Two Lab Activities Demonstrating Some Physics of High Altitude Balloon Launches

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We present two lab activities that involve similar physics to that of high altitude balloon flights. One lab involves a descending helium-filled balloon and the other involves a descending parachute. In both of these activities, the descending object is subject to a sum of forces in the vertical direction. Forces involved include the velocity-dependent drag force, which varies with time and thereby makes theoretical predictions of both our lab activities nontrivial. The aim of both lab activities is to measure and model the time of descent for the falling body.

Nomenclature

a_y	= vertical acceleration
A_s	= surface area
A_c	= cross sectional area
B	= buoyant force
C_d	= drag coefficient
D	= drag force
Δt	= time step size
g	= acceleration due to gravity
m	= mass of various apparatus indicated by subscripts
r	= radius
ρ	= density of materials indicated by the subscripts
v	= velocity
V	= volume
W	= weight

I. Introduction

High altitude balloon launches are an important way researchers can obtain data on the Earth's atmosphere, atmospheres of other planets, and cosmic rays[1]. During ascent, a high altitude balloon will experience air resistance, payload weight, and buoyancy force. After bursting, the parachute is deployed so that the payload descends safely back to Earth. The primary forces acting on the parachute are air resistance and payload weight. In the lab activities we will present, the non-uniformities in density, temperature and pressure of the atmosphere are neglected.

We will first discuss the apparatus. Secondly, we discuss the physics underlying the balloon and parachute activities. Next, a description is given of the iterative numerical method we used to find the time of descent. Finally, we present some sample data from some of our balloon and parachute drops.

II. Apparatus

In our experiment, we used 17 inch latex balloons[5] and an 18 inch parachute[6] as falling bodies. Different amounts of slotted masses or copper shot were attached to parachute and balloon to simulate the payload of a high-altitude balloon. Afterwards, the balloons were inflated with helium to approximately equal diameters of about 36 cm. A digital balance was used to measure mass. The mass of helium was found using the inflated balloon's volume and density of helium.

In Figure 1 below, the measuring tape is shown extending through the distance of the balloon's descent, from the release point to the bottom endpoint. The drop distance was approximately 6 meters.

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Figure 1. This photograph shows the atrium of the Science Building at University of Minnesota, Morris. *In the center, a parachute is held at the release point. The balloons were dropped through approximately the same distance.*

III. Underlying Physics Concepts in the Balloon Activity

A. Balloon Drop

In the balloon experiment, an approximately spherical helium-filled balloon is dropped through a measured distance of 6.01 m. The descending balloon experiences three forces, the drag force due to the surrounding air, weight, and the buoyancy force. The free-body diagram of the balloon is shown in Figure 2.

Applying Newton's 2nd Law to the balloon gives

$$(m_{balloon} + m_{attached\ mass})a_y = B - W + D \tag{1}$$

Each of the forces, B, W, and D, can be explicitly expressed as

$$(m_{balloon} + m_{attached\ mass})a_y = (\rho_{air} - \rho_{He})Vg - (m_{balloon} + m_{attached\ mass})g + \frac{1}{2}\rho_{air}A_cC_dv^2 \tag{2}$$

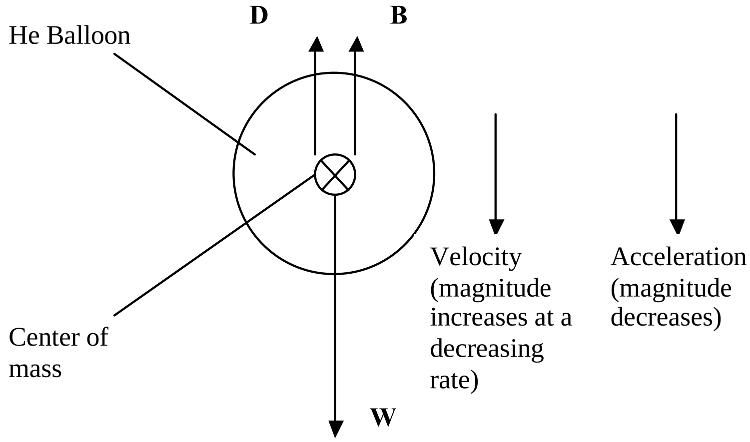

Figure 2. Free-body diagram of descending helium-balloon before reaching terminal velocity. *As the balloon descends, the magnitude of the drag force increases until the drag force and buoyant force balance the weight. When the vertical forces are balanced, the balloon reaches terminal velocity.*

The first term on the right hand sides of (1) and (2) represents the buoyant force. The balloon volume was determined by measuring both the polar and equatorial circumferences and then taking the average. We then used the radius, obtained from the average circumference, to determine the volume. We approximated the balloon as a sphere.

The second term on the right hand sides of (1) and (2) is the weight of the balloon and the weights of the slotted masses that are attached to the balloon. Both the first and second terms of equations (1) and (2) are constant during the balloon's descent.

The third term on the right hand sides of (1) and (2) is the drag force. For the drag coefficient, we chose a value of 0.47 for the nearly spherical-shaped balloon where the reference area is the cross-section perpendicular to the velocity[3]. To calculate the cross-sectional area, A_c, we used πr^2, where r is the equatorial radius of the balloon.

B. Parachute Drop

In the parachute experiment, an 18 inch hemispherical parachute is dropped through a distance of 5.68 m. The descending parachute experiences two principal forces: the drag force from the surrounding air and the weight from the payload. The free-body diagram for the parachute is shown in Figure 3 below.

Applying Newton's 2nd law to the parachute gives

$$(m_{parachute} + m_{attached\ mass})\, a_y = D - W \tag{3}$$

The drag force, D, and the weight, W, can be more explicitly expressed as

$$(m_{parachute} + m_{attached\ mass})a_y = \frac{1}{2}\,\rho_{air}\, A_s\, C_d v^2 - (m_{parachute} + m_{attached\ mass})g \tag{4}$$

The first term on the right hand sides of (3) and (4) is the drag force, where ρ_{air} denotes the density of air, A_s is the surface area of the parachute material if laid out flat, C_d is the drag coefficient of the parachute, and v^2 denotes the square of the instantaneous velocity of the balloon. For drag coefficient, we chose a value of 0.75 for the nearly hemispherical-shaped parachute where the reference area is the surface area of the parachute[7].

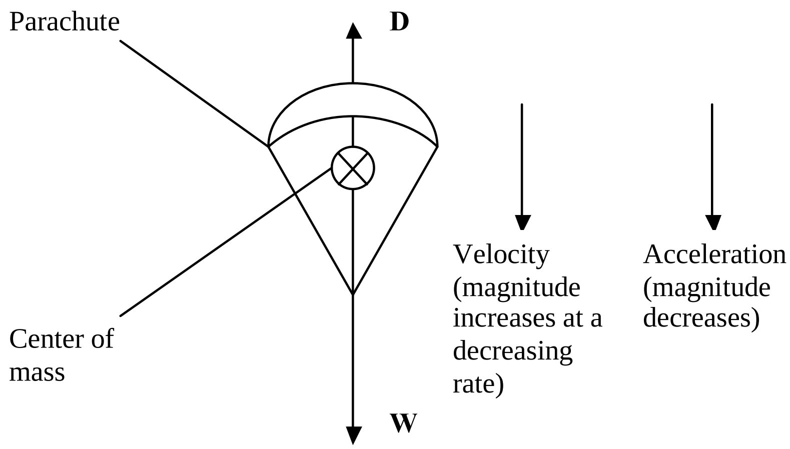

Figure 3. Free-body diagram of descending parachute before reaching terminal velocity. *As the parachute descends, the magnitude of the drag force increases until it balances the weight. When the vertical forces are balanced, the parachute reaches terminal velocity.*

We assumed the parachute to hemisphere-shaped. The factory value for the "size" of the parachute is 18 inches, the arc-length of the hemisphere's cross-section. The radius, r, of the hemisphere was found from equating the size to half the circumference of a circle:18 inches = πr. An 18 inch size corresponds to a radius of approximately 5.7 inches or 0.14 meters.

The surface area, A_s, of the parachute is then found using

$$A_s = 2\pi r^2 \tag{5}$$

From equation (5), we found a surface area of approximately 0.12 square meters.

The second term on the right hand sides of (3) and (4) is the weight of the parachute material ($m_{parachute}$) and the weights of the slotted masses ($m_{attached\ mass}$) that were attached to it. This term is constant during the parachute's descent.

C. Numerical Recursion Method

The quantitative aim of the lab is to measure the time it takes for the balloon to descend through a measured distance. We will refer to this as the *descent time*. To obtain the descent time theoretically, we will use a numerical recursion method. In this discussion, *we will only describe how we applied the numerical method to the balloon's descent*, as a discussion of the parachute's descent is very similar.

To begin, we first chose a step size, Δt, of 0.050 s. In one step from t_n to t_{n+1}, we used the kinematic relations to *approximate the balloon's motion*:

$$t_{n+1} = t_n + \Delta t, \tag{6}$$

and

$$v_{y,n+1} = v_{y,n} + a_y\left(t_n, v_{y,n}\right)\Delta t, \tag{7}$$

and

$$y_{n+1} = y_n + v_{y,n}\,\Delta t + \frac{1}{2}\,a_y\left(t_n, v_{y,n}\right)(\Delta t)^2. \tag{8}$$

The initial conditions were $t_0 = 0,\ y_0 = 0,\ v_{y,0} = 0$, and

$$a_y(t_0, v_{y,0}) = \frac{B - W + D(v_y(t_0))}{m_{balloon+Cu\,pellets+He}} \approx -3.77\,m\,s^{-2}. \tag{9}$$

In the second step of the iteration, we let $t_1 = t_0 + 0.050s = 0.050s$; the variables t, y, and v_y become

$$v_{y,1} = v_{y,0} + a_y\,(t_0, v_{y,0})\,0.050s \approx -0.187\,m\,s^{-1} \tag{10}$$

$$y_1 = y_0 + v_{y,0}\,(0.050\,s) + \frac{1}{2}\,a(t_0, v_{y,0})(0.050\,s)^2 \approx -0.0047\,m. \tag{11}$$

Furthermore, we used the velocity of the first iteration to obtain the acceleration for the next iteration:

$$a_y(t_1, v_{y,1}) = \frac{B - W + D(v_y(t_1))}{m_{balloon+Cu\,pellets+He}} \approx -3.73\,m\,s^{-2} \tag{12}$$

This iteration was continued until the magnitude of the vertical displacement, $|y|$, equaled the measured drop distance.

In Figures 4a and 4b, below, we show graphs of vertical displacement versus time and vertical velocity versus time for the three balloons that were loaded with approximately 0.058 kg, 0.066 kg, and 0.074 kg of copper shot.

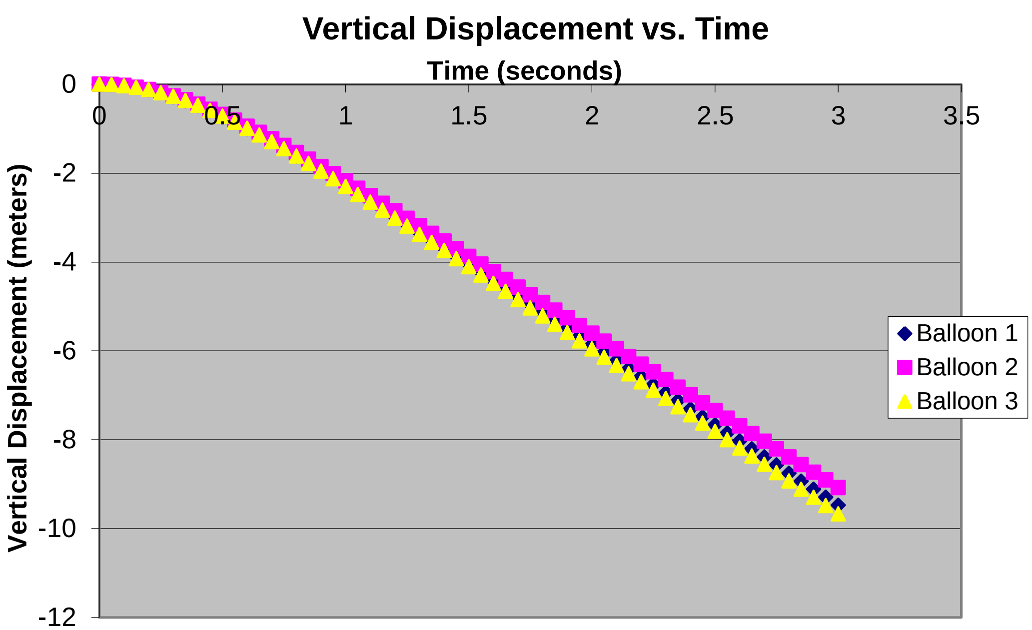

Figure 4a. *Note that the slope of the displacement-time graph starts out horizontal and evolves to a constant negative value. This behavior is consistent with the balloon being released from rest and then eventually reaching terminal velocity (around -3.5 m/s) in its descent.*

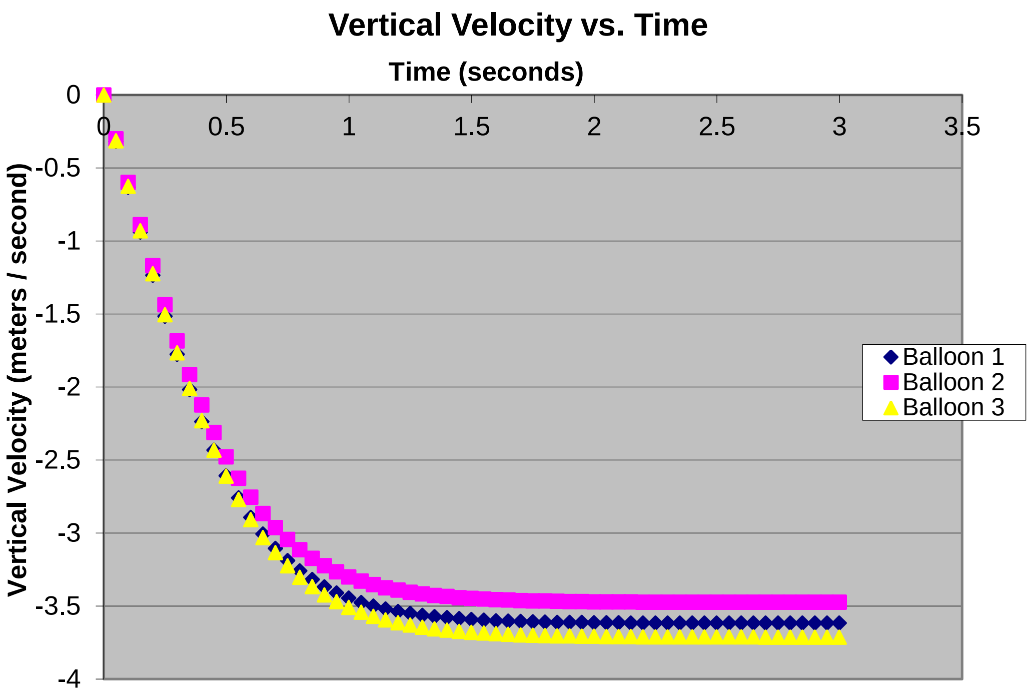

Figure 4b: *Note that the velocity-time graph starts out at zero, but eventually becomes flat at approximately -3.5 m/s. This behavior is consistent with the balloon being released from rest and then eventually reaching terminal velocity (around -3.5 m/s) in its descent.*

In Figures 5a and 5b, we show graphs of vertical displacement versus time and vertical velocity versus time for the parachute with masses of approximately 0.025 kg, 0.035 kg, and 0.045 kg.

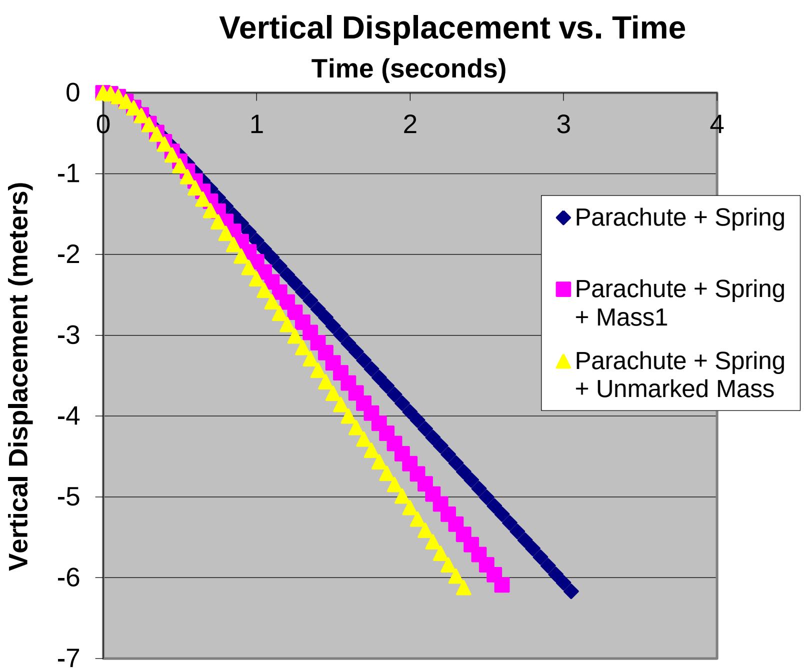

Figure 5a. *Again the slope of the displacement-time graph starts out horizontal and evolves to a constant negative value.*

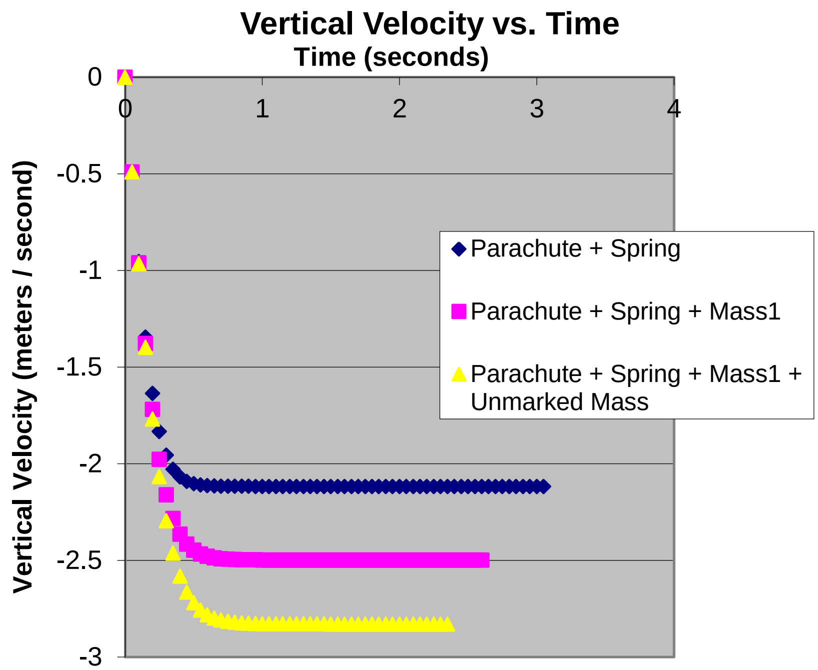

Figure 5b. *Again the velocity-time graphs start out at zero, but eventually becomes horizontal at different velocities depending on the mass.*

Table 1. Balloon Data

	Balloon 1	Balloon 2	Balloon 3
Total Mass (kg)	0.05847 ± 0.00001	0.06638 ± 0.00001	0.07434 ± 0.00001
Drop Distance (m) (Experimental)	6.01 ± 0.08	6.01 ± 0.08	6.01 ± 0.08
Descent Time (s) (Experimental)	2.30 ± 0.06	2.43 ± 0.07	2.37 ± 0.06
Descent Time (s) (Theoretical)	2.35	2.40	2.30
Terminal Velocity (m/s) (Theoretical)	-3.54	-3.44	-3.66

The uncertainty in the mass was estimated by using the least count of the digital balance used to weigh the balloon, payload masses, etc. The uncertainty in the descent time was estimated by using the standard deviation from 10 trials under the same conditions. The uncertainty in the drop distance was found by estimating the possible variation in release position due to manually holding the balloon.

Table 2. Parachute Data

	Parachute w/ Spring	Parachute w/ Spring + 0.010 kg Mass	Parachute w/ Spring + 0.020 kg Mass
Total mass (kg)	0.02535 ± 0.00001	0.03530 ± 0.00001	0.04526 ± 0.00001
Drop Distance (m) (Experimental)	5.68 ± 0.08	5.68 ± 0.08	5.68 ± 0.08
Descent Time (s) (Experimental)	3.30 ± 0.13	2.82 ± 0.12	2.48 ± 0.04
Descent Time (s) (Theoretical)	2.95	2.55	2.30
Terminal Velocity (m/s) (Theoretical)	-2.12	-2.50	-2.83

The uncertainties are as in Table 1.

IV. Conclusions

After having performed this experiment with a range of masses, we believe that if the payload mass is too small, air turbulence will be non-negligible. The air turbulence will cause a large standard deviation in the time measurements and reduce accuracy. We found large standard deviation, ~0.6 s, in the descent time, ~7.9 s, for a balloon payload mass of 0.017 kilograms, for example. On the other hand, if the payload mass is too large, the descent times will be so small that uncertainty due to human reaction time will limit accuracy.

Pedagogically, the activities we have presented require students to read and interpret position-time and velocity-time graphs for variable acceleration. Interpretation of graphs is an important concept in introductory physics courses. The labs we have presented also require students to apply a numerical iteration method to find the time of descent. The instructor can use this activity to introduce students to software such as MatLab, Mathematica, or Excel. Finally, since helium balloons and parachutes are a novelty to most students, we think that the chance to use these “toys” will kindle their scientific curiosity.

Possible improvements to the lab activities include attaching a GPS locator to the parachute or balloon. A GPS locator would keep more accurate position, time and velocity data than the unaided eye and stopwatch. In addition, hydrogen, a cheaper gas than helium, is also viable to do the experiments we have described above. Moreover, if larger balloons are used, the buoyancy force increases. A larger buoyancy force would thereby increase the time of descent and consequently reduce the impact of uncertainty due to the time measurement. We considered using Tracker-type software that was used by Leme et. al.[4], but numerous cameras would be needed to produce images of the balloon without distortion due to changing perspective as the balloon descends through the 6.0 meters.

References

[1] Shane L. Larson, John C. Armstrong, William A. Hiscock, “The first frontier: High altitude ballooning as a platform for student research experiences in science and engineering,” Am. J. Phys. 77 (6), June 2009. http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1430&context=physics_facpub

[2] R. Parthasarathy, “Cars and Kinetic Energy – Some Simple Physics with Real-World Relevance,” Phys. Teach. 50, 395 – 397 (October 2012).

[3] Steven Vogel, “Life in Moving Fluids: The Physical Biology of Flow,” Princeton University Press, Princeton, New Jersey, (1994).

[4] J. C. Leme, C. Moura, C. Costa, “Steel Spheres and Skydiver – Terminal Velocity,” Phys. Teach. 47, 531 – 532 (November 2009).

[5] Balloons were bought from this vendor: http://www.wholesaleballoonsdirect.com. 17 inches is the approximate diameter of the balloon when fully inflated.

[6] The parachute was bought from this vendor: http://spherachutes.com. 18 inches is the approximate arc length of the parachute semi-circular cross-section.

[7] J. Potvin, “Calculating the descent rate of a round parachute,” Parks College Research Group, http://www.pcprg.com/rounddes.pdf