

Gateway Arch Phones & Physics Spreadsheets

Three spreadsheets were created to support analysis of cell phone data to model the tram journey up and down the Gateway Arch in St. Louis. Data were collected via the PhyPhox app during the Winter 2025 Meeting of the American Association of Physics Teachers. Details and citations can be found at (eventual citation). This document is intended as a guide for physics teachers who wish to explore the data and their analysis with their students.

Gateway Arch Pressure Data

It is suggested that teachers start with the pressure data. These data are the simplest to manipulate, and give excellent results. There are four tabs in this spreadsheet. These tabs give the barometer data from the phone, get the height from a simple calculation, compare to the calculation made by the app's code, and calculate an instantaneous velocity.

1 - Raw Pressure Data

The two columns in this tab are the raw output from the phone's barometer, and give pressure as a function of time. Note that pressure is recorded in hPa, and will need to be multiplied by a factor of 100 to be presented in Pa.

2 - Height from Pressure

This sheet calculates height from the pressure data using the relationship

$$P = \rho gh$$

Physically this means that the pressure on a surface is due to the weight of the column of material above the surface.

Since pressure is a measured quantity, a change in pressure can be used to determine a change in height:

$$\Delta h = \frac{\Delta P}{\rho g}$$

The change in pressure is simply the current row's pressure minus the initial pressure. This gives the height at each row referenced to the first row.

Columns A & B give the time and pressure, and column C is the height calculated from our method.

3 - *PhyPhox Height Comparison*

The PhyPhox app does not use our pressure-by-weight approach, instead they use the formula

$$h = (-44330.792) \times \left(\frac{P}{1013.25} \right)^{(0.190294957)}$$

This generates a height that is referenced to a position high in the atmosphere, so height is then referenced to the initial position. These data are compared to the heights calculated by the previous method. The two results never differ by more than half a meter.

Columns A&B are the raw data, Column C is the height from the previous method. Column D uses PhyPhox's algorithm to determine height, and column E is height referenced to the first entry in column D. Column F is the difference between the results of the two methods.

4 - *Velocity from Pressure*

For a number of reasons it is nice to know not only the position, but also the velocity. One can calculate velocity from position by using

$$v = \frac{\Delta x}{\Delta t}$$

However, if one simply does this at every step, the instantaneous velocity is swamped by noise. What is done in the case is that the height at any position is averaged over the span of a full second. With smoothed height data velocity can be found at any point. However, visually the graph generated is still swamped by outliers, so the data are filtered such that the graph only shows data near integer values of time.

Columns A-C are the same as those from tab 2. Column D smooths the height by using the Average function. The command “=AVERAGE(C(Row-12):C(Row+12))” makes the value at each point the mean of 25 surrounding points.

Column E displays filtered data, the command “=IF((A3-TRUNC(A3)<\$G\$13), E3, NA())” performs a test. The TRUNC command pulls out the integer part of the time (e.g. TRUNC(34.3)=34), so the difference between the a number and the truncated number is simply the value to the right of the decimal place. If this is smaller than a reference number (in cell G13), then the value is displaced, otherwise it is suppressed for graphing (NA).

Gateway Arch Data Vertical Spreadsheet

This spreadsheet has three tabs and introduces finding velocity and position from acceleration.

1 - Raw Data

This first tab contains both time and Z acceleration. Note that the Z acceleration is around $9.8 \frac{m}{s^2}$, so gravity is baked in. It will need to be removed to determine the motion.

2 - Round Trip Data

This spreadsheet calculates the velocity and displacement of the tram from the acceleration data. Assuming a constant acceleration over a time step, we know that:

$$v_F = v_i + a(t_F - t_i)$$

To find the velocity for a given row (v_F), take the velocity from the previous row (v_i) and add it to the previous row's acceleration (a) multiplied by the change in time between the two rows ($t_F - t_i$). Note that students who are comfortable with calculus can also understand this in terms of Riemann sums. The local value of a multiplied by ($t_F - t_i$) corresponds to a rectangle under the acceleration curve, and adding up all the rectangles acts as a numerical integration.

From there the displacement can also be found, assuming that the velocity is constant over small intervals,

$$x_F = x_i + v(t_F - t_i)$$

The arguments for this step are the same as those for the velocity. Note that sometimes students will wonder about a $\frac{1}{2}at^2$ term. Point out that the time steps are very small, and this term would have that time step squared.

Note that using the Z acceleration straight out of the sensor would give near-parabolic results for the displacement, as the accelerometer is reading roughly $9.8 \frac{m}{s^2}$. The offset we selected (in cell G1) was chosen because it returns the tram back to its starting position, a reasonable expectation for round-trip data. Feel free to play with this value and explore the results.

Columns A&B are raw time and accelerometer data, respectively. Column C builds the velocity using the algorithm just described:

`"=C(Row-1)+(B(Row-1)-$G$10)*(A(Row)-A(Row-1))"`

Column D repeats the same to determine position, but in this case does not require an offset:

`"=D(Row-1)+(C(Row-1)*(A(Row)-A(Row-1)))"`

3 - Velocity Reset

The Velocity Reset tab builds off of the Round Trip Data tab with one important correction, it resets the velocity data to zero at t=234 seconds. At this point in the data collection, the tram is at rest, the data collection was paused, the experimenters walked around the top of the Arch, returned to the tram, and started collecting data again. In the calculations, the velocity is whatever the accumulated signal from the accelerometer provides. For a more realistic model, two improvements are implemented. The velocity is reset to zero at the time when the data collection is restarted, and two different acceleration offsets are used for the data. For the upwards journey the adjustment was fine-tuned so the velocities neighboring the peak velocity matched, however, this meant that the final velocity was not zero. If the adjustment is tuned to make the final velocity zero, then the tram is modelled to move downwards during part of its ascent, which is

unappealing. The adjustment on the way down tries to optimize for both a zero final velocity and a round trip with zero displacement. Again, teachers and students are encouraged to experiment with these adjustments.

Gateway Arch Data Horizontal Spreadsheet

This is the final spreadsheet, and builds upon work performed in the Vertical spreadsheet. There are five tabs. The first is the raw data, and the second is the analysis for the horizontal accelerometer data. The final three approach the problem of finding the shape of the tramway path in the arch.

1 - Raw Data

This tab contains a column for the time data, and then three more columns for the accelerometer across all three axes.

2 - Analysis

This tab is the equivalent to the Velocity Reset tab in the previous notebook. It calculates both the velocity and displacement in both the X and Y directions. The X direction is better behaved, and the acceleration offsets are tuned to give a zero velocity when the tram is stopped, and also a zero final displacement. The lack of symmetry in the velocity graph makes it clear that the data collection by the sensors was flawed in some way, however the upwards journey is at least sensible. The velocity and position data in Y are unphysical, especially since the velocity and displacement in Y should be zero at all times. This can lead to good discussions about integrating a signal that is purely noise.

3 - Arch

The Arch tab simply builds upon previous work. The first four columns (A-D) are cut-and-pasted from the previous sheet. The fifth column (E) is height data from the Vertical Data spreadsheet. The horizontal data and vertical data are plotted against each other for the upwards journey, plotting out the calculated trajectory of the tram. Note that this curve is influenced by issues in both the horizontal and vertical summations, which leads to the next set of tabs

4a - Filter & 4b - Arch (Pressure)

These two tabs are utilized to make a plot similar to the one in tab 3, but to use the height data from the pressure sensor rather than the accelerometer. Plotting these data

sets against each other is problematic, as they are different sizes. The solution is to sample both at one-second intervals, and to use these subsets for the graph. Tab 4a is used to comb the horizontal data. The first sets of columns are from previous tabs. Columns F&G use the following syntax:

```
=IF((A(Row)-TRUNC(A(Row))<0.002),A(Row),"")
```

And

```
=IF((A(Row)-TRUNC(A(Row))<0.002),D(Row),"")
```

The logic statement tests to see if the timestamp is within 0.002s above an integer value of time, and if it is, to return time and displacement values. Otherwise it will report a blank entry. Users can use Excel's filter function on the columns, removing the blanks. The results are horizontal data at integer values of time, and these are cut-and-pasted into tab 4b.

Tab 4b has displacement data at integer time stamps from both the horizontal accelerometer and the barometer. When plotted against each other, these values give a better approximation to the travel of the tram. This graph is included in tab 3, along with a cut-away of the Gateway Arch with the tram pathway highlighted.