Mini Report on Simulation Results (Cycle 1)

TL;DR version:

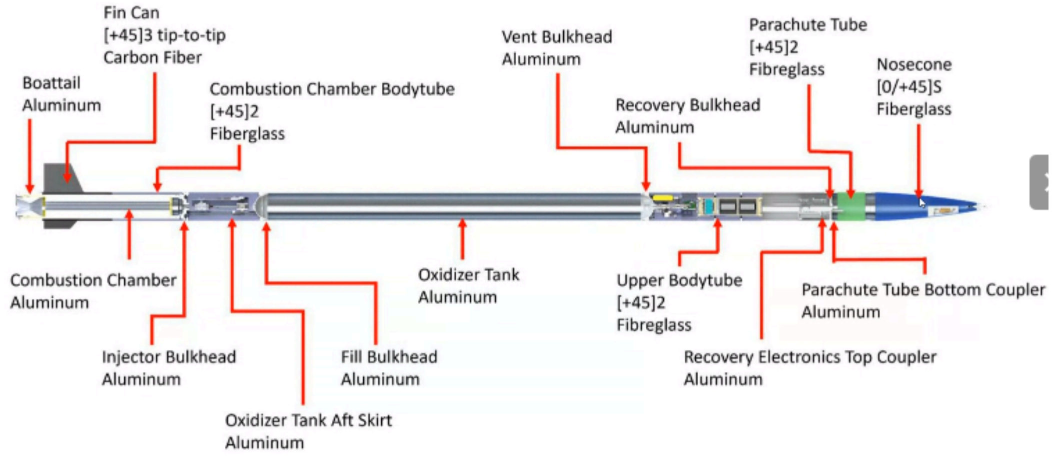
- **What is the current expected rocket performance?**
  - *Expected values are: mass expected, thrust 150%, 2022 fins)*

Characteristic	**Expected value**	**Range across sim cases**
Apogee (ft)	27 268	23 806 - 31 903
Off rail velocity (ft/s)	99.2	72.7 - 108
Off rail stability (calibers)	2.55	2.06 - 3.84
Max stability (calibers)	7.02	6.76 - 8.49
Max Velocity (ft/s)	1507	Data not gathered
Max Mach	1.37	1.05 - 1.57
Max acceleration (G)	9.34	4.98 - 10.85
Length	192in or 16ft	184.1in - 196in (Not explicitly in sim cases)
Dry Mass (lbs)	79	60 - 100
Wet Mass (lbs)	135	100 - 156
Center of Gravity (from nosecone)	109in	104in - 109in
Center of Pressure (from nosecone)	142in	N/A (does not change without changing length/shape)

- **What did this cycle reveal?:**
  - Our rocket is improving significantly from KOTS 2022. Main differences are:
    - Lower mass all around
    - Better “natural” (not fin based) stability
    - Planning to increase peak thrust by 140% while impulse remaining constant. This improves off rail velocity at very least. Note this case was unfortunately not directly simulated so the closest approximation is the 150% thrust case.
    - Rocket is shorter by around 10in
      - Reduction has been made primarily in the OTAS, Vent, and Parachute tube
      - Further sizing needs to be done to solidify these lengths
  - Mass distribution study

- 59% of dry mass is in the propulsion system, with half of that concentrated in tank walls.
    - Reduction of mass in all components would make improvements to overall weight and greatly improve stability performance
- 15% of dry mass is in the airframe structures
    - Reductions in length compared to 2022 weren't factored into this report. But reducing size by employing better strength-weight alloys and lighter composites is encouraged
    - Design for assembly and manufacturing can take precedence in certain cases
- 14% of dry mass is in the recovery system, with 56% taken by the parachute and ~40% taken by the sled & bulkhead.
    - Reducing size by employing better strength-weight alloys and smaller components is encouraged
    - Design for assembly and manufacturing can take precedence in many cases
- 11% is in the payload but that mass can't be changed. Great job being just the right amount of heavy Paylads!
- 1~2% is in the Electronics & software
- Preliminary Design Load Cases
    - Work is ongoing to produce preliminary loads and will be reported in the coming week.
    - 4 Primary cases are Takeoff, MaxQ, Drogue deployment, landing

- **What changes rocket performance?**
    - Lighter = higher apogee (17lbs lighter = 3000ft difference from heaviest case to expected), heavier = lower apogee
    - Mass increasing at the top of the rocket or disappearing from the bottom of the rocket dramatically increases stability (anything that moves center of mass up)
    - While in this round fins were left the same, it is very easy to increase/decrease stability by fin size changes but it results in significant apogee changes (drag).
- **Pictures:**



Fin Can
[+45]3 tip-to-tip
Carbon Fiber
Boattail
Aluminum
Combustion Chamber Bodytube
[+45]2
Fiberglass
Vent Bulkhead
Aluminum
Recovery Bulkhead
Aluminum
Parachute Tube
[+45]2
Fibreglass
Nosecone
[0/+45]S
Fiberglass
Combustion Chamber
Aluminum
Injector Bulkhead
Aluminum
Oxidizer Tank Aft Skirt
Aluminum
Fill Bulkhead
Aluminum
Oxidizer Tank
Aluminum
Upper Bodytube
[+45]2
Fibreglass
Recovery Electronics Top Coupler
Aluminum
Parachute Tube Bottom Coupler
Aluminum

More detailed Mini-Report:

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Fast Rocket Facts:

Our current rocket performance simulations predict apogee of 76 football fields,
barely acceptable off rail velocity slightly faster than a cheetah, pretty acceptable off rail stability unlike KOTS 2022, a max velocity of faster than an F-86 sabre and a max acceleration around the same as fighter jet pilots can take in a sustained high G turn.

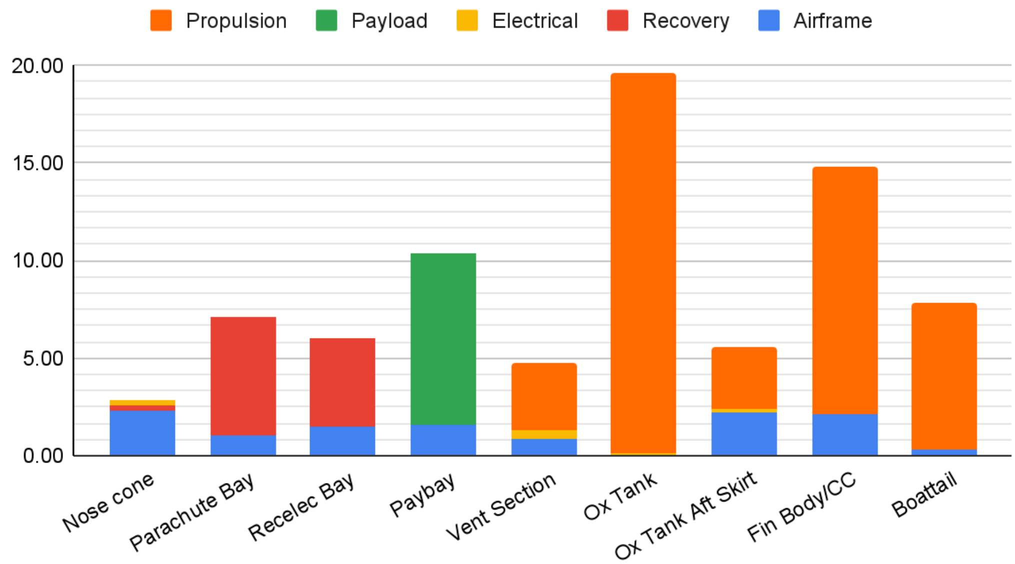
Mass Distribution:

The distribution of system mass in the rocket looks as follows:

System	Airframe	Recovery	Electrical	Payload	Propulsion	Propellant	Total (Wet)
Total (Lb)	**12.05**	**10.76**	**1.06**	**8.82**	**46.25**	**56.00**	**134.94**
% of Dry	15.26%	13.63%	1.34%	11.17%	58.59%		

Dry Mass	78.94	Lb

Prop. Mass Frac.	41.50	%



Of these, the heaviest systems are the propulsion, airframe, and recovery. The payload mass can not be changed per competition rules and is not an area we can look in for improvements. The 3 largest systems are broken down further. These are based on the 'Expected' mass case, the implications per system are -briefly- summarized below each table. For more details see the mass input sheet.

Airframe	Mass (Lb)	% Total System	% Total Dry
Upper Composites	5.73	47.54%	7.25%
Lower Composites	3.67	30.46%	4.65%
Couplers	1.00	8.30%	1.27%
Tip	0.16	1.33%	0.20%
Longerons	1.07	8.85%	1.35%
Payload Adaptor	0.42	3.52%	0.54%
Total	12.05	100.00%	15.26%

Notes: A composite boat tail is considered. The majority of components are using KOTS 2022 weights & Lengths. Reductions in composite and longeron weights are expected.

Propulsion	Mass (Lb)	% Total System	% Total Dry
Plumbing	6.61	14.28%	8.37%
OX Structure	17.33	37.47%	21.95%
OX Bulkhead	2.16	4.68%	2.74%
CC Structure	6.00	12.97%	7.60%
CC Bulkhead	1.40	3.03%	1.77%
CC Contents	5.30	11.46%	6.71%

Nozzle Parts	7.46	16.12%	9.44%
Total	46.25	100.00%	58.59%

Notes: a 7075 Ox tank of ‘conservative’ sizing is considered, it alone is 10lb lighter than the 6061 version.

Recovery	Mass (Lb)	% Total System	% Total Dry
Metallic	1.30	12.08%	1.65%
Parachute	6.05	56.23%	7.66%
Electronics Sled	2.11	19.61%	2.67%
BH Components	1.30	12.08%	1.65%
Total	10.76	100.00%	13.63%

Notes: Most component weights are ‘as measured’ from KOTS 2022, Reductions in parachute, bulkhead, and E-sled are expected. The electronics sled includes both the structure and electrical components, So the split between Recovery & Electrical is not well defined here. Metallic includes the bulkhead and both eyebolts

The rocket's expected dry mass has improved significantly compared to KOTS 2022, However, this ‘expected’ mass case is still predicted to hit 2500 ft short of the 30k mark. It’s expected that a further 19 lb reduction in overall dry mass is required for the rocket to reach the target, which is approximately the ‘minimum’ predicted case (as simulated).

Based on the sources each system listed in the mass audit, the airframe and recovery ‘minimum’ case seemed generally quite conservative, as it was usually a slight reduction from the ‘Expected’ case which itself was usually taken directly from KOTS 2022. Recovery and Airframe are encouraged to continue seeking opportunities to reduce mass below estimated minimums where possible, however the nature of these systems being already relatively light means that design for ease of assembly can take precedence, as long as mass does not increase past the expected case.

The majority of dry mass reductions have come from the propulsion system thus far. The propulsion team is encouraged to continue seeking additional reductions that can be made in the weight of plumbing, bulkheads, tank structures, and nozzle. It’s expected a majority of the remaining 19 lb to be taken out should come from reductions in the propulsion system. However it is also clear from the mass audit sheet that many of the minimum mass case estimates are ideal estimates. Further conversation can be had to identify concrete areas for further mass reduction.

Section Lengths:

Sections	Nosecone	Parachute Bay	Recelec Bay	Paybay	Vent Section	Ox Tank	Ox Tank Aft Skirt	Fin Body / CC	Boattail
Expected	25”	9.36”	14.14”	13.79”	6”	80.28”	9.5”	30.19”	4.2”
Maximum	+0	+0	+0	+0	+1	+0	+3	+0	+0
Minimum	-0	-3	-4.3	-0	-0	-0	-1	-0	-0

Overall Length: 192 inches

These are the allotted section lengths based on discussion of current design concepts. More info on definition and reasoning can be found in the lengths tab of the Length/Mass tracking sheet.

Impact of RF Clear Zone :

In order to understand the impact on flight of creating an RF clear area (for the antenna to get better reception) two simulations were run with slightly decreased length of the rec-elec section - Existing: 14.14”, Reduction one : 11”, Reduction two: 8”.

Note this does not consider the reduction in weight by shortening the structure however this weight change would likely be small (order of 0.5 lb).
The result of these simulations was that the impact of this area is fairly negligible. Most of the main flight characteristics remained nearly identical and the ones that did change did not change significantly. The most notable impact is that a shorter rocket improved off-the-rail, however a small amount

It is thus recommended that if an RF clear zone is required for optimal performance of the high power radios (which is a distinct design goal for this years project), it can exist with negligible impact on rocket performance.

Loads Analysis:

Analysis is ongoing to produce the predicted structural loads for the rocket to resist in flight. Axial, shear, and bending diagrams will be produced for the rocket and it is expected that structural members and joints will be designed to the worst case identified. These loads are expected to be released after being peer-reviewed November 7th.

Design load cases will be tabulated and found HERE when completed.

The four main load cases to be considered are Takeoff, MaxQ, Drogue deployment, and Landing. The document linked above (Rocket design specs) will aim to indicate which load cases should be considered for design of which sections.

Note about Fin Geometry:

It is important to note that for this cycle the fin geometry was frozen with the geometry used on KOTS 2022. This was done as fin sizing mainly impacts stability, drag, and mass. The fins will be sized later for stability and the resulting drag and mass are factors that will just have to be accepted in order to make the rocket stable. As the stability cannot be known before doing simulations, in order to simplify the problem and allow meaningful results to be gathered we are not considering the fin size change at this point.

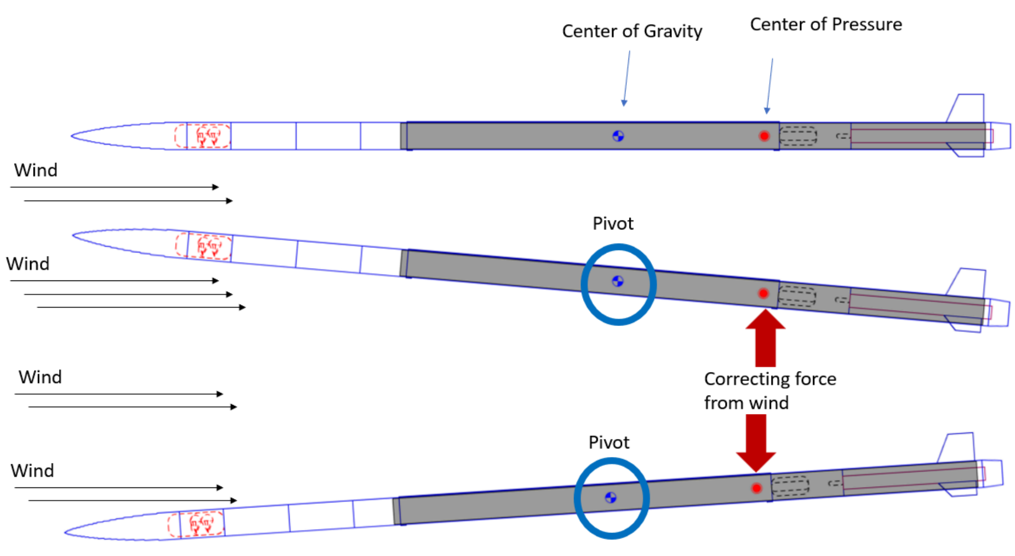
At the same time, based on the results gathered at this time the “natural” stability is significantly better than previously. This means that the fins will almost certainly be shrunk and this will slightly decrease mass while mainly decreasing drag. Therefore we can expect that in actuality the rocket will have increased apogee compared to what we are currently simulating due to the fin size decrease. This decrease will be a focus of a later cycle.

What is “natural” stability?:

We wanted a term to describe how stable the rocket would be discounting the effect of the fins. Therefore Joel created this term to roughly describe how stable the rocket is without the fins acting on the rocket. This is useful as the fins can be changed to make any rocket almost any stability, however some mass distributions enable way better fin designs due to more natural distance between CG and CP. This term does not have a value it is just a relative term. If that does not make sense ask Joel for more clarification or read the section below.

What is stability? (same as last report):

Stability can be defined as the ability of a rocket to right itself when the angle of attack is pushed away from vertical. For a rocket to be stable it’s center of pressure (CP) must be located aft of the center of gravity (CG). One way to make this intuitive is to think of the CG as a pivot point and the CP the location where the wind force is exerted on the rocket. This clearly will push the rocket back into a vertical position if the CP is below the CG as can be seen below:



Note that if the CP were above the CG the force from the wind would push the angle of attack even farther from vertical.

Static stability is defined as the distance between the CP and CG divided by the bodytube diameter. Note however, static stability changes throughout the flight due to the CG moving up the rocket due to losing fuel and oxidizer mass. Also, dynamic stability is more complicated to define as it takes more details into account. Things such as coupling between roll, pitch, yaw and how dampened the rocket's response to oscillations is.

When it comes to how rigorous this method is, as far as I understand, stability margin calibers were invented by model rocket makers to have a ballpark way of understanding if small rockets would succeed or fail. The metric for what is acceptable was largely developed through trial and error as it's quite a challenging problem and not worth solving properly for model rockets. Since then simulations have come a long way, lots of trial and error have happened and openrocket has become widely accepted for the kinds of things we do. However it is still wise to keep in mind that this metric is a little bit unititutive and abstract as it is essentially a rule of thumb based on reality. Honestly, more study into the specific dynamics of stability may be a good thing to do in the future to further understand how much the rules of thumb can be trusted.

What is "Off-Rail":

- Off rail is defined by IREC as the moment when the rocket is able to move in the roll, pitch or yaw direction which they note usually occurs when the last launch rail forward of the CG clears the rail.

What values are reasonable for off rail velocity and stability?

- Both the launch canada and IREC DTEG documents recommend a launch rail velocity of about 100ft/s or good flight simulations/flight proven evidence that the rocket is stable regardless of the lower launch rail velocity. IREC requires launch rail velocity to be above 50ft/s.
    - Note also that a lower off rail velocity makes the rocket more susceptible to wind variation at rail clearance leading to lower stability in high winds.
- IREC DTEG requires rockets to have greater than 1.5 to 2 stability margin calibers at all times throughout ascent
- IREC DTEG states: "A launch vehicle may be considered over-stable when it has a static margin significantly greater than 2 body calibers (e.g., greater than 6 body calibers at liftoff.)"

Summary of work on other simulation software:

All the previous results have been from OpenRocket. Through research of other software, it was determined that RASaero was an efficient option to experiment with, as it includes a decent UI while having self-proclaimed (and vouched for by others) higher accuracy of results. KOTS was modeled in RASaero as a way to test the ease of use of the software, as well as to compare the simulation results to OpenRocket.

The most apparent difference between RASareo and OpenRocket is the design capabilities. Generally, OpenRocket will take more inputs while RASaero only cares about a select few required to model the aerodynamics. It is also important to note that RASaero has some locked settings, such as the inability to change units and the position/number of launch lugs.

Aside from the difference in modeling capabilities, the most time-consuming and the cause of the majority of current problems with the simulation was the engine file. It was mostly dealing with formatting problems as the file format is different from OpenRocket so certain issues had to be worked out before the simulation could be trustworthy. The main part remaining is to ensure the engine file as well as other inputs are fully trustworthy in the current simulation (which models case 1a). After this is done if there is lots of time before cycle 2 more simulations will be done to see how the results vary with changes in variables. Regardless of if this exploration is done before cycle 2, all of the cases for cycle 2 will be modeled in both OpenRocket and RAS Aero to further explore the differences.

At the same time RockSim is another software under consideration that is also being worked on. Currently Shiv Patel is building a simple model of KOTS+ and doing research on accuracy. In a week or two a meeting should be held to discuss the current stage of research however most likely this project will be shelved as RASAero so far appears more promising.
Moving forward, it is difficult to determine what software to trust the most with a lack of flight testing (from our team) and verification of results. There are a few paths currently being considered although they are currently a work in progress and this topic requires more team conversations and discussion.

1. Pick one piece of software which appears most trustworthy and use only its results.
2. Use the results of multiple pieces of software picking and choosing what results are more trustworthy based on research about accuracy.

Joel’s current leaning is to the second. This is due to the team's previous use, experience, and documentation of openrocket making certain characteristics more reliable in Openrocket (stability, off rail velocity etc.). While the research on RASAero suggests that it is more accurate in determining effects of transonic aerodynamics on drag meaning it is better for other characteristics such as apogee where drag is a significant consideration. There are also other considerations to this such as OpenRocket allowing more customization on certain characteristics.

Notable Errors:

1. The mass audit omitted details of the dip tube and the fill disconnect hatch. Thus the impact of these aren’t included in the completed simulations
2. It was noticed late in the process that a spreadsheet formula error omitted the fin can from being considered in the overall mass of the rocket. This error impacts only the simulations and not the mass distribution discussion. The impact of this error on simulation results is expected to be small but not insignificant (2 lb difference). Due to

when this error was found and the inherent uncertainty that exists in other areas, it wasn't deemed productive to re-run simulations with this fixed.

Where is the raw data?

All the raw data can be found in these spreadsheets:

- Simulation Data (Actual sims in GrabCAD\2020 - Kraken of the Sky\Openrocket\KOTS2023 Cycle 1 Simulations) https://docs.google.com/spreadsheets/d/1O7EI6IzpHXXCWCLqXju4nxJKGlHdr366o6npeITfkjM/edit#gid=0
- Mass & Length data https://docs.google.com/spreadsheets/d/1poRCKzhNSZfQRoP2KN2xZRwuLLkZauFutRtuNmLCAjw/edit#gid=0

How Accurate are these Simulations?

While Openrocket is a reasonably good tool for simulations there are sources of error in these simulations that mean this data should only be used for comparative purposes. Some of these reasons are listed below:

1. RSE uncertainty
    a. At competition changes were (heroically but very hastily) made to the way the RSE files are calculated based on temperature which may or may not accurately represent the way the engine responds to said temperature. Some investigation has been done into how accurate this file is and have determined it is accurate enough to hold us over until new static fire data has been gathered. The engine file developed at comp was used for all the simulations in this round (including as the base for the altered engine changes)
    b. Meanwhile we have determined that we want to increase the peak thrust of the engine by 140%. Due to time this RSE file was not created for this round of simulations so the closest to expected case simulated was the 150% thrust case
2. Weight uncertainties
    a. There is some uncertainty as many parts of the rocket have not been designed so far. To capture this a min and max design case was used and as we progress through the design cycle we will discover how accurate those guesses are. Note that the sources of information are listed in the spreadsheet that the masses were collected in.
3. Simulation simplifications
    a. Wind and aerodynamics is a very complicated field and openrocket makes several simplifications about wind and other factors which are generally not a huge deal but do create some uncertainty. A good example is that the atmosphere is made up of multiple layers that often have different wind conditions which openrocket does not account for. Instead openrocket accounts for this using a pink noise generator to generate random wind shear.
    b. Surface roughness is hard to quantify and impacts drag significantly.

Lessons Learned about Process:

- It is important to explain to subsystem leads how important it is for us to get usable estimation data. Some of the sources and values were questionable in this round. One way to help with this would be to have a structure for sanity checking the inputs after they are all imputed. This should be done next cycle. For this cycle this does not have a crazy impact as many of the mass inputs are a rough estimation anyway.
- It is more complicated to define reference planes then Joel assumed at first especially in the absence of a completed CAD model. A conversation should be had about this before next cycle.
- It is hard to stick to timelines but possible.
- Tracking mass distribution by subsystem and subsection was very useful.
- Loads analysis needs to be started earlier and takes time to consider.
- A more rigorous process for double checking (peer reviewing) sim results, load analysis results, mass analysis results, etc. should be determined.
- Masses taken from solidworks are hit-and-miss with accuracy. Particularly for composites.

Other Notes:

- If any other data from these simulations is desired it is fairly easy to grab quickly as the simulations are all stored on grabcad. Please let Joel know if more data would be helpful to you.

Authors:

Joel Godard, Roman Kobets, Ryan Lau
Help with RSE files from Artem and Aaron.

Sources:

- Openrocket technical documentation, RASaero Technical Documentation
- IREC DTEG
- LC DTEG
- SAC Technical report (ours)

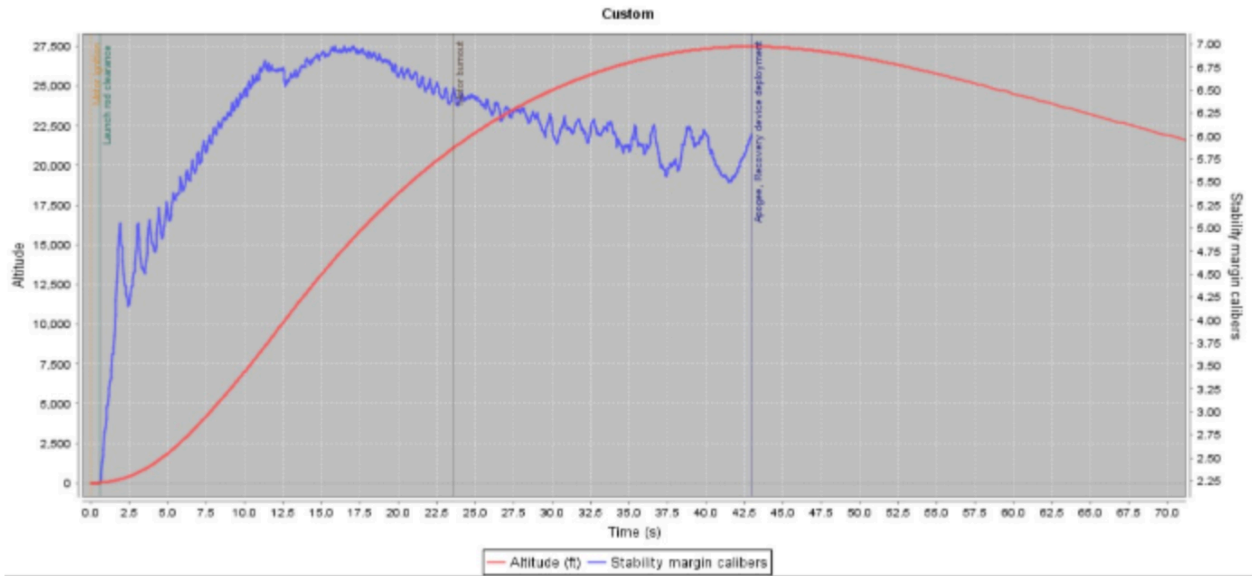
Revision History:

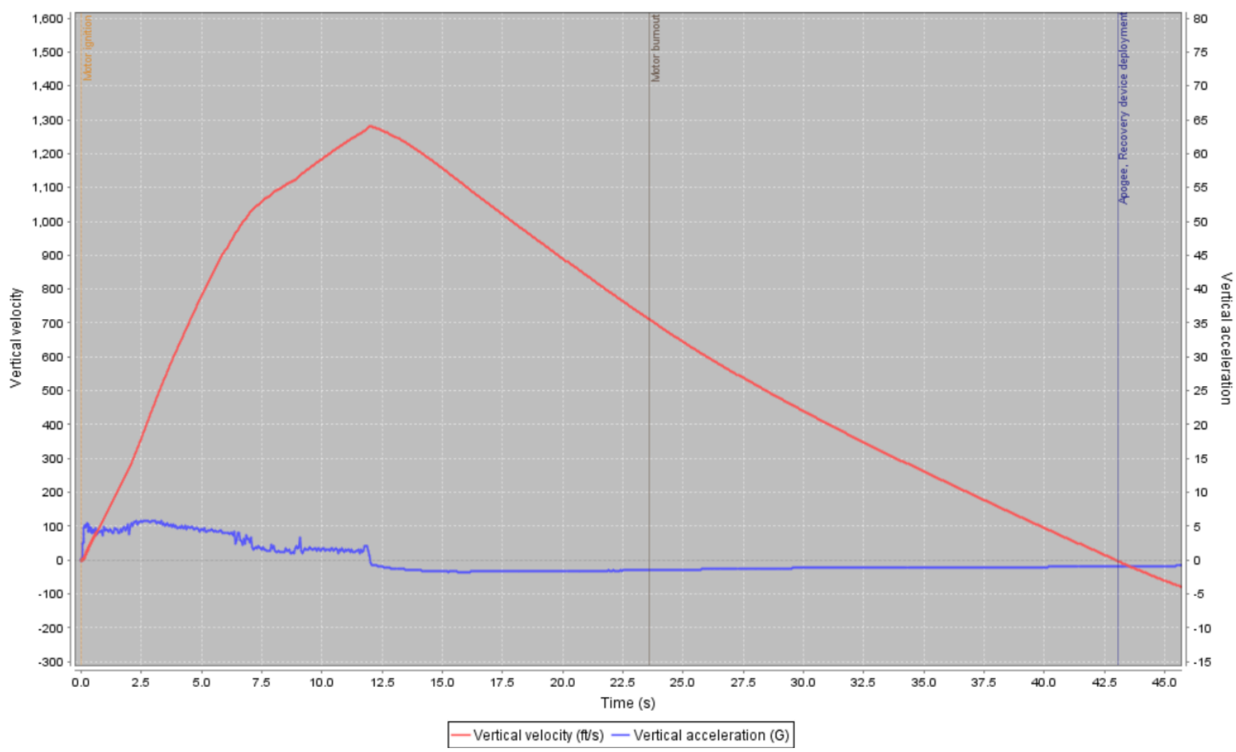
[1/11/2022] Initial Release

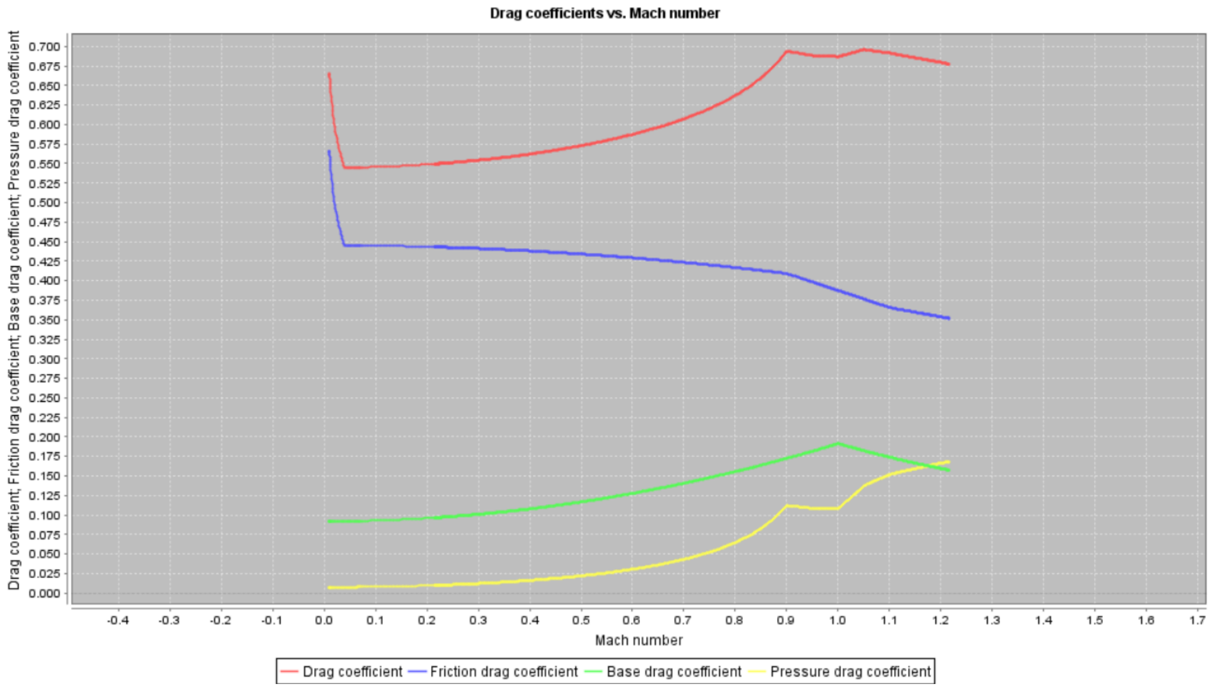
Appendix 1 Flight Characteristic plots

Cases 1a and 1c are pasted here. More plots of parameters from the completed simulation cases can be generated fairly simply. Reach out to Roman or Joel if you'd like anything specific plotted.

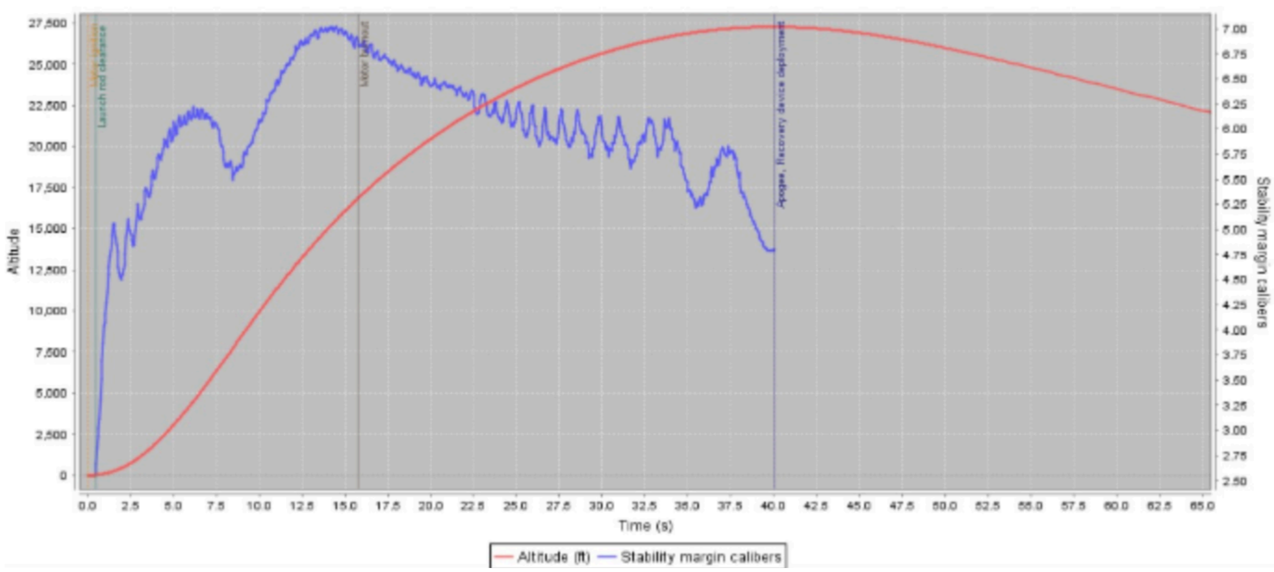
1a. Expected mass case with no changes to engine performance from KismetV3

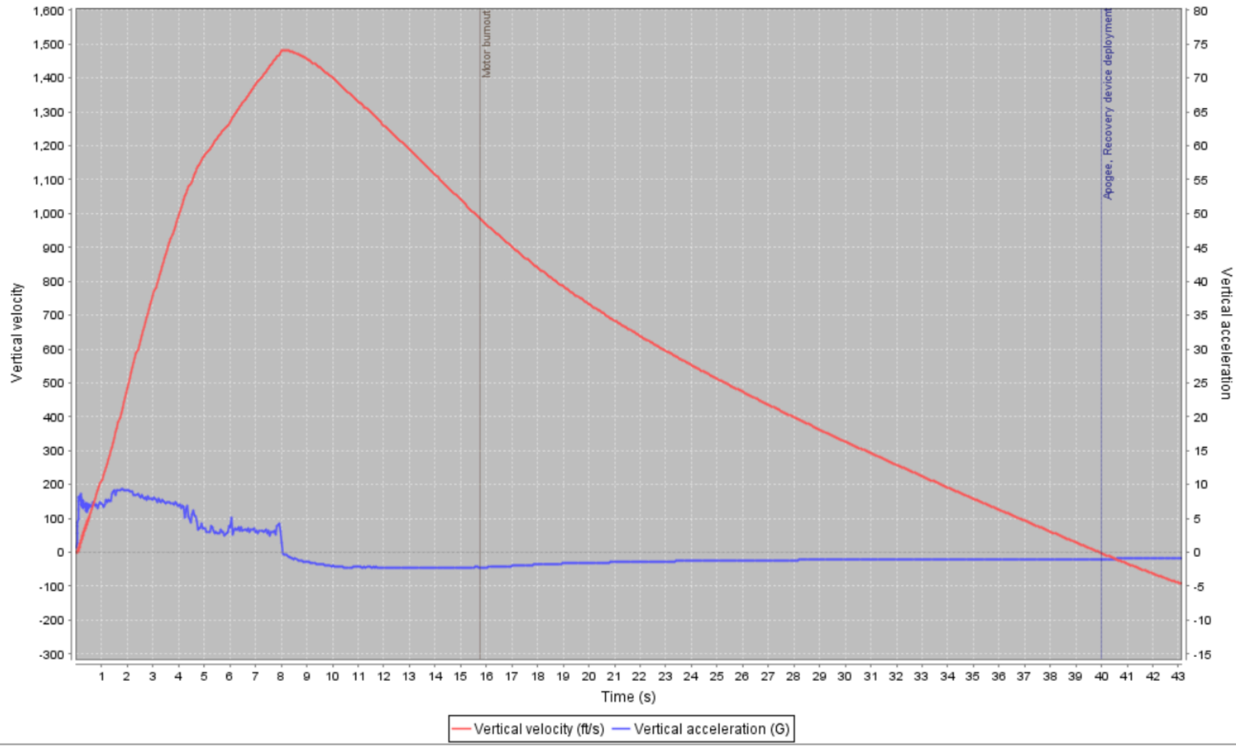


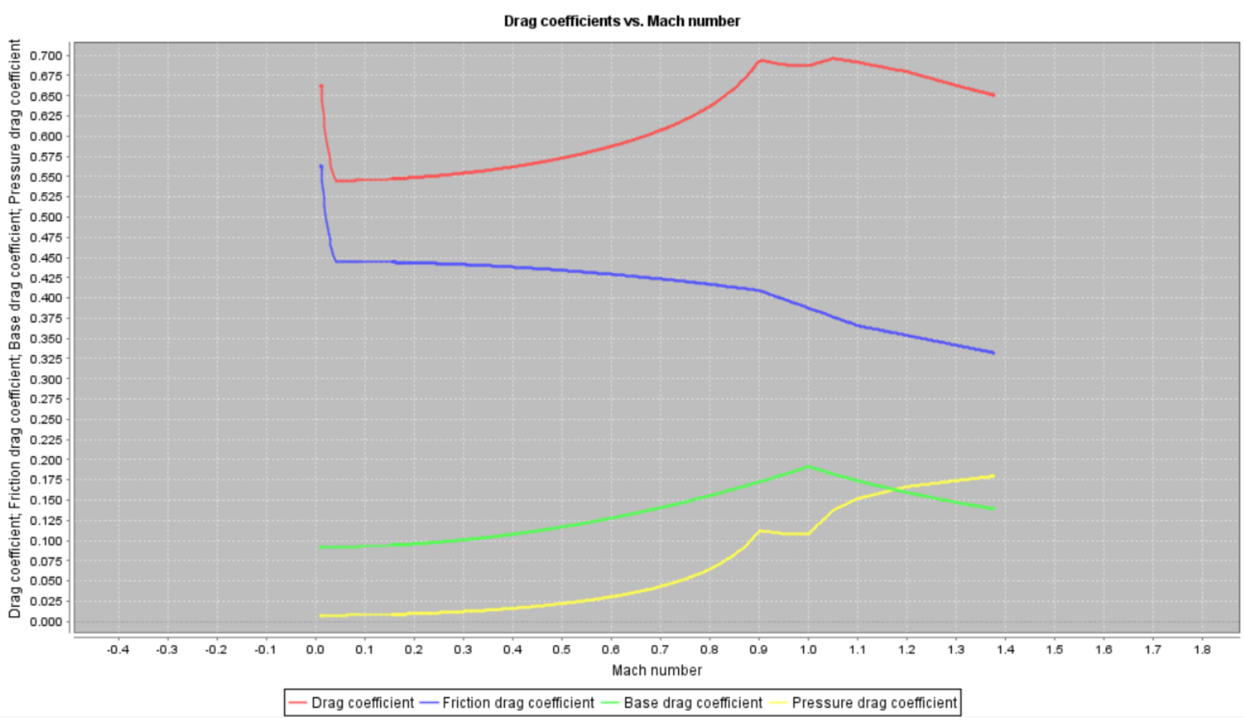




1c. Expected mass case with 150% increase in engine thrust (same impulse)




Motor burnout
Apogee, Recovery device deployment
Vertical velocity
Vertical acceleration
Time (s)
Vertical velocity (ft/s)
Vertical acceleration (G)


Drag coefficients vs. Mach number
Drag coefficient; Friction drag coefficient; Base drag coefficient; Pressure drag coefficient
Mach number
Drag coefficient
Friction drag coefficient
Base drag coefficient
Pressure drag coefficient