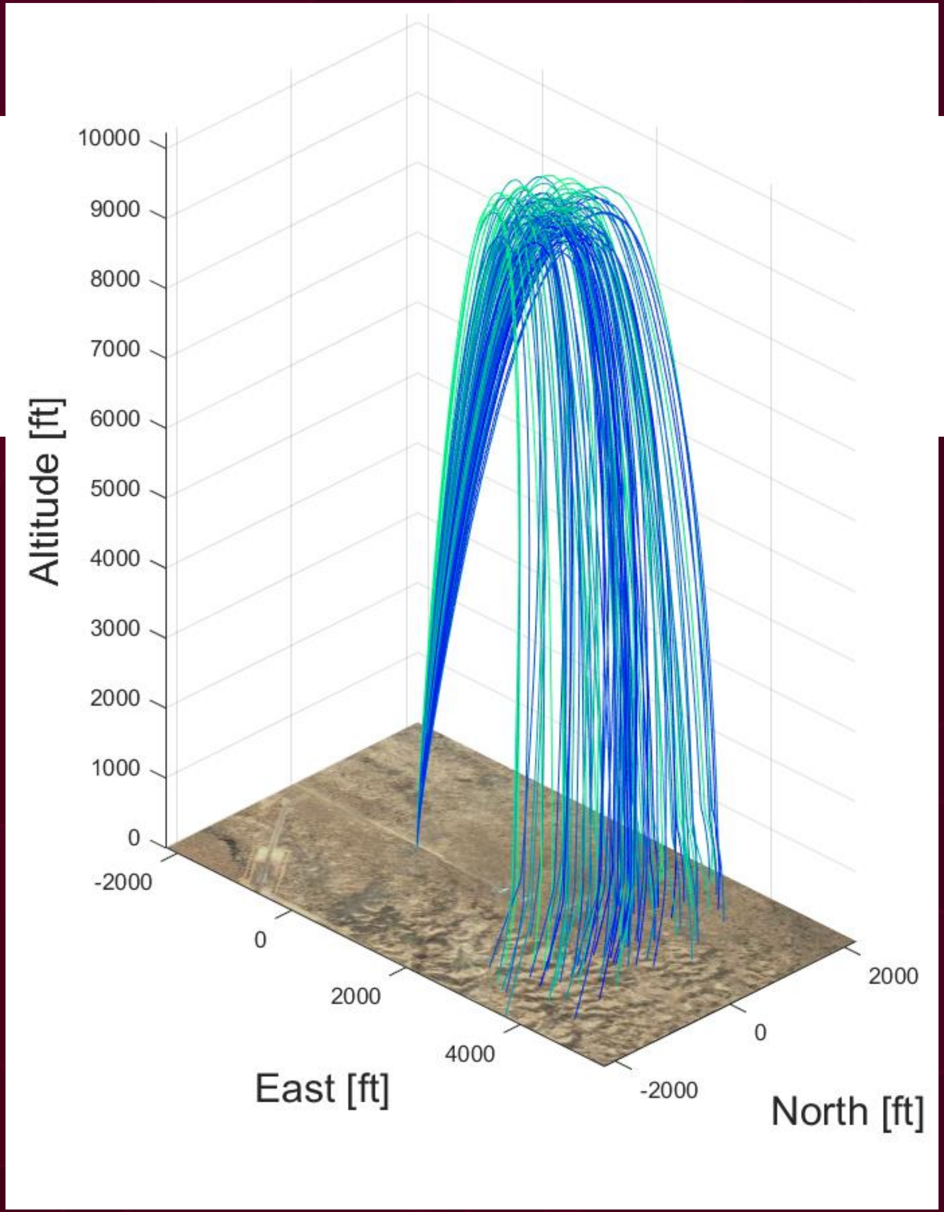


TEXAS A&M UNIVERSITY SOUNDING ROCKETRY TEAM

Integrated Flight Modeling: Trajectory & Hybrid Engine Performance

TEAM 12

Ross Alexander

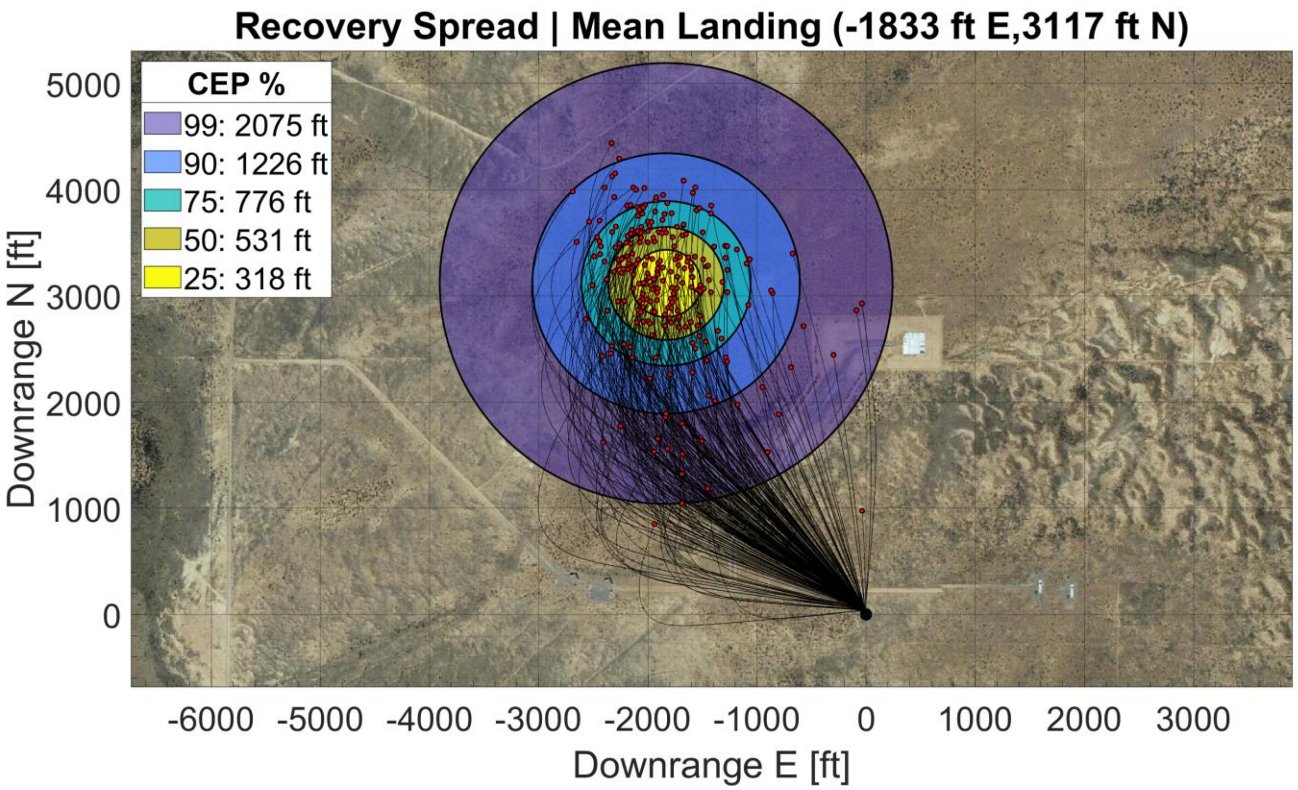
Jacob Caesar

Jacob Doll

OVERVIEW

OUTLINE

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



OVERVIEW | MOTIVATION

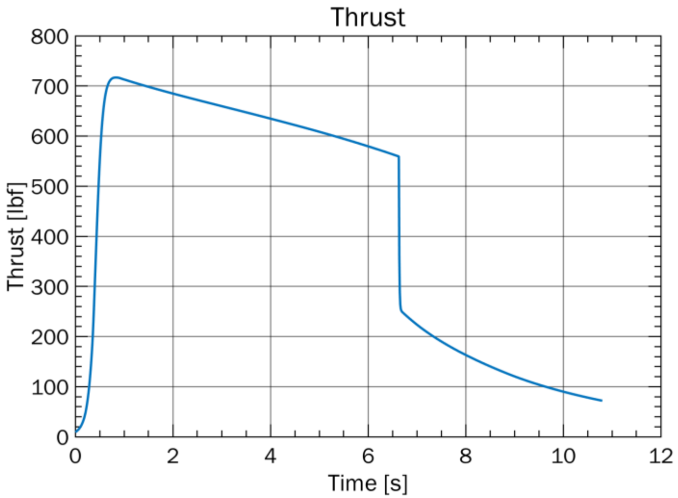
PROBLEM

- **Commercial software programs have many limitations**
  - Limited or no hybrid engine capability
  - Over-simplified input variables
  - No statistical flight analysis

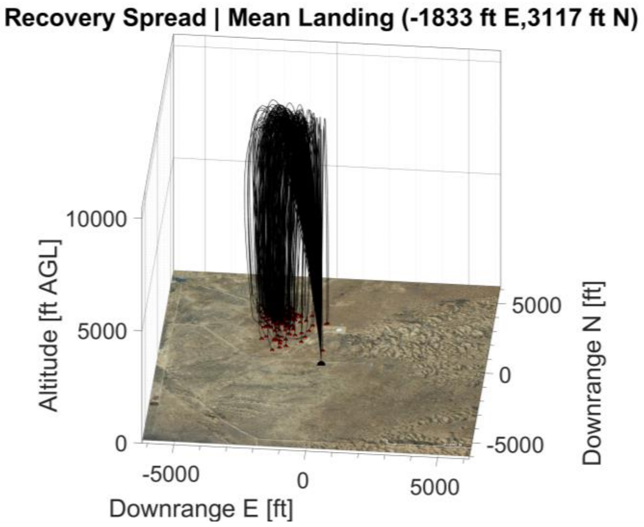
SOLUTION

- **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

HEM



FS

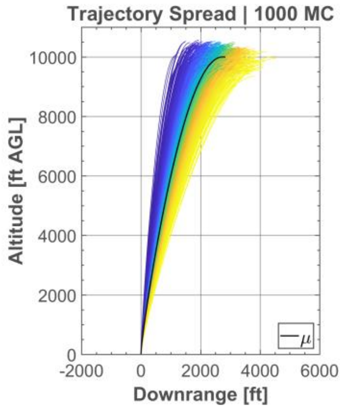


OVERVIEW | MODELS

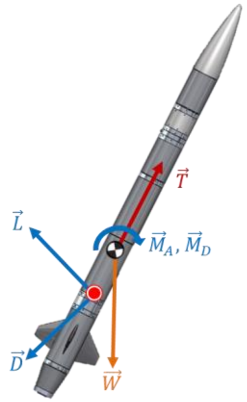
INTEGRATED FLIGHT MODEL

FS

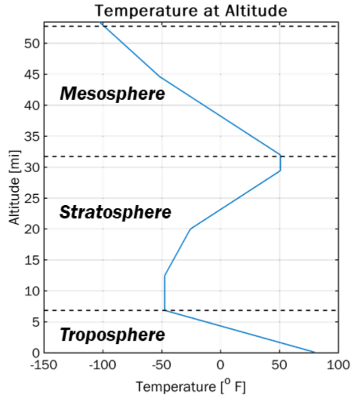
Monte Carlo Simulation
- Stochastic systems
- Historical weather
- Statistical analysis



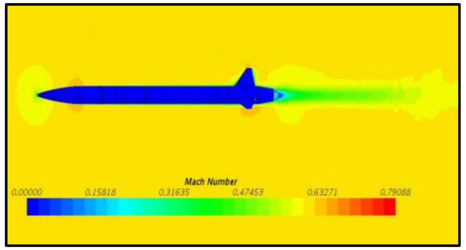
Kinematic Model
- RKF-45 integration
- 6 DoF EOM
- Recovery model



Atmospheric Model
- Modified standard atmosphere
- Dryden wind model

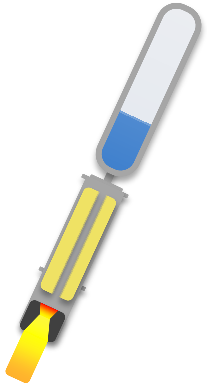


Aerodynamic Model
- High-fidelity CFD refinement
- Wind tunnel testing



HEM

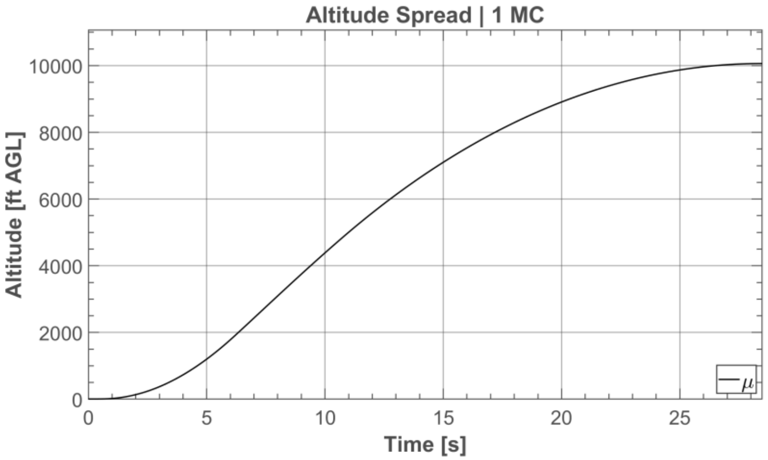
Engine Model
- Multiphase flow model
- Combustion model
- Time-dependent thrust curve

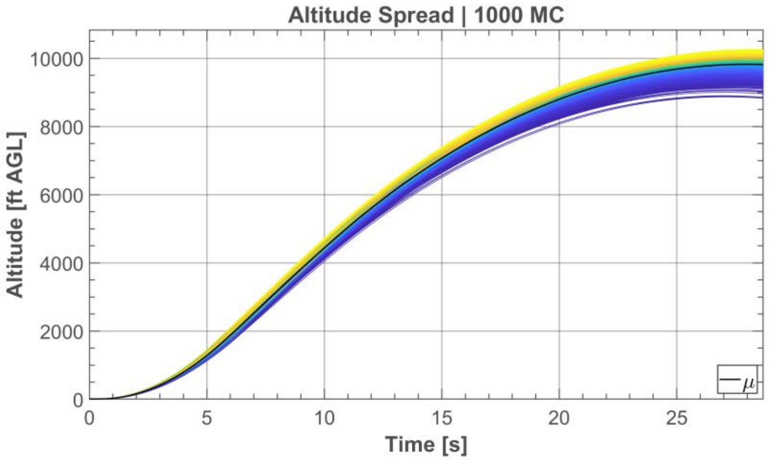


METHODOLOGY

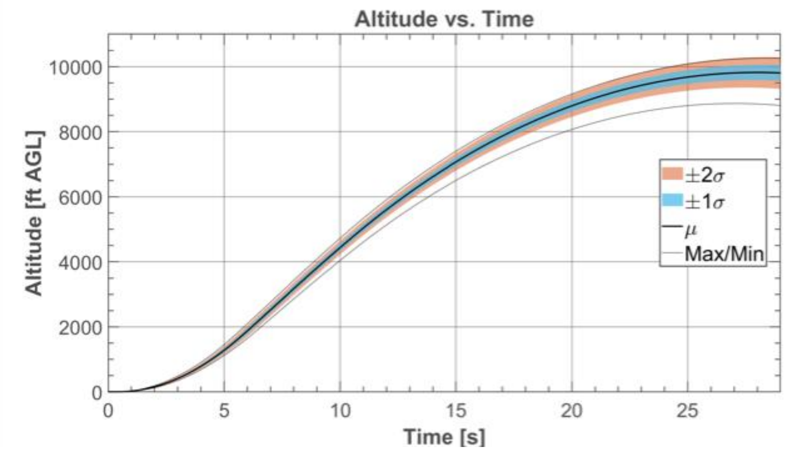
- Quantify uncertainty of stochastic systems
- Assign distributions ⟶ step through many flights
- Improved accuracy by accounting for off-nominal flights

ESTABLISH SPREAD





STATISTICAL ANALYSIS



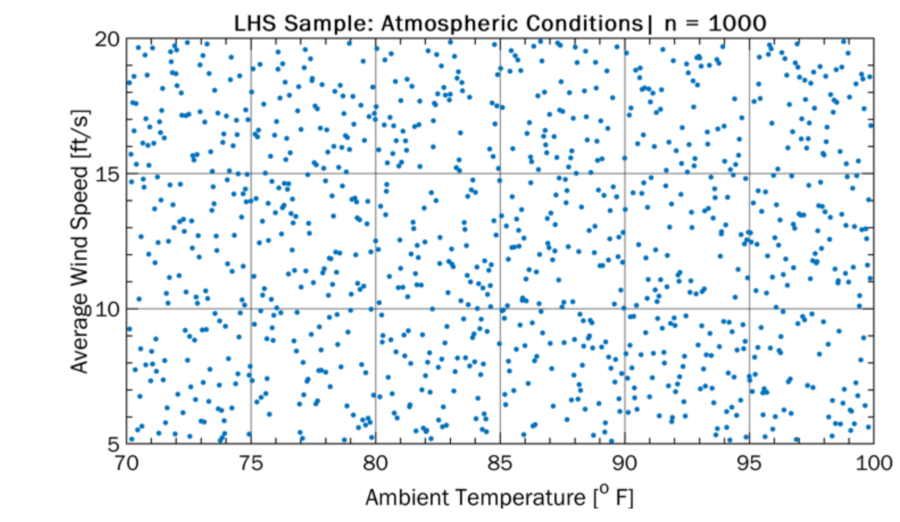
FS | MONTE CARLO SIMULATION

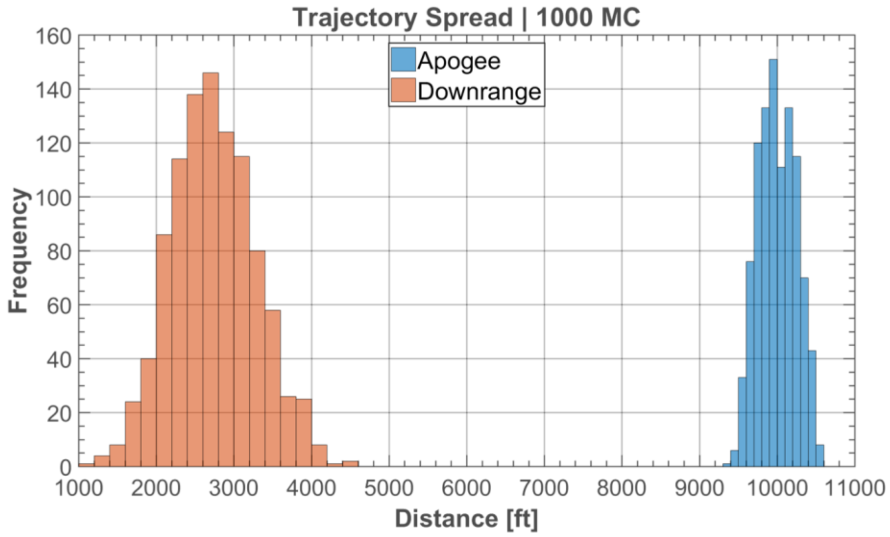
RANDOM SAMPLING

- Pre-flight uncertainties
- Flight day uncertainties
- Uniform, normal, Latin Hypercube Sampling
- Random seed control

POST-PROCESSING

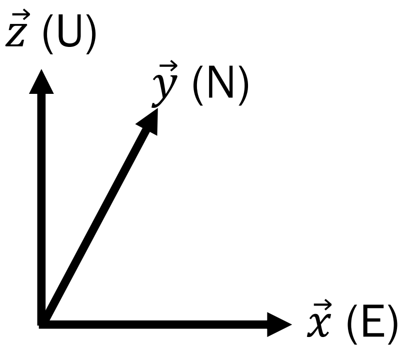
- Mean flight
- Quantify spread of output → min/max, σ
- Confidence in launch safety



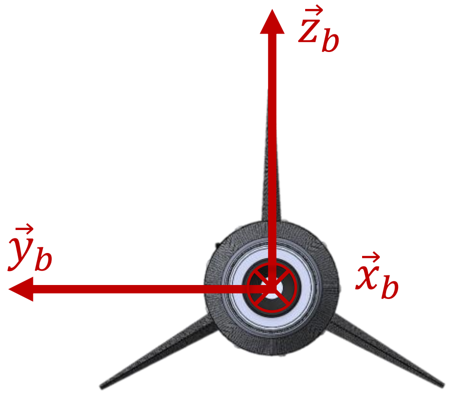


KINEMATICS

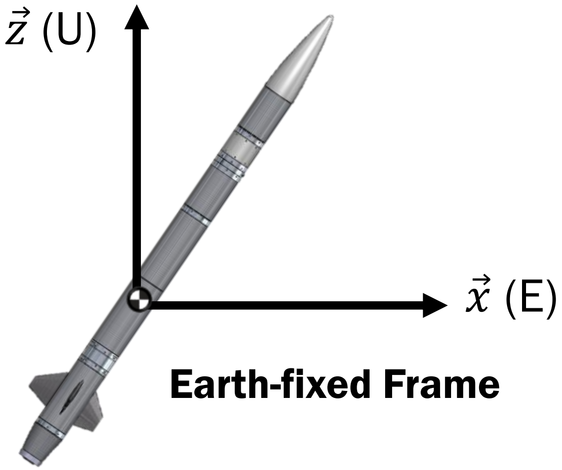
- Quaternion-based angular orientation
- RKF-45 numerical integration
- Reference frames
  1. Inertial (Flat-Earth East-North-Up)
  2. Relative Wind (freestream + wind)
  3. Body Fixed



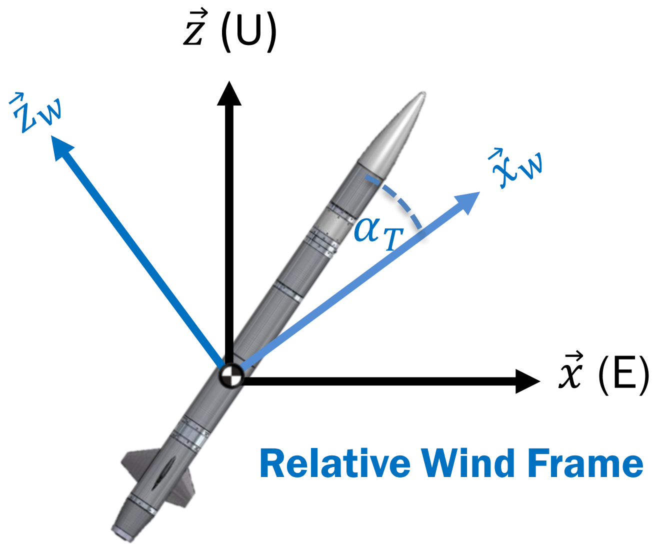
East-North-Up Inertial Frame



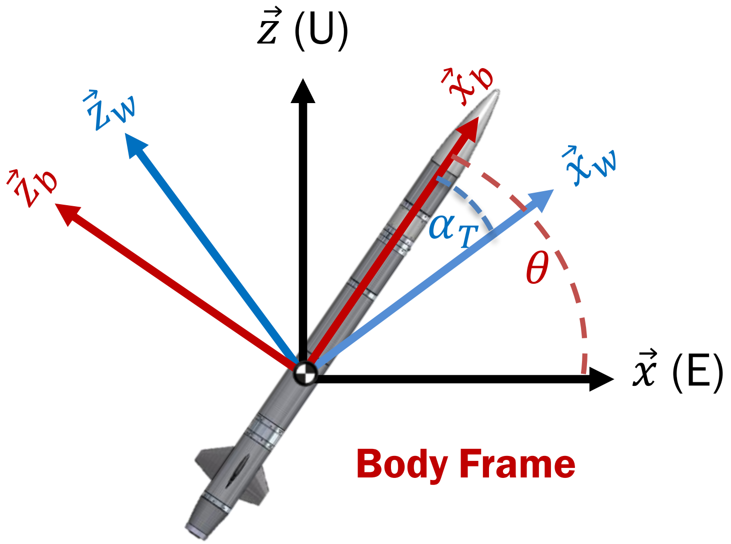
Bottom (x-z)



Earth-fixed Frame



Relative Wind Frame



Body Frame

FS | EQUATIONS OF MOTION

TRANSLATIONAL

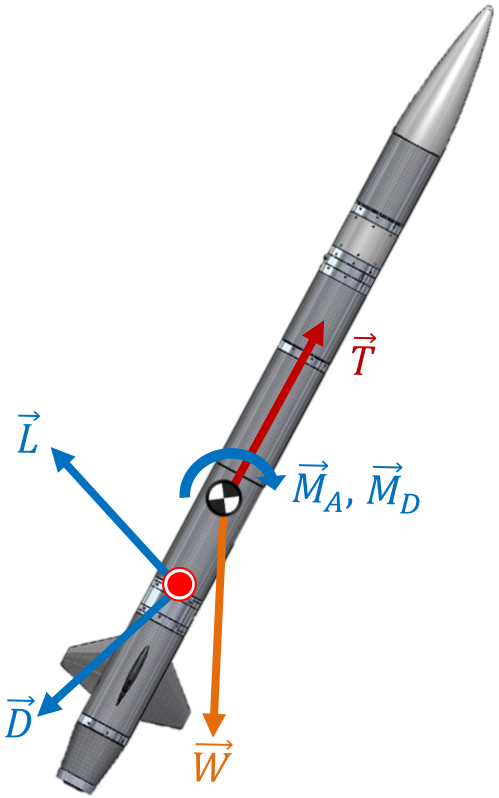
- Body frame: thrust
- Wind frame: lift, drag
- Inertial frame: weight

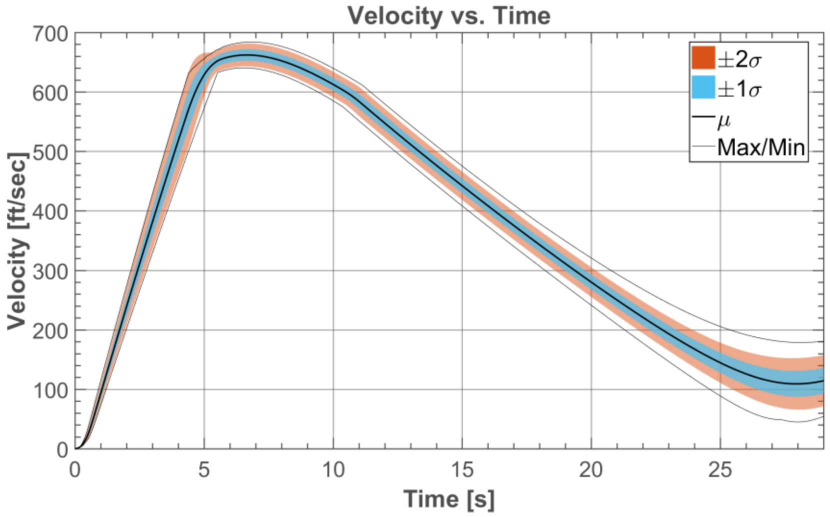
$$\vec{a} = \frac{\vec{T} + (\vec{L} + \vec{D}) + \vec{W}}{m(t)}$$

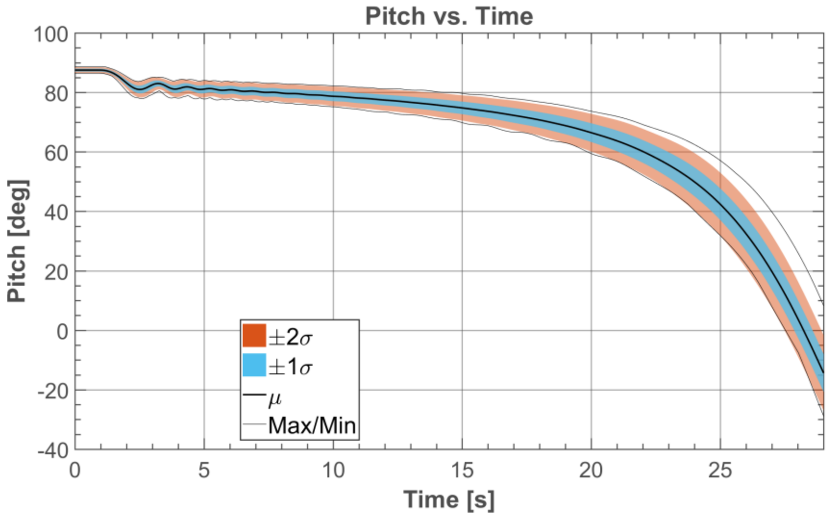
ROTATIONAL

- Moments about shifting CG
- Idealized aerodynamic forces
- Thrust & aerodynamic damping

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



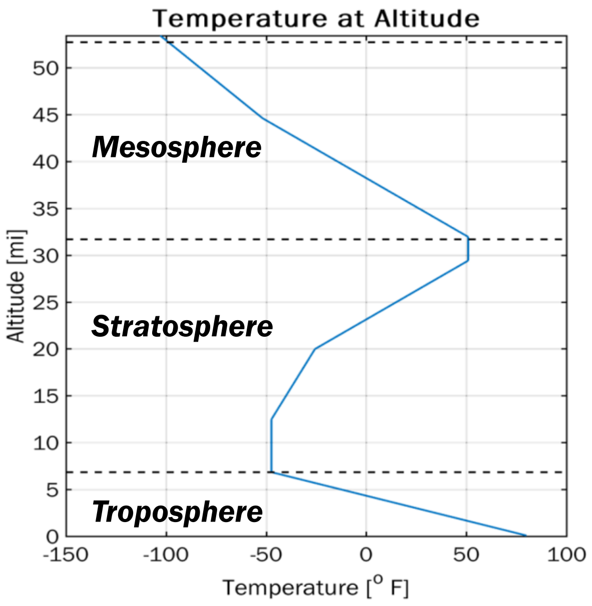


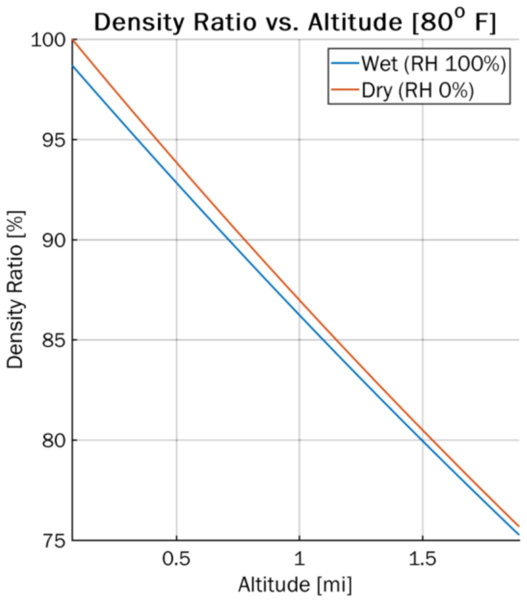


FS | ATMOSPHERIC MODEL

MODIFIED STANDARD ATMOSPHERE

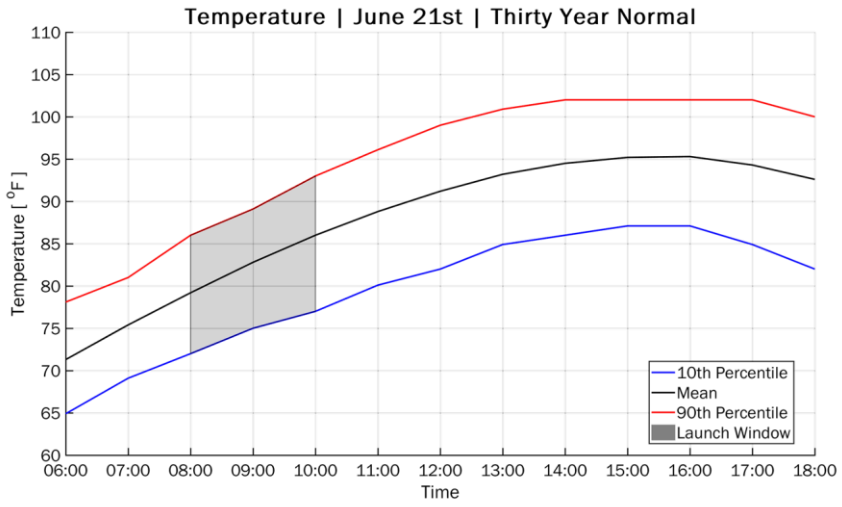
- Isentropic gradient: 0 to ~280,000 ft ASL
- Humidity correction for air density
- WGS-84 gravitational model

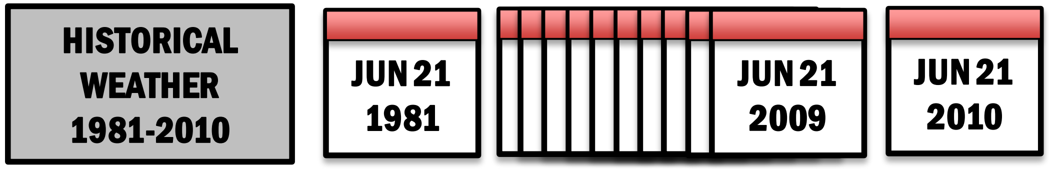




HISTORICAL WEATHER DATA

- 30-year hourly normal (NOAA)
- 10^{th}, 90^{th} percentile – lower, upper bounds
- Feed distribution to Monte Carlo simulation



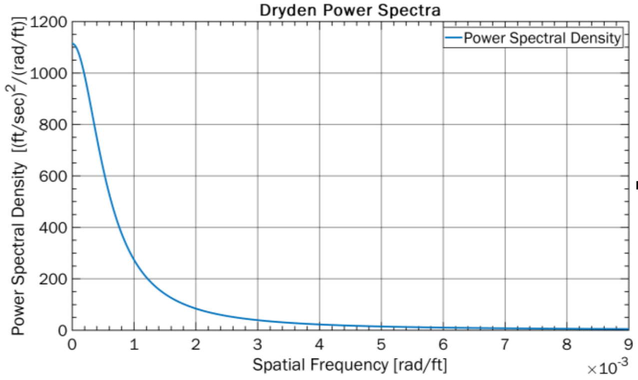


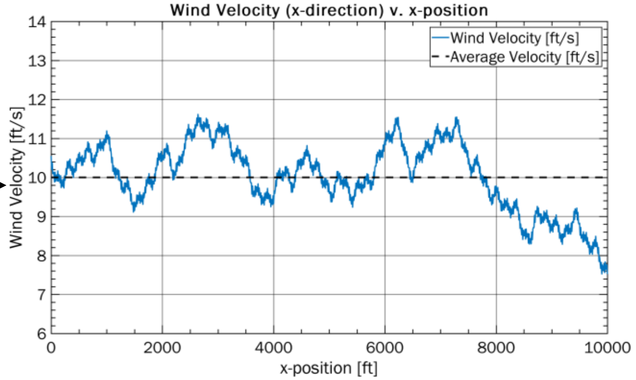
STOCHASTIC WIND MODEL

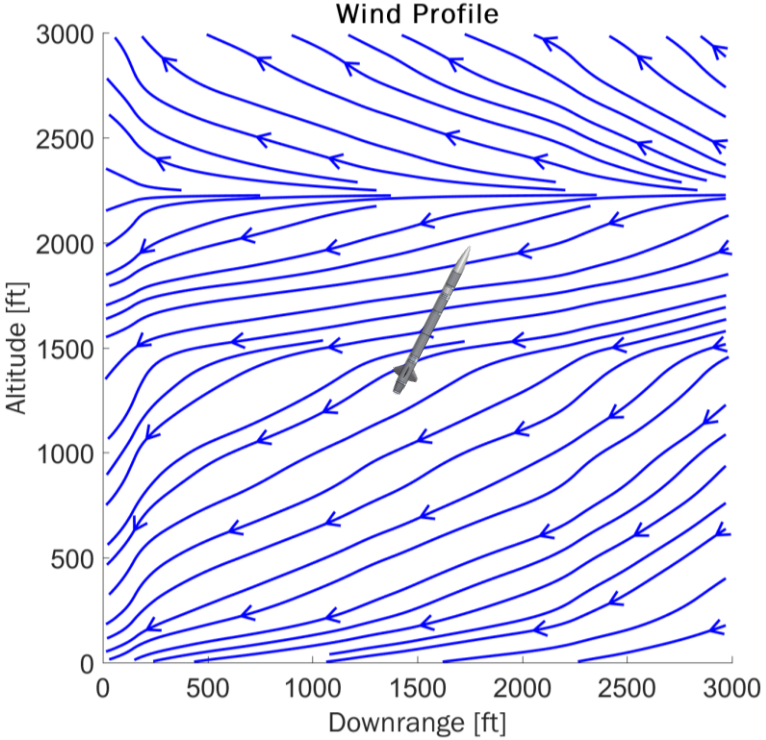
- Three-dimensional, spatially-frozen vector field
- Altitude-dependent, stochastic gusts
- Derived from Dryden power spectral density
- **Augmented from real-world conditions**

Avg. Wind	*Turbulent Intensity*		*Wind Field*
V_{avg}	σ	$\rightarrow$	$V(x,y,z)$

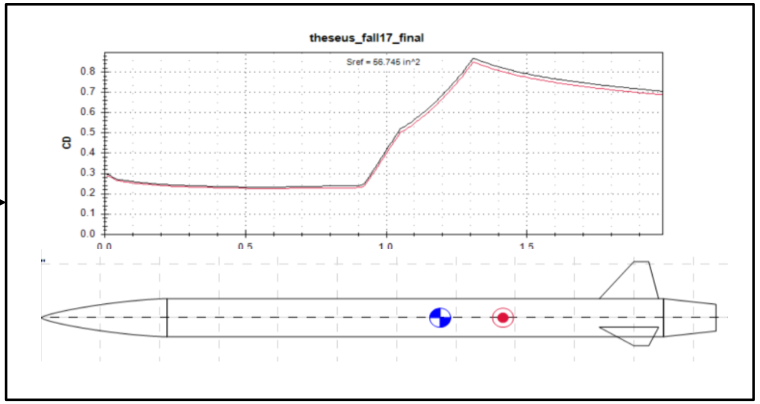
SIGNAL GENERATION



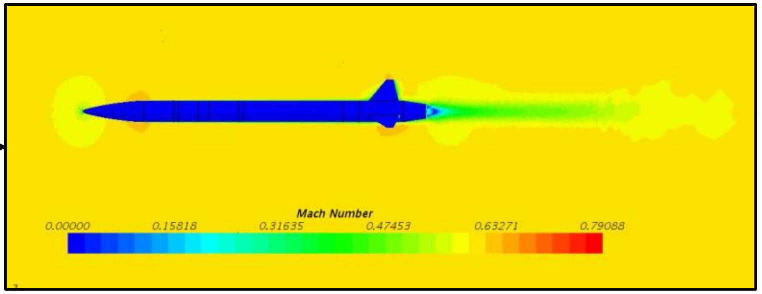




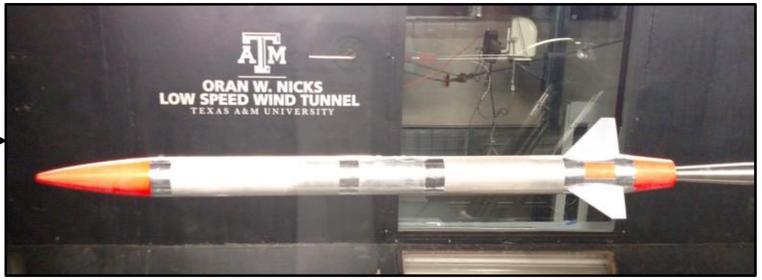
FIRST-ORDER METHODS (DATCOM)



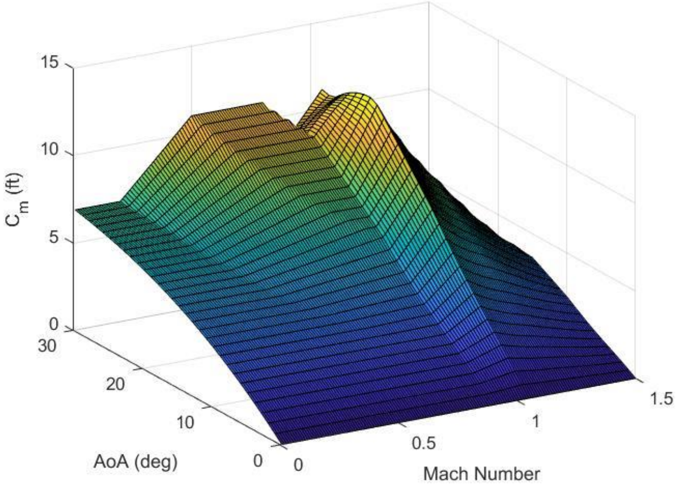
HIGHER-ORDER METHODS (CFD)



WIND TUNNEL TESTING



AERODYNAMIC DATA



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

STAR-CCM+

HEM | MODELING APPROACH

SYSTEM

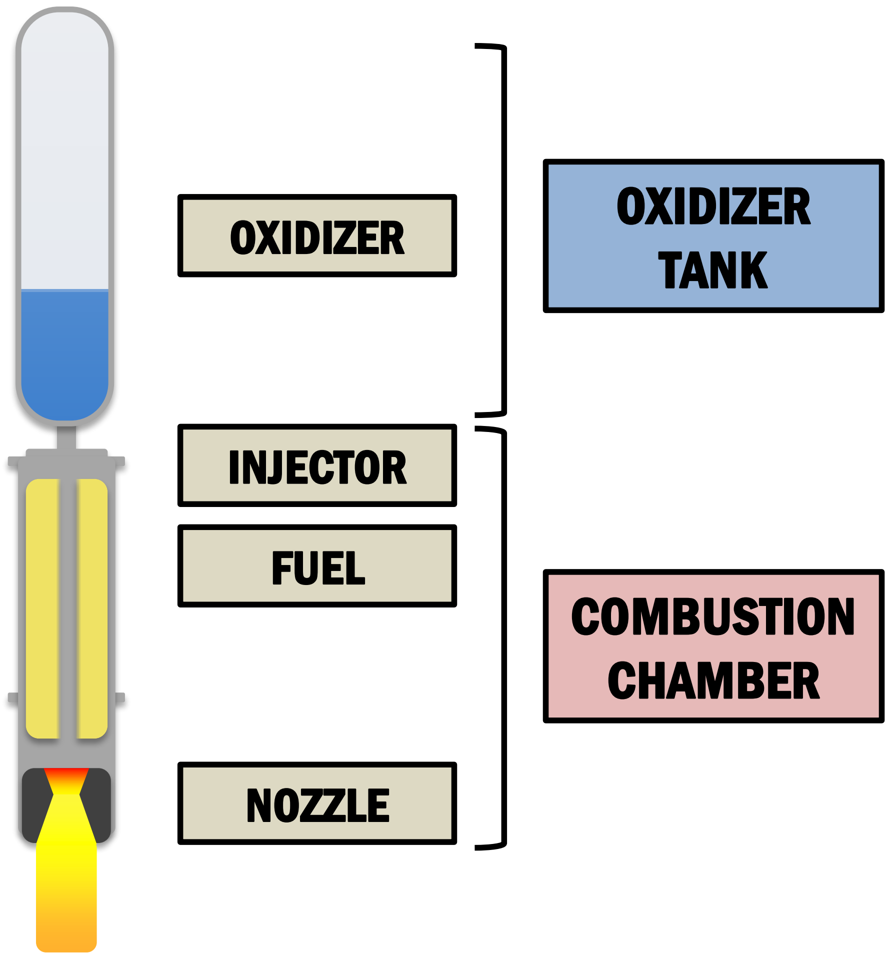
- Oxidizer: nitrous oxide (N_2O)
- Fuel: hydroxyl-terminated polybutadiene (HTPB)

MULTIPHASE FLOW

- N_2O exists in oxidizer tank as a saturated mixture
- Oxidizer tank vapor-liquid equilibrium (VLE)
- Liquid phase or gas phase flow through the injector

COMBUSTION

- Empirical mass-flux-based fuel grain regression model
- Equilibrium chemistry



DISCHARGE COEFFICIENT

- New coin selected based on ***comparative*** empirical test data with water
- Tested 8 coins for average mass flow rate and discharge coefficient (C_d)
- Verified in nitrous oxide cold flow testing

$$\dot{m} = A_{inj} C_d \sqrt{2\rho(\Delta p)}$$

REGRESSION COEFFICIENTS

- Extracted new internal ballistic coefficients based on testing campaign
- Correlation between oxidizer mass flux and regression rate using *a*, *n*
- **Critical hybrid regression research**

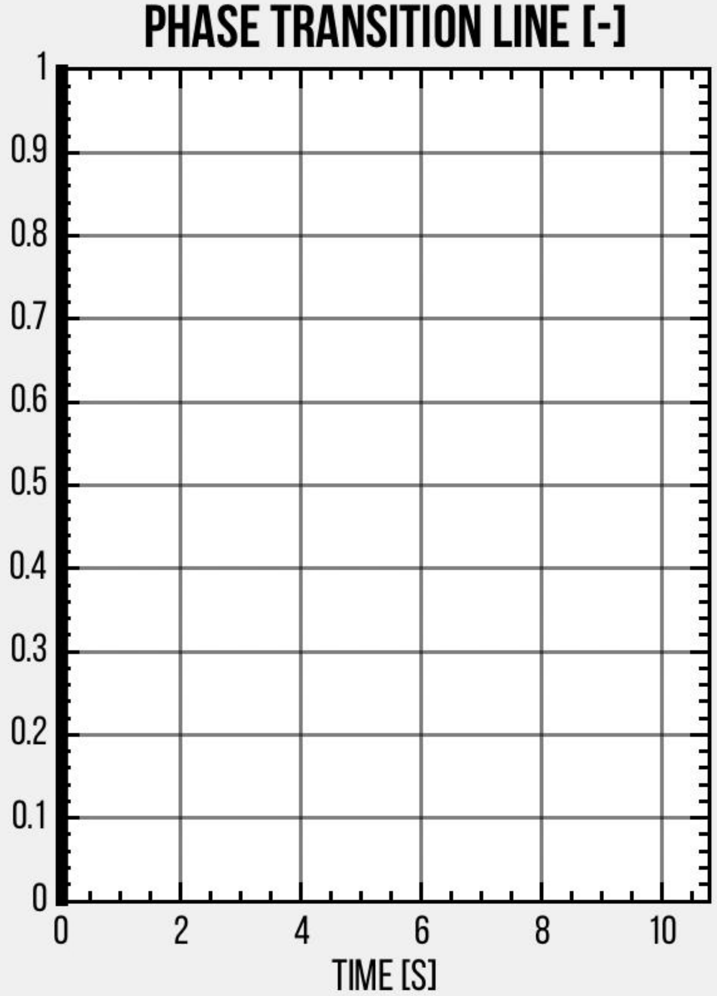
$$\dot{r} = aG_{ox}^{n}$$

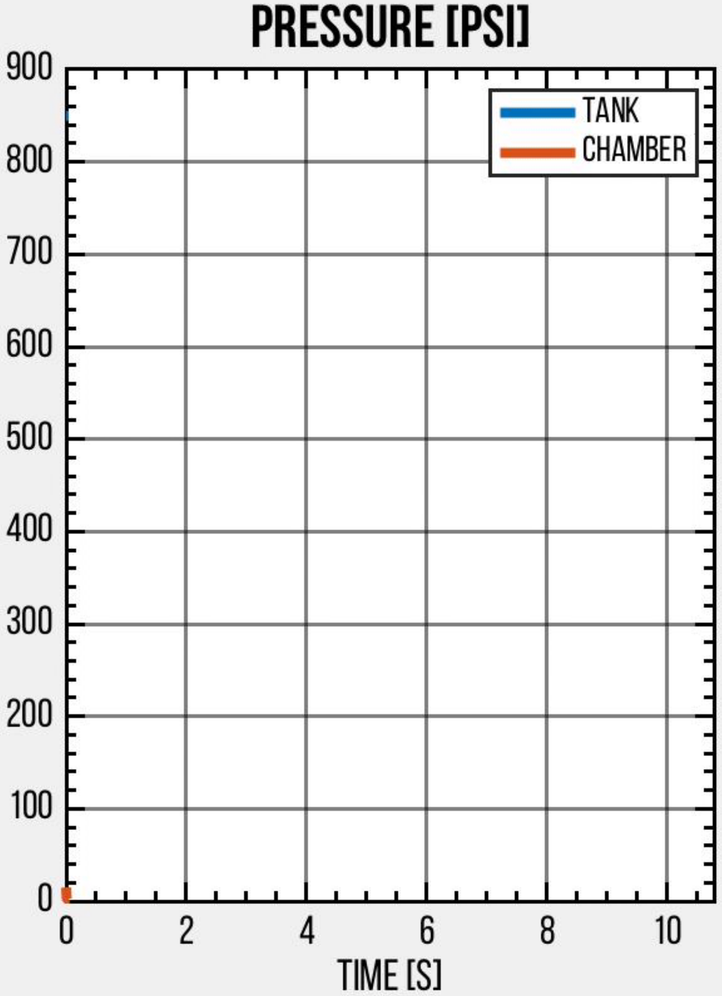
HEM | VISUALIZATION

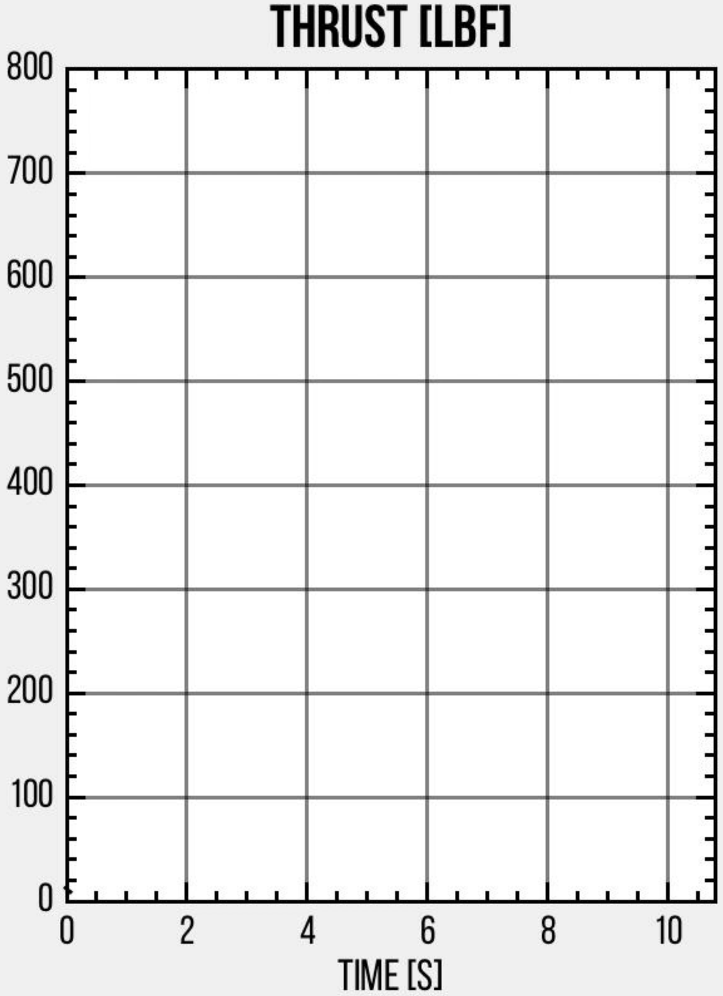
NP-915 ICARUS II | SET-IV

TEST VIDEO | THRUST & PRESSURE MONITORS

HEM | VISUALIZATION







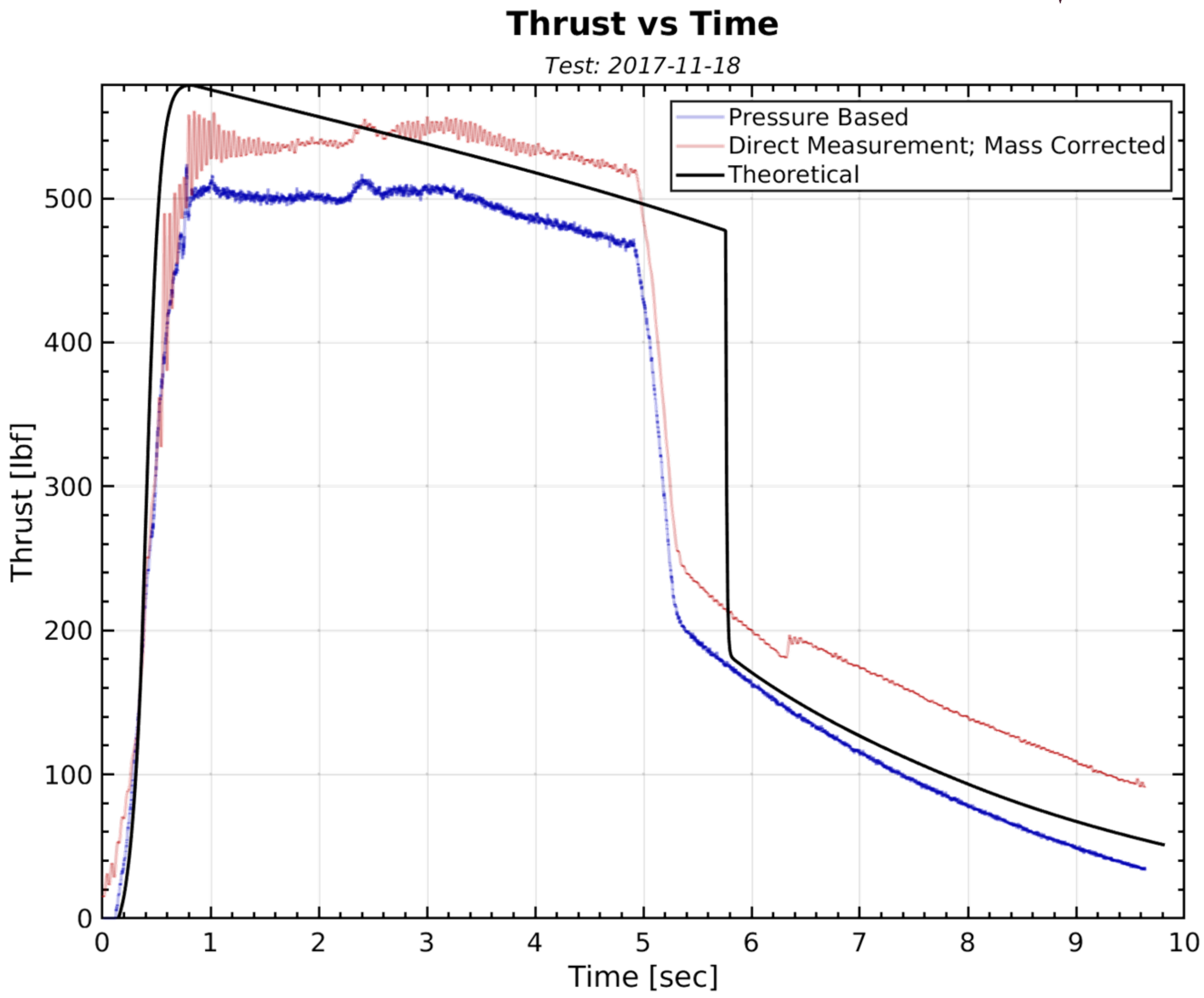
THEORETICAL MODEL VALIDATION

- SRT-5 testing campaign achieved several successful static engine tests (SETs)
- Good first-order model agreement between empirical and theoretical data

CLASS I – LOAD CELL

CLASS II – PRESSURE

HYBRID ENGINE MODEL



DESIGN TOOL

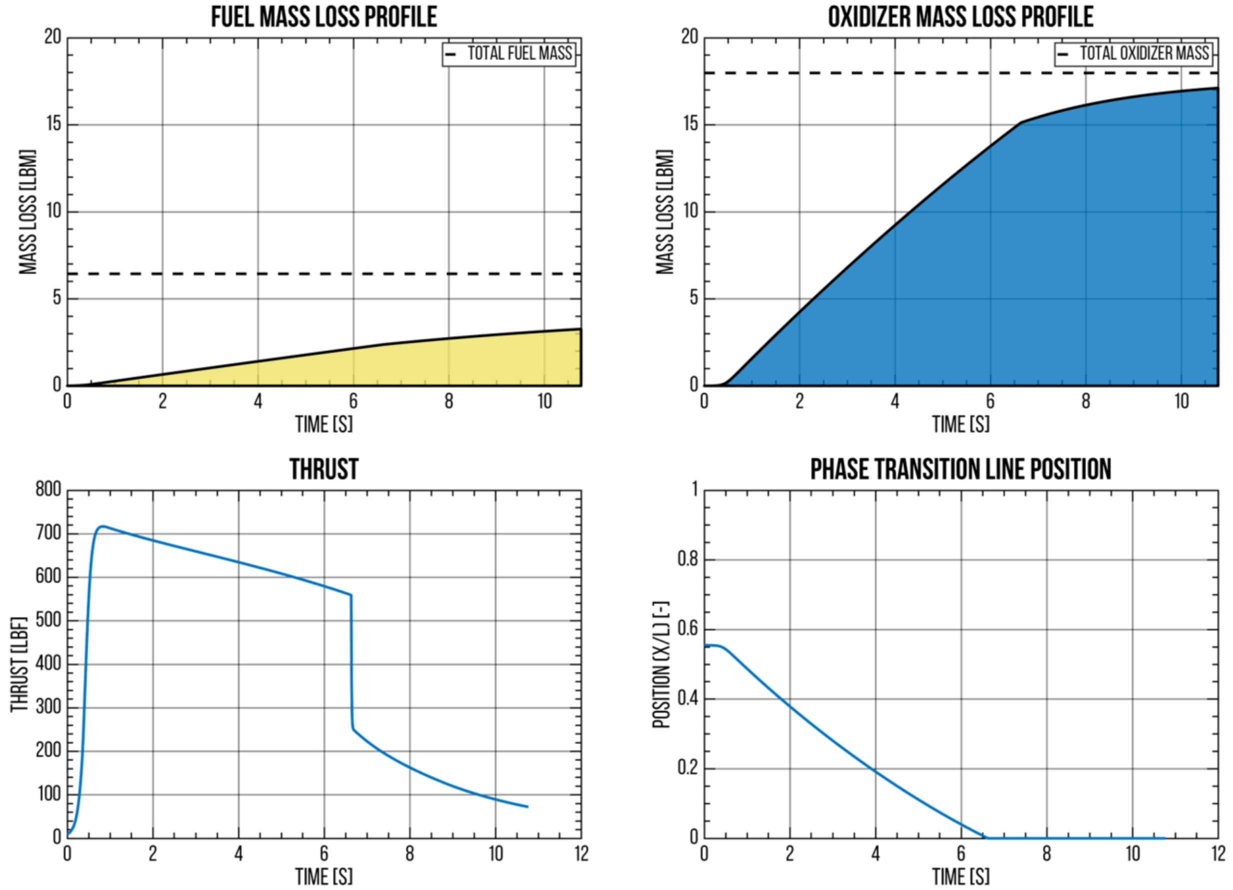
- Study on engine parameters (nozzle, grain, tank, injector, etc.)

COMPARISON TOOL

- Baseline for static engine test or cold flow test data

PREDICTION TOOL

- Estimation of hybrid engine performance
- **Provides FS with:**
  - time-dependent inertial properties
  - time-dependent thrust curve



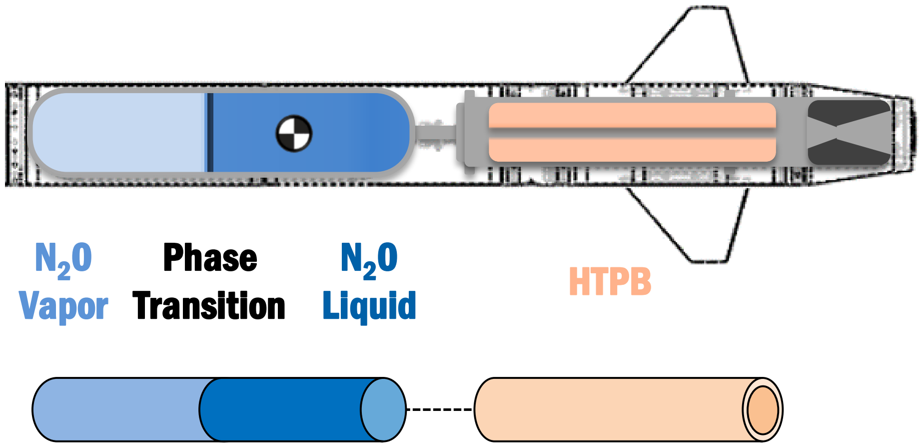
ADVANCED FLIGHT PREDICTION TOOL

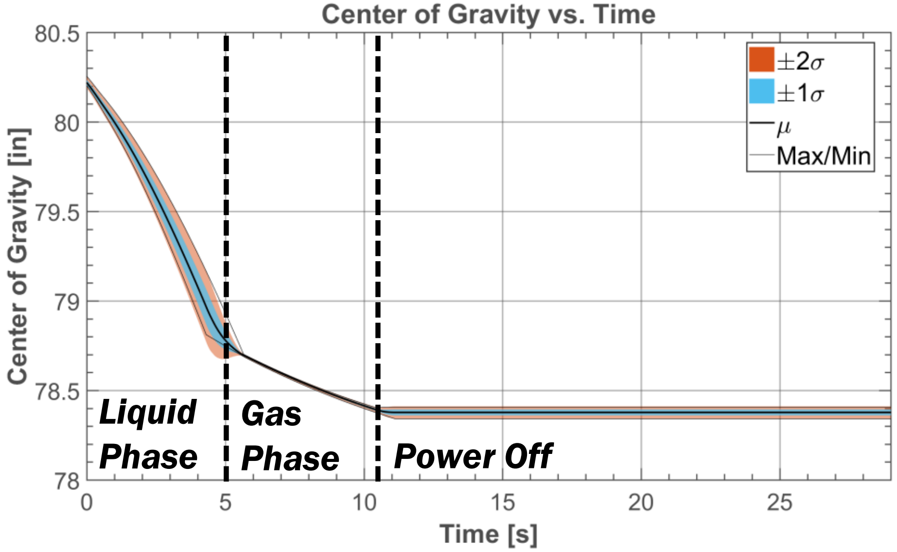
FS | MASS PROPERTIES

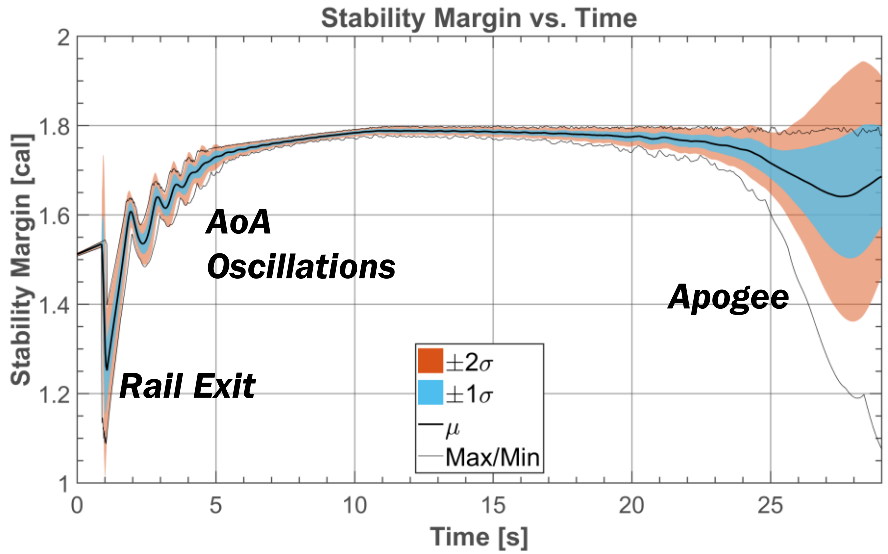
TRANSIENT MASS PROPERTIES

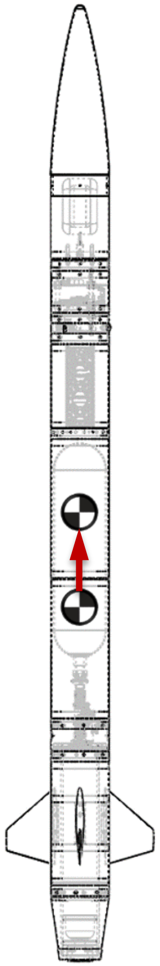
- Mass, CG, moments of inertia vary through burn
- Idealized fuel and oxidizer geometry
- Phase transition line and mass flow from HEM
- Dynamic stability margin calculation

SIMPLIFIED GEOMETRY



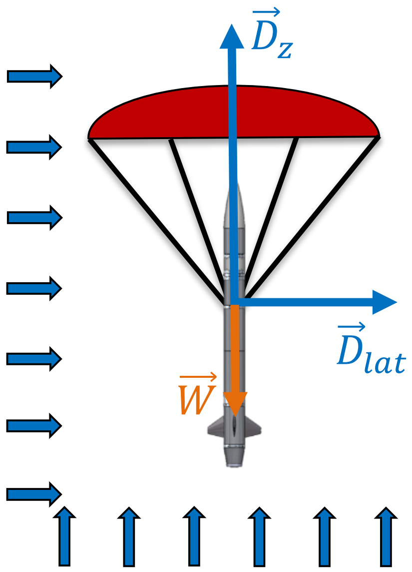


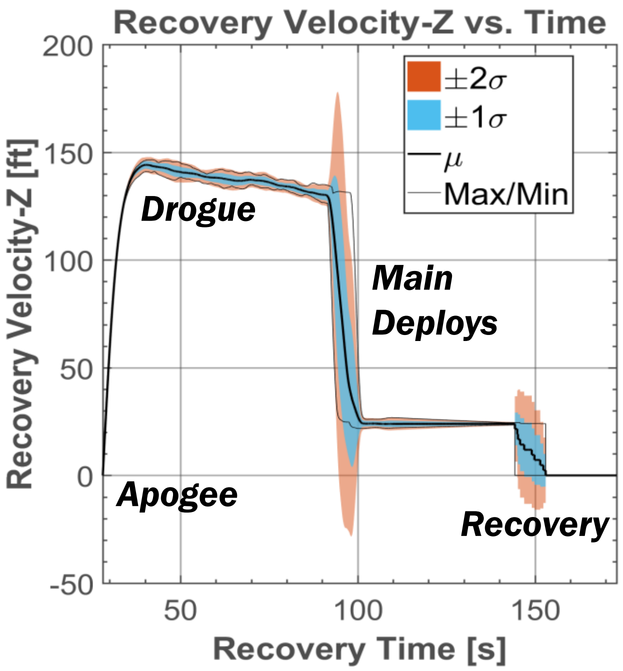




KINEMATICS

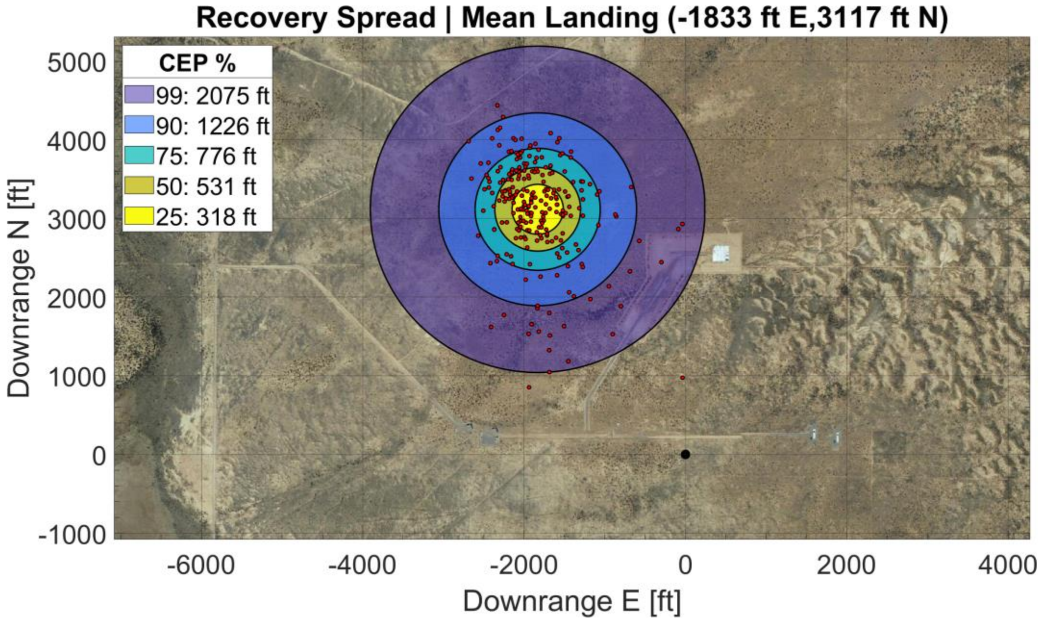
- Post-apogee 3 DoF translational simulation
- Dynamic parachute inflation



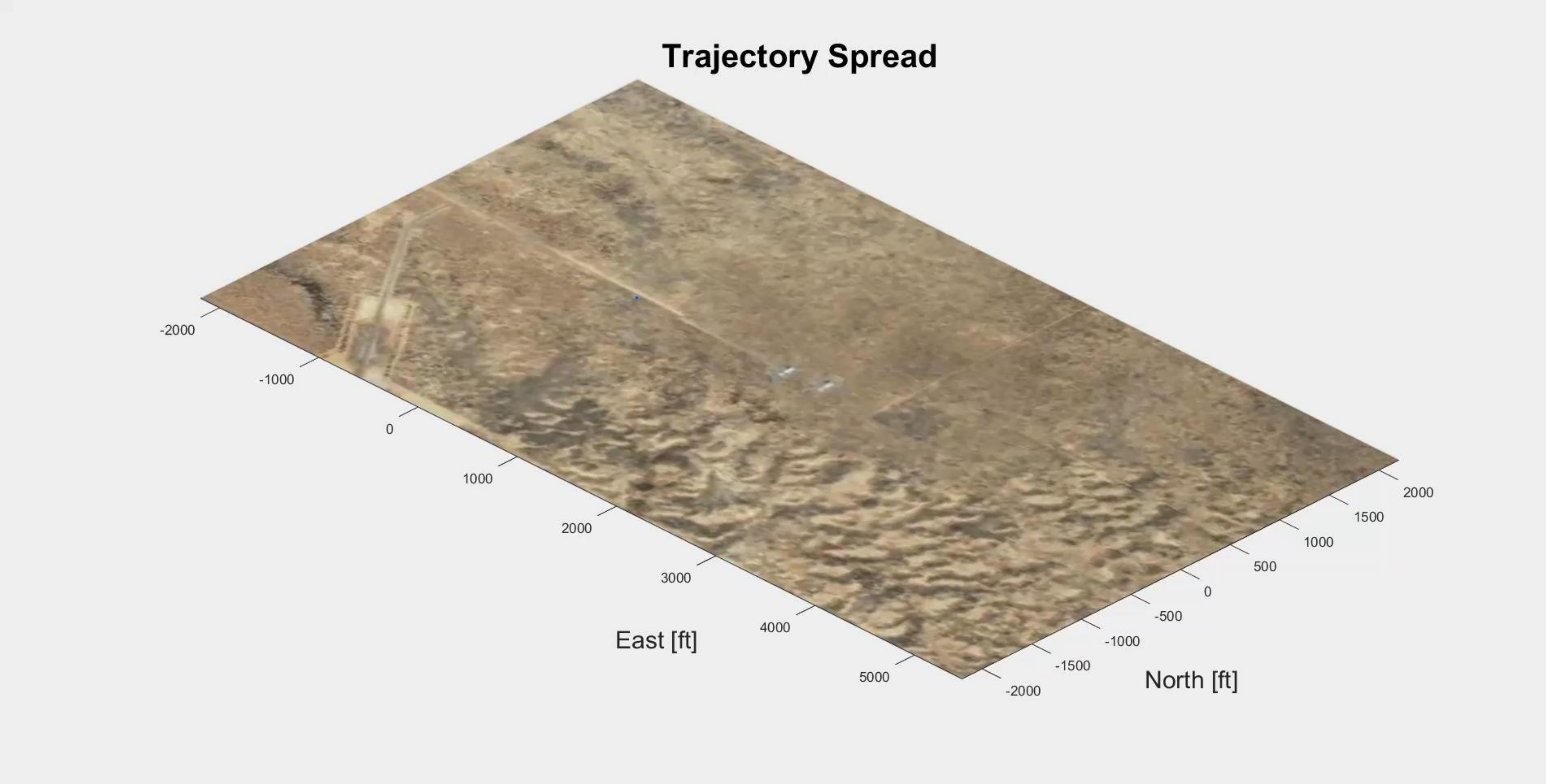


IMPACT MAP

- Google Maps projection – recovery aid
- Circular error probability (CEP) impact zone analysis

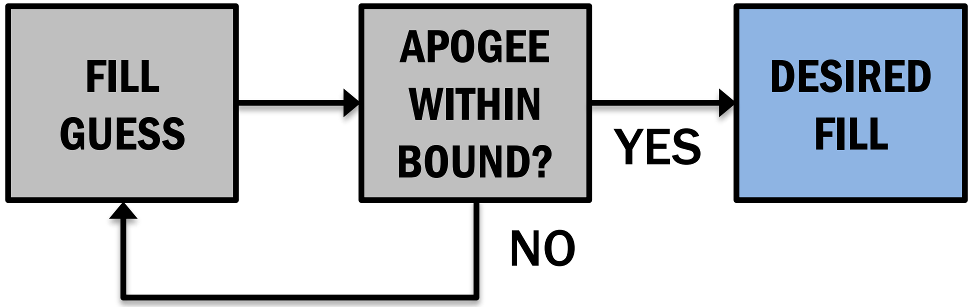


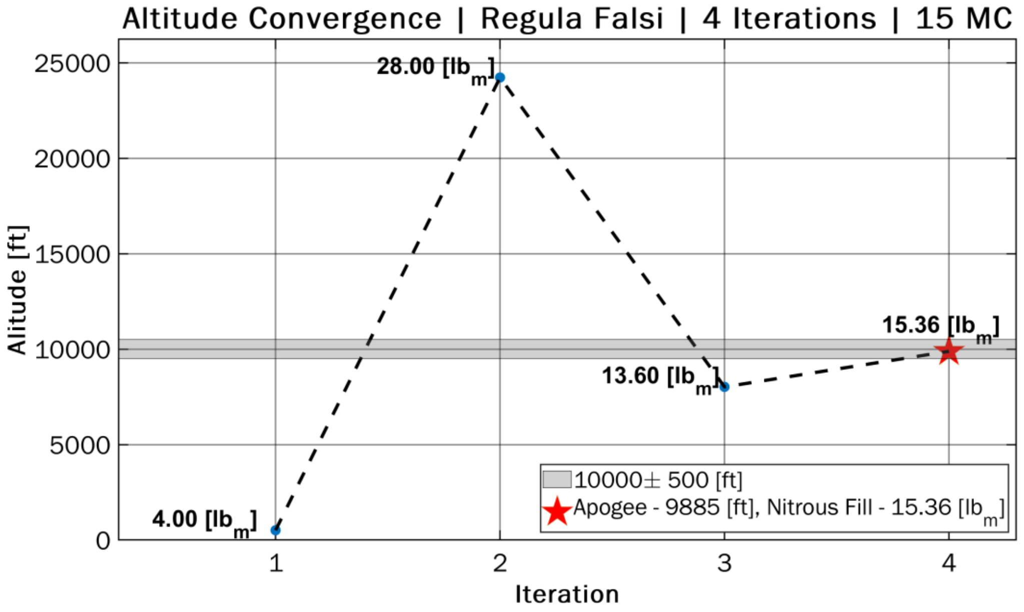
FS | VISUALIZATION

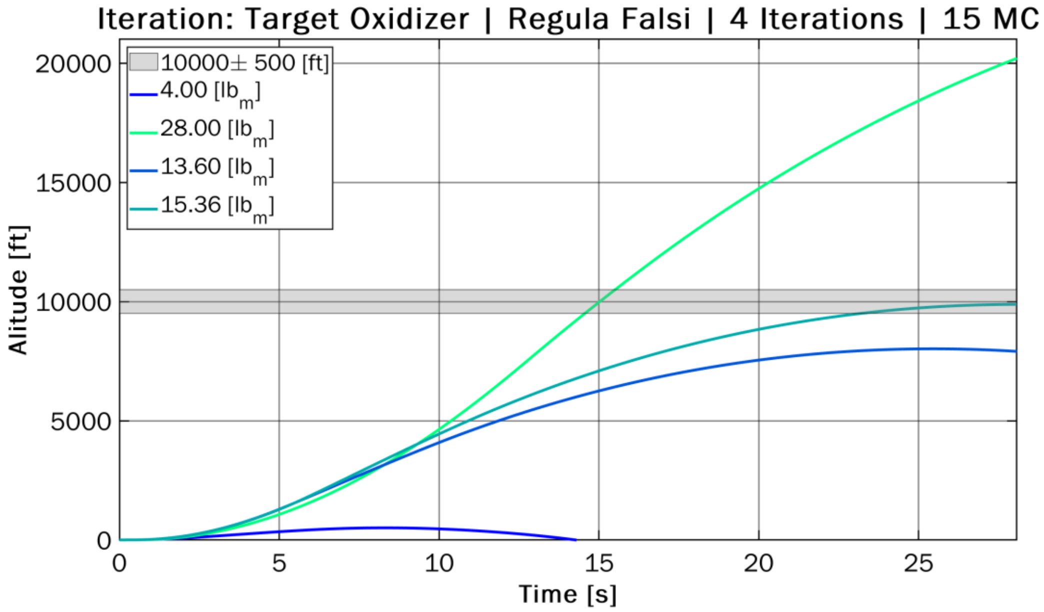


TARGET IMPULSE ALGORITHM

- Given desired apogee, finds required oxidizer fill
- Iterative process → *Regula Falsi* over fill weight
- Interfaces over existing Monte Carlo simulation



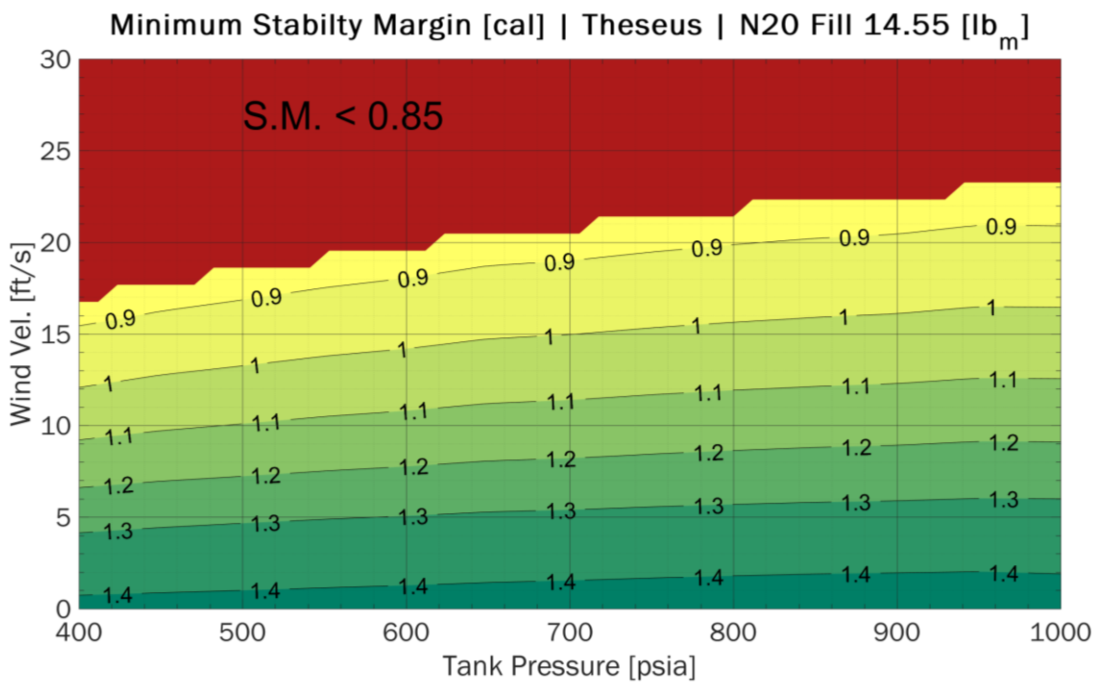




FS | FLIGHT PERFORMANCE ENVELOPE

FLIGHT PERFORMANCE ENVELOPE

- Characterize vehicle performance
- Captures input sensitivity
- Identify no-go regions – launch day safety check
- Avoid delays in launch sequence



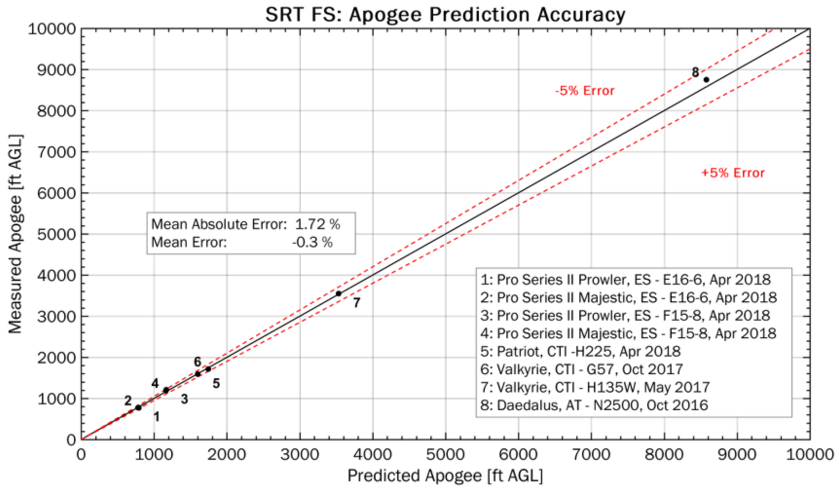
FPE LOOKUP PROCESS

(700 PSIA, 15 FT/S) → MIN STAB: 1.00 CAL

(600 PSIA, 25 FT/S) → MIN STAB: 0.75 CAL

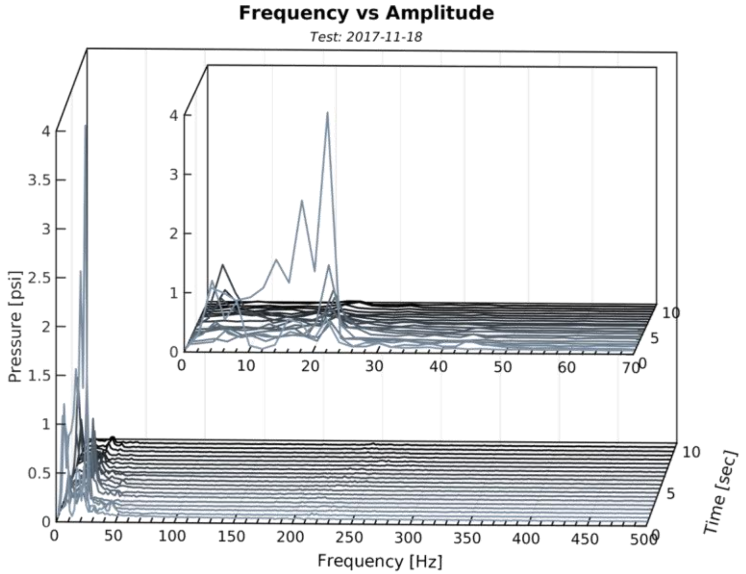
FLIGHT SIMULATION (FS)

- Additional validation testing
- Parallelization
- Extended recovery modeling
- Internally generated first-order aero data



HYBRID ENGINE MODEL (HEM)

- Additional validation testing
- Ballistic coefficient research
- More complex gas models
- Nonlinear regression modes
- Hybrid combustion frequency analysis



ENGINEERING

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