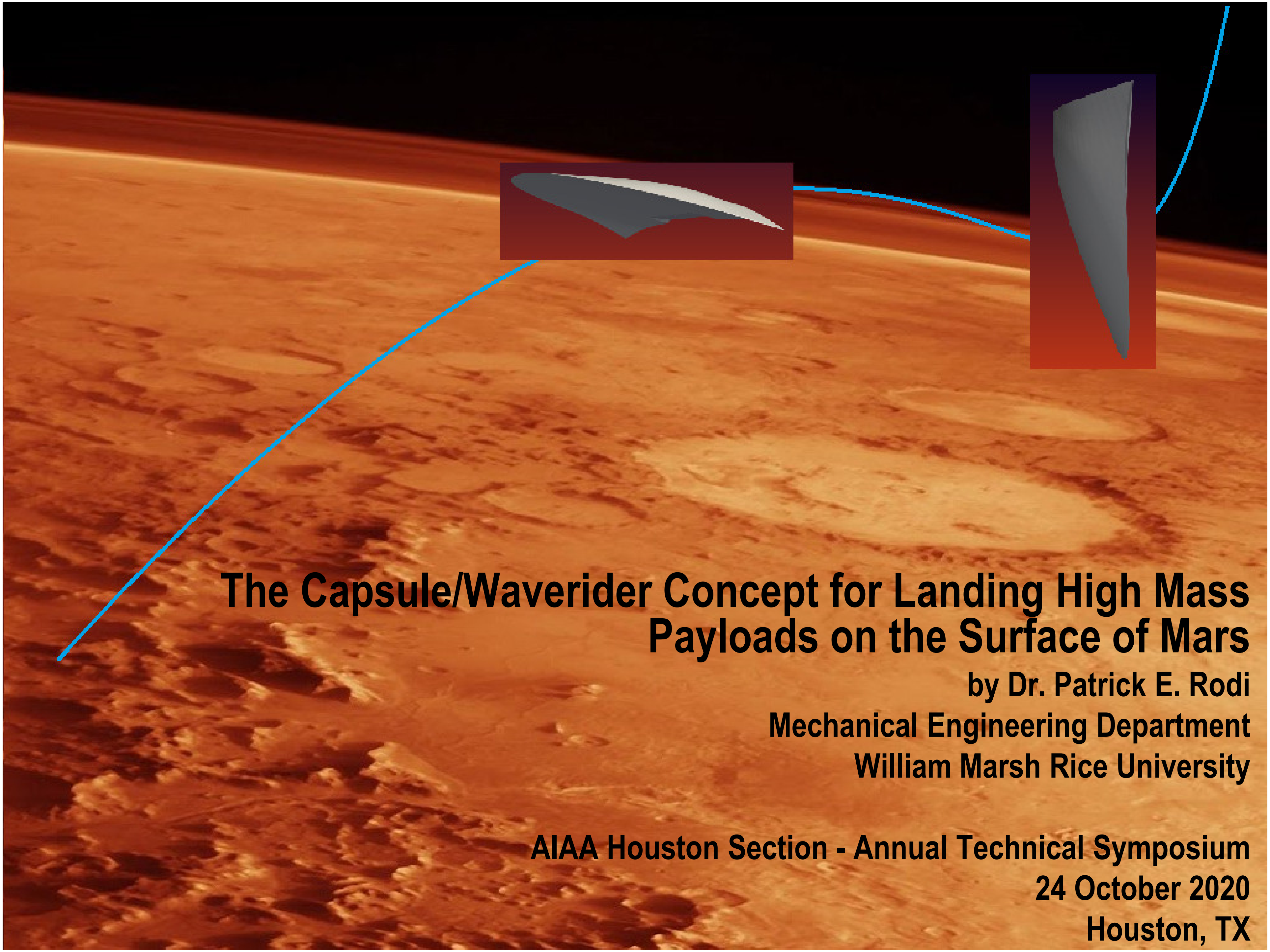

The Capsule/Waverider Concept for Landing High Mass Payloads on the Surface of Mars

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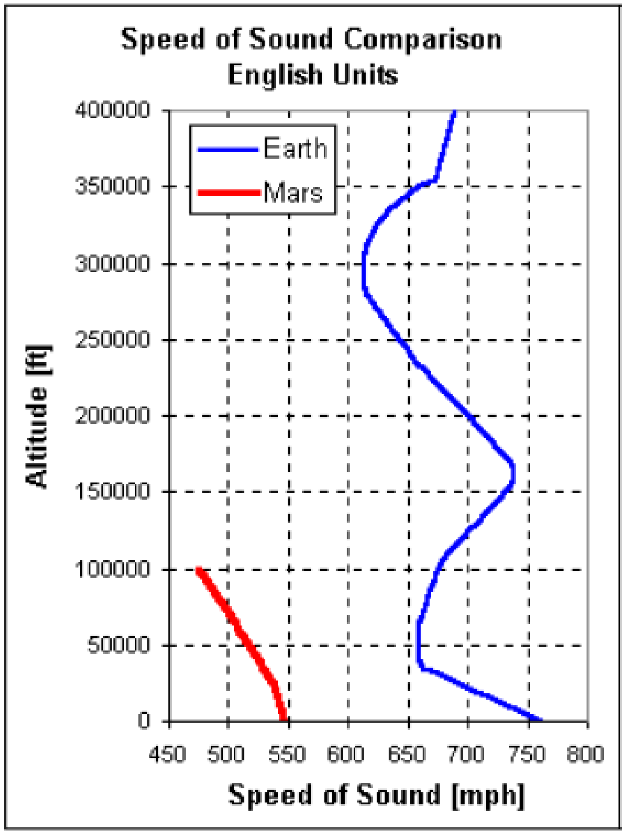
Presentation Outline

- Relevant Facts Regarding Atmospheric Flight at Mars
- The Historical Solutions for Martian Entry, Descent, and Landing (EDL): The Space Capsule
- The Problem – Capsules are Unable to Deliver High Mass Payloads on the Martian Surface
- Alternative Vehicle Concepts – What IS a Waverider?
- New Thinking for the Martian EDL Problem: The Capsule/Waverider
- Two-Dimensional (2D) Pathfinder Vehicle Approach, Optimization, and Results
- Optimized 3D Capsule/Waveriders for Entry and Glide at Mars

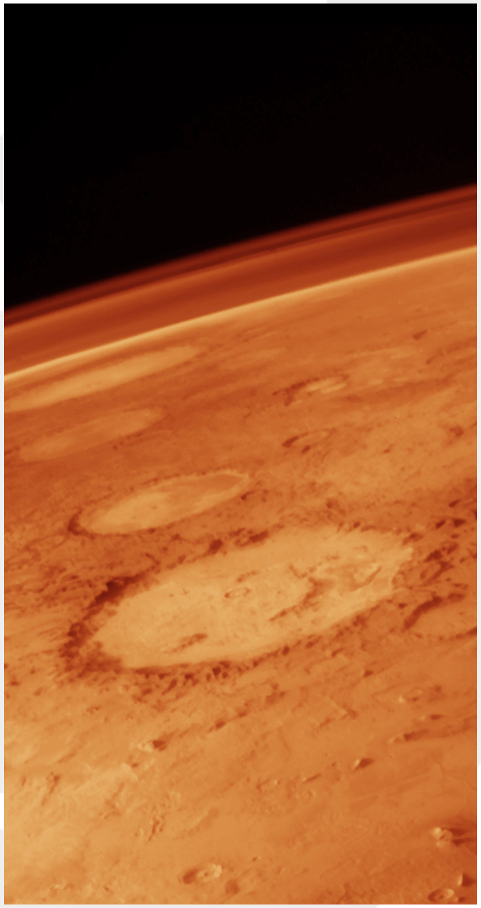
Atmospheric Flight at Mars: CO_2-dominated Atmosphere

- The effects of the CO_2-dominated atmosphere on aerodynamics
  - Ratio of specific heats (i.e. γ), 1.29 vs. 1.4 on Earth, shock waves are slightly more swept on Mars
  - Speed-of-Sound, $a=\sqrt{(\gamma RT)}$, γ is slightly smaller on Mars, but R is a lot smaller on Mars (1147 ft-lbs/slug/°R vs. 1716 ft-lbs/slug/°R on Earth) and the temperatures are lower



Atmospheric Flight at Mars: The Thin Atmosphere

- Thin Atmosphere Greatly Limits Lift Generation
- Surface Pressure is that at h=111,500 ft. on Earth
- Surface Density is that at h=101,700 ft. on Earth
- To Generate Lift,
  - $L=C_L qS$
  - Dynamic pressure, $q=1/2\rho V^2$
  - Density is the key to lift generation!

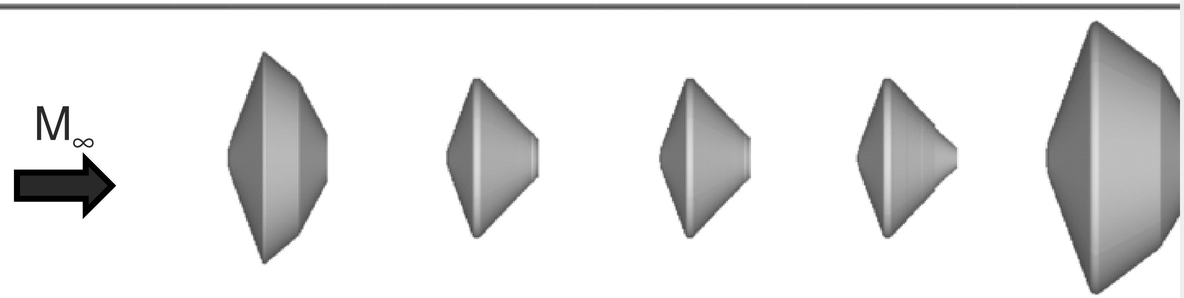


Atmospheric Flight at Mars: Low Gravity

- Low Gravitational Attraction Reducing Lift Requirements
- Surface Gravity is Only 37.6% of that on Earth's Surface, or 12.18ft/sec^2
- Low Altitude Orbital Velocity is only about 11,300 ft/sec vs. 25,000 ft/sec at Earth
- With the Lower Velocity and Lower Speed-of-Sound, The Mach Number at the Outer Edge of the Atmosphere ≈ 18 vs. 25 at Earth.

Historically Solutions for Martian EDL

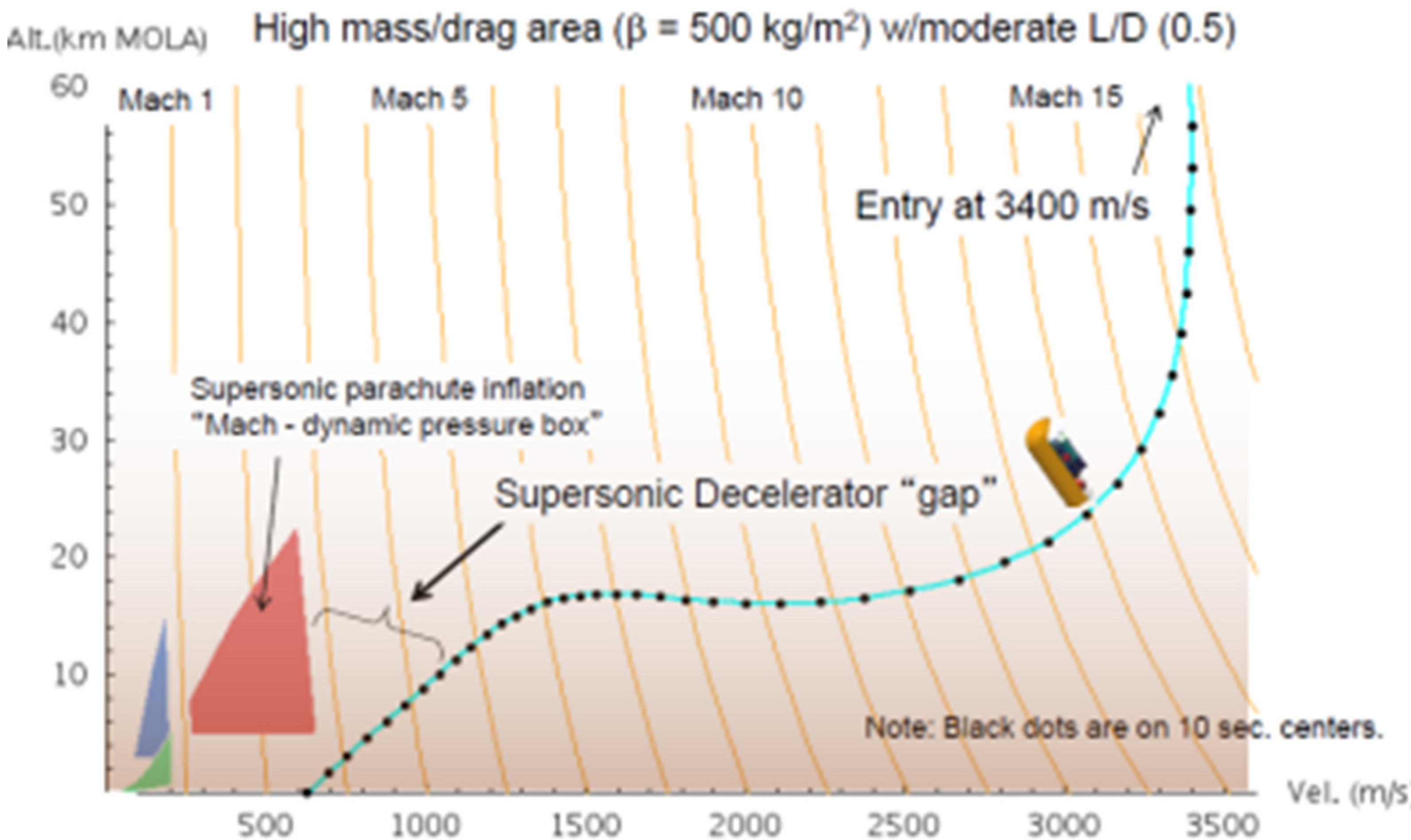
- A Long History of Very Similarly Looking Aeroshells
- All Sphere/Cones with Different Aft Bodies



	Viking 1/2	Pathfinder	MER A/B	Phoenix	MSL
Diameter, m	3.5	2.65	2.65	2.65	4.5
Entry Mass, kg	930	585	840	602	> 3000
Landed Mass, kg	603	360	539	364	> 1700
Landing Altitude, km	-3.5	-1.5	-1.3	-3.5	+1.0
Landing Ellipse, km	420 x 200	100 x 50	80 x 20	75 x 20	< 10 x 10
Relative Entry Vel., km/s	4.5/4.42	7.6	5.5	5.9	> 5.5
Relative Entry FPA, deg	-17.6	-13.8	-11.5	-13	-15.2
$m/(C_D A)$, kg/m^2	63.7	62.3	89.8	65	> 140
Turbulent at Peak Heating?	No	No	No	No	Yes
Peak Heat Flux, W/cm^2	24	115	54	56	> 200
Hypersonic α, deg	-11.2	0	0	0	-15.5
Hypersonic L/D	0.18	0	0	0	0.24
Control	3-axis	Spinning	Spinning	3-axis	3-axis
Guidance	No	No	No	No	Yes

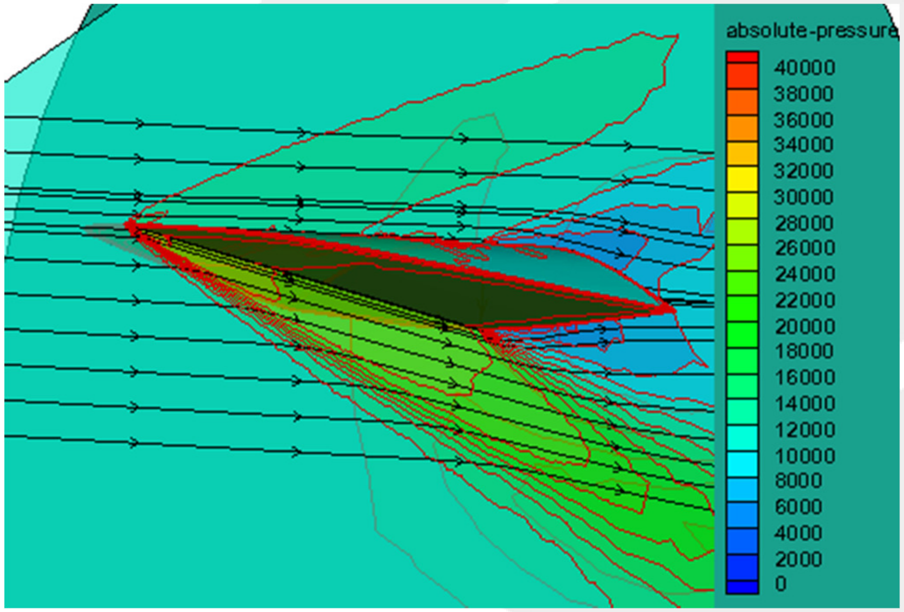
Capsules Are Unable to Delivery Large Masses to the Martian Surface

- Bigger Capsules with Bigger Parachutes leads to a “gap” in Capabilities



What IS a Waverider?

- A Waverider is a Three Dimensional Geometry that "Rides" it's own Shock Wave (i.e. has the shock wave attached to it's leading edge)
- Such a Vehicle is Possible when the Flowfield is Hyperbolic in Nature, where Information Moves Along Characteristics (e.g. supersonic & hypersonic flow)
- The Leading Edge Effectively Delineates the Lower Surface Flowfield from the Upper Surface Flowfield



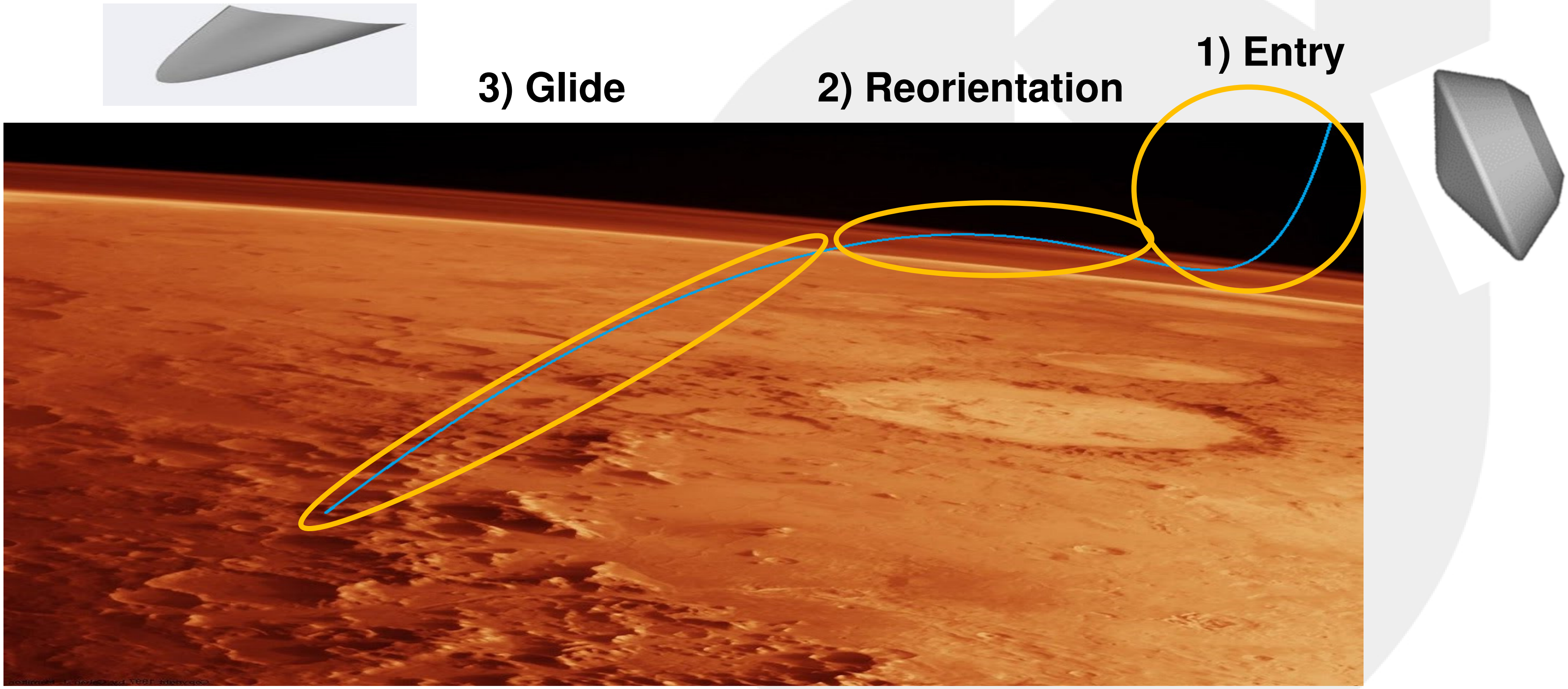
- The Attached Shock Wave prevents High Pressure Gas from "Leaking" from the Lower Surface Region to the Upper Surface Region
- This Effect Greatly Increases the Lift-to-Drag Ratio of the Vehicle

New Thinking for the Martian EDL Problem

- Capsules (with parachutes, sky cranes, etc.) can Withstand Entry but have Low Mass Delivery Capabilities
- Capsules with Retro Propulsion may work, but the extra mass and complexity is significant
- Waverider Vehicle Leading Edges would become Extremely Hot During Entry
- After Entry, a Waverider would Glide Around Very Efficiently
  - Mission flexibility by decoupling entry point from landing point
  - Wide area reconnaissance and final landing site selection
  - Multiple payload/location deliveries
  - Conduct additional observations (e.g. atmospheric sampling over a wide area)
- <u>Can One Vehicle have a Split Personality???</u>
- New Approach: Leverage Knowledge and Experience in Waverider Design, Employ Capsule-Inspired Geometries, and Apply to the Martian EDL Mission
- Solution: The Capsule/Waverider Configuration, a vehicle that acts like a capsule early during entry and then re-orientates to be a Waverider for gliding

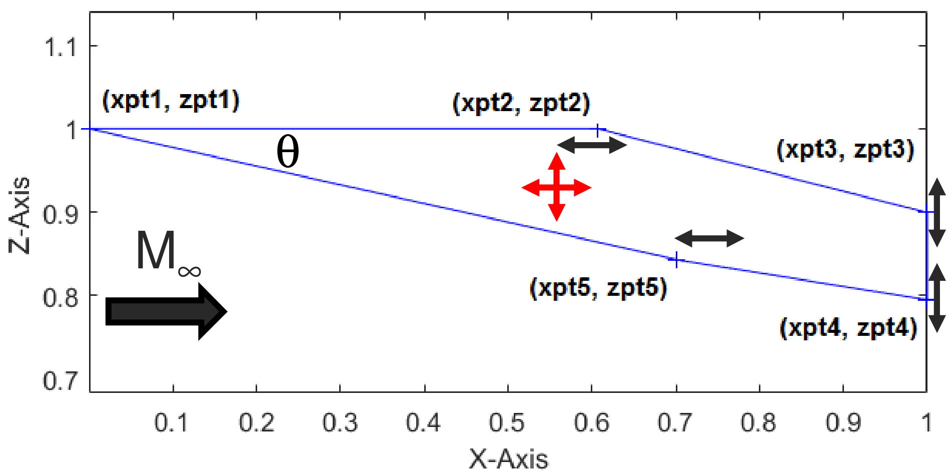
Capsule/Waverider Mars Entry Trajectory

- The Capsule/Waverider's Three Trajectory Segments



Two-Dimensional Pathfinder Approach

- General Vehicle Requirements:
  - Stable longitudinal trim ($C_m = 0$ & $dC_m/d\alpha < 0$) at two angles-of-attack (α)
  - High L/D at both stable trim points
  - Sufficient volume for payload
  - Center-of-Mass in an “obtainable location”
- Begin with a Two-Dimensional (2D) Analog in Earth’s Atmosphere
- Upper Surface – Convex like on Space Capsules
- Lower Surface – Compression Lift as with Waveriders

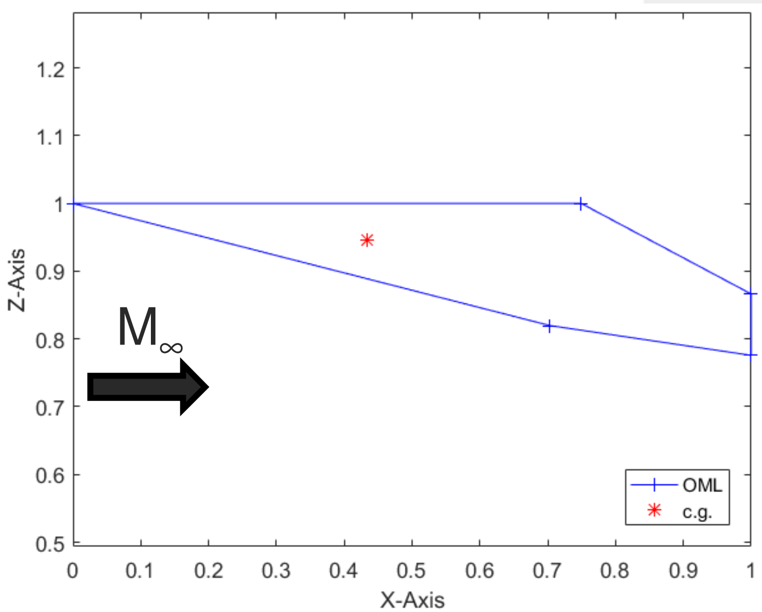


- Improved Performance by Adding a Body Flap (pt #4 – pt #5)

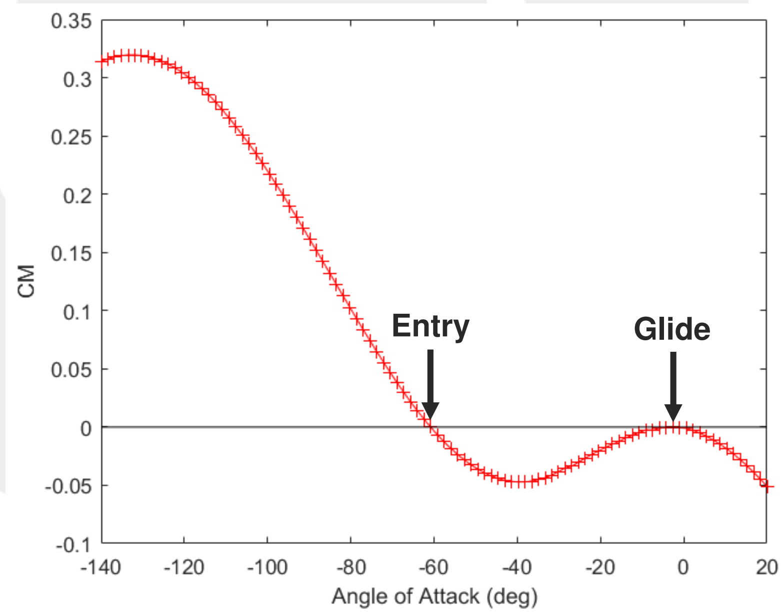
2D Capsule/Waverider Solution for Earth

- Inviscid Pressure Dominate Aerodynamic Forces & Moments (Modified Newtonian and Van Dyke models)
- Matlab-Based Particle Swarm Optimization with L/D-Based Cost Function
  - Seven variables (leading edge angle, control point locals, c.g. local)
  - Penalty functions added when two stable trim points were not obtain
  - $3x\ |L/D_{cap}| + |L/D_{WR}| = \text{cost function}$

Optimized 2D Capsule/Waverider



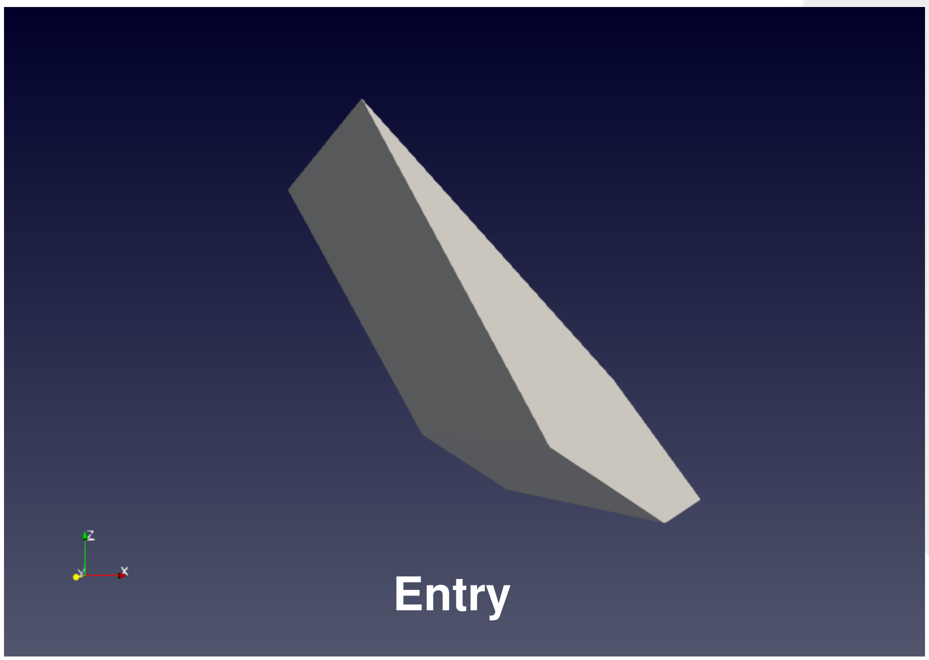
Pitching Moment vs. α Distribution

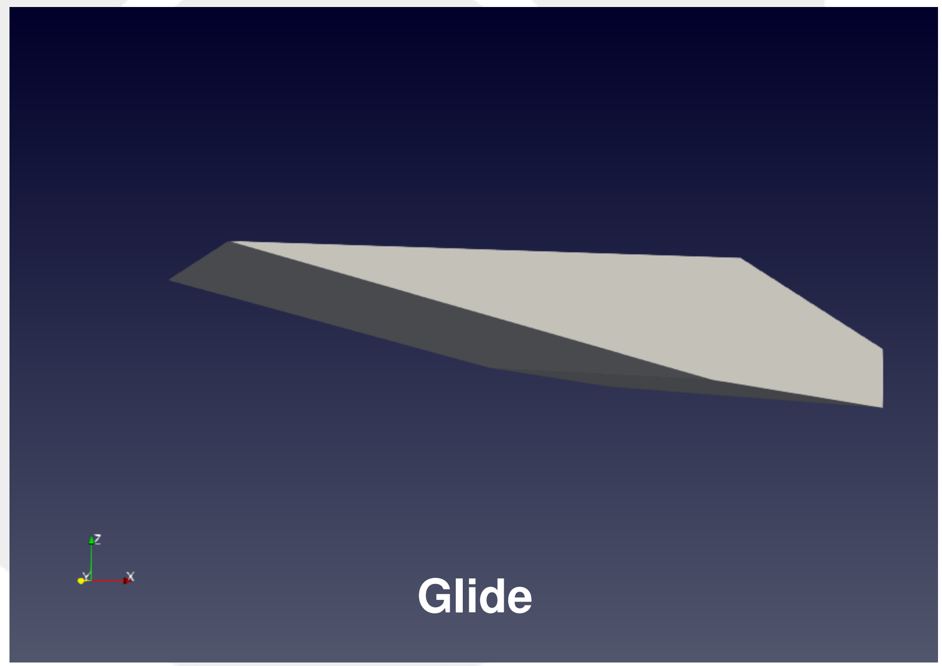


RICE

2D Capsule/Waverider Solution for Earth

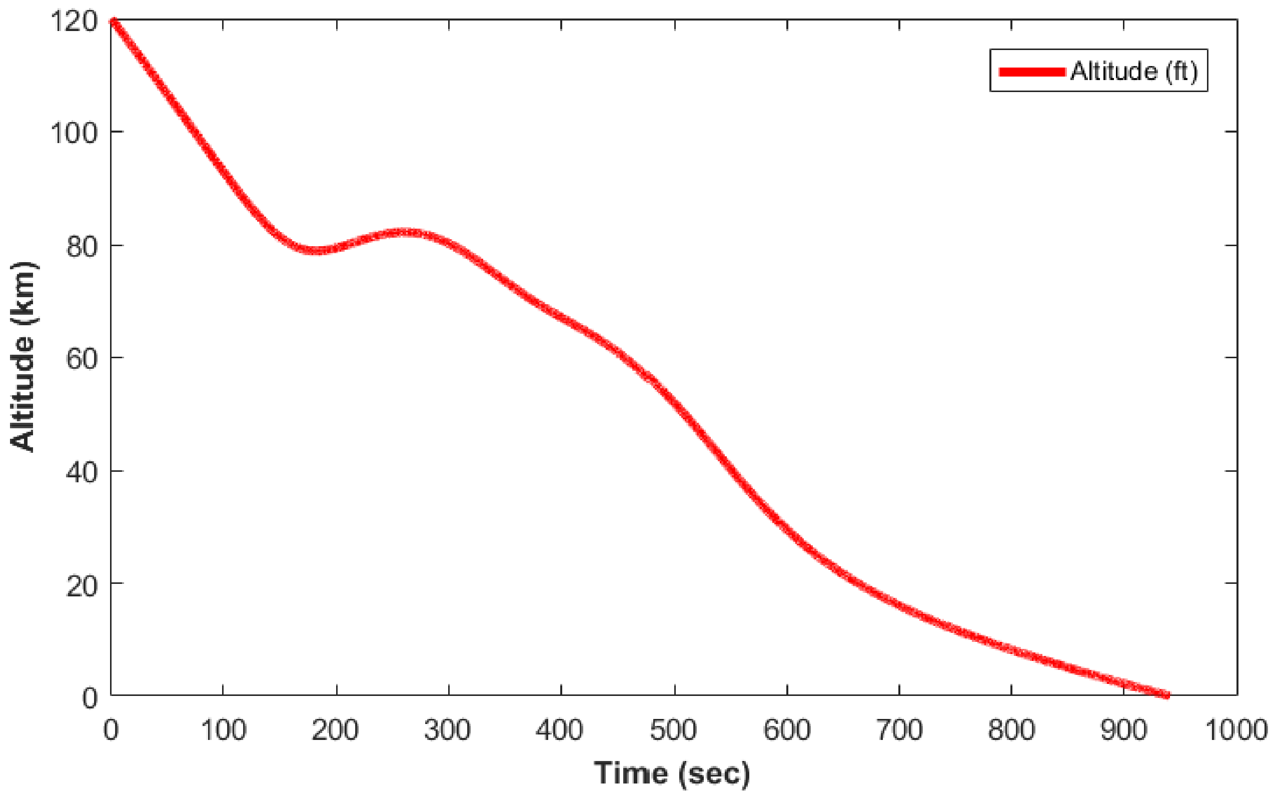
- Trim Angle-of-Attack Points: Entry $\alpha \cong -60°$, Glide $\alpha \cong 0°$
- For a Given Angle-of-Attack, the Vehicle can be Spun Around the Velocity Vector (i.e. to any roll angle) without changing the Flowfield
- 2D Capsule/Waverider in Entry Orientation (rolled 180° to position lift vector to oppose gravity) and Glide Orientation





2D Capsule/Waverider Solution for Earth

- Altitude Time History for a Fast/Steep Earth Entry



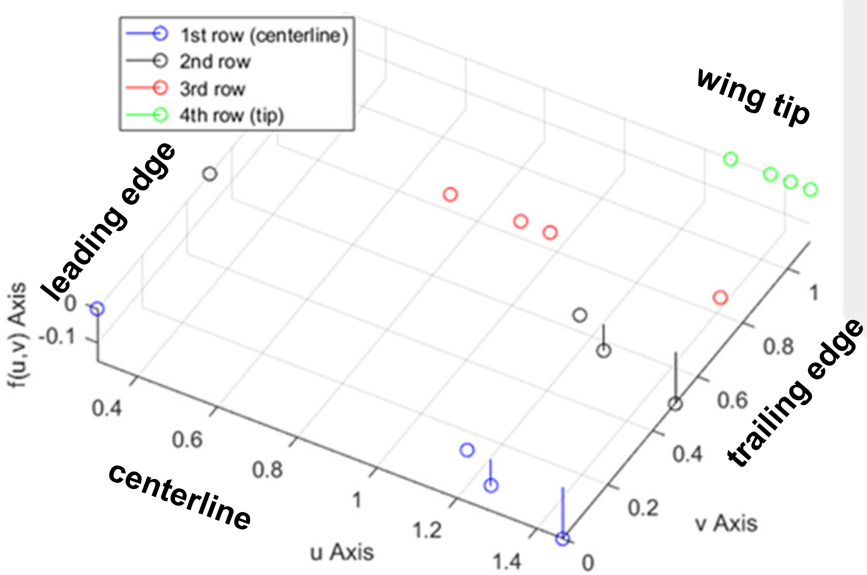
- Entry/Reorientation/Glide Features are Clearly Identifiable
- Changing Initial Velocity and Flight Path Angle can Easily Manipulate These Features over a Wide Range

Rodi, P.E., "Combined Capsule/Waverider Configurations For Boost Glide Missions," AIAA Paper 2020-2423, March 2020.

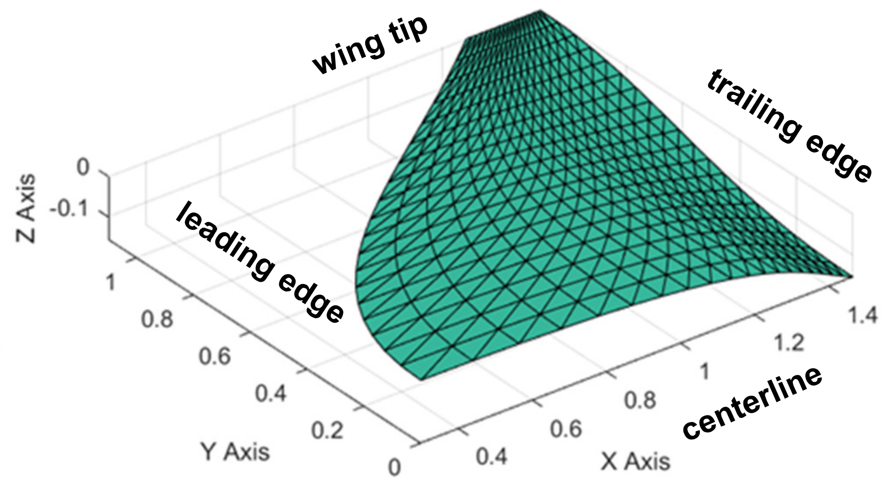
3D Vehicle Upper Surface Shaping

- 3D Capsule/Waverider Configurations require more Sophisticated Modeling of the Geometric Features – Leverage Work on Boost-Glide Vehicles
- The Convex Shaping of the Upper Surface was Modeled as an Off-Set from the Original Waverider Upper Surface (nominally a Cp=0 surface)
- A Third Order Bezier Surface, in both the u- and v-directions, was Employed to Quantify a Smoothly Varying Off-Set Distribution, while meeting the Boundary Conditions (zero off-set along the leading edge, symmetry, tangency), and providing easy and sufficient design flexibility for optimization

Computational Domain



Physical Domain

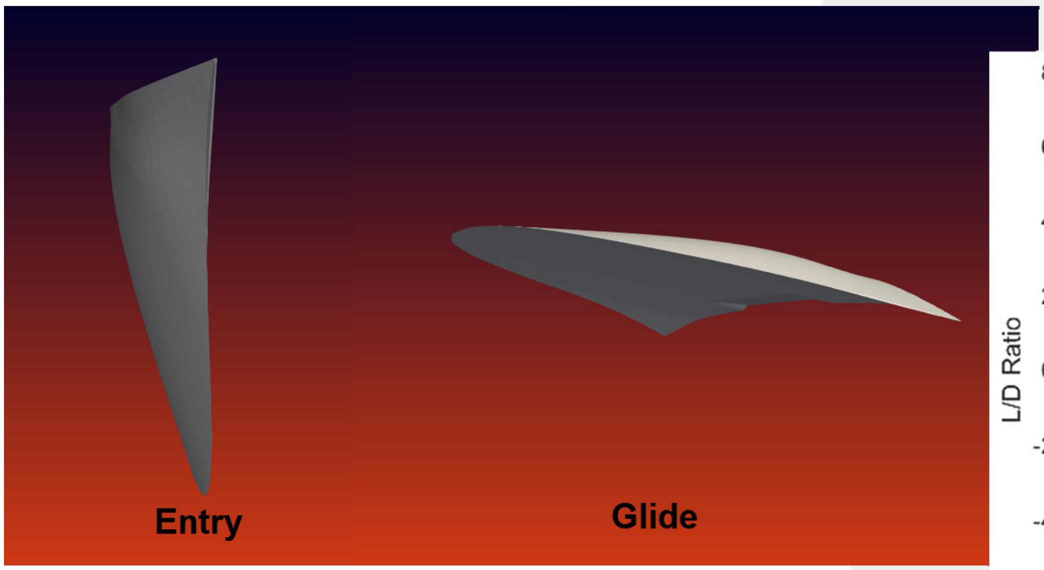


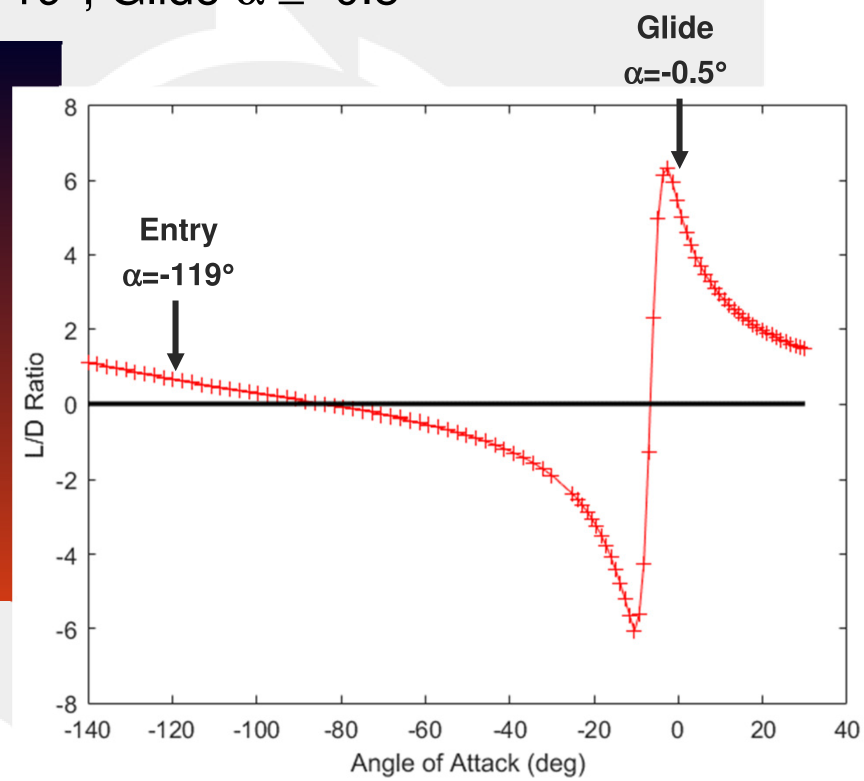
Numerical Optimization for 3D Vehicles

- Inviscid Pressure Dominate Aerodynamic Forces & Moments (Modified Newtonian and Van Dyke models)
- Matlab-Based Particle Swarm Optimization with L/D-Based Cost Function
  - 21 design variables related to,
    - baseplane shock wave shape
    - baseplane upper surface shape
    - osculating planes' power law body information
    - Bezier Surface control points
    - body flap information
  - Penalty functions added when two stable trim points were not obtain
  - $3x\ |L/D_{cap}| + |L/D_{WR}|$ = cost function to be maximized
- Good Convergence Behavior
- Vehicle Shaping is Largely Independent of Trajectory Design
- Vehicle TPS Material Selection is Dependent on Shaping and Trajectory

Optimum 3D Capsule/Waverider for Mars EDL

- Solutions were found that were Stable at Both Entry and Glide Attitudes
- PSO Optimization Produced Vehicles with Very Good Aerodynamic Performance
- Trim Angle-of-Attack Points: Entry $\alpha \cong -119°$, Glide $\alpha \cong -0.5°$

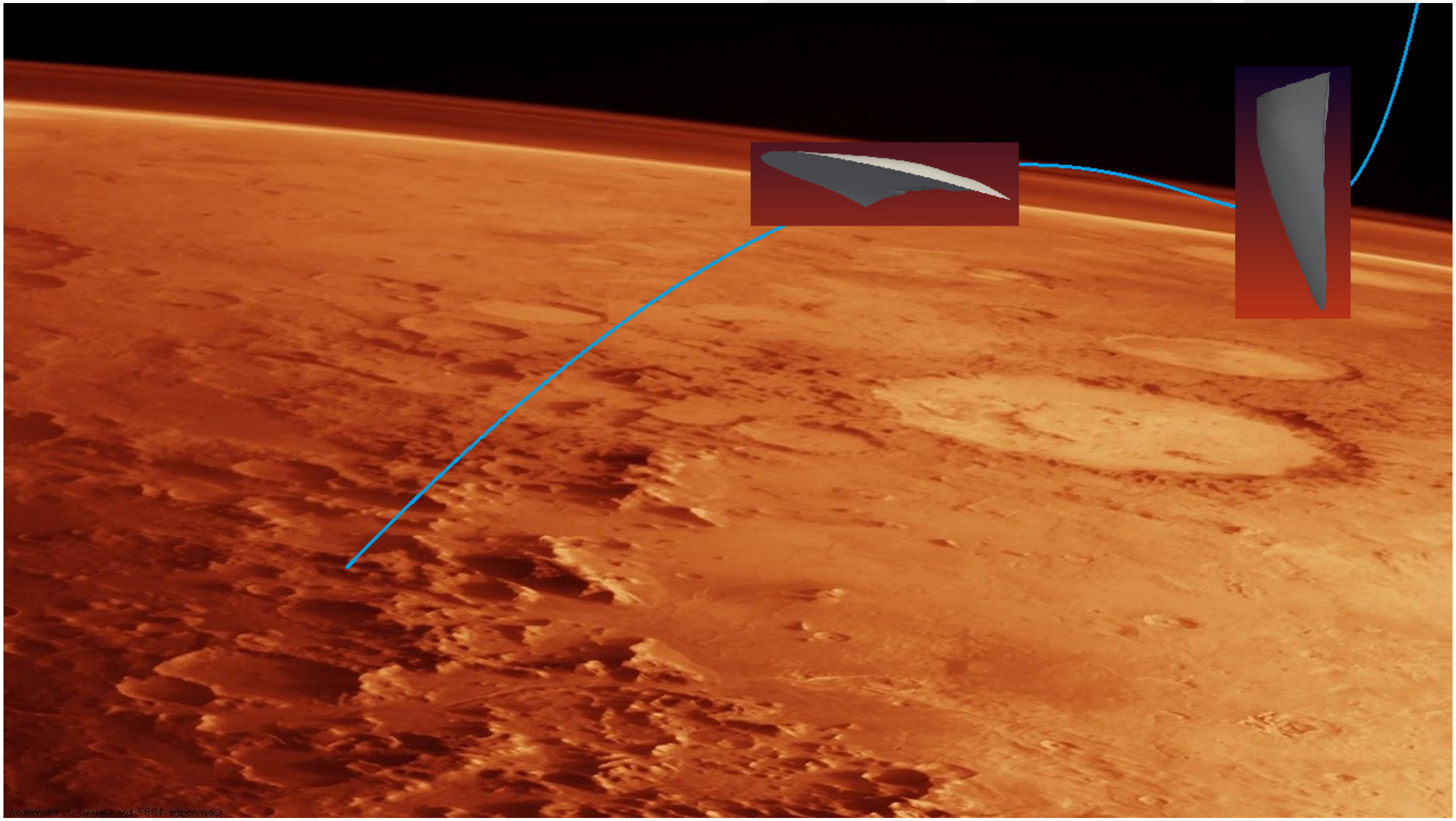




- Vehicles were also found to be Directionally Stable

Optimum 3D Capsule/Waverider for Mars EDL

- The Capsule/Waverider is able to Enter like a Capsule, and then Glide like a Waverider



Gliding Flight Mode over Mars

- For the Capsule/Waverider in Gliding Flight,
  - Employ the Sanger Glide Equation to estimate range of glide,

$$\frac{range}{Mars\ Radius} = \frac{1}{2}\frac{L}{D}\ ln\left(\frac{1}{1-\bar{V}}\right);\ \bar{V} = \left[\frac{V}{11{,}300\ ft/sec}\right]^2$$

    - $\bar{V} \cong [0.85]^2 = 0.722$, L/D ≅ 5.2

$$range\ = (2{,}106\ miles)\frac{1}{2}(5.5)\ ln\left(\frac{1}{1-0.722}\right) = 7{,}414\ miles$$

    - ΔLongitude ≅ 200° (past the opposite side of Mars!)

- Final Payload Delivery Options
  - Release payloads during glide (parachutes, sky cranes, roller balls, etc.)
  - Slide to a landing on the Martian surface (also exposing subsurface soil)
  - Pitch-up and land vertically via rocket power

Summary

- Facts Regarding Atmospheric Flight at Mars
- Sphere/Cone Capsule Configurations are unable to Deliver High Mass Payloads to the Martian Surface
- What IS a Waverider?
- A New Solution for the Martian EDL Problem: The Capsule/Waverider
- 2D Pathfinder Capsule/Waverider Approach, Optimization and Results
- Optimized 3D Capsule/Waverider for Entry and Glide at Mars
- Global Range and Various Landing Options greatly increase Mission Flexibility and Scientific Coverage