2007 Mars Phoenix Entry, Descent, and Landing Simulation and Modeling Analysis

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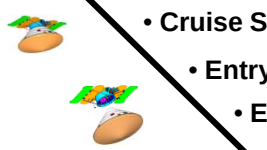
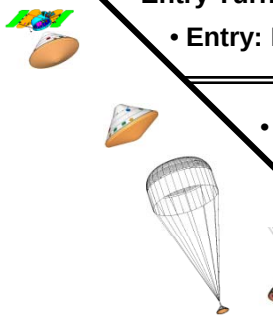
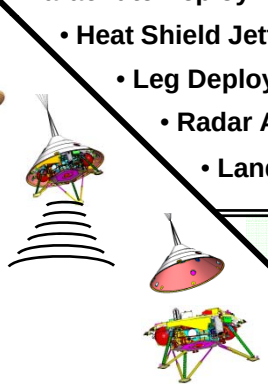
Phoenix Overview

- Launch window: Aug 3-24, 2007
- Arrival: May 25 – June 5, 2008
- Surface operations:
- EDL
  - 600kg entry vehicle
  - Ballistic 3-axis stabilized entry
  - Propulsive terminal descent

EDL Overview







- **Final EDL Parameter Update:** E-12hr; **Entry State Initialization:** E-10min
- **Cruise Stage Separation:** E-7min
- **Entry Turn Starts:** E-6.5 min. Turn completes by E-5min..
- **Entry:** E-0s, L-435s, **125 km***, r=3522.2 km, 5.7 km/s, γ = -13 deg

Pre-Entry

- **Peak Heating:** 44 W/cm2 Peak Deceleration: 9.25G

Hypersonic

- **Parachute Deployment:** E+220 s, L-215 s, **13 km**, Mach 1.7
- **Heat Shield Jettison:** E+235 s, L-200s, **11 km**, 130 m/s
- **Leg Deployments:** E+245 s, L-190s
- **Radar Activated:** E+295 s, L- 140s
- **Lander Separation:** E+399 s, L-36 s, **0.93 km**, 54 m/s

Parachute

- **Throttle Up:** E+402 s, L-33 s, **0.75 km**
- **Constant Velocity Achieved:** E+425 s, L-10 s, **0.025 km**, 2.5 m/s
- **Touchdown:** E+435 s, L-0s, **0 km**, v=2.5 ±1 m/s, h<1.4 m/s

Terminal Descent

- **Vent Pressurant:** L+7 Sec
- **Dust Settling/Gyrocompassing:** L+0 to L+15 min
- **Solar Array Deploy:** L+15min
- **Fire Pyros for Deployments:** ASAP

Lander Prep

* Entry altitude referenced to equatorial radius. All other altitudes referenced to ground level

Note: Nominal Entry Shown. Dispersions exist around all values.

Landing at -3.4 km Elevation (MOLA relative)

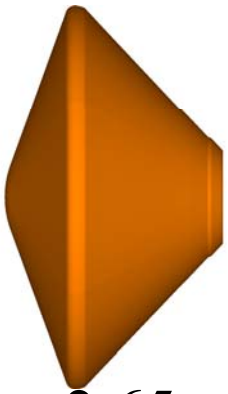
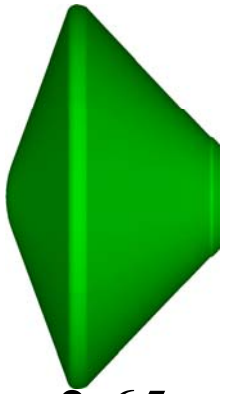
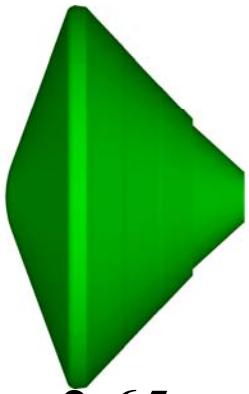
EDL Simulation

- Program to Optimize Simulated Trajectories II (POST2) 6-DOF simulation used to assess metrics, determine entry characteristics to meet EDL requirements
  - POST heritage: MGS, ODY, MER, MPF, MRO, Stardust, Genesis, etc
  - Simulation comparisons have been performed with additional simulation capabilities
- Metrics to track include:
  - Parachute deployment conditions – mach, dynamic pressure, opening loads
  - Lander separation conditions – altitude, velocity, time on parachute
  - Landing – footprint, fuel used, landing velocity

EDL Models

- IMU model
- Active hypersonic control system
- Atmosphere profiles
- Aerodynamics database
- Parachute
  - Deployment algorithm
  - Inflation model
  - Drag model
- Wind profiles
- Radar
- Terminal descent guidance
- Propulsive control model

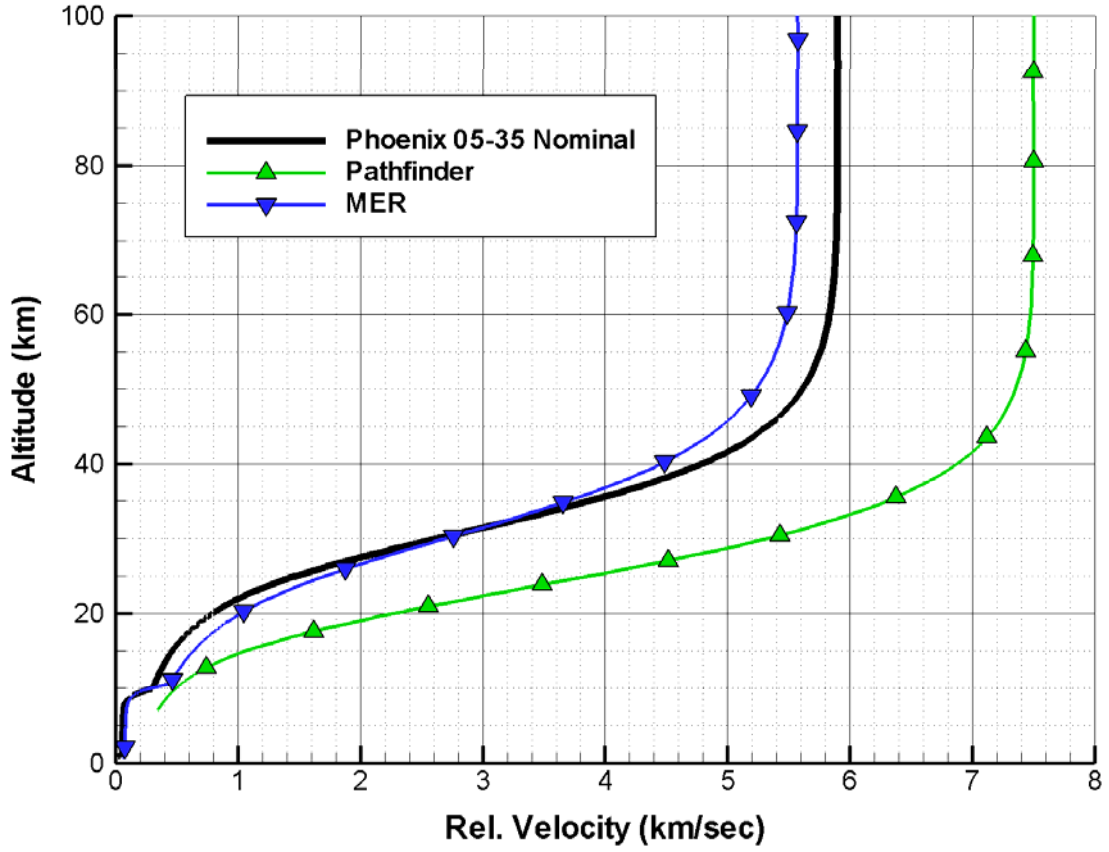
Mars Aeroshell/Entry Comparison

	Pathfinder	MER A/B	Phoenix
Diameter, m	2.65	2.65	2.65
Entry Mass, kg	585	840	602
Relative Entry Vel., km/s	7.6	5.5	5.9
Relative Entry FPA, deg	-13.8	-11.5	-13
$m/(C_DA)$, kg/m^2	62.3	89.8	65

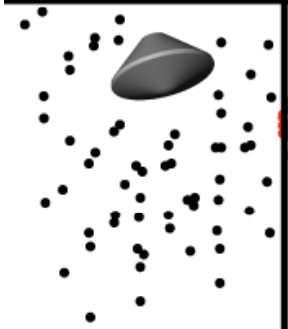
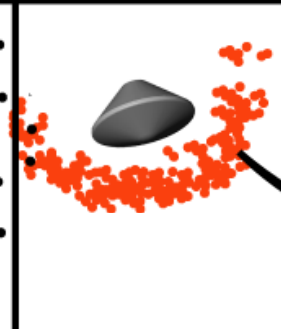
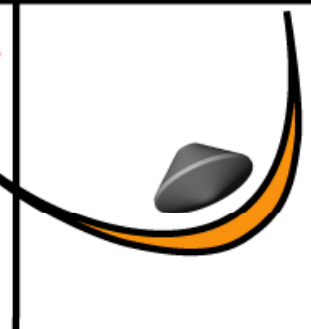
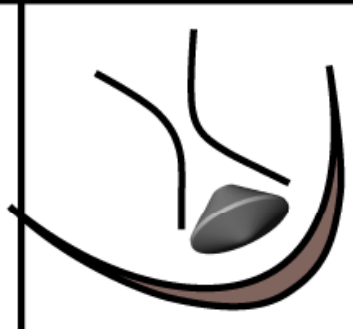
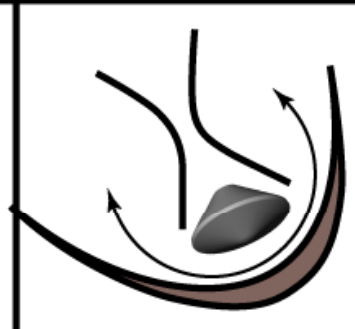
Mars Trajectory Comparison

- The Phoenix entry trajectory is most similar to the MER entries



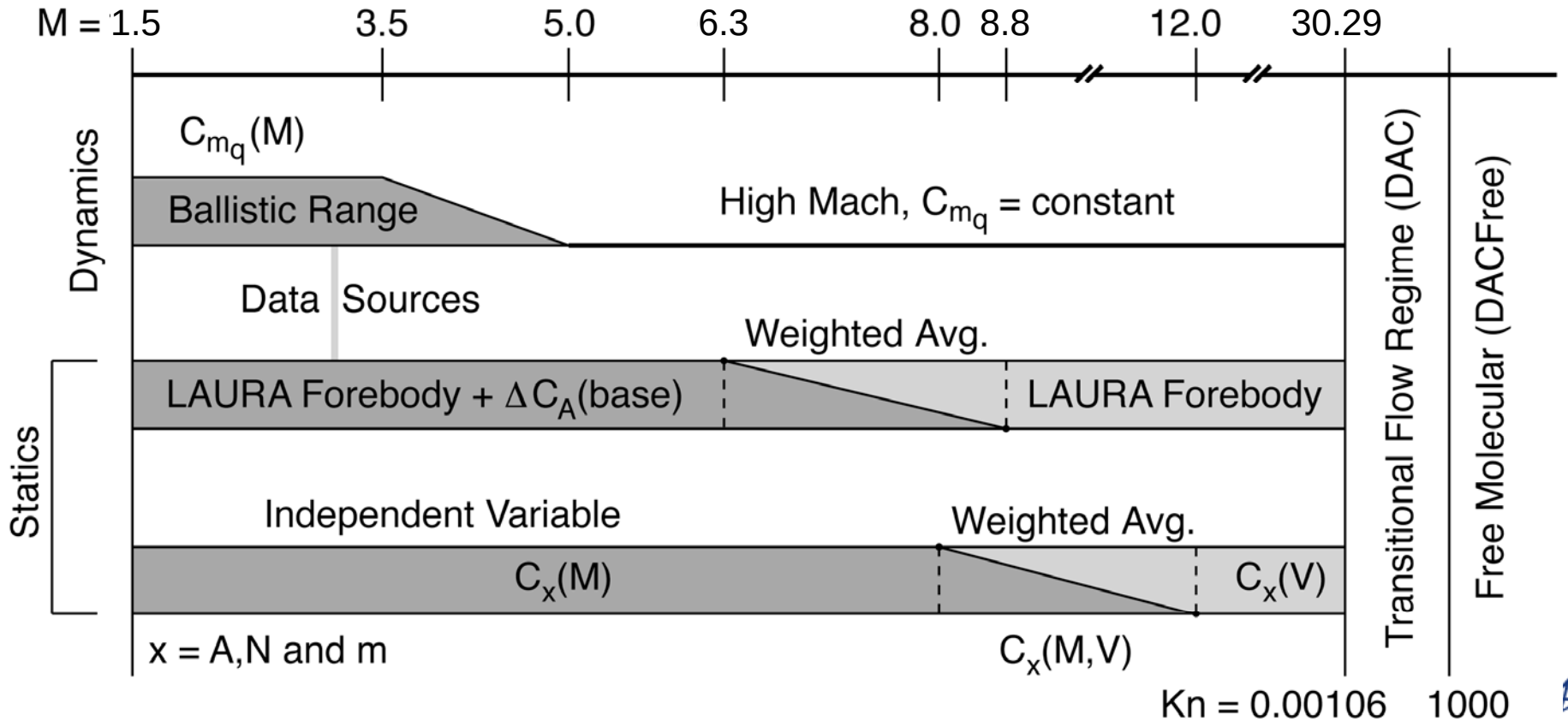
Aerodynamics Database Structure

- The database is divided into flight regimes that reflect different analysis methods and aerodynamics characteristics
  - v2.0 will have updated CFD data for hypersonic/supersonic continuum regimes and Viking data for $0.8 < \text{Mach} \leq 1.5$
  - Still using MER free-molecular, transitional, and dynamics data

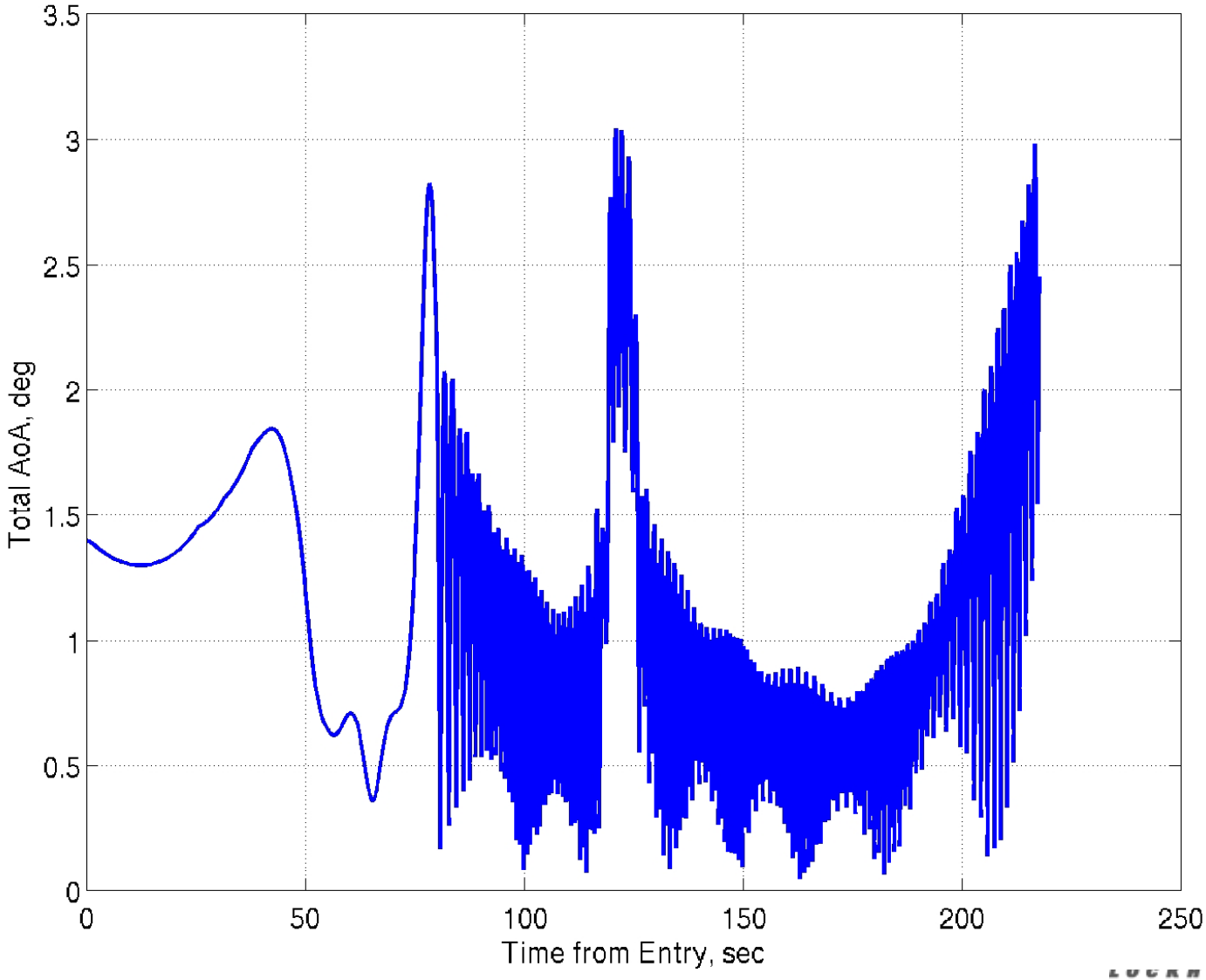
Rarefied	Transitional	Hypersonic	Supersonic	Supersonic Dynamics	Transonic/Subsonic
					
Kn > 1000	1000 > Kn > 0.001	**30.29 > Mach > 6.3**	**6.3 > Mach > 1.5**	5 > Mach > 0.7	**1.5 > Mach > 0.8**
Analysis: DAC DSMC code	**Analysis:** DAC DSMC code	**Analysis:** LAURA CFD (forebody)	**Analysis:** LAURA (full aeroshell)	**Analysis:** Viking Forced Oscillation	**Analysis:** Viking Wind Tunnel
Current Data: Phoenix Database Version 1.4.1	**Current Data:** Phoenix Database Version 1.4.1	**Current Data:** Phoenix Database Version 1.4.1	**Current Data:** Phoenix Database Version 1.4.1	**Current Data:** Phoenix Database Version 1.4.1	**Current Data:** Phoenix Database Version 1.4.1
Heritage Flight: MPF, MER Computation: MPF, MER	**Heritage** Flight: MPF, MER Computation: MPF, MER	**Heritage** Flight: Viking, MPF, MER Experiment: Viking Computation: MPF, MER	**Heritage** Flight: Viking, MPF, MER Experiment: Viking Computation: MPF, MER	**Heritage** Flight: Viking, MPF, MER Experiment: Viking, MER	**Heritage** Flight: Viking, MPF, MER Experiment: Viking, MER

Aerodynamics Database Implementation

- For rarefied flow, C_A, C_N, C_m = f(α_T and Kn)



Nominal Attitude Profile



Monte Carlo Parameters

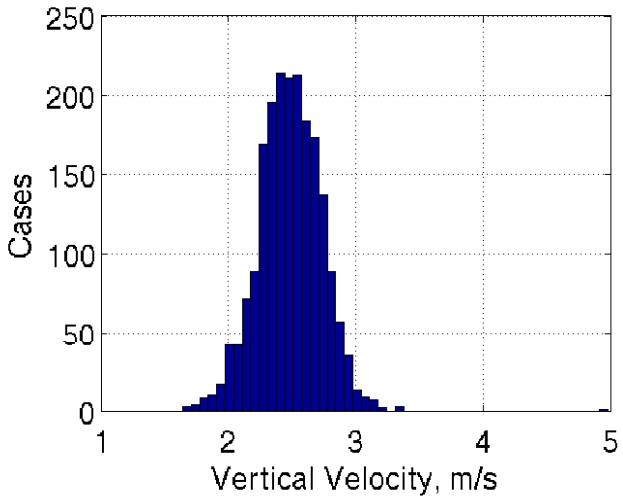
- 2000 atmosphere profiles
- 2000 wind profiles
- Aerodynamics
- Mass properties
- Entry state
- Initial attitude
- Tip-off rates
  - Cruise stage separation
  - Lander separation
- Radar parameters
  - Slope distribution
  - Ground effects
- Propulsion parameters
  - RCS
  - TCM

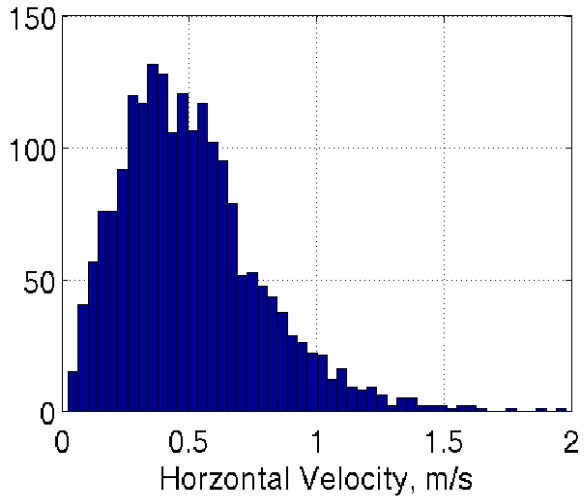
Performance Criteria

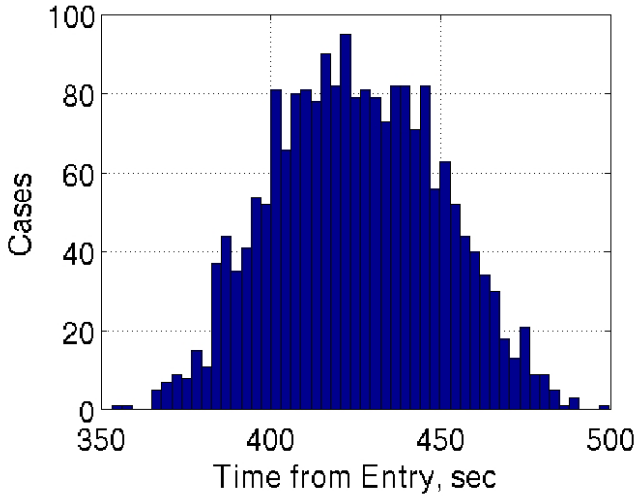
Two basic catagories of performance criteria form the basis for performance assessments

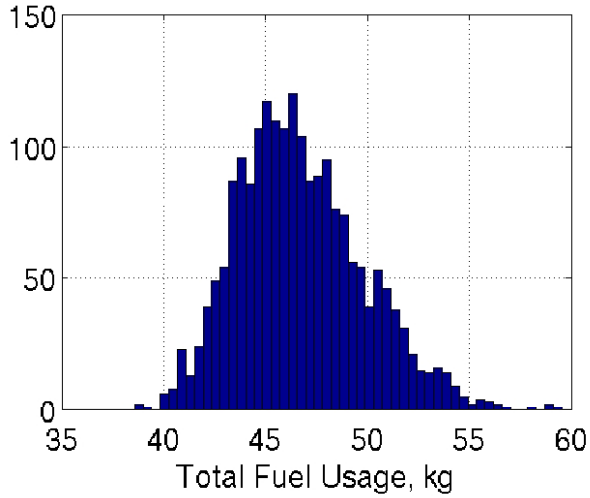
- **Entry and Descent (ED) Criteria**
  - Attitude behavior
  - Heating and loads
  - Deployment/separation conditions
  - Timeline and event timing
  - Sensor performance and state knowledge
  - Vehicle state at touchdown
- **Landing (L) Dynamics Criteria**
  - Touchdown/tip-over dynamics
  - Rock contact at landing
  - Rock contact during solar array deployments

Hypersonic Flight Statistics

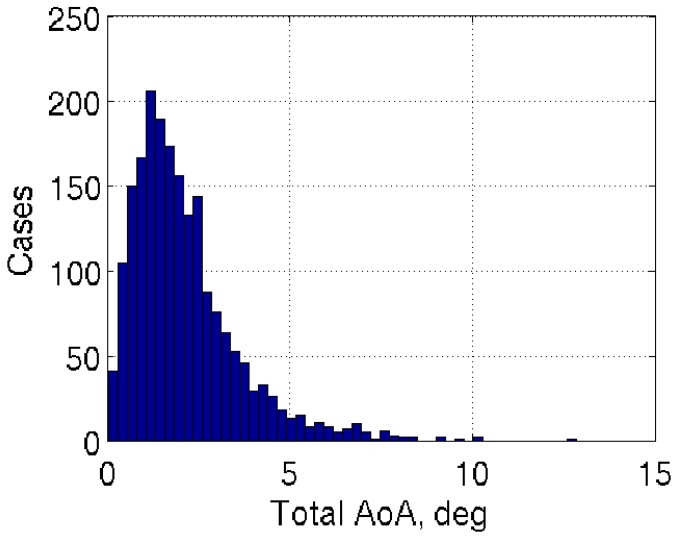


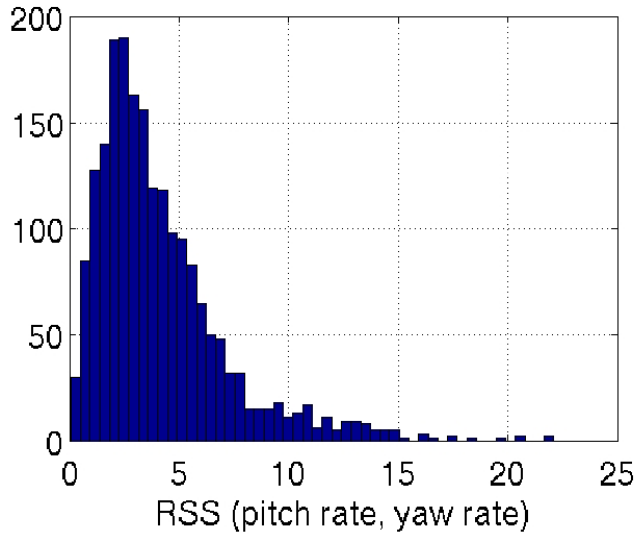


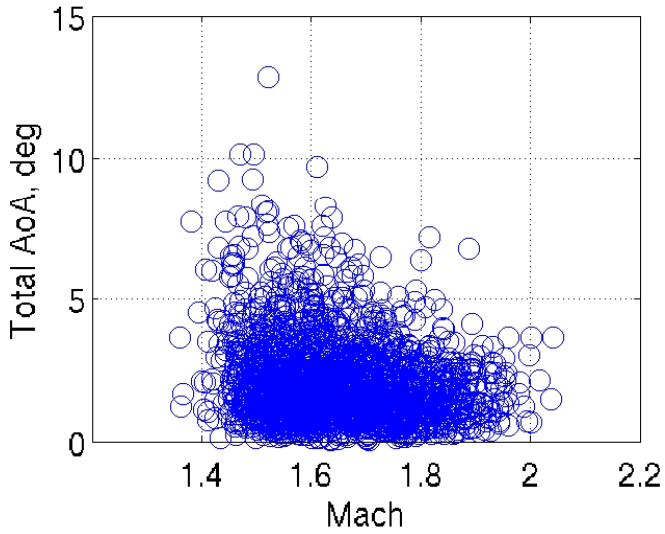




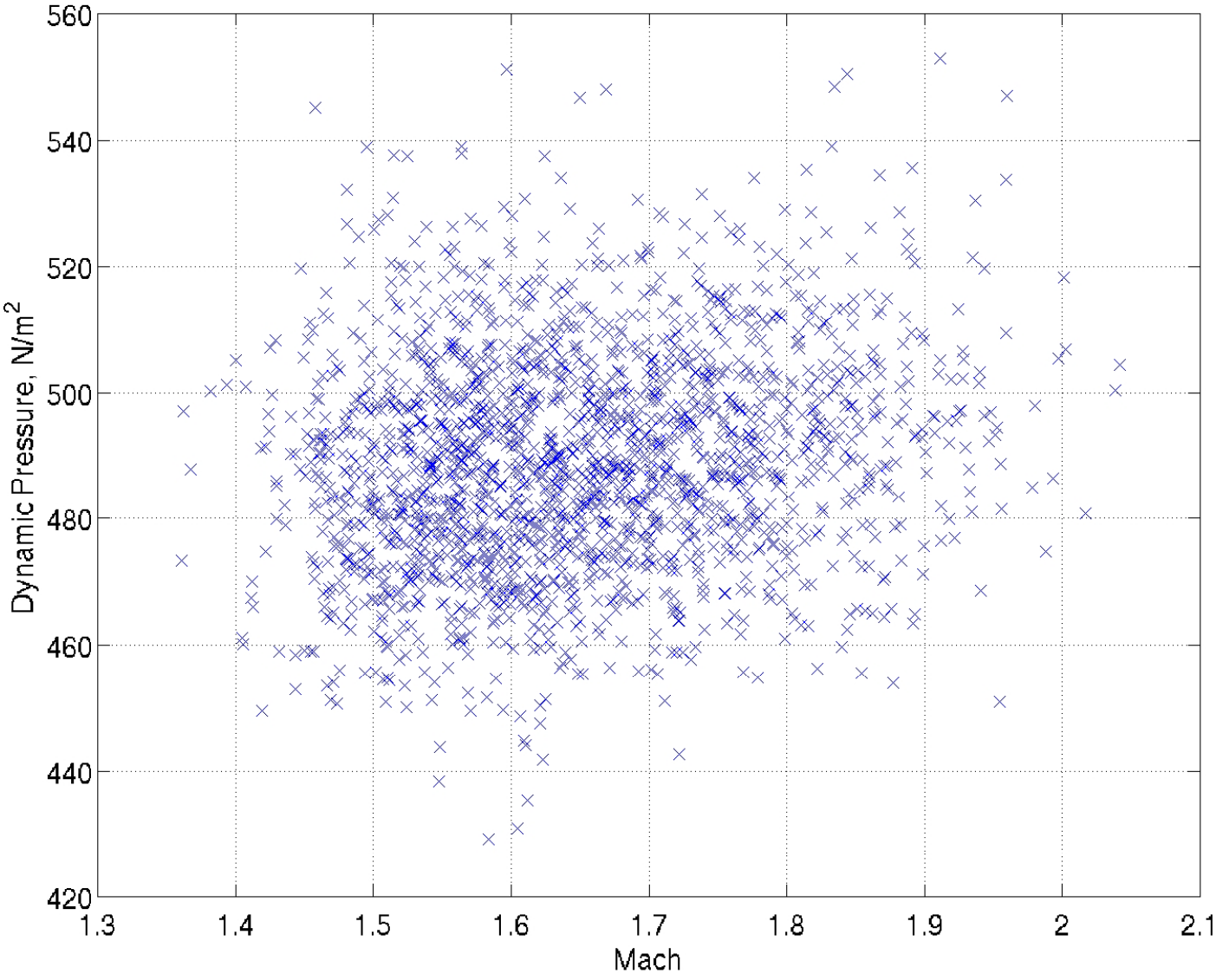
Chute Deploy Statistics



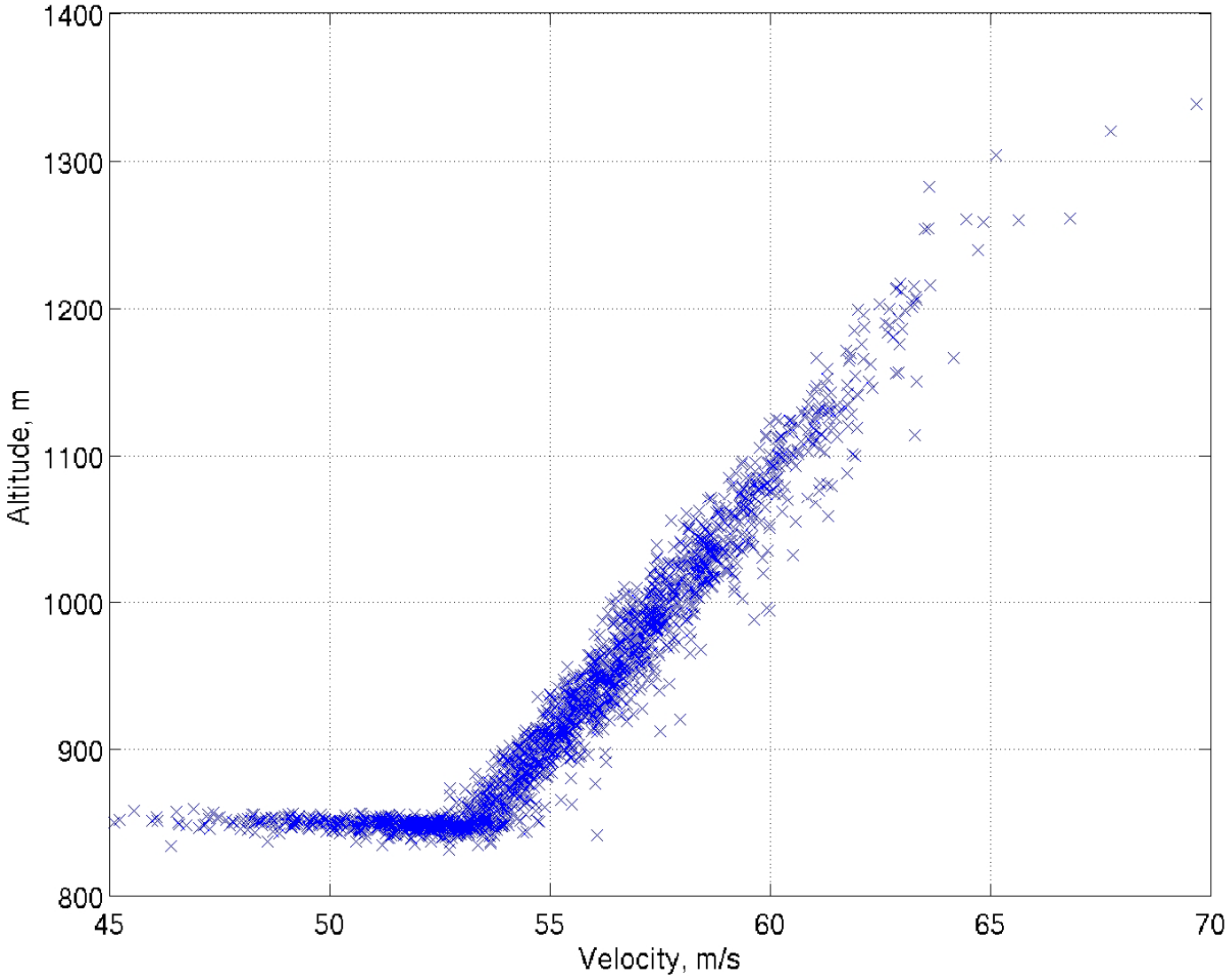




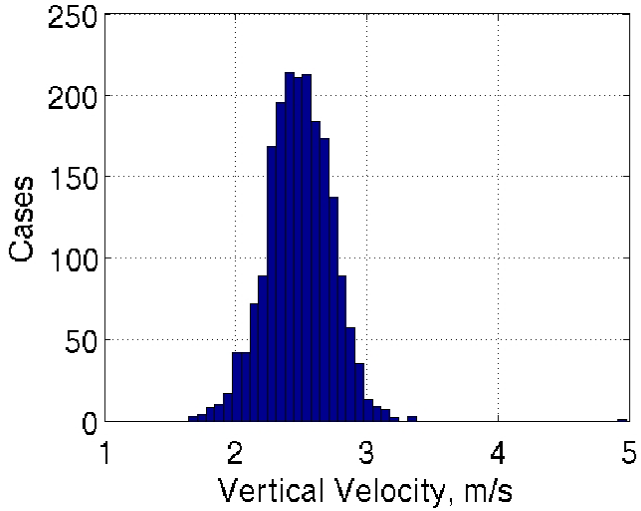
Mach-Q Box

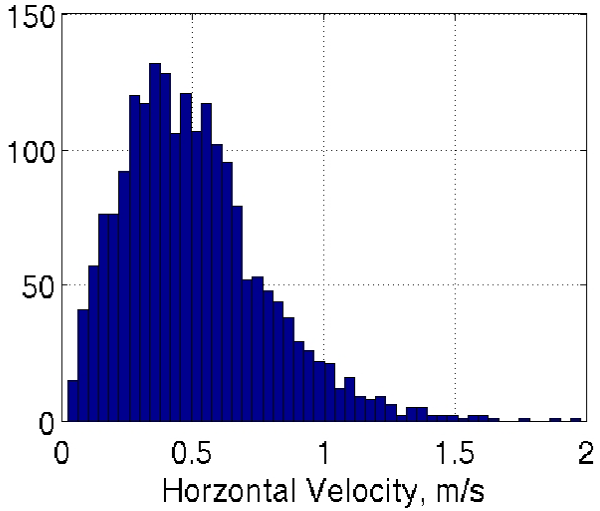

560
540
520
500
480
460
440
420
Dynamic Pressure, N/m2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
2.1
Mach

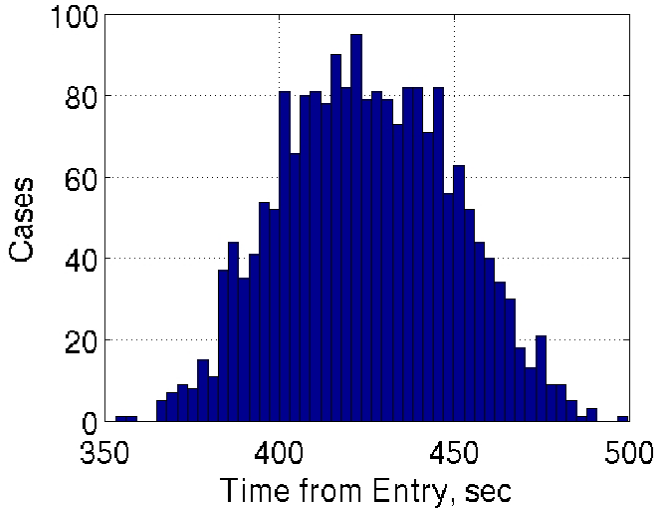
Lander Separation Altitude

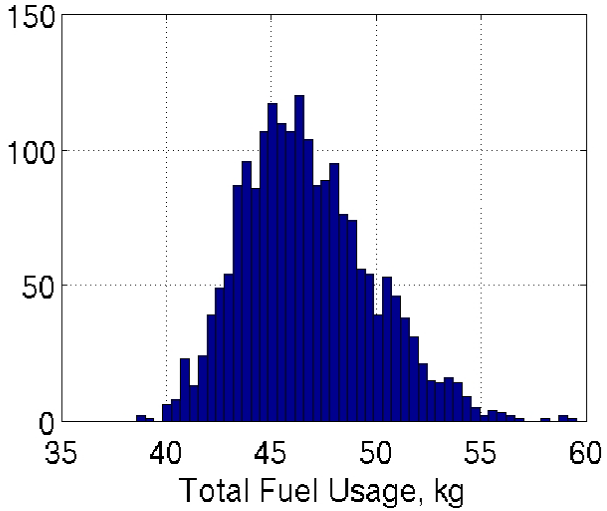


Touchdown Statistics

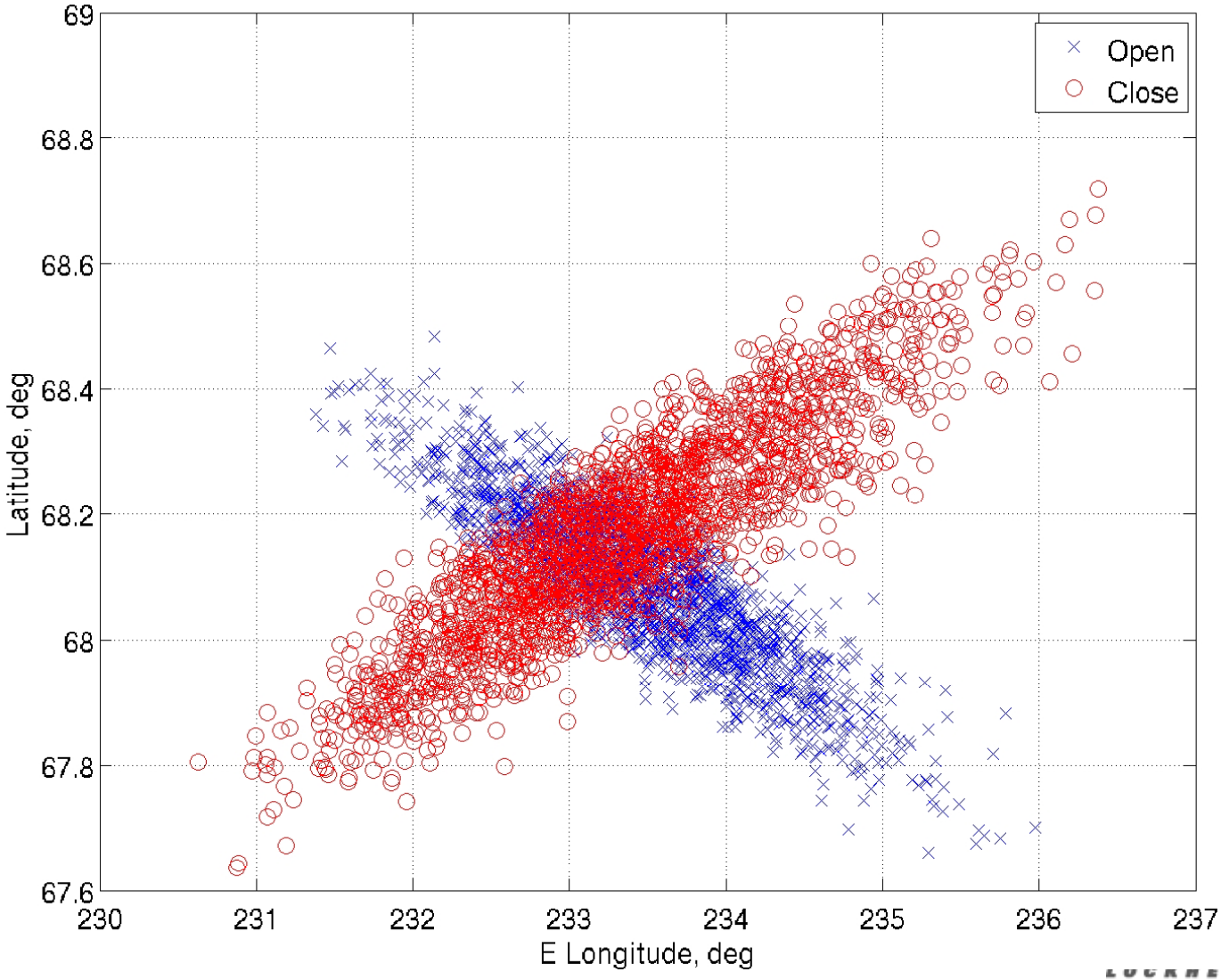








Landing Ellipses

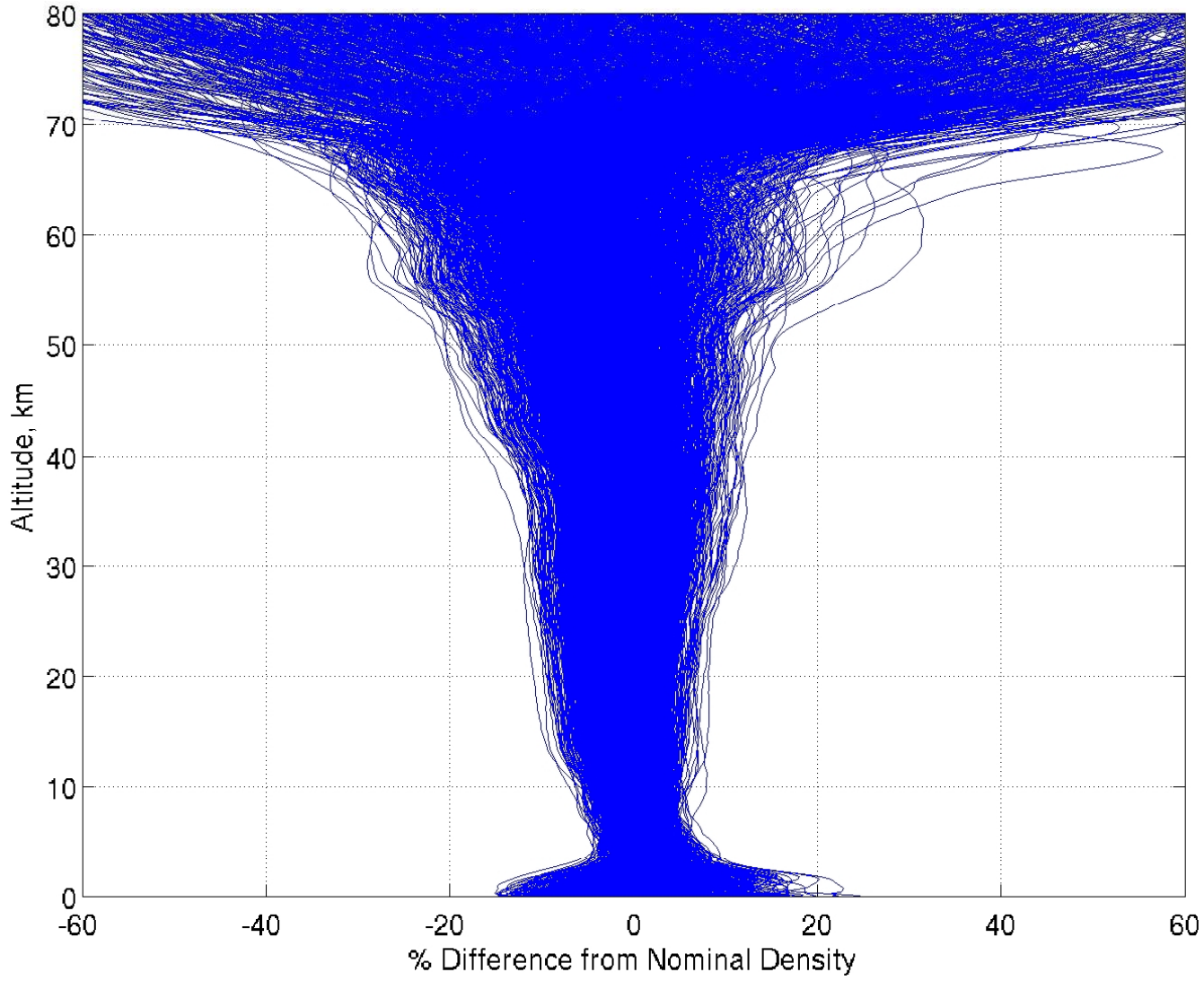


Summary

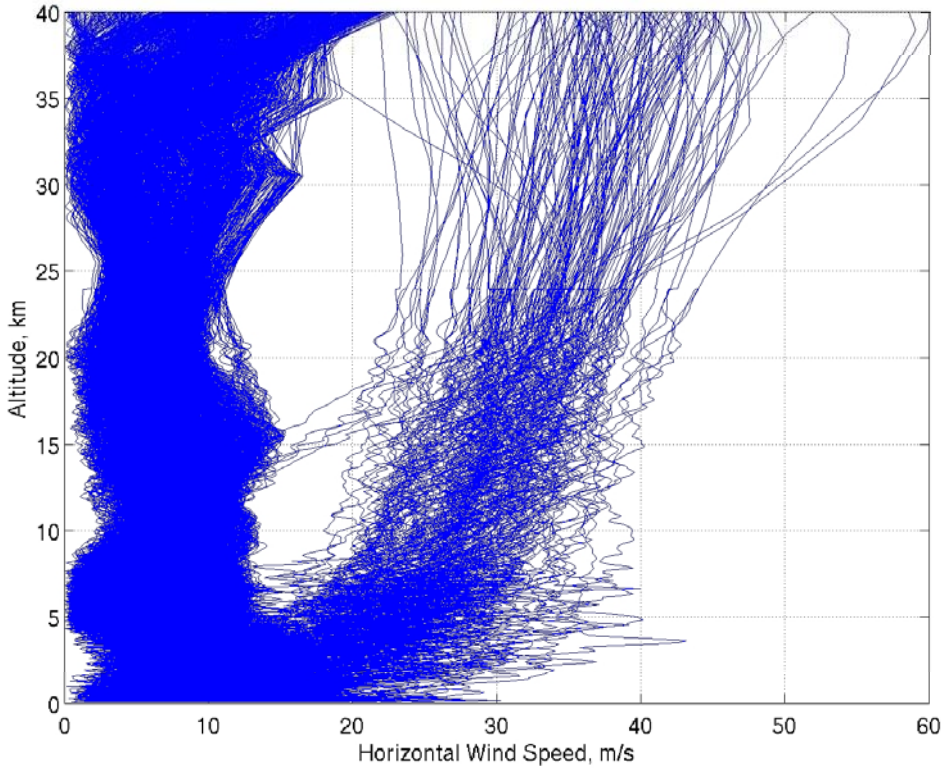
- All results shown are for 68N landing site at open of launch window
- Results vary with latitude and launch date – Monte Carlos are analyzed for several launch and landing site opportunities
- Many trade studies and sensitivities have been analyzed but not discussed here

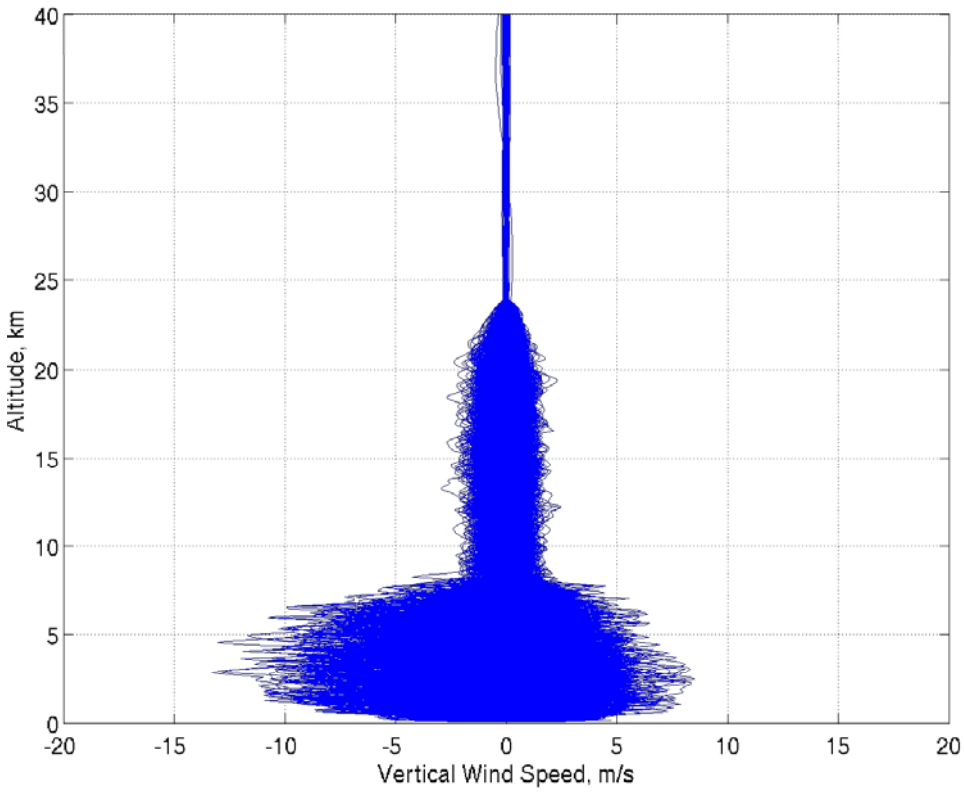
Backup

Atmospheric Variability



Wind Variability





Aerodynamic Uncertainties

Flight Regime	Coefficients	Uncertainty	Distribution
Free Molecular (Kn > 0.1)	C_A C_N, C_Y C_m, C_n C_{ll}	±5% ±0.01 (Adder), ±20% (Multiplier) ±0.005 (Adder), ±20% (Multiplier) 1.24e-6	Normal
Hypersonic Continuum (Kn < 0.001, M > 10)	C_A C_N, C_Y C_m, C_n C_{ll}	±3% ±0.01 (Adder), ±20% (Multiplier) ±0.003 (Adder), ±20% (Multiplier) 1.24e-6	Normal
Supersonic Continuum (Kn < 0.001, M < 5)	C_A C_N, C_Y C_m, C_n C_{ll}	±10% ±0.01 (Adder), ±20% (Multiplier) ±0.005 (Adder), ±20% (Multiplier) 1.24e-6	Normal
Free Molecular/Hypersonic Dynamics (M > 6)	C_{mq}	±0.15	Normal
Supersonic Dynamics (M < 3)	C_{mq}	-50% to 100% (Multiplier), 0 to 0.1 (Adder)	Normal/ Uniform