PEAK OF FLIGHT

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PEAK OF FLIGHT

Simulating Drogueless Dual Deployment Rockets

By Kenneth Karbon

Introduction

Simulating drogueless dual deployment is a common discussion topic on the rocketry forums. “Drogueless” means there is no drogue parachute for the first deployment event. The rocket sections just tumble chaotically while tethered together by a length of harness (**Figure A**). This allows the rocket to fall as fast as possible from apogee and minimize drift before the main parachute is triggered at a set altitude by an altimeter. Since the rocket is constantly changing its orientation and aerodynamic properties as it falls, it is impossible to simulate precisely in software like RockSim. So, some measured flight data is needed to tune the simulations.

Figure A: Drogueless dual deploy rocket

Peak of Flight issue #449 described how to estimate the drag coefficient of a parachute using descent velocity recorded by an altimeter. This article will use a similar method and with more inspection of the measured data to better understand the real world behavior of the flight. In both cases, the concept of terminal velocity applies. This is the theoretical constant rate at which an object falls when the forces of gravity and aerodynamic drag balance against each other:

(Equation 1) $$Terminal\ Velocity = \sqrt{\frac{2mg}{\rho C_D A}}$$

Where:
m = mass
g = gravitational constant
ρ = air density
C_D = drag coefficient
A = reference area

However, this fall rate is not constant because air density, and to a lesser extent, gravity, are changing continuously as the rocket falls through the atmosphere, especially for high altitude flights. Also, the C_D of the drogueless rocket is likely very transient, as it tumbles in various form factors. The best we can hope for is an average drag coefficient to put in the simulations.

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Insight from Simulation

Let's look at a RockSim simulation to see some of these effects. **Figure 1** is a plot of altitude and vertical velocity over time for a dual-deploy flight. I use the directional y-velocity here, not velocity magnitude, so descent speed will always be a negative number. Three velocity phases are evident after the max value is achieved: continued ascent to apogee, drogueless descent, and then main parachute deployment. I used a very small parachute as the first deployment event to trick RockSim into thinking a low-drag, rapid, "drogueless" descent is taking place. This "phantom chute" is what we want tune with altimeter data to mimic the real behavior.

The drogueless descent velocity may look like a flat line at first glance, but it is more complex. It is viewed more closely in **Figure 2 (Page 4)**. After apogee, the rocket falls very quickly and asymptotically approaches terminal velocity of -32 m/s at time = 30 s. This is where gravitational force and aerodynamic drag become equal. However, this velocity does not stay constant as the rocket must adjust to the local atmospheric conditions at each altitude level. The rocket slows down over time to about -28 m/s when the main parachute deploys and puts the rocket at a safe landing speed around -8 m/s.

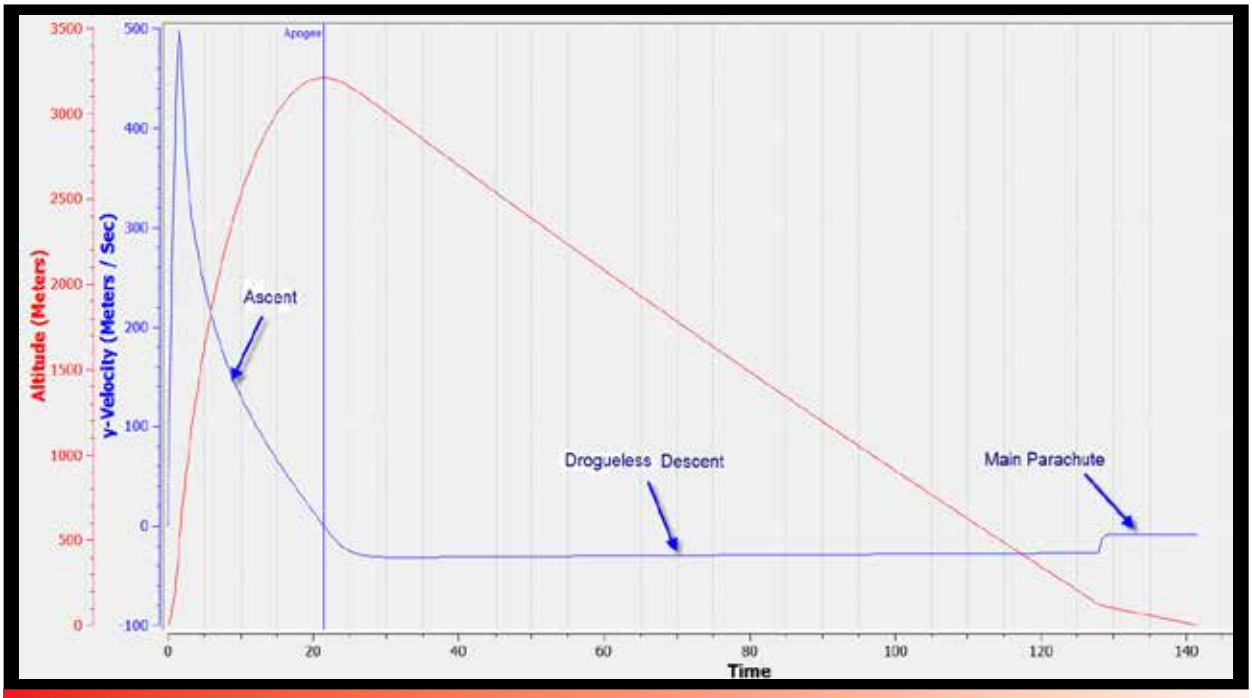

Figure 1. RockSim simulation showing velocity phases of a dual deploy rocket.

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In **Figure 3**, I plot air density along with the drogueless velocity. This simulation reached a max altitude of 3200 m, so the change in air density is significant over the period from apogee to main parachute deployment around 200 m. The gravitational constant also changes over this range, but the change is very small, and we can neglect it. Using the US Standard Atmosphere model, RockSim computes the air density going from 0.90 at the start to 1.2 kg/m3 at the finish, which is a hefty 35% difference. Since RockSim assumes a constant CD and area for the phantom chute, it is this density change alone that forces the terminal velocity to adjust and slow down as it falls over time. Using Equation 1 as a quick check, the square root of 0.90/1.2 density ratio equals the velocity ratio of -28/-32 noted above.

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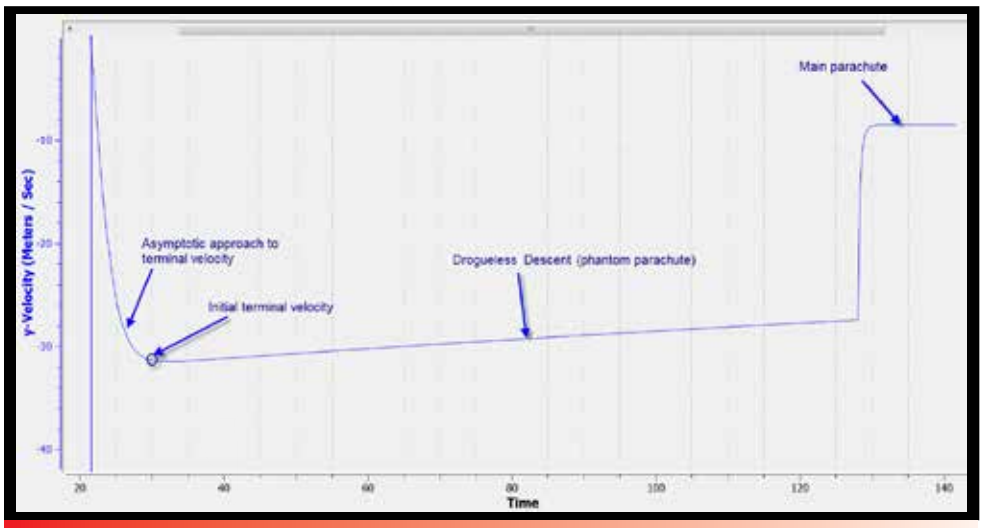
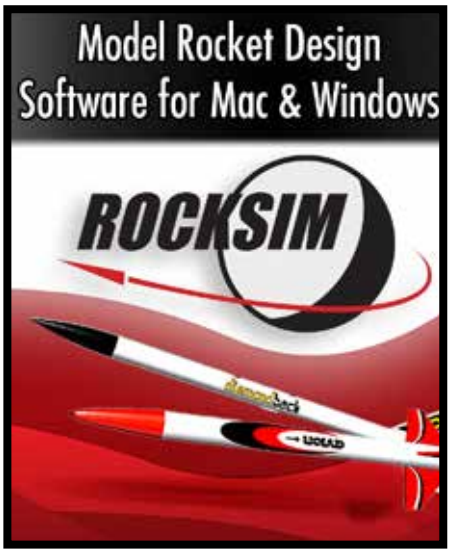


Figure 2: Close up of RockSim velocity in drogueless phase.



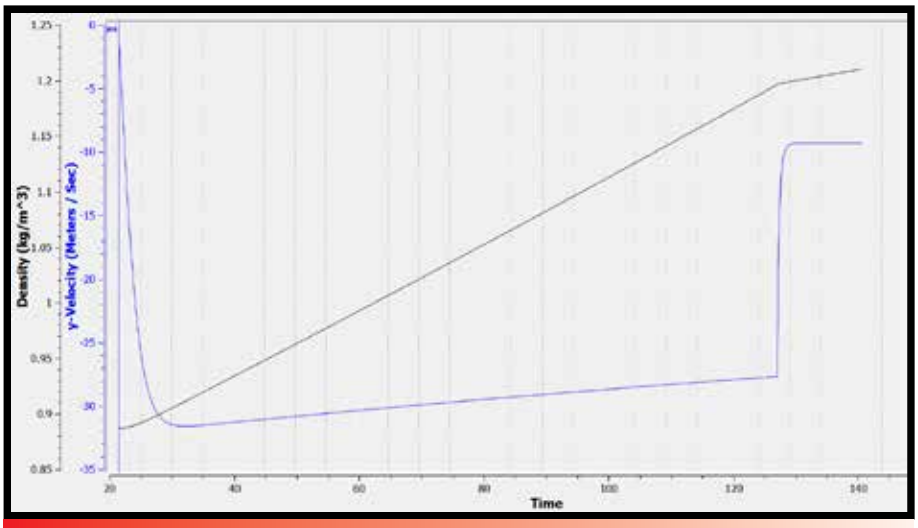


Figure 3: Air density change during drogueless descent.

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Velocity from Recording Altimeter

Figure 4 is the altitude and velocity measured by the Perfectflite Stratologger CF altimeter on one of my recent drogueless, dual deploy, flights. (Well, I did have a mishap in that the main parachute did not unfurl, so there is no significant slowdown in velocity before it hit the ground). This was a 4" diameter rocket, 79" long, and with 3 split fins. It flew to about 5600 ft. on an Aerotech K513, enough for air density change to be noticeable.

Bear in mind that velocity derived from barometric altitude measurements like the Stratologger is not very precise. The reason is that the measured altitude (from air pressure) is noisy, and the derivative (velocity) of noisy data is even noisier data. Perfectflite does some plot smoothing or filtering to help remove the fluctuations, but you can see that the measurements are still not as clean as a RockSim simulation. Nonetheless, the trends we want to study are captured by the altimeter. For example, after apogee, you can see the quick approach to terminal velocity from t = 15 to t = 20 s.

I imported the altimeter data into Excel for further analysis. I also convert everything from English units to SI units because subsequent calculations of force are much easier. I trimmed the data and saved only the drogueless descent phase highlighted in yellow. This velocity is shown in detail in **Figure 5**.

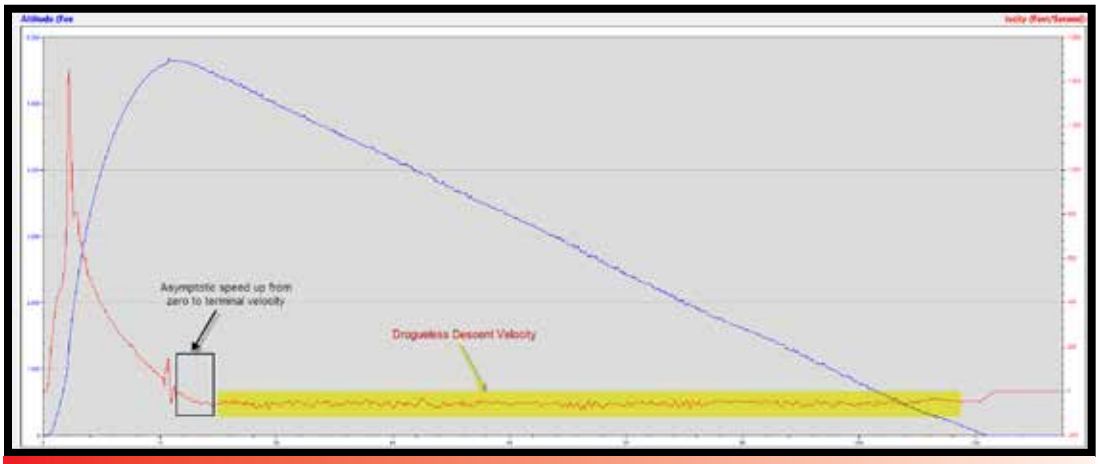

Figure 4: Altitude and velocity measured by altimeter

The velocity data is still pretty noisy and uninteresting in the range of -25 to -10 m/s. So, what can we do about it? There are elaborate mathematical filtering methods used by scientists, but I am not versed in those methods. Instead, I turned to some built-in functions within Excel.

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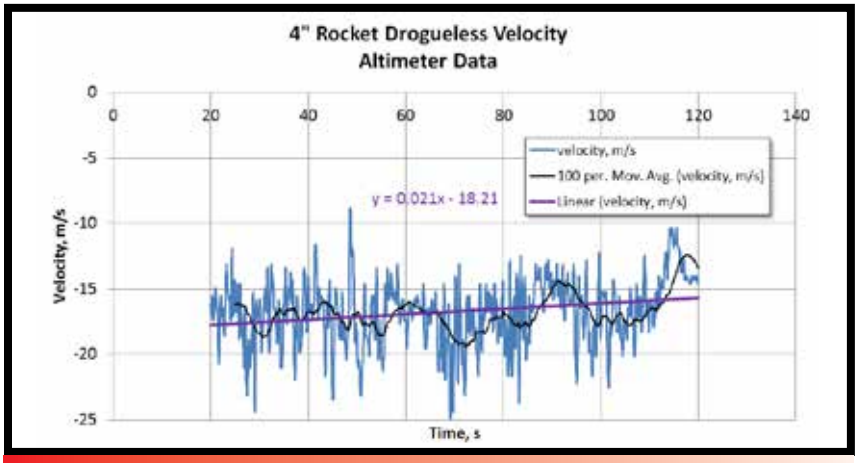

Figure 5: Altimeter velocity during drogueless phase plotted in Excel.

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One way to see the overall trend of ragged data is to take a moving average. This is an option to choose when adding a "trend line" to an Excel chart. I chose an interval of 100, meaning that at each point in time, the previous hundred velocity points are averaged and plotted. This helps clean up the altimeter data in Figure 5, and an upward movement of the velocity over time becomes a little more apparent.

A second way to simplify the noisy data and see the trend is to fit a straight line using the method of least squares. This is also easily done with the Excel chart trend line function. The equation of the line in form of y = mx + b is given. With the straight line, there is a clear slowing down of the rocket as it falls over time. The initial terminal velocity is centered around -18 m/s, but reduces to -16 m/s by the end of drogueless descent phase. The decrease is due in part to the change in air density as the rocket falls from apogee at 5600 feet to ground level. It is pretty cool to see the atmospheric effects directly in our altimeter output!

Using a Phantom Parachute

Now, we want to use this cleaned up velocity data to predict the aerodynamic drag of the drogueless recovery and use this info to mockup the phantom chute in RockSim. First, define a round phantom chute in the booster body tube of the design components (**Figure 6**.) Double click to edit its properties as in **Figure 7**. Inside the properties there are some quick settings for computing descent rates. Simply adjust the slider bar for outer diameter until the descent rate equals 16.74 m/s, which was the average of the straight line fit of the altimeter data. The required phantom parachute diameter is about 587 mm with an assumed C_d of 0.75 to achieve this speed.

It is very important to use the correct mass for descent calculations. In this case, we need the burnout mass, which is the weight of the rocket after the motor burns all its consumables and the rocket is in recovery mode:

Sustainer mass is the dry weight, and it should be the correct weight of your rocket saved in your RockSim design file.

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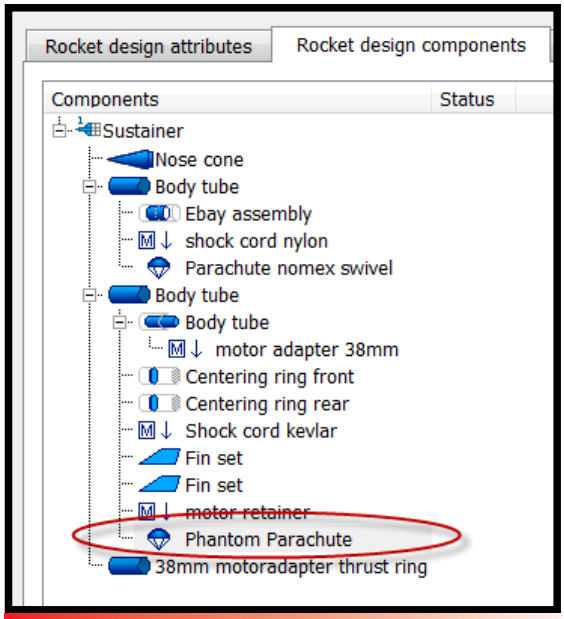

Figure 6: Phantom parachute in the RockSim design.

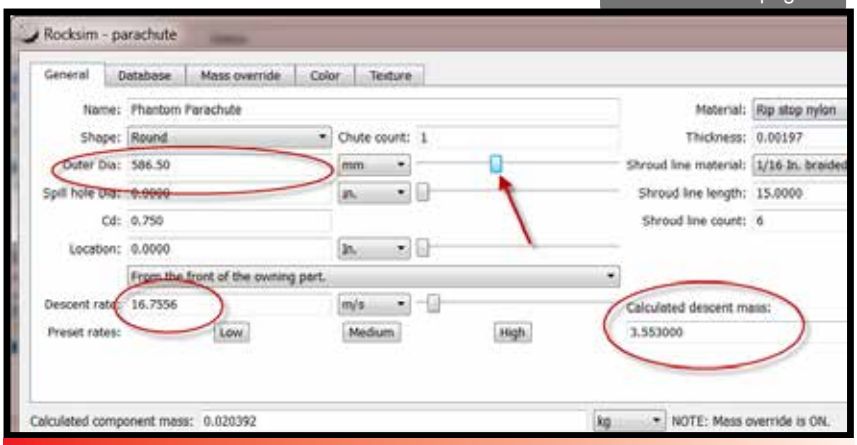

Figure 7: Phantom parachute descent properties.

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Total motor and propellant masses are found in the engine text files (.rse or .eng). In issue #449, Tim made a good recommendation to promptly weigh your rocket after recovery to get the correct burnout mass. However, if you de-prep your rocket and forget to weigh it (as I often do), you can recover the burnout mass in a number of ways via RockSim. For example, simulate the flight with the correct motor, then plot mass vs. time as in **Figure 8**. After motor burnout, the mass remains constant for the remainder of the flight, in this case 3.553 kg.

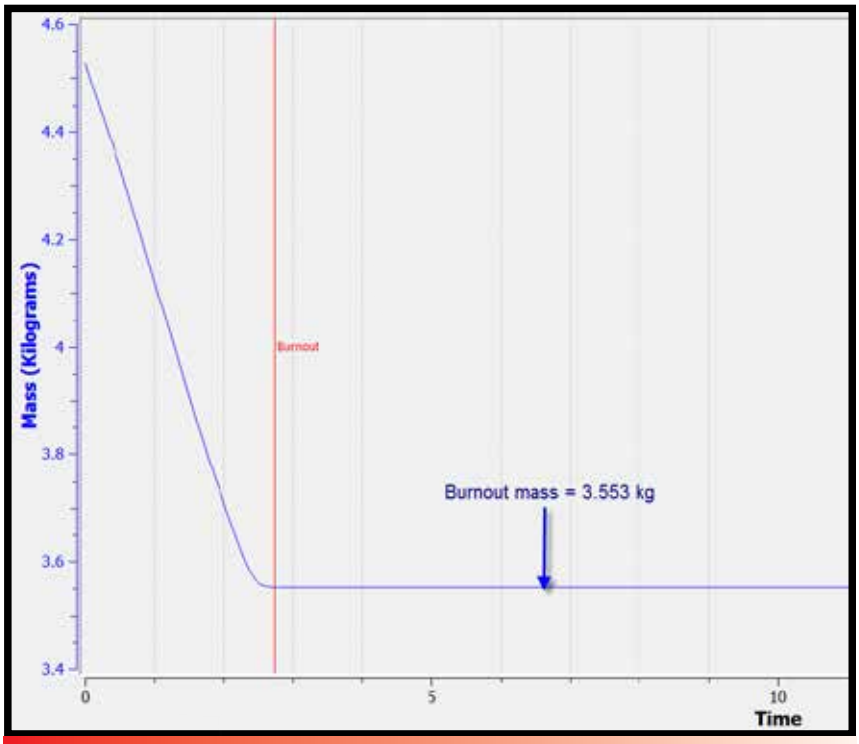

Figure 8: Burnout mass for parachute calculations.

After tuning the phantom parachute descent rate, I re-ran the simulation and plotted the y-velocity on top of the altimeter data. This is shown in **Figure 9**. The RockSim velocity is close and a good approximation, but it is not exactly the same as the linear least squares fit of the altimeter velocity. The reason for the differences is likely due to the fact that the calculations in the simple descent estimator in the parachute properties are not the same as the full simulation. To investigate more, we need to look at the atmospheric model.

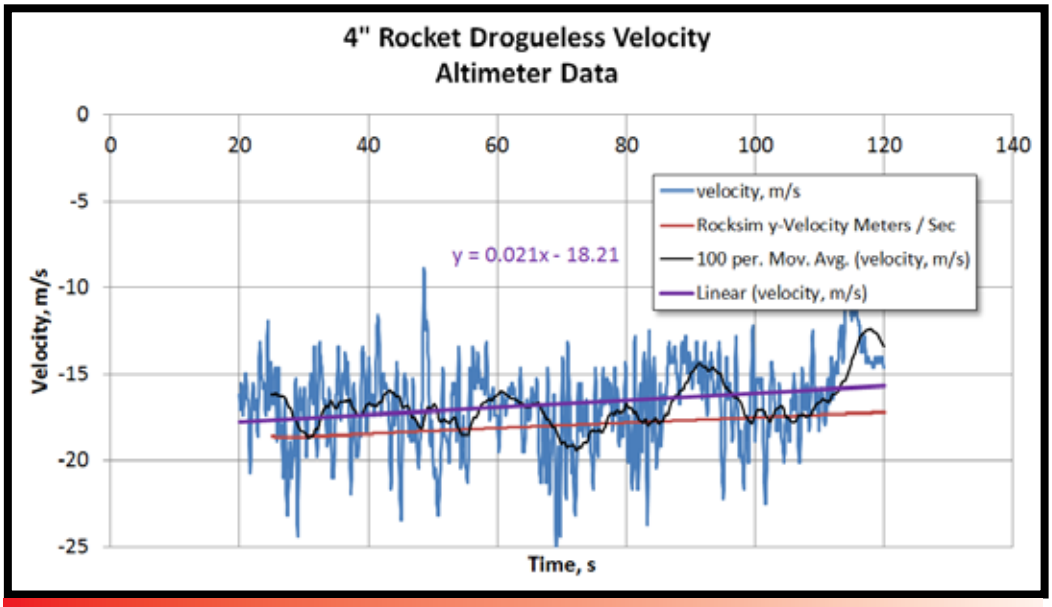

Figure 9: RockSim simulation with phantom chute added to the altimeter plot.

Atmospheric Model

The US Standard Atmosphere is a model of how the pressure, temperature, density, and viscosity of the Earth's atmosphere change over a range of altitudes. The first layer of the model applies to the Troposphere, which is valid up to 11 km. That is good enough for most hobby rocket calculations! In this layer, temperature is assumed to vary linearly at -6.5 °C/km, which is

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called the "lapse rate." From the temperature, equations for air pressure and density at altitude are then solved. The "standard day" conditions of the model are assumed to be at sea level, 15 °C, 101325 Pa, 0% humidity, and density of 1.225 kg/m3.

Barometric altimeters measure the change in air pressure as the rocket ascends/descends, then use the atmospheric model to calculate the change in altitude relative to the launch site. Altimeters usually apply the standard day model without corrections for local humidity, barometric pressure, and most importantly, temperature. This can easily cause measurement errors of 10%. Software like RockSim does adjust the atmospheric properties for launch site conditions, so the simulation is much more accurate than measurements in this regard. When trying to correlate with altimeters that make no adjustments, it may be better to set the simulations at standard day conditions regardless of the local launch weather. For more information, see Peak of Flight issue #380 "The Top 5 Reasons Why Your Altimeter and Computer Simulations Don't Agree."

Computing Drag from Altimeter Measurements with Atmosphere

I programmed the standard day troposphere model into my Excel spreadsheet for more precise calculations of the drogueless aerodynamic drag based on the altimeter velocity. At each time step, I compute the air density from the measured altitude. With all the previously generated info (burnout mass and linear velocity fit), we can rearrange Equation 1 to solve for drag over the course of the descent:

(Equation 2) $$C_D A = \frac{2mg}{\rho V^2}$$

Here I am using the product of C_D and A to characterize the drogueless drag and not worrying about separating drag coefficient and a precise reference area. The correct reference frontal area becomes rather ambiguous as the rocket falls chaotically. $C_D A$ has units of area and is a common measure used by aerodynamicists to normalize the drag force by the dynamic pressure. As long as the input C_D and area calculation used in the phantom parachute properties equal the intended product, the simulation will work correctly.

Figure 10 plots the $C_D A$ over descent time. The curve is fairly constant as expected, as I had hoped the averaged drag characteristics would be uniform during the fall. The $C_D A$ ranges from around 0.210 to 0.230 m2 with an average of 0.223. The curve is not perfectly flat perhaps because of the limitations of the derived velocity data and our straight line assumption.

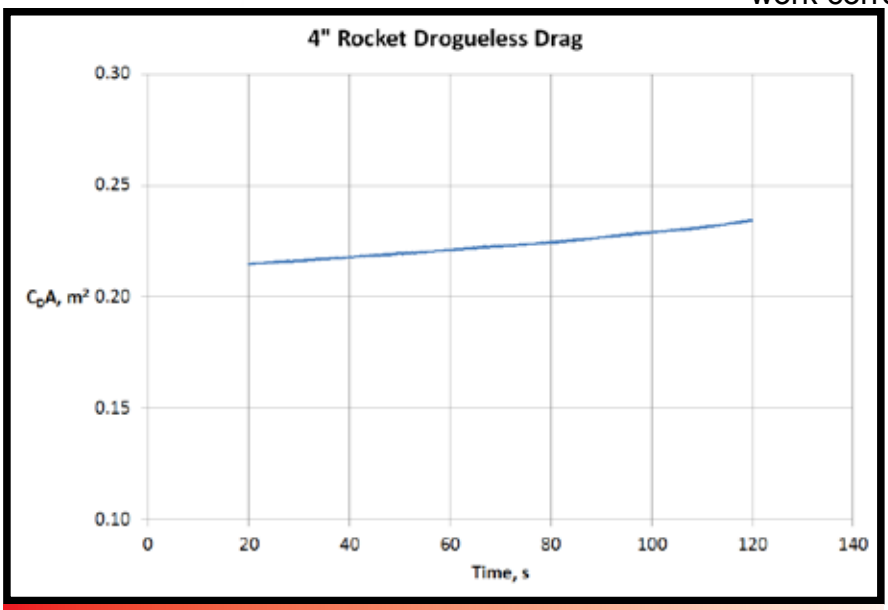

Figure 10: Drag for 4" rocket during drogueless descent.

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Returning to the phantom parachute properties in **Figure 11**, any values of drag coefficient and area can be used to compute the proper C_DA. I use a circular diameter of 1 m to keep things simple, and the area works out to be $\pi (1)^2/4 = 0.785\ m^2$. To give a C_DA of 0.223, the C_d comes to 0.284. Re-running the simulation and plotting the RockSim drogue velocity gives the result in **Figure 12**. There is now a better match between the simulation and the altimeter straight line velocity. More precise tuning of the phantom drag with an accurate atmospheric model improves the agreement.

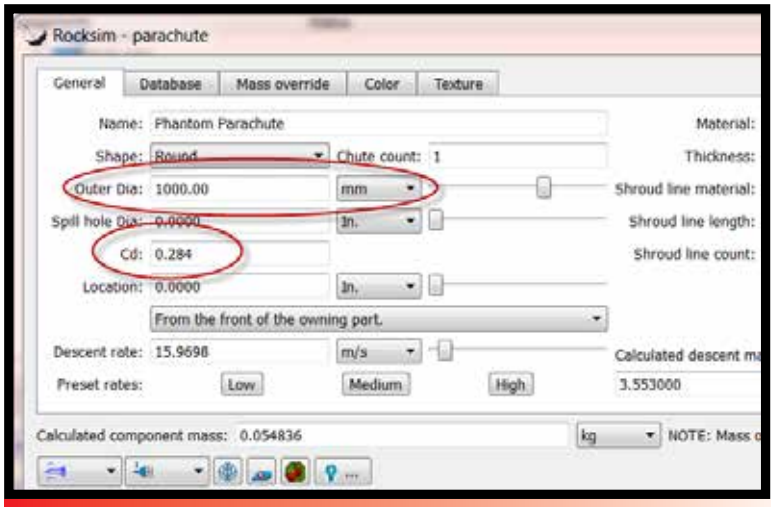

Figure 11. Improved phantom parachute descent properties.

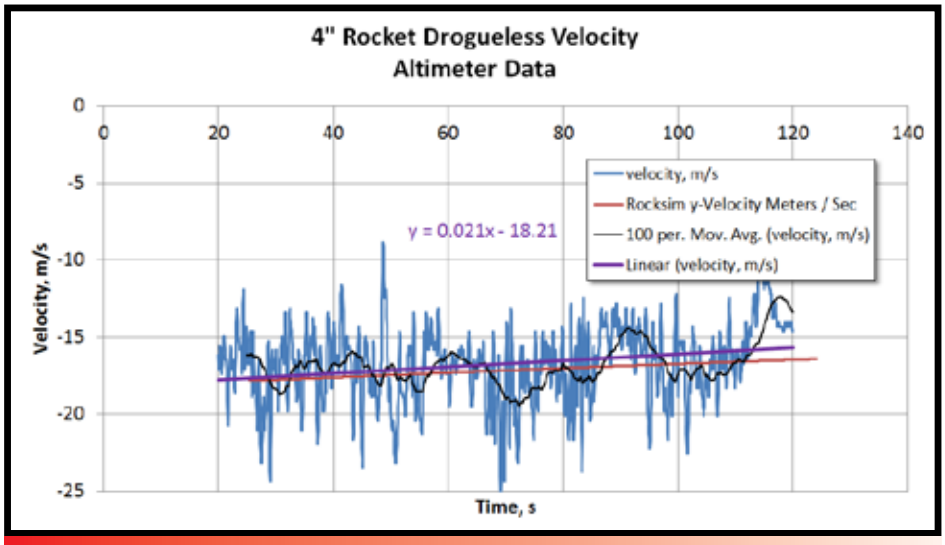

Figure 12. RockSim simulation with improved phantom chute added to the altimeter plot.

Deriving Velocity from Altimeter Altitude by Yourself

Many altimeters generate altitude data only or stop the velocity calculations after apogee is reached. In these cases there is no velocity available to tune the descent rates. Now what? Well, you can easily compute vertical velocity from altitude data and see the trend, just like the altimeter does. Recall that velocity is the derivative, or rate of change, of the height:

(Equation 3) $$V_t = \frac{\Delta h}{\Delta t} = \frac{h_t - h_{t-1}}{\Delta t}$$

Most altimeters measure at a constant interval of 20 Hz or $\Delta t = 0.05$ s. With the height vs time data in columns of a spreadsheet, you can compute this instantaneous velocity for each time stamp using the altitude on that row (t) and the altitude on the previous row (t-1).

Equation 3 is the simplest form of taking a derivative using equally spaced data. It is also considered to be "one-sided" and only "first order" accurate. Engineers should use numerical methods that are at least "second order" accurate for solving problems. A better way to get velocity at time t from the altitude data is this alternative approximation of a derivative:

(Equation 4) $$V_t = \frac{h_{t+1} - h_{t-1}}{2\,\Delta t}$$

Equation 4 is second order accurate and centered-spaced, meaning the calculation uses the data before and after the time of interest. This is the method I used to compute descent velocity from another altimeter that only gives altitude.

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Example 2. Computing Drag with Derived Velocity

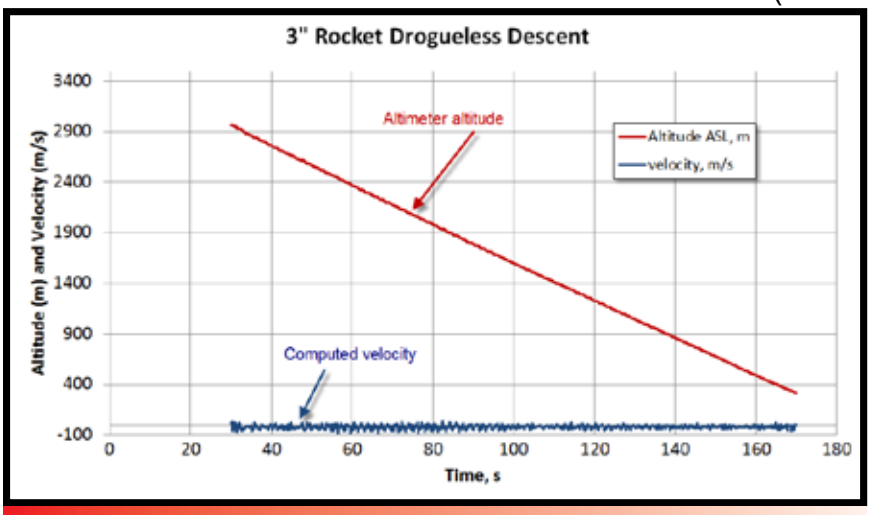

Figure 13: 3″ Drougueless decent graph.

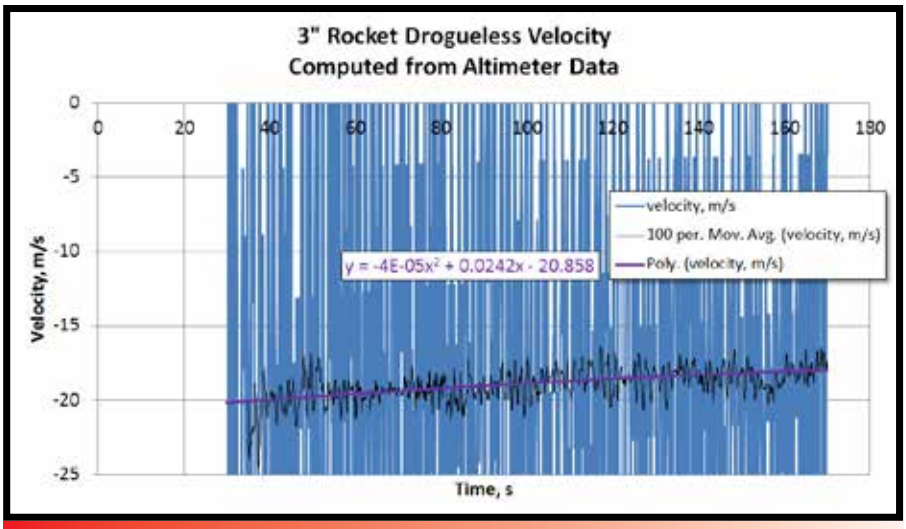

Figure 14: 3″ Drougueless Velocity computed data.

Figure 13 shows the drogueless fall of a 3" rocket after reaching apogee of almost 10,000 ft. (3000 m) on a K550 motor. The rocket is 72" long and with 4 fins. The altitude was measured by the barometric sensor of the onboard altimeter, and the velocity was computed using Equation 4. Even with a higher order derivative scheme, the velocity data still fluctuates wildly, because the derivative of noise is more noise. No other filtering was applied.

Figure 14 is a close up of the drogueless descent velocity. It is so noisy, the extent of the fluctuations are off the chart! However, I still want to get usable data for analysis. As in the first example, a moving average helps filter the plot, and the slowdown of the fall over time is evident.

When I studied the characteristics of parachute descent from RockSim in Figure 2, I saw that the terminal velocity curve is not linear. Indeed, velocity vs. time takes a much more complex form than a straight line. I experimented with different least squares curve fits, like square roots and polynomials, and found that a parabola fits the RockSim velocity data perfectly.

Learning from this, I applied a 2nd order polynomial trend line to my velocity

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in **Figure 14**, and the equation is shown. The curved shape is noticeable, just as in the RockSim simulation. A better approximation to the velocity will hopefully yield a more accurate computation of drag in the end. The effect of air density change is again revealed, as the rocket slows from -20 m/s to -18 m/s during the free fall.

Using the parabolic velocity fit, atmospheric model for density, and Equation 2, I computed the drogueless descent aerodynamic drag of the 3" rocket. It is plotted in Figure 15 along with the 4" rocket in the first example. The drag force is less for the 3" rocket, since the diameter is smaller and with four smaller fins instead of three large split fins. The C_DA is more constant over time, as I expected. This altimeter brand may have more robust pressure measurement, better velocity calculation (by me!), and better velocity curve fit as compared to the first example. The 3" rocket may simply have inherently more uniform drag as it falls, as well.

Summary

Directly determining the aerodynamic drag of the descending rocket, either with parachute or drogueless, is very challenging. It is hard to account for the various sections of body tube, fins, nose cone, harnesses and other recovery gear as they tumble and fall through the airstream. Precise drag measurements in a wind tunnel are difficult to set up. Drop tests and descent analysis are needed, yet these contain variations as well.

In this article, we looked at RockSim simulation to understand the theoretical behavior and the concept of terminal velocity in more detail, including the effect of air density changes. Velocity data was both provided by an altimeter and derived independently from altitude measurements. Least squares fits of the velocity helped smooth the data and allowed computation of the averaged aerodynamic drag of the rocket in its drogueless configuration. Finally, the correlated drag properties were used to define a phantom parachute to mimic the dual deploy events in RockSim more accurately.

About The Author

Ken Karbon is a rocketeer from Michigan. He works in the auto industry, specializing in aerodynamics and CFD simulation.

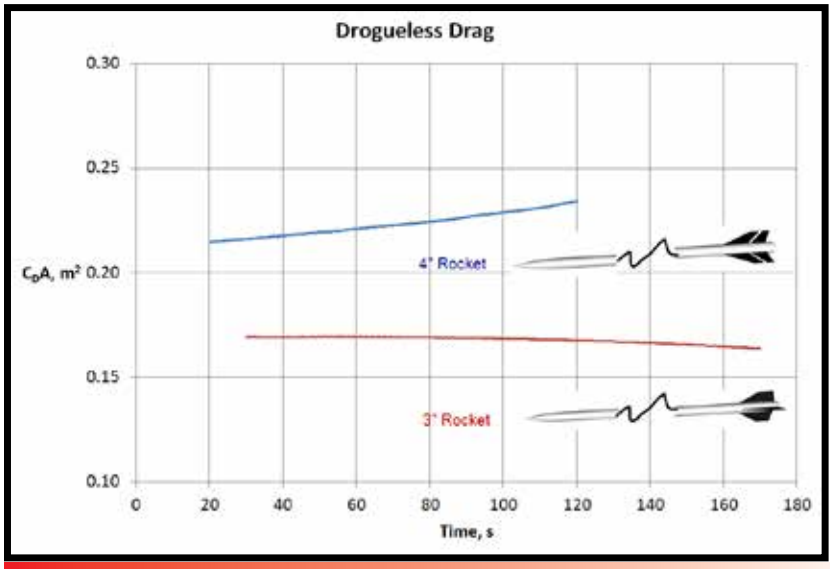

Figure 15: Drougueless drag graph.