CHAPTER 4

EXPERIMENT, RESULT AND DISCUSSION

4.1 Introduction

This chapter describes the experiment in detail, elaborating on the results and discussions for the optical tomography system using the CCD linear sensor, Minitab software, and MATLAB programming.

The experiment is conducted under the following conditions: the room temperature is at 25ºC. The experiment is conducted in a black box. The luminosity or the radiant power emitted by the laser is maintained at 0.5 lux in this experiment.

The results and discussion section in this chapter includes the following analysis:

i. Analysis of the CCD voltage output when the laser is in ON and OFF conditions without the presence of a ruby in the CCD system.
ii. Analysis of the CCD voltage output when the laser is in ON and OFF conditions in the presence of a ruby in the CCD system.

The analysis of the result involves statistical engineering to validate the experimental data. The Minitab 16 software is used to conduct the statistical calculation and analysis. Six hundred data are taken from each of the experiments. The t-test is conducted on the samples to validate the data, and the finalized data is then tested for its accuracy.

4.2 Experiment

The experiment is conducted under the condition when the ruby is placed in a black box and the laser is beamed onto the ruby. The CCD linear sensor receives the light from the ruby and converts the light intensity into a voltage value. For this experiment, the laser light beam should give a voltage value >1.5 V to avoid the CCD linear sensor from being saturated (Idroas et al., 2011; Jamaludin et al., 2016). A filter is used to reduce the light intensity that hits onto the CCD linear sensor surface. High light intensity will cause the CCD linear sensor to be saturated as mentioned in the Sony ILX551A data sheet. Then, a ruby is placed onto the CCD linear sensor glass surface, and the analysis of the light intensity is conducted.

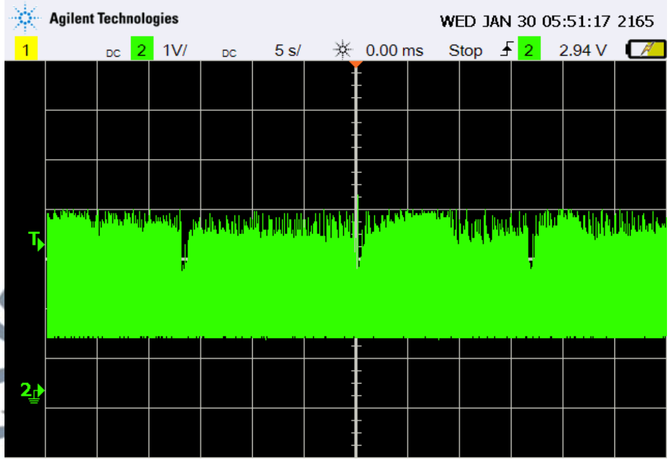


Figure 4.1 Waveform Obtained when the Laser is Beamed Directly to the Ruby without a Filter.

When the laser light is beamed directly to the ruby, the data waveform shown on the oscilloscope contains noise, as shown in Figure 4.1. Alternatively, a lower noise data waveform as depicted in Figure 4.2, can be obtained when the filter is placed at the small aperture which situated at the top of the black box, as shown in Figure 4.2. This proves that the CCD sensor is very sensitive that detects every detail of light, which can affect the data (Mehta et al., 2015). A data waveform with minimum noise is vital to make sure valid data can be extracted from the experiment.

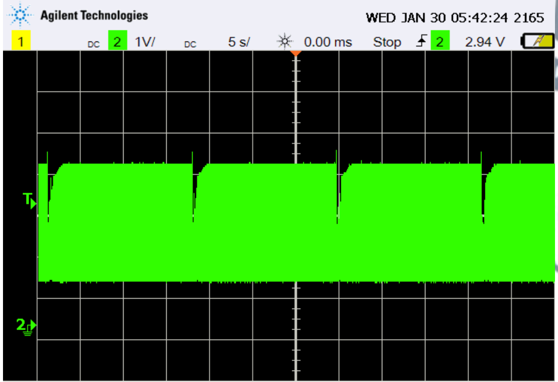
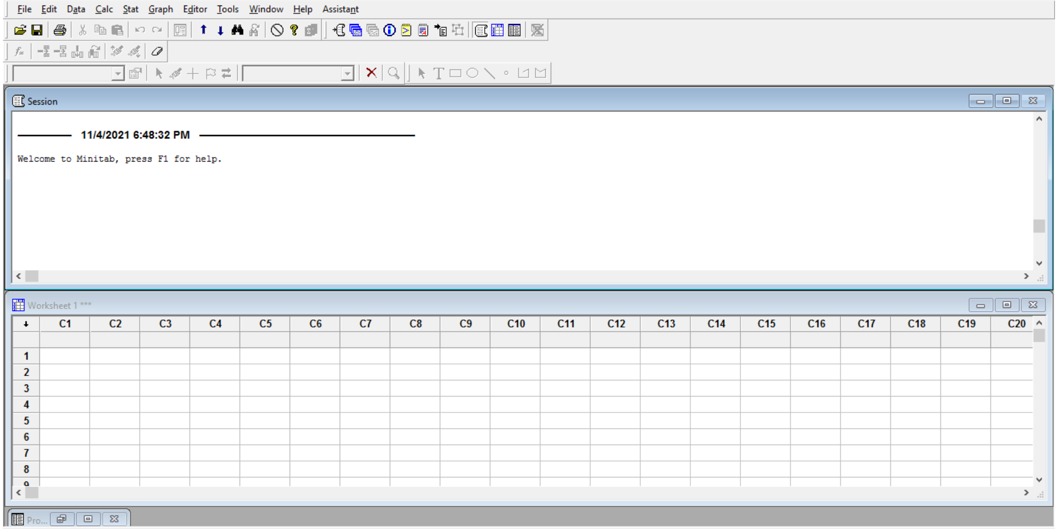


Figure 4.2 Waveform Obtained when the Laser is Beamed toward the Ruby through a Filter.

Figure 4.3 Laser is Beamed toward the Ruby through a Filter.

4.2.1 Experimental CCD Voltage Output when Ruby is Not in the System

When a collimated light is focused at a CCD linear image sensor, the sensor detects the object's shadow cast on the sensor (Ramli et al., 2011). The light intensity is transformed into voltage based on the amount of light detected by the CCD sensor (Jamaludin et al., 2021; Mohd Rahalim et al., 2022). In any situation, the reflection on the front of the CCD linear image sensor is ignored (Idroas, 2014). The CCD output voltage in the OFF and ON conditions of the laser is analyzed using the Minitab 16 software (Figure 4.4).



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———— 11/4/2021 6:48:32 PM ————————————

Welcome to Minitab, press F1 for help.
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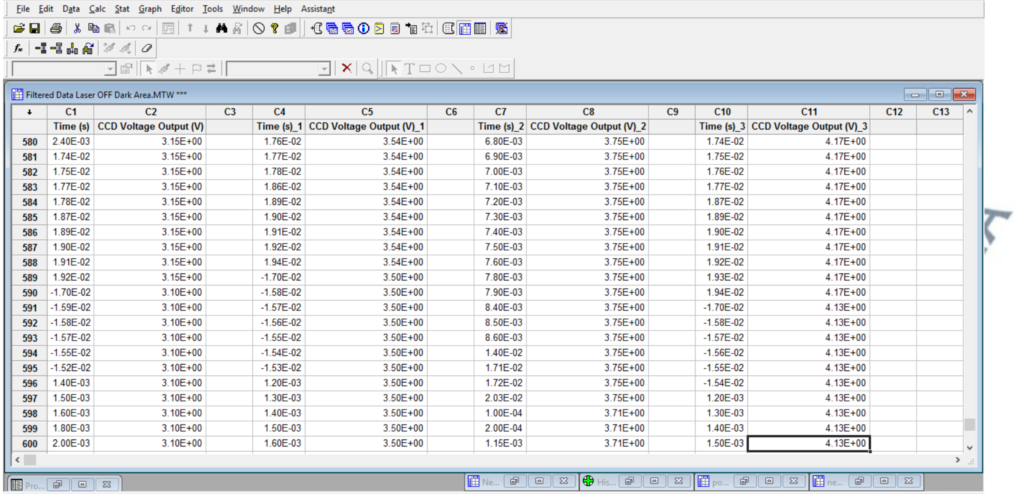
Figure 4.4 Minitab 16 Software.

4.2.1.1 Analysis on the Mean CCD Output Voltage

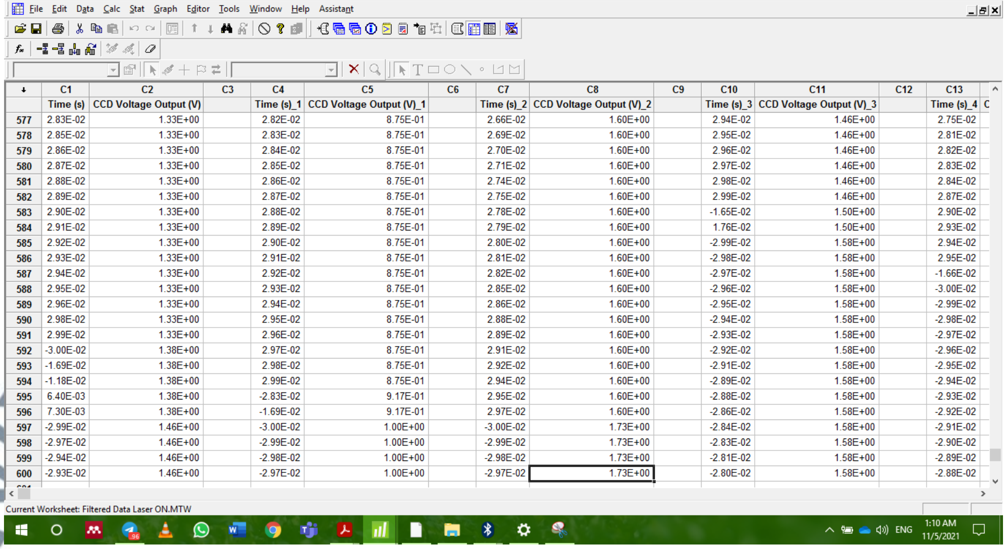
First, the analysis of the samples investigated with the laser in the OFF condition is performed. Six hundred data points are considered (Figure 4.5). The same procedure is repeated with the laser in the ON condition. The mean value from the same amount of 600 data is also recorded (Figure 4.6).



↓	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
	Time (s)	CCD Voltage Output (V)		Time (s)_1	CCD Voltage Output (V)_1		Time (s)_2	CCD Voltage Output (V)_2		Time (s)_3	CCD Voltage Output (V)_3		
580	2.40E-03	3.15E+00		1.76E-02	3.54E+00		6.80E-03	3.75E+00		1.74E-02	4.17E+00		
581	1.74E-02	3.15E+00		1.77E-02	3.54E+00		6.90E-03	3.75E+00		1.75E-02	4.17E+00		
582	1.75E-02	3.15E+00		1.78E-02	3.54E+00		7.00E-03	3.75E+00		1.76E-02	4.17E+00		
583	1.77E-02	3.15E+00		1.86E-02	3.54E+00		7.10E-03	3.75E+00		1.77E-02	4.17E+00		
584	1.78E-02	3.15E+00		1.89E-02	3.54E+00		7.20E-03	3.75E+00		1.87E-02	4.17E+00		
585	1.87E-02	3.15E+00		1.90E-02	3.54E+00		7.30E-03	3.75E+00		1.89E-02	4.17E+00		
586	1.89E-02	3.15E+00		1.91E-02	3.54E+00		7.40E-03	3.75E+00		1.90E-02	4.17E+00		
587	1.90E-02	3.15E+00		1.92E-02	3.54E+00		7.50E-03	3.75E+00		1.91E-02	4.17E+00		
588	1.91E-02	3.15E+00		1.94E-02	3.54E+00		7.60E-03	3.75E+00		1.92E-02	4.17E+00		
589	1.92E-02	3.15E+00		-1.70E-02	3.50E+00		7.80E-03	3.75E+00		1.93E-02	4.17E+00		
590	-1.70E-02	3.10E+00		-1.58E-02	3.50E+00		7.90E-03	3.75E+00		1.94E-02	4.17E+00		
591	-1.59E-02	3.10E+00		-1.57E-02	3.50E+00		8.40E-03	3.75E+00		-1.70E-02	4.13E+00		
592	-1.58E-02	3.10E+00		-1.56E-02	3.50E+00		8.50E-03	3.75E+00		-1.58E-02	4.13E+00		
593	-1.57E-02	3.10E+00		-1.55E-02	3.50E+00		8.60E-03	3.75E+00		-1.57E-02	4.13E+00		
594	-1.55E-02	3.10E+00		-1.54E-02	3.50E+00		1.40E-02	3.75E+00		-1.56E-02	4.13E+00		
595	-1.52E-02	3.10E+00		-1.53E-02	3.50E+00		1.71E-02	3.75E+00		-1.55E-02	4.13E+00		
596	1.40E-03	3.10E+00		1.20E-03	3.50E+00		1.72E-02	3.75E+00		-1.54E-02	4.13E+00		
597	1.50E-03	3.10E+00		1.30E-03	3.50E+00		2.03E-02	3.75E+00		1.20E-03	4.13E+00		
598	1.60E-03	3.10E+00		1.40E-03	3.50E+00		1.00E-04	3.71E+00		1.30E-03	4.13E+00		
599	1.80E-03	3.10E+00		1.50E-03	3.50E+00		2.00E-04	3.71E+00		1.40E-03	4.13E+00		
600	2.00E-03	3.10E+00		1.60E-03	3.50E+00		1.15E-03	3.71E+00		1.50E-03	4.13E+00		

Current Worksheet: Filtered Data Laser OFF Dark Area.MTW

Figure 4.5 Voltage Output Data (600 Data Points) are Analyzed in the Minitab Software with OFF Laser Condition without the Ruby in the System.



↓	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C
	Time (s)	CCD Voltage Output (V)		Time (s)_1	CCD Voltage Output (V)_1		Time (s)_2	CCD Voltage Output (V)_2		Time (s)_3	CCD Voltage Output (V)_3		Time (s)_4	
577	2.83E-02	1.33E+00		2.82E-02	8.75E-01		2.66E-02	1.60E+00		2.94E-02	1.46E+00		2.75E-02	
578	2.85E-02	1.33E+00		2.83E-02	8.75E-01		2.69E-02	1.60E+00		2.95E-02	1.46E+00		2.81E-02	
579	2.86E-02	1.33E+00		2.84E-02	8.75E-01		2.70E-02	1.60E+00		2.96E-02	1.46E+00		2.82E-02	
580	2.87E-02	1.33E+00		2.85E-02	8.75E-01		2.71E-02	1.60E+00		2.97E-02	1.46E+00		2.83E-02	
581	2.88E-02	1.33E+00		2.86E-02	8.75E-01		2.74E-02	1.60E+00		2.98E-02	1.46E+00		2.84E-02	
582	2.89E-02	1.33E+00		2.87E-02	8.75E-01		2.75E-02	1.60E+00		2.99E-02	1.46E+00		2.87E-02	
583	2.90E-02	1.33E+00		2.88E-02	8.75E-01		2.78E-02	1.60E+00		-1.65E-02	1.50E+00		2.90E-02	
584	2.91E-02	1.33E+00		2.89E-02	8.75E-01		2.79E-02	1.60E+00		1.76E-02	1.50E+00		2.93E-02	
585	2.92E-02	1.33E+00		2.90E-02	8.75E-01		2.80E-02	1.60E+00		-2.99E-02	1.58E+00		2.94E-02	
586	2.93E-02	1.33E+00		2.91E-02	8.75E-01		2.81E-02	1.60E+00		-2.98E-02	1.58E+00		2.95E-02	
587	2.94E-02	1.33E+00		2.92E-02	8.75E-01		2.82E-02	1.60E+00		-2.97E-02	1.58E+00		-1.66E-02	
588	2.95E-02	1.33E+00		2.93E-02	8.75E-01		2.85E-02	1.60E+00		-2.96E-02	1.58E+00		-3.00E-02	
589	2.96E-02	1.33E+00		2.94E-02	8.75E-01		2.86E-02	1.60E+00		-2.95E-02	1.58E+00		-2.99E-02	
590	2.98E-02	1.33E+00		2.95E-02	8.75E-01		2.88E-02	1.60E+00		-2.94E-02	1.58E+00		-2.98E-02	
591	2.99E-02	1.33E+00		2.96E-02	8.75E-01		2.89E-02	1.60E+00		-2.93E-02	1.58E+00		-2.97E-02	
592	-3.00E-02	1.38E+00		2.97E-02	8.75E-01		2.91E-02	1.60E+00		-2.92E-02	1.58E+00		-2.96E-02	
593	-1.69E-02	1.38E+00		2.98E-02	8.75E-01		2.92E-02	1.60E+00		-2.91E-02	1.58E+00		-2.95E-02	
594	-1.18E-02	1.38E+00		2.99E-02	8.75E-01		2.94E-02	1.60E+00		-2.89E-02	1.58E+00		-2.94E-02	
595	6.40E-03	1.38E+00		-2.83E-02	9.17E-01		2.95E-02	1.60E+00		-2.88E-02	1.58E+00		-2.93E-02	
596	7.30E-03	1.38E+00		-1.69E-02	9.17E-01		2.97E-02	1.60E+00		-2.86E-02	1.58E+00		-2.92E-02	
597	-2.99E-02	1.46E+00		-3.00E-02	1.00E+00		-3.00E-02	1.73E+00		-2.84E-02	1.58E+00		-2.91E-02	
598	-2.97E-02	1.46E+00		-2.99E-02	1.00E+00		-2.99E-02	1.73E+00		-2.83E-02	1.58E+00		-2.90E-02	
599	-2.94E-02	1.46E+00		-2.98E-02	1.00E+00		-2.98E-02	1.73E+00		-2.81E-02	1.58E+00		-2.89E-02	
600	-2.93E-02	1.46E+00		-2.97E-02	1.00E+00		-2.97E-02	1.73E+00		-2.80E-02	1.58E+00		-2.88E-02	

Current Worksheet: Filtered Data Laser ON.MTW

Figure 4.6 Voltage Output Data (600 Data Points) are Analyzed in the Minitab Software with the Laser ON Condition without the Ruby in the System.

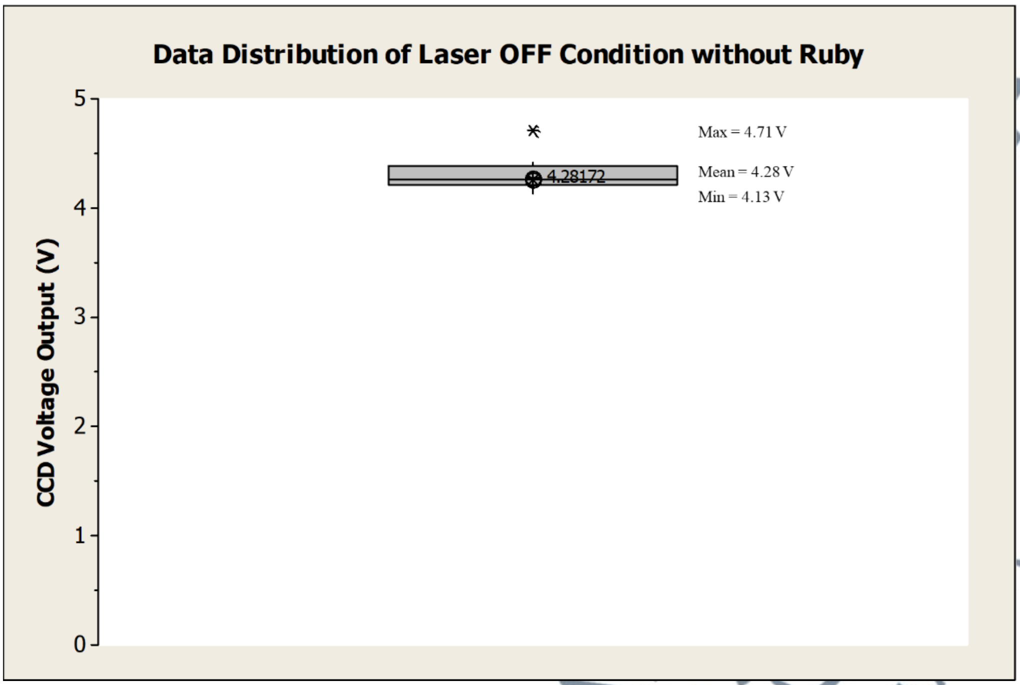


Figure 4.7 CCD Output Voltage in the Laser OFF Condition.

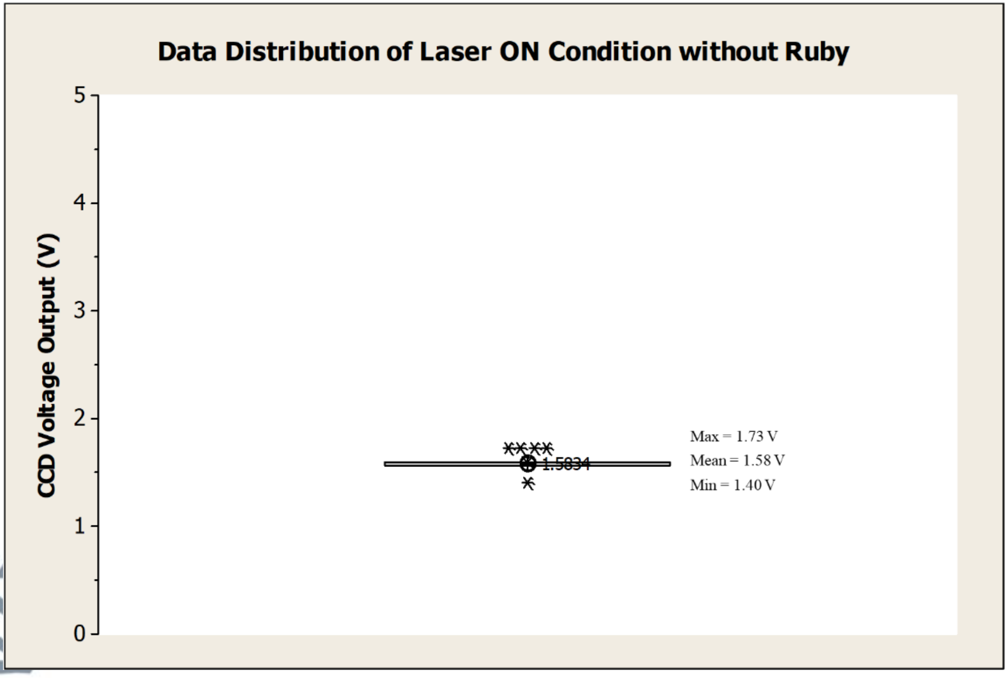


Figure 4.8 CCD Voltage Output in the Laser ON Condition.

From the box plot in Figure 4.7, the CCD output voltage shows a mean value of 4.282 V, with the maximum value of 4.71 V and minimum value of 4.13 of 600 data points considered. In Figure 4.8, the box plot shows a mean CCD output voltage value of 1.583 V, with the maximum value of 1.73 V and minimum value of 1.40 V of 600 data points considered. Table 4.1 shows the value of the CCD voltage output in the two laser conditions, OFF and ON, as well as their respective light intensity.

Table 4.1 The Mean CCD Voltage Output and Laser Light Intensity in the Laser OFF and ON Conditions.

Condition of Laser	CCD Voltage Output (V)	Light Intensity
OFF	4.282	0
ON	1.583	1

The laser intensity is proportional to the CCD output voltage. Figure 4.9 shows the voltage output of the CCD versus the intensity of the laser. Based on this graph, it can be assumed that the CCD voltage output is inversely proportional to the laser intensity, with a gradient of 2.6983 and an interception value of 4.2817 at zero light intensity. The relationship between CCD voltage output and light intensity is represented by Equation (4.1).

$$V = -2.6983I + 4.2817 \tag{4.1}$$

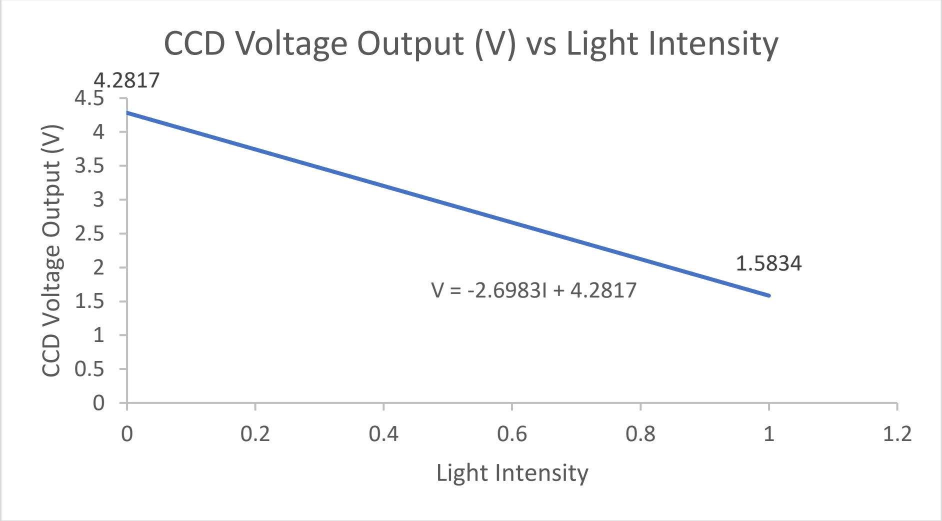


Figure 4.9 Graph of the CCD Voltage Output vs Light Intensity.

4.2.2 Theoretical CCD Voltage Output when Natural Ruby is in the System

Based on the mean CCD voltage output in the laser ON and OFF condition, the Equation 4.1 is executed. Since the calculation on the theoretical light intensity, *I* value for the natural ruby is performed in the section 3.3.3, the theoretical light intensity, *I* is 0.8541. Hence, the theoretical light intensity, *I* = 0.8541 can be included in the Equation 4.1 to get the theoretical CCD voltage output when natural ruby is in the system. The calculation is as follows:

$$V = -2.6983I + 4.2817$$

$$V = -2.6983(0.8541) + 4.2817$$

$$V = 1.9771\,V$$

Hence, the theoretical CCD voltage output is 1.9771 V.

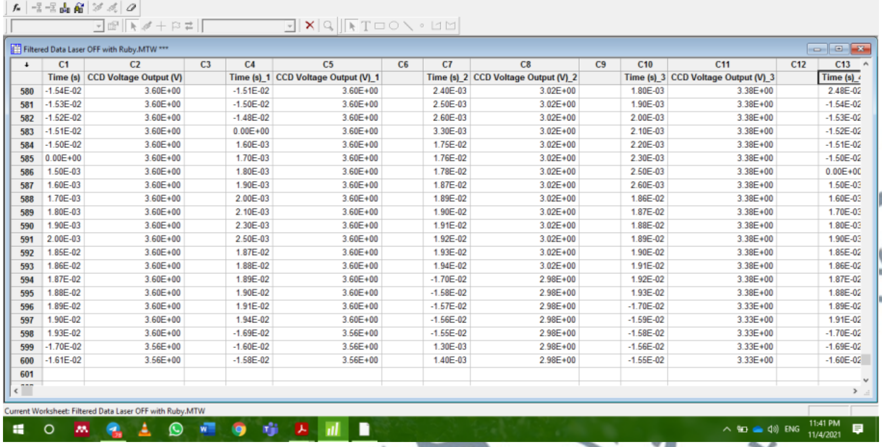
4.2.3 Experimental CCD Voltage Output when Synthetic Ruby is in the System

This experiment investigates the phenomenon of light propagation from the air into the synthetic ruby. Since light goes from air into the synthetic ruby, the refractive index of air to the synthetic ruby is involved in this case. Due to the reflection at the air–ruby interface, the incoming light intensity (I) is lowered at the synthetic ruby's initial surface. Table 4.2 displays the theoretical light intensity and theoretical CCD voltage output obtained by solving Equations (3.2), (3.3), and (4.1). The Equations (3.2) and (3.3) are explained in Chapter 3, where each equation represents light reflectance and absorption, respectively.

Table 4.2 CCD Voltage Output and Laser Light Intensity in Different Situations of Light Propagation

Situation of light propagation	Light Intensity	CCD Voltage Output (V)
Laser ON with Synthetic Ruby	0.8478	1.9941

According to Table 4.2, the voltage output will be higher when an object is present in the system than without any object. The laser light absorption and reflection process resulted in high voltage output (Jamaludin, 2016). Figure 4.11 depicts the distribution of the CCD output voltage value while the synthetic ruby is in the system with the laser turned OFF.



↓	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
	Time (s)	CCD Voltage Output (V)		Time (s)_1	CCD Voltage Output (V)_1		Time (s)_2	CCD Voltage Output (V)_2		Time (s)_3	CCD Voltage Output (V)_3		Time (s)_
580	-1.54E-02	3.60E+00		-1.51E-02	3.60E+00		2.40E-03	3.02E+00		1.80E-03	3.38E+00		2.48E-02
581	-1.53E-02	3.60E+00		-1.50E-02	3.60E+00		2.50E-03	3.02E+00		1.90E-03	3.38E+00		-1.54E-02
582	-1.52E-02	3.60E+00		-1.48E-02	3.60E+00		2.60E-03	3.02E+00		2.00E-03	3.38E+00		-1.53E-02
583	-1.51E-02	3.60E+00		0.00E+00	3.60E+00		3.30E-03	3.02E+00		2.10E-03	3.38E+00		-1.52E-02
584	-1.50E-02	3.60E+00		1.60E-03	3.60E+00		1.75E-02	3.02E+00		2.20E-03	3.38E+00		-1.51E-02
585	0.00E+00	3.60E+00		1.70E-03	3.60E+00		1.76E-02	3.02E+00		2.30E-03	3.38E+00		-1.50E-02
586	1.50E-03	3.60E+00		1.80E-03	3.60E+00		1.78E-02	3.02E+00		2.50E-03	3.38E+00		0.00E+0
587	1.60E-03	3.60E+00		1.90E-03	3.60E+00		1.87E-02	3.02E+00		2.60E-03	3.38E+00		1.50E-0
588	1.70E-03	3.60E+00		2.00E-03	3.60E+00		1.89E-02	3.02E+00		1.86E-02	3.38E+00		1.60E-0
589	1.80E-03	3.60E+00		2.10E-03	3.60E+00		1.90E-02	3.02E+00		1.87E-02	3.38E+00		1.70E-0
590	1.90E-03	3.60E+00		2.30E-03	3.60E+00		1.91E-02	3.02E+00		1.88E-02	3.38E+00		1.80E-0
591	2.00E-03	3.60E+00		2.50E-03	3.60E+00		1.92E-02	3.02E+00		1.89E-02	3.38E+00		1.90E-0
592	1.85E-02	3.60E+00		1.87E-02	3.60E+00		1.93E-02	3.02E+00		1.90E-02	3.38E+00		1.85E-02
593	1.86E-02	3.60E+00		1.88E-02	3.60E+00		1.94E-02	3.02E+00		1.91E-02	3.38E+00		1.86E-02
594	1.87E-02	3.60E+00		1.89E-02	3.60E+00		-1.70E-02	2.98E+00		1.92E-02	3.38E+00		1.87E-02
595	1.88E-02	3.60E+00		1.90E-02	3.60E+00		-1.58E-02	2.98E+00		1.93E-02	3.38E+00		1.88E-02
596	1.89E-02	3.60E+00		1.91E-02	3.60E+00		-1.57E-02	2.98E+00		-1.70E-02	3.33E+00		1.89E-02
597	1.90E-02	3.60E+00		1.94E-02	3.60E+00		-1.56E-02	2.98E+00		-1.59E-02	3.33E+00		1.91E-02
598	1.93E-02	3.60E+00		-1.69E-02	3.56E+00		-1.55E-02	2.98E+00		-1.58E-02	3.33E+00		-1.70E-02
599	-1.70E-02	3.56E+00		-1.60E-02	3.56E+00		1.30E-03	2.98E+00		-1.56E-02	3.33E+00		-1.69E-02
600	-1.61E-02	3.56E+00		-1.58E-02	3.56E+00		1.40E-03	2.98E+00		-1.55E-02	3.33E+00		-1.60E-02
601													

Figure 4.10 Voltage Output Data (600 Data Points) are Analyzed in the Minitab Software with Laser in OFF Condition and the Synthetic Ruby in the System.

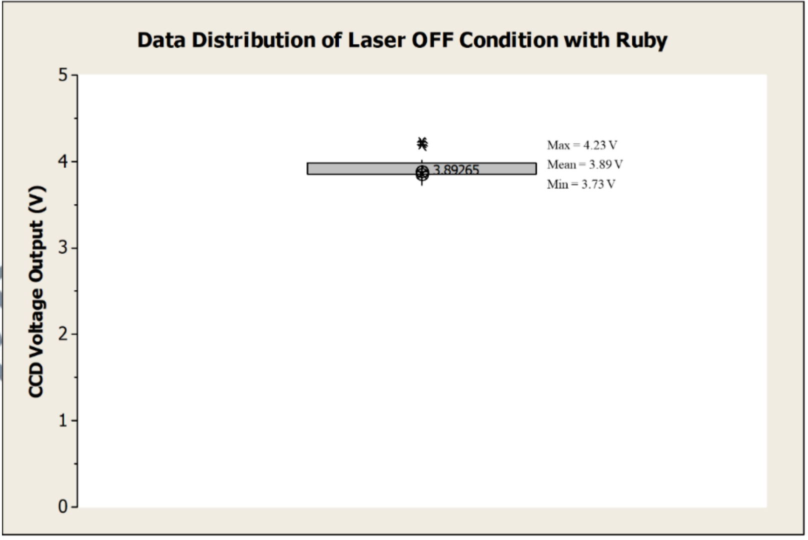
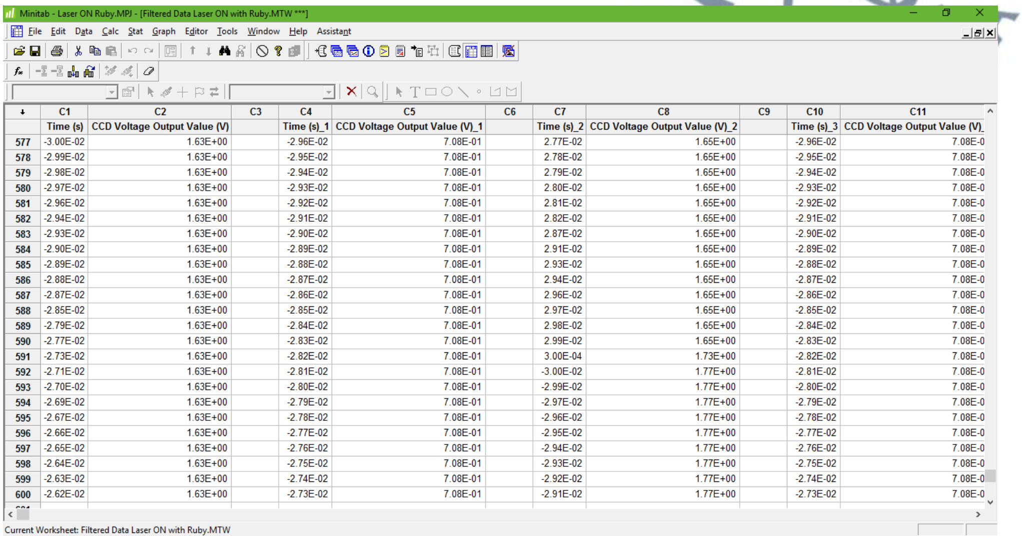


Figure 4.11 Box Plot of the CCD Voltage Output with the Laser in OFF Condition and the Synthetic Ruby in the System.

When the laser is turned on, the data reveals a substantially lower value of the CCD output voltage, as seen in Figure 4.12. Because the laser is turned on, the CCD linear sensor receives significantly increased light intensity. Figure 4.13 depicts the data distribution of the CCD output voltage when the synthetic ruby is present in the system and the laser is turned on.



↓	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
	Time (s)	CCD Voltage Output Value (V)		Time (s)_1	CCD Voltage Output Value (V)_1		Time (s)_2	CCD Voltage Output Value (V)_2		Time (s)_3	CCD Voltage Output Value (V)_
577	-3.00E-02	1.63E+00		-2.96E-02	7.08E-01		2.77E-02	1.65E+00		-2.96E-02	7.08E-0
578	-2.99E-02	1.63E+00		-2.95E-02	7.08E-01		2.78E-02	1.65E+00		-2.95E-02	7.08E-0
579	-2.98E-02	1.63E+00		-2.94E-02	7.08E-01		2.79E-02	1.65E+00		-2.94E-02	7.08E-0
580	-2.97E-02	1.63E+00		-2.93E-02	7.08E-01		2.80E-02	1.65E+00		-2.93E-02	7.08E-0
581	-2.96E-02	1.63E+00		-2.92E-02	7.08E-01		2.81E-02	1.65E+00		-2.92E-02	7.08E-0
582	-2.94E-02	1.63E+00		-2.91E-02	7.08E-01		2.82E-02	1.65E+00		-2.91E-02	7.08E-0
583	-2.93E-02	1.63E+00		-2.90E-02	7.08E-01		2.87E-02	1.65E+00		-2.90E-02	7.08E-0
584	-2.90E-02	1.63E+00		-2.89E-02	7.08E-01		2.91E-02	1.65E+00		-2.89E-02	7.08E-0
585	-2.89E-02	1.63E+00		-2.88E-02	7.08E-01		2.93E-02	1.65E+00		-2.88E-02	7.08E-0
586	-2.88E-02	1.63E+00		-2.87E-02	7.08E-01		2.94E-02	1.65E+00		-2.87E-02	7.08E-0
587	-2.87E-02	1.63E+00		-2.86E-02	7.08E-01		2.96E-02	1.65E+00		-2.86E-02	7.08E-0
588	-2.85E-02	1.63E+00		-2.85E-02	7.08E-01		2.97E-02	1.65E+00		-2.85E-02	7.08E-0
589	-2.79E-02	1.63E+00		-2.84E-02	7.08E-01		2.98E-02	1.65E+00		-2.84E-02	7.08E-0
590	-2.77E-02	1.63E+00		-2.83E-02	7.08E-01		2.99E-02	1.65E+00		-2.83E-02	7.08E-0
591	-2.73E-02	1.63E+00		-2.82E-02	7.08E-01		3.00E-04	1.73E+00		-2.82E-02	7.08E-0
592	-2.71E-02	1.63E+00		-2.81E-02	7.08E-01		-3.00E-02	1.77E+00		-2.81E-02	7.08E-0
593	-2.70E-02	1.63E+00		-2.80E-02	7.08E-01		-2.99E-02	1.77E+00		-2.80E-02	7.08E-0
594	-2.69E-02	1.63E+00		-2.79E-02	7.08E-01		-2.97E-02	1.77E+00		-2.79E-02	7.08E-0
595	-2.67E-02	1.63E+00		-2.78E-02	7.08E-01		-2.96E-02	1.77E+00		-2.78E-02	7.08E-0
596	-2.66E-02	1.63E+00		-2.77E-02	7.08E-01		-2.95E-02	1.77E+00		-2.77E-02	7.08E-0
597	-2.65E-02	1.63E+00		-2.76E-02	7.08E-01		-2.94E-02	1.77E+00		-2.76E-02	7.08E-0
598	-2.64E-02	1.63E+00		-2.75E-02	7.08E-01		-2.93E-02	1.77E+00		-2.75E-02	7.08E-0
599	-2.63E-02	1.63E+00		-2.74E-02	7.08E-01		-2.92E-02	1.77E+00		-2.74E-02	7.08E-0
600	-2.62E-02	1.63E+00		-2.73E-02	7.08E-01		-2.91E-02	1.77E+00		-2.73E-02	7.08E-0

Current Worksheet: Filtered Data Laser ON with Ruby.MTW

Figure 4.12 Voltage Output Data (600 Data Points) are Analyzed in the Minitab Software with the Laser in ON Condition and the Synthetic Ruby in the System.

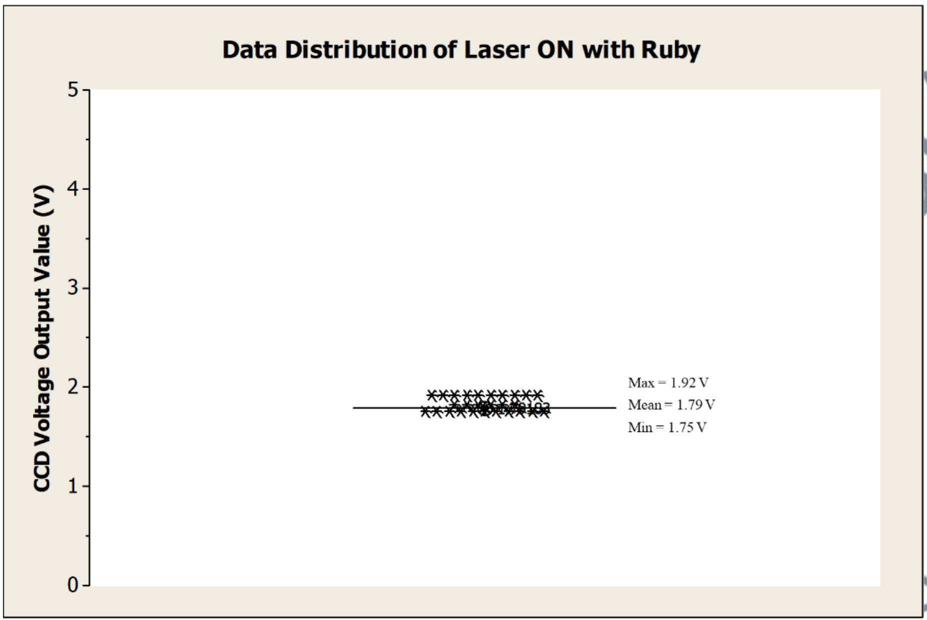


Figure 4.13 Box Plot of the CCD Voltage Output with the Laser in ON Condition and the Synthetic Ruby in the System.

4.3 Statistical Analysis: t-Test

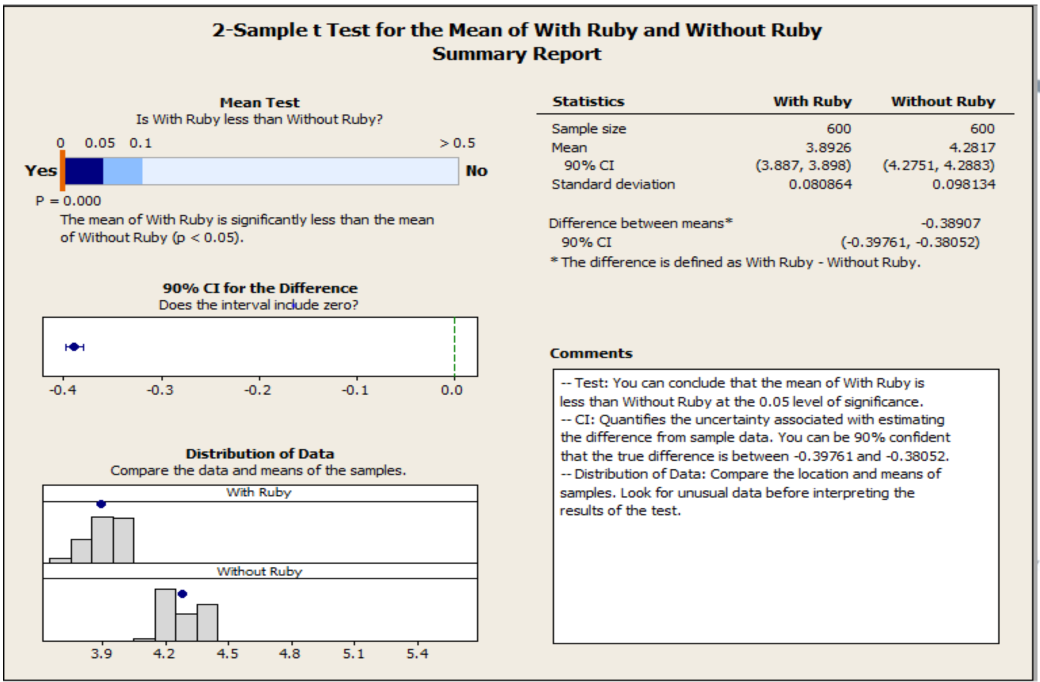
A 2-sample t-test can be used to demonstrate that the means of two samples differ significantly, according to the Minitab 16 software. The mean data collected in the presence of the synthetic and natural rubies in the system is compared to the mean data obtained without the rubies in the system in laser OFF and ON circumstances in this experiment. As a result, the two-sample t-test is the ideal tool for data analysis.

Furthermore, the data size is large enough, with 600 data points for each sample. The data were also taken in a stable condition, where the CCD linear sensor is placed in the most optimum condition, together with the optimum light intensity of the laser and rubies. Thus, the data obtained is in the average stable range, and only minimum outliers occur in the data.

Moreover, there is no need for the data to be normally distributed because the sample sizes are 600 samples for each condition of the experiment. According to Minitab 16, the data need to be normally distributed if the sample sizes are less than 15. Obviously, the data size in this experiment is large enough to ignore the normally distributed data. Similarly, the two samples do not need to have identical variances because the Minitab 16 program employs an alternative test, Welch's t-test, which does not require equal variances. According to research, the test performs well with unequal variances, even when the sample sizes are not equal.

4.3.1 t-Test for the Sample Data with and without the Synthetic Ruby in Laser OFF Condition

In the laser OFF condition, the black opaque box provide the minimum external light possible. The CCD linear sensor captures the luminance of the synthetic ruby only. The t-test is performed on two samples: the first in the laser OFF state with the synthetic ruby in the system, and the second in the laser OFF condition without the synthetic ruby in the system. The null hypothesis for this t-test is that the mean CCD voltage output value when the synthetic ruby is not in the system while the laser is turned off is equal to the mean CCD voltage output value when the synthetic ruby is in the system while the laser is turned off. The alternative hypothesis for this t-test is that the mean CCD voltage output value when the synthetic ruby is not in the system as well as the laser is turned off is not equal to the mean CCD voltage output value when the synthetic ruby is in the system when the laser is turned off.



2-Sample t Test for the Mean of With Ruby and Without Ruby
Summary Report

Mean Test
Is With Ruby less than Without Ruby?

P = 0.000
The mean of With Ruby is significantly less than the mean of Without Ruby (p < 0.05).

90% CI for the Difference
Does the interval include zero?

Distribution of Data
Compare the data and means of the samples.

Statistics	**With Ruby**	**Without Ruby**
Sample size	600	600
Mean	3.8926	4.2817
90% CI	(3.887, 3.898)	(4.2751, 4.2883)
Standard deviation	0.080864	0.098134

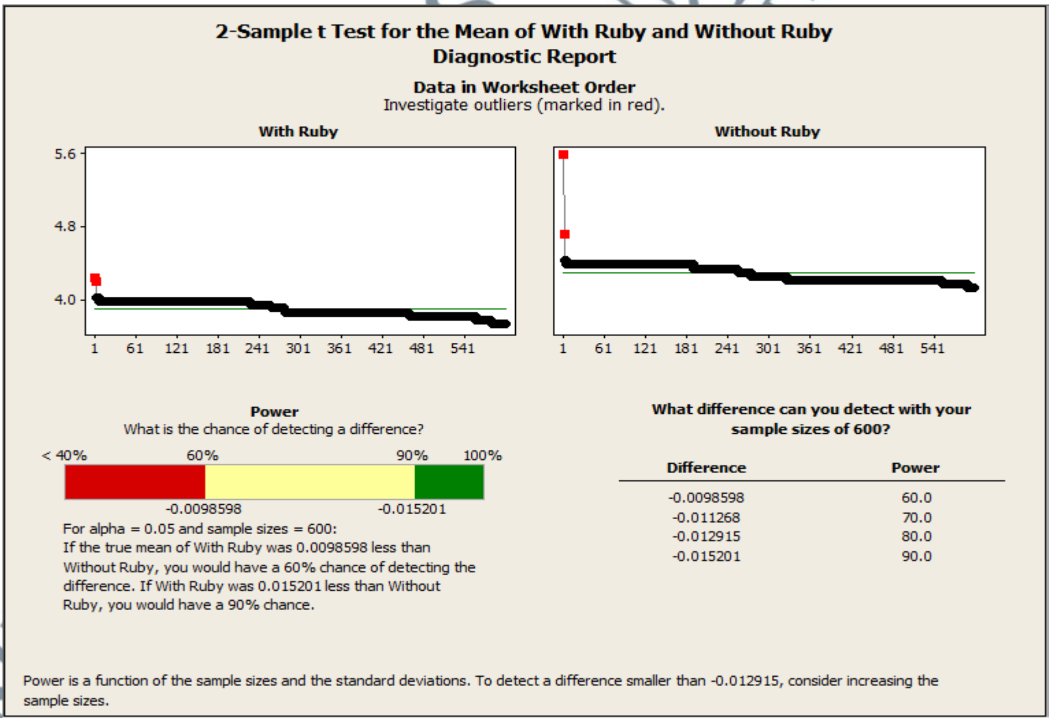
Difference between means*	-0.38907
90% CI	(-0.39761, -0.38052)

* The difference is defined as With Ruby - Without Ruby.

Comments

-- Test: You can conclude that the mean of With Ruby is less than Without Ruby at the 0.05 level of significance.
-- CI: Quantifies the uncertainty associated with estimating the difference from sample data. You can be 90% confident that the true difference is between -0.39761 and -0.38052.
-- Distribution of Data: Compare the location and means of samples. Look for unusual data before interpreting the results of the test.

Figure 4.14 Summary of t-Test: When the Laser is in OFF Condition with and without Synthetic Ruby in the System.



2-Sample t Test for the Mean of With Ruby and Without Ruby
Diagnostic Report

Data in Worksheet Order
Investigate outliers (marked in red).

Power
What is the chance of detecting a difference?

For alpha = 0.05 and sample sizes = 600:
If the true mean of With Ruby was 0.0098598 less than Without Ruby, you would have a 60% chance of detecting the difference. If With Ruby was 0.015201 less than Without Ruby, you would have a 90% chance.

What difference can you detect with your sample sizes of 600?

Difference	**Power**
-0.0098598	60.0
-0.011268	70.0
-0.012915	80.0
-0.015201	90.0

Power is a function of the sample sizes and the standard deviations. To detect a difference smaller than -0.012915, consider increasing the sample sizes.

Figure 4.15 Summary of t-Test: When the Laser is in OFF Condition with and without Synthetic Ruby in the System.

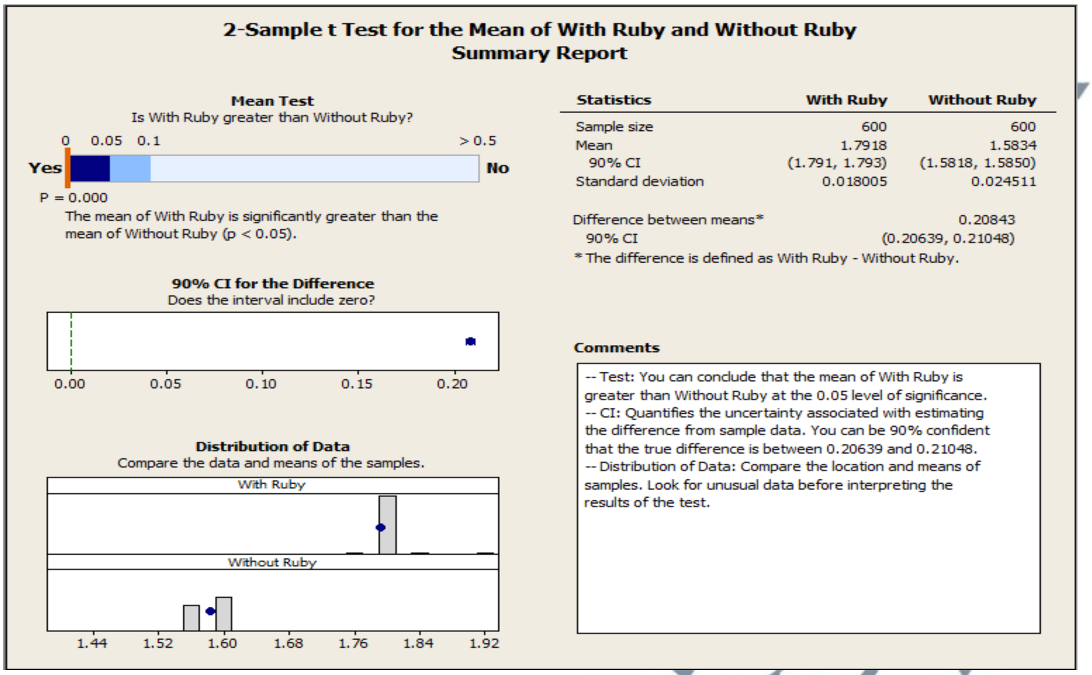
With a 0.05 level of significance, the t-test reported in Figure 4.14 shows that the mean of data with the synthetic ruby is lower than the mean of data without the synthetic ruby. As a result, because the P-value is less than 0.05, the null hypothesis is rejected. The confidence level is the percentage of certainty that the result matches the population outcome. Confidence intervals provide a range of values indicating the likelihood of the outcome occurring in the population. The aforementioned t-test has a 90% confidence level with confidence intervals of different values with and without the synthetic ruby and is in the range of 0.3976–0.3805. This suggests that if the experiment is repeated, this outcome will occur 90% of the time.

From the distribution of the data, it can be seen that the data with the synthetic ruby are distributed in a slightly lower voltage range and do not overlap with the data without the synthetic ruby, as shown in Figure 4.15. This proves that the CCD linear sensor detects higher light intensity when the synthetic ruby is in the system as some of the light from the synthetic ruby is detected by the CCD linear sensor. When there is no ruby in the system, the CCD linear sensor detects low light intensity as the system is in an almost completely dark condition, resulting in a higher CCD voltage output value. Furthermore, this also validates that the CCD linear sensor can detect even the smallest changes in light intensity, as stated in previous research and Chapter 2.

4.3.2 t-Test for the Sample Data with and without the Synthetic Ruby in the Laser ON Condition

In the laser ON condition, the laser is beamed toward the synthetic ruby, and the light that passing through the synthetic ruby falls on the CCD linear sensor. Two samples are analyzed in the t-test. The first sample is the mean data of the CCD voltage output in the laser ON condition with the synthetic ruby in the system, and the second sample is the mean data of the CCD voltage output in the laser ON condition without the synthetic ruby.

The null hypothesis for this t-test is that the mean data of the CCD voltage output in the laser ON condition with the synthetic ruby in the system is equal to the mean data of the CCD voltage output in the laser ON condition without the synthetic ruby. Whereby the alternative hypothesis is that the mean data of the CCD voltage output in the laser ON condition with the synthetic ruby in the system is unequal to the mean data of the CCD voltage output in the laser ON condition without the synthetic ruby.



2-Sample t Test for the Mean of With Ruby and Without Ruby
Summary Report

Mean Test
Is With Ruby greater than Without Ruby?

P = 0.000
The mean of With Ruby is significantly greater than the mean of Without Ruby (p < 0.05).

90% CI for the Difference
Does the interval include zero?

Distribution of Data
Compare the data and means of the samples.

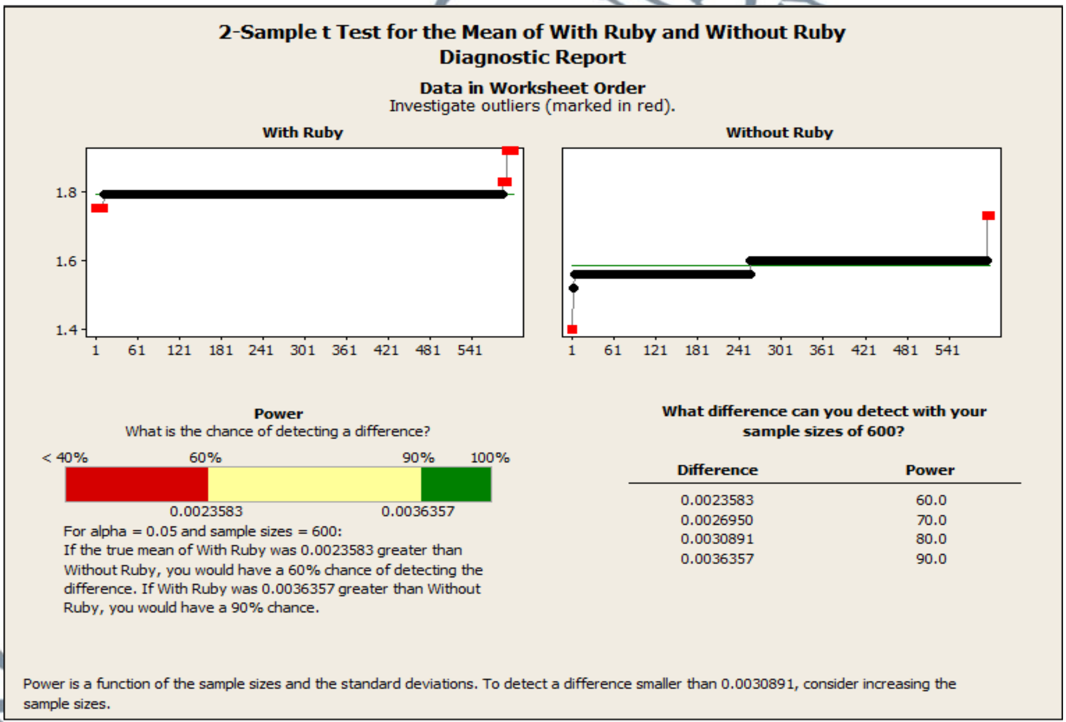
Statistics	With Ruby	Without Ruby
Sample size	600	600
Mean	1.7918	1.5834
90% CI	(1.791, 1.793)	(1.5818, 1.5850)
Standard deviation	0.018005	0.024511

Difference between means* 0.20843
90% CI (0.20639, 0.21048)
* The difference is defined as With Ruby - Without Ruby.

Comments

-- Test: You can conclude that the mean of With Ruby is greater than Without Ruby at the 0.05 level of significance.
-- CI: Quantifies the uncertainty associated with estimating the difference from sample data. You can be 90% confident that the true difference is between 0.20639 and 0.21048.
-- Distribution of Data: Compare the location and means of samples. Look for unusual data before interpreting the results of the test.

Figure 4.16 Summary of t-Test: When the Laser is in ON Condition with and without the Synthetic Ruby in the System.



2-Sample t Test for the Mean of With Ruby and Without Ruby
Diagnostic Report

Data in Worksheet Order
Investigate outliers (marked in red).

Power
What is the chance of detecting a difference?

For alpha = 0.05 and sample sizes = 600:
If the true mean of With Ruby was 0.0023583 greater than Without Ruby, you would have a 60% chance of detecting the difference. If With Ruby was 0.0036357 greater than Without Ruby, you would have a 90% chance.

What difference can you detect with your sample sizes of 600?

Difference	Power
0.0023583	60.0
0.0026950	70.0
0.0030891	80.0
0.0036357	90.0

Power is a function of the sample sizes and the standard deviations. To detect a difference smaller than 0.0030891, consider increasing the sample sizes.

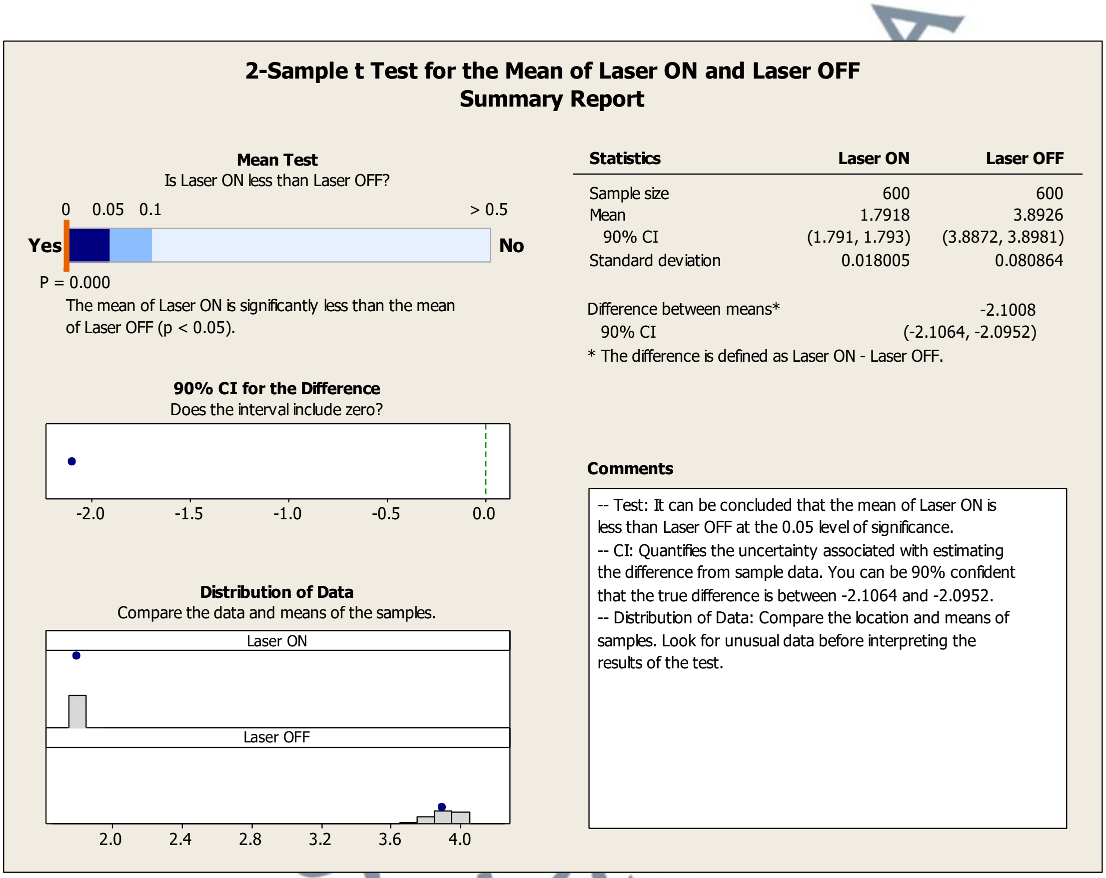
Figure 4.17 Summary of t-Test: When the Laser is in ON Condition with and without the Synthetic Ruby in the System.

With a 0.05 level of significance, the t-test results in Figure 4.16 show that the mean of data with the synthetic ruby is substantially higher than the mean of data without the synthetic ruby. As a result, because the P-value is smaller than 0.05, the alternative hypothesis is accepted. The t-test above has a 90% confidence level, with confidence intervals indicating a difference in value between data with and without the synthetic ruby ranging between 0.2064 and 0.2105. This suggests that if the experiment is repeated, this outcome will occur 90% of the time.

Based on the distribution of the data, the mean of the data without the synthetic ruby does not exceed the 1.68 V, whereas the mean of the data with the synthetic ruby is 1.76 V, as in Figure 4.17. This proves that the CCD detects low light intensity when the synthetic ruby is in the system because some of the light from the laser is absorbed in the synthetic ruby. When there is no ruby in the system, the CCD detects high light intensity as the light from the laser propagates directly to the CCD passing from the air.

4.3.3 t-Test for the Sample Data with the Presence of Synthetic Ruby in Laser OFF and ON Condition

The data is analyzed by comparing the data in the laser ON and OFF conditions with the synthetic ruby in the system. A t-test is conducted to analyze both conditions. The null hypothesis is that the mean CCD voltage output value in the laser in OFF condition with the synthetic ruby is equal to the mean CCD voltage output value in the laser ON condition with the synthetic ruby. The alternative hypothesis is that the mean CCD voltage output value in the laser OFF condition with the synthetic ruby is unequal to the mean CCD voltage output value in the laser in ON condition with the synthetic ruby.



2-Sample t Test for the Mean of Laser ON and Laser OFF
Summary Report

Mean Test
Is Laser ON less than Laser OFF?

P = 0.000
The mean of Laser ON is significantly less than the mean of Laser OFF ($p < 0.05$).

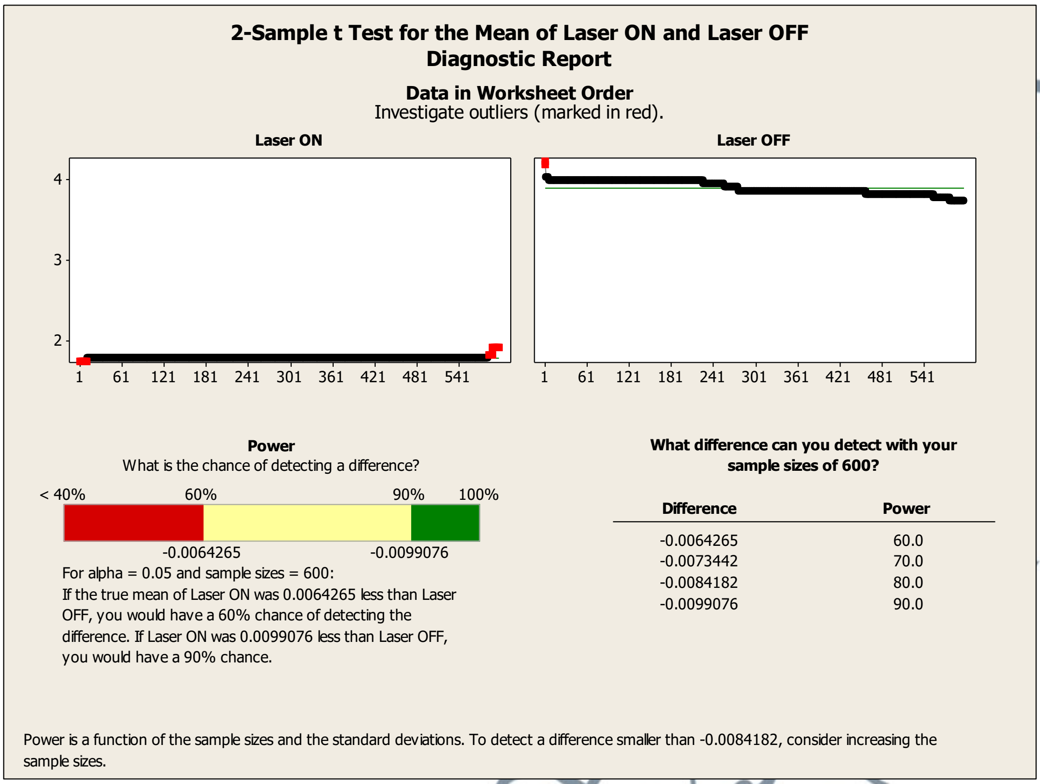
Statistics	Laser ON	Laser OFF
Sample size	600	600
Mean	1.7918	3.8926
90% CI	(1.791, 1.793)	(3.8872, 3.8981)
Standard deviation	0.018005	0.080864

Difference between means* -2.1008
90% CI (-2.1064, -2.0952)
* The difference is defined as Laser ON - Laser OFF.

Comments

-- Test: It can be concluded that the mean of Laser ON is less than Laser OFF at the 0.05 level of significance.
-- CI: Quantifies the uncertainty associated with estimating the difference from sample data. You can be 90% confident that the true difference is between -2.1064 and -2.0952.
-- Distribution of Data: Compare the location and means of samples. Look for unusual data before interpreting the results of the test.

Figure 4.18 Summary of t-Test: The Laser in ON and OFF Conditions with the Synthetic Ruby in the System.



2-Sample t Test for the Mean of Laser ON and Laser OFF
Diagnostic Report

Data in Worksheet Order
Investigate outliers (marked in red).

Power
What is the chance of detecting a difference?

For alpha = 0.05 and sample sizes = 600:
If the true mean of Laser ON was 0.0064265 less than Laser OFF, you would have a 60% chance of detecting the difference. If Laser ON was 0.0099076 less than Laser OFF, you would have a 90% chance.

What difference can you detect with your sample sizes of 600?

Difference	Power
-0.0064265	60.0
-0.0073442	70.0
-0.0084182	80.0
-0.0099076	90.0

Power is a function of the sample sizes and the standard deviations. To detect a difference smaller than -0.0084182, consider increasing the sample sizes.

Figure 4.19 Summary of t-Test: The Laser in ON and OFF Conditions with the Synthetic Ruby in the System.

From the t-test summarized in Figure 4.18, it can be concluded that the mean of data with the laser in ON condition with the synthetic ruby is significantly less than the mean of data with the laser in OFF condition with the synthetic ruby with a 0.05 level of significance. Hence, the null hypothesis is rejected because the P-value is less than 0.05. The t-test above shows a 90% confidence level with the difference in the confidence intervals in the range of the data with the laser in ON and OFF condition is −2.1064 to −2.0952. This means that when the experiment is repeated, 90% of the time, this result will occur, and the difference in value between the condition laser ON and OFF with the presence of synthetic ruby will fall in between the range −2.1064 to −2.0952.

In Figure 4.19, the data with the laser in ON and OFF conditions with the synthetic ruby are arranged according to the worksheet order. The data with the laser in ON condition with the synthetic ruby shows a more uniform distribution, whereas the data with the laser in OFF condition with the synthetic ruby shows a significantly less uniform distribution. This concludes that the probability of the CCD linear sensor showing a value of 1.7918 V in each repeated experiment is high. Otherwise, the data with laser in OFF condition with the synthetic ruby shows a nonuniform distribution where each experiment is likely to show a different voltage value. Thus, the CCD voltage output value with the synthetic ruby in the laser ON condition is selected for the subsequent analysis.

4.3.4 t-Test for the Sample Data with the Presence of Natural Ruby in Laser ON Condition

The experiment is proceeded with the Natural ruby in the laser ON condition since the previous experiment prove that the CCD will produce a uniform distribution of data in the laser ON condition. The data distribution of the CCD voltage output in the laser ON condition with the natural ruby in the system is shown in Figure 4.20 where the mean CCD voltage output value is 1.98 V, the maximum value is 2.04 V, and the minimum value is 1.63 V.

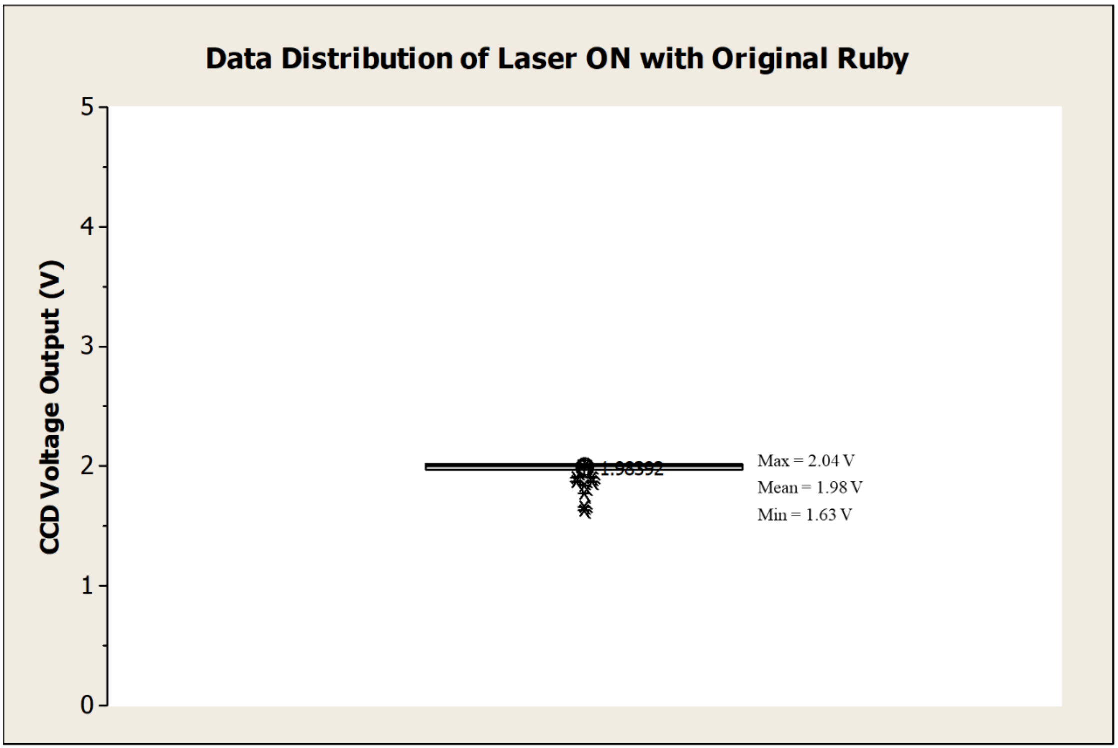
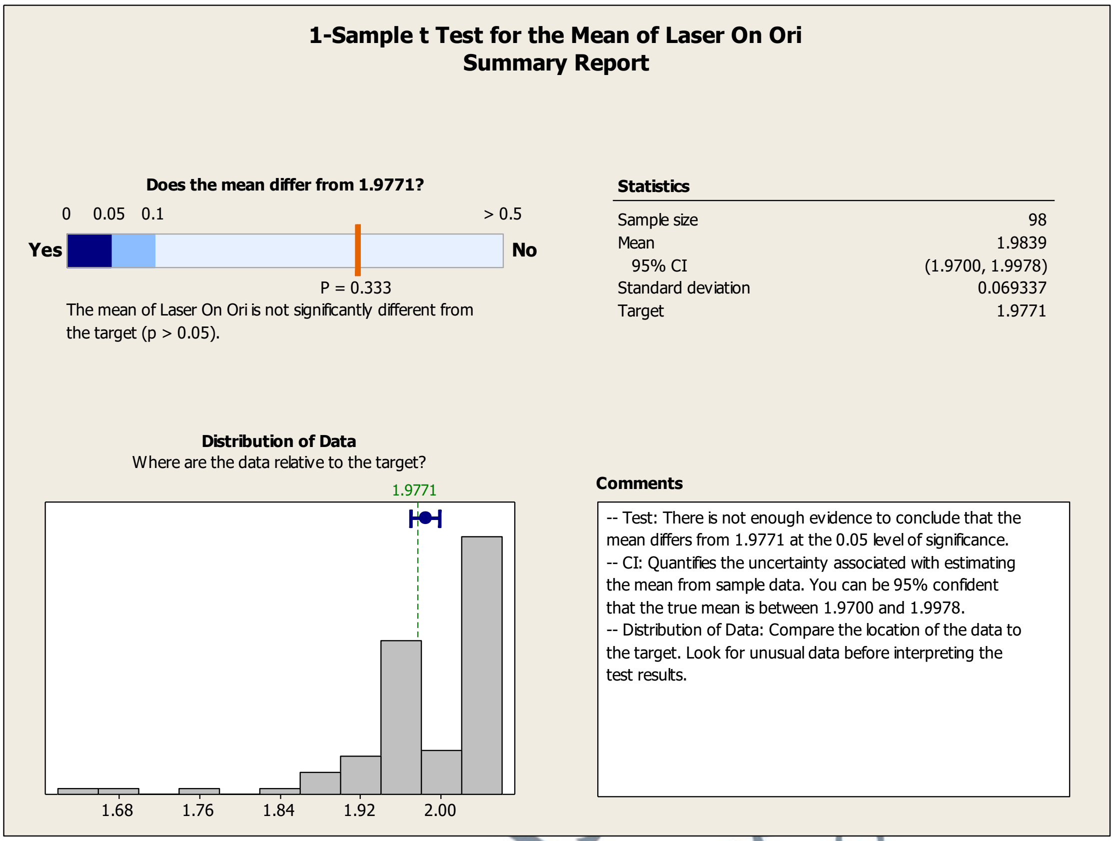


Figure 4.20 Box Plot of the CCD Voltage Output with the Laser in ON Condition and the Natural Ruby in the System.

t-test is conducted on the CCD voltage output data in the laser ON with the natural ruby is in the CCD linear sensor system. 1-sample t-test is conducted where the experimental data from the CCD linear sensor system is compared to the theoretical CCD voltage output value of 1.9771 V when natural ruby is in the system as executed in section 4.2.2. The null hypothesis for this t-test is that the mean data of the CCD voltage output in the laser ON condition with the natural ruby in the system is equal to 1.9771 V. Alternatively, the alternative hypothesis for this t-test is that the mean data of the CCD voltage output in the laser ON condition with the natural ruby in the system not equal to 1.9771 V.



1-Sample t Test for the Mean of Laser On Ori
Summary Report

Does the mean differ from 1.9771?

The mean of Laser On Ori is not significantly different from the target (p > 0.05).

Statistics

Sample size	98
Mean	1.9839
95% CI	(1.9700, 1.9978)
Standard deviation	0.069337
Target	1.9771

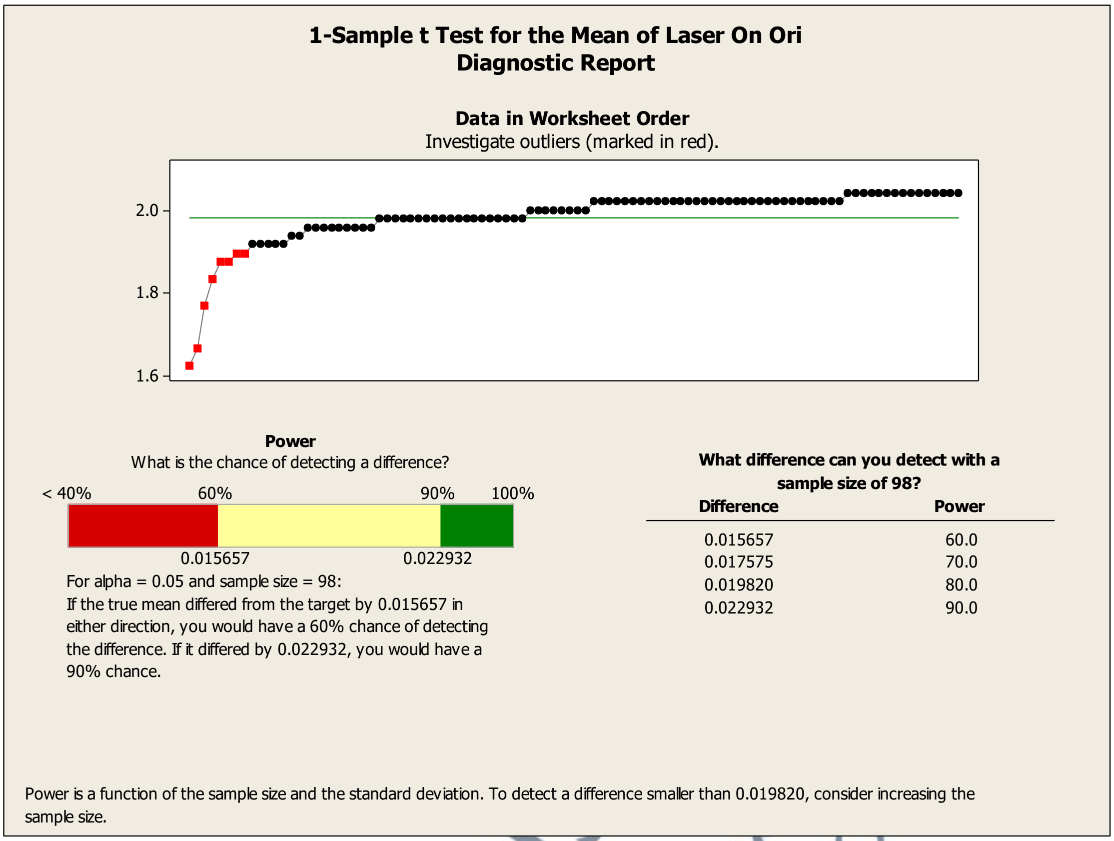
Distribution of Data
Where are the data relative to the target?

Comments

-- Test: There is not enough evidence to conclude that the mean differs from 1.9771 at the 0.05 level of significance.
-- CI: Quantifies the uncertainty associated with estimating the mean from sample data. You can be 95% confident that the true mean is between 1.9700 and 1.9978.
-- Distribution of Data: Compare the location of the data to the target. Look for unusual data before interpreting the test results.

Figure 4.21 Summary of t-Test: The Laser in ON Conditions with the Natural Ruby in the System.

From the t-test summarized in Figure 4.21, it can be concluded that the mean of data with the laser in ON condition with the natural ruby is not significantly different from the target value which is 1.9771 V a 0.333 level of significance. Hence, the null hypothesis is accepted because the P-value is more than 0.05. The t-test above shows a 95% confidence level. This means that when the experiment is repeated, 95% of the time, this result will occur. The data are also distributed uniformly according to the data distribution in Figure 4.22.



1-Sample t Test for the Mean of Laser On Ori
Diagnostic Report

Data in Worksheet Order
Investigate outliers (marked in red).

Power
What is the chance of detecting a difference?

For alpha = 0.05 and sample size = 98:
If the true mean differed from the target by 0.015657 in either direction, you would have a 60% chance of detecting the difference. If it differed by 0.022932, you would have a 90% chance.

What difference can you detect with a sample size of 98?

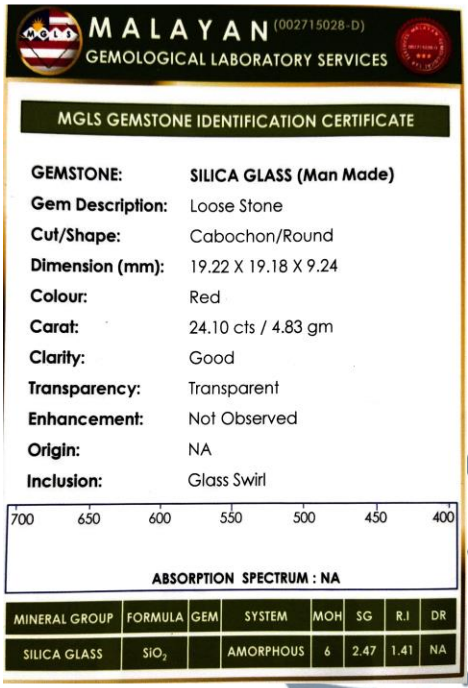
Difference	**Power**
0.015657	60.0
0.017575	70.0
0.019820	80.0
0.022932	90.0

Power is a function of the sample size and the standard deviation. To detect a difference smaller than 0.019820, consider increasing the sample size.

Figure 4.22 Summary of t-Test: The Laser in ON Conditions with the Natural Ruby in the System.

4.4 Mathematical Expression to Identify Real Refractive Index of the Ruby

To prove that the ruby gemstone analyzed in this experiment is either natural or synthetic, the gemstone is sent to the Malayan Gemological Laboratory Services (MGLS). The MGLS provides an identification certificate for the analyzed gemstone with the true characteristics of the gemstone. The identification certificate of the ruby gemstone analyzed in this experiment is shown in Figure 4.23.



MALAYAN (002715028-D)
GEMOLOGICAL LABORATORY SERVICES

MGLS GEMSTONE IDENTIFICATION CERTIFICATE

GEMSTONE:	**SILICA GLASS (Man Made)**
Gem Description:	Loose Stone
Cut/Shape:	Cabochon/Round
Dimension (mm):	19.22 X 19.18 X 9.24
Colour:	Red
Carat:	24.10 cts / 4.83 gm
Clarity:	Good
Transparency:	Transparent
Enhancement:	Not Observed
Origin:	NA
Inclusion:	Glass Swirl

700 650 600 550 500 450 400

ABSORPTION SPECTRUM : NA

MINERAL GROUP	FORMULA	GEM	SYSTEM	MOH	SG	R.I	DR
SILICA GLASS	SiO_2		AMORPHOUS	6	2.47	1.41	NA

Figure 4.23 MGLS Gemstone Identification Certificate for the Synthetic Ruby Analyzed in this Experiment.

MALAYAN (002715028-D)
GEMOLOGICAL LABORATORY SERVICES

MGLS GEMSTONE IDENTIFICATION CERTIFICATE

CERTIFICATE NO: MGLS-10032022-SILICA GLASS-LS-01

Gemological testing and microscopical inclusion studies suggest that the gem is Man-Made Red Silica Glass.

DATE : 10TH MARCH 2022

002715028-D

MAT RUZLIN BIN HJ MAULUD
Principal Gemologist/Economic Geologist
B.Sc (Hons) Mal; M.Sc (Ind. Min), Leic.UK
Adv. Dip (Gemology), Leic.UK

NO. 7, FIRST FLOOR, JALAN 8/1D, SEKSYEN 8, 46050 PETALING JAYA, SELANGOR. HP: 019 988 1958 : matruzlin@gmail.com

Figure 4.24 MGLS Gemstone Identification Certificate for the Synthetic Ruby Analysed in this Experiment.

According to the certificate in Figure 4.24, the gemstone analyzed in this experiment is a man-made red silica glass. Thus, the gemstone analyzed in this experiment is a synthetic ruby or a transparent amorphous stone.

Since the gemstone is proven to be silica glass, the linear attenuation coefficient of silica glass is considered in the mathematical expression. Based on the research conducted by Bam et al. (2020), the attenuation coefficient for silica is 0.96 cm^{-1}. Hence, the calculation of the light reflectance equation is done using the linear attenuation of silica and the final output voltage of the CCD linear sensor (1.7918 V).

The ruby gemstone is analyzed through several optical characteristics. One important optical characteristic that is analyzed in this experiment is the refractive index. On account of the natural ruby supposedly presents a refractive index in the range of 1.762–1.770 (*Gemology Tools Professional*, 2016), a reverse mathematical expression is conducted to determine whether the voltage value obtained by the CCD linear sensor can produce the refractive index in the above range. If it can produce the refractive index in the range of 1.762–1.770, it can be concluded that the gemstone analyzed is a natural ruby gemstone. Otherwise, the gemstone is a synthetic ruby. The Equation (4.3) is the reverse mathematical expression for Equation (3.2), where the light travels from the laser, passes through the ruby, and then finally falls onto the CCD linear sensor.

4.4.1 Analysis of the Synthetic Ruby using the Reverse Mathematical Expression

From the final light reflectance equation obtained in Chapter 3, the equation is derived backward, as shown in the following mathematical expressions.

$$I_2' = I_2 - \left[I_2 \left(\frac{n_{air} - n_{ruby}}{n_{air} + n_{ruby}} \right)^2 \right] \tag{3.2}$$

$$I_2' = I_2 - \left[I_2 \left(\frac{n_{air} - n_{ruby}}{n_{air} + n_{ruby}} \right) \left(\frac{n_{air} - n_{ruby}}{n_{air} + n_{ruby}} \right) \right],$$

$$I_2' = I_1 - \left[I_2 \left(\frac{n_{air}{}^2 - 2n_{air}n_{ruby} + n_{ruby}{}^2}{n_{air}{}^2 + 2n_{air}n_{ruby} + n_{ruby}{}^2} \right) \right],$$

$$I_2'\left(n_{air}{}^2 + 2n_{air}n_{ruby} + n_{ruby}{}^2\right) = I_2\left(n_{air}{}^2 + 2n_{air}n_{ruby} + n_{ruby}{}^2\right) - I_2\left(n_{air}{}^2 - 2n_{air}n_{ruby} + n_{ruby}{}^2\right),$$

$$I_2' n_{air}{}^2 + 2I_2' n_{air}n_{ruby} + I_2' n_{ruby}{}^2 = 4n_{air}n_{ruby}I_2,$$

I_2 is the light absorption equation, which is equal to $I_1' e^{-\alpha x}$,

$$I_2' n_{air}{}^2 + 2I_2' n_{air}n_{ruby} + I_2' n_{ruby}{}^2 = 4n_{air}n_{ruby}I_1' e^{-\alpha x},$$

where I_1' is the light reflectance equation when the light enters the ruby from the laser. The equation of light reflectance is expanded in the form of $I_1' = \frac{4I_i n_{air} n_{ruby}}{n_{ruby}{}^2 + 2n_{air}n_{ruby} + n_{air}{}^2}$,

hence,

$$I_2' {n_{air}}^2 + 2I_2' n_{air} n_{ruby} + I_2' {n_{ruby}}^2 = 4 n_{air} n_{ruby} e^{-\alpha x} \left(\frac{4 I_i n_{air} n_{ruby}}{{n_{ruby}}^2 + 2 n_{air} n_{ruby} + {n_{air}}^2} \right).$$

Hence, the final reverse mathematical expression to find the value of the refractive index is expressed as the Equation (4.2).

$$I_2' {n_{ruby}}^4 + 4I_2' n_{air} {n_{ruby}}^3 + (6I_2' {n_{air}}^2 - 16 {n_{air}}^2 I_i e^{-\alpha x}) {n_{ruby}}^2 + 4I_2' {n_{air}}^3 n_{ruby} + I_2' {n_{air}}^4 = 0 \quad (4.2)$$

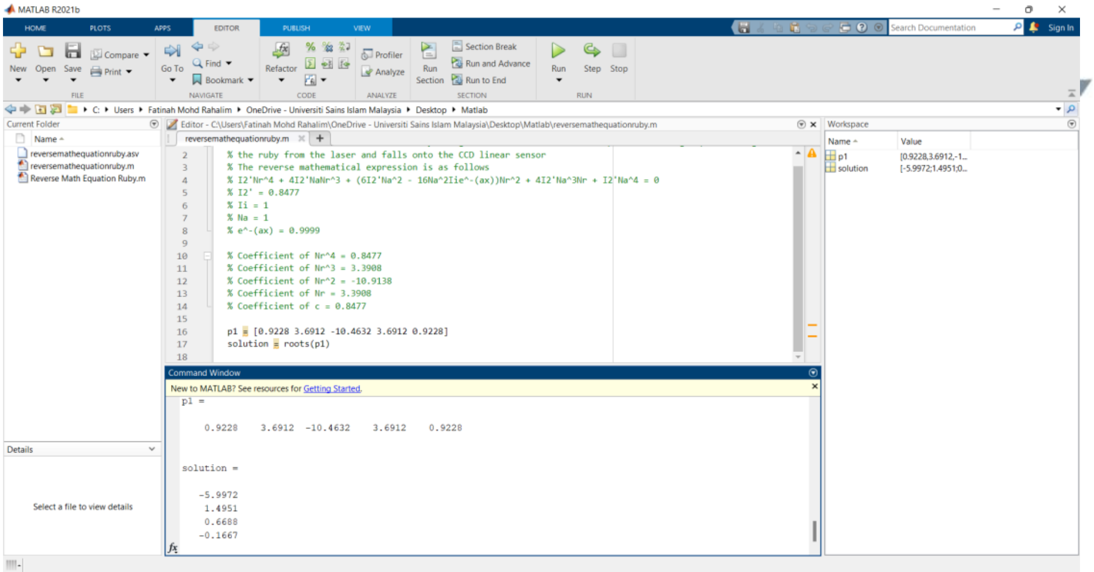
The value of the refractive index of the synthetic ruby is obtained by solving the polynomial equation using the MATLAB software (Figure 4.25), where the roots of the equation are as follows:

$$n_{sruby1} = 1.4951$$

$$n_{sruby2} = 0.6688$$

$$n_{sruby3} = -0.1667$$

$$n_{sruby4} = -5.9972$$



```matlab
% the ruby from the laser and falls onto the CCD linear sensor
% The reverse mathematical expression is as follows
% I2'Nr^4 + 4I2'NaNr^3 + (6I2'Na^2 - 16Na^2Iie^-(ax))Nr^2 + 4I2'Na^3Nr + I2'Na^4 = 0
% I2' = 0.8477
% Ii = 1
% Na = 1
% e^-(ax) = 0.9999

% Coefficient of Nr^4 = 0.8477
% Coefficient of Nr^3 = 3.3908
% Coefficient of Nr^2 = -10.9138
% Coefficient of Nr = 3.3908
% Coefficient of c = 0.8477

p1 = [0.9228 3.6912 -10.4632 3.6912 0.9228]
solution = roots(p1)
```

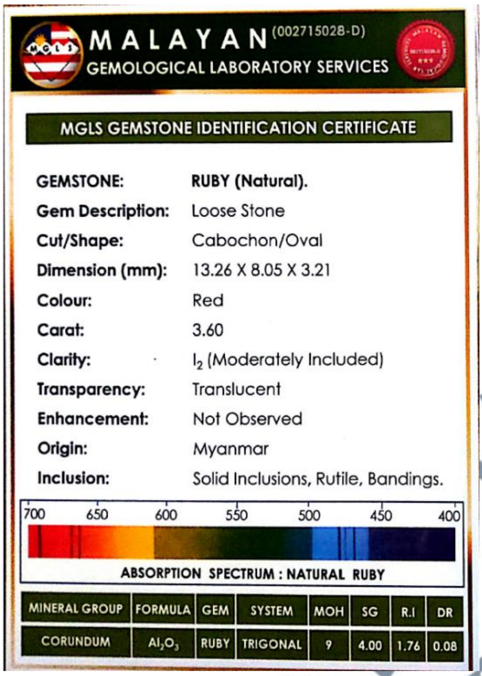
```
p1 =

    0.9228    3.6912  -10.4632    3.6912    0.9228


solution =

   -5.9972
    1.4951
    0.6688
   -0.1667
```

Figure 4.25 MATLAB Simulation of the Reverse Mathematical Expression for Synthetic Ruby.

The refractive index of the synthetic ruby is 1.4951 when calculated using Equation (4.2). The equation is also simulated in the MATLAB software, as shown in Figure 4.25.

4.4.2 Analysis of the Natural Ruby using the Reverse Mathematical Expression

The experiment is repeated using a natural ruby from Myanmar, with the actual refractive index of the ruby as 1.76, stated in the MGLS gemstones identification certificate shown in Figure 4.26 and Figure 4.27.



MALAYAN (002715028-D)
GEMOLOGICAL LABORATORY SERVICES

MGLS GEMSTONE IDENTIFICATION CERTIFICATE

GEMSTONE:	**RUBY (Natural).**
Gem Description:	Loose Stone
Cut/Shape:	Cabochon/Oval
Dimension (mm):	13.26 X 8.05 X 3.21
Colour:	Red
Carat:	3.60
Clarity:	I_2 (Moderately Included)
Transparency:	Translucent
Enhancement:	Not Observed
Origin:	Myanmar
Inclusion:	Solid Inclusions, Rutile, Bandings.

700 650 600 550 500 450 400

ABSORPTION SPECTRUM : NATURAL RUBY

MINERAL GROUP	FORMULA	GEM	SYSTEM	MOH	SG	R.I	DR
CORUNDUM	Al_2O_3	RUBY	TRIGONAL	9	4.00	1.76	0.08

Figure 4.26 MGLS Gemstone Identification Certificate for the Natural Ruby Analyzed in this Experiment.

MALAYAN (002715028-D)
GEMOLOGICAL LABORATORY SERVICES

MGLS GEMSTONE IDENTIFICATION CERTIFICATE

CERTIFICATE NO: MGLS-180222-RUBY-LS-01

DATE : 18TH FEB 2022

Gemological testing and microscopical inclusion studies suggests that the gem is Natural Ruby from Myanmar.

MAT RUZLIN BIN HJ MAULUD
Principal Gemologist/Economic Geologist
B.Sc (Hons) Mal; M.Sc (Ind. Min), Leic.UK
Adv. Dip (Gemology), Leic.UK

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SELANGOR. HP: 019 988 1958 ; matruzlin@gmail.com

Figure 4.27 MGLS Gemstone Identification Certificate for the Natural Ruby Gemstone Analysed in this Experiment.

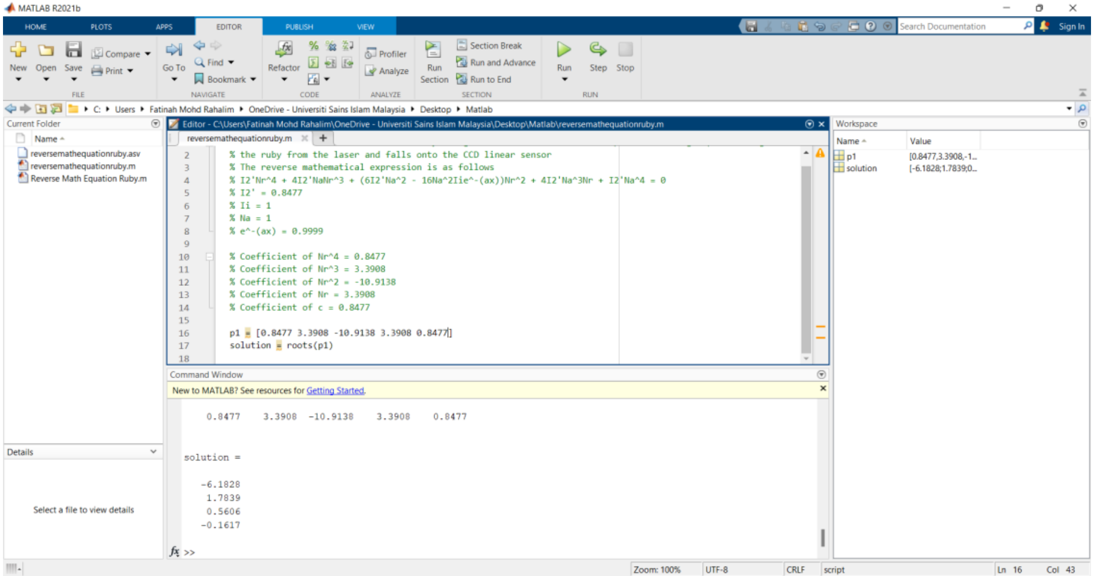
Using the same Equation (4.2) from previous Section 4.4.1, the refractive index of the natural ruby is obtained by simulating the equation in the MATLAB software, as shown in Figure 4.28. The following are the roots of the equation.

$$n_{ruby1} = 1.7839$$

$$n_{ruby2} = 0.5605$$

$$n_{ruby3} = -0.1617$$

$$n_{ruby4} = -6.1828$$



```
% the ruby from the laser and falls onto the CCD linear sensor
% The reverse mathematical expression is as follows
% I2'Nr^4 + 4I2'NaNr^3 + (6I2'Na^2 - 16Na^2Iie^-(ax))Nr^2 + 4I2'Na^3Nr + I2'Na^4 = 0
% I2' = 0.8477
% Ii = 1
% Na = 1
% e^-(ax) = 0.9999

% Coefficient of Nr^4 = 0.8477
% Coefficient of Nr^3 = 3.3908
% Coefficient of Nr^2 = -10.9138
% Coefficient of Nr = 3.3908
% Coefficient of c = 0.8477

p1 = [0.8477 3.3908 -10.9138 3.3908 0.8477]
solution = roots(p1)
```

```
    0.8477    3.3908  -10.9138    3.3908    0.8477


solution =

   -6.1828
    1.7839
    0.5606
   -0.1617

>>
```

Figure 4.28 MATLAB Simulation of the Reverse Mathematical Expression for the Natural Ruby.

In this case, the most suitable value for the refractive index of the natural ruby is the one with the value closest to the real refractive index of the ruby, i.e., 1.7839.

4.5 Accuracy Assessment

An engineering statistical analysis tool is used to analyze all the data collected in this investigation. Based on the light intensity acquired by the CCD sensor, the statistical analysis findings will be used to estimate the quantitative grading value of gemstones. Equation (4.2) is used to determine the theoretical refractive index of the silica glass (synthetic ruby) and natural ruby.

4.5.1 Accuracy Assessment for Synthetic Ruby

The theoretical refractive index for the silica glass is 1.41, as stated in the MGLS gemstone identification certificate, and the experimental refractive index is 1.49. Table 4.3 shows the theoretical and actual refractive indices for the silica glass.

Table 4.3 Theoretical and Experimental Refractive Indices for Silica Glass.

Theoretical Refractive Index	Experimental Refractive Index
1.41	1.49

$$Relative\ accuracy, A = 1 - \left|\frac{Theoretical\ value - Experimental\ value}{Theoretical\ value}\right|$$

$$Relative\ accuracy, A = 1 - \left|\frac{1.41 - 1.49}{1.41}\right| \tag{4.3}$$

$$Relative\ accuracy, A = 0.9433$$

$$Percentage\ Accuracy = 0.9433 \times 100 = 94.33\%$$

There is a slight difference of 0.08 between the theoretical and experimental refractive index. The accuracy of this system is determined using the formula of relative accuracy, as shown in Equation (4.3). From the formula, the accuracy of this system is obtained where the relative accuracy is 0.9433 or 94.33%. This proves that this system can provide a standardized grading system for the ruby.

4.5.2 Accuracy Assessment for Natural Ruby

For the natural ruby, the theoretical refractive index acquired from the reverse mathematical expression is 1.76, and the experimental refractive index is 1.78. Table 4.4 shows the theoretical and actual refractive index of the natural ruby.

Table 4.4 Theoretical and Experimental Refractive Index for the Natural Ruby.

Theoretical Refractive Index	**Experimental Refractive Index**
1.78	1.76

$$Relative\ accuracy,\ A_{natural\ ruby} = 1 - \left|\frac{Theoretical\ value - Experimental\ value}{Theoretical\ value}\right|$$

$$Relative\ accuracy, A = 1 - \left|\frac{1.76 - 1.78}{1.76}\right| \quad (4.4)$$

$$Relative\ accuracy, A = 0.9887$$

$$Percentage\ Accuracy\ =\ 0.9887\ x\ 100\ =\ 98.87\%$$

The theoretical refractive index of the natural ruby shows a slight difference of 0.02 from the experimental refractive index of the same ruby. From the accuracy assessment done in Equation (4.4), the system is proven to be 98.87% accurate.

4.5.3 Overall Accuracy Assessment of the CCD Linear Sensor System

Based on the accuracy assessment calculated in the previous sections, the average accuracy of the CCD linear sensor system is calculated as follows. Table 4.5 shows the refractive index of natural and synthetic rubies with their respective percentage accuracy. The average accuracy of the CCD linear sensor system is calculated using Equation 4.5.

Table 4.5 Refractive Index of Natural and Synthetic Rubies and their Percentage Accuracy.

Types of Rubies	**Refractive Index**		**Percentage accuracy**
	Actual Value	**Experimental Value**	
Synthetic Ruby (man-made silica glass)	1.41	1.49	94.33%
Natural ruby (Myanmar)	1.76	1.78	98.87%

$$Average\ Accuracy = \frac{\%\ accuracy\ of\ synthetic\ ruby + \%\ accuracy\ of\ original\ ruby}{2} \quad (4.5)$$

$$Average\ Accuracy = \frac{94.33\% + 98.87\%}{2}$$

$$Average\ Accuracy = 96.90\%$$

The overall accuracy of the CCD linear system is 96.90% as executed in the calculation above. This also proves that the CCD system developed in this research is a reliable system for determining the grading value of gemstones particularly the rubies.

The Gemology Tools software provides the estimation of clarity of rubies by classifying the rubies into the clarity types such as clarity type II, as shown in Figure 2.22 in Chapter 2. This software needs the researchers or users to input the data observed using other tools such as the data on inclusions, color range, chemical elements, and optical properties of the stone. Then, the software analyzes the input data and provides an estimation of the closest possible types of rubies according to the data.

The CCD system developed in this research provides an exact value of clarity in the form of voltage value, where the CCD linear sensor will produce a higher voltage value when there is no light in the system. When the CCD linear sensor detects light in the system, the voltage output produced will lower as the light intensity increases. A more standardized and accurate clarity value in the form of voltage value is obtained using this system. Hence, this system is proven reliable in quantitatively assessing the clarity of the ruby.

4.6 Comparison between Current Technique and CCD System

In analyzing gemstones, the current technique depends mainly on the magnification tools such as a loupe, several types of microscopes, and other related tools. The tools are expensive and require specific expertise in their usage to ensure the results can be analyzed accurately. Moreover, other techniques such as the LA-ICP-MS, Raman microscopy, X-ray, and others may disturb the internal environment of the gemstones as the observation is conducted invasively. This research shows some advantages over the current techniques in some aspects as tabulated in Table 4.6.

Table 4.6 Difference Between the Current Technique and the CCD System.

Characteristics/Type of Techniques	**Current Techniques**	**CCD System**
Basic Principle	Most of the current techniques are based on the magnification and image capture of the inner environment of the ruby gemstones and then proceed with the human visual analysis.	The CCD linear sensor captures the light beamed from the laser through the ruby. The light intensity captured by the CCD linear sensor is then converted into the voltage value.
Invasive / Noninvasive	Invasive and noninvasive	Noninvasive
Destructive / Nondestructive	Destructive and nondestructive	Nondestructive
Quantitative/Qualitative	Qualitative	Quantitative (the data is analyzed in voltage (V))
Accuracy	Less Accurate - The technique depends highly on the human vision and the data obtained are in qualitative manner.	More Accurate - The technique does not depend on the human vision and the data obtained are in quantitative manner.
Gemstones Analysis Process and Setup	Mostly complicated as the technique requires huge and heavy devices. Most techniques need to be done in the laboratory and need professional skills to operate.	Simple and easy (no skills required to analyze the ruby using the CCD system)

Table 4.6 continued.

Characteristics/Type of Techniques	Current Techniques	CCD System
Sensitivity	Some of the current techniques are sensitive to electrical noises that can result in errors.	The CCD linear sensor is proven to be very sensitive to light and it can detect very detail difference in light intensity when it is in its optimum condition.

4.7 Summary

In this chapter, detail explanation on the experiments and their respective results and discussions focused. The experiment is conducted in various conditions and the data obtained from two different samples of rubies (natural and synthetic) are analyzed. The statistical analysis t-test is conducted on the data to validate the hypothesis deduced before the experiment conducted. Then, reverse mathematical expression is executed to proof the technique is valid as the experimental value is almost similar to the theoretical value. Finally, the accuracy assessment is conducted to justify that the CCD linear sensor system is accurate and reliable.