# Using AI and commodity sensors to support self-management of VR exposure therapy.

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# Abstract

This project is an attempt at researching and developing a multidisciplinary tool to aid people with anxiety based conditions such as phobias or post-traumatic stress disorder (PTSD) by employing the use of commodity sensors in a game engine to deliver therapy. The use of AI is also explored to automate parts of the process with the desired result of lowering the barrier of entry since all the technology involved is commercially available. The project was quite ambitious and the majority of development was focussed on setting up the heart rate (HR) data pipeline from an AD8232 HR sensor to the Unity game engine through an Arduino. Two major development blocks arose during development, these were; the coupling of excess electromagnetic interference onto the HR sensor which prevented the accurate or reliable capture of data, the other was that any movement in the user was interpreted as a heart beat which would trigger false positive detection of heart beats. Both of these were solved to a satisfactory degree although significant time was sunk into these tasks. The AI was not developed at all but the prerequisite components of reliable heart rate capture in the game engine are present to allow for its development. This project could be used as the foundations for the beginning of deeper research with multiple branches of potential research present; such as VR development, HR sensing hardware development, data science, AI development, and psychology.

# Introduction

This document discusses the research and development conducted within the scope of the titled project. The project is inspired by an existing software called “Arachnophobia” in which the application creates an immersive VR environment to expose the user to specific phobic triggers, in this particular case, spiders. The end goal is that the user becomes accustomed to their stimulus and is ‘cured’ of the phobia.

VR has great potential in psychological applications since it provides the user with a very immersive experience, and with additional peripherals, the perceptivity of an experience can be further increased. A user may be more open to undergoing exposure therapy in VR as opposed to being exposed to the real phobia since they know the threat is not real. Since the perceived risk is removed in VR, the patient will be more comfortable, and therefore they will be more accepting of the therapy.

This research aims to develop and combine existing technologies to advance the toolset of psychotherapists. Specifically, some form of ‘director AI’ is planned to direct a users progress through levels of varying ‘difficulty’ relevant to the specific phobia, enabling medical personnel to utilise their time more effectively by automating some of the exposure therapy processes. Consequently, this could allow the therapists to see more patients and to lower the per-patient costs of therapy.

Initially, an inexpensive heart rate sensor will be used with the attached disposable ECG pads, a VR head-mounted display, and a PC capable of running the VR simulation. Later into the research, additional sensors may be included to diversify the biometric data. Hopefully, this technology will also enable end-users to independently undergo treatment at home if they wish, since all the hardware required is commercially available.

A specific phobia needs to be chosen for the interactive artefact to tackle. Some examples of phobias to tackle with the use of VR would be; agoraphobia (open spaces); acrophobia (heights); claustrophobia (enclosed spaces); astraphobia (storms); or some animal-related phobia. Animals could be complicated to create an effective virtual representation which may break immersivity, so it is best to decide on a fear which is based in an environment that is not too challenging to create in a virtual space convincingly. Acrophobia is the chosen phobia to tackle due to the availability of well made 3D assets such as city environments. Claustrophobia could also be a good one to tackle but designing a small fear-inducing space will likely take more time than using a city environment.

In the proposal for this project, a Gantt chart was made that identifies several core tasks that are on the critical path to developing the interactive artefact into a complete deliverable. These tasks were:

1. Research the process of VRET

Firstly, a generic understanding of VRET is required to be able to develop an application that utilises these existing therapy techniques.

2. Design self-report survey based on that research

Some short questionnaires need to be developed so that personal experiences are recorded along with the quantitative data.

3. Design virtual levels

Based on the previous research, some individual levels will be designed with a varying level of exposure to the chosen phobia.

4. Build or acquire biometric sensing hardware

The developed AI will use heart rate data to manage what level of therapy the user will be guided through.

5. Develop the hardware into a functional system

Prove the sensing hardware can detect and output biometric data to an interactive application.

6. Acquire 3D assets for the virtual levels

Reasonably believable environments will be needed for this application to be immersive enough for effective therapy.

7. Build the virtual levels

Various levels will be built from all the acquired assets according to the previously made designs.

8. Interface the hardware into the engine

Once the hardware is proven to work independently of the engine, it will need to be interfaced with the game engine through serial communications.

9. Design and implement the AI (RBS) based on previous research

Further research will be conducted on AI methods to identify how the level manager would best be implemented.

10. Test the whole system and capture some test data

Test the complete system to determine proper functionality before creating and getting a procedure approved for use on other test subjects.

This list of tasks was produced before in-depth research or development had begun, so it is possible for unforeseen progress blocking tasks to appear.

Prior development experience is related to hardware and software development from previous studies and professional knowledge, so it is anticipated that the hardware development should not be too complicated. This experience includes developing AI in Unity and other development environments but lacks any exposure to academic level psychology beyond that explored for this project's proposal.

The project has multiple branches of potential research, at first glance some of these are: hardware design, interfacing data to a VR game engine, accurate detection of physio psychological changes in response to phobia triggers, AI design, perceptivity and design of VR environments, and data science. Each of these is its independent field and could be researched to massive depths in an attempt to create a useful product.

Ultimately this research aims to determine whether the designed product could be used as a legitimate psychology tool. The product's viability will be evaluated once-reliable results are recorded. At this point, it may still not be evident whether the product has achieved its goal without a thorough assessment by a medical professional and live user testing.

# Literature Review

## Exposure Therapy Techniques

Performing a preliminary study of exposure therapy techniques is vital to capture existing, proven techniques in treating phobias. In an attempt to increase the procedure effectiveness, the system development will utilise these researched techniques. The aim is not to design a new treatment technique but to facilitate existing methods in a new simulation-based AI process.

Exposure therapy has its foundations built on the studies of Ivan Pavlov which spawned the school of psychology known as behaviourism. (Kendra Cherry 2020)

Exposure therapy is a psychological technique in behavioural therapy to treat anxiety-related disorders. It involves exposing the patient to the source of their anxiety in a safe environment to assist them in overcoming their phobia. Exposure therapy is used to effectively treat various disorders such as generalised anxiety, social anxiety, obsessive-compulsive disorder, post-traumatic stress disorder and specific phobias.

Exposure therapy aims to disconnect the patients mental association between their trigger and feelings of anxiety and replace it with feelings of relaxation.

This form of therapy is based on the principle of respondent (AKA classical or pavlovian) conditioning; the specific procedure used is ‘extinction’.

Many people are aware of the classic pavlovian dog experiment in which a dog presented with food after a bell is rung. Eventually, the dog will respond and salivate to the sound of the bell even without the presence of any nearby food. In a similar fashion if a behavior is not supported over time it will degrade and undergo extinction. It will not be completely gone and new support of the conditioned stimulus will generate the behaviour more quickly. (Kendra Cherry 2019)

If a phobic object or situation is avoided then the fear will worsen over time due to reinforcement so it is important to tackle the fear in some way.

Can be caused by specific incidents or trauma such as; learned responses from early life, genetics, responses to panic or fear - such as observing other peoples strong reaction to your phobia may support the phobia as you want to avoid that situation again, whether through validation or embarrassment.

Although exposure therapy is the generally accepted treatment for anxiety based conditions such as phobia (De Silva and Rachman 1981, p. 227–232) shows some examples of fear reduction occurring in the absence of exposure.

It is crucial to understand specific triggers and situations of exposure to the feared stimulus rather than just the particular phobia, for example, exposure to an environment that is perceived to contain the triggers could still elicit a phobic response.

Several forms of exposure therapy have been developed, including systematic desensitisation, flooding, implosive therapy, prolonged exposure therapy, in vivo exposure therapy and imaginal exposure therapy. (Anon n.d.; Anon No Date)

A description of each of these forms of exposure therapy:

- Systematic desensitisation

This form of therapy attempts to remove the fear response of a phobia and replace it with a relaxation response to the stimulus gradually using counter conditioning. Counter conditioning is the support of behaviour that counter the conditioned stimulus by rewarding desired actions.

A generalised example of a fear hierarchy

1. Think about phobia subject
2. Observe the phobia subject from safety
3. Observe physical phobia subject
4. First contact with the phobia subject
5. An incremental increase in contact/exposure to the phobia subject

- Flooding

Invented by Thomas Stampfl, flooding therapy exposes the patient to the real feared stimulus. However, instead of starting with a low fear-inducing trigger and working up the hierarchy, it begins at the most fear-inducing and progresses down the fear hierarchy. The theory is that people who have a specific phobia are ultimately afraid of death, complete humiliation, or estrangement, not the stimulus itself. Flooding aims to illustrate how irrational the specific phobia is, and in controlled conditions, utilising psychologically-proven relaxation methods, the patient attempts to replace fear with relaxation.

- Implosive therapy

Implosive therapy works similarly to flooding in the sense that the patient is immediately exposed to highly triggering stimuli for prolonged periods. The crucial difference is that in implosive therapy, the anxiety is only aroused by imaginary triggers. The therapist would guide the patient through an exaggerated scene. (Stampfl and Levis 1967, p. 496–503)

- Prolonged exposure therapy

*"The conceptualization of anxiety disorders was greatly influenced by Mowrer's two-factor model, which explained the acquisition of fear as involving classical conditioning, and the maintenance of the conditioned fear avoidance as involving and operant conditioning. Accordingly, avoidance prevents the organism from extinction learning; that is, from learning that the conditioned stimulus no longer predicts harm. Mowrer's two-factor model implies that therapy must not only promote extinction through confrontation with erroneously feared objects, but also eliminate avoidances that would impede extinction learning."* (Foa 2011, p. 1043–1047)

- In vivo exposure therapy

During in vivo therapy, the patient is immediately exposed to the real specific phobia in the traditional method of following the fear hierarchy.

- Imaginal exposure therapy

During imaginal therapy, the patient is instructed by the therapist to visualise their trigger stimuli mentally.

## Viability of VR in Psychotherapy and Training

Lessons learned from (Wiederhold 2016, p. 577–578);

- We can treat so many conditions with VR enhanced therapy: PTSD, anxiety disorders phobia, help change body dysmorphia, provide relief from both acute and chronic pain and harden civilian and military first responders
- VR can be used as an assessment tool in addition to capturing good biomarkers to predict cognitive impairment which is often a precursor to Alzheimer's
- VR evidence based work is increasing
- Availability at home as well as in a clinic changed how therapy and behavioural health services may be delivered making treatment more available
- Patient driven tools allowing patients to support themselves with positive reinforcement and allowing them to be active in their own health and mental well being.
- Along with the dropping prices of VR technology, various sensors are becoming more ubiquitous with many people having access to various sensors in their smart devices which may be used to objectively measure behaviour or be used in conjunction with other sensing devices for further sensing of biomarkers such as heart rate, respiration, perspiration.

- Mental health is becoming less taboo with open discussion and openness to treatment and self-assessment as seen in the increased use of health tracking tools and services and discussion spaces such as forums focussed on diet, sleep, and mood tracking.

According to (Garcia-Palacios et al. 2007, p. 722–724), 76% of people in the study (150 people total) chose VR over in vivo exposure to their specific phobia. Also, the refusal rate for in vivo exposure (27%) was higher than the refusal rate for VR exposure therapy (3%). This shows that the perceived lack of a real threat from a specific phobia allows patients to be more open to attempting a course of therapy. At first glance, this fact does not indicate whether the treatment was any more or less successful, but even if the treatment is not more successful, clearly the barrier to entry is reduced. That simple first step towards confronting a specific phobia in VR could be the difference between a patient gaining momentum down the path of overcoming their phobia or refusing all treatment.

Can a patient become accustomed to the limited VR environment, and could this cause the VRET to lose efficacy with repeated usage? As shown in (Reger et al. 2016, p. 946–959), a group of people living with PTSD had not experienced significant long term recovery of their symptoms.

PE and VRE subjects were exposed to 10 sessions of therapy and contrary to their hypothesis, post-hoc analysis did not show that VRE was superior to PE, but at the 3 and 6 month follow ups there was a greater improvement among the patients who underwent the PE. It shows that there was no significant difference between the drop-out rates.

This could be due to the VR experience not being as visually detailed as their deeply traumatic flashbacks. This study provides evidence that counters the aim of this project by suggesting that the treatment is not viable for long-term treatment. Considering that the study is in the context of treating PTSD, the underlying mechanism of a patient’s disorder could be too vivid to replace with a virtual environment.

## The Utilisation of Biometric Data in Exposure Therapy

Heart rate (ECG/EKG) is correlated to a user's psychophysiological condition, which can be observed through their heart rate variability. Other biomarkers are discussed below.

Skin conductance: electrodermal activity (EDA) aka Galvanic Skin Response (GSR) measures the electrical activity conducted through sweat glands in the skin. This indicates the intensity of experienced emotion.

Eye-tracking can be utilised to record data that informs precisely where the patient's attention is focussed at any time. The user's gaze can be mapped to produce a heat map over time, or the gaze can be analysed alongside another biometric dataset to identify triggers or other behavioural patterns.

Facial expression analysis can be used during therapy to provide an indicator of a patient's current emotional state. A user's expression can be analysed by a toolkit such as OpenFace. It is based on foundations of computer vision and machine learning and can also be utilised for eye tracking, unfortunately, since it requires facial imagery, in the context of this project the tool conflicts with the inherent face covering of the Oculus Rift CV1. In future, it may be more feasible to utilise facial analysis during VR applications thanks to research and development from FaceBook (Facebook 2019) and other companies such as MindMaze. This research essentially implements the use of various real-time cameras to capture facial features inside the HMD, like the eyes and eyebrows, and outside the HMD such as the mouth.

EEG Electroencephalography records electrical activity using electrodes placed on the surface of the scalp and outputs this electrical activity as a series of underlying brain waves. This data shows how the patient mentally interacts with their current experience.

EMG electromyography records movement of muscles through electrical activity generated by muscle contractions. These could be associated with specific emotions and behavioural patterns.

No data may be recorded that could be used as an identifying metric. This rules out capturing facial expressions; all other biometrics are acceptable to use since the responses are not unique.

Traditionally, exposure therapy relies on patient self-reporting to provide the therapist with information about how the patient feels towards their specific anxiety.

Increase in heart rate is correlated with a fear response which makes heart rate an excellent quantifiable biological indicator which can be analysed to determine the patient's progress.

## Design of Biometric Capturing

To keep the product accessible, a cost-effective heart rate sensor has been specified, the AD8232 from SparkFun, along with an Arduino Uno to communicate the data to a PC.

The device needs to be as unobtrusive as possible to preserve the user's immersion during the experience with minimal weight and freely hanging wires to maximise free mobility.

The biometric data needs to be captured and recorded with the context of what has occurred during therapy. This is to determine if a specific event or trigger has had a quantifiable physiological response, so that the AI may correctly guide the user through a suitable therapy path.

There are packages that exist for Unity to read data from an Arduino through a serial port so that is what will be utilised.

Unfortunately due to the timing of COVID and its effects on education, no other hardware could feasibly be acquired for this project. Ideally, multiple forms of biometric data could be captured to create a more detailed view of the user physio psychological response.

## Application of AI in Exposure Therapy

A biofeedback control system is required for the therapy management system. It is possible to extract emotional stress indicators from biometric data to create a quantitative measure of a patient's fear response. The measurements can then be used in a closed-loop control system to influence the therapy procedure automatically.

The influence may be dynamic in the sense that the experience is changed in real-time such as, in the case of arachnophobia, the number of spiders can be increased, their size can be varied, and even behaviours such as movement patterns and aggressiveness.

Another way to influence a therapeutic experience is more static changes, such as putting the user in a completely different environment during each stage of therapy.

Finite state machines are relatively simple for developers to implement, they are predictable given a set of known inputs and current state. They are quick to design and implement.

In terms of technical disadvantage, an FSM can become very messy if an implementation requires a large number of states and/or state variables so other implementations of AI should be explored.

Fuzzy logic seems very useful since it breaks away from the ‘robotic’ predictable behaviour of a rule-based system or finite state machine (FSM). The point of transition of the agents behaviour isn’t as discrete, having some random element. A great example is that of an AI controlled car, in something like an FSM the car would have a brake state and an accelerated state (simplified). With a fuzzy logic system the AI may also have a more gradual output of braking/acceleration giving the AI more natural looking behaviour.

## Review of Existing Products

“Arachnophobia” did not have many positive reviews on the software distribution platform “Steam”. This project will attempt to build an artefact that tackles the same problems as “Arachnophobia” does but will add some features to deal with them in better ways such as automating the level manager, via heart rate input, rather than leave it to the user.

A more believable environment and progression seem to be the improvement requested by the reviewers, which should be taken note of during the development of this project.

# Methodology

The experiment will be done in stages, due to the nature of the series of component dependencies in the system, such as enabling an AI to detect and act on trigger events first requires the accurate detection of heart rate. This also allows for verification of each component in the project.

The development will start with interfacing the chosen heart rate sensor to an Arduino and to verify the heart rhythm is output correctly over serial communications. Once reliable heart rhythm data is detected it must be processed into a BPM value which is eventually to be detected by the AI to determine whether the user has experienced a phobic trigger or not. Initially a test scene within Unity will be made so that the BPM data may be interfaced into the game engine over serial communications. It is also necessary to create a way for Unity to save the stream of heart rate data to a file for further evaluation. At this point, the correctness of the hardware and datapipe line will be proven if increases in heart rate can be repeatedly and correctly detected by the game engine.

To enable use of the HMD in the application Oculus documentation must be followed. There should be no requirement of low-level programming for the HMD thanks to the Oculus Integration package on the Unity Asset Store. (Oculus 2020)

The next stage of development is to create a convincing environment to trigger a conditioned response in the user suffering from acrophobia. Appropriate assets will be acquired, such as tall buildings, streets, and a landscape to design a realistic city scene within Unity. There should be a substantial number of ‘levels’ for the user to access to allow for a feeling of progression. Each level will be on the roof of a building with varying height and the player will be allowed movement on the rooftops to simulate some player agency for increased immersion.

Development of the AI subsystem can begin once the environment is complete and heart rate data can be accurately collected by the game engine. A rule based system will probably be the best way to implement the AI by defining a set of rules and consequent actions based on which rules are triggered. Ideally the AI will have the capability of sensing significant increases in heart rate, be able to ignore outliers in the data, and have contextual awareness of what the user is doing so that heart rate data may be tied to specific virtual events, such as the user peering over the edge of a building. With these features the AI will then be able to guide a user through a series of levels of varying difficulty depending on the feedback data from the users heart rate.

## Hardware Setup and Testing

To capture biometric data, the chosen device is the SparkFun Single Lead Heart Rate Monitor which is built around the AD8232 integrated circuit from Analog Devices. (SparkFun No Date) This device is not a medical device and is not to be used in any official capacity to treat or diagnose any medical conditions. However, it should be adequate in the design of this proof of concept and capturing valid biofeedback data for the AI's control system.

SparkFun provides a 'hookup guide' for this device which contains the instructions followed to set up the device. (CASEYTHEROBOT @ SparkFun No Date) The guide suggests using an Arduino microcontroller to build the cardiac monitor, specifically the guide uses "Arduino Pro Mini 328" whilst for this project an Arduino Uno has been acquired from Abertay University. The two Arduino's should behave in the same way, as they have the same ATmega328P microcontroller. (Arduino No Date; No Dateb)

The AD8232 heart rate sensor requires an input voltage of 3.3V which both of the Arduinos can provide, although the operating voltage of the Arduino Uno is 5V. This slightly higher operating voltage of the Arduino Uno consequently means that the AD8232 output will lose some resolution. Both the Arduinos have a 10-bit analogue to digital converter (ADC) but considering the AD8232 output is full-scale at 3.3V it will never reach the 5V full-scale analogue input of the Arduino Uno.

$$2^{10} \cdot \frac{3.3V}{5V} = 1024 \cdot 0.66 = 675.84$$

Equation 1 - Maximum value a 3.3V signal can be quantised into a 5V 10 bit ADC.

Detailed in the equation above, using a 10-bit 5V max ADC to read a 3.3V signal voltage, the result will be quantised to 675. Therefore since the full-scale digital value is reduced from 1024 to 675, the resolution of the AD8232 is reduced by 34% in comparison to using a 10-bit 3V3 max ADC. Whether this has any effect on the validity of results will need to be tested. However, it will undoubtedly reduce the range of values that are valid to use as a threshold for detecting the occurrence of heartbeats.

The SparkFun AS8232 circuit has five pins that are required for full functionality, with the last shutdown pin not being connected since power conservation isn't a concern when the device is connected to a constant power source.

| AD8232 Label | Function | Arduino connection |
|---|---|---|
| GND | Ground | GND |
| 3.3V | Power supply input | 3.3V |
| Output | Analogue HR signal output | A5 |
| LO- | Leads-off detection | 11 |
| LO~+ | Leads-off detection | 10 |
| SDN | Shut down pin | Not used |

Table 1 - HR sensor to Arduino pin definitions.

Initially, the AD8232 is socketed into a solderless prototyping breadboard, and the connections made to the Arduino as specified in the above table. The SparkFun guide uses an FTDI board to allow the Arduino Pro Mini to communicate with the desktop, but the Arduino Uno already features an onboard USB port.

The Arduino is then loaded with a simple ‘Sketch’ via the Arduino IDE to test the basic functionality of the sensor. (Casey Kuhns @ SparkFun Electronics 2014)

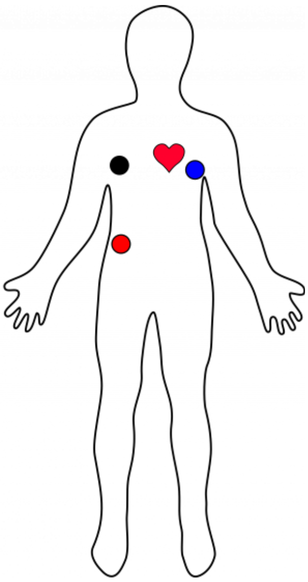


Figure 1 - “Typical sensor placement” (CASEYTHEROBOT @ SparkFun No Date)

The ECG pads were attached according to Figure 1, but initial testing showed that the output was coupled to some high-frequency noise and no obvious heart rate pattern was observable, as shown in figure 2. According to the SparkFun guide, this could be due to improper sensor pad placement. Other possibilities include electromagnetic interference (EMI) coupling from other electronic devices such as phones, screens, and nearby power supplies. (Federal Communications Commission 2013)

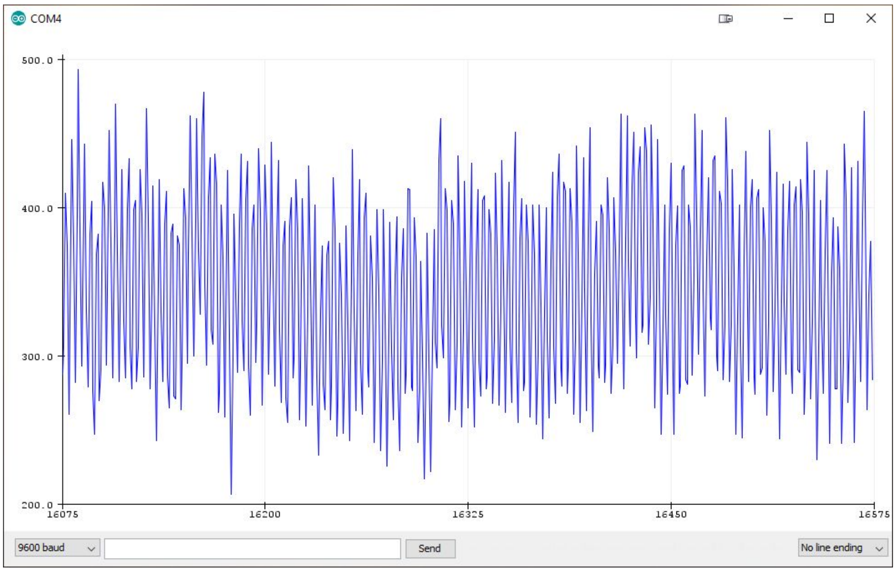


Figure 2 - Initial preprocessed HR sensor output showing excessive noise.

Deeper exploratory testing is needed to determine the cause of the poor signal integrity and to ultimately remedy the issue so that valid data may be captured. Previous electronics experience would suggest that there is some external source of EMI that could be blocked by a grounded enclosure.

After thorough testing of this circuit with no reliably reproducible results a new seemingly identical circuit was acquired, at this point it became apparent that the first circuit was a copycat design, as shown in figure 3. It is instantly obvious that the circuits aren't identical due to the colour difference of the PCBs. Upon further inspection it is noticeable that the configuration of the circuits passive components (resistors, capacitors) are also different, it is possible that this contributes to excessive noise coupling or improper implementation of noise attenuation. The copy cat is made by a Chinese manufacturer called “iHaoSpace“, whereas the official design is manufactured by “SparkFun”.

The experiment relies heavily on the accurate capture of a users heart rate, which is currently not adequate with the results provided by initial testing of the iHaoSpace circuit. If the SparkFun circuit is not a substantial improvement it may be the case that the AD8232 is not adequate for use in this use case.
Testing of the two circuits will be performed to display a visible and quantifiable difference between the two circuits, if any is observable. During testing, variables will be identified and controlled or varied to observe the consequence on the signal integrity, with the aim of determining where the noise is being coupled onto and then hopefully the noise source. If the noise source is identified it becomes easier to design a way of blocking it out. The results and evaluation will be detailed in the following chapters.

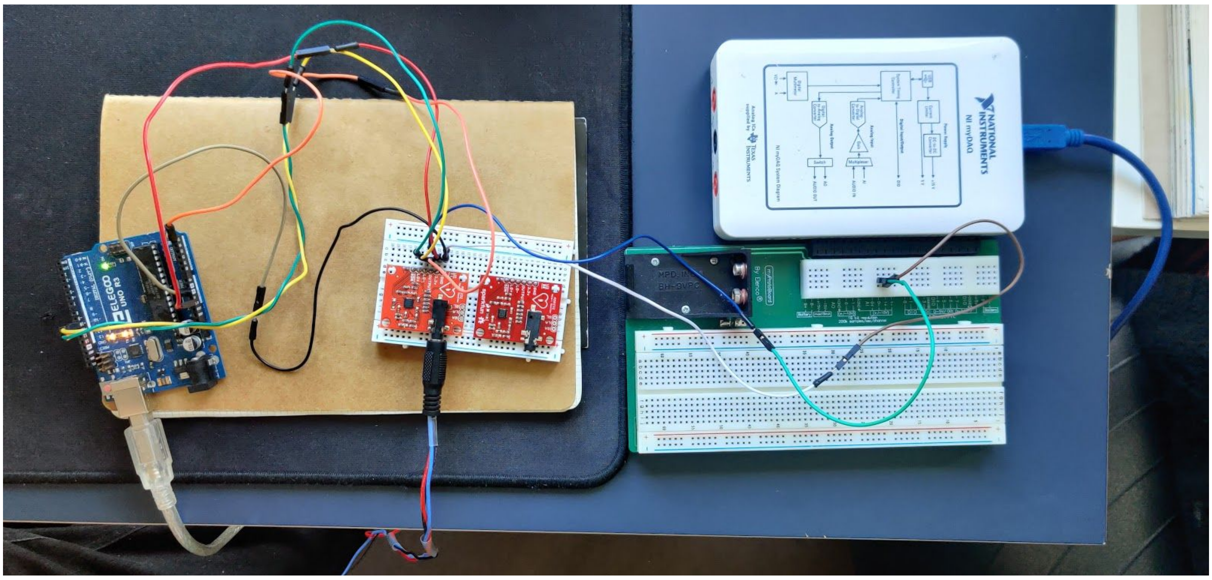


Figure 3 - Open-air testing of the iHaospace circuit (left) with the ECG cable connected. Note the apparent colour difference between the iHaospace board and the SparkFun board (right).

A portable National Instruments MyDAQ (Data Acquisition) device will be used to measure electronic signals in the circuit with it’s oscilloscope function, this is in lieu of a proper electronics lab due to restricted access during the global pandemic. Whilst this will be extremely helpful in testing, it will not completely fill-in for the functionality of a desktop oscilloscope, such missing functionality to measure AC voltages through the use of cursors and a reduced sample rate.

Unfortunately due to the lack of access to an electromagnetic interference (EMI) free zone and the breadth of testing, there is no guarantee that any EMI will be consistent between any tests, which would also be performed on different days. All testing will be performed in a living room which is also used by three adults working from home, all of whom use a variety of electronic devices inconsistently throughout any given day. Whilst this electromagnetically ‘dirty’ environment isn’t ideal for testing this prototype, it might be a more accurate representation of the intended average users environment, and therefore will provide a more accurate view of the systems final performance. Any solutions created to improve signal integrity in this electrically noise environment should enable the system to work in any average user's environment, designing a system that only works effectively in a clean room goes against this project's aim of making an easily accessible therapy product.
Whilst there is some positive aspect to testing at home the limited access to an electronic and mechanical workshop makes problem solving an interesting and ineffective process due to the lack of a full arsenal of equipment. The lack of proper tools will impact the quality and reliability of testing. For example, producing an adequately grounded enclosure will be difficult without access to fully sealed metallic

enclosures and with no way of creating a stable grounded connection to earth there is no guarantee that all electrical noise is blocked out during any given test.

The enclosure used will be an aluminium box with some isolator placed in the bottom to prevent short circuits, the enclosure has a flip top lid and no holes in the sides, which means that the lid will never be fully closed to allow access for power and signal cables.

The ground connection used will be through the Arduino digital ground; this is not the traditional way of grounding an enclosure as it should be earthed through mains to be completely effective. The grounding is implemented by attaching an Arduino cable from Arduino digital ground to the metallic interior of the enclosure, with no way of permanently fixing it, during testing it did come loose. This lessens the reliability of any grounding, but this implies that with a properly grounded enclosure, the results will only improve. To combat this issue a digital multimeter will be used before each test to verify electrical continuity of the grounding.

## Communicating with the Game Engine

To provide the application with use of the heart rate data captured by the Arduino, the game engine and Arduino must be interfaced through a serial port. This will be set up after verification of the reliability of data captured by the Arduino on the in-built Arduino serial monitor.

Communication between the Arduino and the PC is transmitted using the serial port. "Arduino does not come with a sophisticated library for the serial port. While C# has all the expected functions to send strings, Arduino simply does not. This is very frustrating and is often a strong limitation for beginners. To compensate for this, I will be using Steven Cogswell's ArduinoSerialCommand library." (Zucconi 2015; 2016)

Initial test of the threaded communication didn't go well, but that was transmitting one ping per frame and had about 25% successful read rate, going to 60 frames per ping helped significantly. There was a 100% successful read rate, but I am not confident that this data rate is adequate, setting the frames per ping to 10 gave a 100% message success rate.

The messages all arrived at a consistent rate as sent by the Arduino, however the Arduino read thread script in the game engine didn't pull them out of the serial port consistently due to some internal line of execution so the output thread is continuously pinging the Arduino requesting data. This has some overhead and as observed in the first test the Arduino is transmitting more messages than Unity can read in the frame time.

As suggested by Alan Zucconi an input/output queue is implemented to solve this problem, absolutely no messages are lost. The messages still do not arrive in real time due to Unity's process of execution but they do arrive albeit with a small delay.

It might be necessary to send a timestamp with each message if a requirement for accurate time based calculations arises, such as creating an accurate graph of the data. If the HR data is taken from the Arduino and processed in Unity to find the BPM, then all the data needs to be time stamped so that it can be processed correctly in Unity. If the HR data is taken and then the BPM calculated all on the Arduino, then the data won't need to be time stamped. During testing, the Arduino has been made to calculate the BPM to save execution time within Unity due to lower throughput on the serial line.

It would be useful to be able to capture when certain events occur in the game engine, such as, when the player looks over the edge of a building. These events can then be lined up with the HR captured at that time to determine if certain events are indeed a conditioned stimulus or not, and how significant the user responds.

## Designing the VRET Levels

The complete environment was acquired from Windridge City (Unity Technologies 2019) on the Unity Asset Store, and the scene is adequate for use in this experiment out of the box. Windridge city has a complete and believable environment with a detailed skybox, a variety of different buildings, wind sounds, and a busy background of mountains and swaying green scenery. Unfortunately, the textures aren't provided at full resolutions for free, so this will be compromised for the experiment, which will negatively influence the immersion. Along with a lower resolution, there are some minor z-fighting and level of detail (LoD) issues in the scene which may also break a users immersion in VR. Whilst these problems are not ideal for the experiment, they are not a core challenge in the project and will be left with other lower priority tasks.

Another factor missing from 'Windridge City' is significant movement, as described by (Freeman et al. 2017, p. 2393–2400) creating the illusion of active life and movement in a virtual environment will increase perceptivity and therefore the effectiveness of the treatment. Whilst the scene is not entirely still, as there are swaying trees, this might not be enough to immerse a user into a live cityscape. It is possible to add live movement by adding humanoid models walking around the city and vehicles driving around. However, they should be modelled and textured according to the current design of the city; otherwise, they will stand out and act against immersion. For example, adding a cartoony stylised vehicle into a realistic scene will break the cohesive art style in the scene and therefore, will not be believable.

Taking advantage of all the various buildings in the vast city, all the levels of exposure will be designed in this single environment. For example, the first level will be as simple as traversing the ground plane on the roads and directing the user to look up at tall buildings, for most this should not trigger any fear response. However, the first level should be as non-intimidating as possible to accommodate for those with severe acrophobia.

The next level will be to place the user on top of a relatively short building and encourage them to look over the edge at the ground. The intention is to expose the user to incrementally increasing realistic fearful situations.

The penultimate level will teleport the user to the highest building and is made to observe the surrounding and look down over the edge; this is most likely the scariest.

The final challenge will be to push the user over the edge of the tallest building and drop them with real physical properties, such as acceleration and wind noise. The development challenge here is how to present hitting the ground. An easy and obvious solution would be to trigger a ‘splat’ sound and blackout the screen. This could potentially be considered to be unethical even though it is somewhat in line with the techniques utilised by flooding exposure therapy.

## Development of the AI Controlled Level Manager

Initially, a manual level select option will be developed so that each level may be individually loaded and tested. The software will be designed so that an external AI may trigger launching specific game scenes and recording of biometric input to allow appropriate scene selection.

The AI must take a biometric input, in this experiment only heart rate will be used, it should also be able to trigger a change in the user’s environment such as increasing/reducing difficulty or triggering some calming exercise to support the progression of the user’s emotional state. The AI should have the functionality to detect a user's initial heart rate so that future reading can be compared against a steady value. It is crucial that this reading is as accurate as possible, so it is best to record a resting heart rate over a more extended period, such as 30 seconds to a minute.

The AI should reduce the exposure if the heart rate has been detected to go a specified percentage over the baseline reading; in addition to this, a calming exercise should be triggered. Conversely, if the heart rate has not been detected above the threshold, then the exposure should be increased in the next level.

## Data Collection

To collect the data Unity must have functionality to save the input data into some file such as a .csv file. Firstly it is necessary to define the best case circuit configuration first since the data generated with the initial HR sensor tests were of little value. When all the data is saved and the user completes the ‘level’ only at this point will the AI read back and analyse the heart BPM data. This is to avoid any challenges in real time reading of data which, as mentioned, is subject to some lag. This method also reduces the need for high speed communications.

## User Testing

Testing will be performed predominantly on myself and possibly the three adults that I currently live with. No one else is viable due to COVID and the proximity required in setting up the hardware and sharing the HMD.

The user will be instructed about the experience, what to expect, and how to control the experience and use the VR headset.

The 3 ECG pads will be attached onto the user and some velcro straps around the user to emulate bungee cords, and the heart rate sensor along the Arduino will be mounted on these straps. The idea is to try to trigger some further senses and simultaneously solve the issue of carrying the HR sensing hardware.

Before the experience the user will complete some form of phobia assessment questionnaire. During the experience, the simulation will take real-time data of the user's heart rate in certain levels to get a quantitative value of their response, at the end of each level the game will ask for an optional self-report on how they felt that level was in terms of 'fear-factor'. The AI will use these two factors to determine the next appropriate level the user should be taken to.

# Results and Evaluation

## Circuit Testing

The “iHaospace” circuit was the first heart rate sensor acquired for this project, but during initial tests, it was very noisy and inconsistent between uses on different days. After much experimenting and testing, a new circuit was acquired in an attempt to prove the circuit was not the source of the issue and to narrow down the source of the fault. It was at this point that it became clear the first circuit was a Chinese manufacturers copycat, and the newly acquired circuit was the officially manufactured “SparkFun” circuit. The difference is instantly noticeable due to the difference between red solder masks used by the manufacturers. Upon closer inspection it is visible with the naked eye that the circuit schematic is actually different too, with different values of passive components used. This does not necessarily mean that the copycat is ‘incorrect’ since the manufacturer could have adhered to the same line impedances as the official design through different component ratios. This section will show the results from the testing of both circuits in differing configurations to determine any quantifiable differences.

Tables have been generated throughout this section, collecting data from the screenshots taken during testing to improve the readability of the results. All the captured results are presented in the appendix.

If the testing is successful, then the opportunity is opened to capture some average BPM data into a .CSV file to plot over time and design some process for detecting increases in heart rate.

### Initial Testing

During initial testing of the iHaospace circuit, it seemed that the output was extremely noisy and barely readable by eye, let alone any automated software.

In the setup guide (CASEYTHEROBOT @ SparkFun No Date) it is suggested that the placement of the ECG pads could impact that clarity of the HR data so this could be a factor in why the signal quality was so low during initial testing.

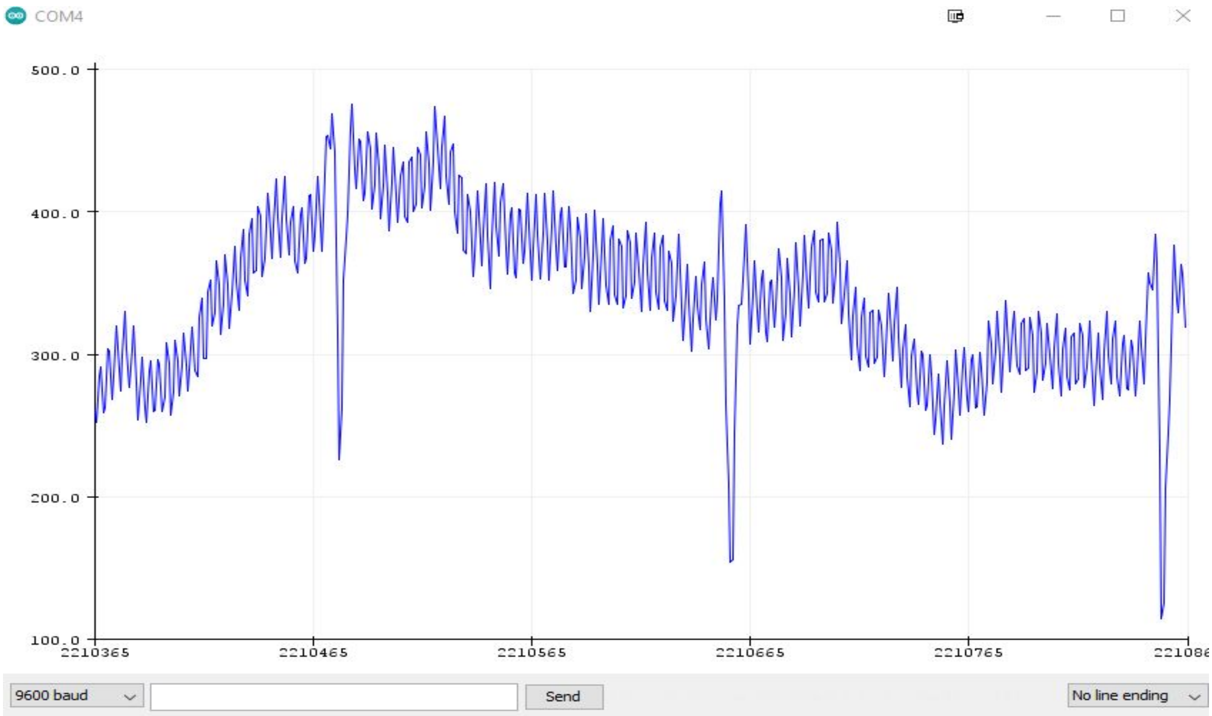



Figure 4 - Similar to the previous figure, there is a distinct QT pulse but there is too much noise present to reliably capture heart rate data. (Copy of appendix 4)

## Effects of Movement

Not only is there a presence of EMI but any movement in the user is picked up by the sensor due to the HR sensors method of capturing data being based on specific muscle contractions. Any sharp movement or even breaths are shown in the heart rhythm data for both circuits, which can be seen in appendix 5 and in appendix 75, the effect is significant in both cases. If movement in the user can induce such outliers in the captured data it would render any analysis based on that data fruitless. Movement is such an important component of becoming immersed in a virtual experience, so asking a user to stay still would negatively impact their response to any therapy. Therefore, some method of detecting outliers in the data and removing them is critical for effective functionality of the system.

## Placement of ECG Pads

Testing can not all be completed in a single day, and the ECG pads are not recommended to be worn for long periods and especially not overnight. This is mainly due to the discomfort of removing the pad once it has been stuck to the user's skin. In any testing procedure, control of specific variables and precisely repeating actions on the subject are essential for maximising reliability of the results.
Since the sensors cannot be placed in precisely the same spot each day, this introduced an uncontrolled variable, and therefore a factor of unreliability. This may possibly not have a significant effect on testing. However, it must be mentioned since during initial testing the output was extremely erratic.

Once any new user is introduced, it is inevitable that their body is different and the initial placement of the ECG pads on their chest may not be 100% correct without the verification of a medical professional or trial and error. The variance introduced into the heart rhythm data by this improper placement must not cross the set threshold for detecting when a heartbeat has occurred, otherwise the reading will be detected as a heartbeat occurrence and trigger the heart rate increase detection, which leads to the system interpreting that the user has had their phobia triggered. It may be the case that individuals require different thresholds to accurately detect their heart beats, in this case it would be necessary to design some calibration procedure before the experiment may begin. The calibration could be automated or even completed manually by observing the heart rhythm data and choosing an appropriate threshold.

## Use of a 9V Battery

Without knowing any source of EMI, it was considered that some AC noise could have coupled into the system through the USB port of the PC. Whilst this is unlikely since USB should be supplied with DC power and the USB cable should have coaxial grounding it may still be possible, so the first proposed test is to see the effects of using a 9V battery to power the Arduino. The Arduino has a connector to accept external power and a transistor that will switch to the external power rail even if a USB is connected, and this is so that it can accept external power but still utilise USB communications, as required by the project.

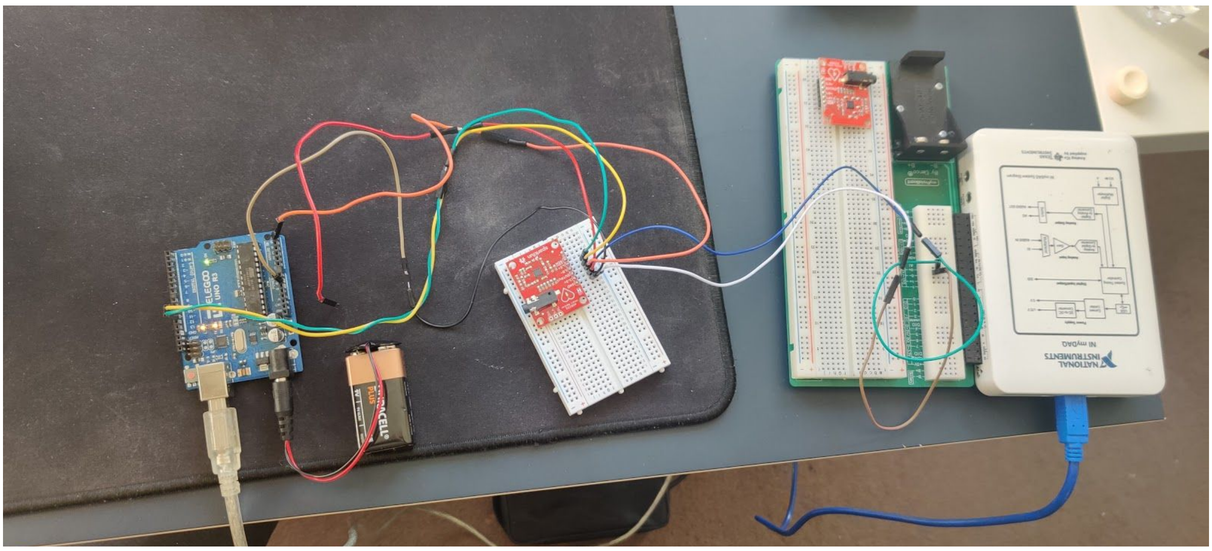


Figure 5 - Circuit configuration with a 9V battery attached and the ECG cable disconnected from the unpowered SparkFun board. The NI MyDAQ is connected across the HR sensor output and ground.

The results of this testing are shown in the table below.

| Powered | Battery | Capacitor | ECG Connected | iHaospace (mV) | SparkFun (mV) |
|---|---|---|---|---|---|
| ✔ | ✔ | | ✔ | 272.27 | 193.27 |
| ✔ | ✔ | ✔ | ✔ | 293.16 | 168.46 |
| ✔ | ✔ | | | 2154 | 131.89 |
| ✔ | | | ✔ | 358.46 | 222.32 |
| ✔ | | | | 2408 | 136.14 |
| | ✔ | | | 383.27 | 151.81 |
| | | | | 393.72 | 155.4 |

Table 2 - Results of testing the HR circuits by varying the power state, the power supply (USB or battery), capacitor usage and ECG connection.

Initial observations of these results showed that the HR circuit output would output an AC voltage without the circuit having any input power; this instantly proved that some external noise was having an effect on the circuit. Connecting the battery to the Arduino at this point did reduce the observed noise in both circuits but it was not significant about 2.5% lower on both circuits. This suggests that there could be some noise coupled into the system through the USB powered Arduino.

With the HR circuit powered and without the ECG cable connected the iHaospace circuit showed huge noise in comparison to the SparkFun circuit, over 2 volts. Whilst this is not a usable circuit configuration it shows a significant disparity between the two circuits capability of attenuating noise. Attaching a battery at this point also decreases the observed peak to peak voltage lowered by 250mV on the iHaospace but only 5mV on the already low SparkFun.

Attempting the same test but in a usable circuit configuration, with the ECG cables connected the difference is not so drastic anymore. The iHaospace starts on 358.46mV and is reduced to 272.27mV once the battery is connected (25% reduction), while the SparkFun starts at an already lower 222.32mV and is reduced to 193.27mV (13% reduction).

Applying power to the Arduino from a 9V battery does seem to reduce the noise slightly, although circuit theory might suggest that it shouldn’t make a significant difference since the computer USB port should be supplying 5V DC. It is possible that the noise is induced in the Arduino due to the USB power not being completely DC and serial communications is exasperating it.

Adding a 100nF decoupling capacitor between AREF and GND pins on the Arduino also reduced the observed noise in the SparkFun circuit (13% reduction) but interestingly it increased in the iHaospace circuit (7% increase). As shown in appendix 83, the effect of USB power is noticeable in the heart rhythm data, although not huge. Conversely, in appendix 17, the signal appears just as noisy.

## Shielded Enclosures

### Complete System Shielding

All tests in this section were done with the Arduino powered by USB, and both the Arduino and HR circuit are placed in a grounded metal enclosure. The opening of the enclosure was varied as an experimental test to observe the effects. It was noticed that while the lid was held, the output would change, this is likely due to natural human conductance inducing a change in the circuit impedance, something that would not happen if the enclosure was adequately earthed. This led to a series of tests where the lid is open, rested against the screen, and finally closed. As illustrated in the below figures.

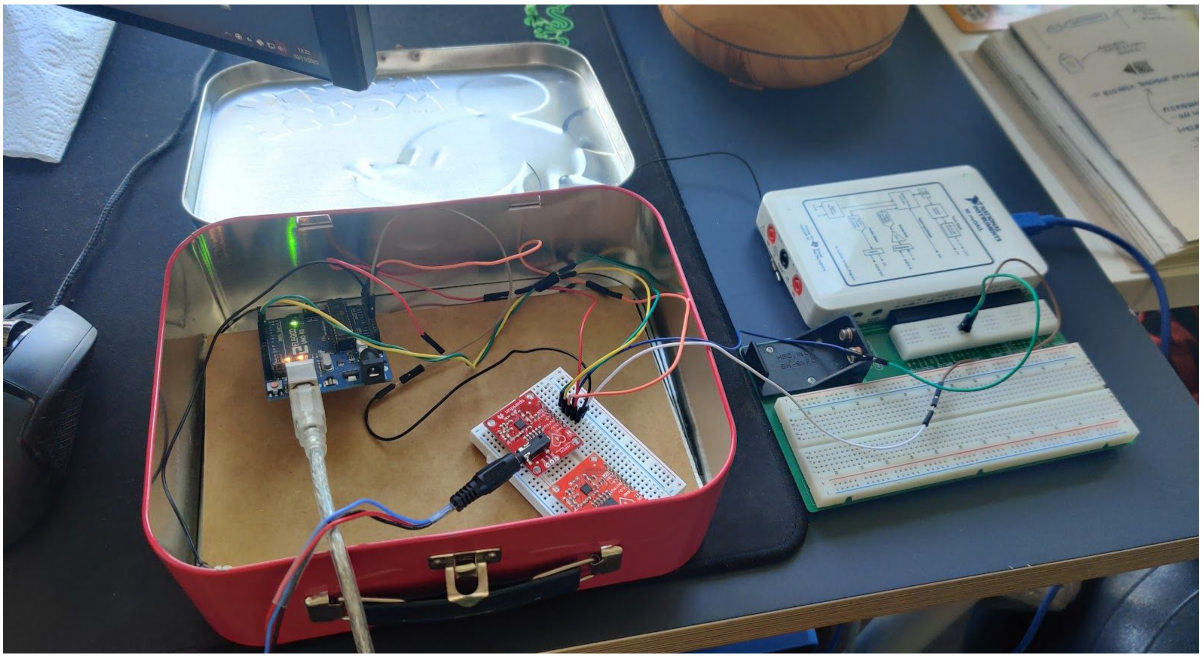


Figure 6 - The complete system placed into an open, grounded metallic enclosure.

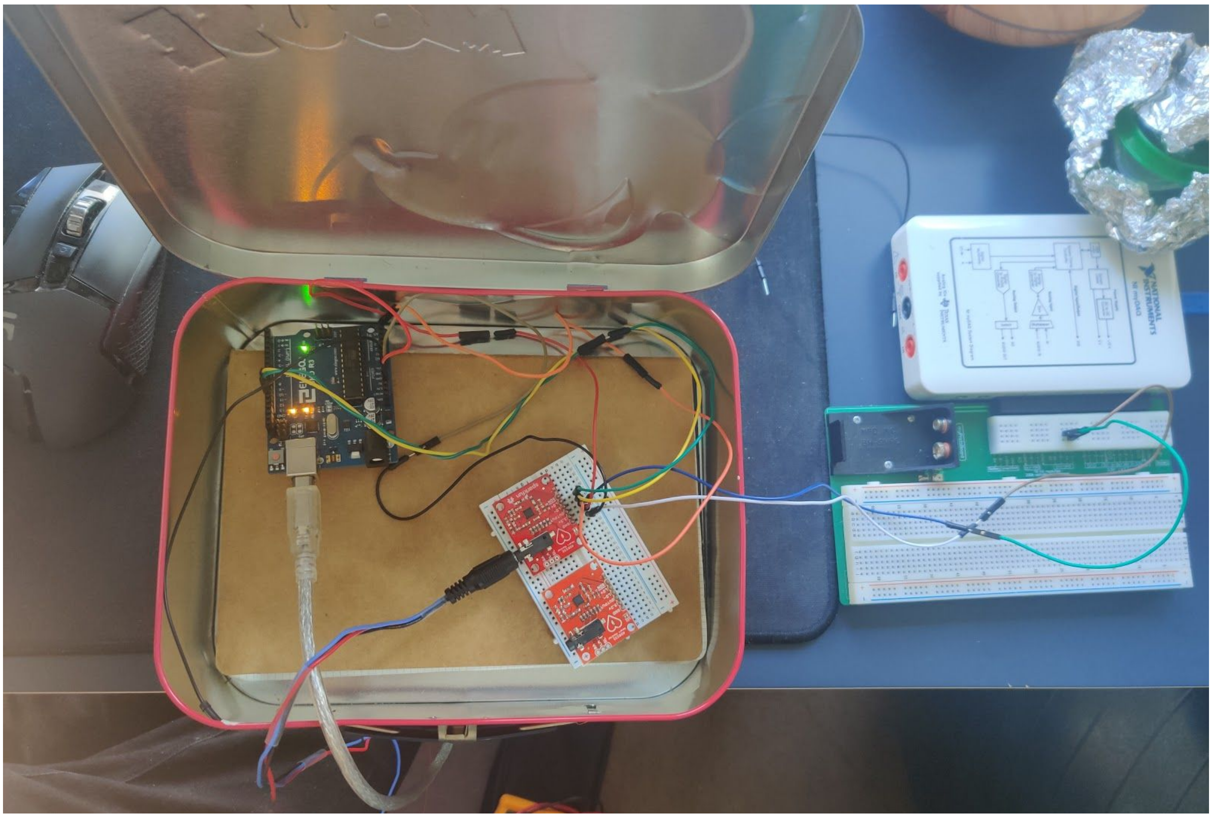


Figure 7 - The complete system placed into a half-open grounded metallic enclosure, the lid is rested on the monitor just behind.

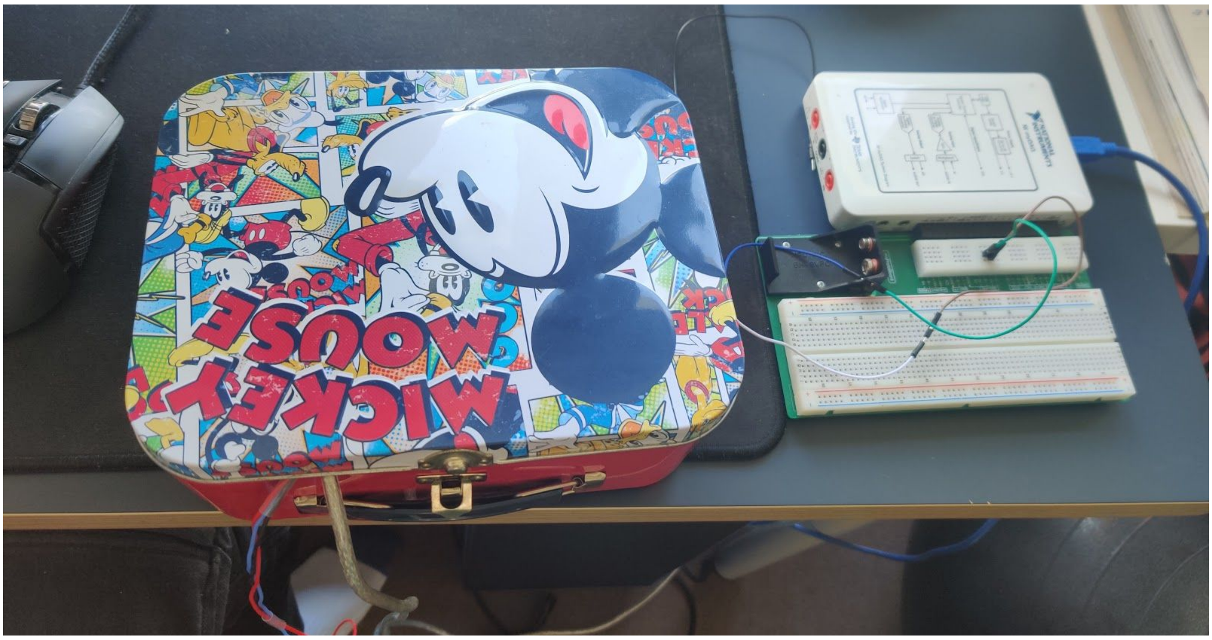



Figure 8 - The complete system placed into a closed grounded metallic enclosure.

| ECG Connected | Grounded | Box Closed | Distance = 120cm | iHaospace (mV) | SparkFun (mV) |
|---|---|---|---|---|---|
| | ✔ | ✔ | ✔ | 69.54 | 24.81 |
| | ✔ | | ✔ | 106.1 | 24.81 |
| | ✔ | ✔ | | 1326 | 111.32 |
| | ✔ | 0.5 | | 1285 | 37.54 |
| | ✔ | | | 1427 | 86.84 |
| ✔ | ✔ | ✔ | | 327.01 | 244.83 |
| ✔ | ✔ | 0.5 | | 325.92 | 147.6 |
| ✔ | ✔ | | | 343.36 | 64.39 |

Table 3 - Results of testing the HR circuits by varying the ECG connection, the grounded enclosures lid opening and its distance from the original EMI exposed position.

During testing, with the ECG cable disconnected it was noticed that the electrical noise seemed to reduce the most with the lid half-open, this implied that it was blocking EMI from a source perpendicular to the lid, most likely the computer monitor. So it was logical to test the effect of moving the whole system as far as possible away from the monitors. Due to USB cable length limitation of the MyDAQ, this was measured to be 120cm away from the original position, illustrated in figure 9. As shown in table 3, this action dramatically reduced the noise observed on both circuits. The iHaospace circuit drops from 1326mV to just 69.54mV, whilst the SparkFun circuit drops from a reasonable 111.32mV to a nearly perfect 24.81mV. This improvement can be seen clearly in the heart rhythm data shown in appendix 30 for the iHaospace circuit and appendix 100 for the SparkFun circuit. Whilst the 50Hz noise is still present the amplitude has been reduced by an order of magnitude. Therefore this is evidence to prove that computer monitors contribute significant noise as shown in the drastic decrease in noise observed on both, the official and copycat HR sensor when they are moved 120cm away from their original testing location which was almost in contact with an LCD monitor and two other monitors were within 40cm.

A slightly strange observation is the SparkFun circuit's seemingly opposing reaction to the grounded enclosure being open. The recorded peak to peak voltage is actually at its highest when the box is closed, this is still a lower amplitude than the iHaospace but it raises another question; is there a source of EMI within the system? Initial speculative reasoning highlights the possibility of EMI getting trapped inside the metallic enclosure and coupling further into the system; as opposed to the case when the enclosure is open and some EMI is escaping the immediate vicinity.

To explore this question further exploratory testing is required, isolating the two circuits from each other and observing their responses.

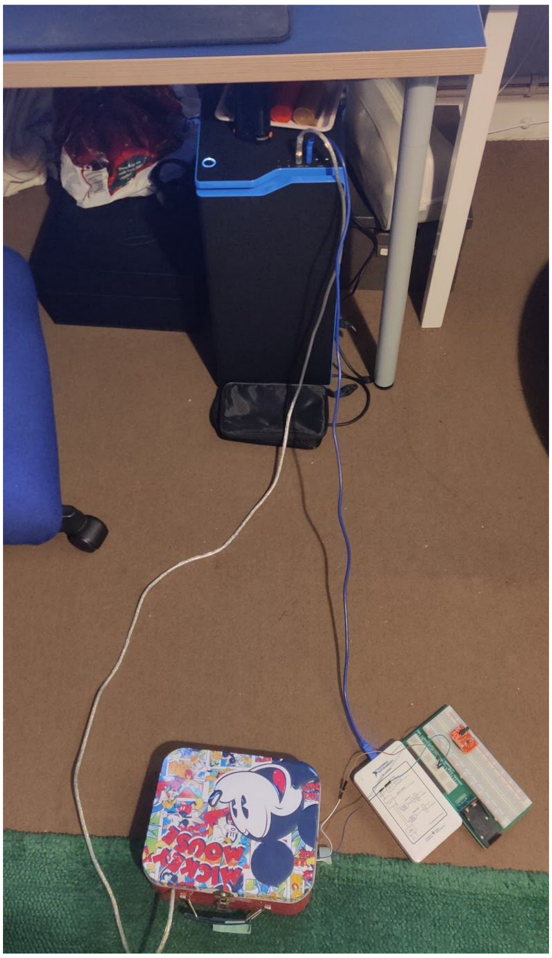


Figure 9 - The complete system placed into a closed grounded metallic enclosure placed 120cm away from the original position.

## Heart Rate Sensor Shielded

In this next test the heart rate sensor is placed into the grounded enclosure whereas the Arduino is left outside. This test has been done during the evening, at which time the testing environment has changed since there is now an absence of two people who were working in the near vicinity with their own wired and wireless electronic devices. The evaluation of this individual test is unaffected but it cannot be closely compared to the other tests since the environment is uncontrolled and has definitely changed, again raising the issue of the lack of an electromagnetic-field clean room. The test is performed in the original position near the computer monitors.

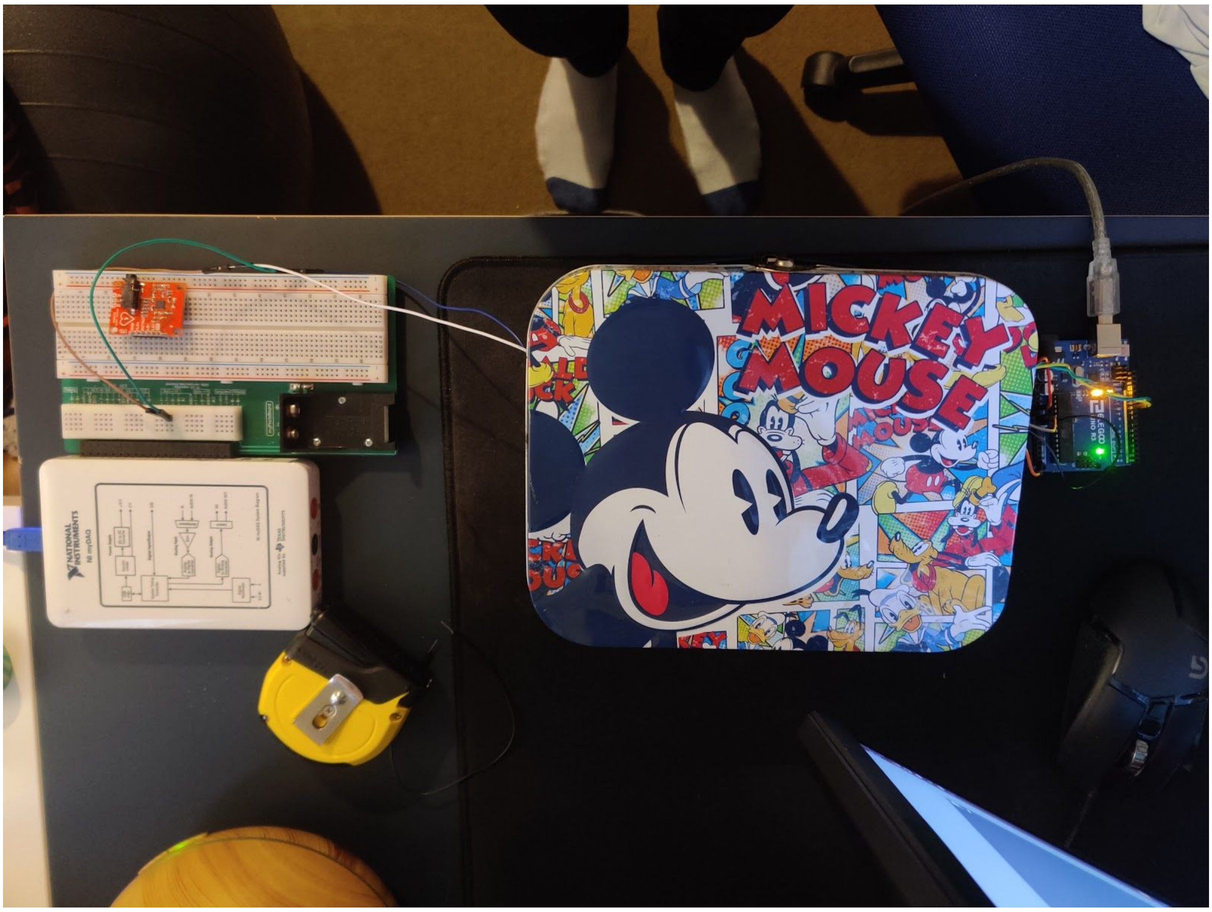


Figure 10 - The HR sensor is placed into the grounded enclosure with the Arduino left outside.

| Powered | Box Closed | Grounded | iHaospace (mV) | SparkFun (mV) |
|---|---|---|---|---|
| ✔ | ✔ | ✔ | 23.83 | 21.55 |
| ✔ | ✔ | | 1868 | 1473.97 |
| ✔ | | ✔ | 87.49 | 66.93 |
| ✔ | | | 2740 | 233.42 |
| | ✔ | ✔ | 128.3 | 141.36 |
| | | ✔ | 157.03 | 159.64 |

Table 4 - Results of testing the system with only the HR circuits placed into a grounded enclosure and then varying the circuit power state, the enclosures lid position and the ground connection.

In an unpowered state with the enclosure grounded the voltage measured is comparable between the systems, once the enclosure is close both values of voltage are reduced although surprisingly the iHaospace reduces more.

In the powered state with the enclosure grounding connection removed, the observed voltage shoots up in both cases with the enclosure closed with both circuits showing over 1V. When the lid is opened the iHaospace experiences more noise whereas according to the results in table 4 the SparkFun circuit drops massively, down to 233mV from 1473mV. It is possible that this is some testing error but assuming it is not, the result points to the SparkFun HR sensor itself being a source of EMI which is worsened in a closed faraday cage. The same could be true for the iHaospace circuit but when the box is opened it displays greater noise, possibly indicating it’s greater susceptibility to EMI.

Once the enclosure is grounded again, the results from both the circuits drop to comparable levels under 100mV again, with the SparkFun circuit performing better.

This test showed the susceptibility of both circuits to EMI, whether that is sourced externally or possibly self-generated due to improper circuit design following electromagnetic compliance guidelines.

### Arduino Shielded

The idea behind this next test is that there could be some noise coming from the HR sensor that is affecting the reliability of the Arduino to read a stable signal. Alternatively, the noise may be coming from an external source, but it could be coupling predominantly through the Arduino.

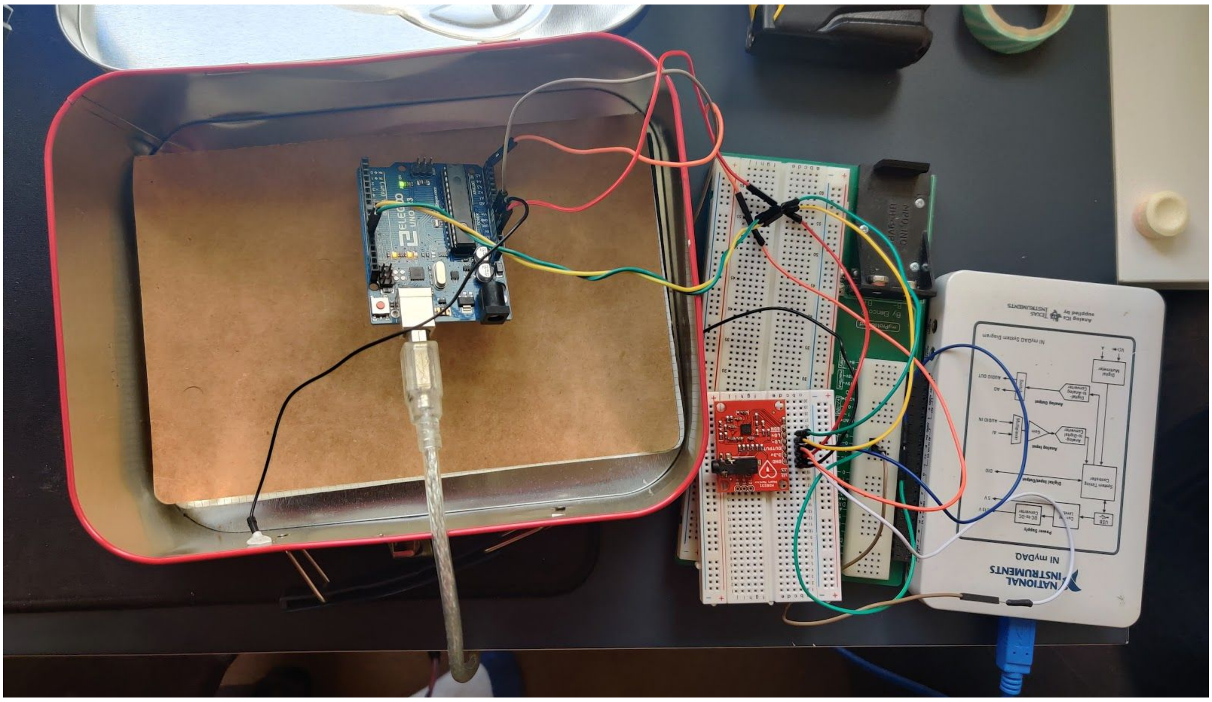


Figure 11 - The Arduino is placed into the grounded enclosure with the HR sensor left outside.

| Powered | Box Closed | Grounded | ECG Connected | iHaospace (mV) | SparkFun (mV) |
|---|---|---|---|---|---|
| ✔ | ✔ | ✔ | | 400.24 | 55.5 |
| ✔ | ✔ | ✔ | ✔ | 357.8 | 144.95 |
| ✔ | ✔ | | ✔ | 438.77 | 228.52 |
| ✔ | ✔ | | | 1852 | 801.47 |
| ✔ | | ✔ | | 438.11 | 75.41 |
| ✔ | | ✔ | ✔ | 406.77 | 165.84 |
| ✔ | | | ✔ | 483.82 | 210.9 |
| ✔ | | | | 2566 | 1320 |
| | ✔ | ✔ | | 240.6 | 188.7 |
| | | ✔ | | 255.95 | 218.73 |

Table 5 - Results from testing the system with only the Arduino placed in a shielded enclosure, varying the power state of the HR sensor, the enclosures lid close/open state, the grounding connection and the connection of the ECG cable on the HR sensor.

In an unpowered state, opening and closing the enclosure has the expected effect of reducing the noise coupled onto the HR sensors. Powering the HR circuit without grounding or the ECG cables has the previously observed effect of massively increasing the voltage amplitude, and similarly grounding the enclosure reduces the amplitude. Although in the case of the iHaospace circuit the noise increases from 255.95mV to 438.11mV compared to the unpowered state, whereas the SparkFun actually reduces from 218.73mV to 75.41mV. When the enclosure is sealed, as expected they both reduce, the iHaospace to 400.24mV and the SparkFun to 55.5mV.

Now to compare states with the ECG cable connected. With the enclosure closed and ungrounded, the iHaospace and SparkFun circuit measure 438.77mV and 228mV respectively. Once ground is connected they drop to 357.8mV and 144.95mV respectively. If the enclosure is then opened they increase to 406.77mV and 165.84mV respectively, so far these findings are all as expected.

Comparing the above results to the results of the complete shielding test in table 3, where the voltage on the SparkFun circuit actually increased when the enclosure was closed. In that specific reading the ECG cable was connected and the enclosure was grounded, the same behaviour is also observed in the case of no ECG cable connected.

The behaviour in this test is the opposite to what is shown in table 3, where the SparkFun HR circuit and Arduino are placed into the grounded enclosure together, which shows the voltage is actually lower if the enclosure is open. This suggests that there is in fact some electromagnetic interaction between the two Arduino and the HR sensor and there should be some shielding between the Arduino and HR sensor.

### Multi-layer Shielding

Taking into account the finding of the previous test a new shielding configuration has been designed with both circuits independently shielded. Since the sensing system is intended to be attached to the user the circuits have been placed into the same enclosure in an attempt to reduce the number of objects the user needs to carry. The circuits will be shielded and grounded independently although both are still grounded to the Arduino digital ground. This test will explore whether this configuration provides any tangible benefit to signal clarity. The testing was performed with the HR circuit placed inside a plastic box covered in foil and then grounded, then this along with the Arduino is placed into the original grounded enclosure. All the oscilloscope data captures were done without the ECG cable connected.

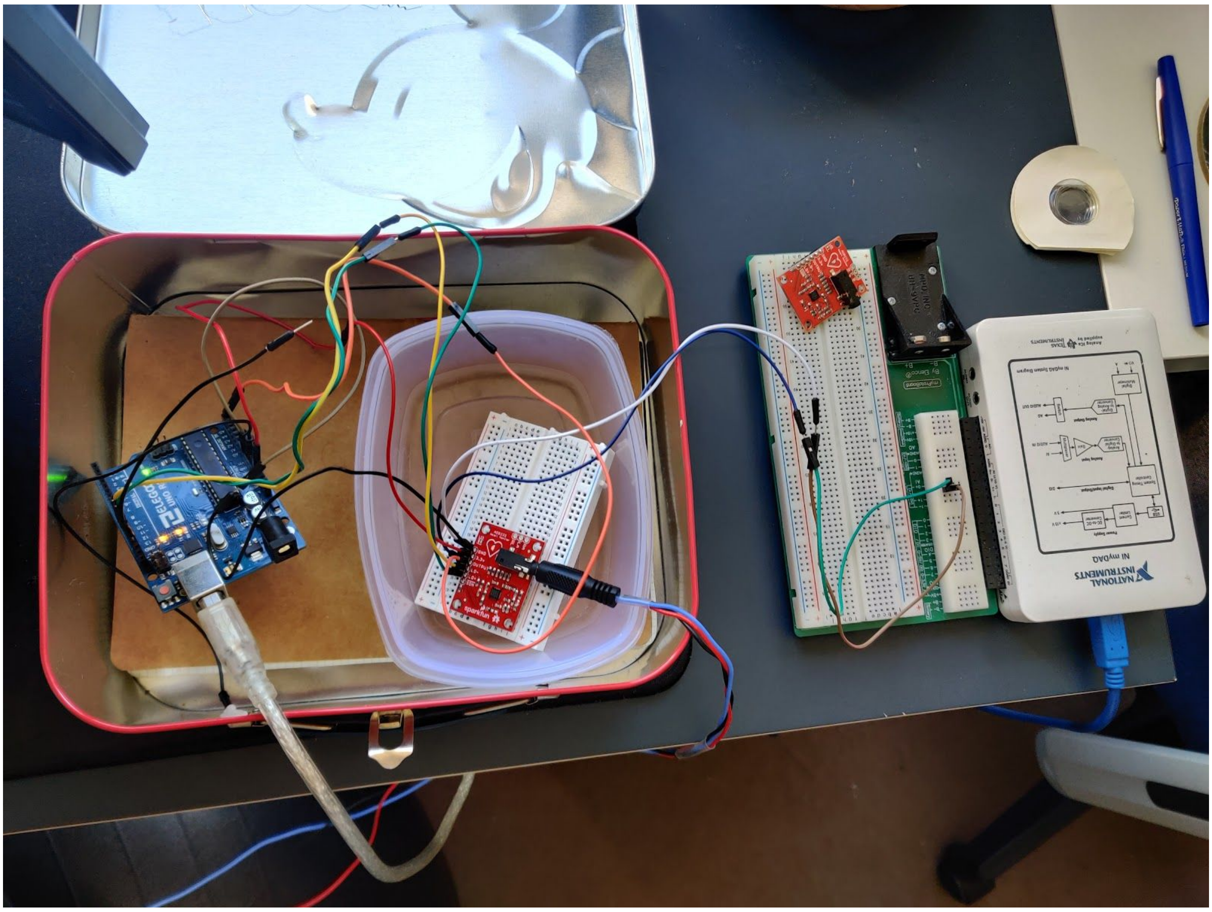


Figure 12 - Both circuits are placed into the grounded enclosure, but the HR sensor is placed into another level of the enclosure, which is also to be grounded.

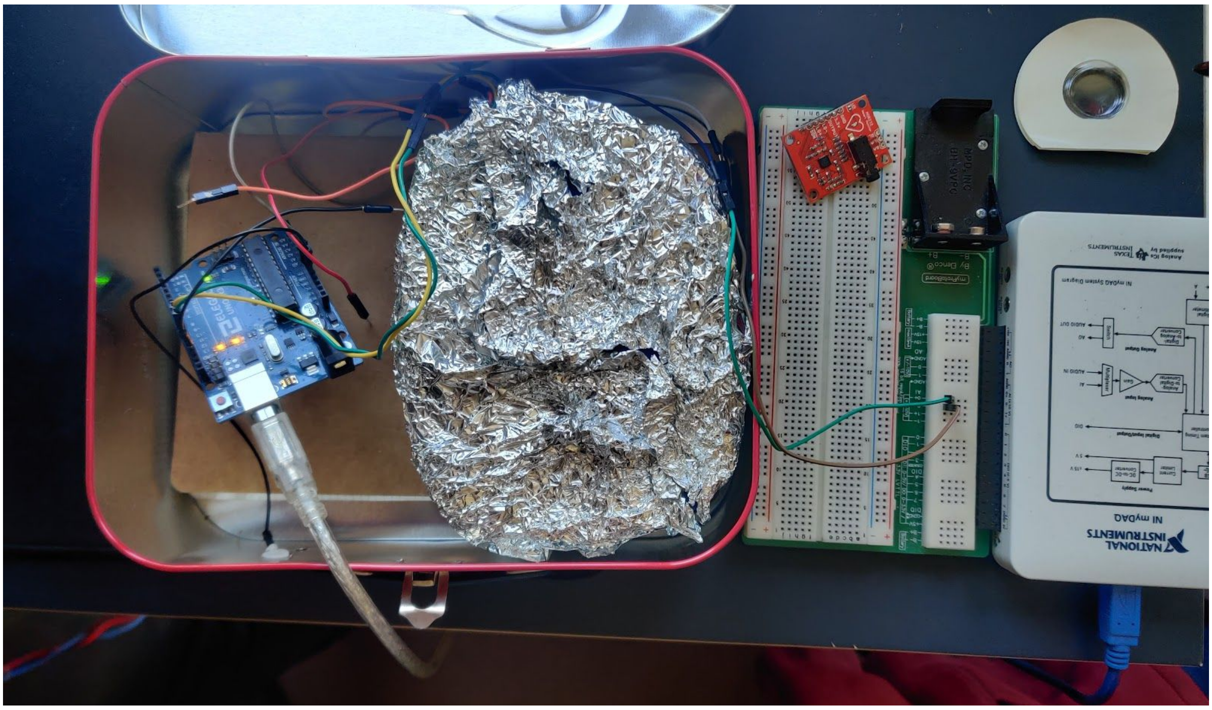


Figure 13 - Both circuits placed into the grounded enclosure with the HR sensor placed into another enclosure, which is grounded by wrapping tin foil around it, which is also connected to the Arduino digital ground.

| Powered | Box Closed | Arduino Grounded | HR Grounded | iHaospace (mV) | SparkFun (mV) |
|---|---|---|---|---|---|
| ✔ | ✔ | ✔ | ✔ | 122.75 | 27.75 |
| ✔ | ✔ | | | 207.3 | 58.76 |
| ✔ | | ✔ | ✔ | 143.64 | 33.3 |
| ✔ | | | | 167.8 | 61.38 |
| | ✔ | ✔ | ✔ | 55.77 | 42.97 |
| | ✔ | | | 378.26 | 371.21 |
| | ✔ | | ✔ | 283.97 | 291.43 |
| | ✔ | ✔ | | 50.02 | 50.64 |
| | | ✔ | ✔ | 70.89 | 60.42 |
| | | | | 405.15 | 402.49 |
| | | | ✔ | 340.76 | 321.4 |
| | | ✔ | | 81.22 | 69.73 |

Table 6 - Results from testing the system with layered shielding, varying the power state of the HR sensor, the enclosures lid close/open state, and the grounding connections to each level of enclosure.

As can be seen from the above table, in the powered on state with both circuits grounded, the SparkFun circuit performs extremely well, reading 27.75mV of noise.

Still considering HR sensors powered on results. With both the Arduino and HR circuits ungrounded, sealing the enclosure actually increases the iHaospace coupled noise from 167.8mV to 207.3mV, similar to the observation from the previous test. The SparkFun reading actually decreases from 61.38mV to 58.76mV but this difference could be down to measurement error.

In all the HR circuit unpowered states, closing the box reduces the coupled noise, interestingly in the case of only one circuit being chosen for grounding, the performance is better when only the top-level enclosure is grounded and the HR sensor is covered in aluminium foil. Obviously if both are grounded that gives the best case result but it seems some aluminium foil is enough to shield the HR sensor from most of the EMI leaked by the Arduino.

These results are a huge improvement on the initially performed open air testing, resulting in the clean heart rhythm data shown below.


Figure 14 - Heart rhythm data when the grounded enclosure is closed.(Copy of appendix 128)

## Best Circuit Configuration

The process of having both HR sensors circuits and having done testing back to back has instructed me on how to get the best out of this equipment. Shown by the difference in the initial iHaospace circuit testing and data captures such as appendix 8. This is likely due to gaining experience through trial and error in placing the ECG pads on myself numerous times.

Throughout all the tests it is generally shown that the iHaospace circuit is influenced more by the EMI. It is possible the official SparkFun sensor has some better noise attenuation implemented or it utilises better quality parts that passively attenuate EMI.

By reviewing all the testing techniques implemented which reduced the noise coupled into the system, a best-case circuit configuration can be designed. I believe that the best configuration using this hardware will use a battery to power the Arduino with a 100nf capacitor between its AREF and GND pins, placed in a grounded enclosure such as the multi-layer shielding configuration, placed at a distance from any significant EMI sources such as computer screens. Technically the heart rate sensor shielded configuration gave the best result with the SparkFun circuit reading 21.55mV but for practical use the circuits should be in one enclosure, to reduce the number of peripherals and ultimately, to preserve as much of the users immersivity as possible.

## Data Collection in Engine

Once the hardware was proven to be reliable and successful data capture was repeatable the best circuit configuration was deployed for testing with the Unity game engine in conjunction with some data capture functions. Heart rate was successfully processed into an instantaneous projected BPM, by triggering a software event on each detected heart beat, and storing the time since the last heartbeat to calculate the average BPM based on the period of that one heartbeat. This calculation is performed on the Arduino and transmitted to the game engine. The BPM values are then stored in a .csv file for post processing. Readings are triggered by each detected heartbeat. An unfortunate side effect of measuring in this manner is that any detected spikes in the heart rhythm, such as those generated by movement, will be interpreted as additional heartbeats and therefore huge spikes in BPM. The alternative method of transmitting all the raw heart rhythm data to the game engine seemed unnecessary since the data wouldn’t arrive in true real time, but through a couple of buffer queues due to Unity’s multithreading limitations. Working on the exact same data set the false positive triggering of heart beats would still be an issue.

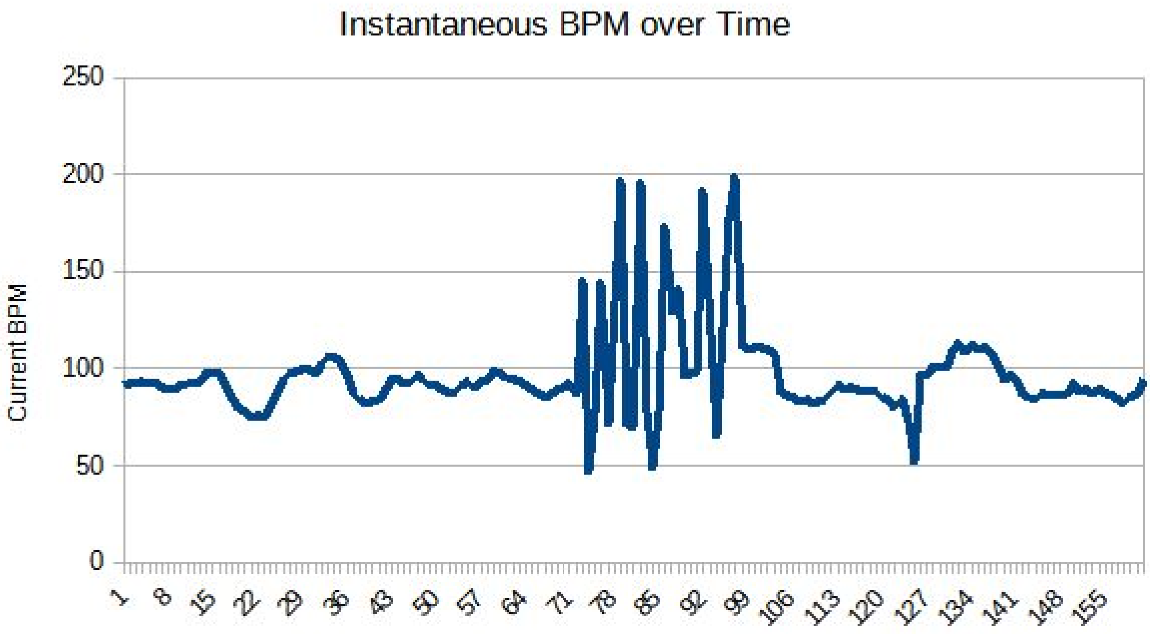



Figure 15 - Instantaneous readings of BPM, including outliers due to movement.

Automated outlier detection is a whole other scientific research field. As it stands with the dataset in figure 15, it is impossible to create an AI that can accurately sense when a users heart rate has increased. A rolling average does smooth out the curve, but any outliers excessively impact each averaged point, and therefore they must be discarded rather than smoothed, as illustrated in the below figures.

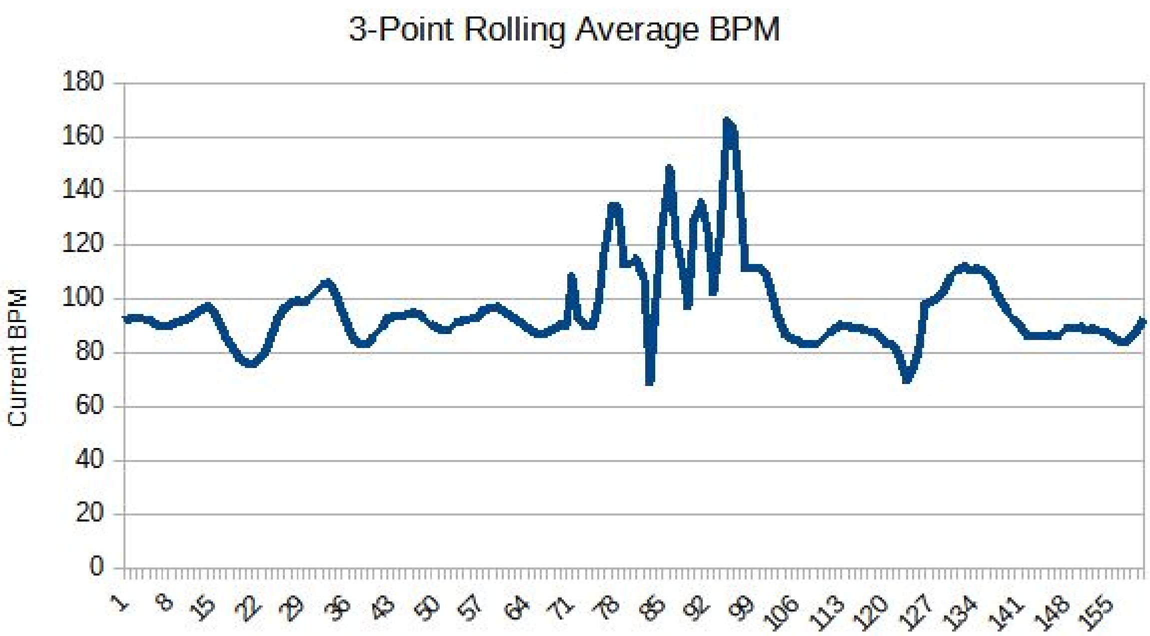



Figure 16 - The same data processed into a 3 point rolling average to smooth out the outliers.

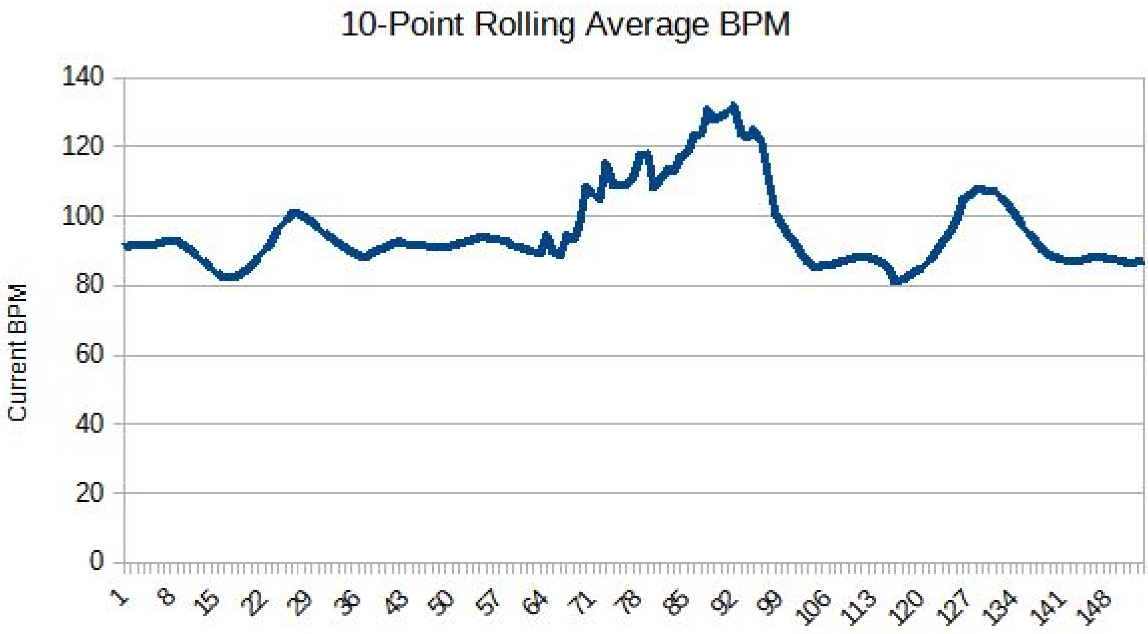



Figure 17 - The same data processed into a 10 point rolling average to smooth the data further.

## Low Pass Filtering

As mentioned in the previous section concerning the effects of movement on measurement results some form of filtering is required. To process the data for appropriate use by an AI it is necessary to pass it through a low pass filter to remove high frequency changes in the data. It is important to balance the desired dampening of outliers with the undesired dampening of real changes in data. The same data from figure 15 was post-processed by linear interpolation between each of the data points by a varying degree, represented by the variable ‘LPF’ or ‘t value’. The ‘ignore’ value was introduced to completely ignore any excessively large jumps in BPM readings. For example, an ignore value of 1 means that if the newly read value is double the last value it will be ignored, or if the ignore value is 0.3 then any new values outside of 1.3 or 0.7 times the last value will be ignored (1 ± 0.3).

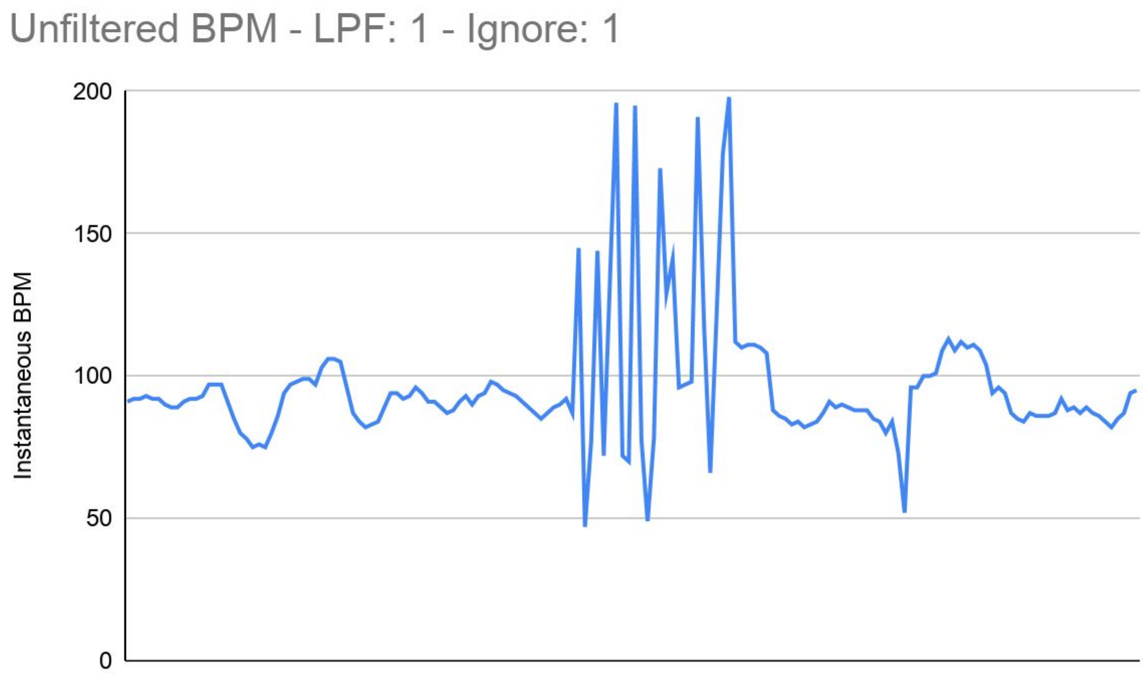



Figure 18 - The same data in Figure 15 passed through the low pass filter with a t value of 1 and an ignore value of 1 (meaning to ignore data 100% larger than the previous point)


Figure 19 - The BPM data passed through the low pass filter with a t value of 0.05 and an ignore value of 1 (meaning to ignore data 100% larger than the previous point)


Figure 20 - The BPM data passed through the low pass filter with a t value of 0.1 and an ignore value of 1 (meaning to ignore data 100% larger than the previous point)


Figure 21 - The BPM data passed through the low pass filter with a t value of 0.2 and an ignore value of 1 (meaning to ignore data 20% larger than the previous point)


Figure 22 - The BPM data passed through the low pass filter with a t value of 0.2 and an ignore value of 1 (meaning to ignore data 40% larger than the previous point)

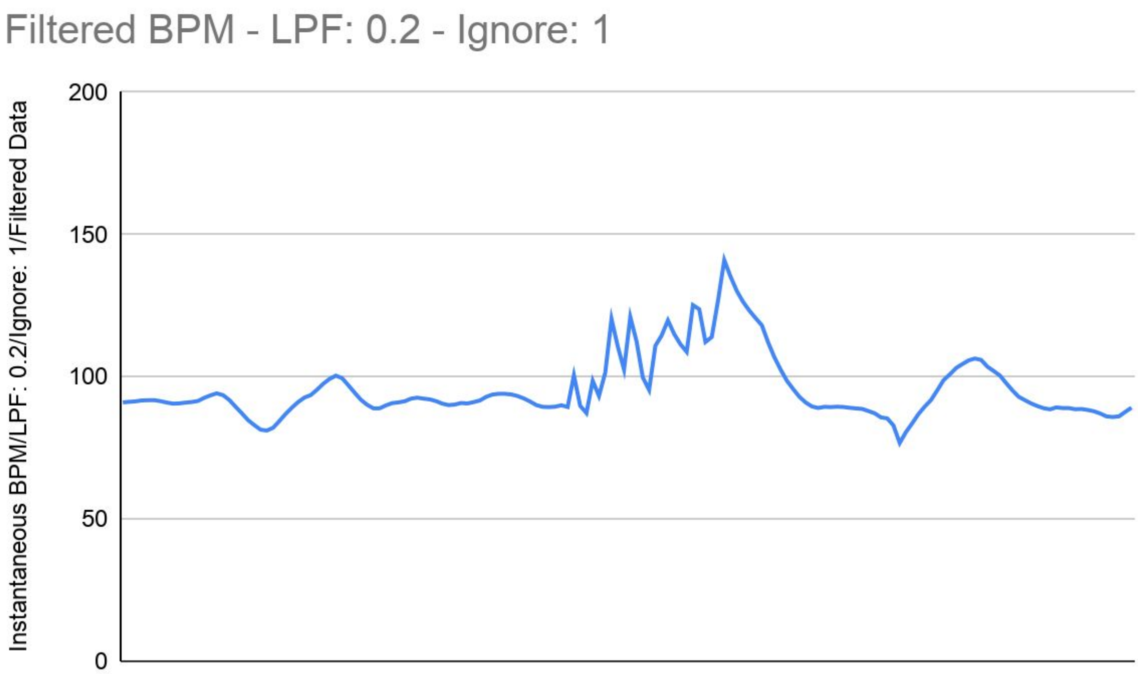



Figure 23 - The BPM data passed through the low pass filter with a t value of 0.2 and an ignore value of 1 (meaning to ignore data 100% larger than the previous point)

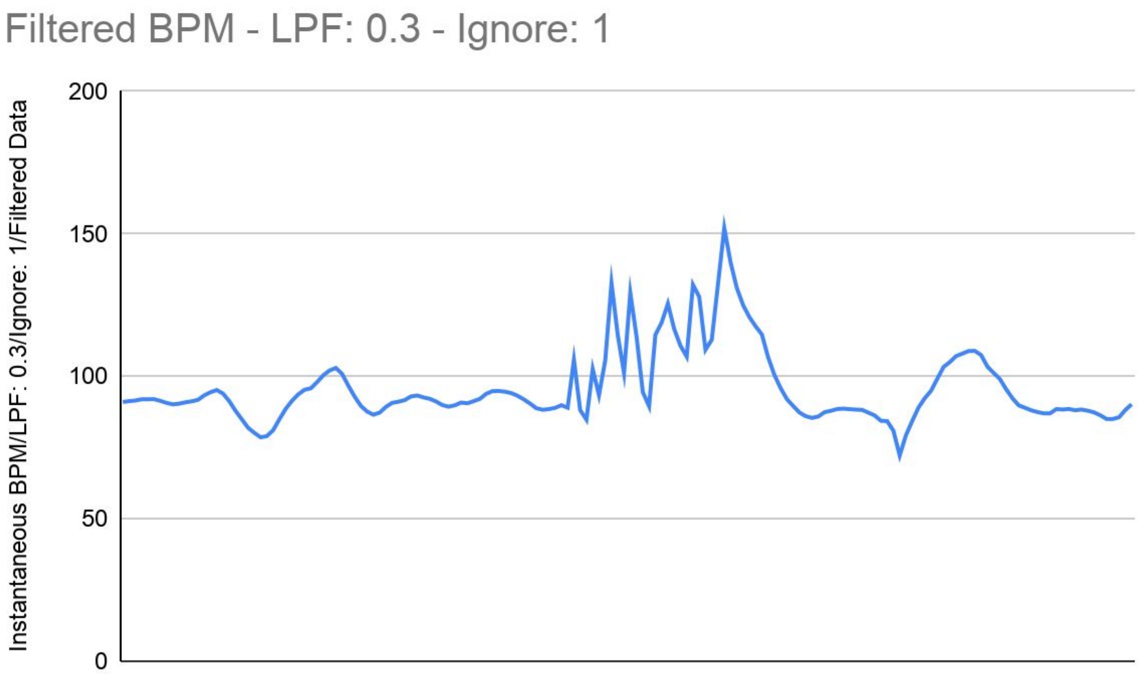



Figure 24 - The BPM data passed through the low pass filter with a t value of 0.3 and an ignore value of 1 (meaning to ignore data 100% larger than the previous point)


Figure 25 - The BPM data passed through the low pass filter with a t value of 0.4 and an ignore value of 1 (meaning to ignore data 20% larger than the previous point)


Figure 26 - The BPM data passed through the low pass filter with a t value of 0.4 and an ignore value of 1 (meaning to ignore data 40% larger than the previous point)

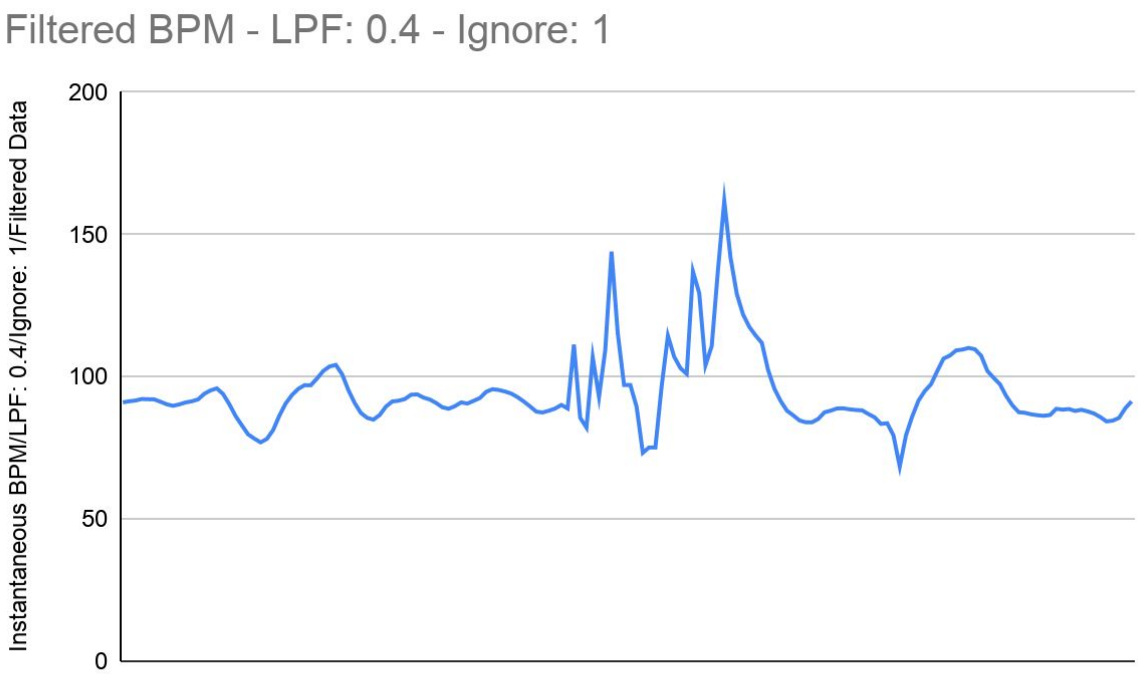



Figure 27 - The BPM data passed through the low pass filter with a t value of 0.4 and an ignore value of 1 (meaning to ignore data 100% larger than the previous point)

An LPF value of 0.05, as shown in figure 19, may be too low, causing a significant lag in detecting changes in heart rate. It is very effective at smoothing out the outliers but all data is excessively smoothed out and any valid increase in heart rate would need to be a stable and significant increase to overcome the LPF value and be visible above the outliers.

An LPF value of 0.1, as shown in fig, is better in the sense that curves are visible outside of the period of time containing the movement induced outliers, but with an ignore value of 1 there is still a significant false peak present in the filtered data.

An LPF value of 0.2, as shown in figure 23, shows even more of the curves, but an ignore value of 1 shows many spikes in the data which is unacceptable. At this point the ignore value is lowered as shown in Figure 22. The spikes are reduced to one peak which is roughly equivalent to the last peak which could be caused by natural heart rate variability. Further reducing the ignore value to 0.2 completely flattens the peak caused by the outliers, as shown in Figure 21.

Out of all options an LPF value of 0.2 combined with an ignore value of 0.2 appears to be the best filter. Of course when the AI is developed it will need to be tested with various filters to determine which is the most effective at dampening outliers while still preserving valuable data.

# Discussion

This project has gone further down the route of research and experimentation than I had first anticipated with the psychological research and hardware development taking significantly more time than expected, generally due to unforeseen issues such as the significant EMI induced noise and the effect of movement on the captured data.

Whilst I believe I created an environment free of electromagnetic fields through distancing from other electronics and a metallic grounded enclosure, the university would have been able to provide a more reliable enclosure with a stable soldered ground connection.

A core goal of this project is to develop and prove the accurate functionality of the heart rate data pipeline, which has been achieved as shown in the filtered BPM data. I had attempted to set up a conventional low-pass filter either through the use of a package such as Math.Net.Filtering (mathnet 2020) or a custom butterworth filter but the tuning proved to be challenging. During tuning of the filter, the overshoot resulting from significant spikes in the data was excessive, causing the filtered data to overshoot continuously eventually moving between negative and positive values of BPM exceeding 1000.

Unfortunately due to time constraints and various difficulties throughout the project the intended design is incomplete, with no form of AI implemented in the application to automatically capture significant rises in BPM. As the project stands now I believe it is ready for AI implementation since the dependency of accurate heart rate capture has been achieved after rigorous experimental testing.

By the end of circuit testing, even the copycat circuit has some readable results, and it could be that my experience with ECG sensor placement has been improved. Having not performed any testing with any third parties I have no guarantee that the placement on myself is identical to any other individual.

For the final aim of this project some questionnaires still need to be produced to measure a user's pre and post-treatment conditions. These may be an attitude towards heights questionnaire (ATHQ), behavioural approach test (BAT), or phobia severity rating assessed by a medical professional. Ideally any of these tests used will be designed by a medical professional to ensure that any user's condition is suitably assessed.

Currently in the application there is only one level present with the user placed on the second highest building, there were a number of levels planned for this project but for a complete product there should be multiple levels for each stage of phobia exposure. This is to prevent the user from becoming accustomed to any environment which would hinder exposure to fearful situations if they are too aware of their safety. It is also important to implement a scripted process to guide the user through some calming exercise such as breathing since a sequence of tension and release is important to build up the users confidence in confronting their phobia. This process is quite similar to the general game design theory of planning difficulty over time, where there is a general trend to increase difficulty over time but with peaks and troughs in the difficulty to keep the user engaged.

An important question raised by this experiment is whether an AI can measure increases in heart rate and tie that to an event in the environment or the users feelings. It is quite simple to push the player off the edge and measure their response but what about, for example, when the user is walking around in the scene mentally talking to themselves, trying to prepare themself to look over the edge?

# Conclusions & Future Work

So much time in this project was spent trying to get a clear and clean signal from the HR sensor. Had I acquired a more expensive sensor, this may not have been a big issue and allowed me to progress closer to completing the final product. Due to COVID19 access to the university labs was forbidden, which added significant difficulty to any hardware development. Acquiring the National Instruments MyDAQ from an old colleague was a saving grace that allowed me to quantify the effects of EMI on the system and determine the source of the noise and consequently, an appropriate solution. Having access to an oscilloscope earlier in the project would have significantly helped push my progress but better late analysis than no analysis.

VR is inherently an experience that users will want to move around in, a crucial part of increasing perceptive. However, the movement of the user affects the reliability of the output biometric data. The developed filtering method is adequate for a prototype but it may be possible that some form of digital signal processing can be implemented to more accurately capture the heart rate data through any noise and movement generated outliers.

Accurately capturing more biometric characteristics would give the application a more diverse data set to make decisions from and possibly sense a conditioned stimulus that would not have been detected through the exclusive use of heart rate data. The complexity of the AI level manager would increase significantly with each added data input. At that stage, it might be valuable to employ the use of neural networks to assess all the various biometrics to evaluate the patient’s progress. Training the neural network would likely take a patient's self-report results to determine when the neural network is rewarded or punished. The neural network is complex enough to be its own project.

This project turned out to have a broader psychological focus than initially intended. Obviously to create an application that treats a psychological disorder the designer must have a relatively deep understanding of those psychological ailments. Unfortunately, I did not start with this understanding of what the exposure therapy process was, I believe this project would have been much more successful had there been a psychologist consultant in the project to provide more detailed specifications for the experience and medical information about various triggers, relaxation techniques, the pacing of therapy, and optimal techniques for capturing biometric data; such as appropriate placement of the ECG pads.

Psychological research was quite challenging throughout this project, I am fully aware of its importance, but having almost no previous medical experience it was difficult trying to research  enough to allow myself to create an effective solution whilst keeping my research focussed and relevant.

Any future work would benefit greatly from a team of specialised researchers in fields such as AI, psychology, data science, electronics and software engineers.

There are multiple tasks present now which may be tackled in any future work:

- Create a smaller properly earthed enclosure which can be attached to the user, with the rift it shouldn't be too difficult to bundle the wires with the HMD wires but new HMDs tend to be wireless. It is possible to transmit the data wirelessly but this could have negative effects on the reliability of the data. Keep in mind to keep cables short, use heavy gauge shields, bundle signal cables, keep power and signal bundles apart, and to maintain good connections such as ground.

- Create more levels in both width of levels with equivalent difficulty and depth of levels with varying difficulty.

- Design a better method of filtering out any erroneous data.

While I have not proven that VR can be effectively used to perform exposure therapy I have set up good foundations or work and knowledge which may be picked up later, ideally by a multidisciplinary team of engineers and medical professionals.

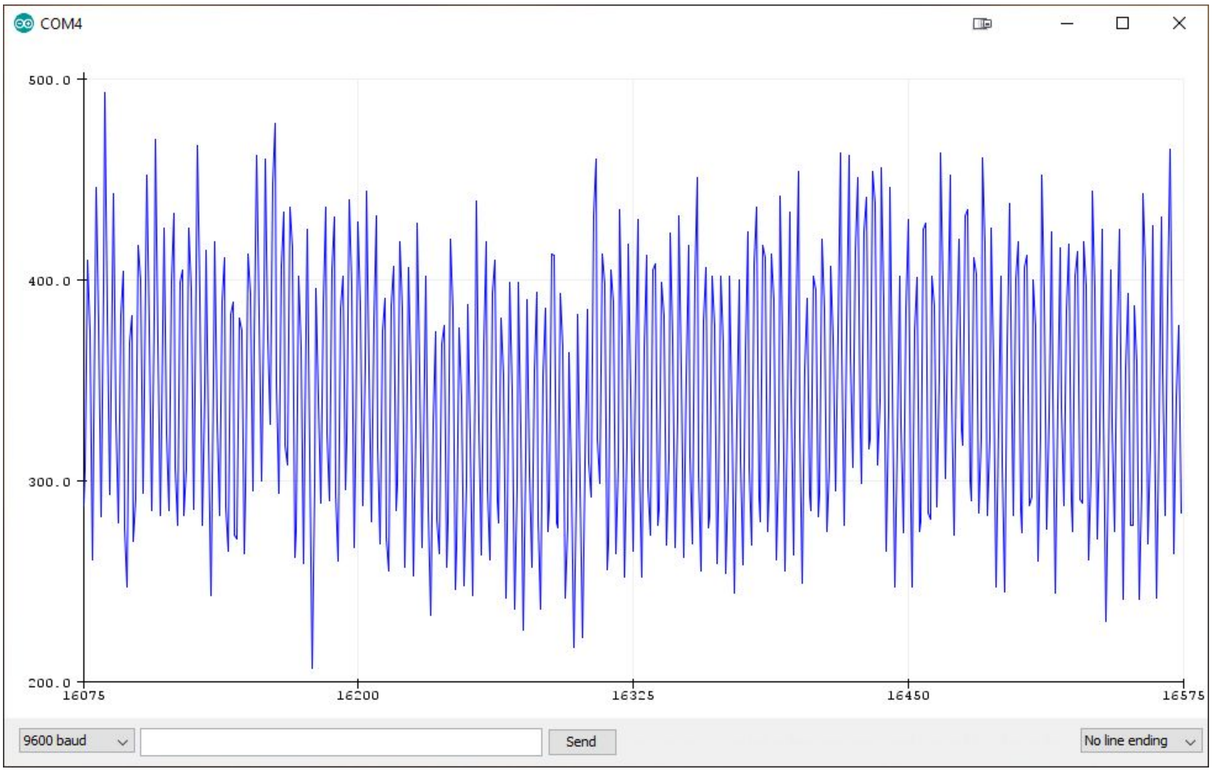
I did not foresee how potentially large my initial project proposal was, in order to make the ideal proposed product, multiple branches of research need to be explored. I believe in the modern world it is the spaces in between fields that should be investigated since there is more space for innovation.

A possible path for development in the future is to create an application that can perform the various techniques of VRET, that is, systematic desensitisation, flooding, implosive, and prolonged exposure. That way a user may choose which they prefer, and if this data is collected it could also be used in future studies to assess the effectiveness of each.

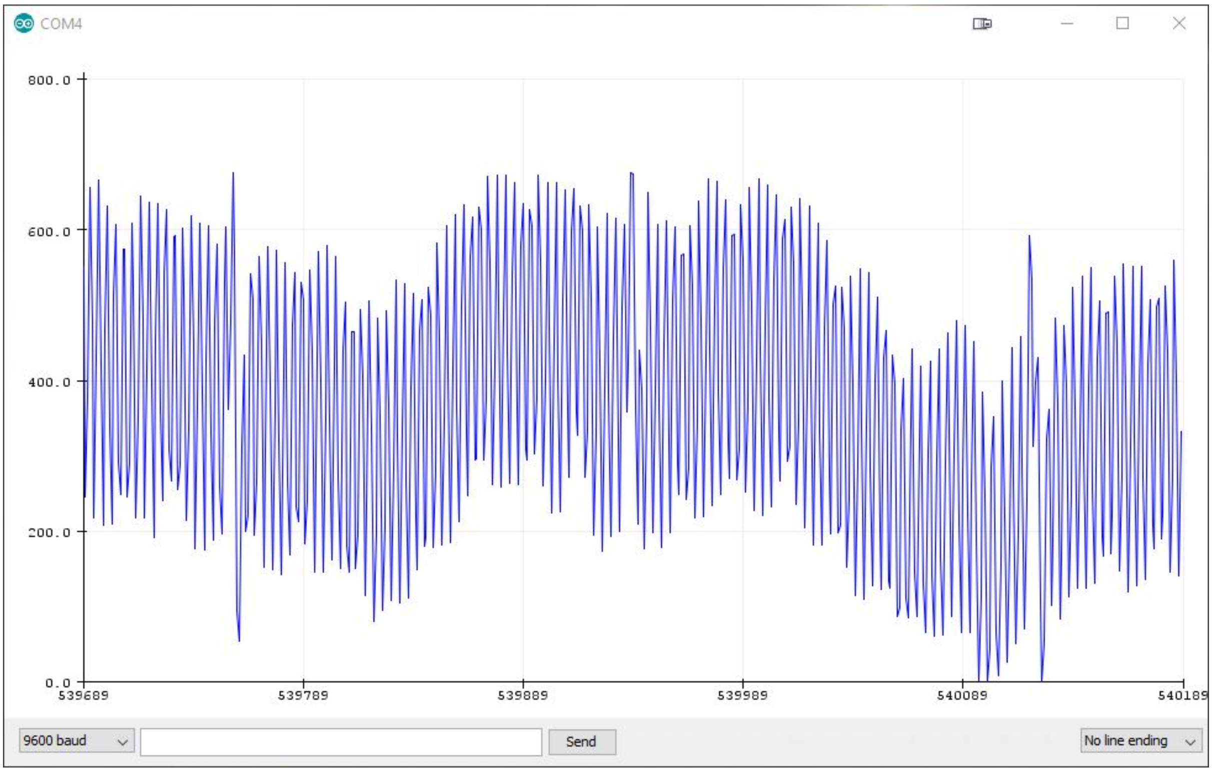
# Appendix

## iHaospace HR Circuit Testing Results

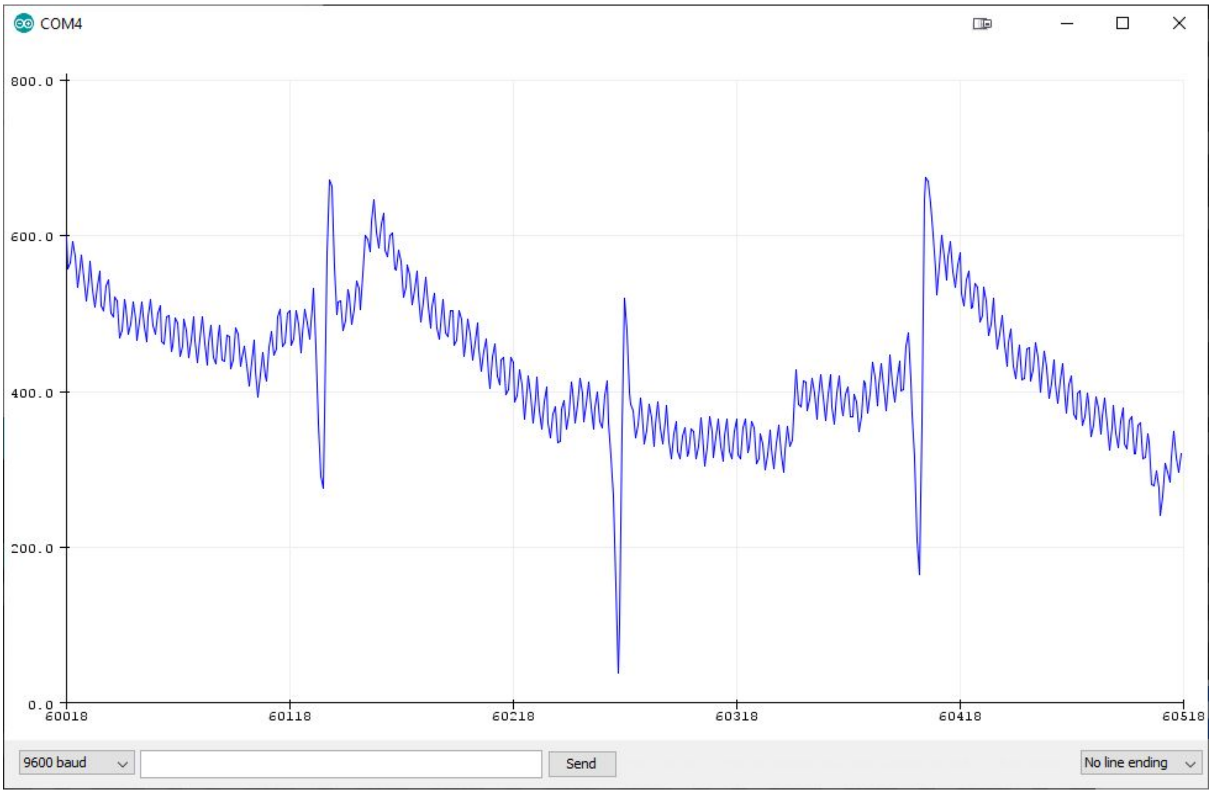
### Initial Testing



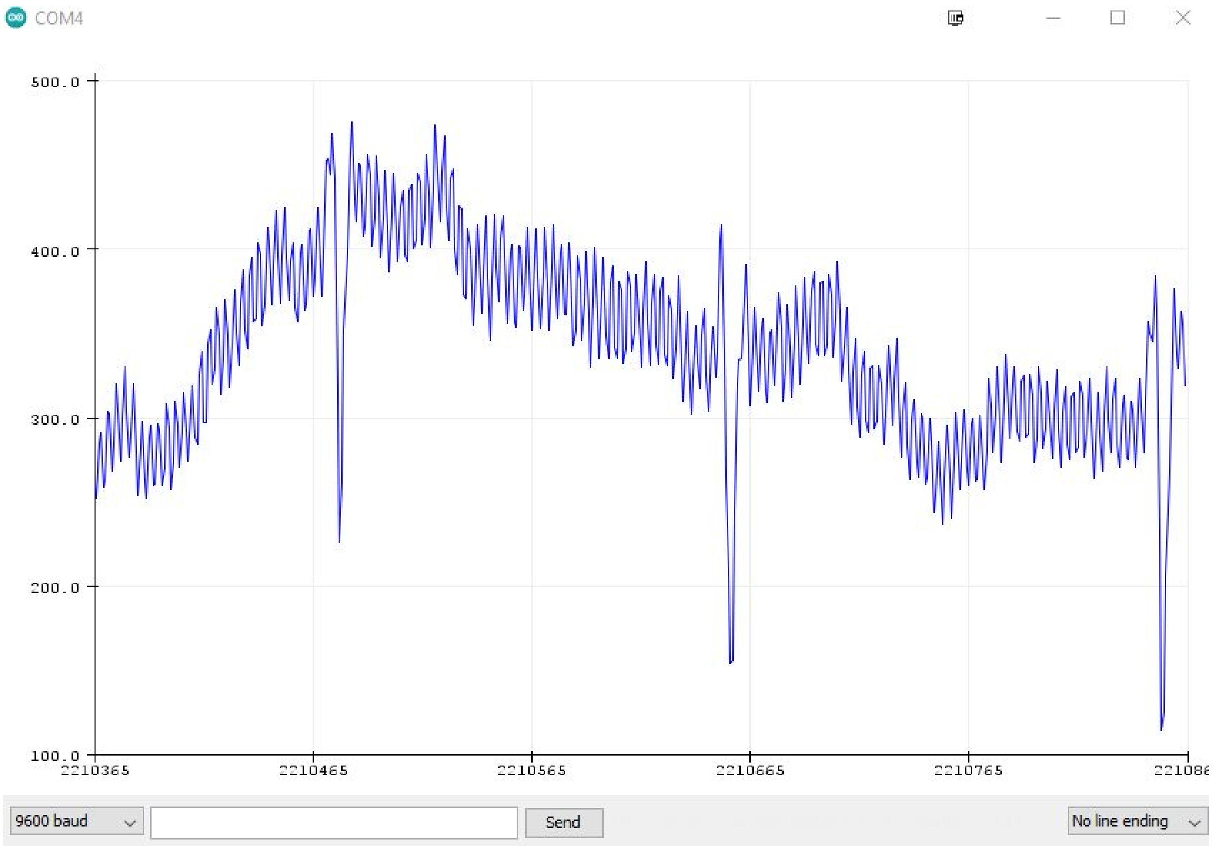

Appendix 1 - Initial testing of HR circuit gave an extremely noisy result.




Appendix 2 - After adjusting the ECG pads, a QT pulse was visible, but the signal readability is not adequate.

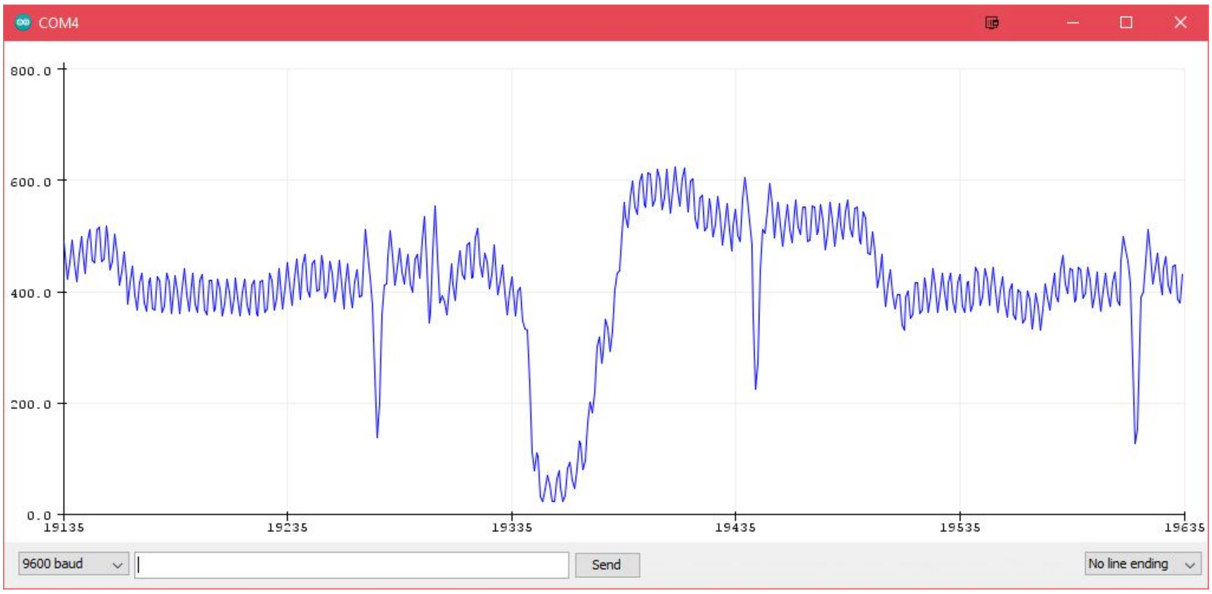



Appendix 3 - This was the best waveform captured during initial testing; there was a lack of a stable threshold for capturing heartbeat events.

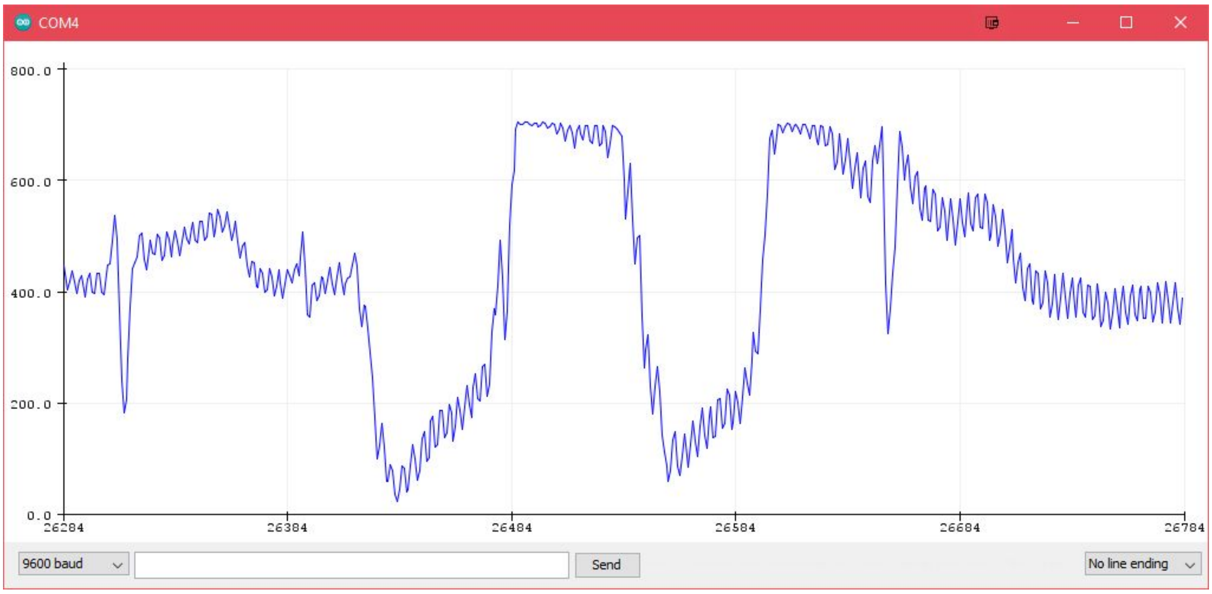



Appendix 4 - Similar to the previous figure, there is a distinct QT pulse but there is too much noise present to reliably capture heart rate data.

## Open Air Testing

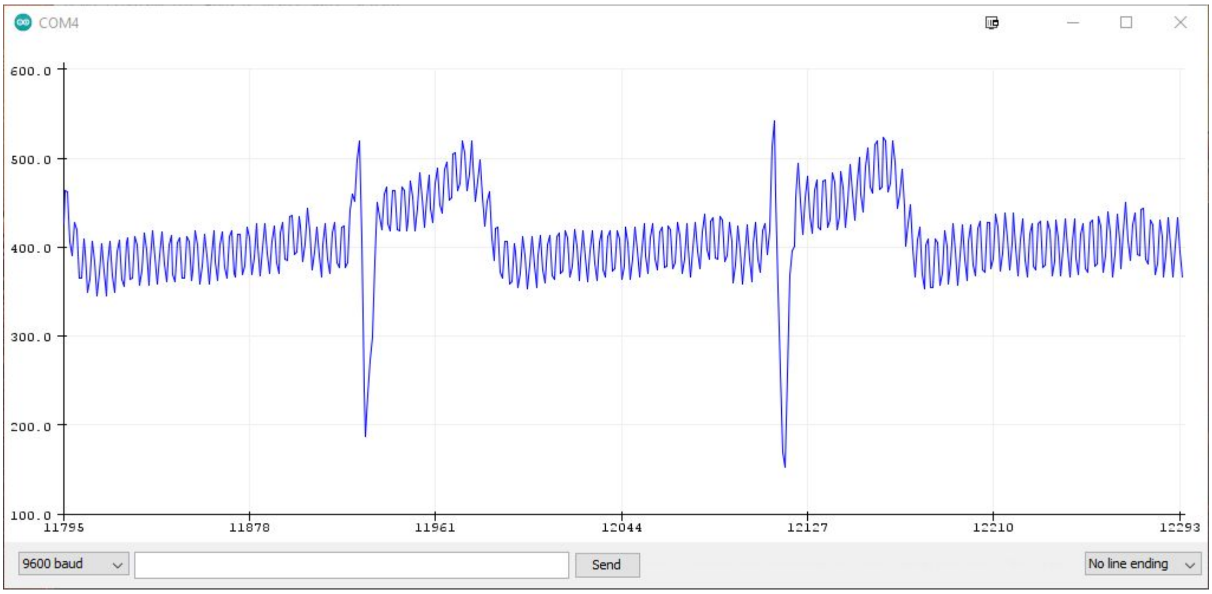



Appendix 5 - Heart rhythm data when the user has moved.

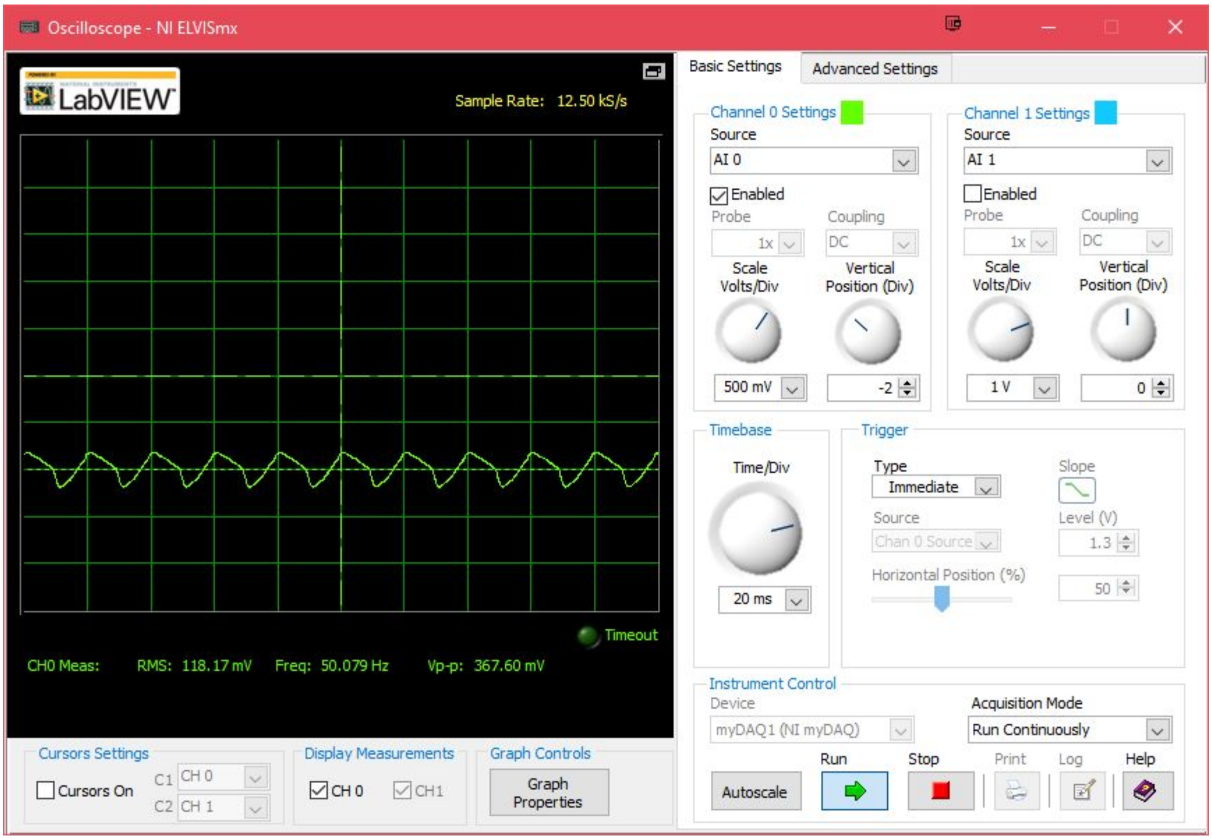


Appendix 6 - Heart rhythm data when the user has moved.

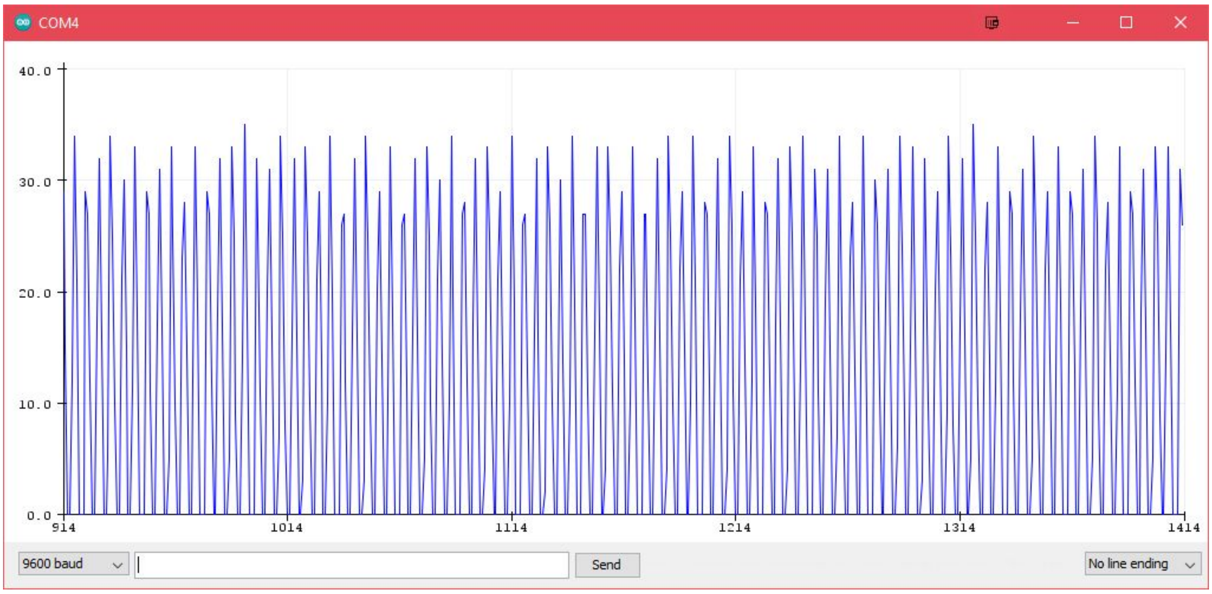
Appendix 7 - Heart rhythm data when the user has moved.




Appendix 8 - Heart rhythm data when the user is still.



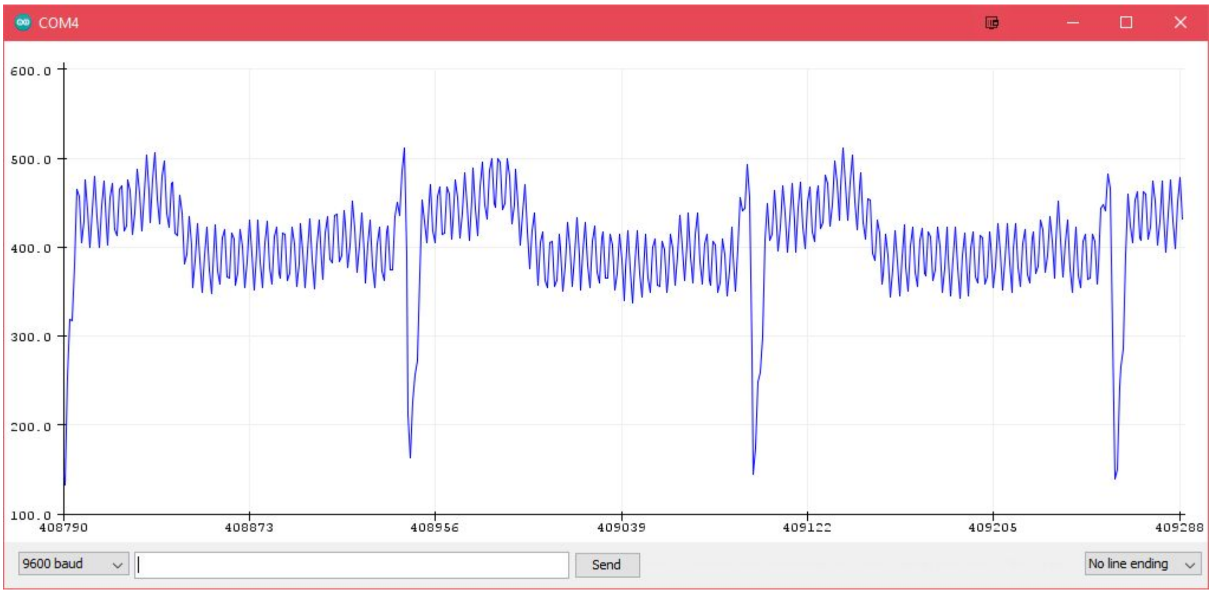

Appendix 9 - Noise on the HR circuit output observed when the circuit is unpowered but is otherwise connected to an Arduino.




Appendix 10 - Heart rhythm data when the HR circuit is unpowered.

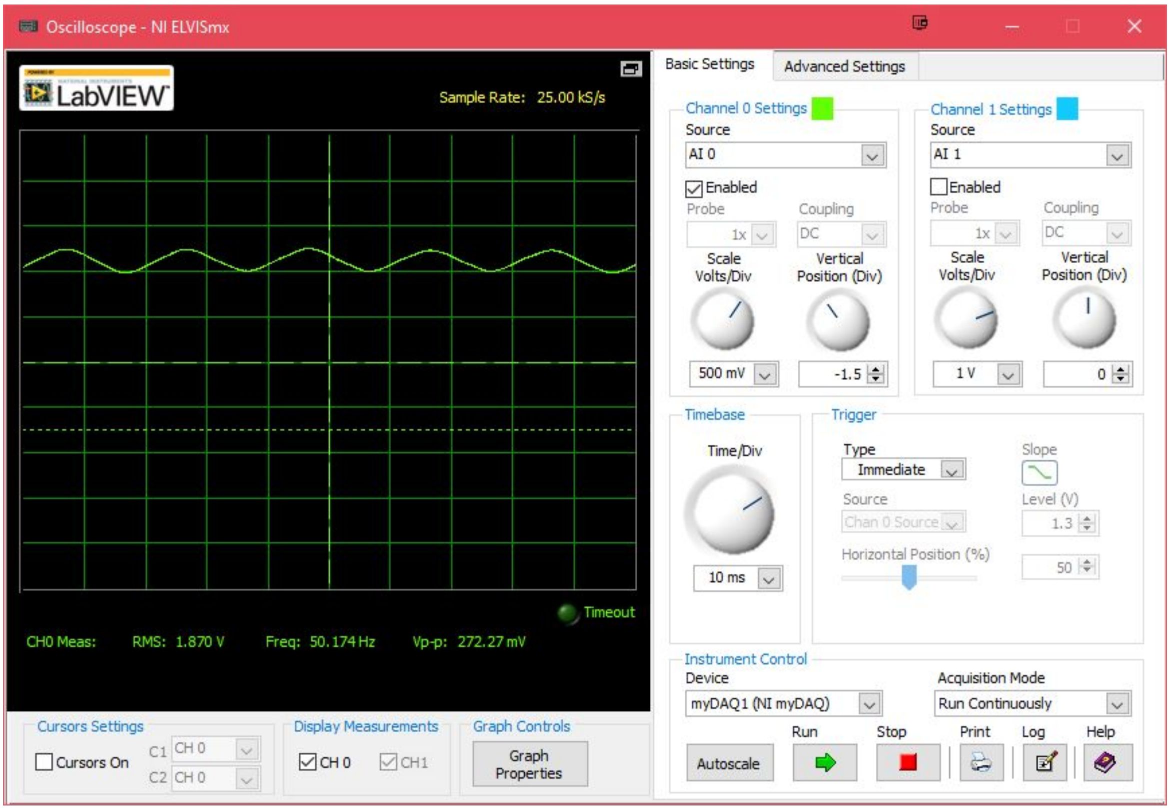
## Arduino Powered by 9V Battery


Appendix 11 - Heart rhythm data when the Arduino is powered by a 9V battery.

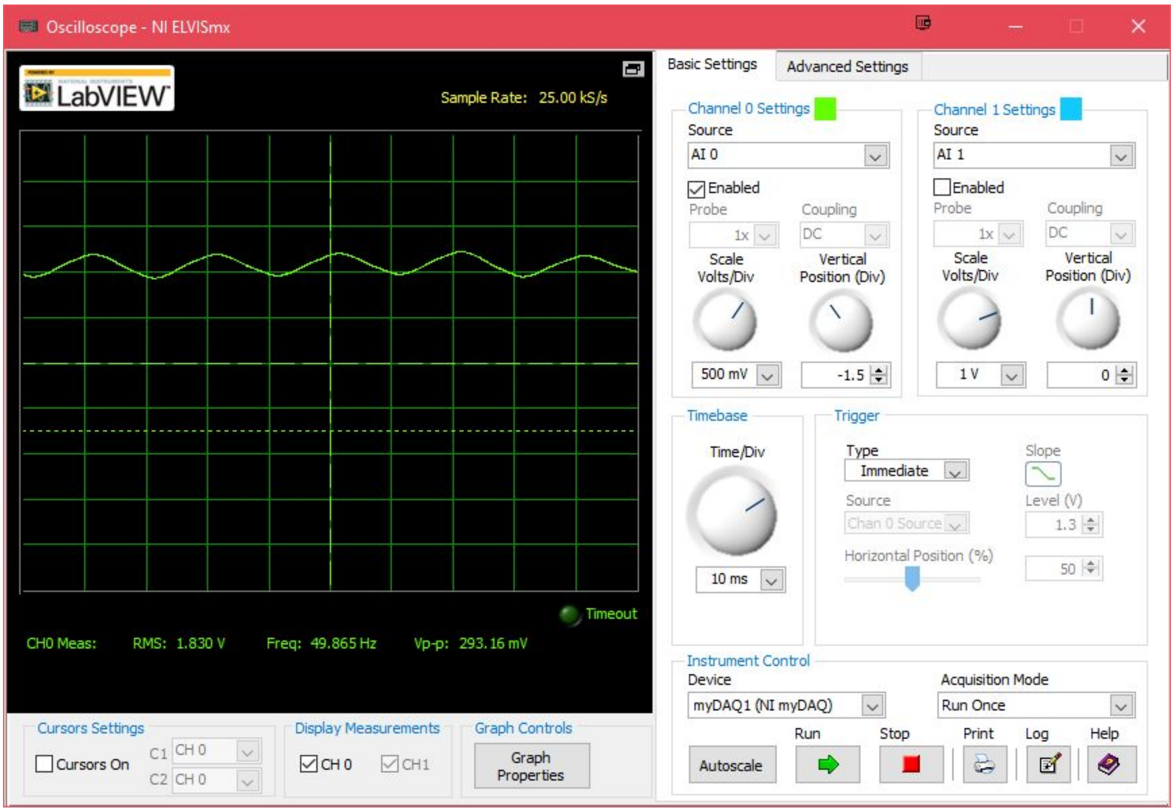



Appendix 12 - Heart rhythm data when the Arduino is powered by a 9V battery with a 100nF capacitor between AREF and GND.

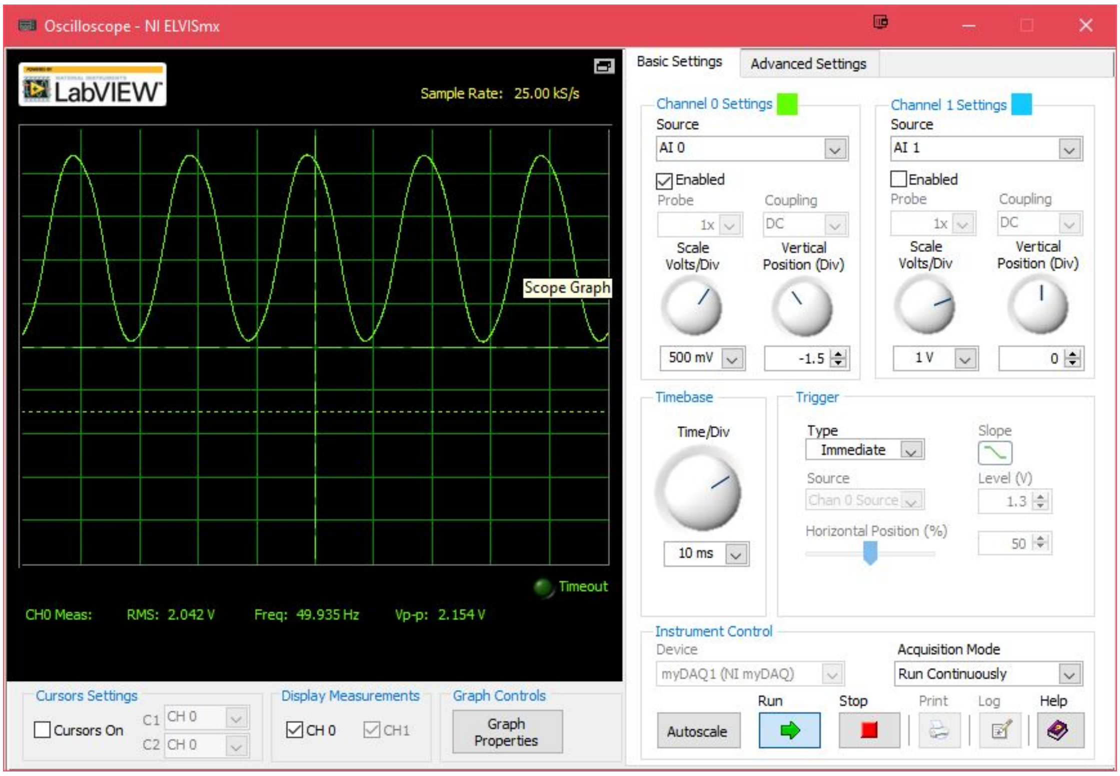

Appendix 13 - Heart rhythm data when the Arduino is USB powered.



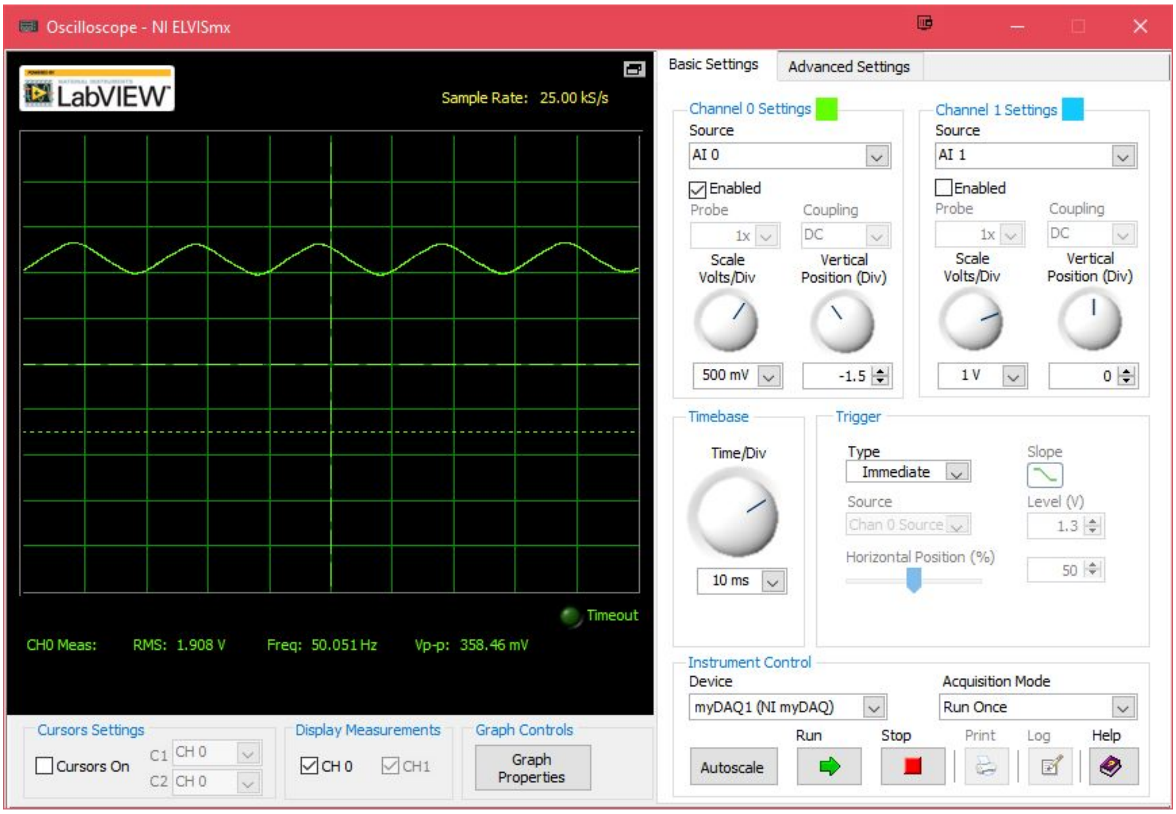

Appendix 14 - Noise on HR circuit output when the Arduino is powered by a 9V battery. 272.27mV



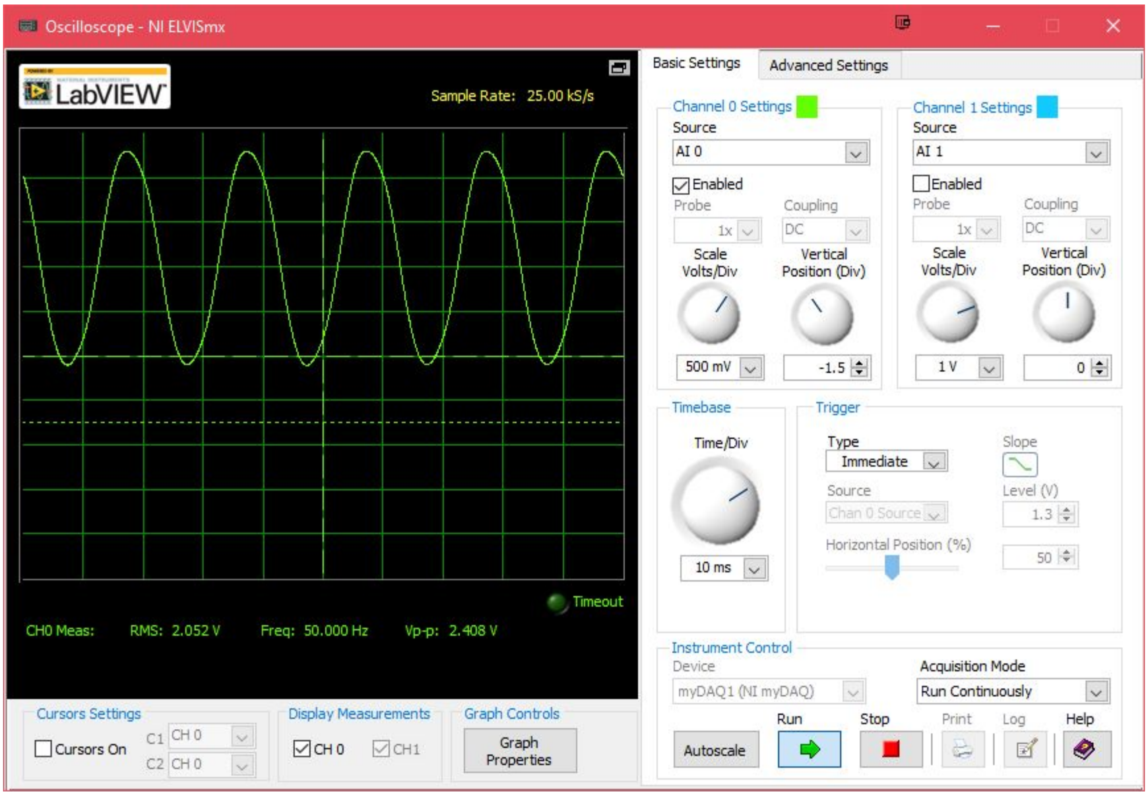

Appendix 15 - Noise on HR circuit output when the Arduino is powered by a 9V battery and a 100nF capacitor between AREF and GND. 293.16mV



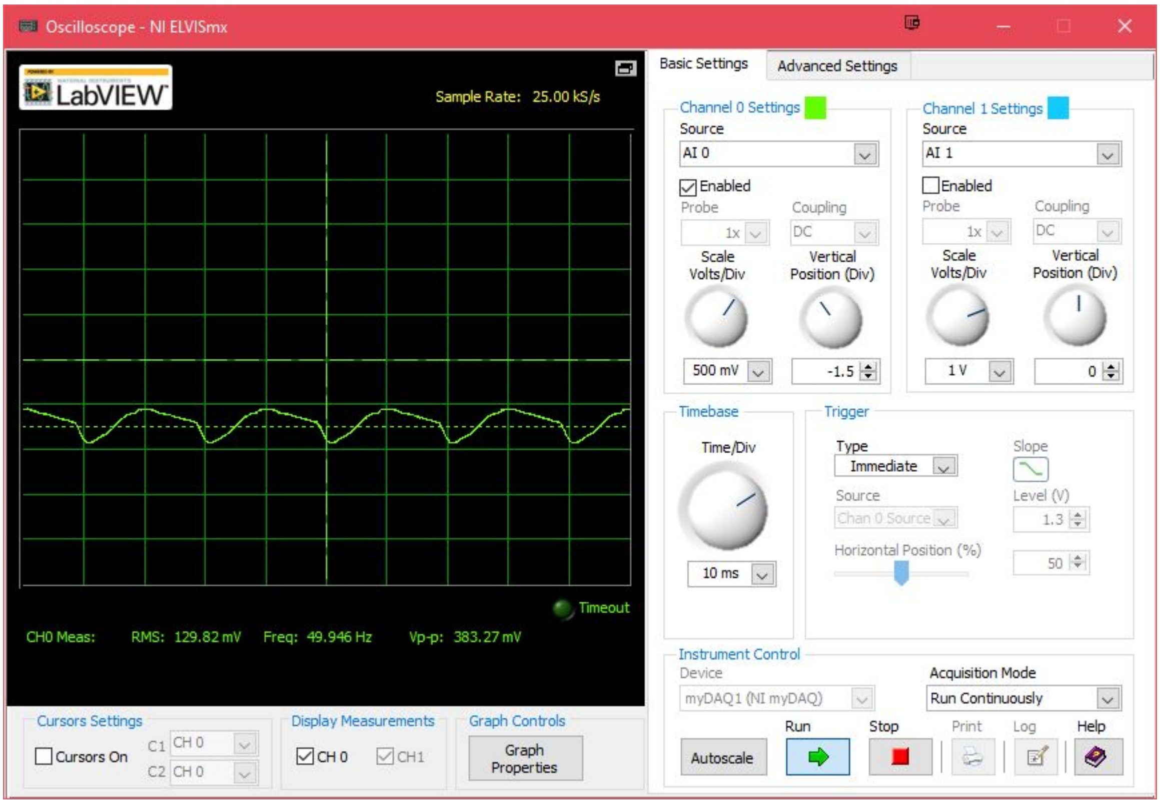

Appendix 16 - Noise on HR circuit output when the Arduino is powered by a 9V battery without the ECG cables attached. 2.154V



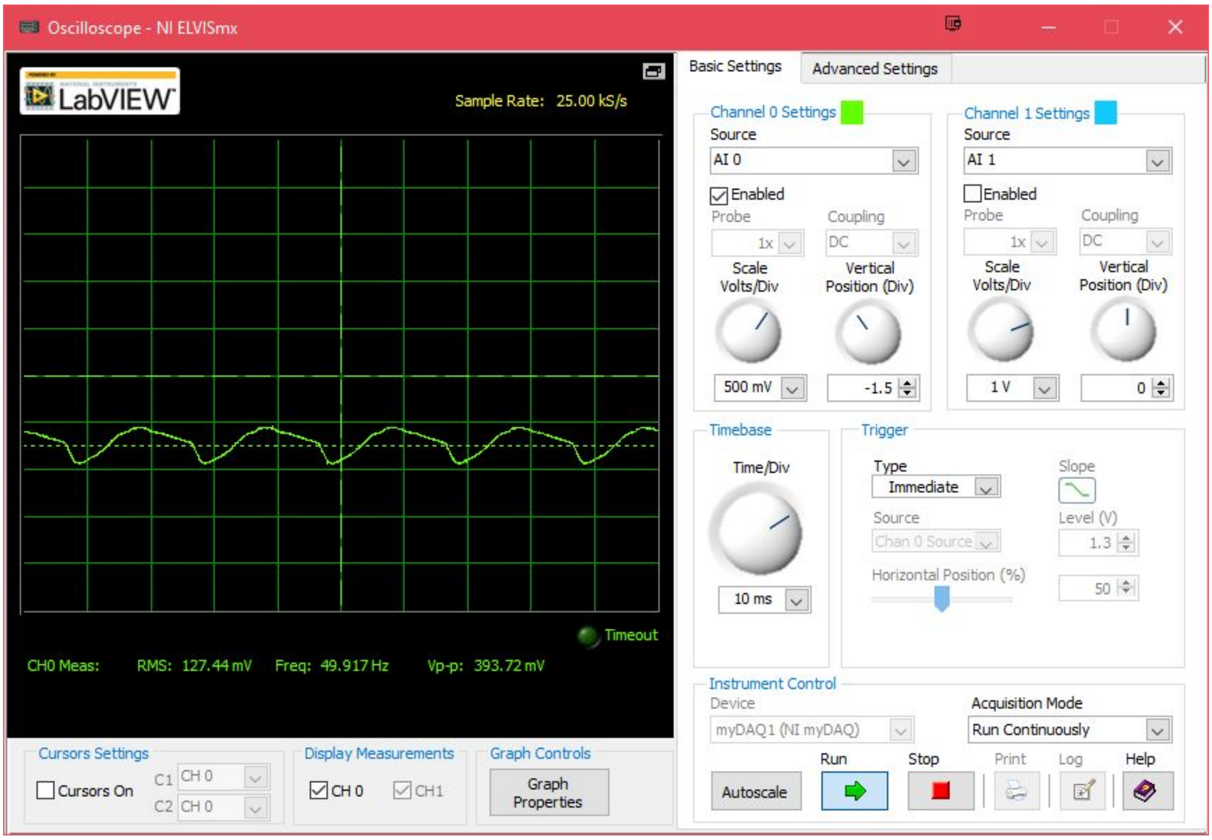

Appendix 17 - Noise on HR circuit output when the Arduino is powered by a USB port. 358.46mV




Appendix 18 - Noise on HR circuit output when the Arduino is powered by a USB port and no ECG cables attached. 2.408V



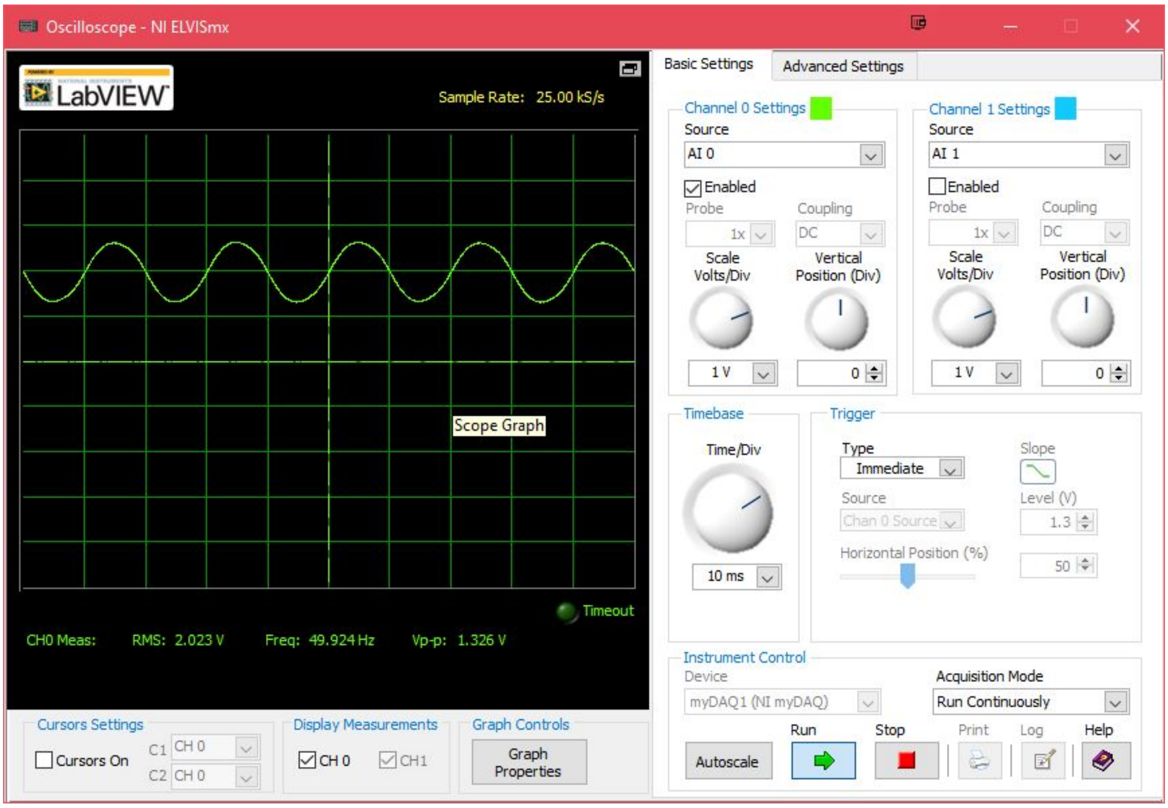

Appendix 19 - Noise on HR circuit output when the Arduino is powered by a 9V battery, and the HR circuit is unpowered without the ECG cable connected. 383.27mV



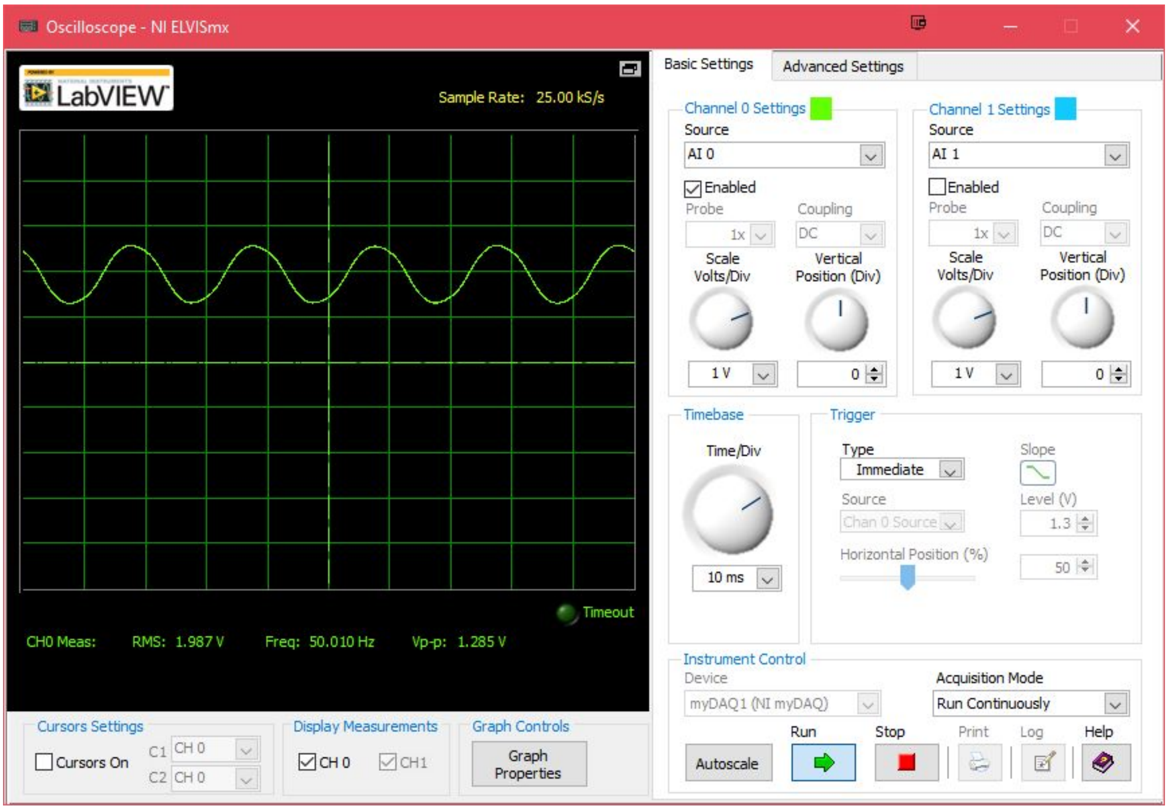

Appendix 20 - Noise on HR circuit output when the Arduino is powered by a USB port, and the HR circuit is unpowered without the ECG cable connected. 393.72mV

## Complete System Shielded

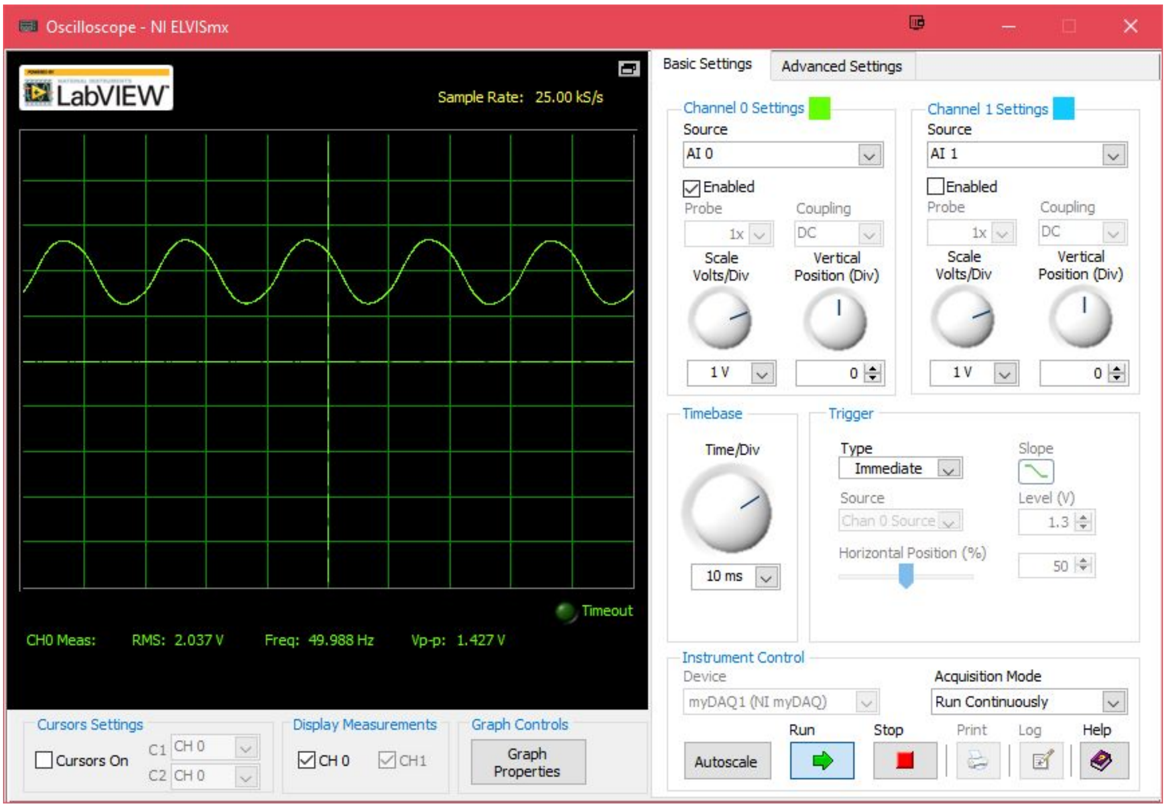
All tests in this section were done with the Arduino powered by USB, and both the Arduino and HR circuit are placed in a grounded metal enclosure.



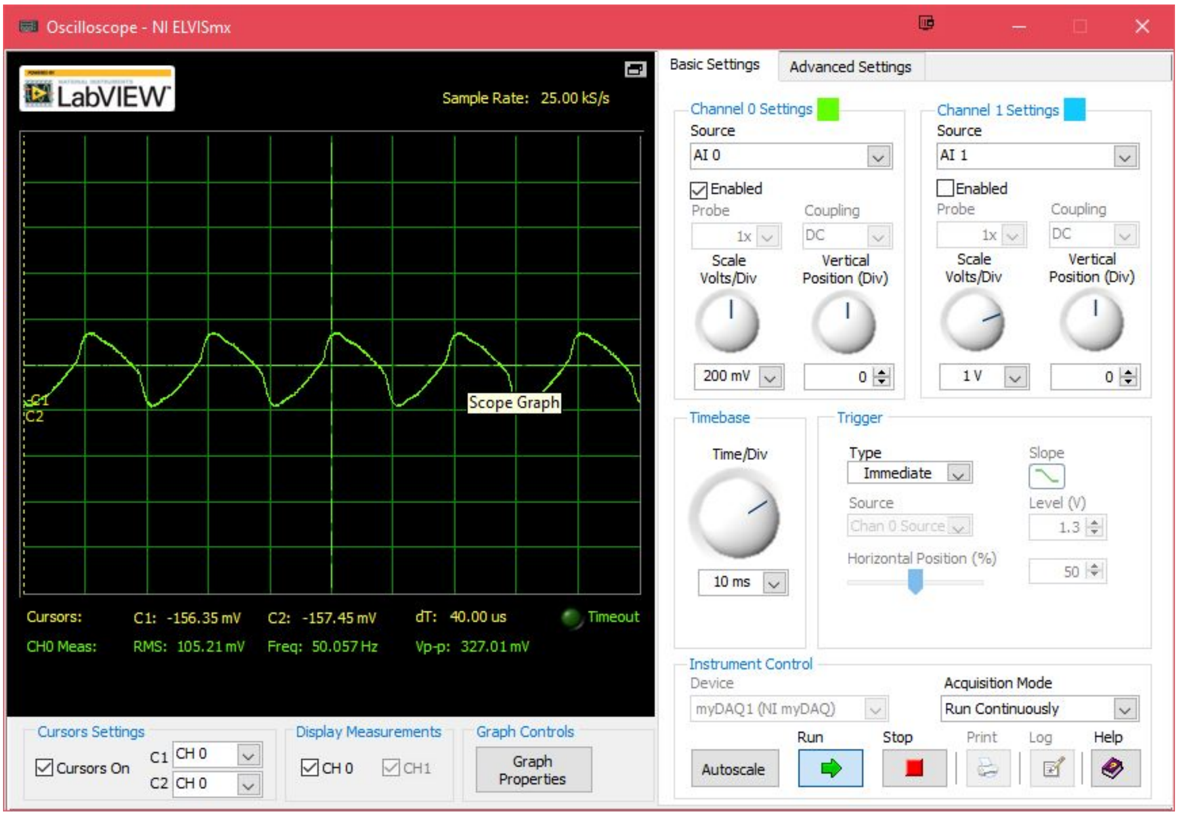

Appendix 21 - Noise on HR circuit output without the ECG cable connected and the grounded enclosure is closed. 1.325V



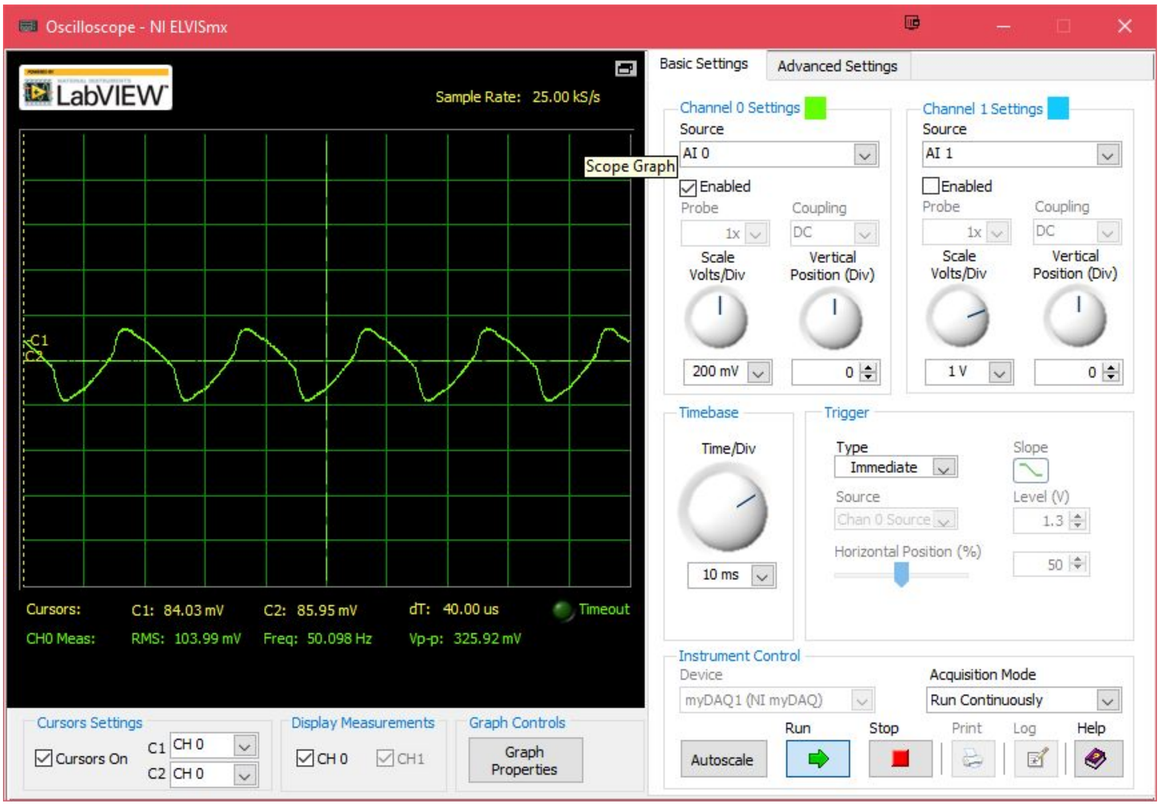

Appendix 22 - Noise on HR circuit output without the ECG cable connected and the grounded enclosure is half-open. 1.285V



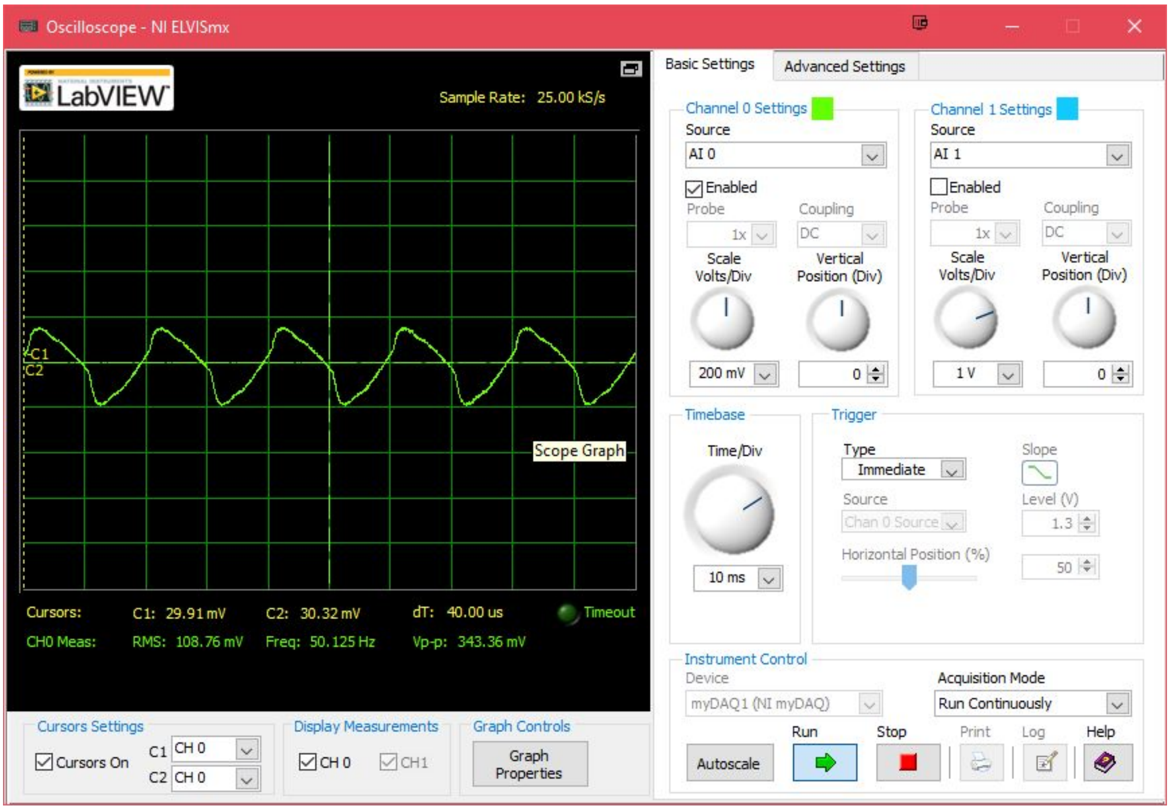

Appendix 23 - Noise on HR circuit output without the ECG cable connected and the grounded enclosure is open. 1.427V



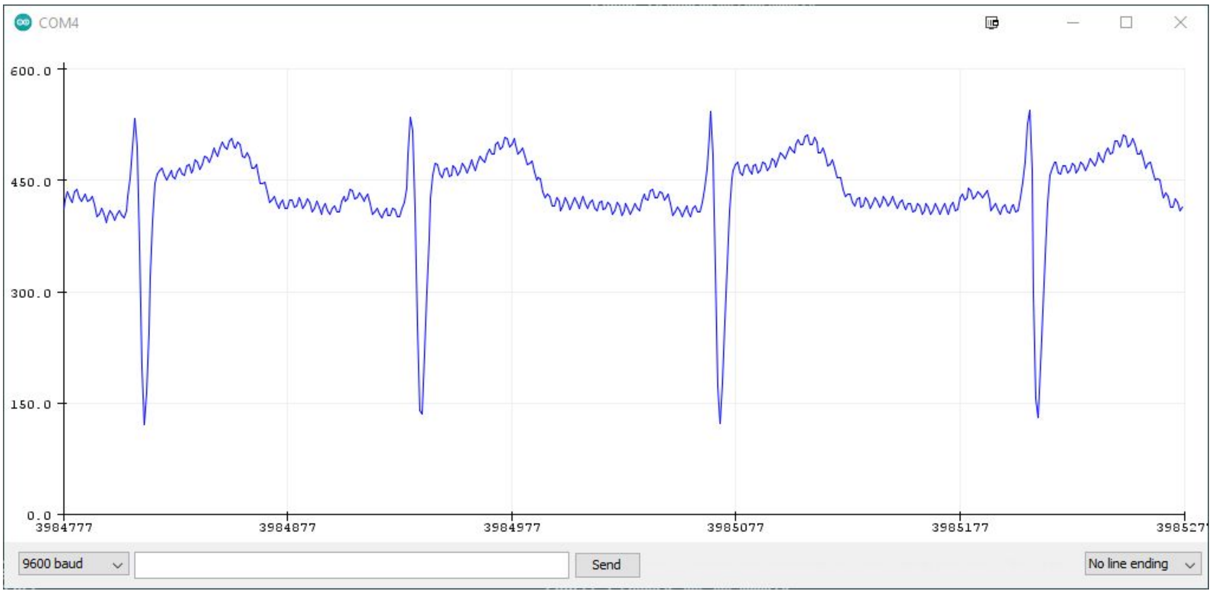

Appendix 24 - Noise on HR circuit output with the ECG cable connected and the grounded enclosure is closed. 327.01mV



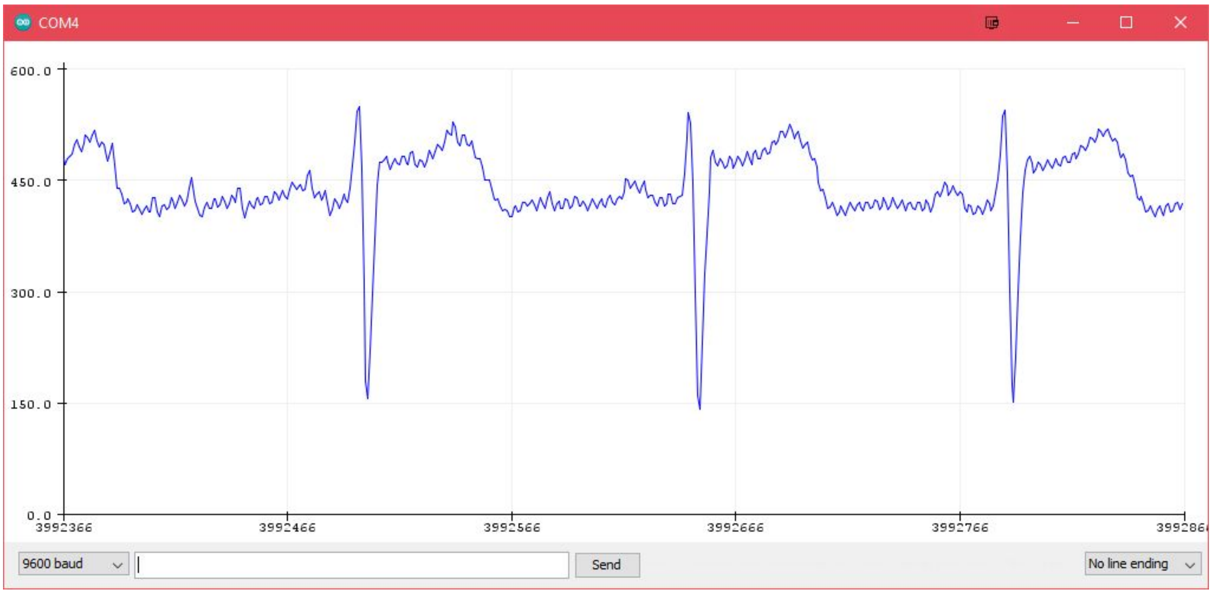

Appendix 25 - Noise on HR circuit output with the ECG cable connected and the grounded enclosure is half-open. 325.92mV



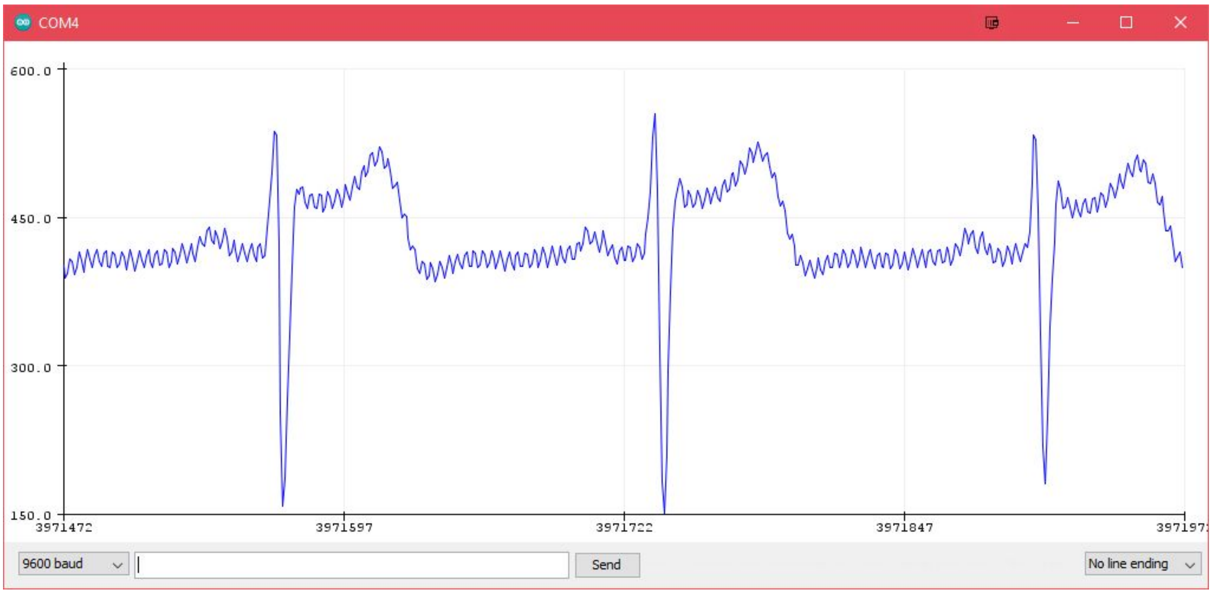

Appendix 26 - Noise on HR circuit output with the ECG cable connected and the grounded enclosure is open. 343.36mV




Appendix 27 - Heart rhythm data when the grounded enclosure is closed.



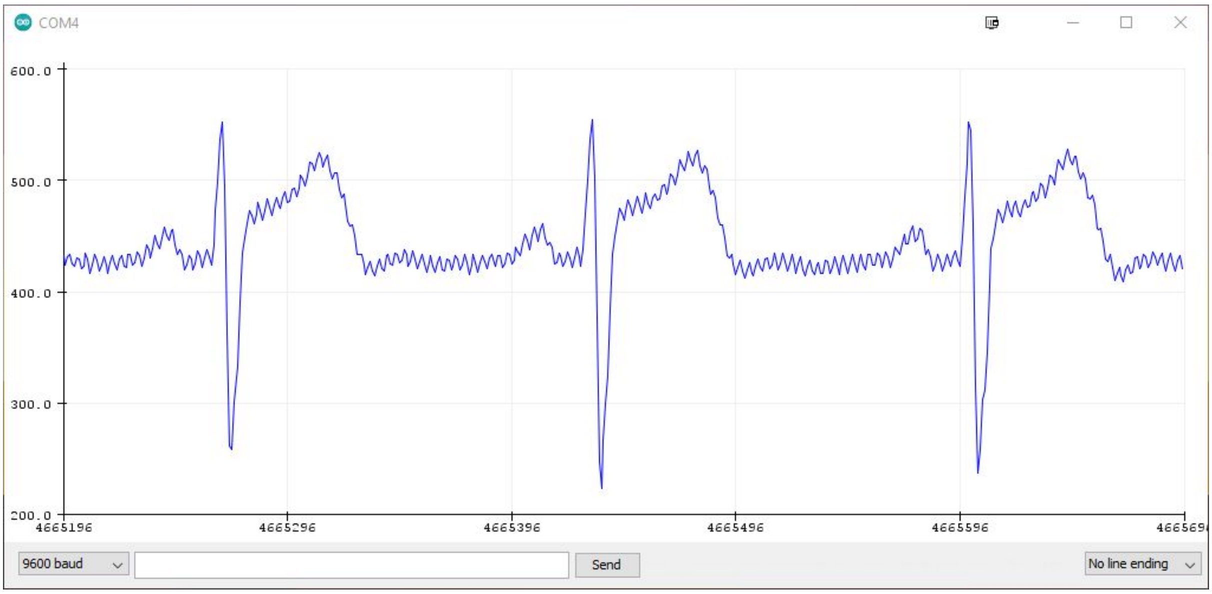

Appendix 28 - Heart rhythm data when the grounded enclosure is closed and the user's arm is not rested.



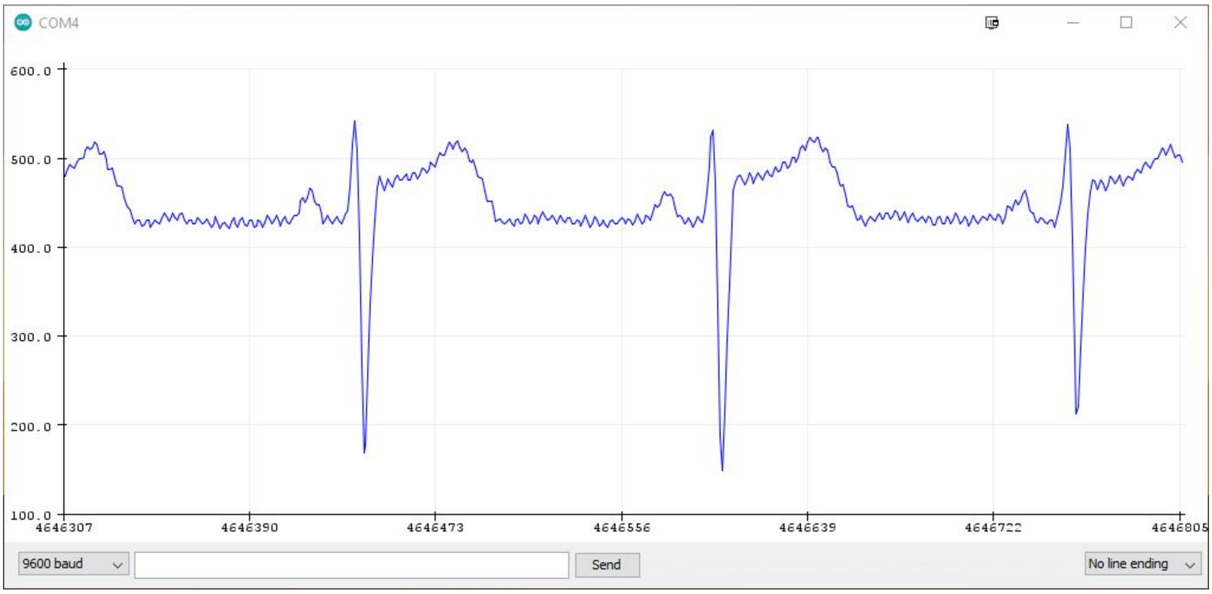

Appendix 29 - Heart rhythm data when the grounded enclosure is open.

## Distance Test

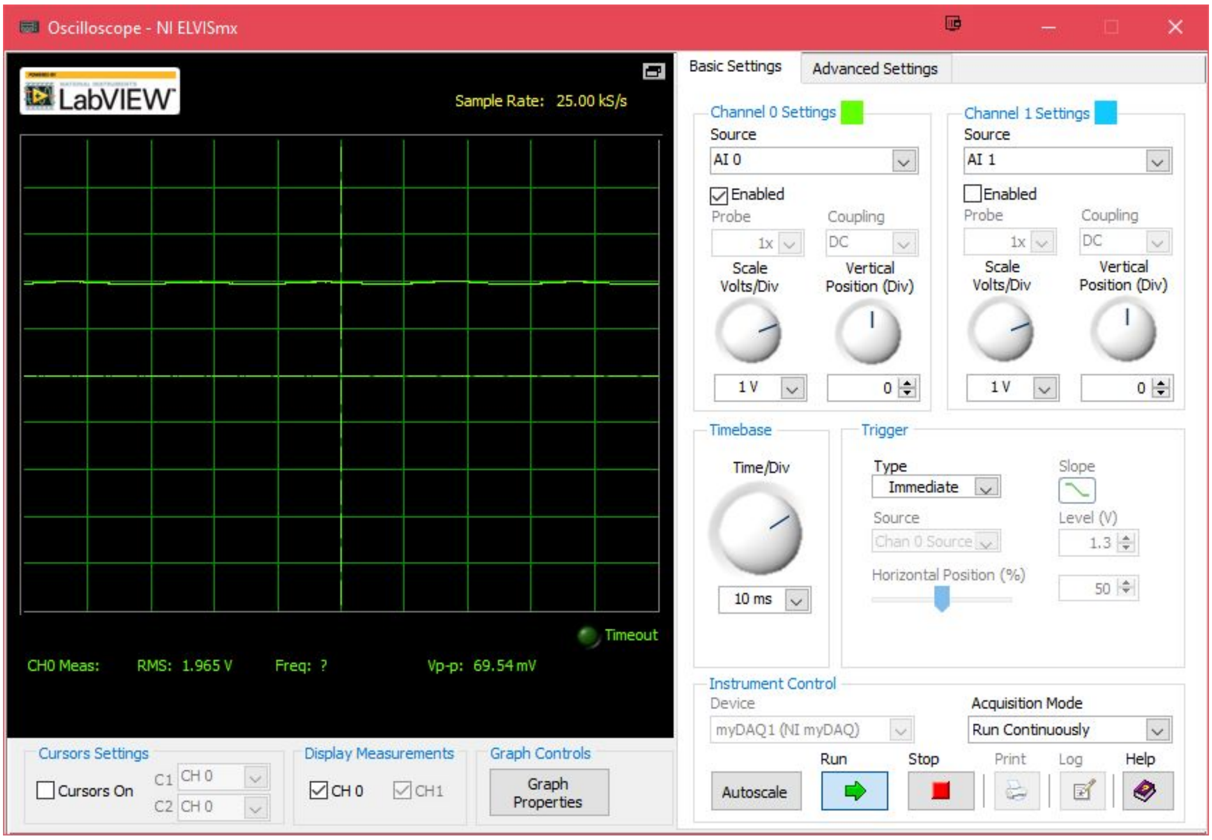
This testing was done with the complete system in the grounded enclosure.



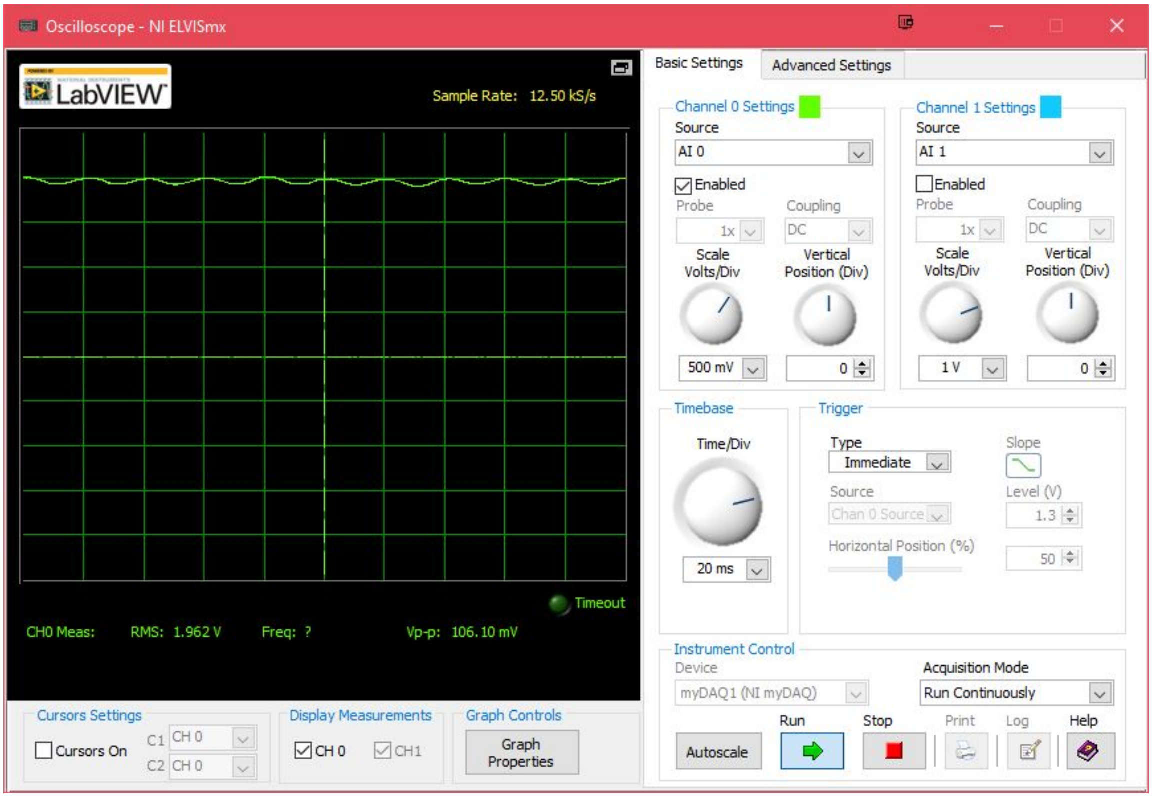

Appendix 30 - Heart rhythm data when the grounded enclosure is closed and moved 120cm away from the original testing position.




Appendix 31 - Heart rhythm data when the grounded enclosure is open and moved 120cm away from the original testing position. Be mindful of the y-axis having a different scale to previous screen capture.




Appendix 32 - Noise on HR circuit output with the ECG cable connected and the grounded enclosure is closed and 120cm away from the original testing position. 69.54mV

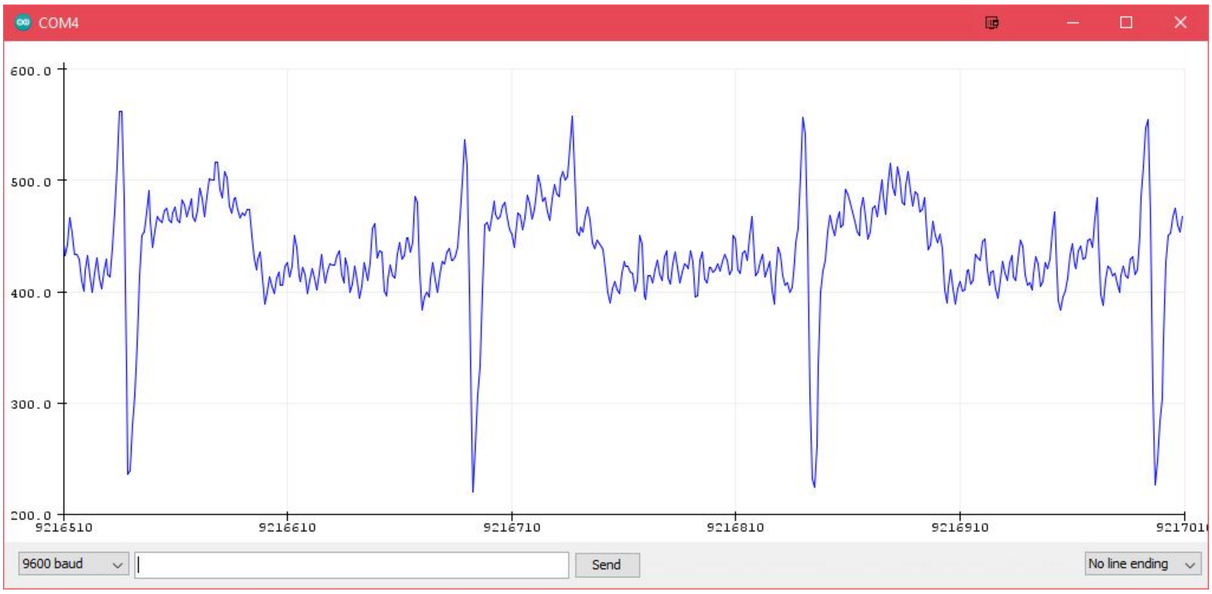



Appendix 33 - Noise on HR circuit output with the ECG cable connected and the grounded enclosure is open and 120cm away from the original testing position. 106.10mV

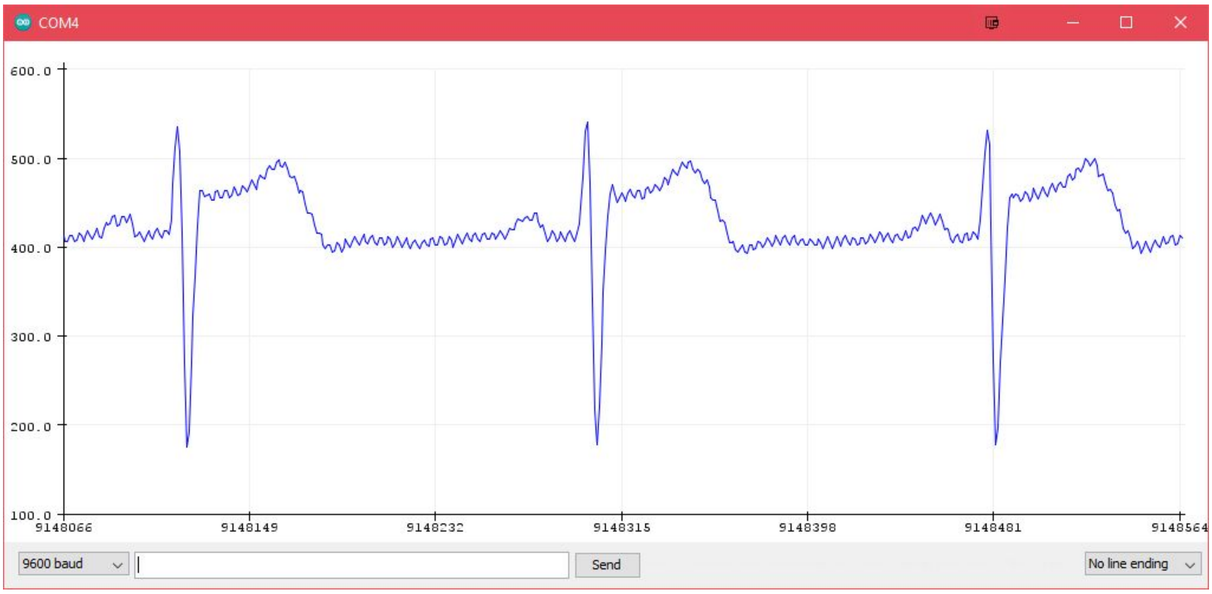
## HR Monitor Shielded

This testing was performed at the original testing location with the HR sensor placed in the grounded enclosure with the Arduino placed outside.

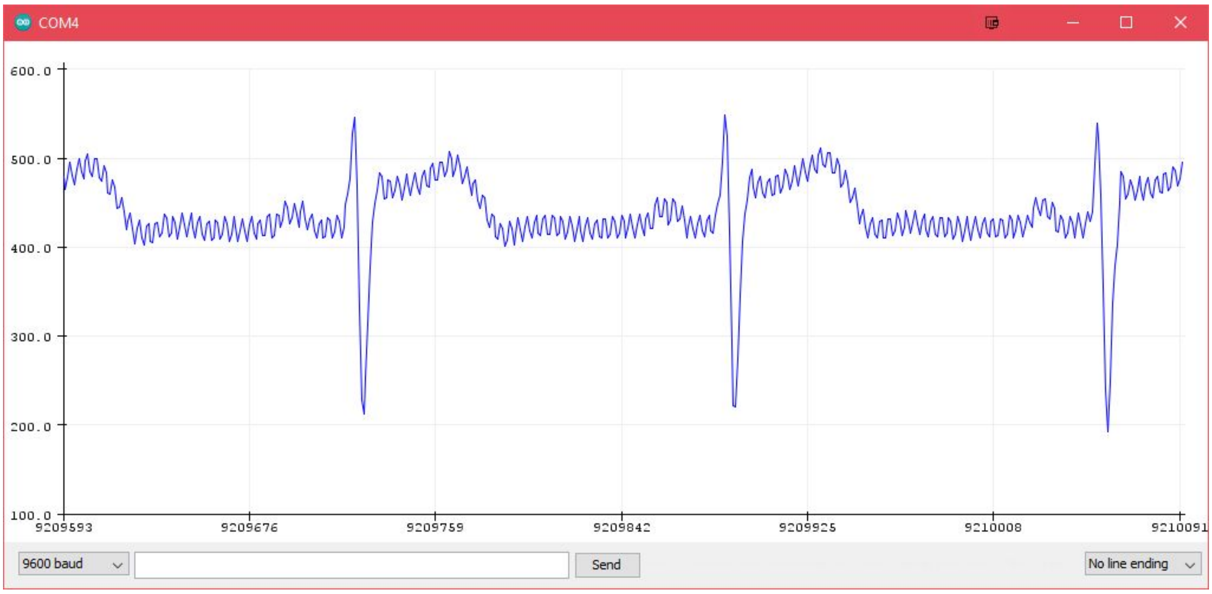

Appendix 34 - Heart rhythm data when the grounded enclosure is closed.



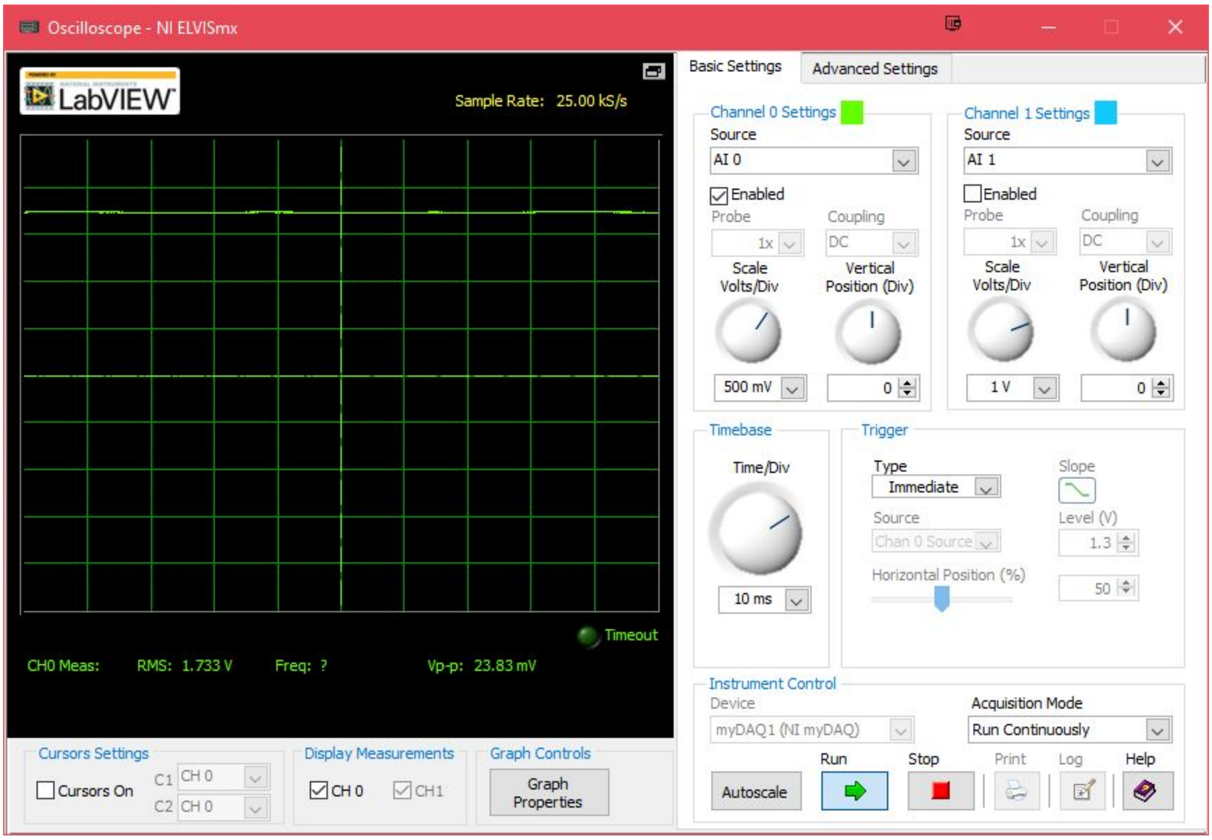

Appendix 35 - Heart rhythm data when the enclosure is closed and disconnected from the ground.



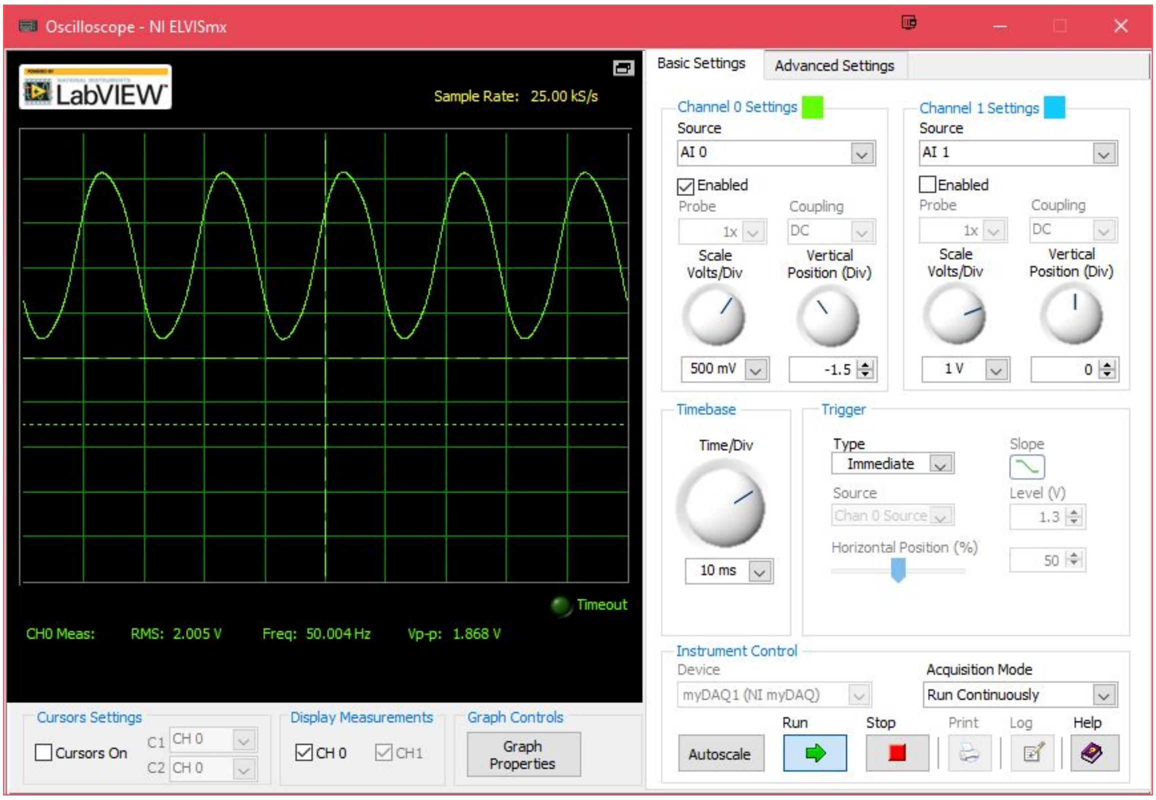

Appendix 36 - Heart rhythm data when the grounded enclosure is open.



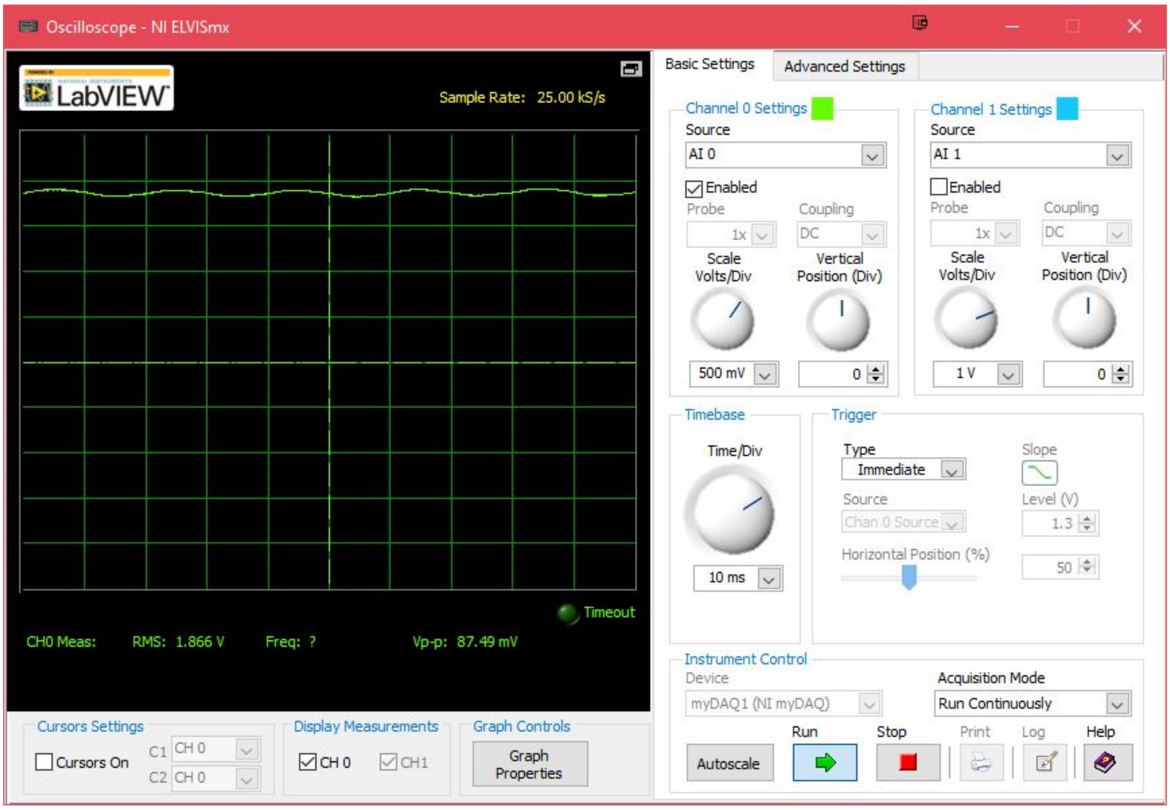

Appendix 37 - Heart rhythm data when the enclosure is open and disconnected from the ground.



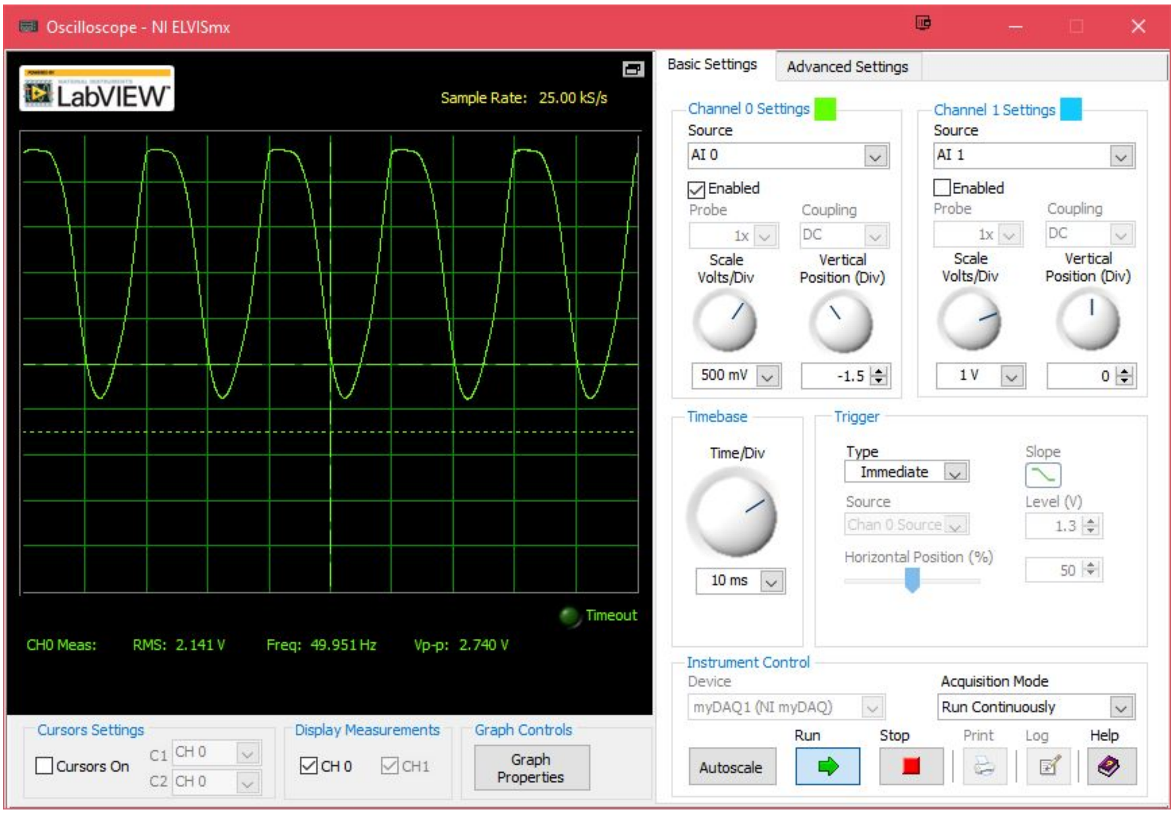

Appendix 38 - Noise on HR circuit output with the ECG cable connected and the grounded enclosure is closed. 23.83mV



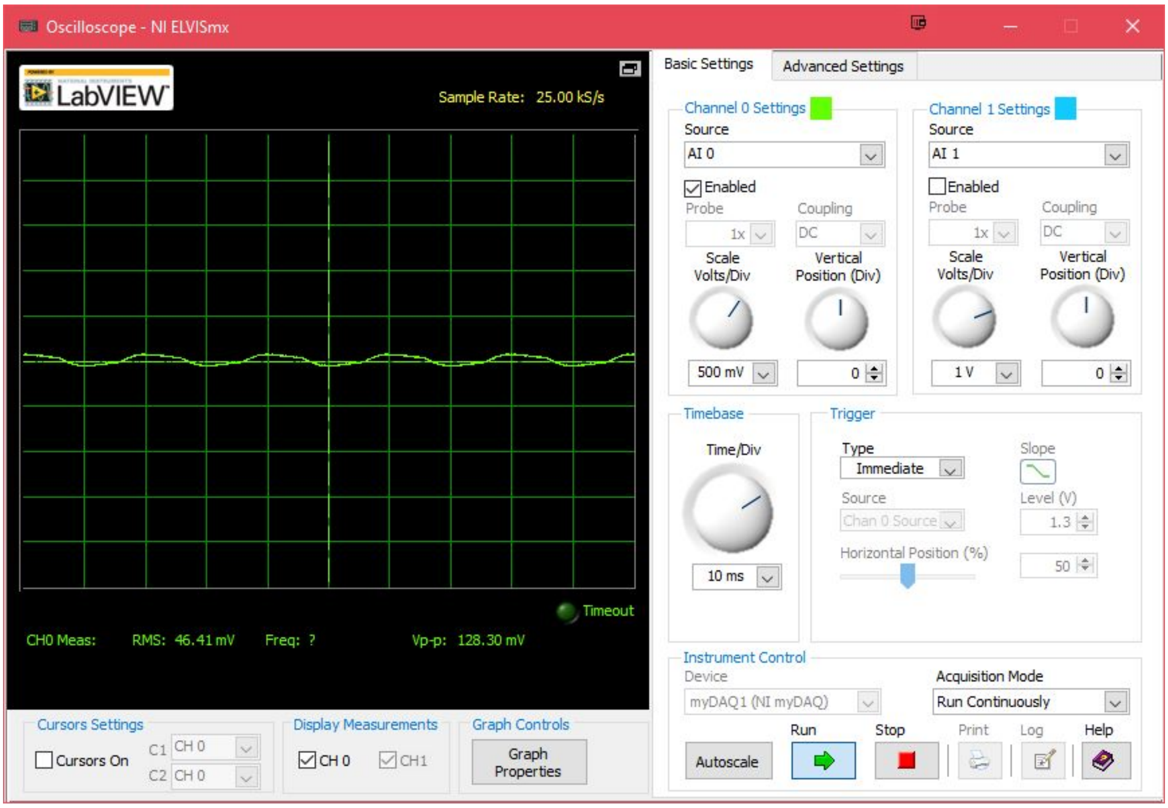

Appendix 39 - Noise on HR circuit output with the ECG cable connected and the enclosure is closed and disconnected from ground. 1.868V



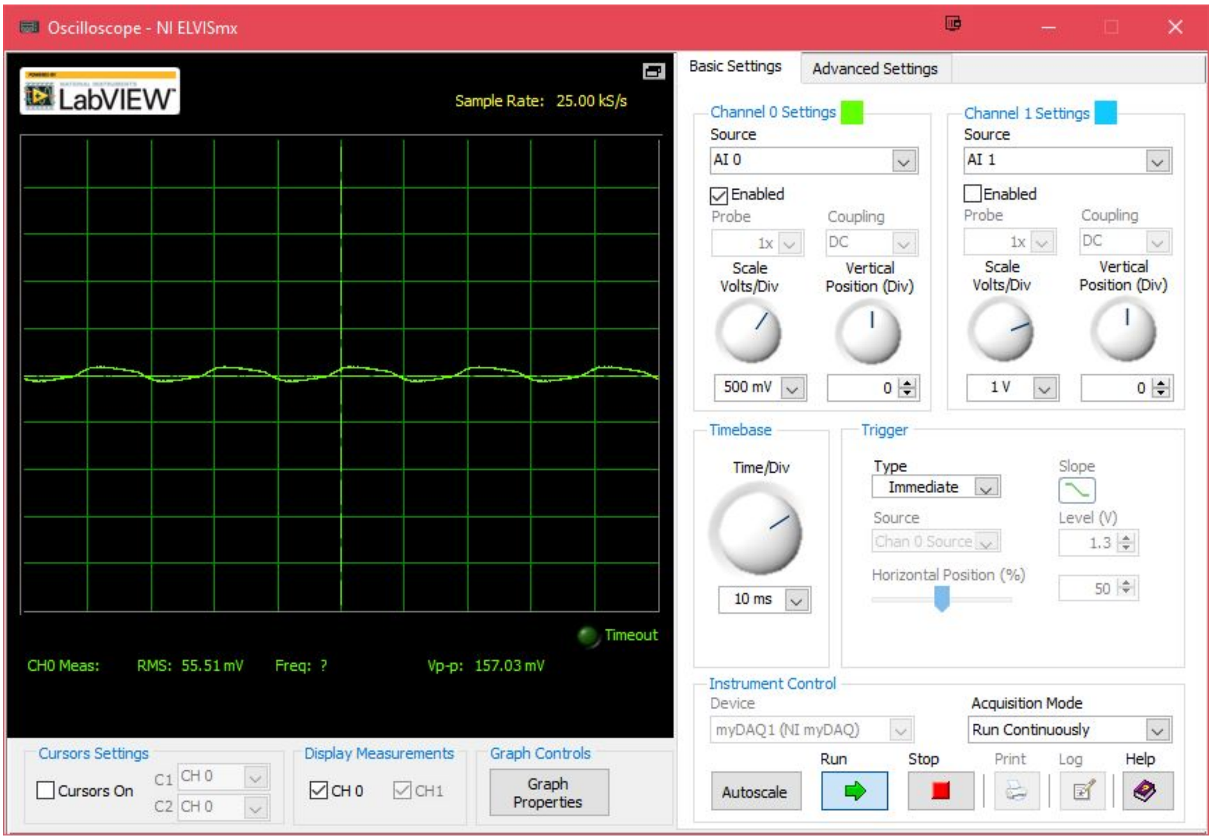

Appendix 40 - Noise on HR circuit output with the ECG cable connected and the grounded enclosure is open. 87.49mV




Appendix 41 - Noise on HR circuit output with the ECG cable connected and the enclosure is open and disconnected from the ground. 2.740V




Appendix 42 - Noise on HR circuit output when the HR circuit is unpowered, and the grounded enclosure is closed. 128.30mV

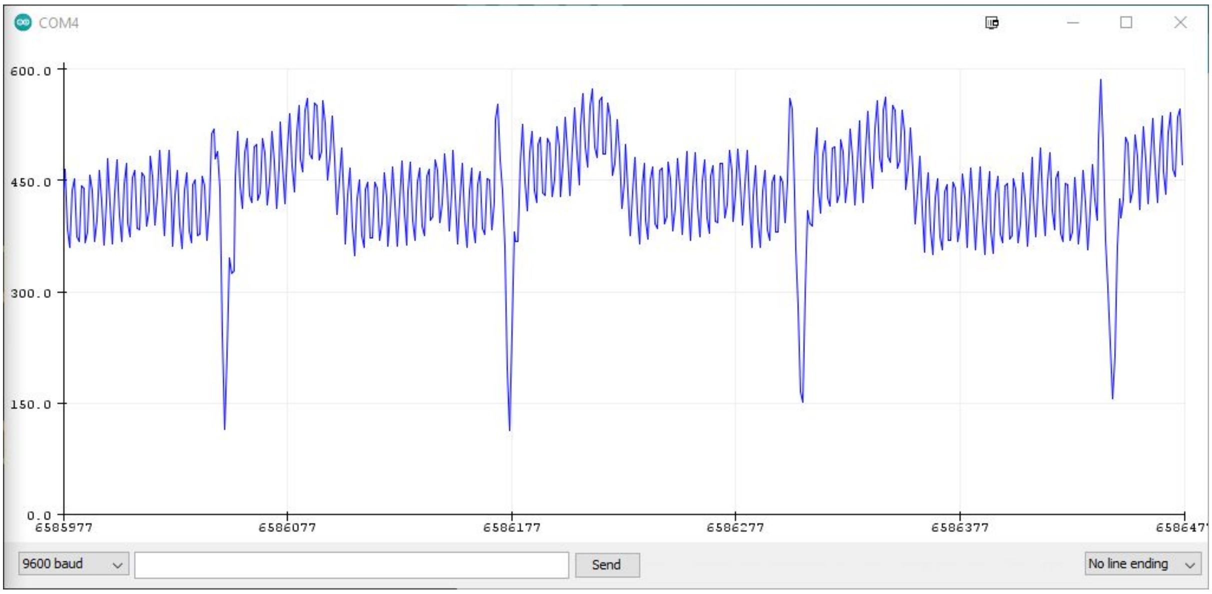



Appendix 43 - Noise on HR circuit output when the HR circuit is unpowered and the grounded enclosure is open. 157.03mV

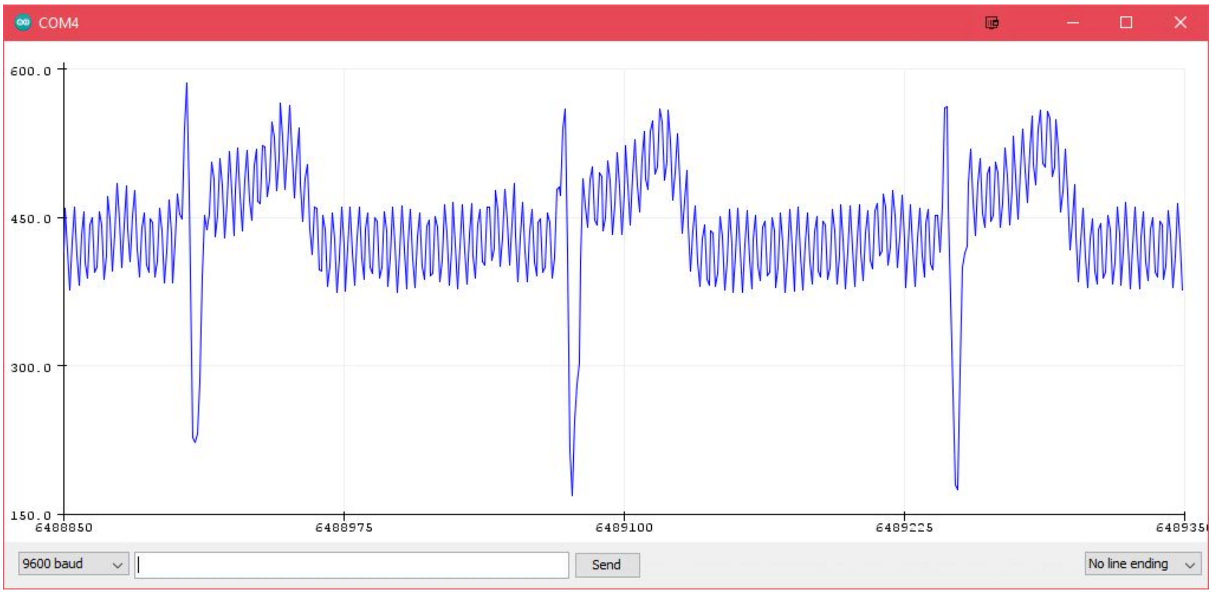
## Arduino Shielded

These tests were performed with the Arduino placed in the grounded enclosure and the HR sensor placed outside.

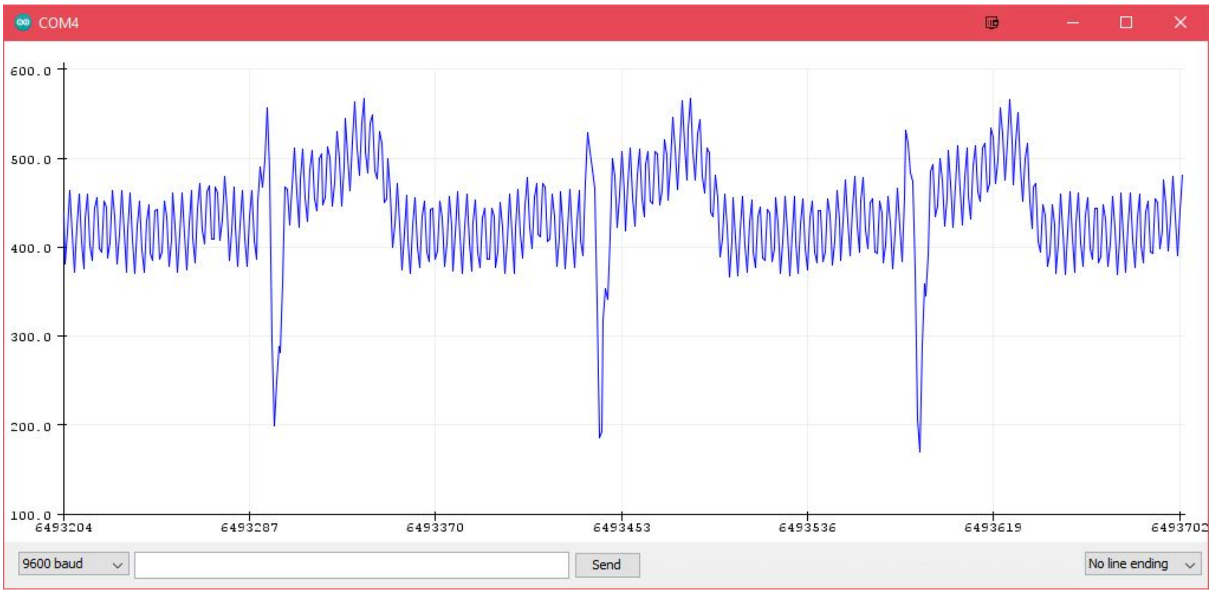

Appendix 44 - Heart rhythm data when the grounded enclosure is closed.



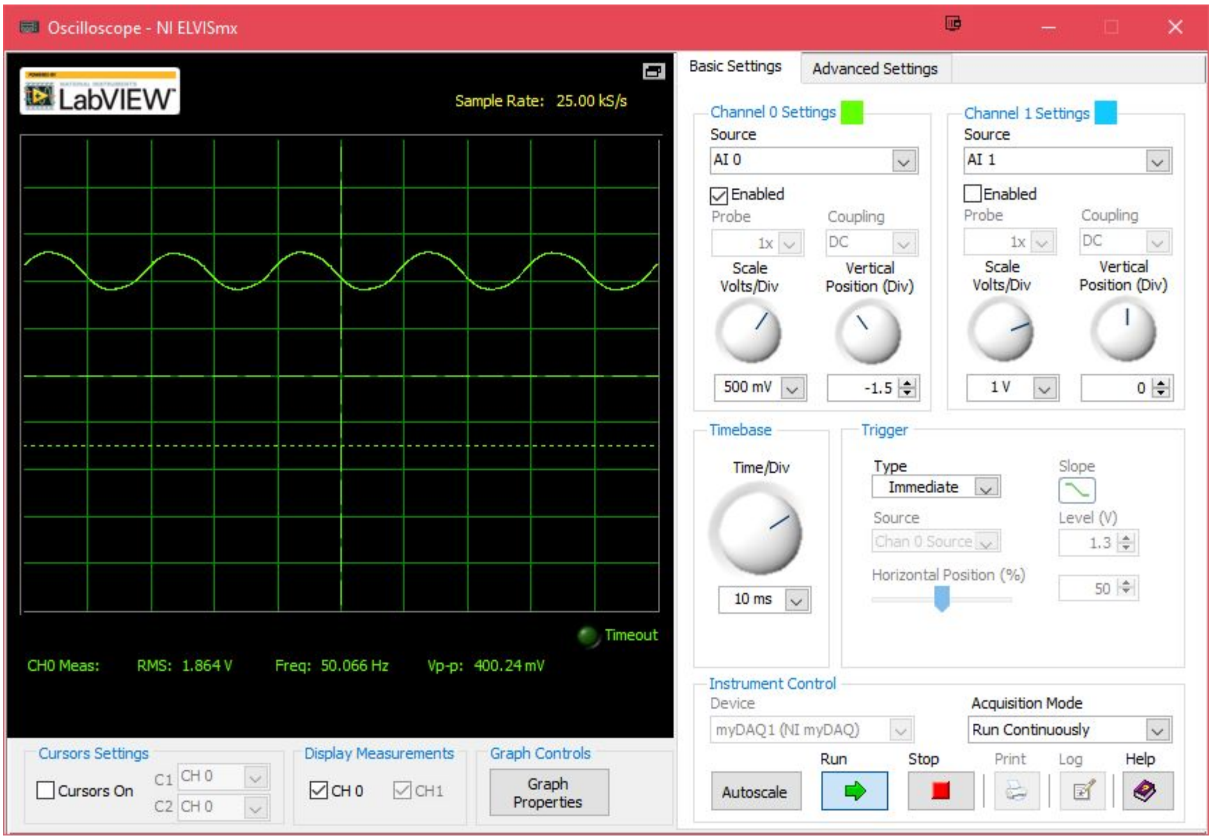

Appendix 45 - Heart rhythm data when the enclosure is closed and disconnected from the ground. Note the change in the y-axis scale.



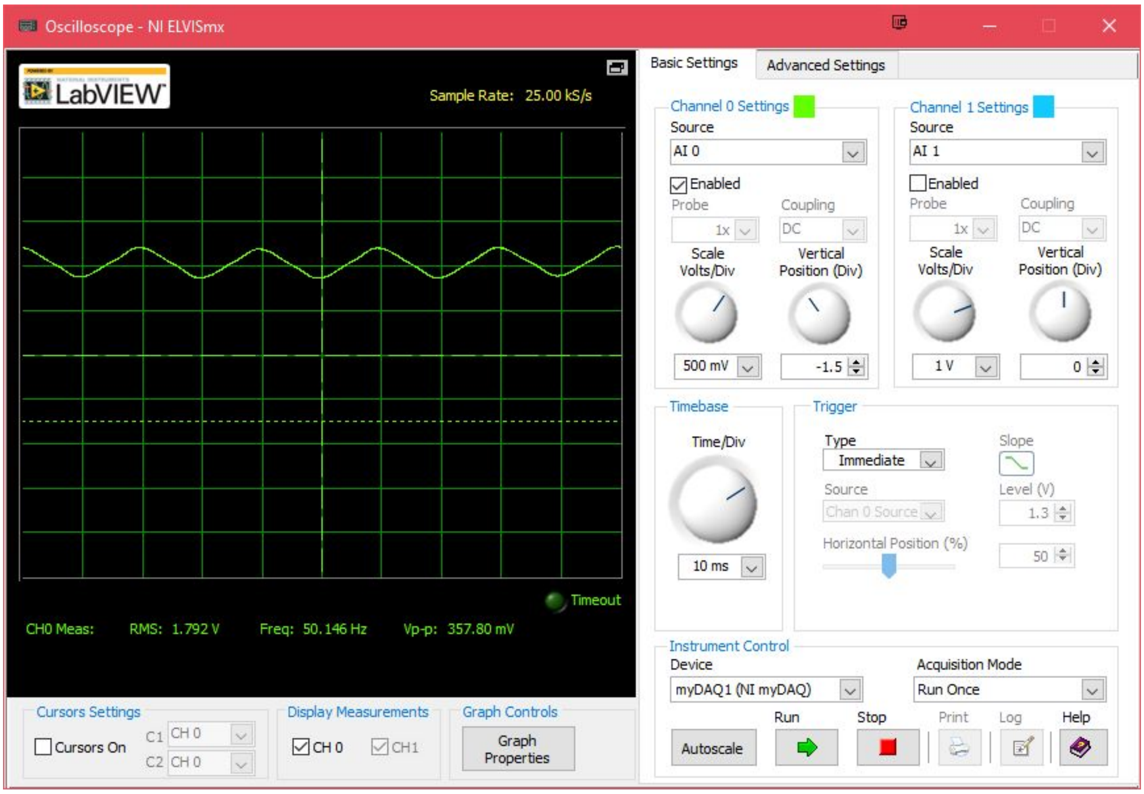

Appendix 46 - Heart rhythm data when the grounded enclosure is open.



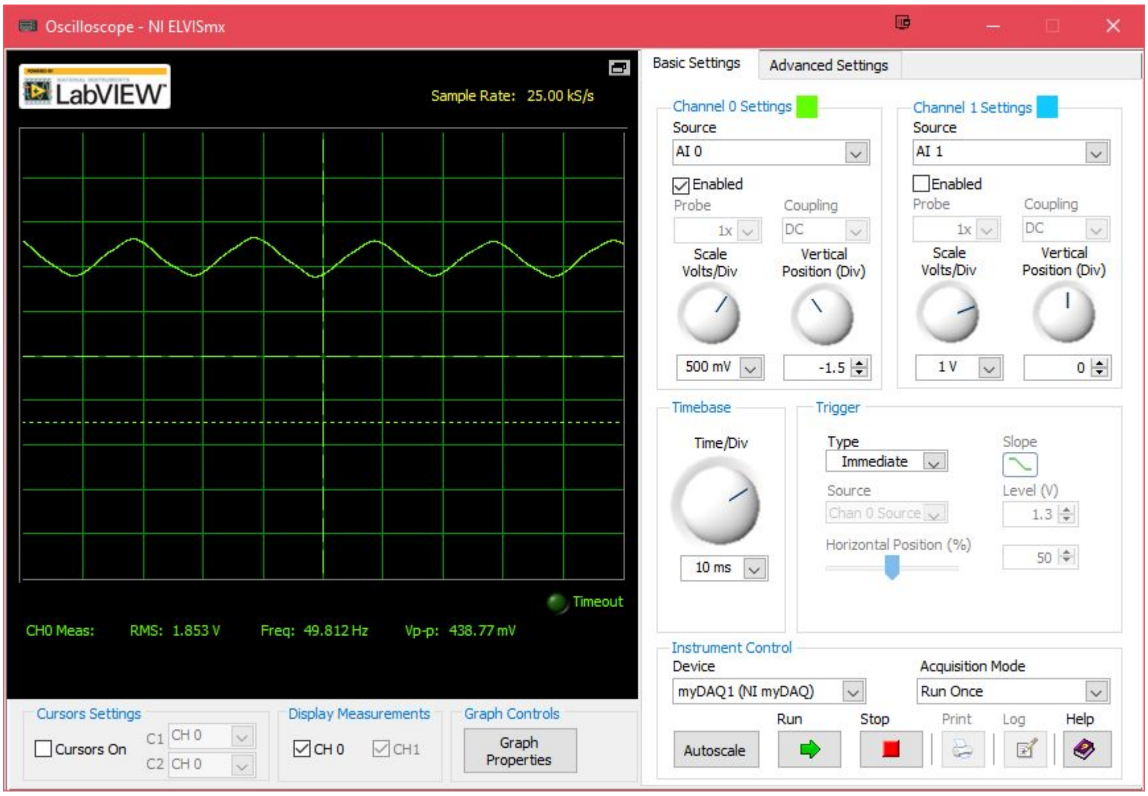

Appendix 47 - Heart rhythm data when the enclosure is open and disconnected from the ground. Note the change in y-axis scale.



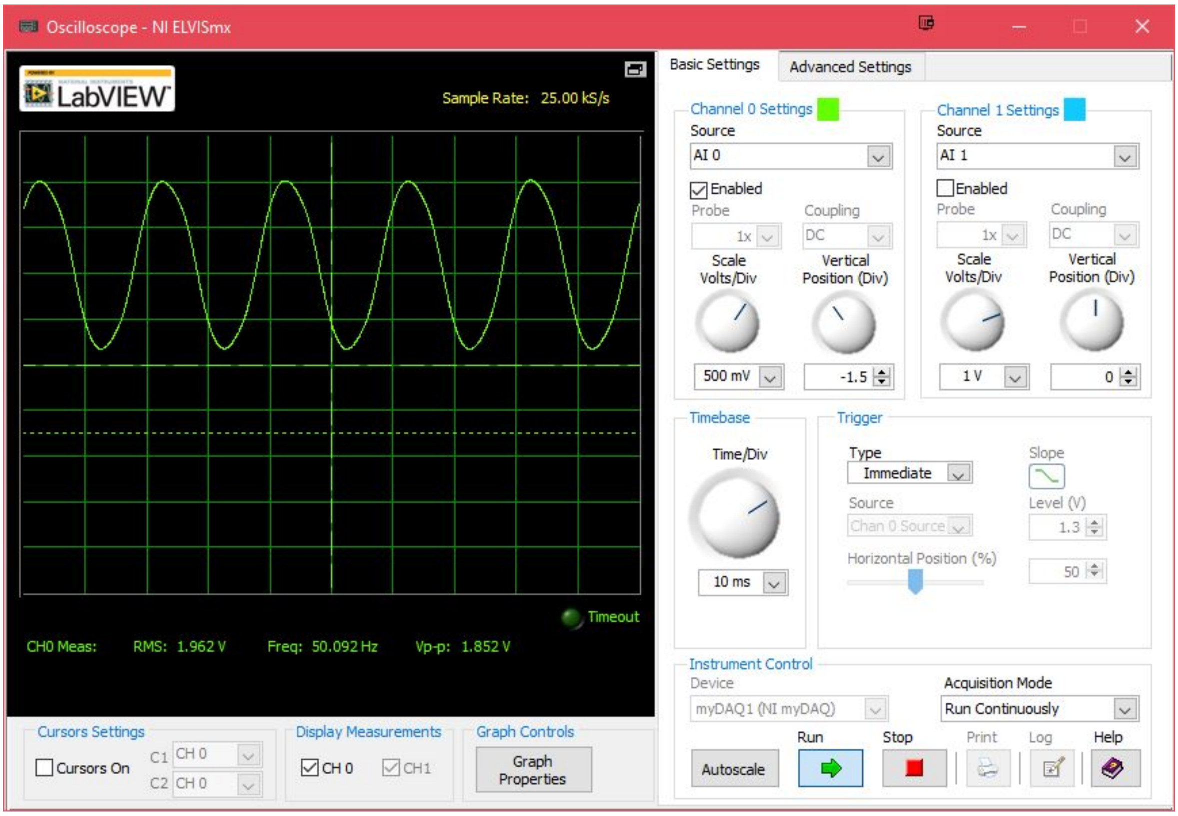

Appendix 48 - Noise on HR circuit output when the HR circuit is powered without the ECG cables and the grounded enclosure is closed. 400.24mV



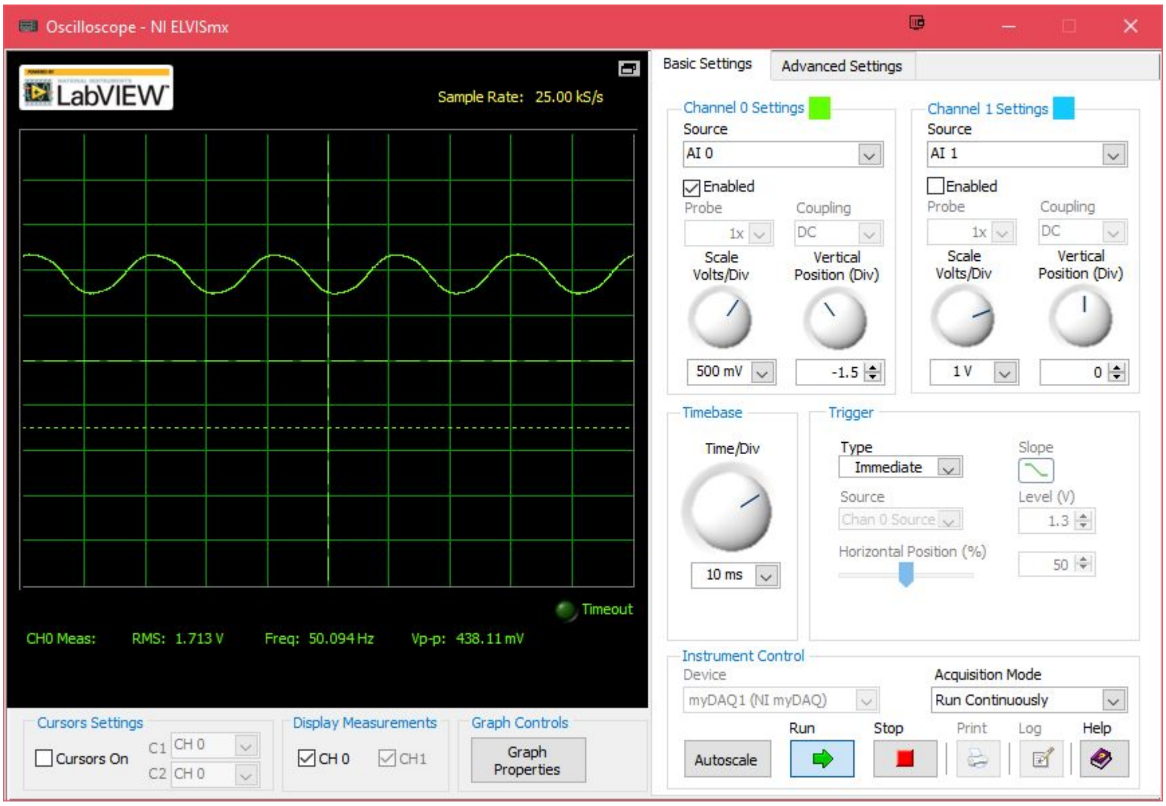

Appendix 49 - Noise on HR circuit output when the HR circuit is powered with the ECG cables and the grounded enclosure is closed. 357.80mV



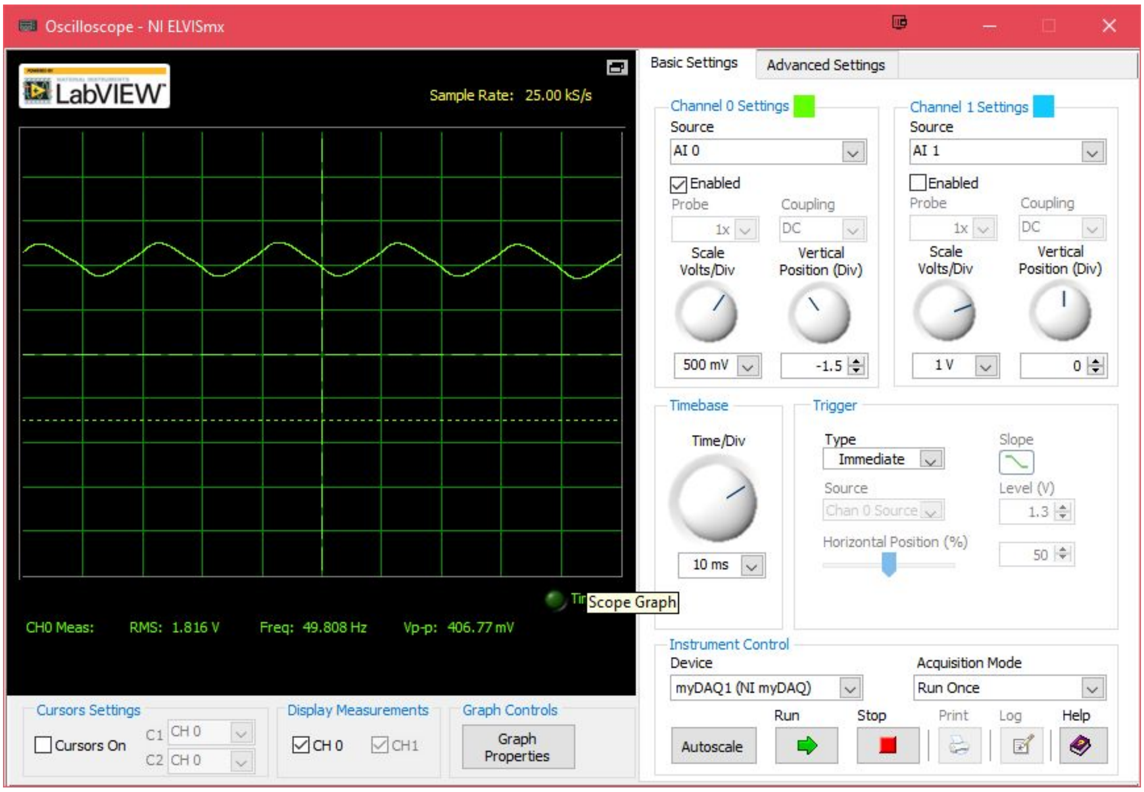

Appendix 50 - Noise on HR circuit output when the HR circuit is powered with the ECG cables connected, the enclosure is closed and disconnected from the ground. 438.77mV



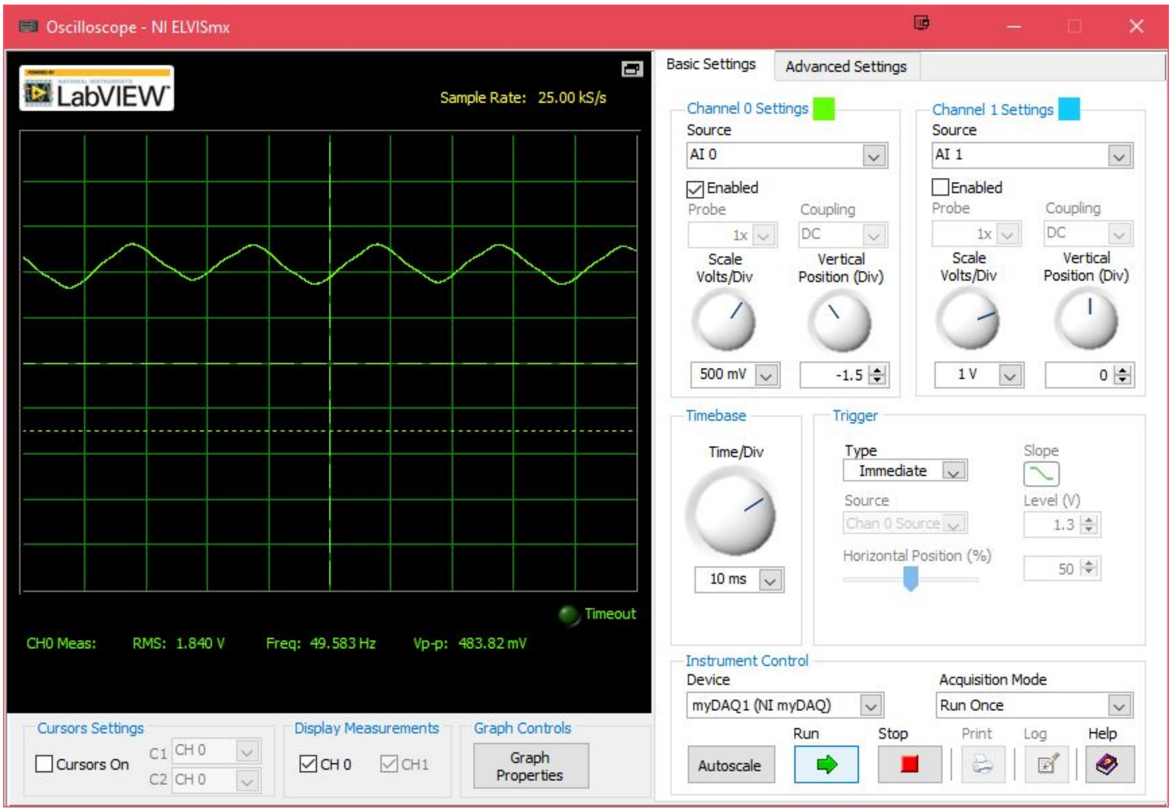

Appendix 51 - Noise on HR circuit output when the HR circuit is powered without the ECG cables and the enclosure is closed and disconnected from ground. 1.852V



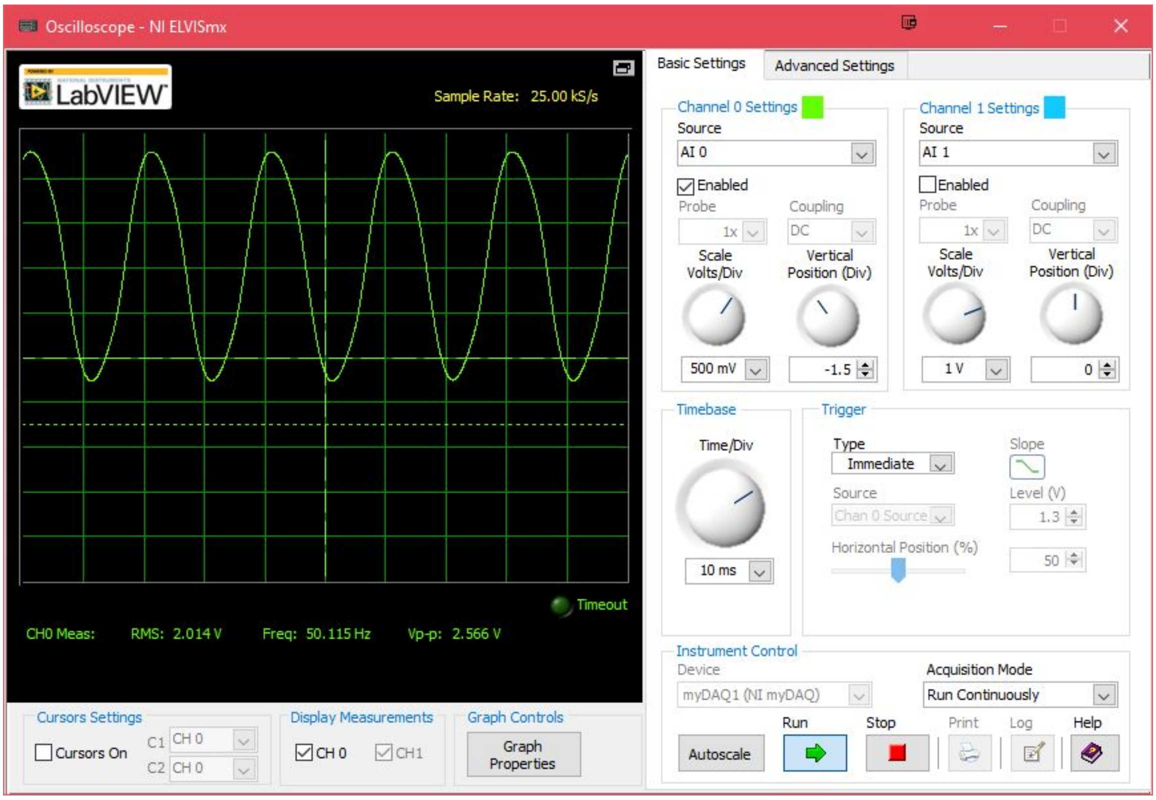

Appendix 52 - Noise on HR circuit output when the HR circuit is powered without the ECG cables, and the grounded enclosure is open. 438.11mV



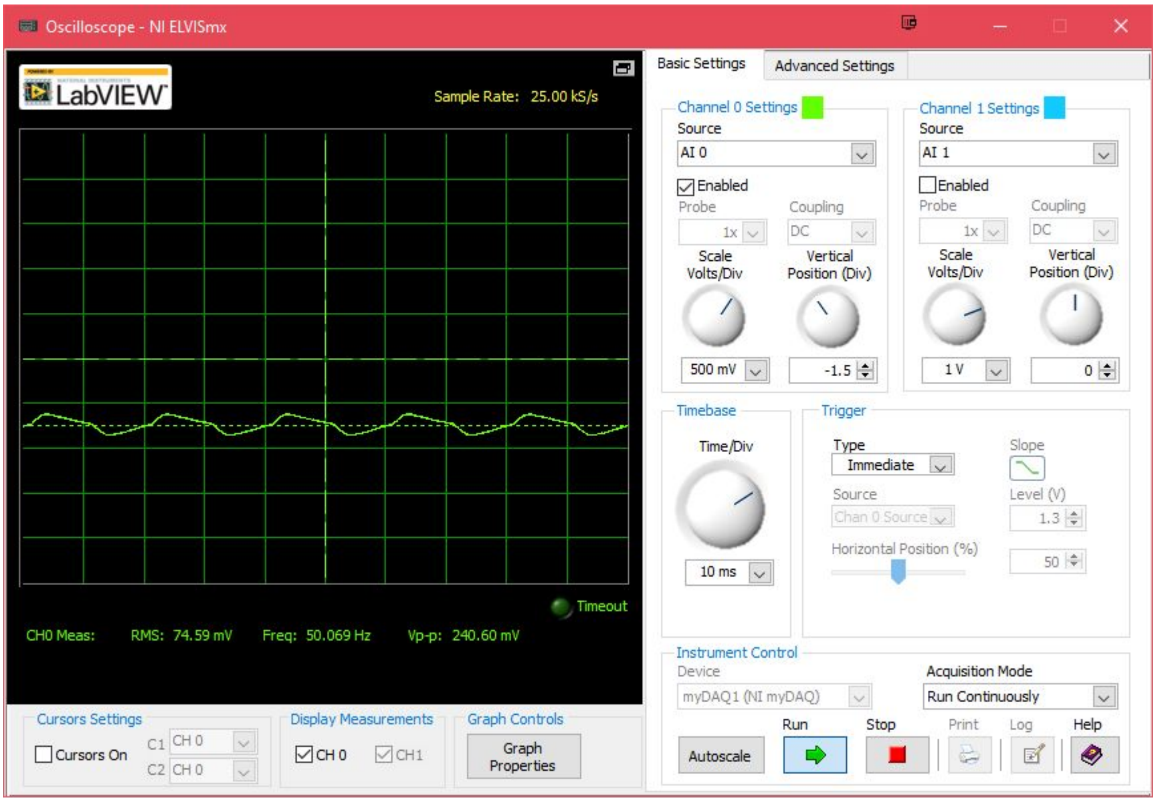

Appendix 53 - Noise on HR circuit output when the HR circuit is powered with the ECG cables and the grounded enclosure is open. 357.80mV



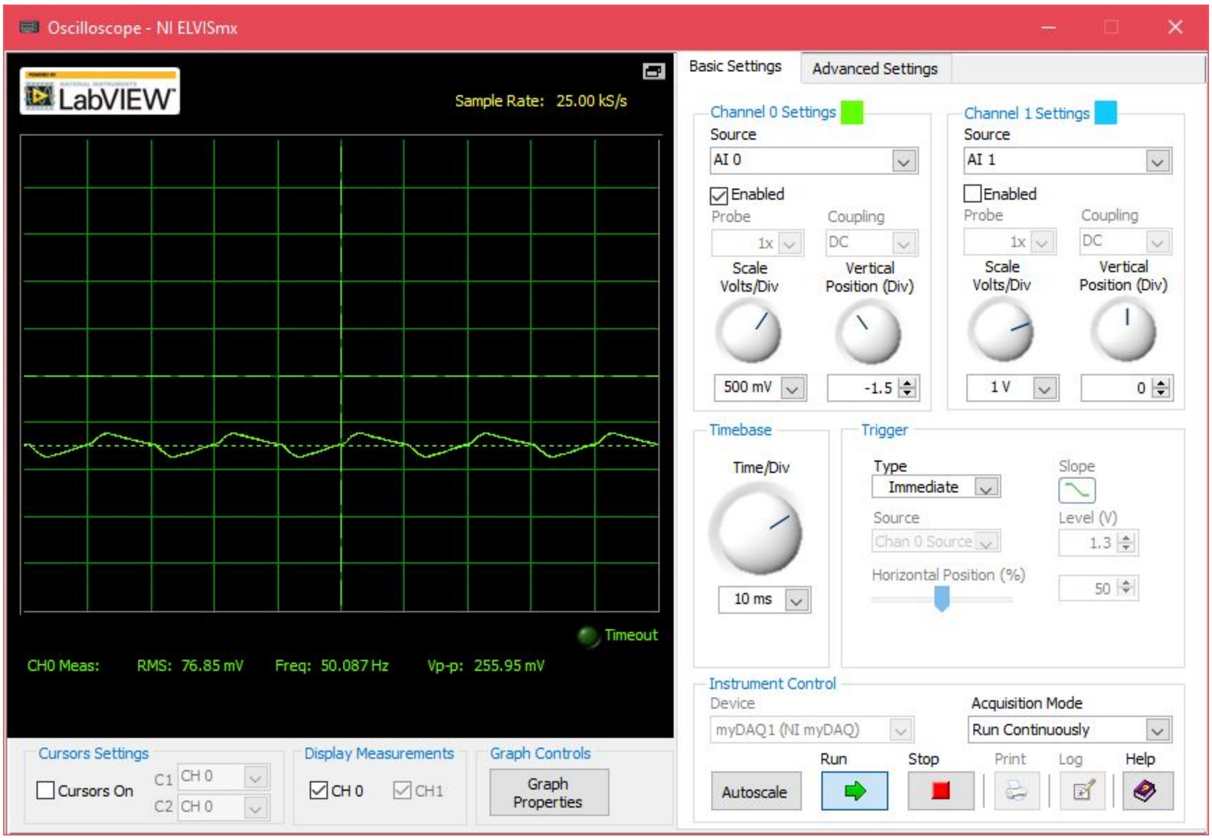

Appendix 54 - Noise on HR circuit output when the HR circuit is powered with the ECG cables connected, the enclosure is open and disconnected from ground. 438.77mV




Appendix 55 - Noise on HR circuit output when the HR circuit is powered without the ECG cables, and the enclosure is open and disconnected from the ground. 2.566V



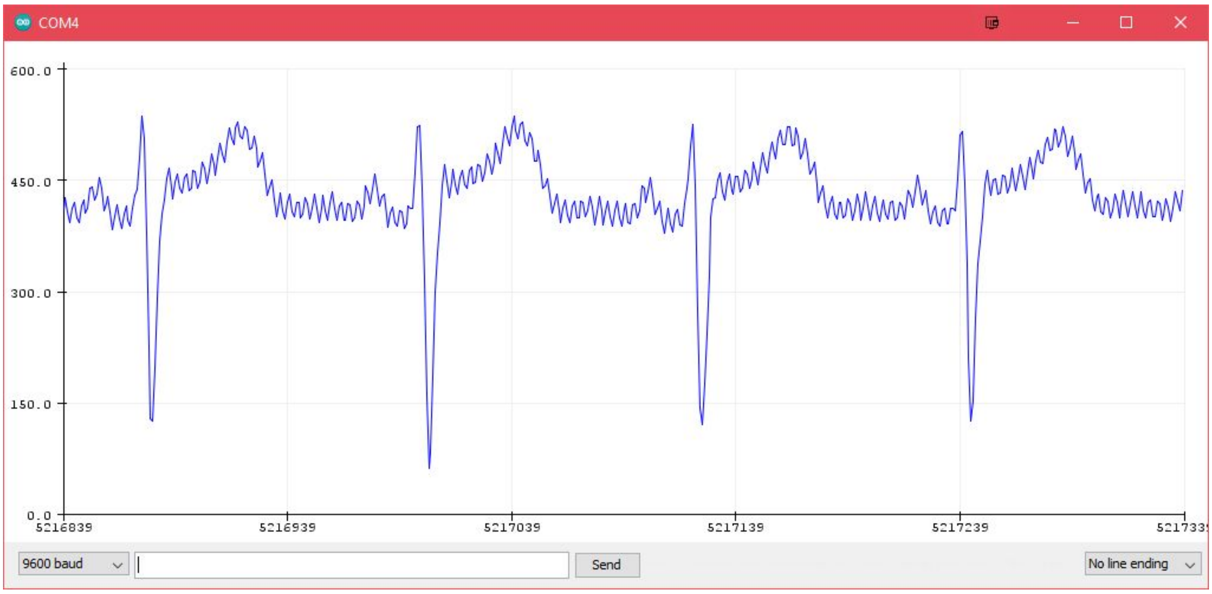

Appendix 56 - Noise on HR circuit output when the HR circuit is unpowered with the ECG cables and the enclosure is closed. 240.60mV



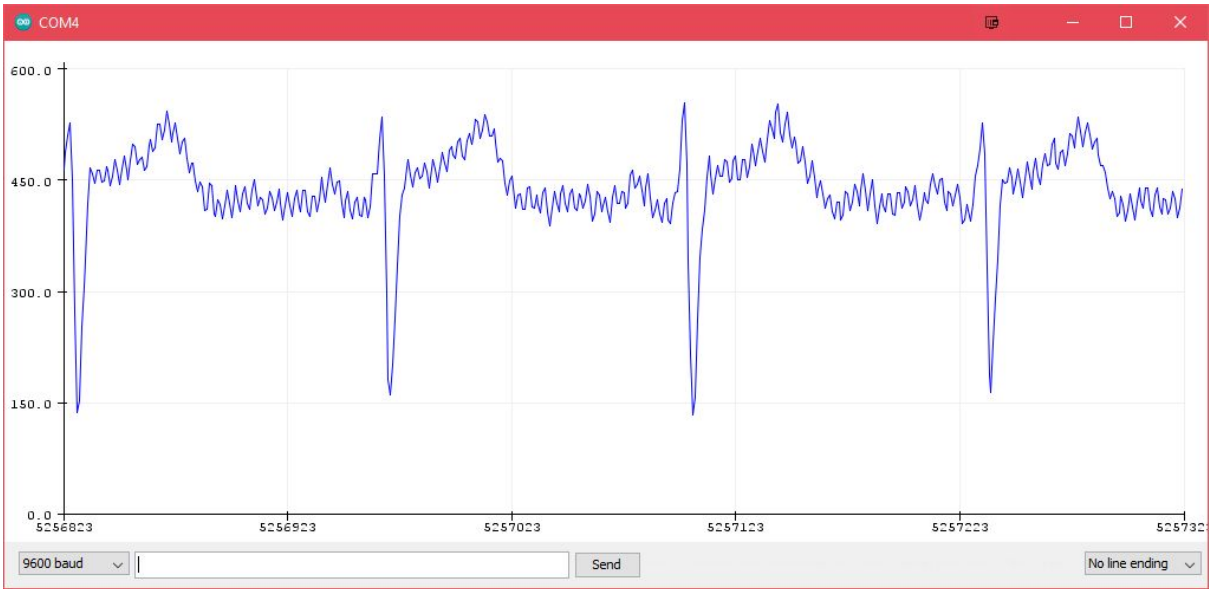

Appendix 57 - Noise on HR circuit output when the HR circuit is unpowered with the ECG cables and the enclosure is open. 255.95mV

## Layered Shielded

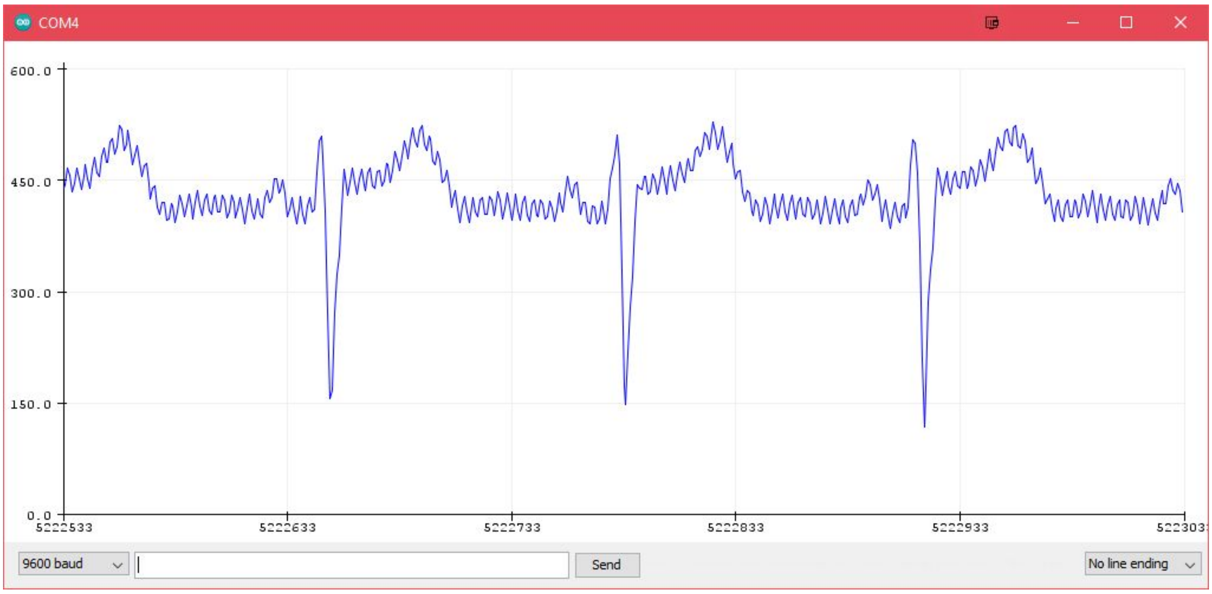
The testing was performed with the HR circuit placed inside a plastic box covered in foil and grounded, then this along with the Arduino is placed into the original grounded enclosure. All the oscilloscope data captures were done without the ECG cable connected.



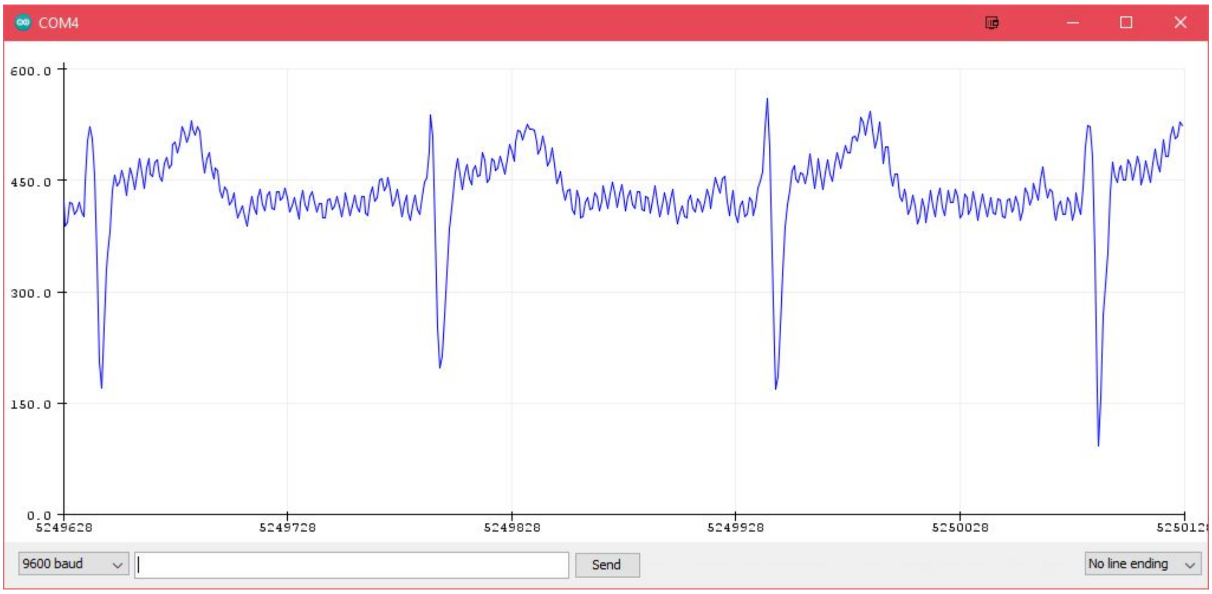

Appendix 58 - Heart rhythm data when the grounded enclosure is closed.



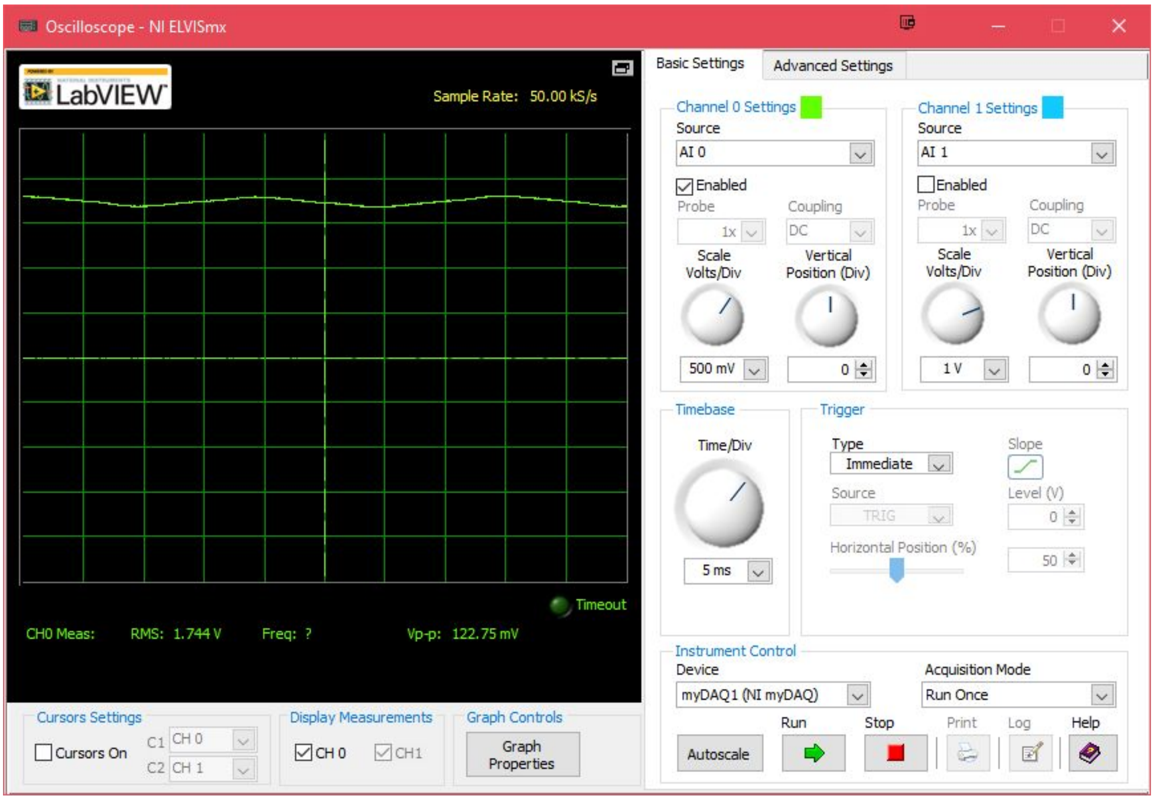

Appendix 59 - Heart rhythm data when the enclosure is closed but disconnected from all ground.



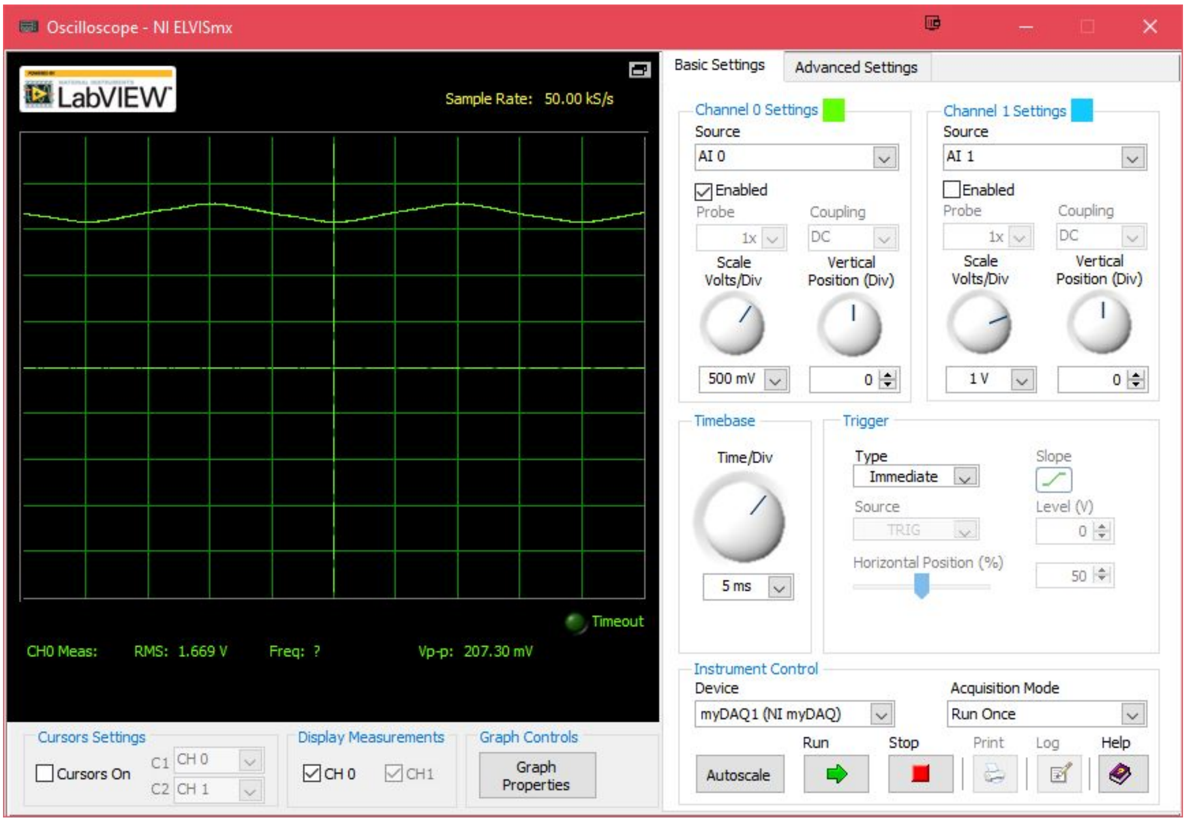

Appendix 60 - Heart rhythm data when the grounded enclosure is open.



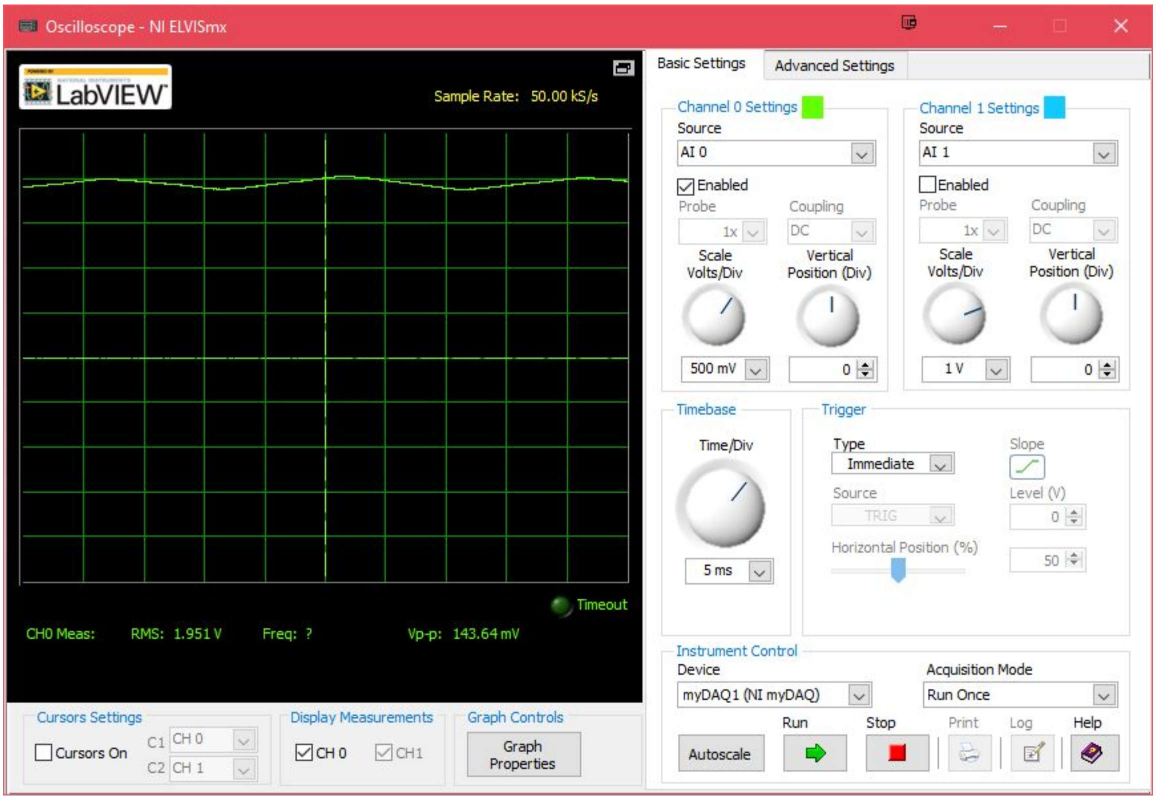

Appendix 61 - Heart rhythm data when the enclosure is open and disconnected from ground.



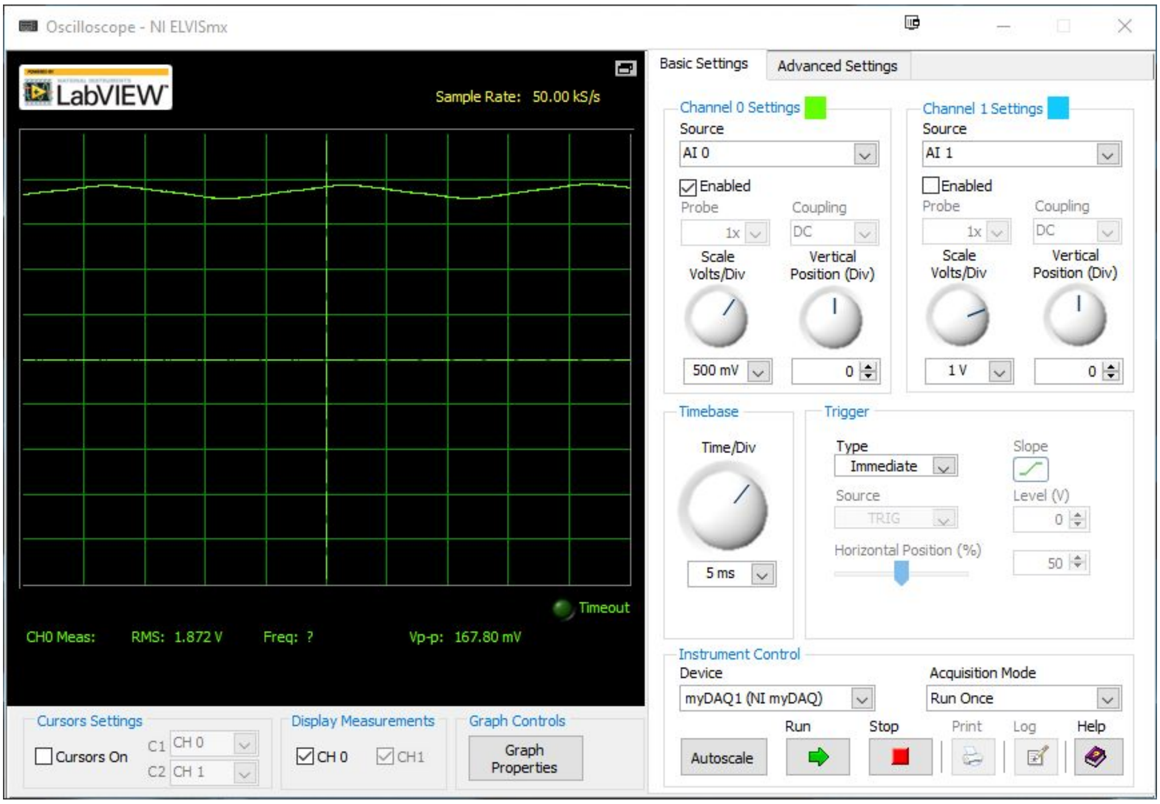

Appendix 62 - Noise on HR circuit output when the HR circuit is powered and the grounded enclosure is closed. 122.75mV



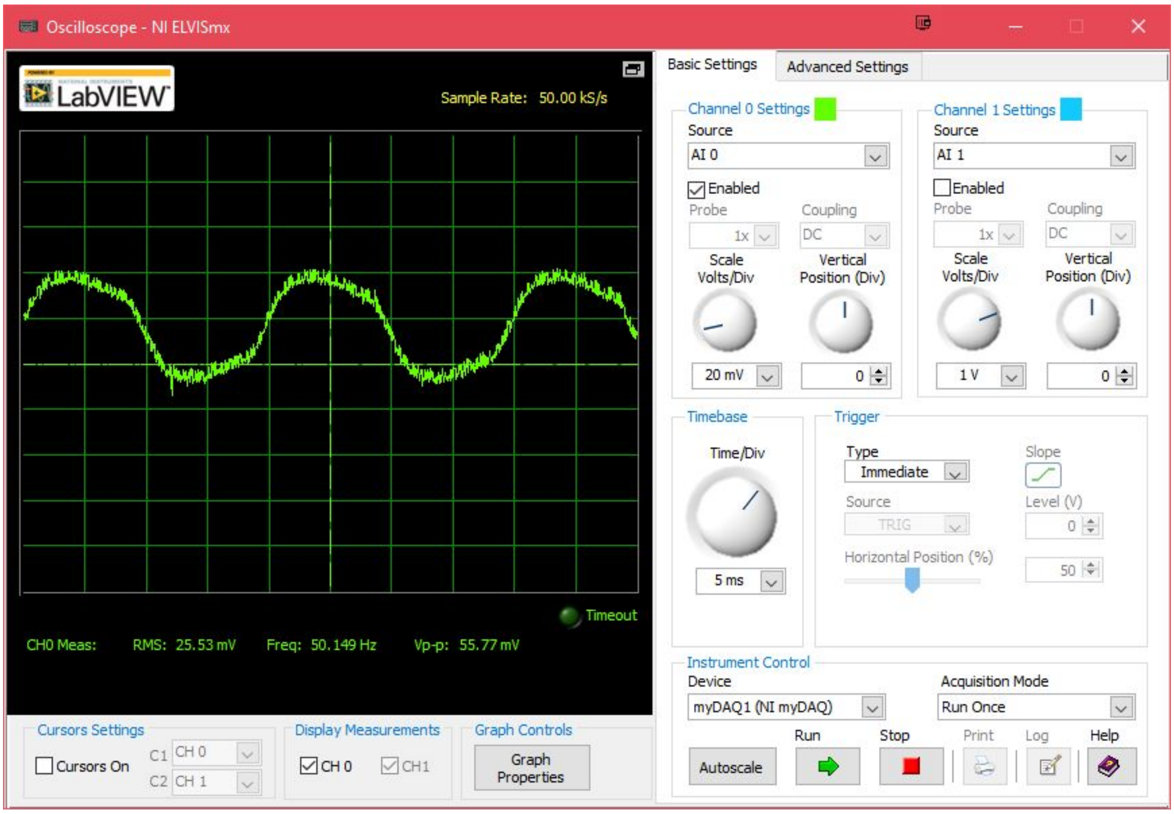

Appendix 63 - Noise on HR circuit output when the HR circuit is powered, and the enclosure is closed but disconnected from the ground. 207.30mV



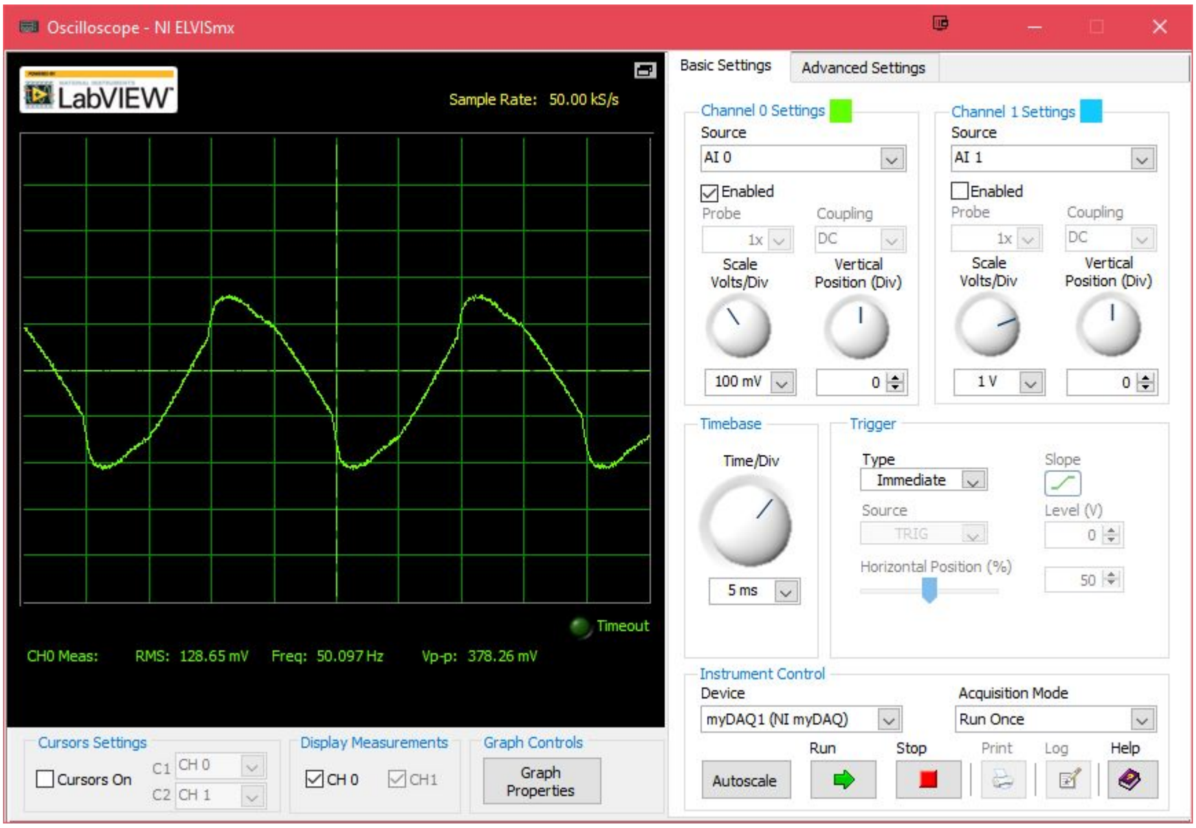

Appendix 64 - Noise on HR circuit output when the HR circuit is powered and the grounded enclosure is open. 143.64mV



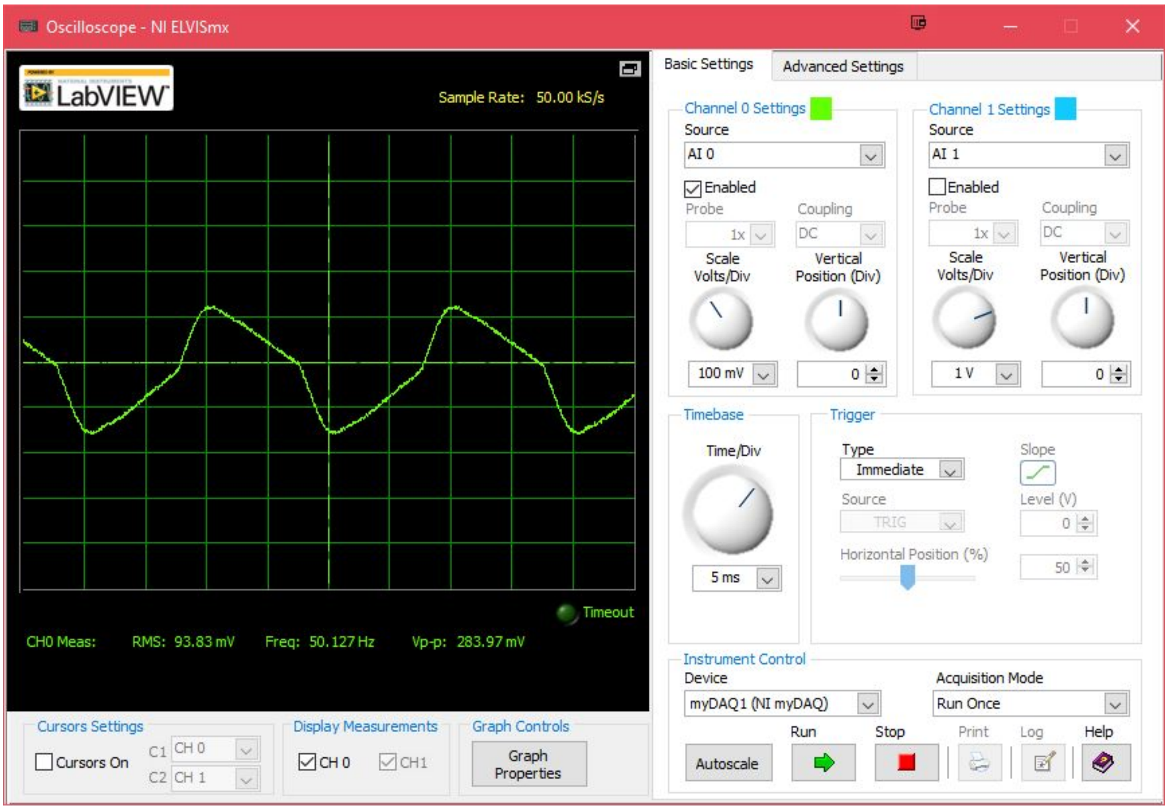

Appendix 65 - Noise on HR circuit output when the HR circuit is powered and the enclosure is open but disconnected from the ground. 167.80mV



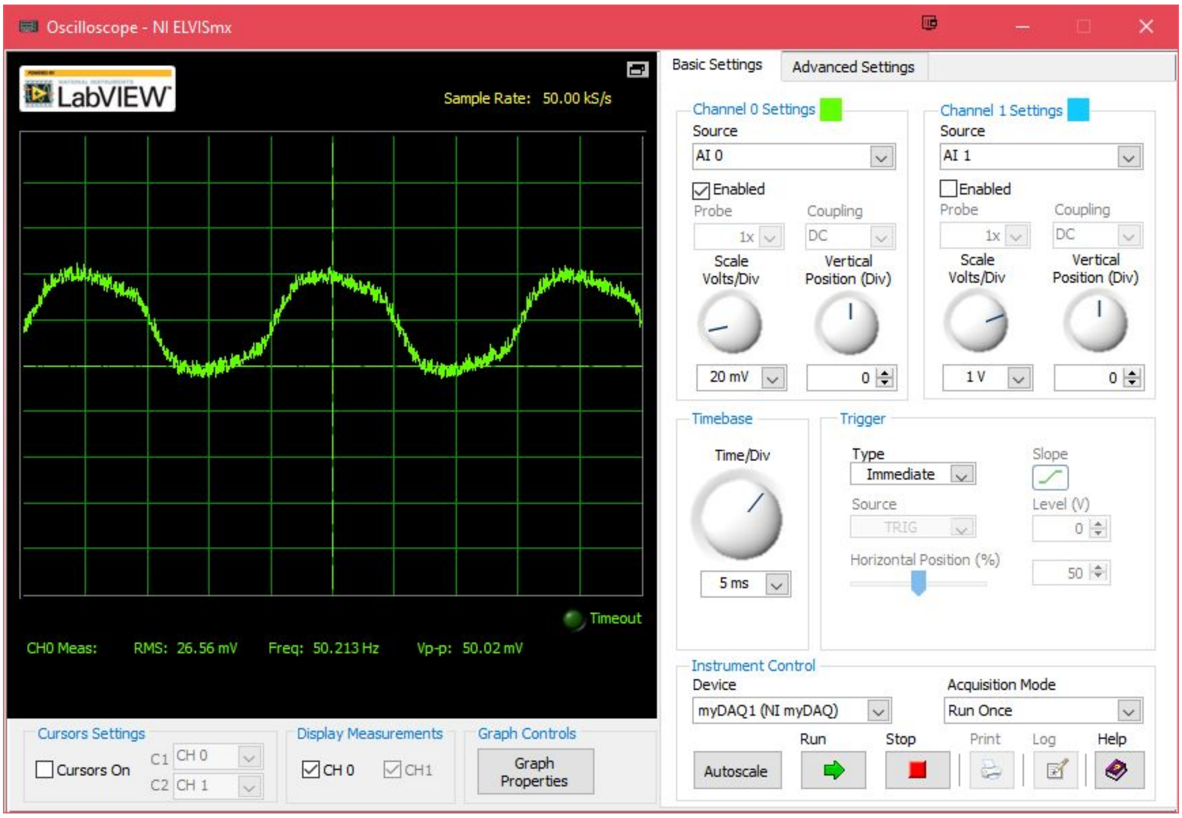

Appendix 66 - Noise on HR circuit output when the HR circuit is unpowered, and the grounded enclosure is closed. 55.77mV



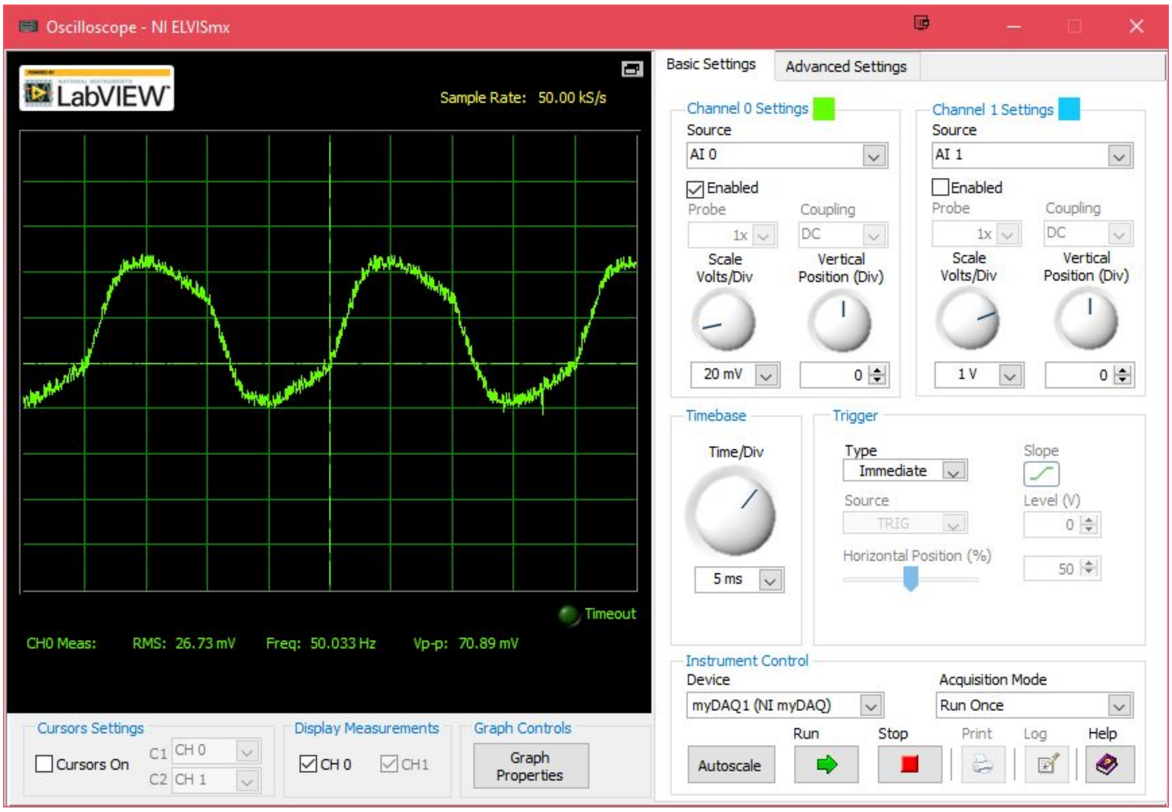

Appendix 67 - Noise on HR circuit output when the HR circuit is unpowered and the enclosure is closed but disconnected from ground. 378.26mV



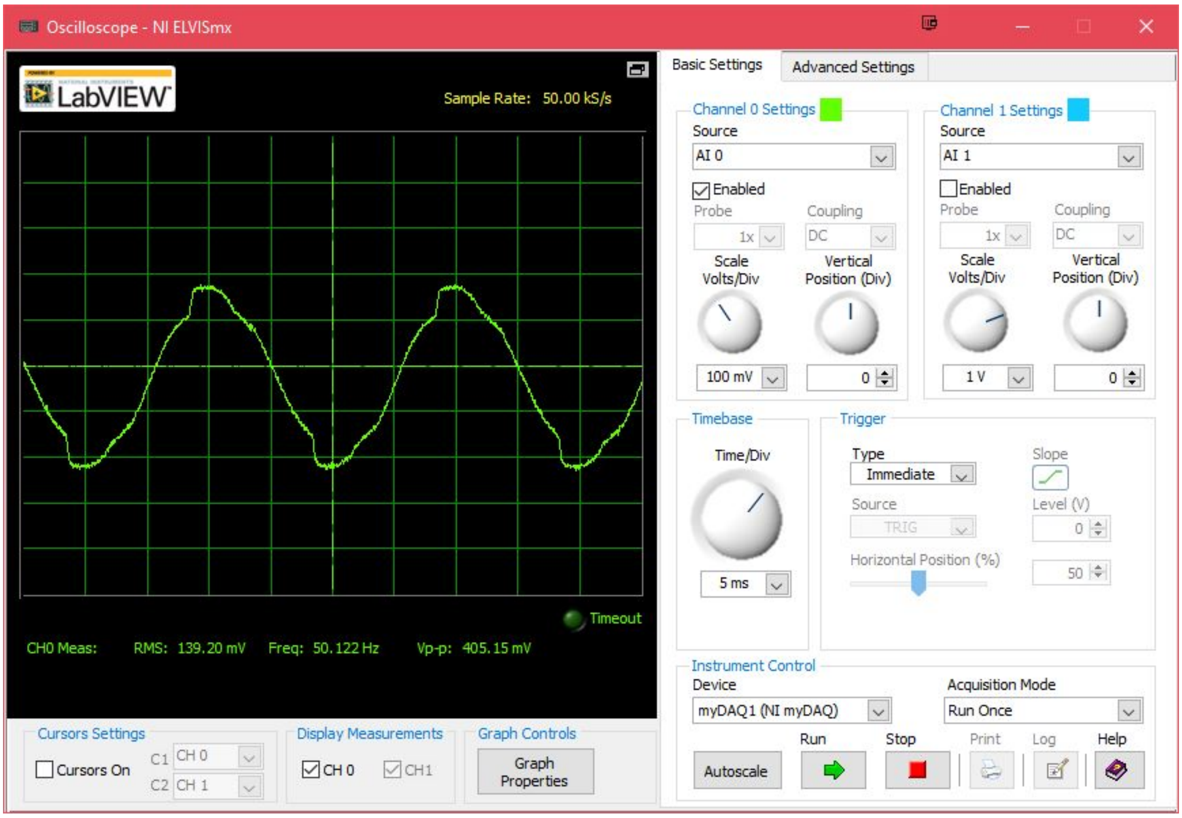

Appendix 68 - Noise on HR circuit output when the HR circuit is unpowered, and the enclosure is closed but the top-level grounding (Arduino) is disconnected. 283.97mV



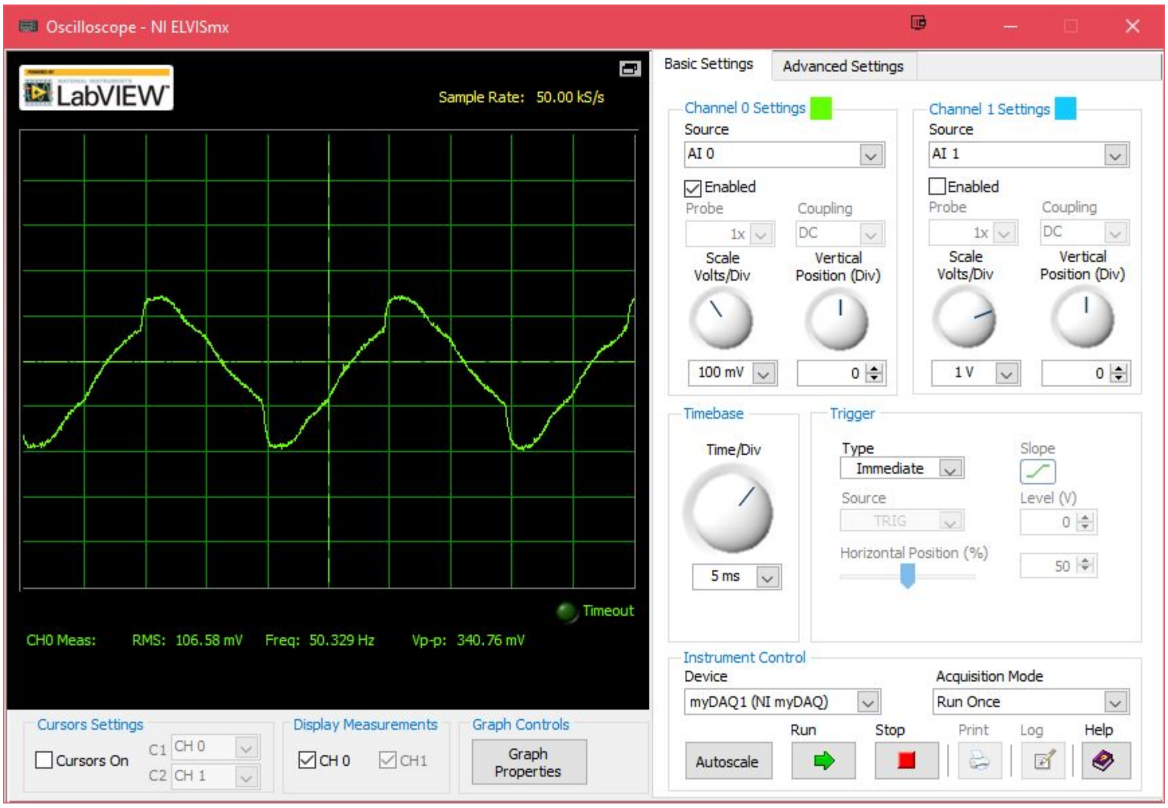

Appendix 69 - Noise on HR circuit output when the HR circuit is unpowered, and the enclosure is closed, but the lower level grounding (HR) is disconnected. 50.02mV



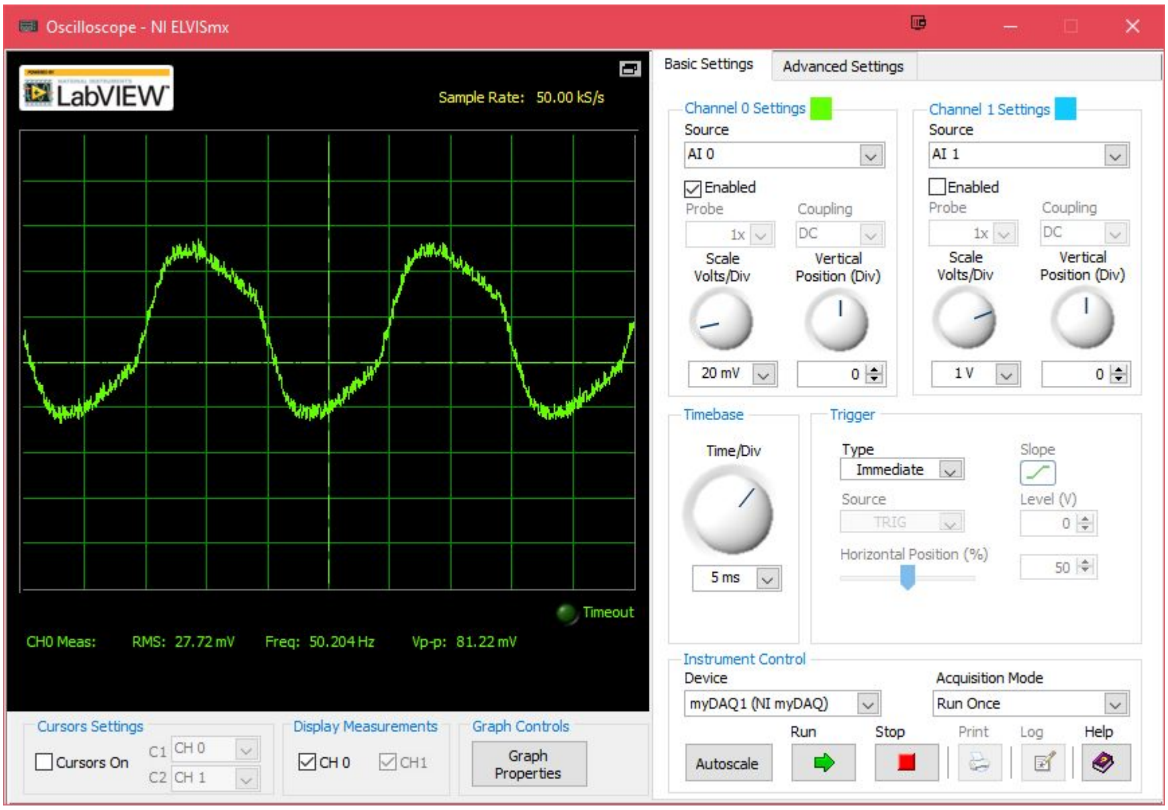

Appendix 70 - Noise on HR circuit output when the HR circuit is unpowered, and the grounded enclosure is open. 70.89mV.




Appendix 71 - Noise on HR circuit output when the HR circuit is unpowered, and the enclosure is open but grounding is disconnected. 405.15mV



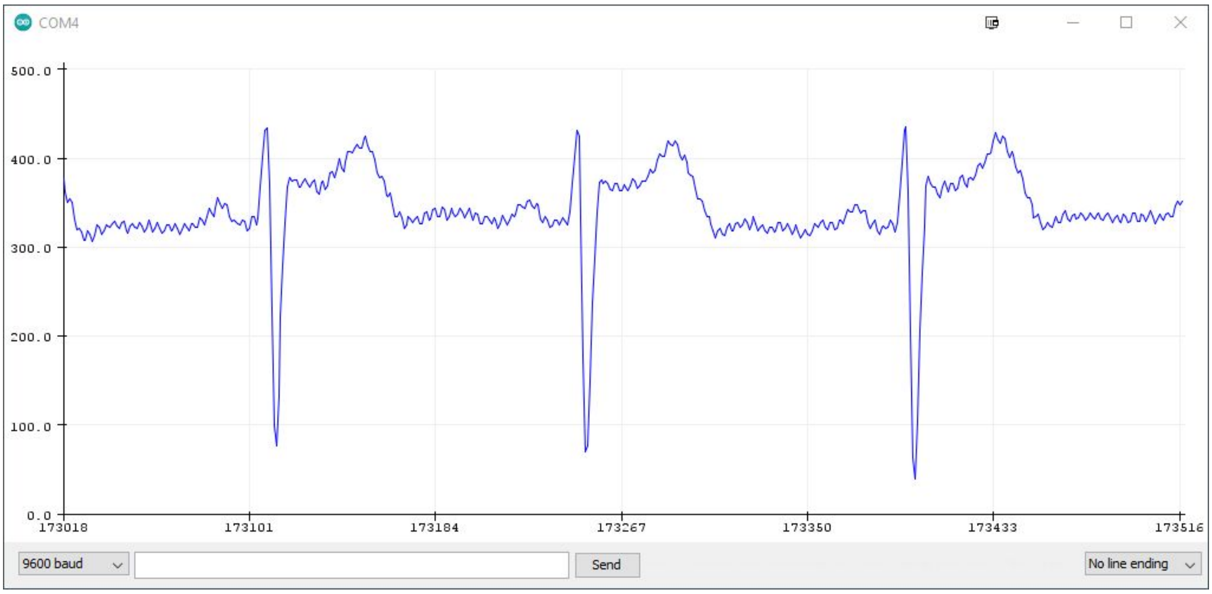

Appendix 72 - Noise on HR circuit output when the HR circuit is unpowered, and the enclosure is open but the top level grounding (Arduino) is disconnected. 340.76mV




Appendix 73 - Noise on HR circuit output when the HR circuit is unpowered, and the enclosure is open but the lower level grounding (HR) is disconnected. 81.22mV

## SparkFun HR Circuit Testing Results

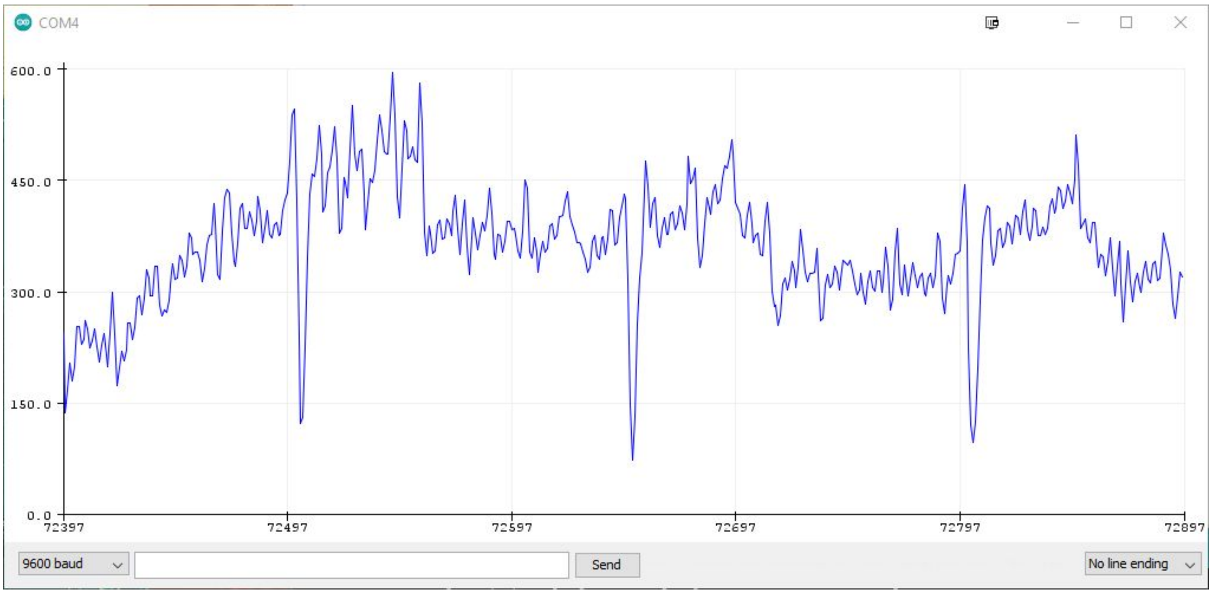
### Initial Testing




Appendix 74 - The first instance of testing the official Sparkfun circuit gave a clean heart rate data output.

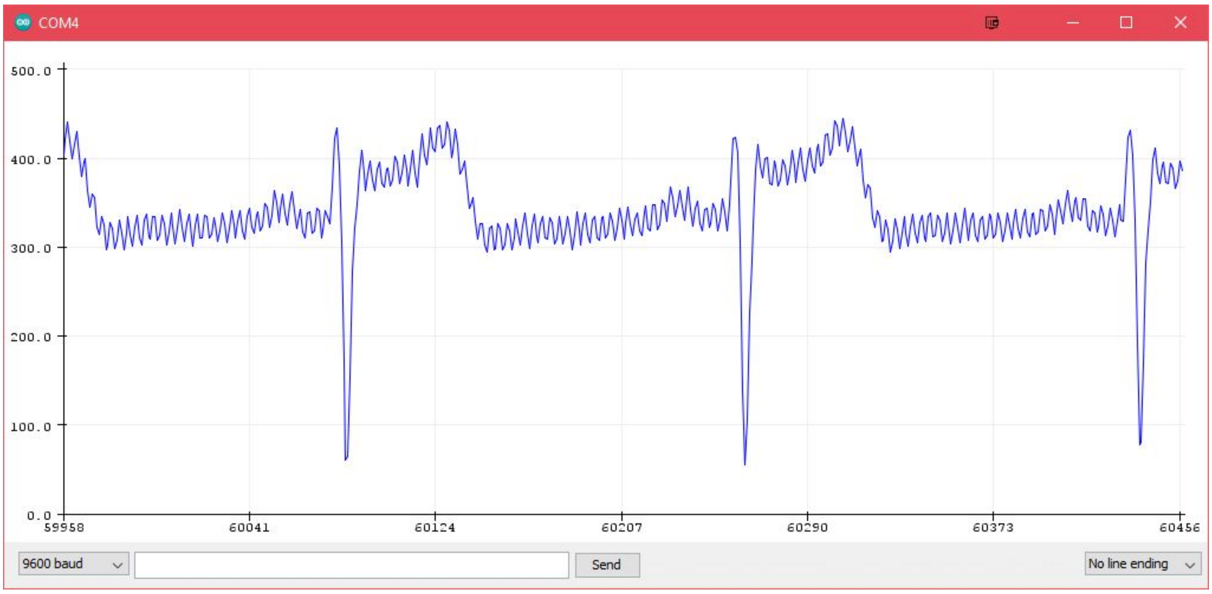
### Open Air Testing


Appendix 75 - Heart rhythm data when the user has moved.

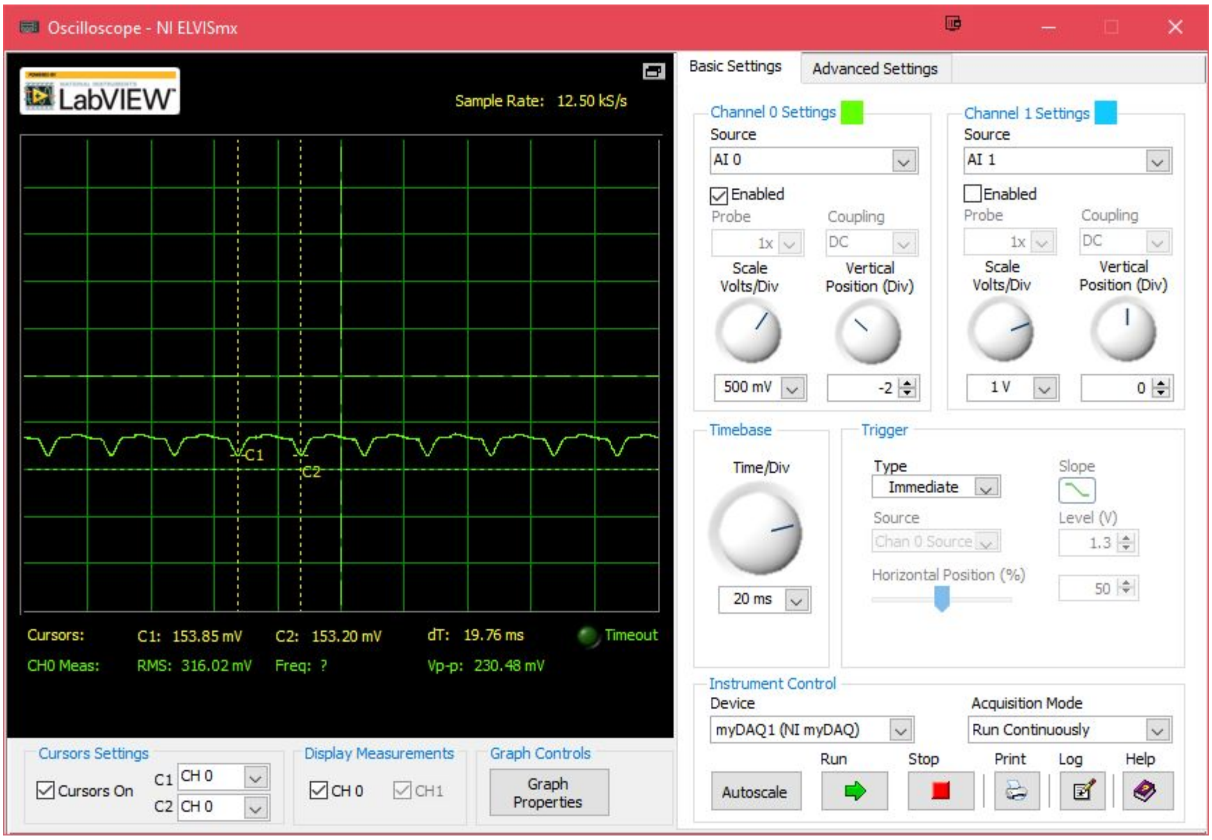



Appendix 76 - Heart rhythm data when the user has moved.

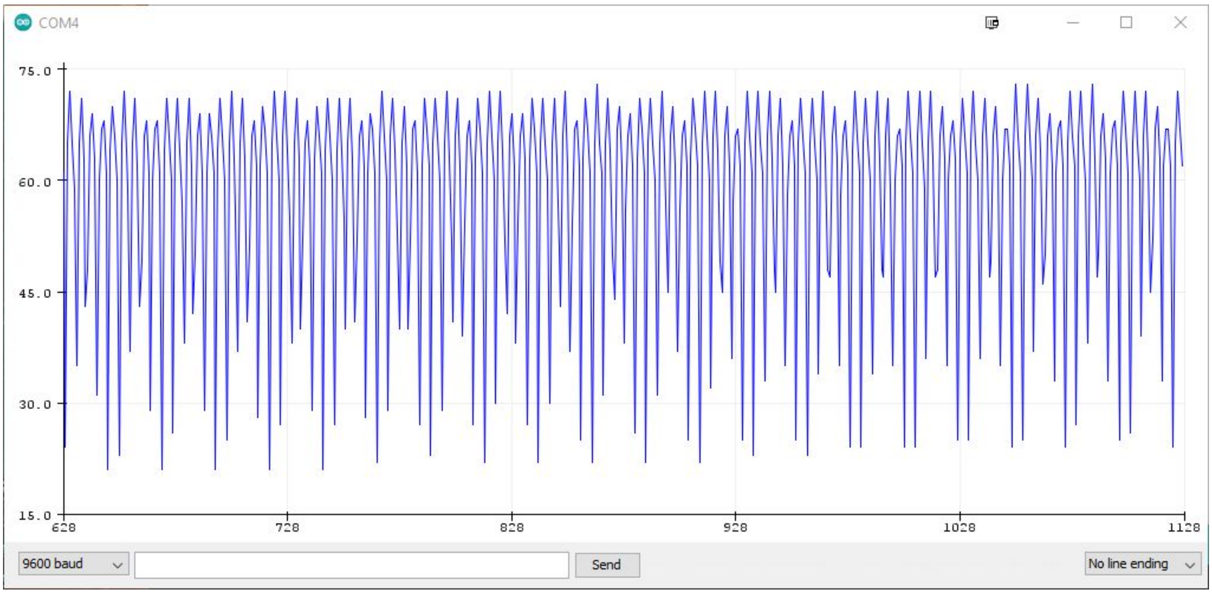

Appendix 77 - Heart rhythm data when the user has moved.




Appendix 78 - Heart rhythm data when the user is still.

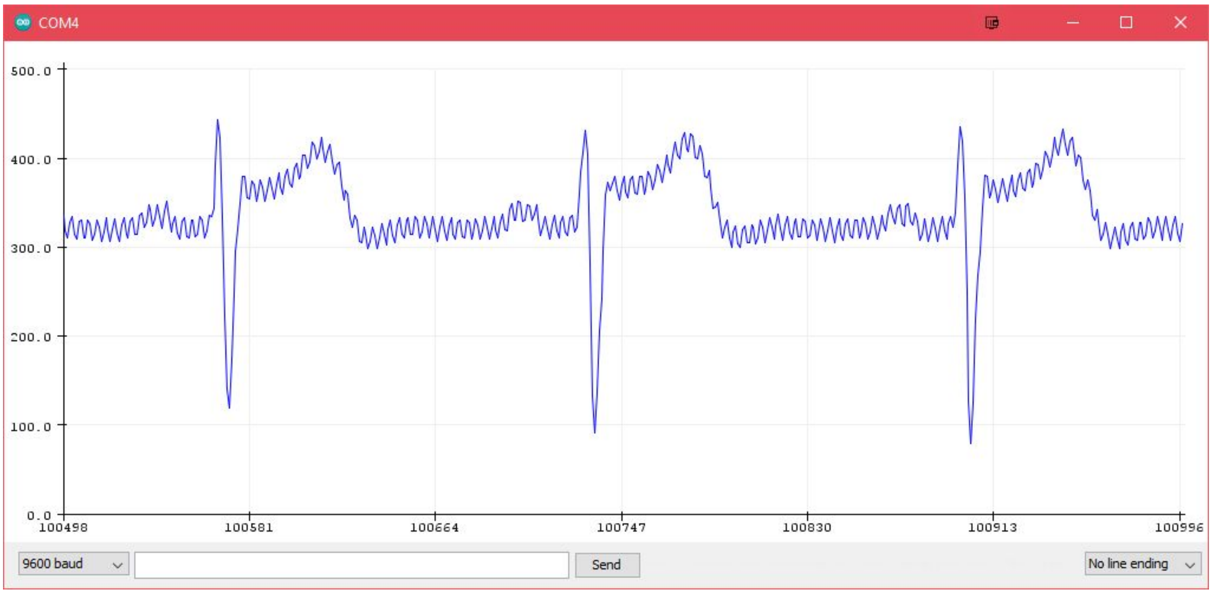



Appendix 79 - Noise on the HR circuit output observed when the circuit is unpowered but is otherwise connected to an Arduino. 230.48mV

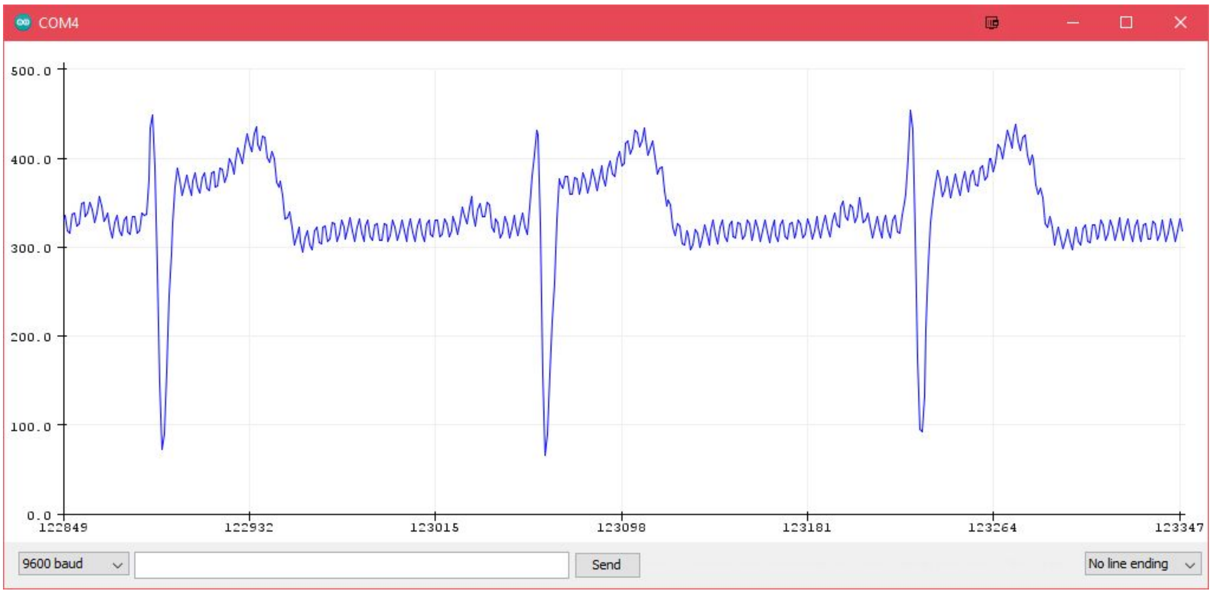



Appendix 80 - Heart rhythm data when the HR circuit is unpowered.

## Arduino Powered by 9V Battery

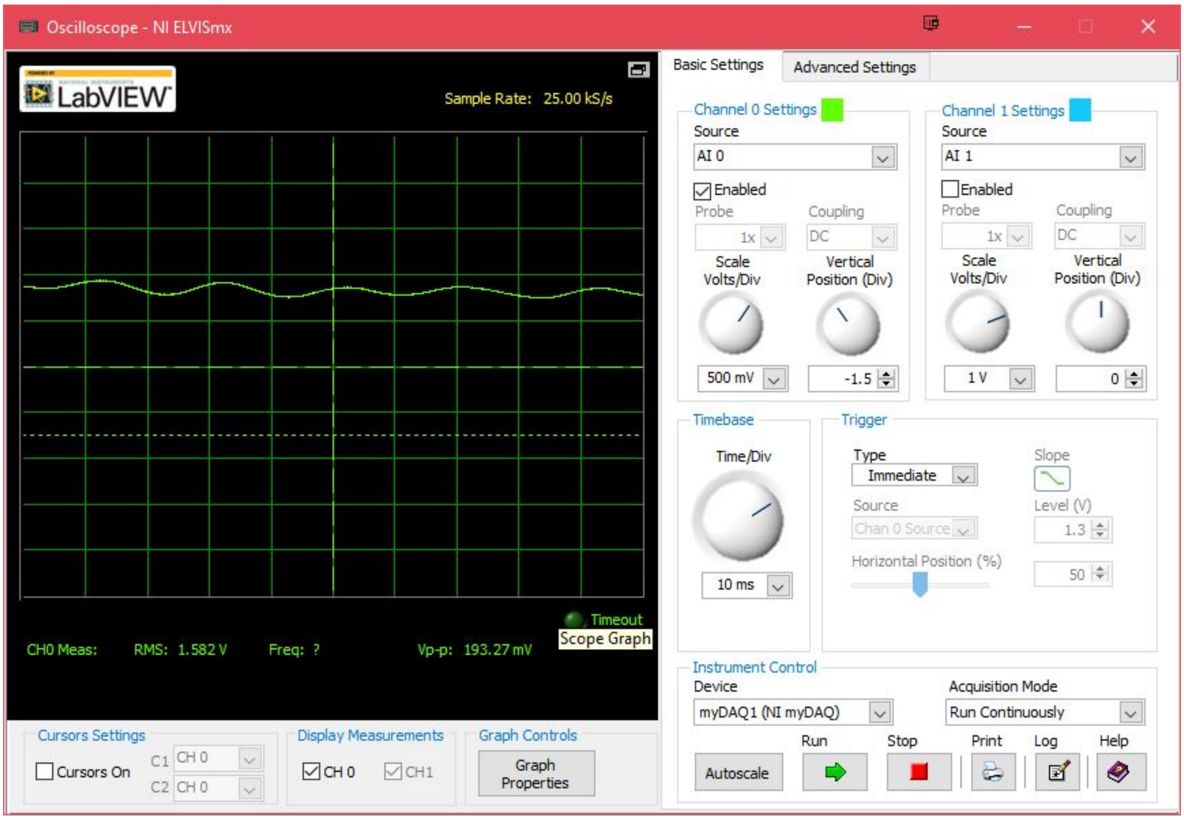



Appendix 81 - Heart rhythm data when the Arduino is powered by a 9V battery.

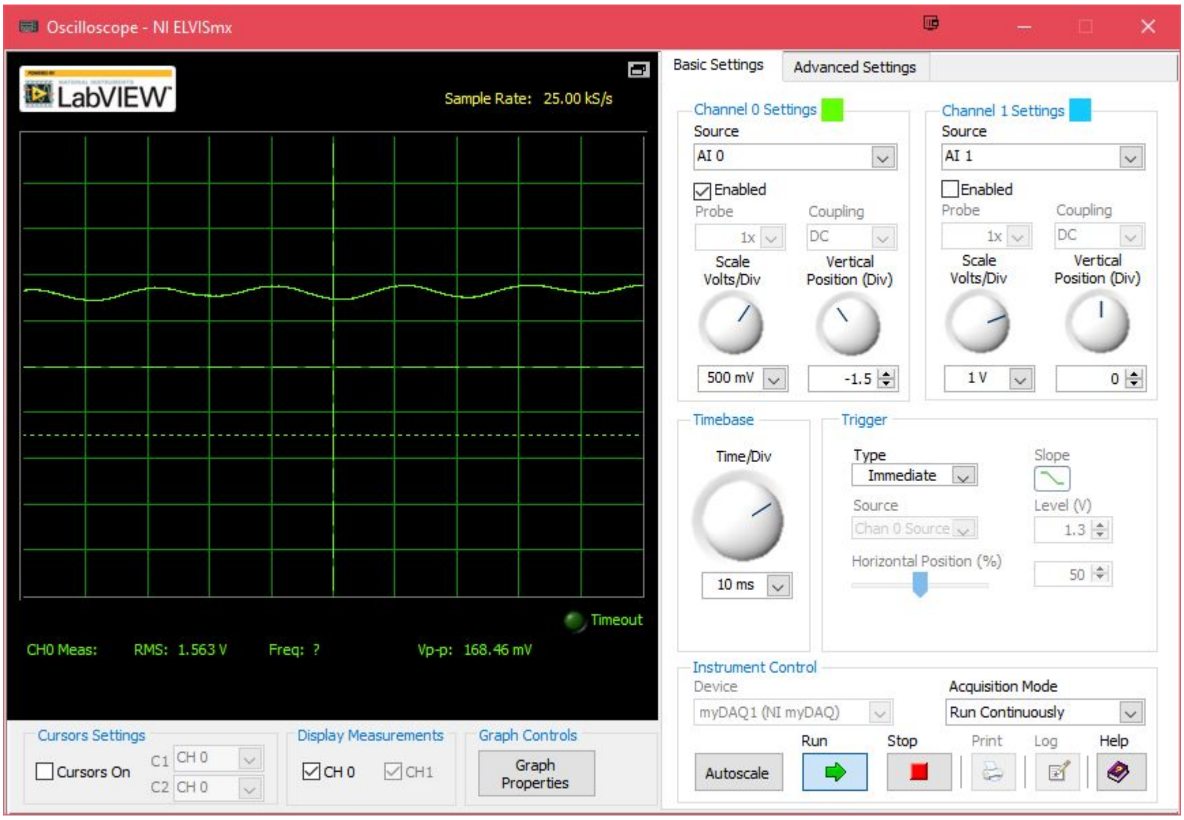



Appendix 82 - Heart rhythm data when the Arduino is powered by a 9V battery with a 100nF capacitor between AREF and GND.

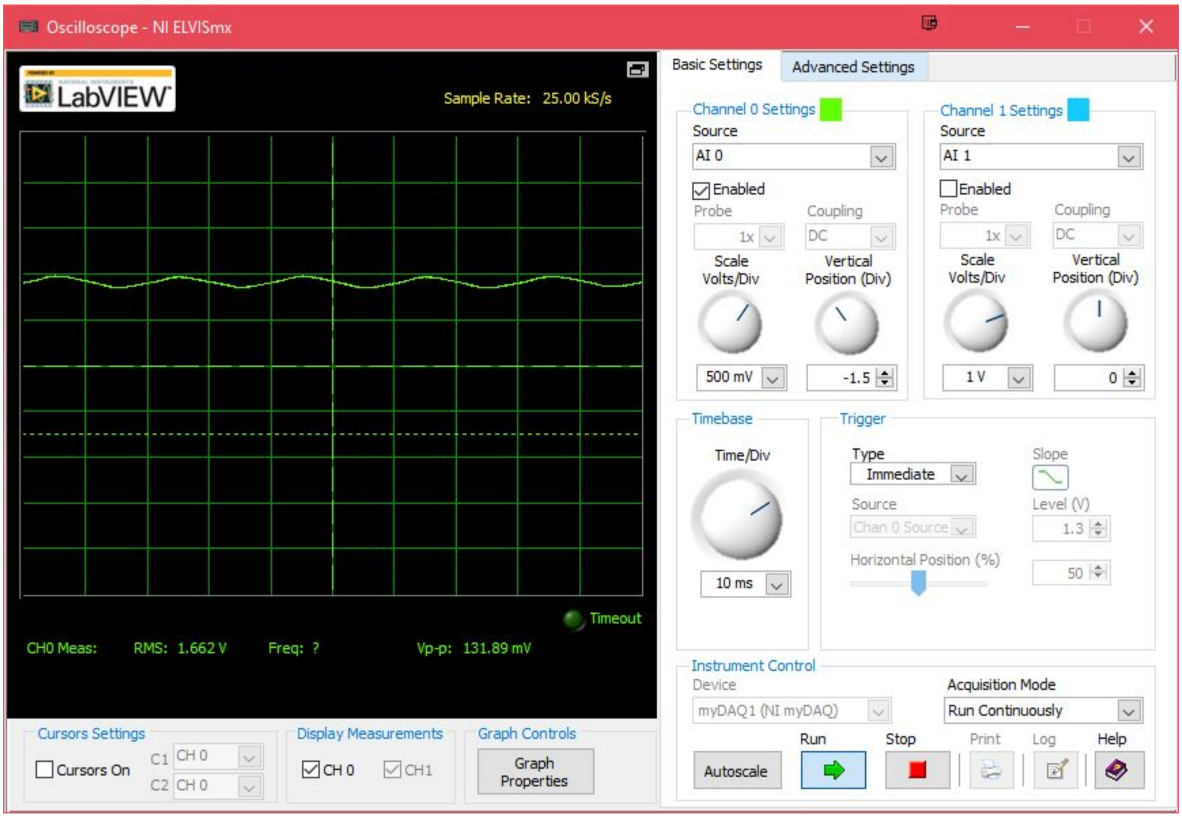

Appendix 83 - Heart rhythm data when the Arduino is USB powered.



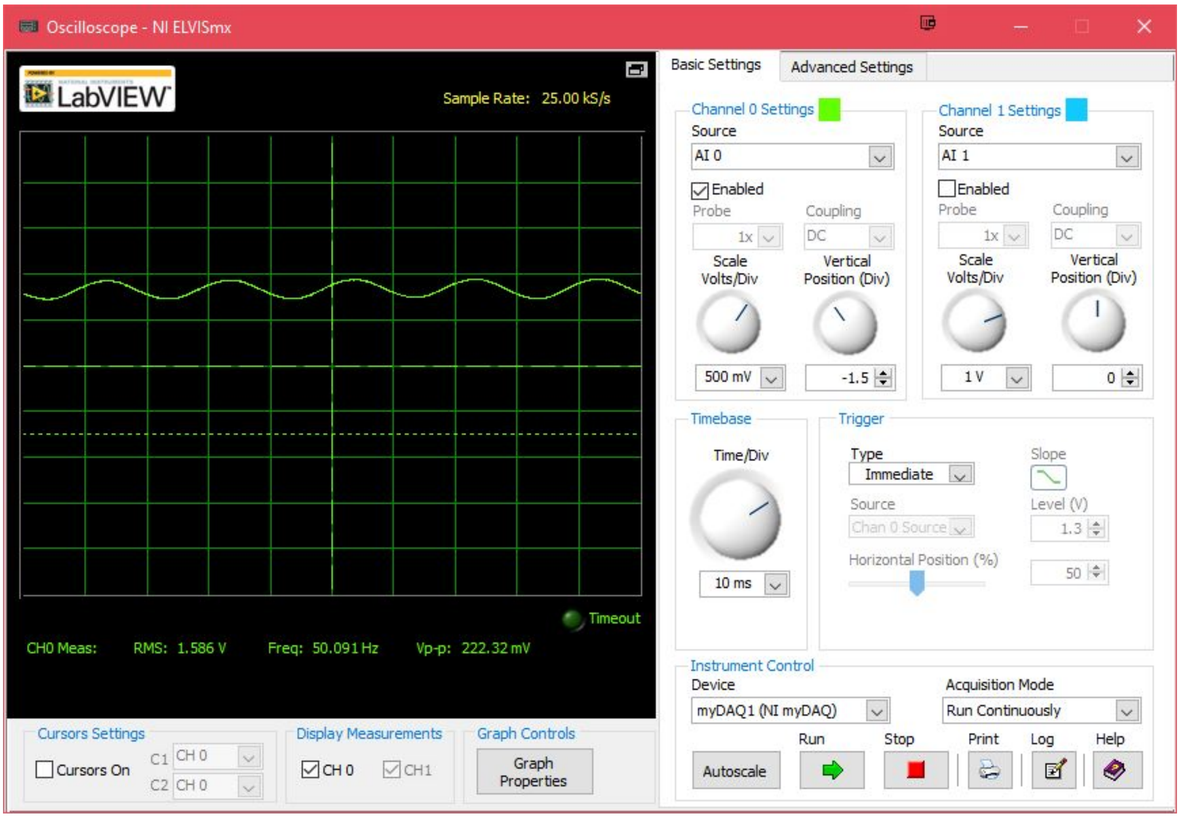

Appendix 84 - Noise on HR circuit output when the Arduino is powered by a 9V battery. 193.27mV



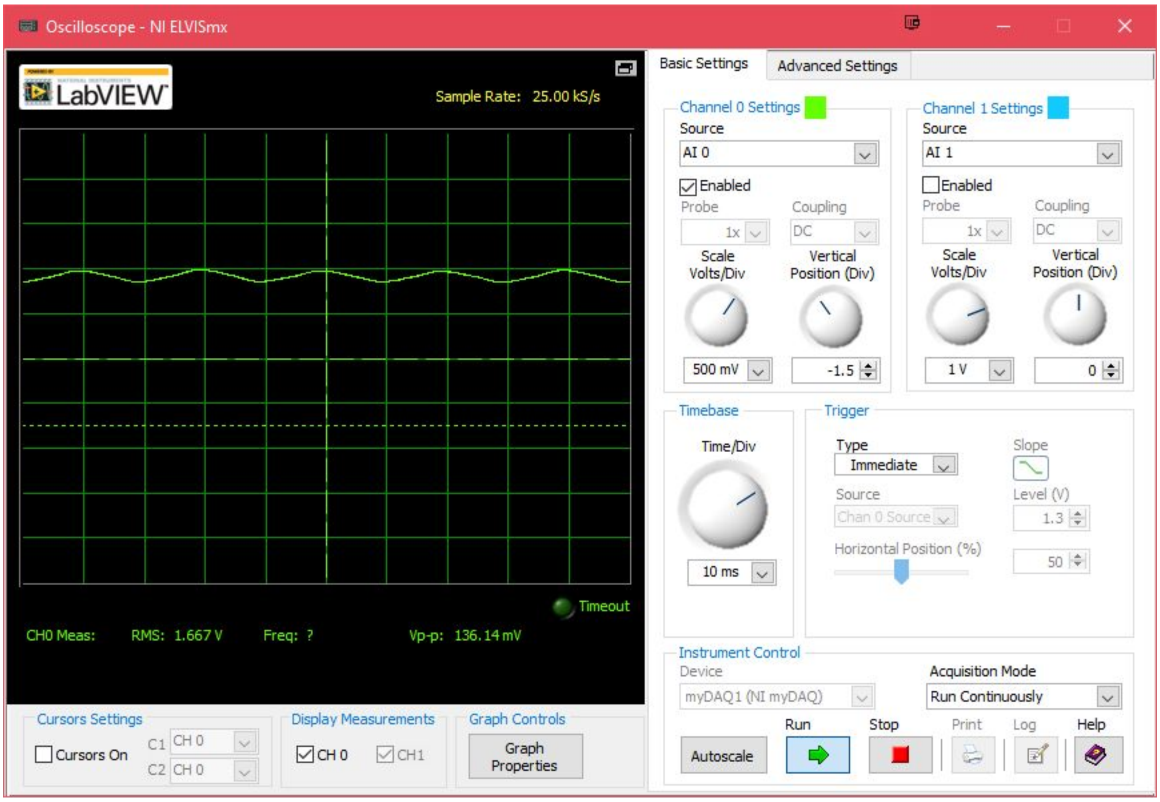

Appendix 85 - Noise on HR circuit output when the Arduino is powered by a 9V battery and a 100nF capacitor between AREF and GND. 168.46mV



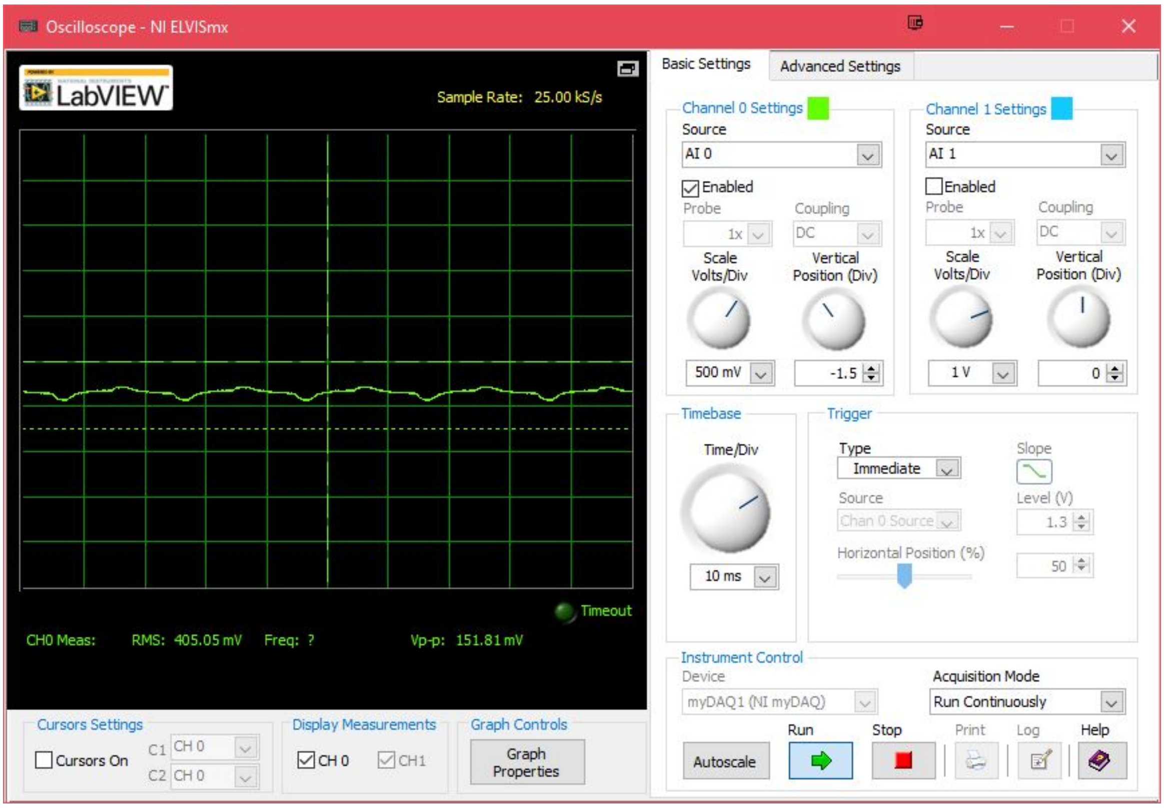

Appendix 86 - Noise on HR circuit output when the Arduino is powered by a 9V battery without the ECG cables attached. 131.89V



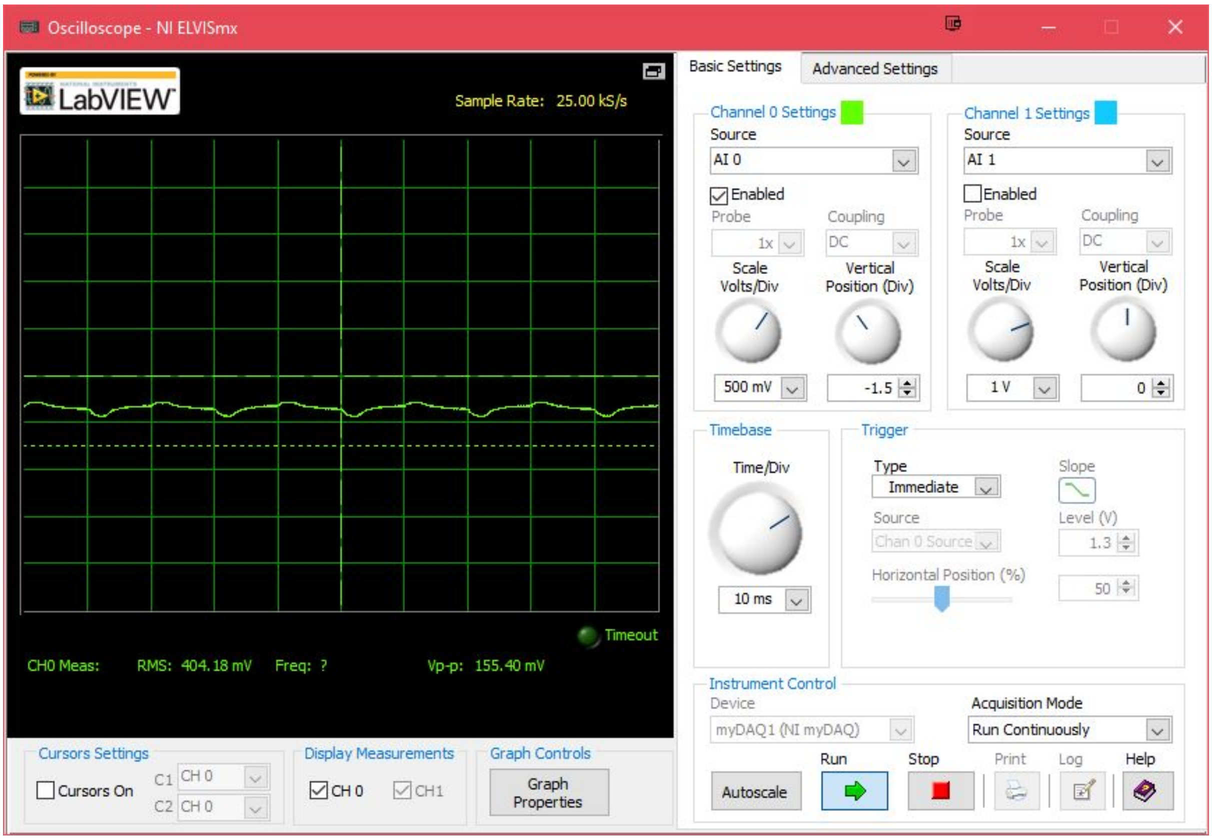

Appendix 87 - Noise on HR circuit output when the Arduino is powered by a USB port. 222.32mV




Appendix 88 - Noise on HR circuit output when the Arduino is powered by a USB port and no ECG cables attached. 136.14mV



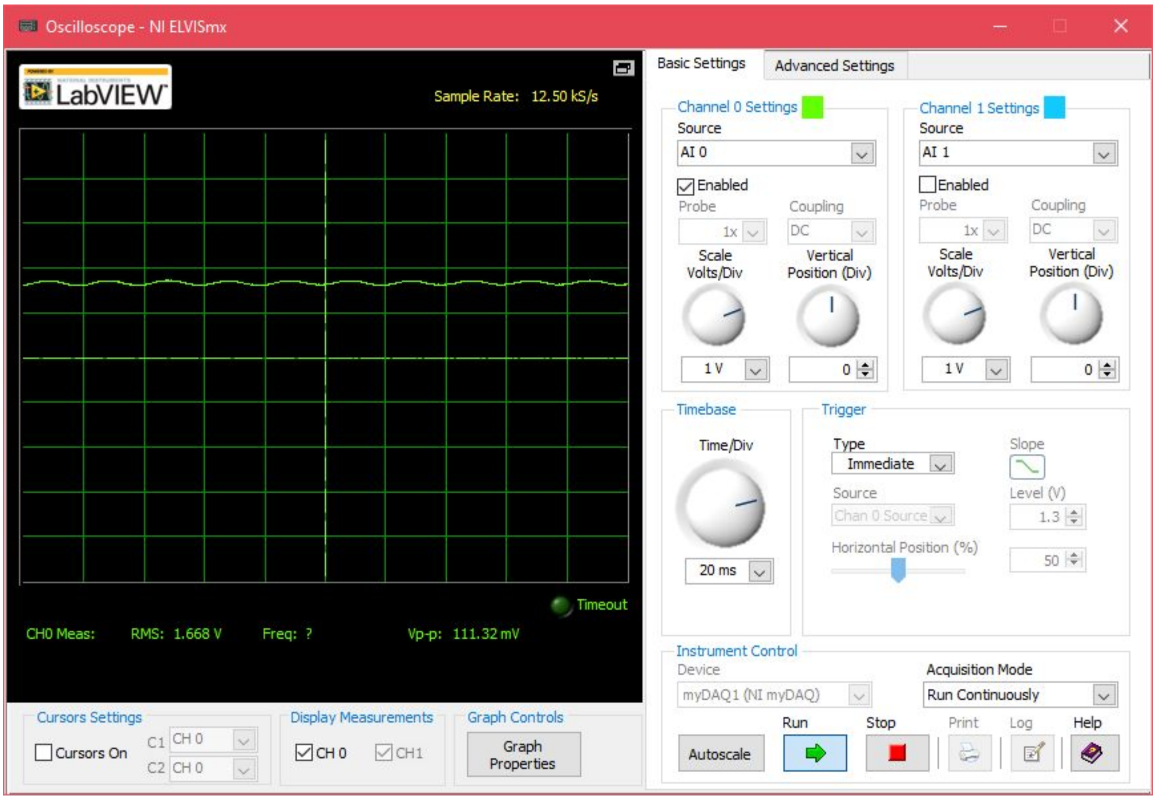

Appendix 89 - Noise on HR circuit output when the Arduino is powered by a 9V battery, and the HR circuit is unpowered without the ECG cable connected. 151.81mV



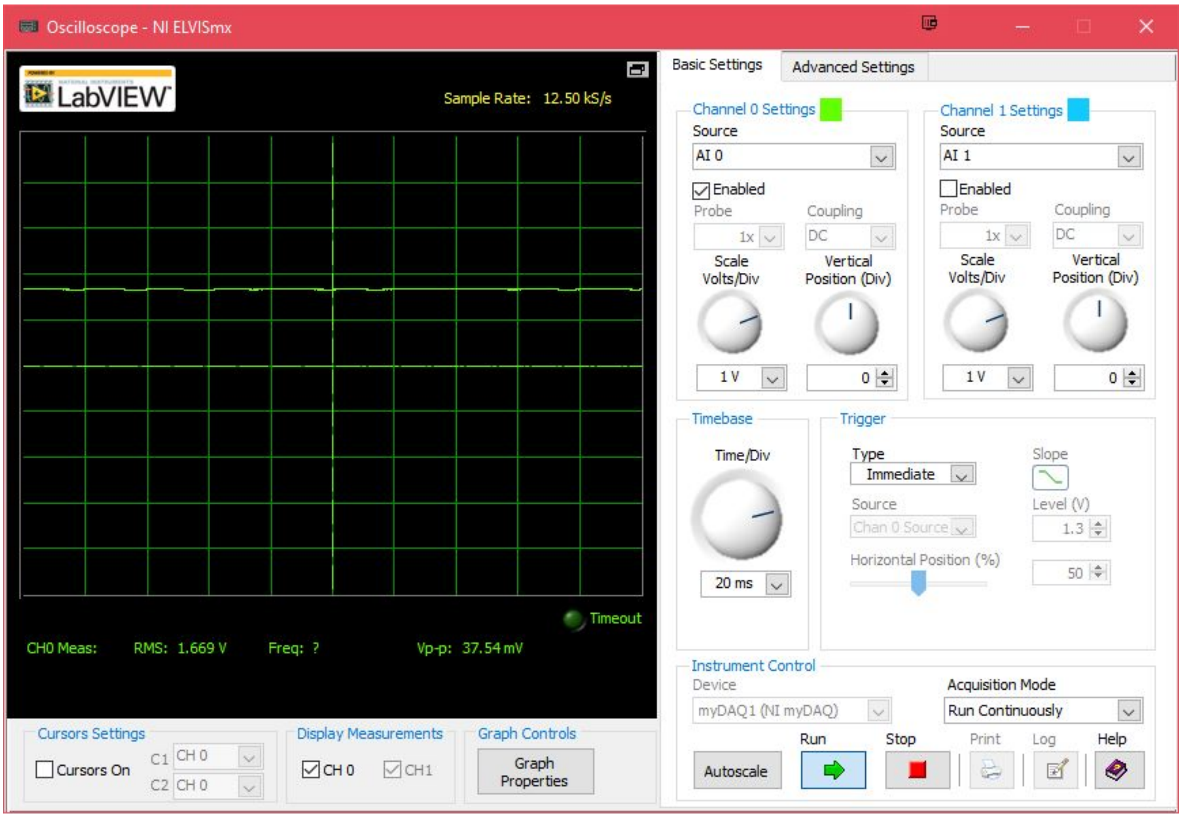

Appendix 90 - Noise on HR circuit output when the Arduino is powered by a USB port, and the HR circuit is unpowered without the ECG cable connected. 155.40mV

## Complete System Shielded

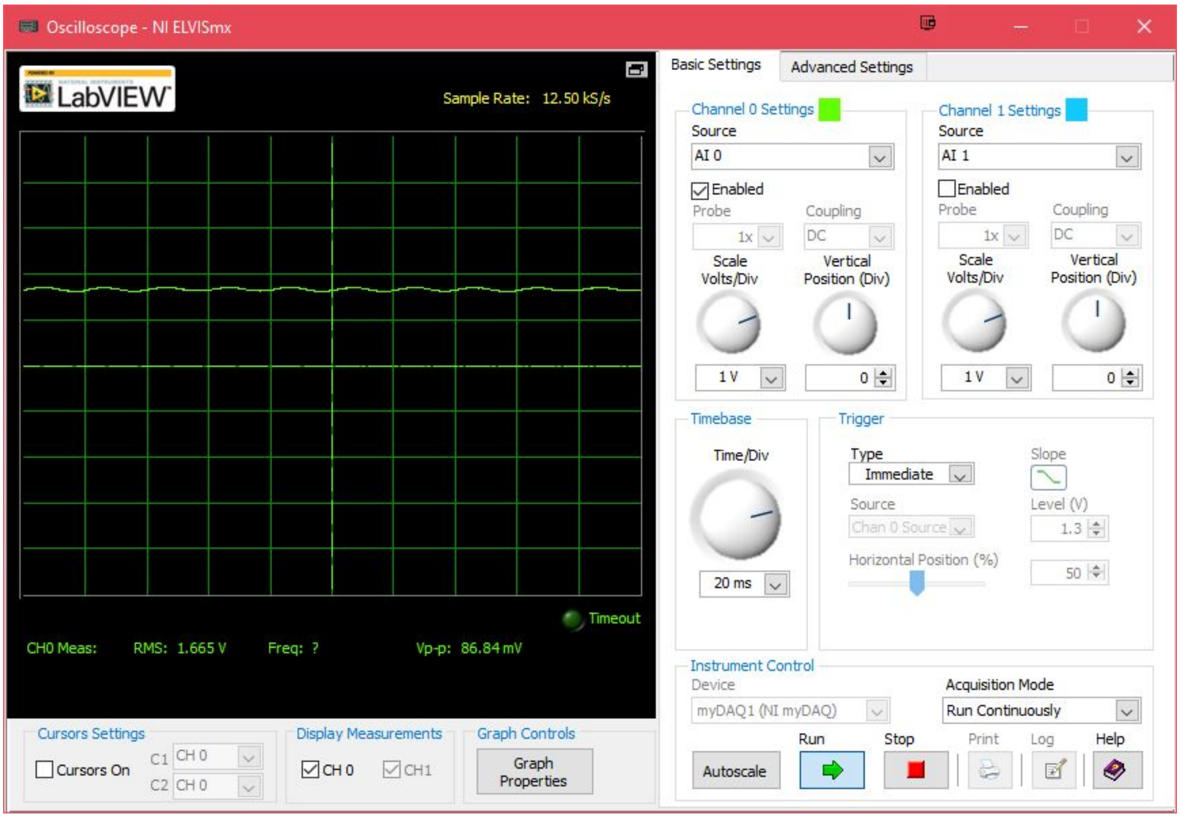
All tests in this section were done with the Arduino powered by USB, and both the Arduino and HR circuit are placed in a grounded metal enclosure.



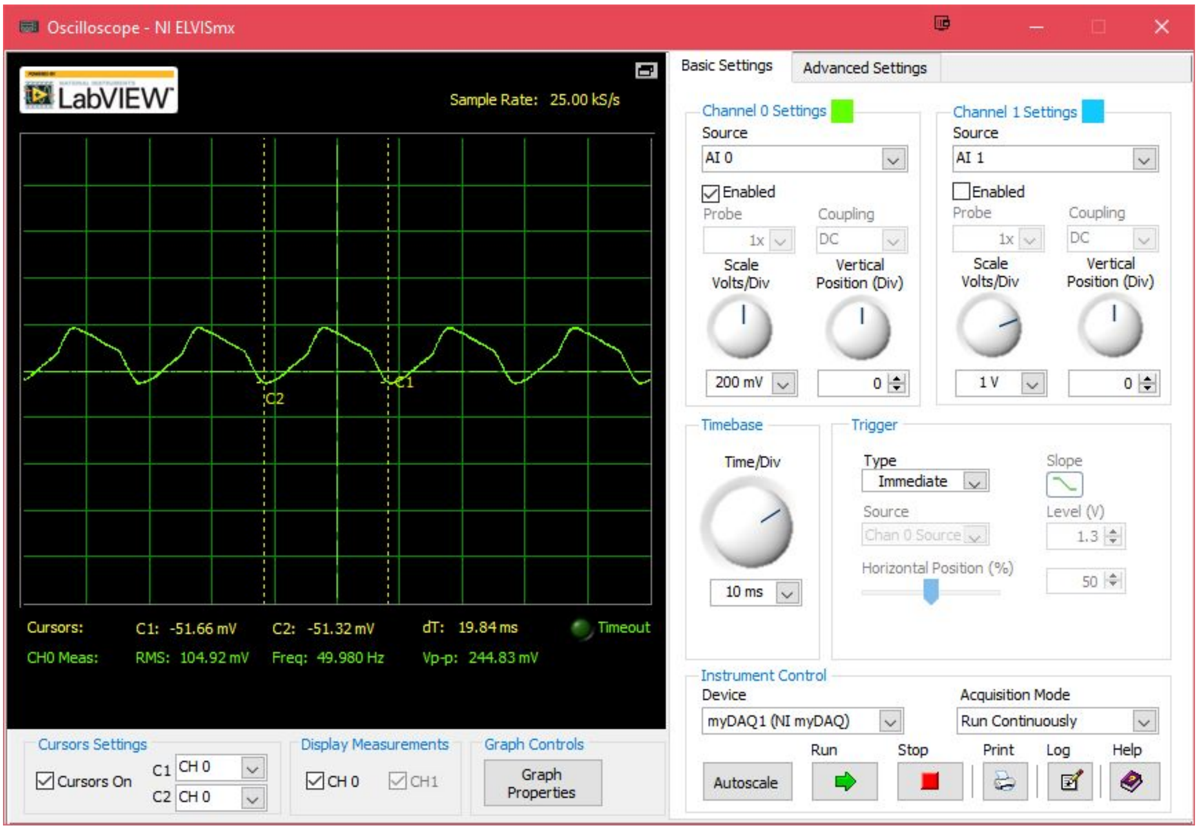

Appendix 91 - Noise on HR circuit output without the ECG cable connected and the grounded enclosure is closed. 111.32mV



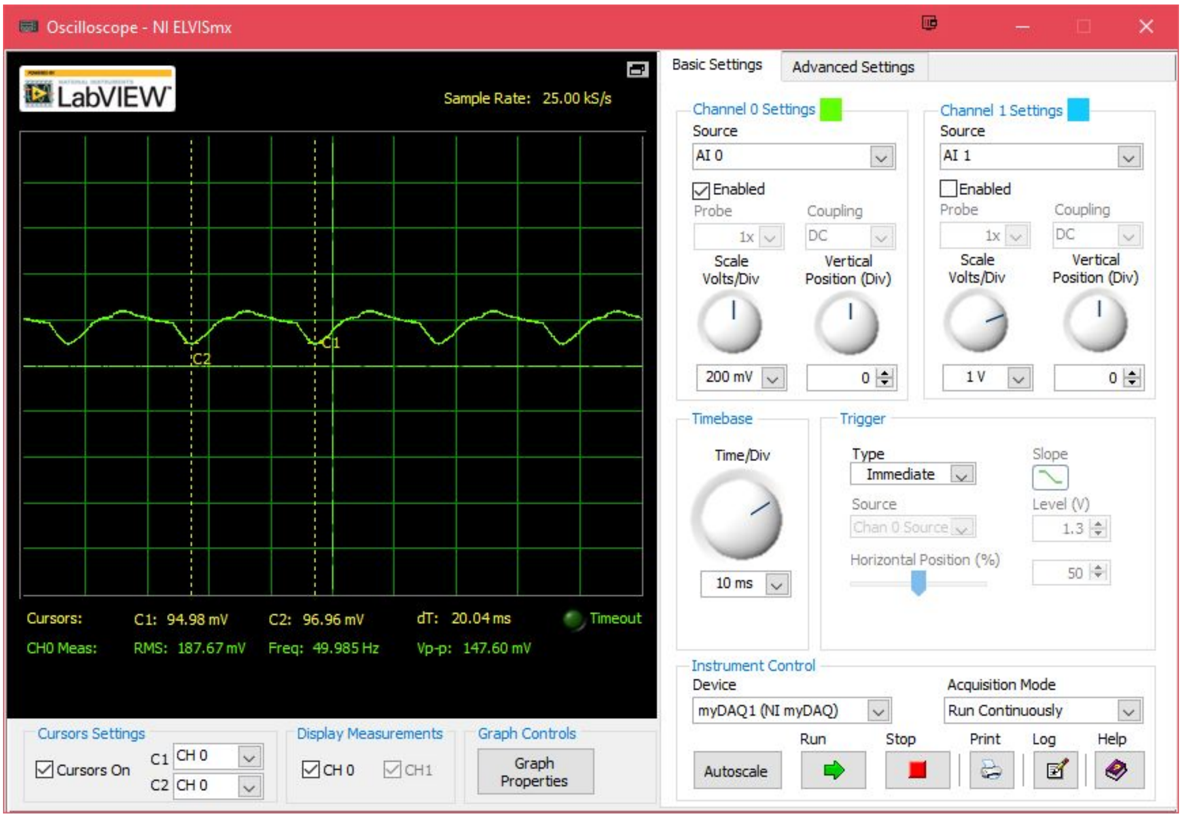

Appendix 92 - Noise on HR circuit output without the ECG cable connected and the grounded enclosure is half-open. 37.54mV



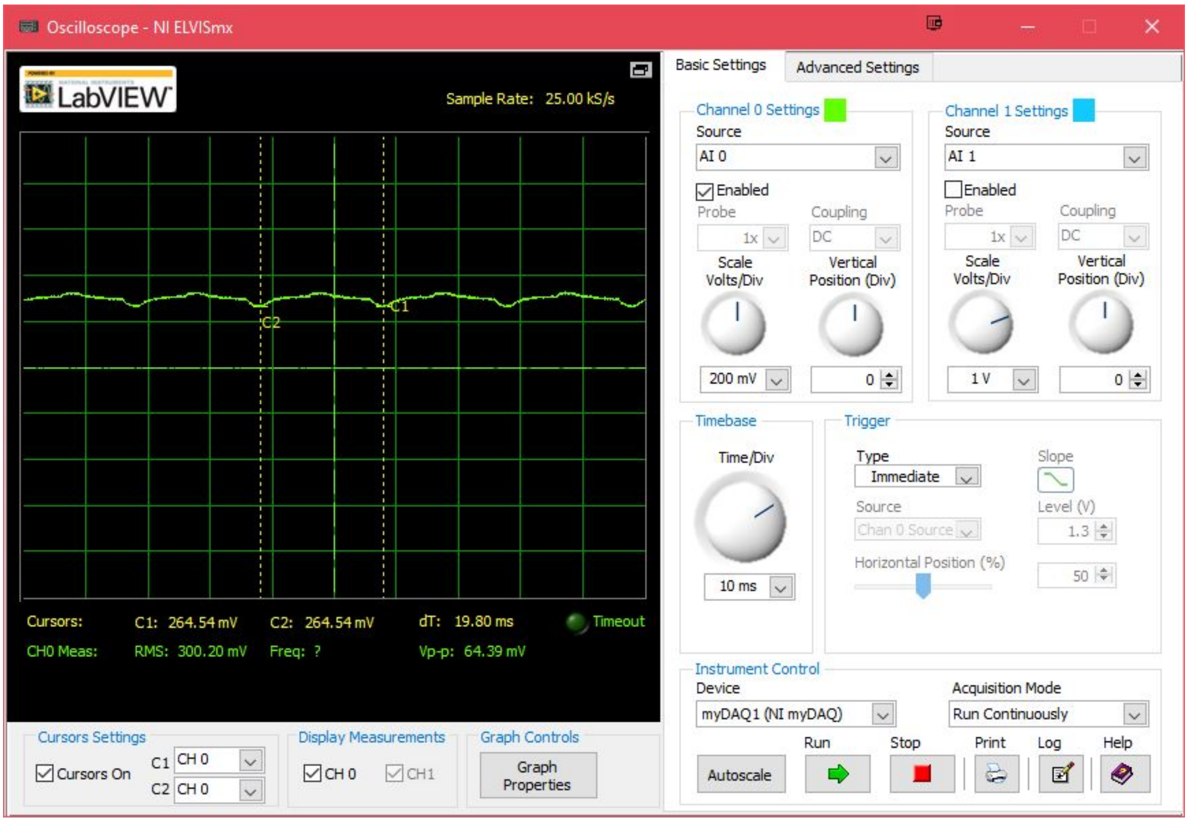

Appendix 93 - Noise on HR circuit output without the ECG cable connected and the grounded enclosure is open. 86.84mV



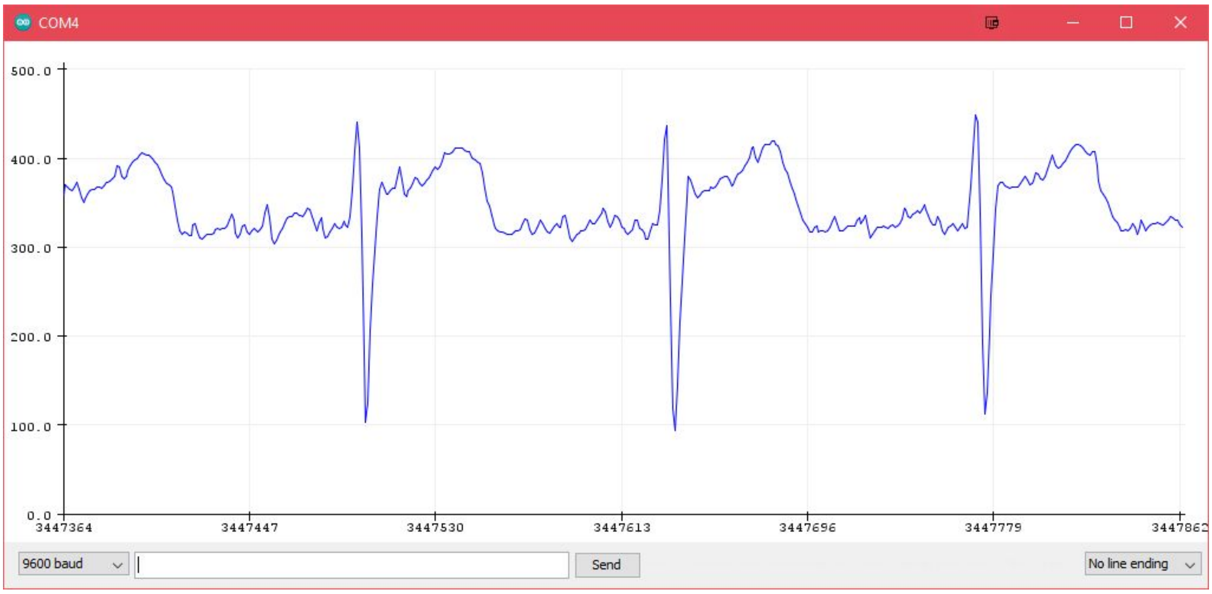

Appendix 94 - Noise on HR circuit output with the ECG cable connected and the grounded enclosure is closed. 244.83mV




Appendix 95 - Noise on HR circuit output with the ECG cable connected and the grounded enclosure is half-open. 147.50mV

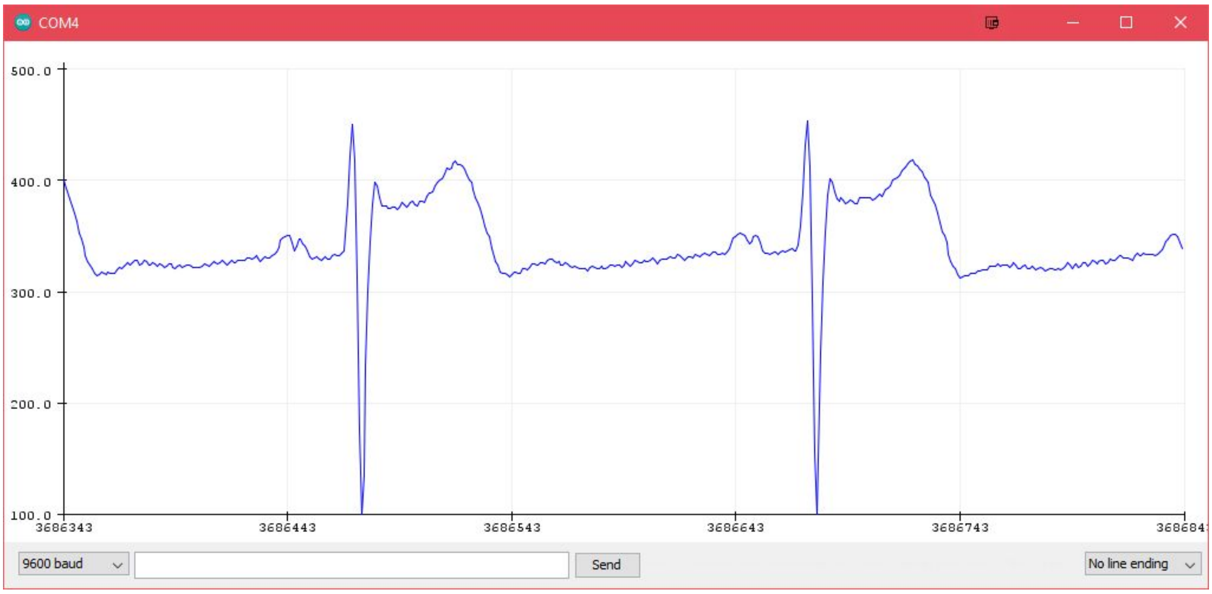



Appendix 96 - Noise on HR circuit output with the ECG cable connected and the grounded enclosure is open. 64.39mV




Appendix 97 - Heart rhythm data when the grounded enclosure is closed.


Appendix 98 - Heart rhythm data when the grounded enclosure is closed and the user's arm is not rested.



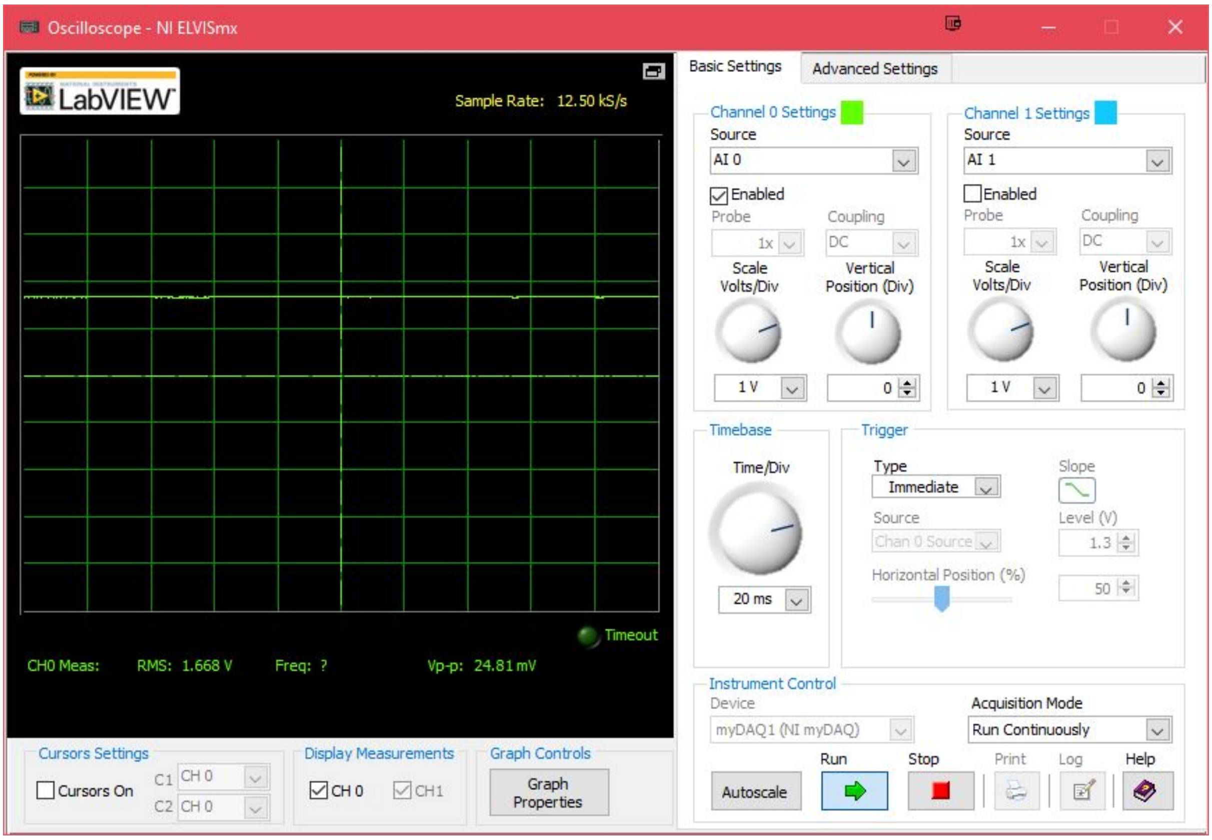

Appendix 99 - Heart rhythm data when the grounded enclosure is open.

## Distance Test

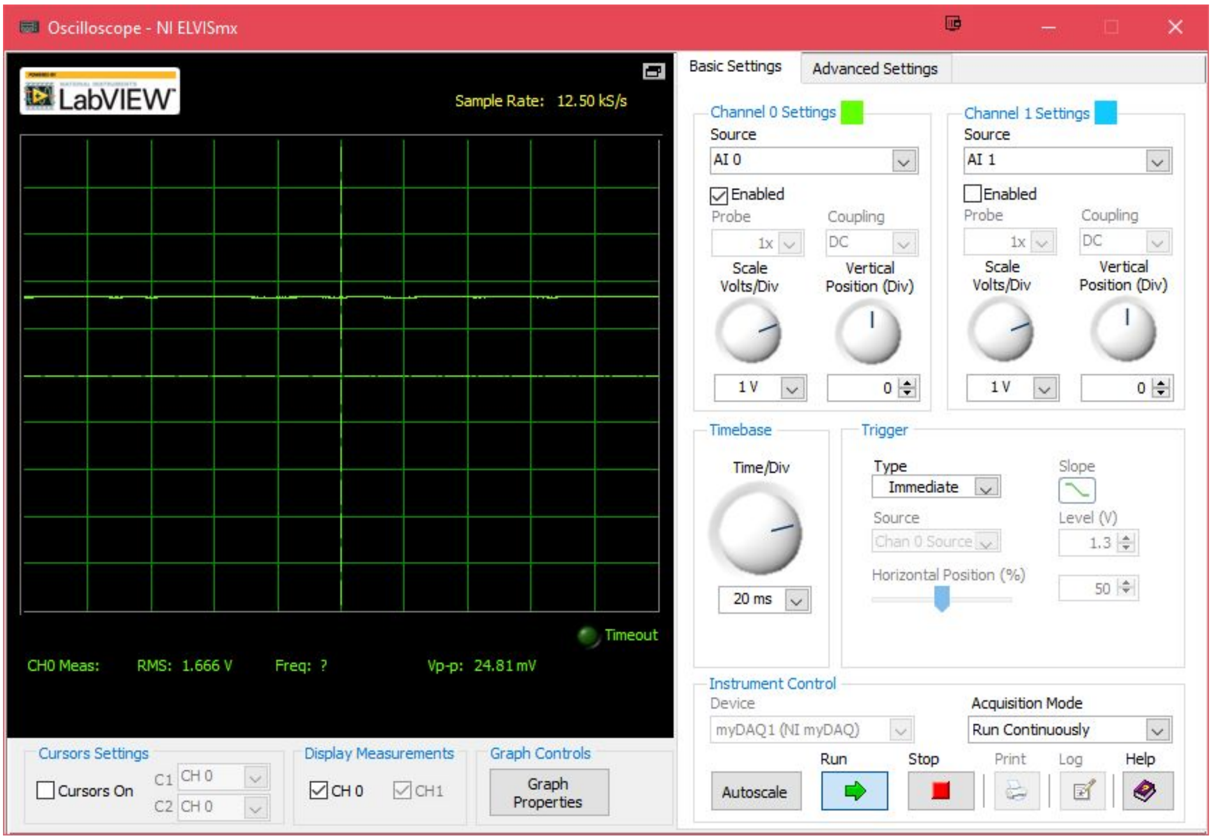
This testing was done with the complete system in the grounded enclosure.


Appendix 100 - Heart rhythm data when the grounded enclosure is closed and moved 120cm away from the original testing position.

Appendix 101 - Heart rhythm data when the grounded enclosure is open and moved 120cm away from the original testing position. Be mindful of the y-axis having a different scale to previous screen capture.



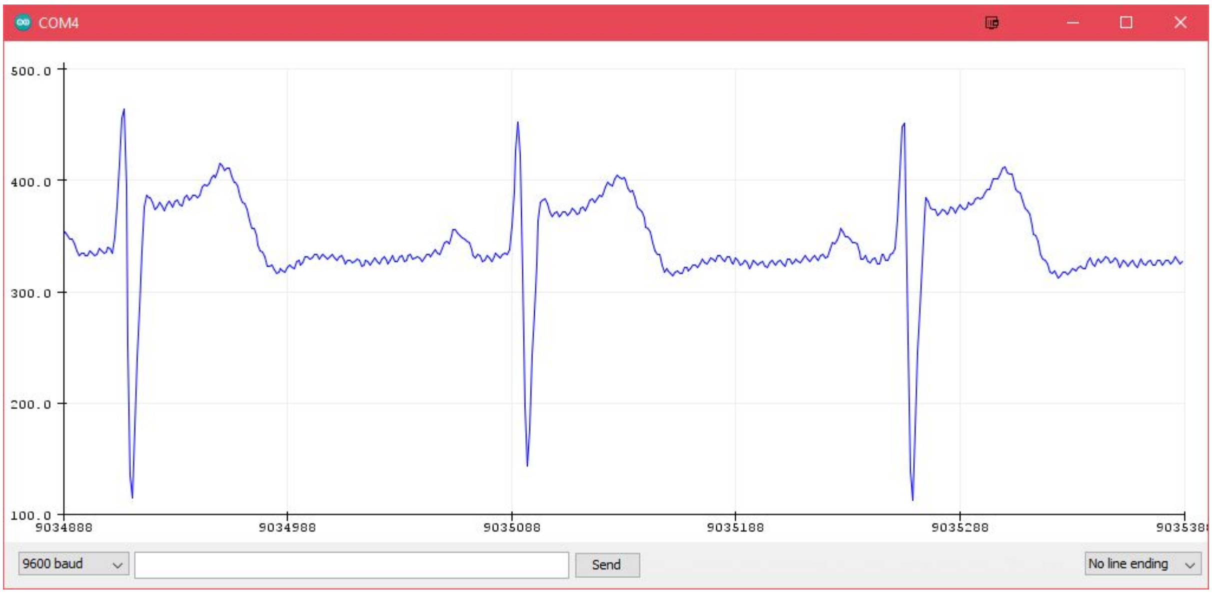
Appendix 102 - Noise on HR circuit output with the ECG cable connected and the grounded enclosure is closed and 120cm away from the original testing position. 24.81mV



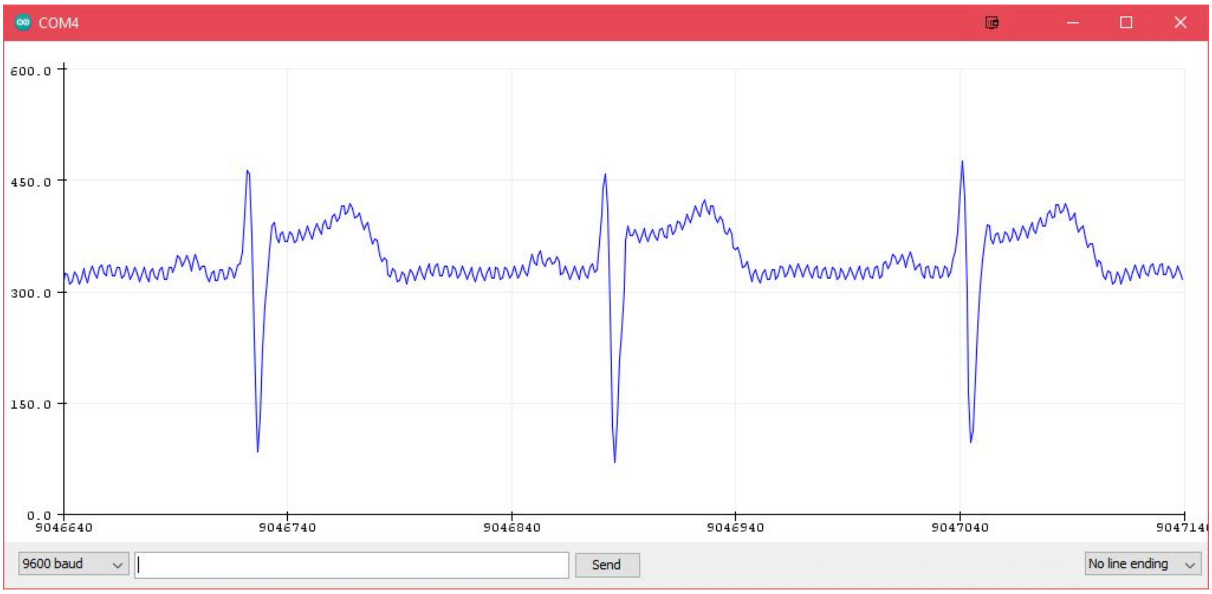

Appendix 103 - Noise on HR circuit output with the ECG cable connected and the grounded enclosure is open and 120cm away from the original testing position. 24.81mV

## HR Monitor Shielded

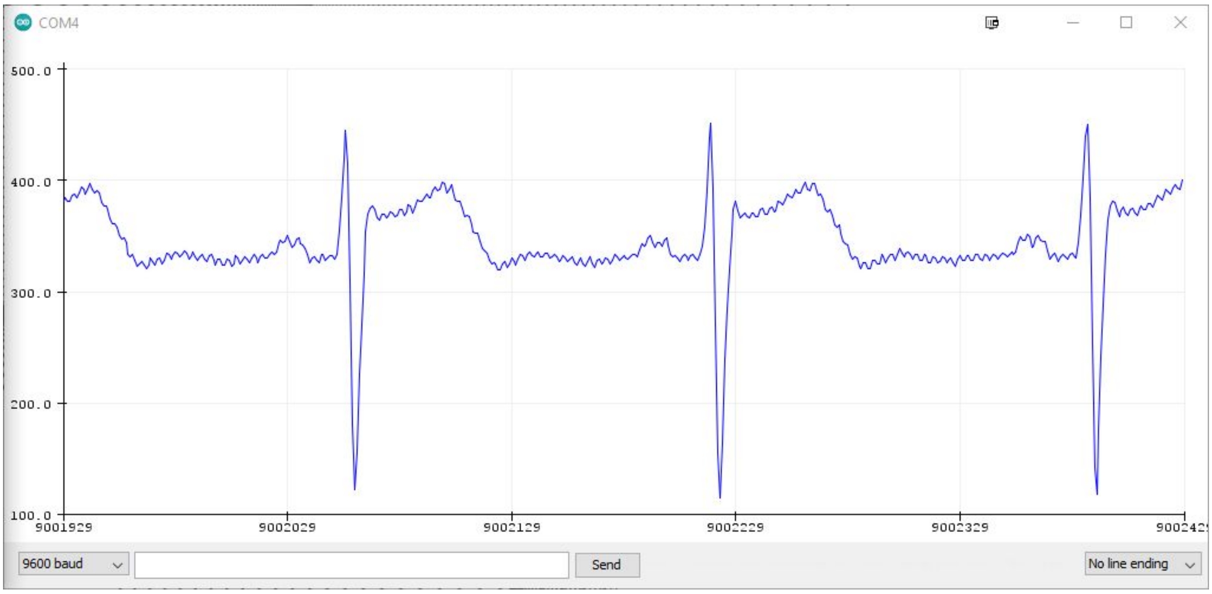
This testing was performed at the original testing location with the HR sensor placed in the grounded enclosure with the Arduino placed outside.



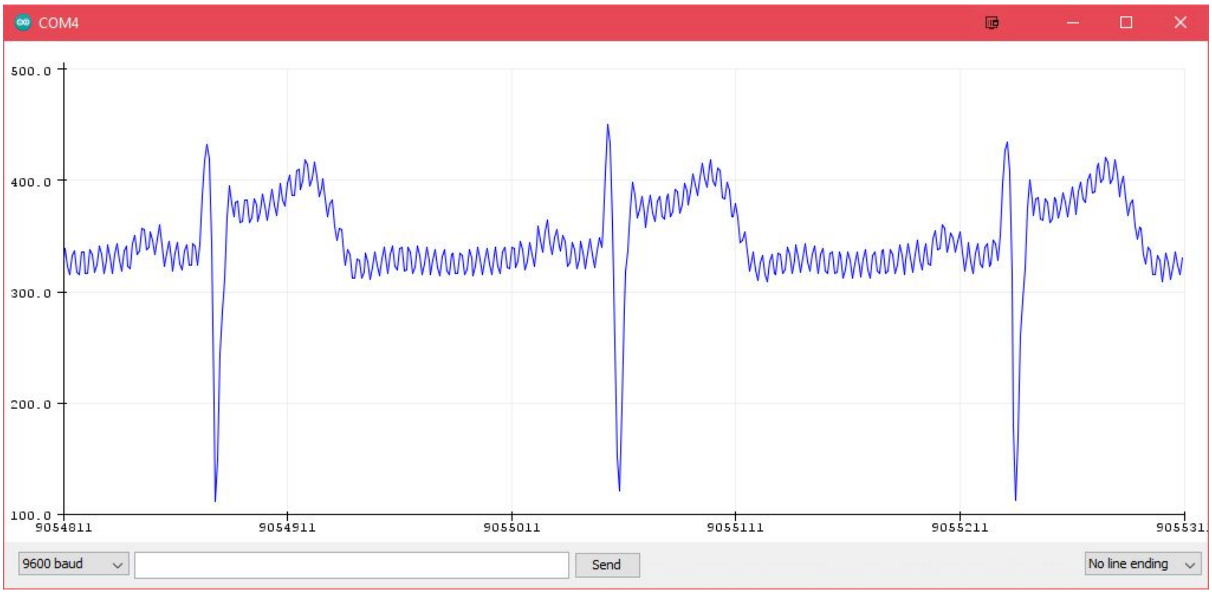
Appendix 104 - Heart rhythm data when the grounded enclosure is closed.



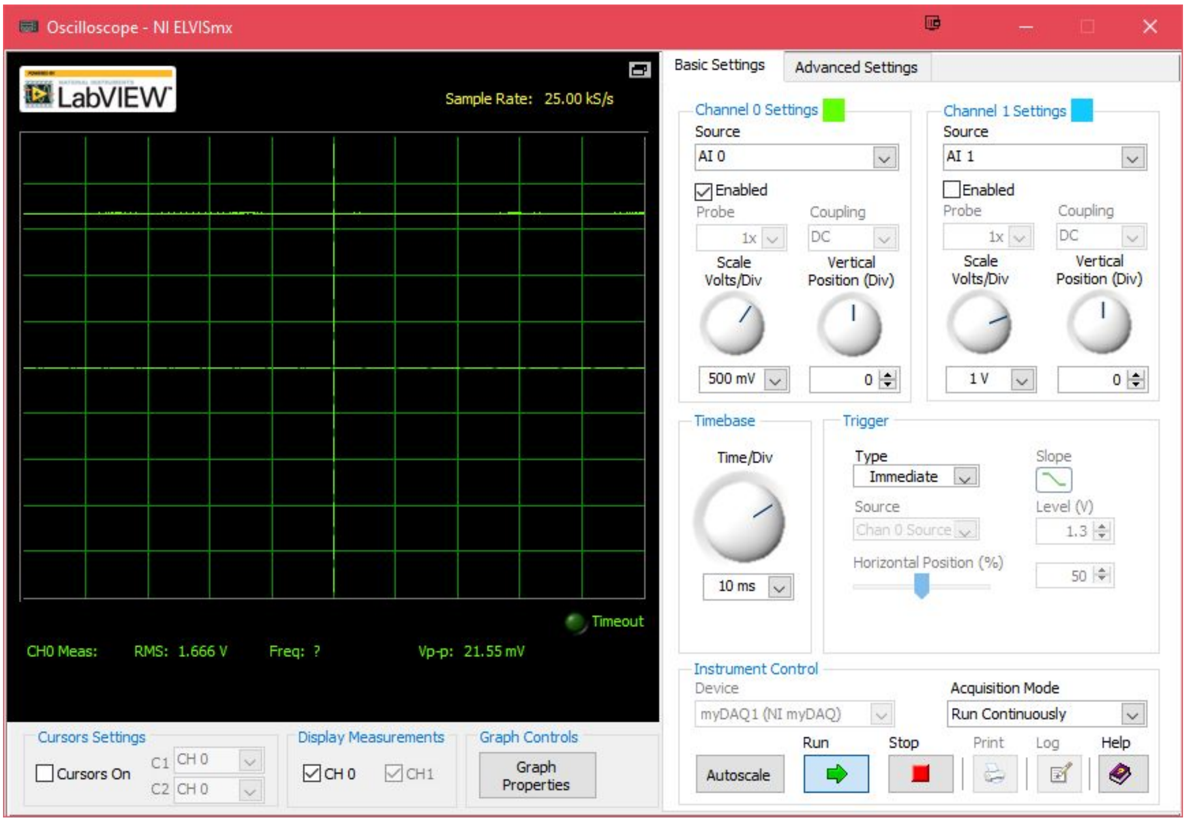
Appendix 105 - Heart rhythm data when the enclosure is closed and disconnected from the ground.



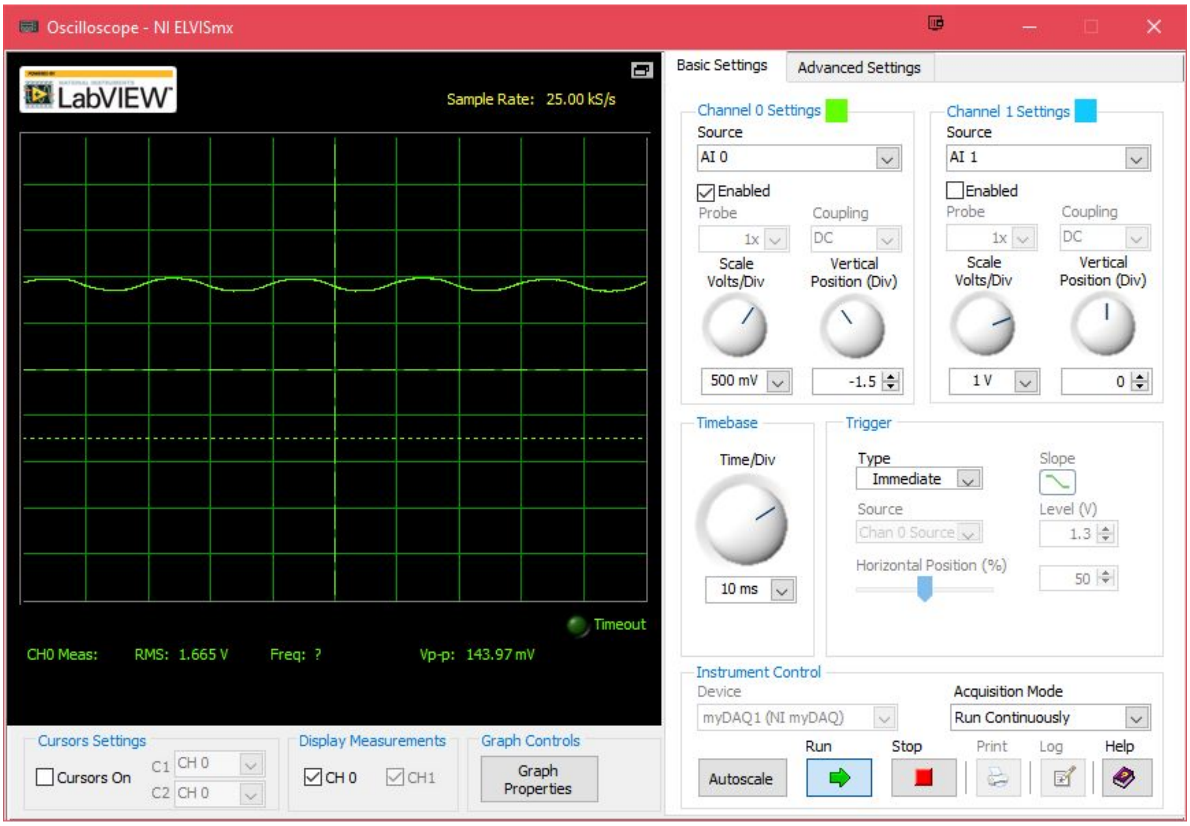

Appendix 106 - Heart rhythm data when the grounded enclosure is open.



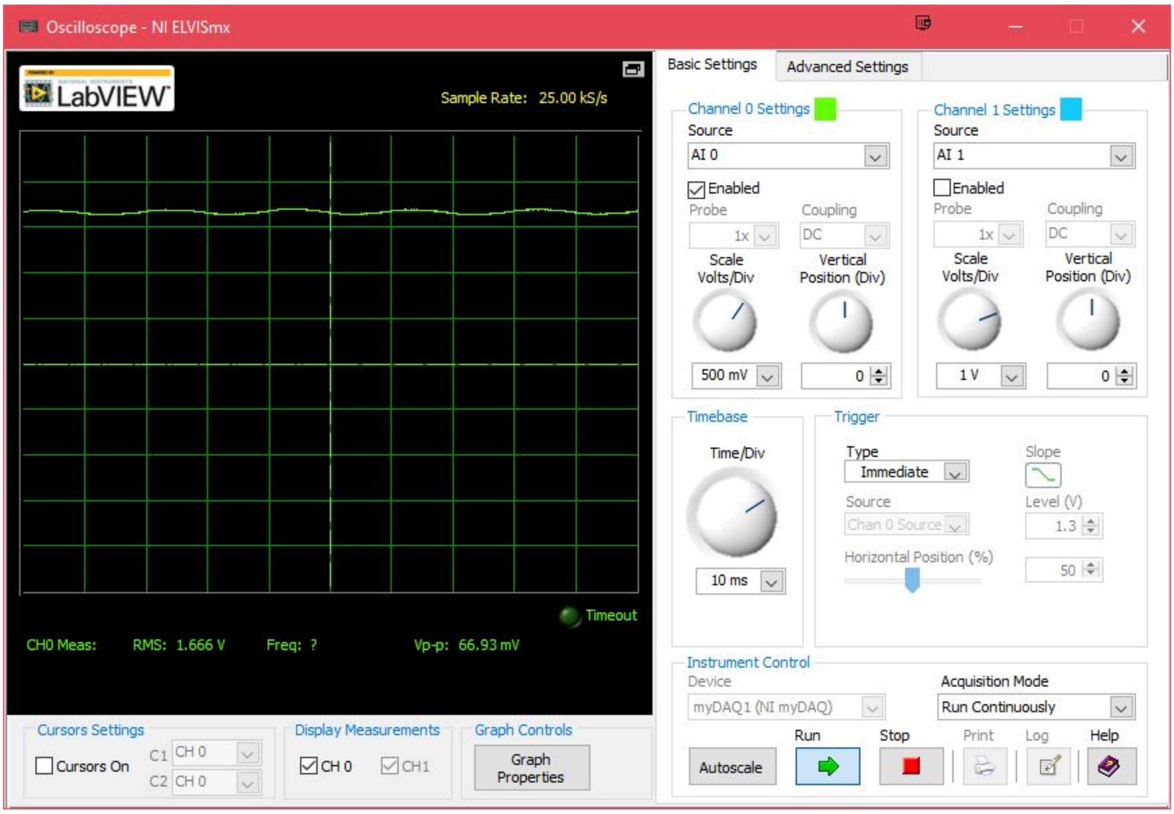

Appendix 107 - Heart rhythm data when the enclosure is open and disconnected from the ground.



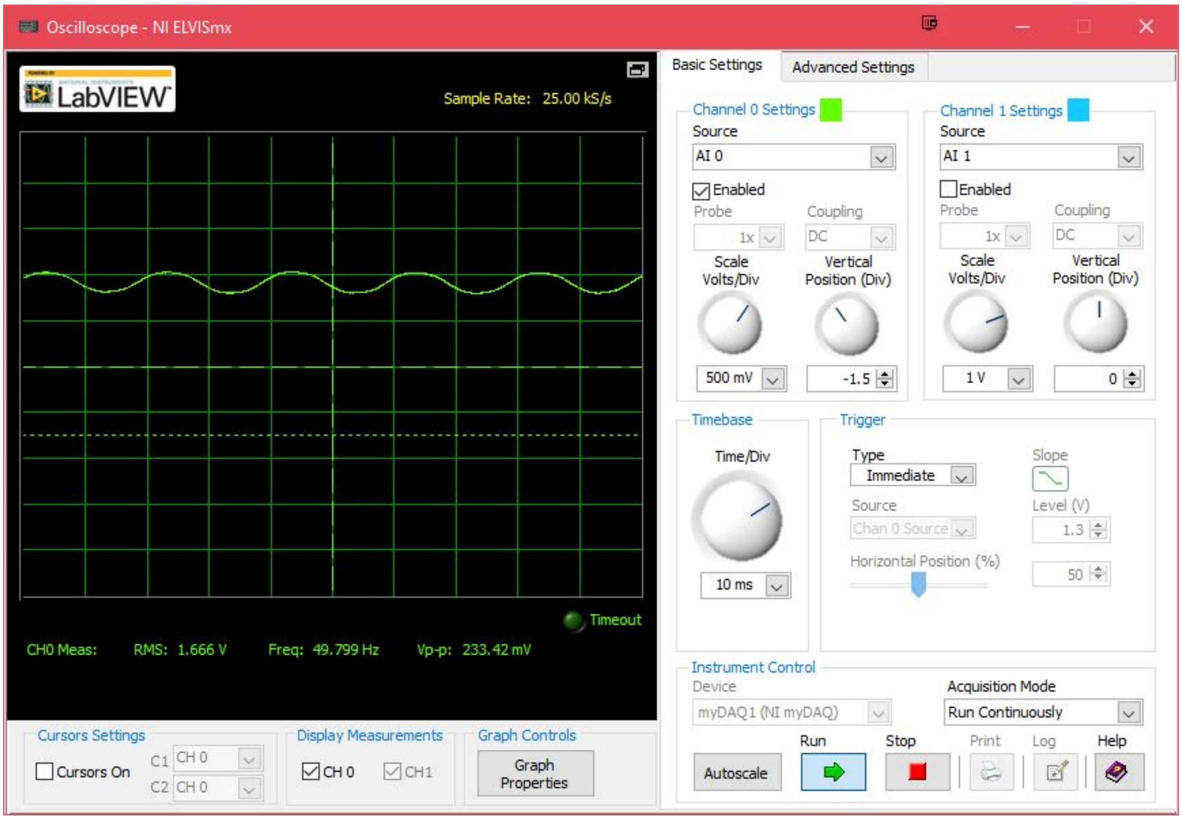

Appendix 108 - Noise on HR circuit output with the ECG cable connected and the grounded enclosure is closed. 21.55mV



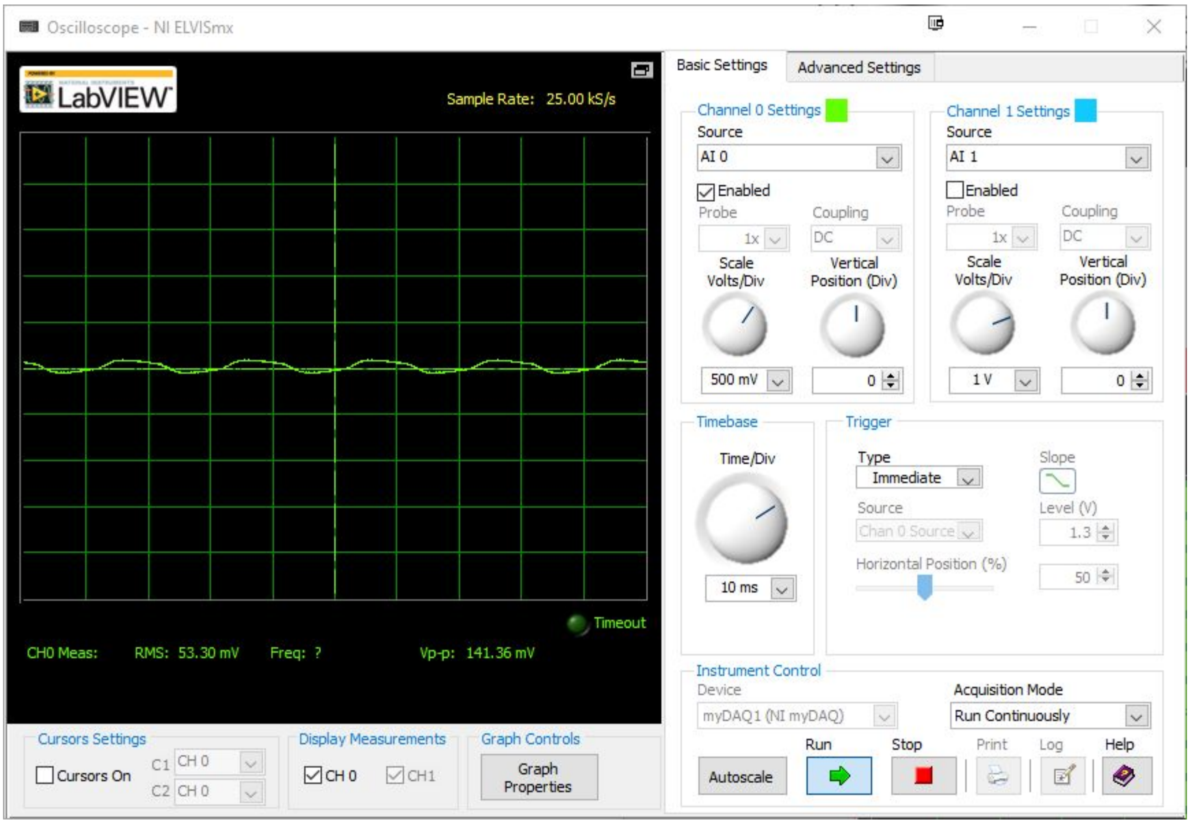

Appendix 109 - Noise on HR circuit output with the ECG cable connected and the enclosure is closed and disconnected from ground. 143.97V



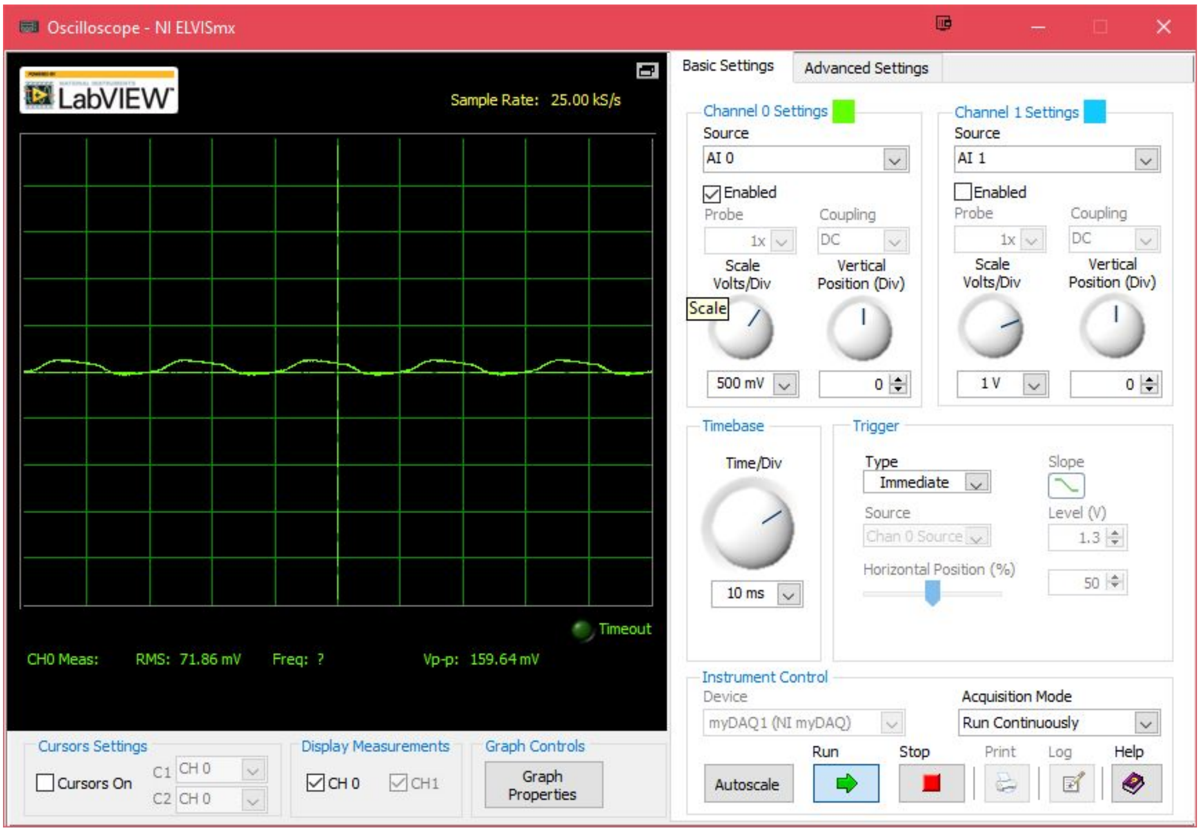

Appendix 110 - Noise on HR circuit output with the ECG cable connected and the grounded enclosure is open. 66.93mV




Appendix 111 - Noise on HR circuit output with the ECG cable connected and the enclosure is open and disconnected from the ground. 233.42V




Appendix 112 - Noise on HR circuit output when the HR circuit is unpowered, and the grounded enclosure is closed. 141.36mV



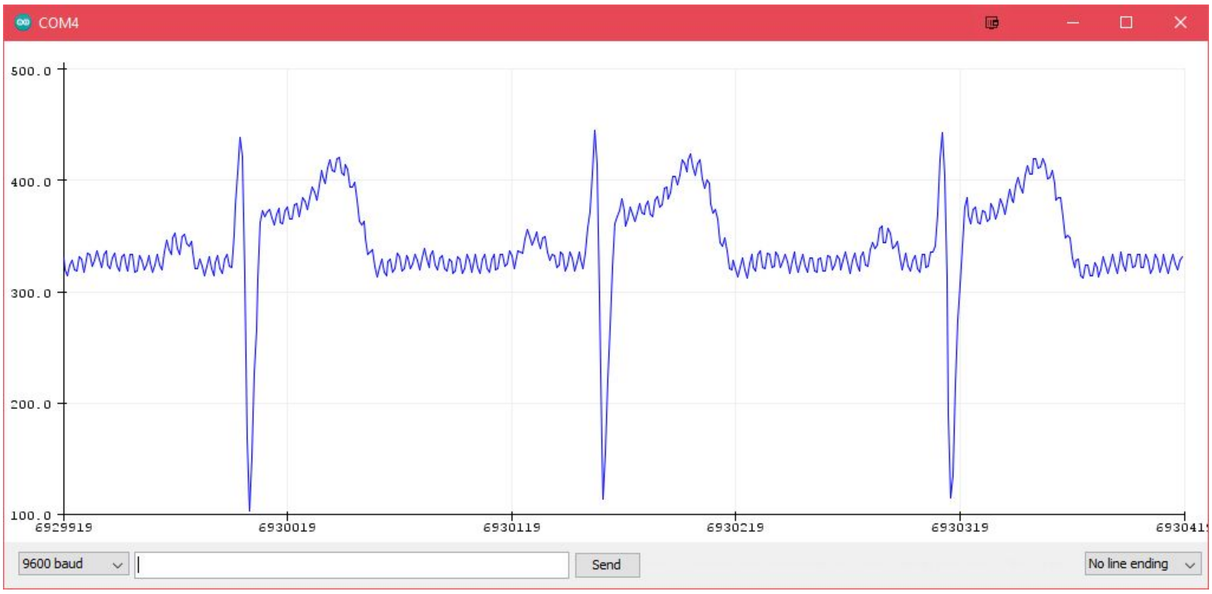

Appendix 113 - Noise on HR circuit output when the HR circuit is unpowered, and the grounded enclosure is open. 159.64mV

## Arduino Shielded

These tests were performed with the Arduino placed in the grounded enclosure and the HR sensor placed outside.

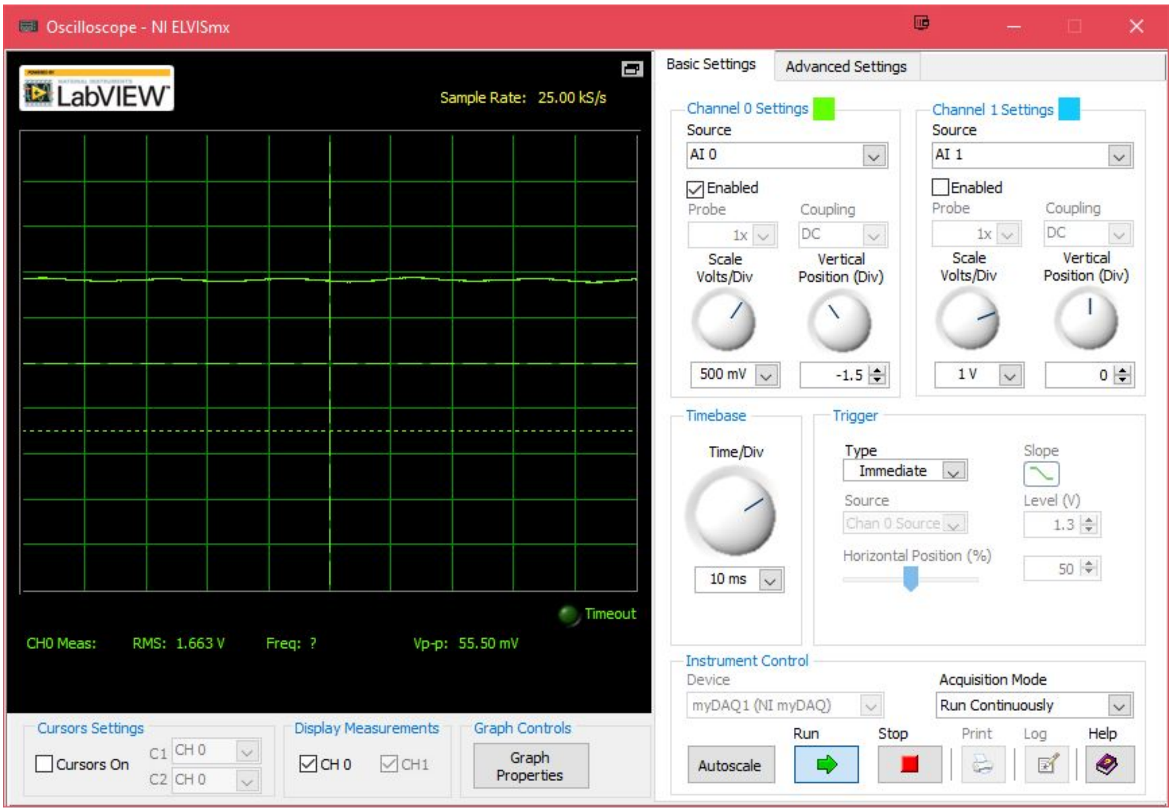

Appendix 114 - Heart rhythm data when the grounded enclosure is closed.


Appendix 115 - Heart rhythm data when the enclosure is closed and disconnected from the ground. Note the change in y-axis scale.

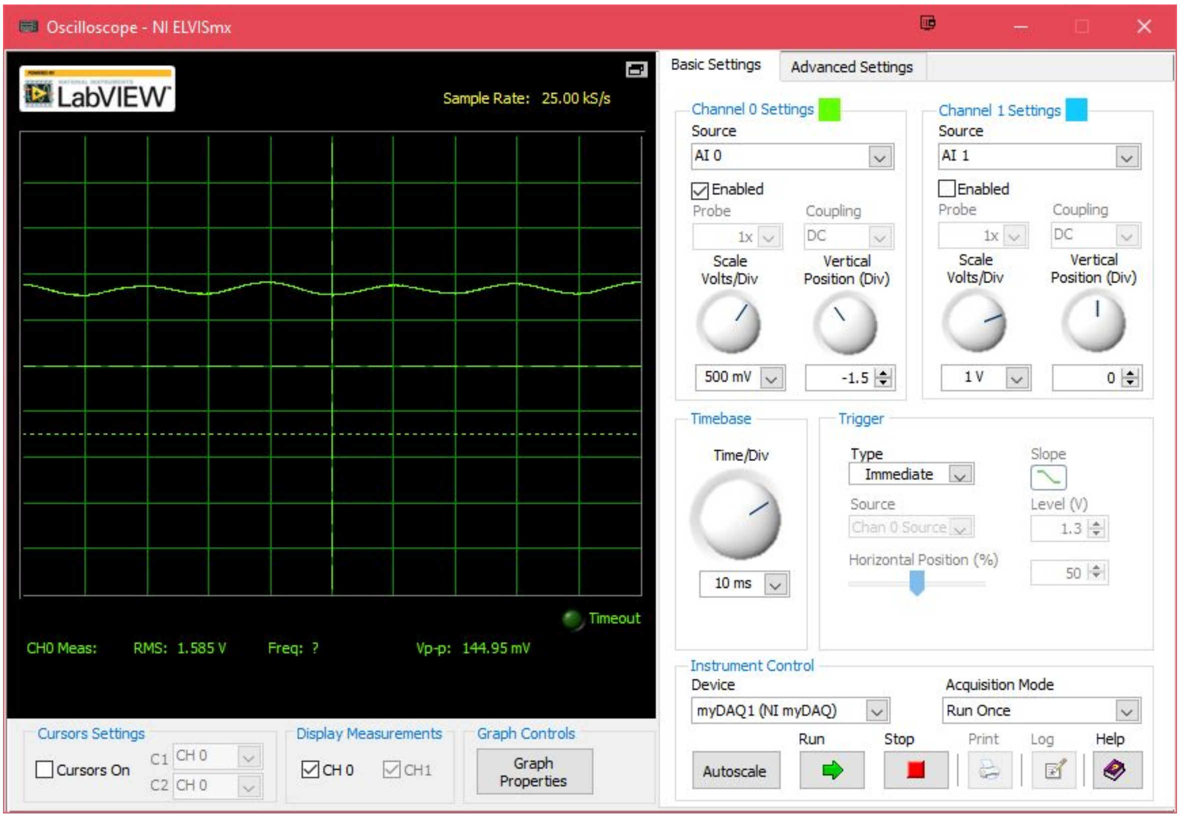



Appendix 116 - Heart rhythm data when the grounded enclosure is open.

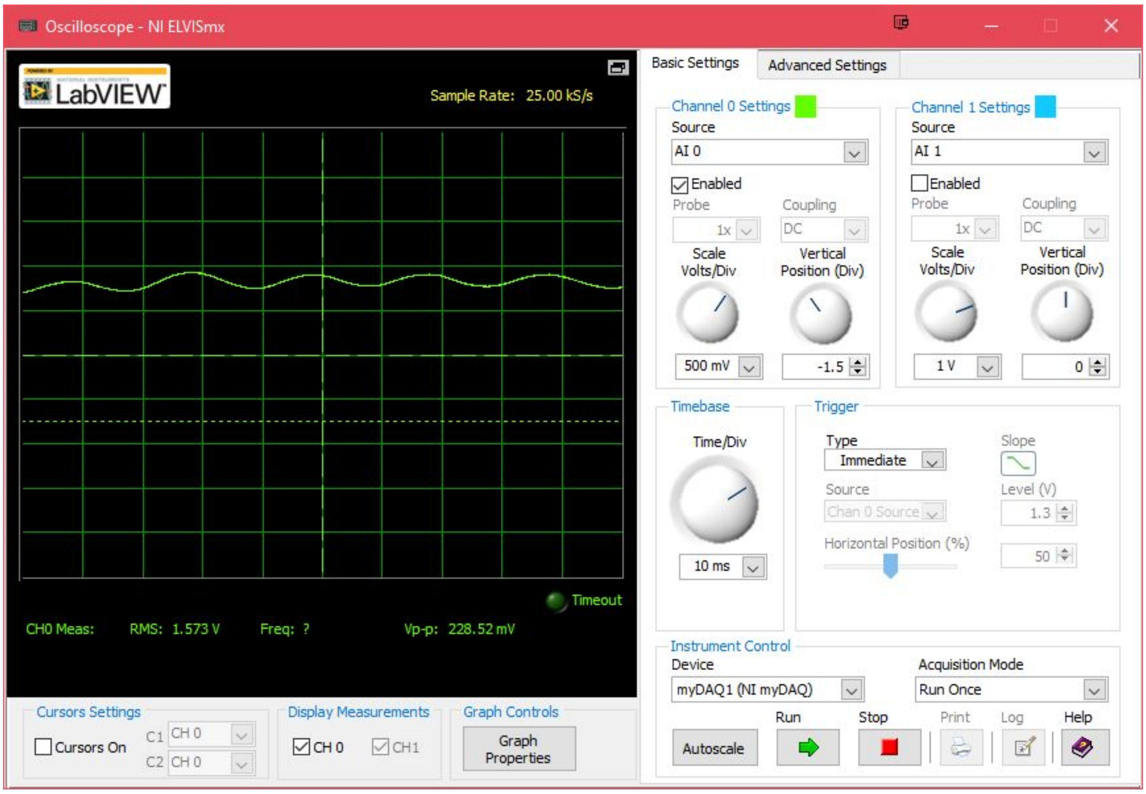

Appendix 117 - Heart rhythm data when the enclosure is open and disconnected from the ground.



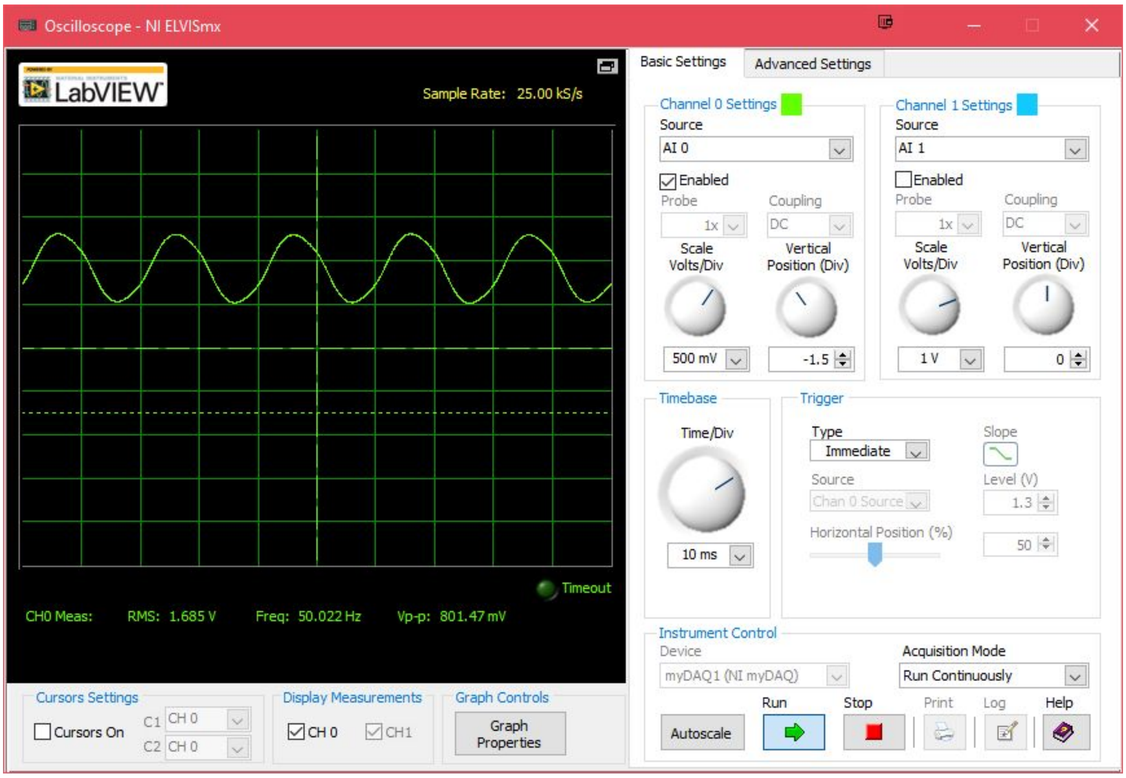

Appendix 118 - Noise on HR circuit output when the HR circuit is powered without the ECG cables, and the grounded enclosure is closed. 55.50mV



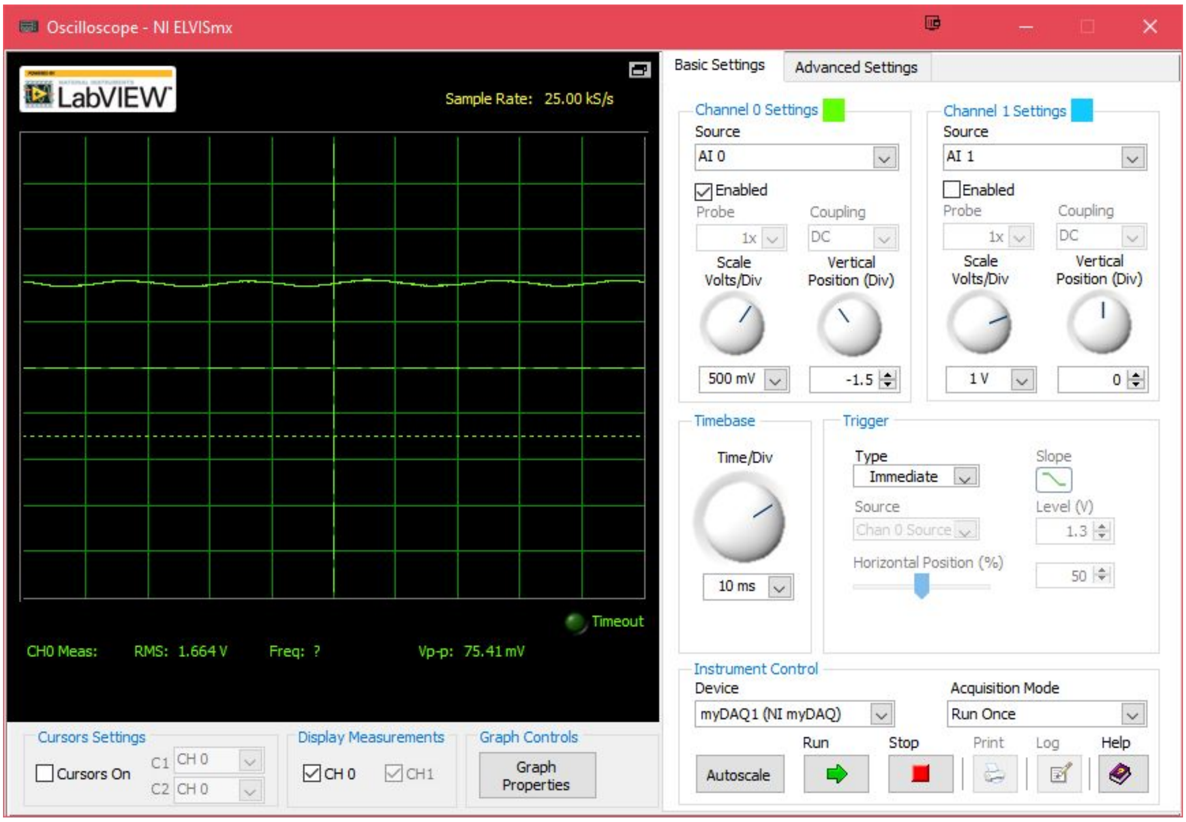

Appendix 119 - Noise on HR circuit output when the HR circuit is powered with the ECG cables and the grounded enclosure is closed. 144.95mV



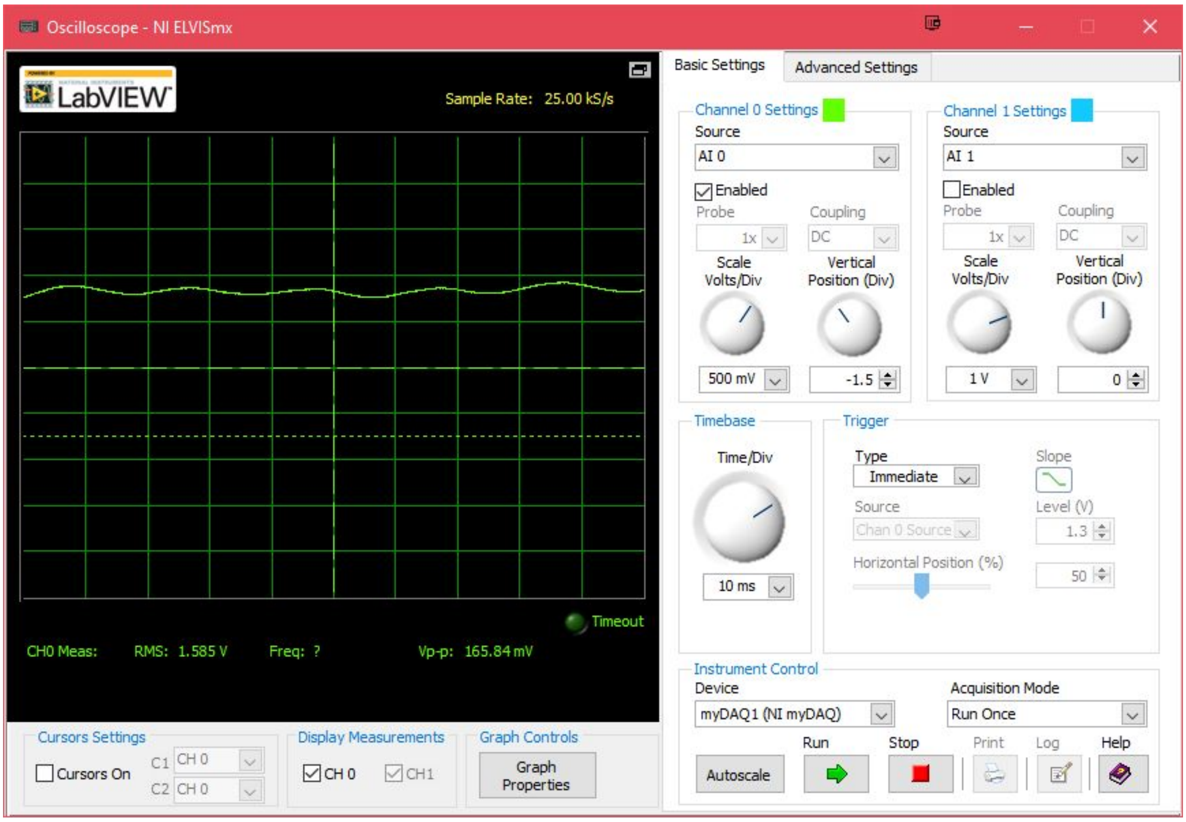

Appendix 120 - Noise on HR circuit output when the HR circuit is powered with the ECG cables connected, the enclosure is closed and disconnected from the ground. 228.52mV



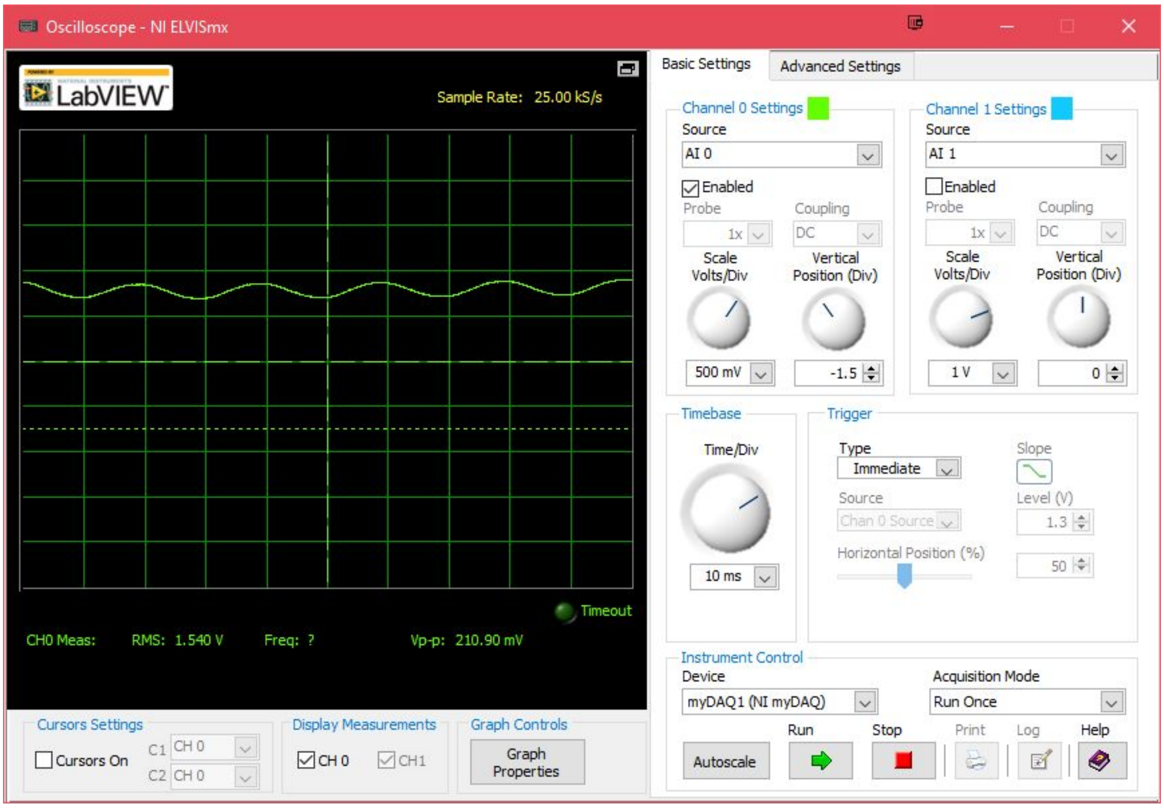

Appendix 121 - Noise on HR circuit output when the HR circuit is powered without the ECG cables, and the enclosure is closed and disconnected from the ground. 801.47mV



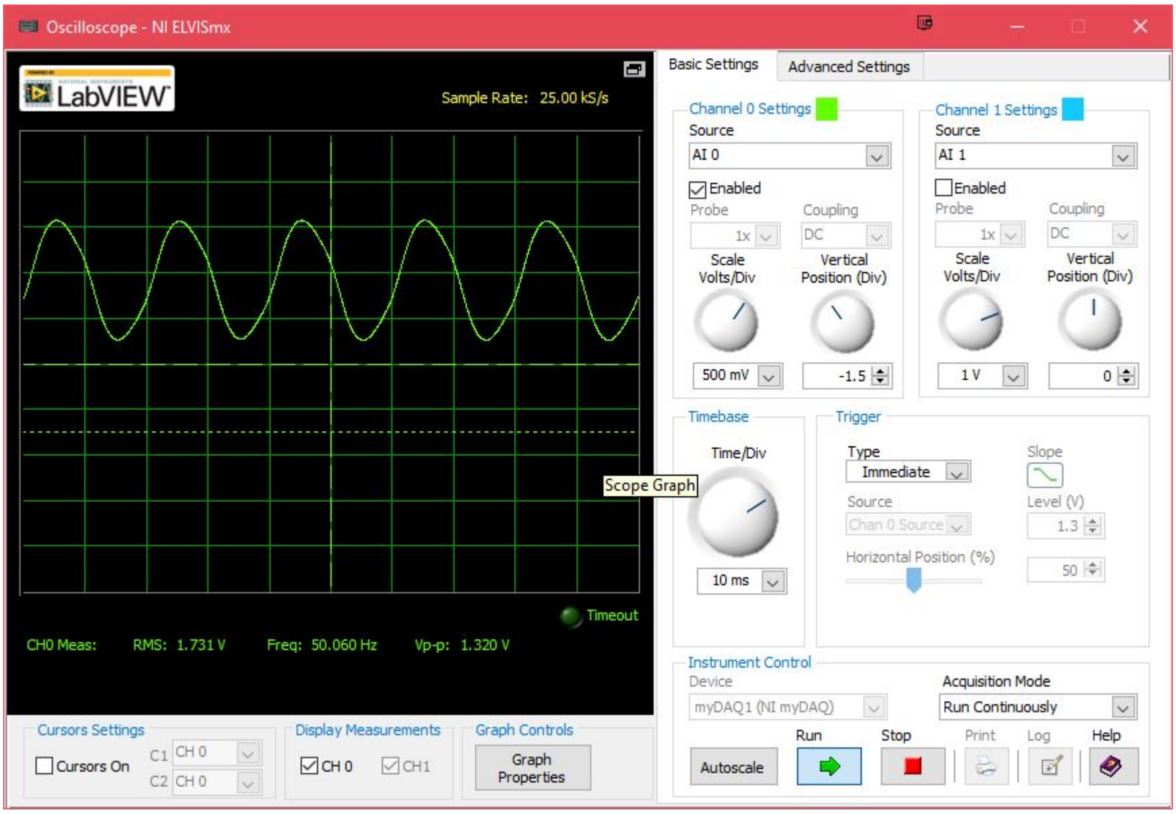

Appendix 122 - Noise on HR circuit output when the HR circuit is powered without the ECG cables, and the grounded enclosure is open. 75.41mV



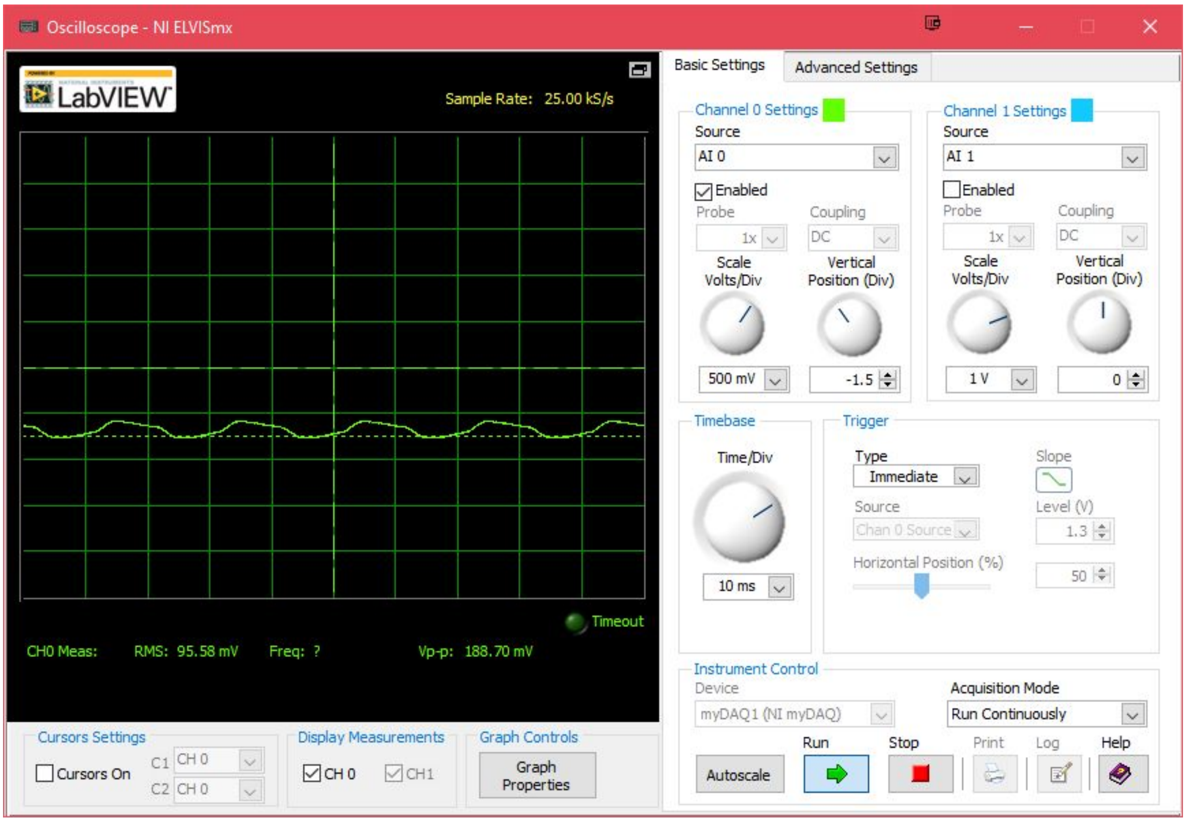

Appendix 123 - Noise on HR circuit output when the HR circuit is powered with the ECG cables and the grounded enclosure is open. 165.84mV



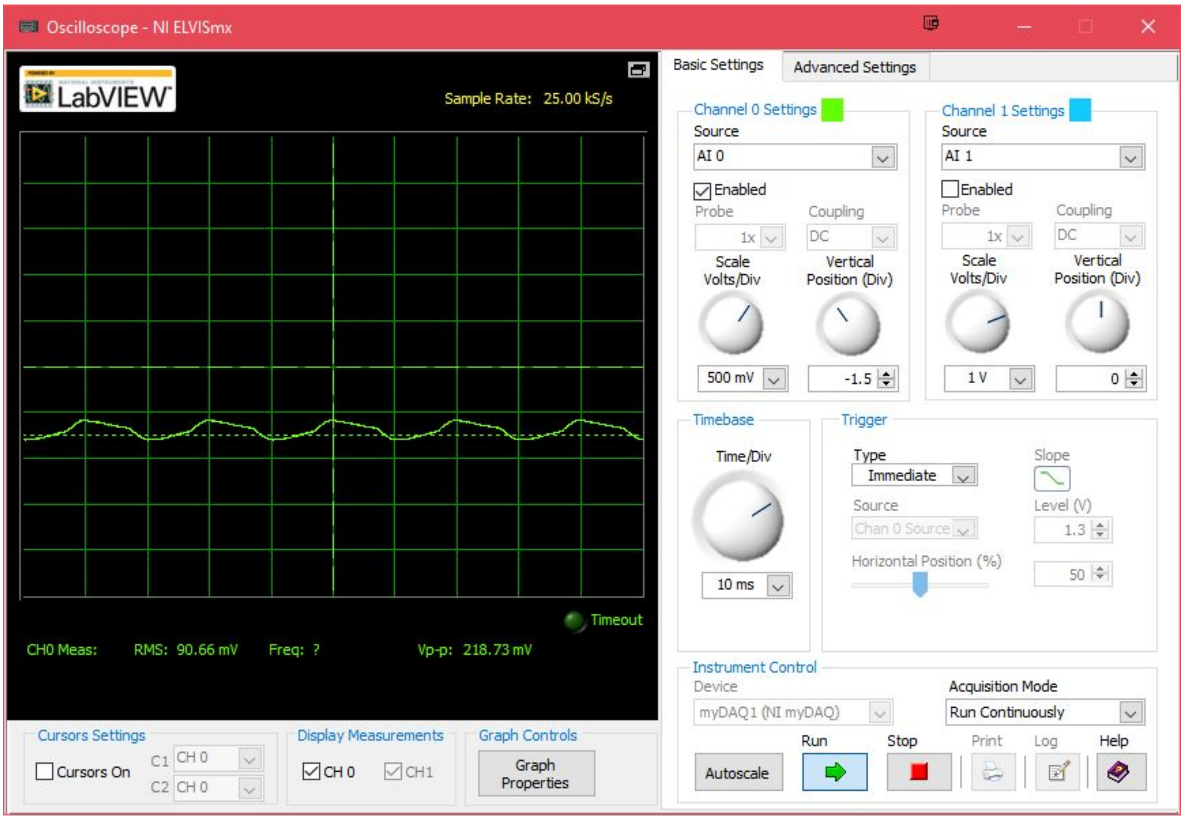

Appendix 124 - Noise on HR circuit output when the HR circuit is powered with the ECG cables connected, the enclosure is open and disconnected from the ground. 210.90mV




Appendix 125 - Noise on HR circuit output when the HR circuit is powered without the ECG cables and the enclosure is open and disconnected from ground. 1.320V




Appendix 126 - Noise on HR circuit output when the HR circuit is unpowered with the ECG cables and the enclosure is closed. 188.70mV

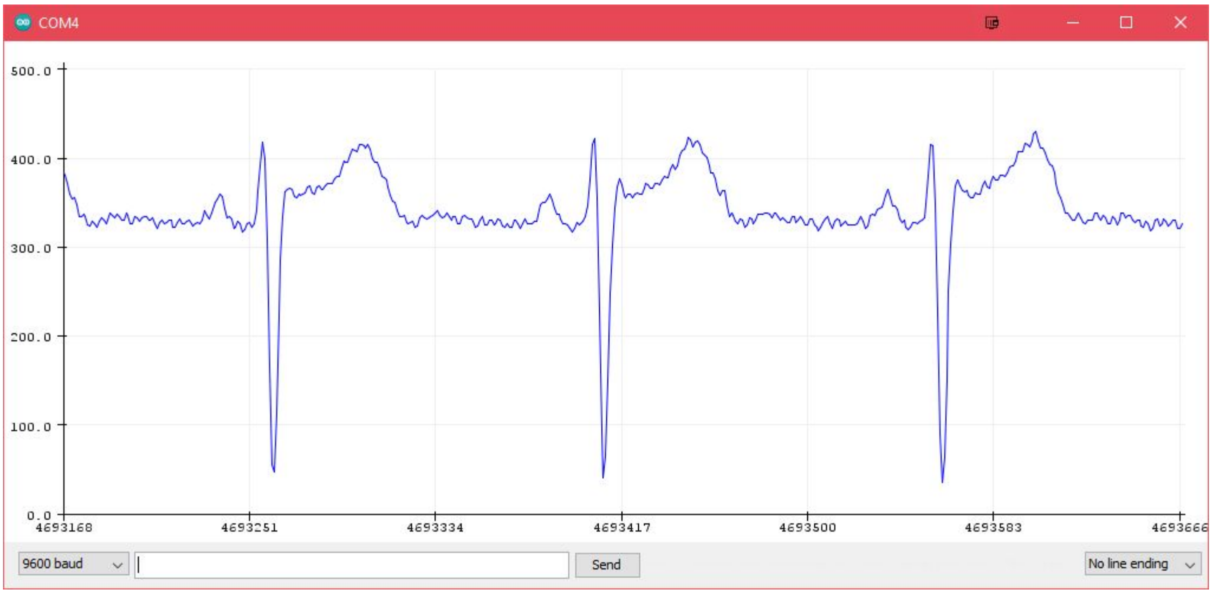



Appendix 127 - Noise on HR circuit output when the HR circuit is unpowered with the ECG cables and the enclosure is open. 218.73mV

## Layered Shielded

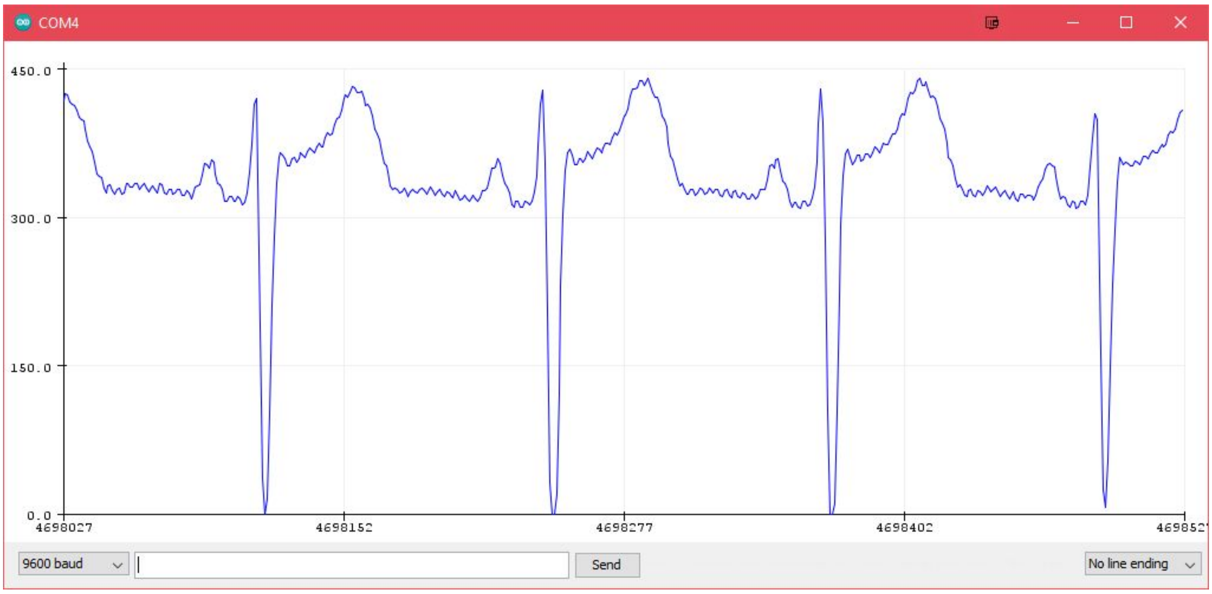
The testing was performed with the HR circuit placed inside a plastic box covered in foil and grounded, then this along with the Arduino is placed into the original grounded enclosure. All the oscilloscope data captures were done without the ECG cable connected.


Appendix 128 - Heart rhythm data when the grounded enclosure is closed.

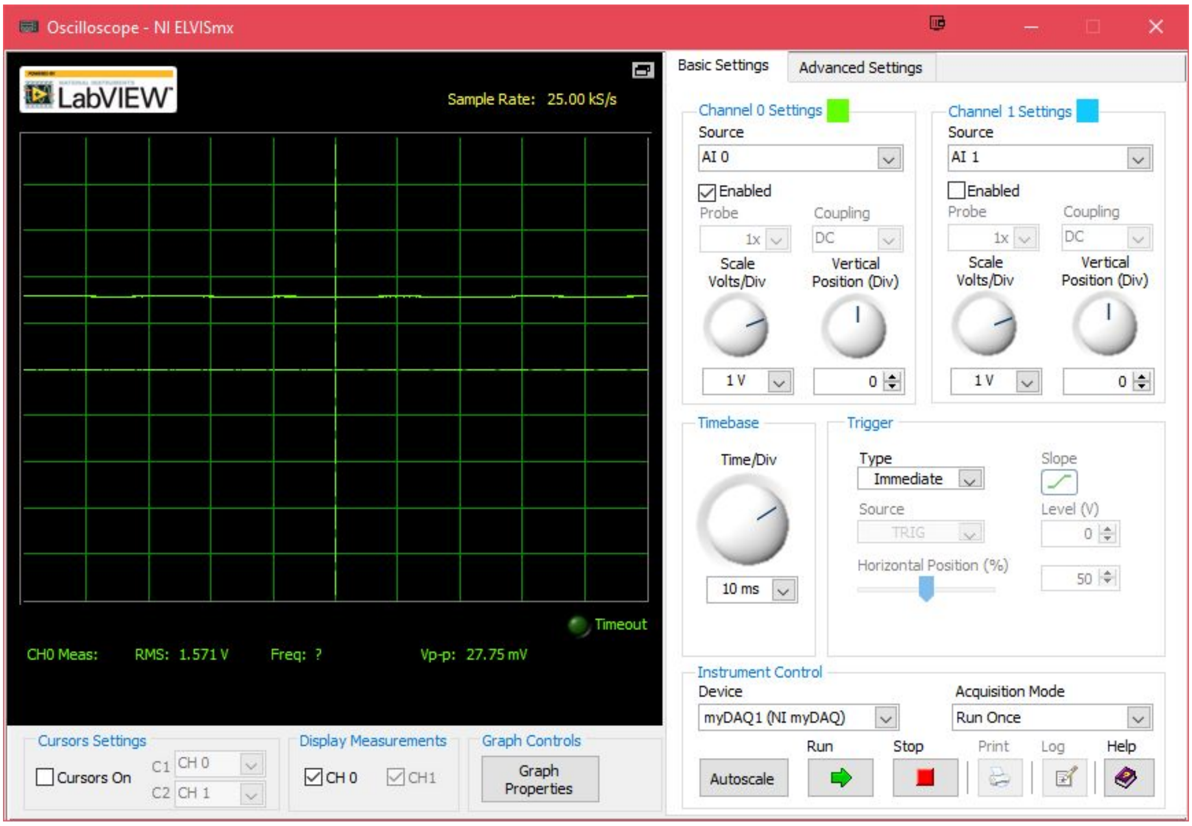



Appendix 129 - Heart rhythm data when the enclosure is closed but disconnected from all ground.

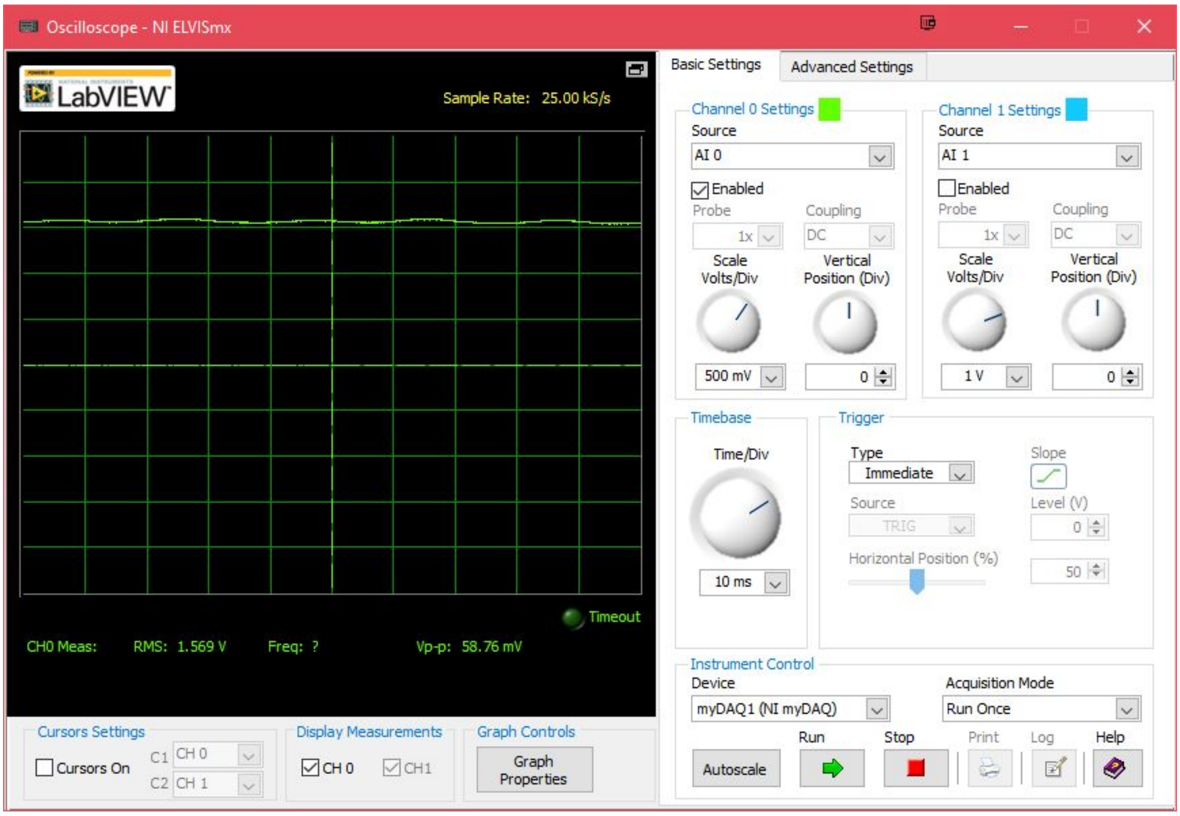

Appendix 130 - Heart rhythm data when the grounded enclosure is open.



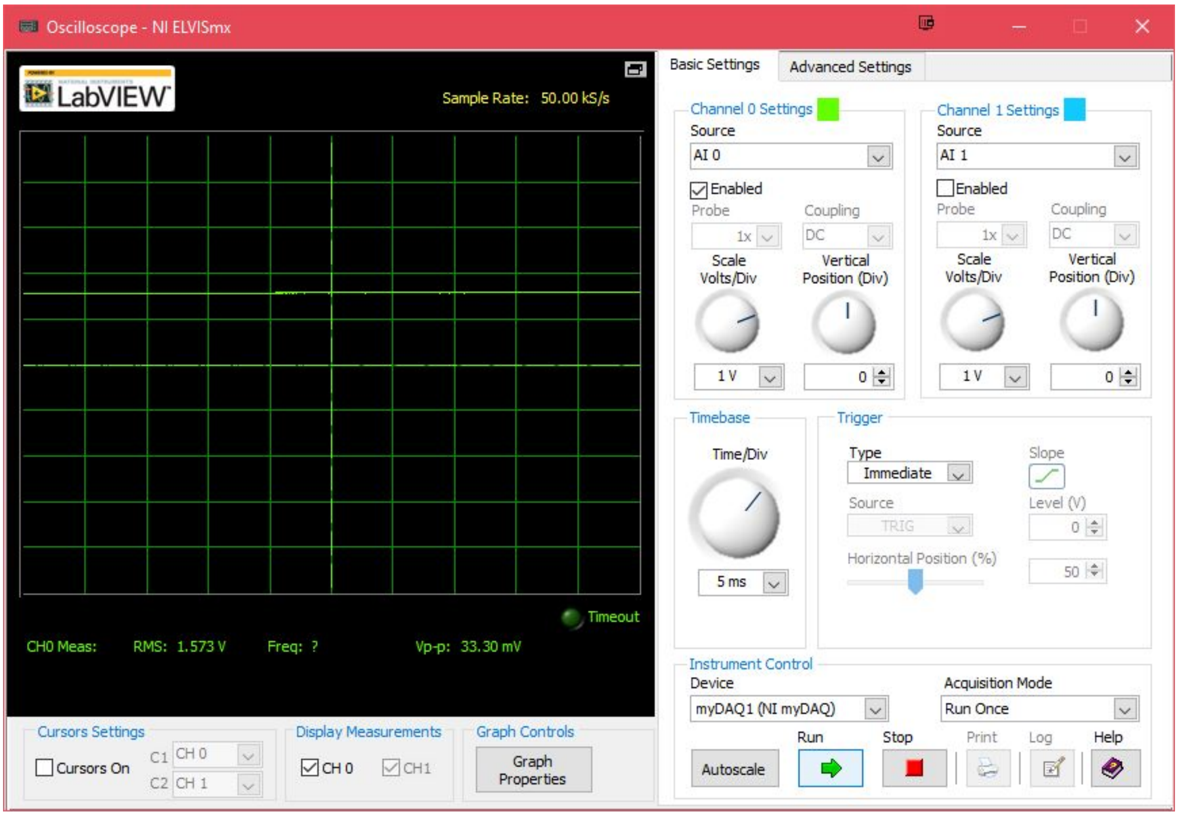

Appendix 131 - Heart rhythm data when the enclosure is open and disconnected from the ground.



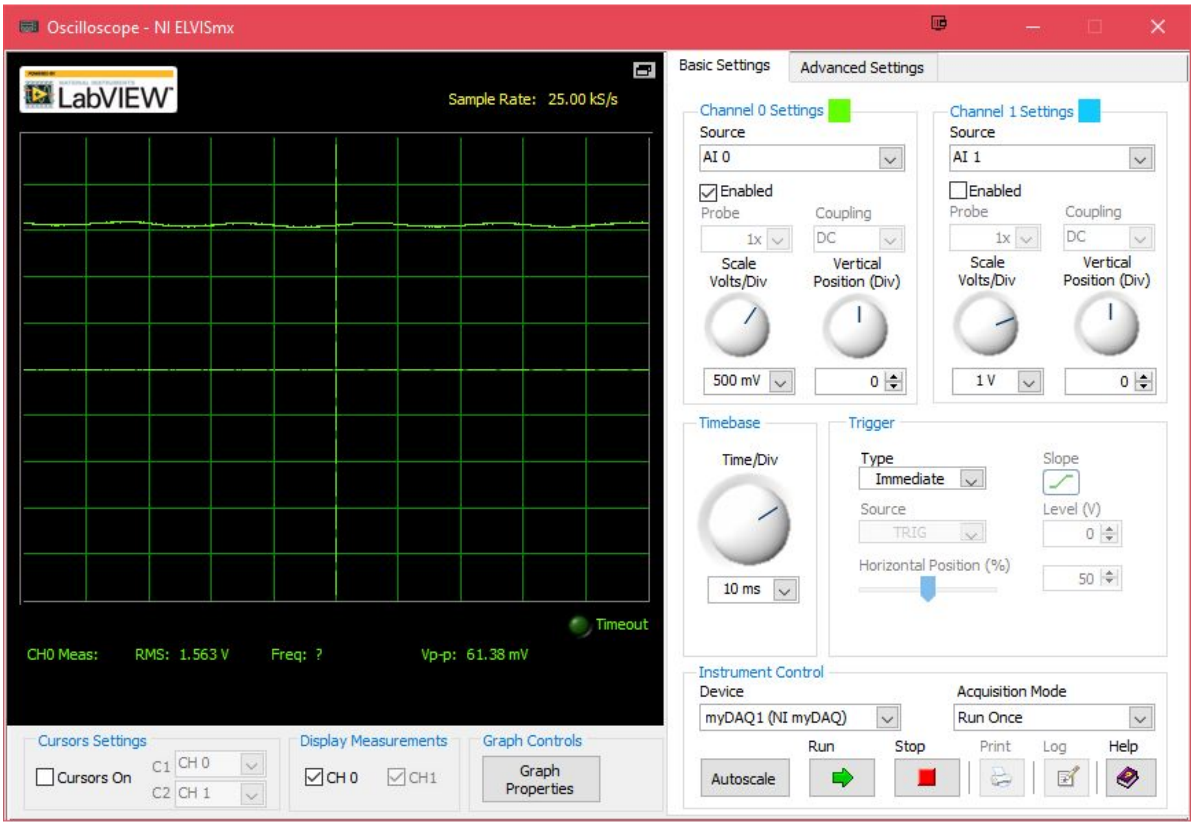
Appendix 132 - Noise on HR circuit output when the HR circuit is powered and the grounded enclosure is closed. 27.75mV



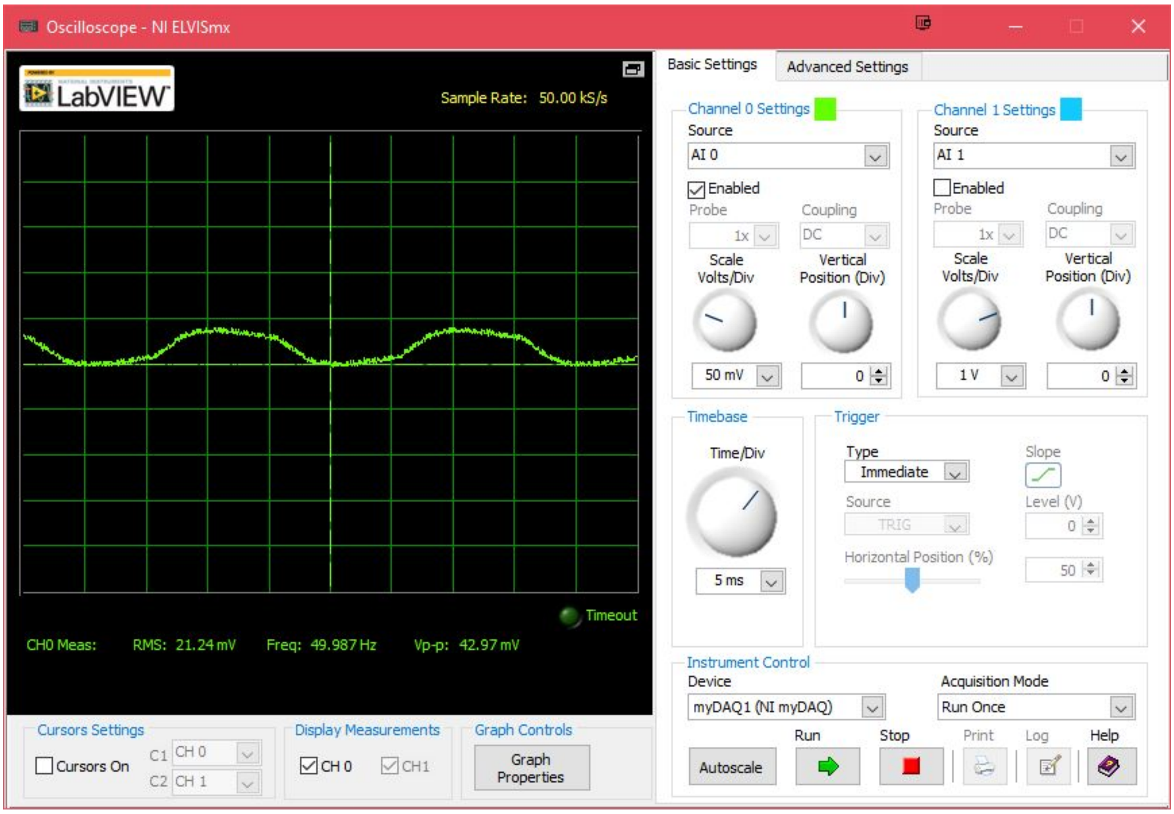
Appendix 133 - Noise on HR circuit output when the HR circuit is powered, and the enclosure is closed but disconnected from ground. 58.76mV



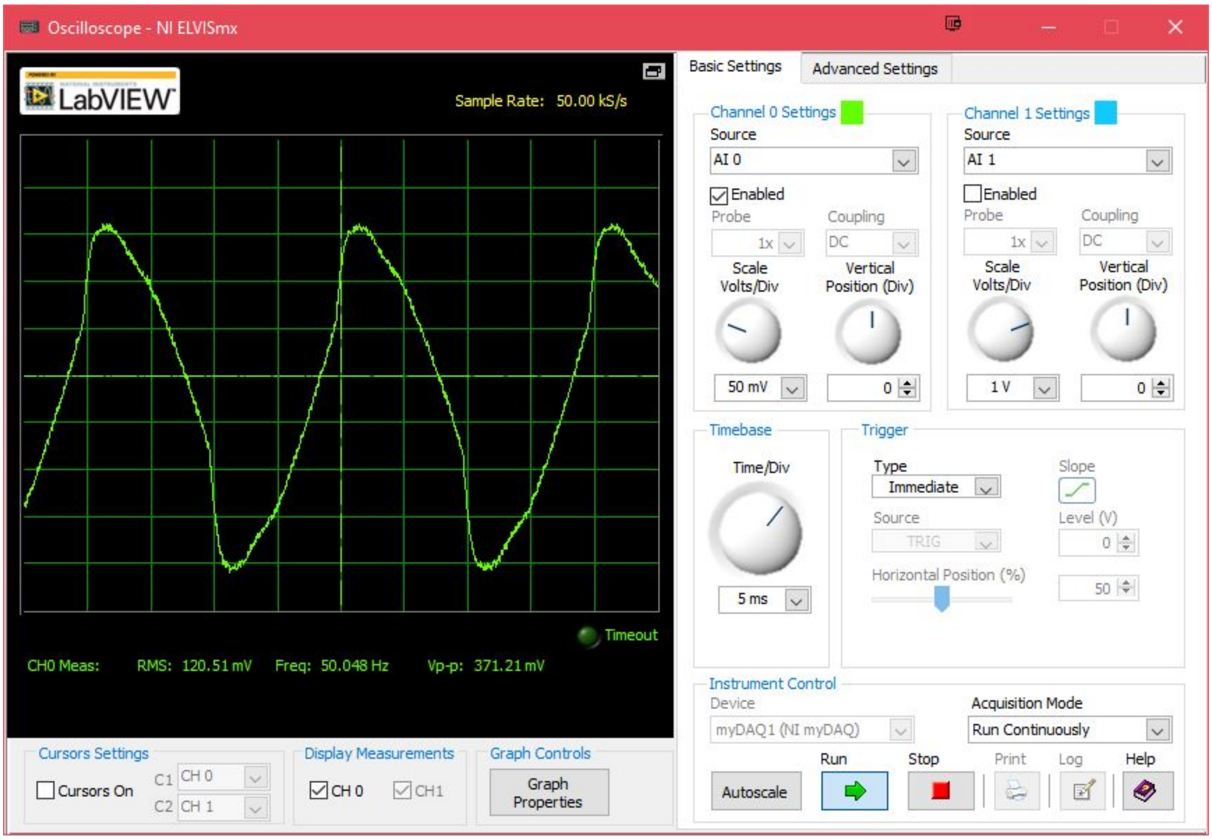

Appendix 134 - Noise on HR circuit output when the HR circuit is powered, and the grounded enclosure is open. 33.30mV



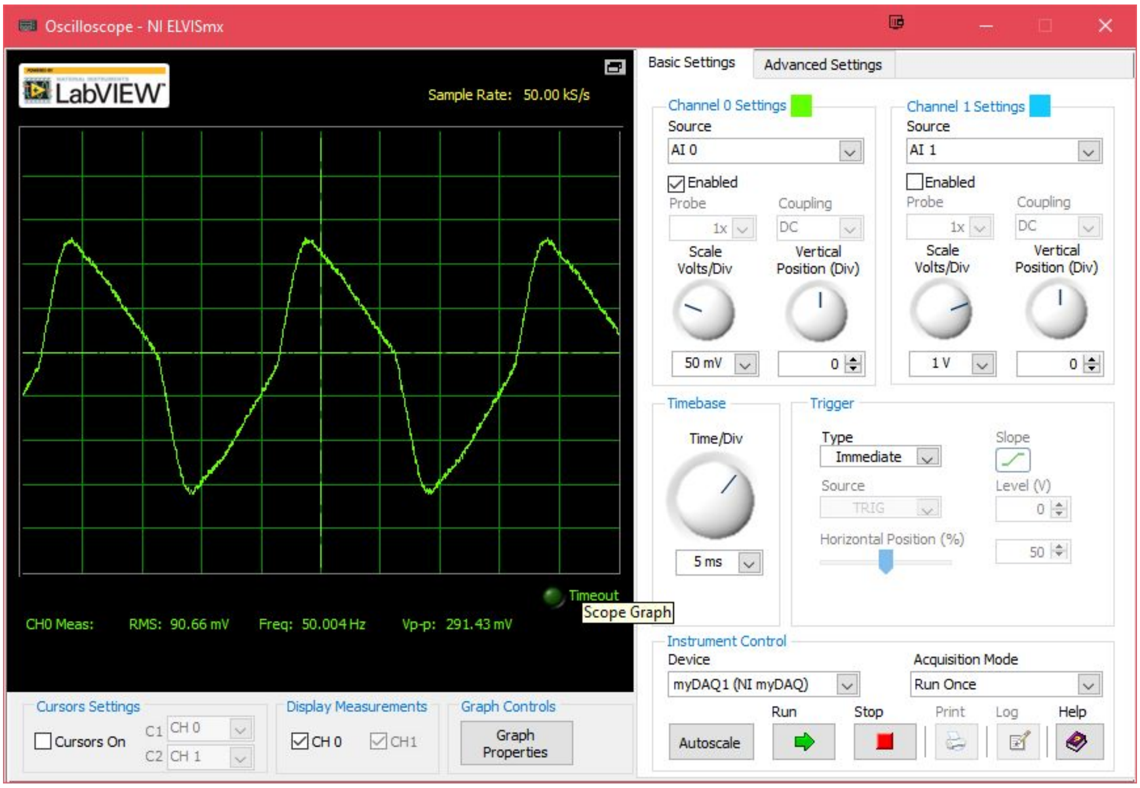

Appendix 135 - Noise on HR circuit output when the HR circuit is powered and the enclosure is open but disconnected from ground. 61.38mV



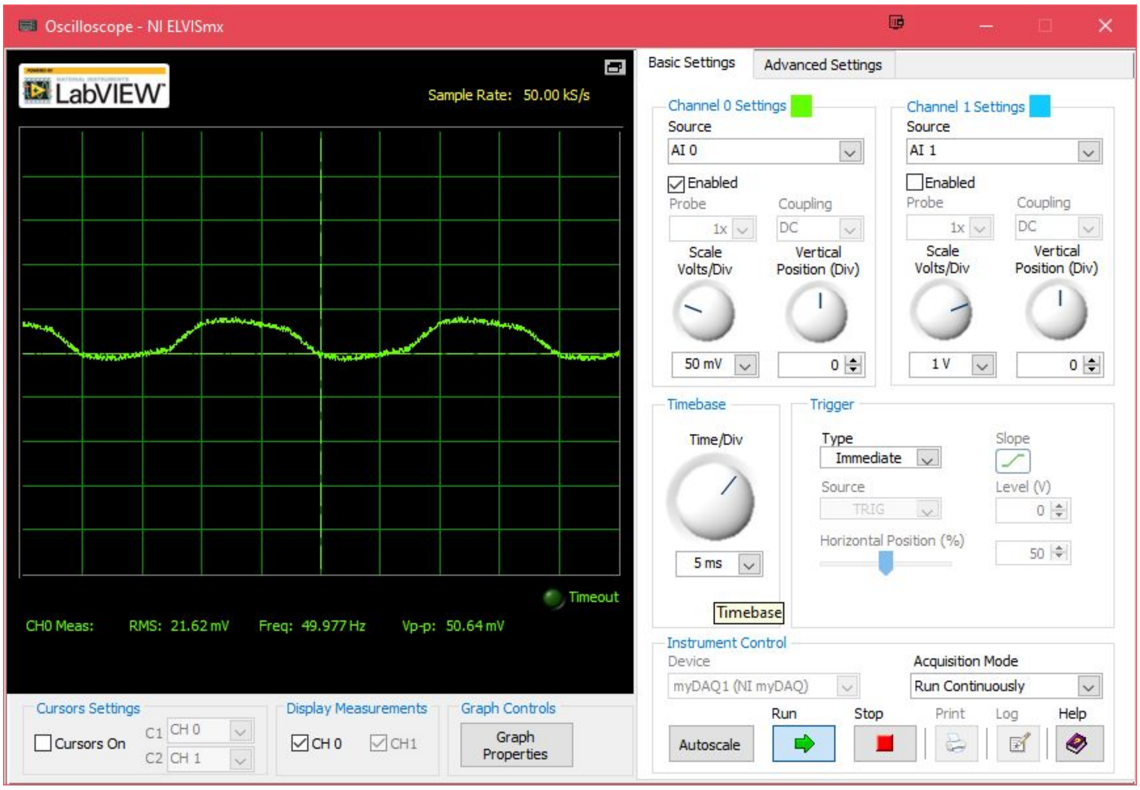

Appendix 136 - Noise on HR circuit output when the HR circuit is unpowered, and the grounded enclosure is closed. 42.97mV



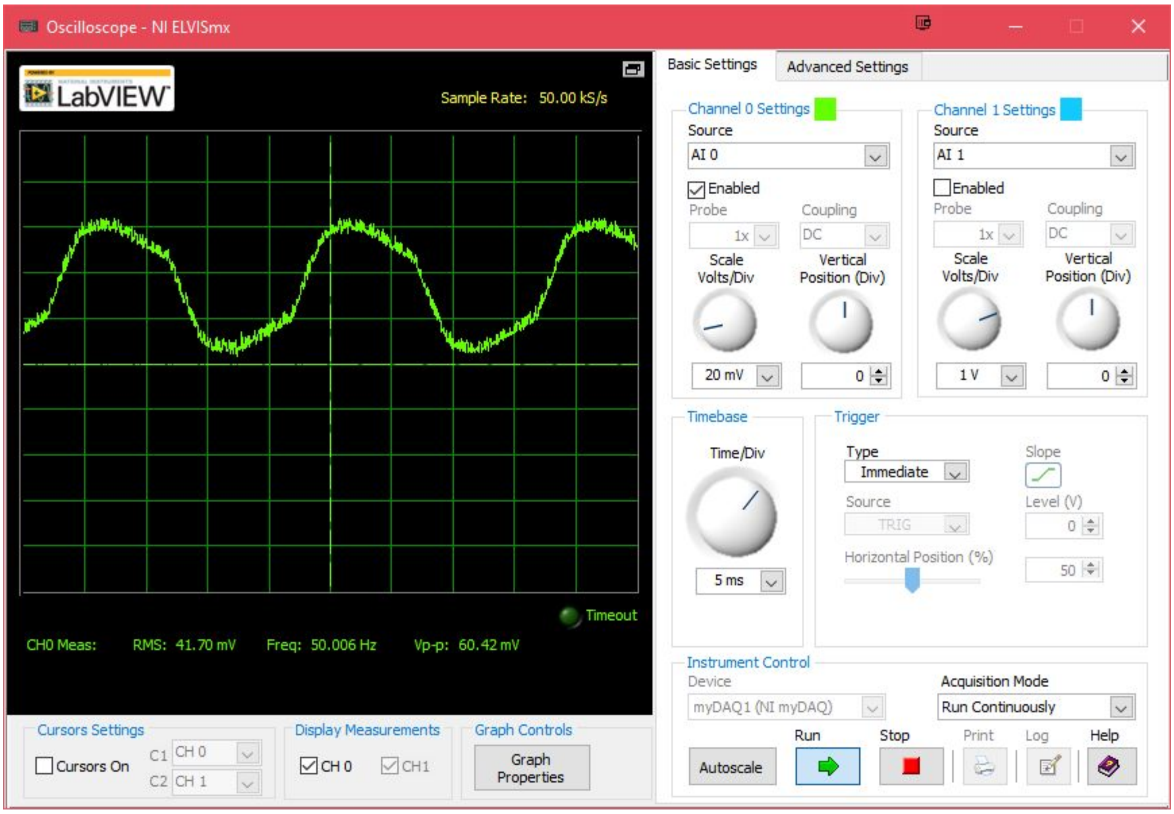

Appendix 137 - Noise on HR circuit output when the HR circuit is unpowered, and the enclosure is closed but disconnected from ground. 372.21mV



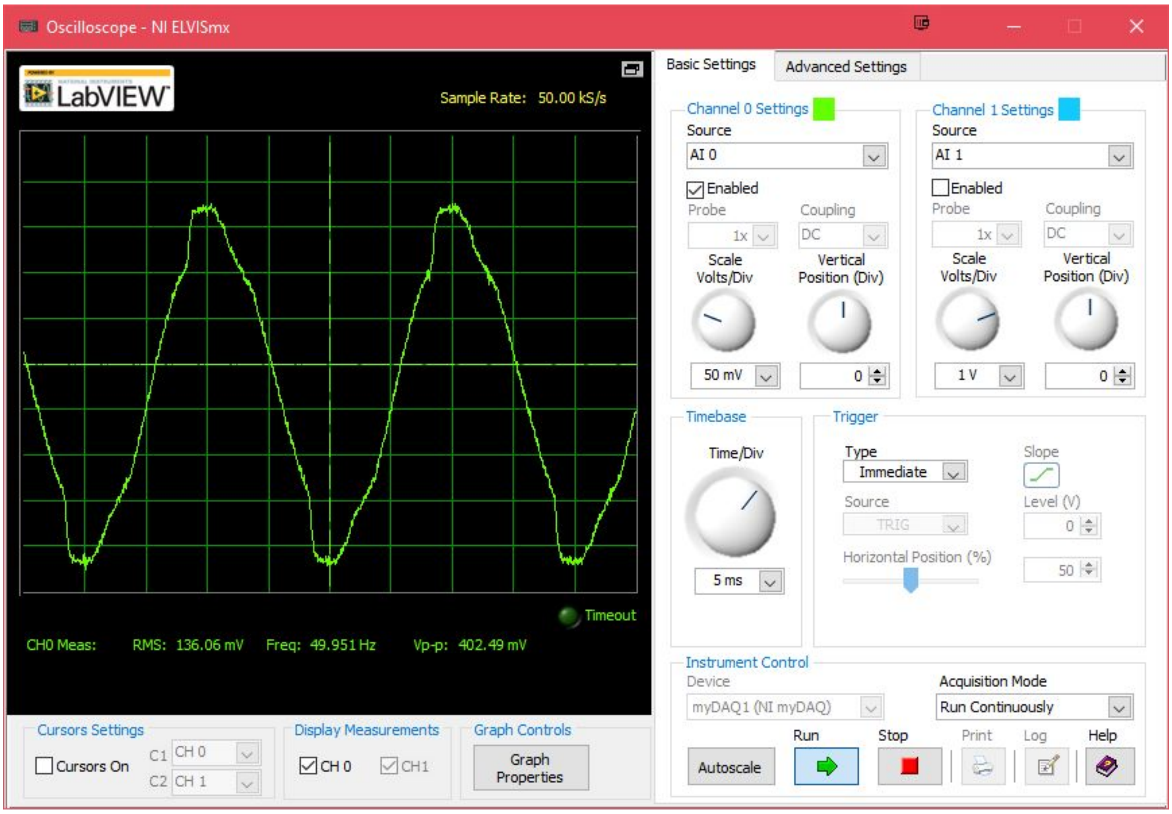

Appendix 138 - Noise on HR circuit output when the HR circuit is unpowered, and the enclosure is closed, but the top-level grounding (Arduino) is disconnected. 291.43mV



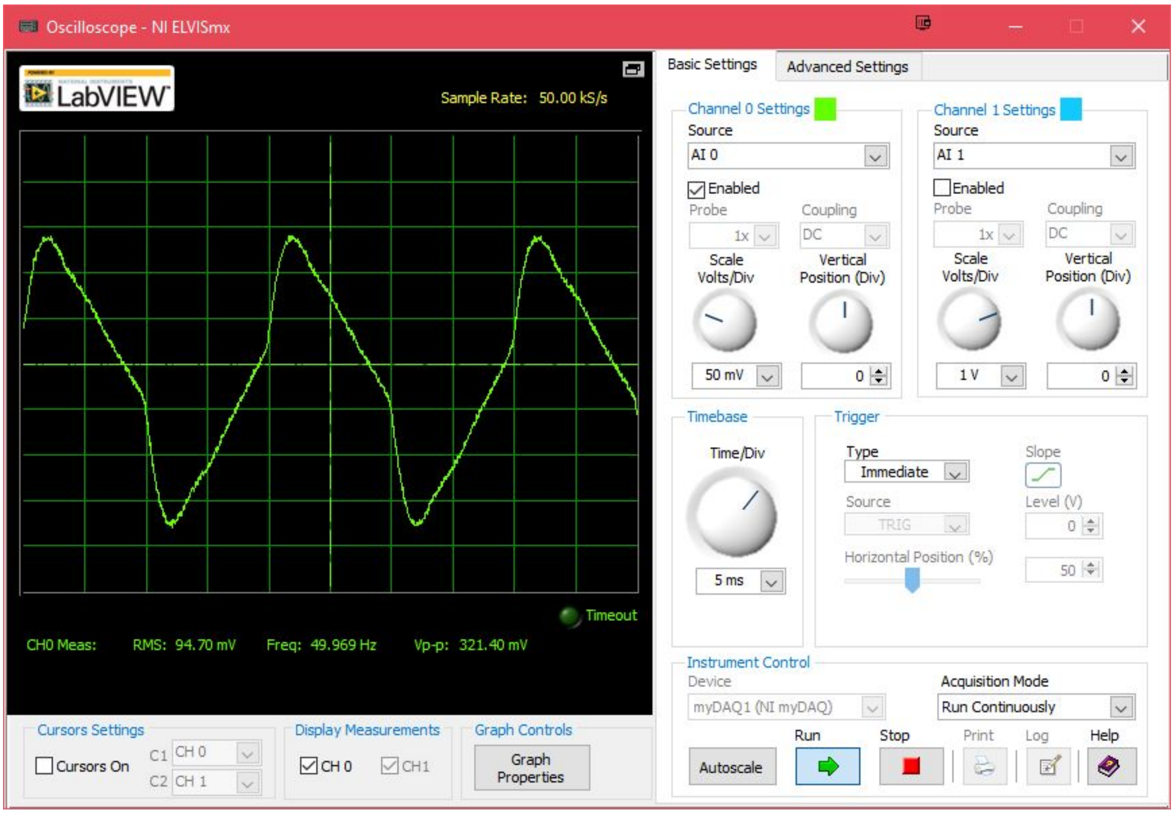

Appendix 139 - Noise on HR circuit output when the HR circuit is unpowered, and the enclosure is closed, but the lower level grounding (HR) is disconnected. 50.64mV



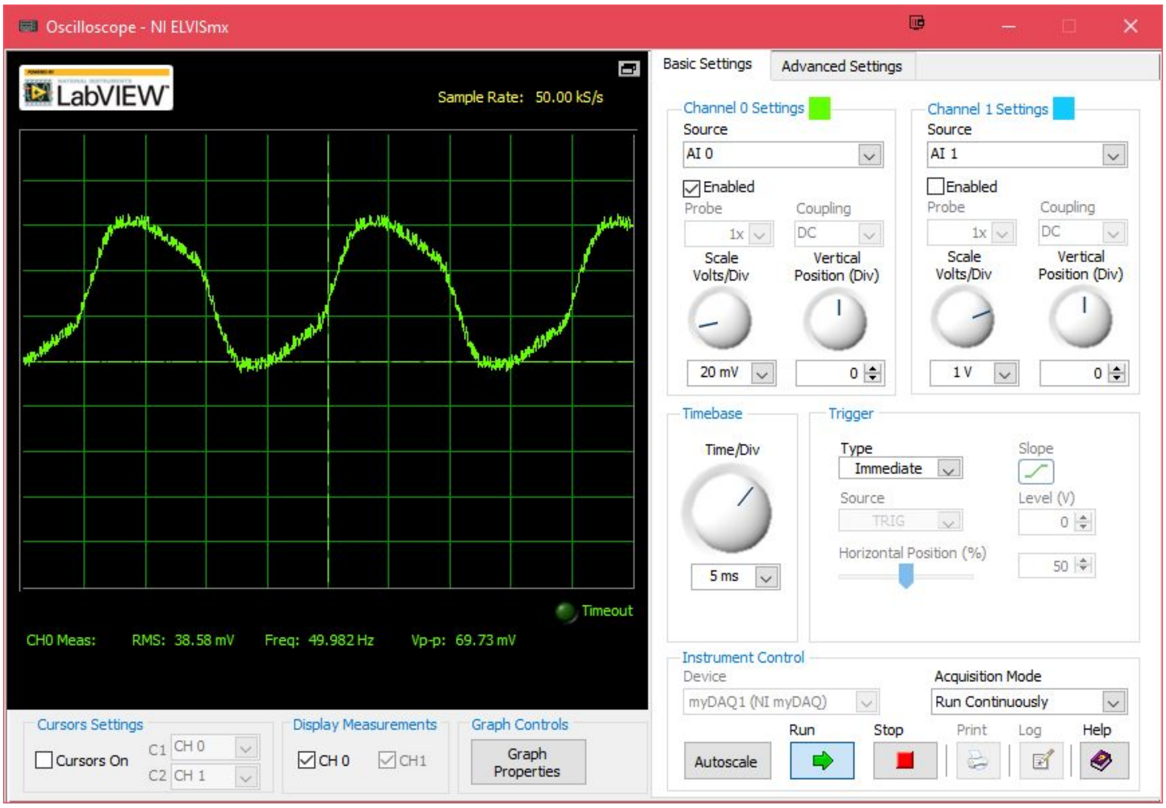

Appendix 140 - Noise on HR circuit output when the HR circuit is unpowered, and the grounded enclosure is open. 60.42mV.




Appendix 141- Noise on HR circuit output when the HR circuit is unpowered, and the enclosure is open but grounding is disconnected. 402.49mV




Appendix 142 - Noise on HR circuit output when the HR circuit is unpowered, and the enclosure is open, but the top-level grounding (Arduino) is disconnected. 321.40mV




Appendix 143 - Noise on HR circuit output when the HR circuit is unpowered and the enclosure is open but the lower level grounding (HR) is disconnected. 69.73mV

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