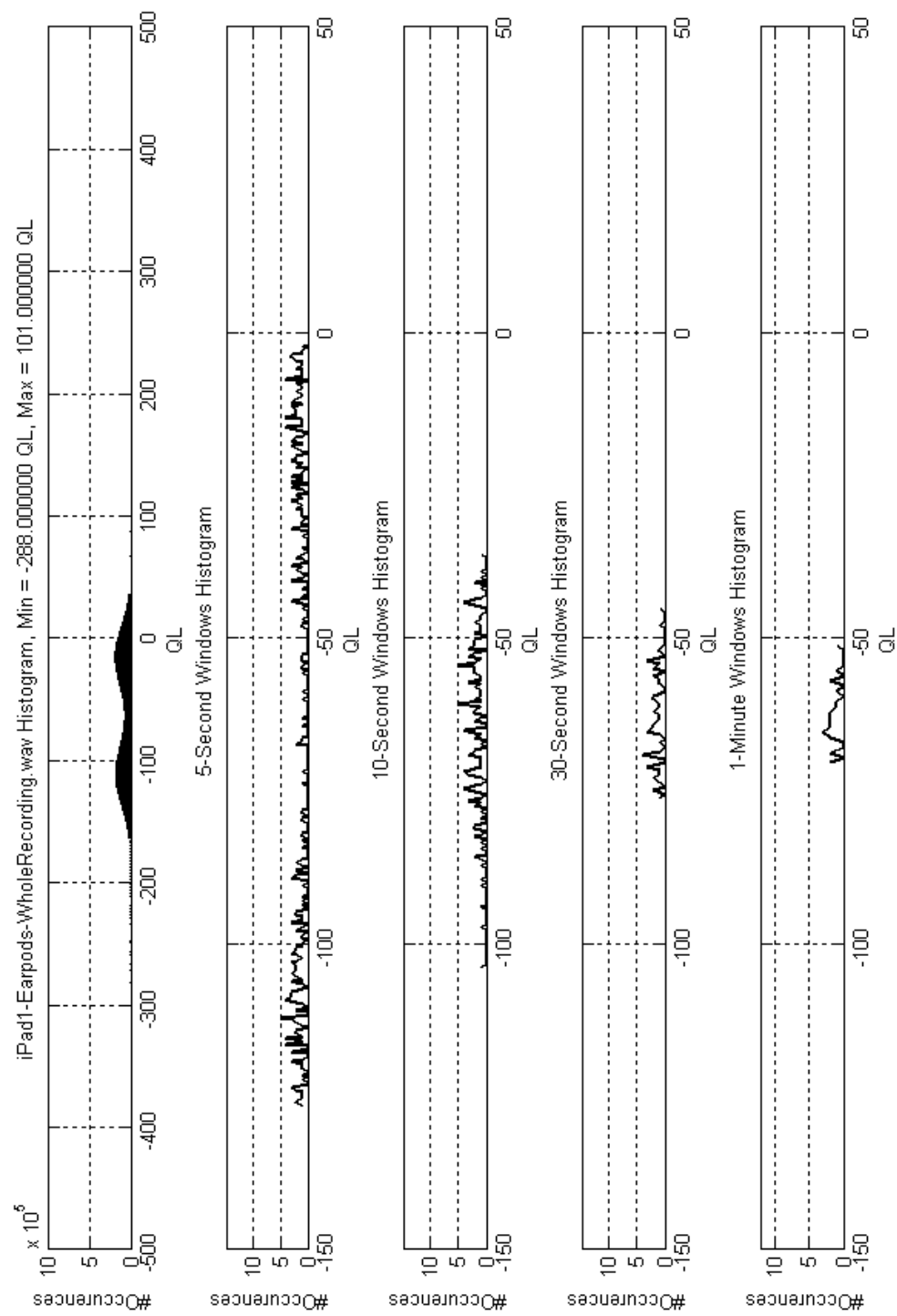


Figure 79 - iPad 2 - EarPods - Histograms

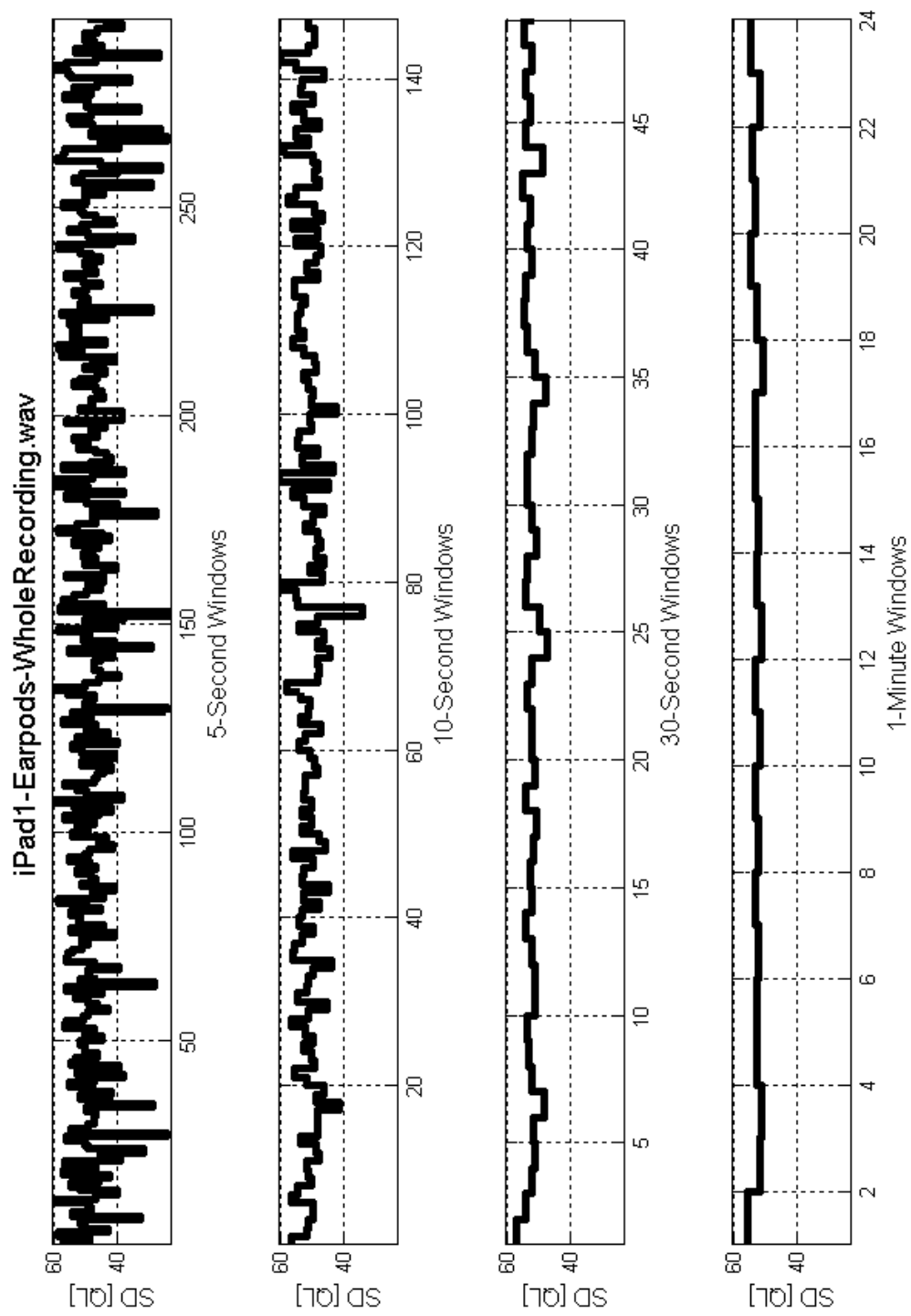


Figure 80 - iPad 2 - EarPods - SD Windows

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