Reaction Control system Design Considerations for Mars Entry Vehicles

Artem Dyakonov

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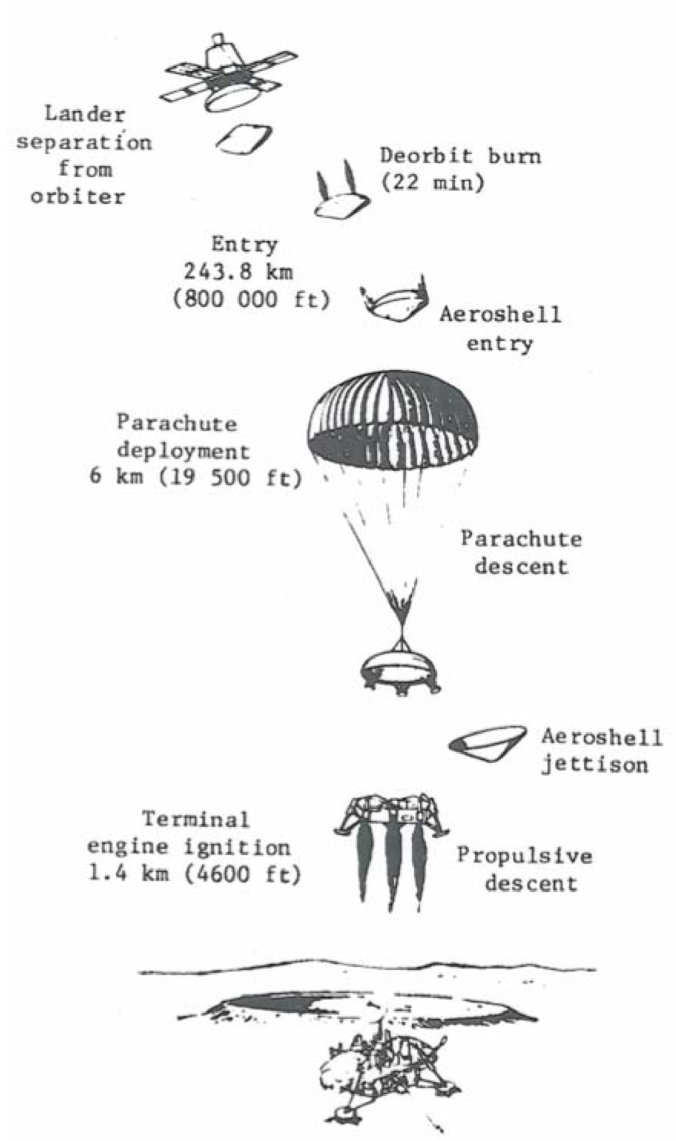
Team

Chris E. Glass, NASA LaRC
Mark Schoenenberger, NASA LaRC
William I. Scallion, NASA LaRC
Artem A. Dyakonov, NASA LaRC
Brian R. Hollis, NASA LaRC
Karl T. Edquist, NASA LaRC
Pawel Chwalowski, AMA
John Van-Norman, AMA
Victor R. Lessard, GENEX
Naru Takashima, APL
Michael J. Wright, NASA Ames
Chun Tang, NASA Ames

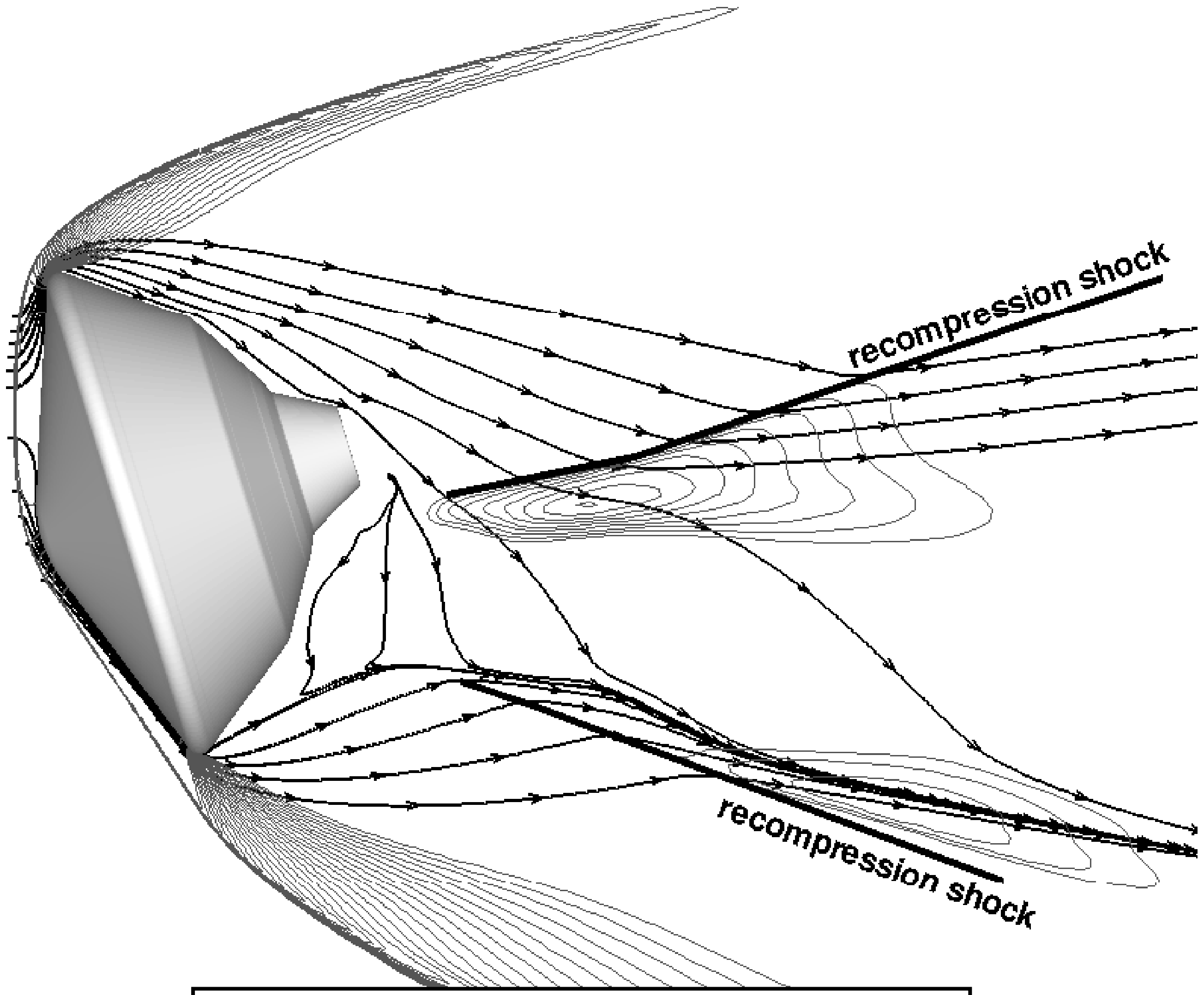
Overview

AAD

- Past Mars missions landed within 100s of km from desegnated target
  - Unguided lifting (Viking 1, 2)
  - Unguided ballistic (Pathfinder, MER)
- New generation of Mars landers to deliver massive payloads to within 10s of km from sites of interest
  - Lifting actively guided entry (MSL)
  - High lift-to-drag ratio
- Guided entry requires a reaction control system (RCS)
  - Active control of direction of the lift vector
  - Rate damping
- Guidance maneuvers take advantage of dynamic pressure, so they take place in hypersonic and supersonic segments of the entry
  - Effect of RCS on aerothermal environment can be significant, impacting TPS
  - RCS interference in aerodynamic characteristics neds to be understood to reliably predict flight



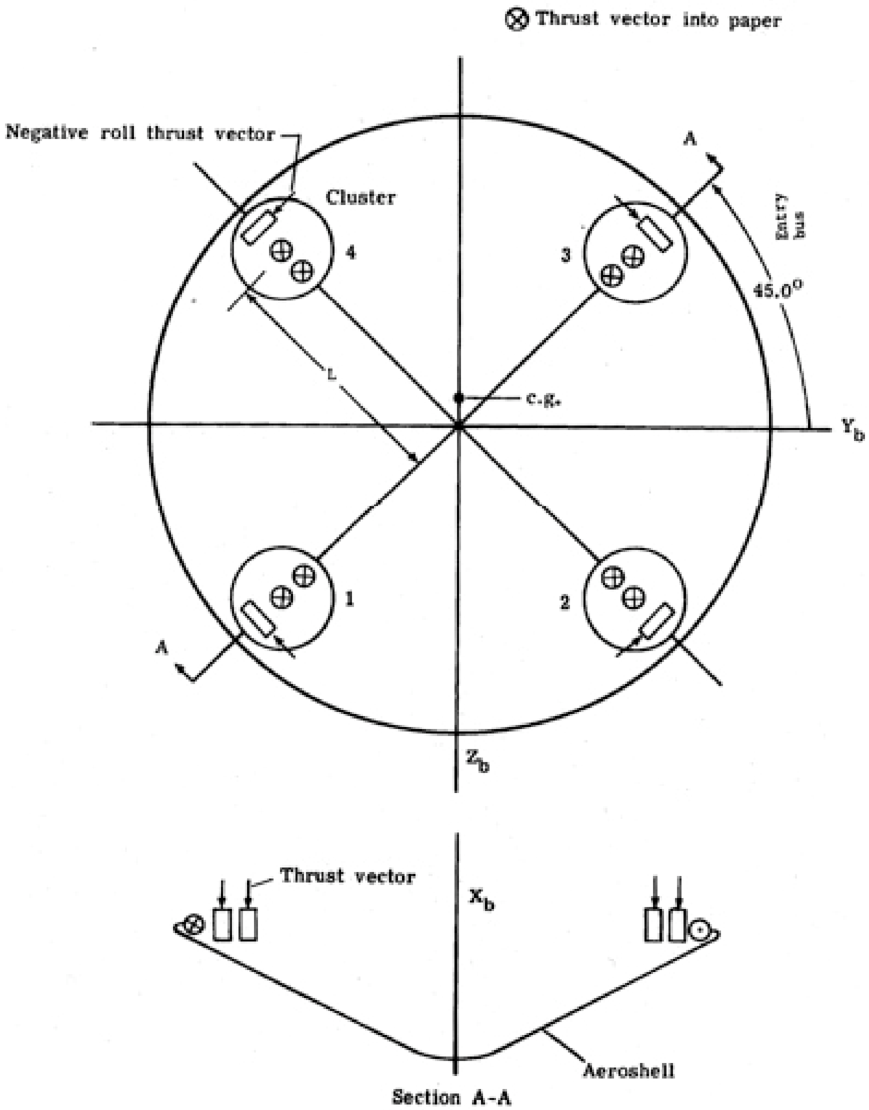
Near-capsule flowfield



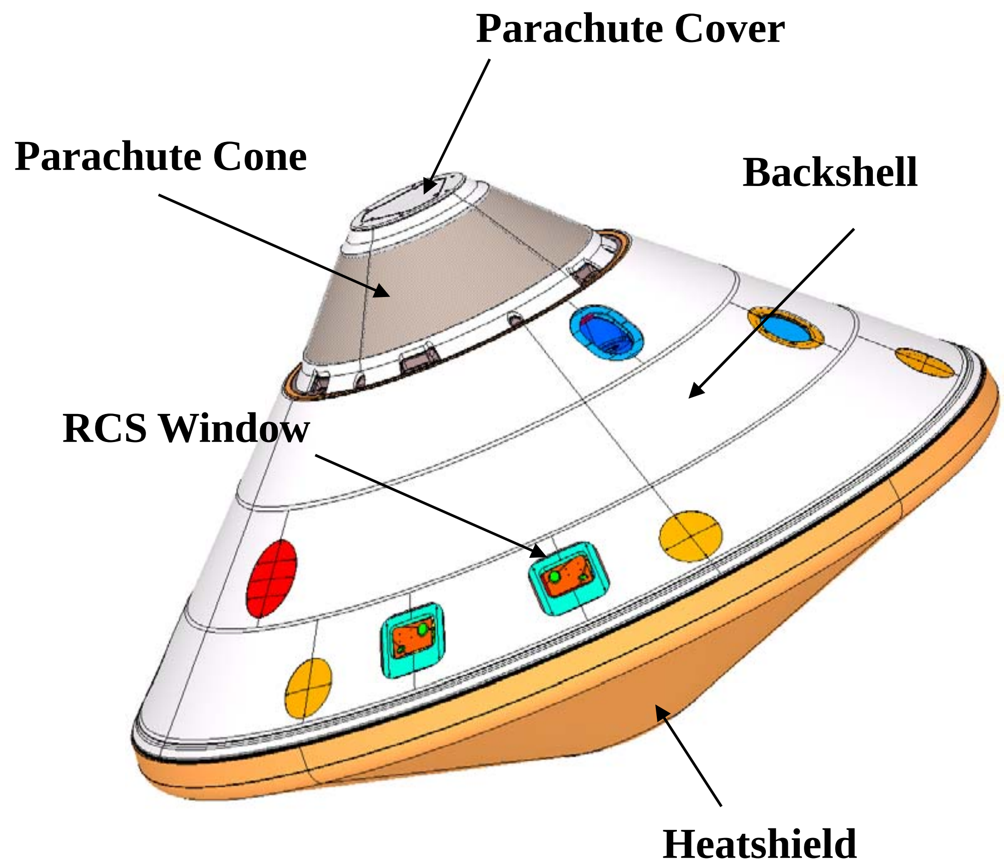
Flow around MSL Capsule at Mach 18.1

Reaction Control Systems

Viking Lander RCS

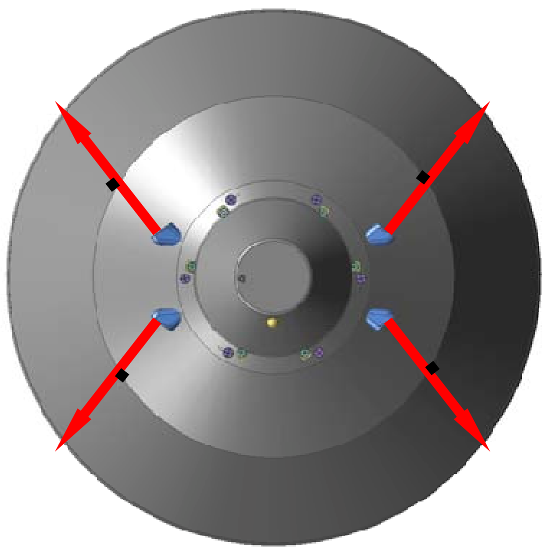


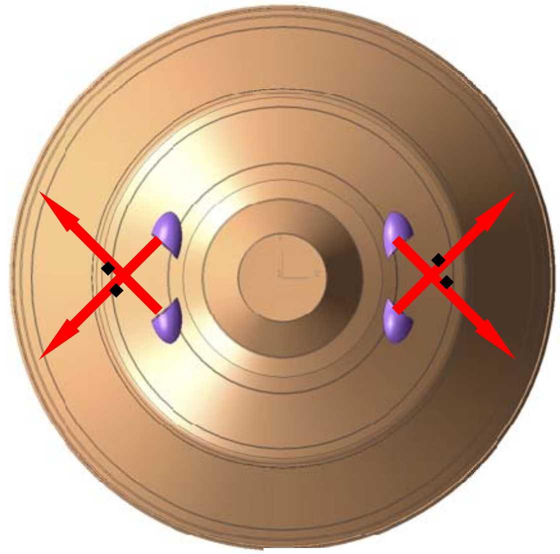
MPL/Phoenix RCS

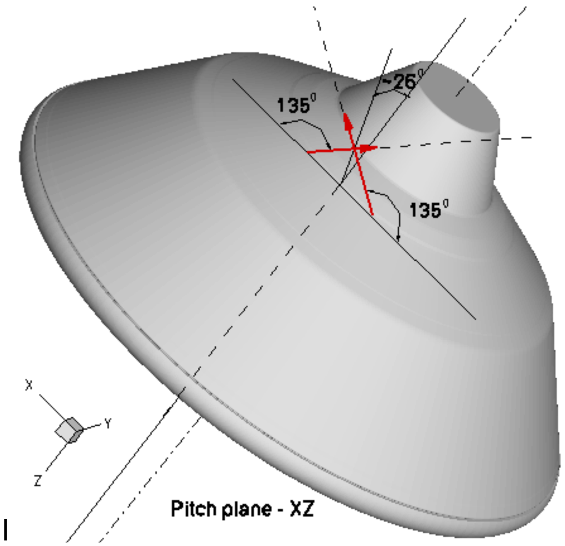


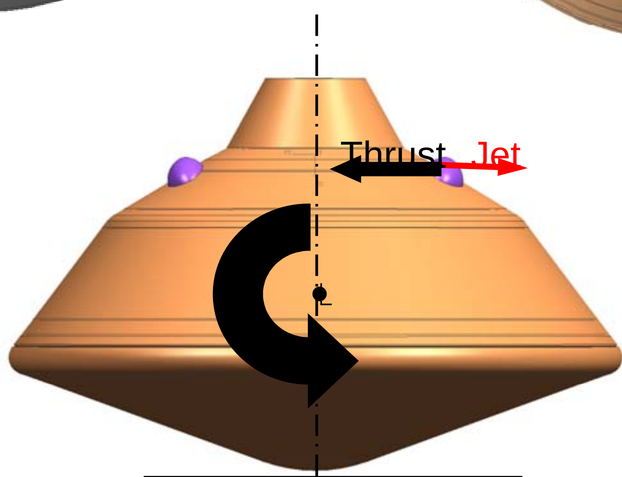
Reaction Control Systems (cont.)

Several Candidate MSL RCS

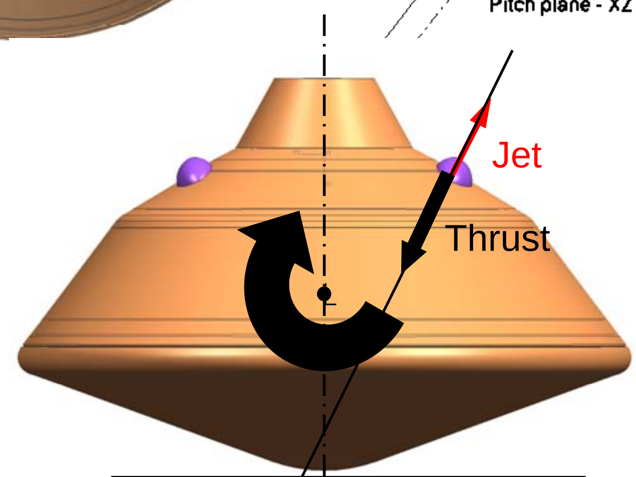








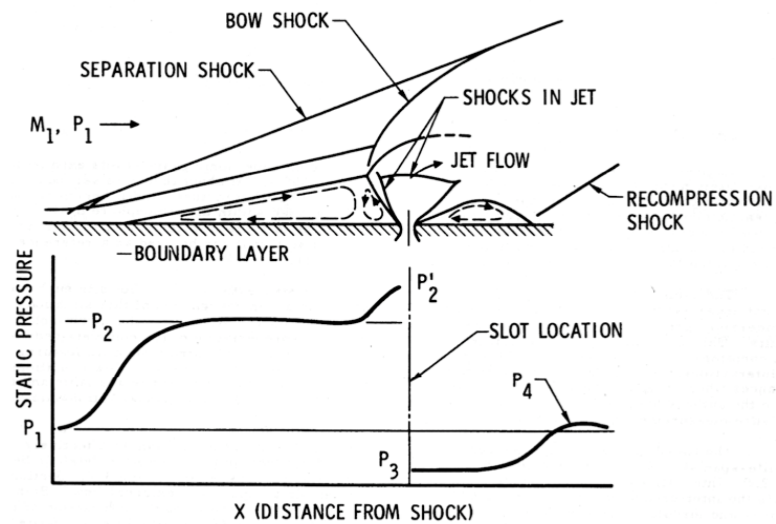
Thust Aft of CG



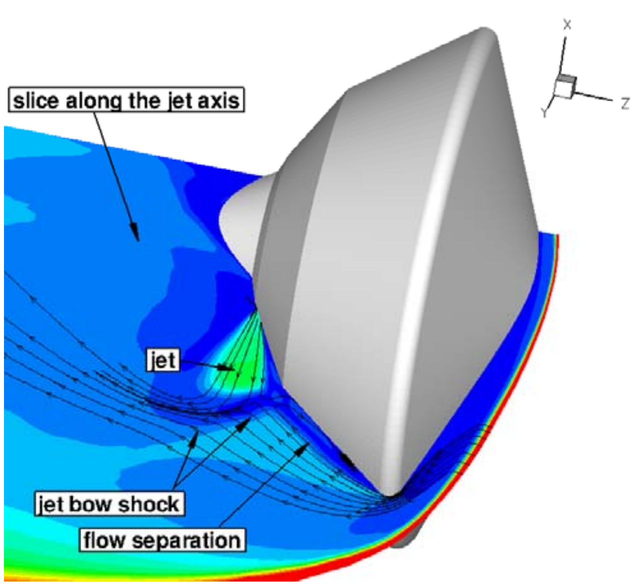
Thrust Ahead of CG

Jet-Wake Interaction

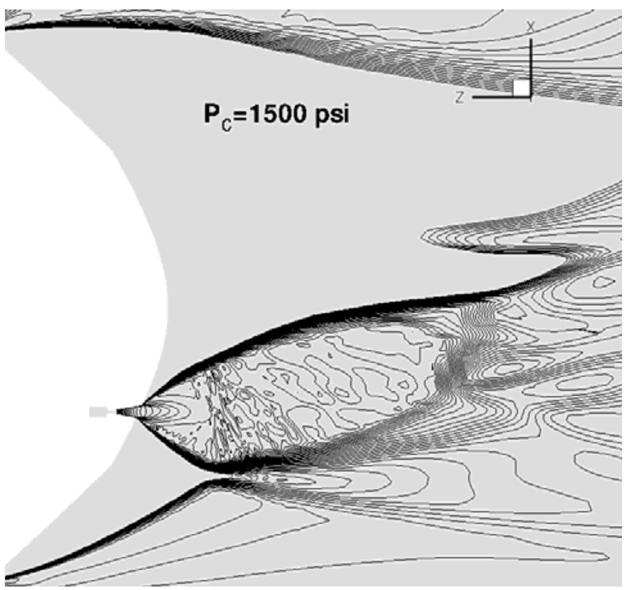
- Interaction of an underexpanded jet with crossflow extensively studied
  - Applicability of existing analyses to scientific planetary entry vehicles is limited
  - Massively separated wake, jet is penetrating flows of changing character
- Analyses and results are configuration specific
  - Interaction with attached vs. separated flow, local flow conditions
  - Pointing of the jet, location on the aftshell



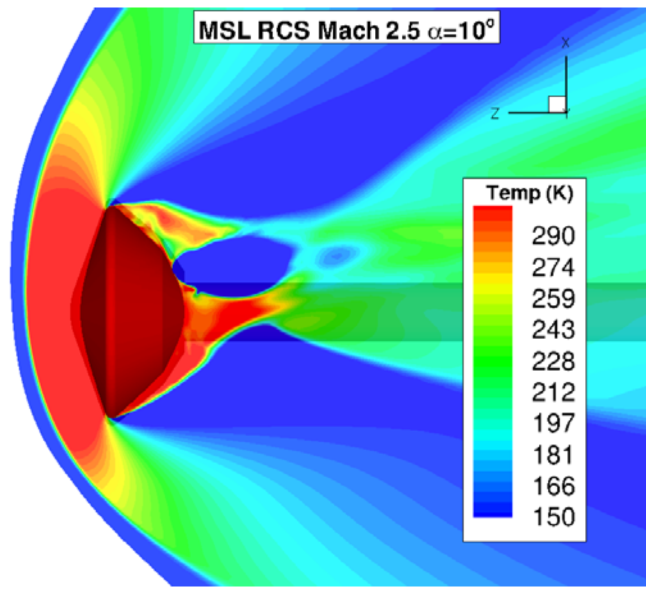
Interaction with attached flow



Interaction with shear layer



Interaction with separated flow



Aerodynamic Effects

Viking-derived base correction

$$C_{A(base)} = C_{p,b} = a_0 + \frac{a_1}{M_\infty} + \frac{a_2}{M_\infty^2} + \frac{a_3}{M_\infty^3}$$

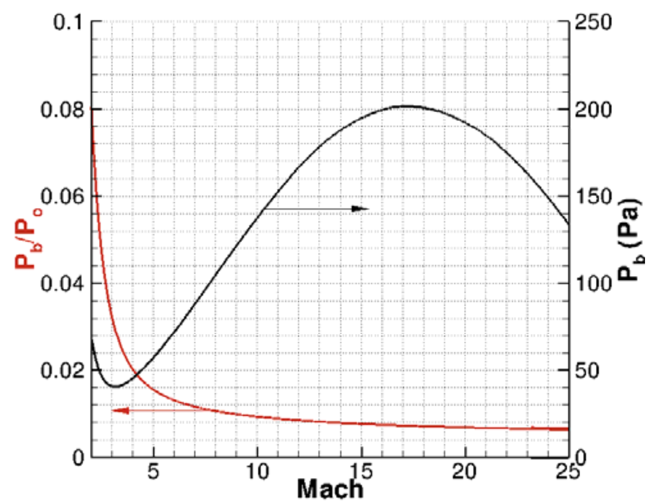
where

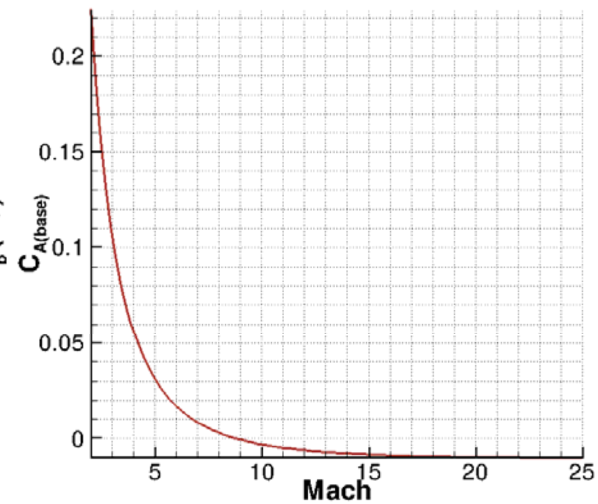
$a_0 = 8.325E\text{-}03$

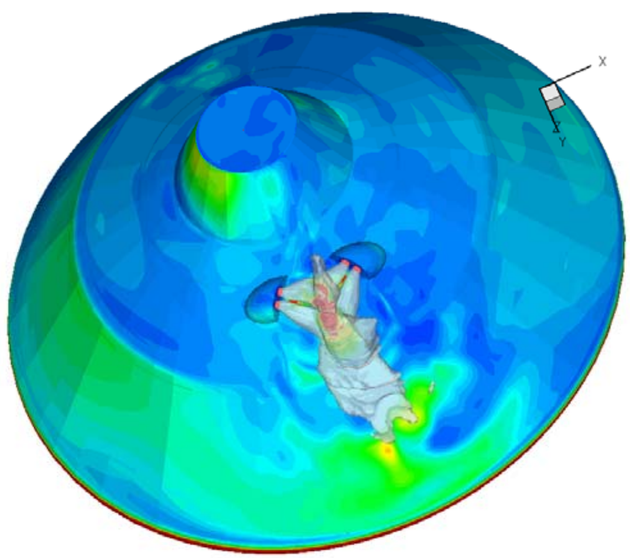
$a_1 = 1.129E\text{-}01$

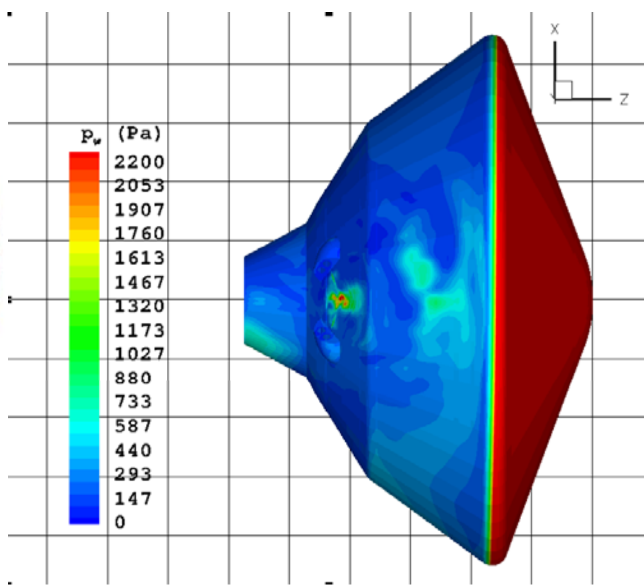
$a_2 = \text{-}1.801E+00$

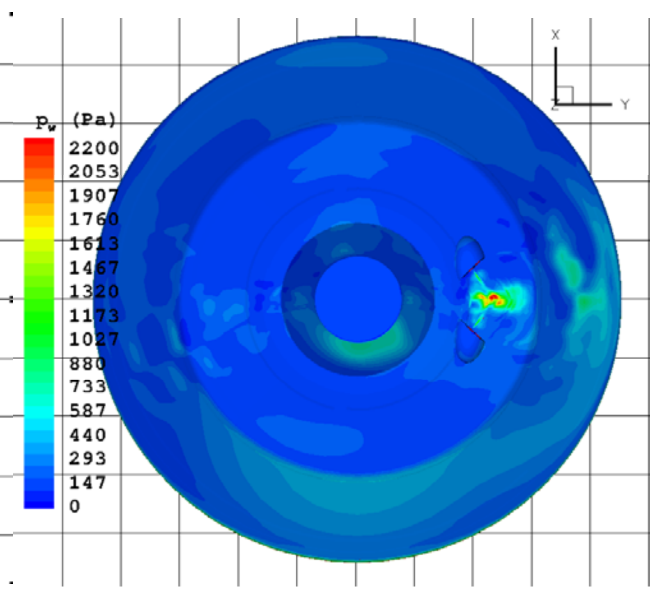
$a_3 = 1.289E+00$



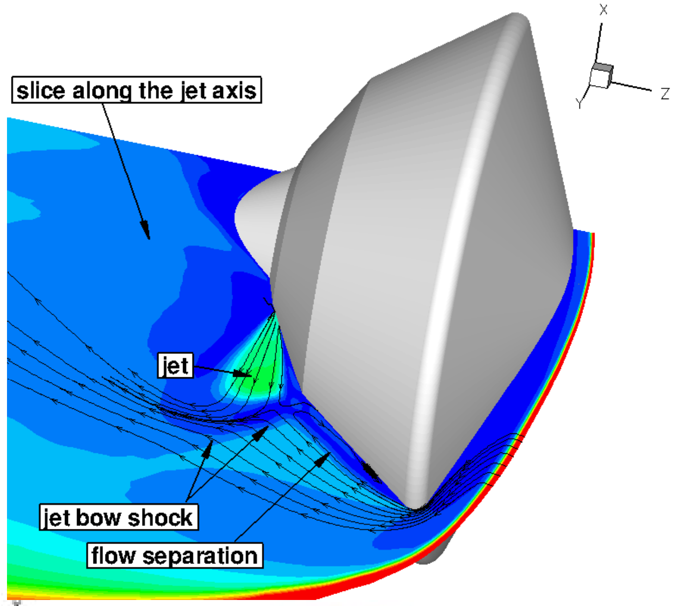


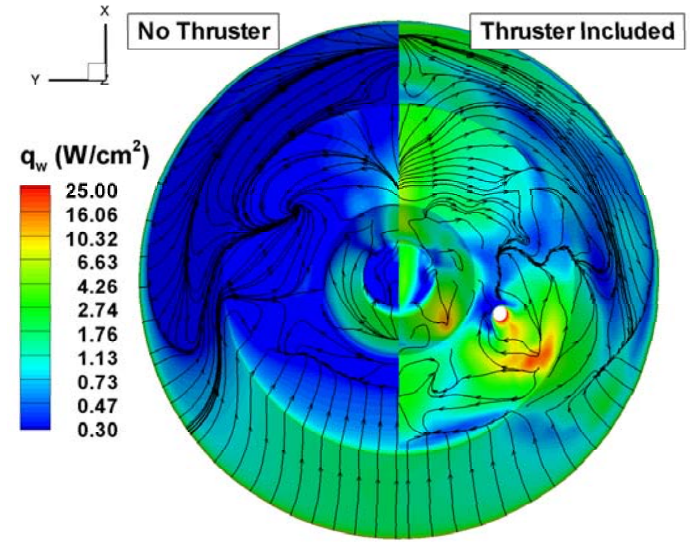


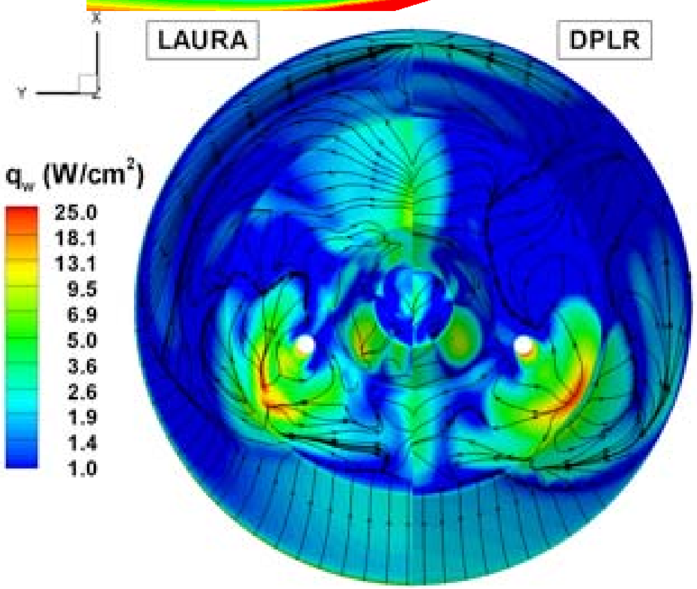


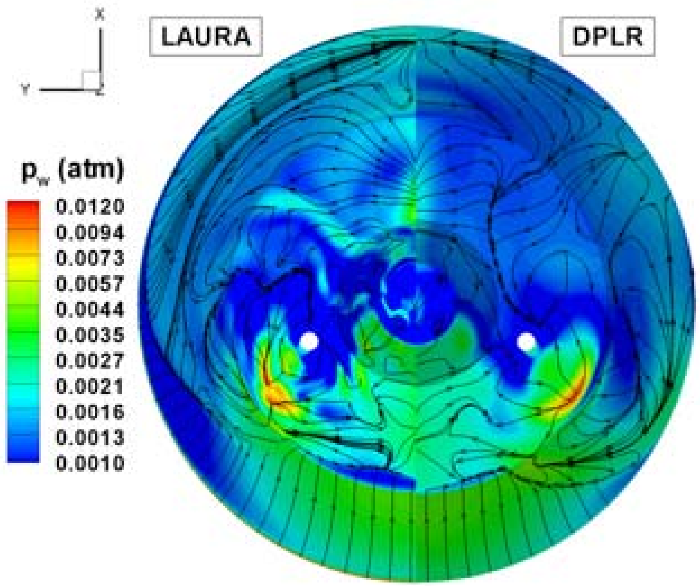


Aerothermal Effects









RCS/Gasdynamic Interaction Heritage

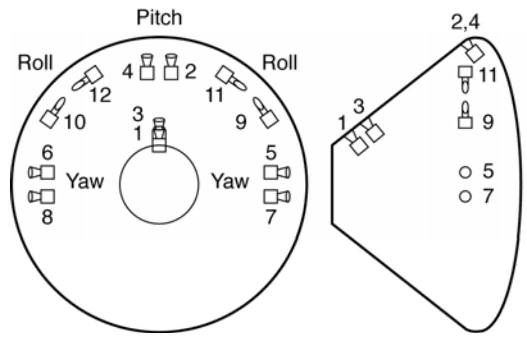
Apollo

- Entry Vehicle Control, NASA SP-8028, November 1969.
  - Apollo 7 reentry: "considerable pitch and yaw control activity in the transonic region during the final 2 min before drogue deployment", from simulation they concluded that this was a result of thruster jet interaction with flow around the vehicle and strong winds.
- NASA TM-X-1063, R. Jones, J. Hunt, Effects of cavities, protuberances, and reaction control jets on heat transfer to the Apollo Command Module
  - Mention of interference patterns on aftbody caused by RCS jets
- NASA TN-D-6028, Dorothy B. Lee, John J. Bertin, Winston D. Goodrich, Heat transfer rate and pressure measurements obtained during Apollo orbital entries
  - Heating on the leeside of the spacecraft increased during RCS firings up to 5 times that measured between firings

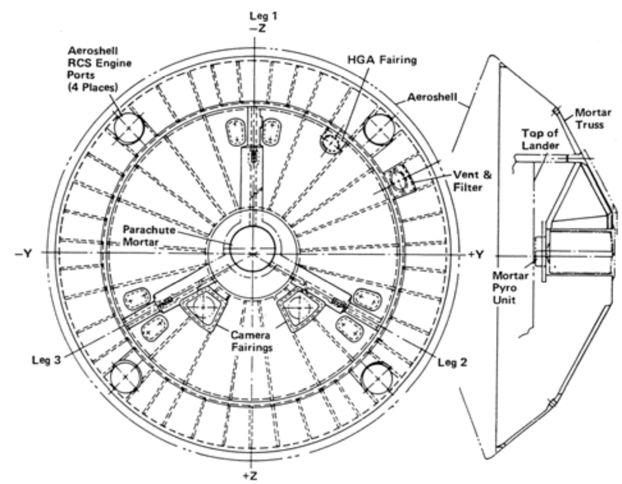
Viking

- Blake, W. W., Polutchko, R. J.,"Hypersonic Experimental Aerodynamic Characteristics of Viking Lander Capsule," Martin Marietta Corporation, TR-3709012, May 8, 1970
  - Aero/RCS interaction estimated in wind tunnel tests at M=20 using solid bodies to represent thruster plumes
  - The data were inconclusive due to insufficient accuracy of the low AOA data
  - The recommendation was use a balance designed to measure small C_N and C_m, and large C_A to minimize data uncertainties, but this apparently was never accomplished for Viking

Apollo



Attitude Command	Reaction Jets Fired
Pitch down	2 and 4
Pitch up	1 and 3
Yaw right	6 and 8
Yaw left	5 and 7
Roll left	10 and 11
Roll right	9 and 12



Viking

Summary

AAD

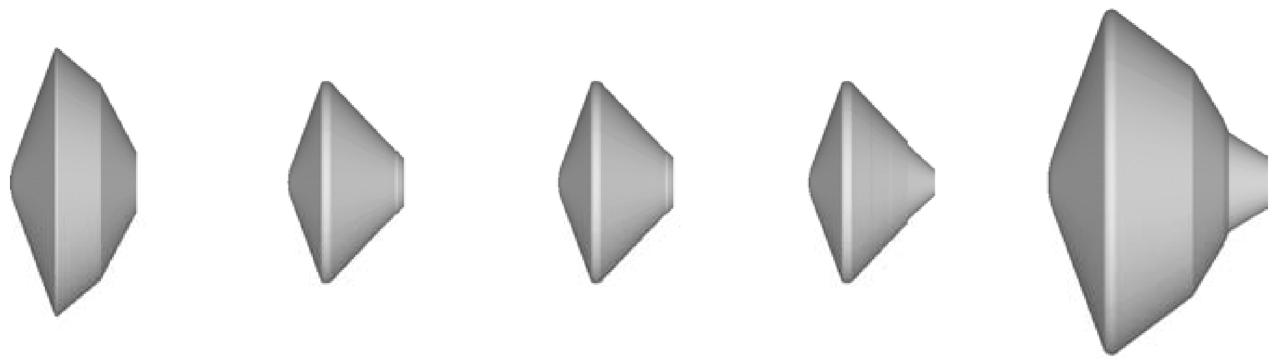
- RCS can interfere with the aerodynamic characteristics of entry vehicle
  - Changes in aerodynamics occur in both supersonic and hypersonic segments of the entry trajectory
    - Control gain and aerodynamic cross coupling can occur
    - In extreme cases the authority of RCS can be negated
  - Computational and experimental analyses help bound the phenomena
    - Difficulties in both computational methods (wakes are hard to solve) and experiment (moments are small in comparisson to the forebody moments)
- Impact of RCS on aerothermal evironments can be significant
  - Aeroheating increase by an order of magnitude depending on the specifics of the jet interaction
  - Impact on TPS selection, cost, schedule
- Based on analyses performed to date, jet interaction with the flow around entry vehicle is better understood
  - Paradigms have been developed to minimize destructive interference of RCS jets

BACKUP

EDL Systems

AAD

Table 1. Comparison of Mars Entry Capsules

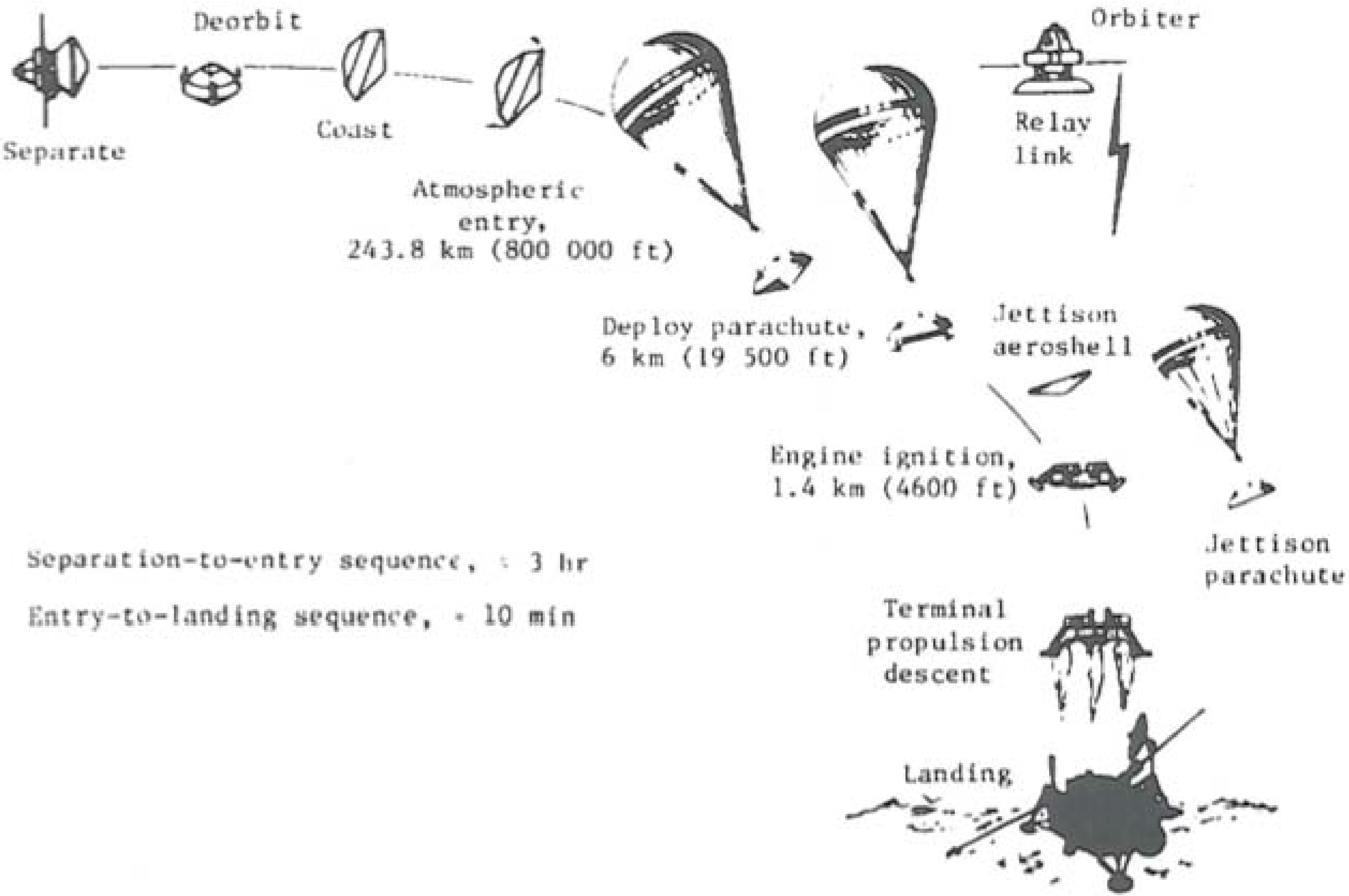
	Viking 1/2	Pathfinder	MER A/B	Phoenix	MSL
					
Diameter, m	3.5	2.65	2.65	2.65	4.5
Entry Mass, kg	930	585	840	602	2919
Landed Mass, kg	603	360	539	364	1541
Landing Altitude, km	-3.5	-1.5	-1.3	-3.5	+1.0
Landing Ellipse, km	420 x 200	100 x 50	80 x 20	75 x 20	< 10 x 10
Relative Entry Vel., km/s	4.5/4.42	7.6	5.5	5.9	> 5.5
Relative Entry FPA, deg	-17.6	-13.8	-11.5	-13	-15.2
$m/(C_DA)$, kg/m^2	63.7	62.3	89.8	65	126
Turbulent at Peak Heating?	No	No	No	No	Yes
Peak Heat Flux, W/cm^2	24	115	54	56	243
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

Ideal Authority

Table 2. Comparison of ideal authority of Viking, MPL/Phoenix and MSL

	N-m			Kg-m^2			deg/sec^2		
	M_X	M_Y	M_Z	I_{XX}	I_{YY}	I_{ZZ}	α_X	α_Y	α_Z
Viking 1, 2	152.7	146/-159.4	108	536	423	786	16.3	19.8/-21.6	7.9
MPL/Phoenix	10.7	58.07	10.06	192	189	286	3.2	17.6	2
MSL	675.4	980.7/-1160	705	3055	3952	4836	12.7	14.2/-16.8	8.4

EDL Sequence



Separation-to-entry sequence, ≈ 3 hr

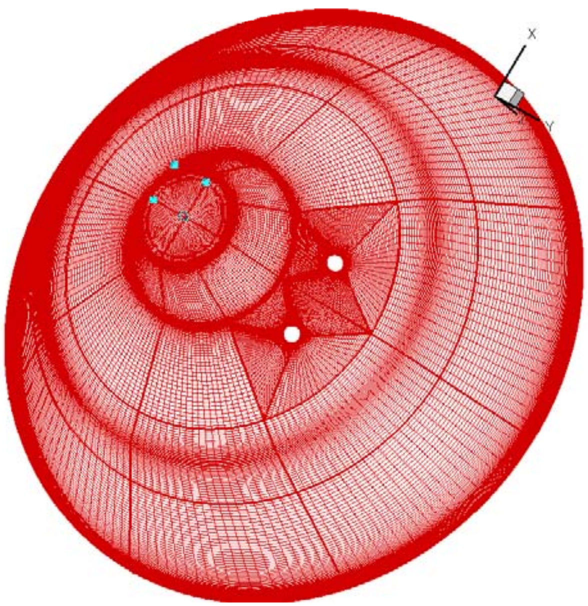
Entry-to-landing sequence, ≈ 10 min

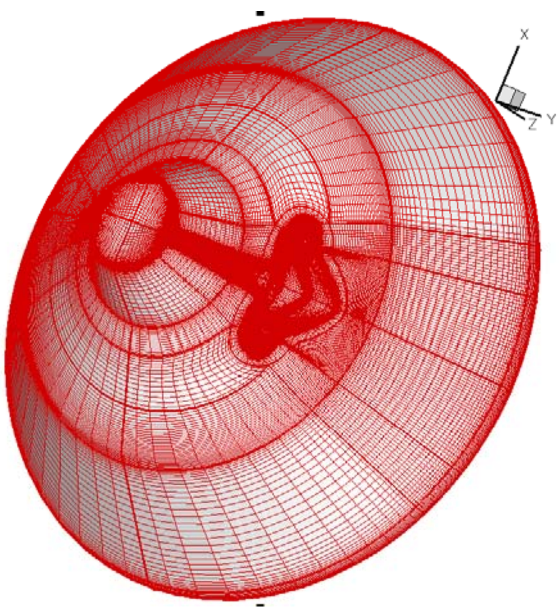
Image courtesy ….

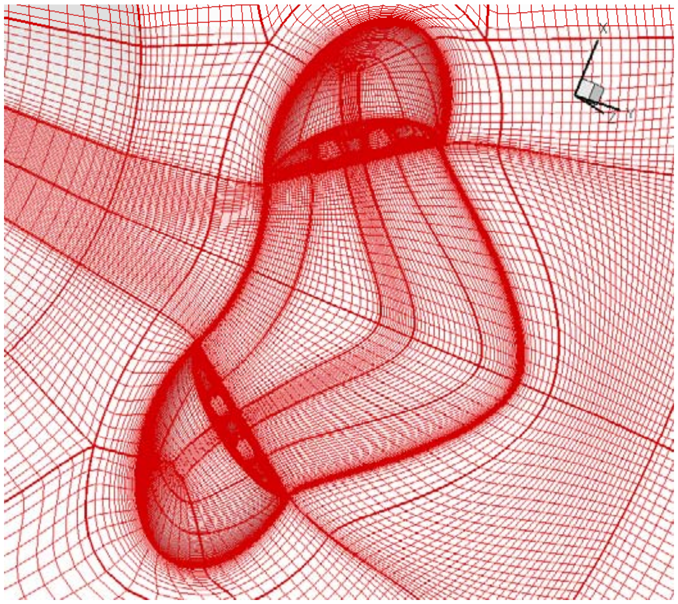
Algorithm/Grids

AAD

- Calculations in LAURA using 8-species Mars gas + ammonia as propellant
- Grids
  - Baseline layout: coarse - 5M, fine - 40 M nodes
    - Created by Victor Lessard, extends to engine chambers
  - 2006 RCS and Proposed layout - 12M nodes
    - Created using RTF MORPH tool and doesn't reflect any internal flow
- Solutions are computed at Mach 18.1, q=15.9 kPa

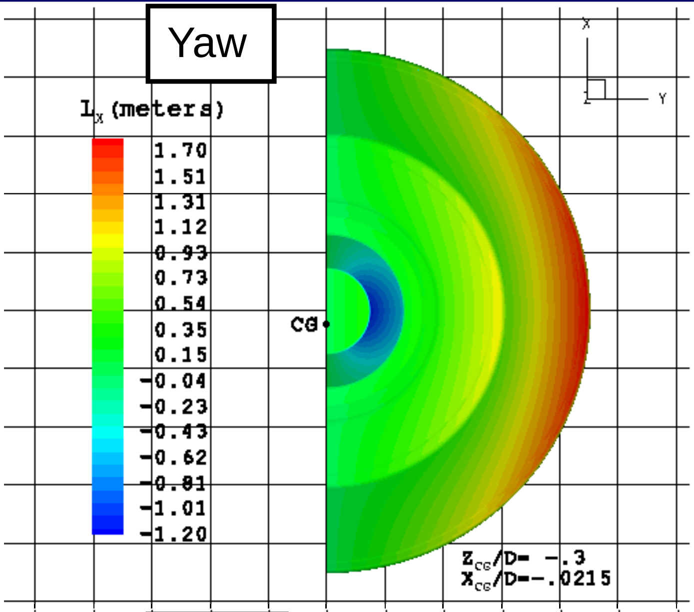


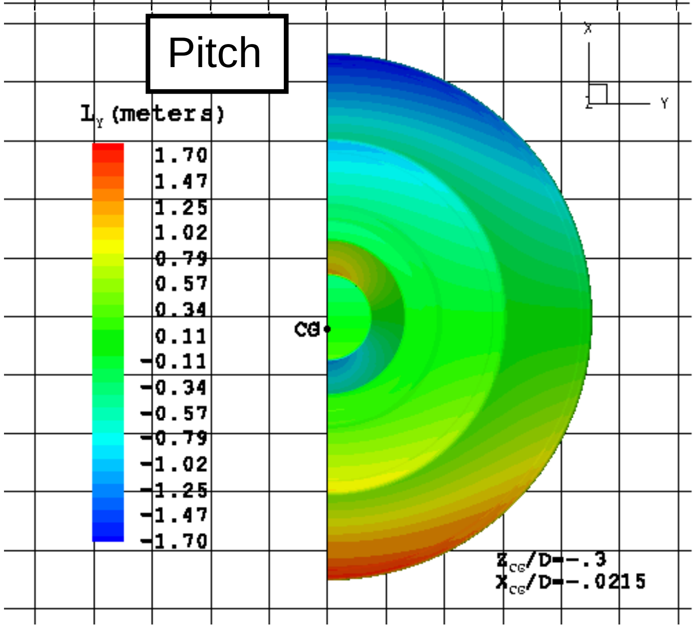




Geometric Considerations

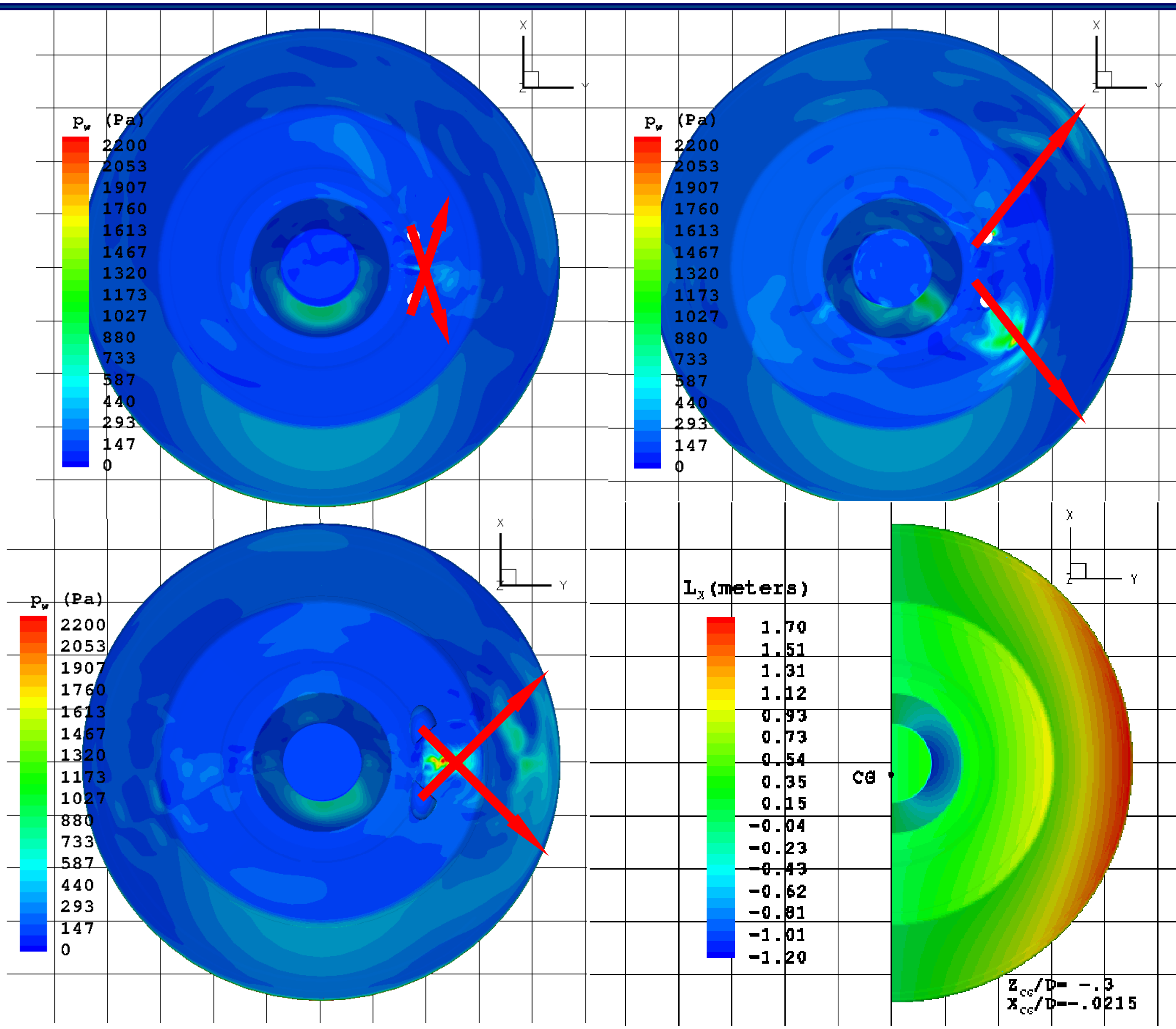
- Same amount of pressure applied to different locations on the backshell wil produce different moments about the CG
- Moment arms (L_X, L_Y), computed from a surface-normal through a point and the location of the CG illustrate the regions of high sensitivity of capsule moments to changes in surface pressure
  - In yaw, capsule moments are very sensitive to change in pressure on the far side, and on the parachute closeout cone
  - In pitch, capsule moments are very sensitive to changes in wind/lee shoulder regions; the parachute closeout cone can also generate significant torques if shocks/plumes impinge on it





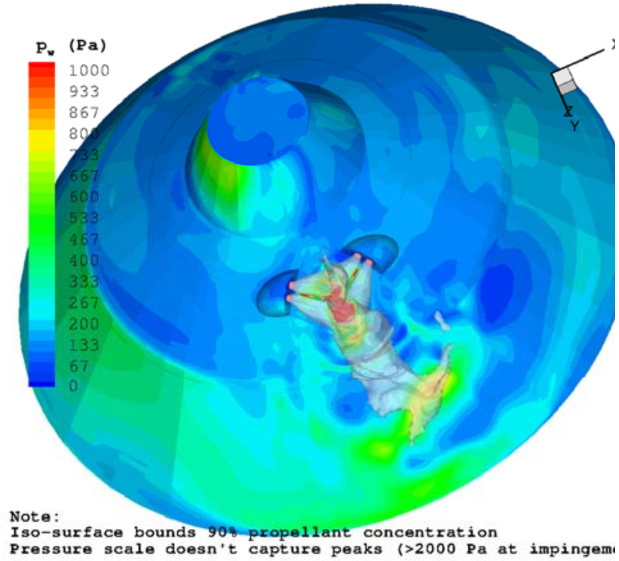
Backshell Pressures

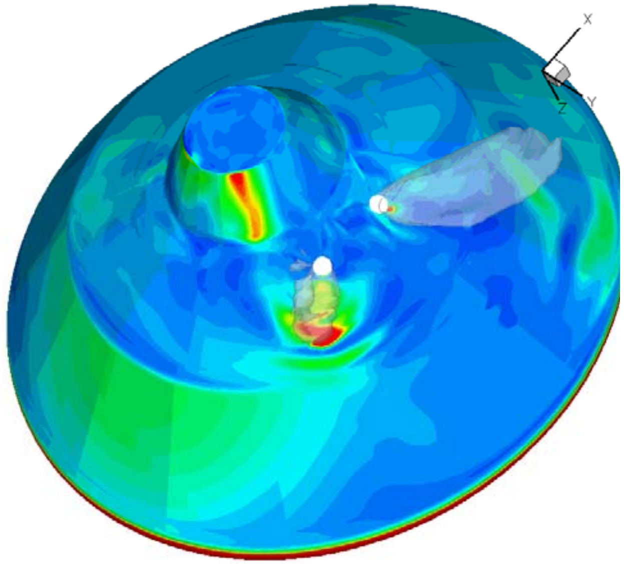
AAD

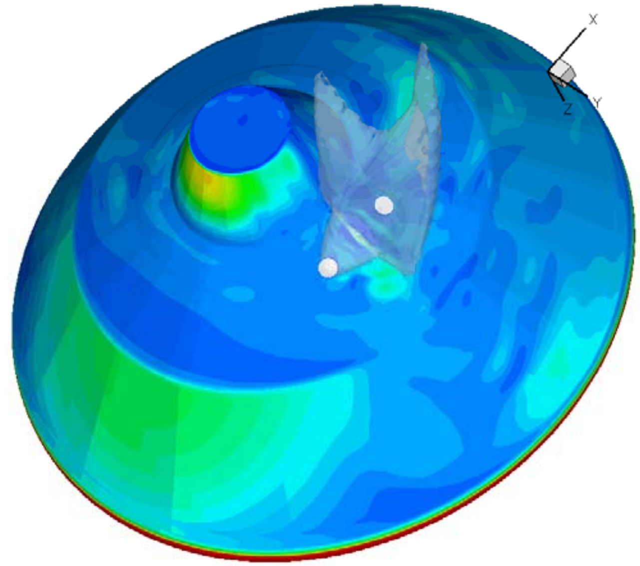


RCS Plumes of Candidate MSL RCS

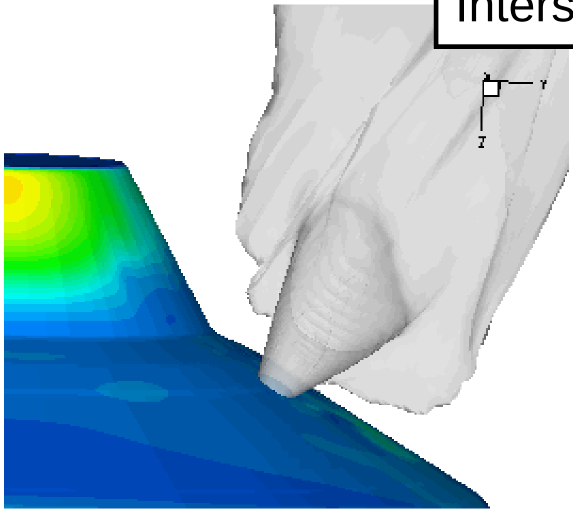
AAD

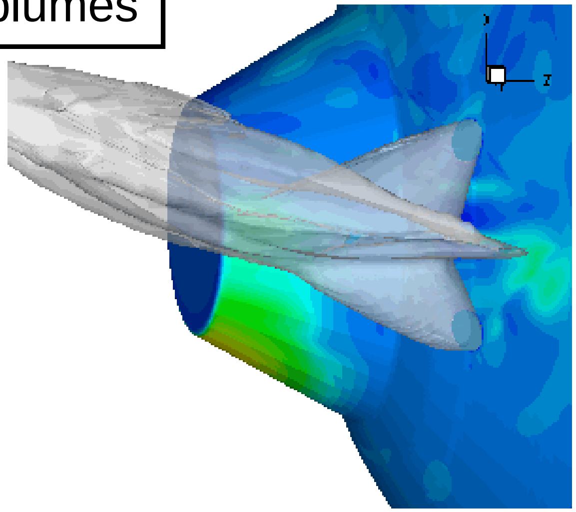






Intersecting plumes





Backshell Heating