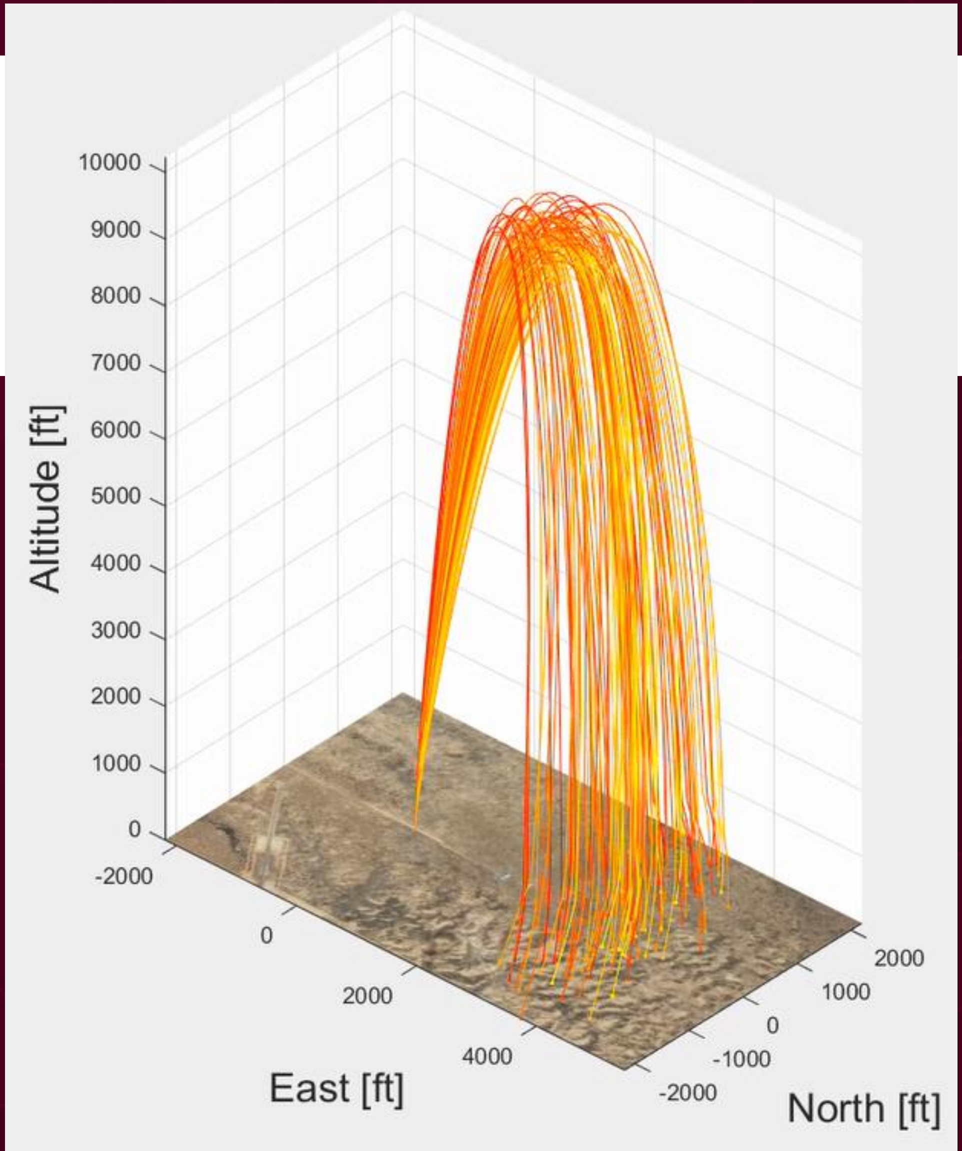


TEXAS A&M UNIVERSITY SOUNDING ROCKETRY TEAM

Integrated Flight Modeling: Trajectory & Hybrid Engine Performance

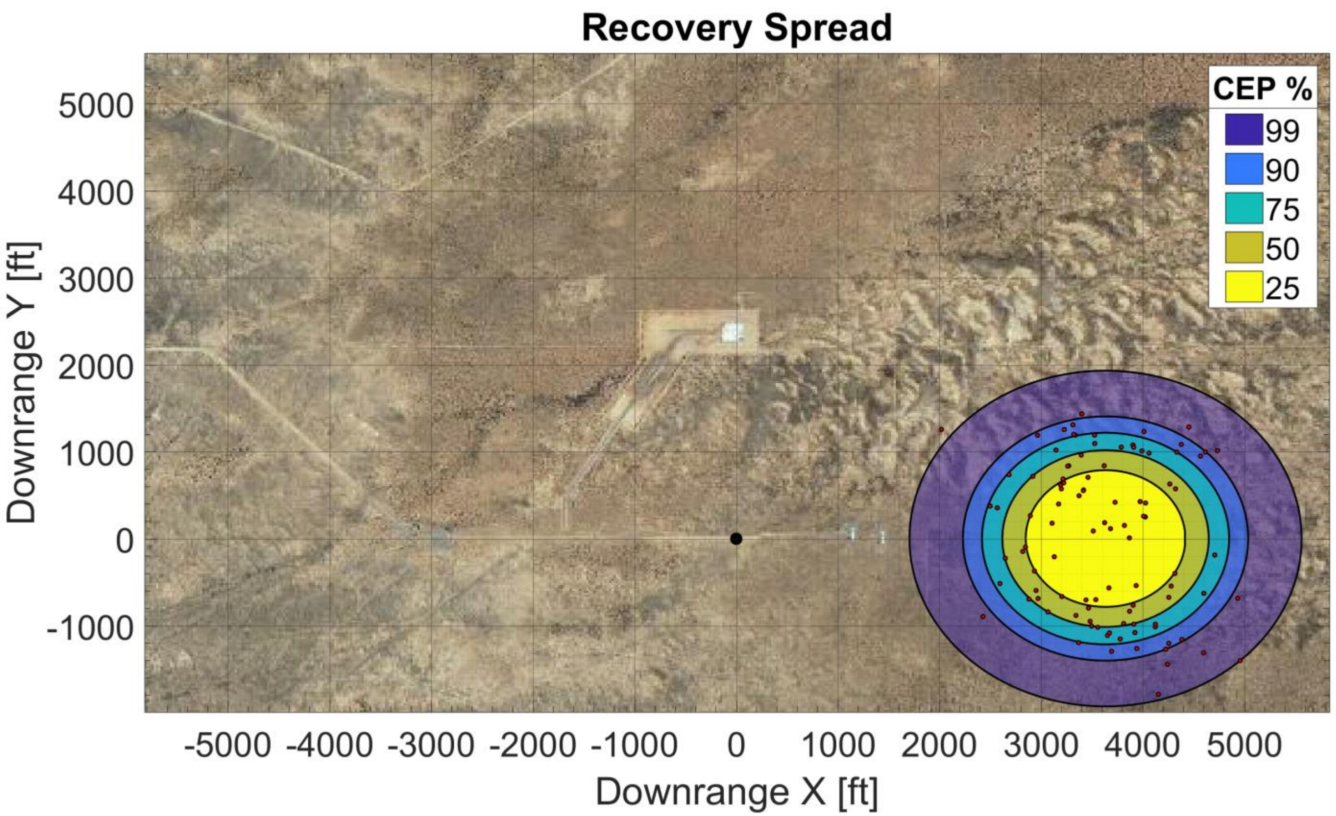
TEAM 12

R.B. Alexander, J.M. Caesar, J.Q. Doll

OVERVIEW

Outline

- Overview
  - Motivation
  - Simulation Path
- Flight Simulation (FS)
  - Simulation
  - Modeling
  - Validation
- Hybrid Engine Model (HEM)
  - Simulation
  - Modeling
  - Validation

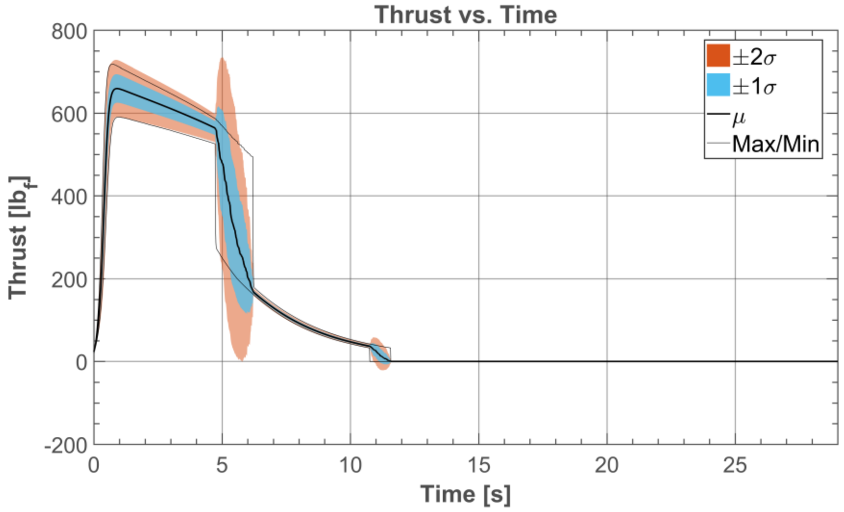


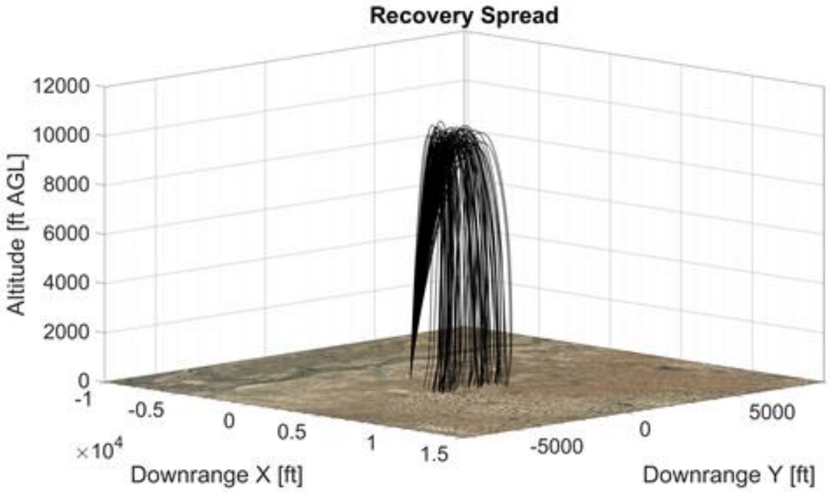
PROBLEM

- **Commercial software programs have many limitations:**
  - Limited or no capability/support for hybrid engines
  - Over-simplified input variables
  - No statistical flight analysis

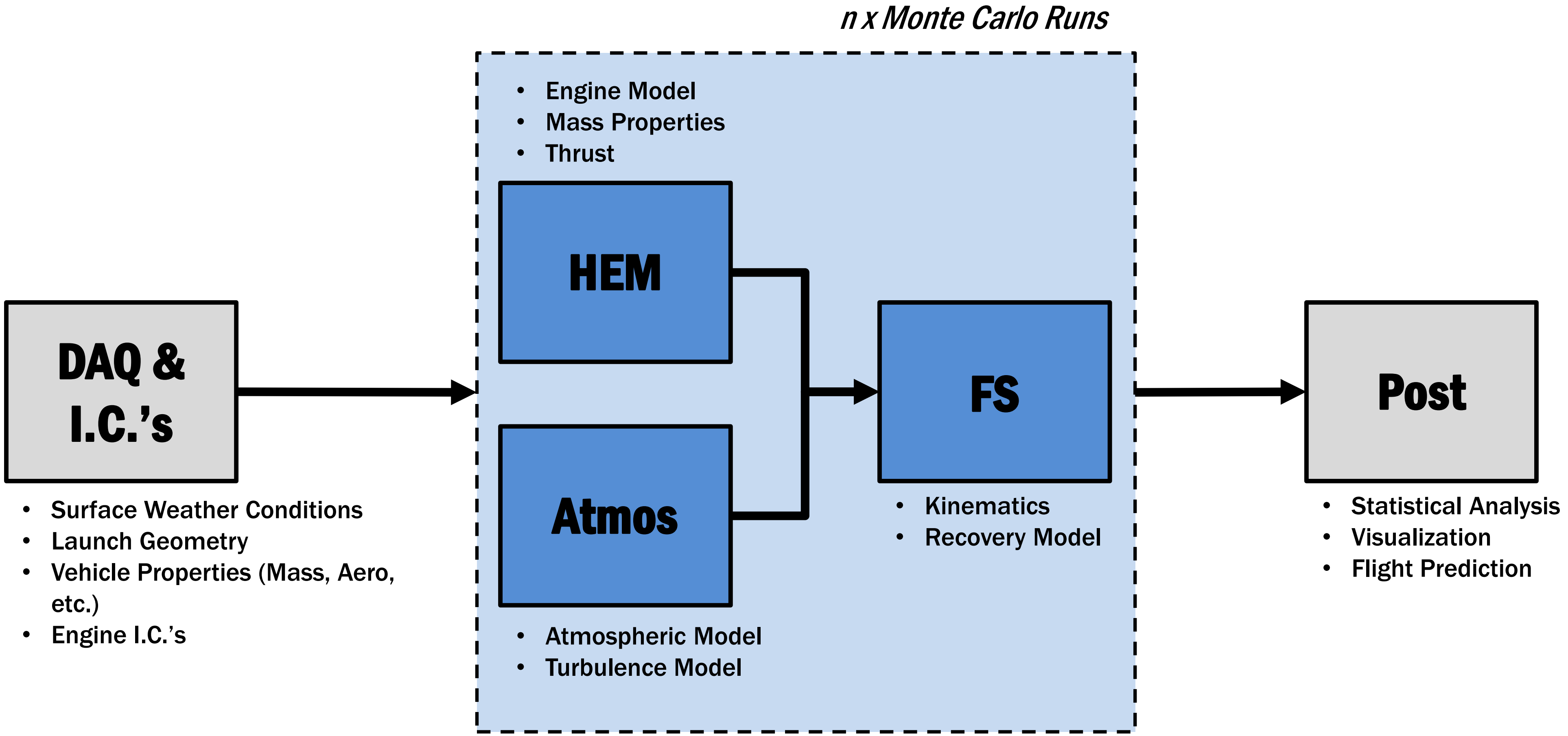
SOLUTION

- **TAMU-SRT Flight Simulation (FS)**
  - 6-DoF flight simulator for ***both solid and hybrid rockets***
- **TAMU-SRT Hybrid Engine Model (HEM)**
  - Full hybrid engine simulation from first principles

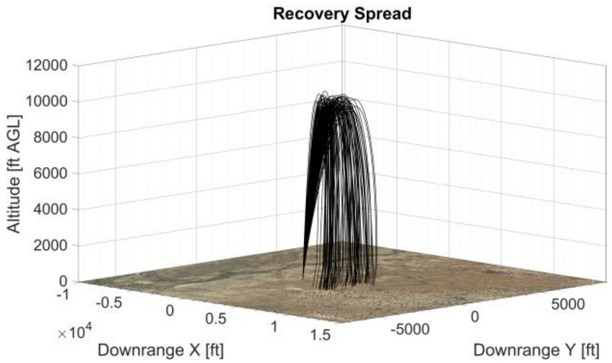




OVERVIEW | SIMULATION PATH



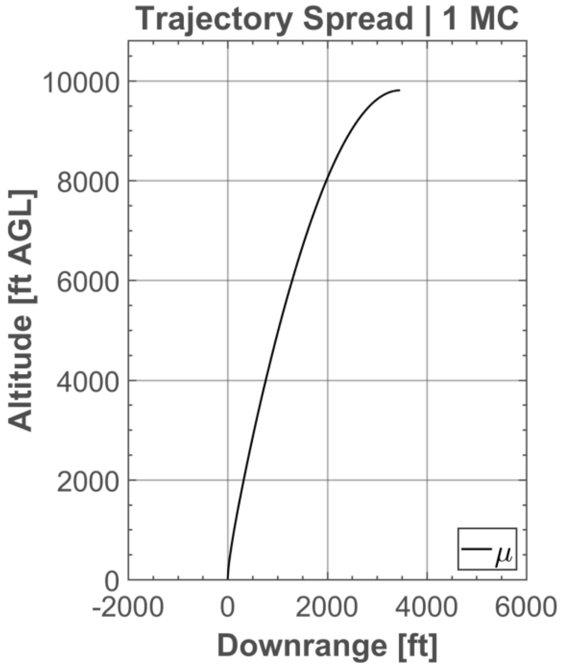
FS | MONTE CARLO SIMULATION

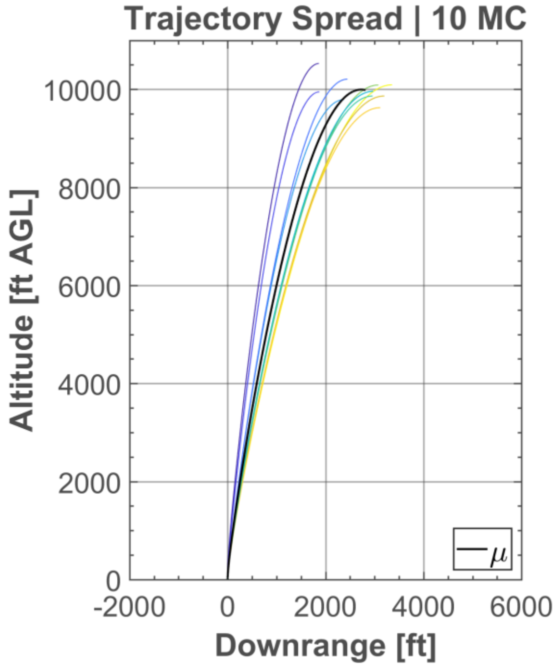


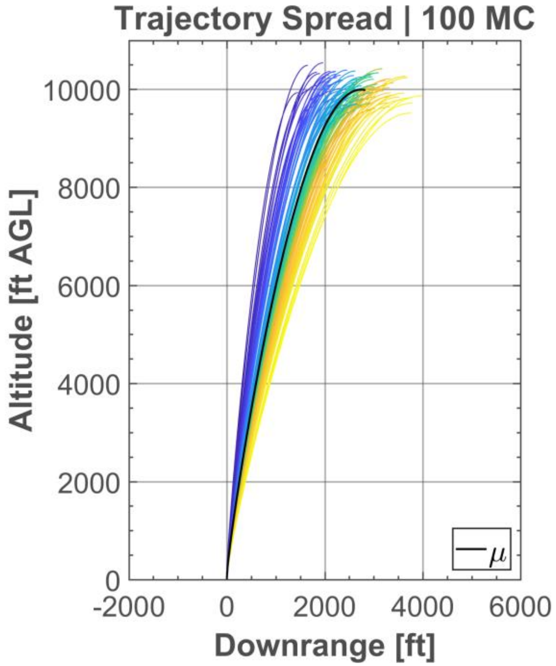
Methodology

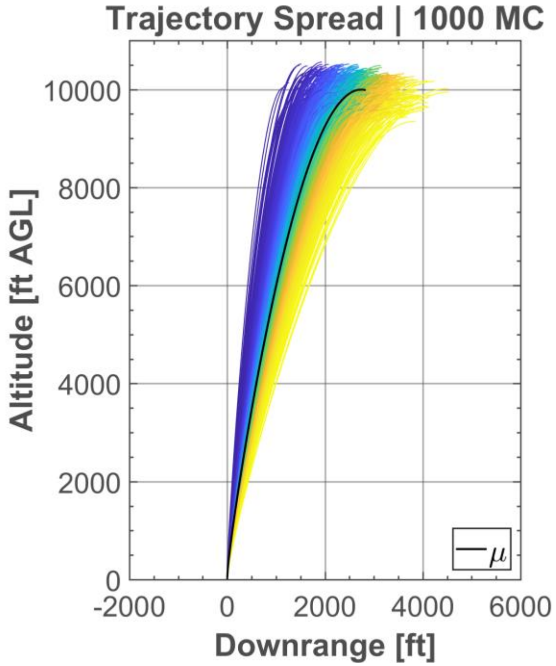
- Stochastic systems → quantify uncertainty
- Assign distributions → step through (n x 100 flights)
- Off-nominal flights → improved accuracy

Establish Spread









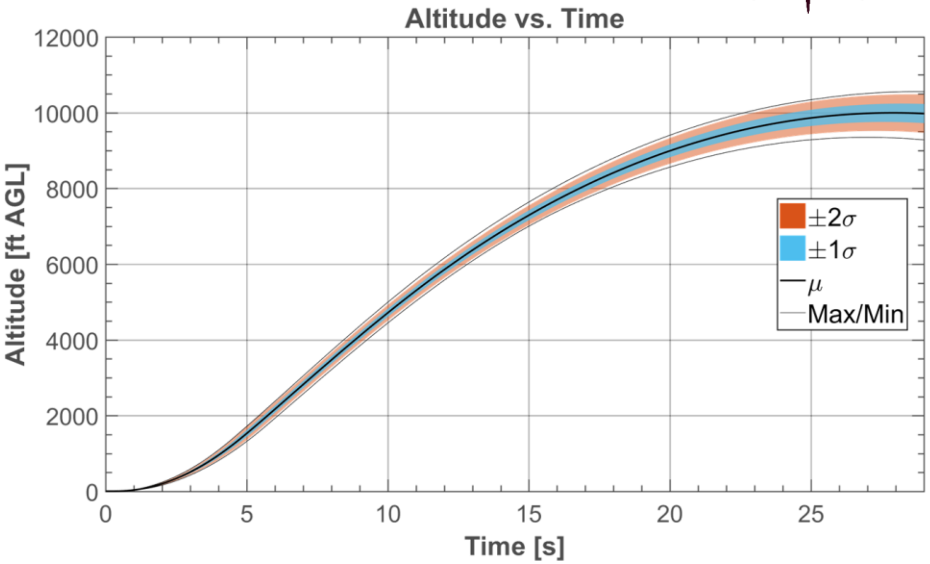
FS | MONTE CARLO SIMULATION

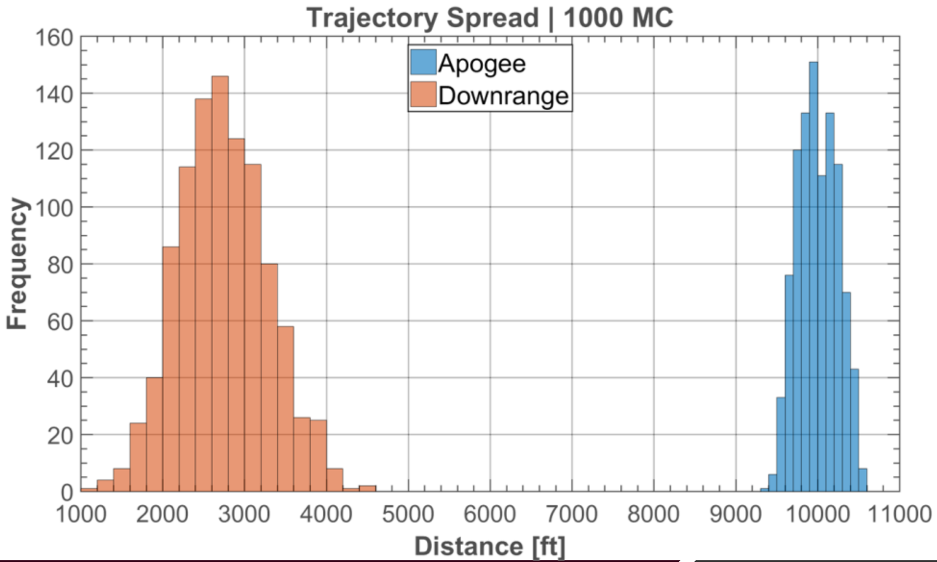
Random Sampling

- Pre-flight uncertainties
  - Ambient conditions
  - Wind average
- Flight day uncertainties
  - Launch rail elevation
  - Wind gusts
  - Engine tank pressure
- Input variables → Uniform, normal, LHS distributions
- Random seed control

Post-processing

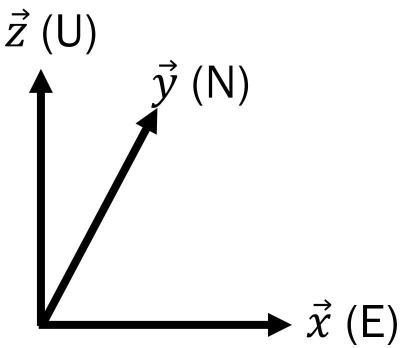
- Mean flight
- Quantify spread of output → min/max, σ
- Confidence in launch safety



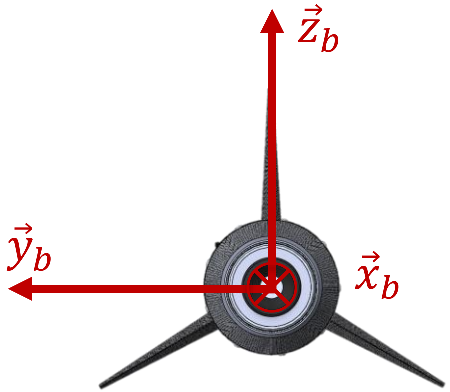


Kinematics

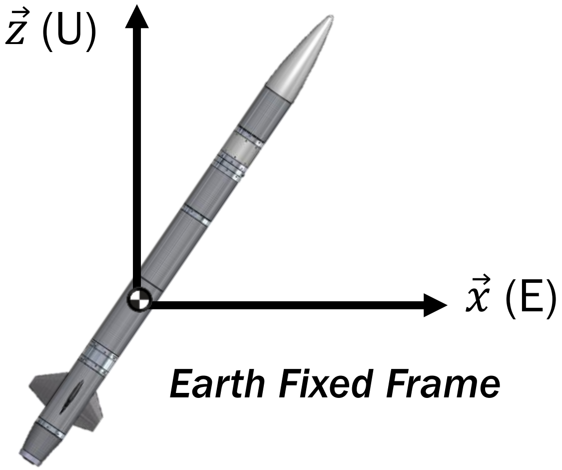
- Quaternion-based angular orientation (*3-2-1 rotation*)
- RKF-45 numerical integration
- Reference frames
    1. Inertial (Flat-Earth East-North-Up)
    2. Relative Wind (free stream + wind)
    3. Body Fixed



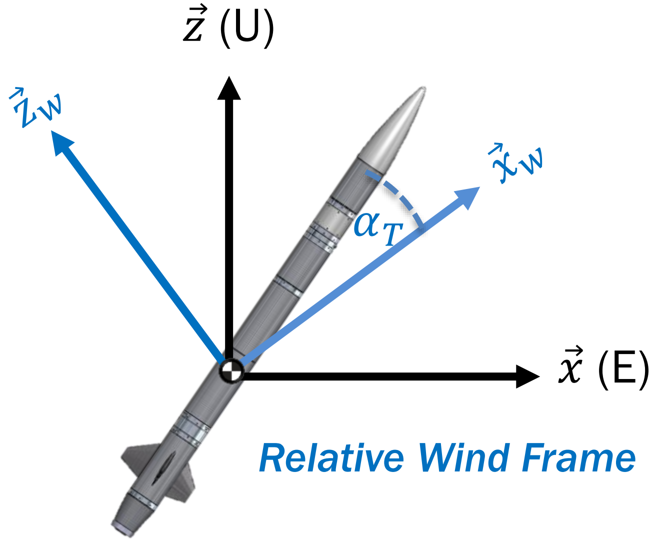
East-North-Up Inertial Frame



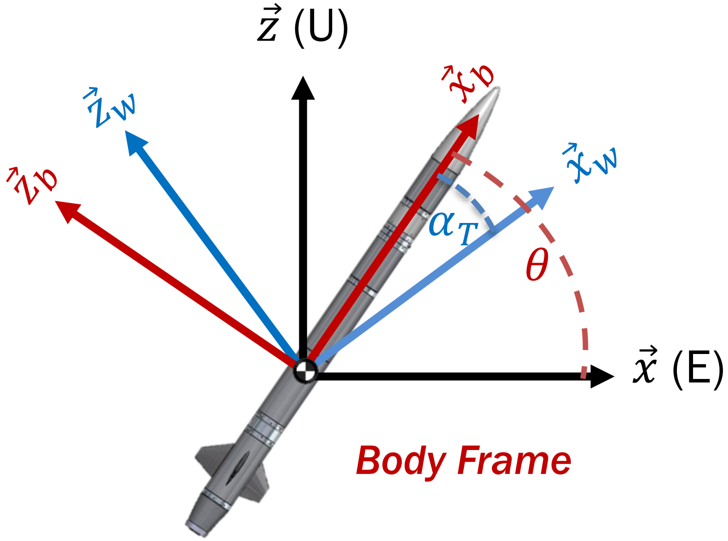
Bottom (x-z)



Earth Fixed Frame



Relative Wind Frame



Body Frame

Translational

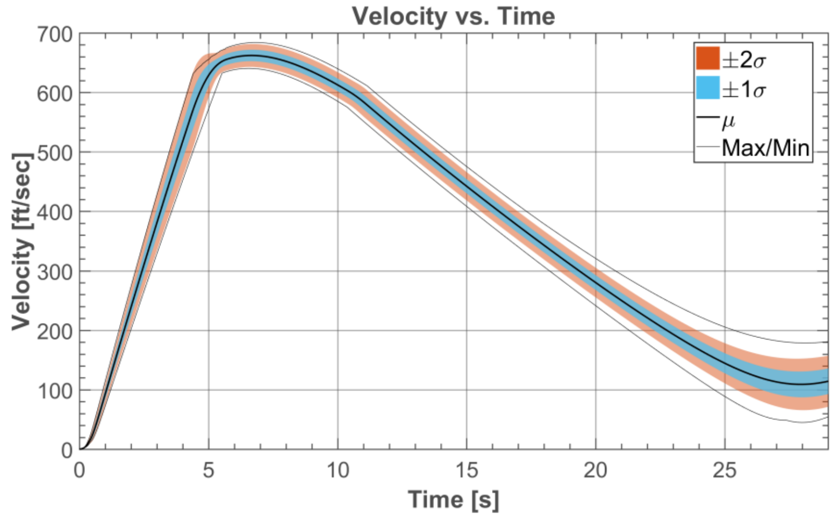
- Body frame – thrust
- Wind frame – lift, drag
- Inertial frame – weight

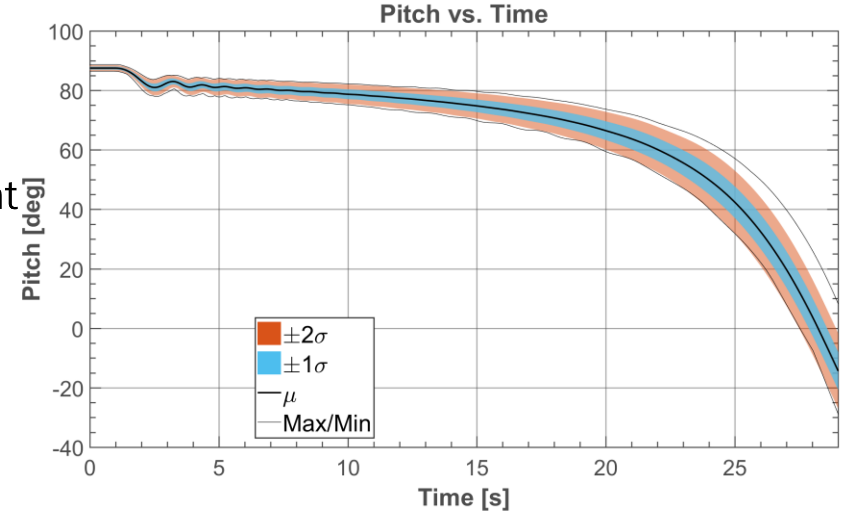
$$\vec{a} = \frac{\vec{T} + (\vec{L} + \vec{D}) + \vec{W}}{m(t)}$$

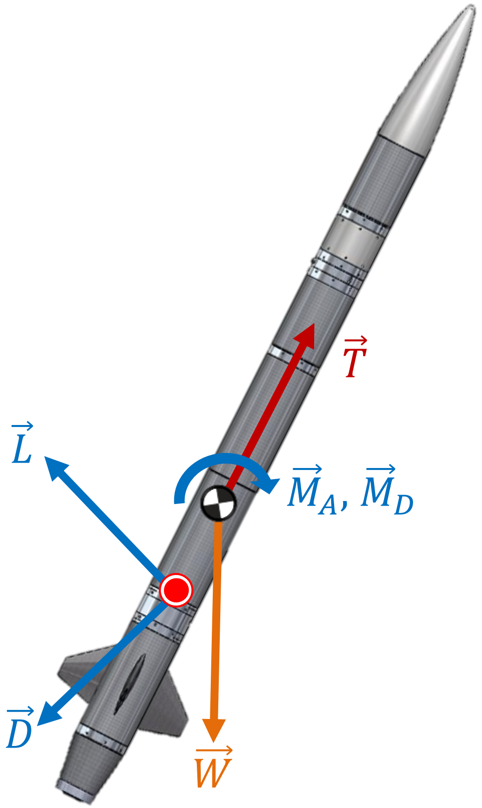
Rotational

- Moments about shifting CG
- Idealized aerodynamic forces → No rolling moment
- Thrust & aerodynamic damping

$$\vec{M}_A + \vec{M}_D = I\dot{\vec{\omega}} + \vec{\omega} \times (I\vec{\omega}) + \dot{I}\vec{\omega}$$





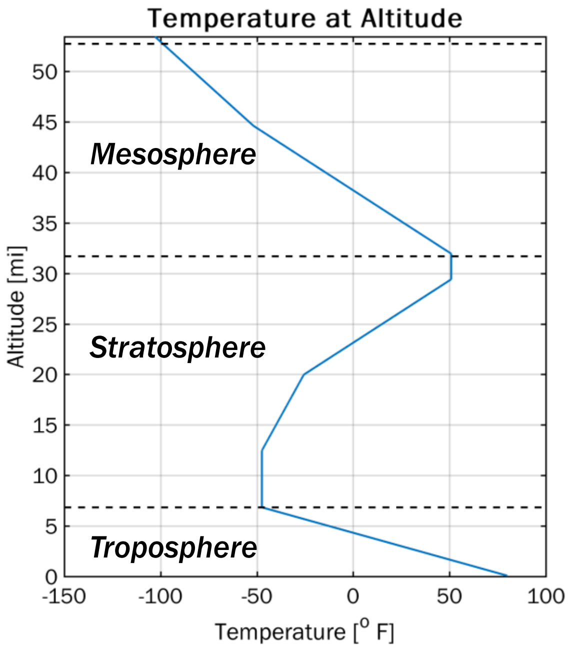


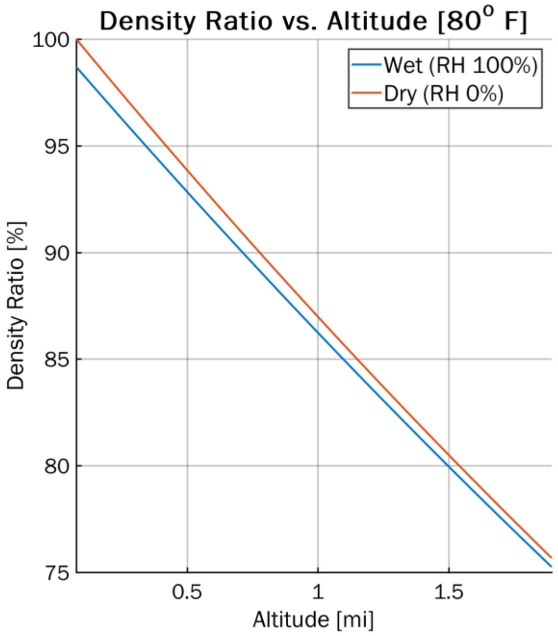
Modified Standard Atmosphere

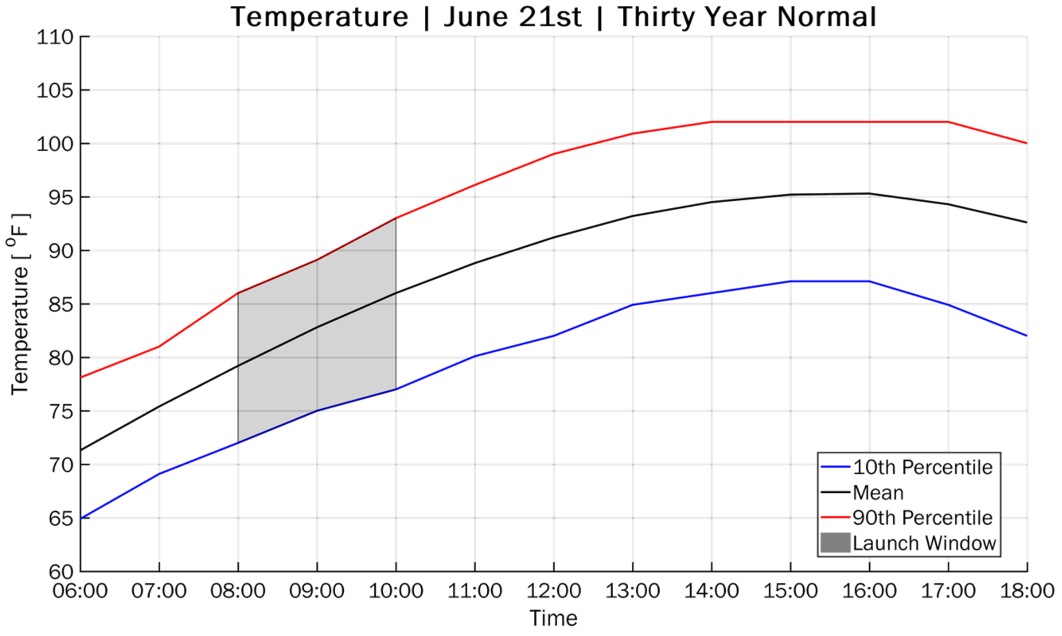
- Isentropic/gradient → 0 to ~280,000 ft ASL
- Humidity correction for air density
- WSG-84 gravitational model

Historical Weather Data

- 30 year hourly normal (NOAA)
- 10th, 90th percentile → lower, upper bound
- Feed distribution to Monte Carlo simulation



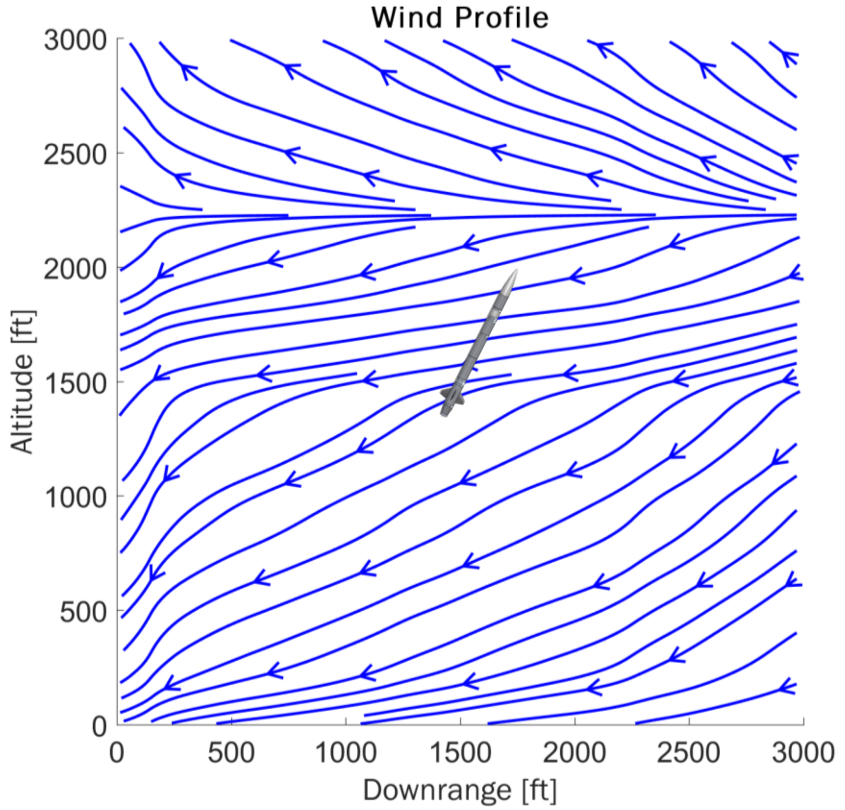


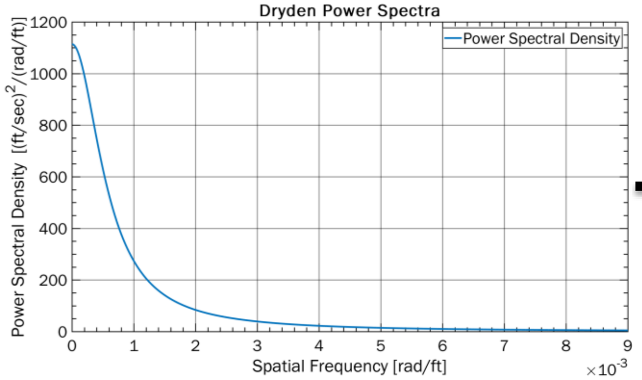


Stochastic Wind Model

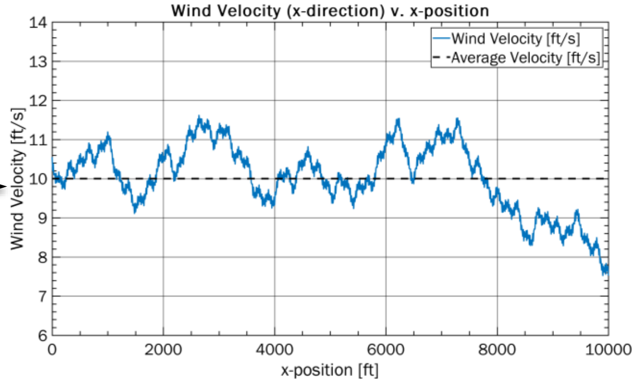
- Three-dimensional, spatially-frozen vector field
- Altitude dependency, stochastic gusts
- Derived from Dryden power spectrum

Avg. Wind	*Altitude Control*	*Turbulent Intensity*	*Random Gusts*		***Wind Field***
V_{avg}	L	σ	ϵ	$\rightarrow$	$V(x,y,z)$



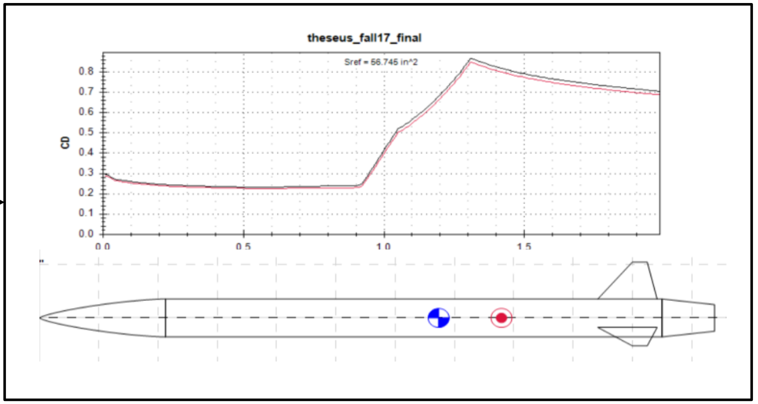


Signal Generation

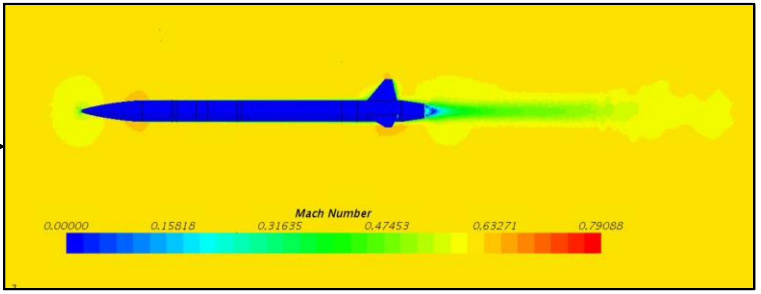


FS | AERODYNAMIC DATA

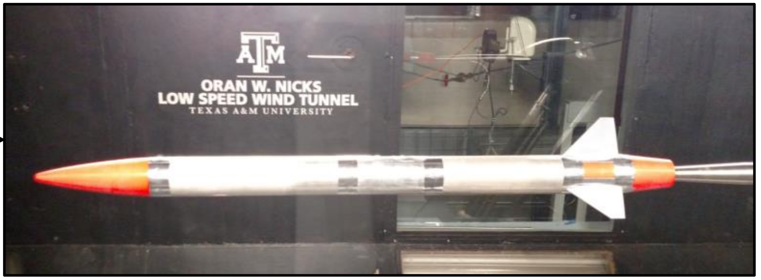
RASAERO 2 (DATCOM STAND-IN)



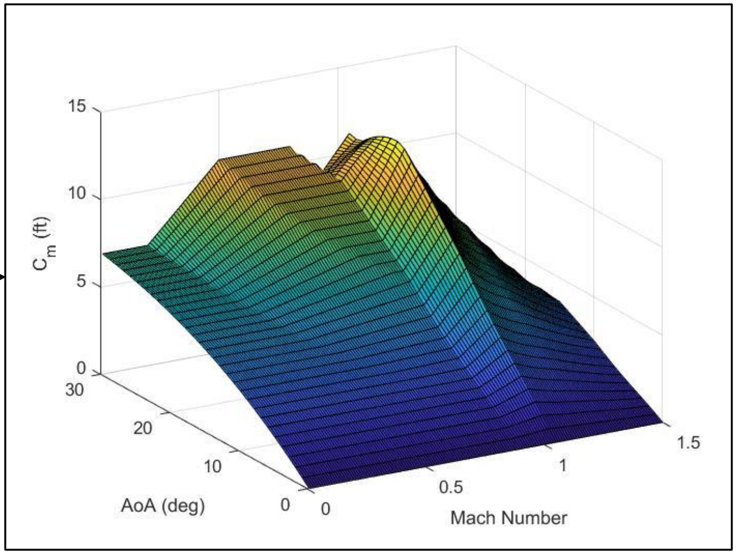
CFD



WIND TUNNEL TESTING



AERODYNAMIC DATA



ORAN W. NICKS
LOW SPEED WIND TUNNEL
TEXAS A&M UNIVERSITY

STAR-CCM+

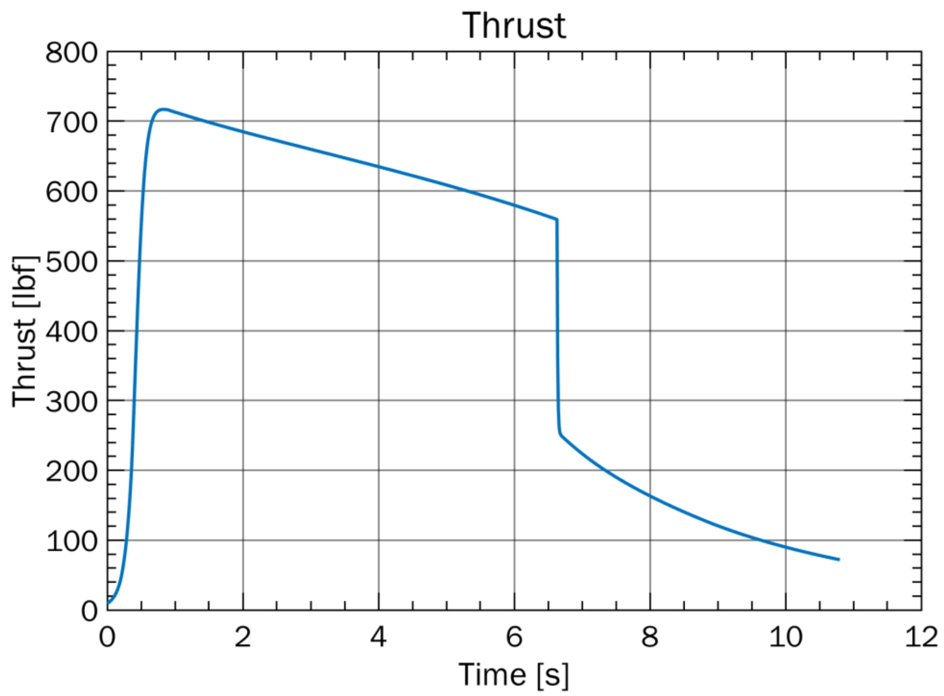
HEM | MODELING APPROACH

Modeling

- Forward finite-difference time-stepping scheme
- Oxidizer tank vapor-liquid equilibrium (VLE)
- Semi-empirical mass-flux-based fuel grain regression model

Limitations and Assumptions

- Ideal combustion and mixing
- Negligible heat transfer effects (adiabatic wall)
- Isentropic expansion
- Frozen flow through nozzle
- Perfect hardware

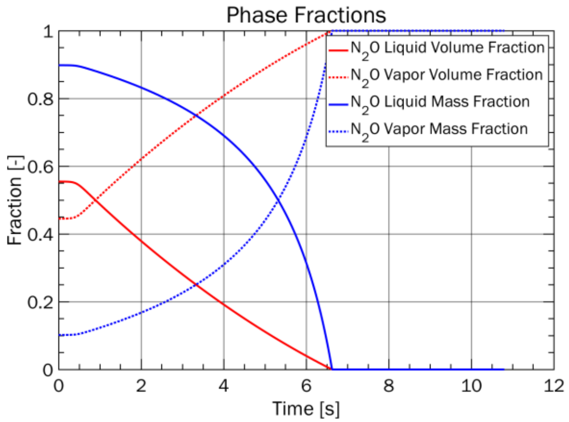


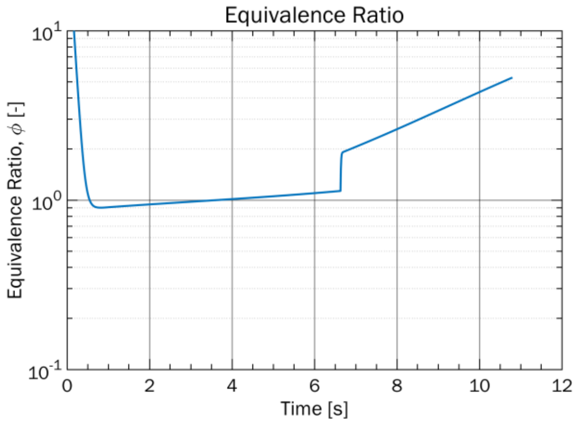
Total Impulse:	4014.05 lbf-sec
Total Impulse Class:	N 73 %
Average Thrust:	604.95 lbf
Burn Time:	6.64 sec
Fuel Lost:	2.38 lbm
Average Mass Flow Rate:	2.64 lbm/sec
Average OF:	6.14
Specific Impulse:	228.83 sec
Average Regression Rate:	0.0405 in/sec

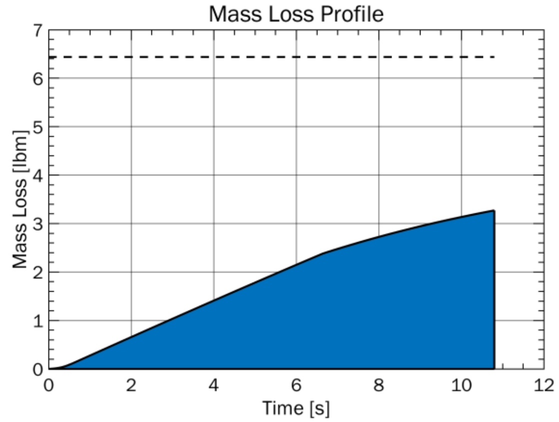
HEM as a _______ Tool

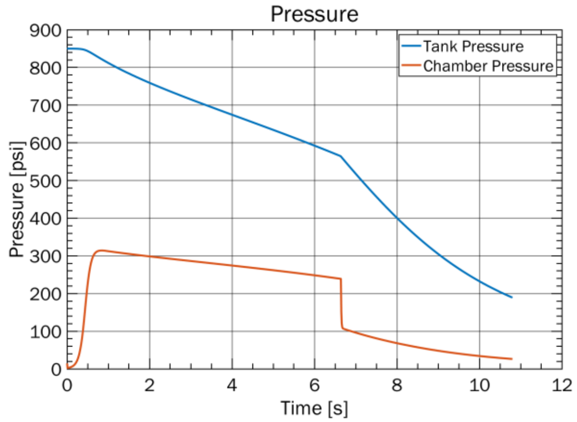
- **Design** – study on engine parameters
  - Tank sizing
  - Combustion chamber and grain sizing
  - Injector geometry selection
  - Fuel and oxidizer selection
  - Nozzle sizing
- **Prediction** – *a priori* estimation of hybrid engine performance
- **Comparison** – baseline for static engine test or cold flow test

HEM AS A
FLIGHT PREDICTION TOOL



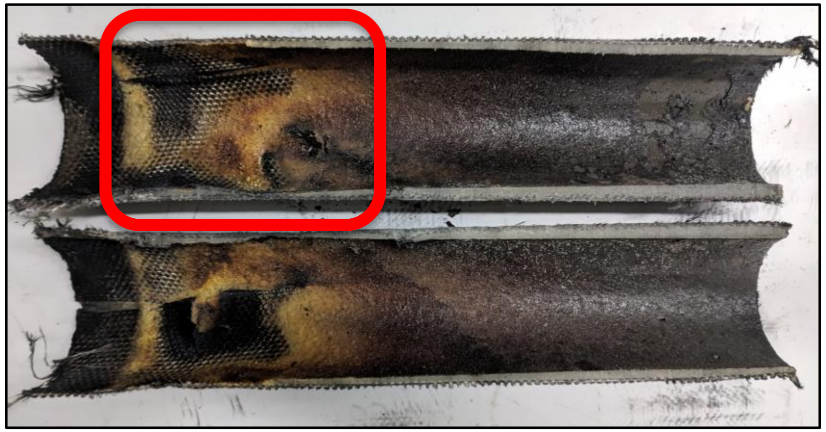




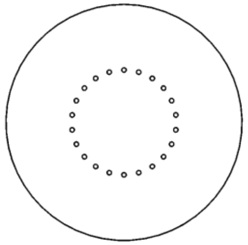


Theoretical Model Validation

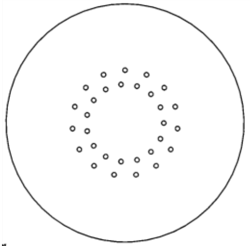
- Highly-nonlinear regression led to injection testing
- New coin selected based on ***comparative*** empirical test data due to improved mass flow rate and discharge coeff.
- Supports existing discharge/injection model



	Coin	Mass Flow Rate [kg/s]	C_d [-]
1	axial (22)	0.0333	0.2221
2	vortex (22)	0.0532	0.3554
3	**impinging (22)**	**0.0477**	**0.3184**
4	vortex (11) + impinging (11)	0.0513	0.3422
5	vortex (8) + impinging (8)	0.0198	0.1817
6	**vortex (15) + impinging (15)**	**0.0705**	**0.3453**
7	vortex (15) + impinging (5, larger area)	0.0694	0.3871
8	axial (1, larger area)	0.0699	0.3422



TESTED INJECTION GEOMETRIES

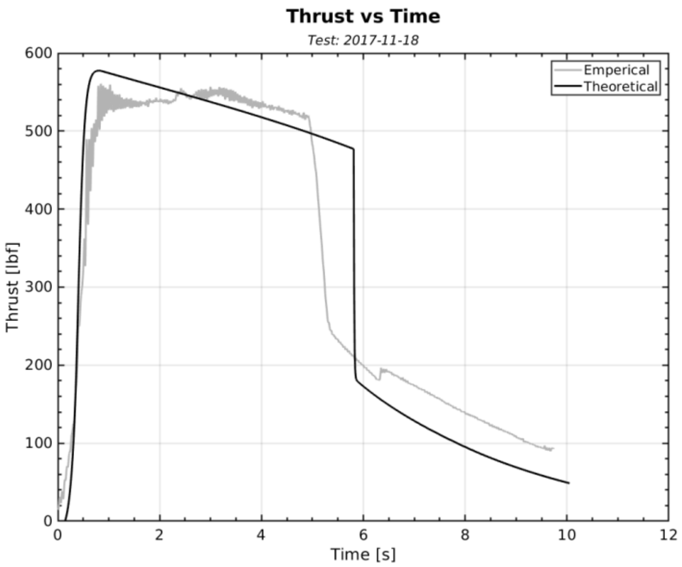


HEM | VALIDATION – THRUST

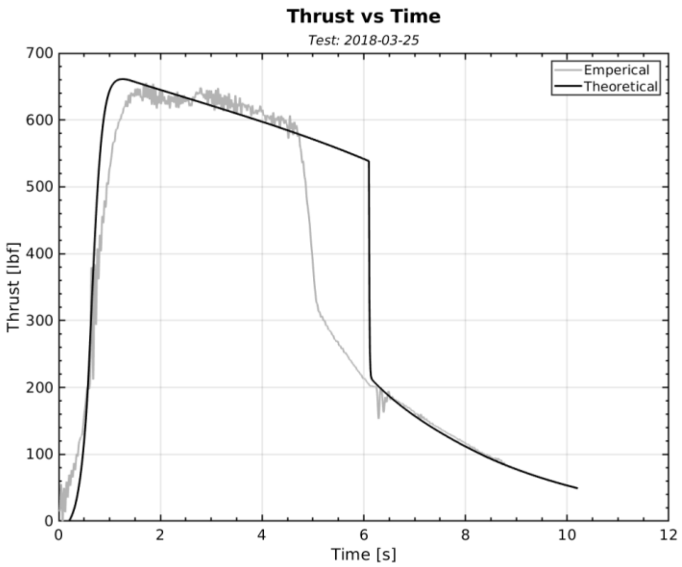
Theoretical Model Validation

- Testing campaign achieved several successful static engine tests (SETs)
- Good first-order agreement between empirical and theoretical data (η ≈ 0.95)

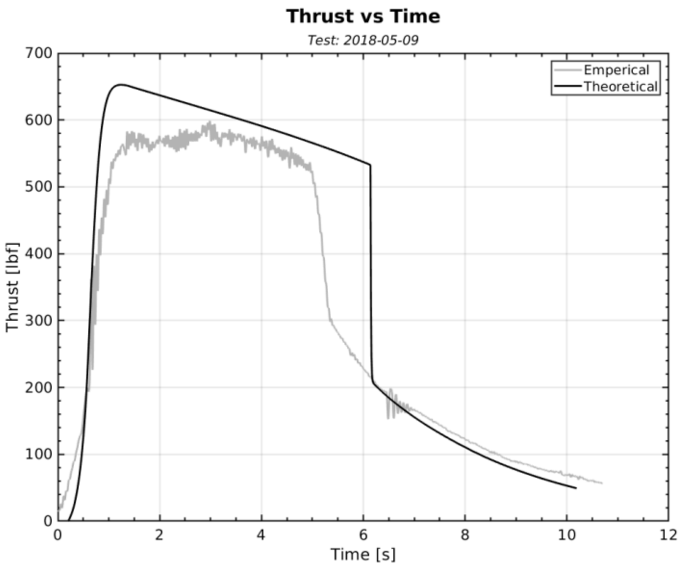
SET-IV



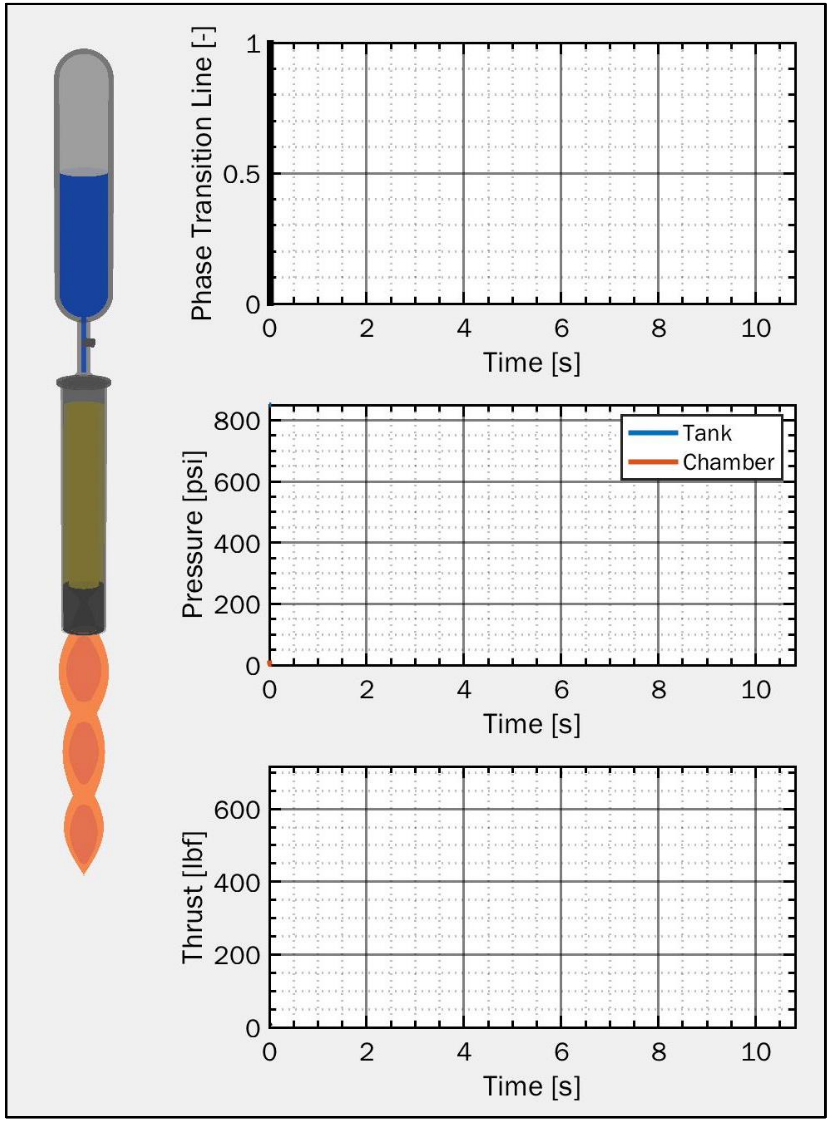
SET-VIII



SET-XII

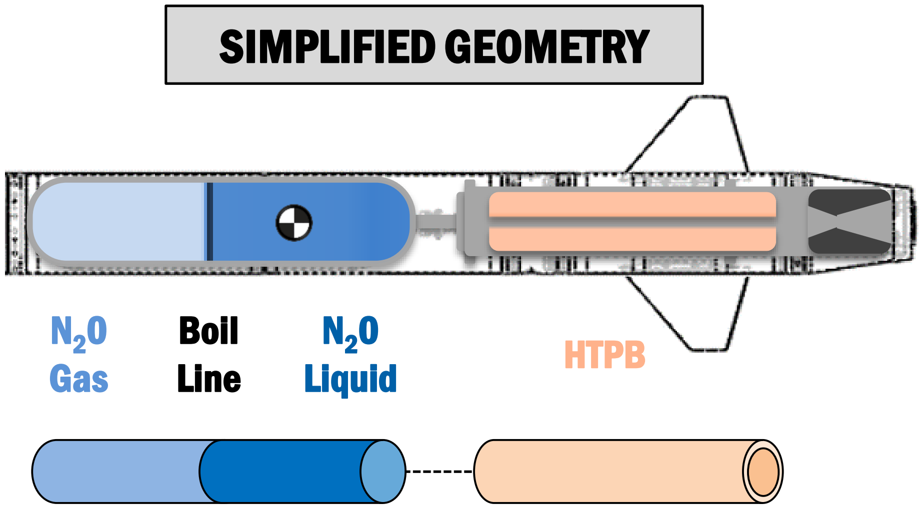


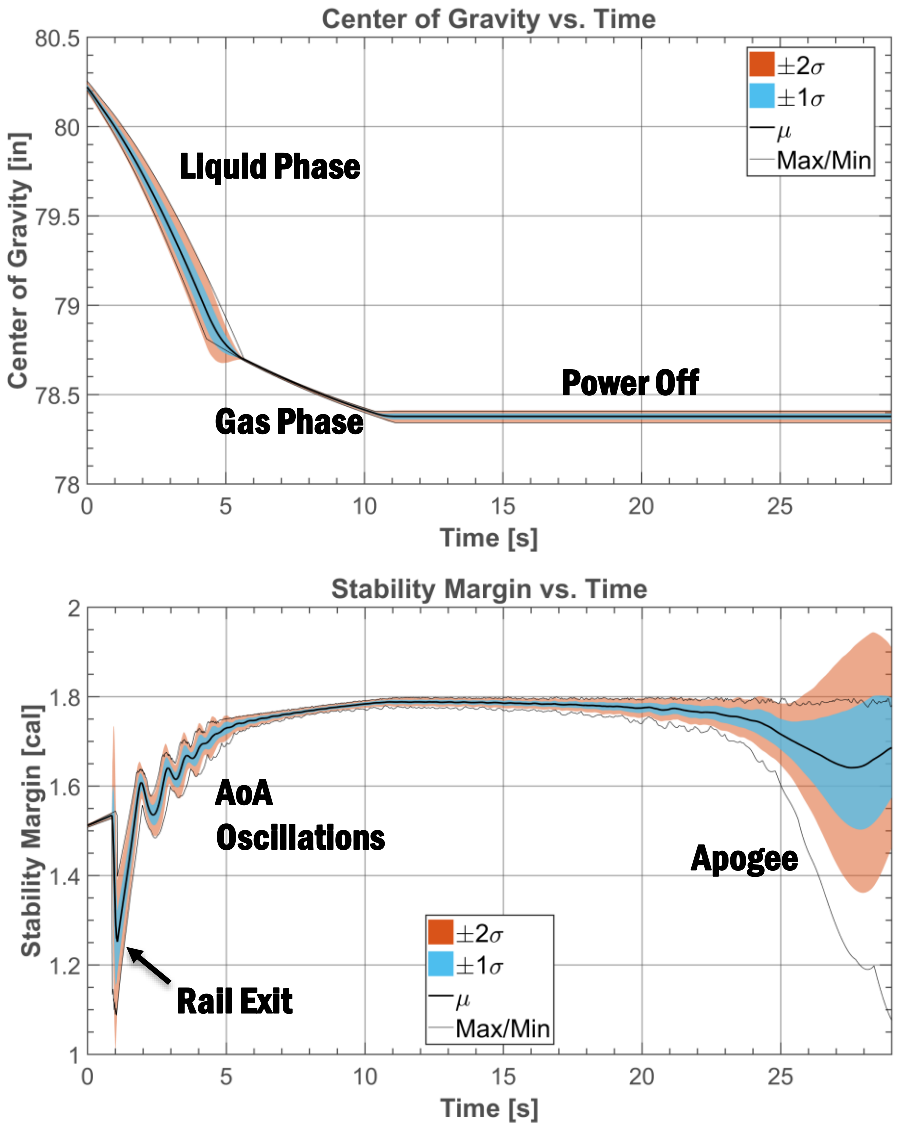
HEM | VISUALIZATION

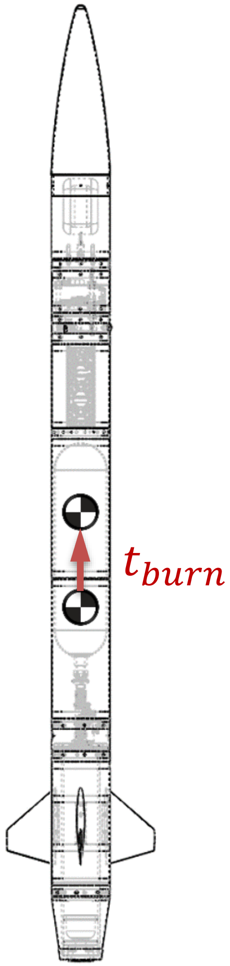


Transient Mass Properties

- Mass, CG, moments of inertia vary through burn
- Idealized fuel/oxidizer geometry
- Boil line and mass flow from HEM
- Dynamic stability margin calculation





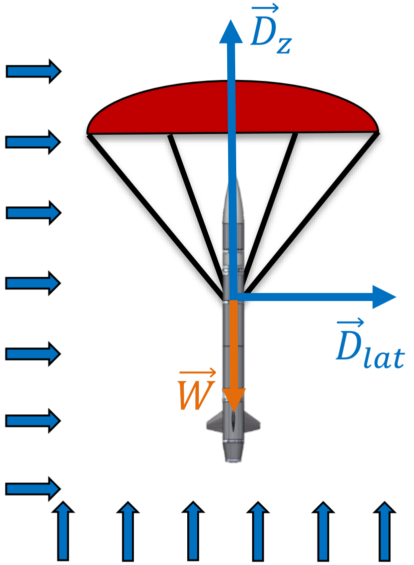


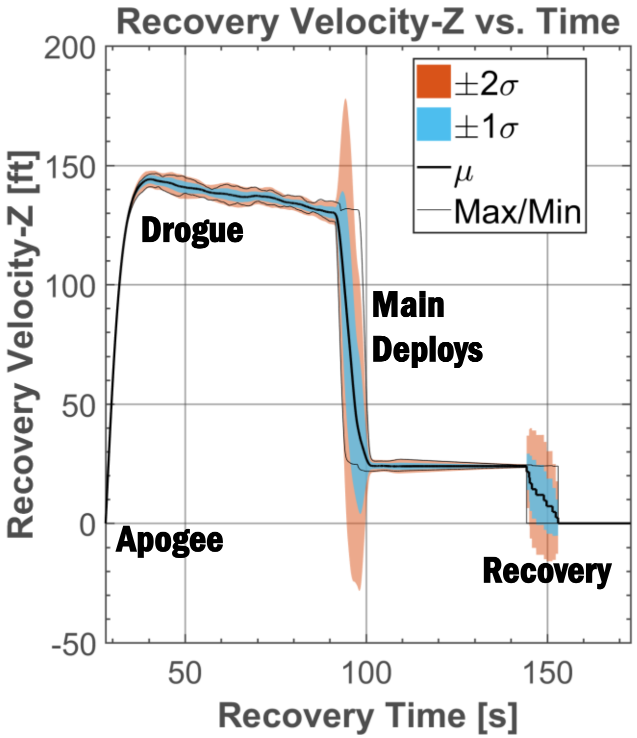
Kinematics

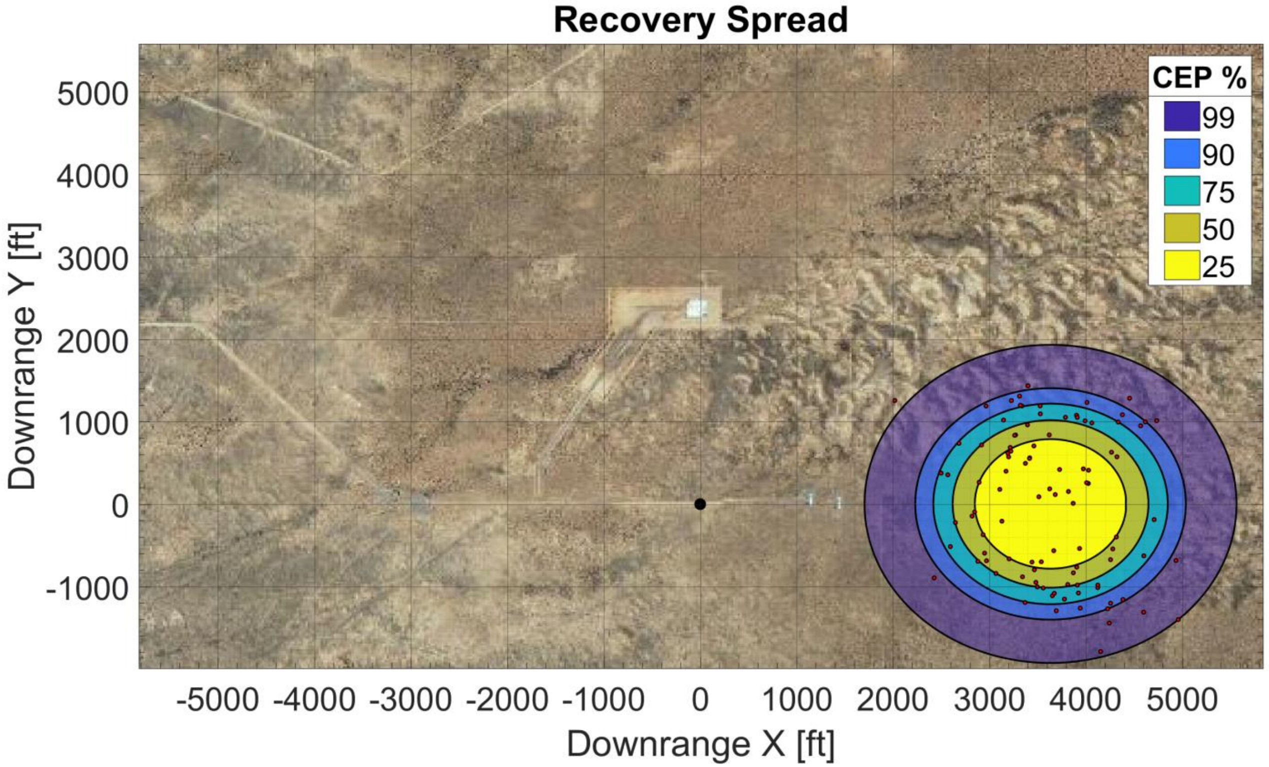
- 3 DoF translational simulation post-apogee
- Dynamic parachute inflation

Impact Map

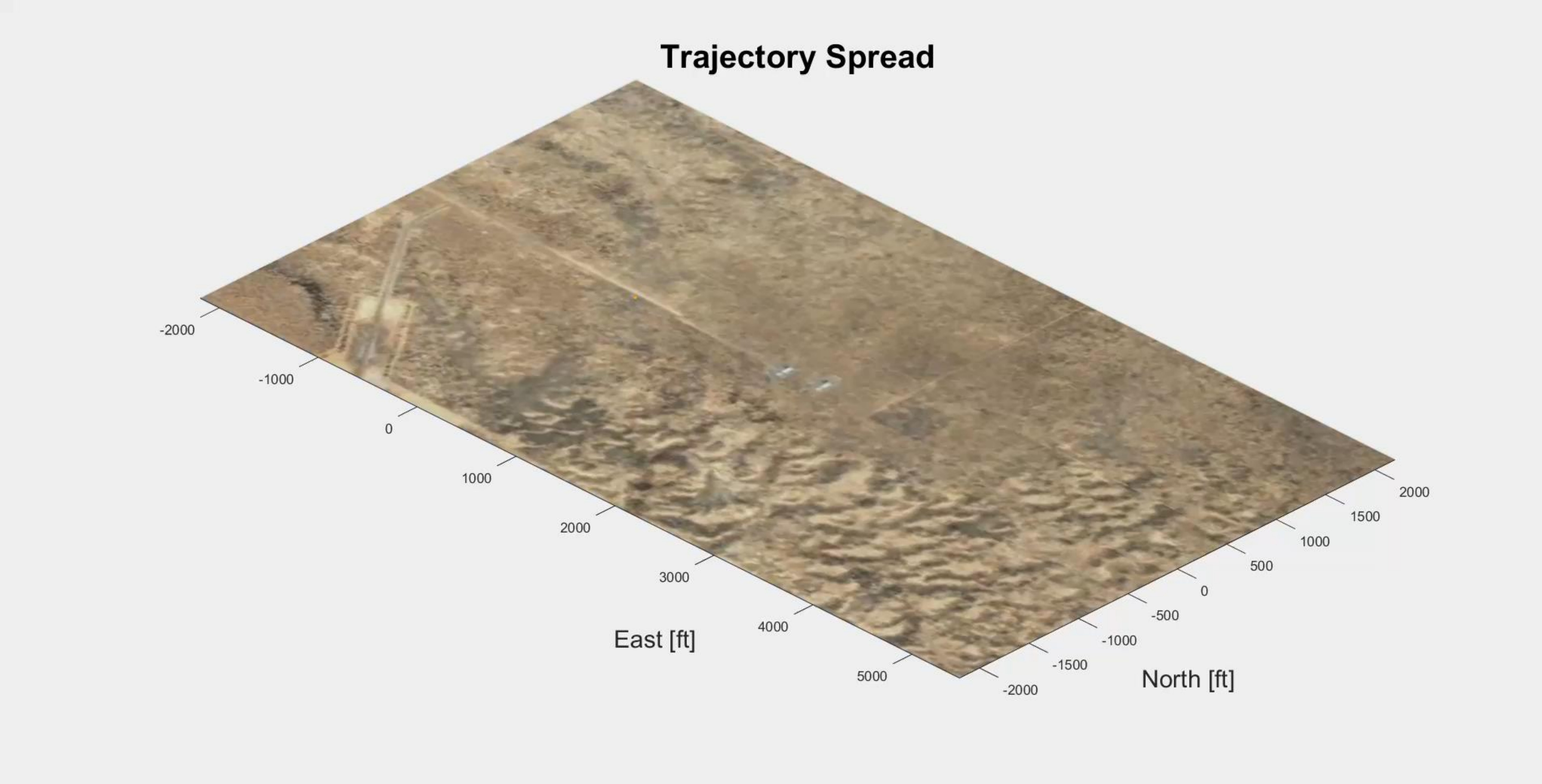
- Google Maps projection → recovery aid
- CEP impact zone analysis





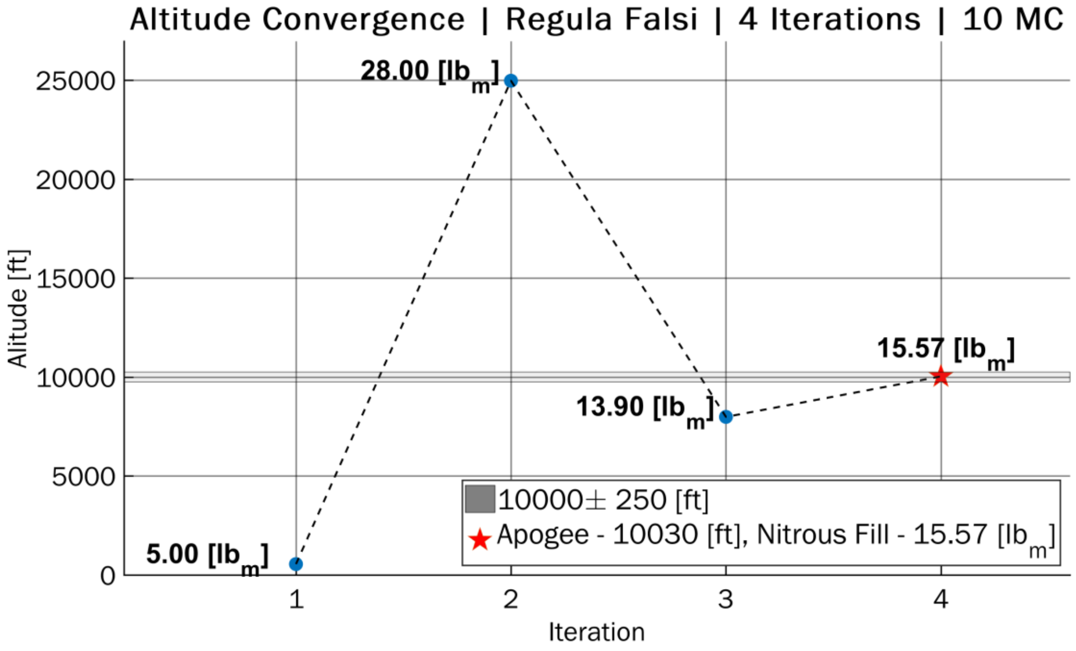


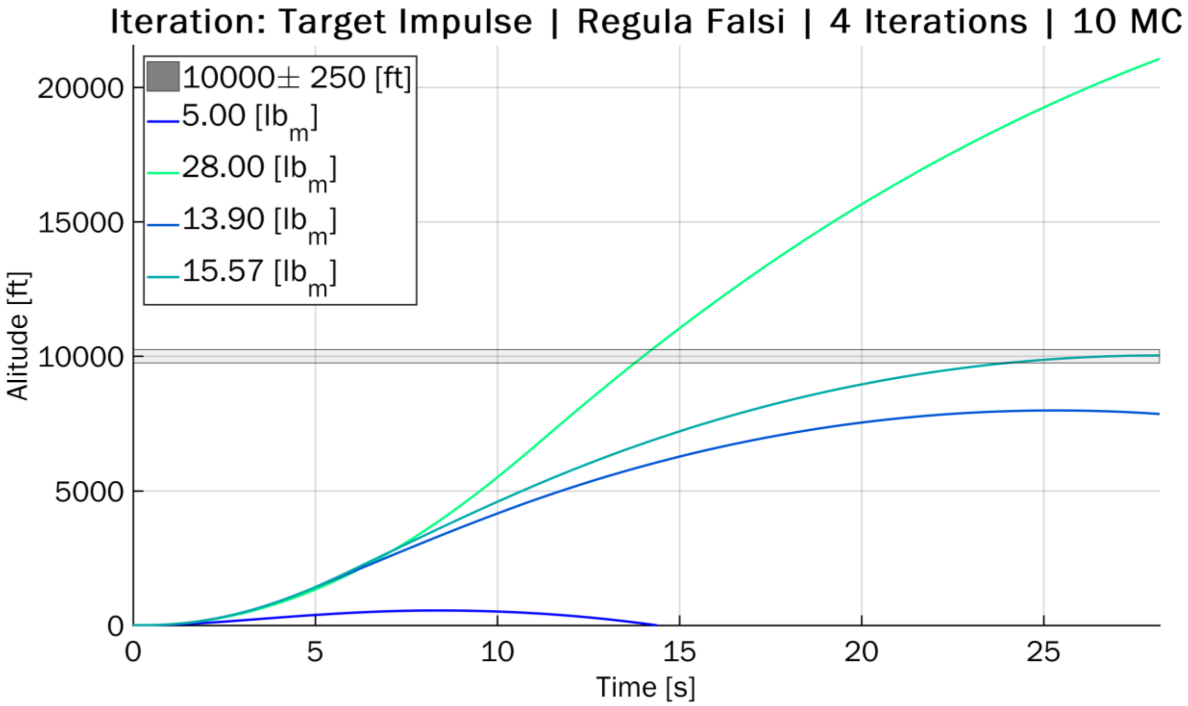
FS | VISUALIZATION



Target Impulse

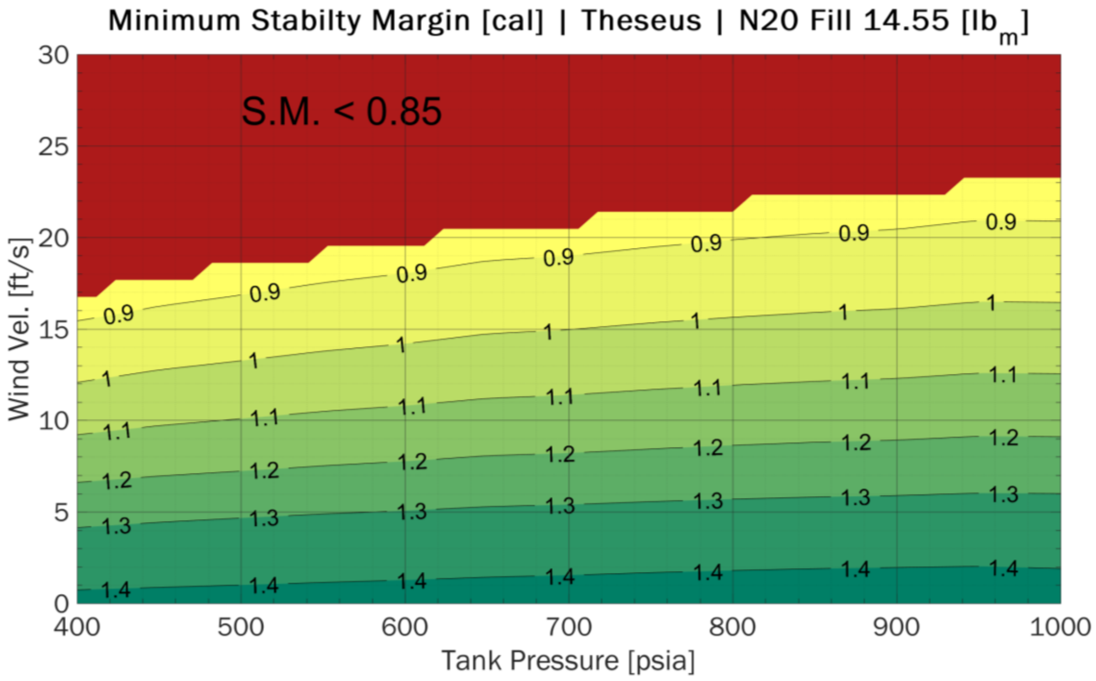
- Desired apogee → required oxidizer fill
- Iterative process → *Regula falsi* over fill weight
- Interfaces over existing Monte Carlo simulation





Flight Performance Envelope

- Characterize vehicle performance
- Captures input sensitivity → identify *no-go* regions
- Launch day safety check
- Avoid delays in launch sequence



FPE LOOKUP PROCESS

(700 [psia], 15 [ft/s]) → Min Stab.: 1.0 [cal]

(600 [psia], 25 [ft/s]) → Min Stab.: 0.75 [cal]

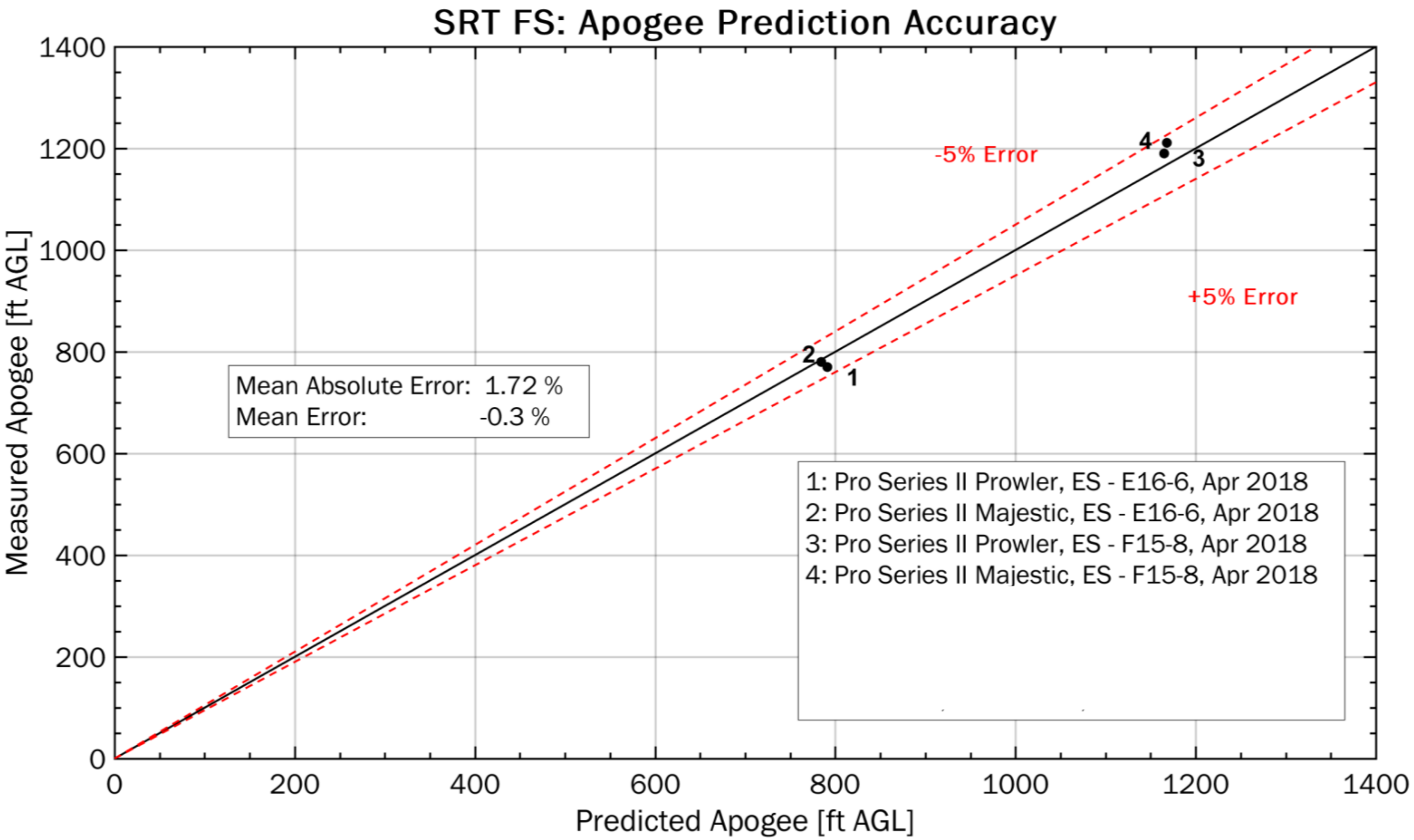
FS | VALIDATION – APOGEE

Test Vehicles:

Pro Series II Majestic
Pro Series II Prowler

Specifications	
Length	~36 [in]
OD	2 [in]
Dry Mass	0.6 [lb_m]
Peak Mach	~0.25

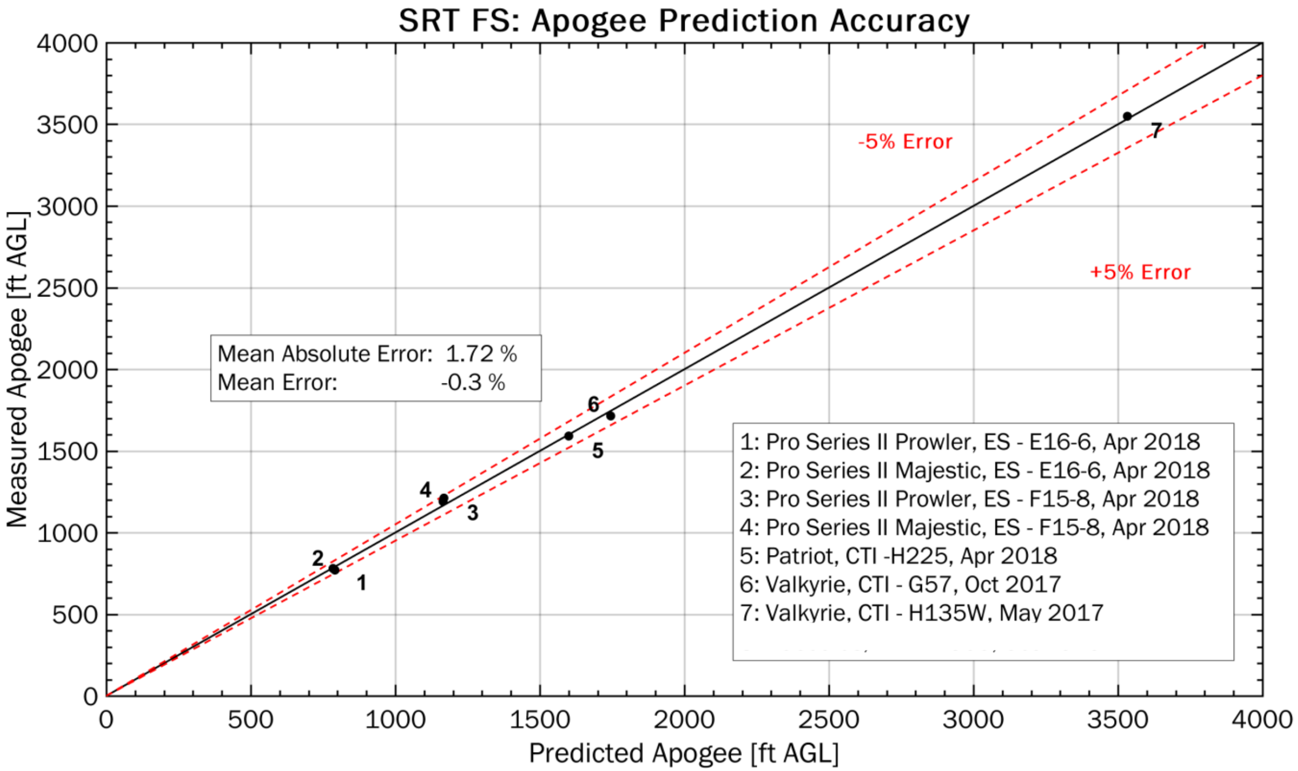
Majestic/Prowler	E16-6	F15-8
Projected Apogee	784/791 [ft]	1168/1165 [ft]
Actual Apogee	780/770 [ft]	1211/1190 [ft]
Percent Error	**0.6/2.7 %**	**3.5/2.1 %**



FS | VALIDATION – APOGEE

Test Vehicles:
Valkyrie (L1)
Patriot

Specs.	Valkyrie	Patriot
Length	40 [in]	53 [in]
OD	2.6 [in]	4 [in]
Dry Mass	1.6 [lb_m]	4.3 [lb_m]
Peak Mach	~0.7	~0.3



Valkyrie	CTI–G57	CTI-H135W
Projected Apogee	1745 [ft]	3532 [ft]
Actual Apogee	1714 [ft]	3549 [ft]
Percent Error	**1.8 %**	**0.5 %**

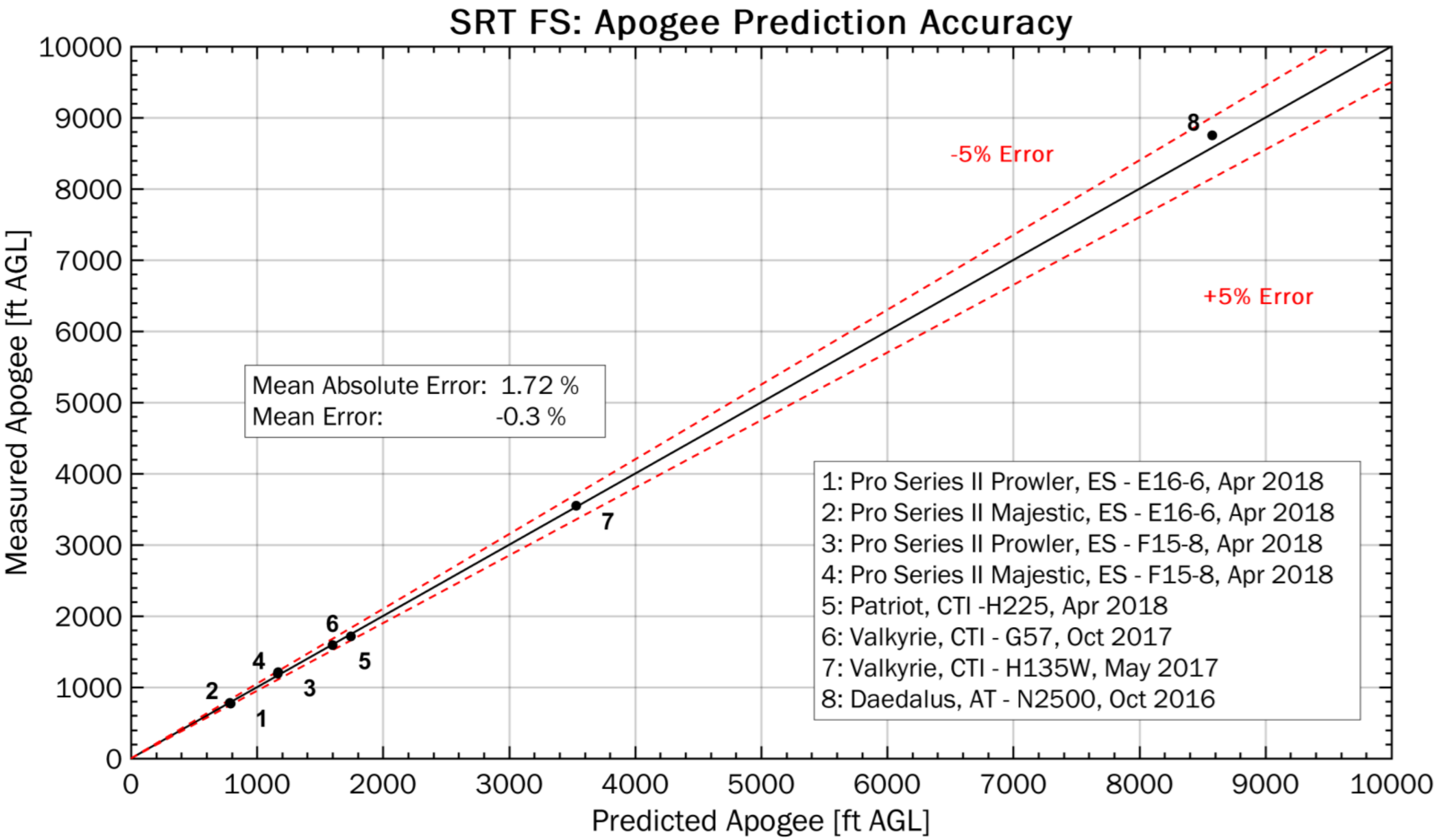
Patriot	CTI–H225
Projected Apogee	1600 [ft]
Actual Apogee	1591 [ft]
Percent Error	**0.56 %**

FS | VALIDATION – APOGEE

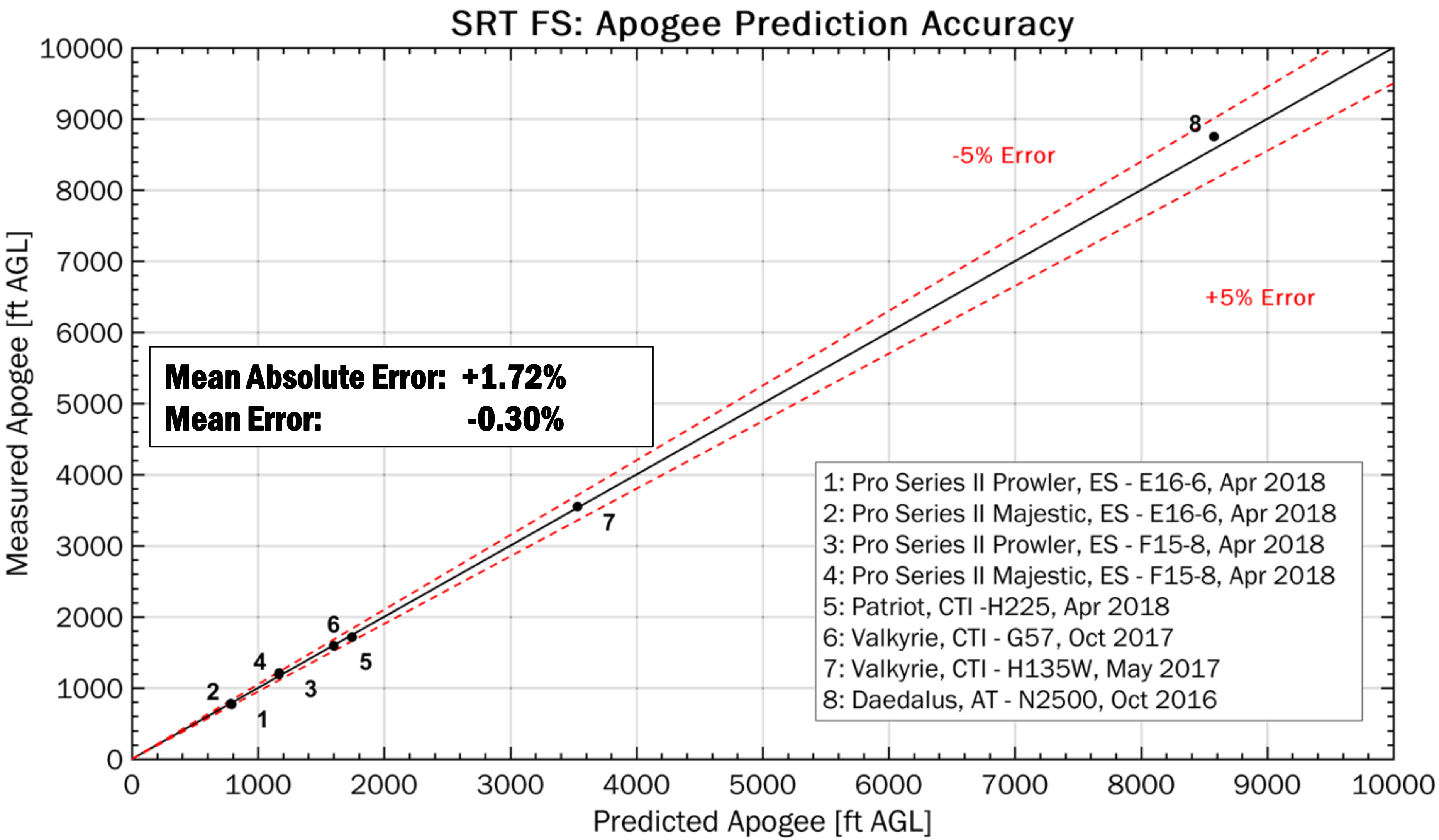
Test Vehicle:
Daedalus

Specifications	
Length	146 [in]
OD	8.5 [in]
Dry Mass	111 [lb_m]
Peak Mach	~0.6

Daedalus	AT - N2500
Projected Apogee	8578 [ft]
Actual Apogee	8751 [ft]
Percent Error	**1.97 %**



FS | VALIDATION - APOGEE



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