1 Introduction
This experiment serves multiple purposes:

- By measuring position, velocity and acceleration of an object you move, it is designed to provide some intuitive feel of the meaning of these kinematic quantities.
- It serves to demonstrate that one way of doing a rough check of your measurement device is to measure something of which you have a rough idea of the true value. Also, measuring something that is precisely known provides a calibration of the device.
- This laboratory will give you some practice in propagation of errors and statistical analysis of random uncertainties.
- Numerical differentiation will be performed.
- Your analysis will involve plotting with Python.
- This lab will introduce you to the DataStudio software system and PASCO hardware that will be used in a number of experiments conducted this semester.

2 Theory
Velocity \( v \) is defined as \( v = \frac{dx}{dt} \) and acceleration \( a \) as \( a = \frac{dv}{dt} = \frac{d^2x}{dt^2} \). Integrating the last definition twice for a situation where \( a \) is constant gives

\[
\begin{align*}
  v &= v_0 + at \\
  x &= x_0 + v_0 t + \frac{1}{2} at^2,
\end{align*}
\]

where the constants \( x_0 \) and \( v_0 \) are the position and velocity when \( t = 0 \). When these are plotted, time is usually chosen as the horizontal axis, with position and velocity as the vertical axes. The first equation is then a straight line and the second a parabola.

3 Equipment Used

**Equipment List:** An air track, 2 gliders, 2 wooden blocks, a meter stick, a motion sensor, and hardware for mounting the motion sensor on the lab bench.
Air Tracks & Gliders: In this experiment you will be using an air track, a long straight metal beam of triangular cross section with many small holes in it. A blower pumps air through the holes so that a glider placed on top of the air track floats on a cushion of air with little friction. The blower sits on the floor and has a switch on the top. The blowers are noisy and run hot. Run them only when you need them!

Please handle the gliders carefully. They are expensive, and if dropped or abused, may be damaged. Do not move the gliders on the air track without the blower on, as this damages both the glider and air track. A motion sensor, which works by detecting reflected sonic (sound) pulses from an index card attached to the glider, can be used to detect the glider’s position. Fix the index card on top of the glider and orient it perpendicular to the track to reflect the sonic pulses.

The Motion Sensor: The motion sensor works by measuring the time from when a sound pulse leaves the sensor to when it is reflected back to the sensor. Like all waves, sound can be reflected (producing an echo). In this experiment, the motion sensor emits a short sound pulse, say at time $t_1$, that travels out in a cone at a speed $v_s$ towards the glider. The pulse is reflected by the index card on the glider and returns to the motion detector where its arrival time $t_{1a}$ is detected. The time of flight $\Delta t_1 = t_{1a} - t_1$ is related to the distance between the position detector and the position of the index card on the glider by the relation

$$x_1 = \frac{1}{2} v_s \Delta t_1 \tag{3}$$

Obtaining the correct distance $x_1$ thus depends on knowing the speed of sound in air. Sound is a pressure wave whose speed depends on the properties of the gas in which it propagates. For a given gas the speed of sound is proportional to $\sqrt{T}$, where $T$ is the absolute temperature. For air at 20°C (= 293 K) the speed is 344 m/s.

In order to measure the position of the glider as a function of time, the motion sensor emits a train of equally-spaced sound pulses at regular intervals, that is, at times $t_1, t_2, t_3, \ldots$. The number of pulses emitted per unit time is called the sample rate, and can be varied from 1 to 250 Hz. The default sample rate is 10 Hz, which means that 10 pulses per second are emitted. The pulses are ultrasonic (pressure variations that are too fast to be heard) but you can hear a click when each pulse is emitted. The motion sensor detects the reflected pulses at times $t_{1a}, t_{2a}, t_{3a}, \ldots$ and measures the time of flight $\Delta t_i = t_{ia} - t_i$ between the emission and reflection of a given pulse. The DataStudio digital display can be programmed to show the time of flight of the pulses. It can also show the distance $x_i = v_s \Delta t_i/2$ of the glider from the motion sensor, as well as the glider’s velocity and acceleration. Note, however, that only the time-of-flight $\Delta t_i$ is measured; the other quantities are calculated by the DataStudio software. You will use these derived quantities in the lab, to get a sense of what is going on. However, you will not rely solely on these derived quantities when you analyze the data for your report. In the last part of the experiment, you will determine the velocities and accelerations for yourself from the position vs time data that are directly measured.
The motion sensor has two plugs. The yellow plug is used to deliver electrical pulses to the sensor that in turn generates the sound pulses; it is inserted into Channel 1 of the DataStudio interface. The black plug is used to send back from the sensor the signal generated by the echo; it is inserted into channel 2 of the interface. The maximum distance that can be measured depends on the sample rate. Some of the motion sensors have a switch that allows you to choose between a pulse emitted in a narrow or somewhat broader cone. Choose the switch position that gives the best results.

**Software:** Use of the software will be practiced in step-by-step instructions below.

4 Overview of the lab procedures

In Part 1 of this lab you set up DataStudio for the motion sensor and digital display. You will use the motion sensor to examine the movement of a notebook that you move manually; you will also learn how to use the DataStudio software. As this is the first lab using DataStudio, the instructions will be more detailed than they will be in future labs. The instructions will also become less detailed further on in this write up. Please remember that the procedures used with respect to the motion sensor window, digits display set up window, and input menu, apply, with very little variation, to other sensors and window displays to be used in other experiments in this course.

In Part 2 of this lab, you will be presented with a curve of position vs time and a curve of speed vs time on the computer screen. It will be your task to match these curves by moving a notebook in front of the motion sensor. The motion sensor will record the position or the speed of the notebook as you move it, and the data will also be presented on the computer screen. IMPORTANT: Before doing the experiments, look at the curves and figure out what motion you must impart to the notebook so that your data most closely matches the curves!

In Part 3 you will study the relationships between position $x$, velocity $v$, acceleration $a$, and time $t$. In general, $x$, $v$, and $a$ are vectors but here, where we consider motion in only one dimension, they can be treated as scalars. For the setup of this part (a glider accelerating due to gravity) we make an assumption that holds fairly well, that $a$ is a constant. This assumption is particular to this experiment; in general, $a$ may be a function of position and/or velocity and/or time.

5 Part 1: Using DataStudio

5.1 Initial Set Up

You will be using the motion sensor to measure the position of objects on the air track. Using the equipment provided, connect the motion sensor to the table and affix index cards to the gliders such that the motion sensors signals will be reflected back to the sensor by the gliders.

5.2 Programming

Launch the DataStudio software by double clicking on the DataStudio icon on the desktop of your lab computer. Once the DataStudio window is open it should display a diagram of the 750 Interface in the box titled Experiment Setup. If not, click Create Experiment, then click
Setup and select the 750 interface. Plug the Motion Sensor into the 750 Interface channel 1 (gold) + 2 (black). Next, program DataStudio for the motion sensor: click on digital channel 1 on the 750 interface diagram and an Add Sensor window will pop up. Scroll and select Motion Sensor.

The motion sensor is calibrated by measuring a known distance and telling it what the right answer is. Click the Motion Sensor tab in the Experiment Setup window to access the calibration window. You see “Standard Distance”, which is the known distance at which you can place an object (use a notebook) and “Present Sensor Distance” which is what the sensor reads. The default standard distance is 1 m. You may vary this if you wish - should you? When you are ready to calibrate, press the Set Sensor Distance = Standard Distance button. This sets the calibration factor so that the sensor reads the standard distance when an object is in the same position as the one the sensor currently detects.

In the experiment setup window the default sample rate of 10 Hz is shown. Change the sample rate to 100 Hz and observe the message dialog window that pops up. Next increase the sample rate to 200 Hz and again observe what the maximum distance the motion sensor can measure. Can you think of why the maximum distance depends on the sample rate? Set the sample rate to 20 Hz and click OK.

Note that a motion sensor icon is now below channels 1 and 2. Open a digits display by dragging the Digits display icon in the Display window onto the motion sensor icon. A box opens showing position and m (for meters). No numbers will be displayed in this box until you press start (later in these instructions). Click on top of the digits display window to try the following.

- Move the digits display window by dragging the title bar.
- See if you can enlarge the digits display window by dragging an edge or a corner. You should be able to enlarge the display and this will be useful.
- In order to add different digits displays to the same window, click and drag “Digits 1” in the Display window to the other measurements in the Data window. First try adding a Velocity Digits display by dragging it to where it says Velocity, Ch 1&2. Repeat for other items in the Data Menu and when you’re done, close all displays except Position by right clicking on the display and selecting Remove Selected Data.
- To add time to the Data window, click “Motion Time” to on in the “Measurements” tab of the Experiment Setup window.
- Click the 3.14 button in the digits display and select statistics. In the toolbar of the digits display, click the arrow next to the \( \sum \). Without changing anything, note that the display can be programmed to give the current, maximum, or minimum value of the position.

### 5.3 Measuring Position

First, you need to verify that the motion sensor is measuring position properly. Place a meter stick on your lab bench so that the end marked “0” is even with the motion sensor grill where sound pulses are emitted and detected. Next, take a notebook in one hand, and hold it near
the 50-cm mark on the meter stick so that it is oriented perpendicular to the meter stick and motion sensor. Have your partner click the START button in the left experiment set-up window and examine the digits display and position of the notebook on the meter stick while you move the notebook in the acoustic beam of the sensor. You should see that the number displayed on the digital display corresponds approximately to the position on the meter stick where you are holding the notebook or card. Click the STOP button when finished. Run # 1 appears in the data box. The digits display shows the last value measured.

Is the number of digits to the right of the decimal point sufficient? If not, increase the number to a reasonable value (Drag the right side of the window enough to the right so that all digits are displayed and then click the arrow of the 3.14 button in the box and select Increase Precision until the number of digits is at the desired precision). Take another run and see how close you can get the notebook to the sensor and get reliable values.

Try deleting Run # 1 by clicking on it anywhere in the Data box and then pressing the delete key. Don’t let too many runs accumulate.

5.4 Checking the DataStudio

It is a good idea to see if equipment you are using is doing what it is supposed to do. For example, if I had just constructed (or am considering buying) a fancy new length-measuring device, I might as well measure a meter stick length to see if I get reasonable results. Here we will check the DataStudio. What the motion sensor actually measures is the round trip pulse time. DataStudio then calculates the distance. Is it doing this calculation correctly?

Set up a stationary stable reflector about 0.6 m in front of the motion sensor. Open two digits displays, one giving position and the other the motion timer. Press Start (Stop) near the top of the DataStudio main window to start (stop) measurements. Measure the position and the motion timer to 3 significant figures. Use the speed of sound and the motion timer to calculate the position. Keep in mind the motion timer gives the round trip pulse time! Compare your calculated value to the DataStudio calculated value as given in one of the digits displays. How do these values compare to what you get with a meter stick?

Repeat this procedure for a reflector 0.7 m from the sensor.

5.5 Measuring Velocity

Change the input of the digits display to velocity and take another run, seeing what happens as you move your notebook in various ways. What does a minus sign mean in the display? What does no sign mean?

5.6 Measuring Max and Min velocity

Carry out an experiment to see how fast you can move your notebook toward and away from the sensor. Hint: open the digits display set up window and examine it. Do you think the default sample rate of 10 Hz is appropriate for this experiment? You can change it if you want. To do so, delete all data and double click on the motion sensor icon in the right experiment set up window. Remember that if you increase the sample rate the maximum distance that the motion sensor will detect is reduced.
5.7 Questions and Analysis for Part 1

This section lists questions and analyses regarding Part 1 that should be addressed in your laboratory report. Some of these are also discussed in context above, but are repeated here to collect in one place all those questions that are required to be answered in your report.

1. In the first part of this procedure you performed a calibration of the motion sensor. The calibration sets the conversion factor from time to distance, which is just the speed of sound. Why might the speed of sound vary from day to day or lab bench to lab bench?

2. Why is 1 m a good calibration distance? Would shorter or longer be better?

3. The maximum measurable distance depends on sample rate. Assuming that the system cannot deal with a second pulse emitted before the first reflected one is detected, estimate the maximum sample rate for a 1m distance.

4. Determine the uncertainty in your calibration.

5. How did you select the number of digits to display?

6. You checked the DataStudio measurement by comparing distances of 0.6 and 0.7 meters with the value calculated by DataStudio.

   (a) List the sources of error in your measurement of 0.6 and 0.7 m and estimate the uncertainty in these measurements.

   (b) List the sources of error in the DataStudio measurement of 0.6 and 0.7 m and estimate the uncertainty in these measurements.

   (c) Are the two measurements consistent within these errors?

7. Calculate the speed of sound using your distance measurements and the DataStudio times. Is the result reasonable?

6 Part 2: Two Library Experiments

DataStudio has a library of experiments. Two of these are included in this lab. These experiments are PO1 (short for PO1_MOT1.SWS) and PO2 (short for PO2_MOT2.SWS).

6.1 Library Experiment P01

6.1.1 Procedures for Experiment P01

Click File, Open Activity, a window will pop up stating “Should DataStudio save this activity?” ALWAYS CLICK NO. A window titled Document appears. Navigate the directory and select PO1_MOT1.SWS.

The 3 windows on the screen are the left experiment set up window, the “Position versus Time - Match” graph display window, and the workbook notes window. Read the experiment notes window if you wish, but the procedures outlined below are somewhat different. Close the workbook notes window to get it out of the way.
Click on the graph window and enlarge it by dragging the lower right hand corner to the lower right hand corner of the screen. Clicking on the Position (vertical) or Time (horizontal) axes brings up a menu that allows you to adjust the plotting limits. You may wish to take advantage of this feature to adjust the plot so that it covers more of the available space.

Determine the slope of the graph line as follows. Click the smart tool button near the top of the Position versus Time Match Graph Window. A smart cursor will open on the graph. Left click and drag the smart cursor and observe that the coordinates of the cursor appears with the crosshairs. Determine the coordinates of the two break points in the graph and calculate the slope. Click the smart button tool to remove the smart cursor.

**Taking data** Now you will try to replicate the graph by moving a notebook in front of the sensor. This will be easier if you first examine the graph and answer the following questions.

- How close should your notebook be to the motion sensor at the beginning?
- How far away should you move it?
- How long should your motion last?

Examine the graph before you take data and predict what your motion should be. Press the START button to begin recording data, and press the stop button to end the recording. The motion sensor will make a soft clicking noise when it is on. Was your prediction a good one? Do more trials and try to improve your accuracy. To print out a copy of a graph for your report, put your bench number or name in the legend title. To label your graph, right click on the graph and select Settings. Click upon the Legend tab and type in the Legend Title either your bench number, or name, or some other unique form of identification. Make sure you check Show Legend Title and click OK. To print, click File, Print, and OK.

**6.1.2 Questions to Answer and Analysis to be Submitted for Experiment P01**

**Analysis**

- Use the cursor to click-and-draw a rectangle around the middle section of your plot. Right click on the graph and select slope. Click the Statistics button and then click the Scale to fit button to resize the graph to fit the data.

- Click the Fit Menu button on the top bar of the Graph. Select Linear Fit. The slope of this part of the position vs time plot is the velocity during the selected region of motion.

**Questions**

1. In the graph, what is the slope of the line of best fit for the middle section of your plot?

2. What is the description of your motion? (Example: Starting at a position of 0.1 m, constant speed of 0.5 m/s for 2 seconds followed by no motion for 3 seconds, etc.)
6.2 Library Experiment P02

6.2.1 Procedures for Experiment P02

Open experiment mot2.ps in the same way that you opened mot1.ps. Again, click NO when asked “Should DataStudio save this activity?” DataStudio will not allow you to recreate the data set seen in PO2 similar to your experiment in PO1. Instead, print out the PO2 graph, cross out the label “Position” on the vertical axis (y-axis) and replace with “Velocity”.

6.2.2 Analysis and Questions for Experiment P02

1. In what direction should your notebook initially move and how far should it move in that direction before changing directions?

2. How far should your notebook move in the opposite direction before changing directions again?

3. At what time (or times) should your notebook be farthest from its starting point? How far should it have moved at that time (or times)?

4. How far should your notebook have moved from its initial position at the end of the run (10 seconds)?

5. With respect to the motion of the notebook, does it matter how far you are from the motion sensor when you take the data, assuming that you are always within the operating range of the sensor? Discuss.

7 Part 3: Motion of a Glider on an Inclined Air Track

7.1 Position, Velocity, Constant Acceleration

In this part, the motion sensor is used to measure the position of a glider on a tilted air track as a function of time. If there were no friction, Newton’s 2nd law predicts that the acceleration of the glider would be \( g \sin \theta \), where \( g \) is the acceleration of gravity and \( \theta \) is the angle between the air track and the horizontal. Note that the acceleration does not depend on the glider mass. DataStudio calculates the velocity and acceleration from the position vs time data.

Level the air track by turning on the blower, putting a glider on the track, and adjusting the single screw at one end of the air track so that the glider does not move. Measure the distance between the single supporting screw at one end of the air track and the line formed by the two supporting screws at the other end of the air track. Measure the thickness of the two blocks of wood with a meter stick and then raise the end of the air track that is closer to the sensor (the closer end must be raised because the power law fit used below assumes that distance gets bigger with time). Calculate \( \sin \theta \) and \( \theta \). On a scale, measure the masses of your 2 gliders.

Program DataStudio for the motion sensor. You may use the default sample rate. Program DataStudio for the graph display, choosing position, velocity, and acceleration. To program the graph display, left click on the “Graph” icon in the displays window and drag it to position in the Data Window. A subsection of “Graph 1” will appear in the display.
window. Now drag the “Graph 1” icon to velocity and do the same for acceleration. Place
the motion sensor near the spring bumper at the high end of the air track so that the grill
looks down the track. The motion sensor does not work for less than 0.4 m, so place an
object under the air track 0.4 m from the sensor and start your gliders from that point. Turn
on the blower, place the smaller glider on the track, and release the glider and click Start
at the same time. Click Stop just before the glider hits the end of the air track. Make a
number of runs, making small adjustments in the orientation of the sensor until you get the
best data you can. You will probably find that if the sensor points slightly up the data will
be best.

7.1.1 First Set of Questions and Analyses to be Submitted for Part 3

1. For your best run, click the scale to fit button (located on the top left of the graph
window) and examine the three graphs in the display and discuss them. Are they what
you expect and what is predicted by the theory? By inspection, are the graphs related,
and if so, how?

2. Is it reasonable that the velocity curve is noisier than the position curve, and the
acceleration curve noisier than the velocity curve? Explain.

3. Click the statistics button and then the scale to fit button. For the position plot
choose fit and then power fit. For the velocity plot choose fit and then linear fit. In
the statistics window, $y$ refers to the vertical axis and $x$ to the horizontal axis. If your
data points are noisy near the ends, draw boxes to exclude the noisy data but include
as much good data as possible. Draw the boxes so that they all begin and end at the
same times. Your boxes should be lined up vertically.

4. For the velocity plot the acceleration is given by the slope $m$. Why?

5. In the acceleration plot the average acceleration for the data in the box is given by the
mean of $y$. Compare this to $m$. Compare these values to the theoretical one.

6. For the position plot, the notation $n($Power$)$ means that the function is raised to a
certain exponent. What is the $n($power$)$? What does the theory say it should be?

7. Once you have data that you are satisfied with, you should save it to an Excel file. To
do so, you first need to make a table of your data by dragging the Table icon over to
position in the data window. Next, drag “Table 1” to velocity and then to acceleration.
You should see a table window that has position, velocity, and acceleration. You can
then save the data by selecting the Export Data button under the File menu. It will
ask you to select either the position, velocity, or acceleration data. Select the position
data and save it to a text file with a descriptive name, say position.txt. Repeat this
for the velocity and acceleration data. When you are done, you should have three files:
position.txt, velocity.txt, acceleration.txt. E-mail the data files to yourself
and to your lab mates so that you have multiple copies for later use.
7.1.2 Additional Analysis for Part 3

We know exactly how the position \( x \) data were obtained, namely by measuring the time-of-flight of sound pulses and converting them to distances using Eq. 3. The velocity and acceleration data were then simply output by the DataStudio software. Evidently, they were obtained by numerically differentiating the position vs time data, but exactly how is not clear—the DataStudio software is thus a kind of “black box” whose inner workings we cannot see. In general, you should be suspicious of data obtained by processing that you do not understand. Therefore we are going to take a closer look.

1. Write a Python program to read in the position, velocity, and acceleration data from the text files using the `loadtxt` function of the Python NumPy library (see the Python manual). The program should then plot these three quantities as a function of time.

2. Consider a situation (like the one in this experiment) where position is measured at fixed time intervals \( \Delta t \). Show that the velocity at time \( i \) can be approximated in terms of positions at neighboring times as

\[
    v_i = \frac{x_{i+1} - x_{i-1}}{2\Delta t}
\]

Show that the acceleration can be approximated from three points using

\[
    a_i = \frac{x_{i+1} - 2x_i + x_{i-1}}{(\Delta t)^2}
\]

Hints: Make sure to think about whether you are determining each quantity’s value at a time \( t_i \) of a measurement or at a time half way between two measurements. Why are these equations only approximate for \( \Delta t > 0 \)?

3. Use the provisional uncertainty rules to find how the uncertainty in velocity and acceleration depend on the uncertainty in position (ignore any uncertainty in time).

4. Modify your program to calculate the velocity and acceleration and their uncertainties as a function of time by using the previous two equations. Graphically compare your results to the velocities and accelerations given by the DataStudio software. You should find that the velocities and accelerations you obtain are noisier than those given by the DataStudio software, especially the acceleration data. In fact, a lot of noise has been filtered out of the DataStudio data using some algorithm that we can only hope is valid. If you want to know more about how this is done, consult your instructor.

5. Note that no matter how the data is processed, the velocity and acceleration data are noisier than the original position data. Why? HINT: When two quantities, say \( a \) and \( b \) are known to a finite number of digits (for example, 8), what happens to the number of significant digits of \( c = a - b \) if \( a \) and \( b \) are very near each other?

6. Based on your responses above, is it better to use a slow or fast sample rate in this experiment? What are the advantages and disadvantages of each of them?

8 Finishing Up

Please leave your lab bench as you found it. Thank you.