NORTHVILLE HIGH SCHOOL
AEROSPACE CLUB

Optimization Through Compromise

22-0000000918
Northville HS TARC Team, MI

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Thank you for reviewing our presentation.
This year was a challenging year, and we hope that this presentation can convey some of the challenges, and how we attempted to overcome them. Much of this presentation builds on the experience from last year. In many cases, we avoided repeating material presented last year.

Team Overview

- 9 members
- Club meetings every Monday
- Launches once a week (weather allowing)
- Started designing/building in October
- Snowy practice launches starting January

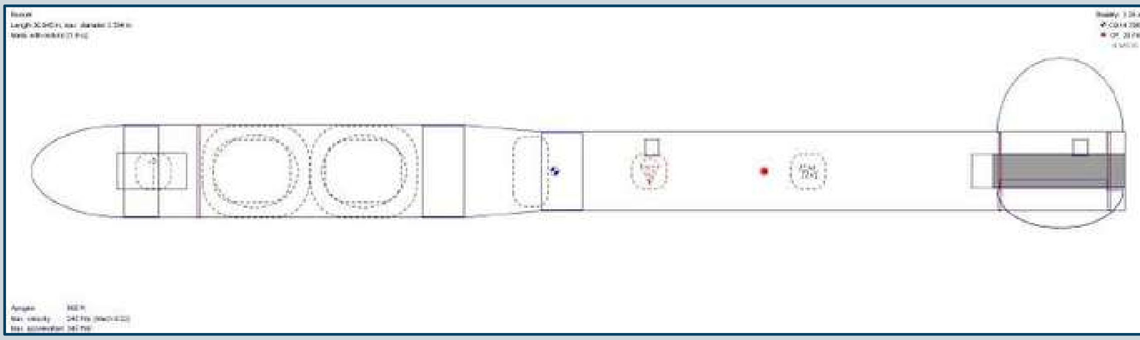
- The TARC team is a subset of the NHS Aerospace Club, a student run, extracurricular club.
- Met every Monday for designing, team discussion on future plans, and building.
- After learning basics, started designing then building around October.
- The team broke up tasks and voluntarily formed teams based on interest level:
    - High Level Rocket Design
    - 3D Modeling
    - Build and Assembly
    - Data Analysis
- Built 5 rockets total, refining the designs (mainly stability) every time
- Launches were every weekend and occasional weeknights, 2-4 flights per launch, when weather cooperated
- Launched despite heavy snow and subzero temperatures

Design Goals

Performance adapted against:
- ➢ Wind
- ➢ Thrust
- ➢ vectoring
  Temperature

Performance maximized by:
- ➢ Higher stability
- ➢ Minimum length payload
- ➢ section Ellipsoidal nose cone
- ➢ Variable mass transition
- ➢ Parabolic parachute
- ➢ Rounded elliptical fins

Final Design:
➢78.6 cm
➢481-650 g
➢F51 motor



- Our design this year was based largely on compromises.
  - Compromising stability to minimize the effect of wind and thrust vectoring.
  - Wind and temperature compensation during flight procedure (our altimeters are temperature dependent and rocket altitude is affected by wind speed)
- Adapting against variables to maximize the consistency of our rocket.
  - Relatively high stability, with the shortest possible payload section to prevent egg movement
  - We use an ellipsoidal nose cone to minimize drag, which also serves as our altimeter bay (Stine, Handbook of Model Rocketry, pp 147-149).
  - The transition doubles as a variable mass component, allowing us to adjust between minimum mass of 481 g up to the limit at 650 g.
  - Parabolic parachute, with spillhole which seemed to be more stable, predictable, and fitted the duration limit better than a flat parachute.
- According to our simulation data, elliptical fins are slightly more efficient than rectangular or trapezoidal fins. The final design uses rounded elliptical fins to give us the most efficient altitude performance. We didn’t airfoil the fins, since simulations predicted less than 10 ft difference between rounded and elliptical (Stine, Handbook of Model Rocketry, pp 151-158).

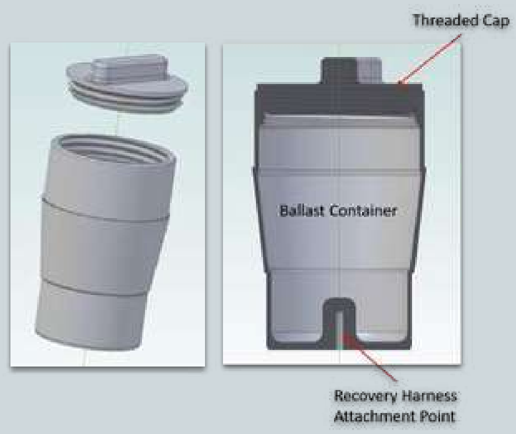
Build Materials

- ➢ Materials follow a traditional TARC rocket construction.
- ➢ Items unique to our rocket are highlighted below.
- ➢ To reduce cost, we built our own components where possible.

- Traditional TARC rocket design. ([Building a TARC Rocket (rocketcontest.org)]())
- Items that make us unique:
  - Made our own custom rail buttons from nylon washers and spacers.
  - Custom designed transition/ballast holder/bulkhead all-in-one component.
  - Tube stiffener above the fin can (not shown) as this is the weakest point in thinwall cardboard airframe.
  - Added heatshrink to recovery harness to prevent Kevlar abrasion/zippering of body tube.
- To save cost, we try to make as much modular as possible to transfer between rockets. Total consumable cost per rocket is only $10.97 (body tubes, plywood, Kevlar).

Booster-To-Payload Coupler

- ➢ Designed custom coupler with the following goals:
  - ○ Adapt BT70 booster to BT80 payload
  - ○ Secure adjustable ballast material near CG
  - ○ Provide recovery harness attachment
  - ○ Secure the payload tube
- ➢ Designed in 3D modeling tools
- ➢ 3D printed in ABS



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- Rocket mass needs to be adjustable over wide range to fine tune altitude.
- By setting the adjustable mass at the center of gravity, adjustments should not change the stability and flight characteristics.
- Our 3D design team designed a custom transition that performed the following functions:
  - ◯Adapted from the BT70 booster to BT80 payload tube.
  - ◯Secured the ballast weight at the center of gravity point.
  - ◯Provided attachment point for the recovery harness.
  - ◯Secured the payload tube with removable plastic rivets.
- Several iterations were performed to determine necessary wall strength vs minimizing mass.
- Final weight was only 58 g, only slightly more than commercially available transition from Apogee Rockets, but adds a lot more functionality.

Altitude Requirements

Temperature (F)	Real Altitude		
	Alt Target = 810 ft	Alt Target = 835 ft	Alt Target = 860 ft
10		756.0	
15		764.0	
20		772.1	
25		780.1	
30		788.2	
35		796.2	
40	780.2	804.3	828.3
45	788.0	812.3	836.6
50	795.8	820.4	844.9
55	803.6	828.4	853.2
60	811.4	836.5	861.5
65	819.2		869.8
70	827.0		878.1
75	834.8		886.4
80	842.7		894.7

- ➢ Must work in all conditions
- ➢ Based on qualification conditions in Michigan and at nationals, must be designed and adjustable to cover a range from 756 ft to 894 ft, almost a 20% range
- ➢ Adhere to requirements

Actual Altitude = Reported Altitude * (273.15 + Launch site temp C) / 288.15

- Weather in Michigan is highly varied through the testing and qualification phase. (10 F through ~50 F).
- Weather in Great Meadows, if we make it, can also be varied.
- Need a rocket/motor combination that will get us 756 ft to 895 ft (plus margin for sim, wind, etc).
- The challenge is to make a rocket that meets stability, conforms to the rules, and preferably, not require us to characterize two different motors.
- Requirements: go 835 ft, mass less than 650g, use the same motor

Motor Selection

Criteria

➢Optimal total impulse: 53-55 N-s
➢Fast burn (higher average impulse)
➢Affordable

Options

➢Single use and Cesaroni: over budget
➢F39: insufficient altitude
➢F62: inconsistency with simulation data, less altitude margin, cost
➢F51: greater margin for altitude
○ Issues on thrust vectoring, mass limit

Designation	F39T-3,6,9	F62T-S,M,L	F51NT-10
Mfgr.	Aerotech	Aerotech	Aerotech
Propellant	Blue Thunder	Blue Thunder	Blue Thunder
Casing Size (mm)	24	29	24
Length (mm)	70	89	70
Mass (g)	22.7	30.5	26.5
Impulse (N-s)	50	51	55.1
Std Deviation	0.49		0.37
	0.98%		0.67%
Ave Thrust	39	62	51
Pack Cost	$32.99	$19.99	$28.99
Qty/Pack	3	1	2
Cost/Motor	$11.00	$19.99	$14.50

- This year's rules and our rocket design narrowed our motor options significantly. The total impulse needs to be 53-55 Ns to meet the altitude requirement without going over the 650g mass limit. A high average impulse motor allows the rocket to leave the rail quickly and have a straighter, more reliable flight. We were also limited in terms of cost because we're a student funded club, eliminating single use and Cesaroni motors.
- We initially tested our rocket on the F39, but both simulation and actual launches proved that we couldn't reach altitude.
- We then debated between the F62 and F51. The F62 overperformed compared to simulation, but we eventually decided to go with the F51 for its lower cost and greater margin to reach altitude.
- The F51 wasn't without its problems though. It is a higher impulse motor which took us precariously near the mass limit in low wind conditions. We also redesigned our rocket to compensate for thrust vectoring (discussed in later slides).
- Motors were also generally difficult to buy this year with supply shortages and time it took to determine the motors we want.

Non-Vertical Flights

- ➢ Initially built with low stability to minimize weathercocking.
- ➢ Even in no wind conditions, we saw a random distribution non-vertical flights.
- ➢ Flights veer between 20 and 40 ft, then fly straight.
- ➢ More than half of the launches
- ➢ Problematic unpredictable altitude loss

- Based on last year, we initially built with lower stability to avoid excessive weathercocking.
- Early in our practice launches though, we saw random non vertical flights occurring, including on no wind days where it should have had a straight flight.
  - In about half of our flights on our initial design, the rocket veered between 20 and 40 ft, corrected itself, and continued on an otherwise straight flight.
- Natural nozzle erosion corrected the skewed flights
  - Resulting altitude loss was still a major issue due to unpredictability
    - We measured fuel grains and nozzles, but there wasn’t a noticeable difference

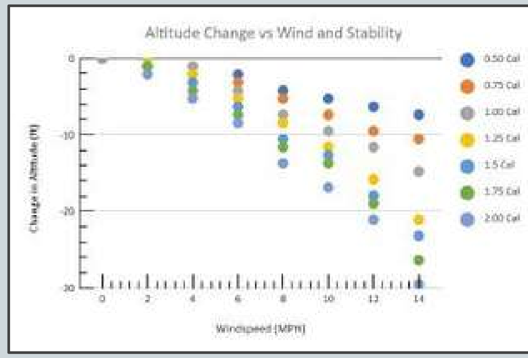
Non-Axial Thrust

- Frame analysis of video footage revealed non-axial thrust between leaving the rail and ~40 ft
- This showed up on every non-vertical flight
- Nearly 2 degrees off axis
- Corrected itself
- Couldn't compensate for altitude loss with mass adjustments
- Possible cause: uneven nozzle erosion

- After analyzing a lot of video frames, we noticed that the non-vertical flights all had thrust directions that were not in line with the rocket.
  - Random. Not correlated to a specific rocket.
  - Only showed up between 10 and 40 ft.
- We believe that the non-axial thrust is changing the thrust vector and rotating the rocket.
- Based on last year, initially built lower stability —> Much more susceptible to non-vertical flight.
- Since we can't predict non-axial thrust, we couldn't compensate for the altitude loss with mass adjustments.
- Nozzle throat diameter is 3.5 mm at the start of the flight. The nozzles throats are 4.7- 5.0 mm post flight. While not a perfect correlation, the nozzles that were larger post flight had a throat that was more elliptical than circular, and slightly larger.
- We suspect, but no way of proving, that we are getting uneven nozzle erosion during the first phase of flight.

Original Design Optimized for Wind Insensitivity

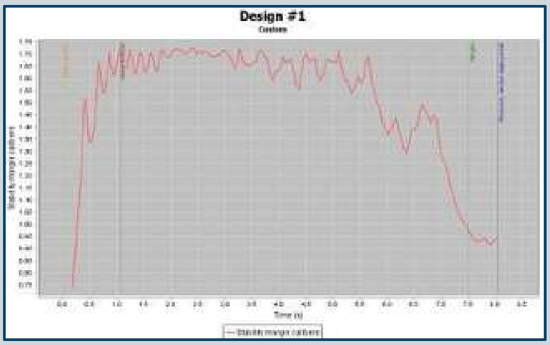
- ➢ Wind is a variable we have to design around
- ➢ Low stability minimizes effects of weathercocking
- ➢ Still seeing non-vertical flights
- ➢ Low stability = greater thrust vectoring

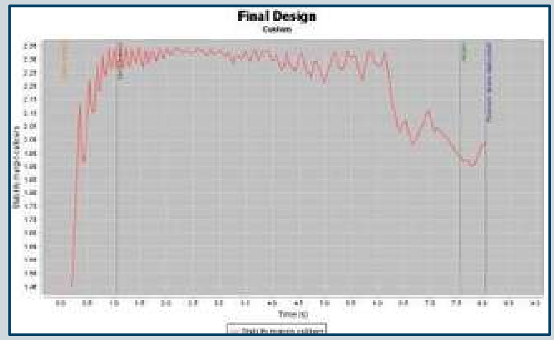


- The past few TARC seasons taught us that low stability and high average impulse can combat weathercocking. Wind is a variable that we can’t control, so we needed to compensate as much as possible to maintain consistent performance over many flights.
- We initially had our stability around 1.7 cal, which optimized for maximum wind insensitivity without compromising the rocket and being under stable. Simulation data predicted a variation of only ±3 feet in 10mph wind.
- Even with low stability though, we kept seeing non vertical flights with our original design. We had optimized against weathercocking, unknowingly making our rocket susceptible to the effects of non axial thrust. Non axial thrust, paired with low stability at take off, caused our non-vertical flights. This is when we learned about the distinction between static and dynamic stability.

Dynamic Stability

- ➢ Static and dynamic stability are different
- ➢ Takes 0.5 seconds after ignition to reach 1.5 cal stability
- ➢ Low stability means greater sensitivity to thrust vectoring

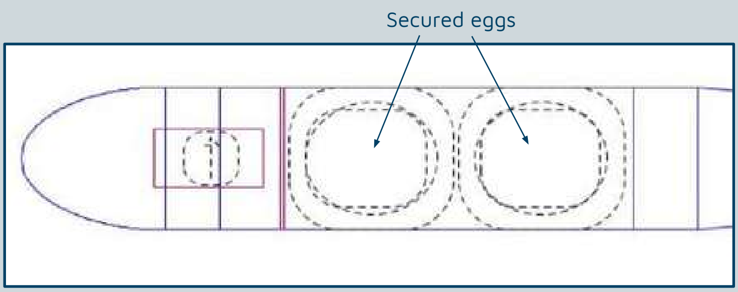




- Even though OpenRocket stated a stability of 1.7 for our first design, when we plotted stability over time, we found that it took 0.5 sec after motor ignition to even reach 1.5 cal of dynamic stability.
- At ignition, the stability was as low as 0.75 cal and rose to 1.7 near burnout. This helps explain why we only saw non vertical flights from off axis thrust for the first 20-30 ft, before it corrected itself to a vertical trajectory, since those initial few feet occur within the first 0.5 sec of flight.
- By lowering our stability overall, we had made the stability at take off very low, making our design prone to thrust vectoring.

Compensating with Higher Stability

- ➢ Shorter payload section length to prevent egg movement
- ➢ Longer booster section
- ➢ Larger fins
- ➢ Increased stability from 1.4 to 2.05 cal
  - ○ Now prone to weathercocking

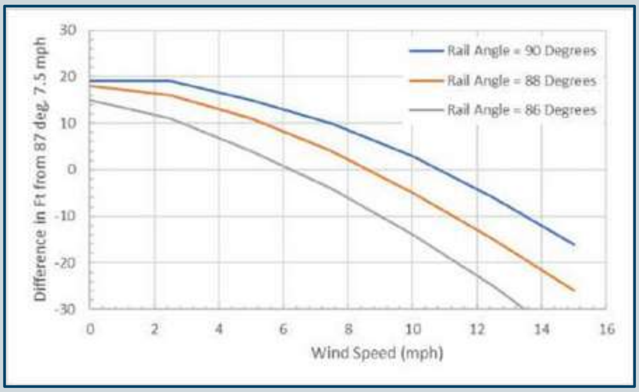


- In our first design, our payload section was long enough that the eggs could slide up and down during flight. The resulting changes in stability caused our rocket to shift slightly after takeoff and then correct itself back to vertical. To avoid the resulting altitude loss, we made the payload section as short as possible. In our final design, the eggs are tightly confined between the forward bulkhead and top end of the transition.
- Shortening the payload section lowered our stability even more. We lengthened the booster section and made our fins larger to compensate.
- We raised the stability of our final design to 2.05 cal, compared with 1.4 cal in the first rocket. Higher stability, however, made our rocket more susceptible to weathercocking, which we were trying to avoid in our first design.
- At higher stability, video footage shows we are still getting non-axial thrust. However, we are getting less non-vertical flight paths in low wind situations.

Weathercocking vs. Thrust Vectoring

- ➢ Compromise between low and high stability
- ➢ Compensating with wind speed and launch angle chart to determine deviation

Simulated Effects of Wind on Altitude



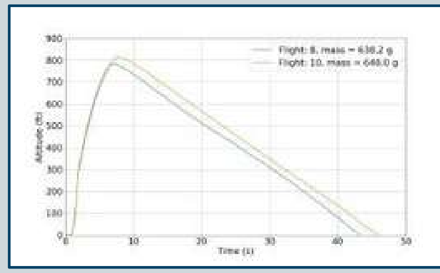
Low stability
thrust vectoring
✔ weathercocking

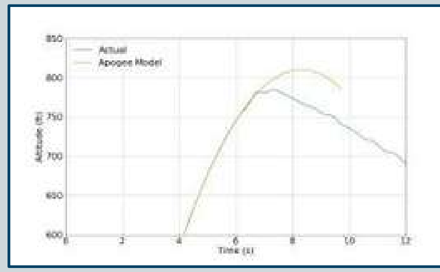
High stability
✔ thrust vectoring
weathercocking

- We added back stability to diminish the thrust vectoring issue. If we set the stability too high though, weathercocking becomes an issue.
- We eventually settled on a stability of 2.05 cal, compromising weathercocking and thrust vectoring.
- During launches, we also accounted for the day’s wind speed and launch rail angle to determine effects on altitude. In low wind conditions and at launch angles closer to vertical, we would get a higher altitude than expected from our mass-altitude plot. In high winds and at angles farther from 90 degrees, we lightened the rocket to compensate for the decrease in altitude (more details on later slides).

Initial Ejection Charge Optimization

- ➢ The ejection delay was optimized to provide ejection at apogee based on initial launches.
- ➢ However, with different date codes and other problems creating random variations in data, we discovered that many of the delays were trimmed too short.
- ➢ In order to make correct in data analysis, we performed a quadratic fit to determine what apogee would be if delay was correctly trimmed.
- ➢ Allows us to use data from imperfect launches.

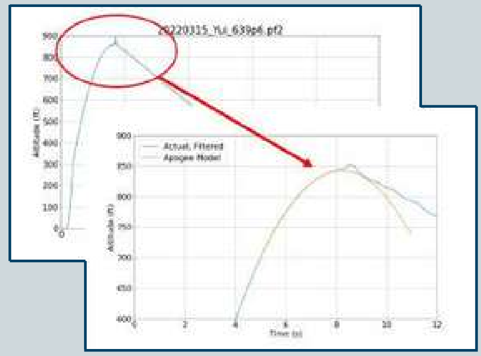


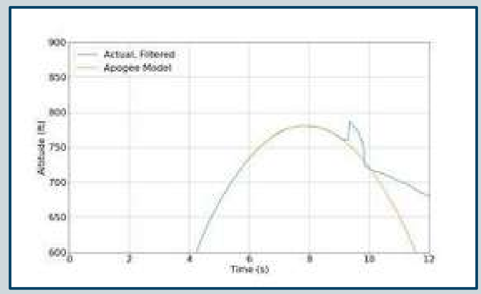


- With all of the problems and inconsistencies, we had yet another variation that showed up. The delays started to trend short.
- A short delay results in lower measured altitude as separation occurs too early.
- After noticing this, we lengthened the delay by 1 second. However, we had probably 5 launches that were not directly usable.
- By applying a polynomial fit to the data around apogee, we were able to predict what altitude *would have been* if the delay had been correct. This allowed us to use the imperfect data.

Altimeter Glitches

- ➢ We were sometimes getting reported altitudes that did not match the apogee of the altimeter data.
- ➢ Most ejection events produce a spike in the data. Some are filtered.
- ➢ In the example to the right, the reported altitude was 854 ft. However, the apogee model shows the rocket probably went to 842 ft.
- ➢ This effect was random and unpredictable.
- ➢ Our solution is to increase the delay by another 1.5 - 2 seconds. This pushes the glitch past apogee where it has little to no effect on reported altitude.

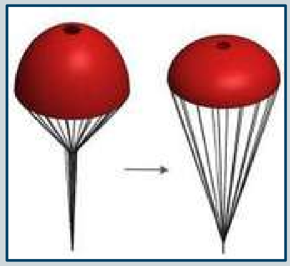




- We were getting random glitches in the altimeter data from the ejection charge. It was originally assumed that these were filtered out by the altimeter when reporting the altitude.
- However, when using a quadratic equation to fit the apogee data, we noticed that the altitude was over reported when this glitch occurred.
- This effect was random, and resulted in a 0 to +20 ft level effect.
- We could match the reported altitude by applying a 7 point moving average.
- We did not notice this on older altimeters. This only started to show up when we replaced old, broken altimeters with new ones.
- To optimize delay, we made a custom washer (3d printed) for the Aerotech delay drill to remove 1.0 s.

Parachute Optimization

- ➢ 18″ parachute too small
- ➢ 24″ parachute too large (by itself)
- ➢ Using a parabolic parachute (quals) with reefing
- ➢ Made time adjustments through reefing



$$v_d = \sqrt{\frac{2W}{C_d r A}}$$

W = Weight
C_d = Coefficient of Drag
r = Air Density
A = Parachute Area

- Initially started with 18” parachute, which turned out to be too small, descending at 24 ft/sec while ideal is around 22 ft/sec (altitude dependent)
- Switched to a 24” parachute, which was in turn too large, descending at 14 ft/sec. However with reefing, adjustable to 15-22 ft/sec
- Compensated by:
  - Cutting a 5 inch diameter spill hole in a flat parachutes, which seemed to work, bringing us closer to ideal descent rates.
  - However, found that using a parabolic parachute was more consistent, and is what we used in the qualification launches
- After choosing parachutes, made time adjustments through reefing (based on wind, target altitude, rocket mass) to reach ideal rate of descent

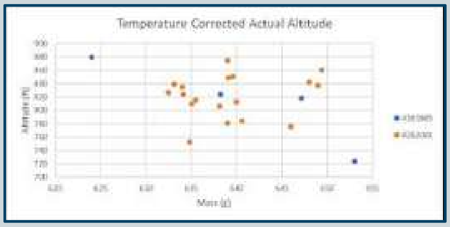
Data Analysis

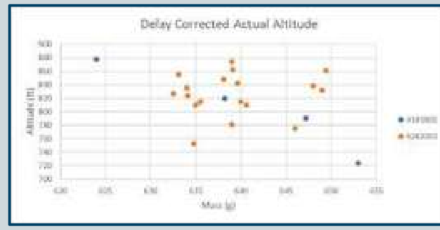
➢ Data analysis proved difficult due to all of the variables involved.
  - Temperature (corrected using Actual Altitude = Reported Altitude * (273.15 + Launch site temp C) / 288.15)
  - Wind/launch angle (corrected using table below)
  - Non-axial Thrust (random, no correction)
  - Delay variations (corrected by quadratic fit on older data, newer data does not need correction)
  - Altimeter glitches (corrected by quadratic fit on older data, newer data does not need correction)

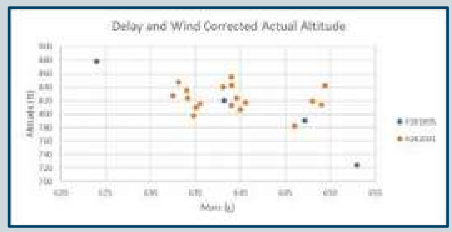
	Launch Rail Angle					
Wind (mph)	90	89	88	87	86	85
0	19	19	18	17	15	13
2.5	19	17	16	14	11	8
5	15	13	11	8	4	0
7.5	10	7	4	0	-4	-9
10	3	-1	-5	-9	-14	-19
12.5	-6	-10	-15	-20	-25	-31
15	-16	-21	-26	-32	-38	-44

- While the score requires the actual altimeter reading, all of our data analysis is performed by actual altitude, corrected for bad delays and altimeter glitches, normalized to typical launch conditions of 7.5 mph winds with an 87 deg launch angle (into the wind).
- Corrections factors are applied for the following:
  - Temperature, based on NARCON presentation for barometric altimeter corrections.
  - Wind/launch angle, based on simulated differences from nominal.
  - Delay corrections, based on quadratic fit of altimeter data around apogee.

Data Analysis

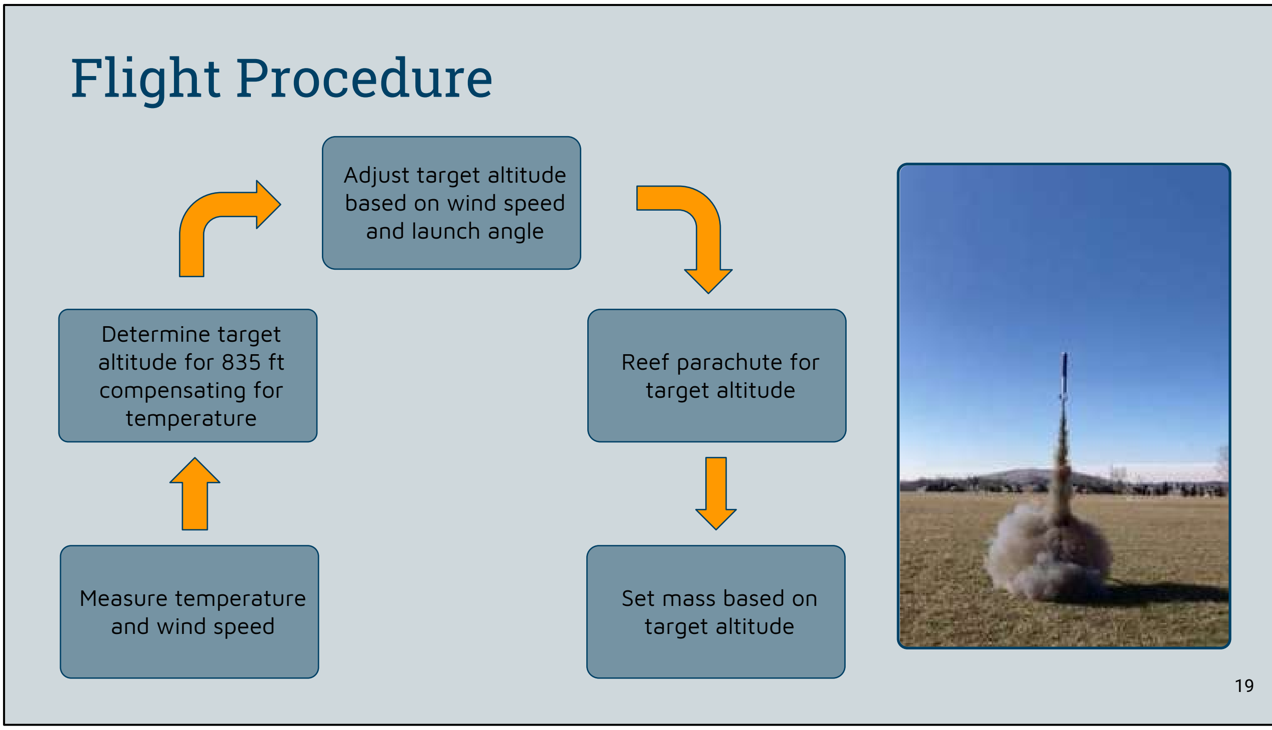






- Attempting to understand the data by accounting for variables does help, but far from perfect.
- Wind measured at ground level does not reflect wind effects at altitude.
- We are still dealing with about ±30 ft of variables that we are not able to fully take into account.

- Ultimately, we are after a graph that correlates mass to altitude in a usable manner.
- By only taking into account temperature, we get pretty much a downward trend with a lot of noise.
- Factoring in the inconsistent delay and altimeter glitches cleans it up a little.
- Once the wind data from the wind/launch angle correction is included, the data starts to clean up quite a bit more.
- Unfortunately, this is far from perfect. Wind is measured at ground level, and does not factor in gusts (remember... Michigan winter/spring).
- We still have a +/- 30 ft variation. Our goal is to at least center launches on the data distribution to minimize error to get “good” scores. Great scores will still require a bit of luck!



Each launch, we have a procedure to ensure we get as close to 835 ft as possible.

1. We start with measuring the launch site temperature and looking up the wind speed. Since altimeter readings and rocket performance are affected by temperature and wind, we need to compensate for them with mass adjustments.
2. We then refer to a mass-altitude plot. We can interpolate the mass we need to to reach actual target altitude (the altitude at which the altimeter will report 835 ft).
3. Next, we reference a wind speed/launch angle chart based on OpenRocket simulations to determine the deviation from target altitude that we'll see due to wind. We keep the deviation in mind for adjusting mass.
4. With the final target altitude determined, we decide on an appropriate amount of reefing for the launch. We also take wind speed into account on windy practice days, sacrificing time to make sure we get our rocket back safely.
5. Based on the final target altitude, we add or remove ballast weight in the variable mass transition.

Team Activities

- ➢ Weekly after school meetings
- ➢ Weekend practice launches
- ➢ Outreach: activities night club fair
- ➢ Club instagram
- ➢ Fundraising

- We meet every Monday to design, plan, and discuss our rockets. We started with introducing our new members to Estes rockets, and moved on building and flying scratch built TARC rockets.
    - Some build sessions were held on weekends to meet with our coach work with machinery.
- Practice launches were held every weekend starting in January, weather allowing. 3-6 students attended each launch to gather characterization data and have fun in the snow!
- Our high school offers a club fair to recruit incoming freshmen for next year. We set up our station showcasing a huge rocket, photos of our TARC launches, and some of the rockets we built.
- One of our club members started a team Instagram, where we uploaded some of our launch videos and pictures.
- TARC cost us about $650 this year. We funded the season with an initial participation fee from club members and several bake sales we held throughout the school year.

Lessons Learned

- There are a LOT of real world effects that we cannot model:
  - Motors with non-axial thrust that varies through the flight.
  - Altimeters that randomly give spikes that are not
  - filtered. Delays grains that vary.
- Just because we cannot model effects, we certainly can find ways to mitigate. This takes practical experience, and a lot of launches.
- We never have enough motors....
- While our qualification scores (12 and 38 points) were not as good as we were hoping, we are optimistic and hoping to advance to Finals. If not, we learned more this year than any other year.

- Things didn't always go as planned, but we learned a lot.
- Many items are completely out of our control:
  - Non-axial thrust showing up randomly.
  - Glitches in altimeters
  - Inconsistent delay grains
  - USPS trucks not delivering when there is snow
  - Motor shortages.
- What ultimately mattered was how to deal with these problems.
- Our scores were not as good as practice launches, and definitely not as good as we had hoped. However, we still hope we are able to qualify. If we had these problems, we are guessing other teams do as well!