Design of an Entry System for Cargo Delivery to Mars

5th International Planetary Probe Workshop (IPPW-5)
Session III
June 25, 2007

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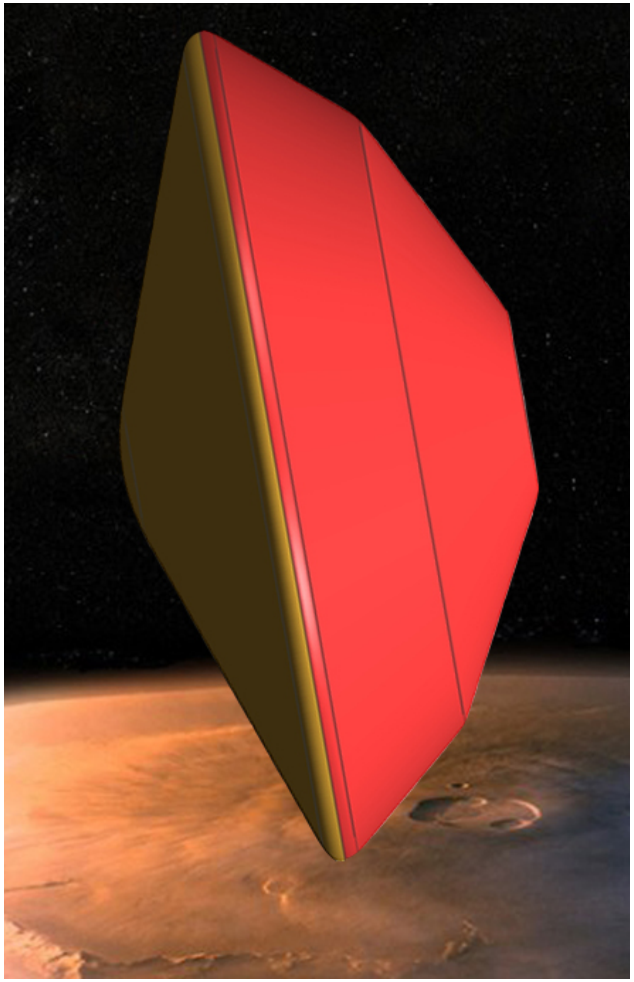
Overview

- Requirements & Assumptions
- Trades Studied
- Baseline Design
- Uncertainty Analysis
- Testing & Qualification Program
- Conclusions



Requirements & Assumptions

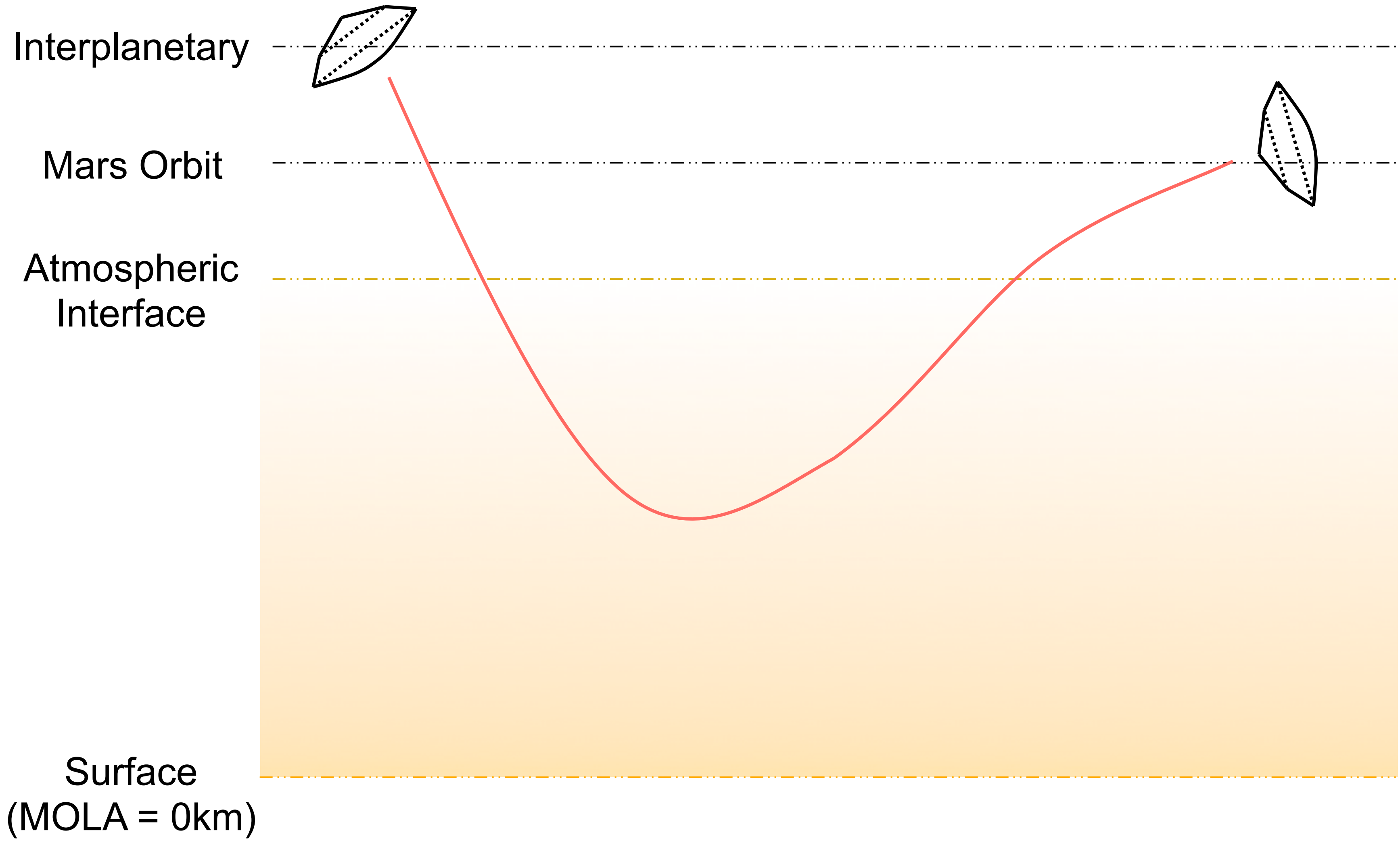
- Requirements
  - Deliver a 20 MT payload
  - Land at 0 km MOLA altitude
  - Land within 1 km of target, with confidence of 99%
- Assumptions
  - Payload is resupply for a human mission
  - Entry uncertainties no better than MSL
  - Northern hemisphere, 40-60 degrees west longitude
  - Intersect Mars sphere of influence @ 3.317 km/s

Trades Studied

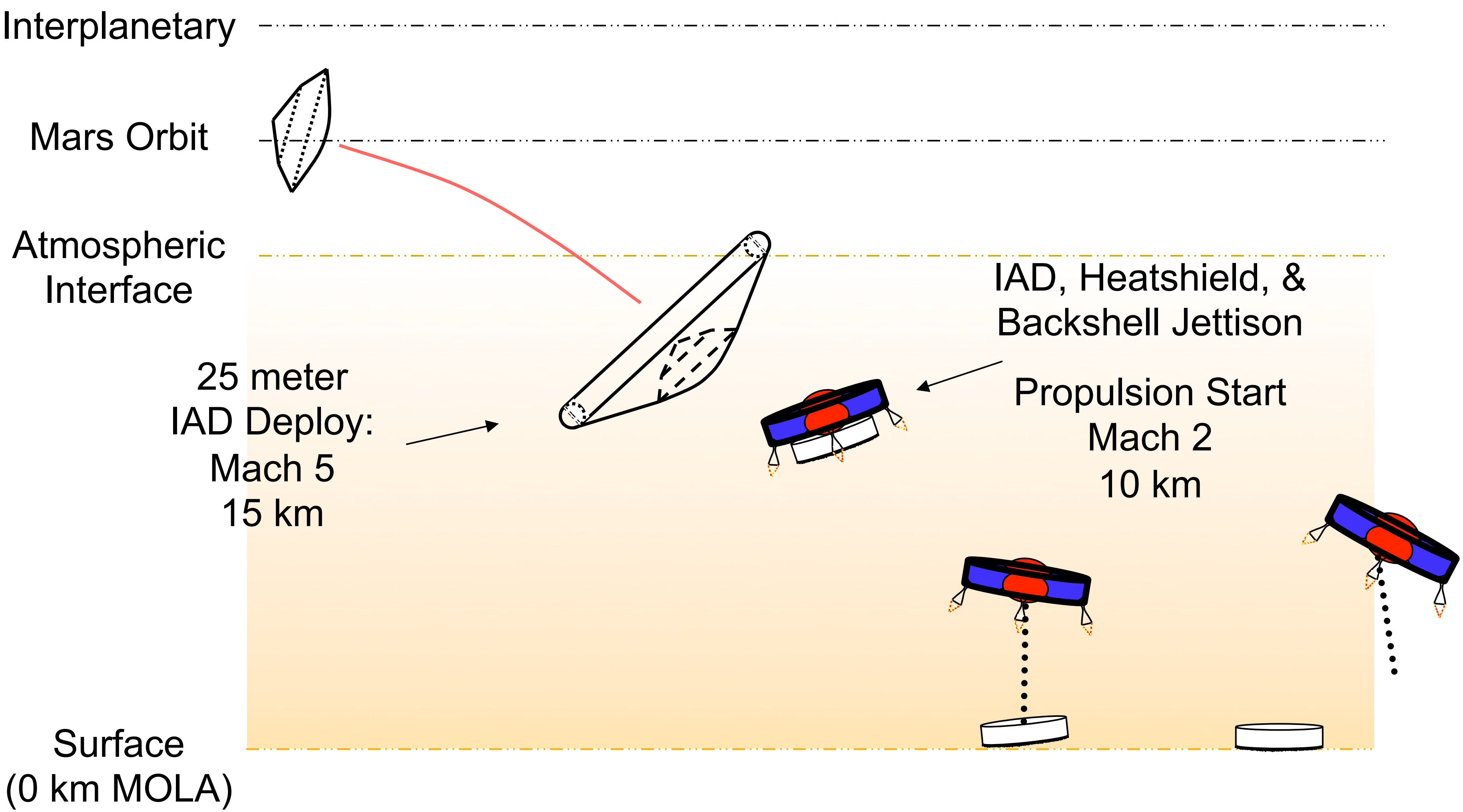
- Entry Mode
  - Direct Entry from interplanetary trajectory
  - Aerocapture into Mars orbit, with subsequent entry from orbit
- Vehicle Shape
  - Blunt body flown at angle of attack (L/D = 0.23)
  - Slender body flown at angle of attack (L/D = 1.0)
- Supersonic Deceleration
  - Inflatable Aerodynamic Decelerator
  - Propulsion
  - Parachutes

- Configuration that provided the most timeline margin was selected as baseline

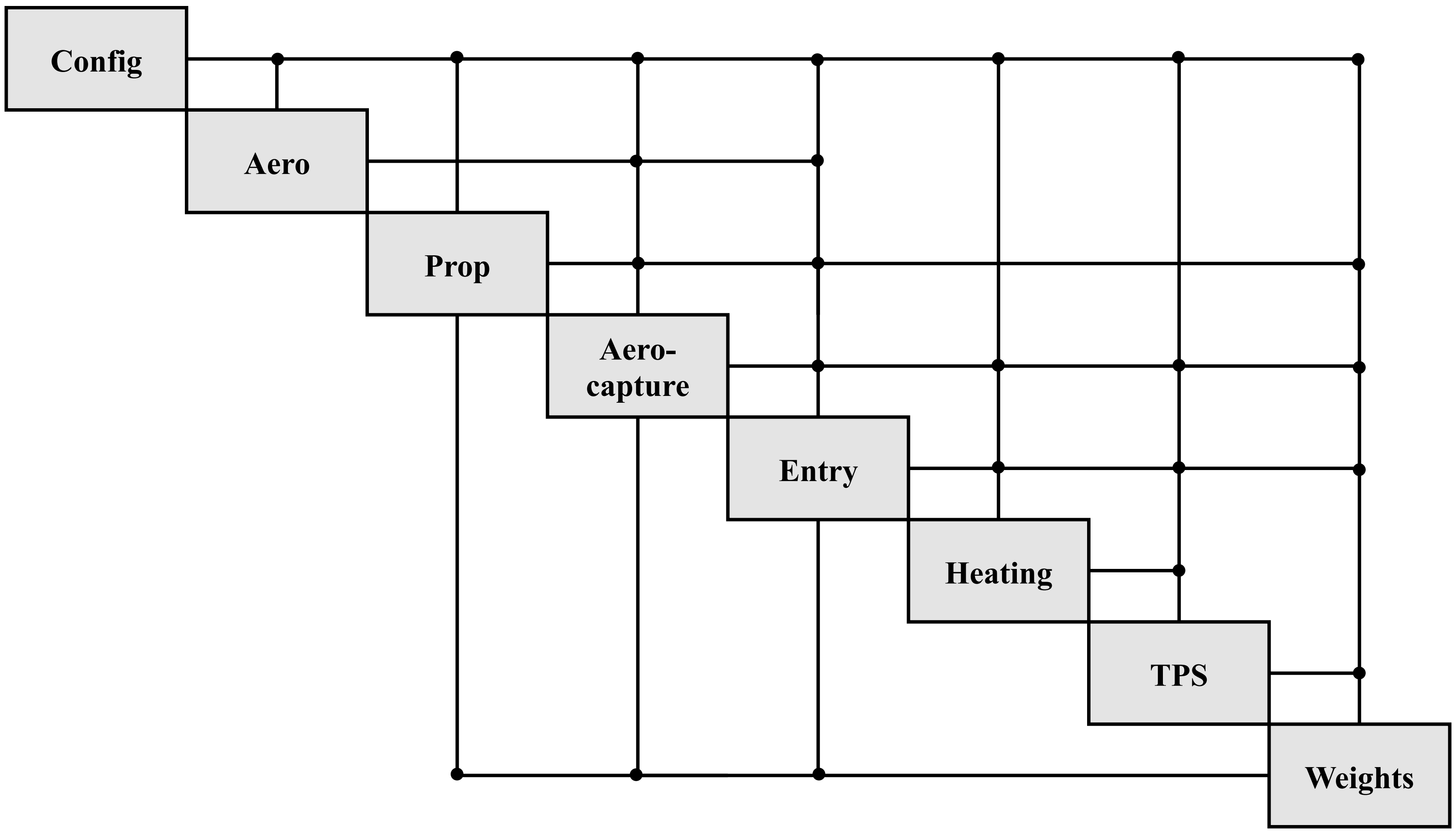
Baseline Design: Mission Overview - Aerocapture



Baseline Design: Mission Overview - Entry

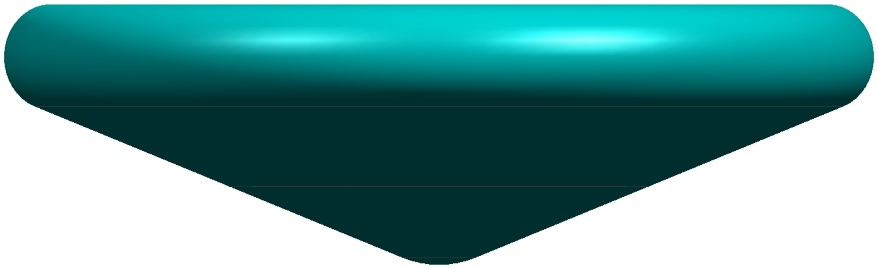


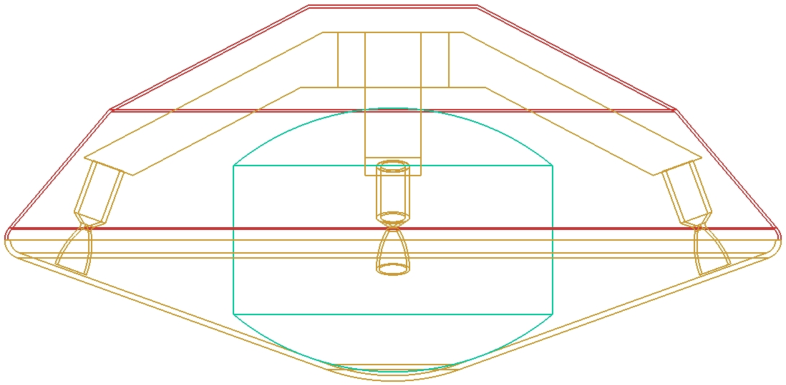
Design Structure Matrix (DSM)



Baseline Design: Configuration

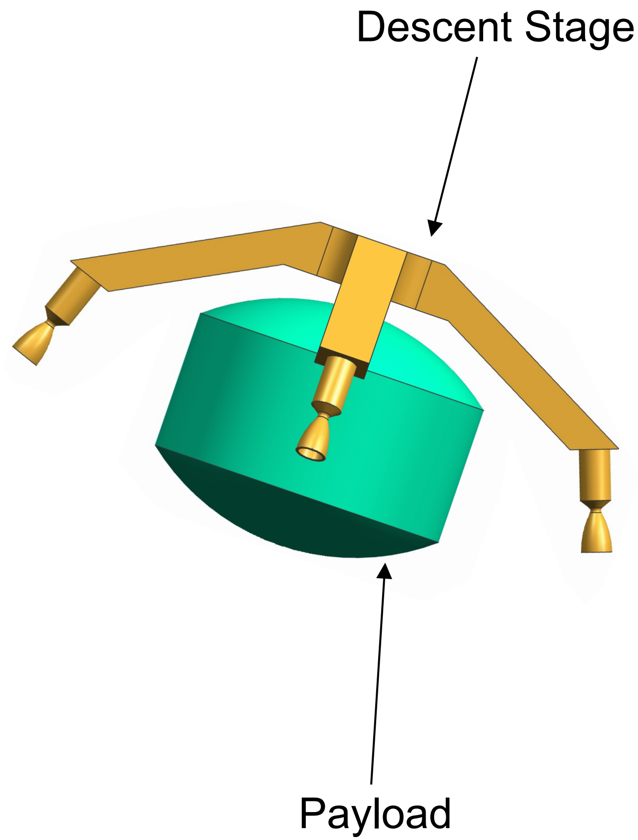
- Aeroshell
  - 70 deg sphere-cone
  - 14 m diameter
- Supersonic IAD
  - Inflatable torus with tension membrane
  - 25 m diameter
  - Gas-generator & Ram-air inflation
- Masses
  - Aerocapture: 78.6 MT
  - Entry: 70.8 MT
  - Landed Mass: 50.1 MT
  - Payload: 20.0 MT





Skycrane Landing System

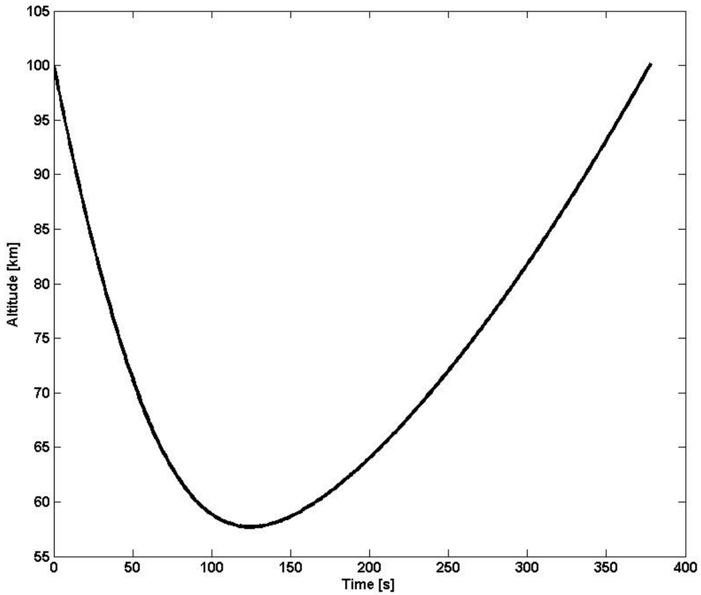
- Overview
  - Heritage derives from MSL Skycrane
  - Descent stage delivers payload module according to timeline
- Advantages
  - Scalable to a large payload
  - Direct payload delivery eliminates extraction complications
  - Exhaust interaction with surface reduced
  - Landing gear mass eliminated
- Notable Features
  - Payload underside protected by crushable aluminum honeycomb
  - LSASS/PALS LIDAR altitude/ attitude sensor



Methodology—Trajectory

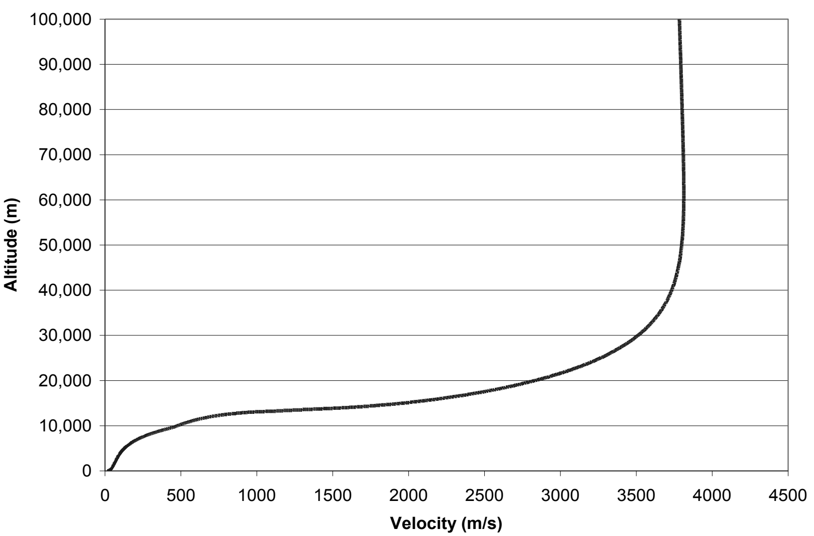
- 3 degree-of-freedom simulation with bank angle modulation, assuming:
    - Spherical planet
    - Gravity effects are only radial
    - Thrust force applied to vehicle oriented in any direction
    - Atmosphere defined by Seiff
    - Winds defined by Kaplan
- Aerocapture
    - Exo-atmospheric flight modeled assuming two-body motion
    - Flight assumed to be fully lift-up
- Entry
    - Triggers for changes in vehicle configuration
    - Propulsive terminal descent guidance targeting sites within 1 km of designated landing target for minimum propellant expenditure

Baseline Trajectory



- Nominal aerocapture trajectory
  - Initial state
    - V=5.9 km/s
    - γ=-8.5º
  - Minimum altitude of 58 km
  - Depletes 59% of the vehicle's energy

- Nominal entry trajectory
  - 14 m diameter aeroshell
  - Initial state
    - V=3.5 km/s
    - γ=-11.5º
  - 25 m diameter IAD inflation
    - M=5.0
    - h=15 km
  - Guided propulsive descent (t_{IAD}+25 s)
    - Backshell and IAD jettison
    - M=2.0
    - h=10 km



Heating Performance

- Heat rates are relatively low due to aerocapture and entry from Mars orbit, enabling the use of existing qualified TPS SLA-561
- Transition to turbulence not modeled; 40% margin added to TPS mass
- Aerocapture heat shield is jettisoned after its use to prevent heat soak back into the entry vehicle

Entry Heating at Stagnation Point	
Peak Convective Heat Rate	19.67 W/cm^2
Altitude at Peak Convective Heat Rate	26.3 km
Peak Radiative Heat Rate	3.13 W/cm^2
Altitude at Peak Radiative Heat Rate	16.0 km
Integrated Heat Load	1,752.4 J/cm^2
Entry TPS Mass + 40% Margin	468.72kg
Aerocapture Heating at Stagnation Point	
Peak Convective Heat Rate	18.03 W/cm^2
Altitude at Peak Convective Heat Rate	53.8 km
Peak Radiative Heat Rate	0.08 W/cm^2
Altitude at Peak Radiative Heat Rate	51.8 km
Integrated Heat Load	1,723.3 J/cm^2
Entry TPS Mass + 40% Margin	473.20 kg

Weights and Sizing

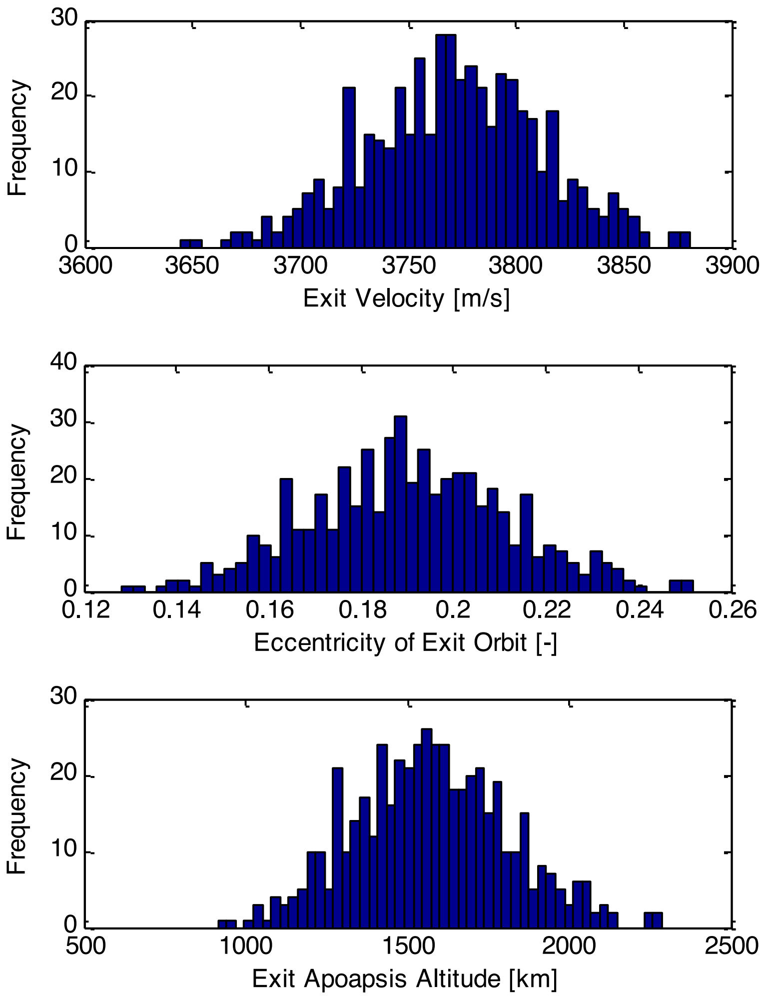
- Mass Estimating Relationships
  - Mars Science Lander
  - Historical MER database
- Propulsion System Sizing with REDTOP-2
- IAD sizing with material areal density & surface area, plus estimate of associated hardware
- TPS sizing used material densities, estimation of ablated mass, and stagnation point TPS thickness

#	Element	Mass
1.0	Body	15,790 kg
2.0	Entry Heat Shield	2,028 kg
3.0	Terminal Descent & Landing	1,918 kg
4.0	Avionics	165 kg
5.0	Power Supply and Distribution	764 kg
6.0	Propulsion	892 kg
7.0	Dry Mass Margin (40%)	8,623 kg
8.0	**Dry Mass**	**30,181 kg**
9.0	Payload	20,000 kg
10.0	**Landed Mass**	**50,181 kg**
11.0	Landing Propellant	17,712 kg
12.0	Inflatable Aerodynamic Decelerator	3,000 kg
13.0	**Entry Mass**	**70,893 kg**
14.0	Deorbit & Circ Propellant	5,085 kg
15.0	Aerocapture Heat Shield	2,704 kg
16.0	**Aerocapture Mass**	**78,683 kg**

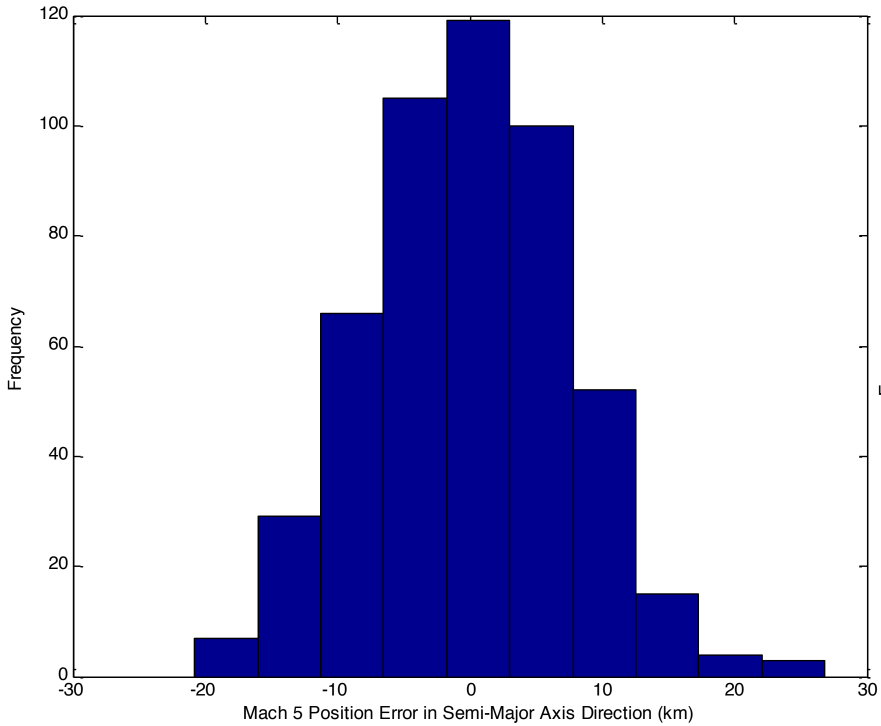
Uncertainty Analysis - Aerocapture

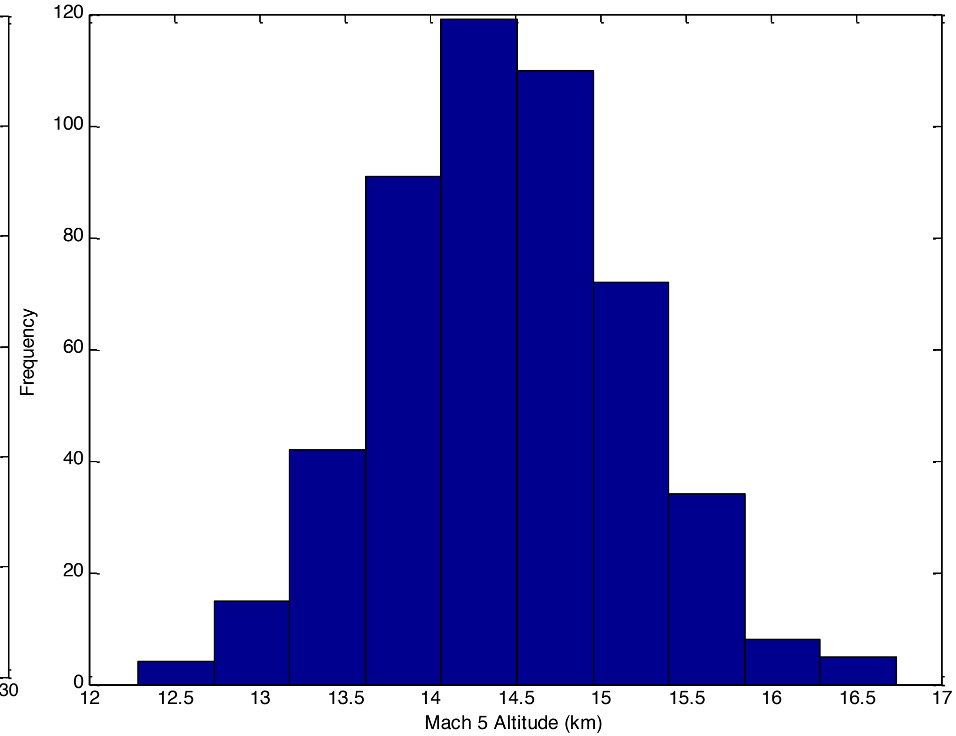
- 500 Case Monte Carlo
- System sized to accommodate in-space delta-V requirement for worst case including:
  - Periapsis raise
  - Apoapsis raise
  - Deorbit

Best Case	145.40 m/s
Nominal Case	156.66 m/s
Worst Case	263.89 m/s



Uncertainty Analysis – Entry





- 500 case entry Monte Carlo Simulation
- Position error at Mach 5 IAD deployment is 25 km in semi-major axis
- Altitude error at Mach 5 IAD deployment is +/- 2 km
- Hypersonic guidance, not used in this simulation, can reduce these errors

Proposed Testing and Qualification Program

- Wind Tunnel Test
  - Scale vehicle model in different IAD configurations
- Scaled Rocket Testing
  - Deploy scale model of vehicle from a sounding rocket at high altitude and Mach number to simulate entry
- Balloon Drop Testing
  - Deploy full-scale model of vehicle from a sounding rocket, first carried by a balloon, at high altitude and Mach number to simulate entry
- Radiative Lamp Testing
  - Supersonic wind tunnel used in combination with radiative lamps to simulate entry conditions experienced by IAD materials
- Arc-plasma Jet Testing
  - Test coupons of TPS material at high enthalpy conditions similar to entry
- Gantry Testing
  - Skycrane supported by gantry will be tested for stability and controller robustness

Conclusions & Future Work

- This baseline design meets the stated requirements:
  - 20 MT Payload
  - 0 km MOLA
  - Accommodates errors in aerodynamic, atmospheric, entry state, and mass parameters with 99% confidence
- Performance benefits of using IADs are significant.
- Propulsive terminal guidance can be very important in meeting a landed accuracy requirement
- Utilize an optimizer in an integrated environment to achieve better performance, optimizing trajectory and configuration