AN INVESTIGATION OF STRUCTURED LIGHT SCANNER CALIBRATION DEGRADATION

by

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A thesis submitted to the faculty of
The University of North Carolina at Charlotte
in partial fulfillment of the requirements
for the degree of Master of Science in
Mechanical Engineering

Charlotte

2020

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ABSTRACT

ROBERT DAVID TURNBULL. An Investigation of Structured Light Scanner Calibration Degradation (Under the direction of DR. ED MORSE)

Structured light scanning is a measurement technique using two images taken at a well-known angle to each other. Using the angle, the distance between where the images were taken, and the principles of triangulation a 3-dimensional surface can be generated. The accuracy can be improved by using additional techniques to improve the measurement. One of the more common techniques seen on commercial structured light scanning systems is the use of fringe projection.

One major inconvenience/workflow interruption with these types of systems is that they require frequent calibration, as the angles and distances described above may change over time. Traditional touch probe coordinate measuring machines in industry typically require calibration every 6 to 12 months. For maximum accuracy most structured light scanners are calibrated at least once a day or before each new measurement. While the calibration is rather quick and simple to perform it still can be an interruption to the workflow in an industrial environment.

The goal of this project is to explore the underlying reasons why the calibration deteriorates so rapidly and develop recommendations for users to mitigate the consequences of this deterioration. The current hypothesis is that the main cause is related to either the environment or to a temporal factor of the system.

If the temperature of the environment is a leading factor for the rapid deterioration it will be rather simple to test. This will be done by measuring a calibrated object over the

course of a couple weeks while at the same time recording the temperature, pressure, and relative humidity of the environment. The data will then be analyzed to determine if there is any correlation between the environmental or temporal factors.

It was found that there was no recognizable correlation to temporal factors. There were correlations to the environmental factors, the strongest being to relative humidity. It is likely the correlation to temperature would have been more noticeable if the temperature range for the environment had been larger, but the experiments were conducted in a lab that was temperature controlled within 2 degrees Celsius.

It is recommended based on the results of this research, to calibrate the system every one to two days. If this is not possible then it would be recommended to track the environment the system is in and recalibrate when the environment changes significantly.

DEDICATION

I would like to dedicate this work to my friends and family for their continued support. I also dedicate it to my Lord and Savior Jesus Christ in whom my faith rests.

ACKNOWLEDGEMENTS

I give my thanks to my advisor, Dr. Morse, and Dr. Miller for their guidance in my thesis and use of equipment. I also thank Dr. Falaggis for his participation in being a part of my committee.

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CHAPTER 1 INTRODUCTION

Metrology is traditionally used nearer the end of the manufacturing process in more of a quality control aspect. There has been a continued push by industry to have metrology to be an in-situ process, practically most systems are at the in-process phase. This allows in the manufacturing process for a reduction in scrapped material and an increase in parts that can be reworked before they must be scrapped. Another major goal has been to increase the accuracy and use of non-contact metrology systems. These systems are typically faster and allow measurement of surfaces whose form deflects under low forces.

One of the technologies that has been rapidly gaining traction and use in industry is structured light scanning. This has some major advantages over other non-contact measurement systems, such as imaging a complete surface at once, the ability to adjust the measurement volume on most systems, and even being able to place the system on a robotic arm to automate it. It also has some major drawbacks that are well known such as inability to measure reflective surfaces. In most cases this includes machined surfaces which makes the system difficult to use in certain industries. One work around has been to use a spray coating that reduces the reflective properties of the surface that can be cleaned off after scanning.

Another weakness of these types of systems is that the systems needs recalibration on a frequent schedule. Most commercial metrology systems, even non-contact systems, only need to be recalibrated once a year at the most. If the conditions are right and the adjustable settings are loose enough the structured light scanners can last a couple months without needing to be recalibrated, but this is not a good practice. Distribution companies typically recommend recalibrating at least every two weeks and some applications companies will calibrate before each measurement. This could cause interruptions in a continuous output industry. This thesis seeks to explore some of the possible causes for the frequent need to calibrate the structured light scanning system.

The main factors explored are time, temperature, pressure, and relative humidity. This is done using a using a linear positioning stage, a calibrated object, the structured light scanner, and an environmental sensor. The calibrated object was measured and the errors in length were analyzed.

Chapter 2 is a literature review which mostly focuses on calibration techniques and how they may influence the speed of decalibration. Chapter 3 is a discussion of the motivation for this research. Chapter 4 is an overview of the experimental procedure. Chapter 5 looks at the data processing done for the experiment. The results are displayed in Chapter 6. Chapter 7 discusses the conclusions made from the results of the experiments. Chapter 8 has some recommendations for those using this type of system.

CHAPTER 2 LITERATURE REVIEW

Structured light scanning is a non-contact measurement technique that is based on the working principle of triangulation [1]. The systems consist of a projector and two cameras. Having two cameras is not a requirement, early forms of the structured light scanning technology only had one camera. Having two cameras does allow the system to be mathematically overdetermined with regards to triangulation [2][3]. One advantage to having multiple cameras is the ability for the system to do photogrammetry as well. The system projects a stripe pattern onto the part surface while the camera(s) take images of the part and the processor analyzes the variances between what the lines appear to be from a different perspective to generate a point cloud [1][4].

It is important to know some basics of taking an image to understand what some of the factors are to take a good measurement. Three of the most important factors to consider are the field of view, focusing, and the exposure [5]. The field of view is just how much of the environment the camera can see. For the structured light system used in this experiment the field of view is fixed by both the sensor size and the optics/lenses that are not interchangeable. One very important factor to capturing a clear image and in turn a good measurement is focusing. For all camera systems there is a depth of focus that is clear while objects outside of that range are not in focus. This depth is a function of a variety of factors including the size of the sensor, the focal length of the lens, the size of the aperture, and some other factors [5]. This is the reason the GOM software has a specific plane indicated in its digital measurement volume, that plane is the mathematically calculated perfect focus plane. The other major factor to consider is the exposure of the image, the exposure is controlled by the aperture size and the shutter speed [5]. In this experiment the structured light system being used is assumed to have a fixed aperture size, so the only metric to adjust is the shutter speed. The GOM ATOS software is helpful in that it highlights areas that are overexposed in red. There also is the option to have the system automatically calculate what it thinks to be the ideal exposure settings.

There are a few differences in structured light systems, one major difference being white and blue light scanning. Blue light scanning is an advancement in the technology of structured light scanning. It has a narrower wavelength band so that it can help to filter out influences from the environmental lighting conditions [4]. A key point to this technology is the fringe projection and what it does. It is basically used to encode the surface with a variety of greyscale values by shifting the stripe pattern a quarter of their phase four times. This is performed with a couple of different stripe widths to be able to absolutely encode the surface [6][7]. In the article by Brenner, Böhm, and Gühring [7] a much more in depth explanation of the reasoning behind performing a phase shift and the mathematics behind it.

These systems must be calibrated periodically to be accurate but there are a few different techniques that manufactures can choose between to accomplish this. There are three which are the most typical a photogrammetric calibration, a triangulation calibration, and a polynomial calibration [7][8]. Triangulation methods work by fully defining the triangle formed between the camera and projectors optical centers and a scene point. The model is one of the simplest but has a major restriction with needing the baseline between the optical centers to be parallel to the reference plane and with restrictions on the pattern direction make this model difficult to use [8]. The photogrammetric calibration can be broken down into three types of sub-techniques, inverse camera, pseudo-camera, and light stripes plane [8]. Both the inverse camera and pseudo-camera techniques work to calibrate the projector. The inverse camera works by knowing the image that is intended to be projected and the resultant image from the calibrated cameras to determine the projector and calibrate it [7][8]. The major weakness in these is either coupling errors or propagating and adding to the correspondence errors. The light stripes plane seeks to circumvent these problems by calculating each stripes plane individually at a series of control depths. The main problem with this is that it is very time intensive with having to do calculations for each individual stripe at each plane. Coincidentally it also doesn’t get around error propagation from the camera because the technique is based on the calibration of the camera [8]. The last technique mentioned is the polynomial calibration. This is done by using an absolute phase greyscale pattern scanned at a precise depth. This is done multiple times and a depth value is found for each pixel using the absolute phase and an approximation function. Then a 5^{th} or 6^{th} order polynomial is fit to the data through the different depths [8]. This can be simplified by approximating the function by a series of linear piecewise functions and interpolating between measured planes [7]. This technique is difficult to implement because a precise linear positioning stage is needed for calibration, there are also problems with approximation errors when each pixel is treated individually for phase decoding [7]. Based on the calibration procedure for the system found in chapter 4.3 the calibration technique is either a completely new proprietary technique or a combination of the techniques discussed above.

The focus of this research is not on how to calibrate a structured light system, but it is important to understand to make decisions on what are the major error contributors. This paper focuses on mostly environmental factors but there are some observations of errors through the measurement volume that seem to be depth related that would be related to the calibration technique. One of the environmental factors that can cause measurement errors with typical parts is the environmental lighting. The environmental lighting can affect inter-reflections, diffusion, and subsurface scattering which can have significantly influence the performance of the scanner [9]. This was circumvented by choice of calibrated object and to make sure the lighting conditions for every experiment was identical. So, if there were errors related to the environmental lighting it would have affected every experiment and essentially been a systematic offset bias. In a paper by Jecić and Dvrar [3] there is an extensive list of a variety of factors that can affect a measurement separated into categories. It specifically mentions environmental factors and how they fall under the umbrella of external factors which do not stem from the method of measurement. Some of the key ones to note are temperature, vibrations, humidity, and lighting conditions. These are important to keep track of because they can change rapidly depending on the room the system is in and can significantly influence the measurement. The paper also mentions some internal factors that are expressly linked to the technology. While they are in most cases not adjustable, they are important to be aware of because it is possible some of the external factors may influence them. Some of the key ones to note are the structural elements of the system, the system calibration, and the software. Each of these can influence how quickly the system could become decalibrated.

CHAPTER 3 EXPERIMENT MOTIVATION

The primary motivation for this experiment was the knowledge that the technology has been rapidly brought into industrial applications while at the same time having some major weaknesses. One of these weaknesses that is widely known is the inability of the scanners to image surfaces with high specular reflection. Another weakness that does not seem to be widely known is that there is an apparent distortion through the depth of the measurement volume.

A previous experiment briefly explored this distortion was conducted for a different research experiment. The basics of the experiment was that a precision matte tooling ball was scanned at a variety of depths through the measurement volume. This experiment was repeated once at the beginning of the first day and again at the end of the day. It was also repeated at a partial way through the week, at the end of the week, and one week later. The results can be seen in FIGURE 3-1.

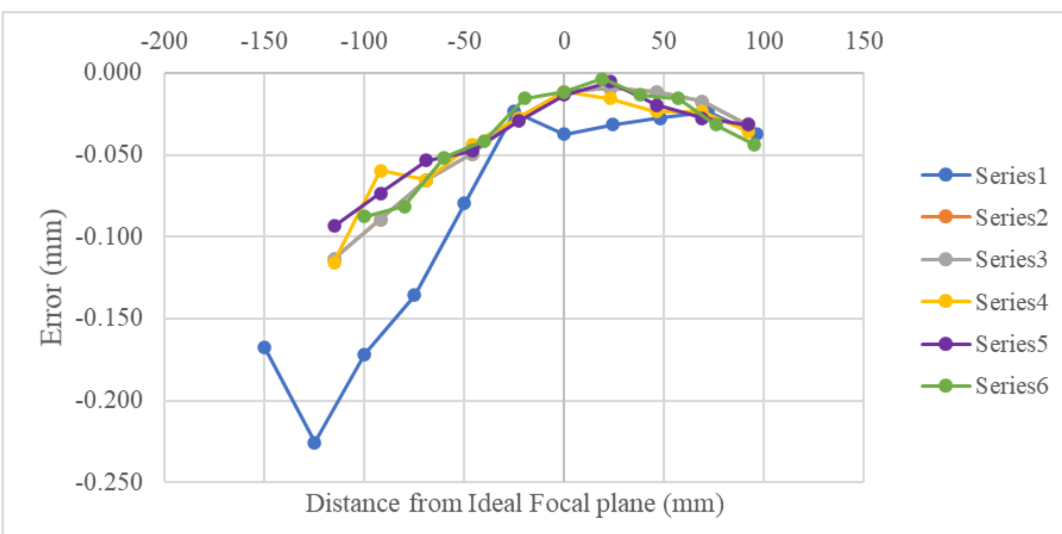

FIGURE 3-1: Calibrated Sphere Results

Series1 was scanned approximately four weeks after a calibration. Series2 and Series3 were both on the same day of the calibration Series2 directly after and Series3 at the end of the day. Series4 was at the end of the second day, Series5 after 4 days and Series6 after a week.

It was seen that the size of the gaussian sphere fit was related to the depth within the measurement volume consistently throughout the whole of the experiment. This information was what was of interest but there was another observation with some use. It was noticed that over the course of a few weeks the errors in the system were increasing as time from the most recent calibration also increased. After some preliminary research there did not seem to be much information as to the relation between the environment and how the systems drift out of calibration, hence the project was proposed and adopted.

CHAPTER 4 EXPERIMENT PROCEDURE

4.1 Equipment and Software Used

There was a variety of equipment, both hardware and software, needed to perform the sets of experiments. The system on which the experiment was conducted was the GOM ATOS CORE 300, a structured light scanner. This is paired together with ATOS Professional, the interfacing software in which some of the parameters of the system can be adjusted. It would be most accurate to say that the experiment is being performed on the combination of the scanner and software. A calibration dot plate that was supplied with the system was used for recalibration before experiments.

A Bal-tec Ball Plate was chosen to be used as the artifact to be scanned repeatedly. This was chosen because the ball locations were calibrated on the Leitz high accuracy PMM that is on campus. It was also used because knowing the ball locations allows for a large variety of different lengths that can be analyzed through the measurement volume.

A Trimos Linear Positioning Stage was used for accurately repositioning the scanner for the 3 positions scanned in. It is important to note that the stage was not used for its accurate measurement of displacement even though the system had a read out to 1 µm accuracy, its sole purpose was to be sure the scanner was repeatably in the same position as it was for previous scans and experiments.

There were two systems that were used for tracking the environment, the Omega iServer Microserver Weather Station and the Raspberry Pi with the Sense HAT. These systems were used to record temperature, pressure, and humidity (THP) information. The reason for having two systems is not for redundancy, instead it is because the iServer system during experiment three had to be taken in and out of the lab because it was being used by Dr. Miller for instruction purposes so it could not be used continuously. The iServer was used for accurate THP recording while performing the scans for experiment three and continuously for the other experiments. The Raspberry Pi and Sense HAT were used to continuously monitor THP for experiment three. The reason they were not used exclusively is that the Sense HAT is known to be inaccurate when acquiring data, it was used more for getting a general picture of the trends of the environment.

There was also software used for processing data, Excel was used for processing the THP data and plotting it. The reason MATLAB was not used for this is because the iServer already directly recorded the data into Excel. MATLAB was used for processing the data of the sphere positions and the lengths between the spheres over the course of the experiment.

4.2 Setup

The physical experimental setup was generally the same for each experiment. The GOM ATOS CORE 300 was hard mounted to the positioning stage on the Trimos position stage, using a custom made mount that had through holes to allow the mount to be clamped to the stage and the scanner to be screwed to the mount. When the scanner needed to be calibrated it was taken off the stage and placed onto a FOBA stand to allow more flexibility, once the calibration was completed the scanner was mounted back to the Trimos stage. The positioning stage was always left on so that it’s position could not reset and the three positions in the measurement volume could reliably be measured at again.

The ball plate also had to be mounted to tail stage of the Trimos positioning stage. This was done with just a couple of toe clamps to keep the ball plate in place. Due to the ball plate hanging off the side of the tail stage a small stand was put together so that the ball plate would not fall if the toe clamps were taken off. Over the course of the 4 experiments the ball plate was not taken off the tail stage. A profile setup can be seen below in FIGURE 4-1.

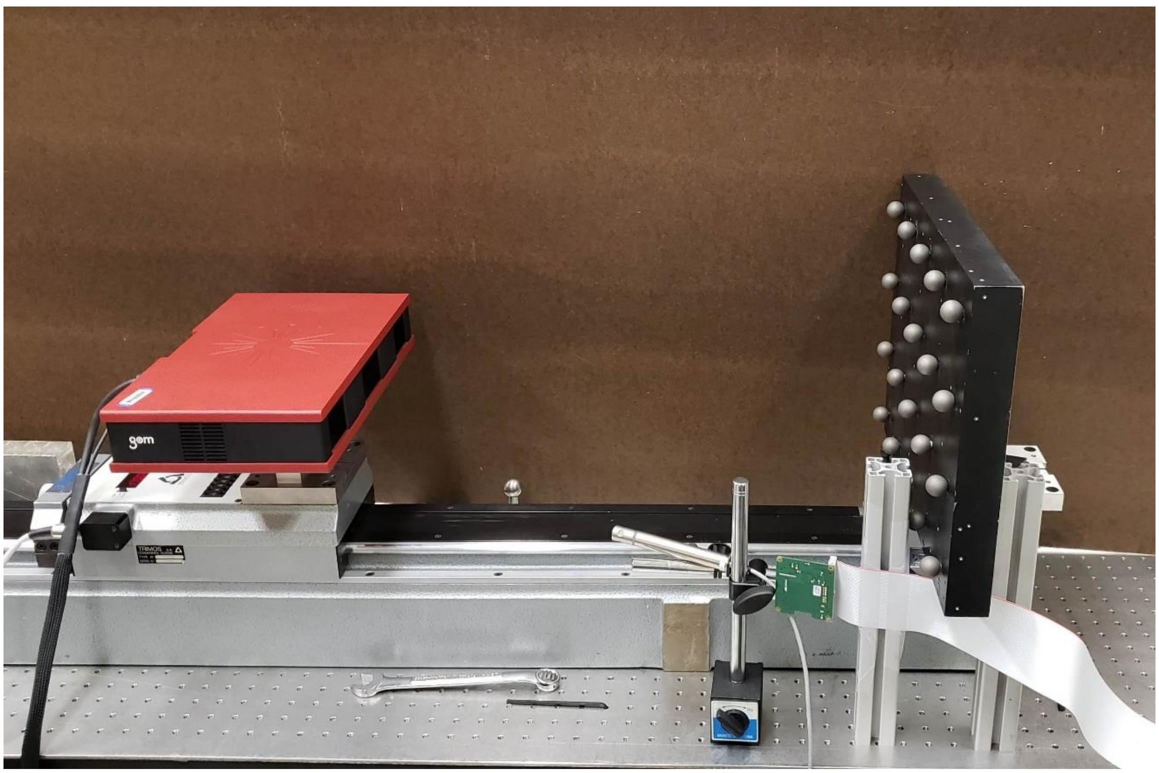

FIGURE 4-1: Experimental Setup

Another crucial part of the experimental setup is the THP recording. So, the sensors for THP recording were positioned close to the halfway point between the scanner and the ball plate in an attempt to record an average value of the environment over the course of the experiment.

4.3 Calibration Procedure

The calibration procedure is rather straightforward. The system is oriented perpendicular to the calibration dot plate and scanned at 12 different heights and at 6 more angled positions. The calibration dot plate can be seen below in FIGURE 4-2.

FIGURE 4-2: Calibration Dot Plate

The dot plate has 5 larger targets in the center used for making sure the scanner is focused on the center of the plate. Three images of the calibration orientations can be seen in APPENDIX A.

The calibration starts perpendicular to the dot plate at the ideal focal plane. Then it goes to the farthest position in the measurement volume and takes equal steps towards the front of the measurement volume. Then it takes two angled scans where still being in plane one of the cameras is closer to the dot plate than the other and then it alternates to the opposite camera. The last scans are with the scanner angled toward the dot plate at 20° and 45° angles.

4.4 General Experimental Procedure

The four experiments all had a very similar general procedure with a few smaller parameters changed across them. The experimental setup was identical for all the experiments as seen in FIGURE 4-1. The procedure was to move the scanner to the position near the front of the measurement volume for the close measurement and perform seven individual scans. The Trimos stage was zeroed at the close position during the first experiment, this would allow an easy way to repeatably find the same position. After the seven scans at the close position the system was moved back toward the middle position which was at the ideal focal plane of the system, the value was recorded at +70 mm from the close position. Again, seven individual scans were performed and saved at the middle position. Then the scanner was moved back again so that the ball plate was at the back of the measurement volume. The distance was recorded as +170 mm from the close position and the seven individual scans were performed. The scanner was then left at the far position until the next day when it was moved back to the close position to start the next day's set of scans.

4.5 Procedure Variations

Even though the general procedure is the same for the four experiments that were conducted there were still some subtle and important differences between each one. The first experiment operated also with the conditions of keeping the lights in the room and the scanner powered on continuously. The motivation was that in some commercial settings that have high volume output for their products the systems are powered continuously. The scanner was calibrated the first day before scanning that day and not calibrated again for the duration of the experiment. The experiment was run for twelve straight days and a final scan on the fifteenth day.

The second experiment was very similar to the first, calibrated only on the first day and following the same general procedures for scanning. The room lights were continuously powered on for the duration of the experiment, but the scanner was not. Each day the scanner was powered on and given time to warm up to proper operating temperature and intensity. The scanner warms up at the far position and then is moved to the close position to go through the scanning procedure. At the end of scanning at the far position the system was powered off until the next day.

The third experiment was unique in that the data from the first two experiments was able to be processed before conducting the experiment. From the information acquired by processing the data of the first two experiments it was determined that five scans at each position would be sufficient for data acquisition. This was determined from the low range and standard deviation of the lengths measured at each position. The intent was to run this experiment until the system was decalibrated but as more information arose it seemed best to stop the experiment. This experiment at the end of each day both lights and the scanner were powered off until the next day. Another difference during this experiment was in inability to use the iServer to monitor and record the environment continuously, this is why the Raspberry Pi was used to show general trends of the environment. During the third experiment scans were only performed during the work week, and near the end of the experiment only partial weeks due to scheduling issues.

The fourth experiment was different from the others in that the system was recalibrated each day using the dot plate. Again only 5 scans at each position were performed based on the data acquired from experiments one and two. Also, a set of scans was performed both before and after each day's calibration. This particular experiment was conducted for only one work week.

4.6 Issues to note

There are some issues to note with each experiment that may cause discrepancies with the interpretation with the results, especially with the correlation plots between the length errors and environmental factors. During experiment one the main issue to note is the movement of the temperature sensor from behind the ball plate to between the scanner and ball plate. This specifically has the potential to cause errors in the correlation plots. During experiment two the issue to note was that the system was needed for scanning a hole plate which added another power cycle to the experiment during day nine. It was originally thought that the calibration was possibly linked to either the number of scans performed, or the time of the scanner being powered on. It was later found by talking to an application engineer at GOM Americas that this is not the case, but this is discussed more in CHAPTER 7. In experiment three the main issue to cause discrepancies in the interpretation of the results was that the main environmental sensor was not run continuously due to outside circumstances. In experiment four the greatest issue to note is the short duration of the experiment. It would have been more beneficial to have the experiment extended for a longer duration but due to how much data was being acquired each day and the time constraints it was note possible.

4.7 Temperature, Pressure, and Humidity Influence

It was originally thought that the calibration was linked most closely to the temperature of the environment. The original plan for the experiment was to record temperature alone during the course of the experiment but since the opportunity to use a sensor that recorded pressure and relative humidity as well it was used. After research of the operating principle of the system it was found to be majorly based on triangulation. This information means that the equation used in interferometry to correct for the difference in index of refraction of the air for time of flight is invalid in this case. This means that there are two other possible relations between the environment and the calibration of the system. Both possible relations are very similar, one is where there is a gradient across the measurement volume. This would cause both camera to “see” different sizes of the ball plate. While this is a possibility, based on the size of the system and with the lenses only being approximately 11 inches apart it is very unlikely such a gradient exists that would cause that much distortion, this also experimentally never occurred. The other possibility is that there is a difference in the environment between the date of calibration and the date of the scanning. With the calibration being linked to the environment this seems to be more likely to be a stronger influencing factor.

CHAPTER 5 DATA PROCESSING

5.1 GOM Processing

It was required for data to be processed to an extent in the GOM ATOS software. This is due to the fact of GOM not allowing the exportation of the raw data. In some ways it is logical for industry because the raw data would likely be nearly 48 megabytes per set of images taken. In most industry situations five to ten images would be taken per measurement, which would result in very large files. Due to raw data not being able to be exported the scan has to be processed inside the GOM software in a process called polygonization. When polygonizing a file there are five options for post-processing the data. The levels are merely descriptive with no quantitative value associated with it. They are as follows, No Postprocessing, More details, Standard, Less details, and Smallest data volume. It was decided that the best course of action would be to use as much data as possible and use the No Postprocessing option for polygonizing the data. Once the data had been polygonized spheres were fit to the scan data in the order which can be seen below in FIGURE 5-1.

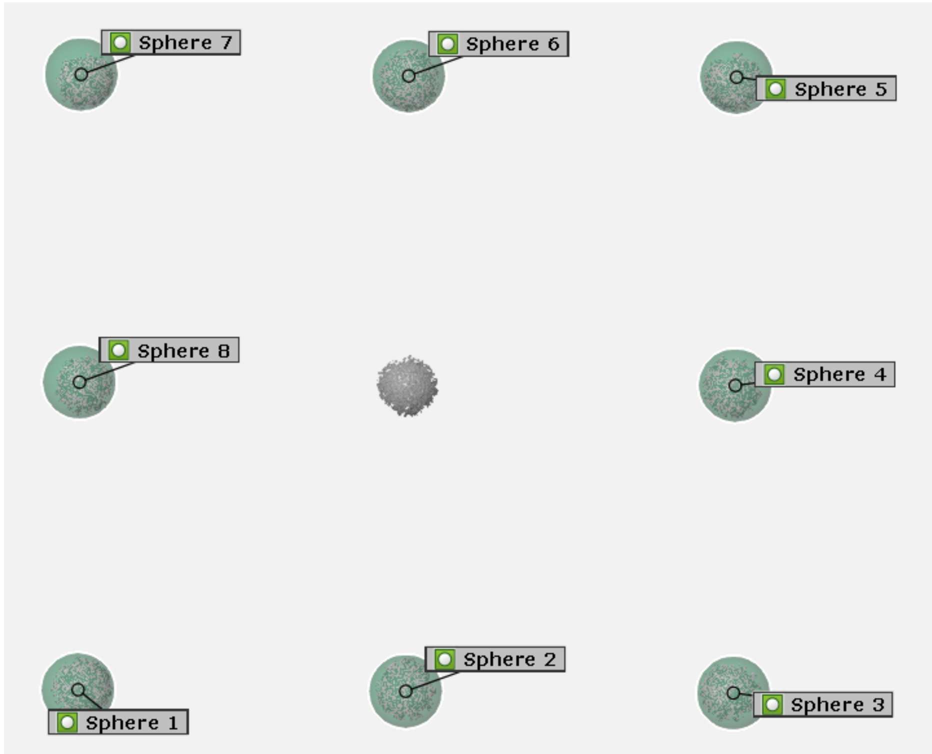

FIGURE 5-1: Sphere Fit Order

Each sphere is fit to the select data around the sphere using a Gaussian sphere fit and 3 sigma of the data to fit the sphere. Care was taken to ensure the same fitting order was taken for all the data. This is imperative so that the MATLAB code can be written to process all the data without having to rewrite a new script every time. Once this process had been completed the geometry data (ie, sphere data) was exported as a CSV file to be read and processed in MATLAB. This file included information about the sphere's origin in space and the spheres radius as well.

5.2 MATLAB Processing

The CSV file with all the geometry information is imported into MATLAB. A text document containing the calibrated lengths between the spheres on the ball plate is also imported. This is so that by the end of the data processing the error between the scanned lengths and the calibrated lengths can be observed and compared.

In the process the first thing done is performing the square root sum of squares between the positions of the calibrated sphere positions to find the desired lengths to be examined and store those values. The lengths in question are in a union jack pattern and they can be seen in FIGURE 5-2 and FIGURE 5-3.

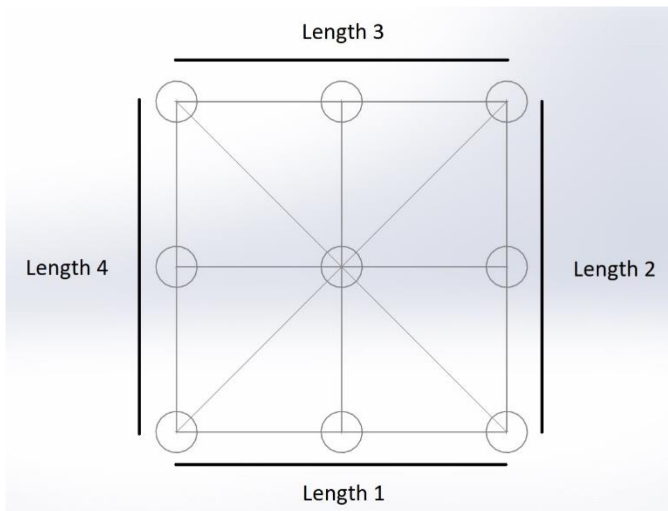

FIGURE 5-2: Union Jack Perimeter

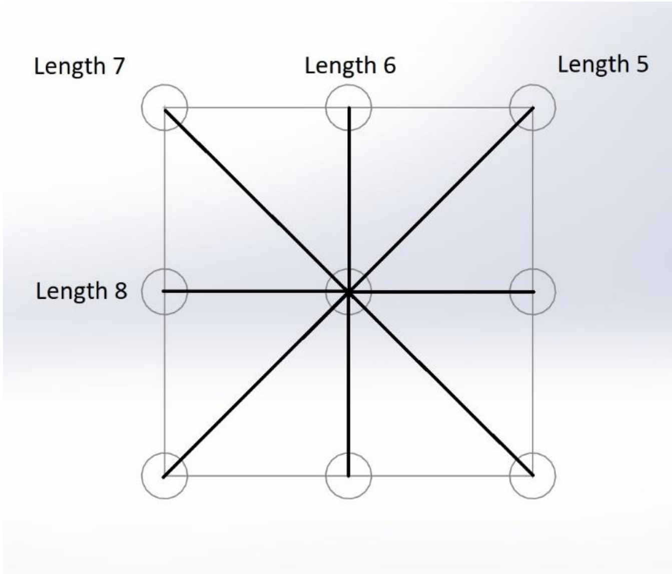

FIGURE 5-3: Union Jack Interior

Then each scan's geometry information is imported and stored in a cell array. The eight lengths are then calculated using the square root sum of the squares between the center of the spheres. The calibrated length is then subtracted from the measured lengths and the error is stored in a cell array and the length errors at each position are averaged together to plot the data. The range and standard deviation are also calculated for each of the length errors of each day, using the seven scans for each position. This information was used to determine the validity of performing less scans in the later experiments. For plotting the correlation charts the data for each day was averaged at each position to display the trends of the daily errors. The eight errors of each day were averaged together to a single error for each day and this value is plotted against the environmental factors, this was done to allow the plots to be more clearly understood. Since there were three different nominal lengths within the union jack pattern, vertical, horizontal, and diagonal, averaging the errors would not have been the best way to display the data. The errors were also normalized to a 100 mm length and plotted against temperature. In these normalized error plots, the slope for aluminum was also plotted to see if there was any relation between the two. This seemed reasonable because the artifact base is aluminum and may been a contributing factor to the errors. This shouldn't be a contributing factor because the ATOS software requires a temperature input before scanning to compensate for changes in temperature. The first order best fit line was also found for the data to compare the slopes to the slope of aluminum.

Since humidity had such a strong correlation it was suggested as well to calculate the partial pressure due to humidity. This was done using the Buck Equation.

$$Vapor\ Pressure\ (kPa) = .61121 \times e^{\left(\left(18.678-\frac{T}{234.5}\right)\left(\frac{T}{257.14+T}\right)\right)} \times Relative\ Humidity\ (\%)$$

T = temperature of the environment

CHAPTER 6 RESULTS

6.1 Experiment 1

The THP recording of the environment at the time of scanning can be seen below in FIGURE 6-1, FIGURE 6-2, and FIGURE 6-3.

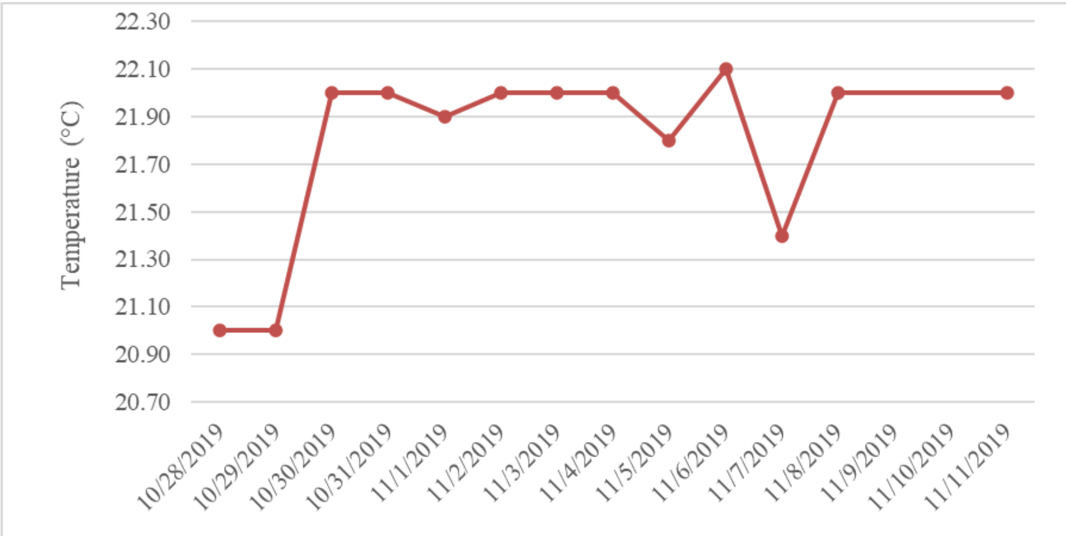

FIGURE 6-1: Experiment 1 Temperature

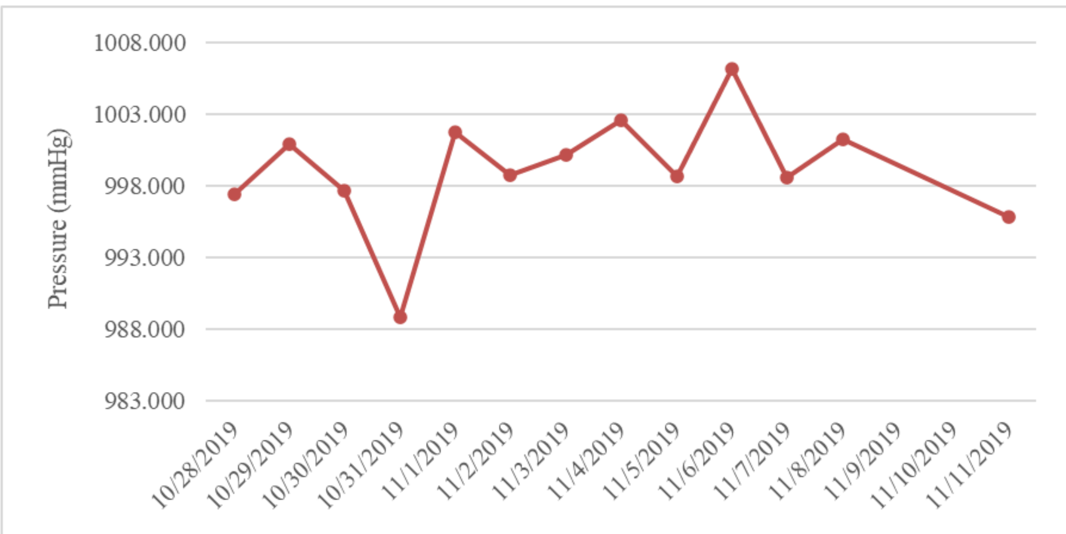

FIGURE 6-2: Experiment 1 Pressure

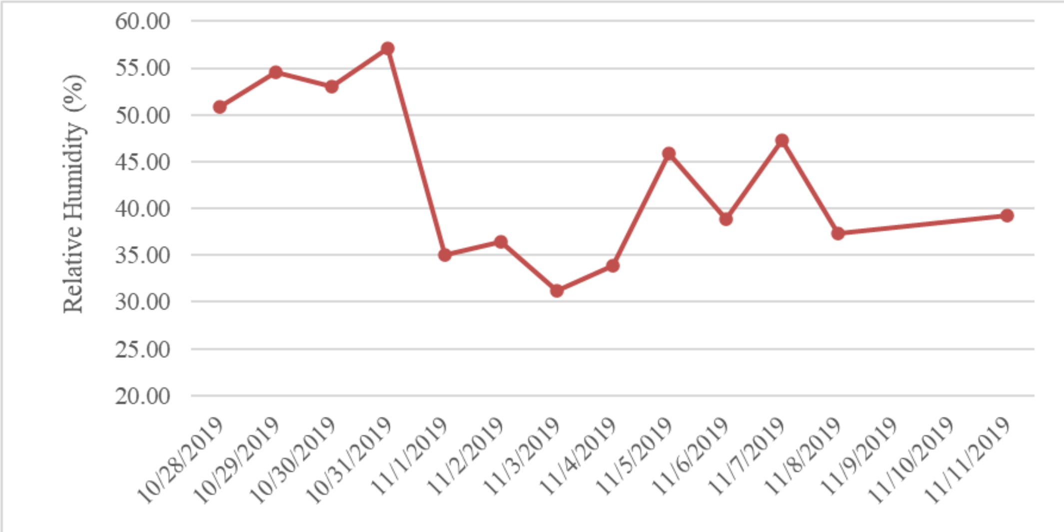

FIGURE 6-3: Experiment 1 Relative Humidity

One thing to note is the jump in temperature near the beginning of the first experiment. This is because the iServer sensor was moved on the third day from behind the ball plate to a position closer to the middle between the scanner and the ball plate. It is also important to take note of the ranges of the various aspects of the environment and how the trends compare to the trends of the errors in length. The temperature range is less than 2° Celsius consistently across all the experiments. The pressure and relative humidity do not seem to be controlled but instead are affected by the weather. The most important things to look at are the trends of the environment to see how it affects the trends of the length errors. The length errors can be seen in APPENDIX C. An example of one of the length errors plotted against time can be seen below in FIGURE 6-4.

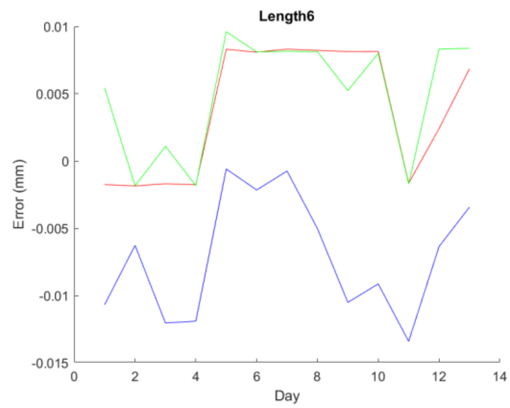

FIGURE 6-4: Experiment 1 Length 6

This plot was chosen to show the trend of having a peak for a couple of days during the middle of experiment. While looking at the length errors in conjunction with the environment plots it seems that there may be some relation to the pressure or an inverse relation to the relative humidity. The partial pressure of humidity was also calculated, and the errors were plotted against those as well. This was to better determine if there was a relationship between the humidity and the errors. The colors correspond to the positions in the measurement volume, red is the close position, green is the middle position, and blue is the far position. If there is a relation it will be easier to see in FIGURE 6-5, FIGURE 6-6, FIGURE 6-7, and FIGURE 6-8.

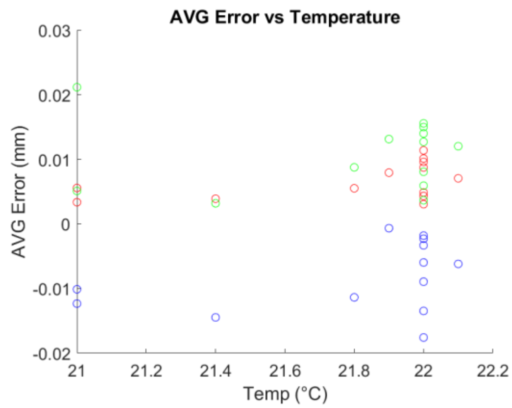

FIGURE 6-5: Experiment 1 Error vs Temperature

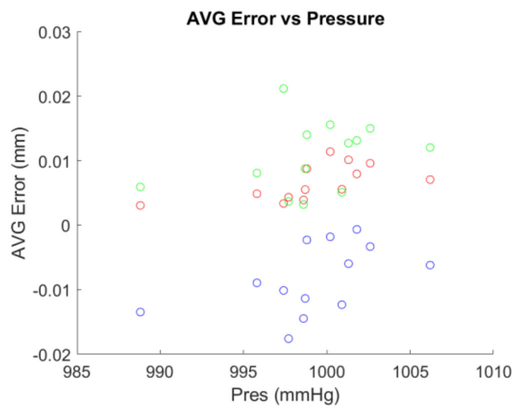

FIGURE 6-6: Experiment 1 Error vs Pressure

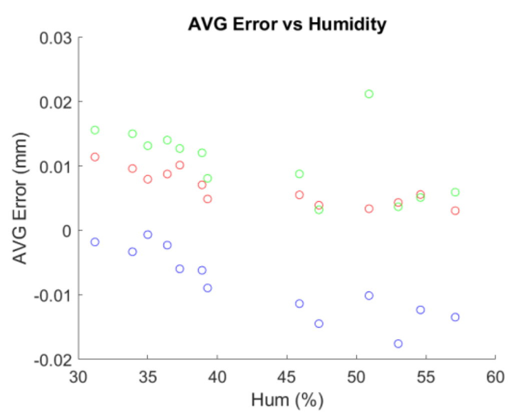

FIGURE 6-7: Experiment 1 Error vs Humidity

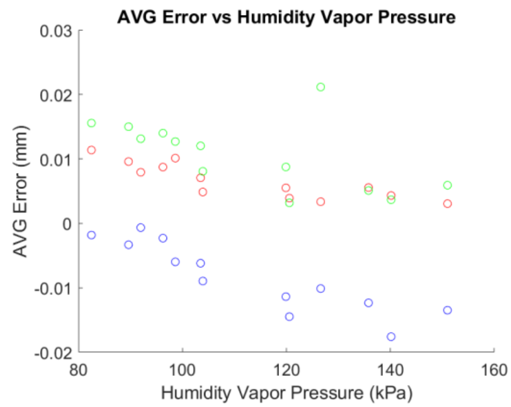

FIGURE 6-8: Experiment 1 Error vs Partial Pressure

Another important chart to consider is to see if there is any correlation between the environment and the standard deviation. If the standard deviation increases as the environmental factor increases, it means that the system is not very stable except for the time directly after a measurement. This also can be used to justify using less scans which can be time consuming to process. These can be seen below in FIGURE 6-9, FIGURE 6-10, and FIGURE 6-11.

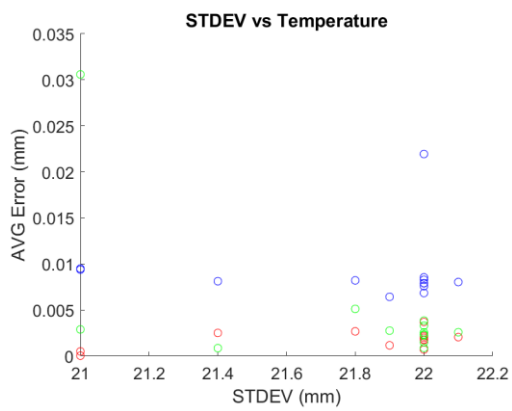

FIGURE 6-9: Experiment 1 STDEV vs Temp

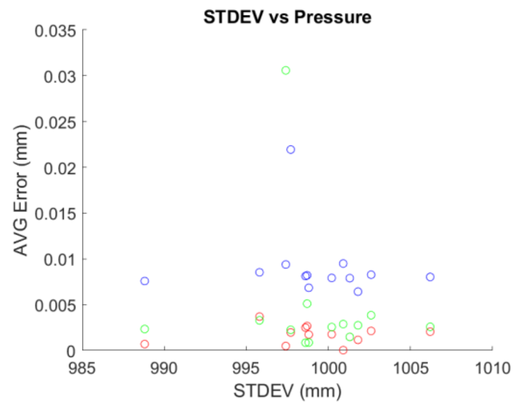

FIGURE 6-10: Experiment 1 STDEV vs Press

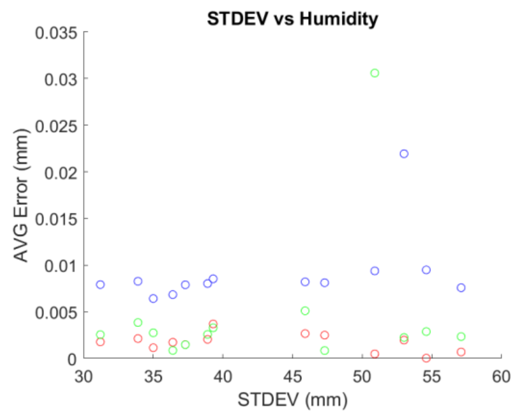

FIGURE 6-11: Experiment 1 STDEV vs Hum

The errors were also normalized to a single length of 100 mm and plotted against temperature. Linear best fit lines were found whose color correspond to their data and the expansion for aluminum at 100 mm was also plotted in magenta. This can be seen below in FIGURE 6-12. The slopes for the lines can be found in **Error! Reference source not found.**.

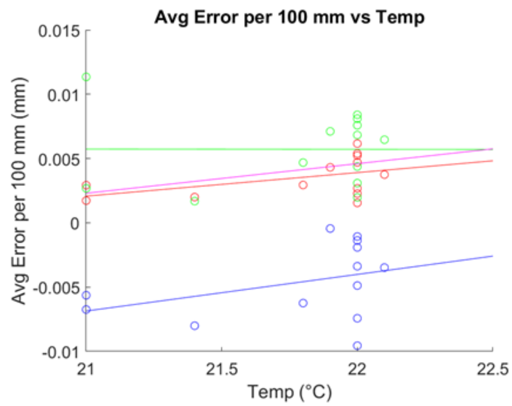

FIGURE 6-12: Experiment 1 Normalized Error

Table 6-1: Experiment 1 Slopes

Slope Identifier	Slope (mm/°C)
Aluminum (Magenta)	0.0023
Close (Red)	0.0018
Middle (Green)	-0.000019
Far (Blue)	0.0028

6.2 Experiment 2

The THP recording for experiment 2 of the environment at the time of scanning can be seen below in FIGURE 6-13, FIGURE 6-14, and FIGURE 6-15.

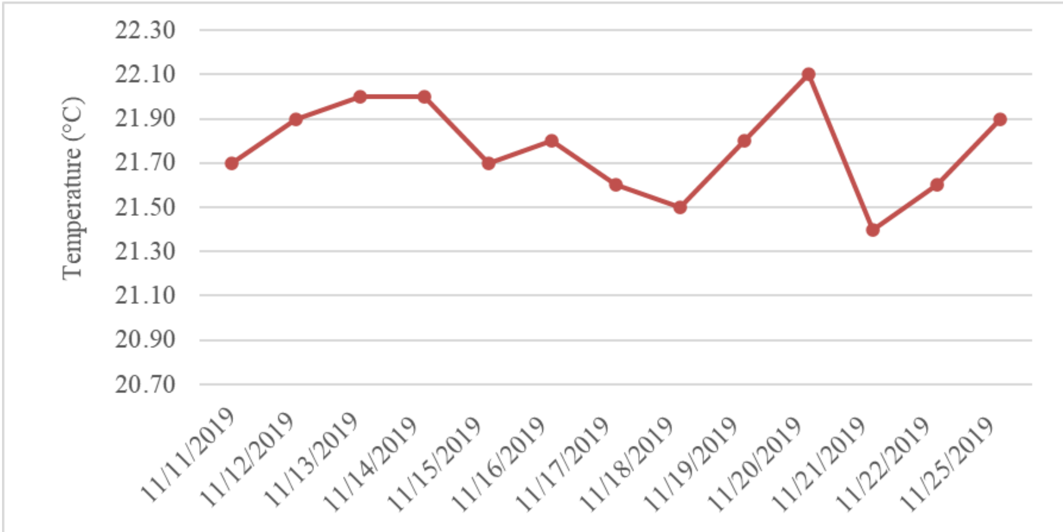

FIGURE 6-13: Experiment 2 Temperature

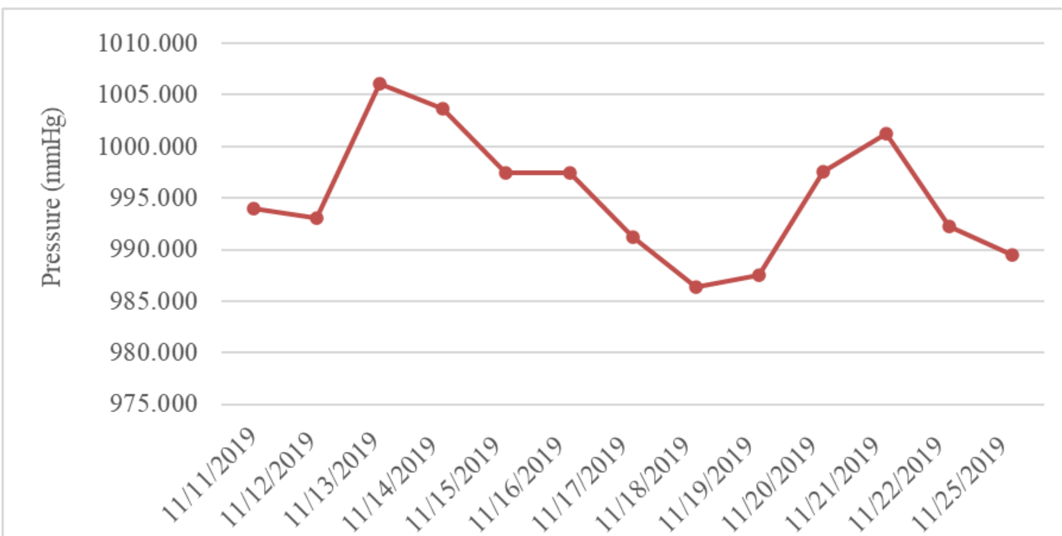

FIGURE 6-14: Experiment 2 Pressure

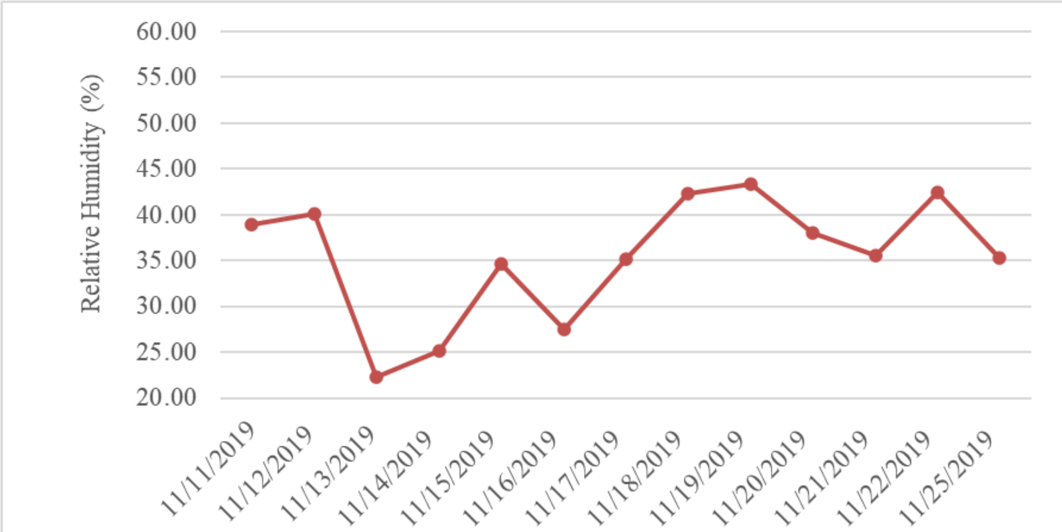

FIGURE 6-15: Experiment 2 Relative Humidity

Again, the most important aspect of the temperature charts is the trends of the environment and how it compares to the trends of the measurements taken. The continuous THP charts can be found in APPENDIX D. The length errors over time can be found in APPENDIX E. An example can be seen below in FIGURE 6-16.

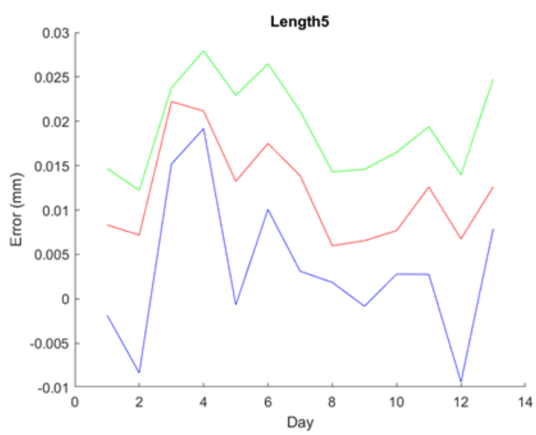

FIGURE 6-16: Experiment 2 Length 5

There doesn't seem to be much of a relationship with the environment besides an inverse relationship with the relative humidity of the environment. The correlation charts can be seen in FIGURE 6-17, FIGURE 6-18, FIGURE 6-19, and FIGURE 6-20.

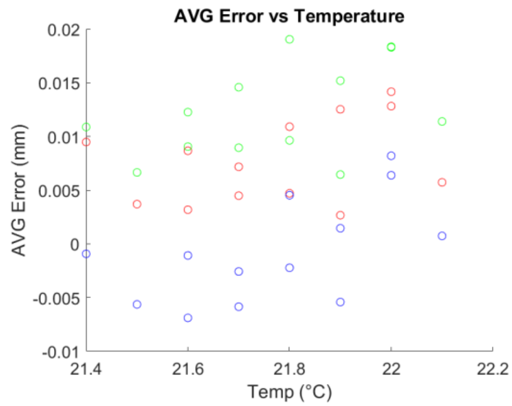

FIGURE 6-17: Experiment 2 Error vs Temperature

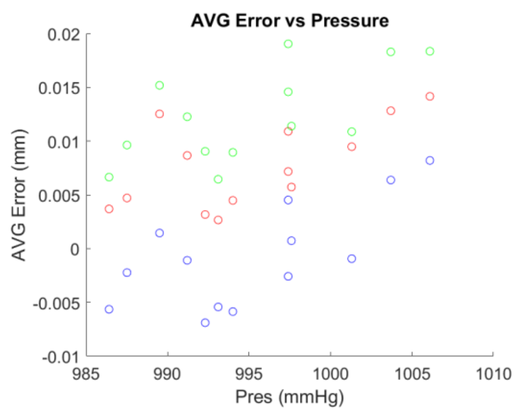

FIGURE 6-18: Experiment 2 Error vs Pressure

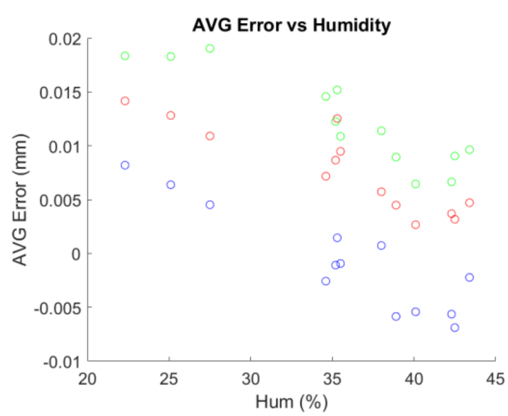

FIGURE 6-19: Experiment 2 Error vs Humidity

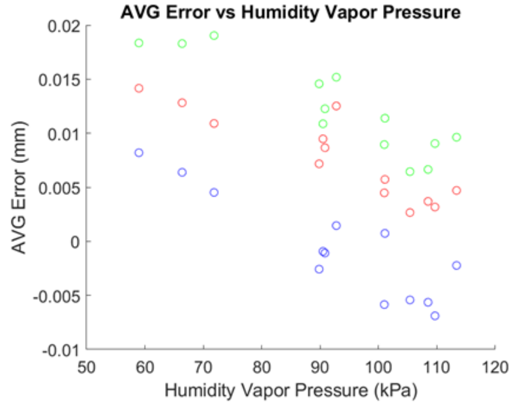

FIGURE 6-20: Experiment 2 Error vs Partial Pressure

The standard deviation plotted against the environmental factors can be seen below in FIGURE 6-21, FIGURE 6-22, and FIGURE 6-23.

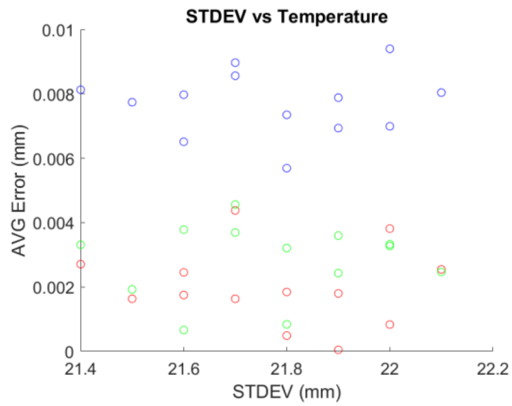

FIGURE 6-21: Experiment 2 STDEV vs Temp

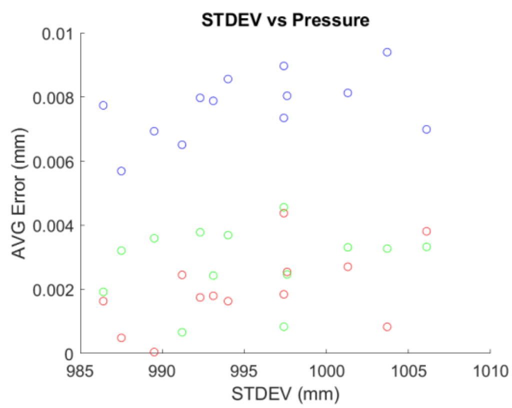

FIGURE 6-22: Experiment 2 STDEV vs Press

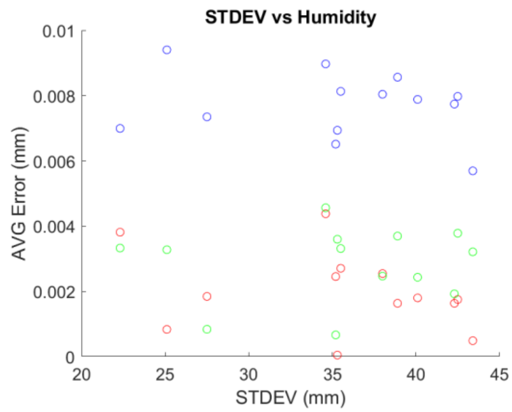

FIGURE 6-23: Experiment 2 STDEV vs Hum

As can be seen by the standard deviations plotted against environmental factors in both experiment 1 and experiment 2 there is no apparent correlation between them. This justifies the choice to reduce from 7 scans at each position during experiment 1 and 2 to five scans at each position for the rest of the experiments.

The normalized error data can be seen below in FIGURE 6-24. The slopes of the best fit lines can be found below in **Error! Reference source not found.**.

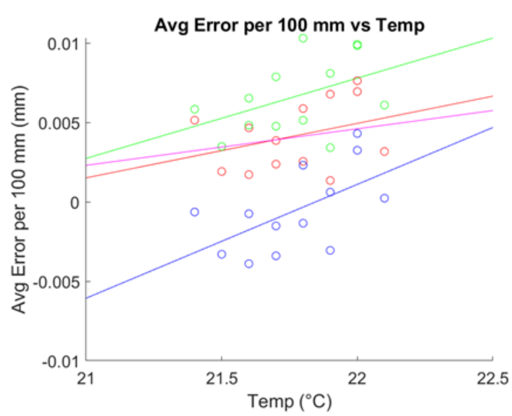

FIGURE 6-24: Experiment 2 Normalized Errors

Table 6-2: Experiment 2 Slopes

Slope Identifier	Slope (mm/°C)
Aluminum (Magenta)	0.0023
Close (Red)	0.0034
Middle (Green)	0.0051
Far (Blue)	0.0072

6.3 Experiment 3

The THP recording for the third experiment can be seen below in FIGURE 6-25, FIGURE 6-26, and FIGURE 6-27.

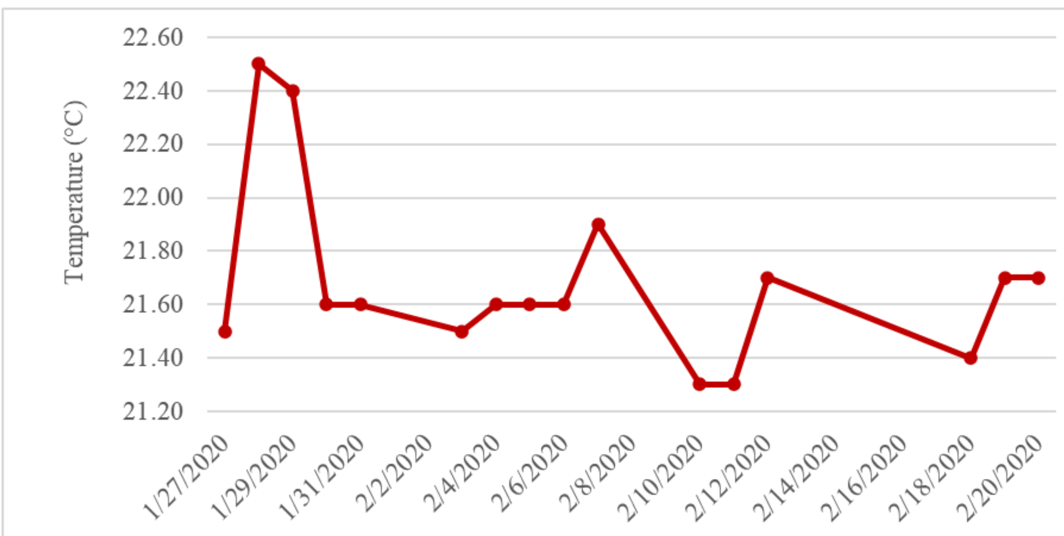

FIGURE 6-25: Experiment 3 Temperature

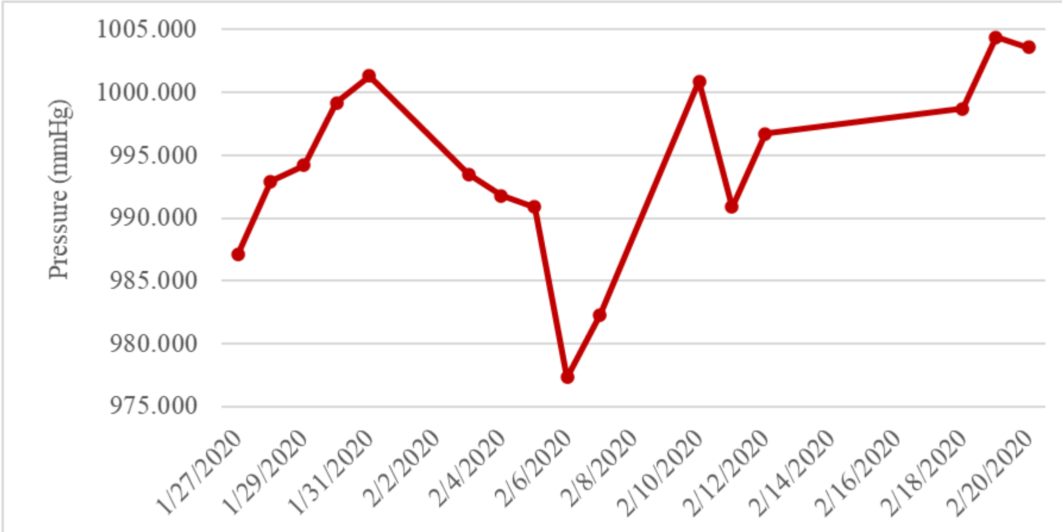

FIGURE 6-26: Experiment 3 Pressure

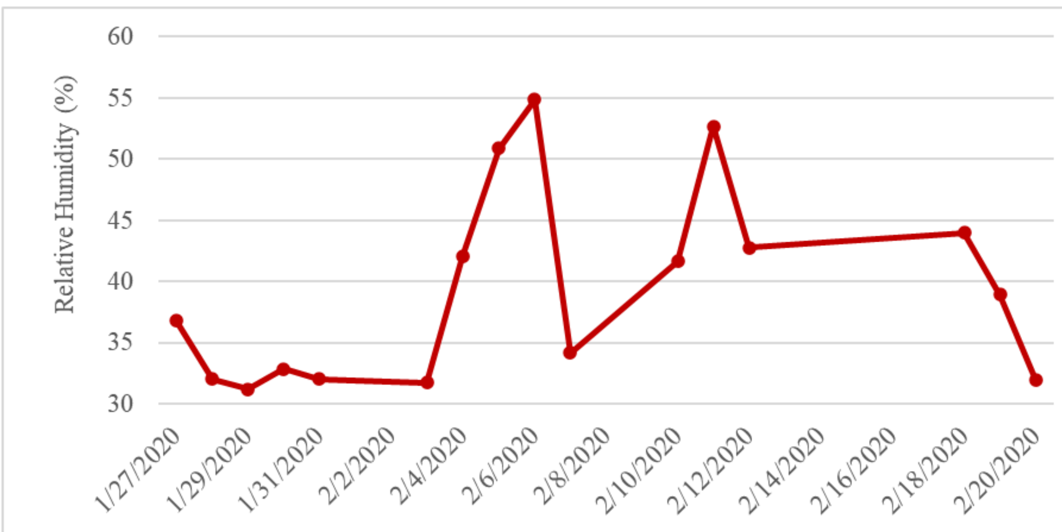

FIGURE 6-27: Experiment 3 Relative Humidity

The very distinct patterns of the environment should help to distinctly make better conclusions and relationships between the length errors and the influences of the environment. The continuous THP tracking of the environment can be found in APPENDIX F. Some things to note about the continuous data is that the iServer data is not continuous as stated in 4.6 Issues to note, but a Raspberry Pi with a SenseHAT was running continuously. In the continuous data the orange data is the SenseHAT data and was time matched to the iServer data to compare them. This was to determine if the SenseHAT data is a good representation of the environment. It can be seen in the appendix data that the pressure followed the same trends but with an offset as compared to the iServer data, the humidity data of the SenseHAT was a very close match to the more accurate sensor. The temperature data was not only offset but there were some errors in the tracking trends, so it was determined not to use the SenseHAT temperature data. An example of the length errors can be seen below in FIGURE 6-28.

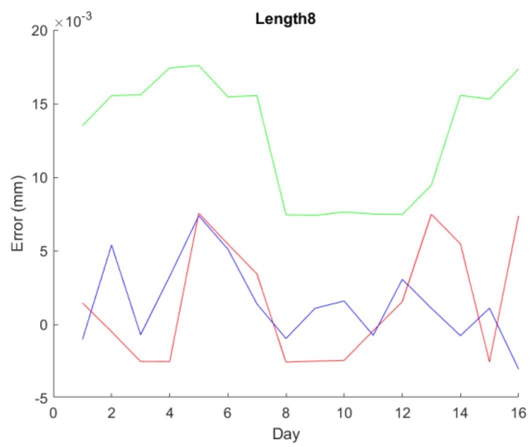

FIGURE 6-28: Experiment 3 Length 8

The environmental correlation charts can be seen in FIGURE 6-29, FIGURE 6-30, FIGURE 6-31, and FIGURE 6-32.

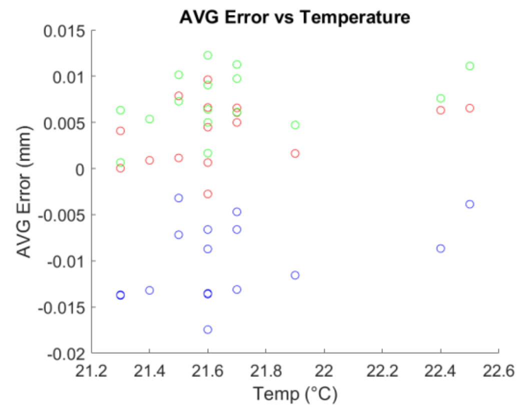

FIGURE 6-29: Experiment 3 Error vs Temperature

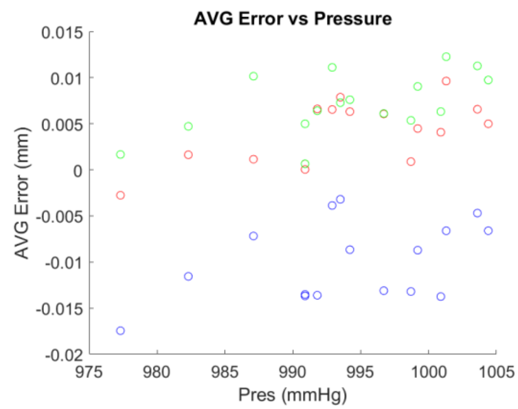

FIGURE 6-30: Experiment 3 Error vs Pressure

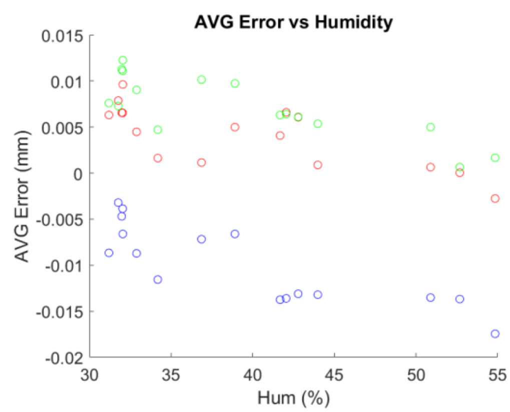

FIGURE 6-31: Experiment 3 Error vs Humidity

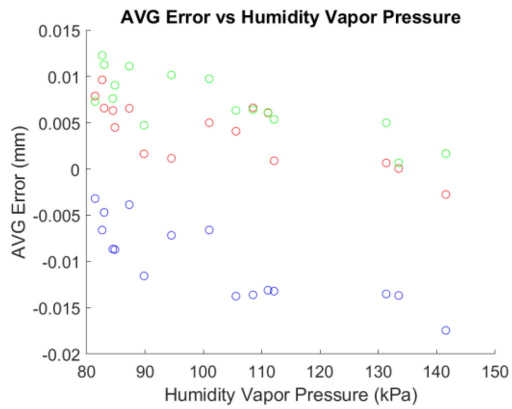

FIGURE 6-32: Experiment 3 Error vs Partial Pressure

The normalized error data can be seen below in FIGURE 6-33. The slopes of the best fit lines can be found below in **Error! Reference source not found.**.

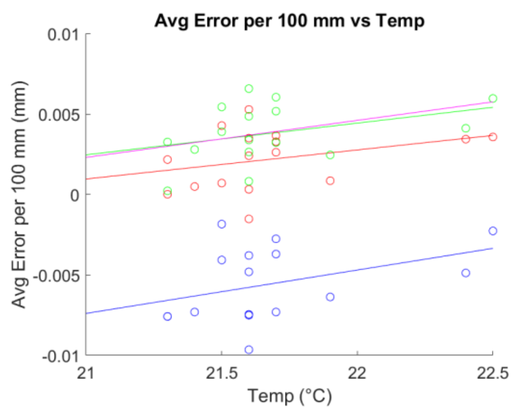

FIGURE 6-33: Experiment 3 Normalized Errors

Table 6-3: Experiment 3 Slopes

Slope Identifier	Slope (mm/°C)
Aluminum (Magenta)	0.0023
Close (Red)	0.0018
Middle (Green)	0.0020
Far (Blue)	0.0027

6.4 Experiment 4

The THP recording for the fourth experiment can be seen below in FIGURE 6-34 and FIGURE 6-35. During the third experiment the humidity sensor stopped working. Since the sensor was able to be used for the full duration of the experiment the RaspberryPi was not used. Due to this there was no humidity data recorded for the fourth experiment.

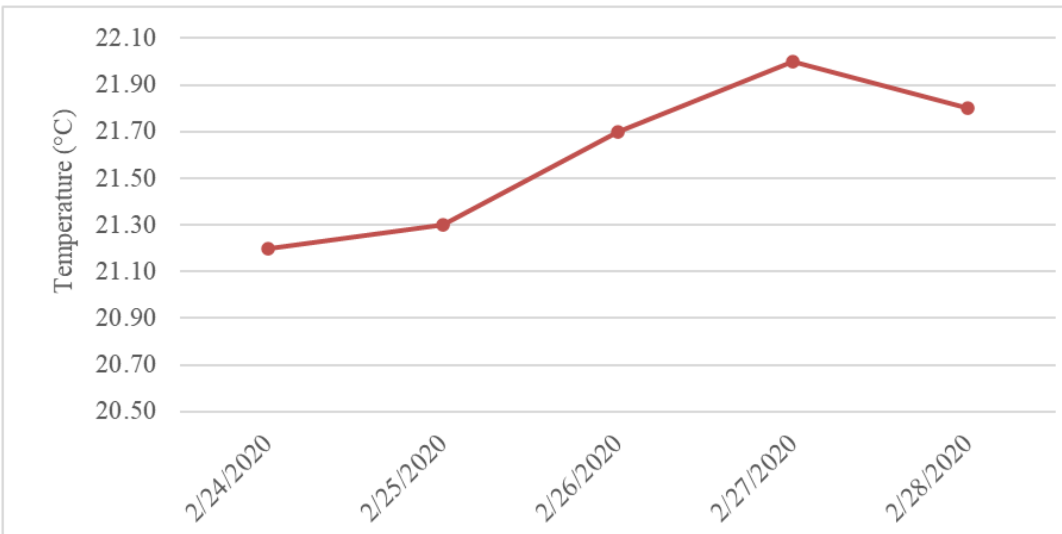

FIGURE 6-34: Experiment 4 Temperature

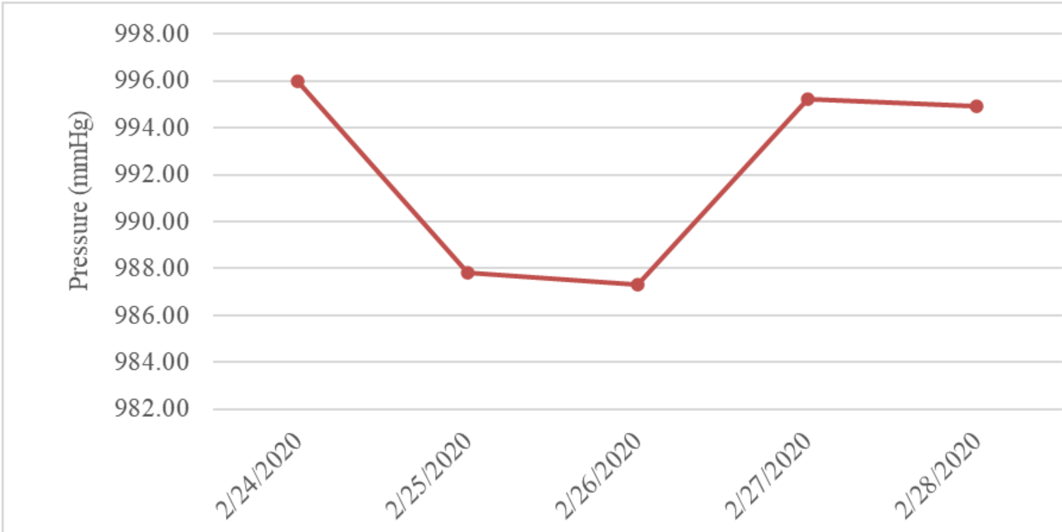

FIGURE 6-35: Experiment 4 Pressure

During this experiment, the ball plate was scanned both before and after each day's calibration. The continuous environmental recording for the fourth experiment can be found in APPENDIX H. An example of the time based length errors before the calibration can be seen below in FIGURE 6-36.

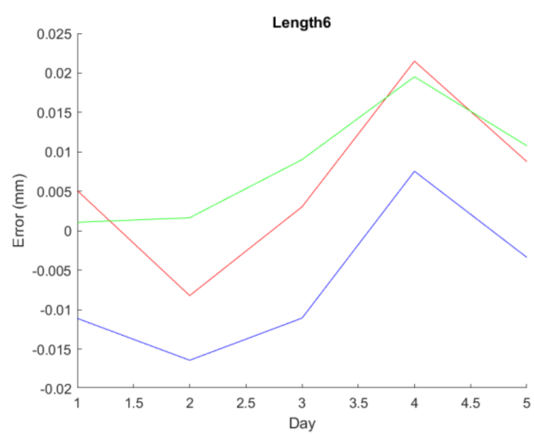

FIGURE 6-36: Experiment 4 Length 6 Before

An example of the time based length errors before the calibration can be seen below in FIGURE 6-37.

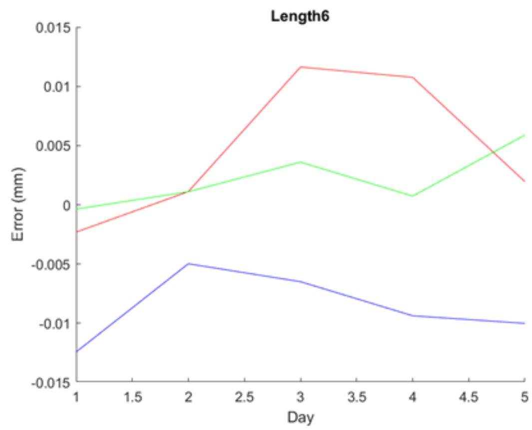

FIGURE 6-37: Experiment 4 Length 6 After

Due to the short duration of the experiment the correlation plots do not have much data to make any determination. The correlation plots of the data scanned before the day's calibration can be seen in FIGURE 6-38 and FIGURE 6-39.

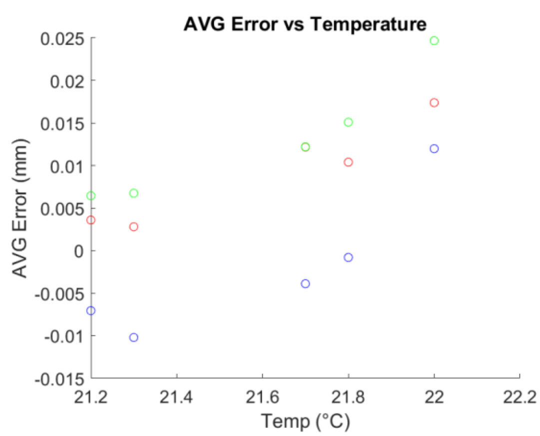

FIGURE 6-38: Experiment 4 Error vs Temperature Before

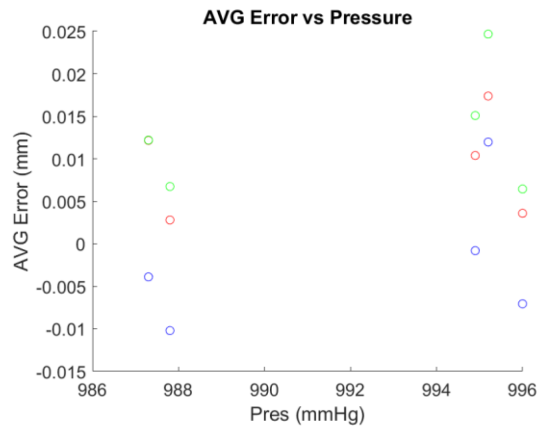

FIGURE 6-39:Experiment 4 Error vs Pressure Before

The correlation plots of the data scanned before the day's calibration can be seen in FIGURE 6-40 and FIGURE 6-41.

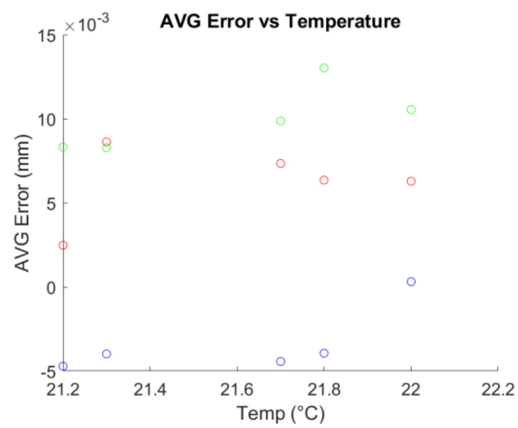

FIGURE 6-40: Experiment 4 Error vs Temperature After

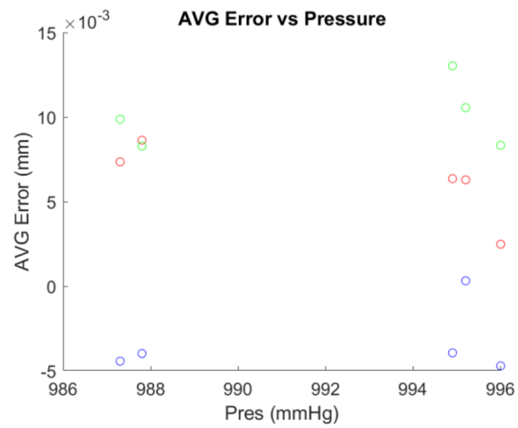

FIGURE 6-41: Experiment 4 Error vs Pressure After

The normalized error data can be seen below in. The slopes of the best fit lines can be found below in .

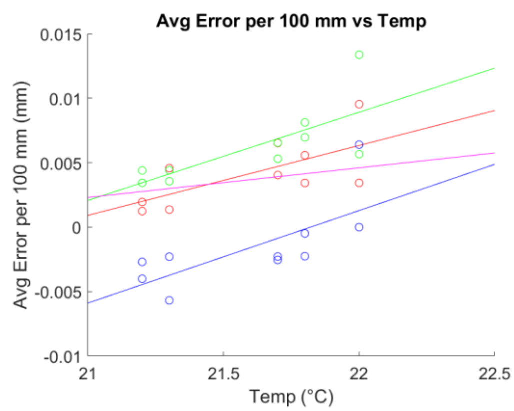

FIGURE 6-42: Experiment 4 Normalized Errors

Table 6-4: Experiment 4 Slopes

Slope Identifier	Slope (mm/°C)
Aluminum (Magenta)	0.0023
Close (Red)	0.0054
Middle (Green)	0.0068
Far (Blue)	0.0072

CHAPTER 7 CONCLUSIONS

There are some interesting things to observe from the previous results and conclusions that can be made from them. There is also some important information from GOM Americas that has some important sway over how to interpret the results. The information from them included the fact that the calibration was not time based. The principle factor is temperature tracking and the acceptable range is determined in the calibration settings. Other self-tests by the system are looking at the sticker targets shape and size and detecting if there is sensor movement when performing scans. While some of these are unrelated to the environment it shows that if the system is handled gently and kept in a stable environment it is possible for the system to remain in calibration according to the self-checks for up to even eight months according to some applications engineers. This is not the recommended practice though.

Analyzing the correlation charts there is an inverse correlation between humidity and the error seen in the measurements, this is supported well by the correlation seen in the partial pressure plots as well. There seems to be a bit of a correlation between pressure and error but not as strong of a relation as humidity. The fourth experiment also shows the strong relationship between the temperature and the error in the before calibration measurements of the experiment. When analyzing the after calibration experiments the relationship is not apparent. This would indicate that the calibration helps to negate influence of the environment. It would also appear to indicate that the calibration is linked to the environment conditions at the time of calibration. This is important because if the temperature changes significantly in any way it would skew measurements. Also, if the humidity changes it would also affect the measurements, just not as much as temperature would. When considering the best fit slopes, the data is inconclusive to if there is a relation. When looking at experiment 1 or 3 it one might be able to justify a relationship. When taking into account experiments 2 and 4 the slopes are too different to suggest a relationship.

Temperature variations obviously would cause things to change with having internal components expanding or shrinking. An explanation to the strong humidity correlation is that the plastic housing for the system is physically expanding or contracting by absorbing some of the moisture from the environment.

There is another affect seen in the correlation charts that may be related to the technique used to calibrate the sensor is the discrepancy with measurements at different depths in the measurement volume. As seen in the CHAPTER 6 the close and medium measurements are in a similar area for errors, the far measurement error is consistently lower than the rest of the measurement volume. One of the possible explanations for this is the optical design. In CHAPTER 2 the cameras focus was discussed, it is possible at the rear of the measurement volume that the images taken are not completely in focus. Another possible and more likely explanation is there is some discrepancy happening during the calibration procedure. It may be related to the type of technique used to calibrate the system and it does fully account for the full depth of the sensing system, or there might be approximation errors doing a polynomial calibration if that is what is being used.

The fourth experiment also shows interesting anomalies directly after calibration. The close measurements crop parts of the spheres right after calibration but then the next day when measuring in that same position those spheres are not cropped. There was also one instance where the spheres were cropped both directly after the calibration and the next day as well. An example of this can be seen in FIGURE 7-1.

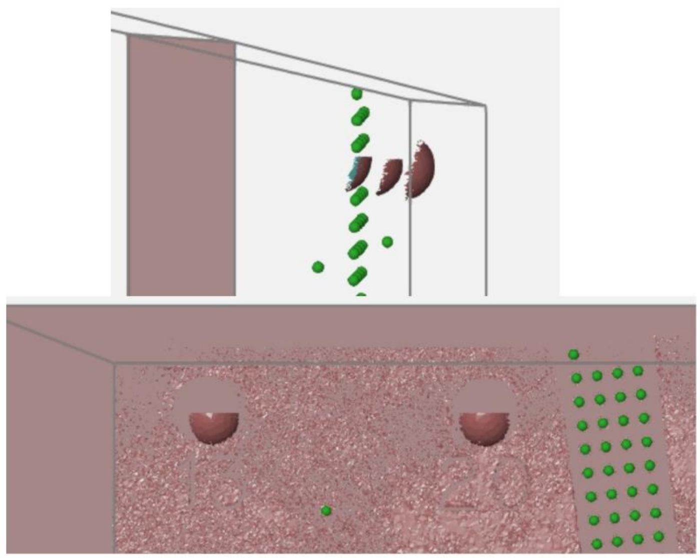

FIGURE 7-1: Cropped Spheres

The spheres are well within the indicated measurement volume but were both cropped along the top while the last sphere in the row was not cropped. It is likely this is due to some error in the calibration or the type of calibration technique.

The structured light systems seem to be highly dependent on any small changes that happen during the calibration procedure. They also are influenced largely by changes in the environment from the time of calibration.

CHAPTER 8 RECOMMENDATIONS

The first and likely most important recommendation would be to track the environment information. Without knowing what the environment is doing to the system it is nearly impossible to know how to properly compensate for it or know what actions to take to mitigate it. Having knowledge about the environment is crucial in properly addressing issues related to performing measurements.

Knowing how the environment changes would also allow the owner to make better decisions as to when to recalibrate. Times to recalibrate would be when major changes in the environment occur such as pressure and humidity changes. The reason to not worry about temperature is because the system internally monitors temperature changes and will notify the user if there is a larger change than what is deemed acceptable in the settings.

How often to calibrate sensors largely is dependent on how well controlled the environment is. If the environment is well controlled, it is possible for the structured light scanning system to remain in a well calibrated for a number of days. If this is the case it would be recommended to go no longer than a work week without preforming a recalibration.

Under ideal circumstances the sensor would be calibrated each day either at the beginning or at the end of each workday. Considering that these systems are being used more and more frequently in continuous production environments this may not be possible. Under such conditions it would be recommended to calibrate at least once every three days.

It can also be seen that there is a relation between the errors in the systems measurement and the depth within the measurement volume. As seen in the correlation charts the close and medium positions are both fairly similar in the errors measured by the system. For most accurate and best use of the scanner it would be best to recommended to scan towards the front and near the indicated ideal focal plane.

CHAPTER 9 FUTURE WORK

To build on the work of this experiment there are a variety of experiments that can and perhaps should be performed to gain more knowledge about these systems. The recommendations to follow would be to further determinize the system. There are at least four experiments that might be able to be performed to isolate correlations between errors and the environmental effects. Three of the experiments rely on having an environment that can be well controlled.

The first experiment would be to isolate the environmental pressure influence on the system. A calibrated artifact should be scanned at a single focal depth in the measurement volume for the entirety of the experiment to isolate the pressure influence. This would be performed over the course of a few days or even weeks where the pressure inside the lab would be steadily increased or decreased each day over the course of the experiment. The experiment would need to start out at one extreme and work its way towards the other. Then a correlation plot could be plotted to better know if there is a relation between the environmental pressure and errors measured by the system.

The second experiment would be to isolate the environmental relative humidity influence on the structured light system. The experiment would be very similar to the one described above. The calibrated object would be scanned at a single focal plane for the same reasons as above over the course of a few days or weeks. Over the course of the experiment it should start at a lower humidity and increase the humidity each day to reach the maximum. Then another correlation plot could be made to better know the relation between the environmental humidity and the errors measured by the system.

The third experiment to better determine the errors of the structured light system would be to keep the environment stable and measure at multiple focal planes. This will allow the systems inherent errors to be better determined. The calibration procedure should be used to mitigate the effects from the physical setup of the optics themselves. From the results seen from these experiments it seems as though there still is some effect of what depth in the measurement volume the object is scanned. This may be system specific, but it would provide important information as to the best place within the measurement volume to scan.

The fourth experiment would be to use multiple types of scanners in an attempt to make sure the previous results were not specific to the GOM ATOS 300 system. These other scanners would run similar if not the same experiments as above to determine if the results were system specific or not. It would be recommended to use not only different systems but systems from different manufacturers as well.

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APPENDIX A CALIBRATION ORIENTATIONS

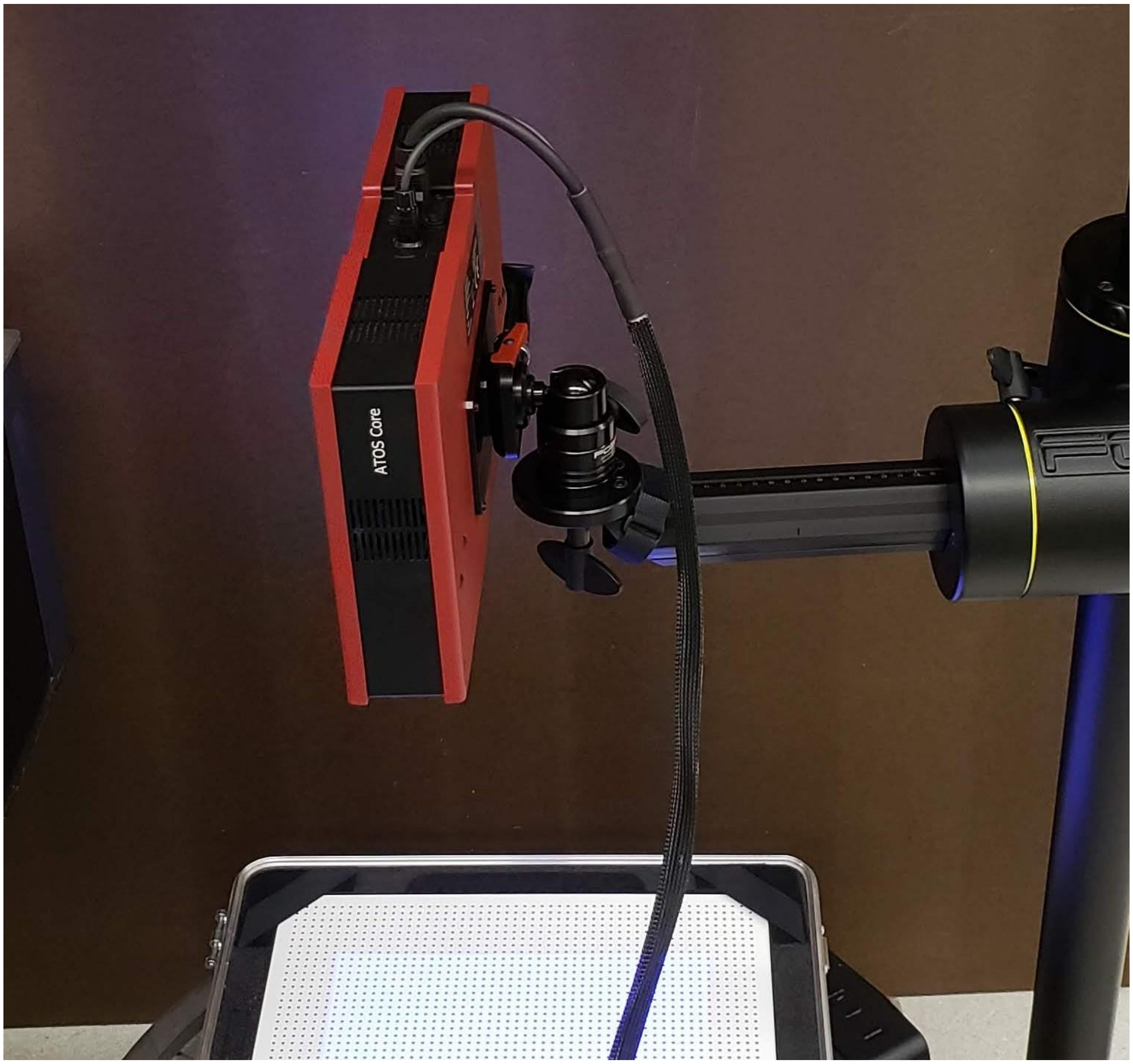

FIGURE A-1: Perpendicular Orientation

FIGURE A-2: 20° Orientation

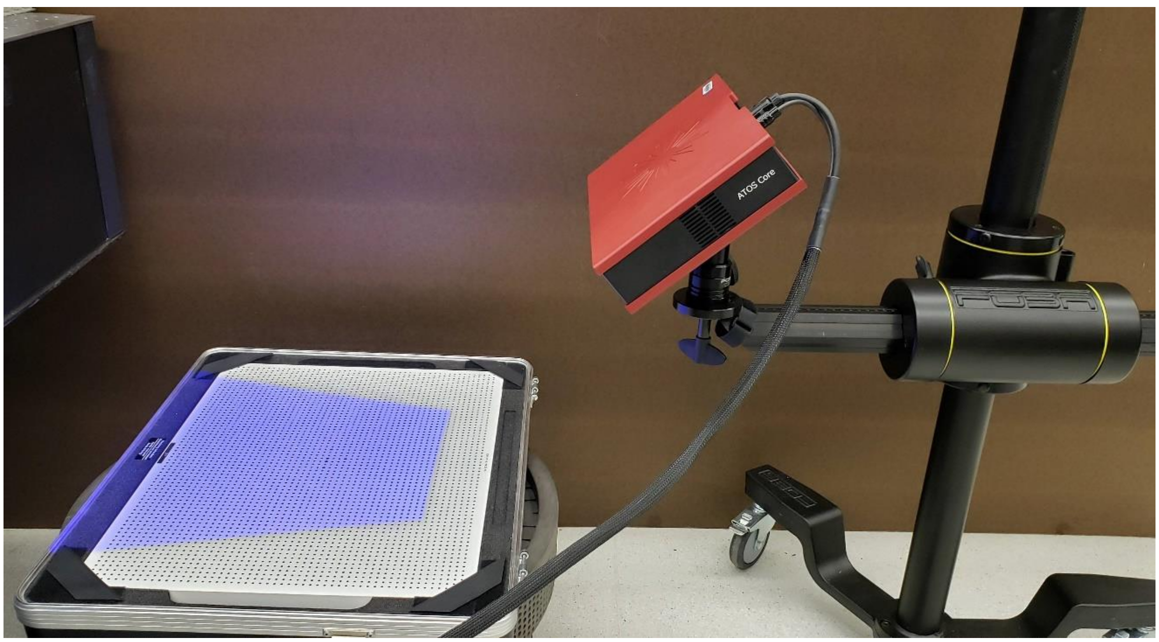

FIGURE A-3: 45° Orientation

APPENDIX B EXPERIMENT 1 ENVIRONMENT DATA RECORD

FIGURE B-1: Experiment 1 Temperature

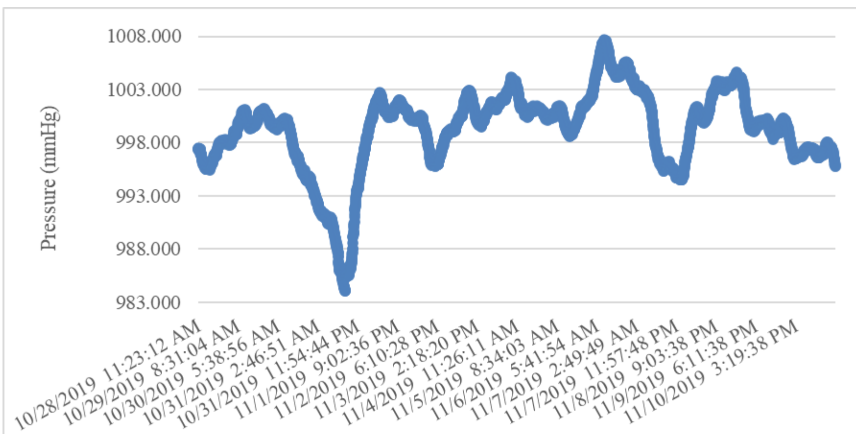

FIGURE B-2: Experiment 1 Pressure

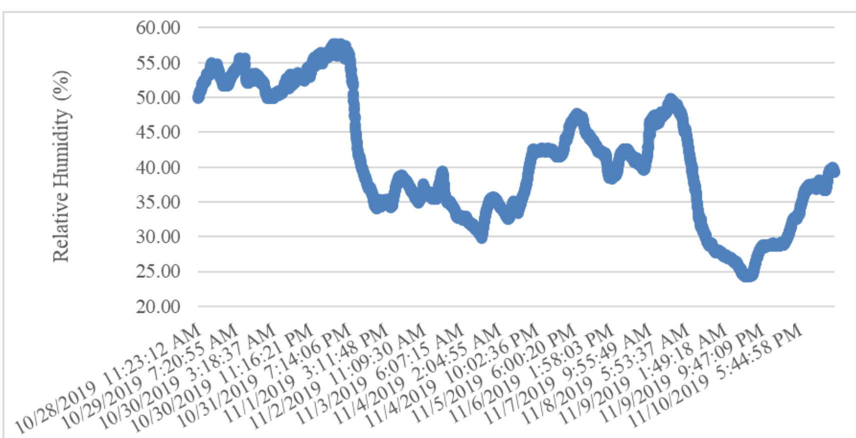

FIGURE B-3: Experiment 1 Relative Humidity

APPENDIX C EXPERIMENT 1 LENGTH ERRORS VS TIME

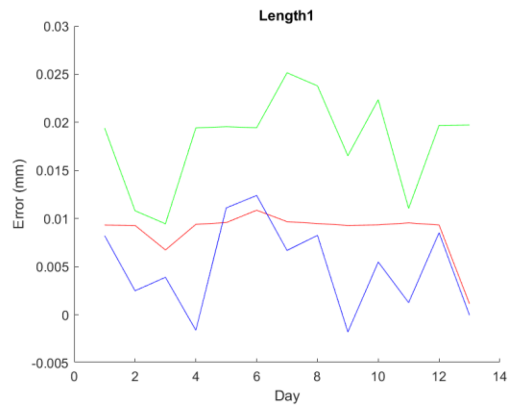

FIGURE C-1: Experiment 1 Length 1

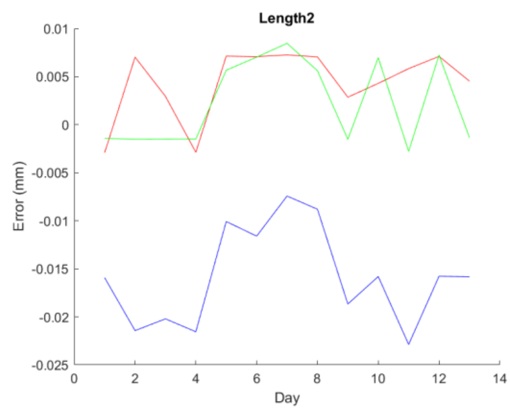

FIGURE C-2: Experiment 1 Length 2

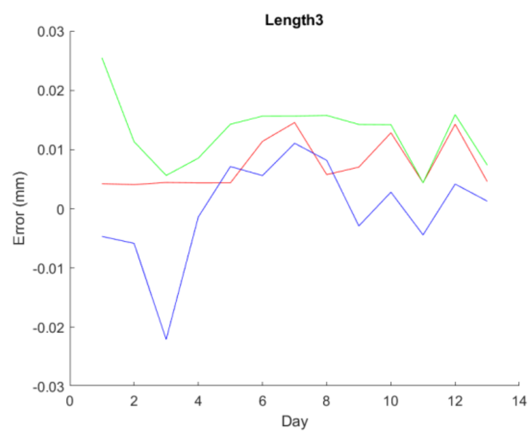

FIGURE C-3: Experiment 1 Length 3

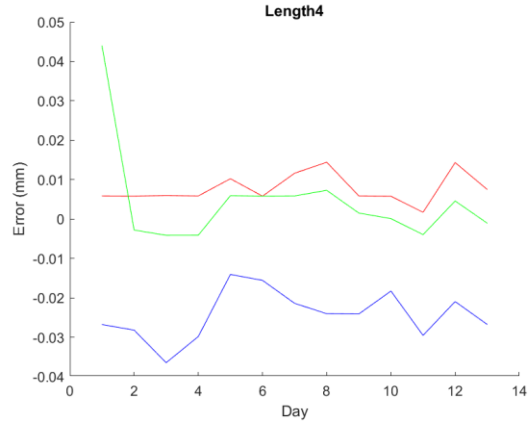

FIGURE C-4: Experiment 1 Length 4

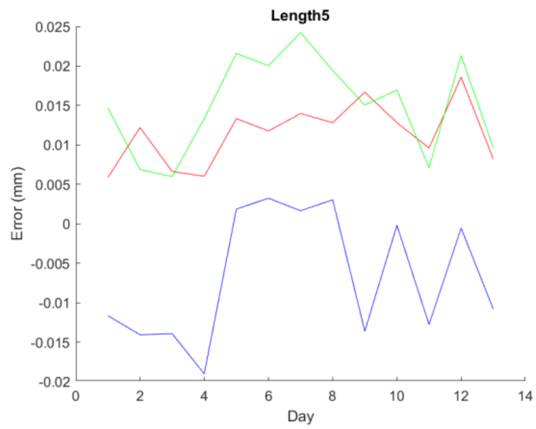

FIGURE C-5: Experiment 1 Length 5

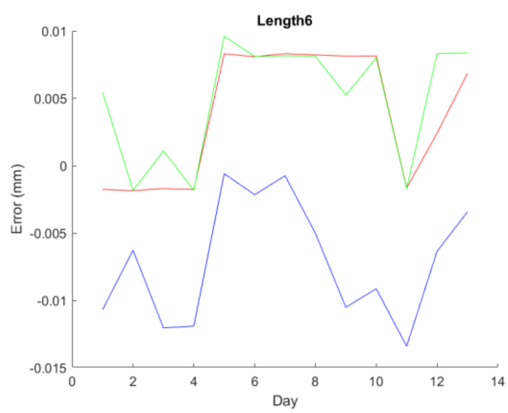

FIGURE C-6: Experiment 1 Length 6

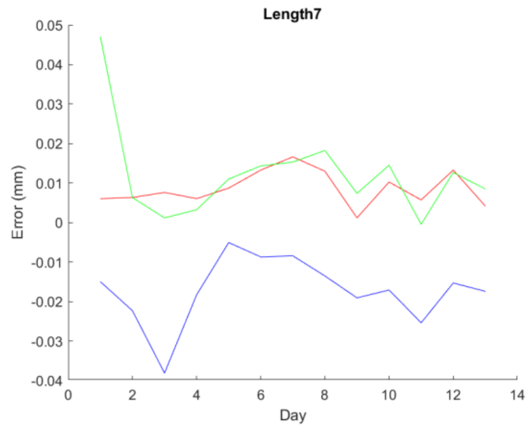

FIGURE C-7: Experiment 1 Length 7

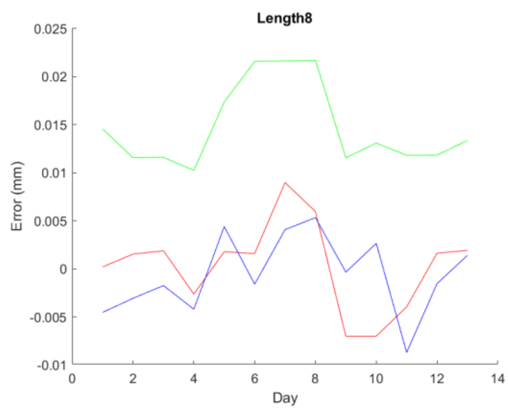

FIGURE C-8: Experiment 1 Length 8

APPENDIX D EXPERIMENT 2 ENVIRONMENT DATA RECORD

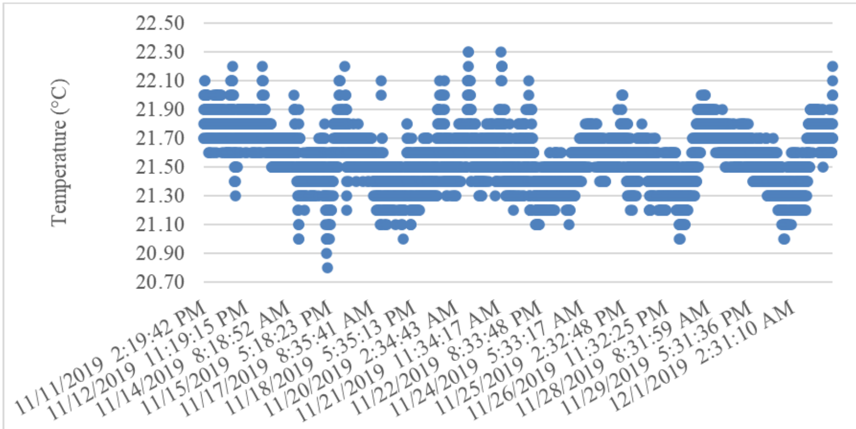

FIGURE D-1: Experiment 2 Temperature

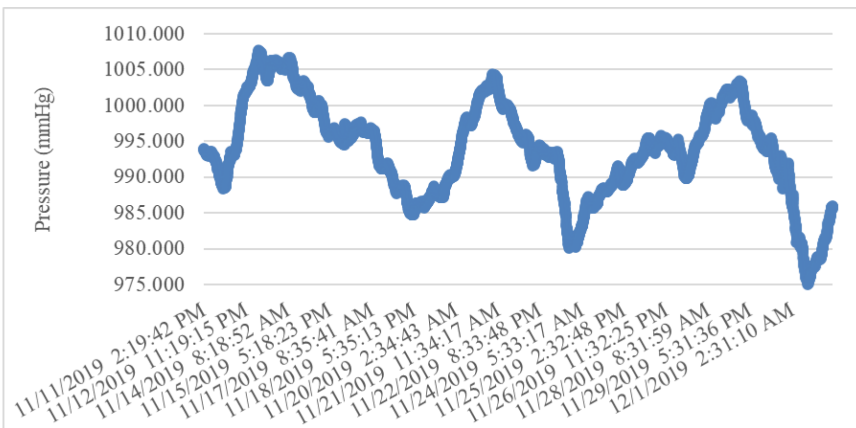

FIGURE D-2: Experiment 2 Pressure

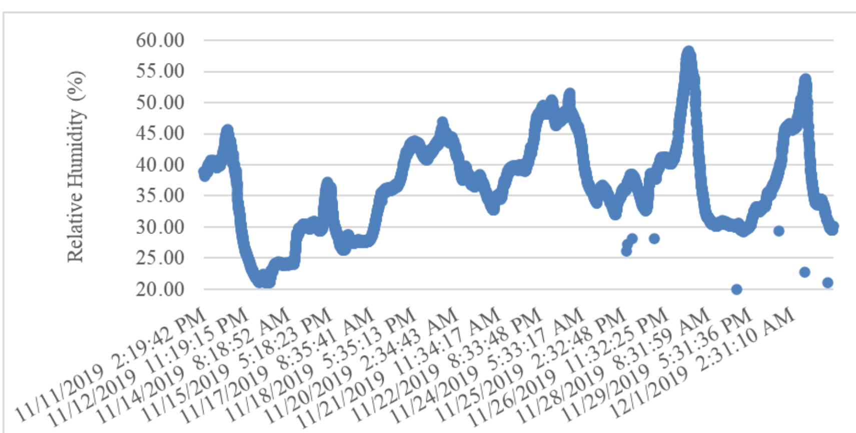

FIGURE D-3: Experiment 2 Relative Humidity

APPENDIX E EXPERIMENT 2 LENGTH ERRORS VS TIME

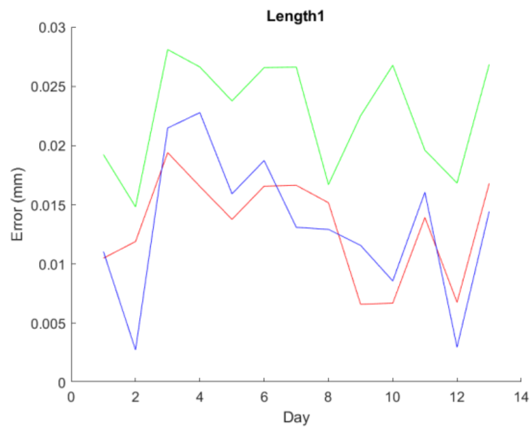

FIGURE E-1: Experiment 2 Length 1

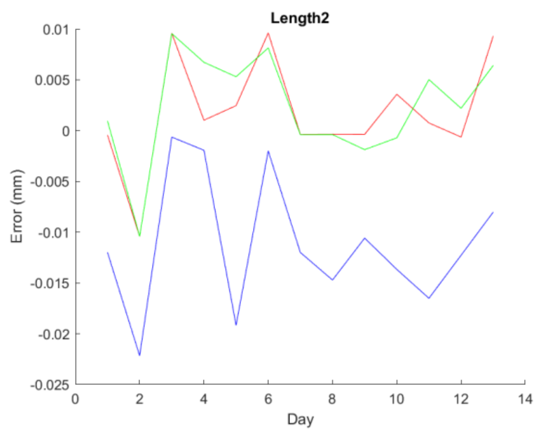

FIGURE E-2: Experiment 2 Length 2

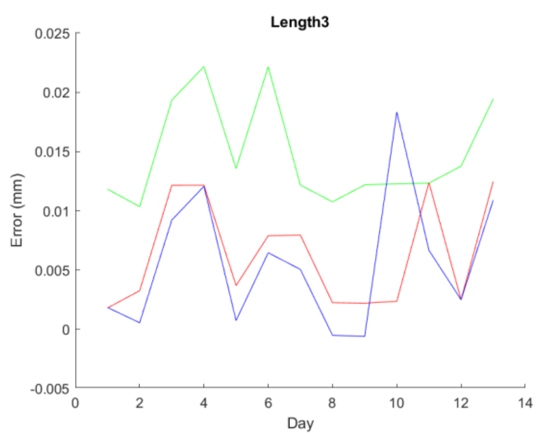

FIGURE E-3: Experiment 2 Length 3

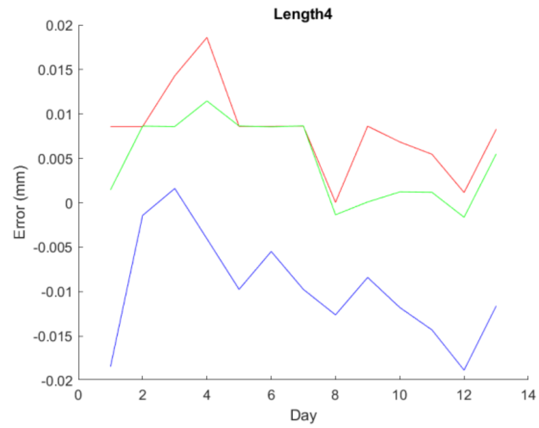

FIGURE E-4: Experiment 2 Length 4

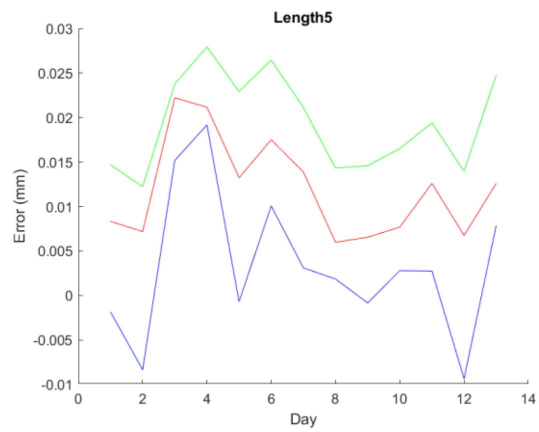

FIGURE E-5: Experiment 2 Length 5

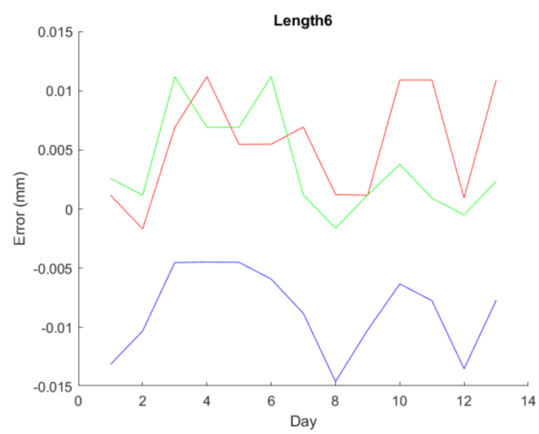

FIGURE E-6: Experiment 2 Length 6

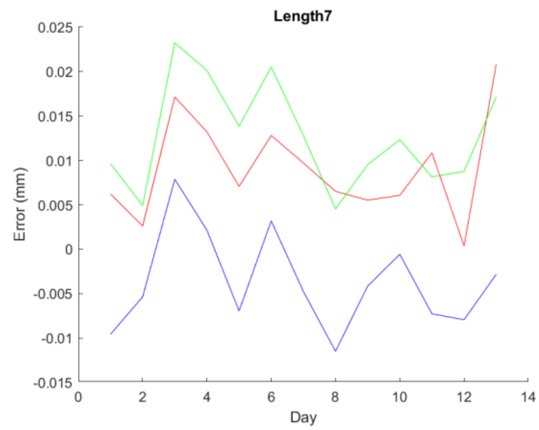

FIGURE E-7: Experiment 2 Length 7

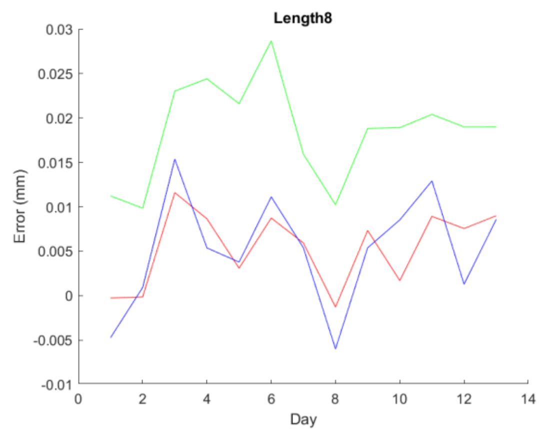

FIGURE E-8: Experiment 2 Length 8

APPENDIX F EXPERIMENT 3 ENVIRONMENT DATA RECORD

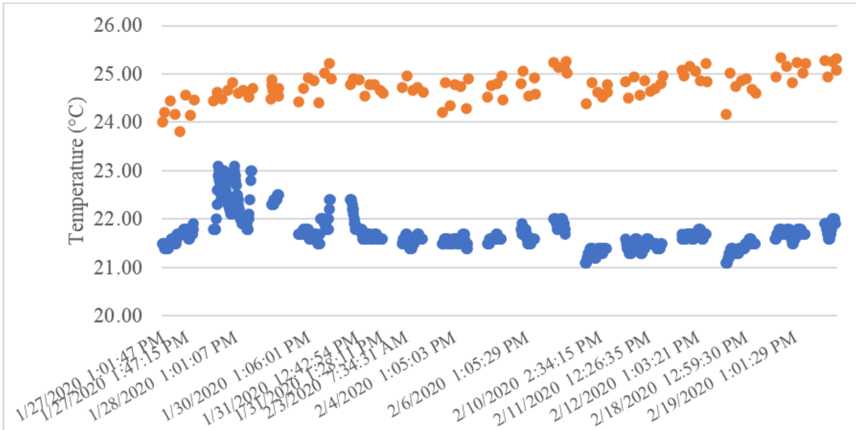

FIGURE F-1: Experiment 3 Temperature iServer & R.Pi

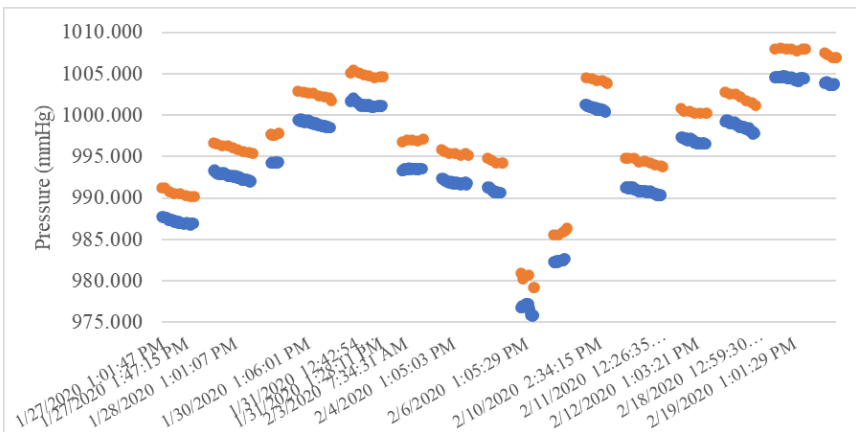

FIGURE F-2: Experiment 3 Pressure iServer & R.Pi

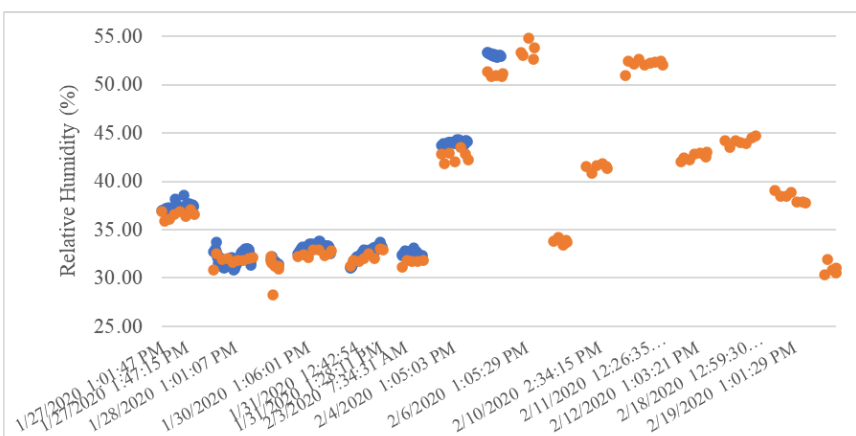

FIGURE F-3: Experiment 3 Relative Humidity iServer & R.Pi

Raspberry Pi data

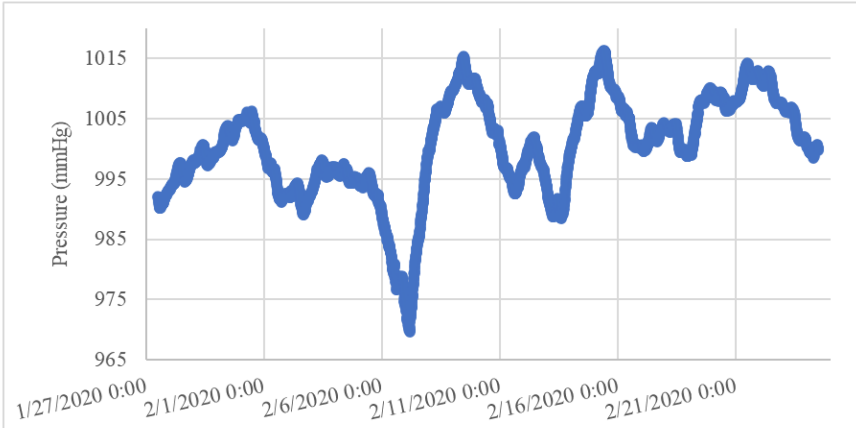

FIGURE F-4: Experiment 3 Pressure Raspberry Pi

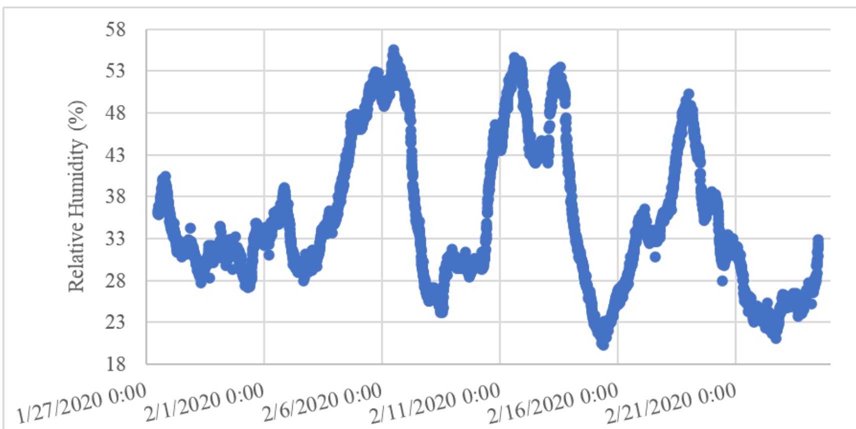

FIGURE F-5: Experiment 3 Relative Humidity Raspberry Pi

APPENDIX G EXPERIMENT 3 LENGTH ERRORS VS TIME

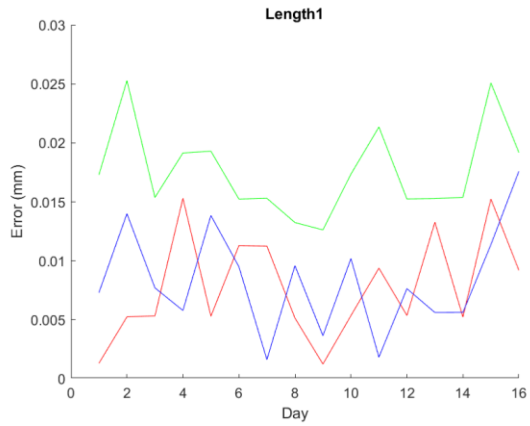

FIGURE G-1: Experiment 3 Length 1

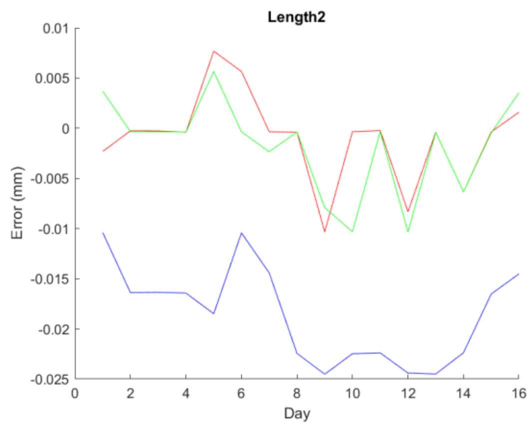

FIGURE G-2: Experiment 3 Length 2

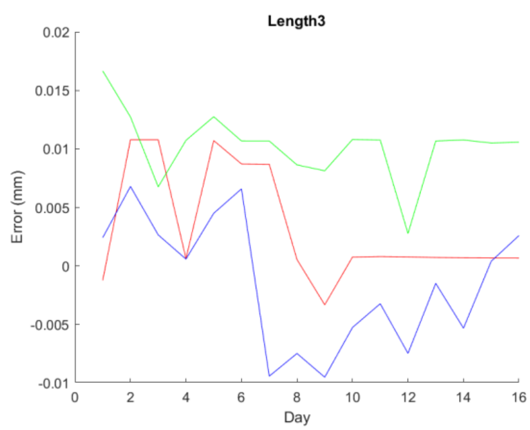

FIGURE G-3: Experiment 3 Length 3

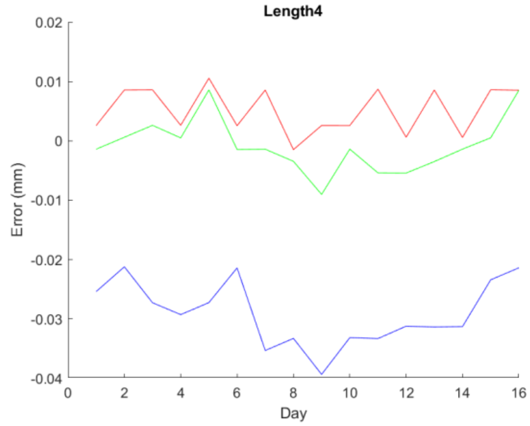

FIGURE G-4: Experiment 3 Length 4

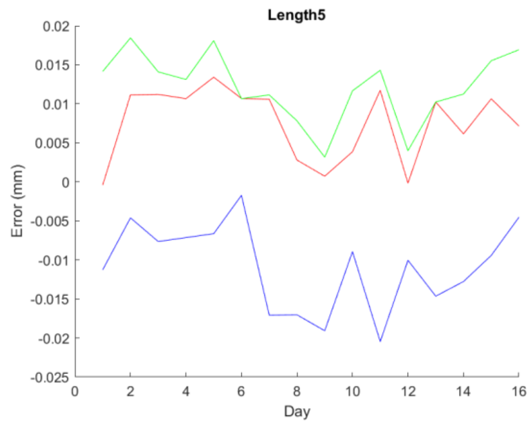

FIGURE G-5: Experiment 3 Length 5

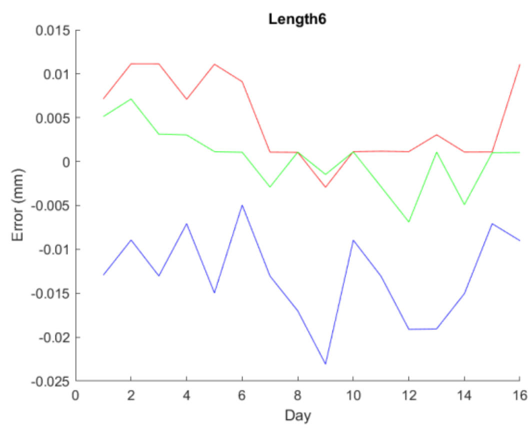

FIGURE G-6: Experiment 3 Length 6

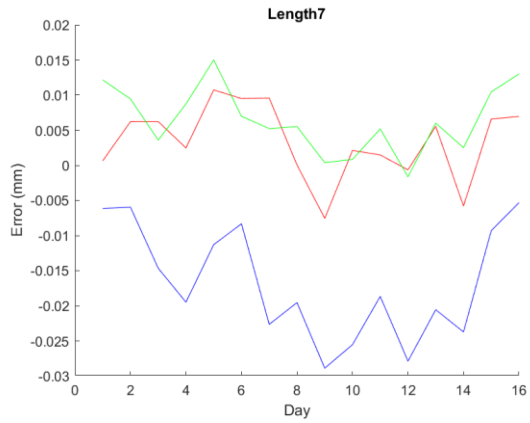

FIGURE G-7: Experiment 3 Length 7

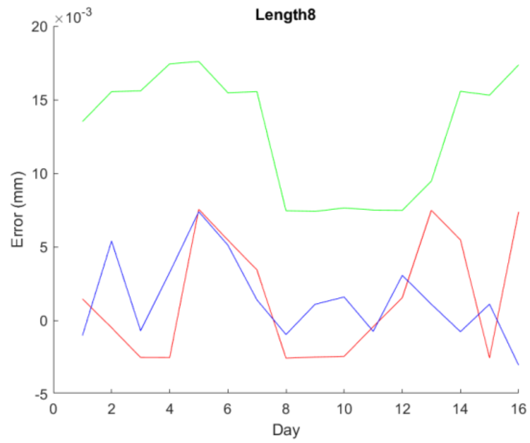

FIGURE G-8: Experiment 3 Length 8

APPENDIX H EXPERIMENT 4 ENVIRONMENT DATA RECORD

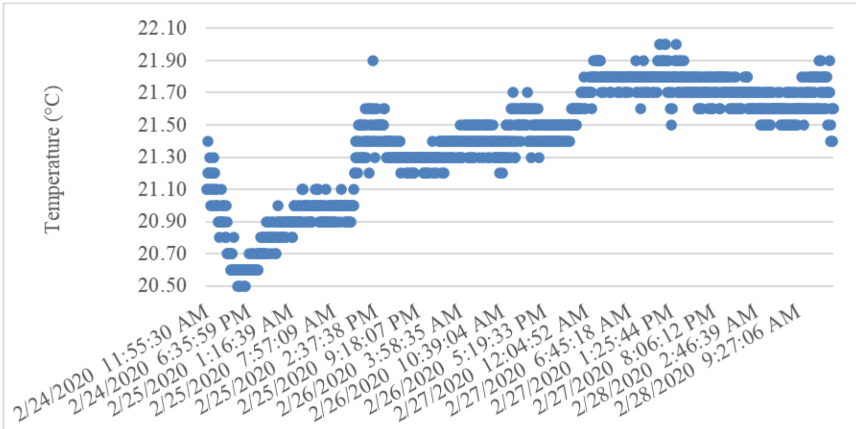

FIGURE H-1: Experiment 4 Temperature

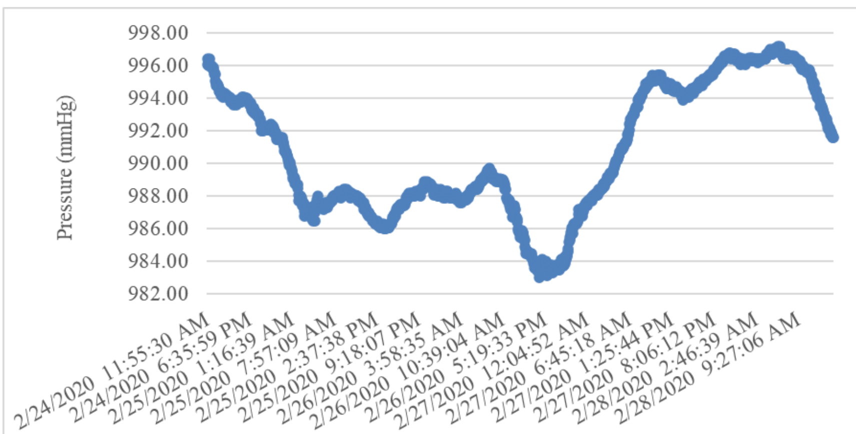

FIGURE H-2: Experiment 4 Pressure

APPENDIX I EXPERIMENT 4 BEFORE CALIBRATION LENGTHS

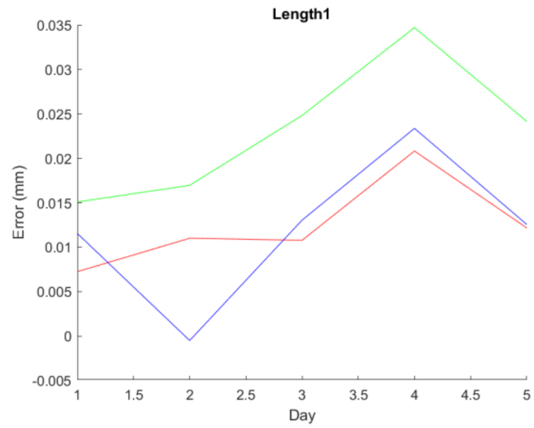

FIGURE I-1: Experiment 4 Length 1 Before

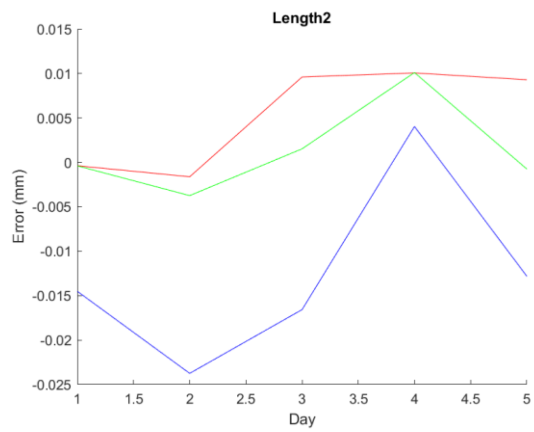

FIGURE I-2: Experiment 4 Length 2 Before

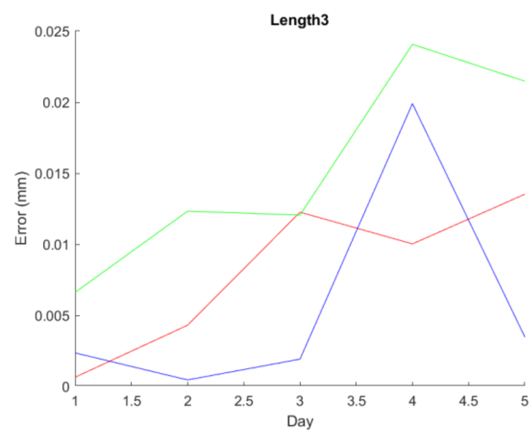

FIGURE I-3: Experiment 4 Length 3 Before

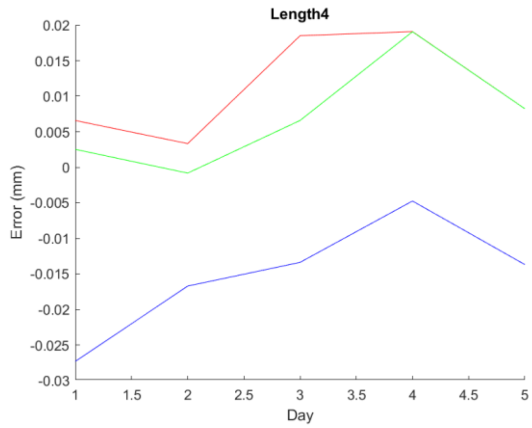

FIGURE I-4: Experiment 4 Length 4 Before

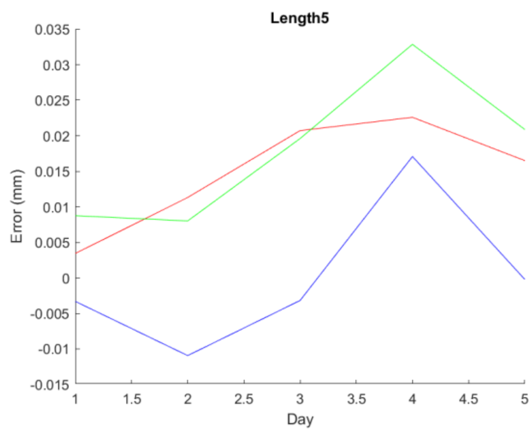

FIGURE I-5: Experiment 4 Length 5 Before

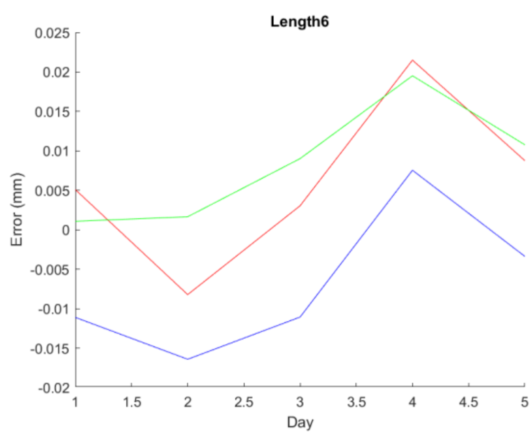

FIGURE I-6: Experiment 4 Length 6 Before

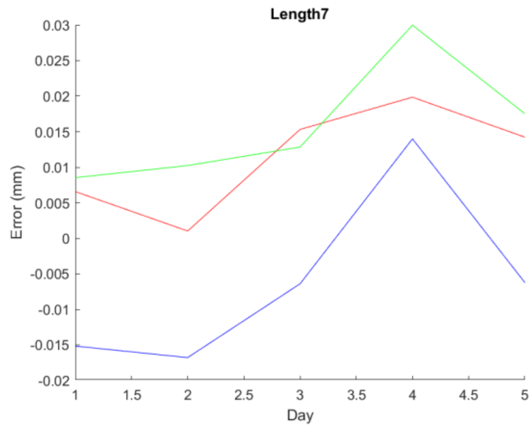

FIGURE I-7: Experiment 4 Length 7 Before

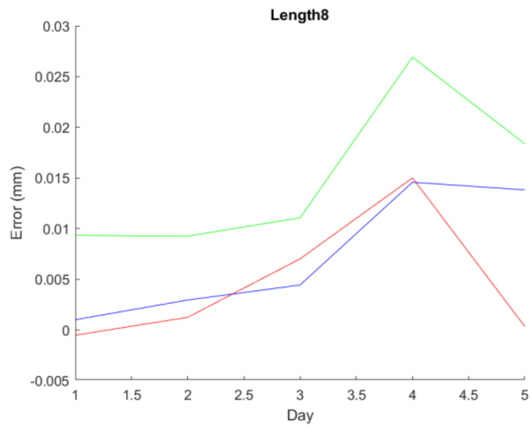

FIGURE I-8: Experiment 4 Length 8 Before

APPENDIX J EXPERIMENT 4 AFTER CALIBRATION LENGTHS

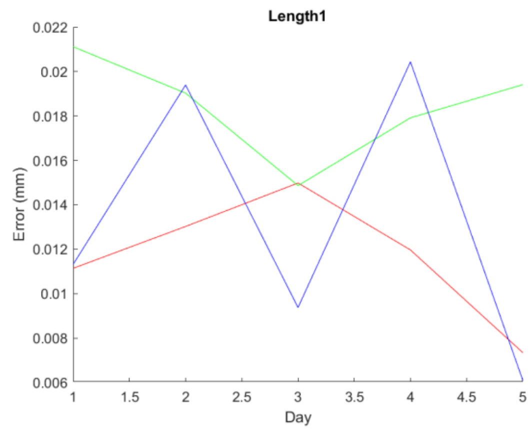

FIGURE J-1: Experiment 4 Length 1 After

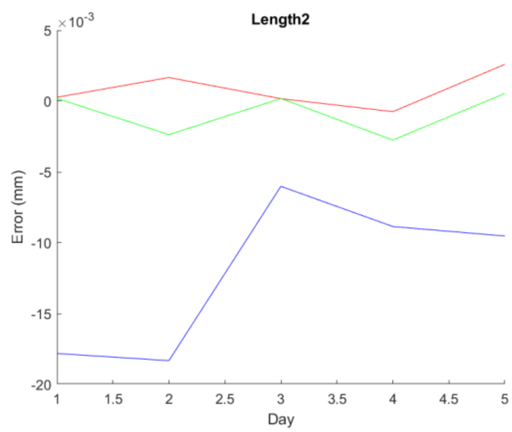

FIGURE J-2: Experiment 4 Length 2 After

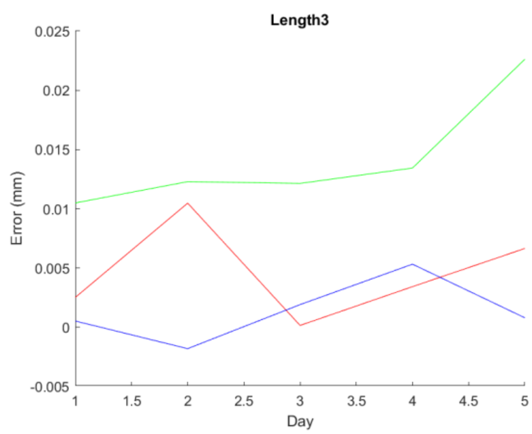

FIGURE J-3: Experiment 4 Length 3 After

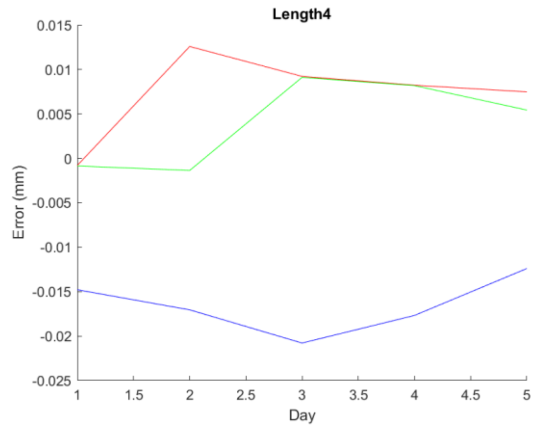

FIGURE J-4: Experiment 4 Length 4 After

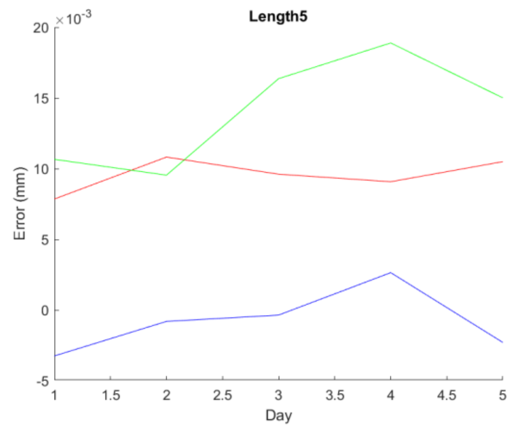

FIGURE J-5: Experiment 4 Length 5 After

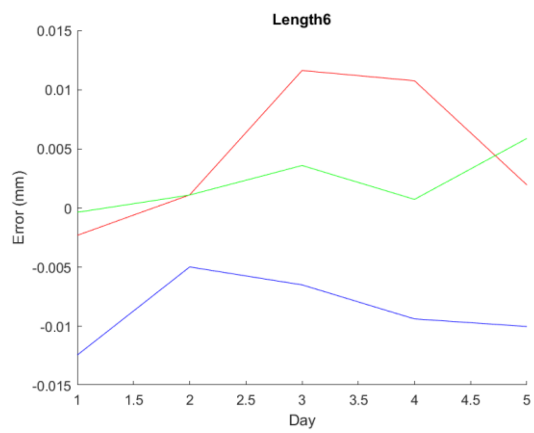

FIGURE J-6: Experiment 4 Length 6 After

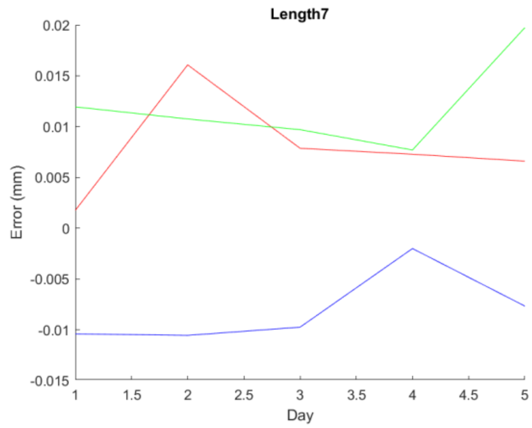

FIGURE J-7: Experiment 4 Length 7 After

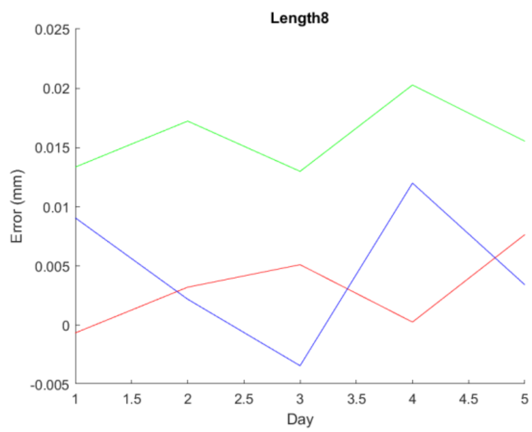

FIGURE J-8: Experiment 4 Length 8 After