PHYSICS
MERCER UNIVERSITY

Physics Lab Report Guidelines

Summary

The following is an outline of the requirements for a physics lab report.

A. Experimental Description

1. Provide a statement of the physical theory or principle observed during the experiment. (page 3)

2. Briefly describe the experiment you performed. (page 3)

3. Discuss the relevance of the experiment to the theory. Consider answering the following question: This experiment was designed to prove theory ‘x’. Did it do so? (page 3)

B. Discussion of Graphs

1. For each graph, discuss the proximity of the data points to the line of best fit. (pages 4-6)

2. For each graph, state the theoretical values for slope and y-intercept. (pages 4-6)

3. For each graph, perform a percent difference calculation between the theoretical slope and y-intercept, and the measured values of slope and y-intercept. (page 6)

C. Uncertainty Analysis Discussion

1. Discuss the method used to determine the measured uncertainty value for each measured quantity. (page 7)

2. Consider each sub-experiment and determine the dominant source of uncertainty. (page 7)

3. Determine the percent difference, percent uncertainty and percent variation. (pages 6-8) Then,

   (a) Determine if each percent difference value is larger than or smaller than the dominant percent uncertainty for the experiment. (page 8)

(b) Draw conclusions based on your findings; for example determine the factors contributing to percent difference values greater than the percent uncertainty value. (page 8)

(c) Determine if the percent variation value corresponds to "constant" measured values, i.e. determine if each percent variation is smaller than the percent uncertainty in the experiment. (page 8)

(d) Determine experimental factors which could have contributed to variation of measurements, i.e. how would you account for measured values that are not "constant." (page 8)

4. What did you think of the experiment?

5. What would you do to improve the experiment?

Inquiry Based Lab Conclusions (page 9)

Section A: Experimental Description

Most experiments performed during the semester will require a typewritten lab report. The guidelines attempt to illustrate the essential topics necessary in lab reports. The lab instructor reserves the right to augment any portion of the guidelines in any way suitable to his/her intent. Therefore you, the lab student, should always refer to your lab instructor with any disputes concerning the guidelines.

This text often makes reference to a sample lab report titled **The Measurement of the Gravitation Acceleration "g"**. The sample lab report can be found on pages 10-13. Though the **Measurement of "g"** report provides an accurate description of 'how to' write a lab report, the successful lab student will benefit from learning the procedures necessary to completely satisfy all requirements of a lab report.

The experimental description section of your lab report provides a brief explanation of the purpose of the experiment. Each lab in the lab manual contains the following subsections: Objective, Equipment List, Theoretical Background, Procedure, Data Analysis, and Selected Questions. The Objective and Theoretical Background subsections are presented to give you some idea of the physics supporting the theory, while the experimental process or the means of testing the theory is provided in the Procedure subsection. Generally the experimental description provides, (1) a summary of the theoretical background, and (2) a summary of the method you followed to test the theory. For example, if you wished to perform an experiment to determine the free fall rate of a ball dropped from the roof of your dormitory, you would first need to know the theory of physics governing the motion of the ball, and you would want to propose a method for testing the theory. Additionally, the experimental description may include a list of the equipment used to perform the experiment. For example, if you performed the **Measurement of "g"** experiment you would state that you used a stopwatch to measure the drop time of a ball, a meter stick to measure the distance of the ball's fall and a mass scale to measure the mass of the ball.

Several lab experiments have multiple components. The separate components of a lab allow you to make broad conclusions about a theory. Often times this involves an examination of the relationship between variables of an equation. For example, the first component for the **Measurement of "g"** experiment may instruct you to position a ball at a fixed height while for each drop you vary the mass of the ball, whereas the second component instructs you to use only one ball while varying the height of the ball's fall. In general the components of a lab are printed in boldface in the procedure section of the lab. Labs containing multiple components must have conclusions for all parts of the experiment within the lab report, i.e. you will provide 5 experimental descriptions, 5 graphs/graphical conclusions (where applicable) and 5 uncertainty conclusions for an experiment that has 5 components.

Section B: Graphs/Graphical Analysis

General Graph Properties

In most experiments you will be required to construct a graph. It is the lab instructor's prerogative to allow you to use Excel or other software packages to construct your graphs. All graphs (manual and electronic) have the following properties:

1. **A good graph fills the whole page.** The data points should extend across as much of the page as possible. This implies that there should be only one graph per page.

2. A good graph has a **title** that describes what is being plotted.

3. A good graph has **axis labels** that describe what is being plotted on each axis.

4. A good graph has **tick marks both major and minor** to indicate the divisions of both the x and y axis.

5. A good graph has **axis units** describing the units represented by the tick marks. Acceptable axis units are those that clearly label each axis with correct units corresponding to the measured quantity plotted along the axis. For example, for the x-axis "$2d$ [cm]" denotes that the quantity $2d$ is measured in cm and each major tick mark represents a multiple of centimeters scaled according to the graph page.

6. A good graph has **evenly spaced tick marks**, unless otherwise indicated by the lab instructor.

7. A good graph must **clearly show the y-intercept** plotted on the graph, that is, graph the point $(x = 0,\ y = b)$, for b is the value of y when $x = 0$. **Consequently, the continuity of the x and y axes must not be broken.** Showing the y-intercept may be easier if the x and y axes are placed inside the graph-paper lines. See the graph examples on pages 12 and 13.

8. On a good graph, **the numerical values of the slope and y-intercept are clearly written.**

9. A good graph has **the points used to measure the slope clearly indicated.** These should be points on the line and not data points. The points used for the slope calculation should be marked differently from the data points. Choose points on the line as far apart as possible.

Two graph examples, one done manually and another using the computer program Excel, are included on pages 12 and 13.

Graphical Analysis

You are required to construct plots representing lines of best fit for your collection of data for every lab experiment. Your graphs will be linear functions for most experiments. There may be a few graph plots that make use of different mathematical functions, in which case your lab instructor will provide you with instructions for constructing the appropriate graph. Analysis by strict linear regression models and techniques are not necessary for physics lab reports. However, you should briefly discuss the 'closeness' of the plotted data points to the line of best fit. You can do this simply by "eye-balling" the graph.

You are required to determine the slope and y-intercept of the line drawn. The slope and y-intercept should be determined from the line of best fit. **Do not use the data points to calculate the slope and y-intercept of the line!** Instead, to determine the y-intercept of the line measure the point of interception between the line of best fit and the y-axis. The rise-over-run method is a practical method used to calculate the slope. In review, to calculate the slope choose two points on the line with the greatest separation. Draw a right triangle using as the hypotenuse the line of best fit. Determine the length of the line segment opposite theta, Θ (the rise) and the length of line segment adjacent to theta Θ (the run). The 'rise' divided by the 'run' determines the slope of the line.

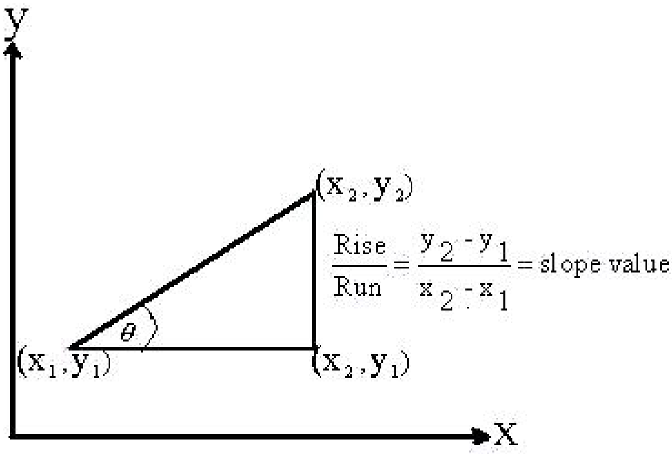


Figure 1: Determination of slope value using the rise-over-run method.

The rise-over-run calculations as demonstrated in Figure 1 must be performed for each graph presented with your lab report.

The graphical analysis provides a discussion of the slope and y-intercept values of your plotted graph(s). The calculated results you obtained from the rise-over-run method are recorded as the measured or actual values of slope and y-intercept. These values are compared to theoretical values; the theoretical values of slope and y-intercept are the accepted values for which your data is tested.

You can determine theoretical values of slope and y-intercept by using the slope-intercept form of the equation of a line. The method used to perform this calculation is provided in the example below. You will notice that this method only works for first order equations.

The theoretical background used for the **Measurement of "g"** experiment provides us with the kinematics equation $h = \frac{1}{2}gt^2$. After collecting data for the experiment we are instructed to plot the height of the ball's drop, h, as a function of the square of the drop time of the ball, t^2 (h values are plotted along the y-axis and t^2 values along the x-axis). The theoretical values of slope and y-intercept are

$$\begin{array}{ccccccc} h & = & \frac{1}{2}g & t^2 & + & 0 \\ \updownarrow & & \updownarrow & \updownarrow & & \updownarrow \\ y & = & m & x & + & b\,. \end{array}$$

Notice that by using the provided theoretical equation and the equation of the line, we are able to determine $\frac{1}{2}g$ and 0 as the theoretical slope and y-intercept values respectively of our graph.

The graphical analysis discussion will provide values for both the theoretical and actual slope and y-intercept measurements. A comparison between the sets of data can be performed by calculating the *percent difference* between the actual values and the theoretical values. The percent difference equation between slope values is

$$\%\ \textit{difference} = 100\% \times \frac{|\ \textit{theoretical slope value} - \textit{experimental slope value}\ |}{\textit{theoretical slope value}}\,.$$

Section C: Uncertainty Analysis

The uncertainty analysis discussion is probably the most crucial section of your lab report. In this section you will interpret your data and conclude whether or not the experiment supports the theory under observation. You will analyze data for experimental error and report your findings. Statements such as “This was a nice experiment and I liked it” or “All of my results are weird therefore I can’t prove anything” are unacceptable. You can include these remarks in your concluding statements, but they will never fulfill the requirements for the uncertainty analysis section.

Experimental error is a measurable quantity present in every lab experiment. You will determine the extent to which experimental error affected your results. **Human error is *not* a valid type of experimental error, thus the term “HUMAN ERROR” should *NEVER* be used in a lab report!!!** Instead the two acceptable types of experimental error explored in physics labs are **systematic** and **random** error. In general systematic errors are unaccountable factors influencing data sets of an experiment. Systematic errors cause all values of a data set to deviate from an expected value by a common factor. Random errors cause individual measurements to vary around an average value. Values of a data set that vary widely from one another where a constant value of the data is expected is indicative of random error. The amount of either type of error is a calculated result based on several factors influencing your measurements. Factors such as the precision of the equipment used and/or repeat performance of a particular measuring device play important roles when calculating experimental error. Three calculations are generally performed to determine the amount of error. They are percent difference, percent uncertainty and percent variation.

Percent Difference

The *percent difference* is a comparison between a theoretical estimate and an experimental result. In most experiments instructions require you to calculate a theoretical value given certain initial conditions. This usually involves a mathematical treatment of an accepted theory. The experimental result is obtained by performing an experiment and recording a measurement. You can compare the experimental and theoretical values using the equation below:

$$\%\ \textit{difference} = 100\% \times \frac{|\ \textit{theoretical value} - \textit{experimental value}\ |}{\textit{theoretical value}} \ .$$

Percent Uncertainty

The *percent uncertainty* is an attempt to estimate the precision of the equipment used during an experiment. Each measurement performed using a particular device is subject to measurement error. Measurement error is controlled by the precision of the device. Small amounts of measurement error result from using a precise device, whereas measurement error is excessively large if the device is not very precise for its intended purpose. For example, suppose a ruler is used to measure the length of an object. If 1 millimeter is the specified precision of the ruler it would be unreasonable to precisely measure an object smaller than a millimeter. Another way of stating the precision of an instrument is "Using a wooden ruler, I can make length measurements of any object to the nearest millimeter."

The uncertainty of a measurement is determined by dividing the smallest increment of the measuring device by 2. In the above example, the uncertainty of the ruler is half of a millimeter, or $\pm 0.5\ mm$. The value $\pm 0.5\ mm$ is known as the *experimental uncertainty* in the measurement.

It is useful to include the experimental uncertainty with your measured values. For example, if an object such as an ink pen has a length of 139 mm, or 13.9 cm using a ruler accurate to the nearest millimeter, then its length should be stated as $13.9\ cm \pm 0.05\ cm$. If L is used to represent the length of the pen, then the uncertainty in the length is written as ΔL, or

$$L \pm \Delta L = 13.9\ cm \pm 0.05\ cm \ .$$

The percent uncertainty makes use of the experimental uncertainty. The percent uncertainty is calculated by determining the ratio as a percentage between the experimental uncertainty of an instrument such as a ruler, and the measured value obtained using the instrument, that is

$$\%\ \textit{uncertainty} = 100\% \times \frac{\textit{experimental uncertainty}}{\textit{measured value}} \ .$$

For example, the percent uncertainty in the length of the ink pen mentioned above is

$$\%\ \textit{uncertainty in } L = 100\% \times \frac{0.05\ cm}{13.9\ cm} = 0.4\% \ .$$

In most lab experiments you will use more than one measuring device. You will need to determine the percent uncertainty of each device and determine the largest or dominant percent uncertainty of the set.

Percent Variation

Often it is necessary to determine the variation of a data set. A theory may not predict a well defined value. Instead a theory may describe observed physical properties. Physical properties are unvarying or constant given prescribed initial conditions. During an experiment for which you observe physical properties you would want to determine the amount of variance your data reflects. For example, lab instructions may require you to calculate the density of several cubes of platinum for which each cube varies by shape and size. After determining the density of each you would calculate an average density of the data set. Further you would determine the extent for which your data varies from the average. *Percent variation* is calculated using the following formula:

$$\%\ variation = 100\% \times \frac{largest\ value - smallest\ value}{2.0 \times \ average\ value}\ .$$

Physical properties of a material are classified as either intrinsic or extrinsic. The details of these properties are explored in an electricity and magnetism experiment.

Uncertainty Analysis

Your lab reports will contain the values of percent difference, uncertainty and variation. Additionally you will make conclusions from your data by reviewing the percentage values. You will do the following: compare the percent difference to the percent uncertainty, and compare the percent variation to the percent uncertainty.

Percent Difference vs. Percent Uncertainty

A comparison of the percent difference and percent uncertainty determines if any difference between experimental and theoretical values is caused by the limitations of the equipment used to make measurements. If the largest percent uncertainty of the experiment is larger than the absolute value of the percent difference, then the difference between the theoretical and experimental values is attributed to the uncertainty in the measurements. If the magnitude of the percent difference is larger than the largest percent uncertainty, then the difference between the theoretical and experimental values should be evaluated.

Suppose after reviewing your data you find that each percent difference value is less than the largest percent uncertainty value. This is indicative of measurement error. Here you would conclude that the error is caused by the limitations of the equipment used to make measurements. The error is **systematic**; for each percent difference, the percent uncertainty is greater.

Suppose a theory predicts that 2 is always the calculated result of an experiment. You perform an experiment and conclude that 1.5 is the calculated result. This gives a percent difference of 10%. You conclude further that the percent difference is greater than the percent uncertainty. You would then make a claim that **external factors** such as friction, air resistance, thermal energy loss, etc. account for this discrepancy. An external factor is a physical quantity unaccounted for by the presented theory. Naturally you would conclude that not enough information is given by the theory. The prediction of 2 does not satisfy all experimental conditions.

Percent Variation vs. Percent Uncertainty

Comparing the percent variation to the largest percent uncertainty determines if any variation between measured values is caused by the limitations of the equipment used to make measurements. If the percent variation is smaller than the largest percent uncertainty in the experiment, then the variation of the experimental values can be attributed to measurement error. If the percent variation is larger than the percent uncertainty, then the variation should be evaluated.

Suppose after reviewing your data you find that each percent variation value is less than the largest percent uncertainty value. Again this is indicative of measurement error. The error is caused by the limitations of the equipment used to make measurements. The error is **systematic**; for each percent variation, the percent uncertainty is greater.

Consider a practice experiment where the average of 10 measurements is 2. Among your 10 measurements you determine that the largest value is 2.3 and the smallest value is 1.8 giving 12.5% as the percent variation. You conclude further that the percent variation is greater than the percent uncertainty. You would then make a claim that **random errors** such as inconsistent measuring techniques account for this discrepancy. You should review the manner in which measurements were made during the experiment. Perhaps the table was bumped during a measurement, or you looked away from the stopwatch for 4 seconds before pressing stop but for the next record you pressed stop when instructed to, etc.

Final Remarks

You should know that the uncertainty or error analysis methods discussed here are not necessarily the methods used by professional scientists. The methods used by scientists are more mathematically intense and often require hundreds of measurements. The lab report guidelines provide a simple method of accounting for measurement uncertainty.

Inquiry-Based Lab Conclusions

Some of the experiments performed in this course are primarily qualitative (i.e. conceptual) rather than quantitative (i.e. containing several calculations). In these experiments, you will be asked to make predictions about the behavior of a system based on your physical understanding of the system. You will also discuss the reasoning behind your prediction. After discussing your prediction, and the reasoning behind your prediction, you will perform an experiment to test your prediction and record the results of this experiment. If the prediction does not agree with the experimental result, you will discuss any modification to the reasoning that led to the erroneous prediction. This cycle will then be repeated with a new set of circumstances which are similar, though not exactly the same. In this manner, a conceptual understanding of the physical system will be developed.

Most of the discussion written above about lab reports will not apply to these conceptual, or inquiry-based, experiments. For these experiments, the conclusions should instead discuss the cycle described above. In particular, a paragraph should be written *for each experiment*. Each paragraph should contain the following information:

1. Prediction
   What was the prediction that was made about the system?

2. Reasoning
   What was the reasoning behind the prediction (i.e. why did you make the prediction that you made)?

3. Experimental Result
   What was the result of the experiment?

4. Analysis

   (a) If the experiment agreed with you prediction, write a brief statement indicating this agreement.

   (b) If the experiment did not agree with the prediction, discuss what was wrong with the reasoning that led to the prediction that you made.

Measurement of Gravitational Acceleration "g" Conclusion

In this experiment we set out to measure g, the acceleration due to gravity, and to demonstrate that this is a constant independent of the mass of the dropped object, and the height from which it is dropped. To determine this, we dropped four balls of different masses and diameters from various preset heights h, and measured the drop times t. Each ball was dropped five times from a given height h, for five different values of h. The times for each height were then averaged. For each height, g was calculated using the average time t_{ave} and the formula $g = \frac{2h}{{t_{ave}}^2}$. The values of g for each height were averaged to produce an overall average value of g for each mass. The percent variation in g for each mass was also calculated. The values of g for all the masses were averaged to produce an experimental value for g. An overall percent variation of g for all the masses was also calculated from the largest and smallest values of g for the entire collection of masses.

The mass m, height h, and drop time t were the measured quantities. Their uncertainties were determined to be $\Delta m = \pm 5. \times 10^{-5}\ kg$, $\Delta h = \pm 1. \times 10^{-3}\ m$, and $\Delta t = \pm 5. \times 10^{-4}\ s$. The uncertainties in the time and in the mass were determined by taking half of the smallest increment on the digital scale and on the timer. Setting the height was difficult, and this led to a larger uncertainty in the height. Overall, the largest percent uncertainty in the experiment was 0.5% and was due to the uncertainty in the height measurements.

The experimental value of g was found to be 9.78 m/s^2, which is 0.2% below the theoretical value of 9.80 m/s^2. Since the percent error in g is below the percent uncertainty in the experiment, the difference between the theoretical and experimental values can be attributed to measurement uncertainty. Therefore, our experiment supports the theoretical result that the acceleration due to gravity is 9.80 m/s^2.

The percent variation in g for the tiny brass sphere, 0.42%, is less than the percent uncertainty in the experiment. From this, we can conclude that the variation in g for the tiny brass sphere is due to measurement uncertainty, and that g for this sphere is a constant.

For the other spheres, the percent variation in g for each sphere is larger than the percent uncertainty in the experiment. Therefore, the variation in g for these spheres cannot be attributed to measurement uncertainty. One possible explanation for this variation could be that these larger spheres were jammed in the release mechanism of the timer, and were not released smoothly. Variation in how smoothly the larger spheres were released may have led to variation in the measured time, producing more variation in the calculated values of g.

The variation in g for all of the masses is 2.53%. Since this is above the percent uncertainty in the experiment, this experiment does not support the theoretical result that the acceleration due to gravity is independent of mass. This variation may be due to the difficulty with the release mechanism mentioned above.

A graph was made of h for the large aluminum sphere as a function of ${t_{ave}}^2$, the square of the average drop time. A line was drawn through the data points, and the data points are fairly close to the line drawn. Theoretically, the y-intercept should be zero. The line has a y-intercept above, but close to the origin of the graph, in agreement with the theory. The slope of the line is 4.64 m/s^2. Theoretically, the line should have a slope equal to $\frac{1}{2}g$, or 4.90 m/s^2. The percent error between these two values is 5.3%, which is above the percent uncertainty in the experiment. Therefore the difference between these two values cannot be attributed to measurement uncertainty. One possible explanation for this difference is the jamming problem mentioned above. Another possible explanation is that air resistance, which is ignored in the theory, slowed the ball down as it fell. This caused the drop time to increase, resulting in a smaller value of g. This is consistent with our data since the value of g from the graph is smaller than the theoretical value of g.

Measurement of Gravitational Acceleration "g"

small steel sphere **m[kg]=** 0.0277 **d[m]=** 0.01900

h[m]	t1[s]	t2	t3	t4	t5	avg(t)	g
0.2	0.202	0.202	0.203	0.203	0.203	0.2026	9.745
0.4	0.285	0.286	0.286	0.286	0.286	0.2858	9.794
0.6	0.35	0.35	0.349	0.351	0.35	0.3500	9.796
0.8	0.403	0.403	0.401	0.403	0.403	0.4026	9.871
1	0.451	0.452	0.451	0.452	0.452	0.4516	9.807
						average =	**9.803**
						% var =	**0.644**

large alum sphere **m[kg]=** 0.0225 **d[m]=** 0.02525

h[m]	t1[s]	t2	t3	t4	t5	avg(t)	g
0.2	0.203	0.203	0.205	0.204	0.203	0.2036	9.649
0.4	0.287	0.287	0.288	0.294	0.272	0.2856	9.808
0.6	0.372	0.34	0.339	0.34	0.34	0.3462	10.012
0.8	0.404	0.404	0.404	0.387	0.407	0.4012	9.940
1	0.478	0.455	0.455	0.452	0.452	0.4584	9.518
						average =	**9.786**
						% var =	**2.525**

small brass sphere **m[kg]=** 0.0176 **d[m]=** 0.01580

h[m]	t1[s]	t2	t3	t4	t5	avg(t)	g
0.2	0.203	0.203	0.203	0.202	0.203	0.2028	9.726
0.4	0.286	0.285	0.285	0.285	0.286	0.2854	9.822
0.6	0.351	0.35	0.35	0.361	0.351	0.3526	9.652
0.8	0.404	0.404	0.404	0.403	0.402	0.4034	9.832
1	0.452	0.453	0.454	0.452	0.452	0.4526	9.763
						average =	**9.759**
						% var =	**0.923**

tiny brass sphere **m[kg]=** 0.0091 **d[m]=** 0.01260

h[m]	t1[s]	t2	t3	t4	t5	avg(t)	g
0.2	0.203	0.203	0.202	0.203	0.203	0.2028	9.726
0.4	0.285	0.286	0.285	0.285	0.287	0.2856	9.808
0.6	0.349	0.351	0.35	0.349	0.35	0.3498	9.807
0.8	0.404	0.405	0.406	0.405	0.406	0.4052	9.745
1	0.454	0.452	0.452	0.452	0.451	0.4522	9.781
						average =	**9.773**
						% var =	**0.420**

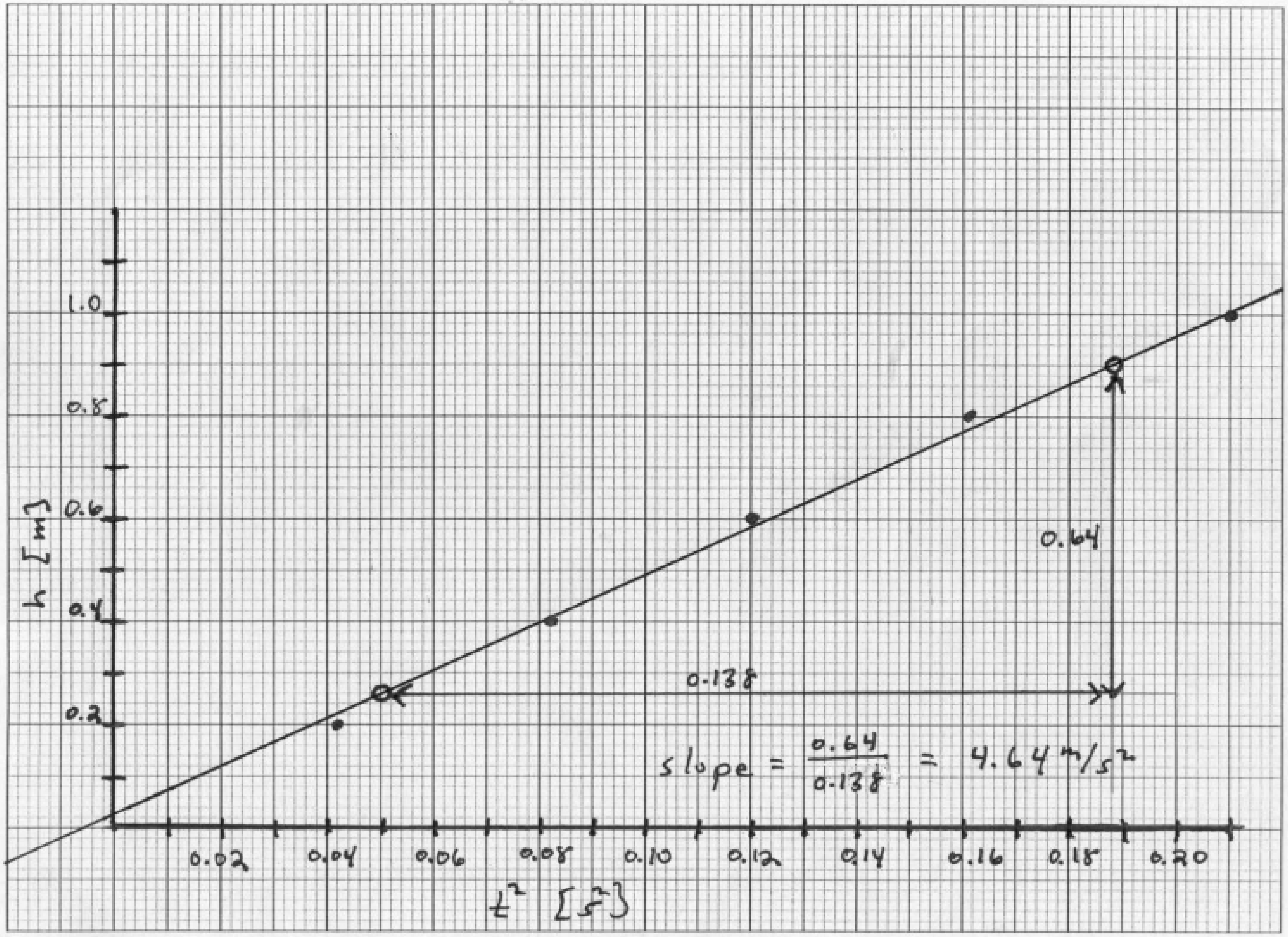
measurement uncertainties

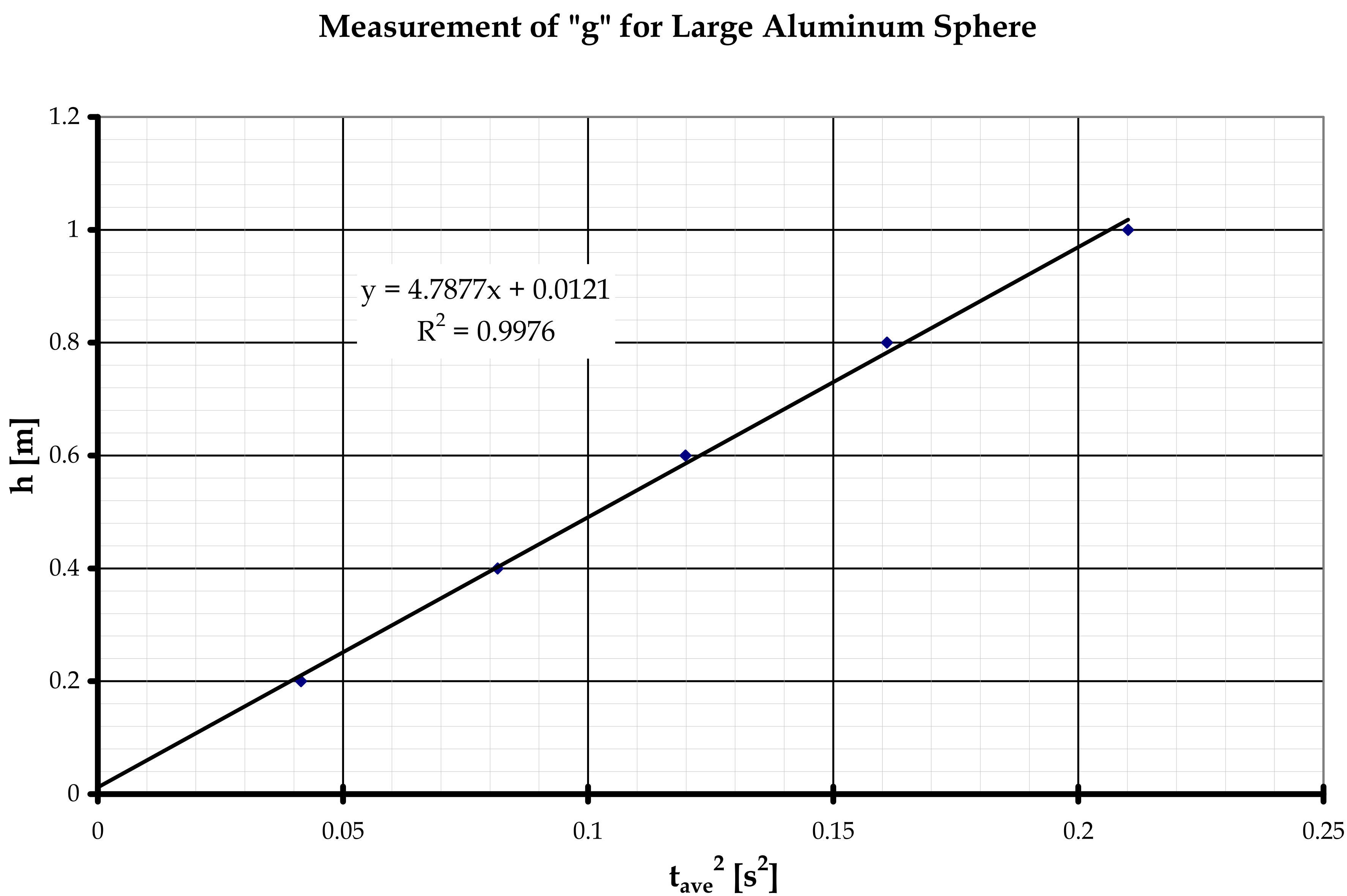
	error	min value	% error	
mass [kg]	5.E-05	0.01260	0.397	
height [m]	1.E-03	0.2	**0.500**	**= max % error**
time [s]	5.E-04	0.202	0.248	

Global average	
avg =	**9.780**
var =	**0.247**
% var =	**2.53**

accepted value =	**9.8**
% error =	**-0.20**

Height as a function of drop time
for aluminum sphere





Measurement of "g" for Large Aluminum Sphere
y = 4.7877x + 0.0121
R^2 = 0.9976
h [m]
t_{ave}^2 [s^2]
0
0.2
0.4
0.6
0.8
1
1.2
0
0.05
0.1
0.15
0.2
0.25