Build Log: L1 Rocket *Soot Princess*

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Introduction

The purpose of this document is to provide a detailed (maybe excruciatingly so), transparent summary of a low-budget L1 high-power rocket design and scratch build process. I hope that this will help to remove barriers to entry in high power rocketry by freely sharing educational material and experience.

Acknowledgements

This project was made possible by the generous technical advice and support of Lavie Ohana and Dan Morgan. I would also like to thank Kemfic, Craig Bosworth Jr., Hamza Khan, and Joe Heimerl for their input on the design and fabrication. Finally, I am also grateful to Xyla Foxlin, Jenna Kay, Joe Barnard and Griffin Brown, all of whom inspired me to get involved in high power rocketry around Hot Nozzle Summer 2021.

Contents

1 Overview

Soot Princess is a scratchbuilt 54mm diameter rocket for low-power and level 1 certification high-power flights. Its design prioritizes simplicity of fabrication and durability for repeated test flights. Optionally, *Soot Princess* will include data logging equipment, recording its altitude, acceleration, and its position via GNSS.

Figure 1: Concept sketch of *Soot Princess*'s paint scheme, based on the "bloody nose" livery of the Southern Pacific Railway.

1.1 Flight series plan

I initially planned to to do four flights to ensure high confidence for the cert flight, and that's still the path I would recommend taking. I ended up deviating from this plan due to self-imposed timeline constraints, but the specific flight objectives are as follows:

1. "Plain" test flight on an F motor: only goal is to launch and recover safely; no avionics will be flown
2. Sensory test flight on an F motor: secondary goal of recovering altimeter, accelerometer and GNSS logs
3. Cert attempt flight: H motor, operational avionics required
4. Cert reflight: optional, H or I motor, operational avionics required

Deviation from the flight series plan had two causes: timeline pressure, and hardware availability. The timeline pressure occurred due to a family emergency within two weeks of LDRS, giving me less than a week to assemble the rocket. "Hardware availability" means that I was able to borrow a motor and GPS earlier than I expected to, giving me undue confidence in my readiness to attempt a cert flight.

2 Design Log

The initial design (v1.0) for *Soot Princess* was made using OpenRocket in late December of 2021. This design was reviewed by Dan Morgan, and revisions were made accordingly (v1.1).

The design configuration for a certification flight uses a disposable Aerotech H70W-10. This configuration has a projected stability of 3.12 cal. For low-power test flights, I used a disposable Aerotech F40-7 configuration, which had a stability of 3.3 cal.

Motor	F40-7	H70-10	H195-10
Velocity off rod	13.1 m/s	17.2 m/s	26.5 m/s
Apogee	419 m	1100 m	1131 m
Velocity at deploy	5.07 m/s	6.88 m/s	14.8 m/s
Optimum Delay	7.22 s	10.5 s	11.5 s
Max velocity	94.1 m/s	207 m/s	286 m/s
Max acceleration	94.1 m/s^2	143 m/s^2	338 m/s^2
Time to apogee	9.28 s	13.3 s	12.3 s
Flight time	42.2 s	96.9 s	97.2 s
Ground hit velocity	13.2 m/s	13 m/s	13.1 m/s

The fiberglassed plywood fins are swept 45 degrees at both ends to reduce the stress of landing. The reductions in fin area as a result of this necessitated the use of four fins rather than three to keep the rocket stable and avoid structurally and aerodynamically demanding increases in chord or span.

The fore body tube is fairly short in design 1.1, in order to maintain a reasonable TWR in low-power flights. If actual built values show stability issues, the fore tube should be lengthened.

Due to motor availability and upon consultation with Lavie Ohana, on April 4 2022 I updated the OpenRocket simulation list with an H195NBT-10 configuration. The higher apogee makes it more important that the rocket's avionics include location tracking capability for recovery.

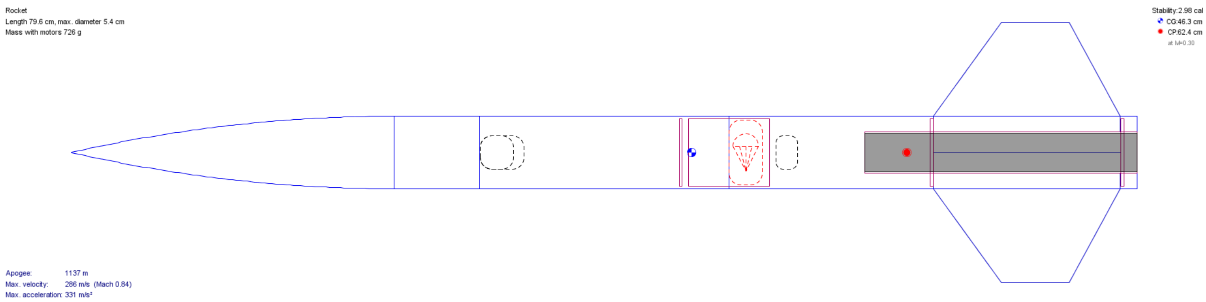


Figure 2: OpenRocket figure of *Soot Princess* v1.1 in H195NBT-10 configuration

2.1 Adjusted design "v1.2"

2.1.1 Parachute Correction

Due to my having no (0) brain cells, the initial design called for a 30 cm parachute rather than a 30 inch parachute. Correcting the parachute dimensions returned a ground hit velocity of 5.27 m/s, an improvement over the erroneous 13.2 m/s.

Upon further consultation with Lavie Ohana regarding acceptable impact velocities at FAR and Lucerne, the parachute diameter was updated to 24" rather than 30". For this diameter, OpenRocket returns a ground hit velocity of 6.55 m/s. Due to *Soot Princess*'s high apogee and expected fin can strength, we decided this was acceptable at these sites, and worthwhile for avoiding excessive drift during descent.

2.1.2 Improved Part Modeling

I've finalized the decision to use a LOC Precision plastic nosecone. A fiberglass Von Karman nosecone from Madcow was considered, but rejected due to higher cost and lack of listed mass specifications. To model the center of mass of the nosecone, I plugged in the OpenRocket preset for the LOC PNC-2.14, and adjusted the body tube diameters to accurately match the dimensions of LOC tubes. The preset model of the nosecone has a slightly larger outer diameter than that listed for the tubes, so there is a small discontinuity in the vehicle's profile. **This will need to be smoothed over during fabircation,** probably using epoxy applied to the body as it rotates slowly on a drill-driven spit-like jig.

I also took steps to specify the masses and positions of the eye bolts for the ejection system. The mass of each bolt was estimated as a simple torus and cylinder based on the dimensions of McMaster part number 3018T14. My estimates gave a mass of $(15.1625cc + 6.4352cc) * 7.85g/cc = 169.542g$

Adjusted bulkhead and centering ring thicknesses to match the 1/8" plywood I plan on using.

At this point the main issue in the OpenRocket model is the lack of good mass estimation for the fin can layup. This will need to be determined by direct measurement after fabrication. A possible concern is that it could move the center of mass too far back for stability, requiring an elongated fore tube and possible additional nose weighting.

Motor	F40-7	H70-10	H195-10
Velocity off rod	11.5 m/s	15.1 m.s	23.1 m/s
Apogee	302 m	989 m	1079 m
Velocity at deploy	8.06 m/s	7.17 m/s	17.9 m/s
Optimum Delay	6.28 s	10.6 s	11.8 s
Max velocity	72.5 m/s	174 m/s	239 m/s
Max acceleration	71.9 m/s^2	112 m/s^2	270 m/s^2
Time to apogee	8.27 s	13.3 s	12.1 s
Flight time	49.5 s	147 s	156 s
Ground hit velocity	7.37 m/s	7.29 m/s	7.35 m/s

3 Nominal Parts List and Bill of Materials

Part Name	Mass (g)	Cost (USD)	Notes
Cardboard Body Tube	192	11.43	
Inner Tube		10.48 USD for 6	29mm thin wall
Coupler		2.88	
Cent'g Rings	Not listed	6.10	Madcow 2.2"x29mm (2x)
Fins		Fraction of stock material	Custom (1/8" plywd)
Bulkhead		Removed from design	Custom, hole-sawn?
Nosecone	112	17.78	LOC, Poly-propylene 9.5"
Shock cord		4.40	1/8" diameter elastic
Eye bolt(s)	Not listed	10.32	2x McMaster Part 3018T14
Parachute	48.19	11.05	Top Flight 24" Nylon chute
Parachute protector		7.37	Dinochutes 9x9
Layup	Vibes-based	TBD (removed from design)	On fin can
Rail Buttons	"Negligible"	N/A (thanks Lavie!)	1010, printed

4 Fabrication Log

4.1 Cutting Body Tubes To Length

After receiving the body tubes on 2022/05/01, I used a 3-sided scale to draw a parallel axis line on the tube. Then I used dial calipers to mark 10-cm increments along this line, and used these marks to reference the lengths for 30.5 and 25.0 cm body tube segments. I then used masking tape to mark circumferences at these lengths which will be the final cut lines for the body tube segments.

Using a utility knife, I made the fore cut roughly and used sandpaper to adjust it to the desired dimension, checking flatness by resting the tube on a table on its cut end to find high and remove high spots.

For the aft cut, I used a miter saw instead due to its ability to cut a straight line with a predictable 2.9mm of removed error. This produced a satisfactorily flat edge, and the change in length will have to be accounted for in simulations.

4.2 Deburring the Nosecone

The nosecone arrived on 2022/05/01 and fits properly with the body tube; the only modification needed is the removal of some surface features from the molding process. These need to be removed symmetrically to create a smooth, uniform aero surface. The easiest way to do this is to turn the cone on a drill and run sandpaper along the surface until the nosecone is uniform. Fixturing the part to the drill chuck

Figure 3: The body tube with segment lengths marked. Fore segment is on the left, aft segment on the right

(a) The unfinished fore cut

(b) The fore cut sanded to dimension

Figure 4: The fore cut, showing the significant amount of error that had to be removed by sanding

is a challenge as the shoulder diameter is substantially wider than the chuck of any drill I have access to.

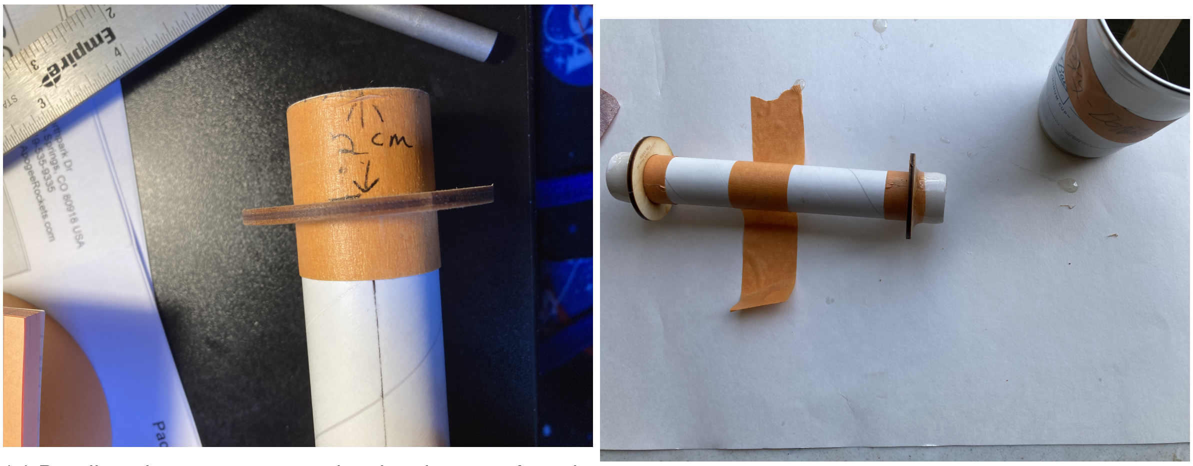
With no machine fixturing options, on 2022/06/10 I deburred the nosecone manually, using sandpaper to support the cone segment while rotating it via the shoulder segment. While this did not achieve a high degree of precision, it was faster to set up and achieved satisfactory results. Possible health and safety issues with getting bits of plastic dust on my hands and possibly inhaling trace amounts of plastic.

4.3 Motor mount

The motor mount assembly uses one 21 cm long section of 29mm diameter thin-wall cardboard body tube (apogee part number 10111) fixed to two plywood centering rings using five-minute epoxy. The centering rings were adapted to fit securely on the tube using several layers of masking tape. To make sure the tape was symmetrical I applied it in single-circumference-long pieces rather than continuously wrapping it. I'm not sure how important this was, and there was still a small amount of play and I used a square ruler to make sure it was perpendicular before applying epoxy.

The centering rings were 2 cm from each end of the inner tube. The epoxy was applied to the outer ends to preserve a right angle for the fin tabs. Most of the masking tape was cut away before applying the epoxy, to make sure the tube and rings were attached to each other and not to the tape.

To make sure the epoxy formed symmetrically while it cured I rotated the whole assembly by hand until it was sufficiently solid. The results of one large fillet for each joint were satisfactory, and I then made the fins using the motor mount's dimensions to drive the tab length.



(a) Detail on the motor mount, showing the use of masking tape to friction fit the centering rings too the inner tube

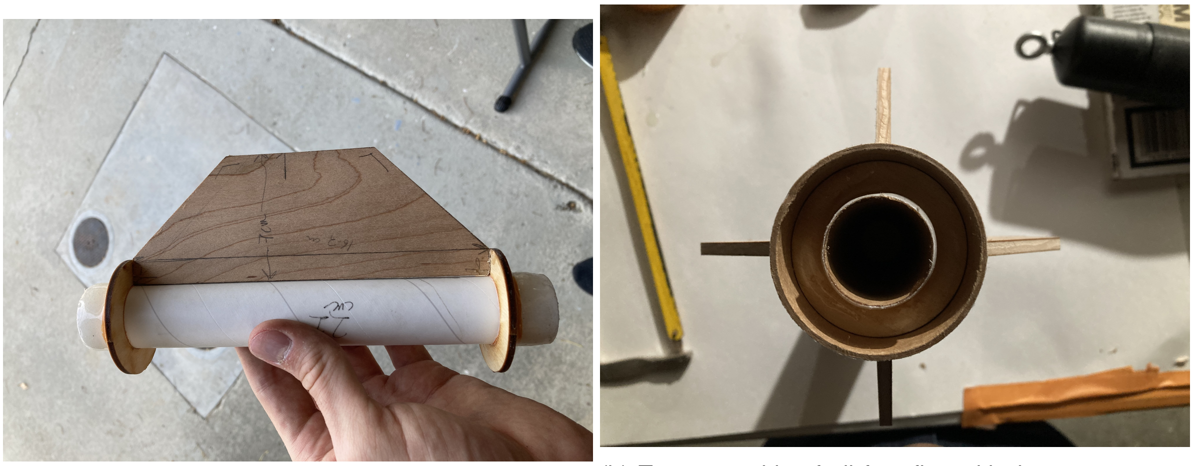
(b) The motor mount curing. Note the removed masking tape under the epoxy fillets.

Figure 5: Motor mount assembly.

4.4 Fins

In the interests of time and to increase factor of safety, I used 1/4" maple plywood rather than 1/8" as planned, and scrapped the plan for fiberglass layup. Critical to making the fins was a mitered chop saw which allowed me to reference the 45 degree sweep on both leading and trailing edges of the fins from the "factory edge" of the stock plywood.

To simplify fabrication by avoiding cutting any concave shapes, the fin tabs occupy the entire root chord of the fins. The size of the fins was checked by test fitting them in the motor mount, then when they all fit they were clamped together and trimmed to match each other using the miter saw.



(a) One fin test fit into the motor mount

(b) Test assembly of all four fins with the motor mount and body tube.

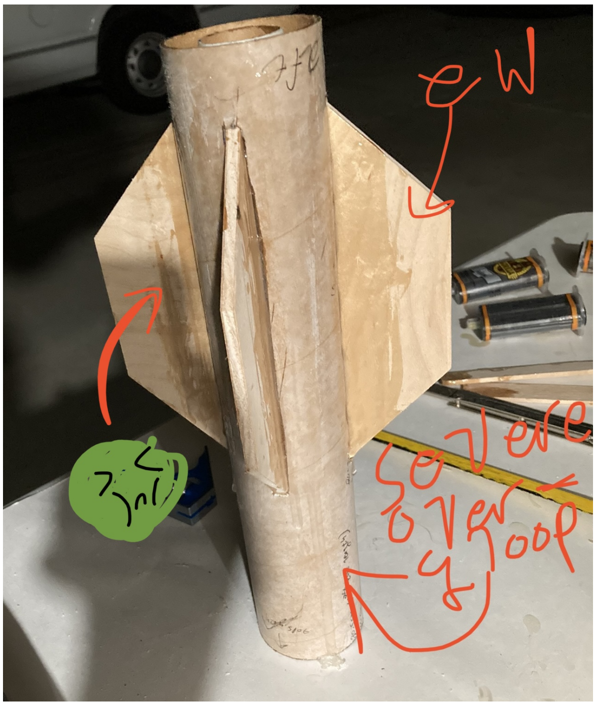
Figure 6: Fin can test fits.

4.5 Fin Can Assembly

The fin can was assembled "through-wall", meaning that the fins fit through slits in the body tube and rest on the inner tube and centering rings. They are attached to the body tube by epoxy fillets on the outside of the body tube.

I cut the slits by hand using a utility knife, following lines drawn using a three-sided scale ruler. I was not happy with how these turned out (there was a lot of inconsistency in the edges), and for a higher-power rocket they would not be sufficiently precise. At L1 scale, however, the precision was sufficient even without using a jig for the fins.

The initial bond was made using small amounts of epoxy to "tack" the fins in place. After giving this epoxy several hours to cure in vertical orientation, I then sanded off excess that had dripped out of place and added the fillets two at a time in horizontal orientation.



(a) The initial "tack" assembly, with excess epoxy labeled.

(b) Two fin fillets curing.

Figure 7: Epoxying the fin can assembly

4.6 Recovery Hardware

The shock cord's aft mounting point was a centering ring with a hole drilled in it for the aft eyebolt, attached to the aft tube segment and reinforced with blobs of epoxy. The fore mounting point was an eyebolt mounted directly in the back of the nosecone, with a nut and epoxy on the inside, applied while I was making the avionics bay. I used anchor hitch knots in the shock cord to attach it to these points, and the chute and its protector are tied to the cord at about 1/3rd of its length.

4.7 Avionics Bay

Avbay design was something of an afterthought. I initially expected to launch at Lucerne, where recovery would be possible using visual navigation only, and did not factor it into my design. For the July 2nd cert attempt at FAR, I added a hole in the nosecone shoulder, into which I epoxied a 29mm tube segment cut at an angle to align with the shoulder. The featherweight GPS and its battery would sit inside this tube, padded by a small sheet of bubble wrap and retained by masking tape around the shoulder.

5 Avionics

5.1 Requirements and Priorities

5.1.1 General

The primary purpose of *Soot Princess*'s avionics is to aid in recovery on high-power flights. Being a small airframe, the rocket will have a high apogee that may make visual tracking difficult, so being able to find its location remotely is critical to ensuring recovery.

The secondary purpose is to record data over the course of the flight and create plots that can be compared to simulated plots. For this, the primary instrument is an accelerometer, and the GNSS component will be used to record altitude and downrange translation.

Additionally, monitoring the environment inside the rocket could yield interesting and useful results, making use of a thermometer and barometer.

5.1.2 Capability Priority List

1. Post-flight GNSS beaconing for recovery
2. in-flight GNSS recording for plotting
3. in-flight acceleration recording
4. in-flight pressure and temperature recording

6 Built Measurements, Re-simulations and Adjustments

6.1 Simulations based on measured model

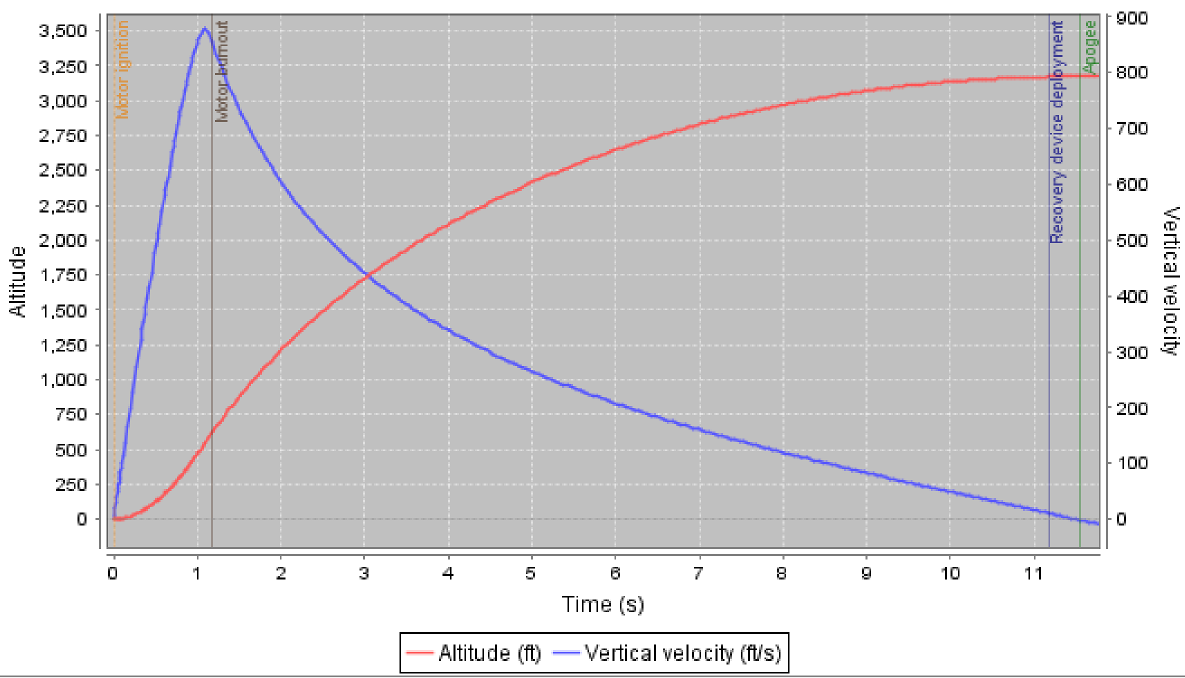


Figure 8: Simulated altitude (above ground level) and vertical velocity over time during the critical phase of flight, based on measured values.

6.2 Build Cost Estimate

7 L1 Cert Attempt Flight (loss of vehicle)

7.1 Procedure

7.1.1 Preparation

On launch day, July 2nd, there were three key tasks that remained to be completed: installing rail buttons, motor integration, and checking that avionics were integrated satisfactorily. The first two were straightforward and experienced no issues. Avionics integration, however, posed a problem when the connectors on both batteries I had were damaged unexpectedly. I was unable to repair them and had to borrow a battery from someone else. I did not have time to check its charge, nor did I know what effect the loading conditions of flight events would have on the structural integrity of the connector. This lack of preparation, stemming from timeline pressure and inexperience with avionics, was a major cause of the failure to cert.

7.1.2 Pre-flight Inspection

There were two items raised during pre-flight inspection. First, the risk of drag separation of the body from the nosecone, which was addressed by wrapping the cone shoulder in masking tape. This also served to retain the avionics in the avbay. Second, the use of an elastic shock cord was advised against due to risk of rebound. Inspector mentioned that it allowed for the possibility of the nosecone impaling itself in the body tube.

7.1.3 Launch and Recovery Efforts

Wind speeds were measured at around 18 mph leading up to launch. The launch rail was angled one increment upwind to compensate for this effect. Launch and chute ejection appeared to have no issues, but due to the high speed and altitude it was difficult to maintain visual contact. Based on simulated apogee and measured wind speed, we estimated that the rocket had probably landed about two miles downrange, to the northeast. This estimate could not be confirmed because the GPS stopped transmitting less than three minutes after launch, well before landing. I was not able to recover on launch day for health and safety reasons (I hadn't brought enough water, and temperature and wind were both very high.)

After exporting and analyzing data from iFIP (see the "Flight Data" subsection), I went back to FAR on July 16th to search the estimated landing area. Because this area was large, and partially overlapped with private property boundaries, I was not able to search it entirely, but thoroughly searched what area I could, finding no sign of the rocket.

7.2 Flight data

Plotting the data recorded by iFIP in Microsoft Excel provides useful information. First, the projected apogee of over 3000 ft was accurate. The vertical velocity is harder to judge the accuracy of, and acceleration was not measured at all. See figures 10-12.

7.2.1 Fault analysis

The loss of signal that made the rocket unrecoverable has multiple possible explanations. My first guess was that the battery was low on charge, which caused the GPS to lose power. It is also possible that the forces of flight caused the battery to disconnect, probably by damaging the point where the wire joins the battery's board. I favor the first explanation, as the loss of signal occurred after a minute of chute descent that looked stable, but both are plausible. Avbay design was lacking, and is something to improve on in future.

Figure 9: *Soot Princess* on the launch rail at FAR, minutes before launch.

7.3 Lessons Learned

7.3.1 High level design

A "low and slow" flight profile is more reliably recoverable, and should be prioritized over cost savings on a lighter airframe. This was something Dan told me early in the design process, and was confirmed by experience.

7.3.2 Low level design

The avionics bay design needs more attention. Care should be taken to address possible loading conditions of flight, and the bay should be easily accessible for pre-launch inspections.

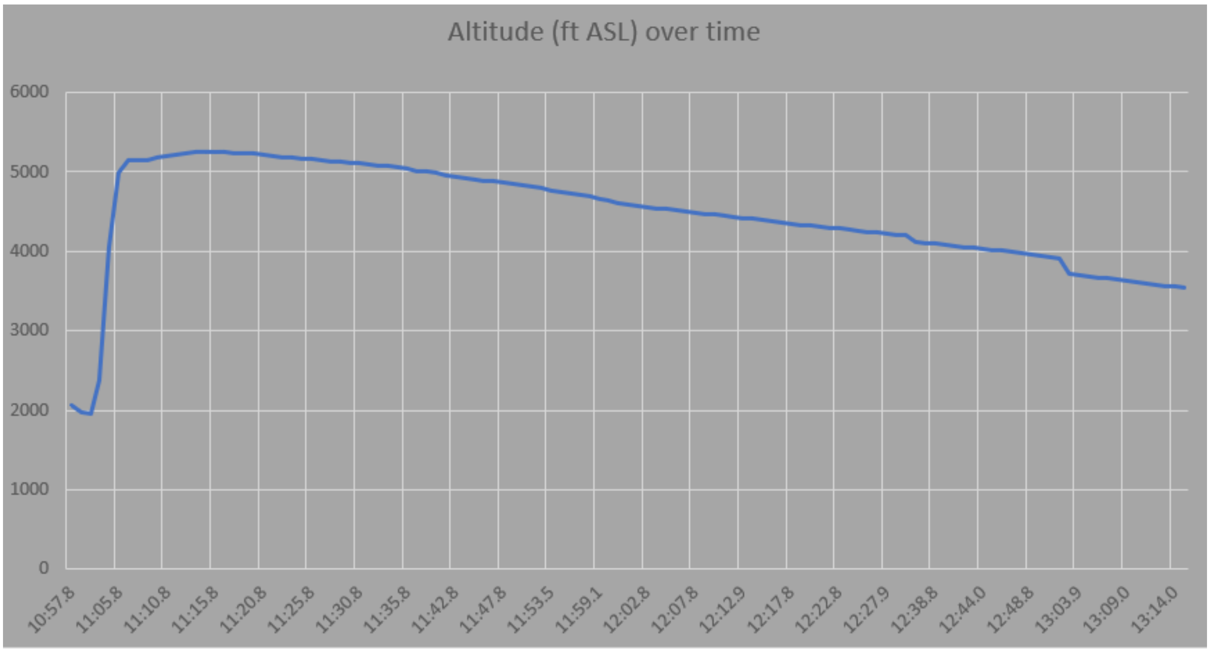


Figure 10: *Soot Princess*'s altitude above sea level over time, from launch to loss of signal, from Featherweight GPS measurements.

7.3.3 Operations

8 Final Parts List and Bill of Materials

Part Name	Cost (USD)	Notes
Cardboard Body Tube	11.43	
Inner Tube	10.48	29mm thin wall (Pack of 6, 1 used)
Coupler	2.88	
Cent'g Rings	17.28	29mm to 54mm (3x)
Fins	20.98	2' by 4' 1/4" plywd stock, small portion used
Nosecone	17.78	LOC, Poly-propylene 9.5"
Shock cord	4.40	1/8" diameter elastic
Eye bolt(s)	10.32	2x McMaster Part 3018T14
Parachute	11.05	Top Flight 24" Nylon chute
Parachute protector	7.37	Dinochutes 9x9
Rail Buttons	N/A	1010, printed
Featherweight GPS	165.00	Borrowed and lost
Battery	17.00	Borrowed and lost
Total	295.97	

Total project costs, factoring in fuel for driving to the launch site and shipping on parts, should also be considered, but I don't feel like listing it.

9 Next Steps

My near-term rocketry plans are to build a different design of rocket for my L1, potentially using denim composite layup structures, wider and more readily available airframe tubes, and more room for avionics and ballast. Greater flexibility of design, operations and recoverable flight envelope will make the next rocket an improvement over *Soot Princess*, using the lessons learned from this project.

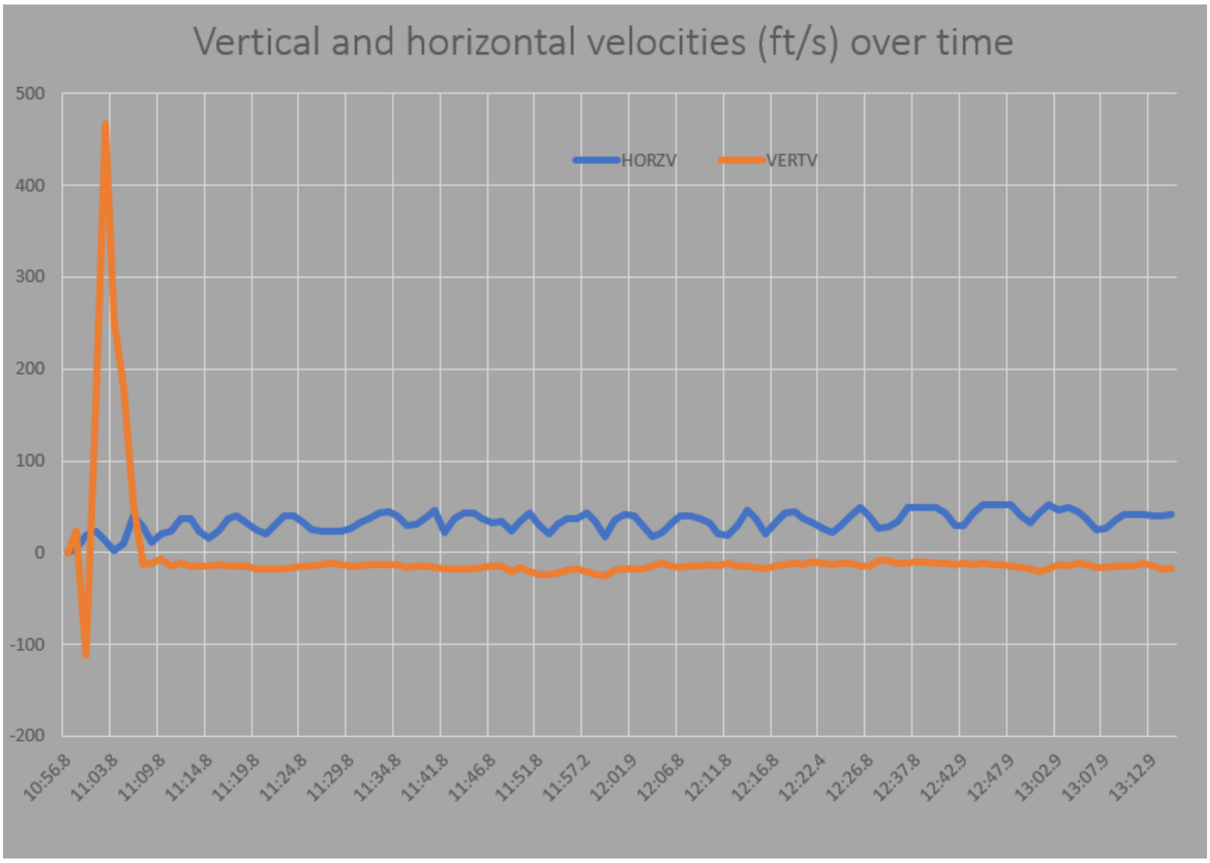


Figure 11: Horizontal and vertical velocities over time after launch, from Featherweight GPS measurements.

Figure 12: *Soot Princess*'s latitude and longitude over time (the yellow pins), exported from iFIP and overlaid onto a Google Earth satellite map as a KMZ. Napkin math for estimating landing time and translation due to drift are also written on this figure.