



Prifysgol Cymru
Y Drindod Dewi Sant
University of Wales
Trinity Saint David

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Ultrasonic Attenuation Coefficient Determination and Probability of
Sizing Analysis

Tharish Ravin Ranjit (2208284)

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Part 1: Ultrasonic Attenuation Coefficient Determination

Abstract

The ultrasonic attenuation coefficient is determined for two metal samples in this part of the paper. Data was gathered using the time-of-flight method and then processed in two ways: trendline fitting of data points and applying a formula to two points simultaneously. Upon completion, the calculated coefficients are compared to outside sources for validation. This showed that the mild steel block is likely annealed 1020 steel while the brake disc is either 1020 or 1030 water-quenched steel.

1. Introduction

1.1. Aim and Objective

To determine the ultrasonic attenuation coefficient values of two material samples via the time-of-flight method.

1.2. Apparatus

The apparatus necessary to complete the assignment are listed below with some pictures:

- Mild steel rectangular block (Figure 1-1)
- A brake disc (Figure 1-2)
- Ultrasonic, zero-degree 5MHz probe (Figure 1-3)
- Ultrasonic Flaw Detector/ Oscilloscope (Figure 1-4)
- Dial calliper (Figure 1-5)
- Styling gel (Figure 1-6)
- Laptop/ MS Excel



Figure 1-1: Mild Steel Rectangular Block



Figure 1-2: Brake Disc (WooCommerce, 2023)



Figure 1-3: Ultrasonic, zero-degree 5MHz probe

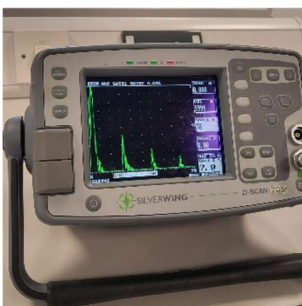


Figure 1-4: Ultrasonic Flaw Detector/ Oscilloscope



Figure 1-5: Dial calliper



Figure 1-6: Styling Gel

1.3. Procedure

The following procedure was applied to both samples:

1. Clean the sample and connect the equipment.
2. Use the dial calliper to measure the depth of the sample. Record it. (Figure 1-7)
3. Apply styling gel to the point of interest. The styling gel fills air gaps between the ultrasonic transducer and the test object, preventing transducer-to-air-to-test object refractions and reflections.
4. Place the transducer on the target area and adjust the gain of the oscilloscope, ensuring that back wall reflections are easy to read. (Figure 1-8)
5. Read and record the 1st, 2nd, and 3rd back-wall reflections. (Figure 1-9)
6. Repeat this 4 – 5 times to improve the reliability of readings while adjusting the gain.
7. Calculate the attenuation coefficient by comparing spikes 1, 2 and 3.
8. Plot the data and apply an exponential trendline to obtain another attenuation coefficient value which should align with the previously calculated value.
9. Find R^2 to assess the fit of the exponential fit line.
10. Calculate the average attenuation coefficient in dB/m and compare it to known values.

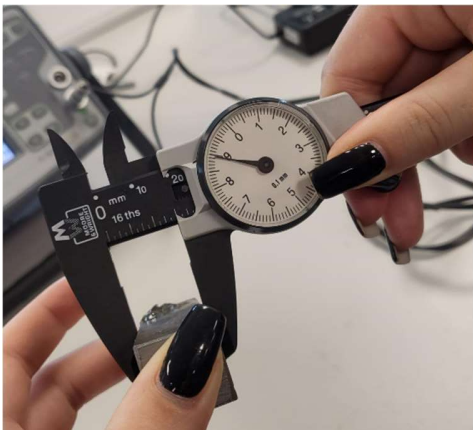


Figure 1-7: Use of Dial Calliper

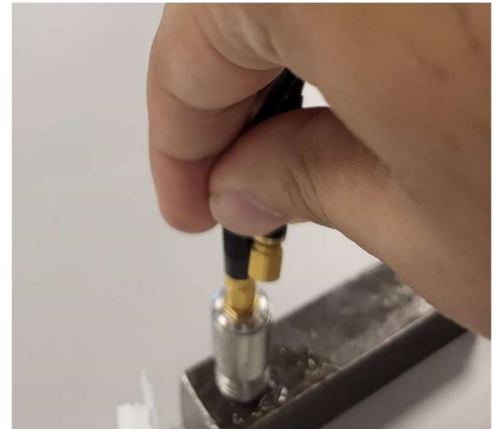


Figure 1-8: Use of Transducer



Figure 1-9: Backwall Reflections on Oscilloscope

2. Measurements and Graphs of Raw Measurements

Table 2-1 and Figure 2-1 show the values attained from the mild steel rectangular block, and Table 2-2 and Figure 2-2 shows brake disc values. Magnitudes are recorded as a percentage as they were taken directly from the oscilloscope.

Table 2-1: Mild Steel Block Data

Pos	E1	E2	E3
1	41	23	15
2	63	38	24
3	77	46	30
4	58	40	27
5	75	41	27

Table 2-2: Brake Disc Data

Pos	E1	E2	E3	Thickness
1	97	24	7	12.6
2	99	24	7	12.65
3	90	19	5	12.6
4	80	17	5	12.62

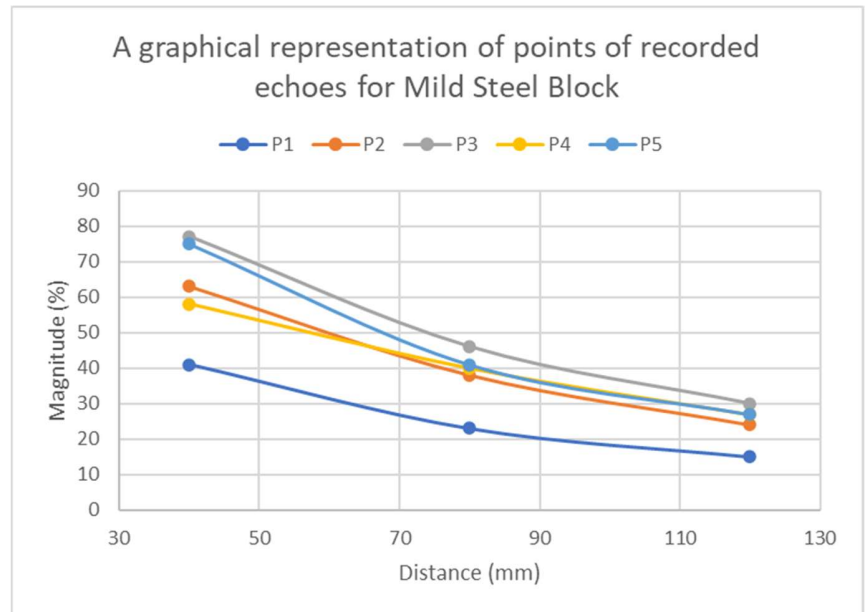


Figure 2-1: A graphical representation of points of recorded echoes for Mild Steel Block

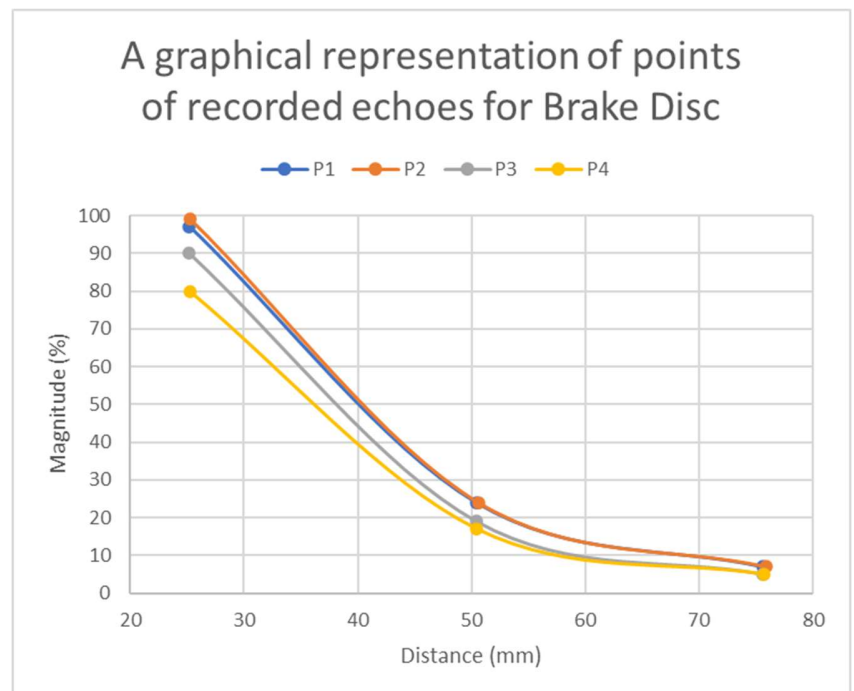


Figure 2-2: A graphical representation of points of recorded echoes for Brake Disc

3. Calculations

Attenuation refers to the effect of scattering and absorption within a medium. Due to this scattering and absorption, the intensity of sound travelling through a medium weakens with distance. Ultrasonic attenuation describes the rate of deterioration of a wave as it propagates through a material (Ono, 2020). The change in amplitude of a decaying plane wave is described by equation 3-1:

$$A = A_0 e^{-\alpha x} \quad (3-1)$$

Where A is the amplitude at a distance x from the A_0 location, e is Napier's constant. α is the attenuation coefficient of the wave with the dimension nepers/length. By dividing α by 0.1151, it can be converted to decibels per unit length. Exponential trendlines were added to the graphs in Figures 2-1 and 2-2 to obtain α . The coefficient was recorded and converted to the appropriate units. Figures 3-1 and 3-2 show the mild steel block and brake disc trendlines, respectively. Tabulated results are shown in Tables 3-1 and 3-2.

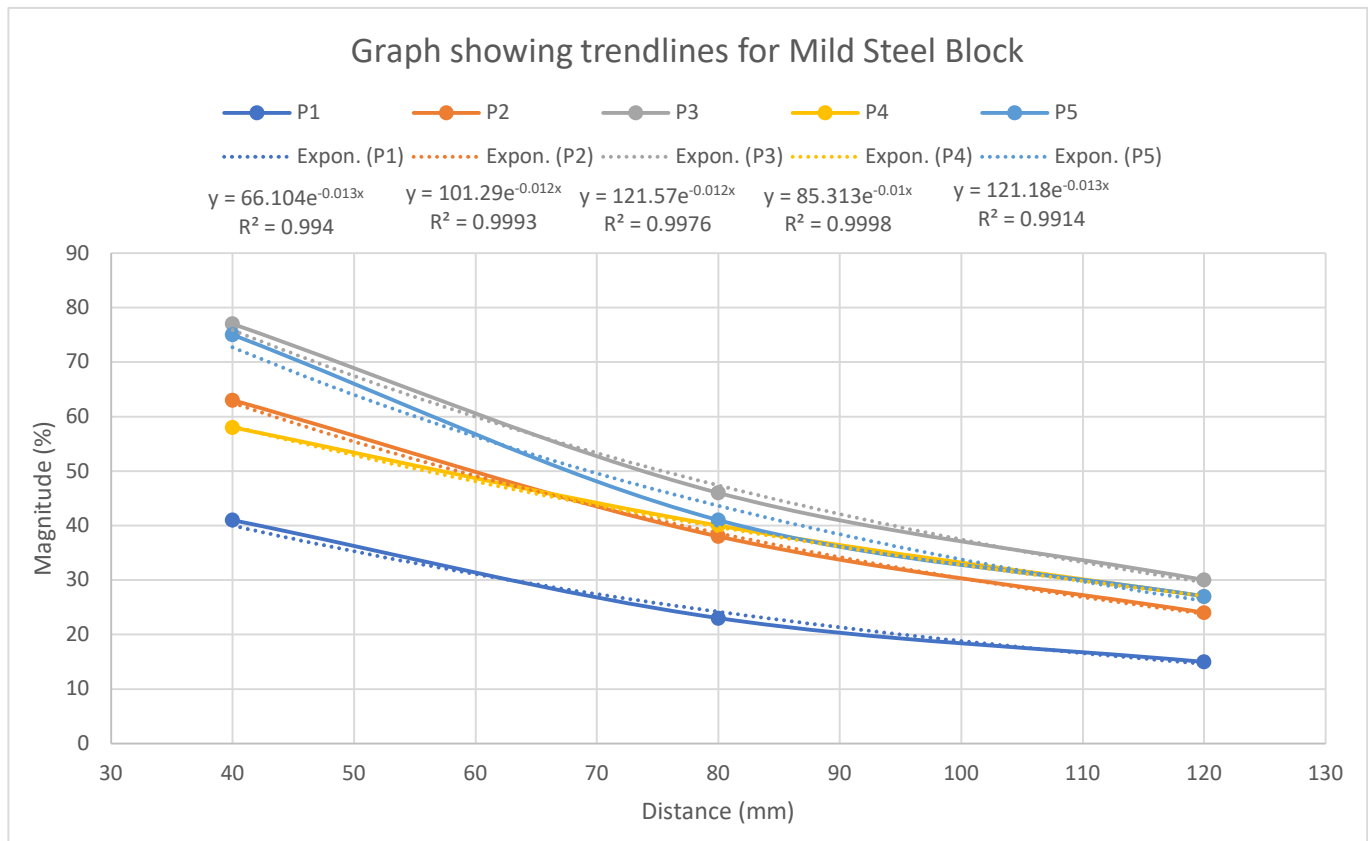


Figure 3-1: Graph showing trendlines for Mild Steel Block

Table 3-1: Mild Steel Block Trendline Results

Pos	α (nepers/length)	α (db/mm)
1	0.0126	0.1092
2	0.0121	0.1048
3	0.0118	0.1023
4	0.0096	0.0830
5	0.0128	0.1109
Average	0.0117	0.1020

A graphical representation of points of recorded echoes for the Brake Disc

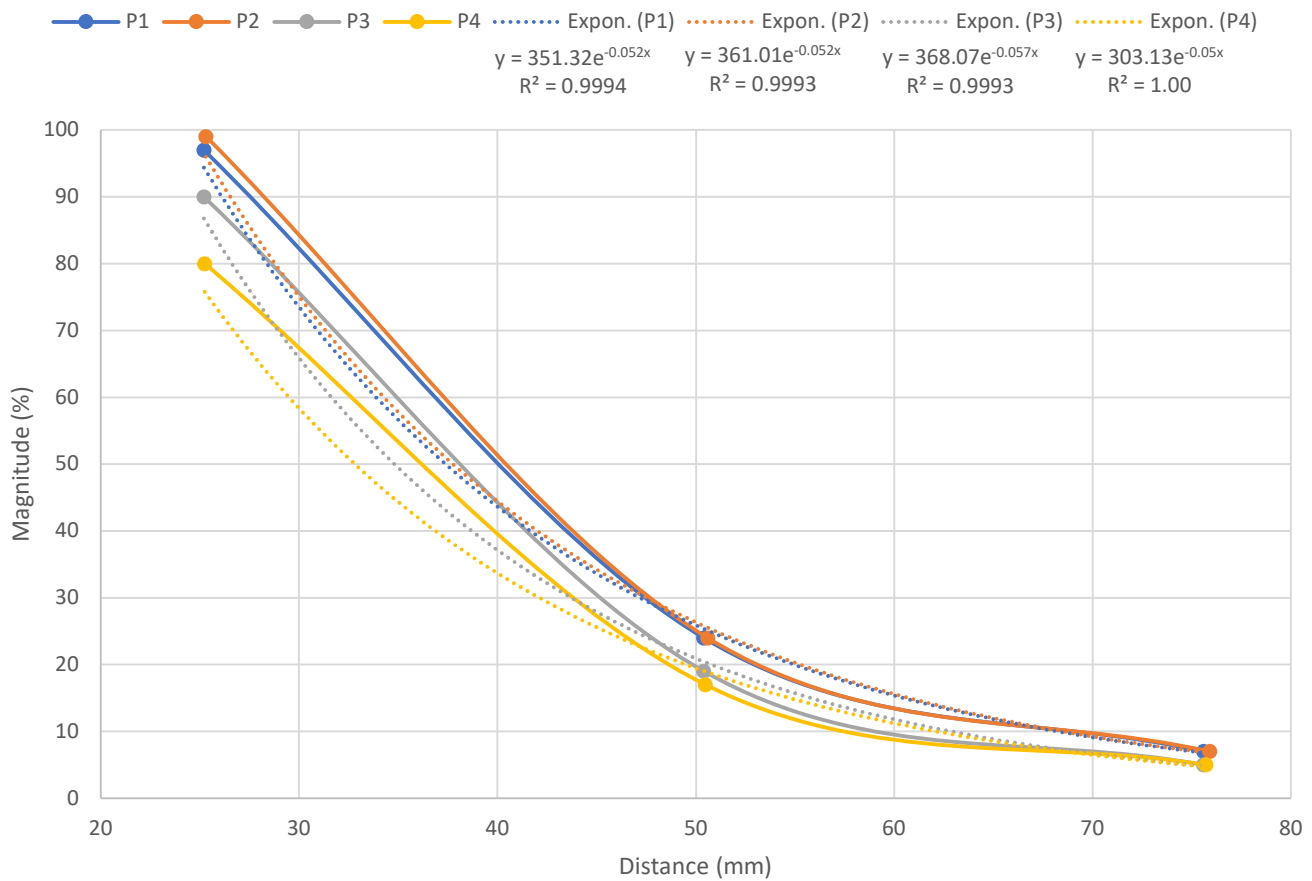


Figure 3-2: Graph showing trendlines for Brake Disc

Table 3-2: Brake Disc Trendline Results

Pos	α (nepers/length)	α (db/mm)
1	0.0522	0.4531
2	0.0524	0.4549
3	0.0573	0.4974
4	0.0549	0.4766
Average	0.0542	0.4705

The attenuation coefficients were also calculated using equation 3-2. This equation compares the magnitude of reflections (E1, E2 and E3) using the data in Tables 2-1 and 2-2. A sample calculation for the Mild Steel Block Position 1 comparing echoes 1 and 2 is given below. Tables 3-3 and 3-4 show the result of applying this equation comparing E1 and E2, E2 and E3, as well as E1 and E3.

$$\alpha_{dB/mm} = \frac{20}{x(mm)} \log_{10}\left(\frac{E1}{E2}\right) \quad (3-2)$$

$$\alpha_{dB/mm} = \frac{20}{40} \log_{10}\left(\frac{41}{23}\right) = 0.1255 \text{ dB/mm}$$

Table 3-3: Mild Steel Block Equation Results

Ratio dB	E1/E2	E2/E3	E1/E3	Average
1	0.1255	0.0928	0.1092	0.1092
2	0.1098	0.0998	0.1048	0.1048
3	0.1119	0.0928	0.1023	0.1023
4	0.0807	0.0853	0.0830	0.0830
5	0.1311	0.0907	0.1109	0.1109
			Tot Avg	0.1020

Table 3-4: Brake Disc Equation Results

Ratio dB	E1/E2	E2/E3	E1/E3	Ave
1	0.4814	0.4247	0.4530	0.4530
2	0.4865	0.4230	0.4548	0.4548
3	0.5361	0.4601	0.4981	0.4981
4	0.5331	0.4213	0.4772	0.4772
			Tot Avg	0.4708

4. Results and Discussion

Tables A-1 and A-2 in Appendix A show a statistical analysis of the results in terms of calculated results mean, standard deviation, and searches for outliers in terms of 3 standard deviations. For both samples, all results fall between three standard deviations.

Accounting for a mean $\pm$ 95% confidence interval: The results of the Mild Steel block showed an Attenuation Coefficient equal to 0.1020 ± 0.028 (dB/mm), and the brake disc showed an Attenuation Coefficient of 0.4707 ± 0.073 (dB/mm). Results were compared to those produced by the Department of Materials Science and Engineering at the University of California. A 1.35% difference is seen between the Mild Steel Block's Attenuation coefficient when compared to a sample of annealed 1020 steel. When accounting for the error range of calculated values, only the 1020 annealed steel is present. The material of the brake disc was not supplied. Comparing the computed results to those of the University of California, it is likely that the brake disc has been water-quenched 1020 or 1030 steel (Ono, 2020). A Vickers Hardness test will help pinpoint the sample's material.

5. Conclusion

The assignment brief was completed with the material attenuation coefficient values for both samples calculated; 0.1020 ± 0.028 (dB/mm) for the Mild Steel Rectangular Block and 0.4707 ± 0.073 (dB/mm) for the Brake Disc. All R^2 values of best-fit lines were greater than 0.99, implying a very strong correlation between data points and the trendline. The calculated value for the Mild Steel Block is identical to the Attenuation Coefficient obtained by graphical means, while the brake disc values vary by 0.06%.

Methods and scope for improvement include taking more readings to increase data reliability. There is a need for further studies to provide more data for correlation.

Part 2: Through Wall Sizing Accuracy Analysis

Abstract

In this assignment section, the sizing accuracy of technicians and the equipment were analysed by statistical means. It was found that the equipment was not suitable for defects smaller than 1.6mm. Technicians should be reassessed on more appropriate defects to provide a greater understanding of the equipment and their respective abilities.

6. Introduction

6.1. Aim and Objective

To assess the sizing accuracy of individual technicians and the equipment and procedure of a new ultrasonic thickness gauging procedure by means of statistical analyses.

6.2. Apparatus

The apparatus necessary to complete the assignment are listed below:

- Microsoft Excel
- 1x Laptop
- 1x External Display

6.3. Procedure

The assignment was conducted with the following procedure:

1. Download the given data.
2. Create an additional sheet in MS Excel and import the data for operator 1.
3. Plot Measured Size vs True Size values using a scatter plot. Apply a Linear trendline showing the equation of the line as well as linear regression. Record the gradient, Y-Axis intercept and R^2 values.
4. Calculate the Absolute Error, Percentage error and Percentage Absolute Error. Find the Mean, Standard Deviation and 95% Confidence of the previously mentioned errors.
5. Graph %Error vs True Size as a scatter plot.
6. Use the Mean Standard Deviation to plot and graph a Normal Distribution for Absolute Error.
7. Plot a Histogram showing the distribution of Absolute Error within the given population.
8. Duplicate this Excel sheet nine times and overwrite operator data creating ten sheets showing each technician's results.
9. Compile the results in a separate sheet and use data visualisation tools to aid in the analysis.
10. Draw conclusions from data about individual technicians and the equipment.

7. Given Data

Table 7-1 shows the data supplied, and Figure 7-1 shows a scatter plot of the data with a straight line depicting accurate results.

Table 7-1: Supplied Data

Defect	true size	Op1	Op2	Op3	Op4	Op5	Op6	Op7	Op8	Op9	Op10
A	0.25	0.50	0.50	0.00	1.00	0.00	0.50	0.50	0.80	1.00	0.30
B	0.27	0.73	1.20	0.50	1.00	0.00	1.00	0.50	0.80	1.00	1.20
C	0.28	0.76	1.00	1.20	1.00	0.00	0.50	0.50	1.30	1.00	0.70
D	0.40	0.91	0.50	1.00	1.20	1.00	1.00	0.60	1.50	1.00	0.80
E	0.40	0.98	1.20	1.00	1.40	1.00	1.10	0.20	1.60	1.00	0.90
F	0.50	0.79	0.90	1.00	1.10	1.00	0.80	0.00	1.00	1.20	0.50
G	0.52	1.01	1.50	1.10	0.90	1.50	1.00	1.00	0.90	1.00	0.70
H	0.55	0.96	1.20	0.80	0.50	0.90	1.20	1.30	1.60	1.00	0.40
I	0.70	1.35	1.50	0.90	2.00	1.60	1.20	1.60	2.20	1.00	1.00
J	0.98	1.31	1.00	0.80	1.90	2.00	1.60	0.50	1.80	1.00	1.40
K	1.12	1.37	0.50	1.00	1.00	1.80	1.80	1.80	2.00	1.50	1.30
L	1.15	1.56	1.80	1.30	2.20	1.00	1.50	1.80	2.00	1.50	1.20
M	1.10	1.60	2.00	1.40	2.00	1.60	1.50	0.50	2.20	2.00	1.60
N	1.30	1.73	2.10	0.90	2.20	2.00	2.00	1.70	2.00	1.50	1.70
O	1.60	1.56	0.80	0.90	2.00	2.00	1.50	1.20	2.00	2.00	1.50
P	1.80	2.14	2.00	1.40	2.40	2.00	3.20	2.20	2.50	2.50	1.10
Q	2.10	2.49	1.80	2.30	3.50	2.50	3.00	2.00	3.20	2.00	2.60
R	2.70	2.97	3.00	3.20	2.80	2.50	3.50	2.50	3.50	3.50	2.20
S	4.90	4.87	4.50	4.50	5.70	4.50	4.40	4.20	5.40	5.50	5.50
T	6.00	6.17	5.50	6.20	7.00	6.50	5.50	5.30	6.70	6.50	6.00
U	7.50	6.99	6.00	6.25	8.00	7.20	6.50	6.50	6.90	8.00	6.50

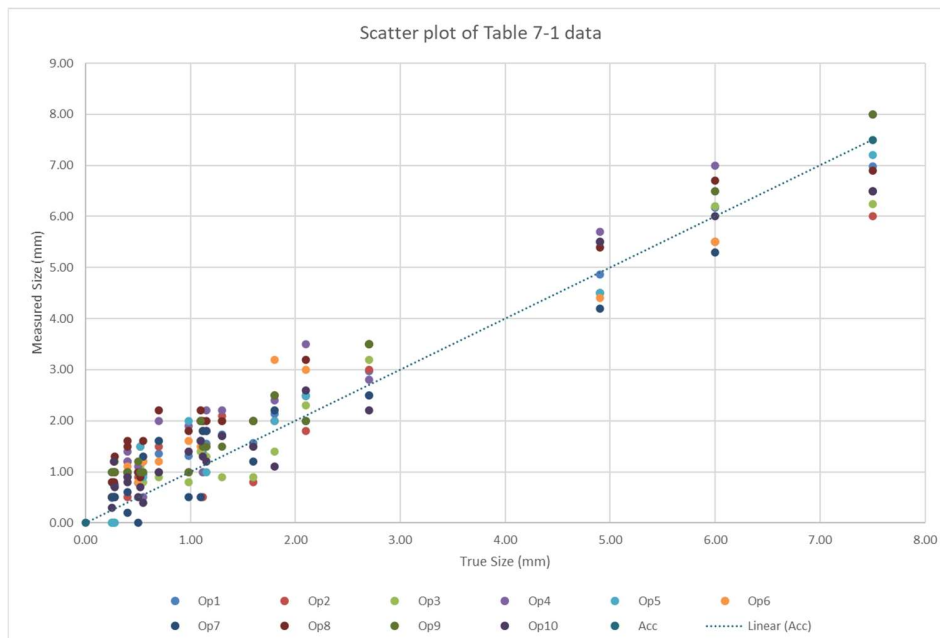


Figure 7-1: Scatter plot of given data

8. Calculations

The following section shows a sample calculation of data from technician 6. Error calculations and the formation of a normal distribution curve follow the generation of a trendline. Appendices B to E contain the results of these calculations applied to all data.

8.1. Trendline Generation

The formation of the trendline and accompanying information is generated in Microsoft Excel. This section discusses the necessary input data, underlying mathematics, and outputs. The input data can be seen in Figure 7-1. True size is the independent variable, and Measured Operator Size is dependent. A sample graph is shown in Figure 8-1. The method of least squares is used to form a trendline. The least-squares method is the most popular method to fit a regression line in the XY plot. The trendline for the given data is computed by minimising the sum of the vertical deviations squared from each data point to the line. The line takes the form of a straight-line graph with equation 8-1, where “m” is the regression coefficient that describes the average change in the Y-Axis per unit of change in the X-Axis. “c” is the intercept on the Y-Axis of the trendline. In a case where a 1:1 graph is expected, this is an offset. R^2 is the correlation coefficient that measures the extent of the relationship between the dependent and independent variables (BYJUS, 2020).

$$y = mx + c \quad (8-1)$$

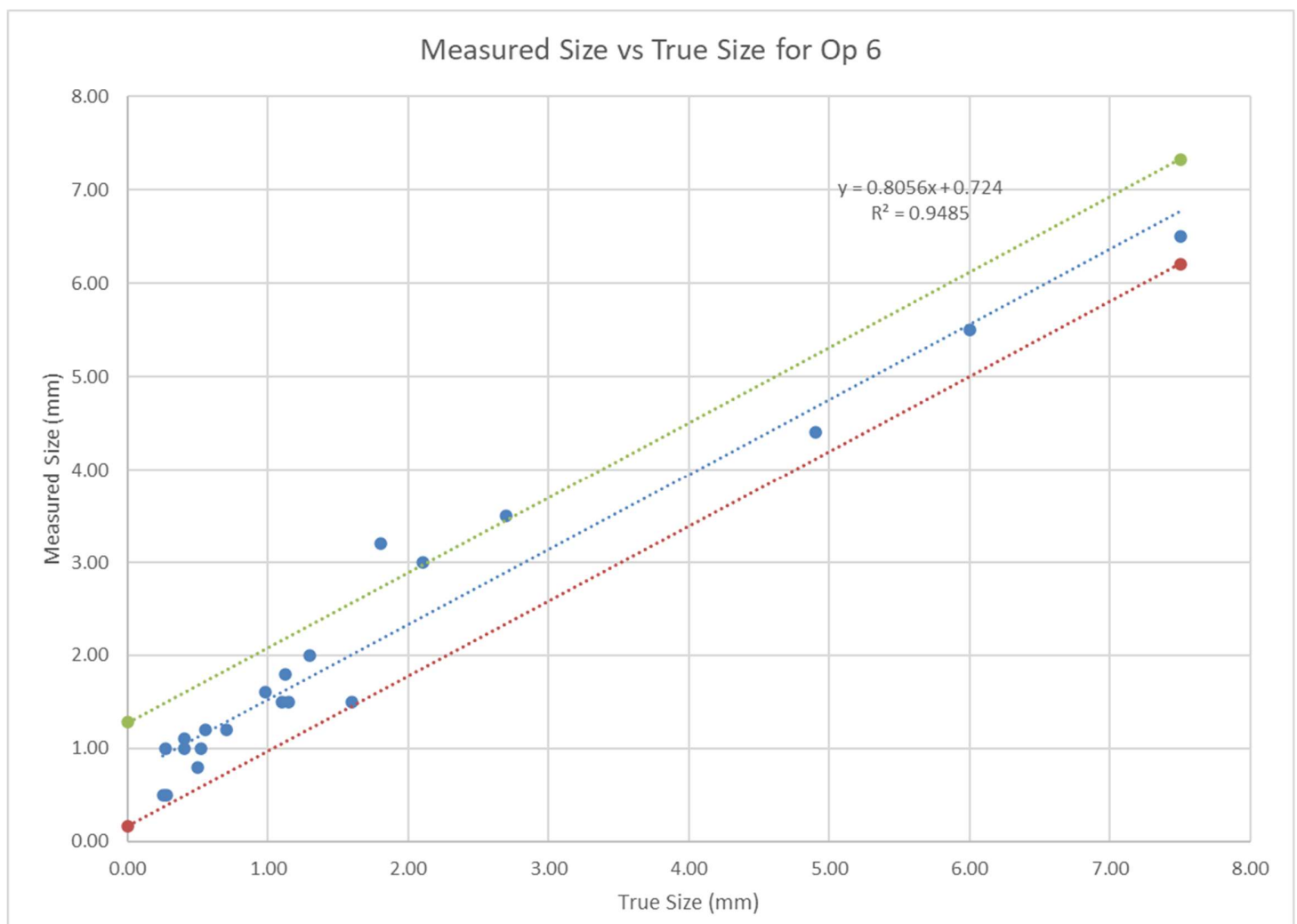


Figure 8-1: Measured Size vs True Size for Technician 6

8.2. Error Calculations

The Absolute Error was calculated by subtracting the Measured Size from the True Size and taking the absolute value of the result. Equation 8-1 shows the formula used and a sample calculation of defect T. Table 8-1 shows the calculation applied to all defect measurements by operator 6.

$$Abs\ Error = |Measured\ size - True\ size| \quad (8-2)$$

$$Abs\ Error = |5.5 - 6.00| = |-0.5| = 0.5\ mm$$

Percentage Error was calculated using equation 8-2, and taking the absolute value produced the Absolute Percentage Error.

$$\% Error = \frac{Measured\ Size - True\ Size}{True\ Size} \% \quad (8-3)$$

$$\% Error = \frac{5.5 - 6}{6} \% = -8\%$$

$$\% Abs\ Error = |\%Error| = |-8| = 8\%$$

Table 8-1: Results of Error calculations for Operator 6

0.27	1.00	0.73	270%	270%
0.28	0.50	0.22	79%	79%
0.40	1.00	0.6	150%	150%
0.40	1.10	0.7	175%	175%
0.50	0.80	0.3	60%	60%
0.52	1.00	0.48	92%	92%
0.55	1.20	0.65	118%	118%
0.70	1.20	0.5	71%	71%
0.98	1.60	0.62	63%	63%
1.12	1.80	0.68	61%	61%
1.15	1.50	0.35	30%	30%
1.10	1.50	0.4	36%	36%
1.30	2.00	0.7	54%	54%
1.60	1.50	0.1	-6%	6%
1.80	3.20	1.4	78%	78%
2.10	3.00	0.9	43%	43%
2.70	3.50	0.8	30%	30%
4.90	4.40	0.5	-10%	10%
6.00	5.50	0.5	-8%	8%
7.50	6.50	1	-13%	13%
Mean		0.59	70%	74%
Std Dev		0.29	66%	62%
95% Confidence		0.559318	129%	121%

8.3. Normal Distribution

The normal distribution is a symmetrical probability distribution. Also known as the Gaussian distribution, the bell curve is symmetrical about the mean and shows that data closer to the mean occur more frequently when compared to data far from the central mean (Chen, 2022). The mean and standard deviation need to be calculated to produce a normal distribution from a data set. The mean is calculated by summing all data point values and dividing by the number of points. A sample calculation follows equation 8-4.

$$\text{Mean} = \frac{\sum \text{Data Point Values}}{\text{No. Data Points}} \quad (8-4)$$

$$\text{Abs Error Mean} = \frac{12.39}{21} = 0.59 \text{ mm}$$

The standard deviation for a population of data is given by equation 8-5. Where σ is the Population Standard Deviation, N is the Total Number of Observations, X is the value in the data distribution and μ the Population Mean. A sample calculation is shown.

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (X_i - \mu)^2} \quad (8-4)$$

$$\sigma = \sqrt{\frac{1}{21} \sum_{i=1}^{21} (X_i - 0.59)^2} = 0.29 \text{ mm}$$

Figure 8-3 shows the normal distribution curve generated by the previously calculated data, and Figure 8-4 is a histogram of the Absolute Error Distribution of operator 6. The SKEW function was then applied to the Absolute Error values. Describing the degree of asymmetry (Microsoft, 2023), results are shown in the following section.

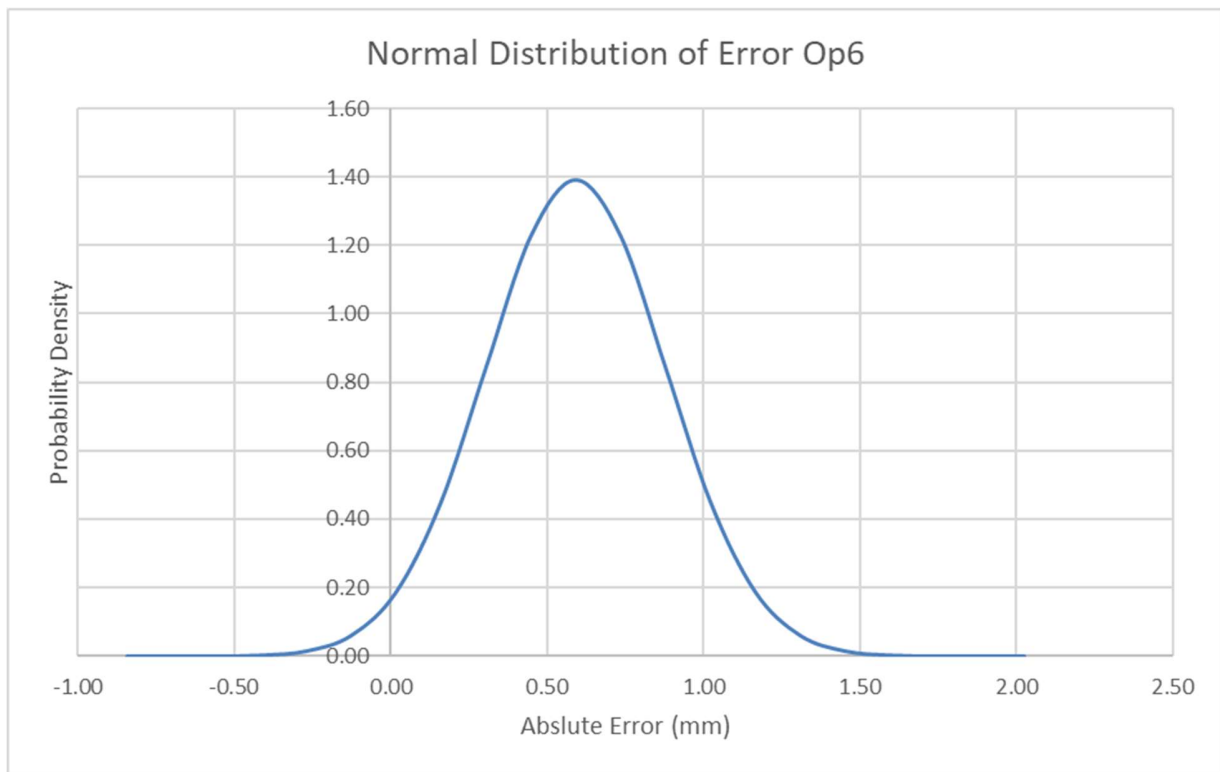


Figure 8-2: Normal Distribution of Error for Operator 6

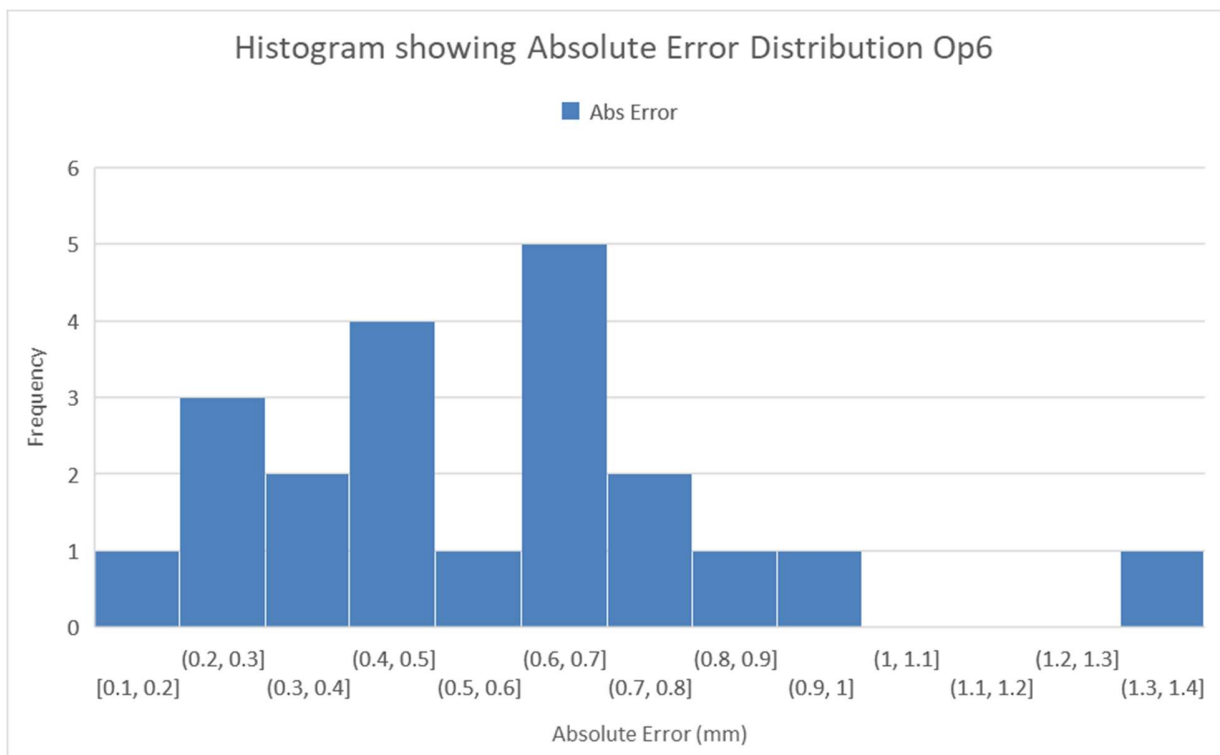


Figure 8-3: Histogram showing Absolute Error Distribution of Operator 6

9. Results and Discussion

The following section analyses the results of the sizing accuracy of individual operators and the equipment and procedure.

9.1. Operator Analysis

Table 9-1 shows the mean, standard deviation, 95% confidence range and skewness of the absolute error of operators. The first three of these are graphed in Figure 9-1. These values being as low as possible is desirable. Table 9-2 and Figure 9-2 contain summarised information about the applied trendline.

Table 9-1: Linear Regression properties of Operators Absolute Errors

Operator	1	2	3	4	5	6	7	8	9	10
Mean	0.37	0.60	0.43	0.72	0.48	0.59	0.48	0.81	0.51	0.38
Std Dev	0.16	0.34	0.28	0.36	0.25	0.29	0.25	0.29	0.23	0.28
95% Confidence	0.31	0.67	0.54	0.70	0.49	0.56	0.48	0.56	0.44	0.54
Skewness	-0.54	0.44	1.36	-0.20	0.74	0.79	0.35	0.45	-0.45	0.55

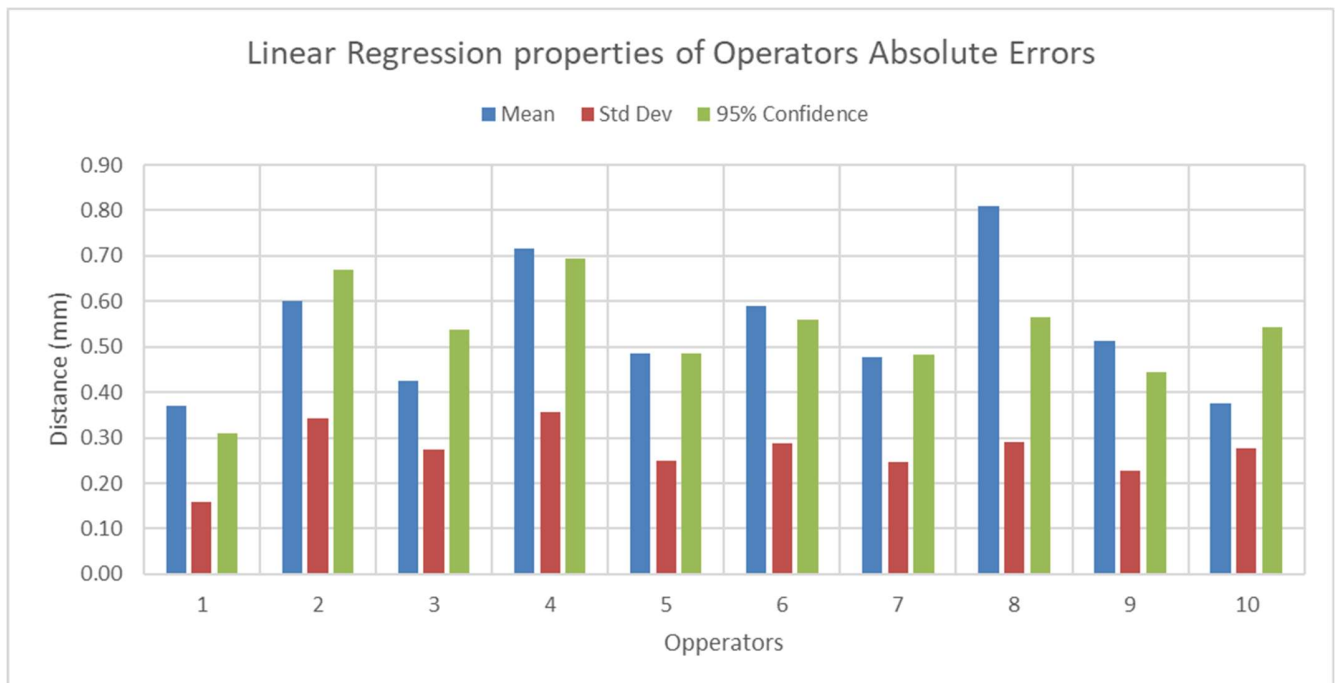


Figure 9-1: Linear Regression properties of Operators Absolute Errors

Table 9-2: Operator Trendline Properties

Operator	1	2	3	4	5	6	7	8	9	10
Offset	0.49	0.64	0.32	0.69	0.44	0.72	0.32	0.97	0.51	0.33
Gradient	0.90	0.75	0.85	1.00	0.92	0.81	0.82	0.87	0.99	0.89
R ²	0.99	0.91	0.94	0.96	0.95	0.95	0.94	0.87	0.98	0.95

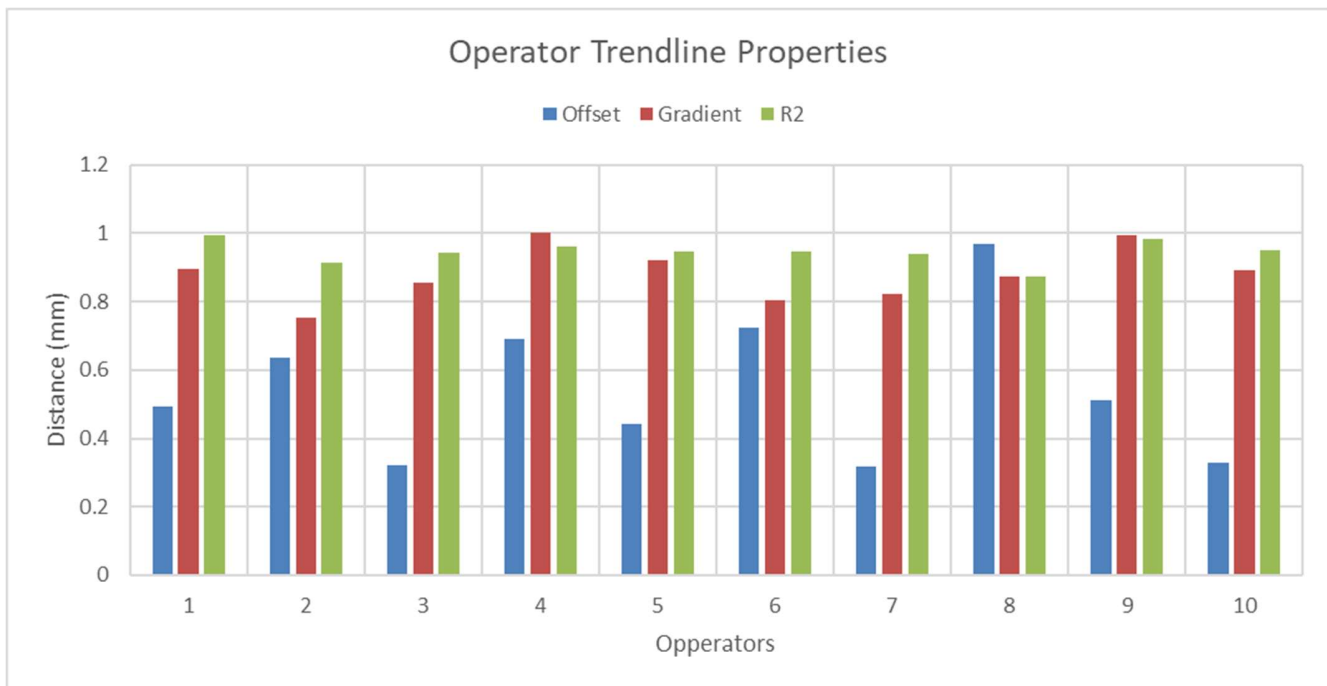


Figure 9-2: Operator Trendline Properties

When assessing Mean Absolute Error, technician one was the most accurate at sizing defects. A low Standard Deviation implies a high confidence level, as seen by the narrow 95% confidence band in Figure C-1. Operator 1's results contained a slight negative skewness. Drawing from the trendline data, this operator's results were consistently offset with a Y-Axis intercept of 0.49mm noted. A gradient of 0.9 and an R^2 value of 0.99 imply a consistency in measurements and an extremely high level of correlation between data points and the line of best fit.

Technician two ranked 8th in terms of Mean Absolute Error. A high Standard Deviation and a low trendline gradient show poor consistency, as seen by the wide confidence band and scattered results in Figure C-2. This results in a relatively low trendline correlation coefficient. This technician data contained a medium positive bias when comparing a histogram, Figure E-5, to the Normal Distribution, Figure E-4.

Despite a low offset and mean absolute error, Technician 3 showed poor quality in sizing defects. This result is due to a moderately large standard deviation and extreme positive skewness. These factors can be seen in Figures C-3 and E-7.

Operator 4 was poor in most respects. A high absolute mean error, standard deviation and offset are present. Technician 4 provided data most akin to the normal distribution with a skewness of -0.2. As seen in Figure C-4, a high R^2 value of 0.96 and a gradient equal to 1 imply consistency but are undermined by a high standard deviation.

Ranking in joint 5th for mean absolute error accuracy and obtaining identical relatively low standards of deviation, technicians 5 and 7 provide moderately accurate results. Technician 5's data had a strong positive skewness, while 7's was less strong. Operator 5 had a moderate to low relative offset and good gradient with high correlation. Technician 7 had the lowest offset value, but a low correlation and gradient imply flaws in their measurements.

From Table 9-1, operators 6, 8 and 10 have almost identical confidence bands, and all pose some degree of positive skewness. Technician 6 has a moderately high mean absolute error and offset, implying inaccuracy. Operator 8 data objectively shows them as the worst performer with the highest mean absolute error, offset, and a low correlation coefficient. Technician 10 is a relatively high performer in sizing accuracy, with a low offset of 0.33mm and a moderately high R^2 value.

While having a moderately poor mean absolute error, offset and negatively skewing data, operator 9 shows a high level of consistency with a narrow 95% confidence interval and a near-perfect trendline gradient and correlation coefficient. These results can be seen in Figure C-9.

9.2. Equipment Analysis

This analysis looks at the procedure and equipment as a collective. Therefore, individual technician data is compiled and investigated for trends. Figure 9-4 summarises in the form of a pie chart the data found in Table 9-3, and Figure 9-5 does so in with a scatter plot.

Figure 9-4 shows that 74% of measured values overestimate the defect size while 20% undersize and 6% are accurate (within 5%). Figure 9-5 shows extreme variation and inaccuracy in results at defect sizes below 0.7 mm. The majority of these errors have oversize defects. As defect size increases, the % Error progressively becomes exponentially smaller.

Table 9-3: % Error vs True Size for all Operators

% Error										
true size	Op1	Op2	Op3	Op4	Op5	Op6	Op7	Op8	Op9	Op10
0.25	98%	100%	-100%	300%	-100%	100%	100%	220%	300%	20%
0.27	169%	344%	85%	270%	-100%	270%	85%	196%	270%	344%
0.28	171%	257%	329%	257%	-100%	79%	79%	364%	257%	150%
0.40	128%	25%	150%	200%	150%	150%	50%	275%	150%	100%
0.40	145%	200%	150%	250%	150%	175%	-50%	300%	150%	125%
0.50	58%	80%	100%	120%	100%	60%	-100%	100%	140%	0%
0.52	95%	188%	112%	73%	188%	92%	92%	73%	92%	35%
0.55	74%	118%	45%	-9%	64%	118%	136%	191%	82%	-27%
0.70	93%	114%	29%	186%	129%	71%	129%	214%	43%	43%
0.98	33%	2%	-18%	94%	104%	63%	-49%	84%	2%	43%
1.12	23%	-55%	-11%	-11%	61%	61%	61%	79%	34%	16%
1.15	35%	57%	13%	91%	-13%	30%	57%	74%	30%	4%
1.10	45%	82%	27%	82%	45%	36%	-55%	100%	82%	45%
1.30	33%	62%	-31%	69%	54%	54%	31%	54%	15%	31%
1.60	-3%	-50%	-44%	25%	25%	-6%	-25%	25%	25%	-6%
1.80	19%	11%	-22%	33%	11%	78%	22%	39%	39%	-39%
2.10	19%	-14%	10%	67%	19%	43%	-5%	52%	-5%	24%
2.70	10%	11%	19%	4%	-7%	30%	-7%	30%	30%	-19%
4.90	-1%	-8%	-8%	16%	-8%	-10%	-14%	10%	12%	12%
6.00	3%	-8%	3%	17%	8%	-8%	-12%	12%	8%	0%
7.50	-7%	-20%	-17%	7%	-4%	-13%	-13%	-8%	7%	-13%

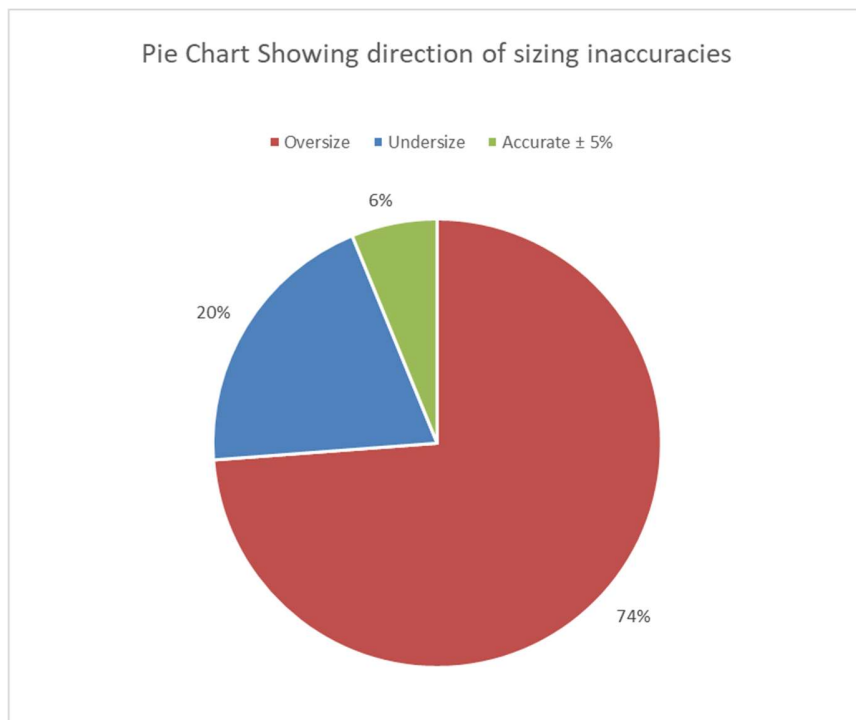


Figure 9-3: Pie Chart Showing direction of sizing inaccuracies

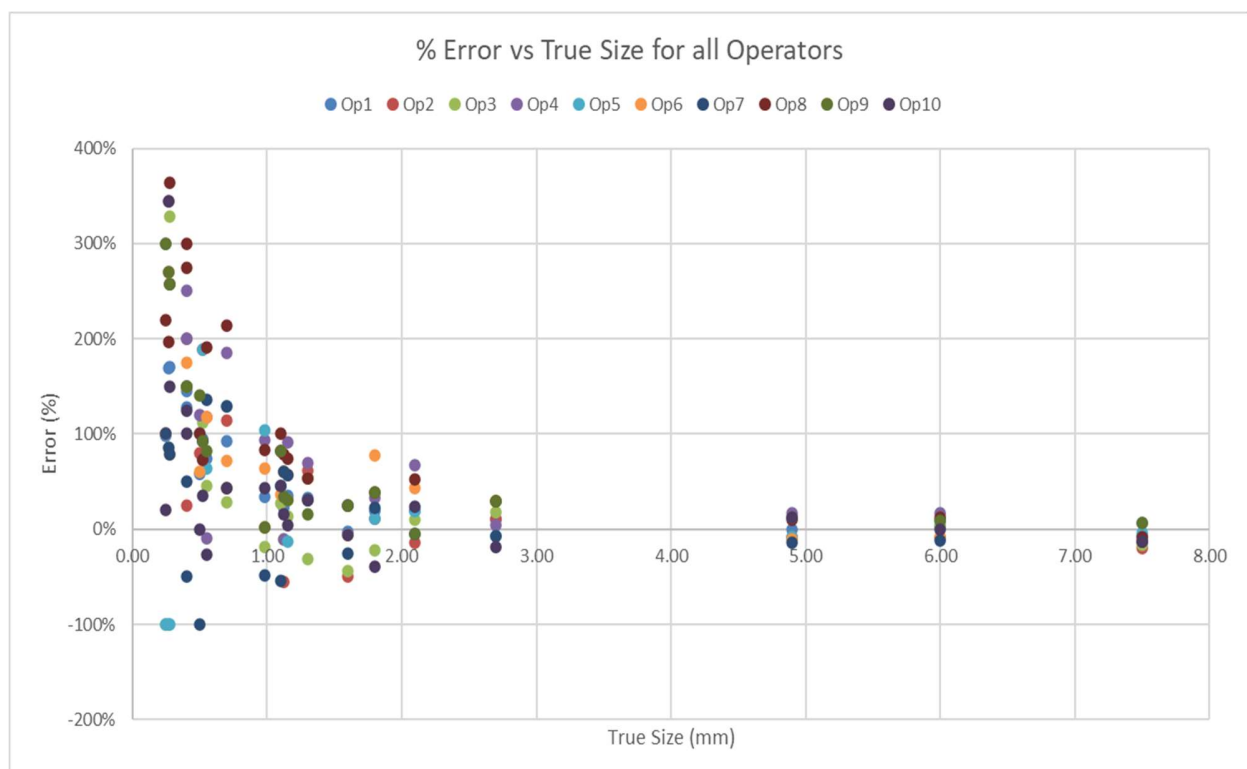


Figure 9-4: % Error vs True Size for all Operators

10. Conclusion

Despite some negative skewness, operator one is the most accurate technician, with results containing a high level of confidence. Operators 3 and 10 are next best in terms of mean absolute error accuracy, but their results are below average in consistency. Technicians 5, 7 and 9 are average performers in terms of mean error, but their consistency is above average. Technicians 2 and 6 are below average in all respects, while 4 and 8 are the poorest operators.

It is clear from Figure 9-5 that this equipment is not suitable for accurately sizing defects smaller than 1.6 mm. The equipment tends to but is not limited to oversizing defects smaller than 1.3 mm. Above 2.7 mm, the equipment tends to be more accurate. Beyond this, there is little to no improvement in sizing accuracy.

Future work should include technicians being assessed on sizing accuracy on defects within the range of 1.5 mm to 10 mm. This will provide more data regarding their technical abilities as well as the accuracy of the procedure. A possible improvement to technician analysis would be creating a weighted scoring table to sort the best-performing to the worst.

Appendix

A. Appendix A – Part 1 Data

Table A-1: Statistical analysis of Mild Steel Block results

	0.5361
	0.5331
	0.4981
	0.4865
	0.4814
	0.4772
	0.4601
	0.4548
	0.4530
	0.4247
	0.4230
	0.4213
Mean	0.4708
Std Dev	0.0375
Mean - 3Std	0.3584
Mean + 3Std	0.5832
Mean - 1.95Std	0.3977
Mean + 1.95Std	0.5438

Table A-2: Statistical analysis of Brake Disc results

	0.1311
	0.1255
	0.1119
	0.1109
	0.1098
	0.1092
	0.1048
	0.1023
	0.0998
	0.0928
	0.0928
	0.0907
	0.0853
	0.0830
	0.0807
Mean	0.1020
Std Dev	0.0144
Mean - 3Std	0.0590
Mean + 3Std	0.1451
Mean - 1.95Std	0.0740
Mean + 1.95Std	0.1300

Test	Material *	C _d	C _R	α at 5 MHz	Velocity	Thickness	Vickers HN	Notes
No.		dB/m/MHz	dB/m/MHz ⁴	dB/m	mm/μs	mm		
F1	Pure Fe	129.0		645.0	6.05	72.1	174	Cold-worked
F2	Pure Fe	125.8		629.0	6.08	30.2	91	Annealed
F3	A36 steel	12.4		62.0	5.90	59.8	159	
F4	1020	91.1		455.5	5.75	13.5	206	Water-quenched
F5	1020	76.9		384.5	5.73	13.2	172	WQ + tempered
F6	1020	51.5		257.5	5.85	13	151	WQ + tempered
F7	1020	23.4		117.0	5.87	12.6	139	WQ + tempered
F8	1020	18.8	1.50 × 10 ⁻²	103.4	5.85	13.3	114	Annealed
F9	1020	9.8	1.41 × 10 ⁻²	57.8	5.91	31.8	100	Annealed
F10	1020	7.6	8.60 × 10 ⁻³	43.4	5.87	139	100	Annealed
F11	1020	7.5	5.74 × 10 ⁻³	41.1	5.87	31.8/139	100	Annealed TDM-1
F12	Low-C steel	0.0	(4.84: n = 2)	243.8	5.93	66.4	161	Same as F13, F14
F13	Low-C steel (T)	0.0	(9.62: n = 2)	241.0	5.70	61.1	161	
F14	Low-C steel (S)	18.4	3.96 × 10 ⁻²	111.1	5.86	31.0	161	
F15	Low-C steel (T)	6.8	1.60 × 10 ⁻³	34.8	5.81	25.0	126	Annealed
F16	Low-C steel (S)	22.5		112.5	5.90	31.0	126	Same as F15
F17	Low-C steel (T)	29.0		145.0	5.88	37.8	158	
F18	Low-C steel (S)	21.6	7.88 × 10 ⁻³	178.5	5.84	19.0	110	Annealed
F19	F30 (1025)	81.6		408.0	5.82	16.3	311	Water-quenched
F20	F30 (1025)	51.6		258.0	5.77	15.3	287	Water-quenched
F21	F30 (1025)	36.3		181.5	5.81	15.5	252	Normalized
F22	F30 (1025)	66.0		330.0	5.78	16.0	197	WQ + tempered
F23	F30 (1025)	14.3		71.5	5.83	15.4	180	WQ + tempered
F24	F50 (1030)	99.3		496.5	5.75	15.1	576	Water-quenched
F25	F50 (1030)	40.3		201.5	5.73	15.6	418	WQ + tempered

Figure A-1: University of California Results (Ono, 2020)

B. Appendix B – Error Tables

Table B-1: Error Table for Operator 1

true size	Op1	Abs Error	% Error	Abs % Error
0.25	0.50	0.245	98%	98%
0.27	0.73	0.457	169%	169%
0.28	0.76	0.478	171%	171%
0.40	0.91	0.51	128%	128%
0.40	0.98	0.58	145%	145%
0.50	0.79	0.29	58%	58%
0.52	1.01	0.492	95%	95%
0.55	0.96	0.405	74%	74%
0.70	1.35	0.65	93%	93%
0.98	1.31	0.328	33%	33%
1.12	1.37	0.252	23%	23%
1.15	1.56	0.405	35%	35%
1.10	1.60	0.5	45%	45%
1.30	1.73	0.43	33%	33%
1.60	1.56	0.04	-3%	3%
1.80	2.14	0.34	19%	19%
2.10	2.49	0.39	19%	19%
2.70	2.97	0.27	10%	10%
4.90	4.87	0.03	-1%	1%
6.00	6.17	0.17	3%	3%
7.50	6.99	0.515	-7%	7%
Mean		0.37	59%	60%
Std Dev		0.16	56%	55%
95% Confidence		0.31	108%	106%

Table B-2: Error Table for Operator 2

true size	Op2	Abs Error	% Error	Abs % Error
0.25	0.50	0.25	100%	100%
0.27	1.20	0.93	344%	344%
0.28	1.00	0.72	257%	257%
0.40	0.50	0.1	25%	25%
0.40	1.20	0.8	200%	200%
0.50	0.90	0.4	80%	80%
0.52	1.50	0.98	188%	188%
0.55	1.20	0.65	118%	118%
0.70	1.50	0.8	114%	114%
0.98	1.00	0.02	2%	2%
1.12	0.50	0.62	-55%	55%
1.15	1.80	0.65	57%	57%
1.10	2.00	0.9	82%	82%
1.30	2.10	0.8	62%	62%
1.60	0.80	0.8	-50%	50%
1.80	2.00	0.2	11%	11%
2.10	1.80	0.3	-14%	14%
2.70	3.00	0.3	11%	11%
4.90	4.50	0.4	-8%	8%
6.00	5.50	0.5	-8%	8%
7.50	6.00	1.5	-20%	20%
Mean		0.60	71%	86%
Std Dev		0.34	102%	90%
95% Confidence		0.67	199%	175%

Table B-3: Error Table for Operator 3

true size	Op3	Abs Error	% Error	Abs % Error
0.25	0.00	0.25	-100%	100%
0.27	0.50	0.23	85%	85%
0.28	1.20	0.92	329%	329%
0.40	1.00	0.6	150%	150%
0.40	1.00	0.6	150%	150%
0.50	1.00	0.5	100%	100%
0.52	1.10	0.58	112%	112%
0.55	0.80	0.25	45%	45%
0.70	0.90	0.2	29%	29%
0.98	0.80	0.18	-18%	18%
1.12	1.00	0.12	-11%	11%
1.15	1.30	0.15	13%	13%
1.10	1.40	0.3	27%	27%
1.30	0.90	0.4	-31%	31%
1.60	0.90	0.7	-44%	44%
1.80	1.40	0.4	-22%	22%
2.10	2.30	0.2	10%	10%
2.70	3.20	0.5	19%	19%
4.90	4.50	0.4	-8%	8%
6.00	6.20	0.2	3%	3%
7.50	6.25	1.25	-17%	17%
Mean		0.43	39%	63%
Std Dev		0.28	90%	75%
95% Confidence		0.54	175%	146%

Table B-4: Error Table for Operator 4

true size	Op4	Abs Error	% Error	Abs % Error
0.25	1.00	0.75	300%	300%
0.27	1.00	0.73	270%	270%
0.28	1.00	0.72	257%	257%
0.40	1.20	0.8	200%	200%
0.40	1.40	1	250%	250%
0.50	1.10	0.6	120%	120%
0.52	0.90	0.38	73%	73%
0.55	0.50	0.05	-9%	9%
0.70	2.00	1.3	186%	186%
0.98	1.90	0.92	94%	94%
1.12	1.00	0.12	-11%	11%
1.15	2.20	1.05	91%	91%
1.10	2.00	0.9	82%	82%
1.30	2.20	0.9	69%	69%
1.60	2.00	0.4	25%	25%
1.80	2.40	0.6	33%	33%
2.10	3.50	1.4	67%	67%
2.70	2.80	0.1	4%	4%
4.90	5.70	0.8	16%	16%
6.00	7.00	1	17%	17%
7.50	8.00	0.5	7%	7%
Mean		0.72	102%	104%
Std Dev		0.36	98%	96%
95% Confidence		0.69546	192%	188%

Table B-5: Error Table for Operator 5

true size	Op5	Abs Error	% Error	Abs % Error
0.25	0.00	0.25	-100%	100%
0.27	0.00	0.27	-100%	100%
0.28	0.00	0.28	-100%	100%
0.40	1.00	0.6	150%	150%
0.40	1.00	0.6	150%	150%
0.50	1.00	0.5	100%	100%
0.52	1.50	0.98	188%	188%
0.55	0.90	0.35	64%	64%
0.70	1.60	0.9	129%	129%
0.98	2.00	1.02	104%	104%
1.12	1.80	0.68	61%	61%
1.15	1.00	0.15	-13%	13%
1.10	1.60	0.5	45%	45%
1.30	2.00	0.7	54%	54%
1.60	2.00	0.4	25%	25%
1.80	2.00	0.2	11%	11%
2.10	2.50	0.4	19%	19%
2.70	2.50	0.2	-7%	7%
4.90	4.50	0.4	-8%	8%
6.00	6.50	0.5	8%	8%
7.50	7.20	0.3	-4%	4%
Mean		0.48	37%	69%
Std Dev		0.25	80%	55%
95% Confidence		0.49	155%	107%

Table B-6: Error Table for Operator 6

true size	Op6	Abs Error	% Error	Abs % Error
0.25	0.50	0.25	100%	100%
0.27	1.00	0.73	270%	270%
0.28	0.50	0.22	79%	79%
0.40	1.00	0.6	150%	150%
0.40	1.10	0.7	175%	175%
0.50	0.80	0.3	60%	60%
0.52	1.00	0.48	92%	92%
0.55	1.20	0.65	118%	118%
0.70	1.20	0.5	71%	71%
0.98	1.60	0.62	63%	63%
1.12	1.80	0.68	61%	61%
1.15	1.50	0.35	30%	30%
1.10	1.50	0.4	36%	36%
1.30	2.00	0.7	54%	54%
1.60	1.50	0.1	-6%	6%
1.80	3.20	1.4	78%	78%
2.10	3.00	0.9	43%	43%
2.70	3.50	0.8	30%	30%
4.90	4.40	0.5	-10%	10%
6.00	5.50	0.5	-8%	8%
7.50	6.50	1	-13%	13%
Mean		0.59	70%	74%
Std Dev		0.29	66%	62%
95% Confidence		0.559318	129%	121%

Table B-7: Error Table for Operator 7

true size	Op7	Abs Error	% Error	Abs % Error
0.25	0.50	0.25	100%	100%
0.27	0.50	0.23	85%	85%
0.28	0.50	0.22	79%	79%
0.40	0.60	0.2	50%	50%
0.40	0.20	0.2	-50%	50%
0.50	0.00	0.5	-100%	100%
0.52	1.00	0.48	92%	92%
0.55	1.30	0.75	136%	136%
0.70	1.60	0.9	129%	129%
0.98	0.50	0.48	-49%	49%
1.12	1.80	0.68	61%	61%
1.15	1.80	0.65	57%	57%
1.10	0.50	0.6	-55%	55%
1.30	1.70	0.4	31%	31%
1.60	1.20	0.4	-25%	25%
1.80	2.20	0.4	22%	22%
2.10	2.00	0.1	-5%	5%
2.70	2.50	0.2	-7%	7%
4.90	4.20	0.7	-14%	14%
6.00	5.30	0.7	-12%	12%
7.50	6.50	1	-13%	13%
Mean		0.48	24%	56%
Std Dev		0.25	63%	39%
95% Confidence		0.481788	124%	76%

Table B-8: Error Table for Operator 8

true size	Op8	Abs Error	% Error	Abs % Error
0.25	0.80	0.55	220%	220%
0.27	0.80	0.53	196%	196%
0.28	1.30	1.02	364%	364%
0.40	1.50	1.1	275%	275%
0.40	1.60	1.2	300%	300%
0.50	1.00	0.5	100%	100%
0.52	0.90	0.38	73%	73%
0.55	1.60	1.05	191%	191%
0.70	2.20	1.5	214%	214%
0.98	1.80	0.82	84%	84%
1.12	2.00	0.88	79%	79%
1.15	2.00	0.85	74%	74%
1.10	2.20	1.1	100%	100%
1.30	2.00	0.7	54%	54%
1.60	2.00	0.4	25%	25%
1.80	2.50	0.7	39%	39%
2.10	3.20	1.1	52%	52%
2.70	3.50	0.8	30%	30%
4.90	5.40	0.5	10%	10%
6.00	6.70	0.7	12%	12%
7.50	6.90	0.6	-8%	8%
Mean		0.81	118%	119%
Std Dev		0.29	104%	103%
95% Confidence		0.564596	203%	201%

Table B-9:Error Table for Operator 9

true size	Op9	Abs Error	% Error	Abs % Error
0.25	1.00	0.75	300%	300%
0.27	1.00	0.73	270%	270%
0.28	1.00	0.72	257%	257%
0.40	1.00	0.6	150%	150%
0.40	1.00	0.6	150%	150%
0.50	1.20	0.7	140%	140%
0.52	1.00	0.48	92%	92%
0.55	1.00	0.45	82%	82%
0.70	1.00	0.3	43%	43%
0.98	1.00	0.02	2%	2%
1.12	1.50	0.38	34%	34%
1.15	1.50	0.35	30%	30%
1.10	2.00	0.9	82%	82%
1.30	1.50	0.2	15%	15%
1.60	2.00	0.4	25%	25%
1.80	2.50	0.7	39%	39%
2.10	2.00	0.1	-5%	5%
2.70	3.50	0.8	30%	30%
4.90	5.50	0.6	12%	12%
6.00	6.50	0.5	8%	8%
7.50	8.00	0.5	7%	7%
Mean		0.51	84%	84%
Std Dev		0.23	91%	91%
95% Confidence		0.44	178%	177%

Table B-10: Error Table for Operator 10

true size	Op10	Abs Error	% Error	Abs % Error
0.25	0.30	0.05	20%	20%
0.27	1.20	0.93	344%	344%
0.28	0.70	0.42	150%	150%
0.40	0.80	0.4	100%	100%
0.40	0.90	0.5	125%	125%
0.50	0.50	0	0%	0%
0.52	0.70	0.18	35%	35%
0.55	0.40	0.15	-27%	27%
0.70	1.00	0.3	43%	43%
0.98	1.40	0.42	43%	43%
1.12	1.30	0.18	16%	16%
1.15	1.20	0.05	4%	4%
1.10	1.60	0.5	45%	45%
1.30	1.70	0.4	31%	31%
1.60	1.50	0.1	-6%	6%
1.80	1.10	0.7	-39%	39%
2.10	2.60	0.5	24%	24%
2.70	2.20	0.5	-19%	19%
4.90	5.50	0.6	12%	12%
6.00	6.00	0	0%	0%
7.50	6.50	1	-13%	13%
Mean		0.38	42%	52%
Std Dev		0.28	82%	76%
95% Confidence		0.54	160%	148%

C. Appendix C – Measured Size vs True Size

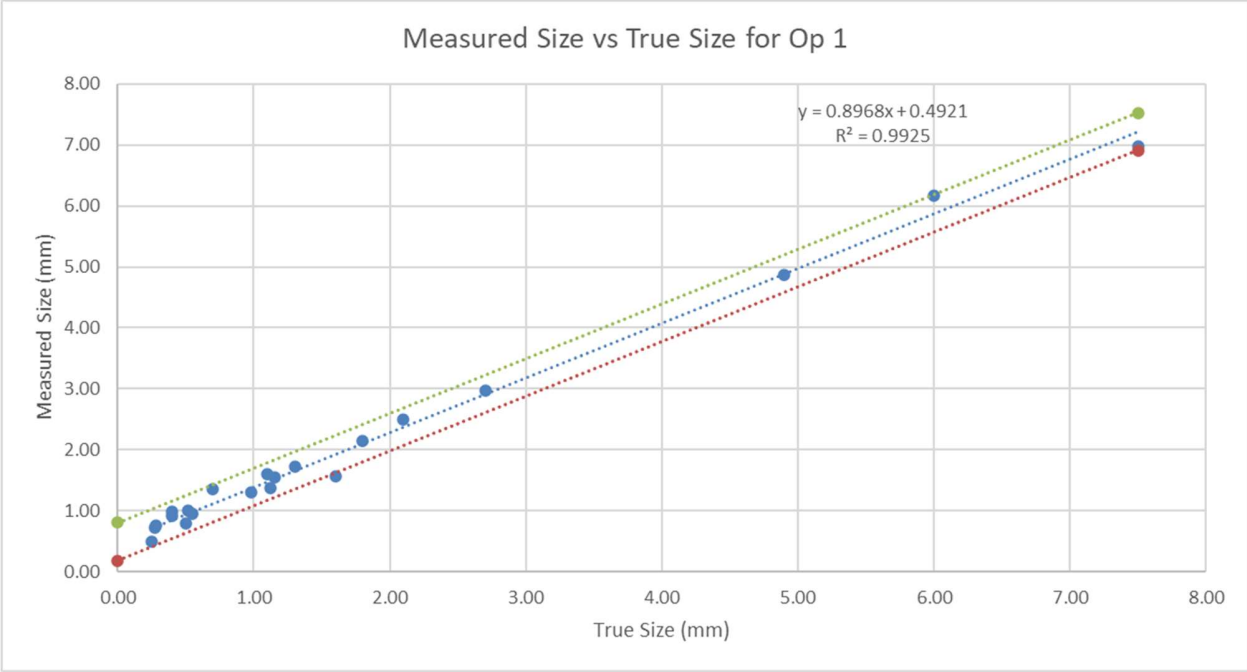


Figure C-1: Measured Size vs True Size for Technician 1

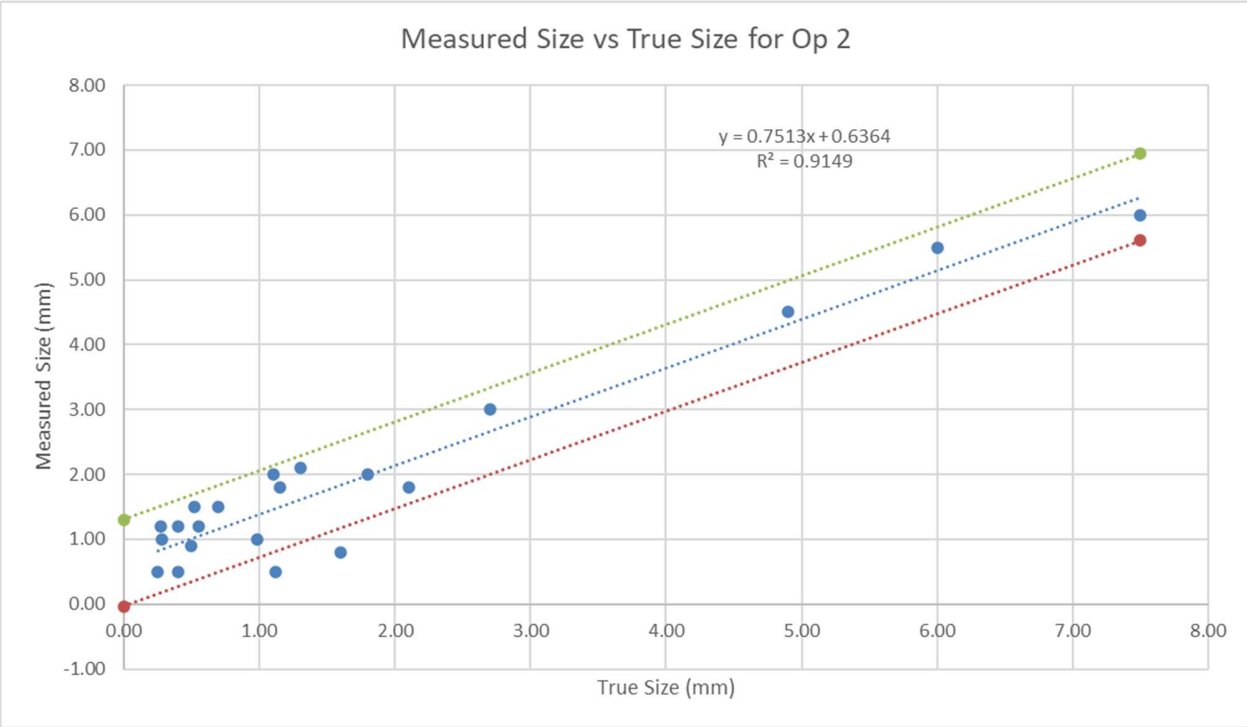


Figure C-2: Measured Size vs True Size for Technician 2



Figure C-3: Measured Size vs True Size for Technician 3

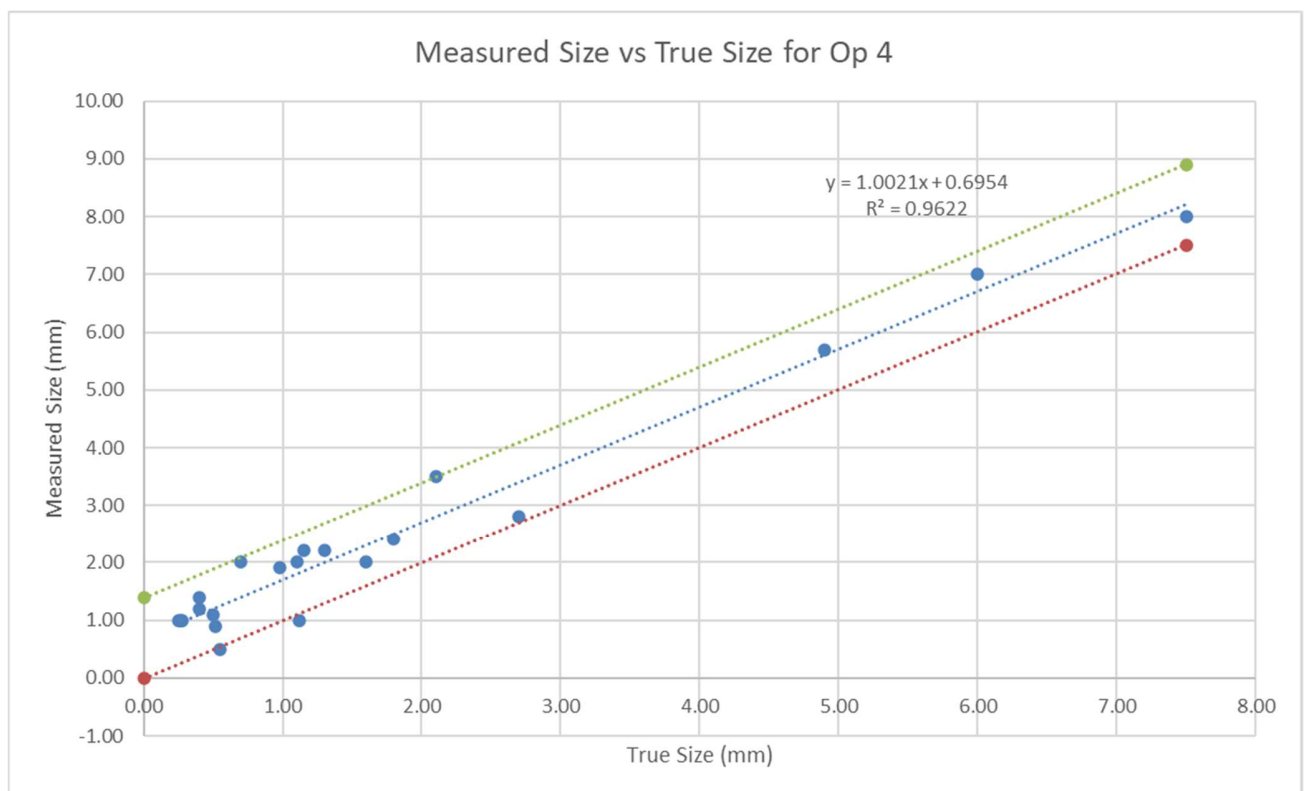


Figure C-4: Measured Size vs True Size for Technician 4

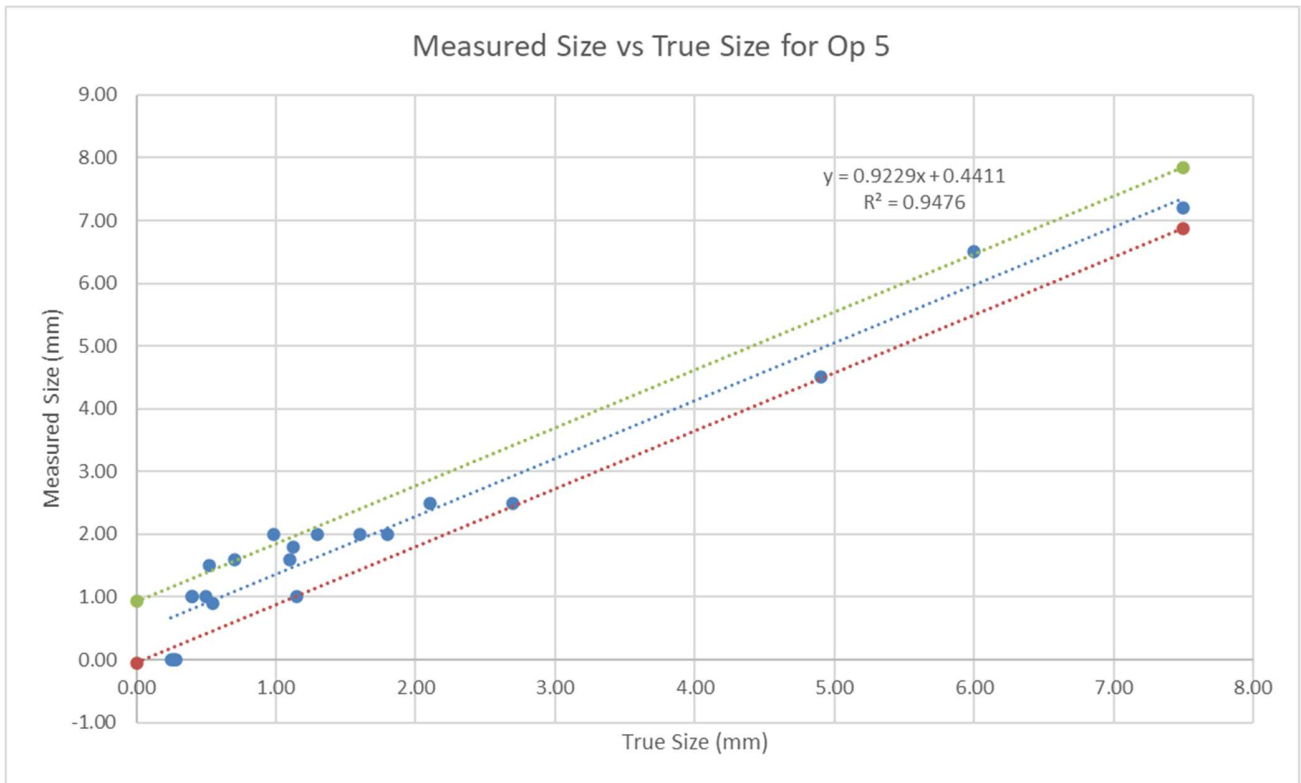


Figure C-5: Measured Size vs True Size for Technician 5

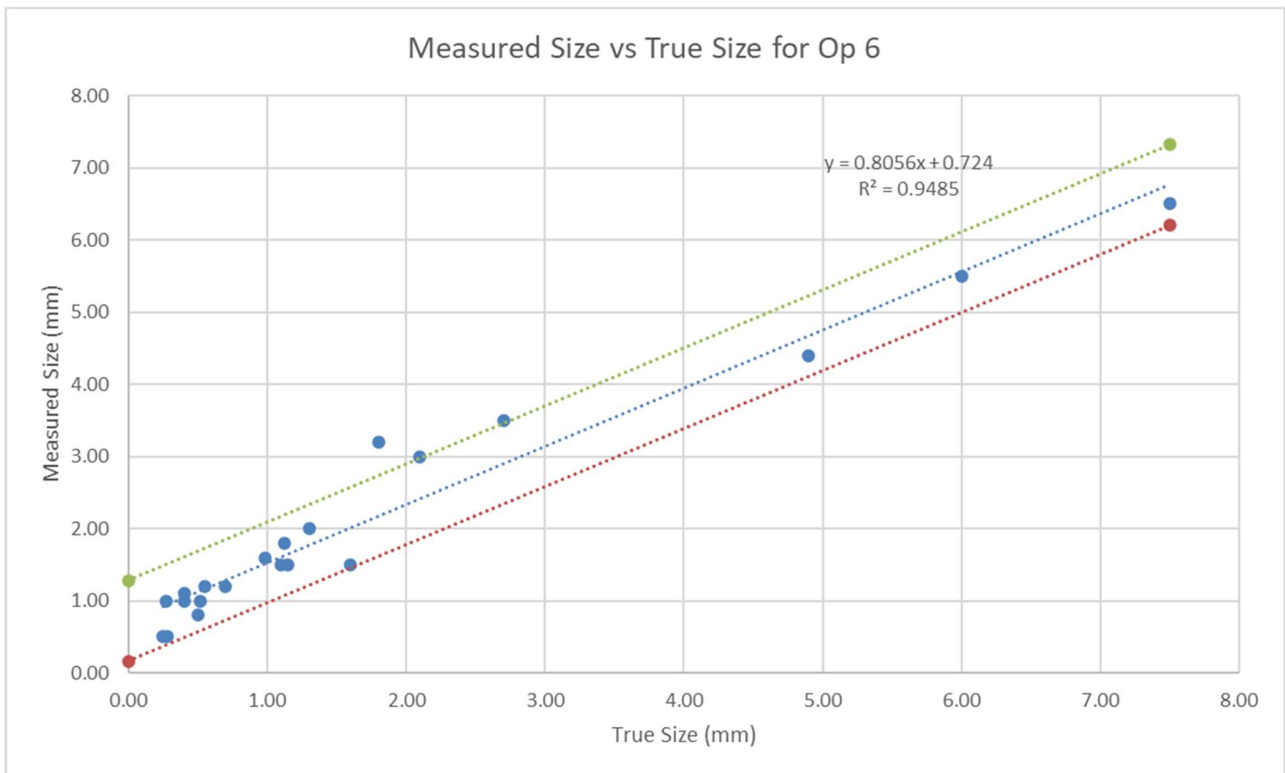


Figure C-6: Measured Size vs True Size for Technician 6



Figure C-7: Measured Size vs True Size for Technician 7

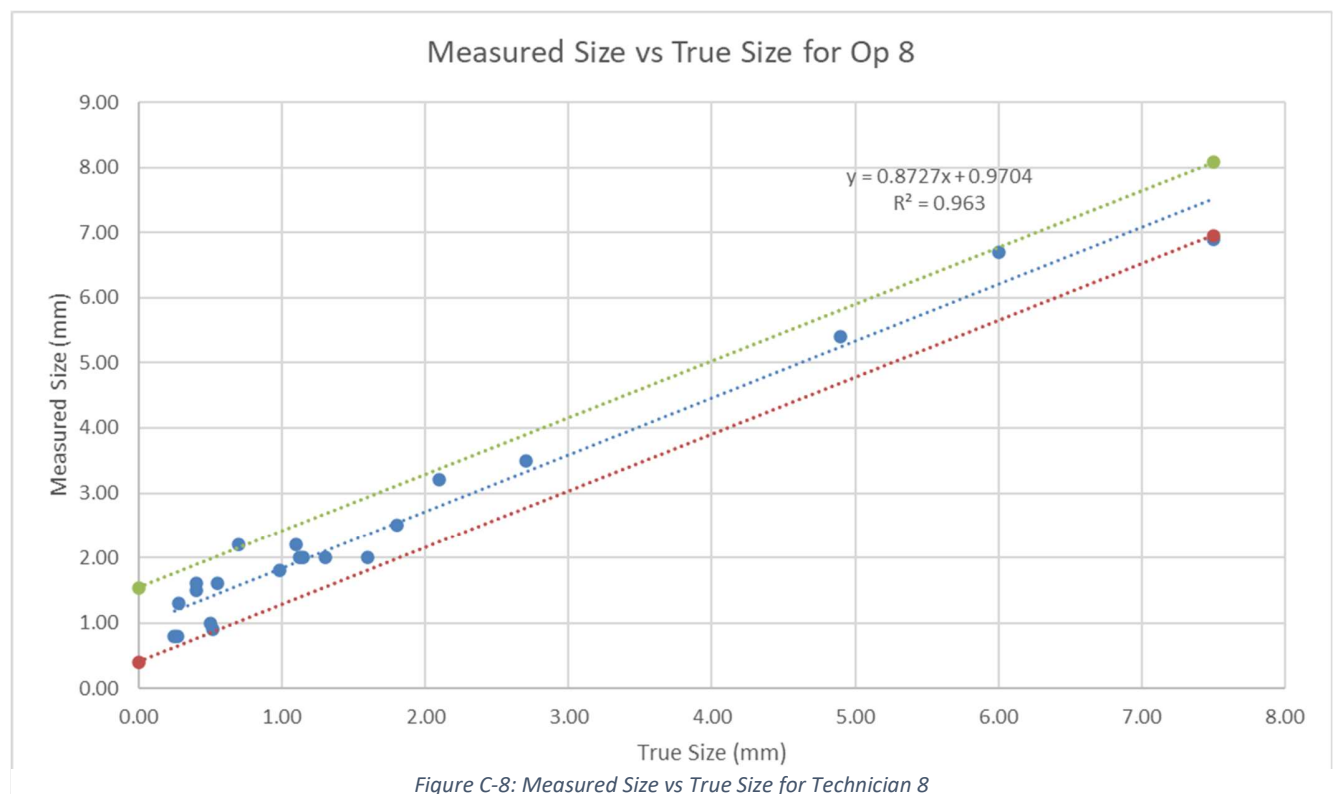


Figure C-8: Measured Size vs True Size for Technician 8

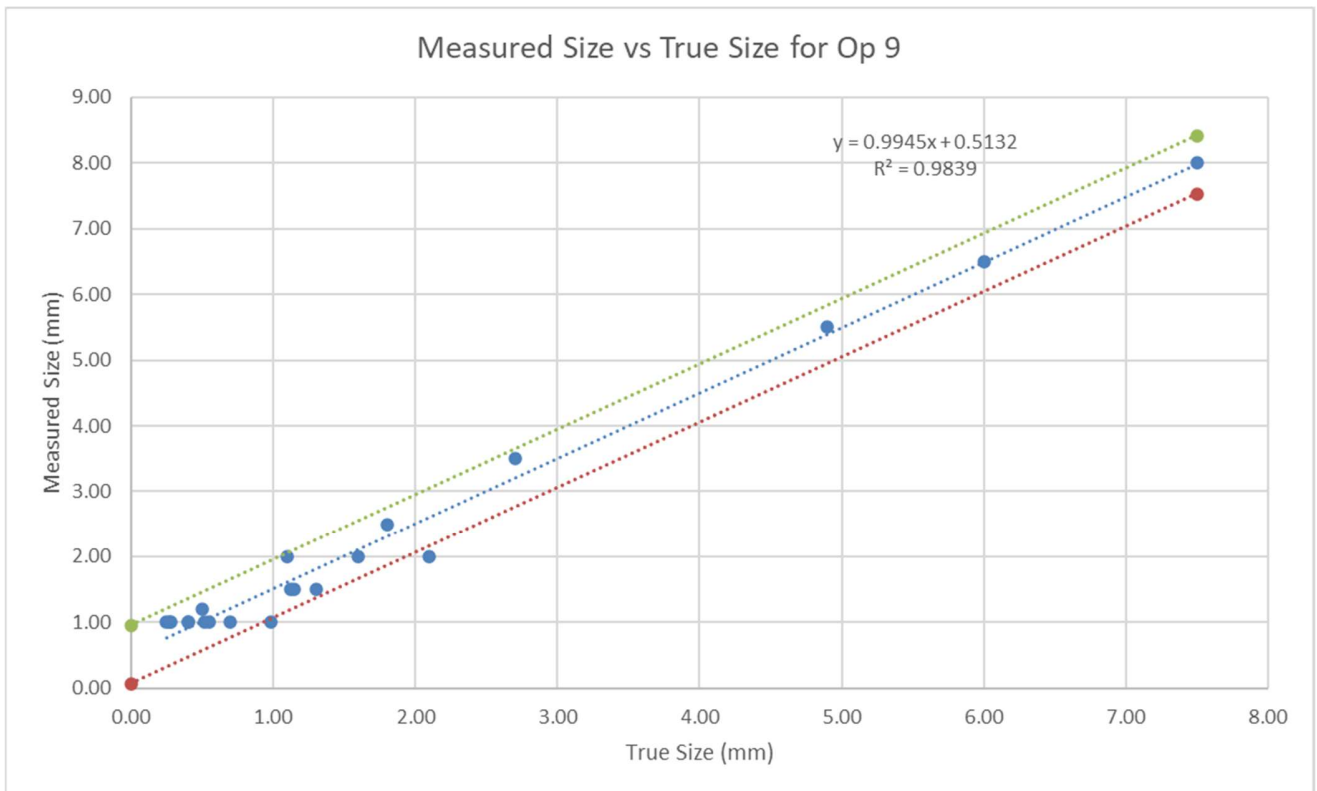


Figure C-9: Measured Size vs True Size for Technician 9

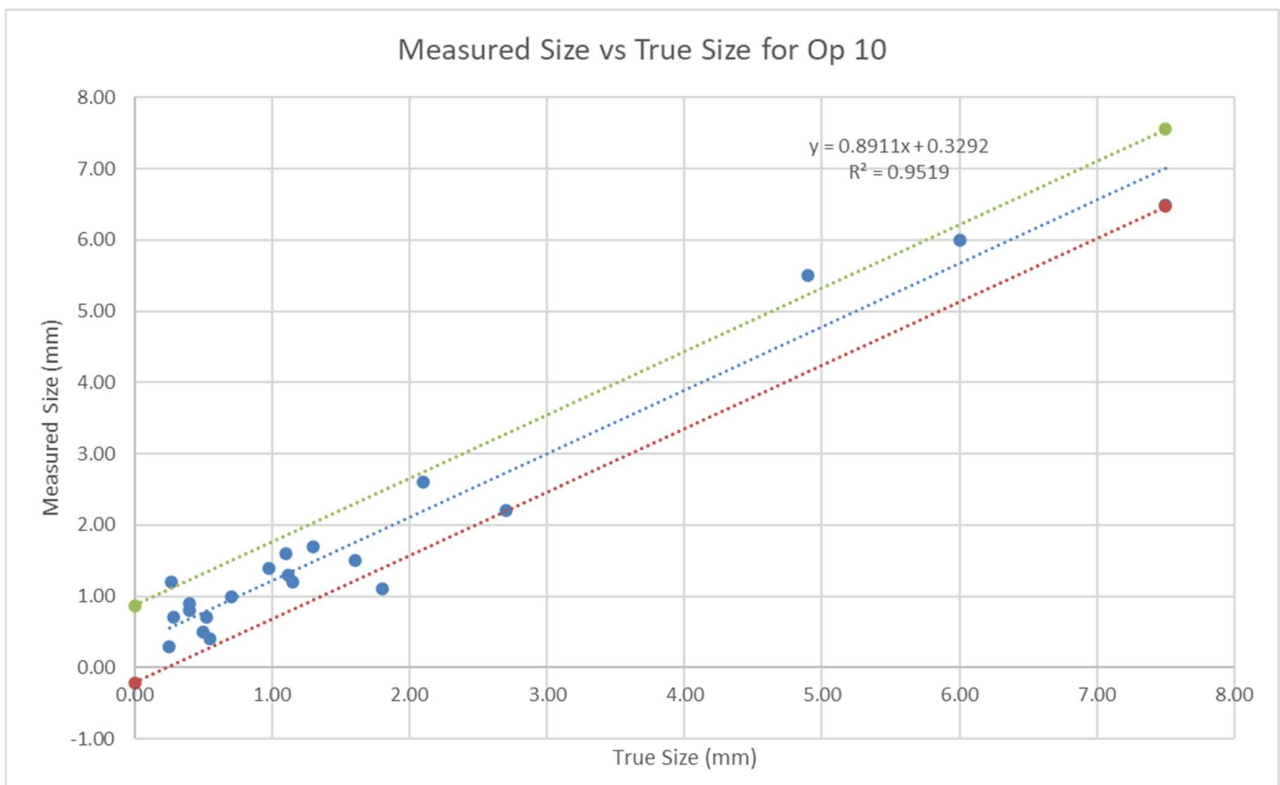


Figure C-10: Measured Size vs True Size for Technician 10

D. Appendix D - %Error vs True Size

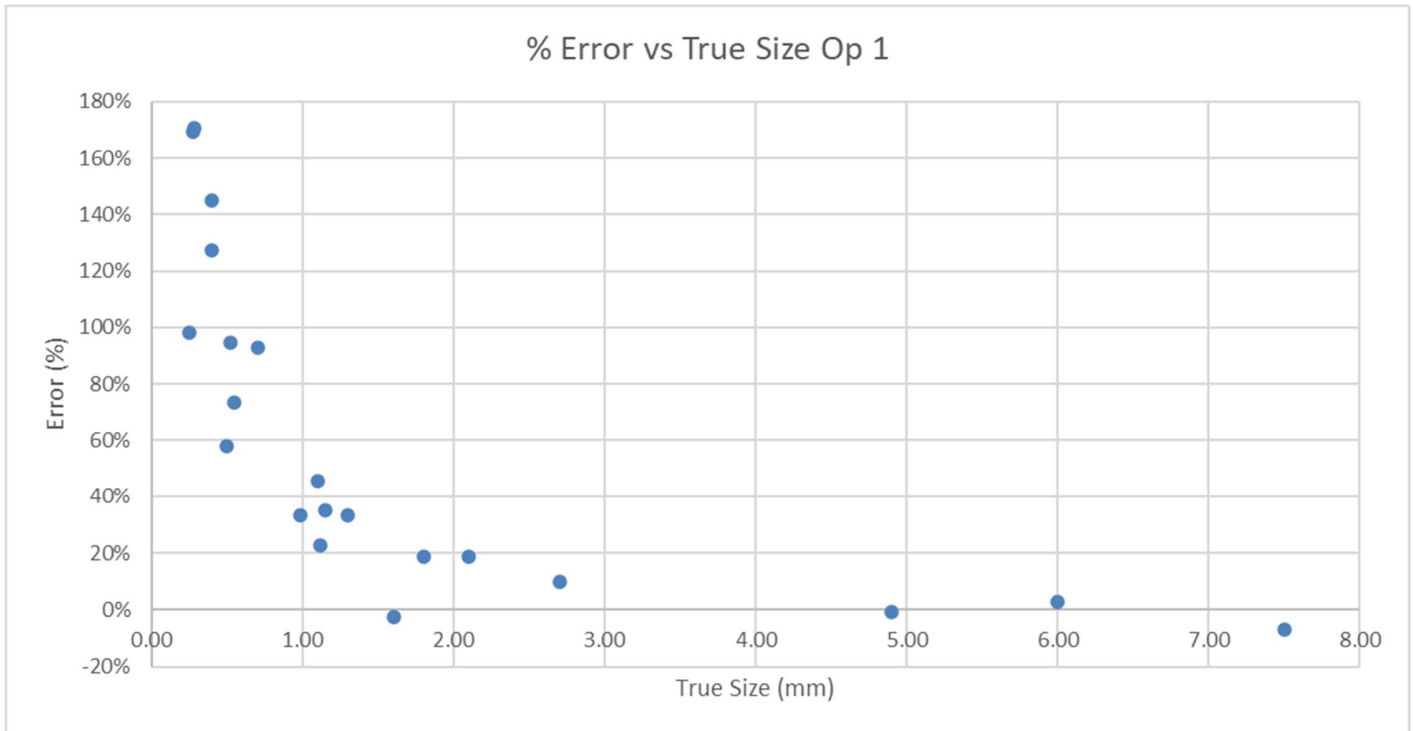


Figure D-1: %Error vs True Size for Technician 1



Figure D-2: %Error vs True Size for Technician 2

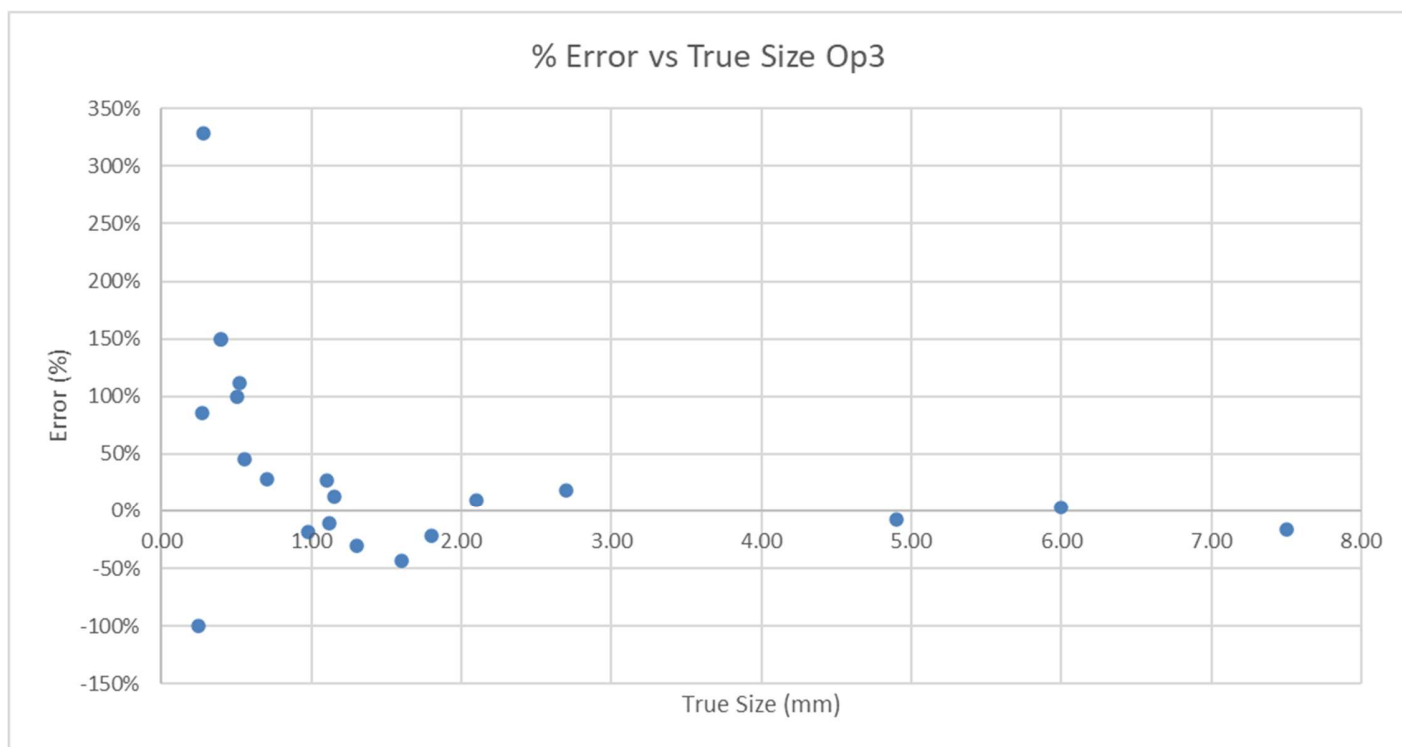


Figure D-3: %Error vs True Size for Technician 3

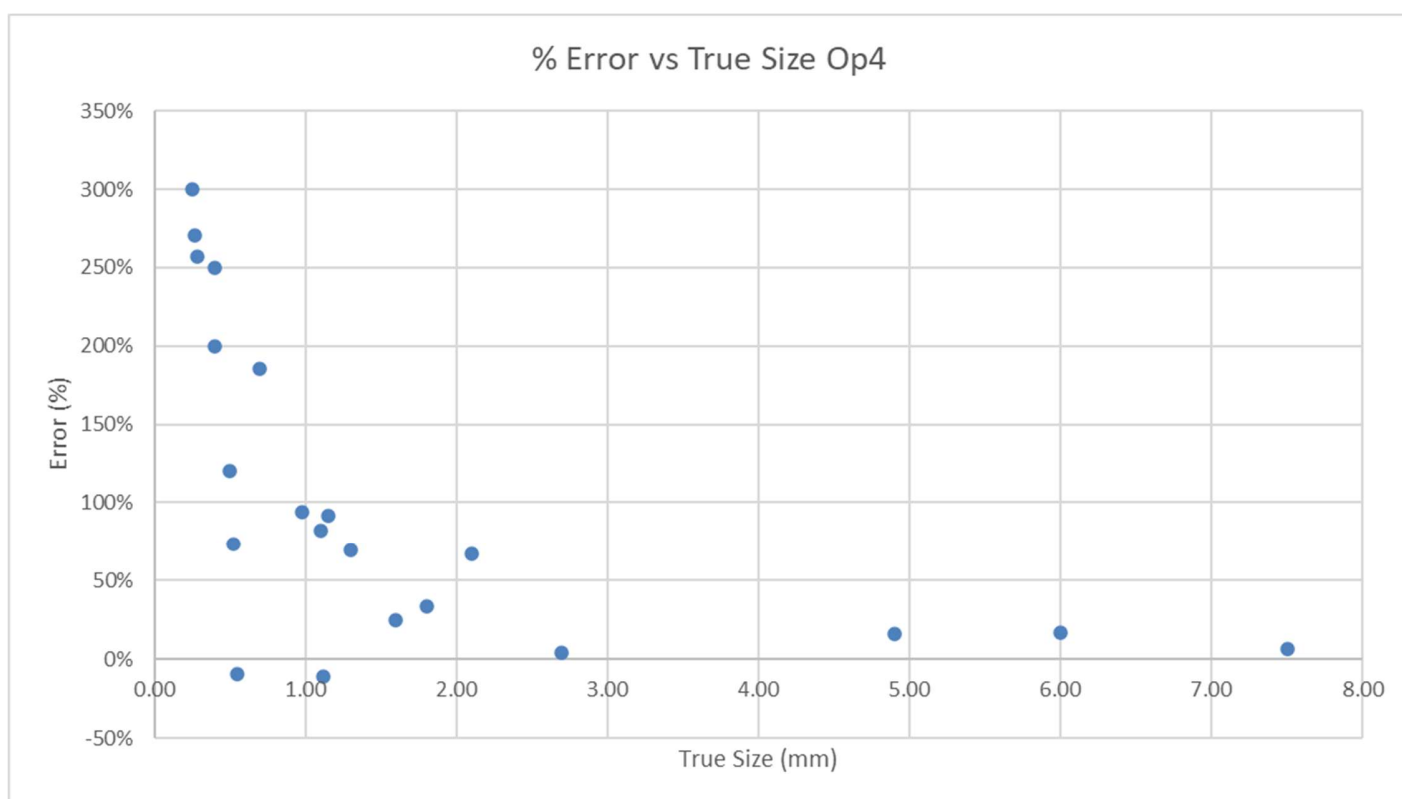


Figure D-4: %Error vs True Size for Technician 4

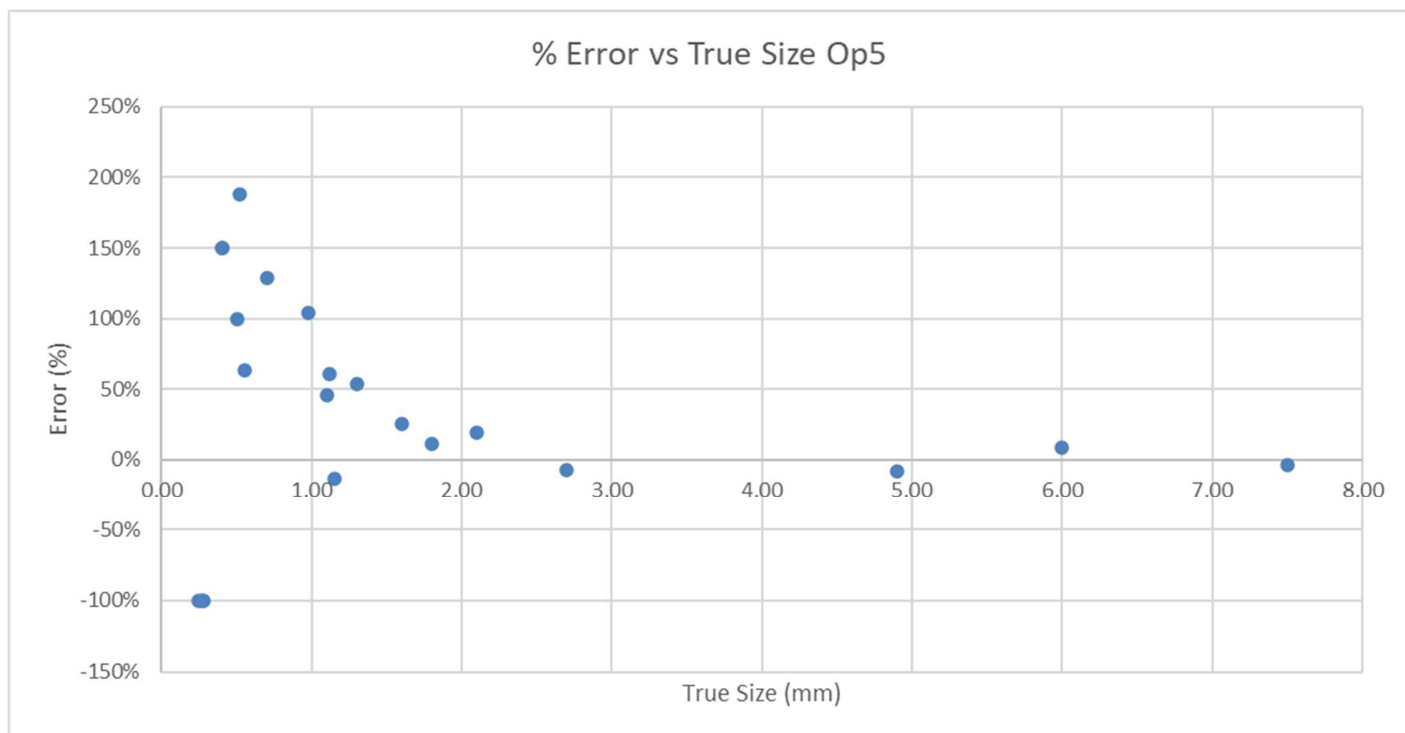


Figure D-5: %Error vs True Size for Technician 5

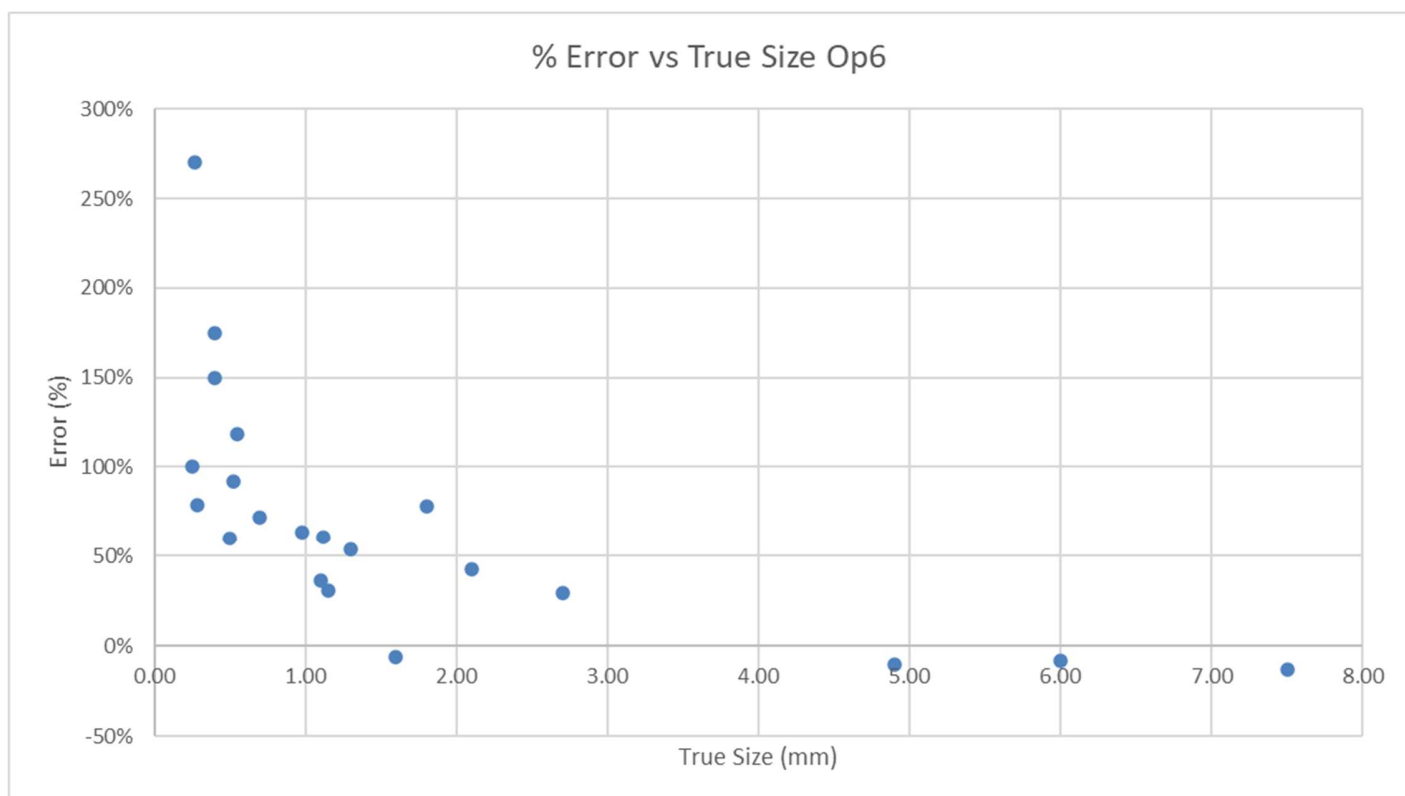


Figure D-6: %Error vs True Size for Technician 6

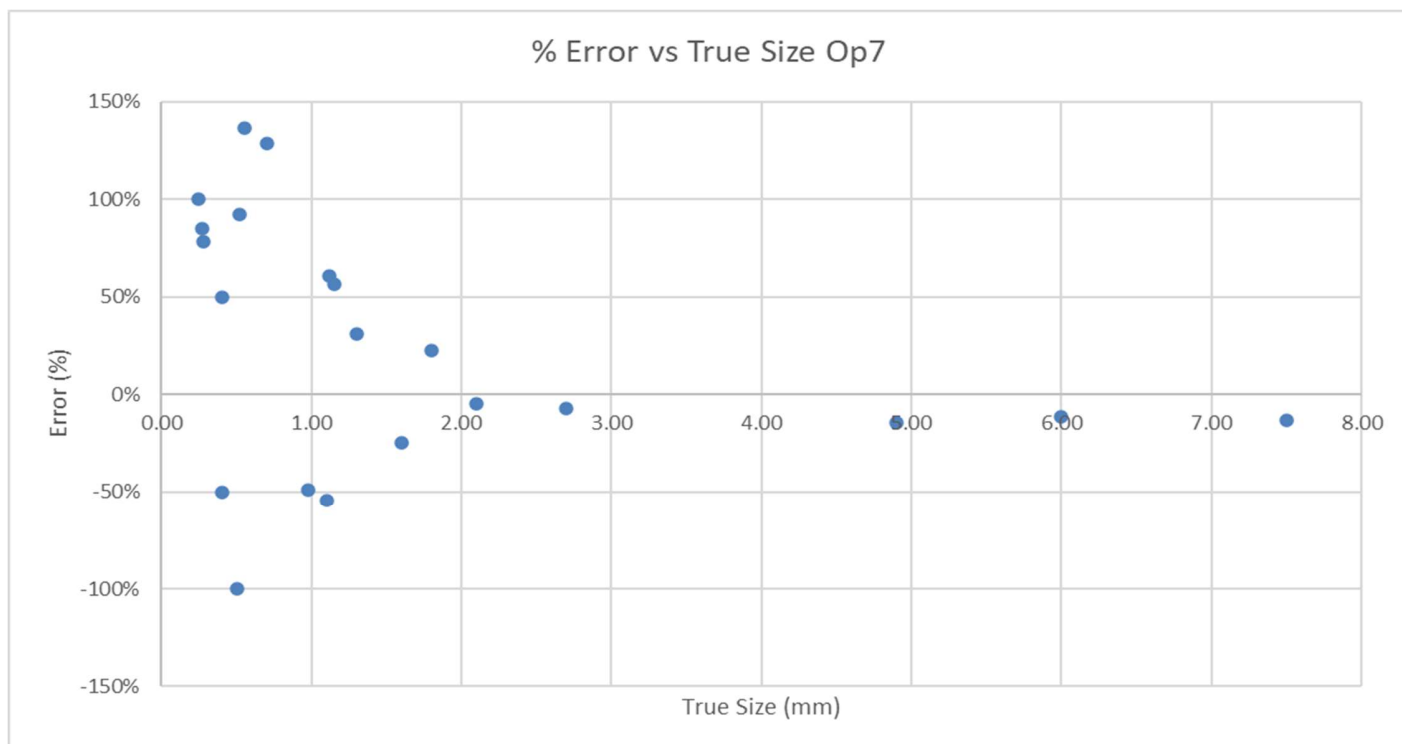


Figure D-7: %Error vs True Size for Technician 7

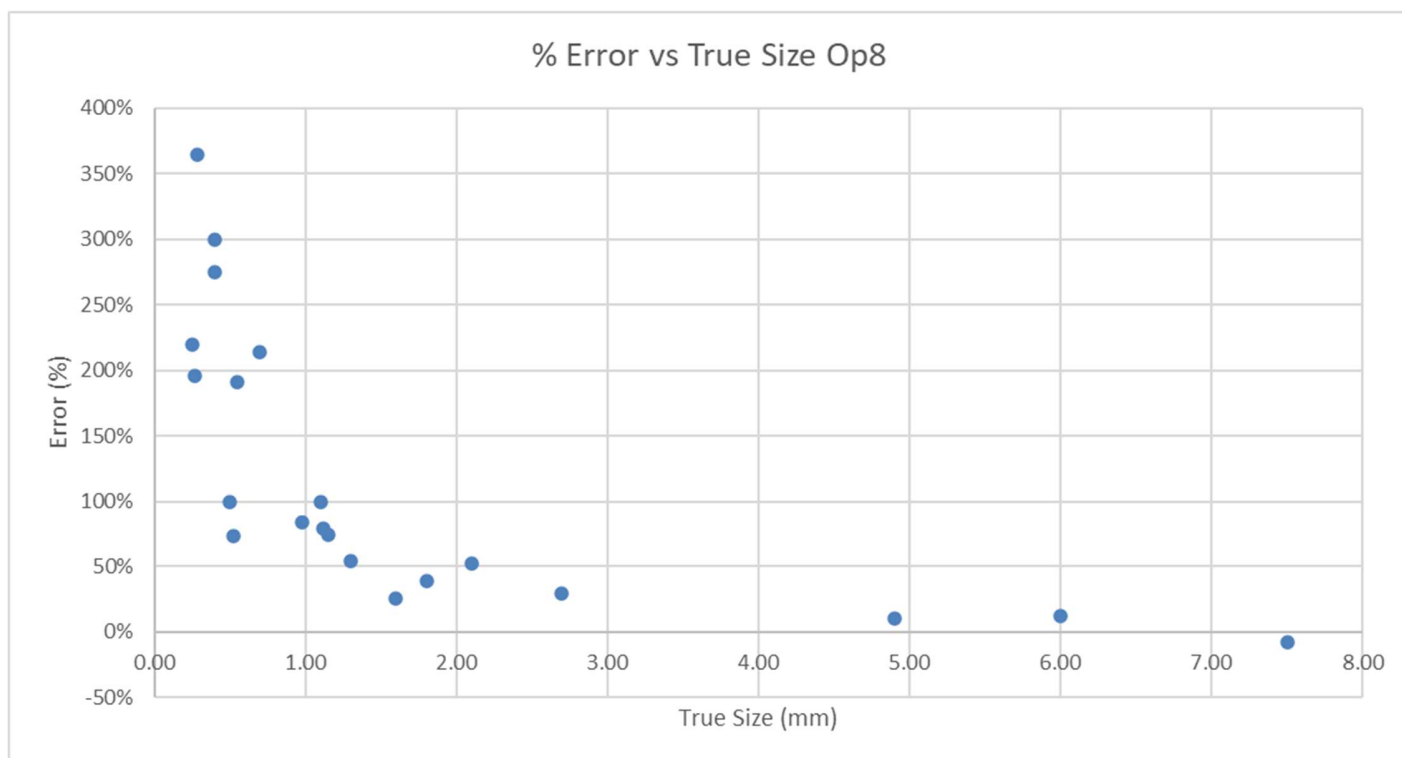


Figure D-8: %Error vs True Size for Technician 8



Figure D-9: %Error vs True Size for Technician 9

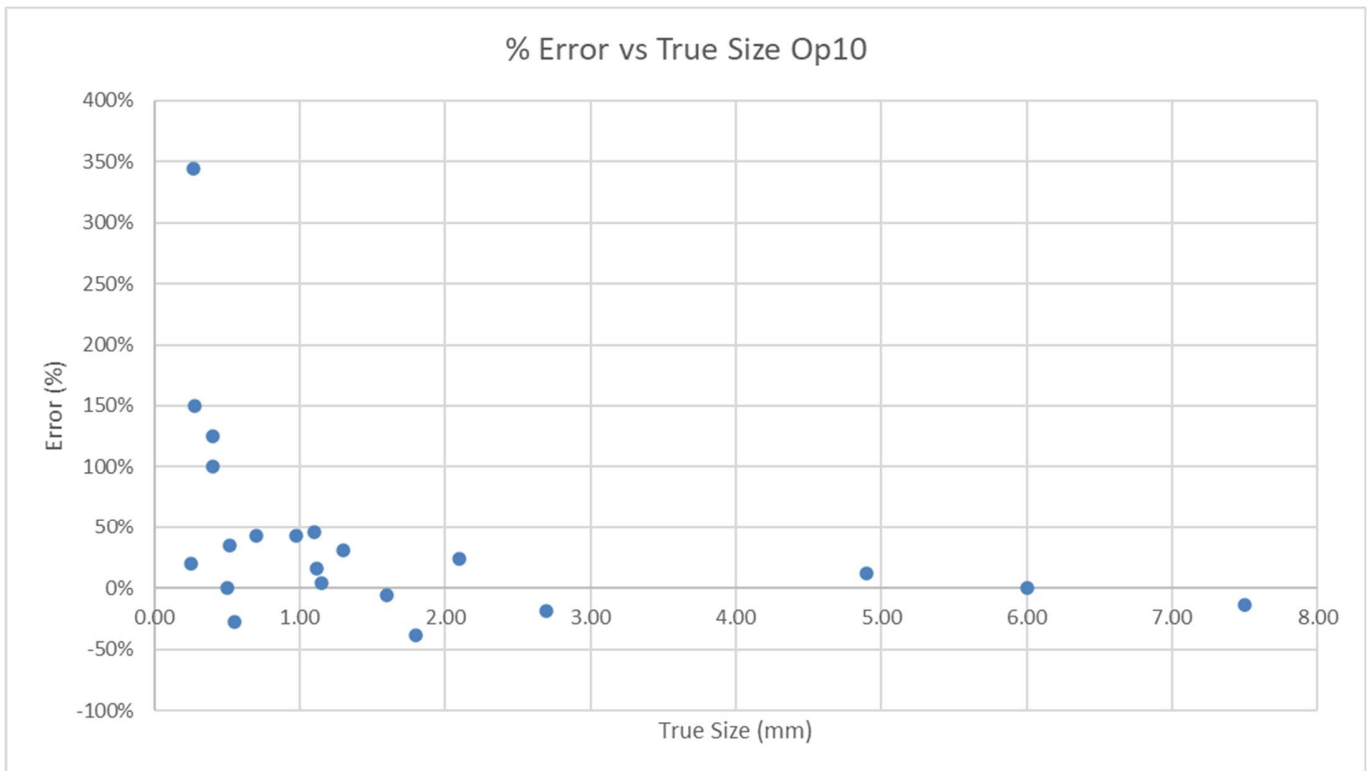


Figure D-10: %Error vs True Size for Technician 9

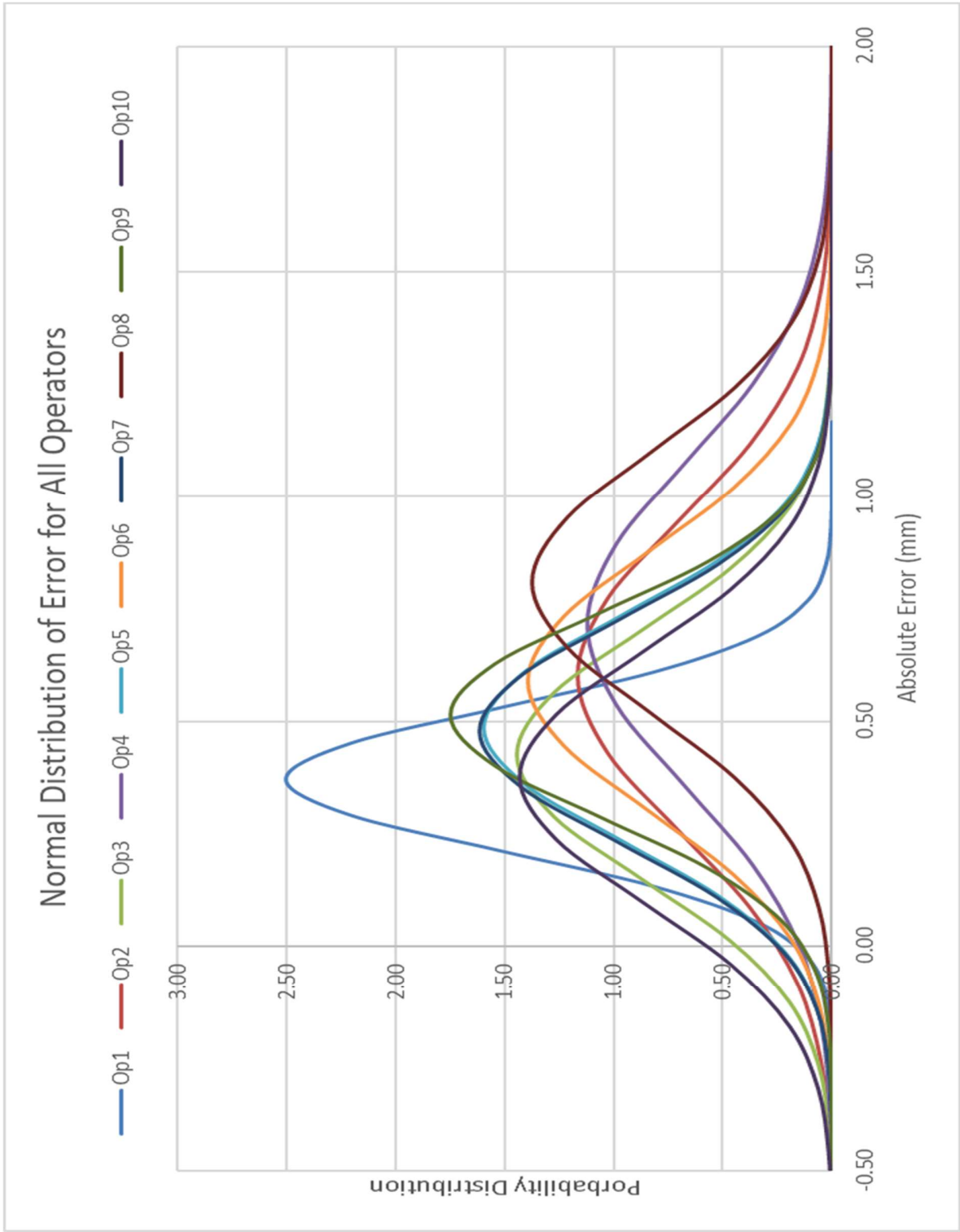


Figure E-1: Combined Normal Distribution

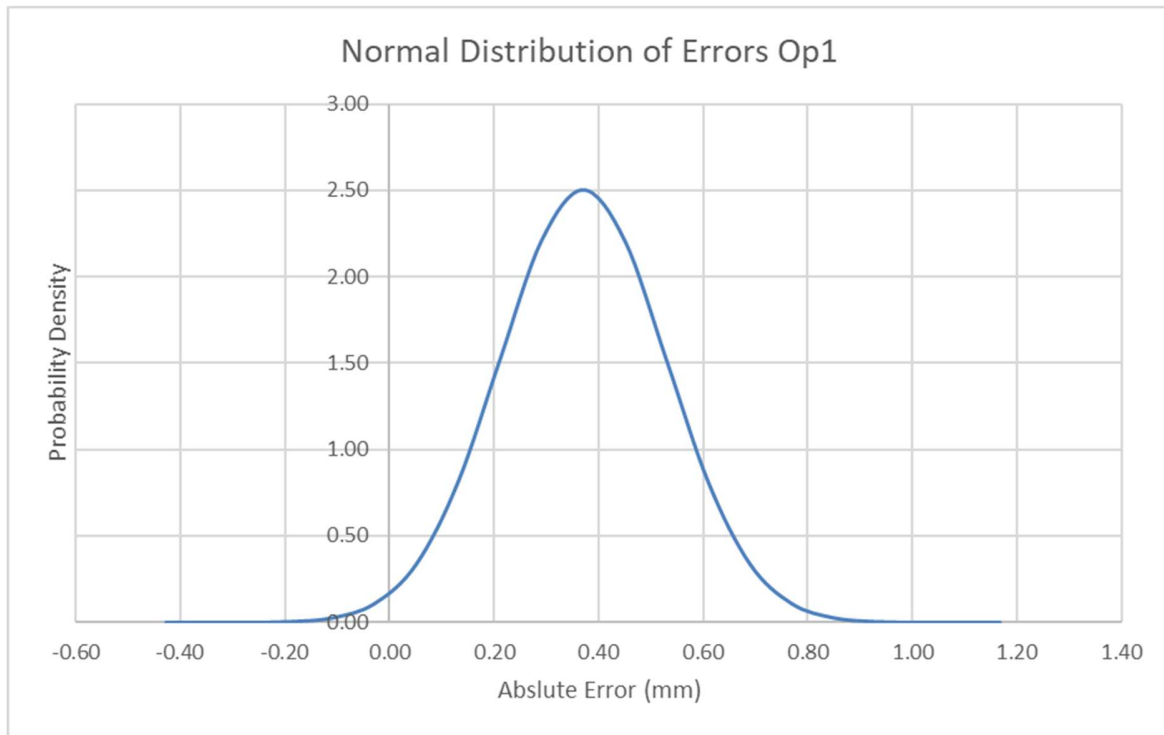


Figure E-2: Normal Distribution of Errors for Technician 1

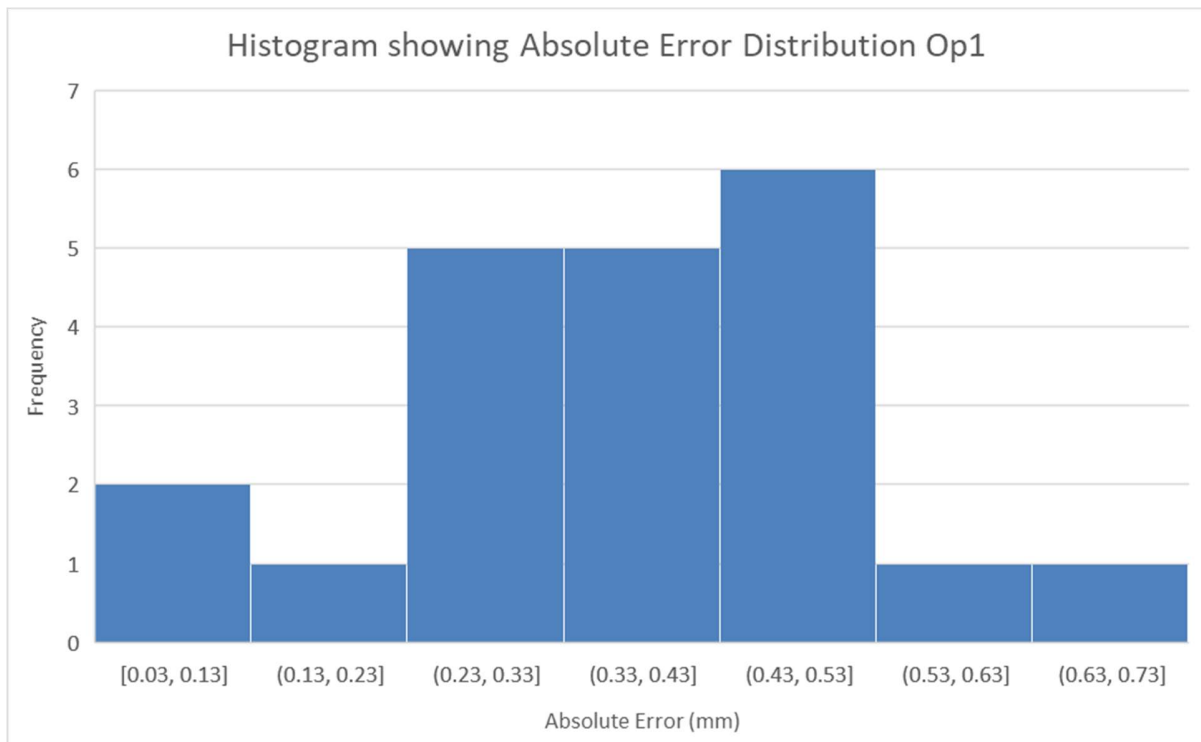


Figure E-3: Histogram of Errors for Technician 1

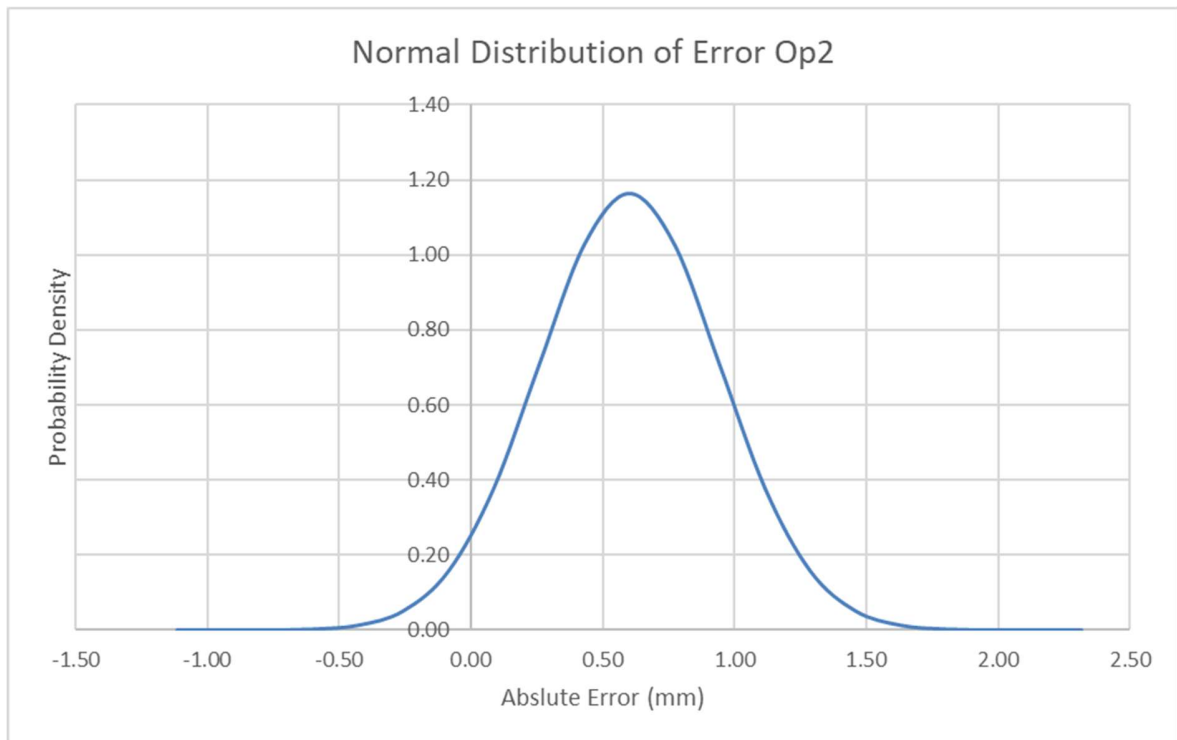


Figure E-4: Normal Distribution of Errors for Technician 2

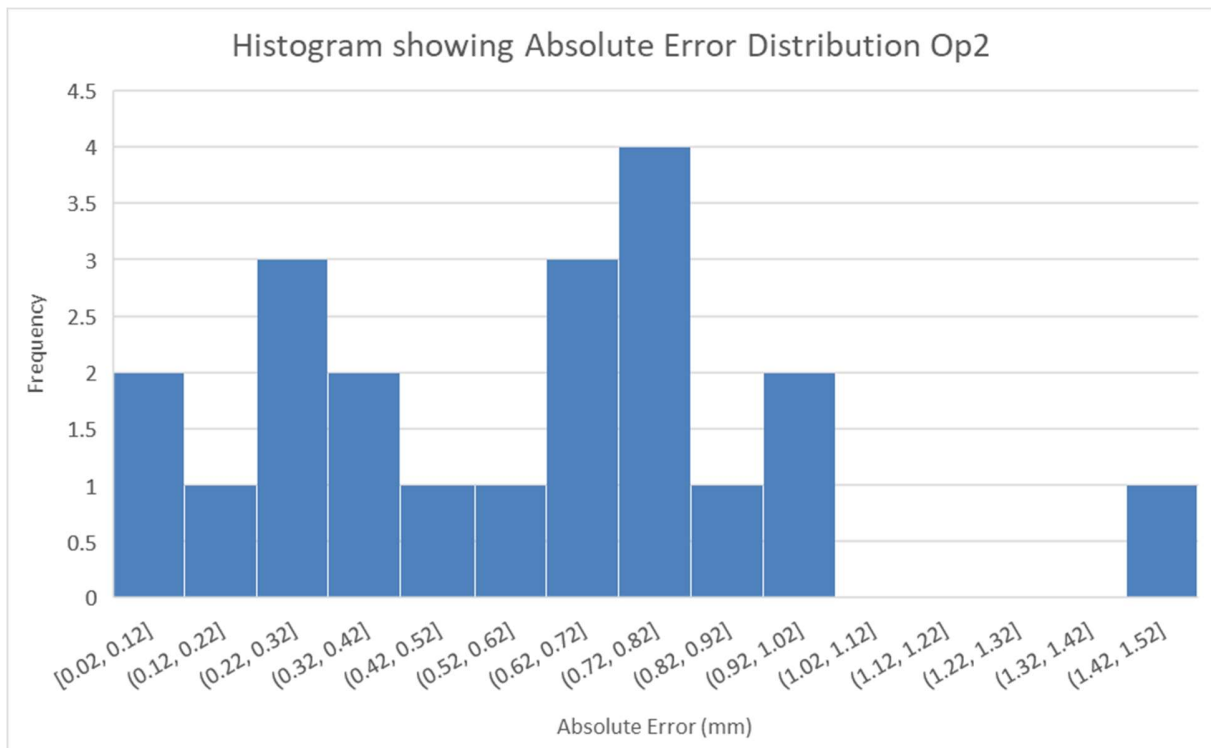


Figure E-5: Histogram of Errors for Technician 2

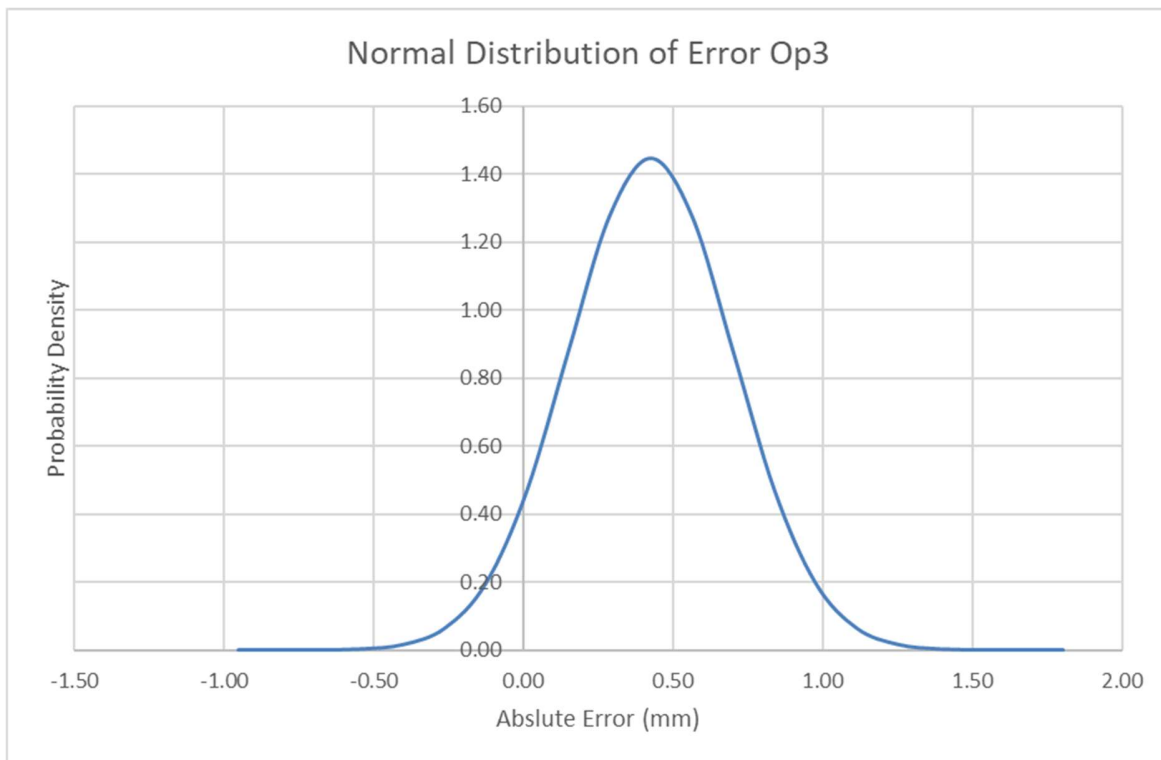


Figure E-6: Normal Distribution of Errors for Technician 3

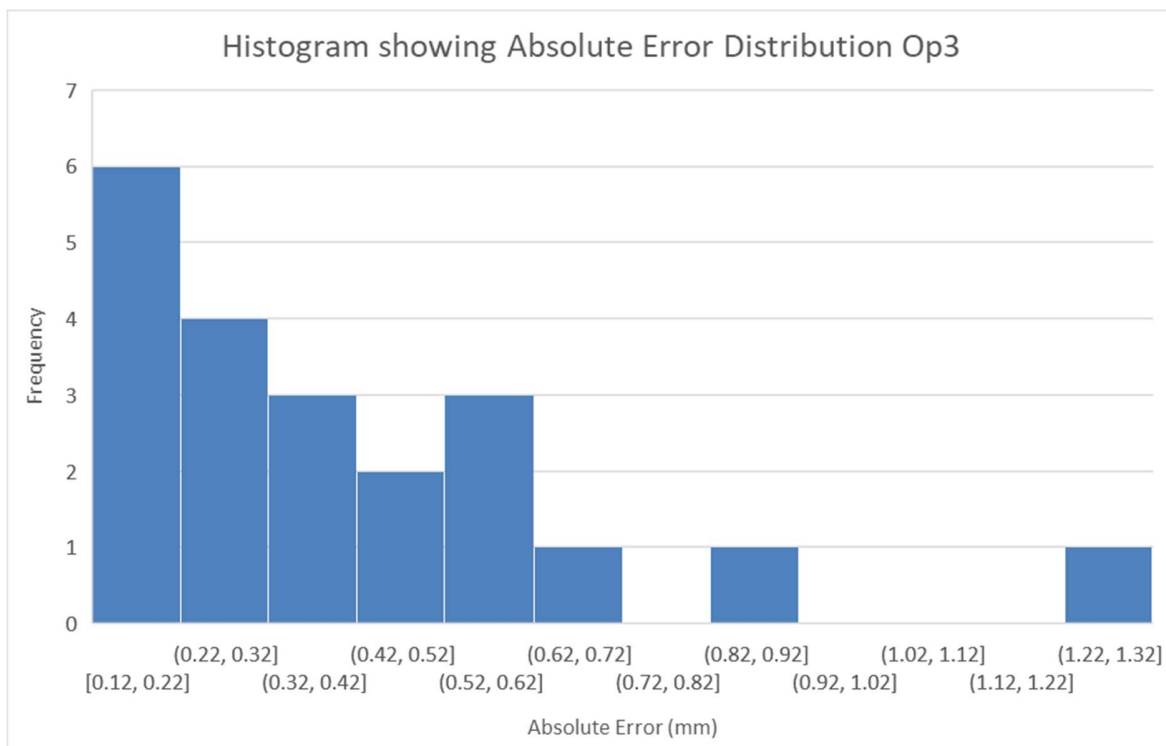


Figure E-7: Histogram of Errors for Technician 2

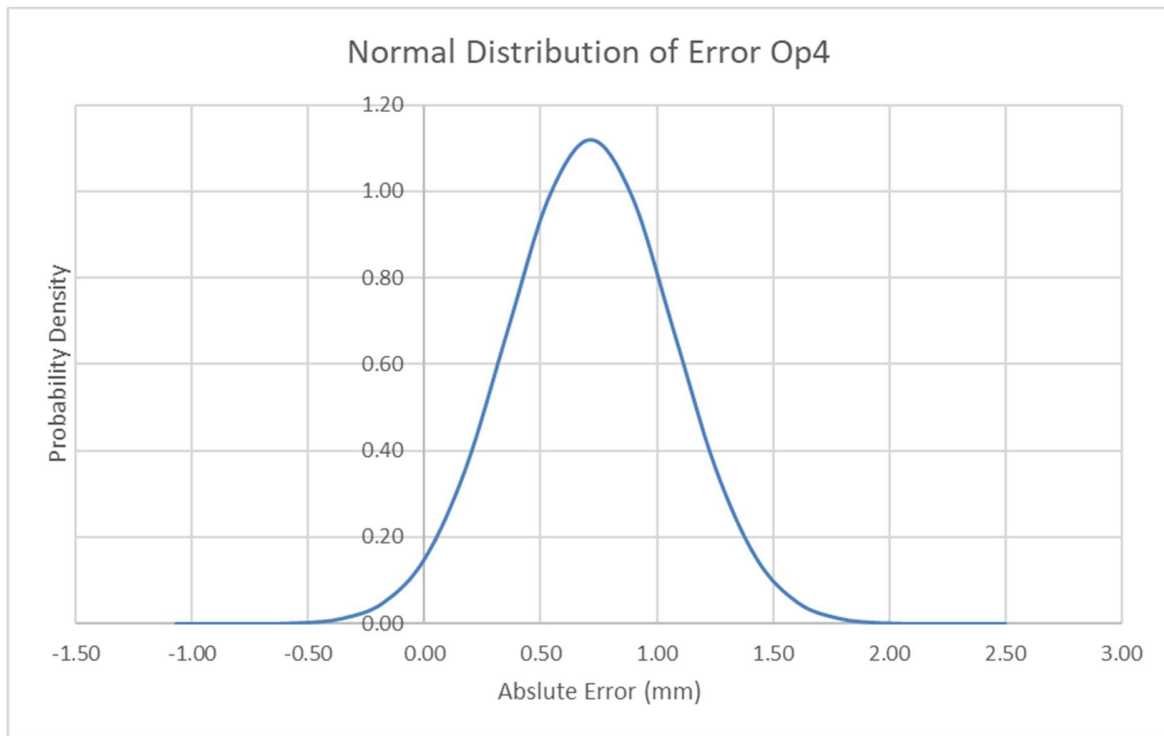


Figure E-8: Normal Distribution of Errors for Technician 4

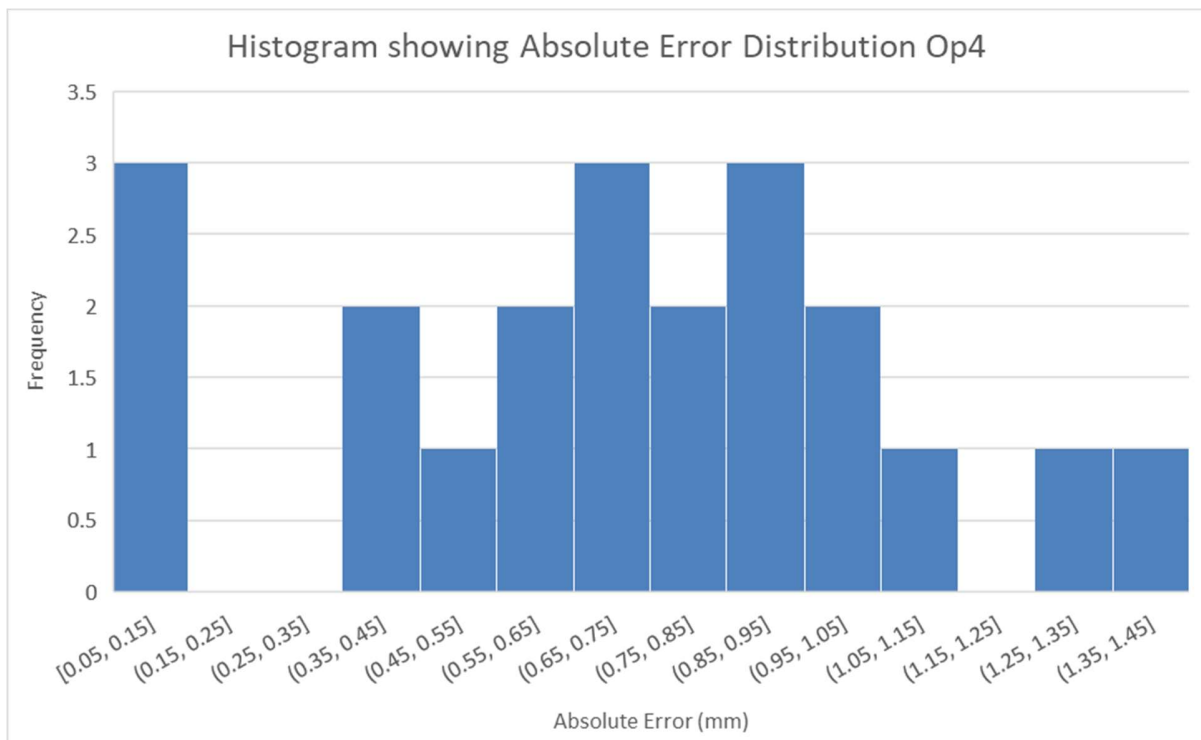


Figure E-9: Histogram of Errors for Technician 4

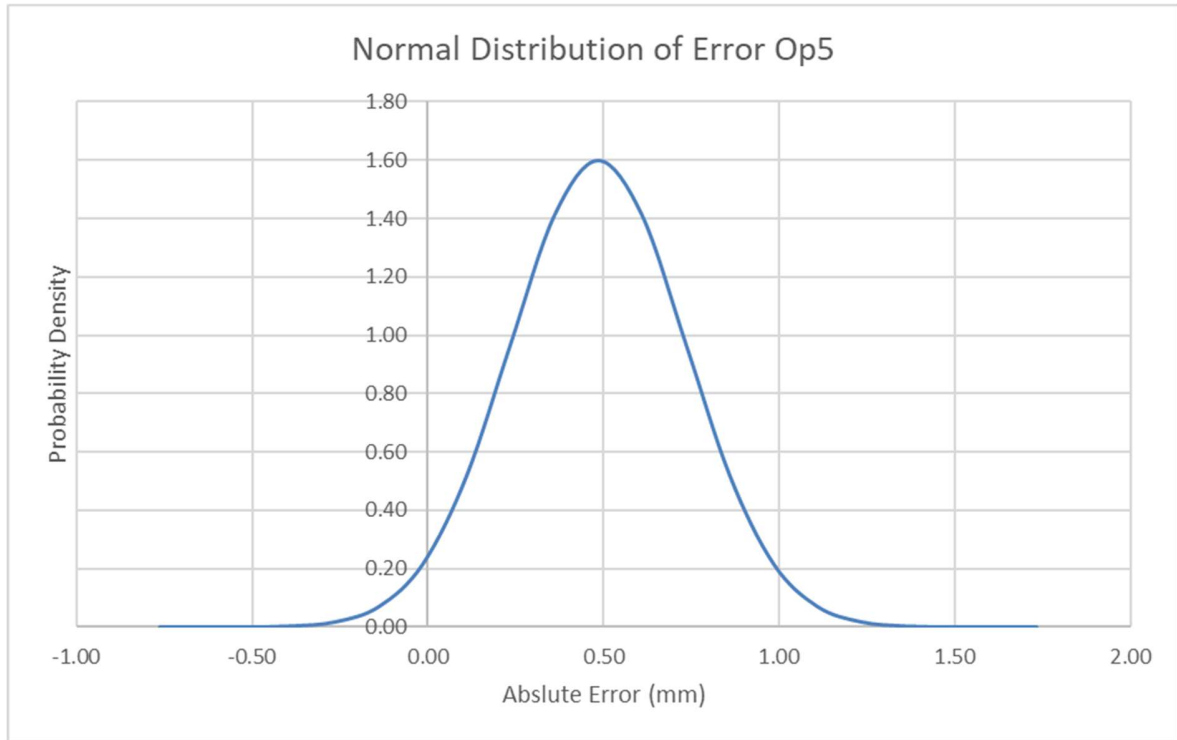


Figure E-10: Normal Distribution of Errors for Technician 5

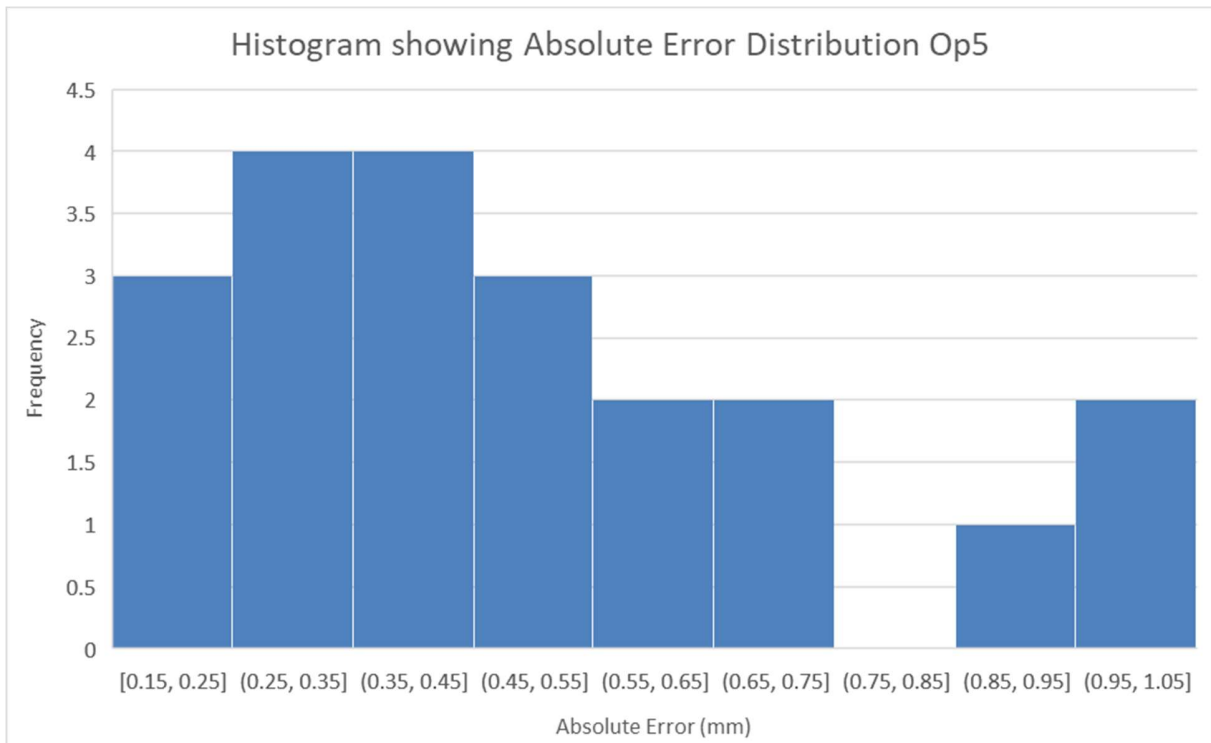


Figure E-11: Histogram of Errors for Technician 5

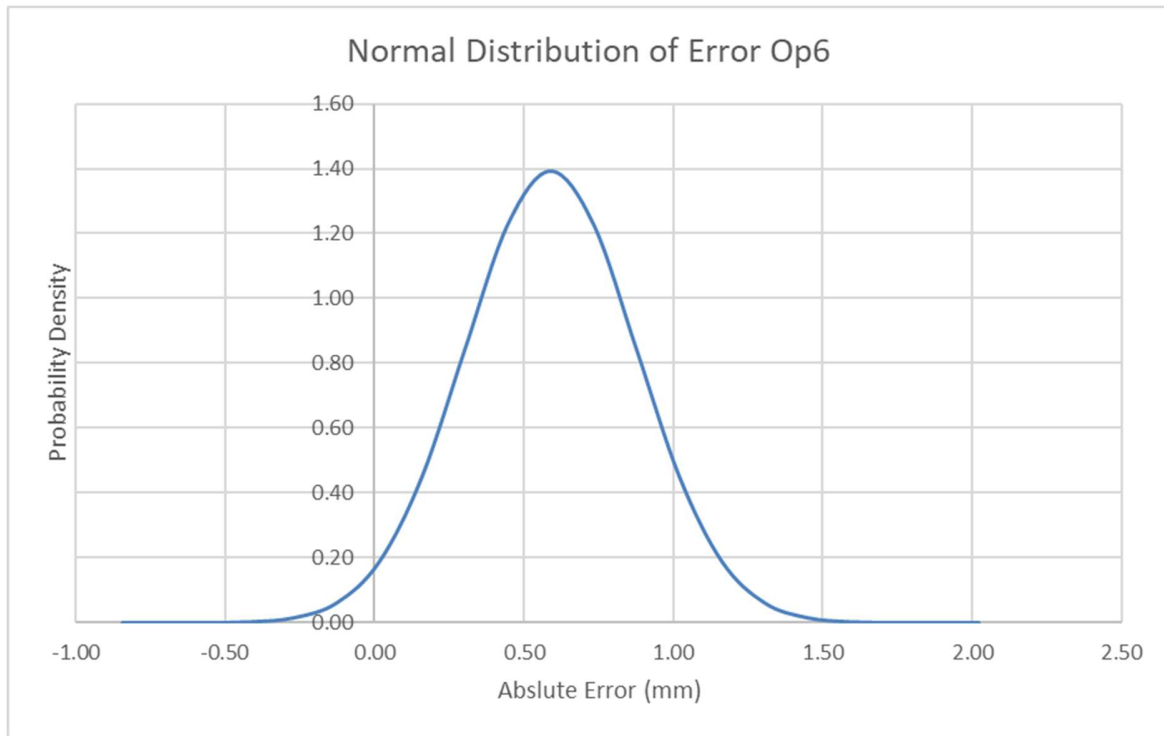


Figure E-12: Normal Distribution of Errors for Technician 6

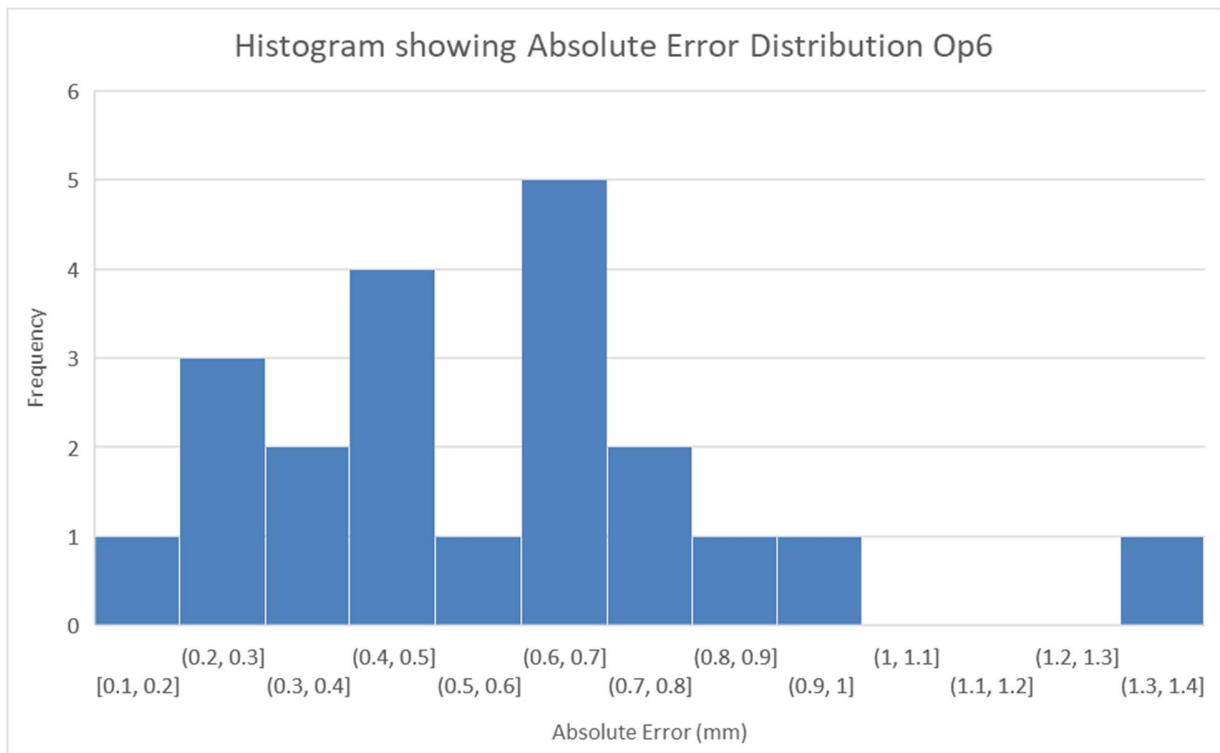


Figure E-13: Histogram of Errors for Technician 6

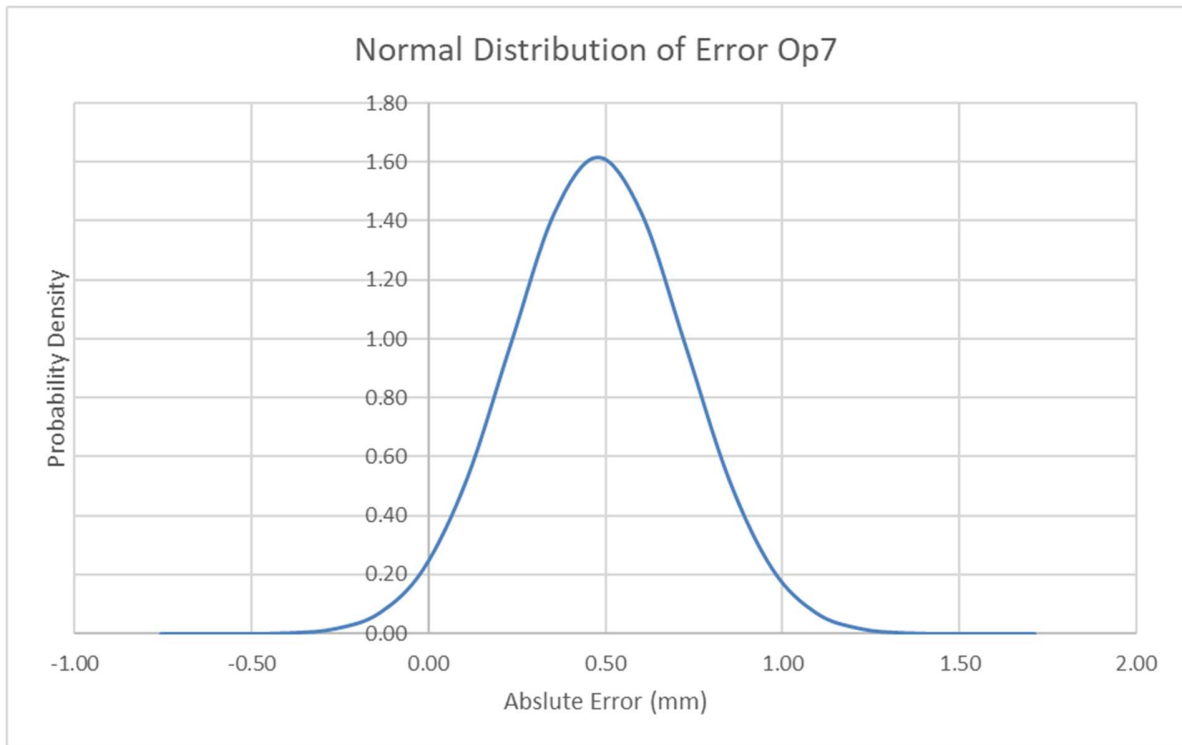


Figure E-14: Normal Distribution of Errors for Technician 7

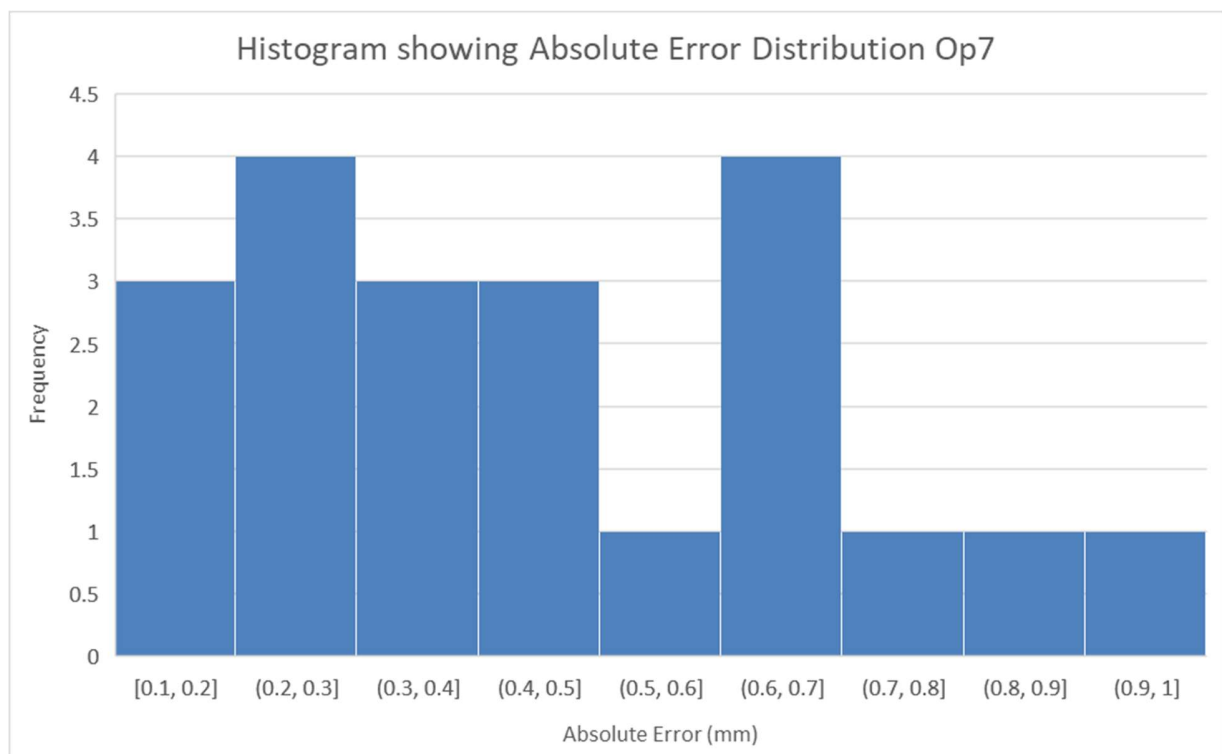


Figure E-15: Histogram of Errors for Technician 6

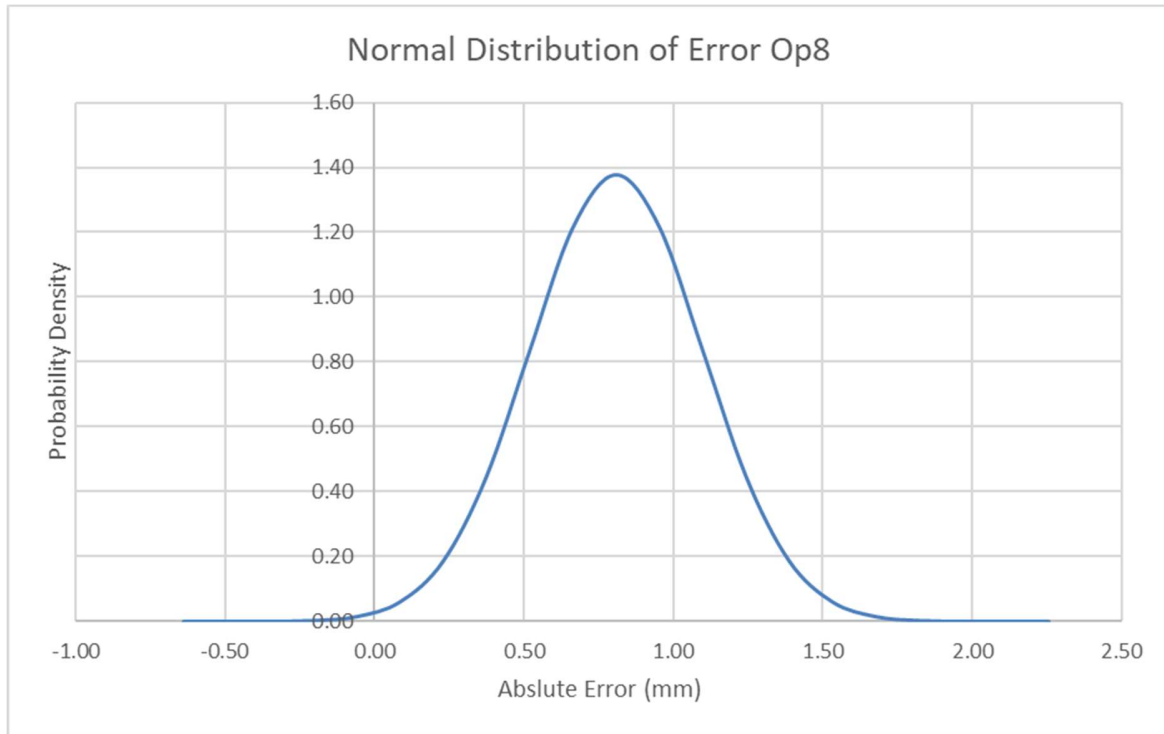


Figure E-16: Normal Distribution of Errors for Technician 8

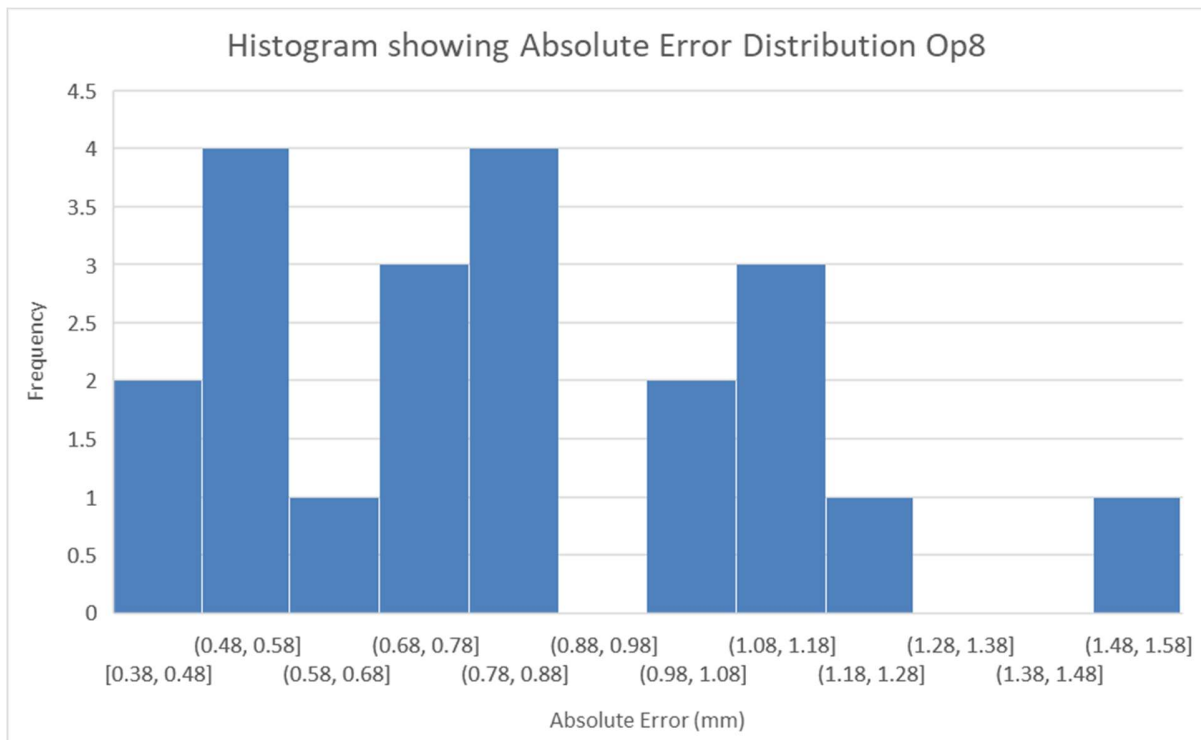


Figure E-17: Histogram of Errors for Technician 8

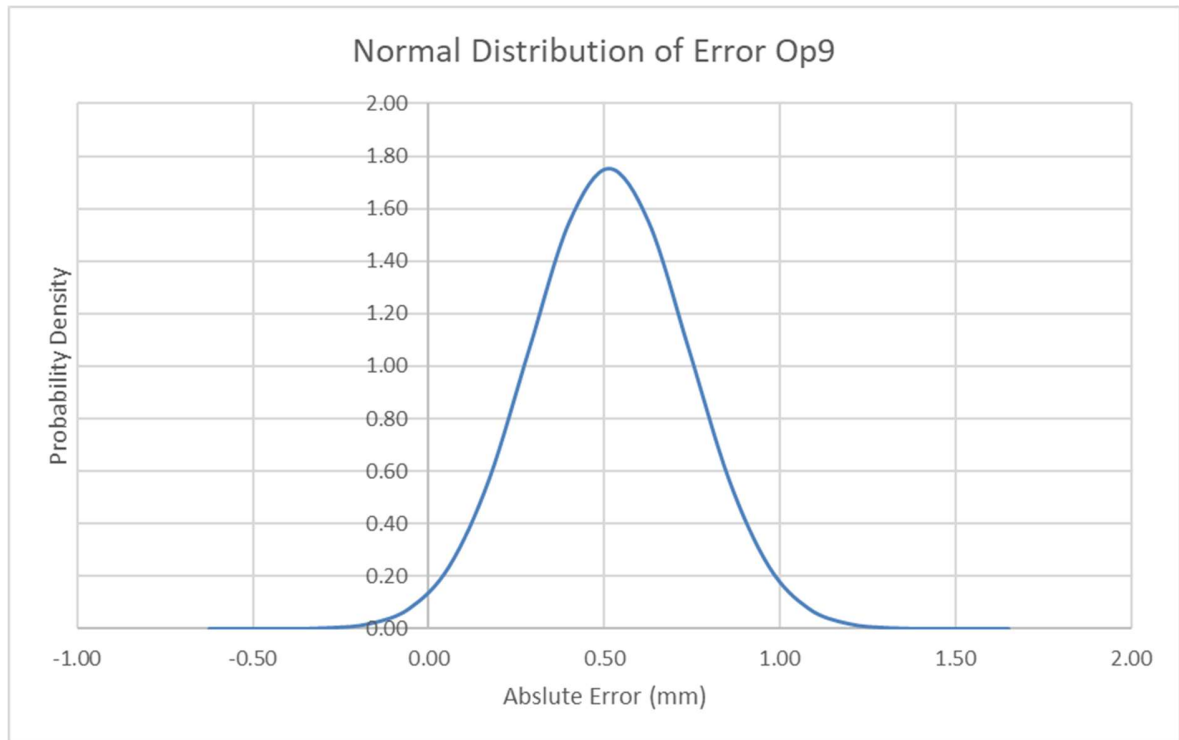


Figure E-18: Normal Distribution of Errors for Technician 9

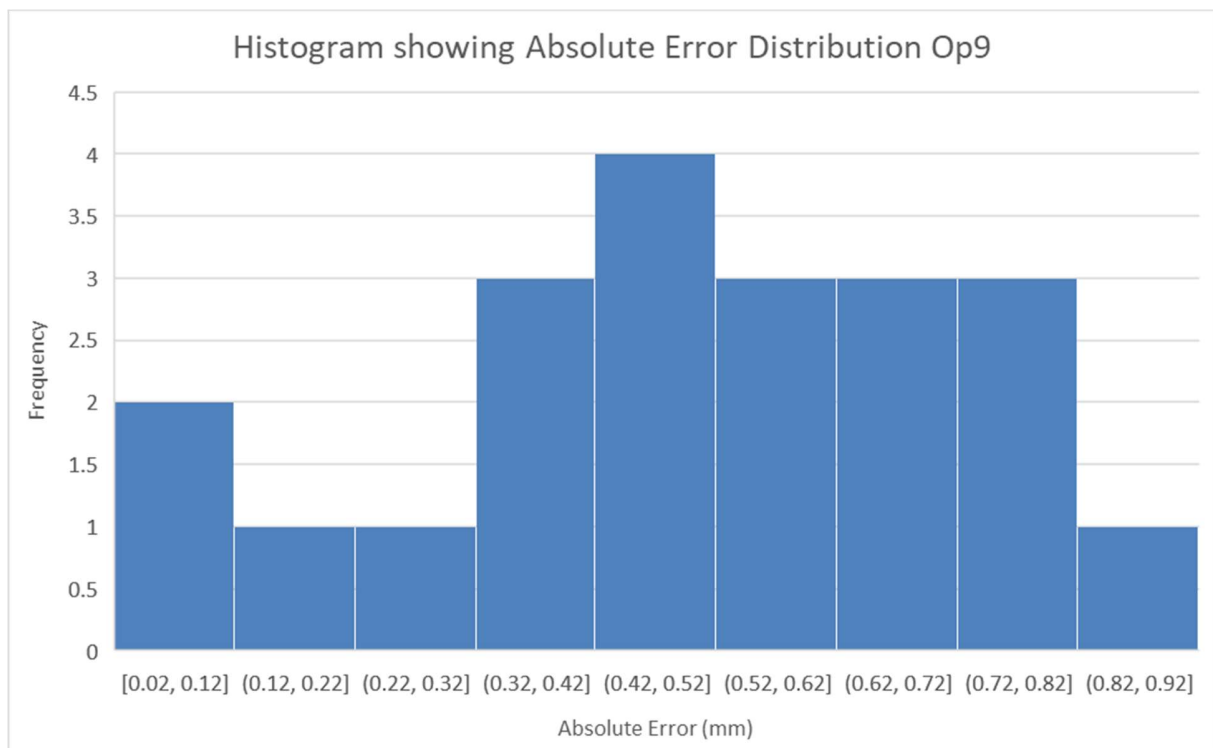


Figure E-19: Histogram of Errors for Technician 9

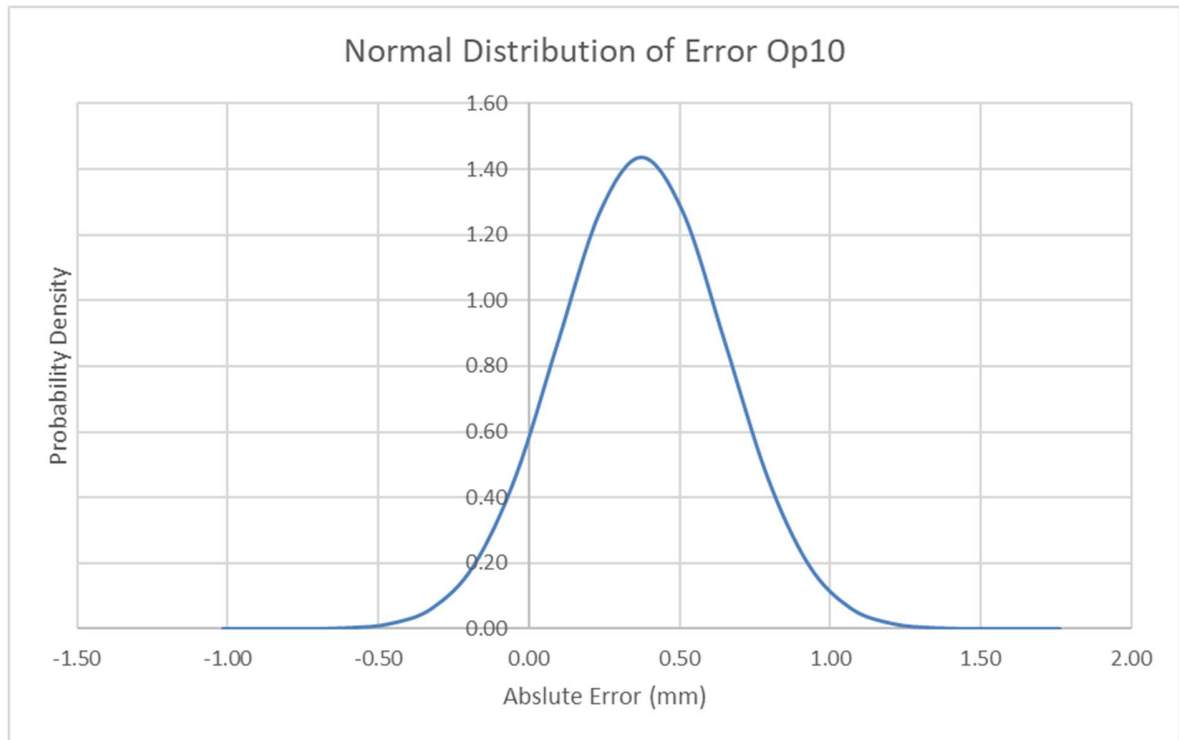


Figure E-20: Normal Distribution of Errors for Technician 10

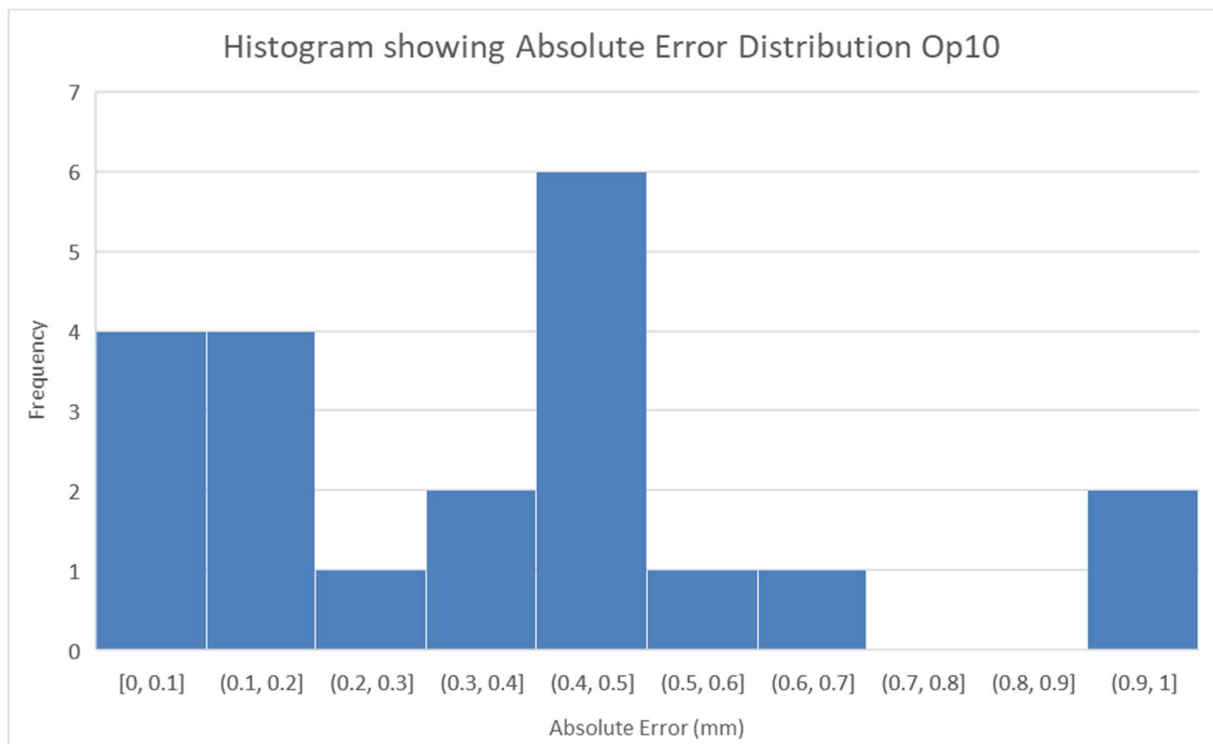


Figure E-21: Histogram of Errors for Technician 10

Table E-1: Normal Distribution of Errors for Technicians 1 - 5

Op1			Op2			Op3			Op4			Op5		
Abs Error	N Dist		Abs Error	N Dist		Abs Error	N Dist		Abs Error	N Dist		Abs Error	N Dist	
-0.43	0.00		-1.11	0.00		-0.95	0.00		-1.07	0.00		-0.76	0.00	
-0.35	0.00		-0.94	0.00		-0.81	0.00		-0.89	0.00		-0.64	0.00	
-0.27	0.00		-0.77	0.00		-0.68	0.00		-0.71	0.00		-0.51	0.00	
-0.19	0.01		-0.60	0.00		-0.54	0.00		-0.53	0.00		-0.39	0.00	
-0.11	0.03		-0.43	0.01		-0.40	0.02		-0.35	0.01		-0.26	0.02	
-0.03	0.11		-0.26	0.05		-0.26	0.06		-0.18	0.05		-0.14	0.07	
0.05	0.34		-0.09	0.16		-0.13	0.20		0.00	0.15		-0.01	0.22	
0.13	0.81		0.09	0.38		0.01	0.47		0.18	0.36		0.11	0.52	
0.21	1.52		0.26	0.71		0.15	0.88		0.36	0.68		0.24	0.97	
0.29	2.21		0.43	1.03		0.29	1.28		0.54	0.99		0.36	1.41	
0.37	2.50		0.60	1.16		0.43	1.45		0.72	1.12		0.48	1.60	
0.45	2.21		0.77	1.03		0.56	1.28		0.89	0.99		0.61	1.41	
0.53	1.52		0.94	0.71		0.70	0.88		1.07	0.68		0.73	0.97	
0.61	0.81		1.12	0.38		0.84	0.47		1.25	0.36		0.86	0.52	
0.69	0.34		1.29	0.16		0.98	0.20		1.43	0.15		0.98	0.22	
0.77	0.11		1.46	0.05		1.11	0.06		1.61	0.05		1.11	0.07	
0.85	0.03		1.63	0.01		1.25	0.02		1.79	0.01		1.23	0.02	
0.93	0.01		1.80	0.00		1.39	0.00		1.96	0.00		1.36	0.00	
1.01	0.00		1.97	0.00		1.53	0.00		2.14	0.00		1.48	0.00	
1.09	0.00		2.14	0.00		1.67	0.00		2.32	0.00		1.61	0.00	
1.17	0.00		2.32	0.00		1.80	0.00		2.50	0.00		1.73	0.00	

Table E-2: Normal Distribution of Errors for Technicians 6 - 10

Op6		Op7		Op8		Op9		Op10	
Abs Error	N Dist	Abs Error	N Dist	Abs Error	N Dist	Abs Error	N Dist	Abs Error	N Dist
-0.84	0.00	-0.76	0.00	-0.64	0.00	-0.63	0.00	-1.01	0.00
-0.70	0.00	-0.63	0.00	-0.49	0.00	-0.51	0.00	-0.88	0.00
-0.56	0.00	-0.51	0.00	-0.35	0.00	-0.40	0.00	-0.74	0.00
-0.41	0.00	-0.39	0.00	-0.20	0.00	-0.28	0.00	-0.60	0.00
-0.27	0.02	-0.26	0.02	-0.06	0.02	-0.17	0.02	-0.46	0.02
-0.13	0.06	-0.14	0.07	0.08	0.06	-0.06	0.08	-0.32	0.06
0.02	0.19	-0.02	0.22	0.23	0.19	0.06	0.24	-0.18	0.19
0.16	0.45	0.11	0.52	0.37	0.45	0.17	0.57	-0.04	0.47
0.30	0.84	0.23	0.98	0.52	0.84	0.29	1.06	0.10	0.87
0.45	1.23	0.35	1.42	0.66	1.22	0.40	1.55	0.24	1.27
0.59	1.39	0.48	1.61	0.81	1.38	0.51	1.75	0.38	1.43
0.73	1.23	0.60	1.42	0.95	1.22	0.63	1.55	0.51	1.27
0.88	0.84	0.73	0.98	1.10	0.84	0.74	1.06	0.65	0.87
1.02	0.45	0.85	0.52	1.24	0.45	0.86	0.57	0.79	0.47
1.16	0.19	0.97	0.22	1.39	0.19	0.97	0.24	0.93	0.19
1.31	0.06	1.10	0.07	1.53	0.06	1.08	0.08	1.07	0.06
1.45	0.02	1.22	0.02	1.68	0.02	1.20	0.02	1.21	0.02
1.59	0.00	1.34	0.00	1.82	0.00	1.31	0.00	1.35	0.00
1.74	0.00	1.47	0.00	1.97	0.00	1.42	0.00	1.49	0.00
1.88	0.00	1.59	0.00	2.11	0.00	1.54	0.00	1.63	0.00
2.02	0.00	1.71	0.00	2.26	0.00	1.65	0.00	1.77	0.00

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