A Study on Stellar Distances

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Abstract

Determining stellar distances is the most fundamental step in learning about the universe, aiding the process of grouping star clusters and the identification of stellar ages. One method to accurately calculate stellar distances is to utilize a relationship between a star's perceived brightness its stellar distance. This investigation therefore studies the relationship between luminous flux density and distance using empirical data. In addition, variations in conditions such as light pollution and binary star systems are considered in order to model real life imperfections.

Light bulbs are sources of light that can model starlight. The intensity of the source light is controlled while the distance from lux sensors to the source is varied from a range of 0.400 meters to 1.900 meters. The distance and perceived lux data is gathered and graphed to identify trends. Initially, ideal conditions of a dark room are used to replicate a perfectly dark night sky, but additional conditions of light pollution and binary stars are simulated with background light and multiple light bulbs, respectively.

Utilizing the collected data, the model $E = \frac{I}{r^2}$ is validated for all investigated cases with minimal variation. Although the light pollution and binary stars cases resulted in an increased amount of error, that error is negligible and can be disregarded. This relationship is confirmed by geometric proofs and is used to correlate Δmagnitude with stellar distances, resulting in the equation $d = 10^{\frac{m-M}{5}+1}$ Therefore, data collected from telescopes such as the Hubble telescope, the Mauna Kea telescopes, and the Observing with NASA (OWN) telescope networks can be used – and is used - for sample stellar distance analysis.

Although this report is limited to non-variable stars, the results clearly show that even amateur astronomers can use personal cameras to investigate stellar distances using personal cameras to a reasonable range of error.

(Word Count: 296)

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1.0 Introduction

Astronomy has been a topic of interest from prehistoric ages, when civilizations gazed up into the heavens and pondered the meaning of these pinpricks of light. As civilization grew and humanity began to discover laws of the natural world, it became of interest to not only admire these stars, but also better understand them. From these humble beginnings was the birth of astronomy and the beginning of modern science.

Space is a very large place, and most of the stars in space are extremely far away from Earth. In terms of light years, or the distance that light would travel in a year, stellar distances range between 4.3 light years to Proxima Centauri[1], the nearest star, to 46 billion light years away at the edges of the observable universe[2]. However, determining the exact distance from Earth to a star is a very complex, though very rewarding, problem. Knowing this information can help group stars into clusters, or otherwise help classify galaxies and regions of the sky.

1.1 The Parallax Distance Measuring Method

Historically, astronomers have been able to calculate stellar distances through a technique known as parallax distance measurements, where the apparent location of star is compared to the background of "fixed" stars. As the Earth revolves around the sun, astronomers would plot the locations of the stars and find the parallax angle. This angle allows for astronomers to use trigonometry to solve for the unknown distance to those stars.

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[1] World Book, Star
[2] Lange, Benjamin

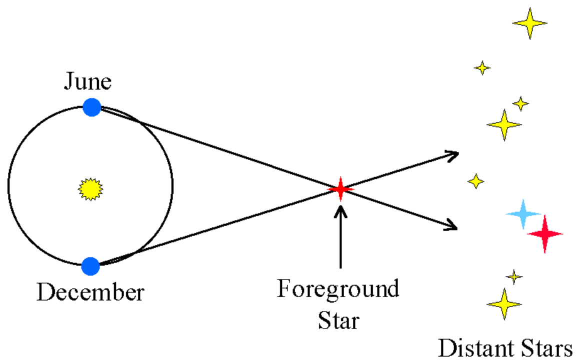


Fig. 1: Diagram of Parallax Method[3]

However, this method is only acceptable for stars within 100 parsecs, or 326.16 light years, of the Earth. Farther stars have such a small parallax angle that they seem to be "fixed" in the sky even as Earth moves. These stars force astronomers to find different analytic methods for measuring distance. Geometric and positional measuring is no longer possible, but it is conceivable to instead use the properties of light and the perceived brightness of a star to measure the distance.

1.2 Exploration of Light

To begin with, we must first understand the terminology used when discussing photometry. Light is generally understood to be photons that are both particle and wave, but not every single light wave appears equally "bright" to the human eye. Instead, the eye is particularly sensitive to light with a wavelength of 540nm. The candela, one of the seven SI units, is therefore defined by the power of light along this specific wavelength[4]. When speaking of a power source producing some candela, it is directly linked to the luminous flux of that object. This is defined in terms of lumens, which is equivalent to one candela multiplied by one

[3] Pogge, Richard
[4] NIST, Basic Unit Definitions: Candela

steradian, a measure of a solid angle. Therefore, an object that produces one candela in all directions has a luminous flux of 4π lumens.

However, the illuminance that our eyes see is not directly linked to the power produced. We measure how much light is incident upon a surface by lux, which is one lumen per one square meter. A point source with some amount of lumen production has a decreasing density of lumens per square meter as the sphere of visible light expands.

Using geometry, we can calculate the surface area of the light sphere as the radius increases. The farther away we get from a light source, the less dense the photons are per square meter, meaning that we observe the object to be less "bright". Using geometry, the following relationship can be determined:

$$E = \frac{I}{r^2} \tag{1.1}$$

Where E is the measured illuminance in lux at the edge of the light sphere, I is luminous flux of the light source in lumens, and r is the distance in meters between the light source and the edge of the light sphere.

See Appendix I for full mathematical derivation.

1.3 The Relationship between Stellar Magnitude and Distance

Even ancient astronomers were able to perceive that the stars were neither uniformly created nor uniformly bright. In the 2nd century BCE, the astronomer Hipparchus established a method of ranking stars by brightness\ by calling the star Vega of "the 1st magnitude" and the dimmest stars perceivable by the human eye to be of "the 6th magnitude"[5]. This classification system was used for many centuries, but as optical instruments improved, stars dimmer than the

[5] Mihos, The Magnitude Scale

6th magnitude could be detected, posing a quandary to the old system. In 1856 the scientist Normal Robert Pogson used Hipparchus's original notes to create a new magnitude scale. He hypothesized that the faintest star that the human eye could detect on its own would be a star that is 100 times less bright than Vega and used a logarithmic scale for each differing magnitude. Because an increase in 5 magnitudes results in an apparent brightness decrease of 100 times, between each magnitude there is a difference[6] of $\sqrt[5]{100} \sim 2.512$, or roughly 2.5 times. Therefore, the magnitude of any star could be found by

$$m_x = -2.5 \log_{10} L \qquad (1.2)$$

Whereas m is the apparent magnitude and L is the apparent luminance of the star.

In addition to this statement, astronomers are able to find an intrinsic property of a star called the "Absolute Magnitude". Through methods not discussed in this paper, they can find the brightness of any star at a distance of 10 parsecs, or approximately 32.616 light years. This term, M, can be represented as

$$M = -2.5 \log_{10} L(10) \qquad (1.3)$$

Whereas L(10) represents the luminosity measured at a distance10 parsecs.

While we will not discuss the exact methods used to determine M, it is valid to note that M is extremely useful in comparing the true power output of any star. It's generally found by measuring the temperature signature of a star and placing it on the main sequence, determining a relationship between temperature, color, and power.

If we assume our geometric representation of how illuminance works to be true, we could also state that

$$L(d) = \frac{I}{d^2} \qquad (1.4)$$

so that the following formula can be found:

[6] Pogson, N

$$d = 10^{\frac{m-M}{5}+1} \tag{1.5}$$

See Appendix II for full derivation. Thus, we can know the distance through measuring the brightness of stars.

1.4 Research Question

However, a strictly geometric derivation ignores other potential factors when calculating illuminance. Therefore, an experiment must be designed in order to verify this trend, as well as to find any errors that may cause deviations between our geometric model and the real world.

2.0 Light Source Distance Experiment

We set up a light bulb and vary the distance a lux meter is from the light source. Controlled variables for our initial experiment include the background lighting (pitch dark), using the same meter, and using the same light source. By plotting the lux against the distance away from the source, we hope to find an inverse squared relationship.

The reason we stop data measurement at roughly 1.90 meters is because after that point, the ΔLux is smaller than the standard deviation of measurement, which implies that the remainder of the data is not accurate enough to be used. We begin at the 0.40 meter mark because before that point, the inaccuracy in the lux meter is too high to be properly considered, as there is a standard deviation of greater than 70 lux.

2.1 Materials

- Ecosmart LED Bright White MR16 GU10 Light bulb with Brightness of 320 Lumens
- Bosch DLR130 Distance Measurer with accuracy ±1.5mm
- Vernier LabPro Connection
- Vernier Light Sensor LS-BTA (accuracy of $\pm$ 0.2 lux)
- Logger Pro 3.8.5.1
- Ring Stand
- Clamp
- Ruler with accuracy of ±0.001 meter
- Pen/Paper
- Dark Room
- Flat Surface

2.2 Diagrams and Illustrations

Fig. 2: Full setup

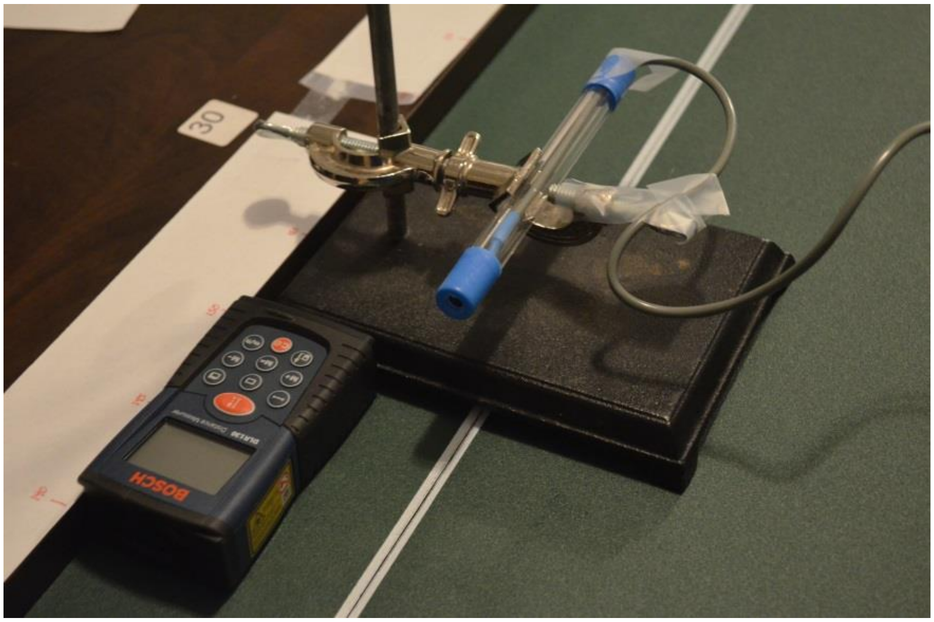


Fig 3: Light Sensor and Laser Distance Meter

Fig 4: Vernier LabPro Collector

2.3 Procedure

1) Place the light source at the very edge of a flat surface.
2) Set up a reference point for the laser distance measurer that is parallel to the light source.
3) Using a ruler, roughly measure out markings of 0.05 meters along the flat surface in a straight line perpendicular to the light source.
4) Place the light sensor securely in the clamp on the ring stand, as shown in Fig 3.
5) Set up and connect the Light Sensor with the LoggerPro sensor collector, creating a new Logger Pro 3.8.5.1 document. Allow for the program to collect data for 10 seconds, taking 2 readings per second.
6) Confirm that the room you are working in is completely dark. Using the lux meter, confirm that the background lux is less than 0.2 lux.
7) Set up the ring stand and clamp such that the light sensor is directly pointed at the light source. Place a long wooden board to the side of the ring stands to ensure that the sensor moves perpendicularly as compared to the light source.
8) Place the ring stand at the 0.400 meter mark

9) Use the Bosch DLR130 laser meter to get a more accurate measurement of distance. Record this value.
10) Begin recording lux data using the Logger Pro software, obtaining 20 data points.
11) Move the ring stand roughly 0.10 meters away from the light source.
12) Repeat steps 9, 10 and 11 until the meter roughly reaches 1.90 meters.
13) Repeat steps 9, 10, and 11, but begin move the lux meter towards the light source every 0.10 meters until the lux meter is back to the 0.40 meter mark.

2.4 Raw Data

Selected Data Trials:

Selected Data Trials of Distance[7] vs. Lux Measurements[8]								
	Distance (±0.0015m)							
Time (±0.1 s)	0.412	0.920	1.471	1.876	1.861	1.472	0.926	0.425
	Lux Measurements (±0.2 lux)							
0.5	422.1	86.7	40.8	23.3	24.3	41.6	79.5	389.0
1.0	390.4	80.5	34.6	28.2	28.6	36.9	93.3	335.6
1.5	448.1	96.5	39.1	25.2	23.3	37.6	89.5	394.1
2.0	446.2	88.6	36.1	26.7	25.4	40.4	84.1	349.7
2.5	408.8	78.4	40.2	25.0	28.0	39.3	88.2	328.3
3.0	411.8	86.7	38.4	27.8	27.8	34.8	79.2	359.0
3.5	447.0	92.3	38.4	24.6	23.7	41.4	93.8	332.1
4.0	418.0	80.5	38.0	23.3	27.8	35.9	87.2	389.2
4.5	400.1	84.1	39.1	26.3	27.6	40.6	79.2	333.6
5.0	430.6	95.5	40.1	27.3	24.3	34.2	93.3	389.8
5.5	432.9	81.4	40.4	23.7	25.4	38.2	90.6	335.5
6.0	396.9	84.1	34.8	23.5	29.0	36.9	80.3	389.6
6.5	428.3	91.9	38.4	27.5	26.3	39.1	84.6	369.3
7.0	445.1	93.3	42.1	26.3	23.1	39.9	92.9	358.0
7.5	384.5	86.3	36.3	23.3	27.3	35.7	81.0	363.1
8.0	447.3	91.0	34.0	24.4	28.0	40.4	82.9	358.8
8.5	398.6	87.4	41.2	28.2	23.9	34.2	93.1	378.9
9.0	448.3	89.5	39.3	24.8	23.9	38.7	84.1	392.2
9.5	406.5	94.4	35.0	23.3	27.6	40.8	81.0	345.6
10.0	447.1	82.9	34.8	25.6	25.6	37.8	90.1	366.9

See appendix III for full data tables.

[7] BOSCH
[8] Vernier Software

To plot the data, we will allow for the x variable to be the direct variable (distance) and the y variable to be the independent variable (lux). We then process the raw data in order to find the average lux values as well as the standard deviation in lux, which we use as the error in the y direction. Uncertainty bars in the x direction are very small and are not noticeable on the graph due to the high precision of the laser distance meter used in measuring distances. The uncertainty bars in the y direction were found by applying a standard deviation to the light intensity trials. Sample calculations can be found in Appendix IV. After processing, the following data is shown:

Selected Processed Data		
Distance (±0.0015m)	Average Lux	Standard Deviation of Lux
0.517	267.4	15.7
0.714	142.8	7.7
1.023	72.2	4.8
1.229	52.5	3.8
1.472	38.2	2.3
1.775	28.5	2.0

See Appendix V for full processed data tables.

This results in the following graph:

2.5 Graph

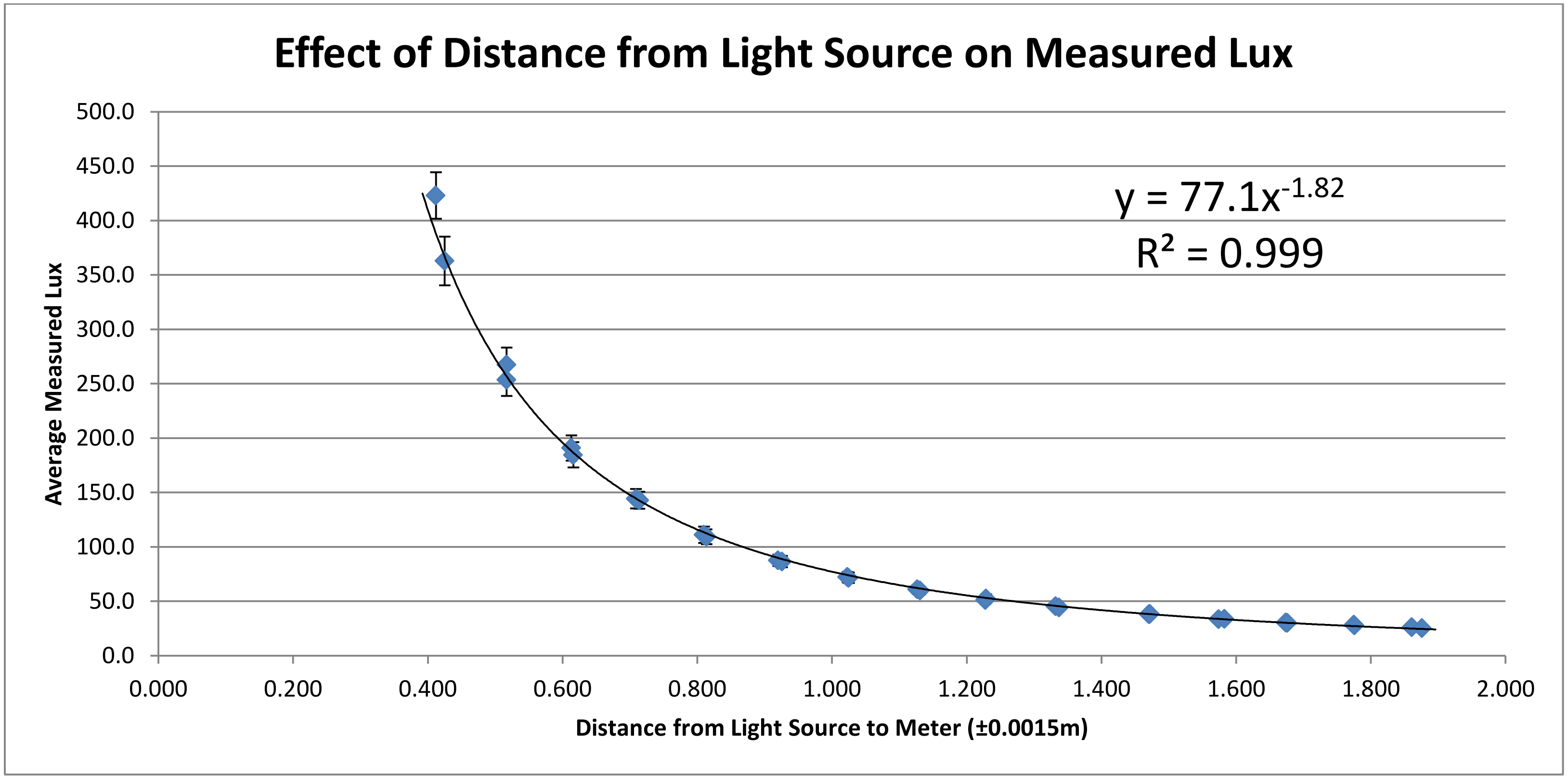


Fig 5: Effect of Distance on Intensity of Light

This graph reveals the following equations:

$$y = 77.1x^{-1.82} \tag{2.1}$$
$$R^2 = 0.999 \tag{2.2}$$

2.6 Linearized Data

From this graph, there are two asymptotes that can be clearly seen: As the lux meter gets infinitely far away from the light source, the perceived lux goes towards 0. Conversely, as the light meter approaches 0 meters away from the light source, the perceived lux approaches infinity. The first horizontal asymptote is easy to understand; if you get very far away from a light source, you can barely detect any light. However, why is there infinite lux when you are 0 meters away from the light source?

A sphere with a radius of zero meters would also have a surface area of zero meters. Because of physical limitations, a meter that is extremely close to the light source would detect an extraordinarily high lux value. Therefore, due to an instrument error that could still record the lux at 0 lux, there would appear to be an infinite or near infinite lux measurement.

This graph demonstrates an inverse square relationship, as shown through the regression line and its approximate value of 2. In order to further investigate this relationship, we shall linearize this information and interpret error in that fashion.

To linearize the data, we will plot $\frac{1}{m^2}$ versus lux on a graph. See Appendix VI for the error propagation and sample calculations and Appendix VII for full linearized data.

Selected Linearized Data			
Linearized Distance (1/m^2)	Propagated Error (1/m^2)	Average Lux	Standard Deviation of Lux
5.536	0.0391	362.9	22.4
1.989	0.0084	144.2	8.9
0.952	0.0028	71.6	4.7
0.462	0.0009	38.0	2.4
0.317	0.0005	27.9	1.9

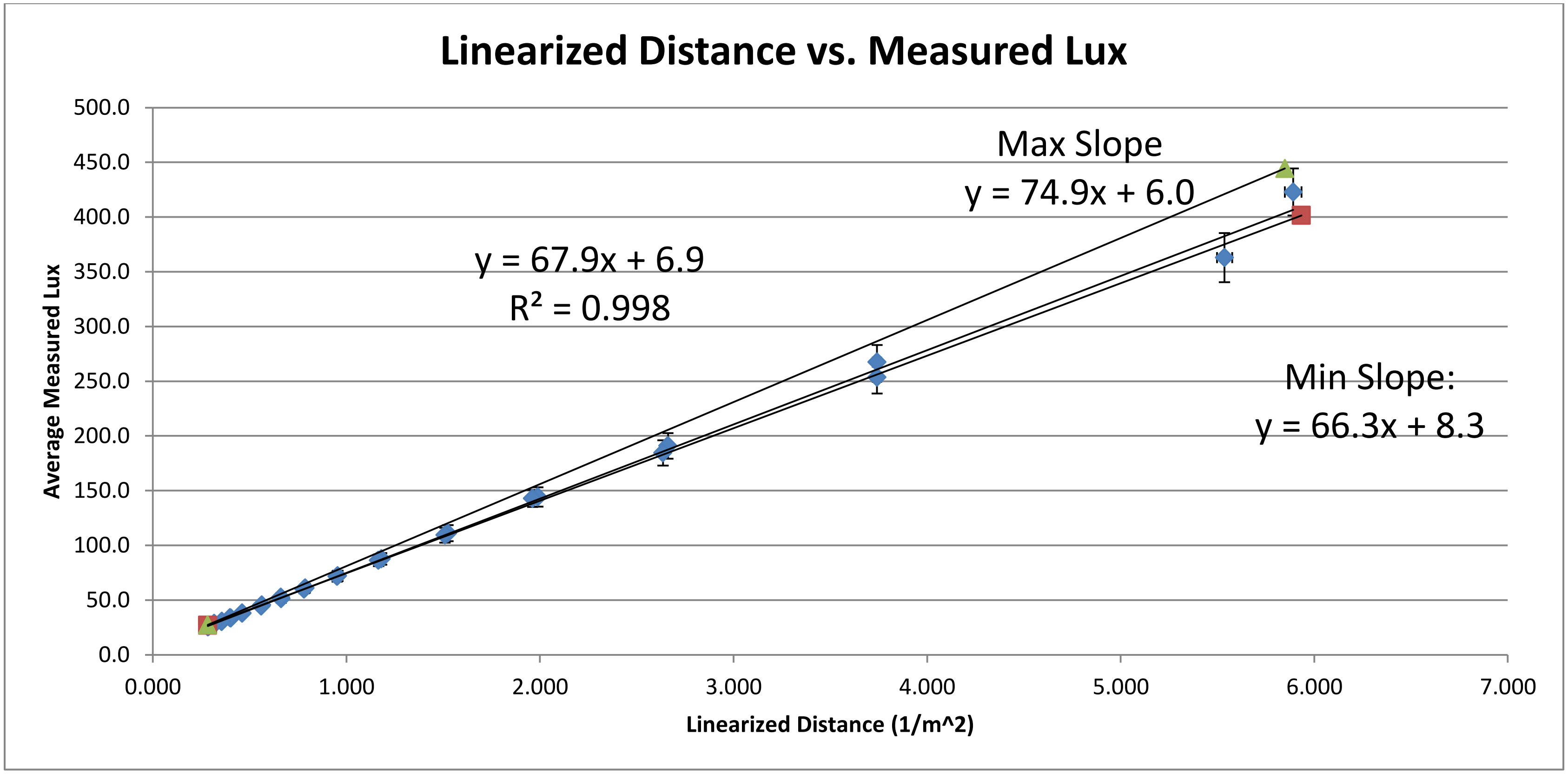


Figure 6: Linearized Distance vs. Lux

$$\text{Regression: } y = 67.9x + 6.9 \quad (2.1)$$

$$R^2 = .998 \quad (2.2)$$

$$\text{Min Slope: } y = 66.3x + 8.3 \quad (2.3)$$

$$\text{Max Slope: } y = 74.9x + 6.0 \quad (2.4)$$

2.6 Explanation of Linear Graph

Power regressions are not enough information to calculate a relationship between variables. Rather, through linearization, we can test to see how accurate our predicted relationship could be. Because this linearized graph shows a high correlation and a tendency for all points to lie within the min/max slope lines, the $\frac{1}{x^2}$ regression is the best one to use.

In an ideal system, the y and x intercept would be very close to the origin. This is because, as mentioned in the earlier asymptote analysis, a meter infinitely far away from a light source should report a very close to zero reading. The error in this case can mostly be attributed to the more inaccurate values at the higher values of this linearized graph. Because we understand that the closer the light meter is, the more error there is, we know that the points farther away from the origin are more distorted, thus propagating the linearization error.

The slope does not have a specific symbolic meaning, because the illuminance is not found by the difference in lux over meters squared, but the value at each point. It does not make sense to analyze the slope.

2.7 Error Analysis

This linearized data shows very little error due to the high correlation value as well as because all of the uncertainty regions are within the minimum and maximum slopes. However, there are several sources of error that can be discussed at length.

One of the reasons for the relatively large standard deviation values is in the form that the lux meter records data. A lux meter uses the photoelectric effect that uses photons to generate a current. That current is then measured against a voltage value that has been calibrated with official lux readings. However, as seen in Fig. 7, there is a fluctuation in this measurement.

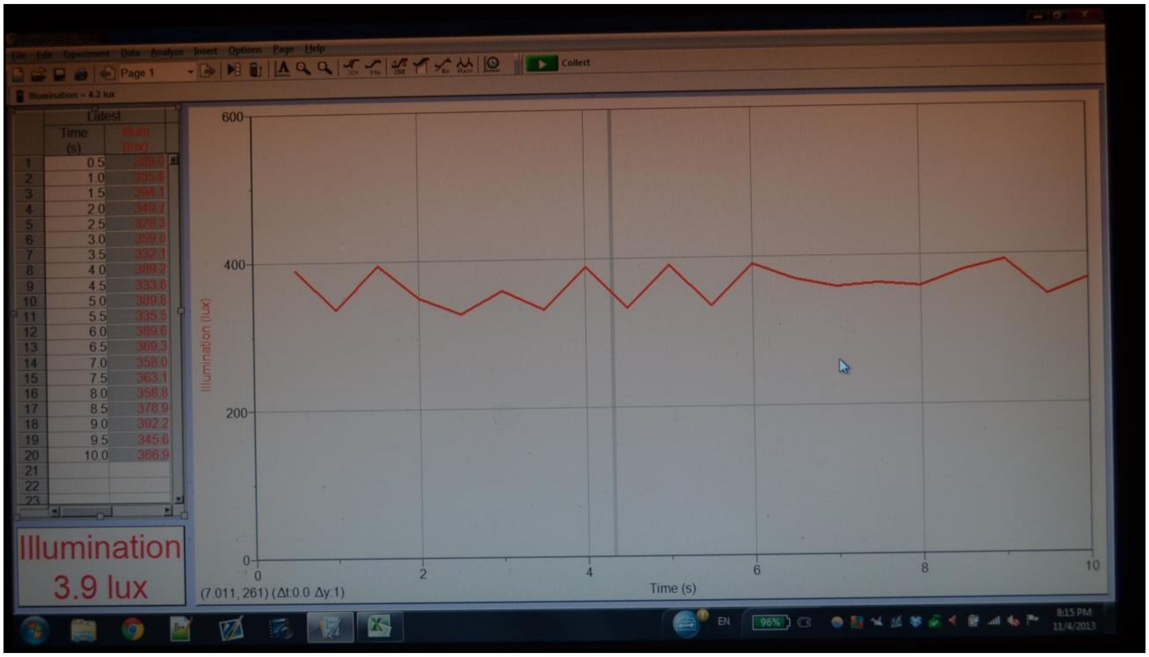


Fig. 7: Screenshot of Data

Instead of measuring a constant lux value, the value seems to be cyclic over a period of every second. This fluctuation of measurements causes a systematic instrumentation error, and is mostly solved with large amounts of data, and taking the average.

Another source of systematic error in this experiment comes from the absorbance coefficient of light in air. This error is primarily found only in an atmospheric condition, and deals with the way that molecules in the air absorb light. According to Beer's Law, this can be modeled by

$$I = I_0 \cdot e^{-\alpha l} \qquad (2.5)$$

Where I=Intensity observed, I_0 = Intensity initial, α is the absorbency coefficient, and ℓ is the distance.

However, because α is extraordinarily small, at a value of $\alpha = \frac{3.05 \cdot 10^{-8}}{m}$ the absorbance coefficient only has a very small effect on the measured intensity[9]. In addition, this constant is drastically reduced in space, as the extinction factor is very small considering the vacuum of space.

Finally, a potential error source is in that the light bulb is not a perfect light source. Instead of radiating light from one exact point, there is some area in which it radiates light. This systematic instrumental error is perhaps the largest contributor to error in our graphs.

While we have shown that the inverse square relationship holds under most cases, we must also investigate certain atmospheric distortions that may taint this relationship as a result of physical measurements.

---

[9] Meyerott, R. E Table 1

3.0 Light Pollution Experiment

Although most astronomical observatories are placed far away from the light pollution that is caused by civilization, the phenomenon of airglow is still persistent everywhere. This phenomenon is caused by chemiluminescence in Earth's atmosphere, where chemical reactions cause light to be emitted[10]. Therefore, understanding the effect that background light may have on the brightness method is very important when trying to calibrate data and sensors.

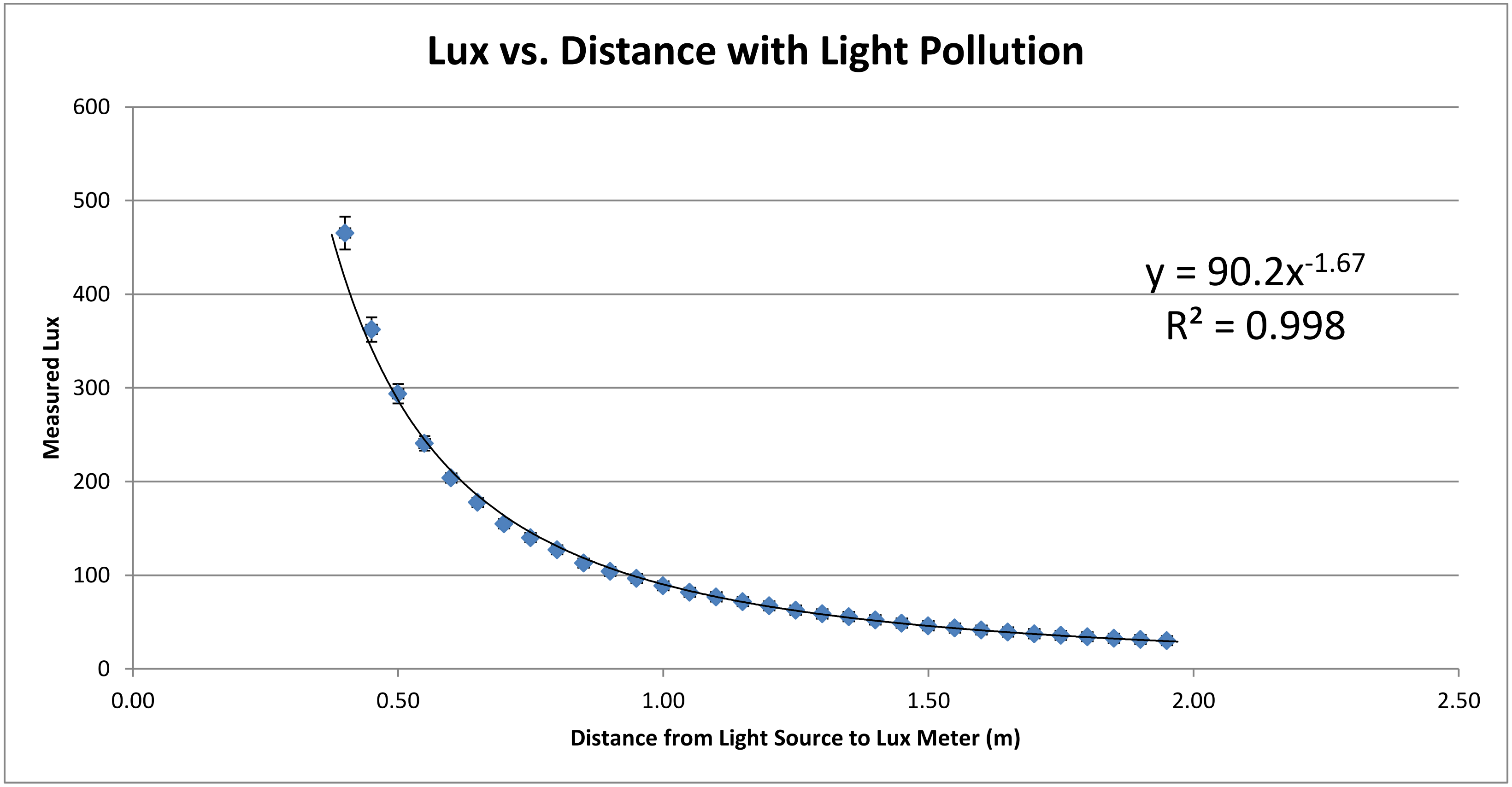
The procedure for this experiment is the same as the procedure outlined in 2.3, with the notable change of being in a dimly lit room rather than a dark room. A light is set up, providing a range of 1.6 to 7.3 lux of illumination across the flat surface where the lux is measured. The raw data for this experiment can be found in Appendix VIII and the methods of generating processed data can be once again found in Appendices IV and VI.

Selected Processed Data for Light Pollution Experiment		
Distance (±0.01m)	Average Lux	Standard Deviation (Lux)
0.50	293.8	10.5
0.75	140.1	1.4
1.00	88.68	0.8
1.25	62.72	0.5
1.50	45.96	0.2
1.75	35.76	0.2

This data results in the following graph:

[10] "Airglow Formation"

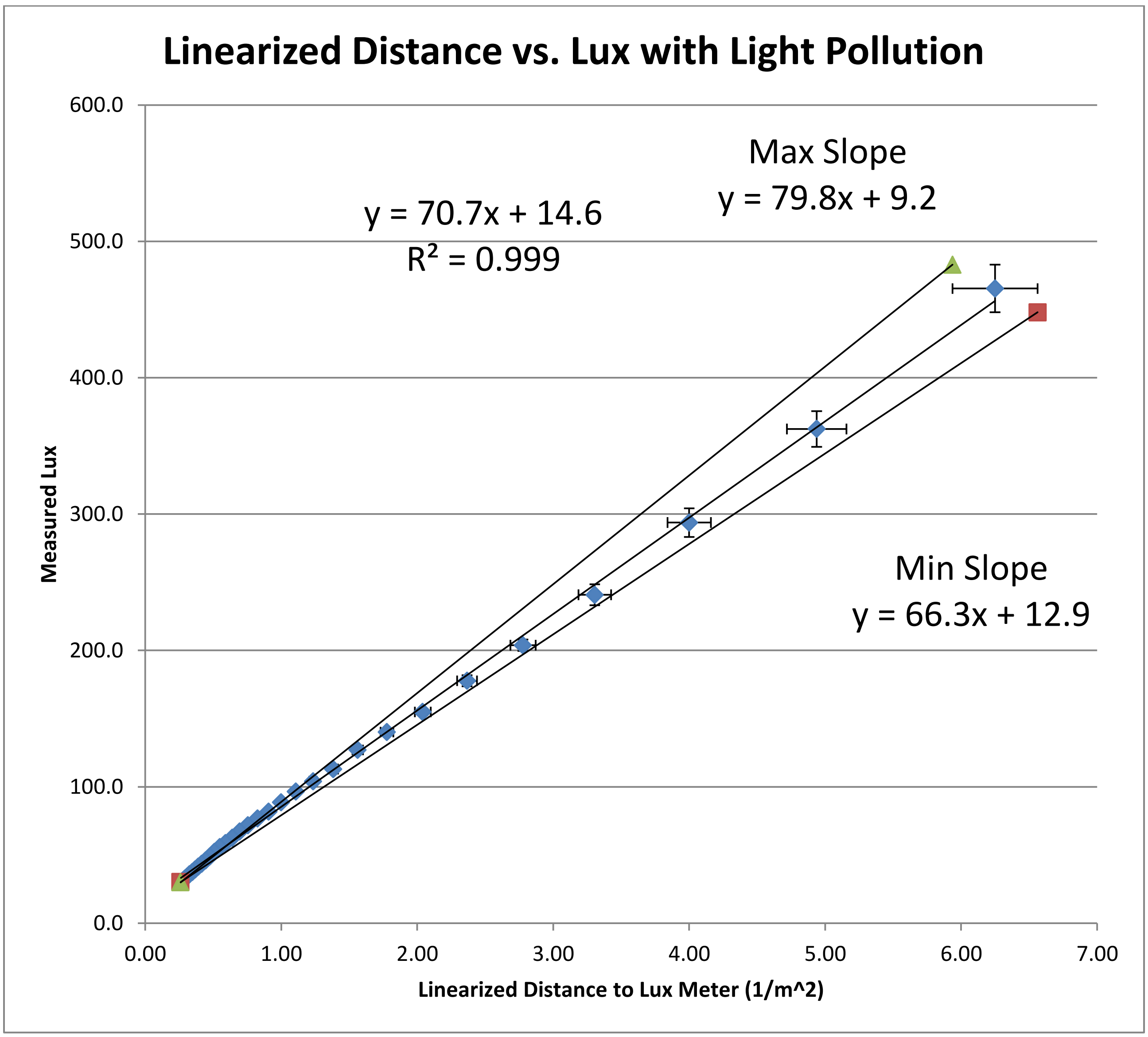
3.1 Graph



$$y = 90.2x^{-1.67}$$
$$R^2 = 0.998 \tag{3.1}$$

This graph looks very similar to the graph from the first experiment as seen in the asymptotes as well as the general correlation.. However, the power regression results in an $x^{-1.67}$ term instead of the more accurate $x^{-1.82}$ term as seen before. This implies that light pollution does have an effect. Before we draw conclusions, we must linearize and see the correlation in order to determine to what extent did light pollution have an effect.

3.2 Linearized Data



$$y = 70.7x + 14.6 \quad (3.2)$$
$$R^2 = 0.999$$
$$\text{Min Slope: } y = 66.3x + 12.9 \quad (3.3)$$
$$\text{Max Slope: } y = 79.8x + 9.2 \quad (3.4)$$

In order to derive the linearized data and error bars, we followed the same procedure as in Appendix VI. This full data set can be found in Appendix IX.

Our linearized data proves that an inverse square model is still the best regression for light pollution data. Every value is well within the min/max slope lines. The trend line is clear and highly correlated.

3.3 Light Pollution Conclusion

We conclude that light pollution generally follows the same patterns that the inverse square law follows. The scatter plot shows a different correlation for x, but when linearized, the relationship still holds. Therefore, light pollution does cause a shift in spectrophotometric analysis, but not significant enough to forgo the inverse square law.

4.0 Multiple Light Sources Experiments

A large portion of the stars are not single stars such as our sun, but rather in binary or multiple star systems. Scientists have recently calculated the percentage of these multiple star systems to be roughly 31% of all stars[11]. This following experiment will test whether if it is plausible to apply the brightness test to a multiple star system.

To elaborate: These star systems are multiple stars, but to an observer on Earth, they often appear as only one point of light. If the two stars are close to each other, is it reasonable to find the distance by using their combined brightness? We would therefore be creating a

[11] Charles J. Lada

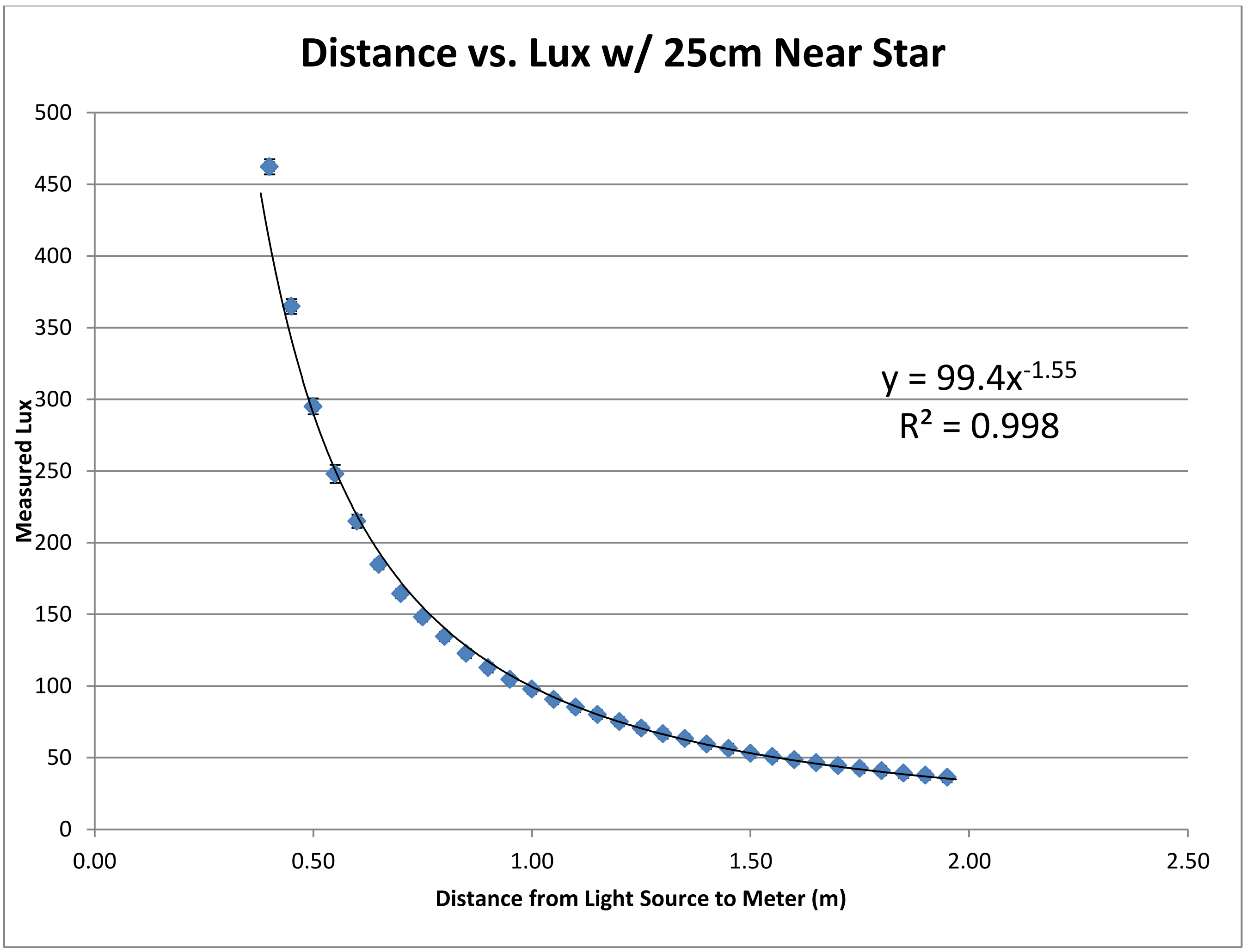
“combined” star with a greater illuminance value. However, does the separation between the stars have an impact on the inverse square relationship?

4.1 25cm Near Light Source

In order to simulate a multiple star system, we follow the same procedure as the first experiment, but introduce a second lamp placed 0.25 meters away from the first lamp. The brightness of these two lamps together will simulate a bright binary star system.

Please see Appendix X for raw data and Appendix XI for processed data.

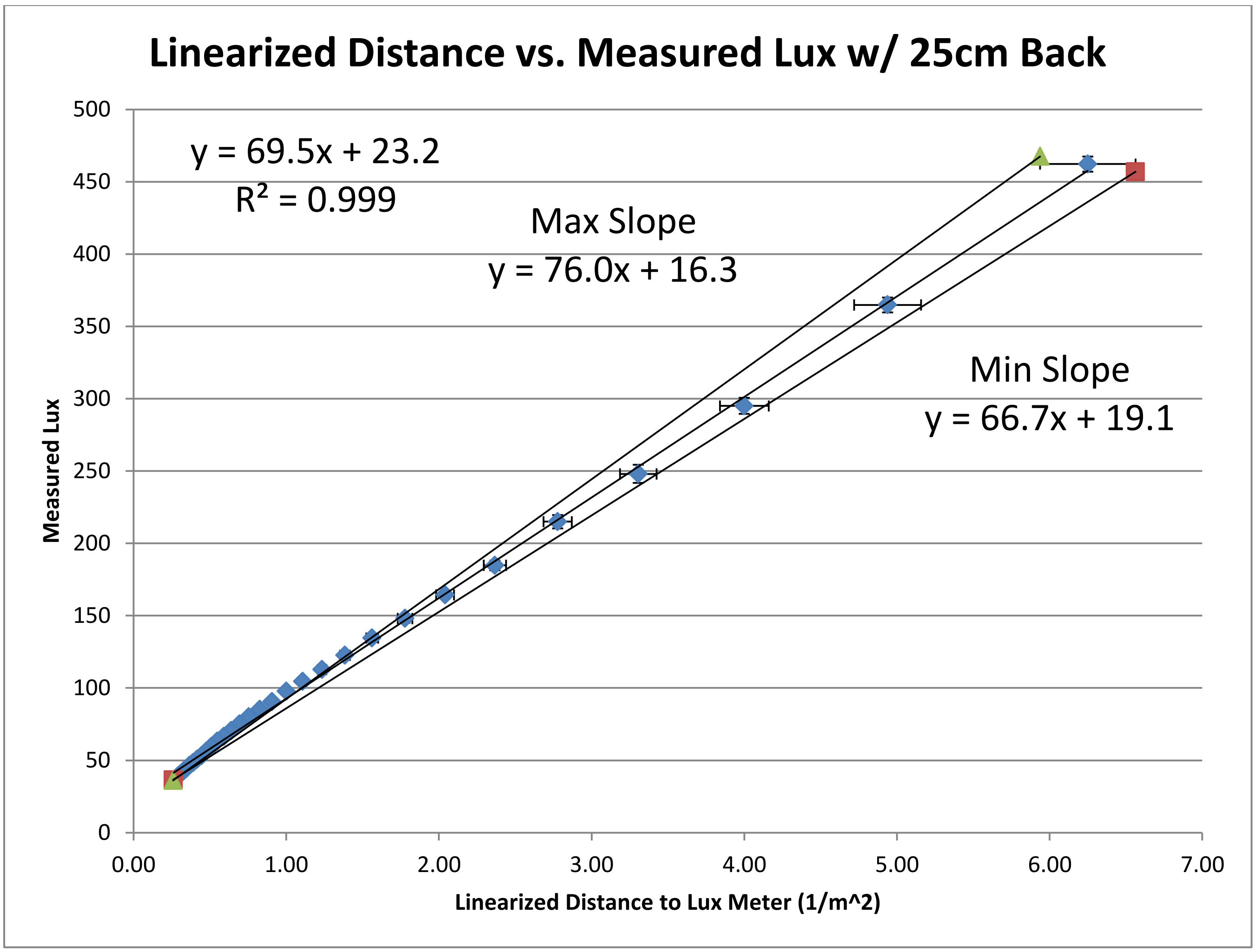
4.1.1 Graph



$$y = 99.4x^{-1.55} \qquad (4.1)$$
$$R^2 = 0.998$$

This graph displays a marked increase in error, given that the regression is more approximately $x^{-1.5}$ than x^{-2}. Although it shows the same asymptotes as in the original experiment, is it possible that the introduction of a second star has resulted in a different correlation? We once again linearize to visualize the correlation. Full linearized data can be found in Appendix XI.

4.1.2 Linearized Data



$$y = 69.5x + 23.2 \quad (4.2)$$

$$R^2 = 0.999$$

$$\text{Min Slope: } y = 66.7x + 19.1 \quad (4.3)$$

$$\text{Max Slope:} y = 76.0x + 16.3 \quad (4.4)$$

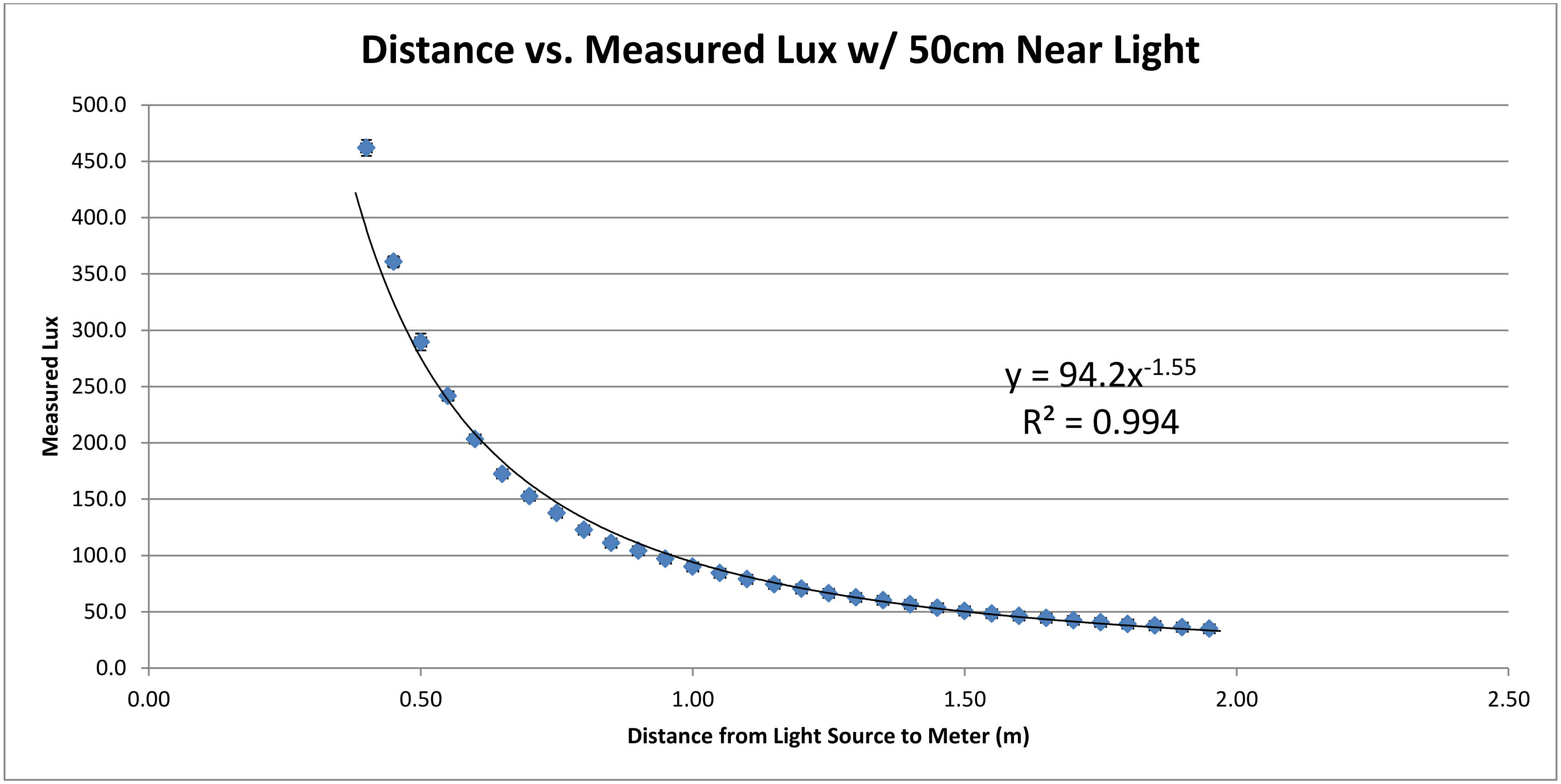
This linearized data proves that despite the increased uncertainty that a binary system brings, the same inverse squared relationship can be found. Therefore, we are able to apply our brightness method to stars even we are not certain if it is one star or multiple stars.

4.2 50 cm Near Light Sources

What if the stars in the binary light source system were farther apart from each other? If two or more stars are only weakly gravitationally attracted to each other, is it still valid to group them into one brightness point? For example, the Alpha Centauri system consists of Alpha Centauri A and B, but also Alpha Centauri C, or Proxima Centauri[12]. Proxima Centauri is only 0.07266 parsecs away from Alpha Centauri A and B, but this is a very vast distance in terms of star systems. Could we apply our brightness method to these star systems as well? See Appendix XII for raw data and Appendix XIII for processed data.

[12] Dolan, Chris

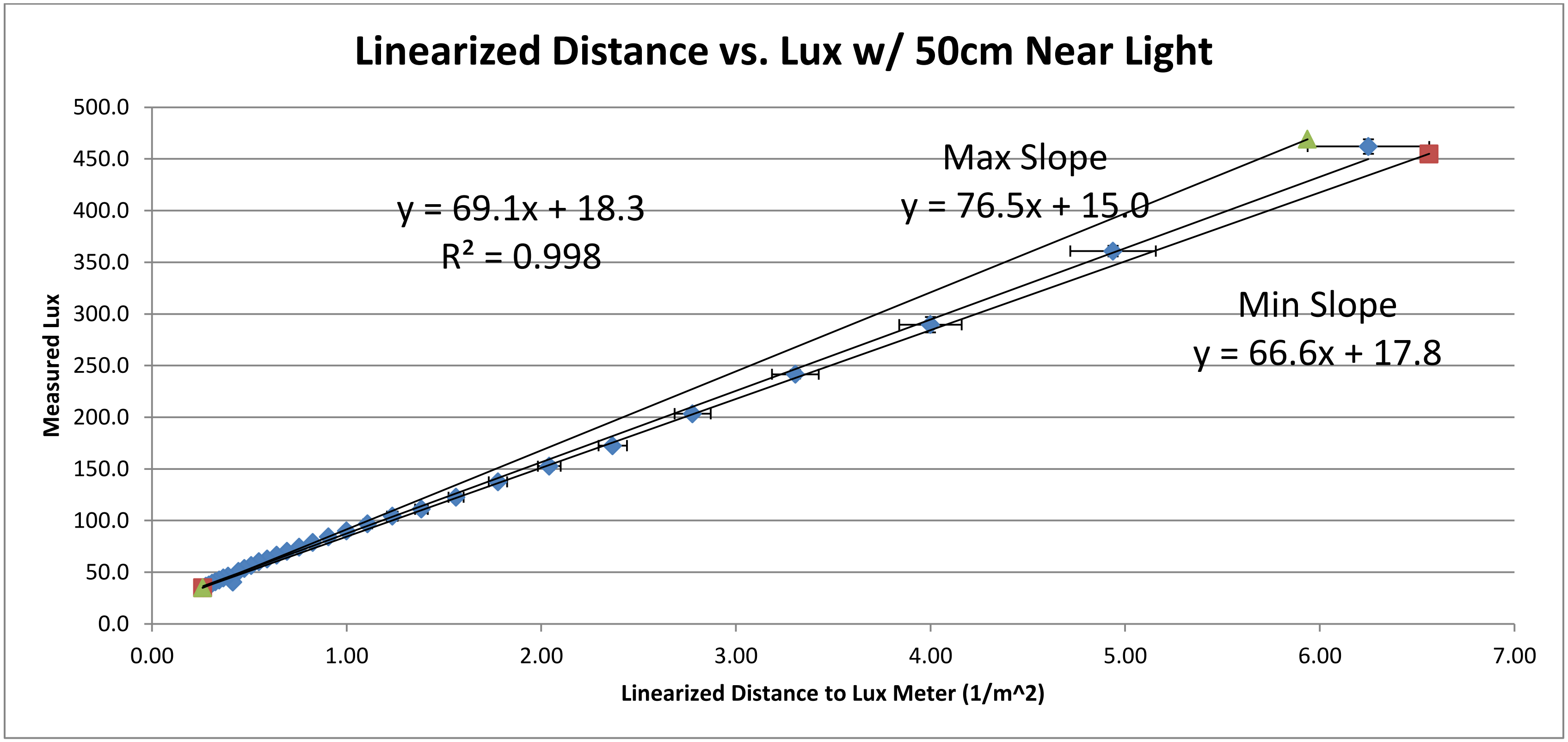
4.2.1 Graph



$$y = 94.2x^{-1.55} \quad (4.5)$$
$$R^2 = 0.994$$

The 50 cm data looks almost exactly the same as the 25 cm data, implying that after linearization, the same conclusions can be made. See Appendix XIII for full linearized data.

4.2.2 Linearized Data



$$y = 69.1x + 18.3 \quad (4.6)$$
$$R^2 = 0.998$$
$$\text{Min Slope: } y = 66.6x + 17.8 \quad (4.7)$$
$$\text{Max Slope: } y = 76.5x + 15.0 \quad (4.8)$$

4.3 Multiple Light Sources Conclusion

There is no large, discernible effect that multiple stars have on the inverse square relationship. Although it seems that introducing multiple stars decreased the correlation in the scatter plot, the linearized plot shows that an inverse squared relationship is still valid. The points are well within the min/max slope lines and there is no remarkable amount of deviation under the current experimental conditions. Therefore, a key conclusion that can be drawn is that the brightness distance method can accurately measure the distance to multiple star groups.

5.0 Analysis of Stars

Through the multiple experiments we have performed regarding the effect of distance and measured lux, we have found no difference in the effect of external factors such as background light or close binary light sources that would influence the inverse square relationship. Although these variables may pollute the intrinsic determination of stellar qualities, it has been shown that they do not influence the nature of the relationship. Regardless of any polluting factors, the inverse square relationship is preserved. Therefore, equation 1.5 is entirely valid, and can be used to calculate actual stellar distances.

In order to use this formula, one can look at real astronomical data and calculate apparent magnitude by hand. NASA's "Observing with NASA program" allows amateur astronomers to remotely control telescopes in Arizona and capture images in FITS files. This data can then be interpreted with the Aperture Photometry Tool to calculate the apparent magnitude of the star, as compared to the dark background.

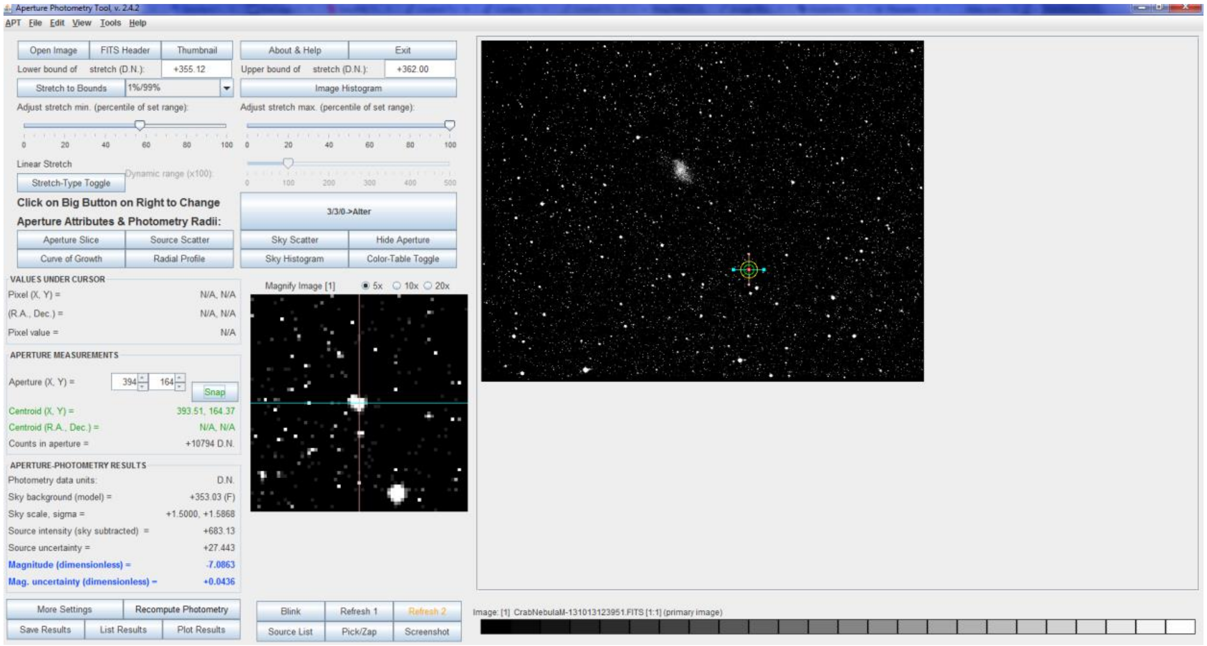


Fig 8: Screenshot of APT Tool Analyzing the Crab Nebula

While it is possible to get and analyze real pictures of stars taken by telescopes, computer the apparent magnitude CCD and FITS interpretation of data, and then find absolute magnitudes by sequencing the star, that process is better suited for another project. Instead, we use published absolute and apparent magnitude data from NASA databases in order to demonstrate our distance algorithm.

5.1 Analysis of Vega

One of the brightest stars in the night sky is Vega of the constellation Lyra, the harp. Not only does it have a high absolute brightness, but it is one of the closer stars to Earth, approximately 7.68 parsecs away from Earth. We shall perform analysis on this star using our calculated formulas as follows:

$$m = 0.03, M = 0.58$$

$$d = 10^{\left(\frac{0.03-0.58}{5}\right)+1}$$

$$d = 10^{.89}$$

$$d = 7.76\, parsecs$$

While this answer is not extraordinarily accurate, it does provide a general answer within 0.1 parsecs. As we can tell, the brightness method is not accurate enough for near stars that can be better analyzed by parallax.

5.2 Analysis of Other Stars

Following is a table of stellar information, the known distances of those stars, and the calculated distances. All data was taken from the Yale Bright Star Catalogue, the Hipparcos Catlogue, and the Tycho Catalogues.

	Apparent Mag	Absolute Mag	Known Distance (parsecs)	Distance Uncertainty (pc)	Calculated Distance (pc)	Difference Between Calculated and Known Distances (pc)	Additional Information
Sirius	-1.46	1.42	2.64	0.01	2.65	0.01	Binary Star System
Vega	0.03	0.58	7.68	0.02	7.76	0.08	
Altair	0.77	2.21	5.13	0.01	5.15	0.02	
Deneb	1.25	-8.38	802	66	843.33	41.33	
Castor	1.98	0.59	15.6	0.9	18.97	3.37	
Polaris	2.02	-3.6	114.25	15.25	133.05	18.80	
Pollux	1.14	1.08	10.36	0.03	10.28	0.08	
Betelgeuse	0.5	-2.99	197	45	49.89	147.11	Variable Star
Rigel	0.12	-7.84	260	20	390.84	130.84	Variable Star
Delta Cygni	2.87	-0.74	51	1	52.72	1.72	
Gamma Pegasi	2.83	-2.22	120	8	102.33	17.67	Variable Star
Delta Orionis (Mintaka)	2.23	-4.99	210	30	277.97	67.97	

As we can see according to our table, the majority of our values correspond with precise accepted measurements of stars. However, there are several stars to note, namely those designated as variable stars. Variable stars are stars that vary in brightness over a period of time due to the star itself growing and shrinking. As seen in the drastically inaccurate calculations for Betelgeuse, Rigel, and Gamma Pegasi, it is not reasonable to calculate the distance to variable stars using the brightness method.

Conclusion

Through this lab report, we have analyzed the pragmatic ability to use the inverse square law of luminous intensity to measure stellar distances, using experimental methods to validate the relationship. We have compared the use of our formula to calculated distances of stars, and have extrapolated bounds of error.

One additional region for continued exploration is the use of non 550 nm to measure distances. Although the results for distances should be the same regardless of which flux band of light you use, there are benefits to using multiple spectrums. Some of the hotter stars output most of their energy in the UV or X-Ray spectrum, making it easier to analyze errors if this band was used. While the properties of light do not change depending on wavelength, it would be better to conduct the experiment in different sources to see what happens.

However, there are still certain astronomical circumstances that this project does not take into consideration. For example, large massive stars, as well as black holes, have the ability to warp space, which means that light could also be worked. How could distorted beams of light be used to measure distances? Also, the redshift effect states that stars always seem to be getting farther away from Earth at all times. How could we correct for this distance gap, as well as for the wavelength shift that would occur? These are questions that require a greater understanding of astrophysics, but the underlying inverse square principle allows for approximate values to be found.

Appendix I: *Geometric Derivation of the Inverse Square Law of Illuminance*

Suppose that some point light source directed x photons in every direction of the source. This distribution of photons would be even across the light sphere that encompassed the source.

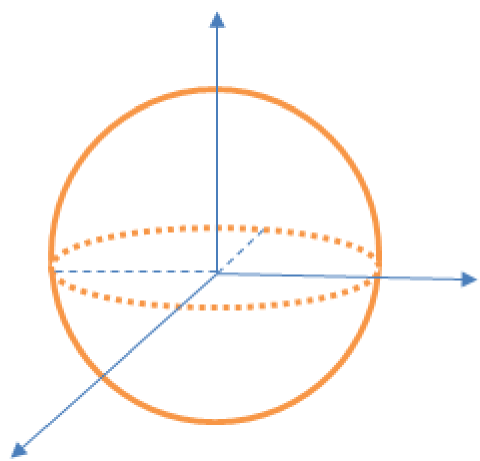


Fig 5: Geometric Display

Therefore, if we would like to find the density of photons for every square meter of the light sphere, the initial number of photons would be taken and divided by the surface area of the sphere at some distance d.

Because the relationship between the distance d away from the light source and the surface area of the surrounding light sphere can be modeled as

$$SA = 4\pi d^2 \tag{I.1}$$

the density of photons per square meter at some distance away from the light source would be

$$Density = \frac{Initial}{4\pi d^2} \tag{I.2}$$

so that without constants, the relationship between the density of photons and the distance is simply

$$Density = \frac{Initial}{d^2} \tag{I.3}$$

Using the scientific terms for what the density of photons is as well as what “initial” number of photons is, we arrive at the conclusion that

$$E = \frac{I}{d^2} \tag{I.4}$$

Whereas E is the luminous flux and I is the luminosity.

Appendix II: *Mathematical Derivation for Magnitude Relationship with Distance*

Because luminous intensity is also an intrinsic property of a star, the luminous intensity of a star at any wavelength is the same regardless of the distance where the lux is measured. We can therefore use it as a constant to relate L(10) and L(d) together, through:

$$L(d) = \frac{I}{d^2} \quad \text{(defined)}$$

$$L(10) = \frac{I}{10^2} \quad \text{(defined)}$$

$$10^2 \cdot L(10) = I$$

$$L(d) = \frac{L(10) \cdot 10^2}{d^2}$$

$$L(d) = L(10) \cdot \left(\frac{10}{d}\right)^2 \quad \text{(II.1)}$$

Furthermore, given the equations for the magnitudes as defined by

$$m = -2.5 \log_{10} L(d) \quad \text{(II.2)}$$

$$M = -2.5 \log_{10} L(10)$$

$$m - M = -2.5 \log_{10} L(d) + 2.5 \log_{10} L(10)$$

$$m - M = -2.5 \log_{10} \left(L(10) \cdot \left(\frac{10}{d}\right)^2\right) + 2.5 \log_{10} L(10)$$

$$m - M = -2.5 \log_{10} \left(\frac{10}{d}\right)^2 - 2.5 \log_{10} L(10) + 2.5 \log_{10} L(10)$$

$$m - M = -2.5 \log_{10} 100 + 2.5 \log_{10} d^2$$

$$m - M = -5 + 5 \log_{10} d$$

$$m - M + 5 = 5 \log_{10} d$$

$$\log_{10} d = \frac{m - M + 5}{5}$$

$$d = 10^{\frac{m-M}{5}+1} \tag{II.3}$$

Whereas m is the apparent magnitude of a star, M is the absolute magnitude of a star, L is the lux measurement of a star, and d is the distance away from the star.

Appendix III: *Raw data from light intensity vs. length experiment*

Data Trials of Distance vs. Lux Measurements (Part I)								
	Distance (±0.0015m)							
Time (±0.1 s)	0.412	0.517	0.613	0.709	0.810	0.920	1.023	1.131
	Lux Measurements (±0.2 lux)							
0.5	422.1	267.4	184.1	143.3	107.2	86.7	76.9	56.2
1.0	390.4	246.1	206.3	154.9	104.9	80.5	69.0	65.1
1.5	448.1	291.1	178.3	131.4	121.8	96.5	76.3	61.7
2.0	446.2	278.9	178.1	146.9	111.9	88.6	66.4	61.3
2.5	408.8	248.8	200.1	157.8	101.9	78.4	69.8	58.1
3.0	411.8	264.4	207.6	138.4	112.4	86.7	76.2	57.0
3.5	447.0	284.3	173.6	145.2	114.7	92.3	68.1	62.6
4.0	418.0	254.2	193.7	156.8	103.2	80.5	66.6	58.9
4.5	400.1	255.4	208.2	144.8	110.0	84.1	75.2	57.5
5.0	430.6	282.8	188.0	131.2	120.7	95.5	73.7	66.6
5.5	432.9	260.8	189.7	153.8	105.3	81.4	77.3	58.5
6.0	396.9	247.3	194.8	149.5	103.8	84.1	69.2	54.7
6.5	428.3	275.5	183.7	134.1	116.0	91.9	74.8	61.9
7.0	445.1	293.5	196.5	147.8	120.5	93.3	65.8	63.2
7.5	384.5	247.1	199.7	144.8	102.3	86.3	78.6	56.4
8.0	447.3	267.9	184.5	131.4	111.7	91.0	65.4	56.4
8.5	398.6	292.8	196.5	143.7	122.8	87.4	79.0	66.0
9.0	448.3	250.1	173.2	157.6	105.5	89.5	67.9	59.4
9.5	406.5	273.8	207.8	132.8	122.8	94.4	79.5	55.3
10.0	447.1	265.9	173.6	137.3	101.7	82.9	69.2	58.9

Data Trials of Distance vs. Lux Measurements (Part II)							
	Distance (±0.0015m)						
Time (±0.1 s)	1.229	1.332	1.471	1.574	1.676	1.775	1.876
	Lux Measurements (±0.2 lux)						
0.5	57.7	41.0	40.8	32.5	31.8	26.9	23.3
1.0	50.4	47.8	34.6	30.8	27.6	30.8	28.2
1.5	55.3	40.8	39.1	37.2	30.5	25.4	25.2
2.0	56.8	42.5	36.1	33.1	30.5	29.5	26.7
2.5	51.3	48.9	40.2	30.3	31.4	29.9	25.0
3.0	47.6	47.9	38.4	37.4	31.8	28.6	27.8
3.5	55.5	41.4	38.4	31.2	29.3	25.9	24.6
4.0	55.8	44.9	38.0	37.0	29.3	30.1	23.3
4.5	50.2	49.3	39.1	30.6	31.8	29.9	26.3
5.0	47.8	45.3	40.1	35.7	29.5	27.3	27.3
5.5	57.2	43.8	40.4	32.3	27.5	26.7	23.7
6.0	55.1	48.3	34.8	36.1	30.5	31.2	23.5
6.5	47.8	48.3	38.4	33.8	33.1	29.5	27.5
7.0	48.5	41.9	42.1	37.2	28.0	25.6	26.3
7.5	57.2	46.3	36.3	31.4	27.8	27.8	23.3
8.0	52.5	48.5	34.0	31.2	32.2	31.4	24.4
8.5	47.0	46.1	41.2	36.5	32.9	28.6	28.2
9.0	49.6	41.0	39.3	34.6	27.8	25.6	24.8
9.5	57.2	47.8	35.0	30.5	28.8	27.8	23.3
10.0	50.2	47.6	34.8	32.3	32.9	31.0	25.6

Data Trials of Distance vs. Lux Measurements (Part III)								
	Distance (±0.0015m)							
Time (±0.1 s)	1.861	1.776	1.674	1.583	1.472	1.337	1.228	1.127
	Lux Measurements (±0.2 lux)							
0.5	24.3	26.3	33.5	36.1	41.6	41.2	47.9	55.3
1.0	28.6	27.8	28.0	33.7	36.9	46.8	47.9	64.1
1.5	23.3	28.0	33.5	32.3	37.6	42.9	56.0	62.8
2.0	25.4	24.8	27.8	35.0	40.4	47.9	50.4	57.9
2.5	28.0	27.1	32.9	35.4	39.3	44.0	47.4	64.7
3.0	27.8	29.7	27.3	31.0	34.8	47.8	51.9	55.3
3.5	23.7	26.5	31.4	34.6	41.4	46.6	52.5	65.6
4.0	27.8	25.0	28.6	32.3	35.9	41.2	46.4	64.9
4.5	27.6	28.8	32.5	34.6	40.6	42.1	51.1	56.2
5.0	24.3	30.1	30.5	31.6	34.2	47.6	55.7	64.1
5.5	25.4	25.6	30.1	35.9	38.2	42.9	47.4	66.4
6.0	29.0	26.1	31.2	29.9	36.9	42.1	48.3	56.0
6.5	26.3	29.7	29.5	36.9	39.1	45.1	56.2	63.9
7.0	23.1	29.7	28.2	31.4	39.9	44.6	53.6	64.1
7.5	27.3	25.2	30.6	36.1	35.7	40.1	49.1	56.8
8.0	28.0	27.1	33.5	31.8	40.4	45.3	55.8	57.0
8.5	23.9	31.0	27.1	32.3	34.2	47.9	47.4	64.9
9.0	23.9	28.6	29.7	32.0	38.7	40.6	54.7	58.1
9.5	27.6	29.5	32.7	35.0	40.8	42.1	47.0	57.7
10.0	25.6	30.6	32.0	36.5	37.8	48.3	56.4	63.0

Data Trials of Distance vs. Lux Measurements (Part IV)							
	Distance (±0.0015m)						
Time (±0.1 s)	1.025	0.926	0.814	0.714	0.616	0.517	0.425
	Lux Measurements (±0.2 lux)						
0.5	67.3	79.5	106.4	138.6	181.1	253.1	389.0
1.0	73.3	93.3	117.7	153.4	186.7	277.0	335.6
1.5	70.3	89.5	105.7	140.8	168.5	231.3	394.1
2.0	66.2	84.1	102.7	146.7	198.8	247.1	349.7
2.5	74.6	88.2	111.3	135.6	169.6	274.7	328.3
3.0	78.2	79.2	119.6	150.2	195.9	266.1	359.0
3.5	65.6	93.8	99.5	146.5	171.5	258.5	332.1
4.0	78.0	87.2	109.2	139.7	200.3	232.4	389.2
4.5	65.1	79.2	119.0	144.0	176.2	247.8	333.6
5.0	79.0	93.3	99.7	129.7	184.6	272.3	389.8
5.5	69.6	90.6	116.8	150.8	199.5	240.9	335.5
6.0	73.7	80.3	101.2	140.1	183.5	237.3	389.6
6.5	69.6	84.6	119.2	140.3	167.4	266.3	369.3
7.0	68.3	92.9	100.4	152.7	200.1	271.9	358.0
7.5	76.9	81.0	111.9	147.8	190.1	232.0	363.1
8.0	67.7	82.9	106.6	130.9	187.7	257.4	358.8
8.5	74.5	93.1	112.6	149.5	181.1	255.0	378.9
9.0	66.4	84.1	114.1	153.8	166.6	251.4	392.2
9.5	69.2	81.0	103.6	135.9	182.4	234.7	345.6
10.0	78.4	90.1	108.1	129.6	199.3	266.1	366.9

Appendix IV: *Processing Raw Data*

The arithmetic average for the light intensity is found by

$$\bar{x} = \frac{x_1 + x_2 + x_3 + x_4 + x_5 + \cdots x_n}{n}$$

Using the 0.412 m data, we can see that

$$\bar{x} = \frac{422.1 + 390.4 + 448.1 + 446.2 + 408.8 + \cdots + 447.1}{20}$$

$$\bar{x} = 422.9\ lux$$

In order to find the error, the standard derivation will be used across the 20 trials, which is a sufficient number of trials to apply the standard deviation formula.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \mu)^2}{n}}$$

Using the 0.412 m data once again, we have

$$\sigma = \sqrt{\frac{(422.1 - 422.9)^2 + (390.4 - 422.9)^2 + \cdots + (447.1 - 422.9)^2}{20}}$$

$$\sigma = 21.44$$

Appendix V: *Processed Data Tables*

Processed Data of Distance vs. Lux		
Distance (±0.0015m)	Average Lux	Standard Deviation of Lux
0.412	422.9	21.4
0.425	362.9	22.4
0.517	267.4	15.7
0.517	253.7	14.9
0.613	190.9	11.7
0.616	184.5	11.6
0.709	144.2	8.9
0.714	142.8	7.7
0.810	111.1	7.4
0.814	109.3	6.8
0.920	87.6	5.3
0.926	86.4	5.3
1.023	72.2	4.8
1.025	71.6	4.7
1.127	60.9	4.0
1.131	59.8	3.5
1.228	51.2	3.6
1.229	52.5	3.8
1.332	45.5	3.0
1.337	44.4	2.7
1.471	38.0	2.4
1.472	38.2	2.3
1.574	33.6	2.6
1.583	33.7	2.1
1.674	30.5	2.1
1.676	30.2	1.9
1.775	28.5	2.0
1.776	27.9	1.9
1.861	26.0	1.9
1.876	25.4	1.7

Appendix VI: *Error Propagation and Linearization*

In order to linearize the data, which had an approximate power regression of x^{-2}, we plot $\frac{1}{x^2}$ versus the Lux. Therefore, the new x values are all converted. However, in order to propagate error, we use the following formula[13]:

$$(A \pm \Delta A)^n = A^n \pm n\Delta A\% \qquad \text{(VI.1)}$$

Therefore, for the distance of 0.412 data, we have:

$$X_{new} = \frac{1}{(X_{old})^2}$$

$$X_{new} = \frac{1}{.412^2}$$

$$X_{new} = \frac{5.819}{m^2}$$

$$\Delta A_{new} = n \cdot \Delta A\% \cdot X_{new}$$

$$\Delta A_{new} = 2 \cdot \frac{0.0015}{.412} \cdot 5.819$$

$$\Delta A_{new} = \frac{0.04219}{m^2}$$

[13] IB Physics Student Booklet

Appendix VII: *Linearized Data*

Linearized Data			
Linearized Distance (1/m^2)	Propagated Error (1/m^2)	Average Lux	Standard Deviation of Lux
5.891	0.0429	422.9	21.4
5.536	0.0391	362.9	22.4
3.741	0.0217	267.4	15.7
3.741	0.0217	253.7	14.9
2.661	0.0130	190.9	11.7
2.635	0.0128	184.5	11.6
1.989	0.0084	144.2	8.9
1.962	0.0082	142.8	7.7
1.524	0.0056	111.1	7.4
1.509	0.0056	109.3	6.8
1.181	0.0039	87.6	5.3
1.166	0.0038	86.4	5.3
0.956	0.0028	72.2	4.8
0.952	0.0028	71.6	4.7
0.787	0.0021	60.9	4.0
0.782	0.0021	59.8	3.5
0.663	0.0016	51.2	3.6
0.662	0.0016	52.5	3.8
0.564	0.0013	45.5	3.0
0.559	0.0013	44.4	2.7
0.462	0.0009	38.0	2.4
0.462	0.0009	38.2	2.3
0.404	0.0008	33.6	2.6
0.399	0.0008	33.7	2.1
0.357	0.0006	30.5	2.1
0.356	0.0006	30.2	1.9
0.317	0.0005	28.5	2.0
0.317	0.0005	27.9	1.9
0.289	0.0005	26.0	1.9
0.284	0.0005	25.4	1.7

Appendix VIII: *Raw Data for Light Pollution Experiment*

	Measured Lux				
Distance (±0.01m)	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
0.40	497	450	458	471	451
0.45	383	357	351	372	349
0.50	313	291	288	295	282
0.55	250	244	235	246	229
0.60	202	208	202	209	198
0.65	178.0	182.3	172.9	182.0	173.4
0.70	155.4	158.4	153.5	156.0	151.3
0.75	138.6	142.2	138.5	141.0	140.2
0.80	126.6	126.3	125.6	130.0	126.8
0.85	112.6	109.1	112.7	114.1	116.4
0.90	103.9	101.4	104.1	105.6	105.3
0.95	96.5	94.0	96.0	96.7	99.2
1.00	88.6	87.7	88.2	88.8	90.1
1.05	82.3	79.6	81.7	81.5	83.7
1.10	77.5	76.2	75.6	77.2	77.7
1.15	71.9	70.4	70.9	71.9	73.5
1.20	67.9	66.6	66.8	67.1	67.9
1.25	62.9	62.4	62.2	62.5	63.6
1.30	58.9	58.2	58.5	58.5	59.3
1.35	56.2	55.4	55.4	55.7	56.0
1.40	52.7	52.1	52.2	52.2	52.3
1.45	48.9	48.5	48.8	49.0	49.1
1.50	46.2	45.7	45.9	45.8	46.2
1.55	43.7	43.4	43.7	43.5	43.5
1.60	41.5	41.2	41.5	41.5	41.4
1.65	39.4	39.4	39.3	39.3	39.6
1.70	37.4	37.5	37.5	37.5	37.7
1.75	35.6	35.6	35.7	35.9	36.0
1.80	34.2	34.0	34.2	34.3	34.5
1.85	32.7	32.5	32.6	32.8	32.9
1.90	31.4	31.3	31.2	31.3	31.5
1.95	30.2	29.9	30.0	30.0	30.2

Appendix IX: *Processed/ Linearized Data for Light Pollution Experiment*

Processed Data for Light Pollution Experiment		
Distance (±0.01m)	Average Lux	Standard Deviation (Lux)
0.40	465.4	17.5
0.45	362.4	13.1
0.50	293.8	10.5
0.55	240.8	7.7
0.60	203.8	4.1
0.65	177.7	4.0
0.70	154.9	2.4
0.75	140.1	1.4
0.80	127.1	1.5
0.85	113.0	2.4
0.90	104.1	1.5
0.95	96.5	1.7
1.00	88.7	0.8
1.05	81.8	1.3
1.10	76.8	0.8
1.15	71.7	1.1
1.20	67.3	0.5
1.25	62.7	0.5
1.30	58.7	0.4
1.35	55.7	0.3
1.40	52.3	0.2
1.45	48.9	0.2
1.50	46.0	0.2
1.55	43.6	0.1
1.60	41.4	0.1
1.65	39.4	0.1
1.70	37.5	0.1
1.75	35.8	0.2
1.80	34.2	0.2
1.85	32.7	0.1
1.90	31.3	0.1
1.95	30.1	0.1

Linearized Data for Light Pollution Experiment			
Linearized Data	Linearized Uncert	Average Lux	Standard Deviation (Lux)
6.25	0.313	465.4	17.5
4.94	0.219	362.4	13.1
4.00	0.160	293.8	10.5
3.31	0.120	240.8	7.7
2.78	0.093	203.8	4.1
2.37	0.073	177.7	4.0
2.04	0.058	154.9	2.4
1.78	0.047	140.1	1.4
1.56	0.039	127.1	1.5
1.38	0.033	113.0	2.4
1.23	0.027	104.1	1.5
1.11	0.023	96.5	1.7
1.00	0.020	88.7	0.8
0.91	0.017	81.8	1.3
0.83	0.015	76.8	0.8
0.76	0.013	71.7	1.1
0.69	0.012	67.3	0.5
0.64	0.010	62.7	0.5
0.59	0.009	58.7	0.4
0.55	0.008	55.7	0.3
0.51	0.007	52.3	0.2
0.48	0.007	48.9	0.2
0.44	0.006	46.0	0.2
0.42	0.005	43.6	0.1
0.39	0.005	41.4	0.1
0.37	0.004	39.4	0.1
0.35	0.004	37.5	0.1
0.33	0.004	35.8	0.2
0.31	0.003	34.2	0.2
0.29	0.003	32.7	0.1
0.28	0.003	31.3	0.1
0.26	0.003	30.1	0.1

Appendix X: *Raw Data for Near Star .25m Experiment*

	Measured Lux				
Distance (±0.01m)	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
0.40	458	470	467	457	459
0.45	362	369	368	356	369
0.50	292	305	297	291	290
0.55	249	254	252	249	236
0.60	216	219	218	216	206
0.65	185.2	189.3	182.7	187.2	179.6
0.70	166.1	166.5	163.8	164.5	161.0
0.75	148.1	149.9	151.1	148.4	142.8
0.80	134.7	133.9	138.2	136.0	129.8
0.85	123.2	123.4	124.1	125.3	117.2
0.90	113.4	112.2	113.1	115.0	110.1
0.95	105.5	105.2	105.1	105.0	101.9
1.00	98.3	98.2	98.5	98.0	96.0
1.05	92.3	90.2	91.8	90.1	88.7
1.10	86.3	85.5	86.1	84.5	83.8
1.15	80.7	79.7	80.1	80.2	79.7
1.20	75.7	75.2	75.1	75.5	74.2
1.25	70.6	71.3	70.7	71.1	69.5
1.30	66.8	66.8	66.7	66.9	65.6
1.35	63.8	63.1	63.8	63.1	62.4
1.40	59.9	59.6	60.2	59.1	58.5
1.45	56.8	56.2	56.6	56.0	55.7
1.50	53.5	53.2	53.3	52.9	52.1
1.55	51.3	50.8	50.8	50.7	49.9
1.60	48.8	48.6	48.8	48.4	47.7
1.65	46.8	46.5	46.7	46.3	45.8
1.70	44.6	44.4	44.6	44.3	43.8
1.75	42.8	42.7	42.7	42.4	41.8
1.80	41.0	41.0	40.8	40.8	40.4
1.85	39.3	39.4	39.2	39.0	38.6
1.90	37.8	37.8	37.8	37.7	37.5
1.95	36.4	36.4	36.0	36.4	36.1

Appendix XI: *Processed and Linearized Data for Near Star .25m Experiment*

Processed Data for 25cm Near		
Distance (±0.01m)	Average Lux	Standard Deviation (Lux)
0.40	462	5.27
0.45	365	5.11
0.50	295	5.55
0.55	248	6.29
0.60	215	4.65
0.65	184.8	3.39
0.70	164.4	1.96
0.75	148.1	2.84
0.80	134.5	2.77
0.85	122.6	2.82
0.90	112.8	1.61
0.95	104.5	1.33
1.00	97.8	0.91
1.05	90.6	1.29
1.10	85.2	0.95
1.15	80.1	0.37
1.20	75.1	0.52
1.25	70.6	0.62
1.30	66.6	0.48
1.35	63.2	0.52
1.40	59.5	0.60
1.45	56.3	0.40
1.50	53.0	0.49
1.55	50.7	0.45
1.60	48.5	0.41
1.65	46.4	0.35
1.70	44.3	0.29
1.75	42.5	0.37
1.80	40.8	0.22
1.85	39.1	0.28
1.90	37.7	0.12
1.95	36.3	0.17

Linearized Data for 25cm Near Experiment			
Linearized Data	Linearized Uncert	Average Lux	Standard Deviation (Lux)
6.25	0.313	462	5.27
4.94	0.219	365	5.11
4.00	0.160	295	5.55
3.31	0.120	248	6.29
2.78	0.093	215	4.65
2.37	0.073	184.8	3.39
2.04	0.058	164.4	1.96
1.78	0.047	148.1	2.84
1.56	0.039	134.5	2.77
1.38	0.033	122.6	2.82
1.23	0.027	112.8	1.61
1.11	0.023	104.5	1.33
1.00	0.020	97.8	0.91
0.91	0.017	90.6	1.29
0.83	0.015	85.2	0.95
0.76	0.013	80.1	0.37
0.69	0.012	75.1	0.52
0.64	0.010	70.6	0.62
0.59	0.009	66.6	0.48
0.55	0.008	63.2	0.52
0.51	0.007	59.5	0.60
0.48	0.007	56.3	0.40
0.44	0.006	53.0	0.49
0.42	0.005	50.7	0.45
0.39	0.005	48.5	0.41
0.37	0.004	46.4	0.35
0.35	0.004	44.3	0.29
0.33	0.004	42.5	0.37
0.31	0.003	40.8	0.22
0.29	0.003	39.1	0.28
0.28	0.003	37.7	0.12
0.26	0.003	36.3	0.17

Appendix XII: *Raw Data for Near Star .50m Experiment*

	Measured Lux				
Distance (±0.01m)	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
0.40	452	465	472	456	465
0.45	360	360	369	353	362
0.50	289	282	302	293	282
0.55	243	235	248	242	240
0.60	202	203	203	205	204
0.65	172.0	176.0	170.8	172.5	171.1
0.70	154.7	156.0	151.6	155.3	145.8
0.75	138.4	142.0	136.1	136.7	134.4
0.80	120.6	124.3	121.4	124.6	122.1
0.85	114.3	103.6	111.9	113.5	111.8
0.90	105.6	105.0	101.4	105.6	103.5
0.95	98.4	97.1	93.9	98.4	96.5
1.00	91.2	89.6	87.8	90.3	90.7
1.05	84.7	84.5	82.5	85.1	84.4
1.10	80.2	77.9	77.3	80.3	78.5
1.15	74.8	74.2	73.6	74.9	74.3
1.20	71.2	69.7	69.6	70.6	70.6
1.25	67.1	65.8	65.7	67.3	66.1
1.30	63.0	62.3	62.0	63.2	63.1
1.35	60.7	59.8	59.8	60.3	60.1
1.40	56.8	56.3	56.1	56.7	56.8
1.45	54.1	53.4	53.1	54.0	53.3
1.50	51.2	50.5	50.7	51.0	50.2
1.55	48.8	48.0	48.1	48.7	48.0
1.60	46.7	46.3	46.1	46.3	46.1
1.65	44.6	44.5	44.1	44.5	44.2
1.70	42.6	42.6	42.3	42.4	42.4
1.75	40.9	40.7	40.4	40.7	40.4
1.80	39.2	39.3	39.1	39.4	38.9
1.85	37.9	37.8	37.6	37.6	37.5
1.90	36.4	36.3	36.6	36.2	36.1
1.95	35.1	35.1	34.9	35.0	34.9

Appendix XIII: *Processed and Linearized Data for Near Star .50m Experiment*

Processed Data for 25cm Back		
Distance (±0.01m)	Average Lux	Standard Deviation (Lux)
0.40	462.0	7.13
0.45	360.8	5.11
0.50	289.6	7.50
0.55	241.6	4.22
0.60	203.4	1.02
0.65	172.5	1.86
0.70	152.7	3.75
0.75	137.5	2.58
0.80	122.6	1.59
0.85	111.0	3.83
0.90	104.2	1.61
0.95	96.9	1.65
1.00	89.9	1.18
1.05	84.2	0.90
1.10	78.8	1.21
1.15	74.4	0.47
1.20	70.3	0.61
1.25	66.4	0.67
1.30	62.7	0.48
1.35	60.1	0.34
1.40	56.5	0.29
1.45	53.6	0.40
1.50	50.7	0.35
1.55	48.3	0.35
1.60	46.3	0.22
1.65	44.4	0.19
1.70	42.5	0.12
1.75	40.6	0.19
1.80	39.2	0.17
1.85	37.7	0.15
1.90	36.3	0.17
1.95	35.0	0.09

Linearized Data for 25cm Back Experiment			
Linearized Data	Linearized Uncert	Average Lux	Standard Deviation (Lux)
6.25	0.313	462.0	7.13
4.94	0.219	360.8	5.11
4.00	0.160	289.6	7.50
3.31	0.120	241.6	4.22
2.78	0.093	203.4	1.02
2.37	0.073	172.5	1.86
2.04	0.058	152.7	3.75
1.78	0.047	137.5	2.58
1.56	0.039	122.6	1.59
1.38	0.033	111.0	3.83
1.23	0.027	104.2	1.61
1.11	0.023	96.9	1.65
1.00	0.020	89.9	1.18
0.91	0.017	84.2	0.90
0.83	0.015	78.8	1.21
0.76	0.013	74.4	0.47
0.69	0.012	70.3	0.61
0.64	0.010	66.4	0.67
0.59	0.009	62.7	0.48
0.55	0.008	60.1	0.34
0.51	0.007	56.5	0.29
0.48	0.007	53.6	0.40
0.44	0.006	50.7	0.35
0.42	0.005	40.3	0.35
0.39	0.005	46.3	0.22
0.37	0.004	44.4	0.19
0.35	0.004	42.5	0.12
0.33	0.004	40.6	0.19
0.31	0.003	39.2	0.17
0.29	0.003	37.7	0.15
0.28	0.003	36.3	0.17
0.26	0.003	35.0	0.09

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