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THESIS

**DATA ANALYSIS FOR THE DETECTION OF
HIGH-VOLTAGE ACTIVITY USING NON-CONTACT
SENSORS**

by

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**DATA ANALYSIS FOR THE DETECTION OF HIGH-VOLTAGE ACTIVITY
USING NON-CONTACT SENSORS**

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Submitted in partial fulfillment of the
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ABSTRACT

This research examines the ability to detect the electrostatic field generated by an electric current moving through a medium- and low-voltage system. Two different commercially available electrostatic fieldmeters were purchased in order to collect data within the range of zero to five meters from the power source. Detection of this electrostatic field is useful in predicting the operational state of equipment that is connected to the power source. This data is particularly important if access to the power source is blocked by HAZMAT contamination, radioactive contamination, or barriers established by foreign governments and nongovernmental organizations. This experiment includes the collection of data utilizing electrostatic fieldmeters on known voltage sources. For this study, the voltage sources tested are 110V, 460V, and 4160V. Data collected with the two non-contact electrostatic fieldmeters was analyzed statistically utilizing the independent sample t-test. This test is particularly informative when the sample size is small and the variance is unknown. Since this research utilizes a sample of the data, it is necessary to perform hypothesis testing to analyze if the sample is a good representation of the entire data set. Results of this test show that the electrostatic field around an energized piece of equipment is detectable using both of the commercially purchased sensors on the 110V, 460V, and 4160V systems.

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LIST OF ACRONYMS AND ABBREVIATIONS

A	Amperes
AC	Alternating Current
cm	Centimeter
DC	Direct Current
DOD	Department of Defense
ft	Feet
HAZMAT	Hazardous Materials
IEEE	Institute of Electrical and Electronics Engineers
in	Inch
kV	Kilovolts
LED	Light Emitting Diode
m	Meter
mm	Millimeters
NGO	Nongovernmental Organization
NPS	Naval Postgraduate School
UAV	Unmanned Aerial Vehicle
USN	U.S. Navy
USG	United States Government
V	Volts
VWT	Vertical Wind Tunnel

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I. INTRODUCTION

This research examines the ability to detect the electrostatic field generated by current moving through a medium voltage system utilizing two different commercially purchased electrostatic fieldmeters. This experiment includes the collection of data utilizing electrostatic voltmeters on sources of known voltage. For this study, the voltage sources tested are 110V, 460V, and 4160V. The distances measured from the sensor to the electrical source range from zero meters to five meters. Data collected by the two non-contact electrostatic fieldmeters was analyzed statistically utilizing hypothesis testing based on sample standard deviation. This research utilized the independent sample t-test to determine if a current is detectable in an electric system. Data collection for this research occurred over a period of eight weeks but was abruptly halted due to the COVID-19 quarantine requirements. If this research is revisited in future studies, it is recommended that all results be validated by conducting additional testing on the three different voltages used in this study.

The purpose of this thesis is to explore the detectability of voltage in a system utilizing commercially available, non-contact, electrostatic fieldmeters. The manufacturers designed the devices to obtain measurements at a distance of one inch from the power source [1], [2]. This research seeks to understand if any viable information can be drawn from collecting electrostatic measurements beyond the manufacturers recommended distance to the voltage source. The information gathered will be analyzed to determine if the electrical state of the equipment can be identified. The data collected during this study includes values within and beyond the recommended distance. Instead of providing an accurate measure of voltage, the goal of this research is to develop data analysis tools that can determine if a system is energized based on data collected in an environment where accurate positioning of a sensor is impossible. Data collected from an energized system is compared to the results of a sample of data collected from an unknown system utilizing the independent sample t-test. Results of this comparison will provide information about current flow in the unknown system. Application of this research is of particular interest to the DOD and USN in order to determine voltage flow from a system where access is

blocked. This area denial could include physical barriers like HAZMAT contamination, radioactive contamination, or any other risks to personal health. Additional reasons for barriers to the power source include legal considerations of ownership or barriers established by foreign governments or nongovernmental organizations.

Limitations of this research include the requirement to zero the devices before measuring. Zeroing requires the use of a one-foot square steel plate that is properly grounded. In real world applications, it may not be feasible to carry a zeroing plate near the voltage location. Another limitation involves the design of the sensors. The sensors are designed to measure the electrostatic field generated. In a closed and isolated system this presents no issues, but rarely are systems closed and isolated. Electrostatic fields are created by other electrical devices even by static buildup as humans move through an area. It is important to note that the further the electrostatic sensor is from the voltage source, the higher the chance of electrostatic interference from a different source.

The electrostatic fieldmeters also have a limitation on their accuracy. The Desco 19492 has an accuracy of $\pm 5\%$ [1], while the Simco FMX has an accuracy of $\pm 10\%$ [2]. Since this research involves low and medium voltage current, there is a possibility of a statistically significant amount of voltage difference between the actual voltage and the measured voltage. Therefore, this research only explores detection of an energized electrical system and not the actual magnitude of current detected.

The zeroing requirement and the accuracy of the sensors are known limitations that can potentially inject error into the results. Field conditions can vary, and additional limitations could affect the detection of an electrostatic field. This research examines the detection of an electrostatic field while experiencing limitations of the commercially purchased sensors. Thus, attempting to prove that these limitations do not affect the results of the experiment.

II. THEORETICAL FOUNDATION

The development of the voltmeter revolved around the need to accurately measure the amount of voltage moving through an electrical system. This requirement was realized in the late 1800s as electricity became the premier choice for power throughout the industrial world. In order to regulate and properly charge electricity consumers, it was necessary to develop an accurate measuring device for electric currents. In 1886, Edward Weston invented a device known as the portable DC ammeter [3]. This ammeter measured both voltage and current with an accuracy between 0.25% and 0.5%. The portable DC ammeter provided accuracy and portability to electric current measurement, but it still required physical contact between the electric current and the ammeter. The non-contact voltmeter was not developed until 1922. E.B. Moullin while working at the University of Cambridge, created the first vacuum-tube voltmeter that advertised the ability to measure electric voltage without disrupting the electric circuit [3]. This marked the creation of the non-contact electric voltmeter. Further developments have improved accuracy and the ability to measure voltage at further distances from the power source.

A. ELECTROSTATIC FIELD GENERATION

An electrostatic field exists between two objects if there is a difference in electrical charge. This difference in charge is also known as the voltage gradient [4]. During the testing phase for this thesis, the electrostatic field is generated between the charged electrical circuit and the air surrounding the measuring device.

As shown in Figure 1, the red cylinder represents a cut section of an electric cable with electricity flowing through the cable. The green arrows represent the static electricity emanating outward from the cable. If there is no external interference, the static electricity is emitted outward and perpendicular to the current flow. This transmission of electrostatic voltage occurs around the entire perimeter of the cable. The diagram represents a positively charged electrostatic field. If the electrostatic field is negatively charged, the green arrows would point directly at the electric cable.

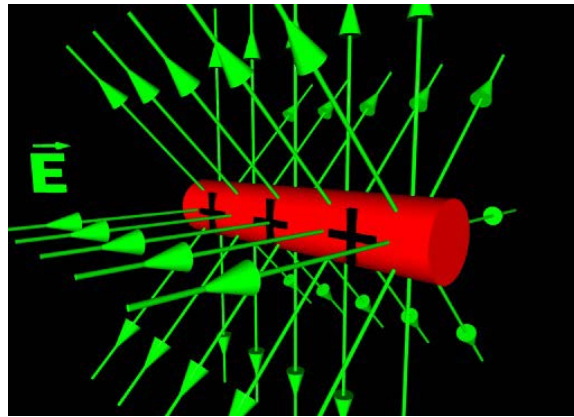


Figure 1. Electrostatic Field. Source: [5].

Figure 2 depicts the charge per unit length (λ) inline with the charged wire.

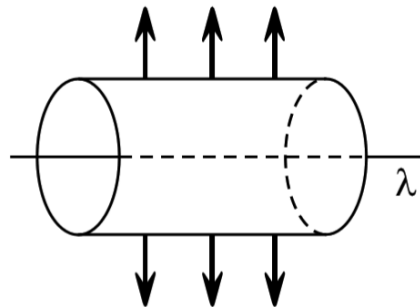


Figure 2. To the Calculation of the Electric Field Generated by an Infinite String Using Gauss's Theorem. Source: [6].

The magnitude of the electric field around the charged wire is described in Gauss' law:

$$E(R)2\pi RL = \frac{\lambda L}{\epsilon_0}.$$

The variable $E(R)$ is the electric field strength at a perpendicular distance R from the wire, λ is the charge per unit length, R is the radius, L is the length, and ϵ_0 is the electric permittivity of free space [6]. Rearranging the equation and solving for the electric field strength yields:

$$E(R) = \frac{\lambda}{2\pi\epsilon_0 R}.$$

As the radius R increases to infinity, the denominator in the equation goes to infinity. As a result, the electric field strength $E(R)$ tends toward zero. For this experiment, the measured electrostatic charge decreases to zero as the measured distance increases away from the voltage source.

B. CONTEMPORARY DETECTION METHODS

This section will discuss the current methods that non-contact sensors employ to measure voltage in an electric system. The two main categories for non-contact voltage sensors are electrostatic voltmeters and electrostatic fieldmeters.

Electrostatic voltmeters are designed to measure surface voltage. Voltmeters contain an amplifier that amplifies the voltage of the testing probe so that it is equal to the surface voltage of the object [7]. The amount that the voltmeter has to be amplified to match the surface voltage is utilized to calculate the surface voltage. Electrostatic voltmeters are highly accurate and typically return measurements $\pm 0.1\%$ of the actual surface voltage. Electrostatic voltmeters are designed to take measurements very close to the surface of the object being measured. Typically, the probe to source distance is 3/32 of an inch (2.5 mm) or less [7]. Figure 3 shows the Trek model 400 electrostatic voltmeter with an attached sensing probe.



Figure 3. Trek Model 400 Electrostatic Voltmeter. Source: [8].

Electrostatic fieldmeters are utilized to measure electrostatic fields at a given distance from a voltage source. Numerous external elements can affect the accuracy of the measured voltage. These external elements include other electrostatic fields coming into contact with the sensor and physical barriers between the measuring device and the source. The distance between the sensor and the voltage source also affects the accuracy of the measurement. Electrostatic fieldmeters typically have an accuracy of $\pm 5\%$ of the actual voltage. Typically, the device to source distance is one inch (25.4 mm), but electrostatic fields can register at much larger distances [7]. Figure 4 shows the exterior design of the Desco model 19492. Electrostatic measurements are collected at the top of the device. This design does not require an external probe.



Figure 4. Desco Model 19492 Digital Static Fieldmeter. Source: [1].

C. INDEPENDENT SAMPLE T-TEST AND HYPOTHESIS TESTING

The independent sample t-test, also known as the Student t-test, was created by William Sealey Gosset in 1908 [9]. The article “The Probable Error of a Mean” was published in the journal of statistics, *Biometrika* [9]. Gosset published the article under the fictitious name, Student, in order to maintain anonymity. The independent sample t-test was developed by Gosset while working for the Guinness brewery in Dublin Ireland. Production of beer required raw ingredients from numerous sources. The quality of the beverage produced depended directly on the quality of the ingredients. Since it was impractical and inefficient to test large quantities of raw materials, Gosset focused on testing small samples [9]. His development of the independent sample t-test helped determine which batches of barley and hops would produce the highest quality beer. Since manufacturing processes are typically guarded, Guinness required anonymity so that competitors would not know that the brewery employed a statistician [9].

Hypothesis testing is the statistical comparison of a sample of data versus the population or a known value. A hypothesis test involves the designation of a null hypothesis and an alternative hypothesis. The null hypothesis is the declaration that needs to be tested [10]. The alternative hypothesis is the conclusion if the null hypothesis is proven to be false [10]. In this case, the sample is the data collected utilizing an electrostatic fieldmeter on an unknown power source. This data is compared to the known population of data collected from experiments conducted on known power sources that are energized.

Hypothesis testing requires the calculation of the critical value (t_A). The critical value is determined by selecting a significance level (α) and determining the probability distribution of the model [10]. For this research, the significance level is 0.05. The data is assumed to be independently sampled from a normal distribution. The standard variation of the sample mean is unknown. Therefore, an independent sample t-test is applicable. Utilizing the sample data, it is now possible to calculate the test statistic (t) utilizing to following formula:

$$t = \frac{\bar{x} - \mu_0}{\left(\frac{s}{\sqrt{n}}\right)}$$

7

In the previous equation, \bar{x} is the sample mean, μ_0 is the population mean, s is the sample standard deviation, and n is the number of observations. Once the test statistic is calculated, it is analyzed to see how it compares to the critical value [10]. For a one-sided independent sample t-test, this means determining if the test statistic is larger or smaller than the critical value [10]. If the test statistic is larger than the critical value, then the null hypothesis is accepted [10]. The null hypothesis is rejected if the test statistic is smaller than the critical value [10]. In this case the alternative hypothesis is accepted. The acceptance and rejection regions are detailed in Figure 5.

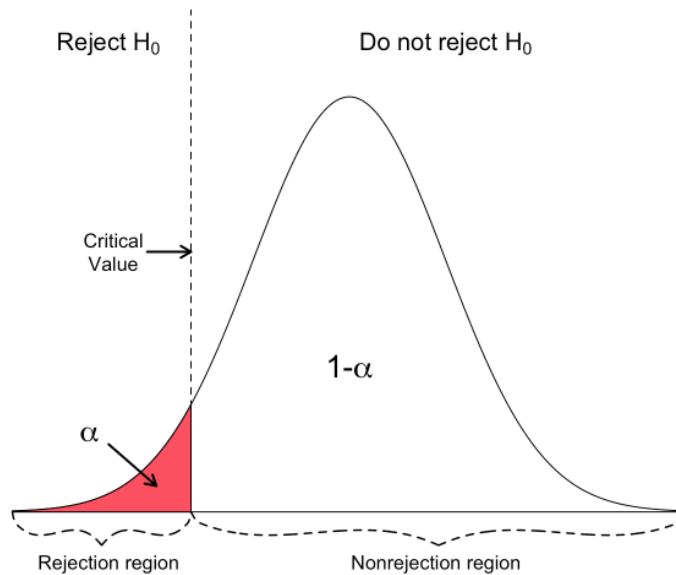


Figure 5. Left-Tailed Hypothesis Test. Source: [10].

Hypothesis testing only determines if a sample of data collected is statistically similar to a population or a known value. This process has been proven to be effective, but it is not free from errors. With this evaluation, there are two types of errors that can occur. Type I errors occur if the null hypothesis is rejected but it turns out to be true [10]. Type II errors occur when the null hypothesis is not rejected but it turns out to be false [10]. Since hypothesis testing involves analyzing a sample of a population, it is possible that the sample will contain anomalies in the data. Therefore, there is no way to completely eliminate all possibilities of error. Figure 6 is a summary of the types of errors that can occur during hypothesis testing.

	H_0 is true	H_0 is false
Do not reject H_0	Correct decision	Type II error
Reject H_0	Type I error	Correct decision

Figure 6. Error Type Designation. Source: [10].

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III. TESTING PROCEDURE

This chapter details the entire testing procedure and any considerations or assumptions assessed for each phase of the test. The test consists of three phases.

Testing Phases:

- Zero the sensor
- Data collection (power source off)
- Data collection (power source on)

The testing procedure was utilized to gather data on three different known voltages, 110V, 460V, and 4160V.

A. TESTING APPARATUS

For all phases of the testing procedure, it is important to control or minimize the external elements that could introduce electric charge into the testing area. The electrostatic field sensors have the ability to read electric charge that is coming in contact with the sensor. This charge can travel through the air or through metal located near the sensor. The testing apparatus designed for the collection of data is constructed out of a wooden base. The non-conductive properties of wood provide the perfect platform for measurement. One end of the base is placed directly in contact with the electrical source being measured, while the opposite end is supported so that the entire testing platform is perpendicular to the voltage source. The end in contact with the voltage source is referred to as the null end. The sensor is laid directly on top of the testing platform, and in contact with the voltage source. Measurement in this position provides the 0 cm measurement. Once the measurement is recorded, the sensor is moved away from the voltage source to the next desired distance from the voltage. The range for this thesis is from 0 to 5 meters. The data is collected at every centimeter from 0 to 10 centimeters. From 10 to 100 centimeters the data is gathered every decimeter. For the range of 1 to 5 meters, the data is gathered at every meter. In order to standardize measurements, the testing apparatus includes a non-

conductive meter rule that is adhered to the top of the device. This aids in the speed of measurement and also provides the distance standard for each series of tests. Figure 7 details the design of the testing apparatus.

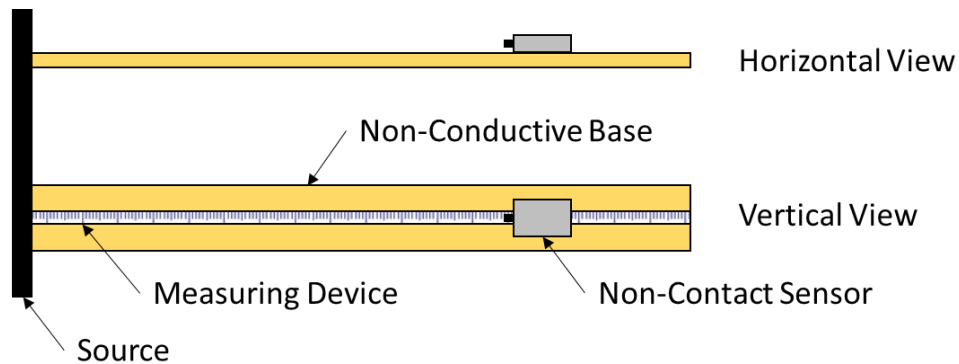


Figure 7. Schematic of Testing Apparatus

B. ZEROING PROCEDURE

Before any data collection can begin, it is necessary to zero the electrostatic fieldmeters. The process for zeroing the fieldmeter is described in the DESCO technical bulletin 3040 [1]. The process requires the use of a steel plate that is properly grounded so it emits no electrostatic field. This step requires a 12in x 16in steel plate connected to a grounding rod that extends 4 feet into the earth.

Below is the step-by-step procedure for zeroing the DESCO 19492 device.

1. Turn the meter on by pressing the POWER button [1].
2. Press the RANGE / ZERO button to set the meter to the 2 kV (3 decimal places) range [1].
3. Point the top of the meter towards a grounded metal surface [1]. The distance from the meter to the metal surface should be approximately one inch (25.4 mm) [1]. Using the red LED range guide, the meter is properly positioned when the projected red bullseyes are centered on top of each other [1].

4. Press and hold the RANGE / ZERO button until the meter displays .000 [1].

After completing the zeroing procedure, the fieldmeter should read zero and is ready to collect data.

Electrostatic voltmeters also require a similar zeroing procedure. The measuring probe must be pointed directly towards a grounded metal surface. Then, the zero button is pressed until the digital readout registers zero. Electrostatic voltmeters need to have a much smaller surface-to-probe distance than electrostatic fieldmeters. Depending on the exact model of voltmeter, the surface-to-probe distance is $\frac{3}{32}$ of an inch (2.5 mm) or less.

C. DATA COLLECTION (POWER SOURCE OFF)

After the electrostatic sensor has been properly zeroed, it is necessary to gather a set of measurements while the electric source is powered off. The testing apparatus is positioned perpendicular to the voltage source with the null end touching the voltage source. The sensor is placed with the front edge of the sensor in line with the 0 cm measurement on the apparatus rule. The sensor is aimed directly at the voltage source. It typically takes 3 to 5 seconds for the sensor to settle on a reading; this time needs to be allowed for each measurement collected. Once the measurement is recorded, the sensor is moved away from the voltage source and aligned with the next required measurement distance from the voltage source. This process is repeated until all required measurements are collected between 0 and 5 m. Collecting this series of measurements with the power turned off establishes the baseline or noise floor of testing location.

D. DATA COLLECTION (POWER SOURCE ON)

Gathering data with the power source on is exactly the same process as collecting data with the power source off. The main difference is that the equipment being measured is energized or turned on. Special consideration is taken at this step to ensure that the electrical equipment has been given the proper time to cycle through the startup procedure and enter the run phase. During the startup of electrical equipment, the current usage can fluctuate throughout the startup process. Test 1 has no requirement to wait for equipment

startup. The compressor used in test 2 only requires 25 seconds to reach the run phase. Test 3 of this thesis utilizes the blower motor for the linear cascade in the NPS turbo propulsion laboratory. This machine takes approximately five minutes to cycle through the startup and reach the run phase. It is important to understand each piece of tested equipment to ensure that the electrical draw from the equipment will remain constant throughout the data gathering procedure.

The testing apparatus remains in the same position used for measuring with the power source off. The null end of the apparatus is placed in contact with the voltage source while the apparatus is oriented perpendicular to the voltage source. Data is collected starting at 0 centimeters. Care is taken to allow the sensor 3 to 5 seconds to settle on a reading for each measurement collected. Measurements are recorded between distances of 0 to 5 m. The increments of these measurement match the increments used with the power source turned off.

E. TESTING APPARATUS 110V SYSTEM

The initial electrical source utilized for data collection was the 110V system. Since most commercial and residential buildings in the United States are configured to utilize 110V, it was only necessary to locate an electrical outlet that could be switched off at the power source. The power source for this portion of the testing is an outlet located in the garage at my residence. This outlet is located in an open space that has no other power sources within four meters. The outlet can also be switched on and off from the electric panel that controls all of the electrical outlets and overhead lights in that room. It was necessary to verify that there was no stray voltage in the outlet when the electrical panel was turned off. Validation of this was accomplished by using a handheld voltmeter when the power was turned off. The testing board was supported off the ground with non-conductive material. Raising the testing board aided in placing the electrostatic fieldmeter perpendicular to the power source. Measurements were taken within the range of zero to five meters from the power source. The process of data collection was repeated five times and the fieldmeter was zeroed between every series of data collection. Figure 8 shows the data collection setup constructed for 110V current.



Figure 8. Testing Apparatus for 110V System

F. TESTING APPARATUS 460V SYSTEM

For the purpose of gathering data on the 460V system, an air compressor located at the NPS turbo propulsion laboratory was used. Under normal operation the air compressor does not run continuously. Once the desired air pressure is reached in the holding tank, the air compressor shuts down until the air pressure in the holding tank drops below a certain threshold. This cycling of power would provide inconsistent results because the power consumption needs to remain constant throughout the entire period of data collection. In order to even out the power usage, the drainage valve on the holding tank remained open during data collection. As the air pressure built up in the holding tank, air would simultaneously escape through the drainage valve. This process of relieving pressure in the holding tank prevented the air compressor from cycling off during the experiment.

During the series of 460V testing, the measuring board was placed nine inches above the ground. The board was positioned perpendicular to the power supply cable that was connected to the air compressor. Directly next to the testing board was an electronic air dryer. This piece of equipment was powered off during the testing. Electrical interference during this phase of the testing included three power outlets and three fluorescent lights that were within five meters of the air compressor. Due to ongoing experiments and occupants in the lab, it was not possible to power off all of the electric

sources surrounding the air compressor. Figure 9 shows the data collection setup constructed for the 460V current.



Figure 9. Testing Apparatus for 460V System

G. TESTING APPARATUS 4160V SYSTEM

The NPS turbo propulsion laboratory utilizes a vertical wind tunnel that is powered by a 4160V power source. Vertical wind tunnels are designed for research that desires to study the effects of gravity in direct opposition to the drag on an object. The wind tunnel is powered by an electric motor that is connected to a blower located in the basement of the facility. The blower draws in air from outside the building and forces it up through vents in the floor. Air that has traveled through the system is exhausted by means of vents in the ceiling. Drawing in air from the outside and exhausting back to the outside helps maintain the atmospheric pressure within the building. The power to this system can be turned on and off at the control panel on the equipment. The startup procedure is automated, and it achieves three-phase 4160V in less than five minutes. Once the system has been powered up, it maintains a consistent energy draw until it is powered down. Figure 10 depicts the design of the vertical wind tunnel.

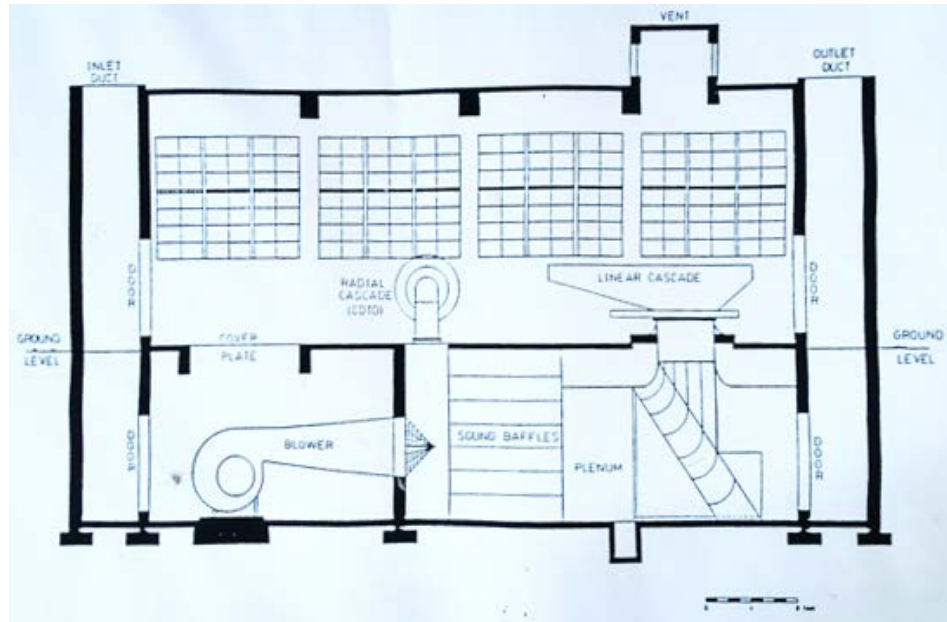


Figure 10. Schematic of VWT, NPS Propulsion Laboratory

The testing board was placed five feet above the ground and perpendicular to the viewing port in the electric control panel (figure 11). Data was collected at distances of zero to five meters from the viewing window. The viewing window is approximately six inches from the electrical source. Due to the risk of electric shock, it is not possible to open the viewing window during machine operation. The air gap between the voltage source and the viewing window coupled with the shielding from the electrical enclosure has the possibility to affect the measured electrostatic field. Figure 12 shows the control panel and the viewing port on the vertical wind tunnel. Electric interference within a five meter radius of the power source includes three power outlets and one computer. All other systems within the radius were powered down during the testing. The process of data collection was repeated six times and the fieldmeter was zeroed between every series of data collection.



Figure 11. Testing Apparatus for 4160V System



Figure 12. NPS VWT Control Panel and Viewing Window

IV. COLLECTED DATA

A. 110V SYSTEM RESULTS

The data was collected from the 110V system during five separate trials. Before each trial began, the electric fieldmeter was zeroed. During data collection, the overhead lights and electronics in the testing area were left off in order to minimize electric interference. Figure 13 summarizes the occurrences of the data collected with Sensor 1 on the 110V system. Figure 14 shows the mean and standard deviation of the data collected with Sensor 1 on the 110V system.

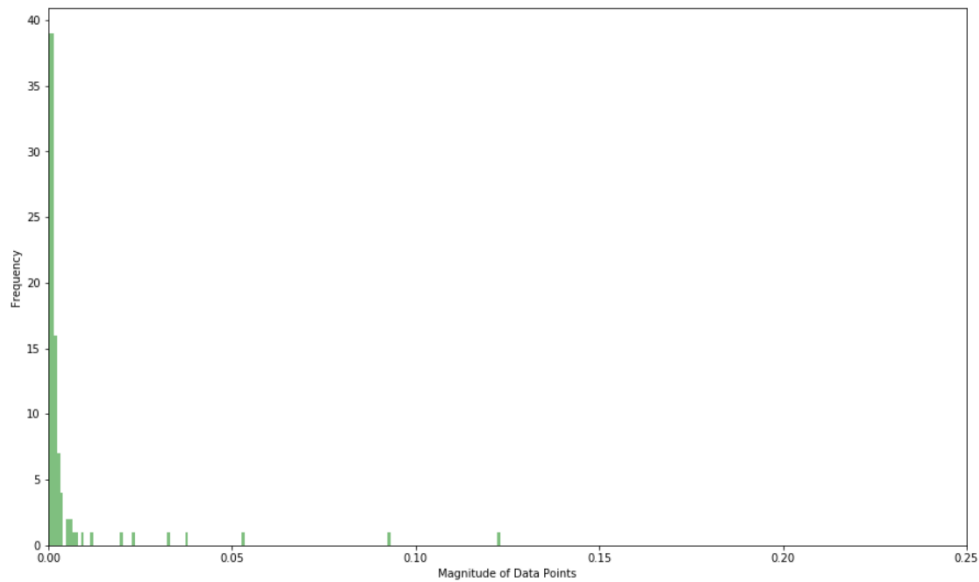


Figure 13. Occurrence Histogram Test 1, Sensor 1 (110V)

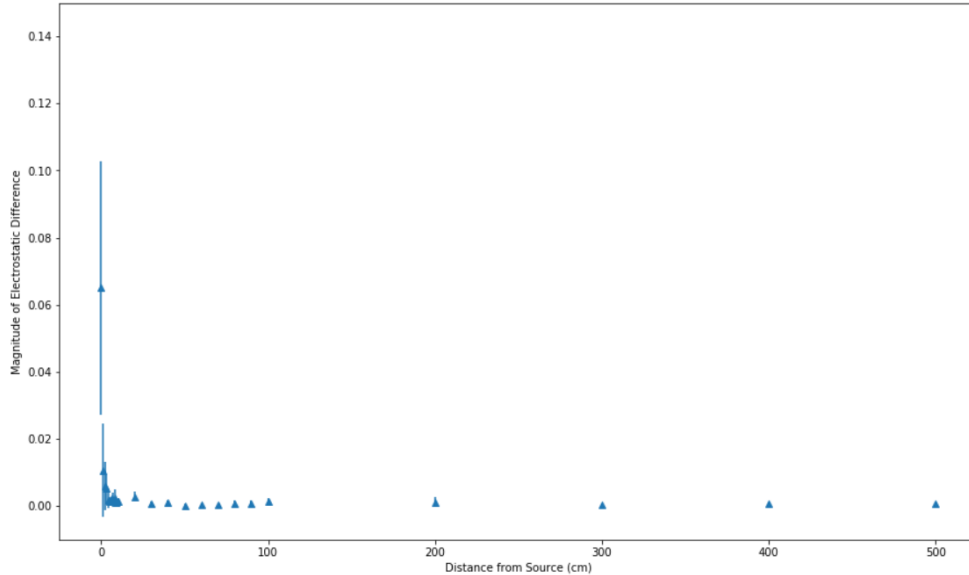


Figure 14. Mean and Standard Deviation Test 1, Sensor 1 (110V)

The data collected during Test 1 with Sensor 1 shows that the largest magnitudes of the five tests conducted were collected when the meter was in direct contact with the electric outlet cover plate. This is the closest possible point to the voltage source without physically disrupting the electric box. The relatively large standard deviation at this point signifies how much the measured voltage changed between each series of measurements. The measured voltage also trends towards zero after the fieldmeter is moved more than eight centimeters from the voltage source. Figure 15 summarizes the occurrences of the data collected with Sensor 2 on the 110V system. Figure 16 shows the mean and standard deviation of the data collected with Sensor 2 on the 110V system.

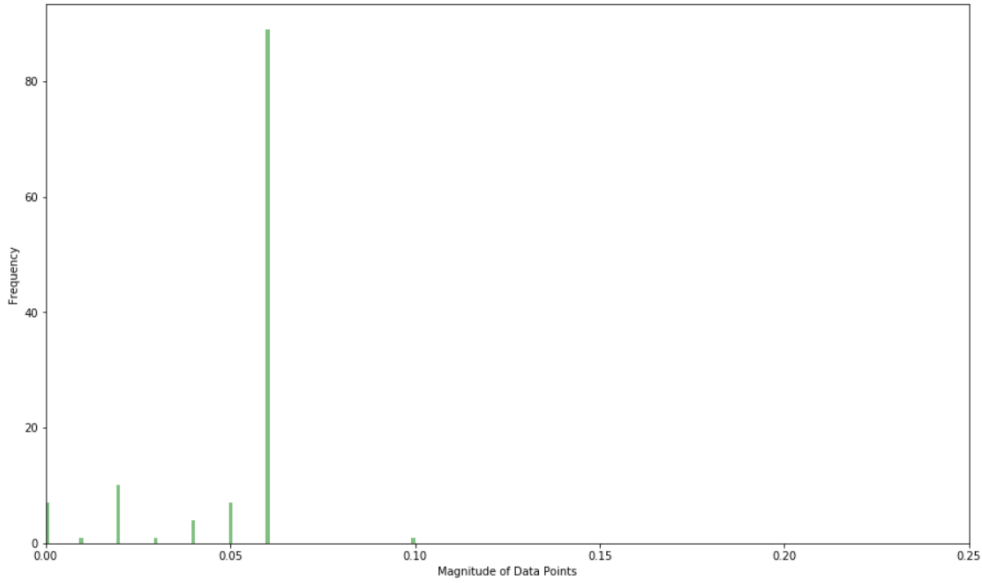


Figure 15. Occurrence Histogram Test 1, Sensor 2 (110V)

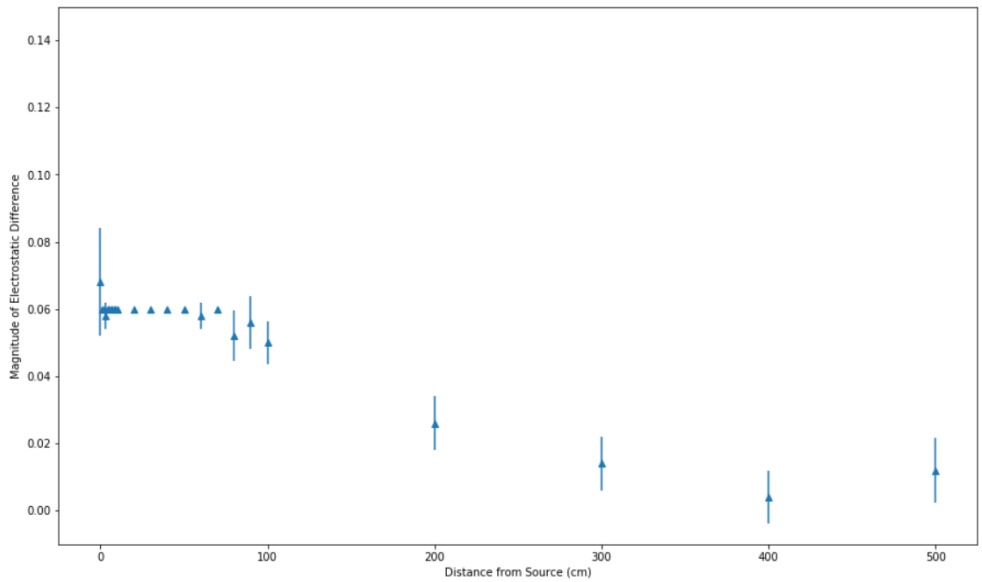


Figure 16. Mean and Standard Deviation Test 1, Sensor 2 (110V)

The data collected from Sensor 2 remains relatively stable from zero to one meter from the voltage source. The standard deviation of the data is relatively small which suggests that the measurements from each series is similar to one another. In this test, the measured voltage falls off and trends towards zero once the meter is more than two meters from the voltage source.

B. 460V SYSTEM RESULTS

The data was collected from the 460V system during three separate trials. Before each trial began, the electric fieldmeter was zeroed. The air compressor was also allowed to start up and reach air pressure equalization before any data was collected. Due to the location of the air compressor in the lab, the data collected beyond three meters from the source had to be measured from outside the roll up door to the lab. To minimize this external influence, the door was left open and there were no other physical barriers between the voltage source and the fieldmeter. Figure 17 summarizes the occurrences of the data collected with Sensor 1 on the 460V system. Figure 18 shows the mean and standard deviation of the data collected with Sensor 1 on the 460V system. The largest magnitude measured with Sensors 1 and 2 was a magnitude of 90V. The difference between the measured voltage and the actual voltage identifies that there is some type of electrostatic shielding occurring near the electrical source. This shielding could come from the metal structure composing the compressor exterior, or from the plastic covering protecting the electrical cable.

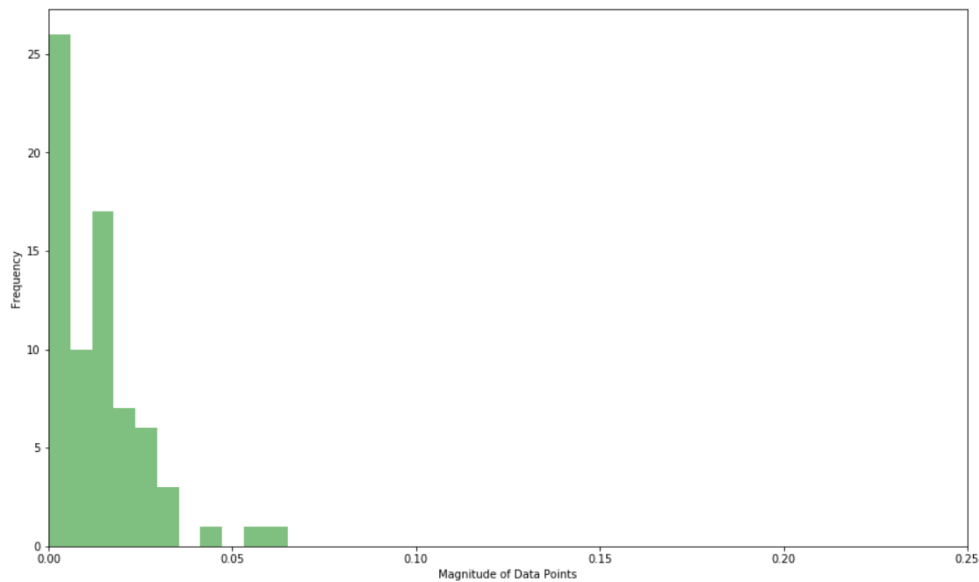


Figure 17. Occurrence Histogram Test 2, Sensor 1 (460V)

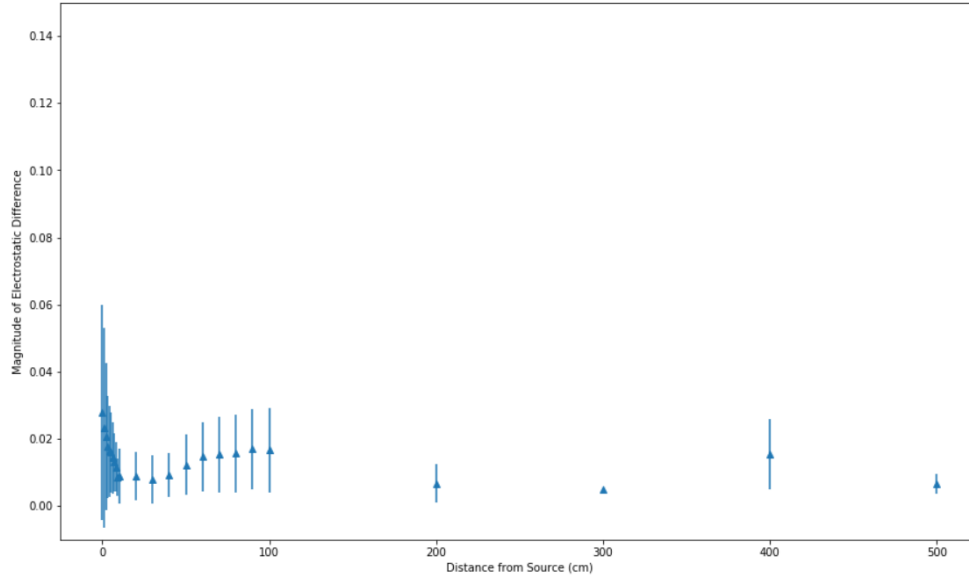


Figure 18. Mean and Standard Deviation Test 2, Sensor 1 (460V)

For the 460V system, Sensor 1 registers smaller magnitudes of voltage than the 110V results. These results remain consistent and trail off towards zero once the distance to voltage source becomes larger than one meter. On average, the standard deviation was larger from the distance of zero to one meter when compared to Test 1, Sensor 1. This shows a larger difference in magnitudes measured between each trial. Figure 19 summarizes the occurrences of the data collected with Sensor 2 on the 460V system. Figure 20 shows the mean and standard deviation of the data collected with Sensor 2 on the 460V system.

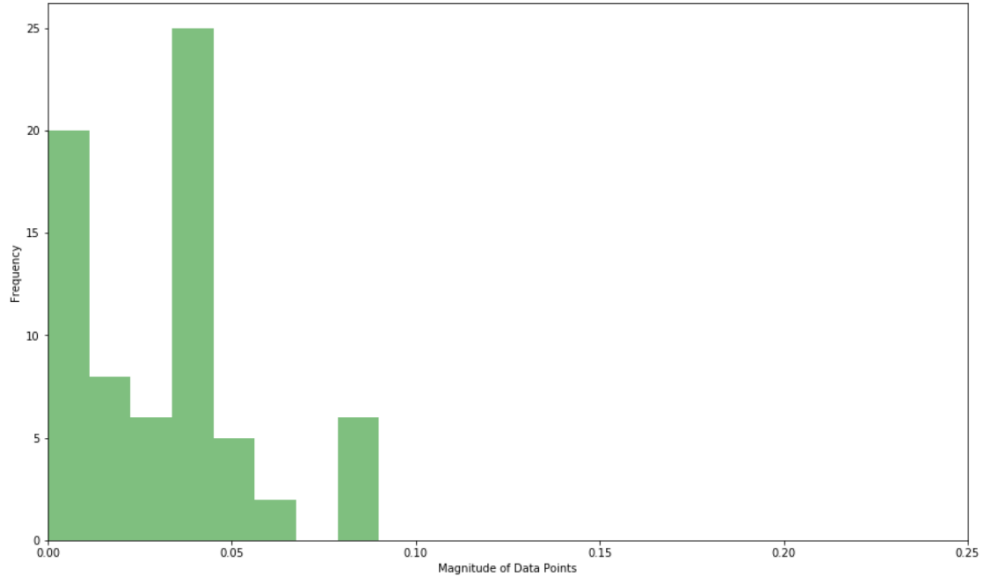


Figure 19. Occurrence Histogram Test 2, Sensor 2 (460V)

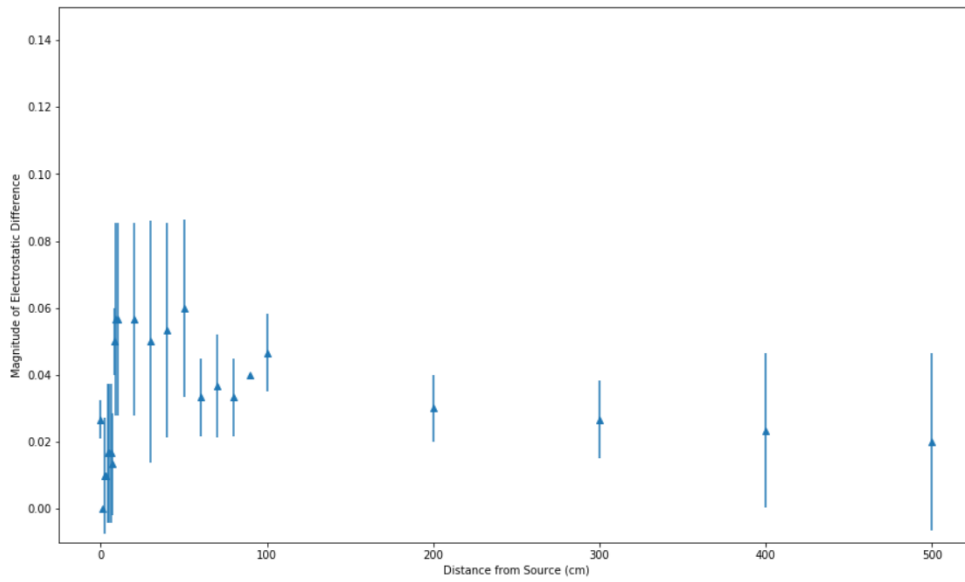


Figure 20. Mean and Standard Deviation Test 2, Sensor 2 (460V)

The largest magnitudes for Test 2, Sensor 2 were recorded between the distances of 8 and 50 centimeters from the power source. The standard deviation in that same range is over 60% of the mean value. Test 2, Sensor 2 results also include significant magnitudes measured out to five meters from the power source. The standard deviations at the distances of four and five meters indicates a large fluctuation of measurements between three trials at those distances.

C. 4160V SYSTEM RESULTS

The data was collected from the 4160V system during six separate trials. Before each trial began, the electric fieldmeter was zeroed. The wind tunnel was also allowed to start up and reach running speed prior to the collection of data. Figure 21 summarizes the occurrences of the data collected with Sensor 1 on the 4160V system. Figure 22 shows the mean and standard deviation of the data collected with Sensor 1 on the 4160V system.

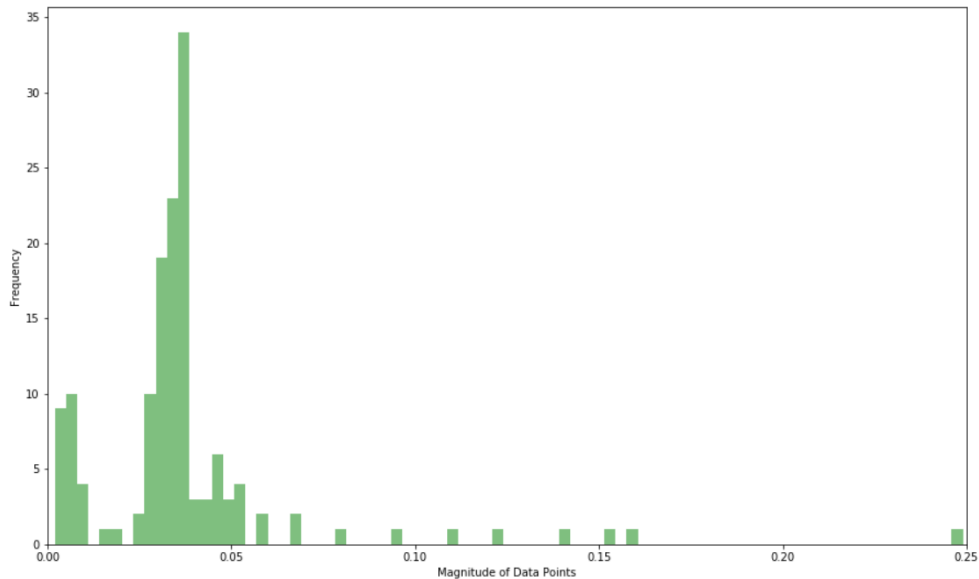


Figure 21. Occurrence Histogram Test 3, Sensor 1 (4160V)

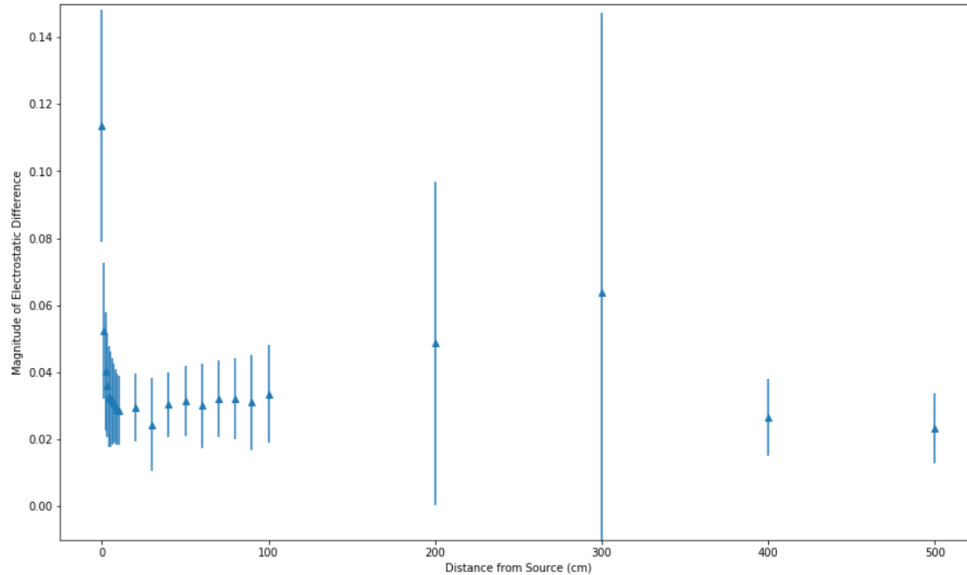


Figure 22. Mean and Standard Deviation Test 3, Sensor 1 (4160V)

The magnitudes of voltage differences between the powered and unpowered system drop significantly from zero to four centimeters from the power source. Beyond four centimeters the magnitudes appear to remain around 0.025, with the exception of two and three meters. The measurements taken at those two distances are significantly larger than nearby measurements. These two distances also have large standard deviations that signify large fluctuations in the measured data. Figure 23 summarizes the occurrences of the data collected with Sensor 2 on the 4160V system. Figure 24 shows the mean and standard deviation of the data collected with Sensor 2 on the 4160V system.

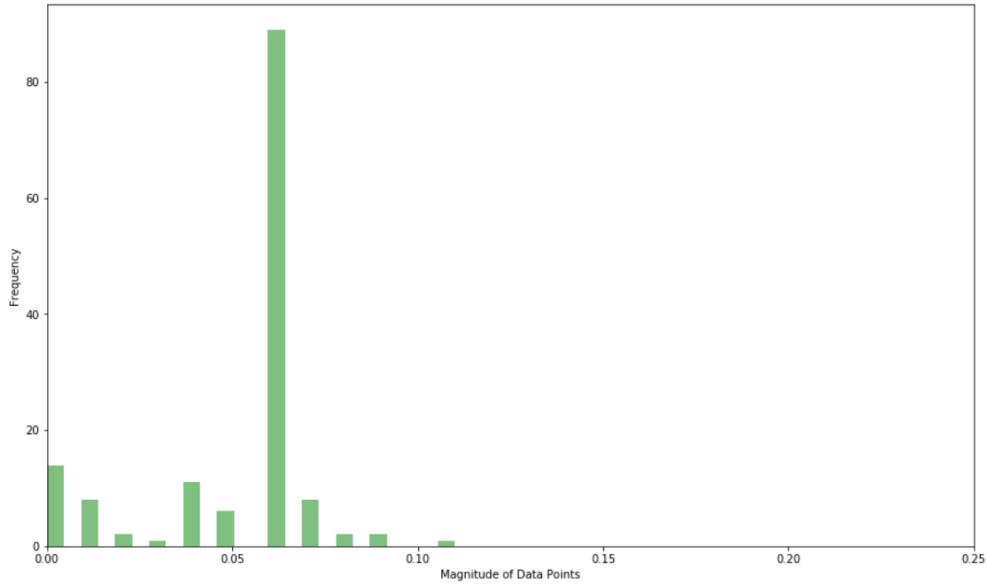


Figure 23. Occurrence Histogram Test 3, Sensor 2 (4160V)

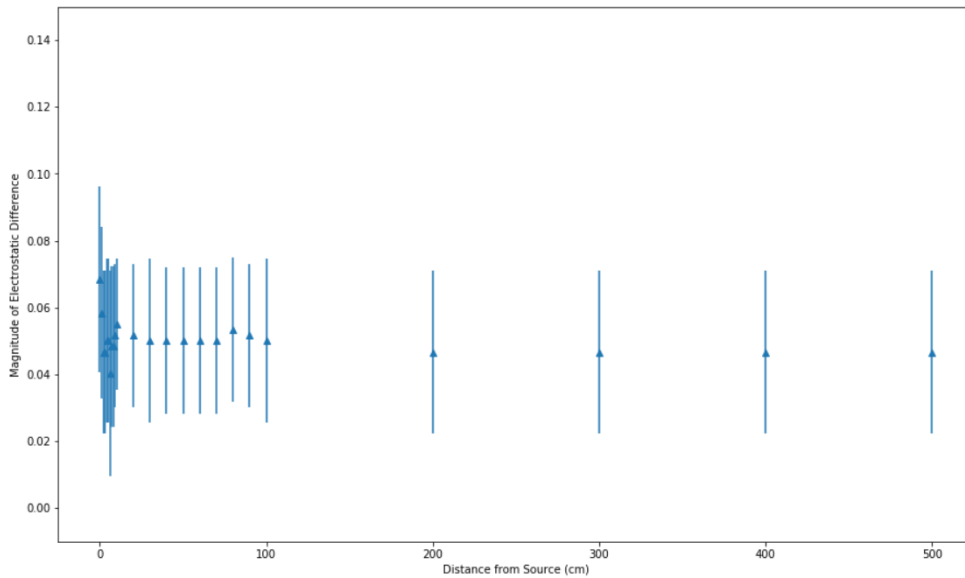


Figure 24. Mean and Standard Deviation Test 3, Sensor 2 (4160V)

The magnitudes of electrostatic difference measured in test 3 with Sensor 2 remain consistent across the full range of measured data. Similar to Sensor 1, there is a large fall in magnitude from zero to five centimeters distance from the power source. After four centimeters, the means of the magnitudes remain around the value of 0.05. The standard deviation is also similar in size for all of those measured distances.

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V. STATISTICAL ANALYSIS

A. INDEPENDENT SAMPLE T-TEST ON 110V (SENSOR 1)

When using the independent sample t-test, there are six main steps to complete in order to determine whether to accept or reject the null hypothesis. These steps are stated as the following:

1. State the null hypothesis (H_0) and the alternative Hypothesis (H_A) [10].
2. Determine a significance level to use [10].
3. Compute the value of the test statistic [10].
4. Determine the critical value [10].
5. If the value of the test statistic falls in the rejection region, reject H_0 ; otherwise, do not reject H_0 [10].
6. Interpret the results of the hypothesis test [10].

The question that needs to be answered for this research is the following: Is the mean of the magnitudes in the sample data equal to the mean of the magnitudes in the data collected? Is there a significant difference between the sample and the data collected?

1. State the null hypothesis (H_0) and the alternative hypothesis (H_A) [10].

Null Hypothesis

$$H_0 \quad \mu = \mu_0$$

In this situation it is assumed that the machine is on

Alternative Hypothesis

$$H_A \quad \mu < \mu_0$$

In this situation it is assumed that the machine is off

2. Determine a significance level to use [10].

The significance level used for this comparison is 0.05.

3. Compute the value of the test statistic [10].

During hypothesis testing, the known mean (μ_0) is calculated using data collected from electric equipment with a known voltage. For the purpose of detecting the operating status of another piece of equipment, it is necessary to collect additional data so that the sample mean and sample standard deviation can be used to compute the test statistic (t). For this study, the sample data set was represented by randomly selecting data from the previously measured data set. The sample collected from the data set was created by utilizing a random number generator that selected the index numbers of the data points collected. Test 1, Sensor 1 contains 120 data points and 10 random numbers were selected within the range of 1 to 120. Table 1 shows the data used in the sample from Test 1, Sensor 1.

Table 1. Sample Data for Test 1, Sensor 1 (110V)

Index	Value
2	0.003
19	0.003
36	0.001
63	0.001
67	0
70	0.001
75	0.02
87	0
95	0
118	0

Calculate the test statistic for the sample using the following formula:

$$t = \frac{\bar{x} - \mu_0}{\left(\frac{s}{\sqrt{n}}\right)}$$

During this step it is also necessary to calculate the sample standard deviation for the testing conditions. Standard deviation of a sample is defined as the following:

$$s = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^n (x_i - \bar{x})^2}$$

4. Determine the critical value [10].

The data points collected represent the magnitude of the change in electrostatic voltmeter measurements when the machine is powered or unpowered. The one-tailed t-test is appropriate to analyze these results. Utilizing the t-table with a significance level of 0.05 and 119 degrees of freedom, the critical value for the left-hand tail is -1.655580. Table 2 summarizes the information collected and calculated from the independent sample t-test for Test 1, Sensor 1.

Table 2. Independent Sample T-test Data Test 1, Sensor 1 (110V)

	Test 1, Sensor 1 (110V)
Population Mean (μ_0)	0.004575
Sample Mean (\bar{x})	0.002900
Number of Observations in Population (N)	120
Number of Observations in Sample (n)	10
Sample Standard Deviation (s)	0.006118
Test Statistic (t)	-0.865736
Critical Value (t_A)	-1.657759

5. If the value of the test statistic falls in the rejection region, reject H_0 ; otherwise, do not reject H_0 [10].

The computed test statistic is larger than the critical value for Test 1, Sensor 1. Since the value of the test statistic does not fall in the rejection region, this concludes that the null hypothesis is not rejected.

6. Interpret the results of the hypothesis test [10].

The sample data of this experiment statistically shows that the machine tested with Sensor 1 is switched on. There is a binary relationship with the machines power supply. Accepting the null hypothesis means that there is a high probability that the machine must have been switched on during the data collection period.

B. INDEPENDENT SAMPLE T-TEST ON 110V (SENSOR 2)

Hypothesis testing utilizing Sensor 2 is the same process for Sensor 1. The null and alternative hypotheses remain unchanged. The steps in the analysis are listed below.

1. State the null hypothesis (H_0) and the alternative Hypothesis (H_A) [10].

Null Hypothesis

$$H_0 \quad \mu = \mu_0$$

In this situation it is assumed that the machine is on

Alternative Hypothesis

$$H_A \quad \mu < \mu_0$$

In this situation it is assumed that the machine is off

2. Determine a significance level to use [10].

The significance level used for this comparison is 0.05.

3. Compute the value of the test statistic [10].

The sample collected from the data set was created by utilizing a random number generator that selected the index numbers of the data points collected. Test 1, Sensor 2 contained 120 data points and 10 random numbers were selected within the range of 1 to 120. Table 3 shows the data used in the sample from Test 1, Sensor 2.

Table 3. Sample Data for Test 1, Sensor 2 (110V)

Index	Value
1	0.1
11	0.06
28	0.06
43	0.06
66	0.06
81	0.06
87	0.06
91	0.06
94	0.01
119	0

Calculate the test statistic for the sample using the following formula:

$$t = \frac{\bar{x} - \mu_0}{\left(\frac{s}{\sqrt{n}}\right)}$$

During this step it is also necessary to calculate the sample standard deviation for the testing conditions. Standard deviation of a sample is defined as the following:

$$s = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^n (x_i - \bar{x})^2}$$

- Determine the critical value [10].

The data points collected represent the magnitude of the change in electrostatic voltmeter measurements when the machine is powered or unpowered. The one-tailed t-test is appropriate to analyze these results. Utilizing the t-table with a significance level of 0.05 and 119 degrees of freedom, the critical value for the left-hand tail is -1.655580. Table 4 summarizes the information collected and calculated from the independent sample t-test for Test 1, Sensor 2.

Table 4. Independent Sample T-test Data Test 1, Sensor 2 (110V)

	Test 1, Sensor 2 (110V)
Population Mean (μ_0)	0.051583
Sample Mean (\bar{x})	0.053000
Number of Observations in Population (N)	120
Number of Observations in Sample (n)	10
Sample Standard Deviation (s)	0.028304
Test Statistic (t)	0.158278
Critical Value (t_A)	-1.657759

- If the value of the test statistic falls in the rejection region, reject H_0 ; otherwise, do not reject H_0 [10].

The computed test statistic is larger than the critical value for Test 1, Sensor 2. Since the value of the test statistic does not fall in the rejection region, this concludes that the null hypothesis is not rejected.

- Interpret the results of the hypothesis test [10].

The sample data of this experiment statistically shows that the machine tested with Sensor 2 is switched on. There is a binary relationship with the machine's power supply. Accepting the null hypothesis means that there is a high probability that the machine must have been switched on during the data collection period.

C. INDEPENDENT SAMPLE T-TEST ON 460V (SENSOR 1)

Hypothesis testing on the 460V system is exactly the same process as listed for the 110V system. The data utilized for this test was collected from the 460V compressor in the NPS turbo propulsion laboratory. The null and alternative hypotheses remain unchanged. The steps in the analysis are listed below.

1. State the null hypothesis (H_0) and the alternative hypothesis (H_A) [10].

Null Hypothesis $H_0 \quad \mu = \mu_0$

In this situation it is assumed that the machine is on

Alternative Hypothesis $H_A \quad \mu < \mu_0$

In this situation it is assumed that the machine is off

2. Determine a significance level to use [10].

The significance level used for this comparison is 0.05.

3. Compute the value of the test statistic [10].

The sample collected from the data set was created by utilizing a random number generator that selected the index numbers of the data points collected. Test 2, Sensor 1 contained 72 data points and 10 random numbers were selected within the range of 1 to 72. Table 5 shows the data used in the sample from Test 2, Sensor 1.

Table 5. Sample Data for Test 2, Sensor 1 (460V)

Index	Value
15	0.002
16	0.003
24	0.005
34	0.014
36	0.017
37	0.016
43	0.017
51	0.045
68	0.03
71	0.026

Calculate the test statistic for the sample using the following formula:

$$t = \frac{\bar{x} - \mu_0}{\left(\frac{s}{\sqrt{n}}\right)}$$

During this step it is also necessary to calculate the sample standard deviation for the testing conditions. Standard deviation of a sample is defined as the following:

$$s = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^n (x_i - \bar{x})^2}$$

4. Determine the critical value [10].

The data points collected represent the magnitude of the change in electrostatic voltmeter measurements when the machine is powered or unpowered. The one-tailed t-test is appropriate to analyze these results. Utilizing the t-table with a significance level of 0.05 and 71 degrees of freedom, the critical value for the left-hand tail is -1.655580. Table 6 summarizes the information collected and calculated from the independent sample t-test for Test 2, Sensor 1.

Table 6. Independent Sample T-test Data Test 2, Sensor 1 (460V).

	Test 2, Sensor 1 (460V)
Population Mean (μ_0)	0.013764
Sample Mean (\bar{x})	0.017500
Number of Observations in Population (N)	72
Number of Observations in Sample (n)	10
Sample Standard Deviation (s)	0.013360
Test Statistic (t)	0.884302
Critical Value (t_A)	-1.666667

5. If the value of the test statistic falls in the rejection region, reject H_0 ; otherwise, do not reject H_0 [10].

The computed test statistic is larger than the critical value for Test 2, Sensor 1. Since the value of the test statistic does not fall in the rejection region, this concludes that the null hypothesis is not rejected.

6. Interpret the results of the hypothesis test [10].

The sample data of this experiment statistically shows that the machine tested with Sensor 1 is switched on. There is a binary relationship with the machine's power supply. Accepting the null hypothesis means that there is a high probability that the machine must have been switched on during the data collection period.

D. INDEPENDENT SAMPLE T-TEST ON 460V (SENSOR 2)

The testing procedure for Sensor 2 is the same as Sensor 1. The steps in the analysis are listed below.

1. State the null hypothesis (H_0) and the alternative hypothesis (H_A) [10].

Null Hypothesis

$$H_0 \quad \mu = \mu_0$$

In this situation it is assumed that the machine is on

Alternative Hypothesis

$$H_A \quad \mu < \mu_0$$

In this situation it is assumed that the machine is off

2. Determine a significance level to use [10].

The significance level used for this comparison is 0.05.

3. Compute the value of the test statistic [10].

The sample collected from the data set was created by utilizing a random number generator that selected the index numbers of the data points collected. Test 2, Sensor 2 contained 72 data points and 10 random numbers were selected within the range of 1 to 72. Table 7 shows the data used in the sample from Test 2, Sensor 2.

Table 7. Sample Data for Test 2, Sensor 2 (460V)

Index	Value
6	0.04
14	0.09
17	0.04
38	0.03
50	0
52	0.01
59	0.04
61	0.04
64	0.04
67	0.04

Calculate the test statistic for the sample using the following formula:

$$t = \frac{\bar{x} - \mu_0}{\left(\frac{s}{\sqrt{n}}\right)}$$

During this step it is also necessary to calculate the sample standard deviation for the testing conditions. Standard deviation of a sample is defined as the following:

$$s = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^n (x_i - \bar{x})^2}$$

4. Determine the critical value [10].

The data points collected represent the magnitude of the change in electrostatic voltmeter measurements when the machine is powered or unpowered. The one-tailed t-test is appropriate to analyze these results. Utilizing the t-table with a significance level of 0.05 and 71 degrees of freedom, the critical value for the left-hand tail is -1.655580. Table 8 summarizes the information collected and calculated from the independent sample t-test for Test 2, Sensor 2.

Table 8. Independent Sample T-test Data Test 2, Sensor 2 (460V)

	Test 2, Sensor 2 (460V)
Population Mean (μ_0)	0.032639
Sample Mean (\bar{x})	0.037000
Number of Observations in Population (N)	72
Number of Observations in Sample (n)	10
Sample Standard Deviation (s)	0.023594
Test Statistic (t)	0.584520
Critical Value (t_A)	-1.666667

5. If the value of the test statistic falls in the rejection region, reject H_0 ; otherwise, do not reject H_0 [10].

The computed test statistic is larger than the critical value for Test 2, Sensor 2. Since the value of the test statistic does not fall in the rejection region, this concludes that the null hypothesis is not rejected.

6. Interpret the results of the hypothesis test [10].

The sample data of this experiment statistically shows that the machine tested with Sensor 2 is switched on. There is a binary relationship with the machine's power supply. Accepting the null hypothesis means that there is a high probability that the machine must have been switched on during the data collection period.

E. INDEPENDENT SAMPLE T-TEST ON 4160V (SENSOR 1)

Hypothesis testing on the 4160V system is exactly the same process listed for the 110V system and the 460V system. The data utilized for this test was collected from the 4160V vertical wind tunnel at the NPS turbo propulsion laboratory. The null and alternative hypotheses remain unchanged. The steps in the analysis are listed below.

1. State the null hypothesis (H_0) and the alternative hypothesis (H_A) [10].

Null Hypothesis $H_0 \quad \mu = \mu_0$

In this situation it is assumed that the machine is on

Alternative Hypothesis $H_A \quad \mu < \mu_0$

In this situation it is assumed that the machine is off

2. Determine a significance level to use [10].

The significance level used for this comparison is 0.05.

3. Compute the value of the test statistic [10].

The sample collected from the data set was created by utilizing a random number generator that selected the index numbers of the data points collected. Test 3, Sensor 1 contained 144 data points and 10 random numbers were selected within the range of 1 to 144. Table 9 shows the data used in the sample from Test 3, Sensor 1.

Table 9. Sample Data for Test 3, Sensor 1 (4160V)

Index	Value
5	0.053
14	0.032
26	0.015
82	0.036
83	0.035
85	0.035
104	0.036
109	0.036
131	0.035
135	0.035

Calculate the test statistic for the sample using the following formula:

$$t = \frac{\bar{x} - \mu_0}{\left(\frac{s}{\sqrt{n}}\right)}$$

During this step it is also necessary to calculate the sample standard deviation for the testing conditions. Standard deviation of a sample is defined as the following:

$$s = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^n (x_i - \bar{x})^2}$$

4. Determine the critical value [10].

The data points collected represent the magnitude of the change in electrostatic voltmeter measurements when the machine is powered or unpowered. The one-tailed t-test is appropriate to analyze these results. Utilizing the t-table with a significance level of 0.05 and 143 degrees of freedom, the critical value for the left-hand tail is -1.655580. Table 10 summarizes the information collected and calculated from the independent sample t-test for Test 3, Sensor 1.

Table 10. Independent Sample T-test Data Test 3, Sensor 1 (4160V)

	Test 3, Sensor 1 (4160V)
Population Mean (μ_0)	0.037229
Sample Mean (\bar{x})	0.034800
Number of Observations in Population (N)	144
Number of Observations in Sample (n)	10
Sample Standard Deviation (s)	0.009041
Test Statistic (t)	-0.849685
Critical Value (t_A)	-1.655579

5. If the value of the test statistic falls in the rejection region, reject H_0 ; otherwise, do not reject H_0 [10].

The computed test statistic is larger than the critical value for Test 3, Sensor 1. Since the value of the test statistic does not fall in the rejection region, this concludes that the null hypothesis is not rejected.

6. Interpret the results of the hypothesis test [10].

The sample data of this experiment statistically shows that the machine tested with Sensor 1 is switched on. There is a binary relationship with the machine's power supply. Accepting the null hypothesis means that there is a high probability that the machine must have been switched on during the data collection period.

F. INDEPENDENT SAMPLE T-TEST ON 4160V (SENSOR 2)

The process for hypothesis testing with Sensor 2 is exactly the same as Sensor 1. The data utilized for this test was collected on the same testing apparatus and under similar conditions to Sensor 1. The question that needs to be answered is the following: Is the mean of the magnitudes in the sample data equal to the mean of the magnitudes in the data collected? Is there a significant difference between the sample and the data collected?

1. State the null hypothesis (H_0) and the alternative hypothesis (H_A) [10].

Null Hypothesis

$$H_0 \quad \mu = \mu_0$$

In this situation it is assumed that the machine is on

Alternative Hypothesis

$$H_A \quad \mu < \mu_0$$

In this situation it is assumed that the machine is off

2. Determine a significance level to use [10].

The significance level used for this comparison is 0.05.

3. Compute the value of the test statistic [10].

The sample collected from the data set was created by utilizing a random number generator that selected the index numbers of the data points collected. Test 3, Sensor 2 contained 144 data points and 10 random numbers were selected within the range of 1 to 144. Table 11 shows the data used in the sample from Test 3, Sensor 2.

Table 11. Sample Data for Test 3, Sensor 2 (4160V).

Index	Value
8	0.05
32	0.06
40	0.06
58	0.06
80	0.06
87	0.07
90	0.07
94	0.06
120	0.06
131	0.02

Calculate the test statistic for the sample using the following formula:

$$t = \frac{\bar{x} - \mu_0}{\left(\frac{s}{\sqrt{n}}\right)}$$

During this step it is also necessary to calculate the sample standard deviation for the testing conditions. Standard deviation of a sample is defined as the following:

$$s = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^n (x_i - \bar{x})^2}$$

4. Determine the critical value [10].

The data points collected represent the magnitude of the change in electrostatic voltmeter measurements when the machine is powered or unpowered. The one-tailed t-test is appropriate to analyze these results. Utilizing the t-table with a significance level of 0.05 and 143 degrees of freedom, the critical value for the left-hand tail is -1.655580. Table 12 summarizes the information collected and calculated from the independent sample t-test for Test 3, Sensor 2.

Table 12. Independent Sample T-test Data Test 3, Sensor 2 (4160V)

	Test 3, Sensor 2 (4160V)
Population Mean (μ_0)	0.059653
Sample Mean (\bar{x})	0.057000
Number of Observations in Population (N)	144
Number of Observations in Sample (n)	10
Sample Standard Deviation (s)	0.014181
Test Statistic (t)	-0.591538
Critical Value (t_A)	-1.655579

5. If the value of the test statistic falls in the rejection region, reject H_0 ; otherwise, do not reject H_0 [10].

The computed test statistic is larger than the critical value for Test 3, Sensor 2. Since the value of the test statistic does not fall in the rejection region, this concludes that the null hypothesis is not rejected.

6. Interpret the results of the hypothesis test [10].

The sample data of this experiment statistically shows that the machine tested with Sensor 2 is switched on. There is a binary relationship with the machine's power supply. Accepting the null hypothesis means that there is a high probability that the machine must have been switched on during the data collection period.

VI. CONCLUSION AND FUTURE WORK

A. CONCLUSION

Based on the data collected, the results of the independent sample t-test show that the proposed method is applicable to detect if a piece of equipment is energized. In all three examples, commercially available sensors were used to measure data outside of the manufacturers intended range, but within five meters from the power source. The test statistic calculated for the three different tests did not fall into the rejection region for Sensor 1 or Sensor 2. This shows that Sensor 1 and Sensor 2 will detect an energized system when analyzed using a significance value of 0.05. Table 13 shows the summary of results for the three tests utilizing Sensor 1 and Sensor 2.

Table 13. Summary of Statistic Analysis

	Critical Value (t_A)	Test Statistic (t)
Test 1 Sensor 1	-1.657759	-0.865736
Test 1 Sensor 2	-1.657759	0.158278
Test 2 Sensor 1	-1.666667	0.884302
Test 2 Sensor 2	-1.666667	0.584520
Test 3 Sensor 1	-1.655579	-0.849685
Test 3 Sensor 2	-1.655579	-0.591538

For all three tests conducted, the test statistic is larger than the critical value. This occurs with both Sensor 1 and Sensor 2. The critical value in all of the tests does not fall into the rejection region for the null hypothesis. These facts imply that there is not sufficient evidence to reject the claim in the null hypothesis. These testing results agree with the

laboratory environment in which the electric equipment measured in each of the three tests is powered on.

B. FUTURE WORK

This thesis shows that the electrostatic field is detectable for low and medium voltage systems. The application of this research is limitless. Commercially purchased electrostatic sensors could be used by hand, permanently mounted, or attached to a vehicle to gather real time data that could be used to predict electricity usage. In areas that prevent human access, sensors could be attached to unmanned vehicles. Unmanned aerial vehicles have the ability to fly close to power lines and gather data without risk to personnel. UAV could also be programmed to periodically collect data from multiple locations. This data could be analyzed to establish a baseline of electricity usage in the survey area. Any significant change to this baseline would identify a significant change to the power usage in the area.

APPENDIX A. PYTHON CODE

A. PLOT HISTOGRAM

```
import math #Load required libraries and shortcuts
import statistics
import matplotlib.pyplot as plt
import numpy as np
import matplotlib.pyplot as plt
import pandas as pd

df = pd.read_csv('test_1_sensor_1_occurrence.csv') #Read the data file

y = df['data points'] #Define y axis as the data points

kwargs = dict(alpha=0.5, bins='auto', density=False, stacked=True) #Set parameters

plt.figure(figsize=(15,9)) #Set plot size

plt.hist(y, **kwargs, color='g') #Plot command

plt.gca().set(xlabel='Magnitude of Data Points', ylabel='Frequency') #Label graph

plt.xlim(0,.25); #Set x axis length
```

B. PLOT MEAN AND STANDARD DEVIATION

```
import math #Load required libraries and shortcuts
import statistics
import matplotlib.pyplot as plt
import numpy as np
import matplotlib.pyplot as plt
import pandas as pd

df = pd.read_csv('test_1_sensor_1_modified_results.csv') #Read the data file
x = df['index'] #Define the variable x as the index number of the data point
y = df['mean'] #Define the variable y as the mean at each distance
e = df['std'] #Define the variable e as the standard deviation at each distance
g = df['var'] #Define the variable g as the variance at each distance

plt.figure(figsize=(15,9)) #Set plot size
plt.errorbar(x, y, e, linestyle='None', marker='^') #Plot standard deviation bar
plt.xlabel('Distance from Source (cm)') #Plot x Label
plt.ylabel('Magnitude of Electrostatic Difference') #Plot y Label
plt.axis([-25, 525, -.01, .15]) #Set x and y axis range
plt.show(); #Show the plot
```

APPENDIX B. COLLECTED DATA

A. TEST 1, SENSOR 1

Table 14. Collected Data for Test 1, Sensor 1 (110V)

TEST 1, SENSOR 1 - Magnitude of Electrostatic Difference						
Date 29 DEC 2019		Time 10:03		Location	Home Garage	
Kilowatts	110 V	110 V	110 V	110 V	110 V	
	Sensor 1	Sensor 1	Sensor 1	Sensor 1	Sensor 1	
Distance(cm)	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	
0	0.053	0.033	0.023	0.123	0.093	
1	0.003	0.001	0.003	0.038	0.008	
2	0.004	0	0.001	0.02	0.005	
3	0.012	0.001	0.001	0.009	0.003	
4	0.002	0	0	0.006	0.001	
5	0.001	0	0.001	0.004	0.001	
6	0.003	0.002	0.002	0.002	0.002	
7	0.001	0.001	0	0.001	0.006	
8	0	0.002	0.002	0.001	0.007	
9	0	0.001	0.002	0.001	0.001	
10	0	0.002	0.001	0.002	0.002	
20	0.005	0.001	0.004	0.002	0.002	
30	0.002	0	0	0	0.001	
40	0.002	0.001	0	0.001	0.001	
50	0	0	0.001	0	0	
60	0	0.001	0	0.001	0	
70	0.001	0	0	0	0.001	
80	0.003	0	0	0	0	
90	0.003	0	0	0	0	
100	0.002	0.001	0.003	0.001	0	
200	0	0.004	0	0.001	0.001	
300	0	0.001	0.001	0	0	
400	0.001	0.001	0	0	0.001	
500	0.001	0.001	0.001	0	0.001	

B. TEST 1, SENSOR 2

Table 15. Collected Data for Test 1, Sensor 2 (110V)

TEST 1, SENSOR 2 - Magnitude of Electrostatic Difference						
Date 29 DEC 2019		Time 10:35		Location	Home Garage	
Kilowatts	110 V	110 V	110 V	110 V	110 V	
	Sensor 2	Sensor 2	Sensor 2	Sensor 2	Sensor 2	
Distance(cm)	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	
0	0.1	0.06	0.06	0.06	0.06	0.06
1	0.06	0.06	0.06	0.06	0.06	0.06
2	0.06	0.06	0.06	0.06	0.06	0.06
3	0.05	0.06	0.06	0.06	0.06	0.06
4	0.06	0.06	0.06	0.06	0.06	0.06
5	0.06	0.06	0.06	0.06	0.06	0.06
6	0.06	0.06	0.06	0.06	0.06	0.06
7	0.06	0.06	0.06	0.06	0.06	0.06
8	0.06	0.06	0.06	0.06	0.06	0.06
9	0.06	0.06	0.06	0.06	0.06	0.06
10	0.06	0.06	0.06	0.06	0.06	0.06
20	0.06	0.06	0.06	0.06	0.06	0.06
30	0.06	0.06	0.06	0.06	0.06	0.06
40	0.06	0.06	0.06	0.06	0.06	0.06
50	0.06	0.06	0.06	0.06	0.06	0.06
60	0.06	0.06	0.06	0.06	0.05	0.06
70	0.06	0.06	0.06	0.06	0.06	0.06
80	0.06	0.05	0.06	0.05	0.04	0.04
90	0.06	0.06	0.06	0.06	0.04	0.04
100	0.06	0.05	0.05	0.05	0.04	0.04
200	0.04	0.02	0.03	0.02	0.02	0.02
300	0.02	0.02	0	0.01	0.02	0.02
400	0.02	0	0	0	0	0
500	0.02	0.02	0	0	0.02	0.02

C. TEST 2, SENSOR 1

Table 16. Collected Data for Test 2, Sensor 1 (460V)

TEST 2, SENSOR 1 - Magnitude of Electrostatic Difference						
Date 10 JAN 2020		Time 14:06		Location	NPS Lab	
Kilowatts	460V	460V	460V			
	Sensor 1	Sensor 1	Sensor 1			
Distance(cm)	Trial 1	Trial 2	Trial 3			
0	0.01	0.009	0.065			
1	0	0.013	0.057			
2	0.002	0.015	0.045			
3	0.004	0.015	0.034			
4	0.003	0.016	0.03			
5	0.004	0.016	0.028			
6	0.003	0.016	0.024			
7	0.003	0.017	0.019			
8	0.003	0.016	0.016			
9	0.003	0.014	0.009			
10	0.002	0.018	0.007			
20	0.003	0.017	0.007			
30	0.002	0.016	0.006			
40	0.003	0.016	0.009			
50	0.002	0.017	0.018			
60	0.003	0.018	0.023			
70	0.003	0.018	0.025			
80	0.003	0.018	0.026			
90	0.005	0.017	0.029			
100	0.005	0.015	0.03			
200	0	0.01	0.01			
300	0.005	0.005	0.005			
400	0.005	0.015	0.026			
500	0.005	0.005	0.01			

D. TEST 2, SENSOR 2

Table 17. Collected Data for Test 2, Sensor 2 (460V)

TEST 2, SENSOR 2 - Magnitude of Electrostatic Difference						
Date 10 JAN 2020		Time 15:20		Location	NPS Lab	
Kilowatts	460V	460V	460V			
	Sensor 2	Sensor 2	Sensor 2			
Distance(cm)	Trial 1	Trial 2	Trial 3			
0	0.01	0.009	0.065			
1	0	0.013	0.057			
2	0.002	0.015	0.045			
3	0.004	0.015	0.034			
4	0.003	0.016	0.03			
5	0.004	0.016	0.028			
6	0.003	0.016	0.024			
7	0.003	0.017	0.019			
8	0.003	0.016	0.016			
9	0.003	0.014	0.009			
10	0.002	0.018	0.007			
20	0.003	0.017	0.007			
30	0.002	0.016	0.006			
40	0.003	0.016	0.009			
50	0.002	0.017	0.018			
60	0.003	0.018	0.023			
70	0.003	0.018	0.025			
80	0.003	0.018	0.026			
90	0.005	0.017	0.029			
100	0.005	0.015	0.03			
200	0	0.01	0.01			
300	0.005	0.005	0.005			
400	0.005	0.015	0.026			
500	0.005	0.005	0.01			

E. TEST 3, SENSOR 1

Table 18. Collected Data for Test 3, Sensor 1 (4160V)

TEST 3, SENSOR 1 - Magnitude of Electrostatic Difference						
Date 14 FEB 2020		Time 13:35		Location	NPS Lab	
Kilowatts	4160V	4160V	4160V	4160V	4160V	4160V
	Sensor 1	Sensor 1	Sensor 1	Sensor 1	Sensor 1	Sensor 1
Distance(cm)	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6
0	0.16	0.051	0.096	0.111	0.142	0.121
1	0.08	0.015	0.044	0.057	0.067	0.052
2	0.069	0.01	0.032	0.041	0.045	0.045
3	0.057	0.007	0.031	0.037	0.046	0.038
4	0.053	0.003	0.03	0.036	0.038	0.037
5	0.05	0.003	0.031	0.036	0.036	0.036
6	0.047	0.005	0.029	0.035	0.036	0.036
7	0.042	0.006	0.029	0.036	0.036	0.036
8	0.039	0.006	0.029	0.035	0.035	0.035
9	0.032	0.006	0.029	0.036	0.036	0.035
10	0.031	0.006	0.029	0.035	0.036	0.035
20	0.029	0.008	0.031	0.036	0.037	0.036
30	0.002	0.008	0.031	0.035	0.036	0.034
40	0.032	0.009	0.032	0.036	0.037	0.036
50	0.041	0.009	0.03	0.036	0.037	0.036
60	0.045	0.004	0.029	0.035	0.034	0.033
70	0.047	0.009	0.032	0.036	0.032	0.036
80	0.048	0.008	0.029	0.036	0.036	0.036
90	0.05	0.003	0.028	0.034	0.037	0.034
100	0.051	0.004	0.042	0.037	0.034	0.033
200	0.154	0.006	0.03	0.035	0.034	0.033
300	0.249	0.006	0.029	0.033	0.033	0.033
400	0.036	0.002	0.024	0.032	0.033	0.032
500	0.02	0.002	0.024	0.031	0.032	0.031

F. TEST 3, SENSOR 2

Table 19. Collected Data for Test 3, Sensor 2 (4160V)

TEST 3, SENSOR 2 - Magnitude of Electrostatic Difference						
Date 14 FEB 2020		Time 14:40		Location	NPS Lab	
Kilowatts	4160V	4160V	4160V	4160V	4160V	4160V
	Sensor 2	Sensor 2	Sensor 2	Sensor 2	Sensor 2	Sensor 2
Distance(cm)	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6
0	0.16	0.051	0.096	0.111	0.142	0.121
1	0.08	0.015	0.044	0.057	0.067	0.052
2	0.069	0.01	0.032	0.041	0.045	0.045
3	0.057	0.007	0.031	0.037	0.046	0.038
4	0.053	0.003	0.03	0.036	0.038	0.037
5	0.05	0.003	0.031	0.036	0.036	0.036
6	0.047	0.005	0.029	0.035	0.036	0.036
7	0.042	0.006	0.029	0.036	0.036	0.036
8	0.039	0.006	0.029	0.035	0.035	0.035
9	0.032	0.006	0.029	0.036	0.036	0.035
10	0.031	0.006	0.029	0.035	0.036	0.035
20	0.029	0.008	0.031	0.036	0.037	0.036
30	0.002	0.008	0.031	0.035	0.036	0.034
40	0.032	0.009	0.032	0.036	0.037	0.036
50	0.041	0.009	0.03	0.036	0.037	0.036
60	0.045	0.004	0.029	0.035	0.034	0.033
70	0.047	0.009	0.032	0.036	0.032	0.036
80	0.048	0.008	0.029	0.036	0.036	0.036
90	0.05	0.003	0.028	0.034	0.037	0.034
100	0.051	0.004	0.042	0.037	0.034	0.033
200	0.154	0.006	0.03	0.035	0.034	0.033
300	0.249	0.006	0.029	0.033	0.033	0.033
400	0.036	0.002	0.024	0.032	0.033	0.032
500	0.02	0.002	0.024	0.031	0.032	0.031

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