# Stray Voltage Detector

A Major Qualifying Project Report

Submitted to the Faculty

Of

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the requirements for the

Degree of Bachelor of Science

In

Electrical and Computer Engineering

By

_____

Jacqueline Ciesynski

_____

Kelly MacNeill

_____

Christopher Nolan

March 14, 2011

_____

Professor Stephen J. Bitar, Major Advisor

_____

Professor Alexander Emanuel, Co-Advisor

# Acknowledgement

We would like to thank our advisors Professor Stephen J. Bitar and Professor Alexander E. Emanuel, for all their support and guidance throughout this entire project. Without their expertise and knowledge we would not have been able to produce a functioning prototype.

We would also like to thank the ECE shop personnel, Tom Angelotti and Patrick Morrison, for their help and supplies for this project. The accessibility to a multitude of parts and equipment, for little to no cost, allowed us to work on this project efficiently, on site, and for a low budget.

Finally, we would like our friends and family. They gave us advice and support whenever it was needed. We were also to gain insight from an outside perspective on how we can change or better our project in order to be successful.

# Abstract

This project proposes the design of a system capable of detecting hazardous stray voltage levels that may appear on surrounding objects due to faulty wiring.  The device consists of two sensing directional antennas, analog and digital signal processing circuitry and an LCD display. Utilizing differential signal analysis techniques, the device is capable of determining the direction and distance to a stray voltage source.  In lab tests, the device successfully detected and located a four foot electrified pole at a distance of seven feet.

# Executive Summary

Every year in cities across the country, many instances of stray voltages are reported and threaten public safety. The most common culprits are lampposts or manhole covers that have been charged by mistake via incorrect wiring or corroded electrical components. The main problem is that there are currently no consumer grade products available that can detect stray voltage preemptively. All existing products sense the voltage while in contact with the source, or only at a distance of a few inches away. The purpose of this project was to develop a handheld device that would detect stray voltage from a distance of at minimum a yard away. The final product would also have the ability to determine in which direction the voltage source was located in relation to the user, as well as the distance away.

The first step in designing our product was to create an antenna which would only sense voltages in one direction. This was done by placing a metal plate inside a grounded metallic box with one side open. This antenna would then be mounted onto a metal turntable to allow for rotation that would work in tandem with an identical circuit. The antenna was then attached to an amplifier with variable gain. This was done to create different levels of sensitivity which would allow for the device to sense voltages at different distance ranges. As stray voltage has a low frequency, 60 Hz, a low pass filter was then implemented to filter out any unwanted high-frequency noise. The resulting signal was then passed through an amplifier as the high output impedance of the filter was not suited to drive the input of the microcontroller we used for signal processing. The signals are then handled in the microcontroller, which is connected to a LCD screen that printed the amplitude of each signal and the difference between the two channels.

In order to begin testing, we had to first create a stray voltage. We connected an aluminum pole to a wall socket, causing it to be electrified with $120V_{AC}$, 60Hz. The next step was to come up with a way to detect this voltage. The initial conceptual design was just a piece of aluminum foil connected to an oscilloscope probe. This showed that the aluminum foil was able to capacitively couple with the aluminum pole. With this concept proven, we then set up a more stable design with an aluminum plate on a wooden stand. Since we couldn't have the oscilloscope with us all the time, a circuit was built that would give identical results to the oscilloscope. This circuit was designed and changed multiple times, but the final circuit contains a variable gain amplification stage, followed by a low-pass filter stage, then a buffer stage, and finally connected to an analog input of the microcontroller that displayed our results on an LCD screen.

The next design implementation was the shielding of our antenna. This shielding allowed us to detect the voltage on only one side of the antenna, thus creating the ability to detect the direction of the stray voltage source. After that was proven to work, we duplicated our entire design and added a second antenna. This second antenna had the same exact circuit as the first antenna and the output of the circuit went into a second analog input of the microcontroller. These antennas, with their shielding, were both placed on metal turntables that were then placed

on a wooden board, to act as a stable platform. This use of metal turntables allowed us to rotate the antennas at precise angles to determine the distance of the source with respect to the voltage reading that was displayed.

With the previously discussed design, we had to perform many tests to provide evidence of a working prototype. These tests were the motivations behind most of our design changes and modifications. The first test was the stray voltage concept test, which entailed us to hold up a piece of aluminum foil that is connected to an oscilloscope probe. This was just to show that we can capacitively couple the aluminum foil and the pole, thus demonstrating the detection of stray voltage. Next, after the metal plates were implemented, we had to test our system with an amplifier and without an amplifier. This demonstrated that we needed an amplifier in order to see the resulting signal produced by stray voltage source. In parallel with the amplifier testing we decided to test with a filter also. This filter removed any signal that was higher in frequency than 60Hz, which is referred to as "noise". This was a successful test because our signal was smooth and we are able to achieve more accurate voltage peak readings.

We then performed a series of tests for different size and orientations of plates to determine how area effects the detection of the stray source. This series of tests also involved a test comparing the difference of the resulting signal with the implementation of a half-wave rectifier and a full-wave precision rectifier. After these tests we decided on one size of a plate to use for further testing and that the full-wave precision rectifier produced better results. We removed the full-wave precision rectifier because we could implement the rectification of the signal through the microcontroller. We went onto our next test which was the implementation of variable gain. This test was performed because we realized that we couldn't detect a signal from a great distance. This test showed that as we moved further from the source, we can increase the gain and still detect the source. The next test was the angle test, which involved rotating the shielded antenna at different angles. This showed that as the antenna is rotated the voltage detected decreases, thus proving the success of the shielding and directionality.

The final two tests involved determining the distance with an angle and detecting the source from a far distance. The first one only worked at close distances of 1 foot or closer from the source. We rotated the antennas at increments of 10 degree angles and where the highest voltage reading displayed, we calculated the distance. The final test was with the dual plates oriented directly at the source and we moved them at increments of a foot from the source until we reached a limit. This limit was 7 to 8 feet away from the source at which we can still detect the stray voltage.

The results of this project demonstrated concrete support that stray voltage can indeed be detected from a distance of much larger than touching the source and one foot away, which is the limit of other existing products. We are very satisfied with the outcome of this project and we are excited to see future renditions of this project. Improvements such as automatic rotation of the

antennas, automatic gain control, and more active indicators of source detection are the first steps of a future project.

# Table of Contents

# Table of Figures

# Table of Tables

# Table of Equations

# Introduction

In today's society, electricity is used everywhere and as such electrical wires are needed to convey electrical power to meet this demand. It is nearly impossible to make sure that every wiring connection is setup correctly, thus wiring errors have been known to occur. One side effect of these errors is stray voltage. While not a problem that the public is aware of or fully understands, it is an important issue that has plagued the public with potentially lethal voltage in seemingly benign areas.  But what is this unknown threat and how is it being dealt with?

The easiest way to describe stray voltage would be to imagine a metal fence, and right above this fence is a high voltage power line.  Unbeknownst to the owner of the fence, the power line has made the poorly grounded fence electrically charged.  So naturally the next time an unsuspecting person touches the fence, zap, the person has been hit by stray voltage. Stray voltage can be found in some unusual places and is not limited to fences.  For example, there has been a reported case where a man found that his shower had become electrically charged due to a miss-wired lamppost. Cities are in the most danger as there are many potential sources of stray voltage.

In order to fix this problem, companies have tried to create detectors what can determine if an object is electrically charged or not.  The problem is that most of these devices can only be used to confirm that the item is charged, someone has to report that the item is charged first before anything can be done.  This is where our project comes in, by trying to develop a device to detect the stray voltage from a distance. Our product could potentially prevent civilians from being shocked unnecessarily.  This product has the potential to save lives, as well as millions of dollars in law suits filed by the disgruntled civilians that have been shocked.

In order to accomplish this goal, antennas were used to sense a mock voltage source. This report will go through the design process and discuss how the final product came about. In the background and literature review section, we further discuss what stray voltage is in accordance with articles found with the IEEE xplore digital library. We also discuss different case studies, where if stray voltage was previously detected the tragic events could have been prevented. These cases talk about the severity of stray voltage, how the faults could have been prevented, the consequences companies face and how they plan and try to prevent future incidents. Current products and patents that exist, and how our device will differ from those is also discussed.

In the problem statement, we discuss our goals in producing a stray voltage detector and the specifications for this proposed product. The next section dives into our methodology behind this project. Here, the block diagram of our prototype is highlighted and how each part contributes to the system.

We then discuss our design in the following section, which includes schematics and details about our designs from beginning to end. In this section, we discuss the different ways we have conducted testing and the equipment we have used. We show the different designs we created and motivations for our design modifications we've done throughout the design process. These changes and improvements include the use of the Variac voltage transformer, adding

insulation to the pole, distance measuring, adding a rectifier circuit, applying filtering and amplification, shielding, variable gain, improving robustness and much more.

With these designs we did several different tests. The next section contains the analysis and results of these tests. With different designs, we had different results. We discuss those results and how they differ, or indicate improvements upon our previous designs.

Although we successfully made a working prototype, there are also some things we were hoping to complete but time prevented us from doing so. The last section will discuss our recommendations for future renditions of our project.

# Background/Literature Review

Stray voltage is a very real and potentially lethal danger that the public should be made aware of.  But what exactly is stray voltage?

## *Literature Review*

It is evident from the quantity of articles regarding the clarification of terms on stray voltage that there exists some amount of confusion in the professional community over what stray voltage is. The article The Confusion Surrounding 'Stray Voltage', summarized below, is exemplary in delineating the differences between the usages of the term 'stray voltage'.

These articles are useful for our research because we are trying to detect stray voltage. For our project, we need to know in which conditions stray voltage is a problem, and what the professional community believes about stray voltage. It is clear from the articles that more education about stray voltage is needed and that a clear-cut definition of stray voltage needs to be provided.  We are working off the assumption that stray voltage is dangerous and needs to be detected and remedied before it can cause serious injuries or death. In some of the definitions of stray voltage, such as the original definition: neutral to earth voltage, it is not considered dangerous or unusual. This undoubtedly creates some confusion when referring to stray voltage without context.

## Article 1

The Confusion Surrounding "Stray Voltage" by Jim Burke

This article elaborates on classic usage of the term 'stray voltage' and the commonly used term today. He states that the term today is used to mean:

- Neutral to earth voltage - the voltage on a neutral conductor as a result of unbalanced loading.

- Temporary Overvoltages - the high voltage caused temporarily by overcurrent protection.

- Contact voltage - where a live conductor makes contact with an exposed housing or other conductive surface.

- Step and Touch voltages - the voltage that can result across the body between the feet or hands due to currents passing nearby.

- Static discharge - charge distribution caused by friction.

- High impedance faults - a difficult fault to protect against because currents are usually too low for overcurrent mechanisms.

- Stray current - currents traveling through the earth.

He argues that the term stray voltage should be used only to refer to neutral to earth voltage. Furthermore, neutral to earth voltage is usually only a few volts and is not typically considered dangerous. He states that because of decreasing industry participation in standards writing "has created a situation where non-professionals, such as state legislators and lawyers are rewriting definitions, creating new terms and creating arbitrary limits and testing procedures costing the industry many millions of dollars which could have been used far more wisely to promote both safety and reliability."[1]

## Article 2

Diagnosis and Trouble Shooting of Stray Voltage Problems by Alvin C. Bierbaum

This IEEE conference paper discusses the historical significance of stray voltage in agricultural settings, giving the rationale behind The Nation Electric Code (NEC). His discussion of stray voltage is primarily focused on three phase power in dairy farms. The NEC requires that the neutral conductor be bonded to the neutral bus bar. He states "The neutral bus bar must also be bonded to the panel box, ground rod and another grounding source that makes contact with a metallic surface that has sufficient contact with the earth." He explains that the reason for this is that any wire to wire or wire to ground faults will be quickly resolved by fusing or breakers. His experience indicates that "at least 80 percent of stray voltage problems occur on the farmer's side of the meter." He created a flow chart for diagnosing stray voltage problems which was not included with the report.[2]

## Article 3

Was the Stray Voltage Really Stray? By Charlie Williams

This report is a narrative about a residential customer's complaint of high voltage from a shower faucet. The customer was being shocked when he touched the faucet while taking a shower. The customer was measuring 26 volts on his faucet to ground. The author states that stray voltage complaints usually occur around water because the current is more easily perceived. The narrative continues with several failed attempts to find the source of the energized neutral, and investigations eventually find that there was a miswired street lamp, where the neutral was connected to the energized conductor from the transformer. The street light created a short circuit about 0.85 miles in length. He then poses the question "Was the stray voltage really stray?" because the neutral was connected directly to the transformer, it would seem as if it were not caused by a 'stray' effect. This article shows how difficult it can be to diagnose stray voltage problems, because the voltage on the customer's faucet was caused by a lamp post fairly far away.[3]

## *Case Studies*

As stated in the section before, stray voltage is an important concern in everyday life. Since as early as the 1990's there have been several cases in which people and animals have been shocked, even electrocuted, by a stray voltage from something poorly wired or broken (i.e.

---

[1]Burke, J. (2007). *The Confusion Surrounding "Stray Voltage".* Rapid City, SD: IEEE.
[2]Bierbaum, A. C. (1992). *Diagnosis and Trouble Shooting of Stray Voltage Problems.* New Orleans, LA: IEEE.
[3]Williams, C. (2006). *Was the Stray Voltage Really Stray?* Dallas, TX: IEEE.

lamp post, manhole cover, etc.). This section discusses incidents that have occurred that could have been prevented if a detector was used. It also talks about what can be done and has been done to help prevent further incidents.

## Case 1

A fairly recent incident happened in December 2009, in Santa Fe, New Mexico. Two women were walking their dogs, when one dog suddenly began jumping around and searching for what had just happened to it and then started to run away. Meanwhile, the other dog fell to the ground as if it had stepped on something sharp, like glass. Concerned with the situation the owners picked up their dogs and headed back to their cars. As they were returning to the car, the women passed by a lamp post and realized that there was some sort of a short circuit in the lamp post. When they investigated the lamppost, they felt a charge when touching both the wet concrete and the lamp post with their bare hands.[4]

## Case 2

Another incident happened in 2004, in New York. A woman was walking down the street in East Village with her two dogs, when she was electrocuted. This happened when she stepped on the metal cover of a utility box. After this happened she sued Consolidate Edison, the electrical company in charge, resulting in a cash settlement. This lawsuit caused Consolidated Edison to take a look at the utility box and see why such an event happened. After reviewing the box Consolidated Edison concluded that there were improperly wrapped and exposed wires in a box.[5]

## Case 3

In March 1994 a very severe incident occurred, in which a person was rushed to the hospital after being knocked unconscious from a severe electrical shock. A man was severely injured after being shocked by a trailer loader, called a Cascade, being used to deliver a load of logs. While trying to raise the unit to make it easier to drive, he was shocked and knocked unconscious and suffered from internal electrical burns.

On the day of the injury, it had been raining, and the man was standing in a puddle of water to operate this machine. He reached over with his stomach pressing against the truck and reached with one hand to connect the loader's hook and the other hand pressing the button. When the button was pressed he was shocked and knocked unconscious.[6]

## Consolidate Edison

All of these incidents ended in a lawsuit or some kind of settlement because of the hazard of these voltages that were "invisible" until an electric shock occurred. These incidents could have been prevented if stray voltage detectors were used. Some precautions are now being made since these incidents happened. The one company that has been affected the most by lawsuits is Consolidated Edison Electric Company.

---

[4]http://www.santafenewmexican.com/Local%20News/Shocker--Lamppost-short-circuits-pets
[5]http://www.mba.state.mn.us/resource.html?Id=17470
[6]http://caselaw.findlaw.com/wa-court-of-appeals/1323678.html

Consolidated Edison spent around $10 million on stray voltage detectors and other safety precautions to try to prevent more incidents involving electrical shocks from happening. One precaution made is that they must "undertake annual surveys of the underground system plus additional surveys within five days of storms that result in the salting of city roadways".[7]

From December 2004 through November 2005, 728,789 pieces of equipment were tested and of those a total of 1,214 pieces of equipment were detected for having stray voltage. These included "1,083 streetlights, 99 utility poles, and 32 power-distribution structures like manholes, service boxes, and transformer vaults."[8]

Although this testing was done and seemed effective, it was proven to be inadequate. This is said because various incidents still occurred shortly after the test was completed. In January 2005, a woman was killed after stepping on a metal plate walking down the street. In February 2005, four people were shocked, in which two were hospitalized, from an energized service box.

Consolidated Edison has spent approximately 100 million dollars on stray voltage mitigations. This included 15 mobile stay voltage detectors and 4 different kinds of hand held devices. The mobile detectors are stray voltage detectors attached to a pick-up truck that would be used year round to detect voltages as low as one volt. These measurements would be taken on manhole covers, gratings, service boxes, light poles, neon signs and other structures. The truck would roam the street and if a stray voltage was found the area was secured and all metal objects in the vicinity were tested by crews using hand-held devices. Images of these devices along with the corresponding reference websites can be found in Appendix A.

From the use of these devices and regular testing, the number of incidents has decreased. According to the "City Room blog" for the New York Times, the number of shocks per a month has decreased substantially since the start of 2008 to about 24. In addition, the number of electrified objects has increased by 900 per month. Around three-fourths of these 900 objects are street lights, traffic lights, sidewalks, manholes and fences.[9]

There have been several incidents involving some type of electrical shock over at least the past sixteen years. This is a large amount of time involving many injuries to people and animals. As the years went by, technology increased and awareness of this stray voltage has increased. With this technological increase and heightened awareness, people have been able to come up with ways to help prevent future incidents from happening, or at least decrease the amount.

### *Patents*

New technology is a growing thing. Everyday someone comes up with something better than the day before. We are creating a stray voltage detector. Since it is not a unique idea, we will be looking into existing patents and products to see what we can do to make our device

---

[7]http://www.mba.state.mn.us/resource.html?Id=17470
[8]http://caselaw.findlaw.com/wa-court-of-appeals/1323678.html
[9]http://cityroom.blogs.nytimes.com/2009/11/05/stray-voltage/

better and different. In this section we discuss three different patents that have similar features to our desired product but differ from our actual design.
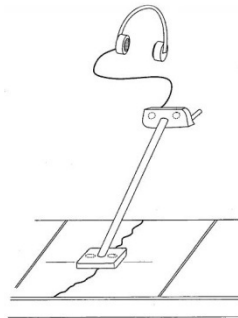
## Patent 1



**Figure 1: Stray Voltage Detector**

This first device was invented by Daniel C. Wiswell, Meredith P. Peterson, and Jianping Sun[10]. This device is used to detect stray voltage by defining a capacitance between a point of elevated voltage and two electrostatic plates. The signal is processed through a gain stage first and then an adjustable gain stage, which is used to squelch background noise. The overall effective gain is between 1 and 10,000. After the signal is processed, it is fed into the audible and visual feedback mechanisms, such as headphones and LEDs. The LEDs can either light up in a series to indicate field strength or change illumination intensity to indicate field strength. An interesting detail is that the patent specifically mentions that the conductive plate is "substantially flat" and that it is less than about 0.005 inch or 0.13 mm. The housing can also contain an LCD for visual feedback, a data storage system to log stray voltage information, a GPS receiver to locate faults and a cellular connection to transmit data wirelessly while in the field.

The patent also mentions that the conductive plates can be embedded within a PCB, being made from copper planes. The patent states that the housing could be incorporated into an automated robot that crawls the sidewalks or streets after hours to automatically detect faults.

The patent also mentions an ability to use fore-aft sensors to locate the fault in two dimensions and that these additional sensors could also be mounted on a vehicle to detect faults while driving on roads.

Interestingly, the patent does not mention the minimum magnitude of the detectable voltage or the range, but this is possibly because these values vary with the plate size or implementation of the device.

---

[10]http://www.google.com/patents?id=66ClAAAAEBAJ&printsec=abstract&zoom=4#v=onepage&q&f=false
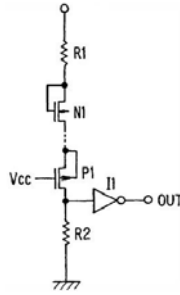
**Patent 2**



**Figure 2: High Voltage Switching Circuit**

This next device is a high voltage switching circuit[11]. By using the properties of transistors, this circuit uses P and N type MOSFETs to send a signal depending on the level of the input voltage. This is done by tying the input to the gate and the drain of the n-MOS device. This allows the device to be constantly on as the voltage on the gate will always be driven higher than the threshold when voltage is applied. The p-MOS device decides whether the output is high or low depending on the input.

The way the p-MOS works is when the voltage is lower than Vcc, the transistor has the properties of $V_G > V_S$. This means that the transistor is turned off, creating the output of HIGH as the inverter is connected to ground. When the input is higher than Vcc, the p-MOS is turned on and the voltage that the inverter sees is depended on the resistor values used. Regardless of the actual voltage, the inverter outputs a signal of LOW.

While the circuit could work the same with or without the n-MOS device, it does play a role in the circuit design. With the n-MOS device attached, the equation to find the current can be described as follows:

$$Idc = \frac{Vin - Vds - n * Vth}{r1 + r2}$$

**Equation 1: DC Current with N-MOS Attached**

This equation shows that in order to get the same response as the circuit without the n-MOS device, smaller resistors can be used. Without the n-MOS device the equation would be different, as seen below:

$$Idc = \frac{Vin - Vds}{r1 + r2}$$

**Equation 2: DC Current without N-MOS Attached**

For this circuit, the n-MOS is purely for the use of lowering the resistor values. This circuit could be used to our advantage as it would be possible to choose a voltage where a LED or speaker could turn on. This would allow for the user to know that a high voltage was discovered. This circuit could also be used in tandem with other features, such as amplifications once a voltage goes down a certain value.

---

[11]http://www.google.com/patents?id=U-kYAAAAEBAJ&printsec=abstract&zoom=4#v=onepage&q&f=false
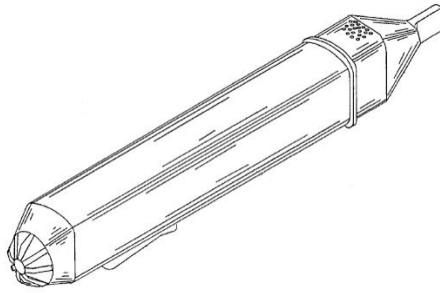
## Patent 3



**Figure 3: Hand Held Voltage Detection Probe**

This final device is a hand held voltage detection probe[12]. This device is designed to sense AC voltages through an antenna, and alerts the user when voltages are sensed. The device also protects against false reading due to static build up on the antenna. This is done by only allowing signals of high enough frequency to activate the device, thus ensuring little or no false readings. The device is setup so that only frequencies from 50 to 400Hz and voltages greater than approximately 40 or 50 V can activate the device. Once the device is activated, the user is told that the device has sensed an AC voltage that meets the required activation standards. This is done by activation of an LED and a speaker.

This device could be used to sense whether or not our antenna is receiving a powerful enough signal to be deemed stray voltages or just noise. The problem however is that this device allows for signals far above 60 Hz to activate the LED and speaker. In our case, this may be unwanted noise as our device primarily focuses on the lower frequencies than higher ones.

---

[12]http://www.google.com/patents?id=m6URAAAAEBAJ&printsec=abstract&zoom=4#v=onepage&q&f=false

# Problem Statement

We have seen that stray voltage, while not usually lethal, can result in painful shocks. Current mitigation techniques are only reactionary. When a stray voltage or contact voltage starts effecting humans or livestock, measures are then taken to correct the faults that caused the effects. This is inadequate because stray voltages may become dangerous before they are detected. In saying this, we created a device to safely and easily detect stray voltages with the goal of resolving the faults that cause them before they can cause damage or do harm.

This device is a handheld stray voltage detector that allows a user to detect whether there is a stray voltage that could be harmful in the vicinity from a distance. It is able to detect a voltage of 120V, 60Hz and even lower. High voltages are easier to detect than low voltages. Although low voltages are not as harmful as high voltages, they are harmful and need to be detected as well. Our goal was for the device to detect the voltage from a distance of at least one yard away from a source and in some cases was able to detect from up to two yards away from the source in some cases.

This device also is able to detect the exact, or at least almost exact, location of the stray voltage. This device uses two antennas to detect where the source of the stray voltage is by displaying on the LCD display the values being detected and indicating whether to turn right, left, or ahead. In this context, ahead means the antennas are facing directly at the source.

There are a few products in the market today that help detect stray voltage. The majority of these products available in the market are pen sized voltage detectors. The problem with these devices is that each one of them has to be touching, or very close to touching the item that has been charged to confirm the existence of a stray voltage. Because of this limitation, these devices do not help prevent such accidents mentioned previously. This is said because the person testing would most likely have already experienced a shock of some sort from the stray voltage before they can get close enough for the device to confirm it. These products, although very efficient, do not work in the situations we are dealing with. We want our device to be handheld but to be able to detect stray voltage from a distance.
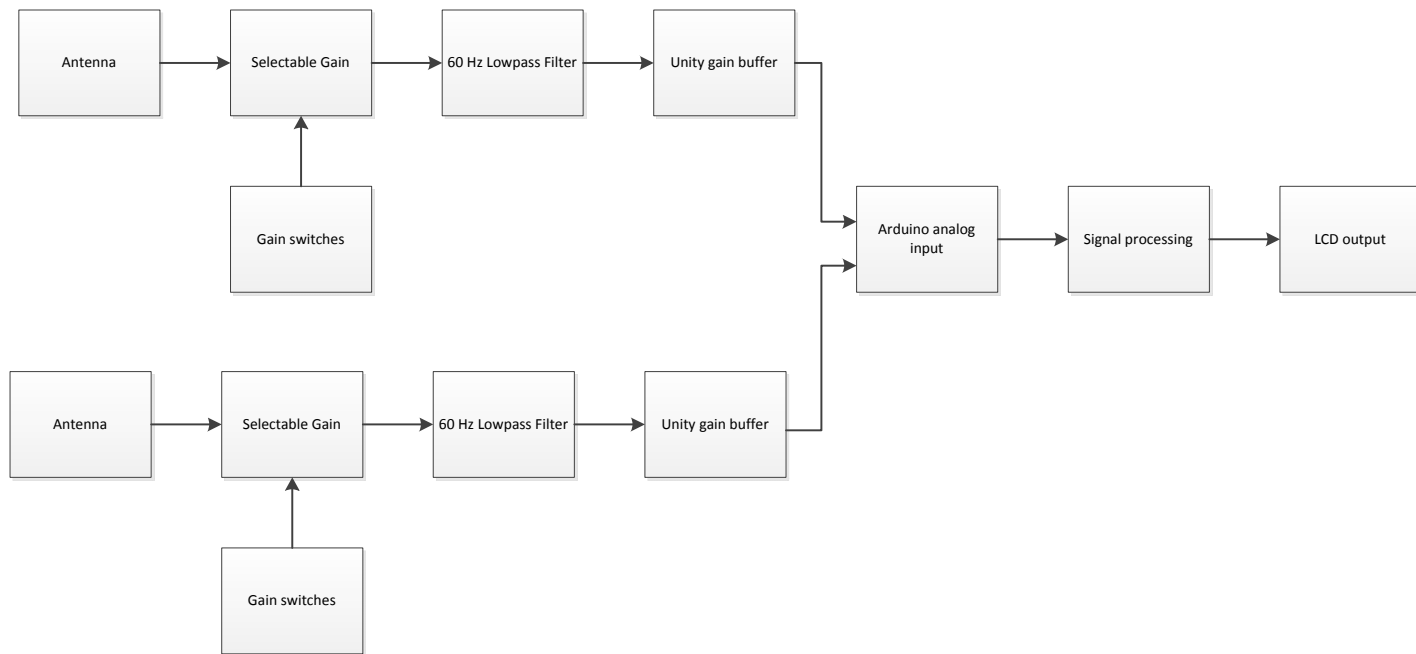
# Methodology



**Figure 4: Block diagram of final prototype**

       The prototype consists of two identical input conditioning circuits that outputs into the analog inputs of the Arduino microcontroller. The microcontroller then processes the inputs and outputs values to the display.

## *Antenna*

       The antenna block is the sensing component of our prototype. It consists of an aluminum plate inside of an open aluminum box. Wood is placed under each plate to insulate it from the outer aluminum box.  The purpose of the plate is to couple the electric field from a voltage source. The outer aluminum box is used to shield the plate from electrical signals that are you not originating in a direction facing the open end of the box. Each box has a bulkhead connector built into the back side to allow for easy attachment of coaxial cables to shield the antenna signal from interference until it reaches the input circuits. The antennas are mounted on metal turntables to allow the user to set the angle at which the antennas are pointed. The angle of the antennas is used to calculate the distance to the voltage source.
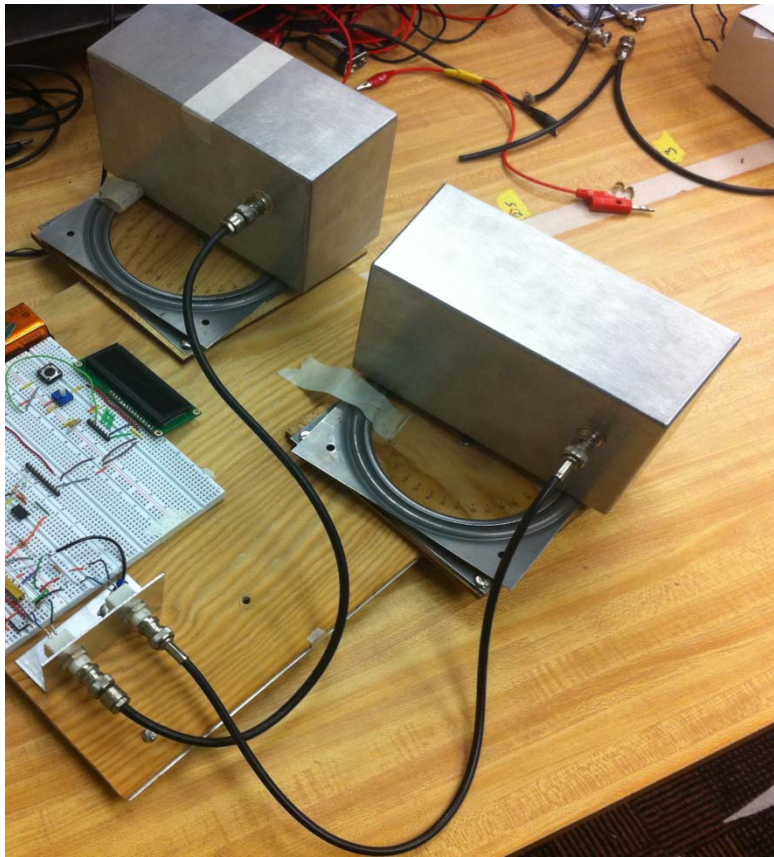
**Figure 5: Prototype antennas**



**Figure 6: Rear view of BNC connectors and Turntables**

## Selectable Gain

This stage amplifies the input signal by a selectable amount. The gain amount is controlled by a set of switches that change the feedback resistors of a non-inverting amplifier, allowing us to choose from gains of 100, 1,000 or 10,000. The amplifier starts hitting the rails at ±8V.
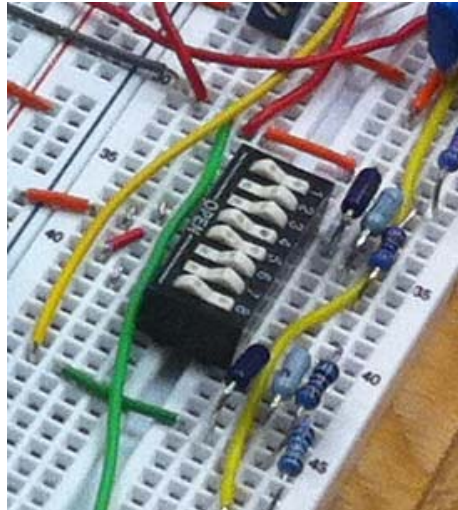


**Figure 7: Selectable gain switches.**

## Filtering

The next stage is the filtering stage. The signal provided by the amplifier is noisy and not suitable for signal processing. We implemented a 60 Hz low-pass filter to attenuate undesirable high frequency noise. This block is implemented using a carefully selected resistor and capacitor combination.

## Unity gain buffer

The unity gain buffer isolates the filter circuit from the input of the Arduino. The output of the filter is high resistance so it is not suitable to drive the input of the Arduino. We use a simple unity gain non-inverting amplifier to implement this stage.

## Arduino analog input

This stage simply contains a resistor and the actual input pins of the Arduino. The resistor is used for limiting the current output by the buffer stage.

## Signal processing

This stage we perform analysis on the signal received by the analog inputs of the microcontroller.  We continuously sample the left and right channels, looking for the peak of the signal and then subtract the signals from each other to determine the direction of the voltage source. If either the left signal or right signal is stronger, then it means the voltage source must

be in that direction. If they are the same, then it means the voltage source is straight ahead. Source code is available in Appendix C.

## *LCD output*

Once we have determined the direction of the voltage source using the signal processing techniques described above, we output the decision to a liquid crystal display to help guide the user toward the source.
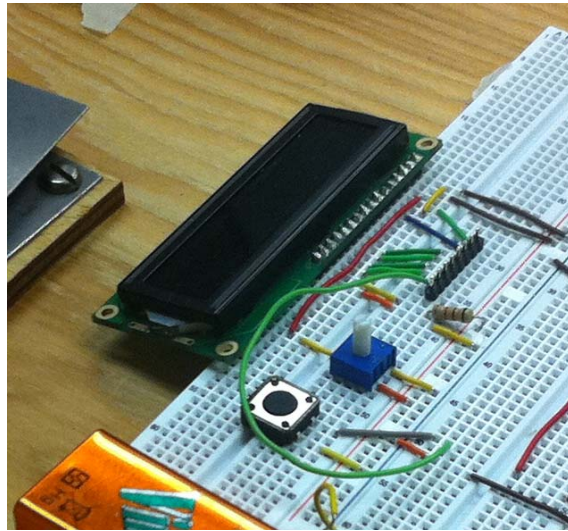


**Figure 8: LCD circuit (Arduino not in picture).**

# Implementation / Design

## *Simulated Stray Voltage Source*

The first step of designing our product was to create a situation in which there is stray voltage. We did this by attaching an aluminum pole to a wooden block and connecting the pole to a voltage source. The pole is covered by a PVC tube that is slightly bigger in diameter and height. This is done to prevent us from directly touching the pole. The aluminum foil was connected to the ground of the Variac transformer, which is also the voltage source for the pole.
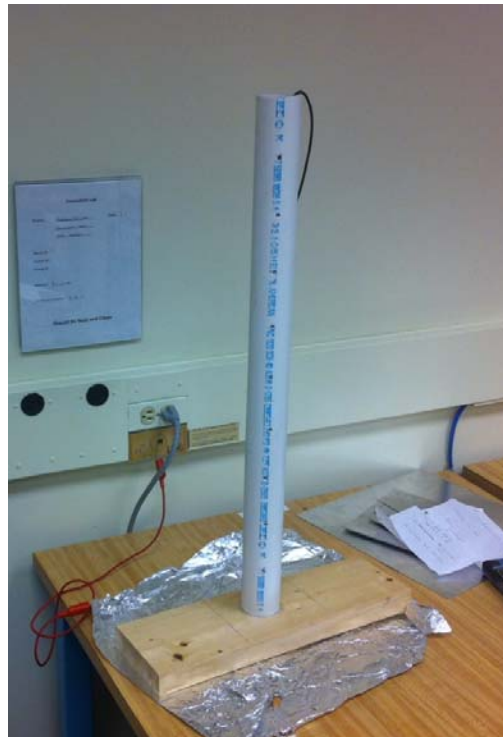


**Figure 9: Voltage source**

Our motivation for using the Variac was twofold: an adjustable voltage would allow us to test various sensing thresholds, and it would provide some protection in case of shorting. We received the Variac from the basement of Atwater-Kent Laboratories, so we did not have any data sheets or specifications for the device. It had a maximum voltage of 102 V, and ran on 3-phase power. After a few hours of reverse engineering it, we got it up and running and attached to the pole. We used alligator clamps to attach the transformer to the pole, and we soldered a 3-prong electrical cord to power the Variac from the wall. There were three individual transformers in the entire device, but we only used one of them for our testing setup.

## *Proof of Concept*

The next step in designing our product was to test multiple methods of sensing the stray voltage. The first method used to sense the stray voltage was to use different sizes of aluminum foil. The foil was held by a person with both hands and the foil was attached to an oscilloscope probe. The aluminum pole used was set to a 102V 60Hz signal that was generated by the Variac

for the purpose of this testing. The first size foil was 15x19 inches and was tested twice. The foil was held three inches away and then eight inches away from the pole and the scope readings were $0.08V_{pk-pk}$ and $1.08V_{pk-pk}$ respectively. With the thought of the size being an issue we decided to cut the foil to be 15x9 inches. With these dimensions the oscilloscope readings were $0.720V_{pk-pk}$ and $1.02 V_{pk-pk}$ for three inches and eight inches away from the pole respectively.

## *Improving the Antenna and Voltage Source*

Verifying that we could detect stray voltage, the next step was to improve our design. This was done by first creating a metal plate to replace the aluminum foil, a wooden stand was built to hold the metal plate, as opposed to hands, and the Variac that was being used was discarded.

The disposal of the Variac was motivated by some testing. We did some testing with the Variac and were surprised to discover that we were receiving a lot of interference from the Variac itself. We verified this by unclipping the Variac from the pole and reading an increased voltage on our electrode. The difference in voltage was approximately 10%, showing that the majority of the signal was not coming from the pole.

Our remedy to this problem was to bypass the Variac all together. We unplugged the Variac and hooked the pole to the hot terminal of the wall socket via alligator clip. This arrangement, while lacking the ability to adjust voltage, freed us from the interference generated by the Variac and also increased safety by eliminating the exposed conductors on the transformer. This direct connection caused the pole to be electrified to $120V_{AC}$, 60Hz. The aluminum foil, which was once connected to the ground of the Variac, was then connected to the ground of the wall socket.

## *Amplification and Filtering*

The next design implementation we had for our prototype was to create something that would produce a clean and usable sinusoidal voltage from the rather noisy output that came from the electrode directly. Our first successful design was with a non-inverting operational amplifier configuration with a second RC filter stage after it. We discovered several issues during our testing processes, some of which were: grounding through the oscilloscope probe and antenna effects from the workbench equipment. The first issue was actually of some benefit for our early circuit, because we did not include a DC path to ground for our capacitive coupled signal to our non-inverting amplifier. The scope provided that path for us. We were quite surprised to find that the signal was peaking erratically when the oscilloscope was disconnected. We remedied this by inserting a 10MΩ resistor to ground at the input. Again, the second issue was of some benefit as well. When we were reading from the oscilloscope and the multimeter simultaneously, we found that the signal would increase by 50% if any of the lab equipment was connected to the circuit.

The filtering stage is a simple RC first order low-pass filter as seen in Figure 10. This filtering stage consists of a 10kΩ resistor followed by a 200nF capacitor to ground. The resistor and capacitor values were selected for a cutoff frequency of 80Hz which was determined using Equation 3.

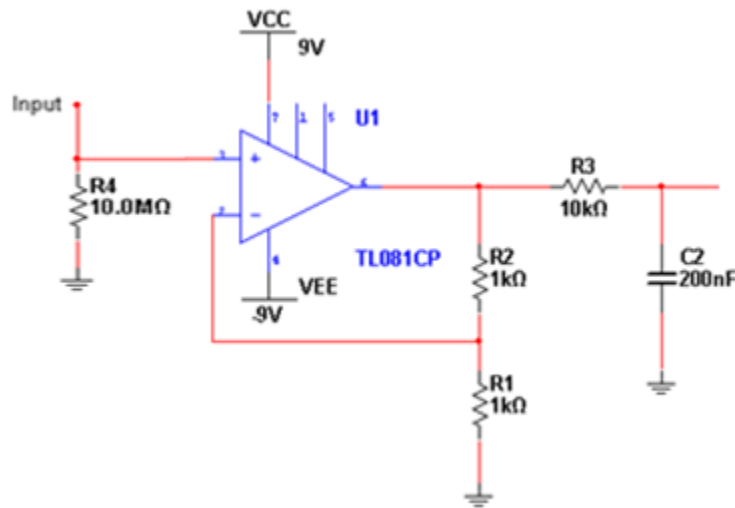$$f_c = \frac{1}{2\pi RC}$$

**Equation 3: Low Pass Filter**



**Figure 10: Amplification and Filter Stage**

The following two simulations demonstrate the filtering of the circuit.
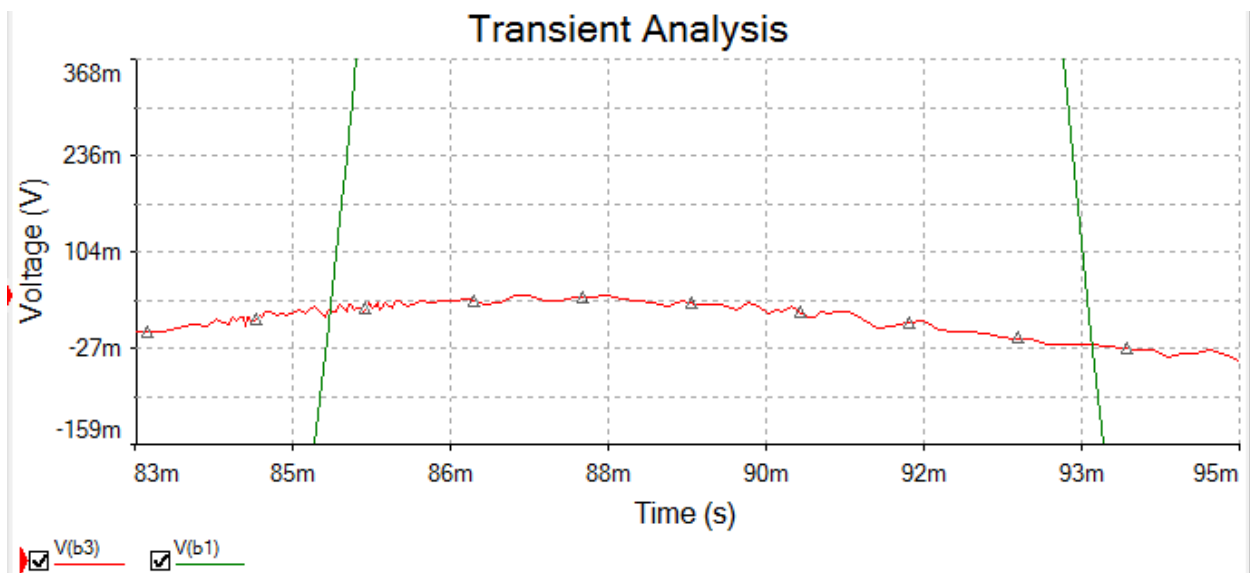


**Figure 11: Noisy input signal**

This simulation in Figure 11shows a noisy input signal (red) and the output produced by it with substantial gain and filtering from our circuit.
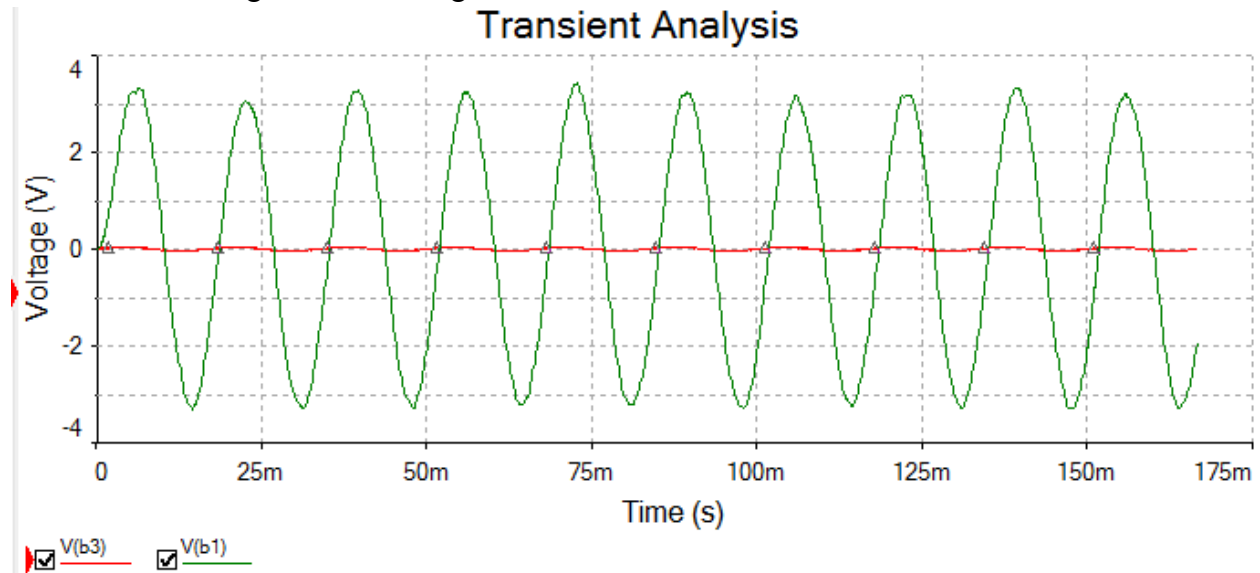


**Figure 12: Smooth output signal**

Figure 12 is the same as Figure 11, but zoomed out so that you can see the smoothness of the output signal (green).  This simulation shows that the filter would behave as needed.  With this, noise and signals with high frequencies will be ignored.

We also tried another design that included the filtering stage in with the amplification stage. The circuit can be seen in Figure 13. This filtering is dependent on the amplification we want as well, so it is less modular than the two stage gain-filter design. This circuit also gave us some very slow (5 second period, ± 10 mV) oscillation when we were reading voltages in the 200 mV range.
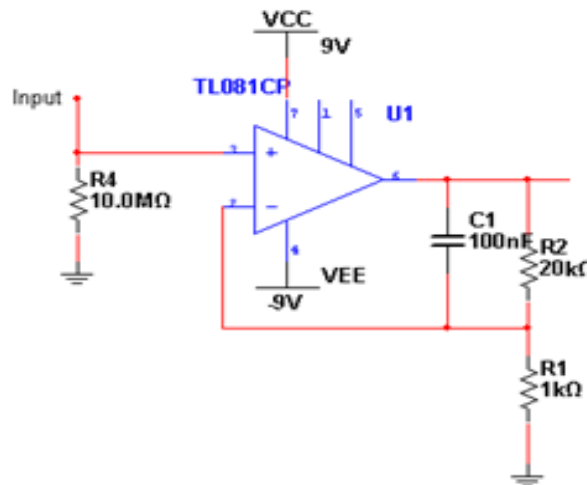


**Figure 13: Filtering and Amplification Circuit**

With this new design we did some testing. The distance used in this testing ranged from 3.25 inches to 4 feet, with increments of an inch until two feet where the values stopped changing drastically.  Without the amplifier, our readings seen on the oscilloscope ranged from 9.2V$_{pk\text{-}pk}$, close up, to 0.63 V$_{pk\text{-}pk}$, far away. After testing with the amplifier, we realized that the amplification was actually too high, since the first few readings were clipping at the positive rails. The minimum voltage seen with the amplifier was 750 mV$_{pk\text{-}pk}$.

## *Improving Antenna design*

Seeing how the circuit and testing worked, the next step was to test plates of different sizes and shapes.  Using the same set up as the previous test, we discovered that certain shapes had advantages over others, as well as the fact that the surface area of the plate corresponded to the resulting output voltages.  It was also discovered that the orientation of the metal plates mattered as well. When the plate was turned so that the height was maximized, vertical orientation, the voltages that were read were much greater than when the plate was in its horizontal orientation. In this testing we now took down measurements at 6 inch intervals from 1 foot to 4 feet away from the pole.

Since the testing before was taking when we just found plates of different sizes and shapes, we had no actual equal differentiation between the plates. The next step was to modify these plates to create new plates so that they are either square or rectangular with a drastic change in height and length. Each plate would also have different areas.  We numbered the plates 1-8. From our original plates and then modifying them we decided to omit Plate 2 from the remaining tests because it was deemed too similar to Plate 4, with the dimensions being almost identical.

## *Portability and Stability*

Along with modifying our testing plates, we also modified our circuit to reduce interference from the testing equipment on the workbench and make our prototype portable and more robust. In order to do this, we decided that we needed a way to measure the signal coming from the electrode using a hand held digital multimeter. One problem with common portable multimeters is that the AC range is too far for our application. The range on the two multimeters we had was 300 volts AC. Our signal was between 0 and 7 volts, so it would not be possible to precisely measure the signal using the AC setting on the multimeter. However, the DC voltage range on the multimeter would go down to 200 milivolts, which was high enough for our needs, if we were to convert our AC signal to a DC signal.

To do this at first, we used a simple half wave rectifier circuit using a diode and a capacitor. We used a 1N4148 switching diode and a 200nF capacitor. We found the capacitor value by experimentation: we increased the capacitance value until we saw a signal that remained constant on the oscilloscope. With this addition, this also meant that the oscilloscope was no longer necessary and a Digital Multimeter (DMM) was used in its place.  When we did testing with the DMM we found smaller results, but this was due to the fact that the DMM was reading the average half-wave voltage instead of the peak-to-peak voltage on the oscilloscope. The new circuit used can be seen in the Figure 14.
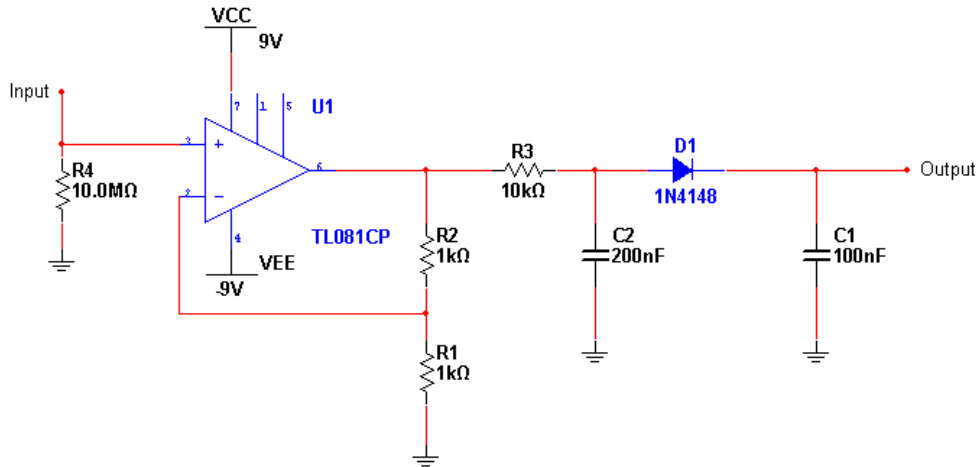
**Figure 14: Half-Wave Rectifier Amplifier Circuit**

Although we were getting better results than when using the oscilloscope and were no longer limited by the oscilloscope, we wanted to better the circuit even more. The half-wave rectifier worked well for initial testing, but we were also losing a large part of our signal from the 0.7 volt drop through the diode. With this, we decided that our next design setup was to replace the half-wave rectifier with a full-wave precision rectifier. In addition to the full-wave rectifier, the amplification portion was changed from 2x to 20x and the capacitor responsible for filtering was included within the amplification stage of the circuit instead of after. The precision rectifier circuit we are using only rectifies and does not actually produce a DC value, so our multimeter is reading the DC average of the rectified output. The results from this circuit also created a smoother curve when viewed on the oscilloscope and resulted in higher voltage readings than previously detected. This circuit can be seen in Figure 15.
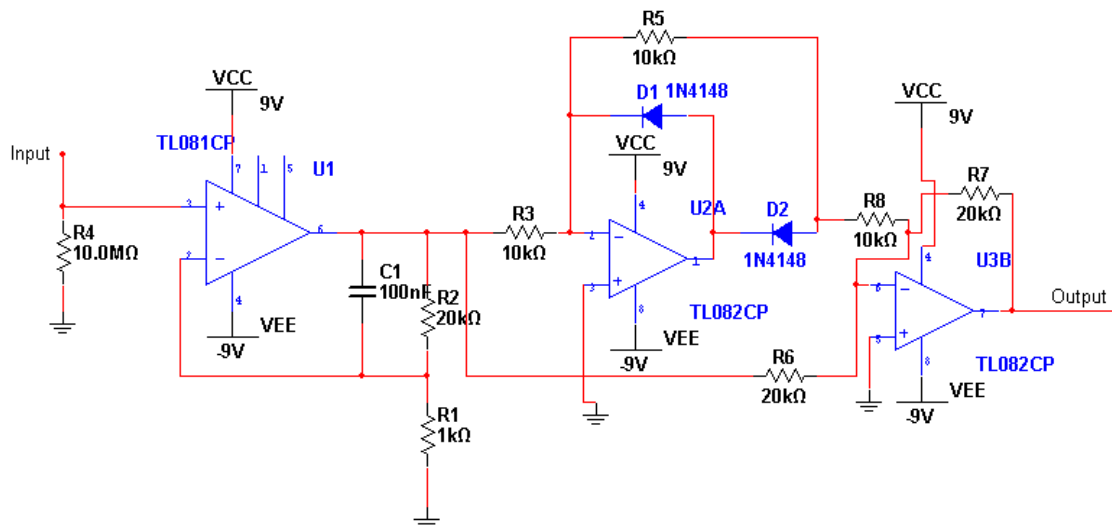


**Figure 15: Full- Wave Precision Rectifier Circuit**

One persistent problem throughout the testing was made clear, as it was noticed that as we moved further away from the pole and smaller voltages were detected, the smaller voltages still needed to be amplified further. The problem with this is that if the amplification is higher,

when we record higher voltages at a closer distance to the pole, the higher voltages would cause the circuit to clip at the rails. This problem is fixed with our next design modification.

## *Increasing Range*

To increase the range of the device, we implemented an 8-way on-off dip switch. For our device we only use four switches with each connected to a different resistor. These resistors, when individually selected, allow us to create a gain ranging from 10 to 10,000, incrementing by x10. These range settings allow us to read voltages at close proximity of the source and far away from the source, by adjusting the gain of the amplifier to output a signal within the readable range. This also caused us to change the second resistor in the gain stage from 20kΩ to a 100kΩ. We also moved the filter stage from within the amplification stage to after since this relies on the resistor values of the amplification stage when included in that stage. The new schematic can be seen in Figure 16.



**Figure 16: Variable Gain**

## *Inserting the Microcontroller*

With the goal of eventually automating measurement parameters and increasing the functionality of our prototype while decreasing size, we exchanged the portable multimeter for an Arduino Duemilanove microcontroller development board and a digital liquid crystal display (LCD). The development board is a custom PCB for the ATMEL ATmega328 microcontroller chip. We chose to use this microcontroller board because of its ease of implementation and prior experience with the platform. A few key details about the board are listed below:

- It has an onboard regulator which can accept 7-12V input for power.
- 14 digital I/O pins and 6 analog I/O pins.
- It has 32KB on board flash memory for code and data storage.
- Clock speed of 16 MHz

The chip is powerful enough for any application we could use it for in this project, excepting heavy real-time digital signal processing. There is enough space in the flash to store some data, but an external solution will have to be implemented for long term data storage. We power the board using the positive end of our 9V battery. The complete details for the board can be found at http://arduino.cc/en/Main/ArduinoBoardDuemilanove.

Where the output of the rectifier once went into the hand held multimeter, it now goes into analog input zero (A0) of the microcontroller, as seen in Figure 16. The analog input is a 10 bit analog to digital converter (ADC) that can only read values between 0 and 5 volts (sensitivity of 5V/1024), so any voltages higher are reported as 5V. The output of the rectifier is still an AC signal, so to get a useful number that represents the signal strength. We sampled the signal at a rate of 200Hz and averaged the values over that window. This produced results that were very similar to those of the multimeter. The voltage is reported on a standard 16x2 character LCD.

## *Shielding and Hardware Improvement*

The next addition was to provide shielding to allow us to detect in one direction and to decrease interference in all other directions. This shielding originates as a cardboard box covered in aluminum foil that blocked all sides of the plate except the front. After proving that this was effective, we ordered an aluminum box to have a more robust shield. With this robust shield we decided to increase robustness of our entire design to make it less prone to mechanical failure.

The first set of improvements we made to our prototype for improving robustness were the inclusion of battery housings and an on/off switch. The 9V battery housings were fastened to either side the wood block that makes up the base of the prototype with screws. Wires were soldered to the battery housings to provide power to our circuit. This improvement allowed us to easily move the prototype without having to worry about the batteries coming disconnected. Likewise, the inclusion of an on/off switch allowed us to easily remove power from the circuit to conserve battery life.

These changes however proved to be insufficient in completely fixing the mechanical problems. The next step was to create a whole new base which took our original design of a block of wood with a wooden pole holding an antenna and changed it to be more spacious. We created a wooden base with a metal base connected under it and attached our switch, the protoboards, and the shielding box to this base. This made our circuit easier to handle, as we no longer had the raised antenna and had more room to work with. The shielding for the antenna is also connected directly to the new base, which adds stability to the sensing portions of our circuit. Inside the shielding box, we had made a small block of wood about the same length of the metal plate and about an inch in height and 2 inches in width and are attached to the new board as well. A drawing of the shielding set-up can be seen in Figure 17.
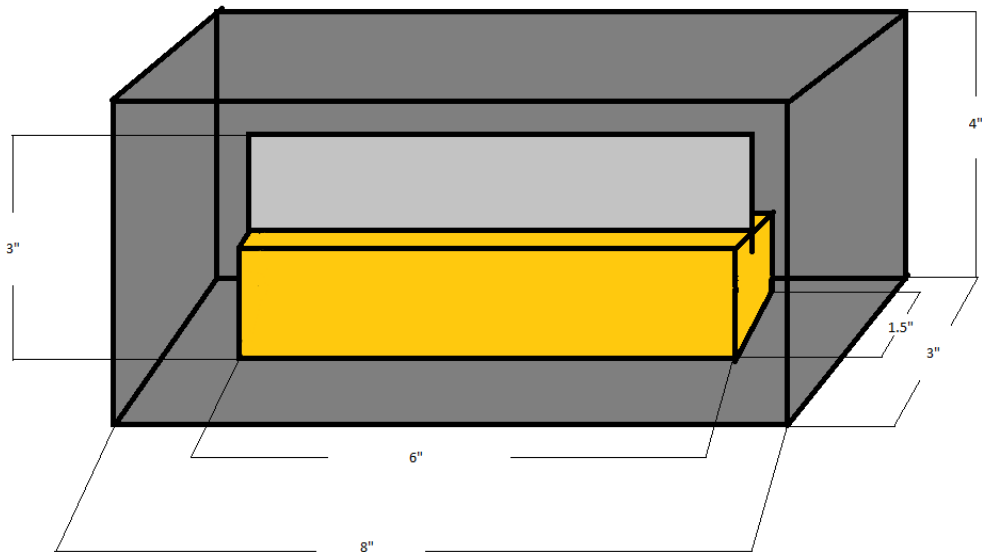
**Figure 17: Shielding Box**

The new base also allowed for loose wires to be replaced, allowing for less noise created by outside sources that we weren't sensing.  For the wires that needed to be loose, the wire connected to the antenna for example, each was replaced with coaxial cable with a BNC connector on both sides connecting to secure connections. This also made it easier to ground our shielding, since sensing and shielding could now be done with one wire.  This was fixed by replacing the cable and placing proper connections to the board and shielding.

## Minimizing the Design

After several tests we realized that we no longer needed the full-wave precision rectifier because the Arduino microcontroller could rectify the signal through its analog inputs, which are buffered with diodes that prevent the signal from swinging above 5.7 and below -0.7 Volts.
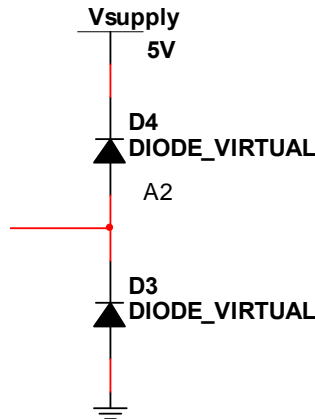


**Figure 18: Analog input circuitry**

We removed the full-wave precision rectifier. A simulation of the output with just the Arduino inputs is below.
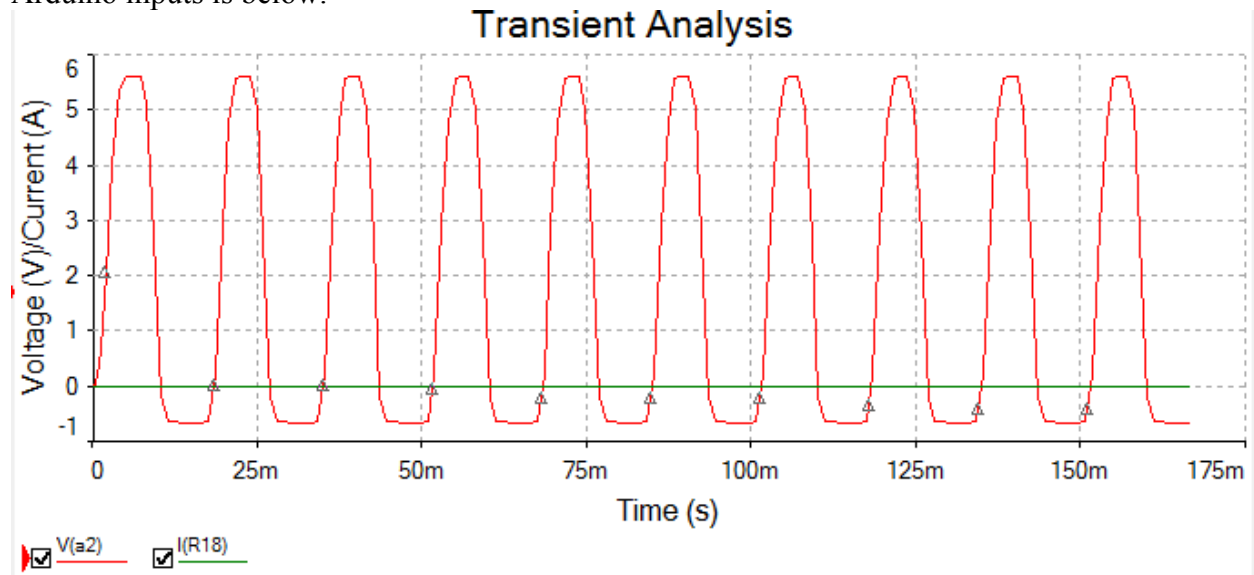


**Figure 19: Simulation of analog input circuitry.**

Another realization was that we no longer needed to have a gain of ten, so we removed the 10kΩ resistor from the variable gain stage. The attenuation of the signal from the aluminum box made a gain of ten too small to produce a usable signal. This new circuit is shown in Figure 20.
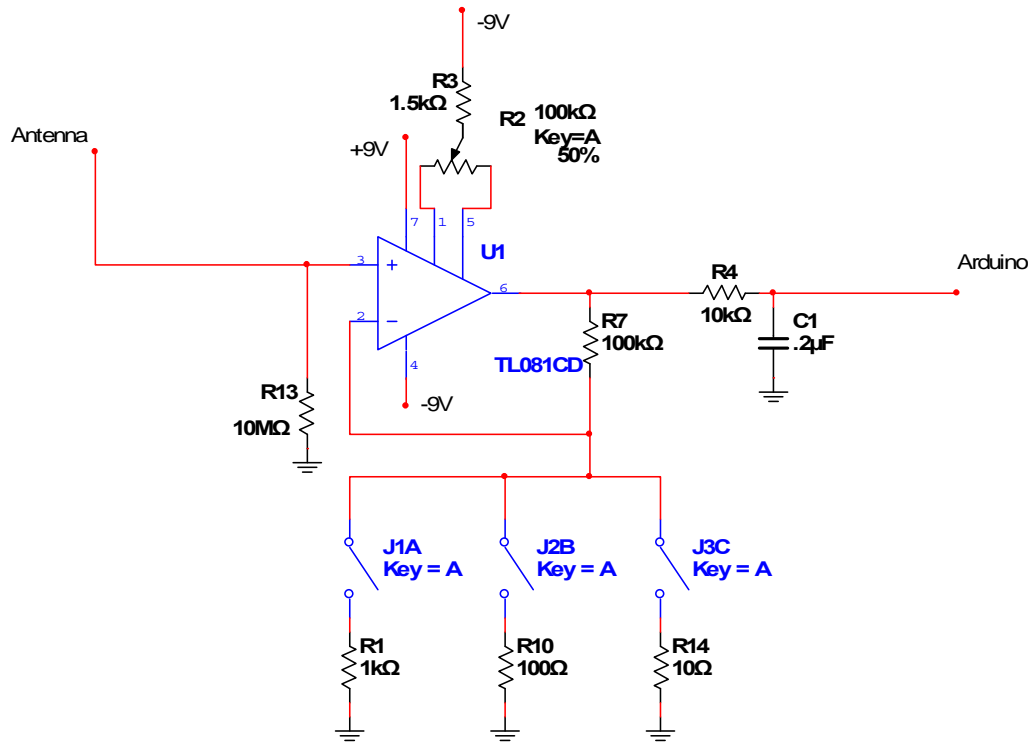
**Figure 20: Removal of Full-Wave Precision Rectifier**

## *Adding an Additional Antenna*

In this project thus far, we were detecting the source location and intensity of the voltage using one antenna. To increase efficiency and absolute source location we added a second antenna and a duplicate circuit to our existing device. With this addition, we had to make sure the circuits were as close to equal as possible. With this being said, we changed all of our resistors to 1% tolerance resistors for the gain and filtering stages to keep the two antennas consistent with each other. We also wanted to find the difference between the two antennas, in order to determine which way the user should turn or if they are pointing directly at the source. In order to do this, we implemented an instrumentation amplifier. An instrumentation amplifier consists of two unity gain buffers and a difference amplifier. The entire circuit can be seen in Figure 21.
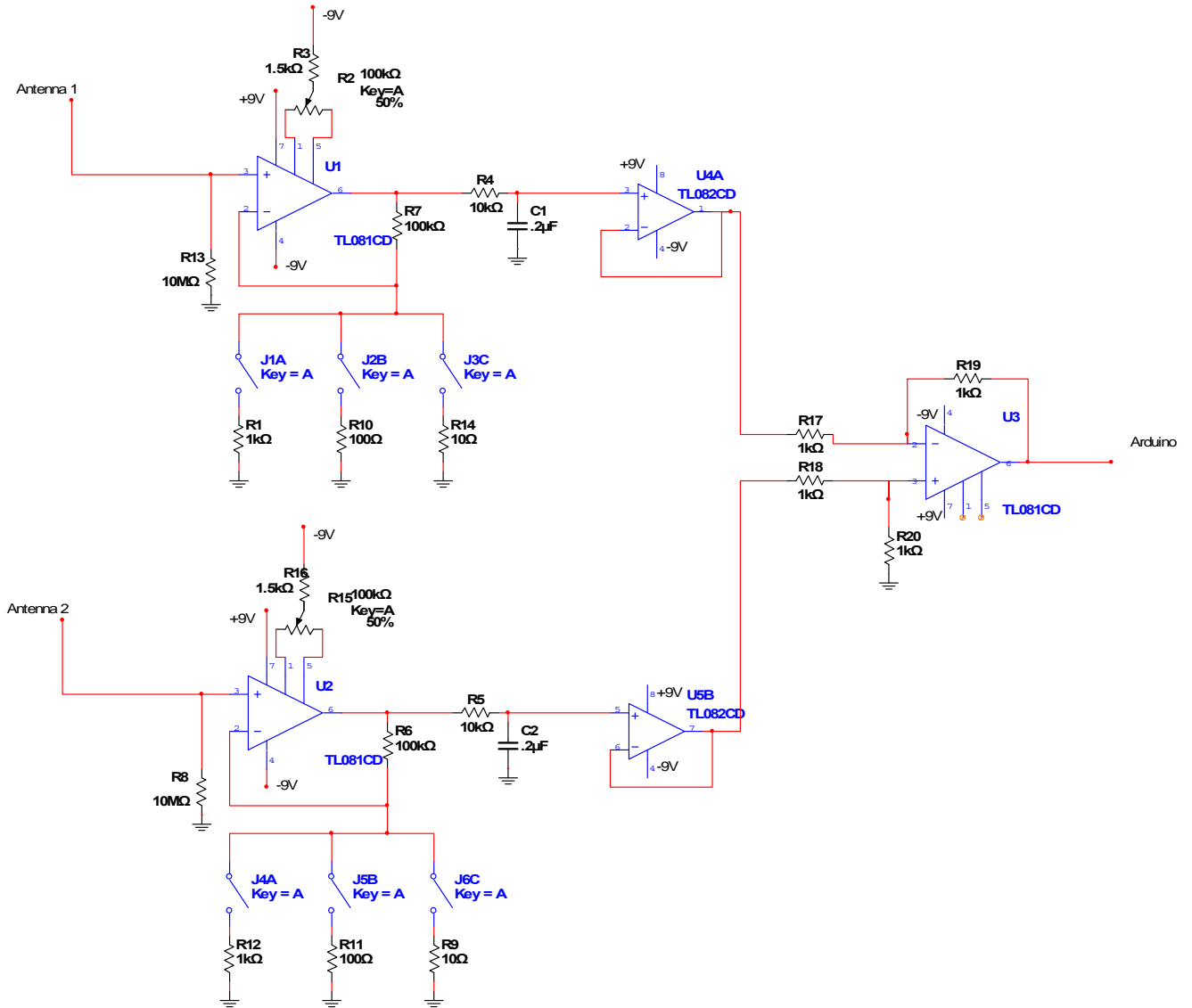
**Figure 21: Dual Antenna with instrumentation amplifier**

After building this circuit we did some conceptual testing with two non-shielded antennas connected to the circuit to show the function conceptually. We did not record values, but we looked at the oscilloscope and saw that there was a change between facing the source, turning right, and turning left.
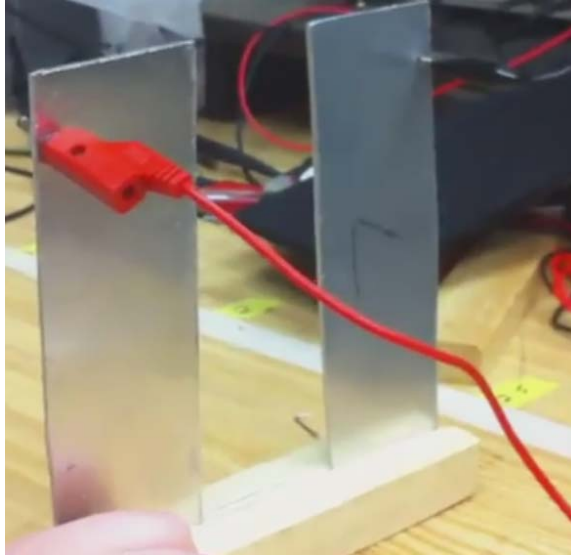
**Figure 22: Dual Antennas red: left black : right**

Figure 22shows our set-up for this conceptual test. The antenna with the red wire is referred to as the left antenna and the antenna with the black wire is referred to as the right antenna.
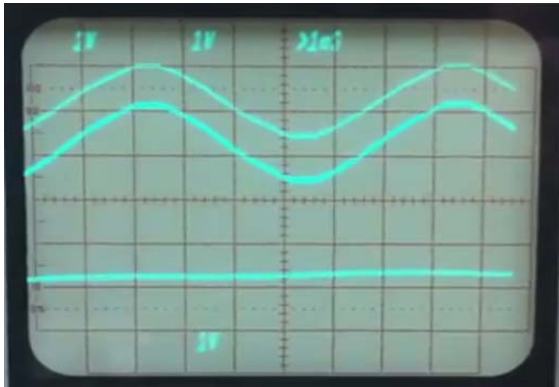


**Figure 23: Both Antennas facing source**
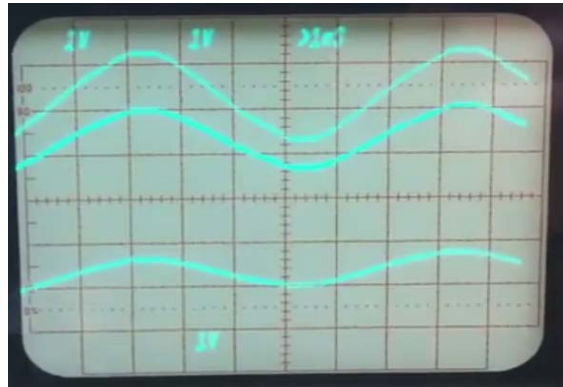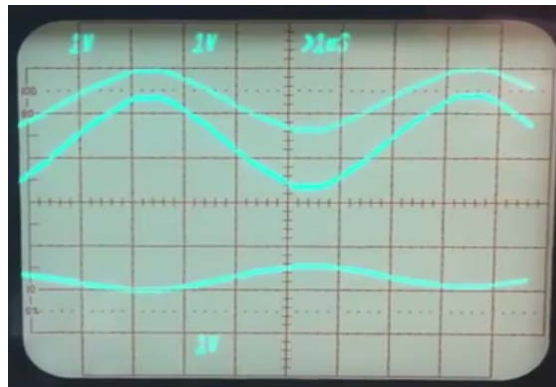


**Figure 24: Antennas turned to the right**



**Figure 25: Antennas turned to the left**

The above figures, Figure 23, Figure 24, and Figure 25, are oscillograms taken with the set-up that was previously mentioned. The top line is the output of the left antenna, the middle line is the output of the right antenna, and the bottom line is the output of the instrumentation

amplifier which is the difference of the right and left antennas. Figure 23 shows the top two lines being equal and the bottom line straight. This indicates that the antennas are facing directly at the source. Figure 24 is the result when we turned the antennas to the right. The top line, the left antenna, is larger and we can see that the difference is no longer straight. When the difference looks like this then it means we need to turn left to find the source because the left antenna is receiving a larger signal than the right. Figure 25 is the result of when we turned the antennas to the left of the source. The middle line, the right antenna, is larger so this means the signal it is receiving is larger than the left antenna. The difference line is now inverted, which indicates we need to turn right to locate the source.

With a successful conceptual test, we then further replicated our original setup, which included shielding for the antenna and a replicated circuit for the second antenna. They were also placed on two metal turntables that allowed the antennas to rotate 360°. We then had two identical setups and placed the antennas 9.5 inches away from the centers of the antennas.  This distance was determined because of the space on the existing board that allows the antennas to rotate without colliding with each other.

Although we proved that the instrumentation amplifier circuit to be successful, we realized that we could take the difference between the two antennas through software. With this being said we removed the difference amplifier section of the circuit and our new circuit can be seen in Figure 26
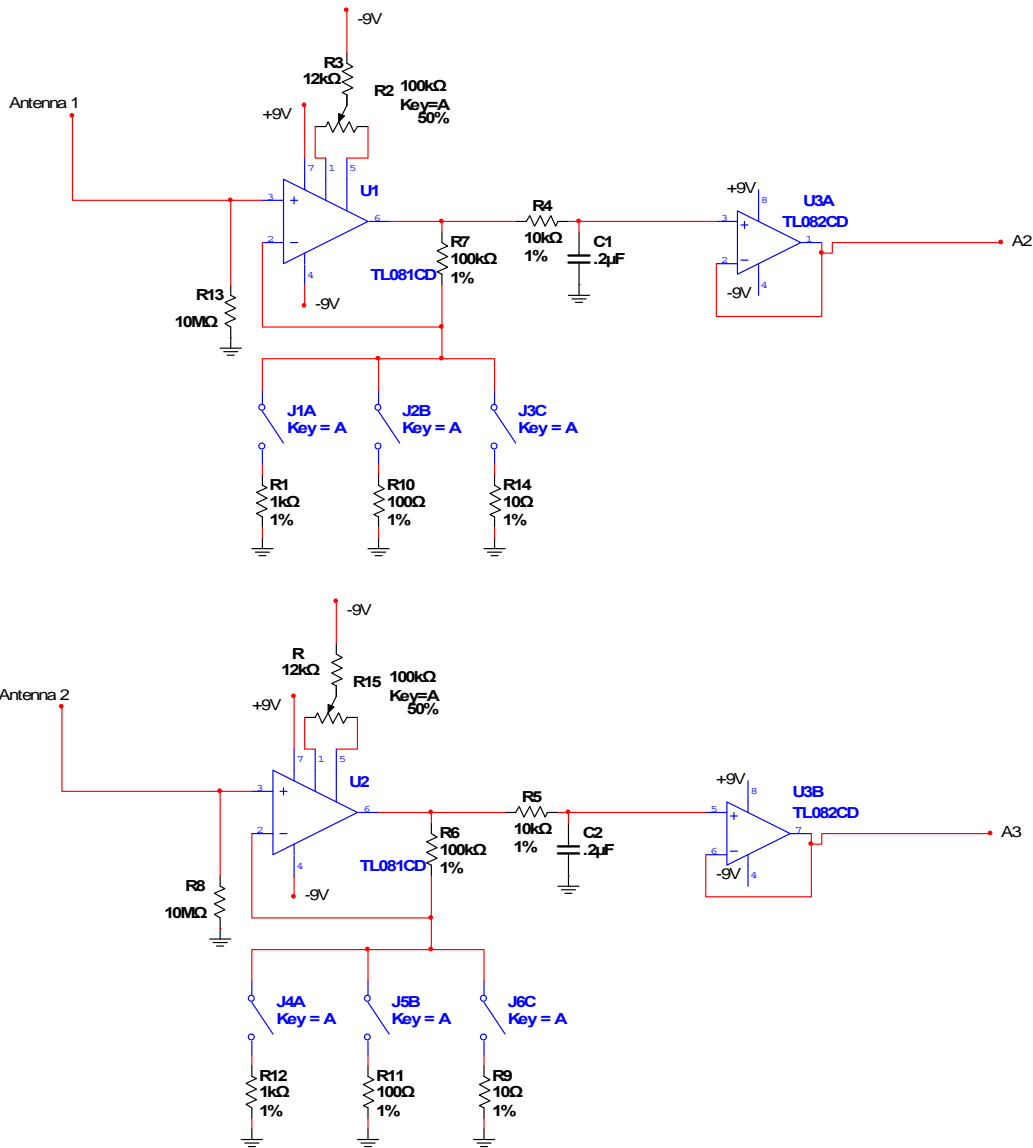
**Figure 26: Dual Antennas, Amplifiers, Filters, Buffers, Analog Inputs to Arduino Microcontroller**

## *Accommodating Two Antennas on One Microcontroller*

This circuit, however, was giving us some bizarre nonlinear results. The Arduino's ADC is a single channel device, so it would be impossible to sample both left and right signals simultaneously, without adding an external ADC chip. Given this, our sampling methodology was to sample one channel and then the other in sequence as quickly as possible. Our first thought of what possibly could have been the reason for this weirdness was sampling delay error. By this, we mean that the time between samples on each channel was long enough such that the input signal was significantly different. Below is a graph that shows the maximum sampling delay error for a 5V peak to peak signal and a delay time of 0.107 microseconds (the measured average time between samples). This was calculated by using Equation 4.

$$5\sin(x*60*2\pi) - 5\sin((x-.000107)*60*2\pi)$$
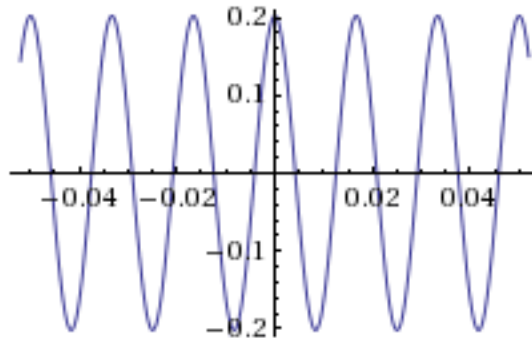
**Equation 4: Maximum Sampling Delay Error**



**Figure 27: Maximum Sampling Delay**

According to this graph, Figure 27, the maximum sampling delay error is 0.2 volts. This is a significant fraction of our signal, but did not account for the non-linear results we were getting.

To fix this sampling delay error, we devised a Schmitt trigger sub circuit to create a square wave 'clock' off of our input signal. The point of this clock is to trigger our sampling code synchronously with the input signal. Using external interrupts to trigger the code, we would sample the right signal channel and then the left signal channel each time the clock rose high, thereby pseudo-synchronously sampling each signal. It is only pseudo-synchronous because it doesn't really sample both signals at the same time, but it samples each signal at the same *part* of the wave, assuming the Schmitt trigger is configured such that the input signal regularly produces square wave pulses and the sampling delay is approximately the same each time (interestingly, our measurements showed that the sampling delay varied between 105µs and 113µs).

The implementation of the Schmitt trigger would have required us to choose one of the channels for generating the trigger clock and building isolated gain and filtering stages for it. For a proof of concept, we wired a74HC14Ninverting Schmitt trigger, a digital I/O chip, to the output of one of the buffer stages and discovered we were still getting the same nonlinear behavior from the Schmitt trigger input. This led to headaches and then an important discovery.

Assuming the digital I/O Schmitt trigger had the same input circuitry as the Arduino, we could be saturating the output current of the TL082 buffers we were using. The nonlinear behavior we were getting was the combination of the digital input circuitry and the saturation of the TL082. Figure 28is a schematic of the buffer and the input circuitry.
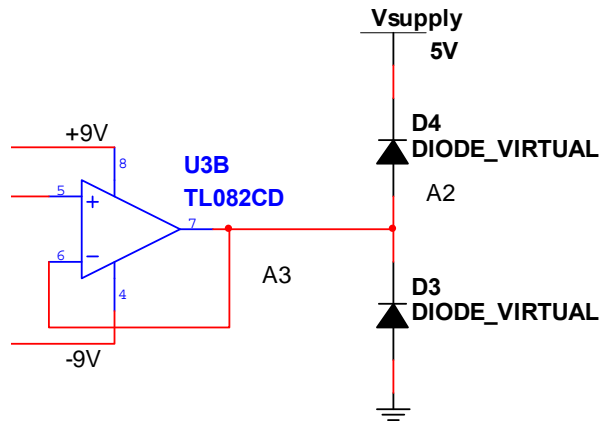
**Figure 28: Buffer output with input circuitry**

When the voltage exceeds 5.7 Volts or drops below -0.7 Volts, one of the diodes becomes biased on and the buffer saturates its output current. This causes everything to go crazy, not to mention wastes power and risks burning out the I/O pin. Luckily, the TL082's output current maximum is 25mA.

To limit this current, and stop the saturating of the TL082, we inserted a 4.3kΩ resistor in between the output of the buffer and the input circuitry. The following simulation shows the current with and without the resistor.
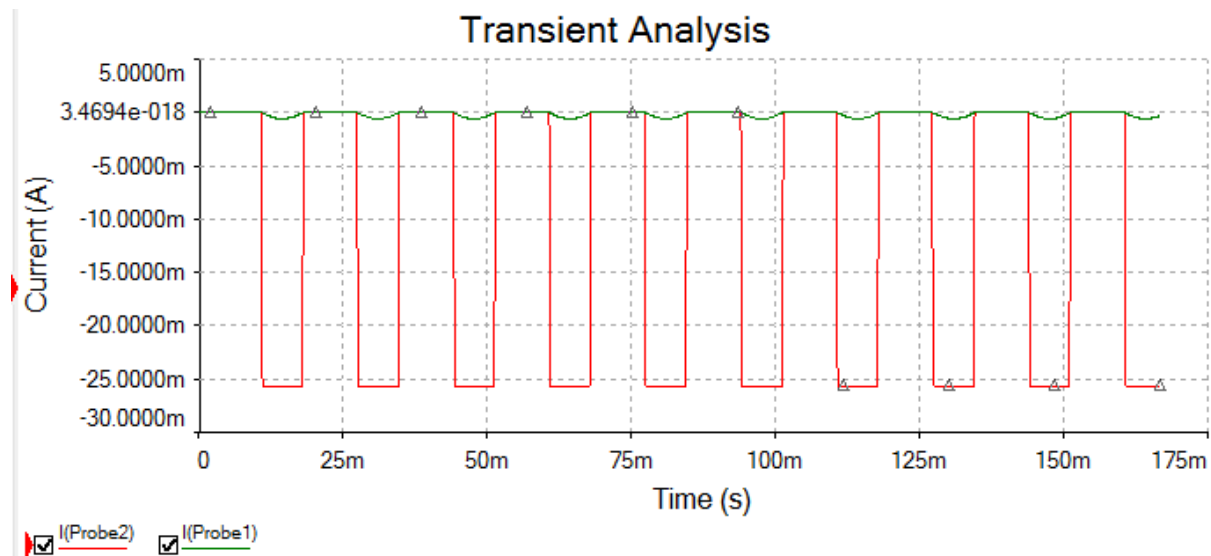


**Figure 29: Simulation of input current.**

The red signal is the input current without a current limiting resistor and the green signal is the signal with the current limiting resistor.
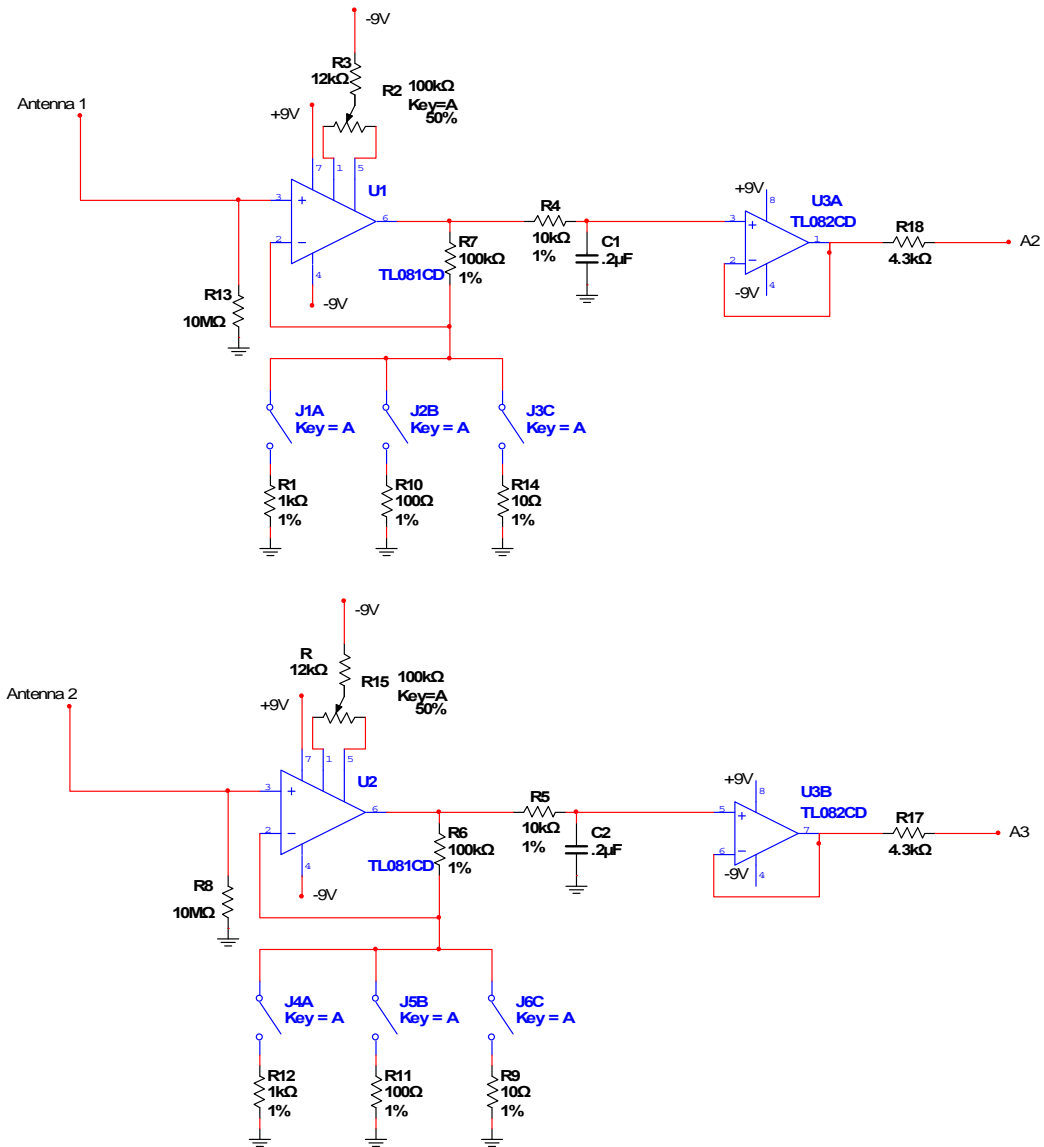
## Final Prototype



**Figure 30: Final circuit design**

This design is the one that was mentioned before in the methodology section. The circuit shown begins with the dual antennas, two identical variable gain amplification stages, two identical filter stages and two identical unity gain buffers that finally end at the analog inputs A2 and A3 of the Arduino microcontroller. The code that controls the final output of this device can be seen in Appendix C.

We ultimately scrapped the Schmitt trigger sub circuit because once we inserted these current limiting resistors the circuit began to behave as expected. We postulate that the external triggering scheme would have been a valid method for reducing the sampling delay error. In our case, the difficulty of implementation and cost in bread board real-estate was not worth the time and resources given the immediate success of our circuit once we introduced the resistors.

# Results

## *Stray Voltage Concept Test*

Our initial test was done using a sheet of aluminum foil. The results were seen to have an exponential decaying voltage with respect to distance from the pole. The testing set up consisted of a person holding the foil with their hands at fixed distances from the pole. The pole was energized by the Variac transformer. We found that the results varied depending on the person holding the foil, because the human body acts as a capacitor, thus this test is only suitable for a preliminary proof-of-concept. The results seen below are from one person holding it for the duration of the test.

The testing conditions were: Piece of aluminum foil 15" x 19" and with a person holding it with two hands with the lights on in the room.

| Distance from source | Voltage |
|---|---|
| 3 feet | 1.08 $V_{pk-pk}$ |
| 8 feet | 80m$V_{pk-pk}$ |

<div align="center">**Table 1: Conceptual Test**</div>

During this test we discovered that the Variac was creating a lot of noise due to the fact that it was unshielded. We also tested with the overhead lights while they were on and off and found no change in the results. We found that we were causing lots of little changes in testing setup each time we tried to repeat the test, making our results unreliable. After these tests, we endeavored to build a more robust and stable system for taking measurements.

## Amplifier and Filter Tests

The next testing that was done was with the metal plate and a simple amplifier, set to a gain of 2. Due to the noise of the Variac, it was discarded, and the pole was connected directly to the power outlet. The tests also included results when using the amplifier and filter, and just the filter. The results are shown in Figure 31.
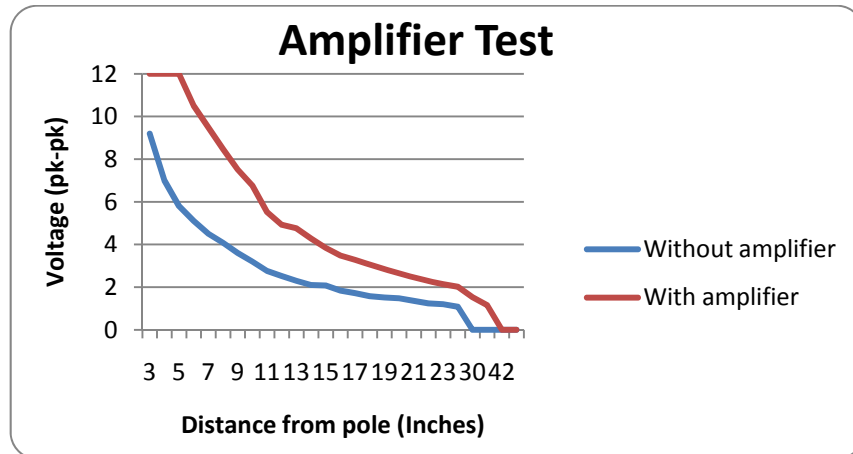


**Figure 31: Distance Test With and Without Amplifier**

The graph shows the measurements taken from the oscilloscope from the trials with and without the amplifier. The voltages drop in correlation to the distance from the pole. This was to be expected, which is further proof that the circuit works. We can also see that the amplifier successfully works, since higher voltages were measured. As the device was moved further from the pole, the circuit detects little or no voltage. This is also to be expected because the amplification never changes as we get further away from the pole. This means that we will need higher amplification in the circuit, so voltages can be detected from farther distances.

This trial also showed that the filter works properly because from the oscillograms we can see the difference between the same reading before and after the filter. This filter removed most of the outside noise created by machines that were being used in the building where the testing was being done. We took an oscillogram at one foot away from the pole to show the difference between the use of the filter and without it. This is seen in Figure 32 and Figure 33.
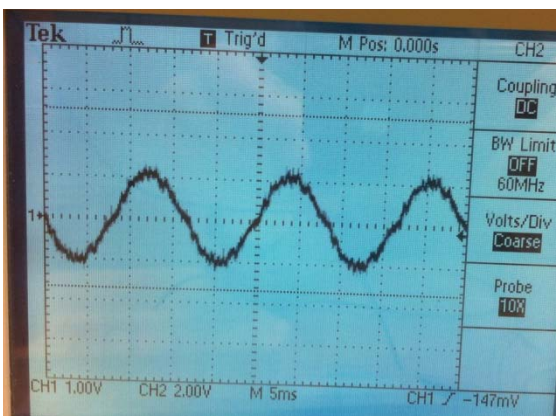


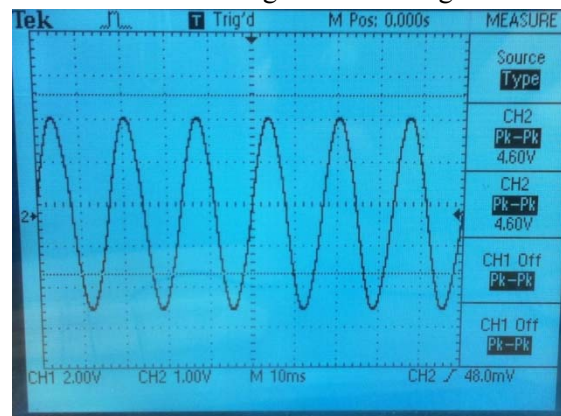**Figure 32: Output without filtering or amplification**

**Figure 33: Output with filtering and amplification**

43

## Square Plate Tests

The next sets of tests were done with square plates that differed in area. This also marked the end of the use of the oscilloscope, as the half wave rectifier was added to the circuit. The new dimensions of the plates are as follows: Plate 4 is 4.5"x4.5", Plate 1 is 6"x6", and Plate 5 is 8.5"x8.5".

Since the oscilloscope was no longer being used the workbench could be unplugged to further reduce the interference from devices in the room. The following is the result of this test with the three square plates.

For this test the multimeter was attached to the wood so that the multimeter is in the same place relative to the device for every reading. When we were three feet from the pole we switched the scale on the multimeter from 2V to 200mV for a more accurate reading. Results are shown in Figure 34.
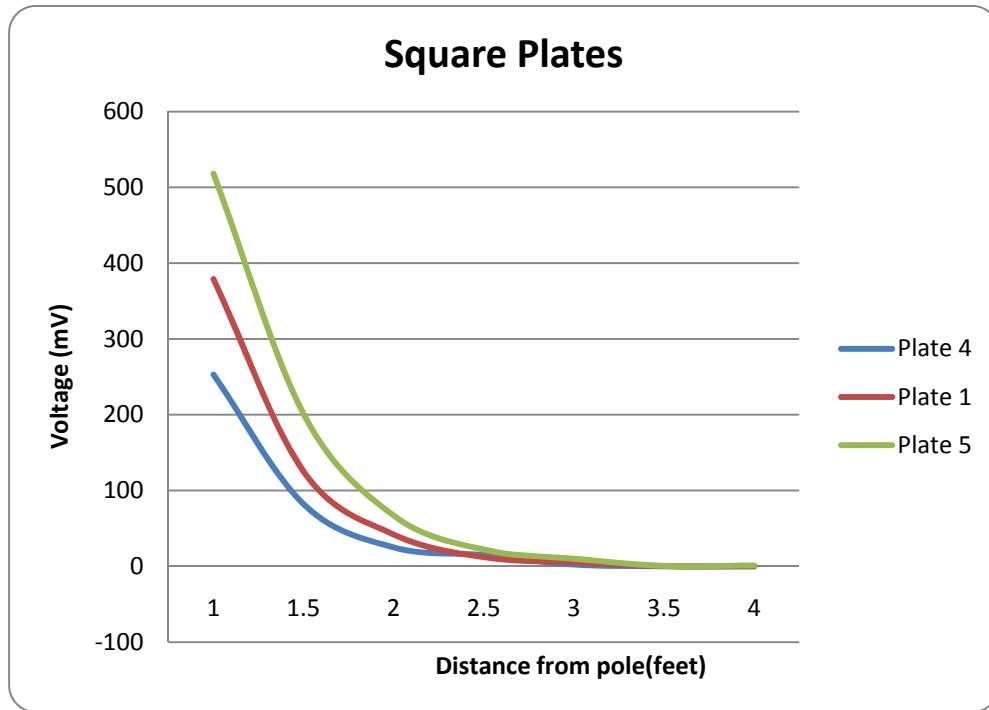


**Figure 34: Square Plates test**

Since all the plates are square, the results are now based on area. The results of this test indicate that signal strength is proportional to plate area. We suspected this relationship because a capacitor of greater area will couple more of the electric field.

## *Rectangular Plate Orientation Tests*

The next trial was done with rectangle plates. We wanted to test a plate with an acute aspect ratio to see if changing the orientation of the plate would result in a change in the signal strength. As mentioned before, the multimeter is attached to the wood for this trial, the workbench is not plugged in, and after three feet we switched the scale on the multimeter from 2V to 200mV for a more accurate reading.

We conducted this test with several plates of varying dimensions, all plates showed the same trend: the plate in vertical orientation had a stronger signal than the same plate in horizontal orientation, but plate #3 showed the most dramatic change. We believe plate #3 showed the most dramatic change because it has the greatest aspect ratio. The plate dimensions are the following: Plate 3 is 2"x10", Plate 6 is 2"x8.5", Plate 7 is 2"x6", and Plate 8 is 1.75"x4.25". The results for the other rectangle plates can be seen in Appendix B.
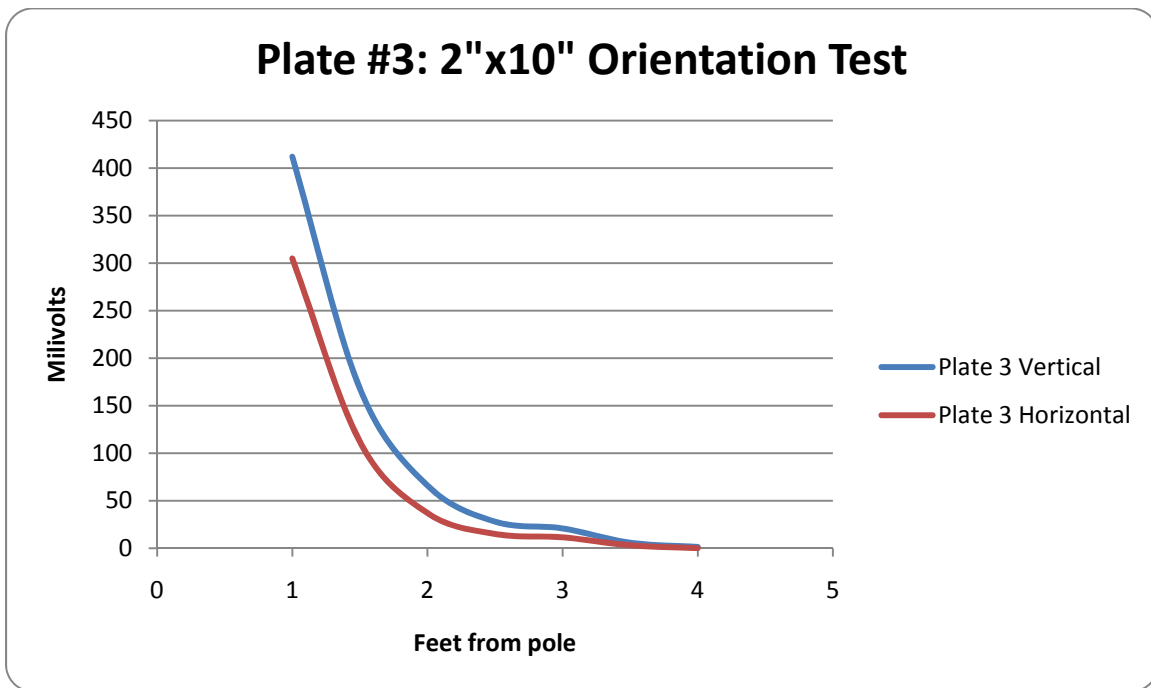


**Figure 35: Plate #3 orientation test.**

This result makes sense because a plate in the vertical orientation has more projected area against a vertical pole. More area projected against the pole yields more coupled electric field which yields higher voltage.

## Hallway Test

We have done several distance tests but were limited to a maximum distance of 4-4.5 feet from the pole. This is because the workbench on which we were testing. To test how far we can actually detect the source from, we borrowed a cart and did tests in an isolated hallway. Our results, however, were different from all other previous distance tests. We believe the reason for this was the change in our setup to accommodate the new testing environment (surface the pole sits on, the room we were in, and any other noise or objects surrounding that area). Although the results were different, we were able to detect the source from 5-5.5 feet away using the higher gains (1,000 and 10,000). We also repeated the test with our bodies grounded through the device. The results were not significantly different (a small positive offset). Figure 36 shows the results of the hallway test without our bodies being grounded by the device.
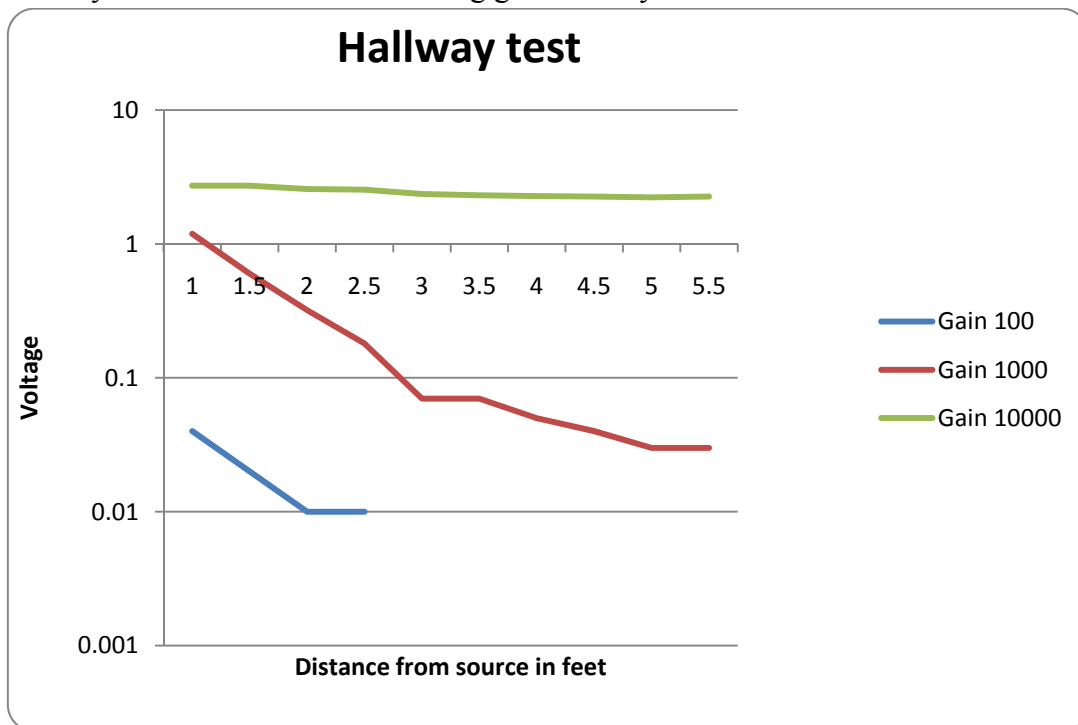


**Figure 36: Hallway test, note Y-axis is logarithmic scale.**

At the gain of 100 the values read were very low and could only be read a few inches away from the source. At gain of 1,000 there was an exponential decrease in the reading as we moved farther away from the source (indicated as a straight line on a logarithmic scale). This is what we expect of our device. We were able to detect the source up to 5.5 feet from the source. At a gain of 10,000 our values fluctuated rapidly during this test, but maintained a very high offset. We believe this was caused by an unknown source of interference in the hallway.

From these results, we can conclude that increasing the gain (at least from 100 to 1,000) gave us a greater range in which we could sense the voltage source.

## *Angle Tests with Shielded Antenna*

In this set of tests we placed our device at a distance of 30 inches from the pole and used a protractor to mark the angle in regular intervals around the antenna. We rotated the device to see if our antenna shielding was actually functioning as expected. If the shielding worked correctly, the signal should be strongest when the exposed side of the antenna is facing the voltage source. We did several tests using each gain (100, 1,000, and 10,000) and varying from 0 to 180 degrees of rotation (0 degrees means the open end was facing the source, 180 degrees means the open end was facing away from the source). The following graph, Figure 37, shows that there is a decrease in the voltage as we turn away from the source.
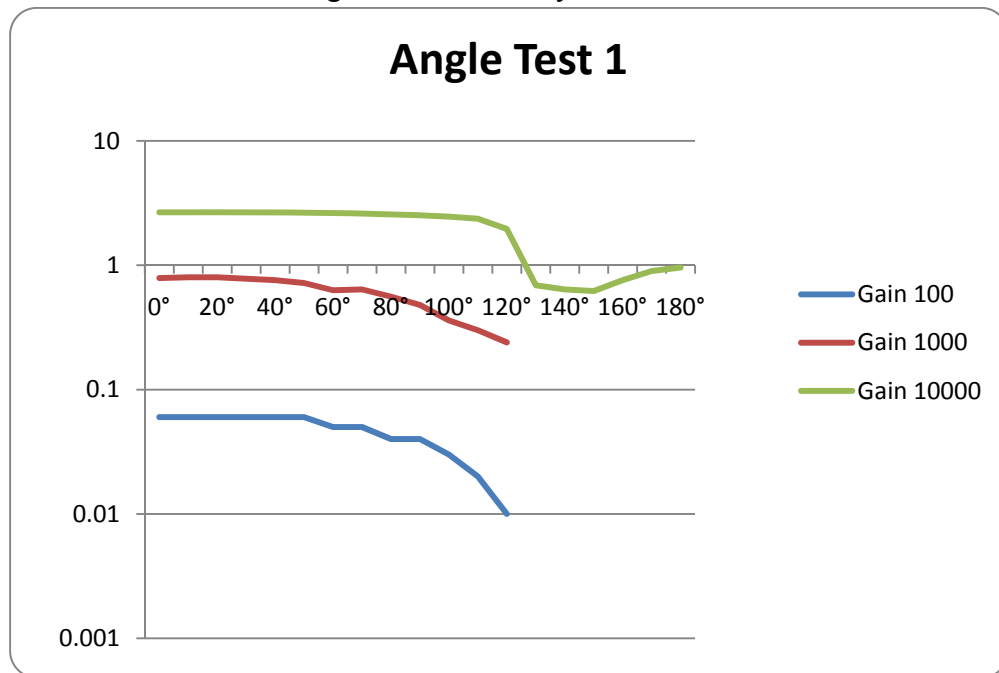


**Figure 37: Angle Test**

As seen in Figure 37, the lines follow basically the same path. As we rotated the antenna away from the source the value displayed decreased. This shows that the shielding works as expected. There is also an additional benefit to this: if we rotate the device in an environment where the location of a voltage source is unknown, we can deduce the direction in which it is located by comparing the signal strength values until we find the direction in which it is strongest. We use this technique in the next test to determine both direction, and distance of the source.

## *Determining Distance from Source with Dual Antennas*

As previously mentioned, this device is able to determine in which direction the source is located. With the addition of a second identical antenna, we can use geometry to determine the distance to the voltage source. A diagram of our setup is found in Figure 38.
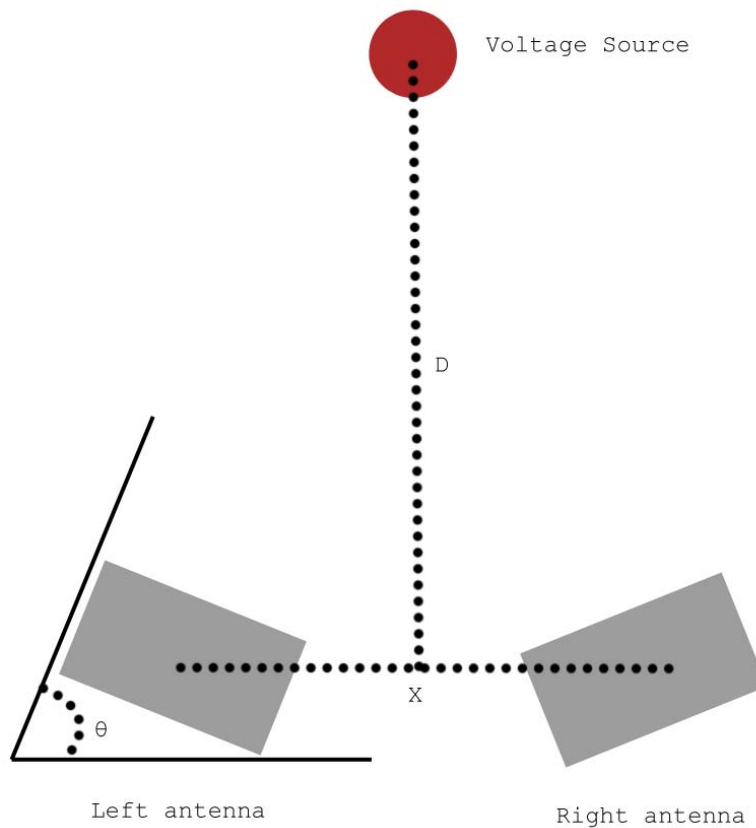


**Figure 38: Dual antenna setup**

The method for determining the distance to the voltage source is simple. First we rotate the two antennas until the signal reported is at a maximum for both antennas. According to the results of our angle testing, this should mean that the antennas are facing the voltage source. Once the signal strength is maximized, we record the angle at which the plates are rotated. Using the angle$\theta$, and the fixed distance between the plates, X we can determine the distance to the voltage source, D by using Equation 5.

$$\frac{X}{2} * \tan(\theta) = D$$

**Equation 5: Determining Distance Using an Angle**

In our actual setup, where X = 9.5 inches, we used a protractor to mark the angle around the antennas evenly in 10 degree increments. We quickly discovered that our antennas were too

close together to accurately find D much beyond one foot. It was nearly impossible to find the angle of maximum signal strength without the ability to more finely adjust the angle (a problem remedied by increasing the distance, X, which gives a greater maximum angle for distant objects). Due to time constraints, we were unable to create a prototype with a greater plate separation. The following table displays the results of the two tests we conducted.

| Angle with maximum signal | Calculated distance | Actual distance |
|---|---|---|
| 90 degrees | Infinity | 30 in. |
| 80 degrees | 26.9 in. | 12 in. |

**Table 2: Angle Distance Test**

Unfortunately, due to the construction of our device and testing set up, we were unable to measure distances closer than one foot from our signal source (at this distance the prototype edge was flush with the edge of the source mount) and even at that distance it was not very accurate due to the closeness of the antennas. Greater test distances yielded a calculated distance of infinity, indicated by the maximum signal strength angle of 90 degrees, or having the plates angled parallel to one another.

## *Dual-Antenna Distance Testing on Cart*

We decided to perform one last test with this prototype, which entailed placing our source in one spot and orienting the antennas directly at the source. With this setup we moved our device straight back by increments of one foot, beginning at a distance one foot from the source and ending when we saw that movement created no change in the displayed values. The values recorded were the ADC reads of the microcontroller. The values range from 0 to 1023, which is mapped linearly to the values between 0 and 5 volts. We performed two sets of this test to confirm consistency.

This test was only performed with a gain of 100 because when we began performing this test at higher gains, our outputs were not what were expected. The oscillograms for the three different gains at 1foot away from the source are shown in Figure 39, Figure 40, and Figure 41.
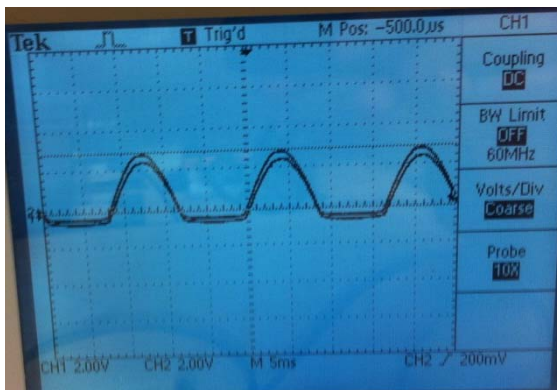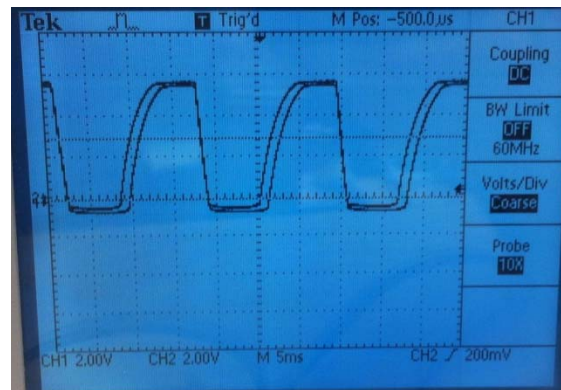


**Figure 39: Oscillogram 100 Gain**



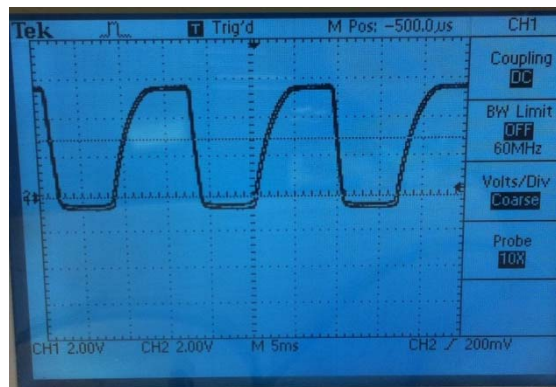**Figure 40: Oscillogram 1000 Gain**



**Figure 41: Oscillogram 10000 Gain**

In Figure 40and Figure 41, the results indicate that our amplifiers are hitting the positive and negative rails of their supplies. In Figure 40, we see that there is a slope difference between the two outputs. We did not know why this was happening. In Figure 41we can see that the graphs are approximately the same but the values displayed on the LCD were off by a sampling rate for the left and right antennas. With these results we decided to test functionality of the design with the gain of 100.

In our tests we were able to detect the voltage source at a maximum distance of seven feet away. In Figure 42the left and right values are approximately equal, making the difference close to zero.
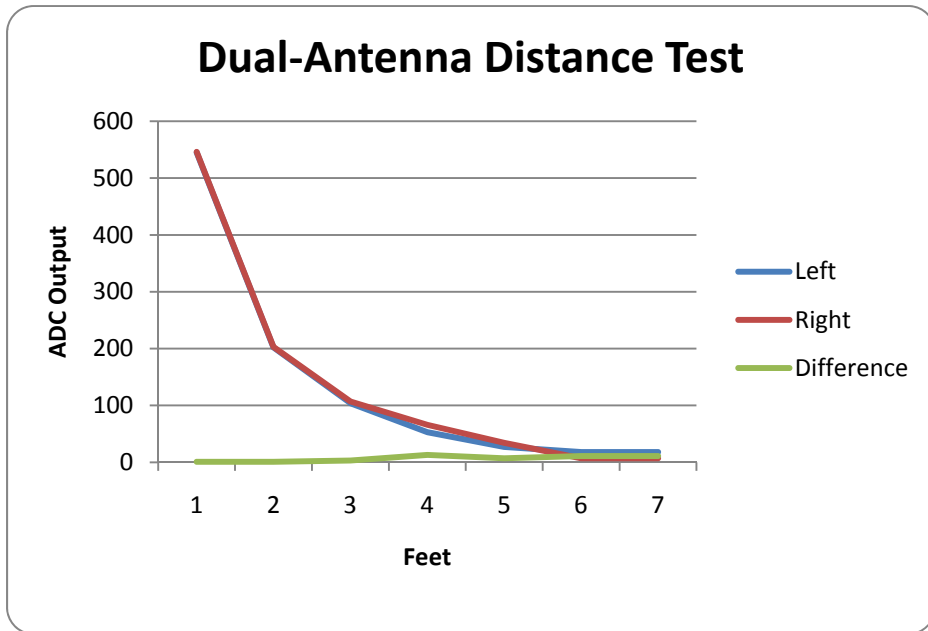


**Figure 42: Dual- Antenna Distance Test**

# Recommendations

Although this project proved to be a success, due to time constraints, we were unable to implement everything we wanted for this product. Therefore, there are many recommendations for future groups that take up this project. While some are only cosmetic, some are very important in achieving better results.

Our first recommendation is the improvement of the distance between the two antennas. With the current set up, the antennas are much too close and it would be difficult to calculate the distance from the source when testing at long distances. This is shown in the fact that with our final circuit, we were only able to determine the distance using the method of angles from very short distances from the source. While the antennas must be placed further apart, it is still possible to have a handheld device. If the distance between to two antennas is not feasible to change, another suggestion is to create smaller antennas. These antennas, however, have to be proportional to the system.

This issue leads into another, mainly how the angles are read. As of now, the antennas must be moved manually, meaning that the readings may be off or not turned to some small value not tested. During our testing, we turned the antennas in 10 degree increments according to marks made by a protractor. This way of rotating the antennas was only as accurate as our markings. This also limited us to only taking measurement at these 10 degree increments, this not recording the in between values. One way to fix this is to have a microcontroller responsible for controlling two motors that would change the angle of the antennas automatically. This would be a better measuring device because the microcontroller could move by itself while running a code to find the angle in which the two antennas received the maximum readings.

Another modification that could be implemented via automation is variable gain. The current system has three choices of gain levels with no selectable gain in between. This is also done with switches needing to be switched by hand. The problem with this is that at certain distances it would be beneficial to have more options of gain selection. One recommendation is to have the microcontroller automatically select an appropriate gain that is determined based on readings on the antenna and distance from the source.

Our final recommendation is more of a features design. The current product has no method of actively telling the user that a stray voltage was detected, it is only displayed on the LCD. We suggest for the future product, that there should be an implementation of LEDs and a speaker. There would be three LEDS, one for left, right, and ahead. This would indicate that the user must turn left, right, or they are pointing the device directly at the source. The speaker would be used more as an intensity detector. As the user gets closer to where the source is the frequency heard through the speaker would be faster and louder. Both of these could be controlled by the microcontroller or by an analog solution. With all of these recommendations for a more autonomous device being controlled by a microcontroller it would be practical to

invest in a different microcontroller that can handle many inputs, outputs, and has a large amount of memory for storage.

## Conclusion

This project was a success because we were able to meet the proposed goals. Our main goal was to create a device that can detect the approximate location of a stray voltage source from a distance of at least one yard. After completing this project, we were able to achieve this goal and produce a functional product.

We were able to detect a stray voltage source from up to a distance of seven feet. The direction the user should turn the device to locate the position of the source was successfully displayed on an LCD screen. A proof of concept for the ability of our device to determine the distance from the source was demonstrated by measuring the angle of the antennas when at the highest voltage. Finally, our device was able to display the limit at which we can detect the voltage provided by the source.

In summary, the ability to detect a stray voltage from a distance of further than a foot was proven to be possible. We hope for this project to be used for future products that protect society from hazardous and sometimes lethal electric shocks caused by stray voltage.

# References

1. Bierbaum, A. C. (1992). *Diagnosis and Trouble Shooting of Stray Voltage Problems.* New Orleans, LA: IEEE.

2. Burke, J. (2007). *The Confusion Surrounding "Stray Voltage".* Rapid City, SD: IEEE.

3. Williams, C. (2006). *Was the Stray Voltage Really Stray?* Dallas, TX: IEEE.

4. http://www.santafenewmexican.com/Local%20News/Shocker--Lamppost-short-circuits-pets

5. http://www.mba.state.mn.us/resource.html?Id=17470

6. http://caselaw.findlaw.com/wa-court-of-appeals/1323678.html

7. http://www.nytimes.com/2006/03/04/nyregion/04voltage.html?_r=2

8. http://cityroom.blogs.nytimes.com/2008/01/18/stray-voltage-still-a-problem-4-years-later/

9. http://www.google.com/patents?id=66ClAAAAEBAJ&printsec=abstract&zoom=4#v=onepage&q&f=false

10. http://www.google.com/patents?id=U-kYAAAAEBAJ&printsec=abstract&zoom=4#v=onepage&q&f=false

11. http://www.google.com/patents?id=m6URAAAAEBAJ&printsec=abstract&zoom=4#v=onepage&q&f=false

12. http://www.hdelectriccompany.com/assets/files/lvs5.pdf

13. http://www.valuetesters.com/Greenlee-2010-Touchless-AC-Voltage-Indicator.php

14. http://www.myflukestore.com/crm_uploads/fluke_77iv_digital_multimeter_datasheet.pdf

15. http://www.myflukestore.com/crm_uploads/fluke_73_77_175_177_and_179_digital_multimeter_datasheet.pdf

16. http://cityroom.blogs.nytimes.com/2009/11/05/stray-voltage/

17. http://www.dps.state.ny.us/04M0159_ConED_annualreport_05.pdf

# Appendix A

This appendix shows the images of the devices used by Consolidated Edison in their efforts to detect stray voltage and to prevent future incidents from happening.

## DC stray voltage detectors

**Fluke 77-IV Digital Multimeter**



http://www.myflukestore.com/p1355/fluke_77-iv.php

**Fluke 177 Digital True RMS Multimeter**



http://www.myflukestore.com/p1224/fluke_177.php

## AC stray voltage detectors

**HD Electric LV-S-5/K01**



http://www.transcat.com/Catalog/productdetail.aspx?itemnum=LV-S-5/K01&utm_source=google&utm_medium=base

**Greenlee Model 2010 Voltage Detector**



http://www.drillspot.com/products/72262/Greenlee_Beha_2010_Voltage_Detector?s=1

## Mobile Detector



https://www.newyorkcompanion.com/2010_Winter_Stray_Voltage.html

# Appendix B

      The following are results of the individual rectangle plates in their horizontal and vertical orientations. Most of them have a difference between the two orientations but only plate 3 has the most dramatic change. The dimensions for the plates in the horizontal orientation are as follows: Plate 3 is 2"x10", Plate 6 is 2"x8.5", Plate 7 is 2"x6", and Plate 8 is 1.75"x4.25". The vertical dimensions are the same as the horizontal but switched.
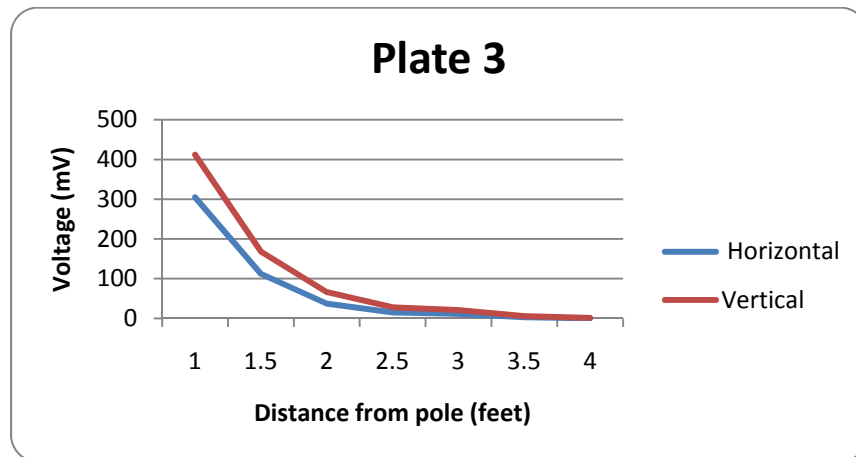


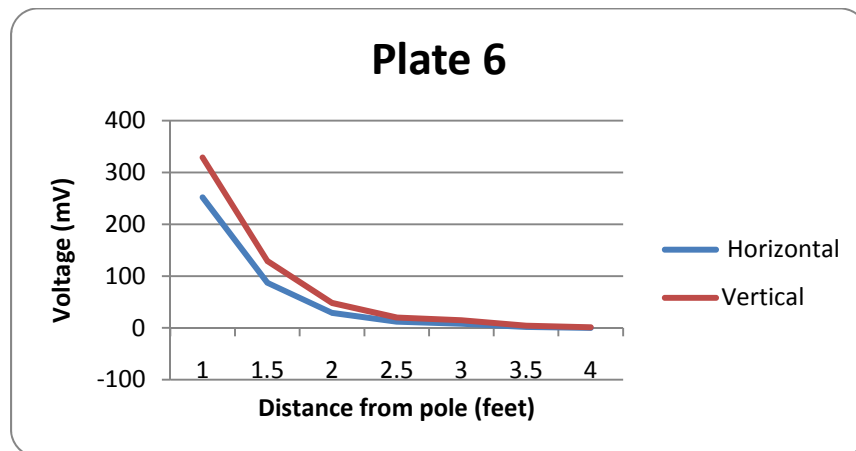**Figure 43: Plate 3 Orientation Test**
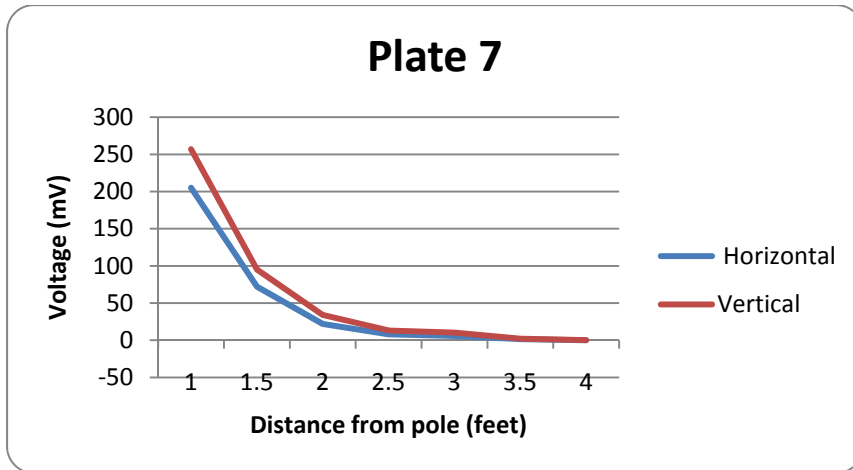


**Figure 44: Plate 6 Orientation Test**

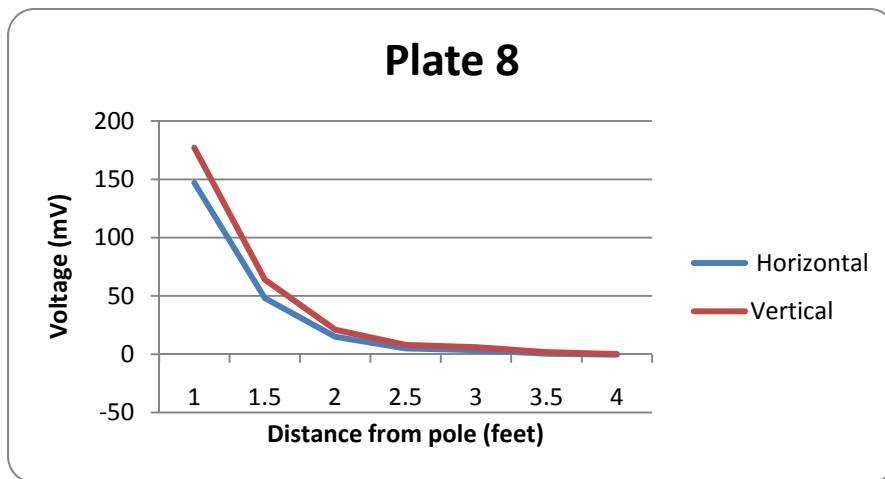**Figure 45: Plate 7 Orientation Test**



**Figure 46: Plate 8 Orientation Test**

# Appendix C

The following is the Code that we use for programming our microcontroller to display the detected voltage:

```
#include <LiquidCrystal.h>

#include <avr/interrupt.h>

#include <avr/io.h>

#define DIVISOR 300

// initialize the library with the numbers of the interface pins

LiquidCrystallcd(7, 6, 5, 4, 3, 2);

intleftPin = A2;

intrightPin = A3;

unsigned int rightValue, leftValue, rightValueP, leftValueP;

unsigned int rightTotal, leftTotal = 0;

int diff;

int counter = 0;

intintCounter = 0;

int tcnt2;

String the_direction;

intprevValue= 0;

int peak = 1;

void setup() {

  // set up the LCD's number of columns and rows:

  //Serial.begin(9600);

lcd.begin(6,2);

  //set up interrupts

   /* First disable the timer overflow interrupt while we're configuring */

  TIMSK2 &= ~(1<<TOIE2);

  /* Configure timer2 in normal mode (pure counting, no PWM etc.) */

TCCR2A &= ~((1<<WGM21) | (1<<WGM20));

TCCR2B &= ~(1<<WGM22);

   /* Select clock source: internal I/O clock */

  ASSR &= ~(1<<AS2);
```

```c
  /* Disable Compare Match A interrupt enable (only want overflow) */
 TIMSK2 &= ~(1<<OCIE2A);
  /* Now configure the prescaler to CPU clock divided by 1024 */
 TCCR2B = TCCR2B & 0b11111000 | 0x07;
 /* We need to calculate a proper value to load the timer counter.
  * The following loads the value 131 into the Timer 2 counter register
  * The math behind this is:
  * (CPU frequency) / (prescaler value) = 64us period.
  * (desired period) / 64us = 156.
  * MAX(uint8) + 1 - 156 = 100;
  // interrupts  every 10 ms.
  */
 /* Save value globally for later reload in ISR */
  tcnt2 = 100;
  /* Finally load end enable the timer */
 TCNT2 = tcnt2;
 TIMSK2 |= (1<<TOIE2);
 }
ISR(TIMER2_OVF_vect) {
 /* Reload the timer */
  TCNT2 = tcnt2;
if(intCounter == 33){
lcd.clear();
lcd.setCursor(0,0);
lcd.println(the_direction);
lcd.print(" D: ");
lcd.print(diff, DEC);
lcd.setCursor(0,1);
lcd.print("R: ");
lcd.print(rightValueP, DEC);
lcd.print(" L: ");
lcd.print(leftValueP, DEC);
intCounter = 0;
```

```
  }
intCounter ++;
 }
void loop() { //this section is executed continuously.
  //read both channels
rightValue = analogRead(rightPin);
leftValue  =analogRead(leftPin);
if(rightValue<prevValue&&rightValue !=0 && peak){
diff = rightValue - leftValue;
leftValueP = leftValue;
rightValueP = rightValue;
if (diff > 30)
the_direction = "Right";
else if (diff < -30)
the_direction = "Leftt";
else
the_direction = "Ahead";
peak = 0;
 }
prevValue = rightValue;
if (rightValue == 0)
peak = 1;
///sample time ~ 115 uS.
}
```