# Term Project/Entry, Descent, Landing

- Term project discussion
- Entry, Descent, and Landing
- Case study: Mars EDL
- Case study: Mars Exploration Rovers
- Case study: Mars Science Laboratory

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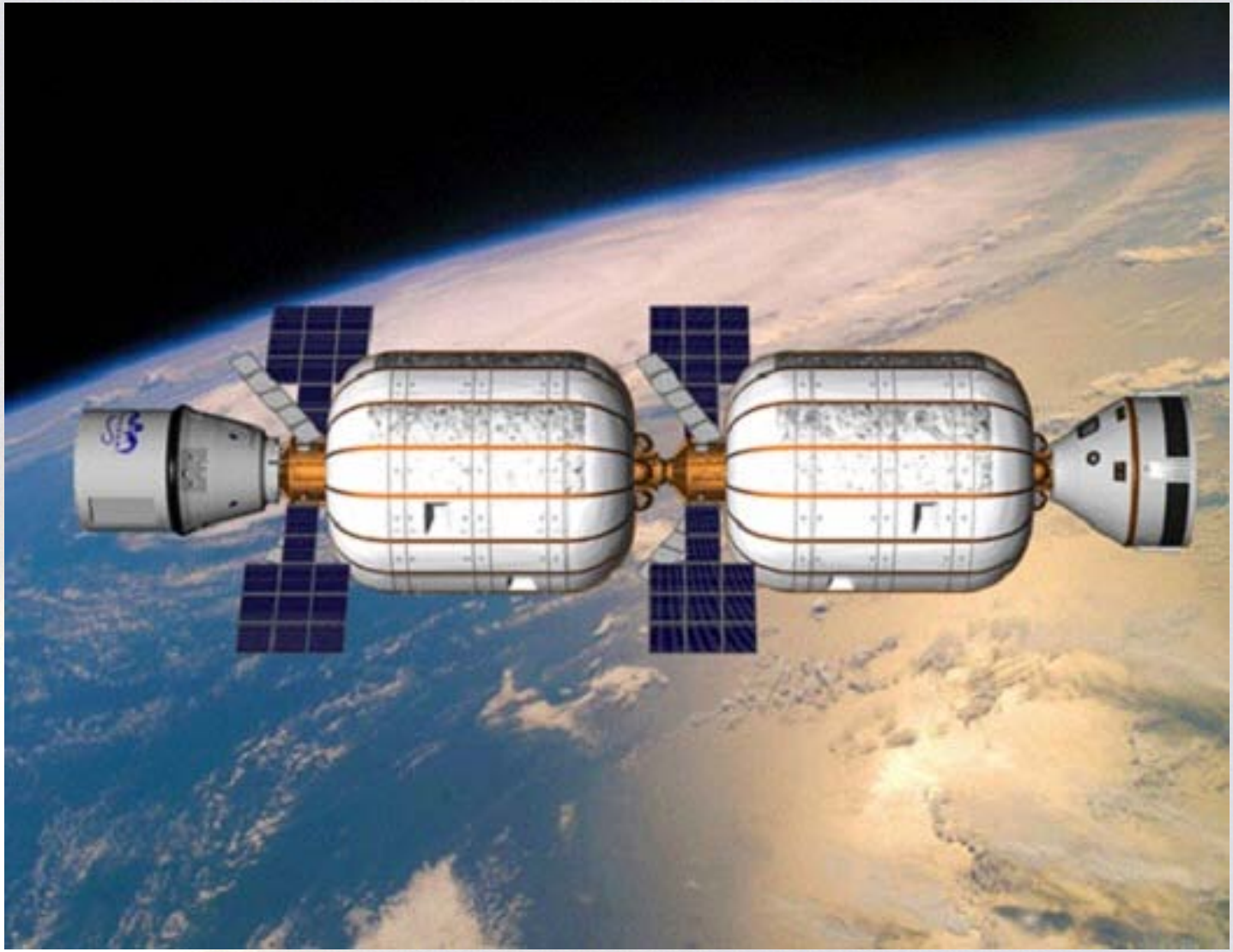
# Term Project - Space Tourism Transport



# Term Project - Top Level Requirements

- Design a system to allow the transport of tourists to low Earth orbit for an economically viable cost
  - Launch vehicle
  - Launch and entry vehicle
  - Parametric payload models (mass/volume) to be provided
- Mission models
  - Market a function of transportation cost
  - Cost-optimized design process
  - Goal is "breakthrough" level of $300/kg

# Term Project

- Work as individuals or two-person teams (your choice)
- Design an architecture to support tourist flight operations in the most cost effective manner possible
- All vehicles will be conceptually designed from scratch (no "catalog engineering"!)
- Parametric design parameters will be provided for human spacecraft systems not ENAE791-relevant
- Design process should proceed throughout the term
- Formal design presentations at end of term

# LEO Tourism Market Analysis

- There are
  - 1 person/year willing to pay $30M for an orbital flight
  - 10 people/year willing to pay $10M
  - 100 people/year willing to pay $3M
  - 1000 people/year willing to pay $1M
  - 10,000 people/year willing to pay $300K
- Market model

$$\frac{\text{customers}}{\text{year}} = 1000 \left[ \frac{\text{cost}}{\text{ticket}} (\$M] \right]^{-2}$$

# Spacecraft Mass

- Basic spacecraft mass without heat shield or other EDL systems

$$\text{Mass (kg)} = 460\left[\text{volume (m}^3\text{)}\right]^{0.76}$$

- Options for target mission:
  - 2-4 day orbital excursion (no space station) requires 5 $m^3$/person
  - 12-hour transport to/from space station requires 1.5 $m^3$/person and additional 1000 kg in docking systems

# Other Mass Estimating Relations

- Mass of heat shield

$$m_{shield} = 0.2 m_{protected}$$

- Mass of landing gear

$$m_{LG} = 0.03 m_{landed}$$

- Mass of parachutes

$$m_{chutes} = 0.03 m_{supported}$$

# Elements of Term Project - Caveat

Note: this is a list of all of the analysis that you should be *able* to do on your project by the end of the term. It is not the same as saying that you are *required* to do all of these elements. This is particularly true of projects done by single individuals as compared to teams of two. I expect you to be able to accomplish *many* of them, and to *use your judgement* to focus on elements which will most affect your final design.

# Term Project Elements - Launch Vehicle

- Trade studies on vehicle configuration
  - Payload mass
  - Number and ΔV distribution between stages
  - Cost-optimal configuration
- Vehicle systems design using MERs
- Launch trajectory simulation
- Evolutionary growth paths (e.g., higher performance upper stages, strap-on boosters, etc.)
- Reusable/expendable trade studies

# Term Project Elements - Spacecraft

- Spacecraft size and configuration
- Design L/D (mass offset)
- Entry trajectory calculations
  - Maximum heating and decelerations
  - Landing footprint
- EDL systems
  - Heat shield configuration
  - Landing system(s) including impact attenuation
- Reaction control/deorbit propulsion configuration

# Term Project Elements - Spacecraft

- Launch abort system design
  - Conceptual design
  - Trajectory analysis
- Expendable/reusable trades

# Term Project Elements - Costing

- Overall program cost estimation
  - Nonrecurring costs spread over 7 years with beta function
  - Use of learning curve in recurring systems procurement
  - Reasonable assumption of refurbishment fraction
- Calculation of required cost/passenger to achieve 50% rate of return over life of program (est. 10-20 years)

# Term Project Elements - Systems

- Analysis of required systems reliability to achieve LOC<$10^{-4}$
- Analysis of system resiliency
- Solid models of launch vehicle and spacecraft
  - Dimensioned three-views
  - Perspective images
- Entire project submitted in the form of a slide package with maximal information transfer rate
  - Full slide package
  - Reduced slide package for presentation (10 minutes)

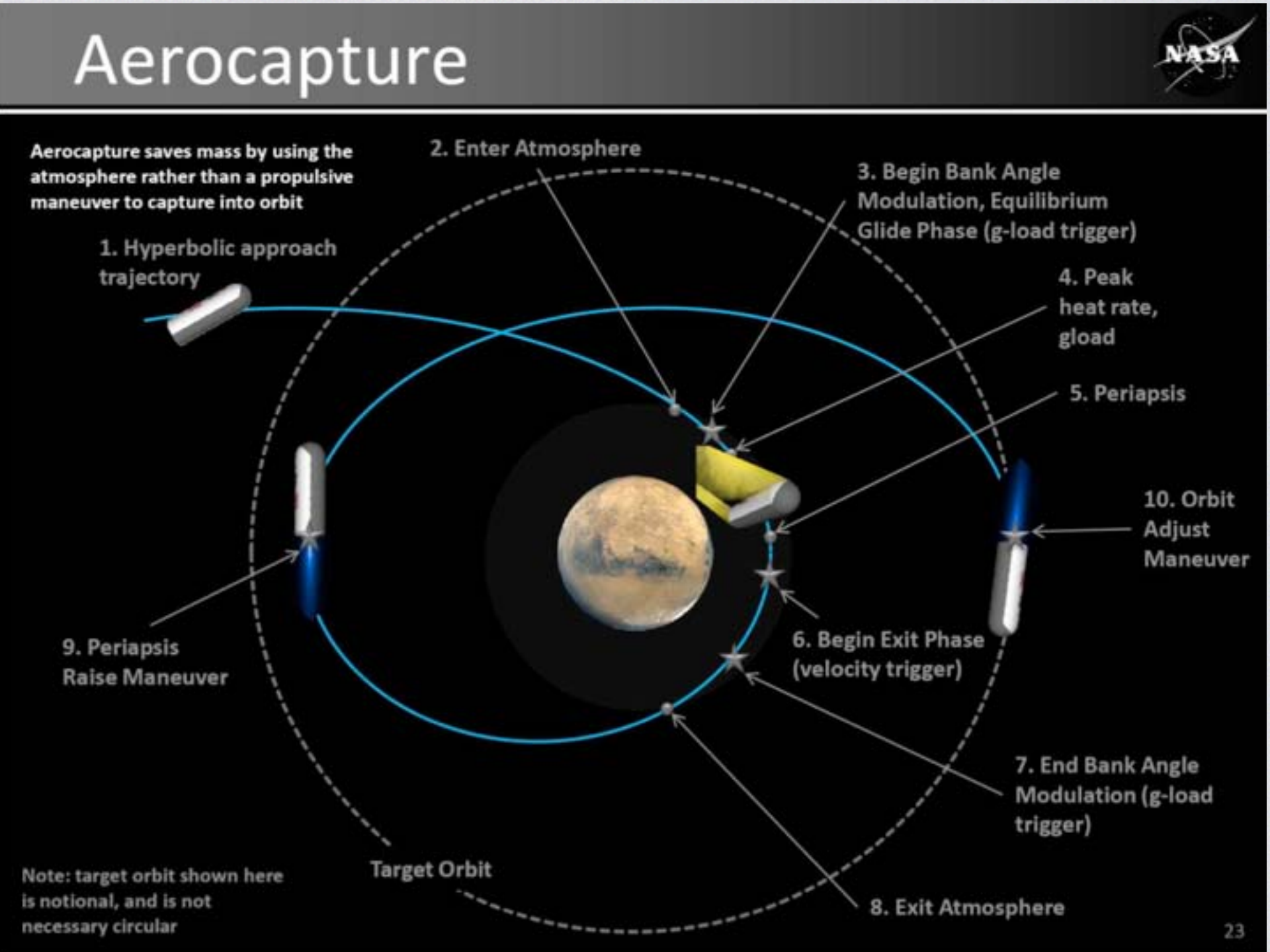
# The Challenge of Mars EDL (Entry, Descent, and Landing)

*Ron Sostaric*
*NASA Johnson Space Center*
*AIAA Senior Member*
*April 2010*

# Aeromaneuvering

- Using atmospheric flight forces to affect orbit changes while minimizing propellents
- Aerocapture - decelerating into planetary orbit from a single pass
- Aerobraking - lowering apoapsis by atmospheric passes (single or multiple)
- Aeromaneuvering - using aerodynamic forces (e.g., lift) to perform advanced maneuvers such as plane change

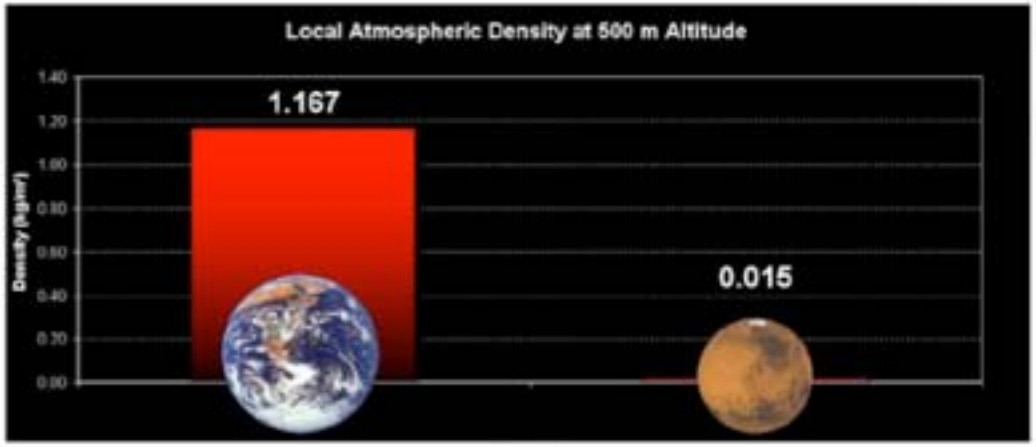
# Aerocapture



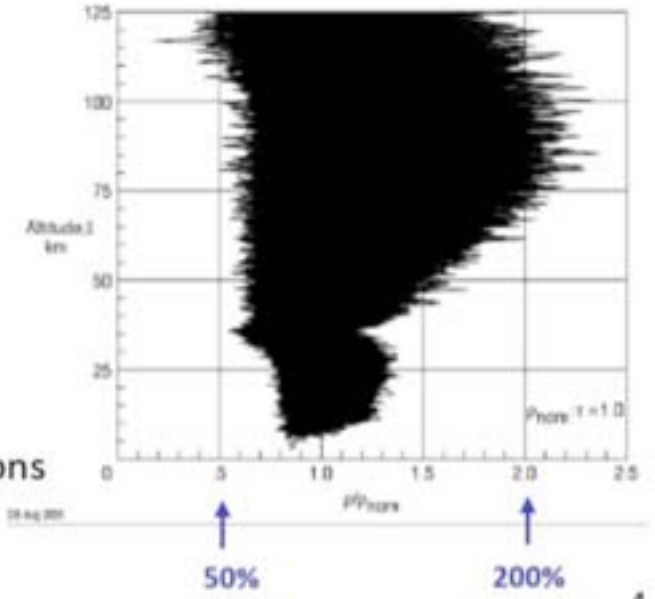
# Why is Mars EDL so difficult?

## ATMOSPHERE:

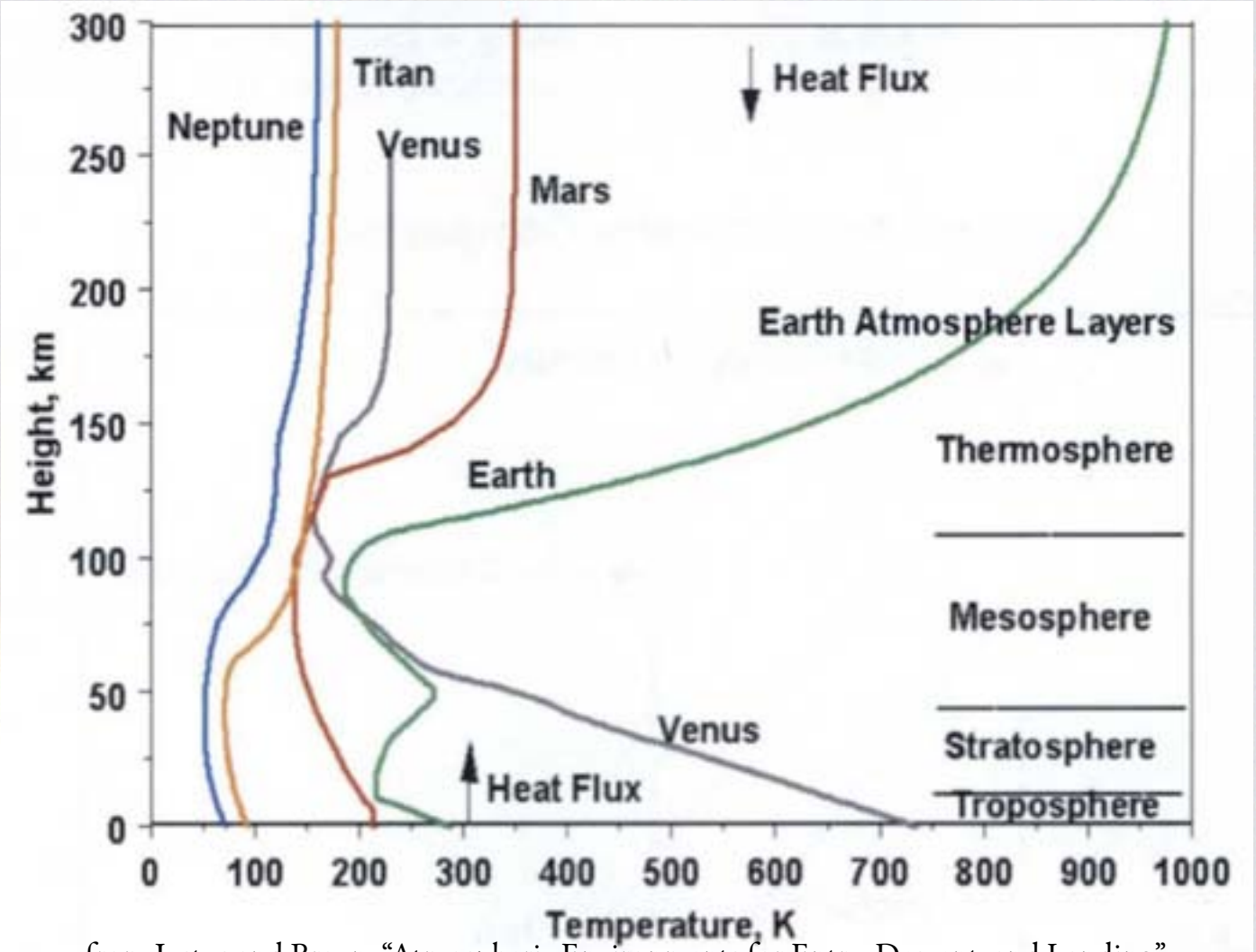
- Thin Martian atmosphere (surface density equivalent to Earth's at 30 km)
- Too little atmosphere to decelerate and land like we do at Earth
- Atmosphere is thick enough to create significant heating during entry




- Lack of understanding of the atmosphere:
  - Aerodynamics, aeroheating, winds, and density variations

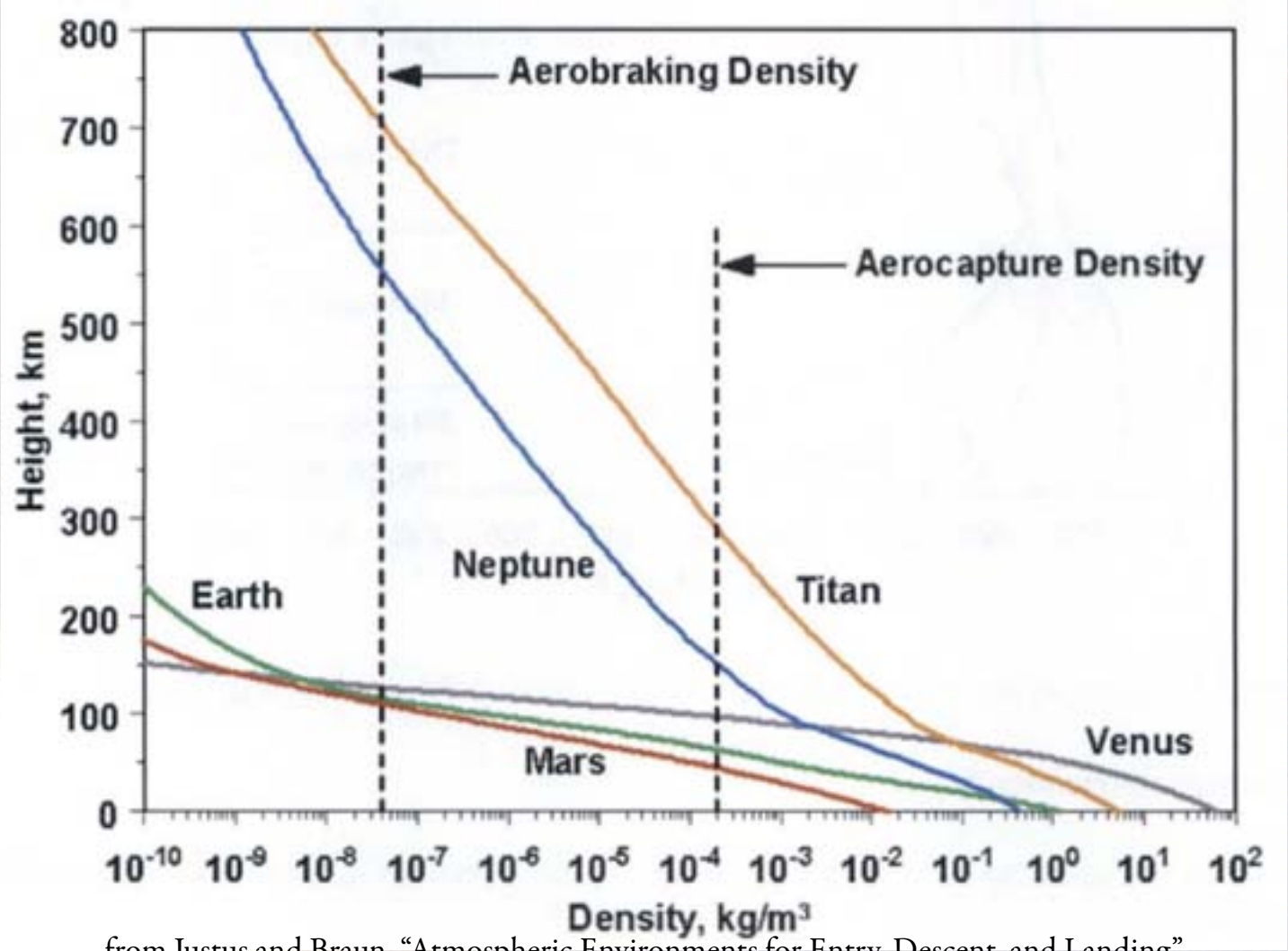


# Atmospheric Thermal Profiles




from Justus and Braun, "Atmospheric Environments for Entry, Descent, and Landing", 5th International Planetary Probes Workshop, August 2006

# Atmospheric Density Profiles




from Justus and Braun, "Atmospheric Environments for Entry, Descent, and Landing", 5th International Planetary Probes Workshop, August 2006

# Mars EDL History

All six of the successful U.S. Mars EDL systems had:

- Low Landing Site: elevation sites below –1 km MOLA ← that's Mars Sea Level
- Low Mass: Had landed masses of less than 0.6 MT
- UNGUIDED: Had large uncertainty in targeted landing location (300 km for Mars Pathfinder, 80 km for MER)

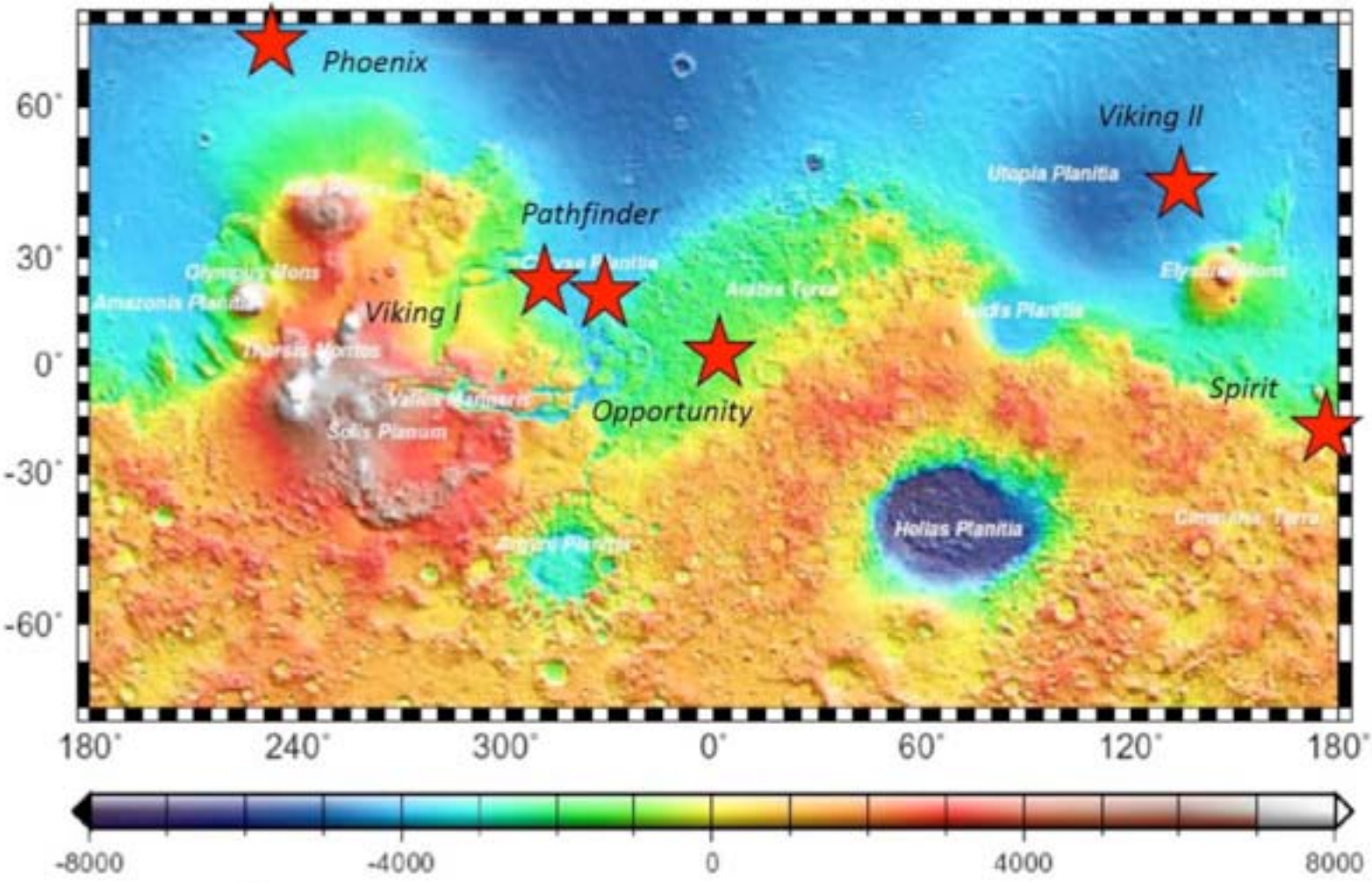
Mars Science Laboratory (MSL) '11 EDL Architecture:

- Low Landing Site: Landed elevation requirement for sites below 0 km MOLA
- Low Mass: Has landed mass of 0.9 MT
- GUIDED: Has uncertainty in targeted landing location of 10km

HUMANS need more capability:

- All of the current Mars missions have relied on large technology investments made in the late 1960s and early 1970's as part of the Viking Program (heatshield shape, thermal protection material, and parachute)
- Large Mass (Entry Mass of ~100 – 150 MT)
- Higher elevations – interesting science
- Precision Landing

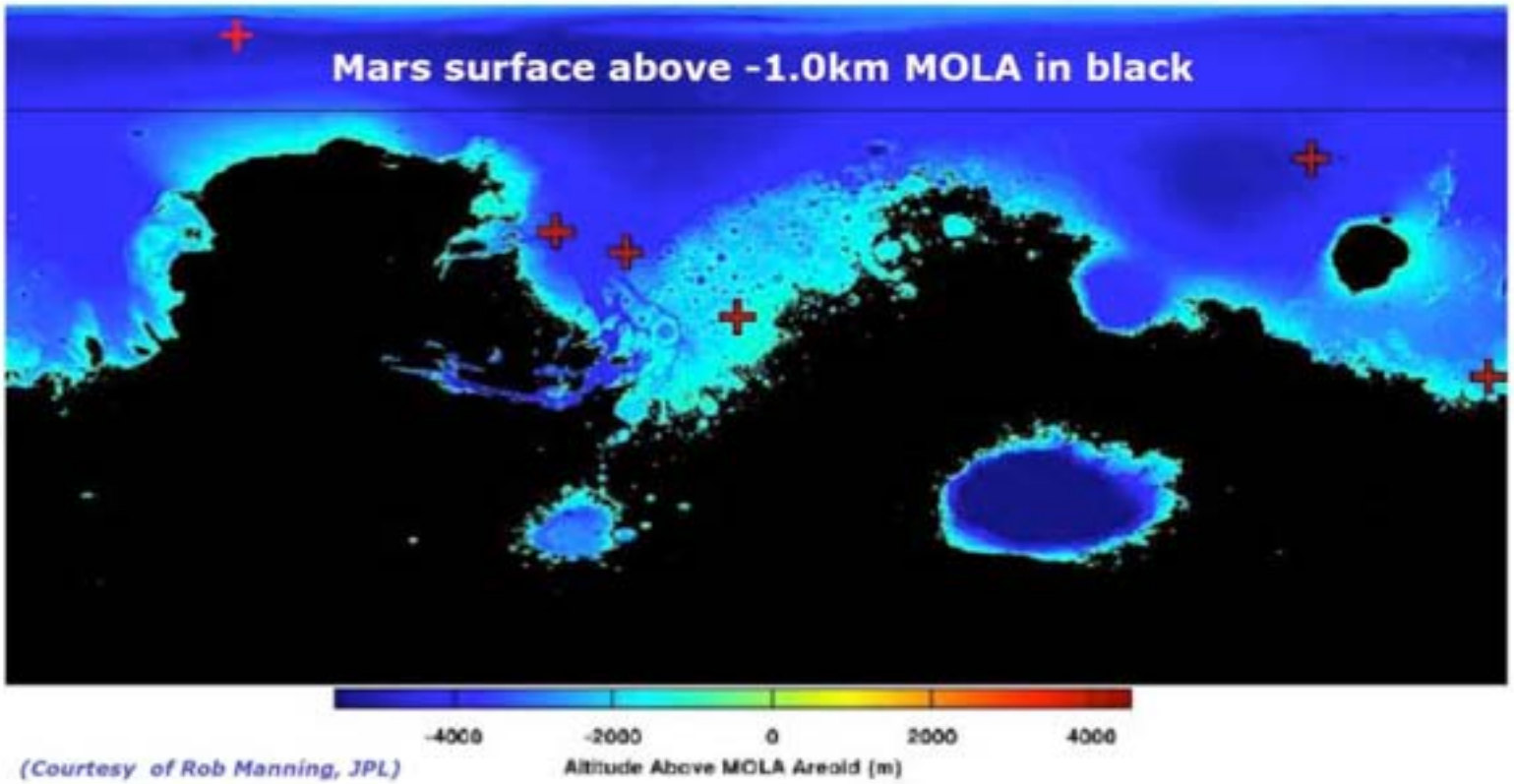
# 6 U.S. Mars Entry, Descent, and Landing Successes



# Current Mars Accessibility

Previous Viking derived EDL systems and the thin Martian atmosphere and small scale height have limited accessible landing sites to those below -1.0km MOLA

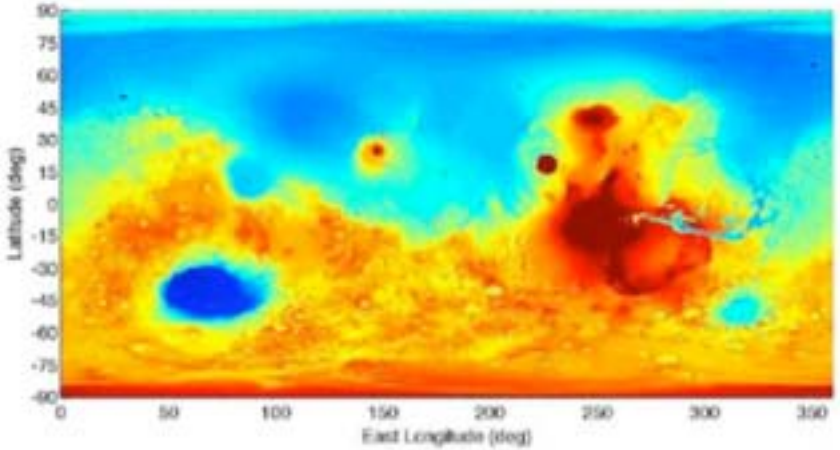
To date the southern hemisphere has been largely out of reach (approximately 50% of the planet surface remains inaccessible with current EDL technologies)



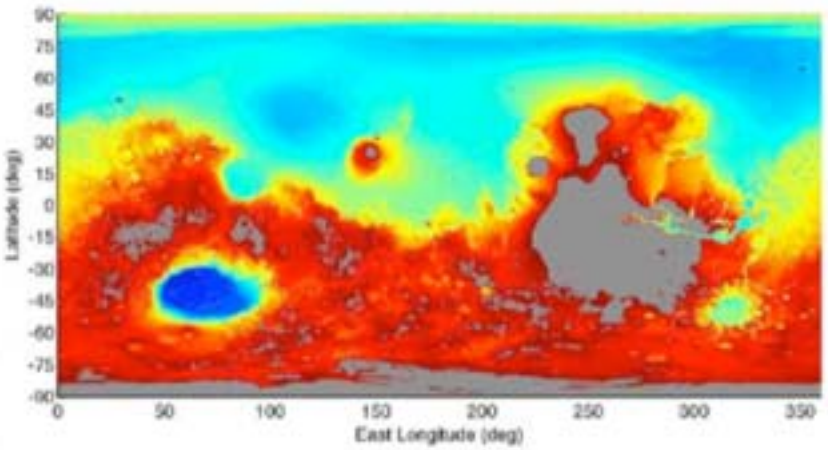

*(Courtesy of Rob Manning, JPL)*

# Landing Site Elevation / Accessibility

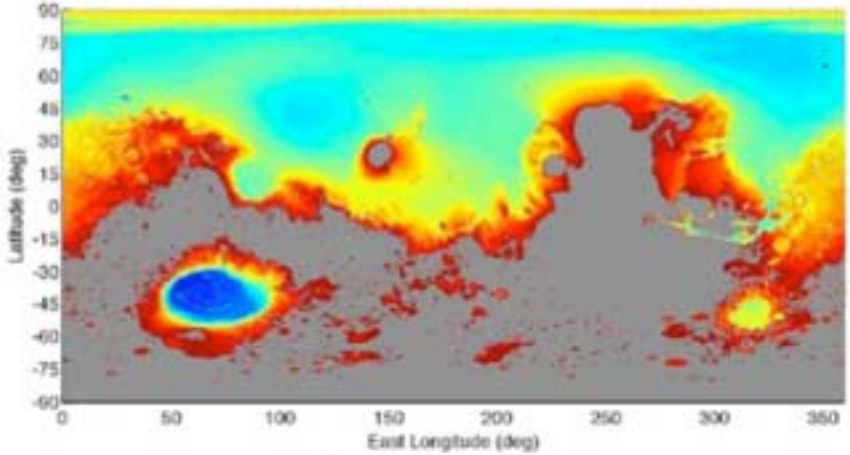
MOLA 1/4° Topographic Data



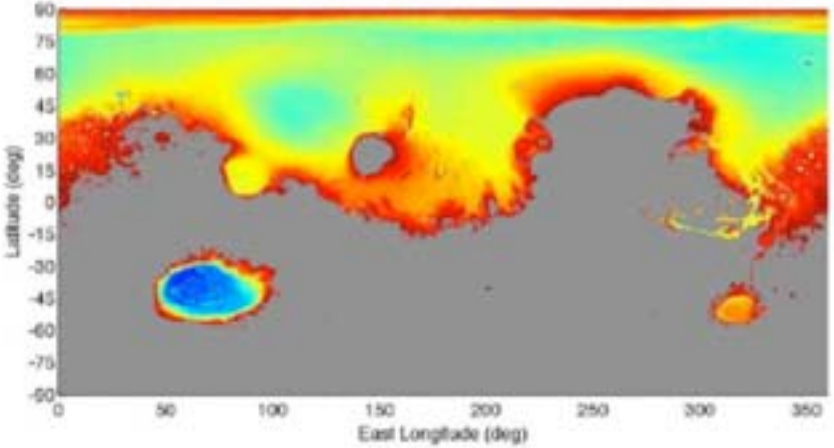

< 2.5 km (90% of Surface)




< 1.0 km (65% of Surface)

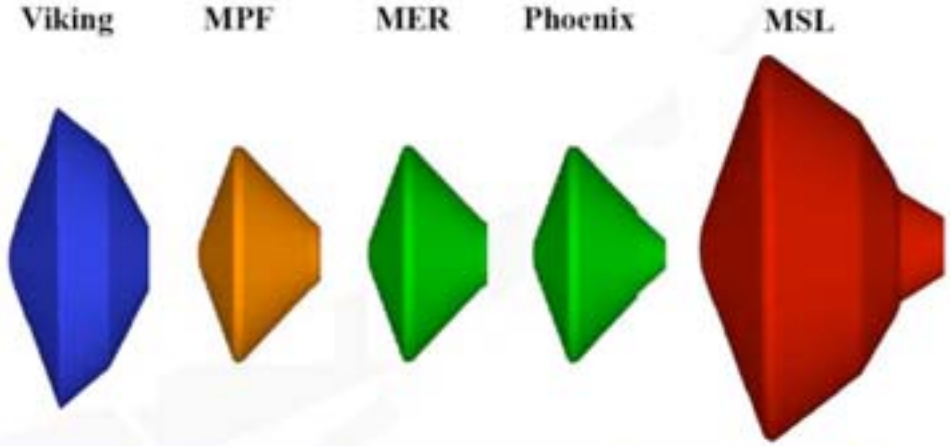



< -1.0 km (45% of Surface)



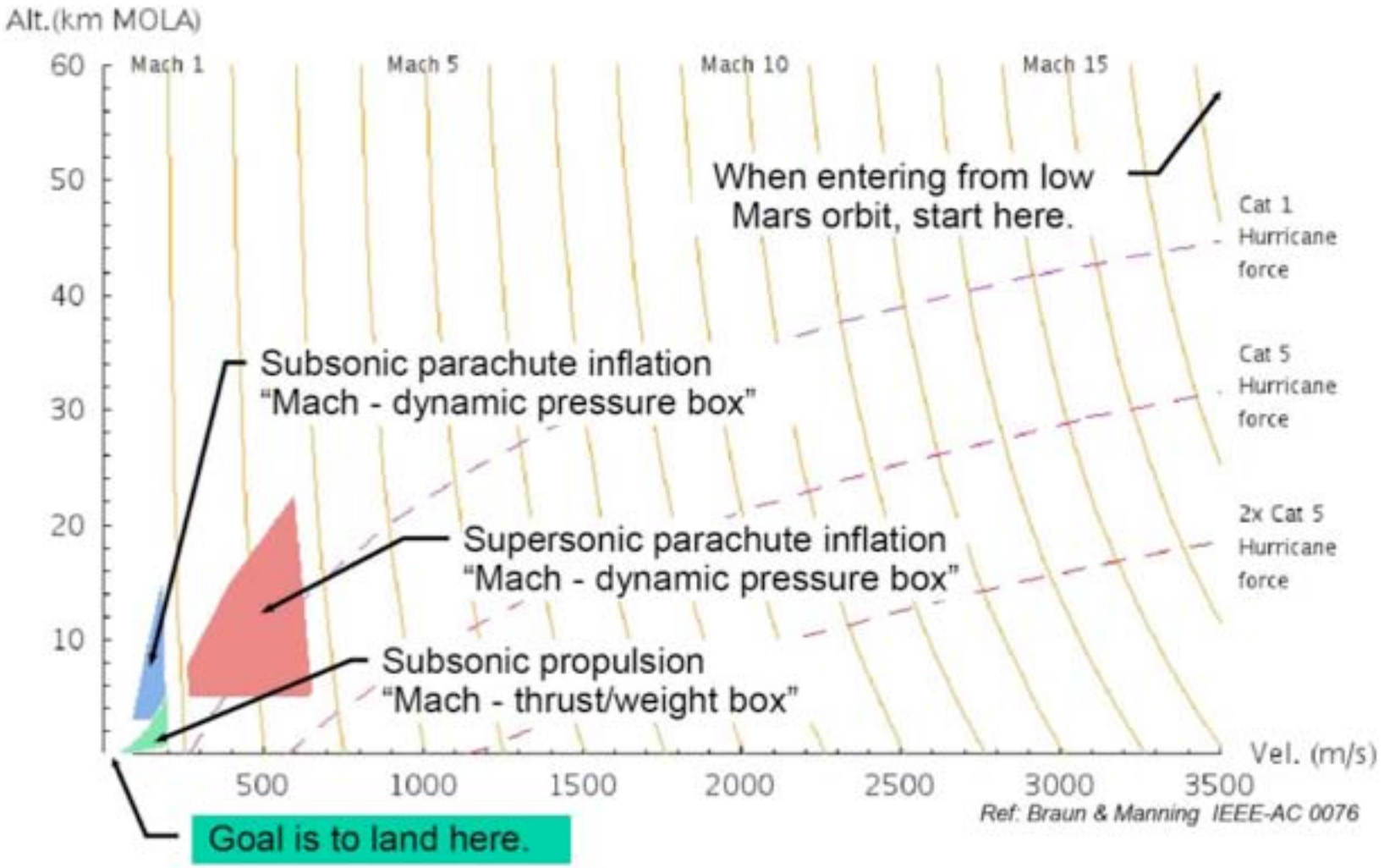
# Mars Heritage Aeroshell - Mission Comparisons

Core Viking Technologies:
70° sphere-cone aeroshell

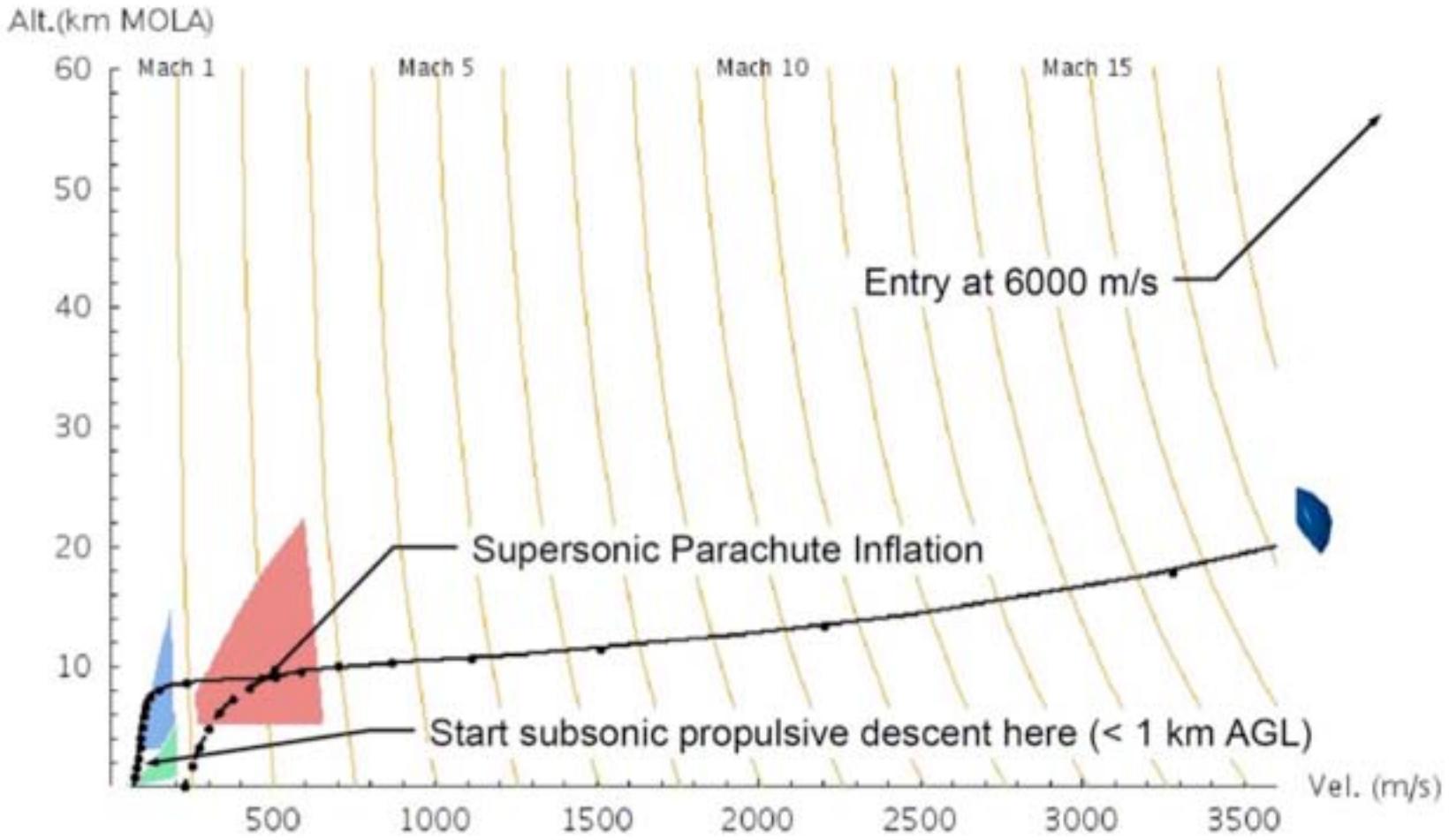



| Parameter | Viking | MPF | MER | Phoenix | MSL |
|---|---|---|---|---|---|
| Entry Mass (kg) / Ballistic Coeff. (kg/m$^2$) | 980 / 66 | 585 / 63 | 836 / 90 | 603 / 65 | 3257 / 140 |
| Lander/Rover Mass (kg) | 612 | 11 | 173 | 64 | 850 |
| Aeroshell Diameter (m) | 3.5 | 2.65 | 2.65 | 2.65 | 4.5 |
| Angle-of-Attack (deg) / L/D | 11.1° / 0.18 | 0° / 0.0 | 0° / 0.0 | 0° / 0.0 | -15.5° / 0.24 |
| Peak Heatrate (W/cm$^2$) | 21 | 106 | 44 | 59 | <210 |
| Parachute Diameter (m) | 16.15 | 12.4 | 14.1 | 11.5 | 19.7 |
| Landing Site Elevation (km) | -3.5 | -1.5 | -1.3 | -3.5 | 0.0 |

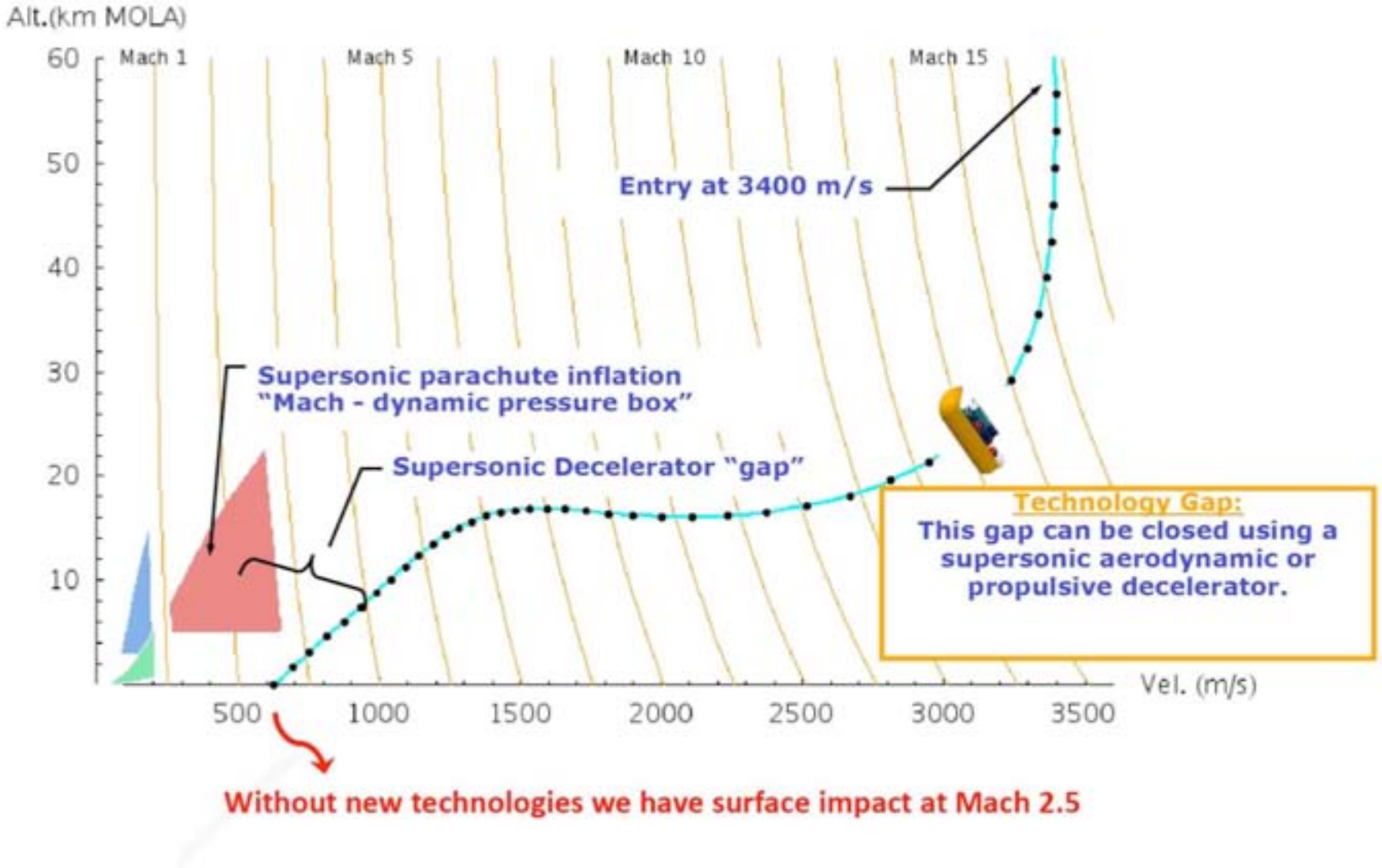
# EDL Phase Plot – A Handy Way to Visualize EDL



# Robotic program: No gap so far ....



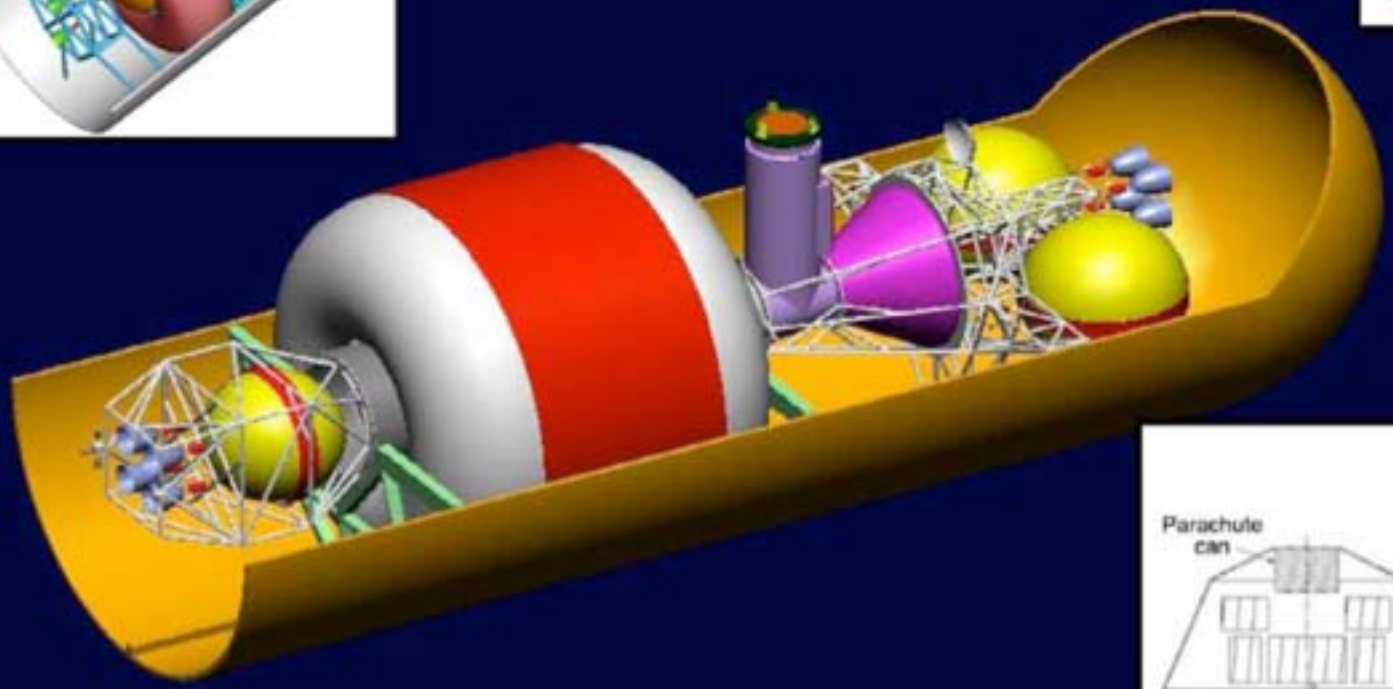
# How would Humans Land?

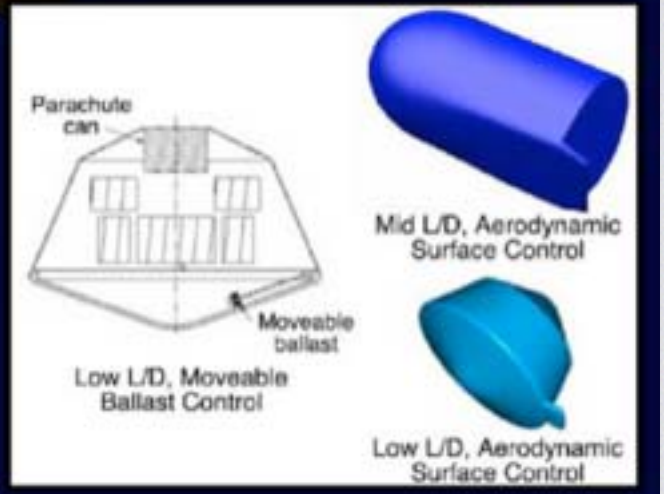


# EDL Technology Development

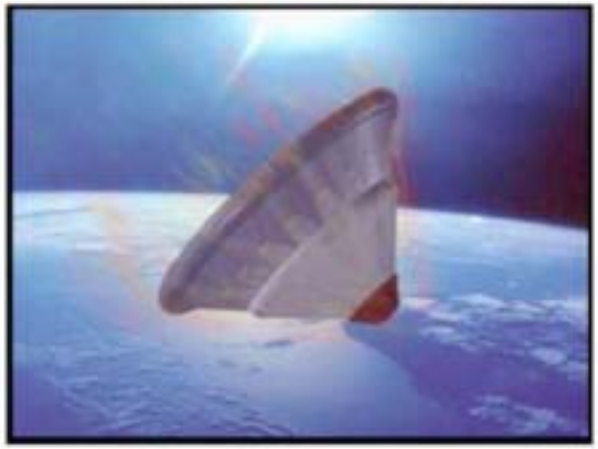
- **Technologies that can help close the "gap"**
  - Rigid Aeroshell
  - Inflatable Aerodynamic Decelerator (IAD)
  - Supersonic Retro-Propulsion
- **Other technologies of interest**
  - Aerocapture
  - Precision Landing
  - Hazard Detection and Avoidance

# Rigid Aeroshells



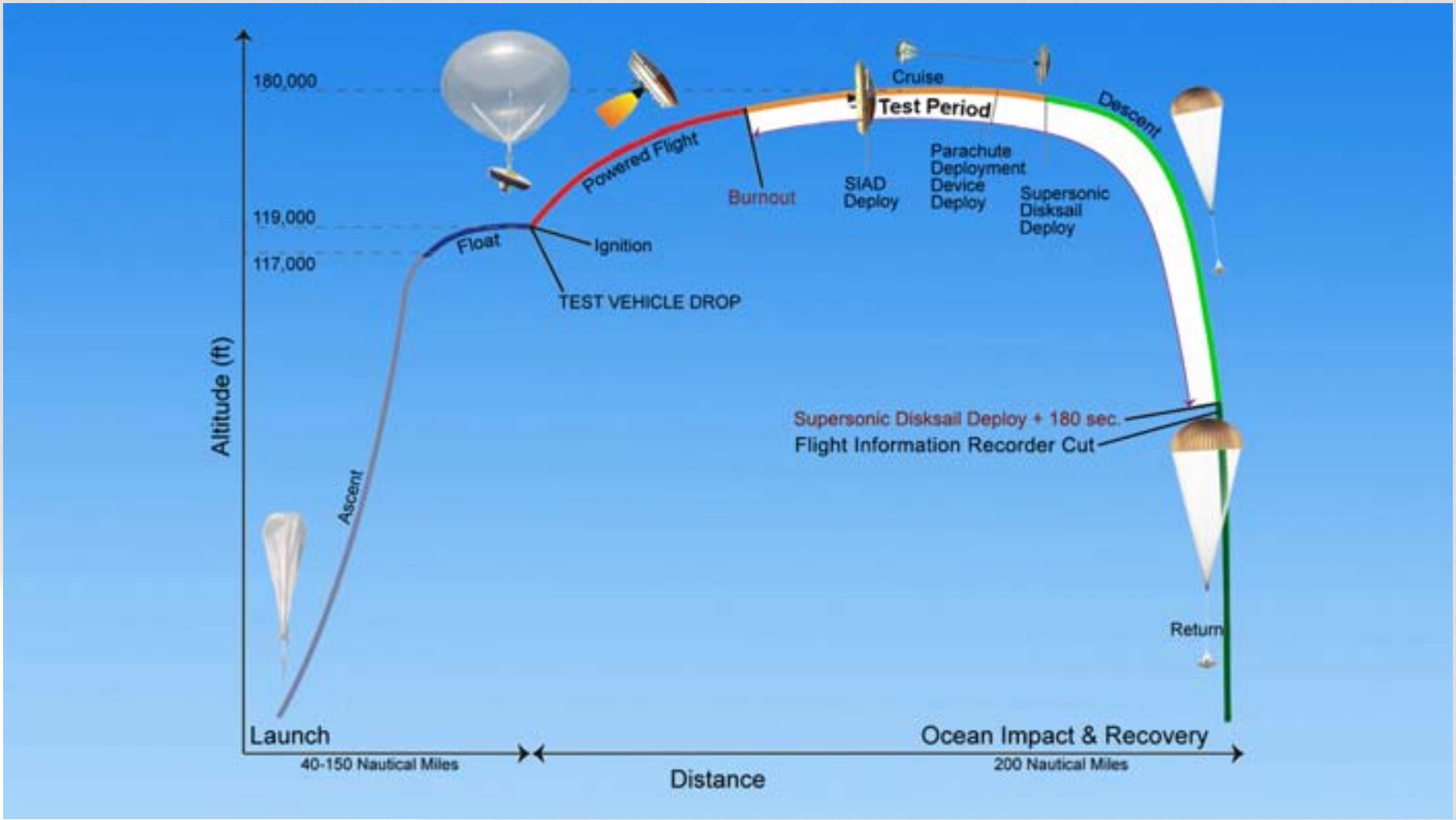


# Inflatable Aerodynamic Decelerators

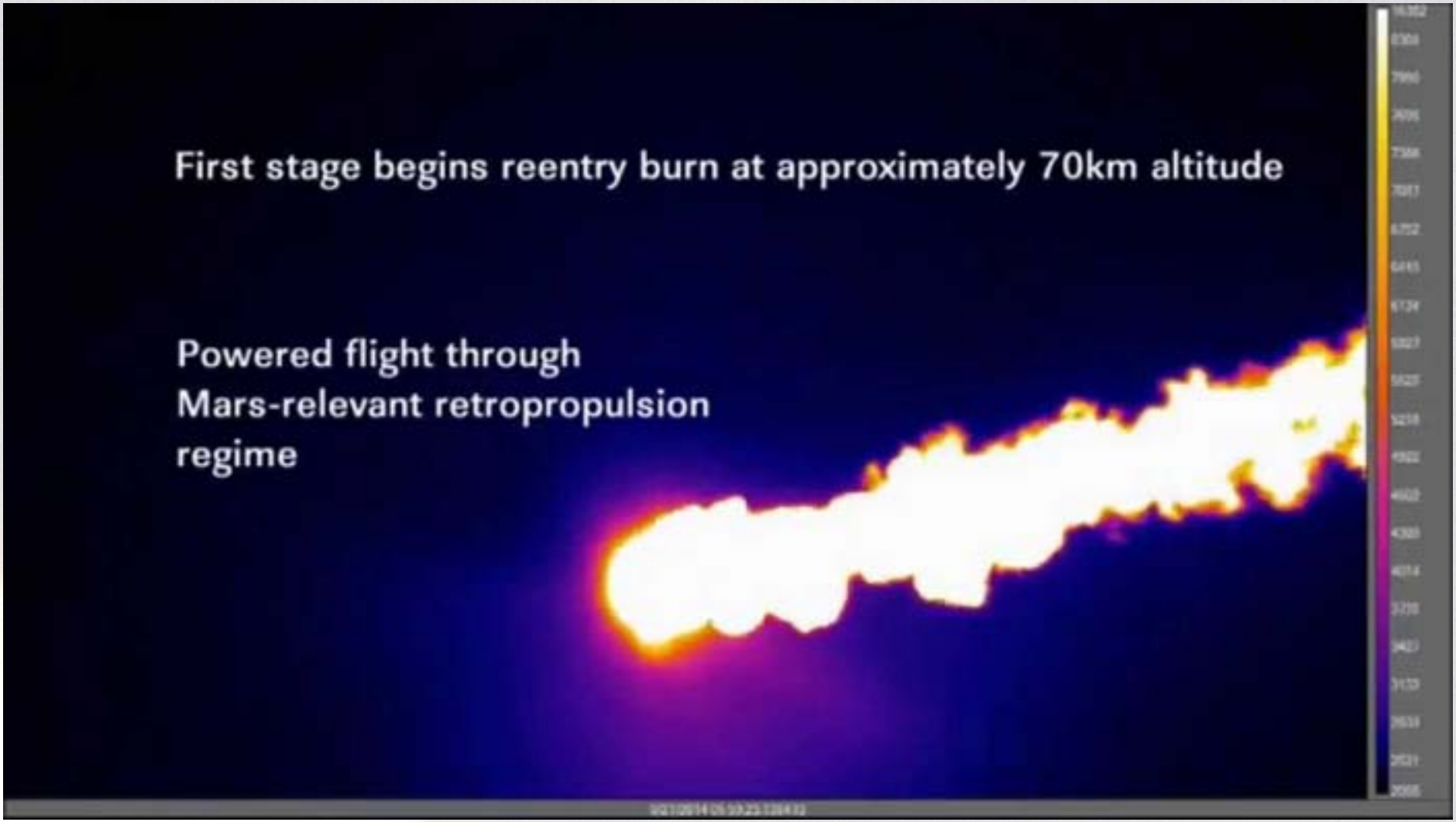


# Low-Density Supersonic Decelerator

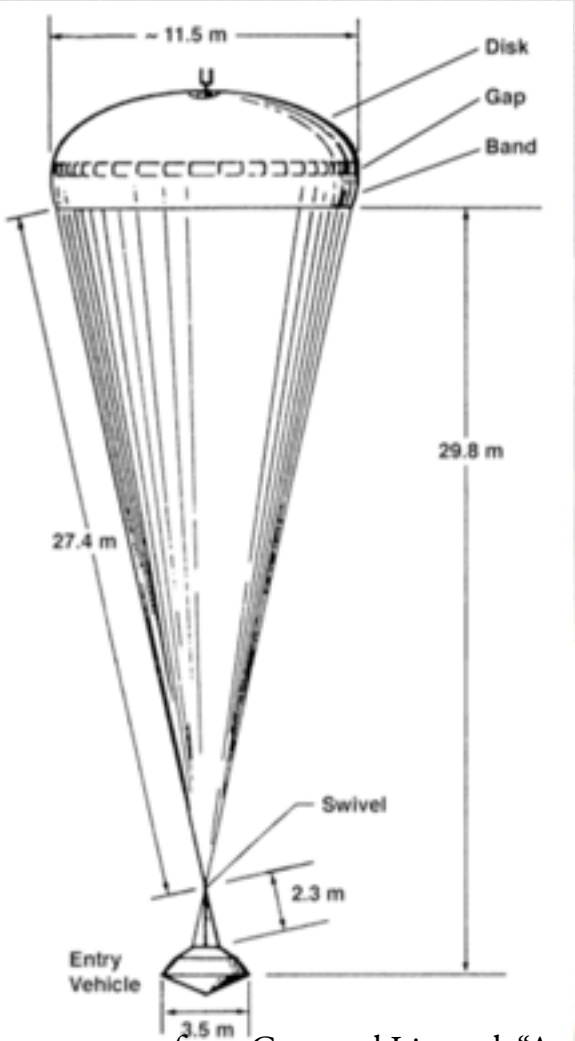
# LDSD Flight Test Profile



# Supersonic Retropropulsion



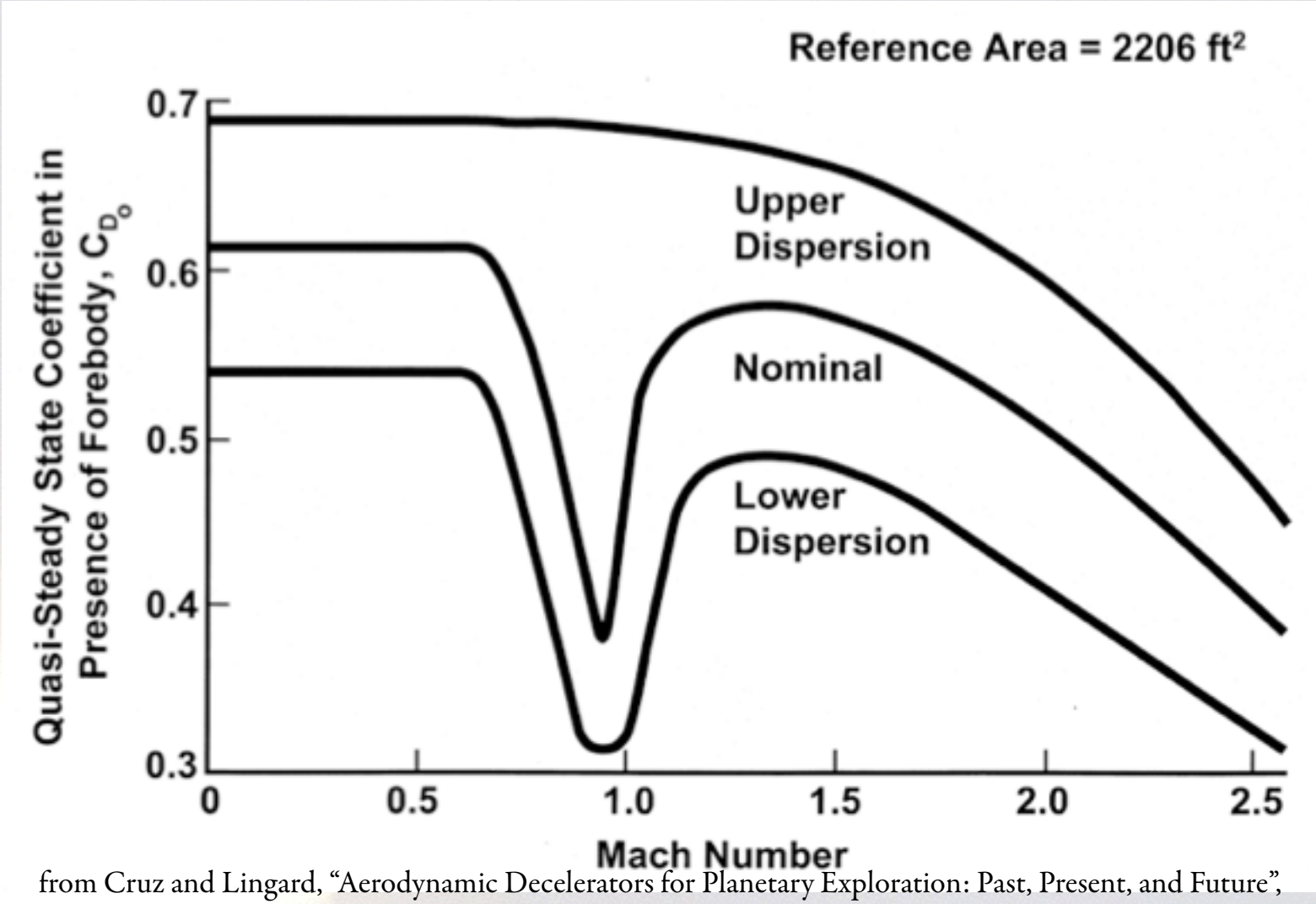
# Viking Parachute Configuration




- "Disk-Gap-Band" (DGB) or "bandgap" parachute
- Deployed at Mach 2
- Had to have sufficient deceleration to allow jettison of heat shield and dropping of lander from aeroshell

from Cruz and Lingard, "Aerodynamic Decelerators for Planetary Exploration: Past, Present, and Future", AIAA 2006-6792, AIAA Guidance, Navigation, and Control Conference, August 2006

# Viking Chute Drag Coefficient Model




from Cruz and Lingard, "Aerodynamic Decelerators for Planetary Exploration: Past, Present, and Future", AIAA 2006-6792, AIAA Guidance, Navigation, and Control Conference, August 2006

# Terminal Velocity

Full form of ODE -

$$\frac{d\left(v^2\right)}{d\rho} - \frac{h_s}{\beta \sin\gamma} v^2 = \frac{2gh_s}{\rho}$$

At terminal velocity, $v = \text{constant} \equiv v_T$

$$-\frac{h_s}{\beta \sin\gamma} v_T^2 = \frac{2gh_s}{\rho}$$

$$v_T = \sqrt{-\frac{2g\beta \sin\gamma}{\rho}}$$

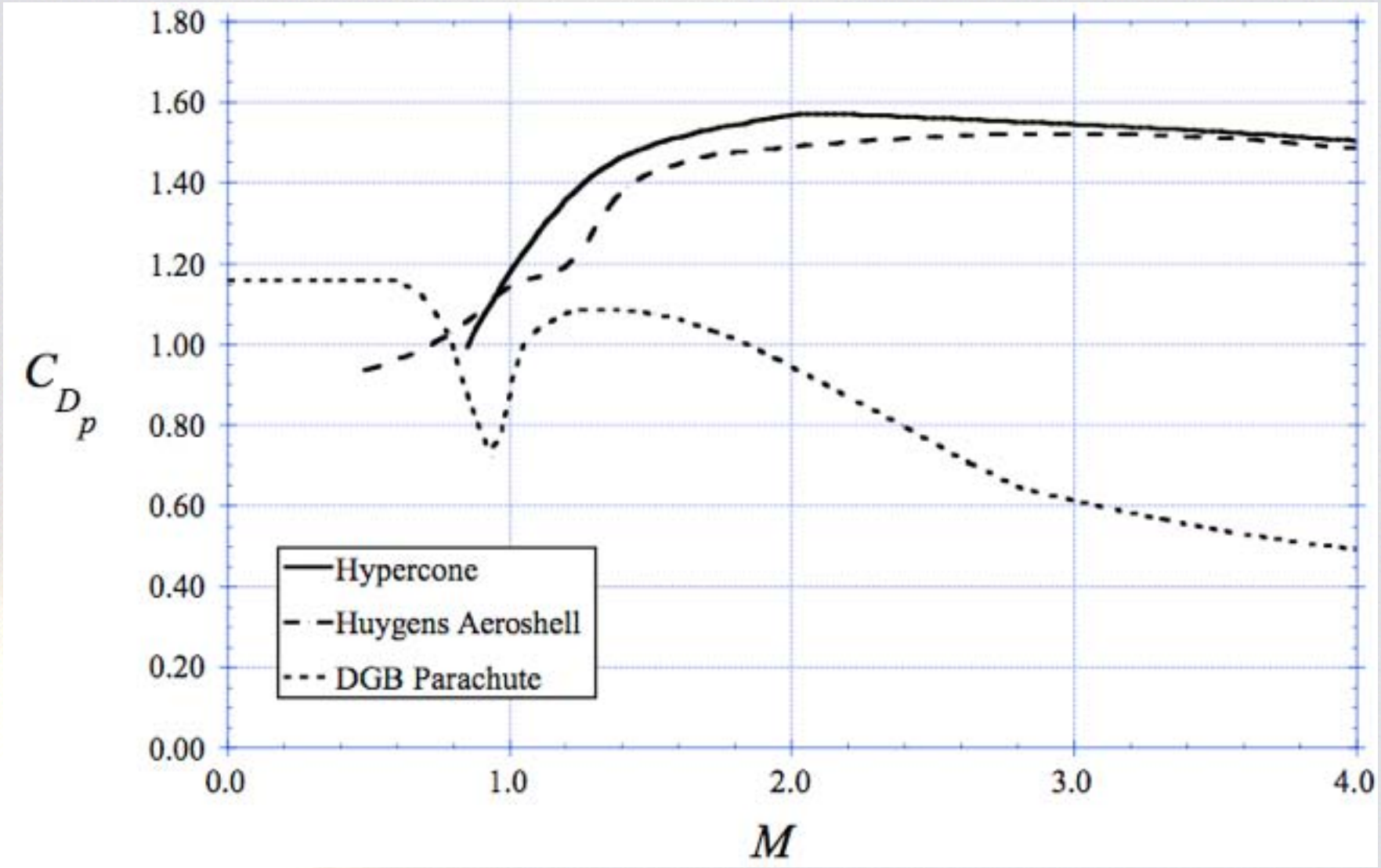
# Viking Terminal Velocity Under Chute

$$\beta = \frac{m}{c_D A} = \frac{930\ kg}{0.62\left(\frac{\pi}{4}\right)(16.15\ m)^2} = 7.322\ \frac{kg}{m^2}$$

$$v_T = \sqrt{-\frac{2g\beta\sin\gamma}{\rho}} = \sqrt{-\frac{2(3.711\ m/s^2)(7.322\ kg/m^2)\sin(-30^o)}{0.02\ kg/m^3}} = 36.9\ \frac{m}{sec}$$

$$\beta_{crit} = -\frac{\rho_o h_s}{\sin\gamma} = -\frac{0.02\ kg/m^3(10,800\ m)}{\sin(-30^o)} = 432\ \frac{kg}{m^2}$$

# Rigid and Inflatable Aeroshell vs. Chute



# Low Ballistic Coefficient Hypersonic Decelerator Development Challenges

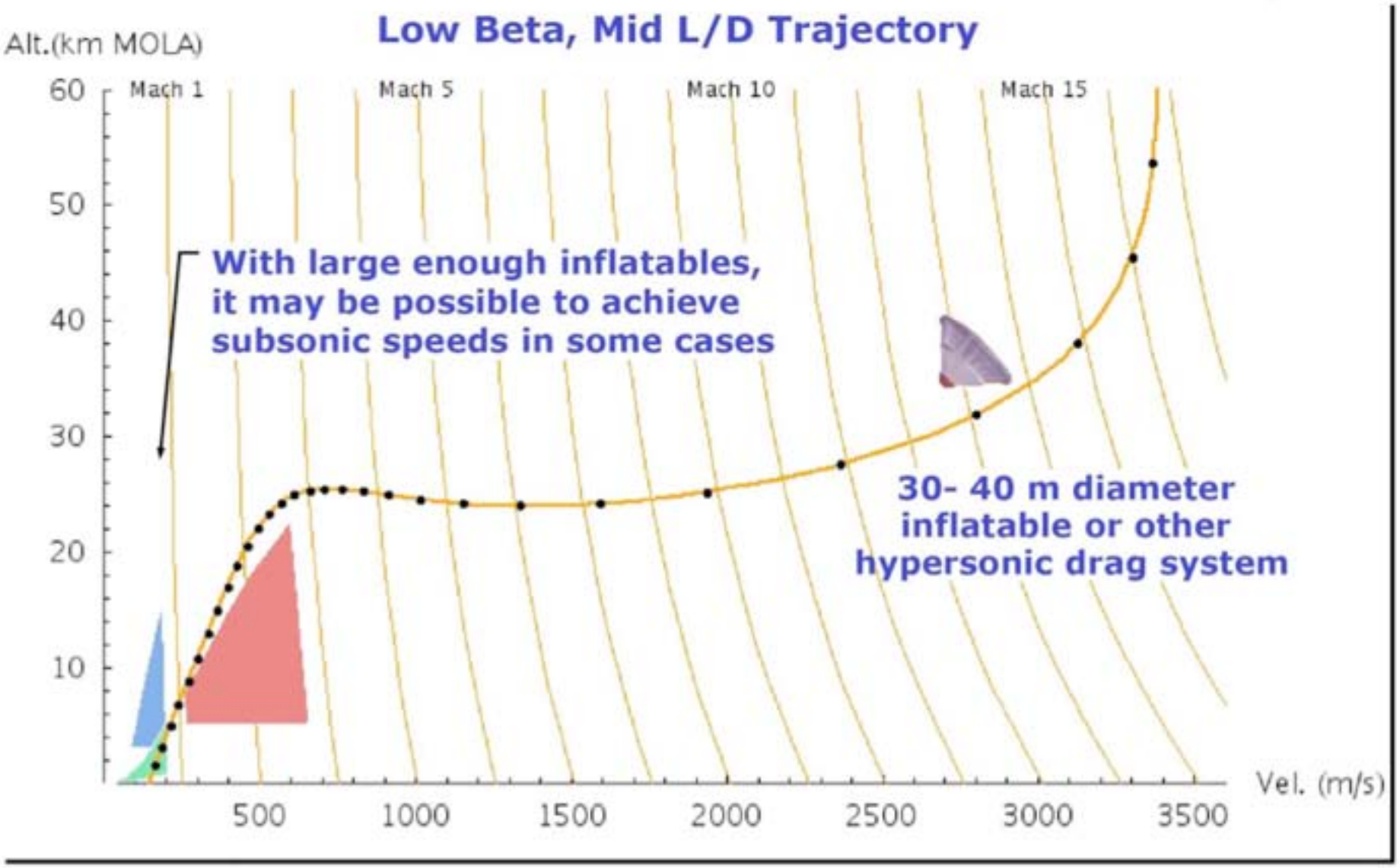
- **For 50-100 MT entry masses we need a 20-40 m diameter aeroshell.**
- **Large uncertainties (unknown-unknowns):**
  - Lift control (how to modulate drag) with large density uncertainties
  - Dynamic stability issues at supersonic and transonic conditions
  - Subsonic position correction
  - Subsonic separation mechanism

  Specifically for an Inflatable Hypersonic Decelerator:
  - Lift control
  - RCS
  - Fluid structures interactions
  - Light weight flexible TPS with large radiative heating

  Specifically for a Rigid On-orbit-deployed Hypersonic Decelerator:
  - Mass fraction of Aeroshell & deployment device

- **Again, there are NO Earth analog for these systems.**
  - NASA, Russia and ESA have tested very small scale inflatable Earth entry systems (IRVE, IRDT)

# What about Large Inflatable Entry Vehicles? (ballistic coefficient = 50 kg/m$^2$ & L/D = 0.3)



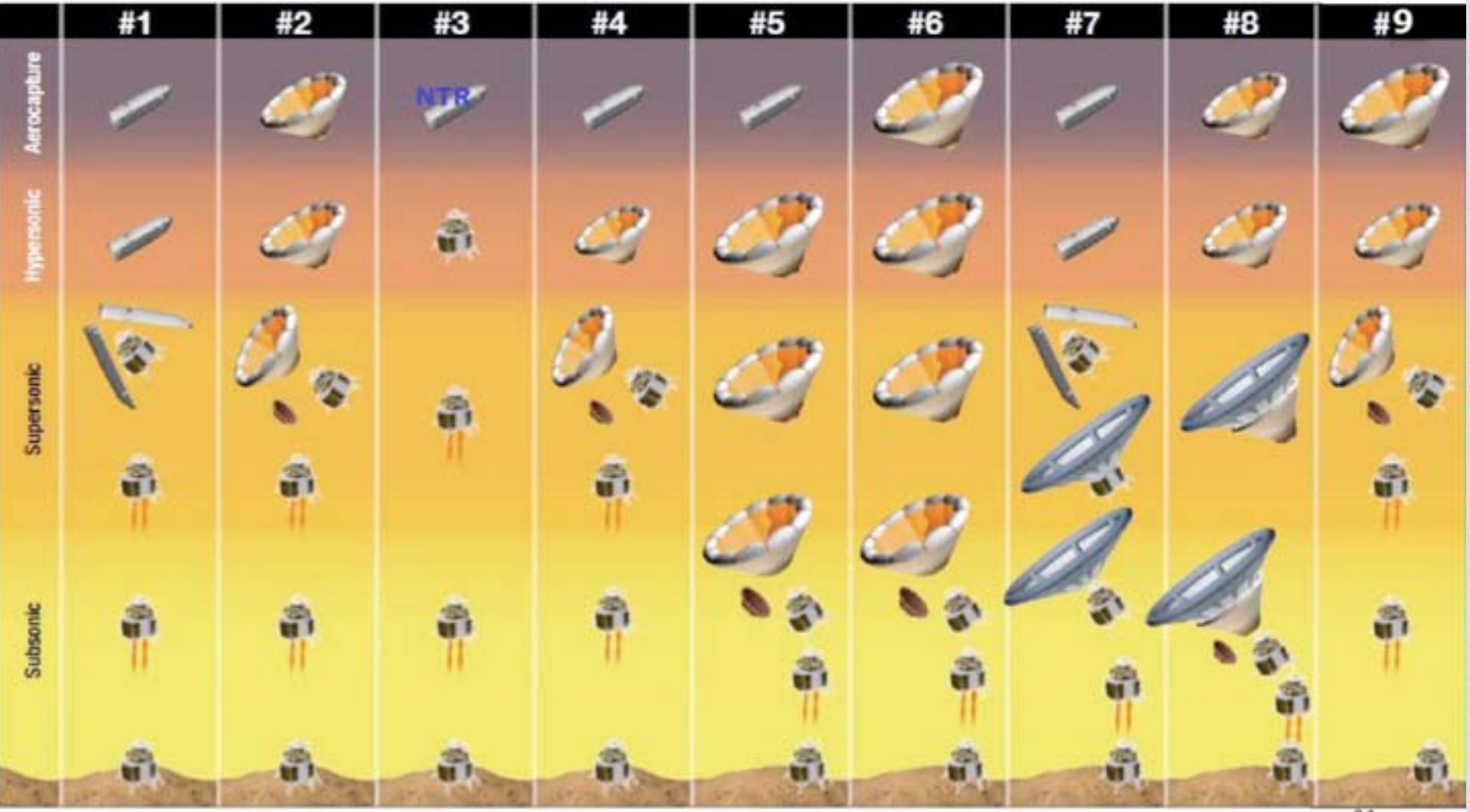
# Supersonic Retro-Propulsion

- **Advantages:**
  - More precise landing – aerodynamics / winds now secondary effect
  - Control authority and altitude from Mach > 3 to the ground
  - Fewer complex systems (e.g.parachutes, deployable systems)

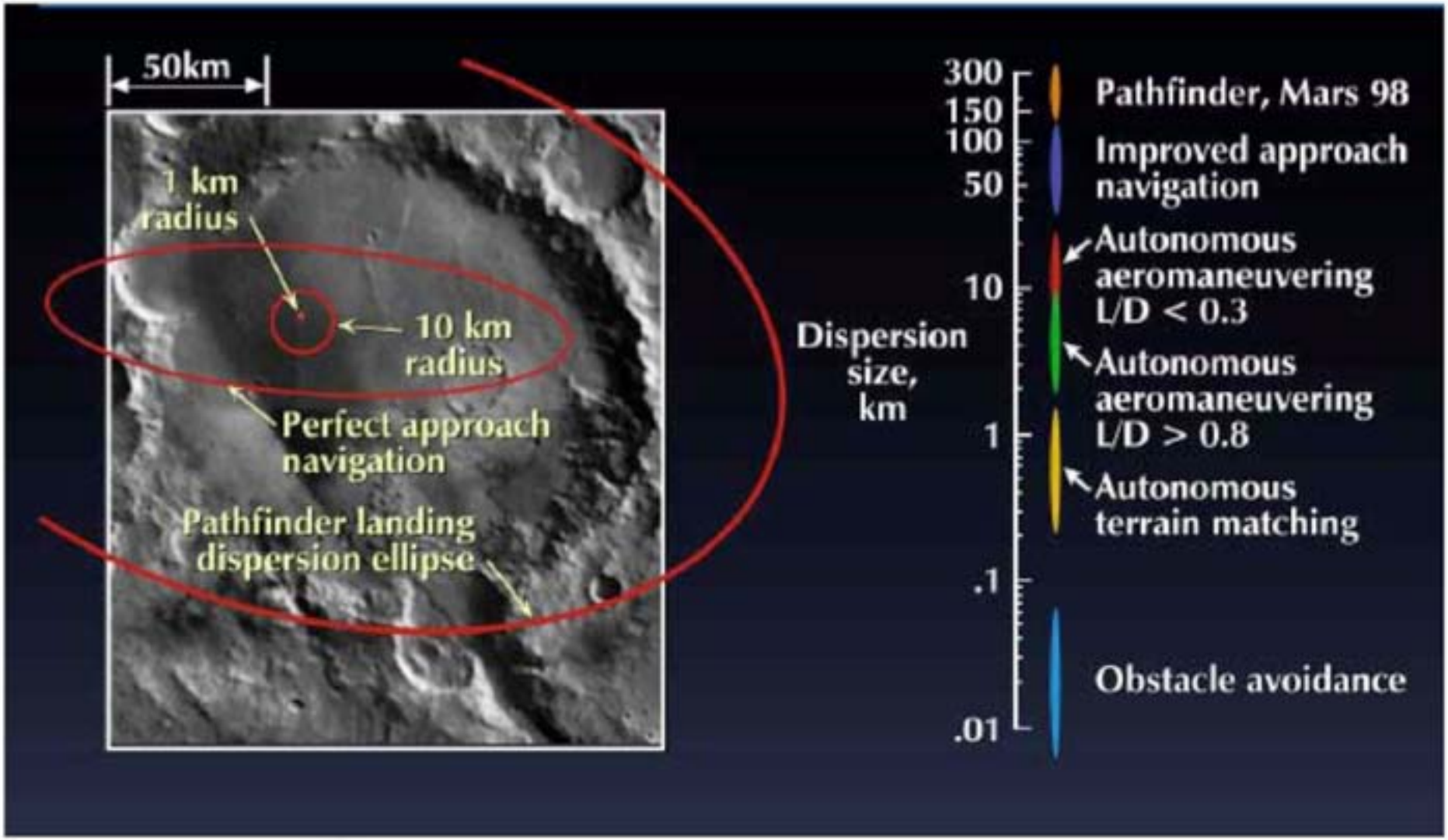
- **Disadvantages:**
  - Large propellant mass fractions
  - Aerodynamic stability of the vehicle plume and flow impingements
  - RCS / flow interactions
    - Aerodynamic / propulsion flow interactions
    - Plume / flow aeroheating
  - Surface contamination issues

# Potential Exploration Architectures

*Some possible combinations…*

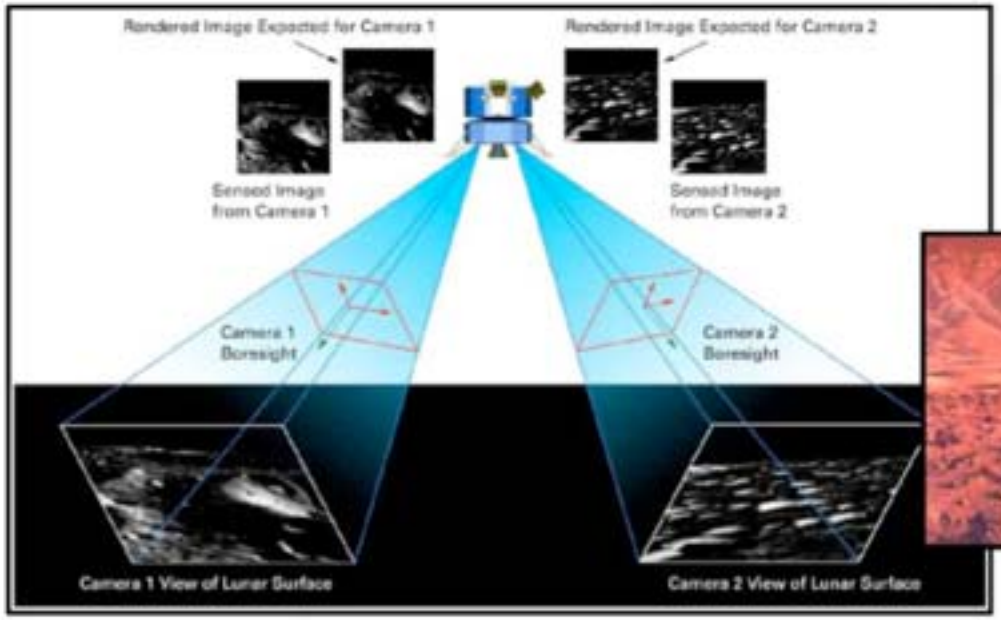


# The Case for Precision Landing, Hazard Avoidance, and Pinpoint Landing



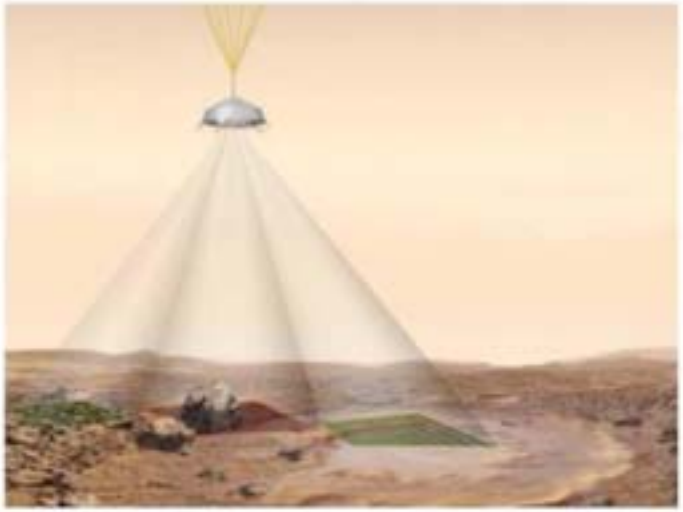
# Precision Landing

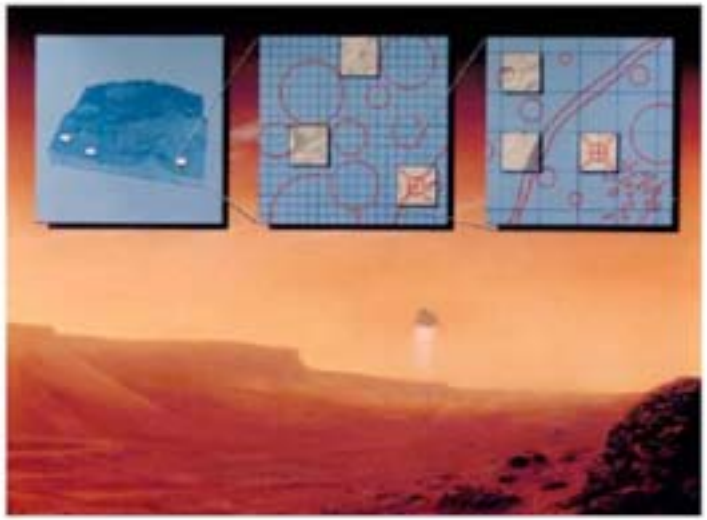
- Precision landing is the capability to land very accurately
- Requires very good knowledge of the vehicle state (navigation) at the right time, in addition to the ability to correct for state errors (guidance and control)
- A combination of sensors including star tracker, inertial measurement unit (IMU), altimeter, and velocimeter are used for state estimation
- Terrain Relative Navigation is a technology being developed for the Moon and Mars which may enable a precision landing level of performance



# Hazard Detection and Avoidance (HDA)

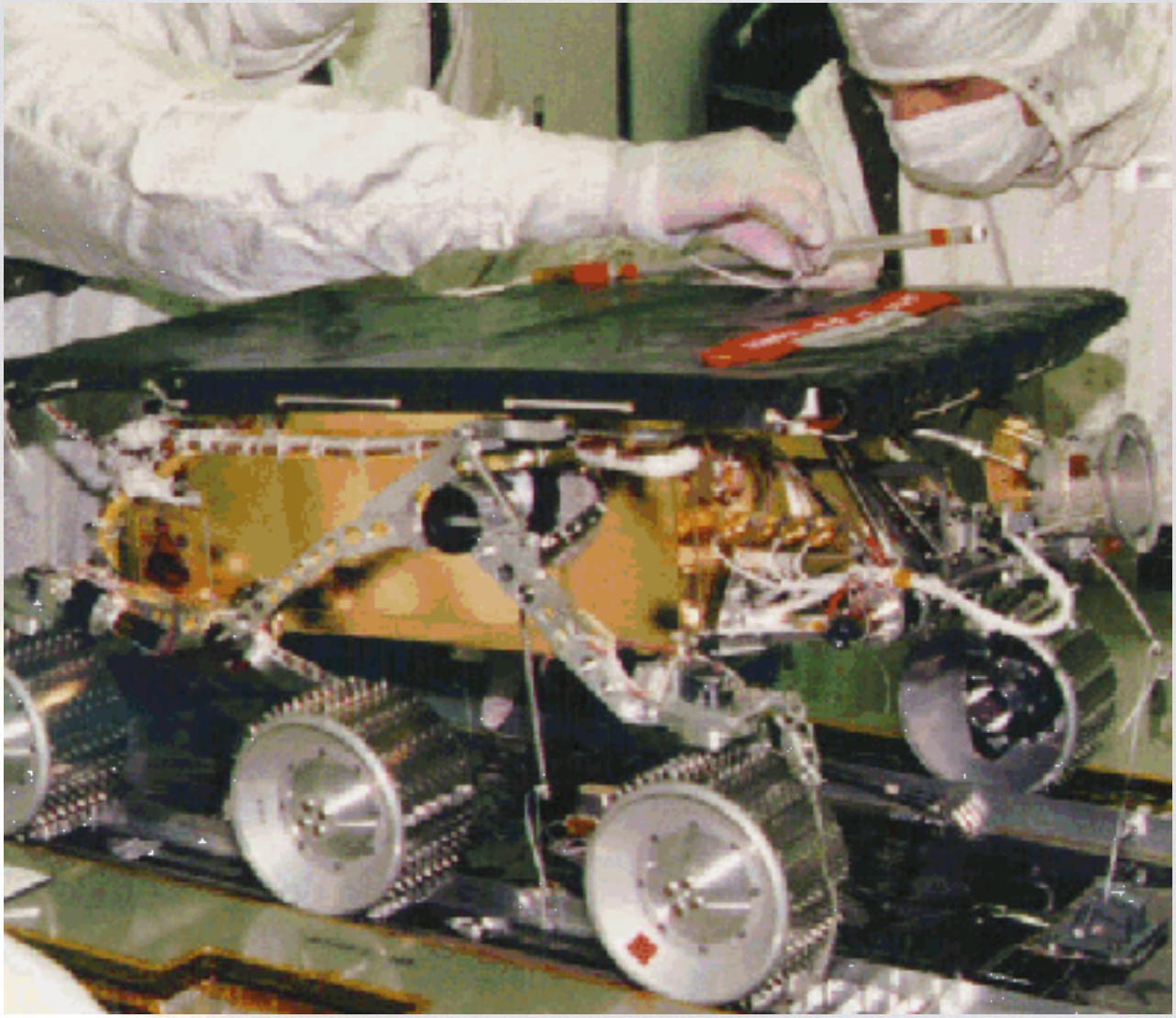
- HDA is the capability to detect and avoid hazards during the landing
- An onboard hazard map is developed real time during the descent using flash LIDAR
- The flash LIDAR returns a 3-D image of the landing area which contains higher resolution information of the landing area than currently possible using orbit reconnaissance
- An updated landing point is then selected (either automatically or via crew intervention) and the vehicle re-targets to the new landing point



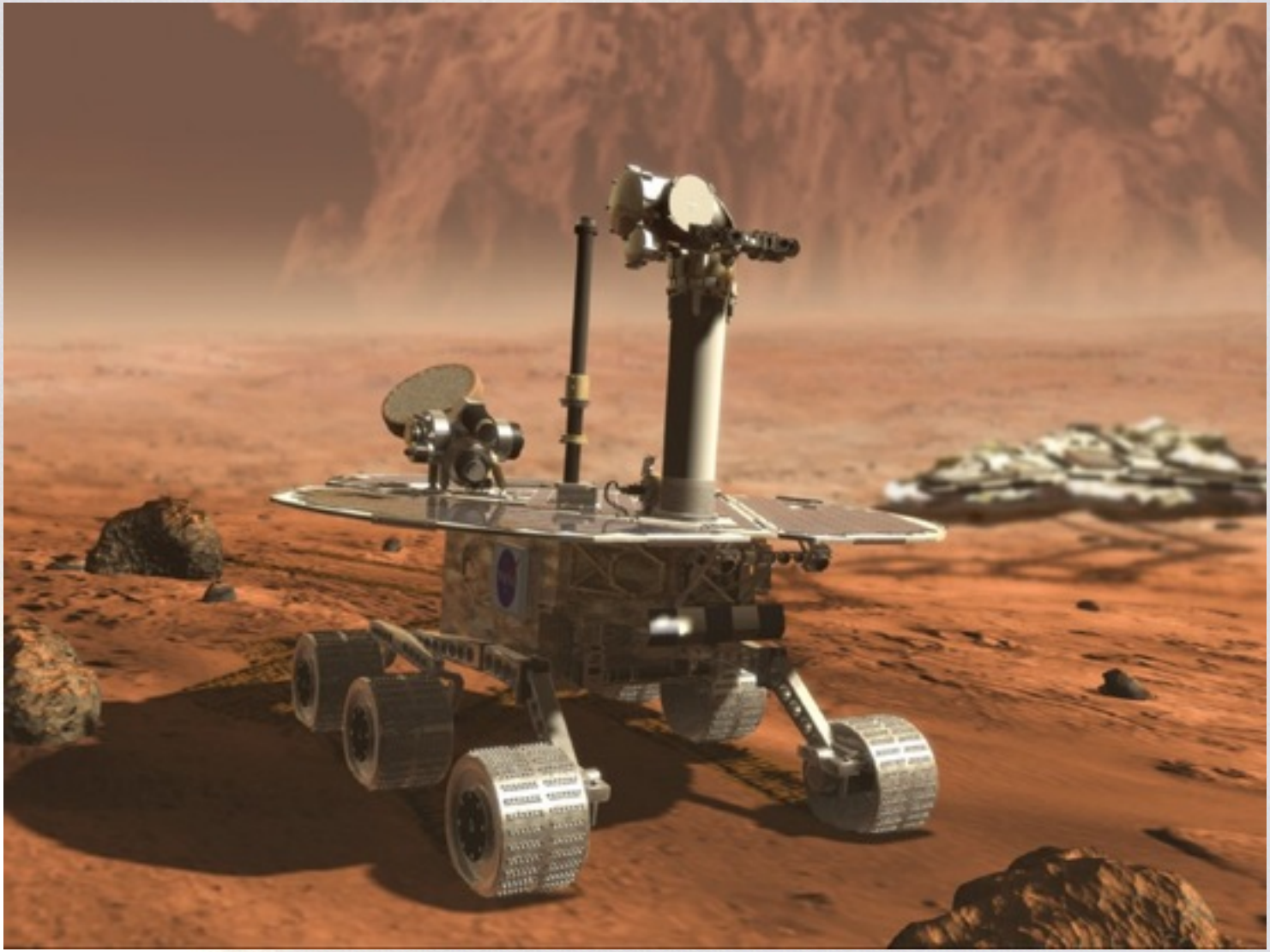


# Viking Panoramas (1976)

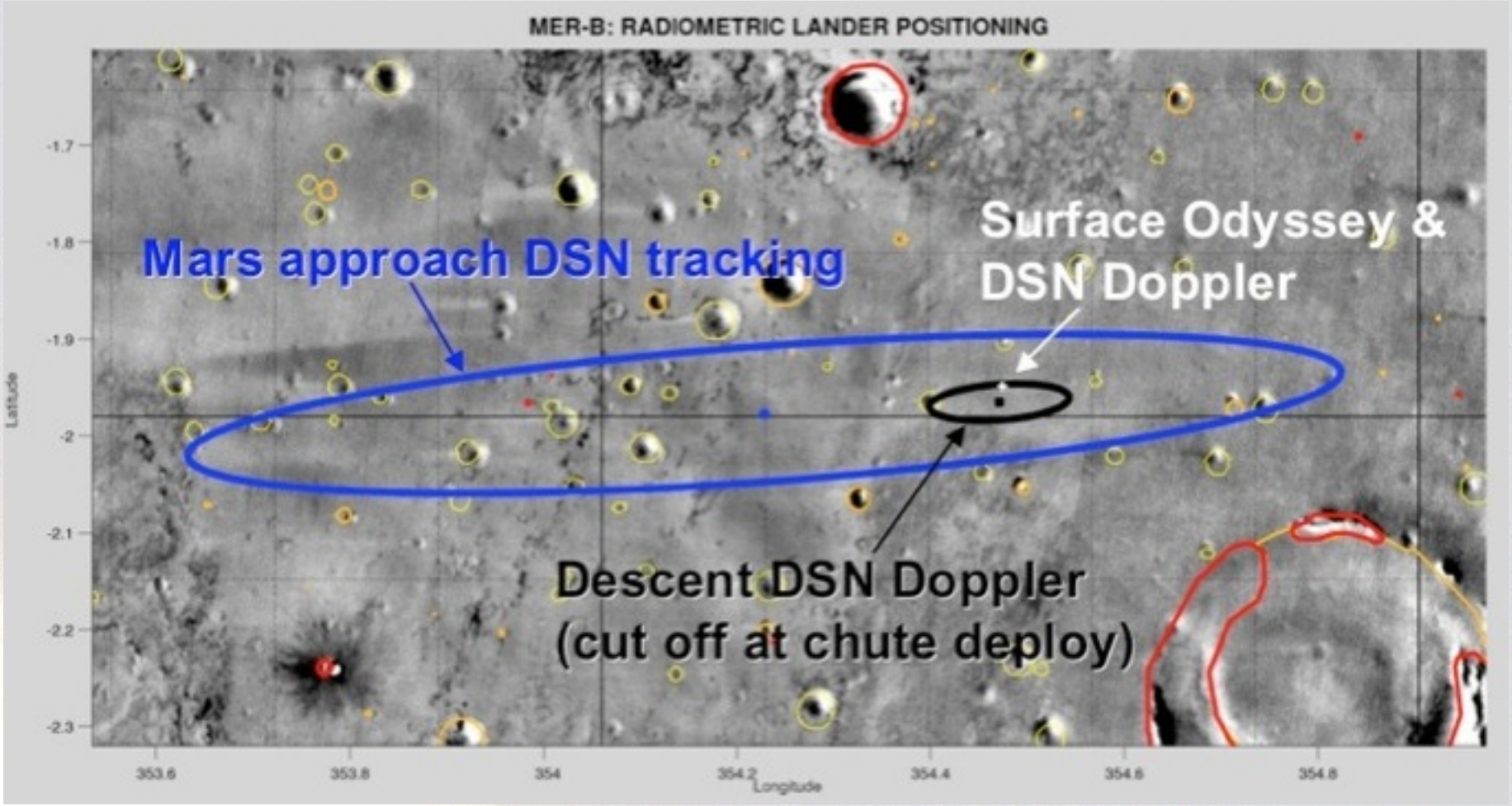
# Mars Pathfinder Rover ("Sojourner")



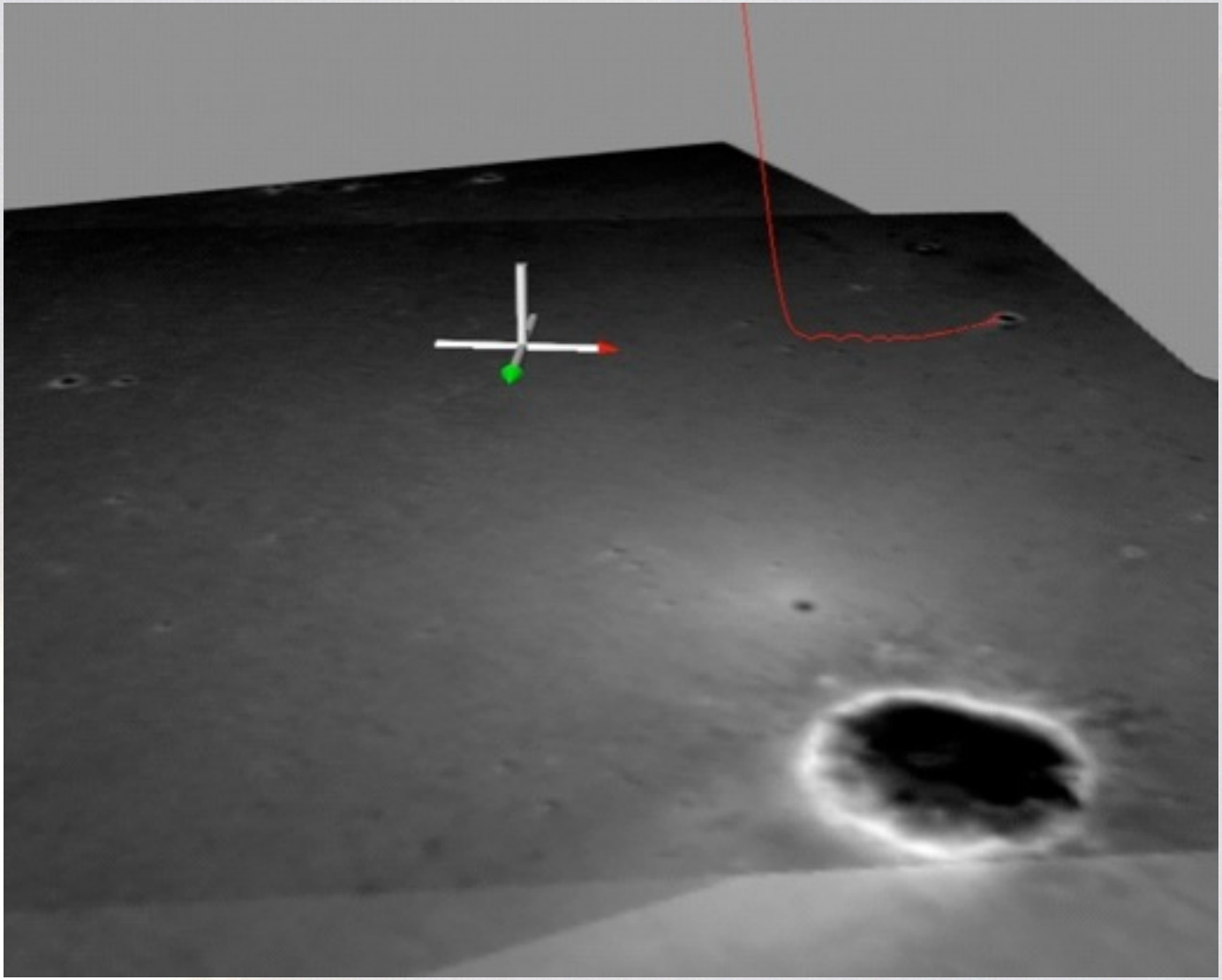
# Mars Exploration Rover



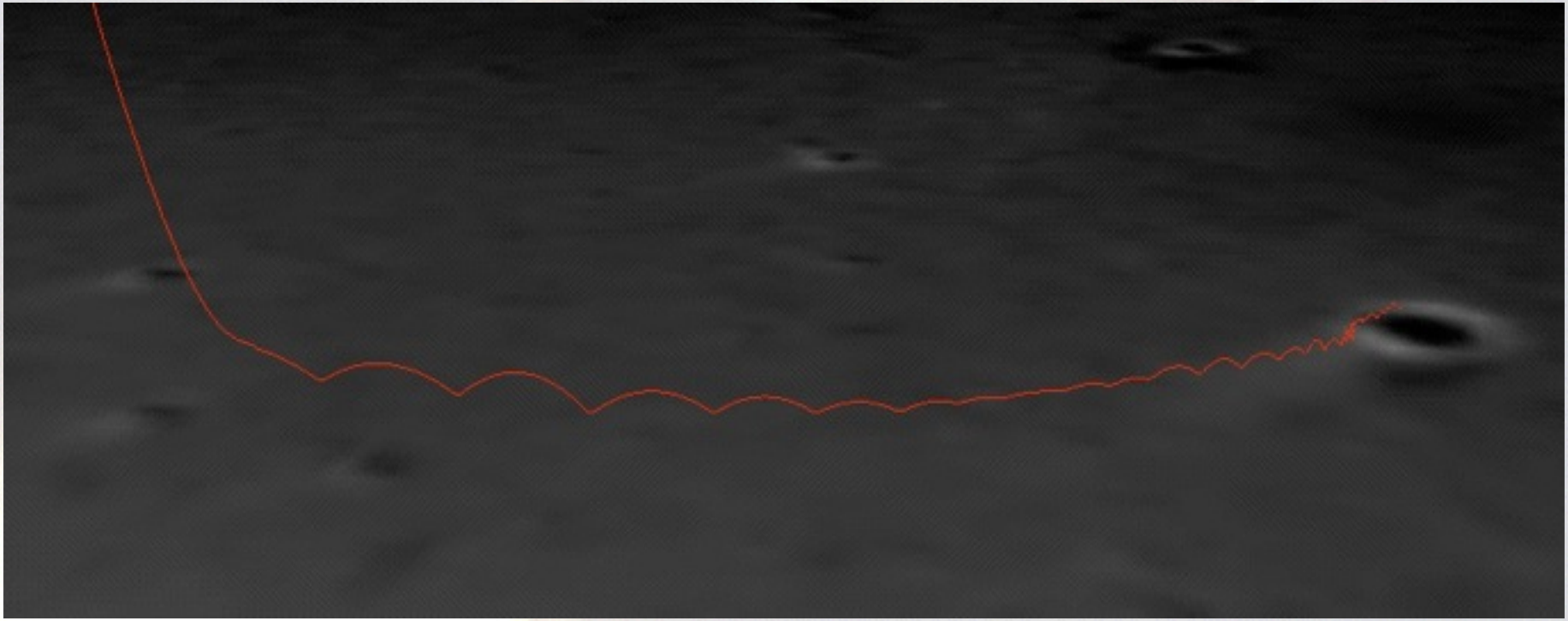
# Opportunity Landing Targeting



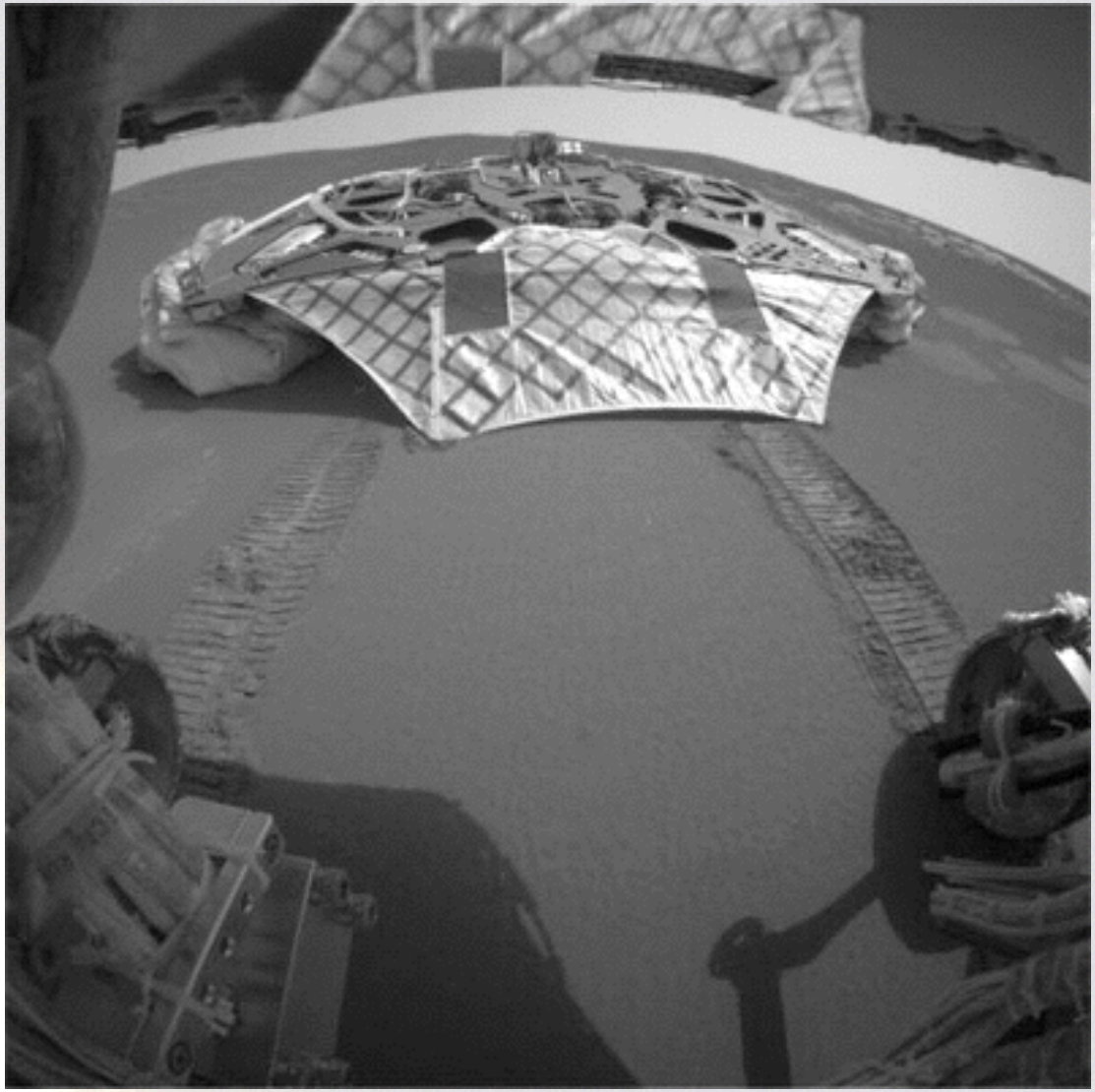
# Sometimes the Bounces Go Your Way...



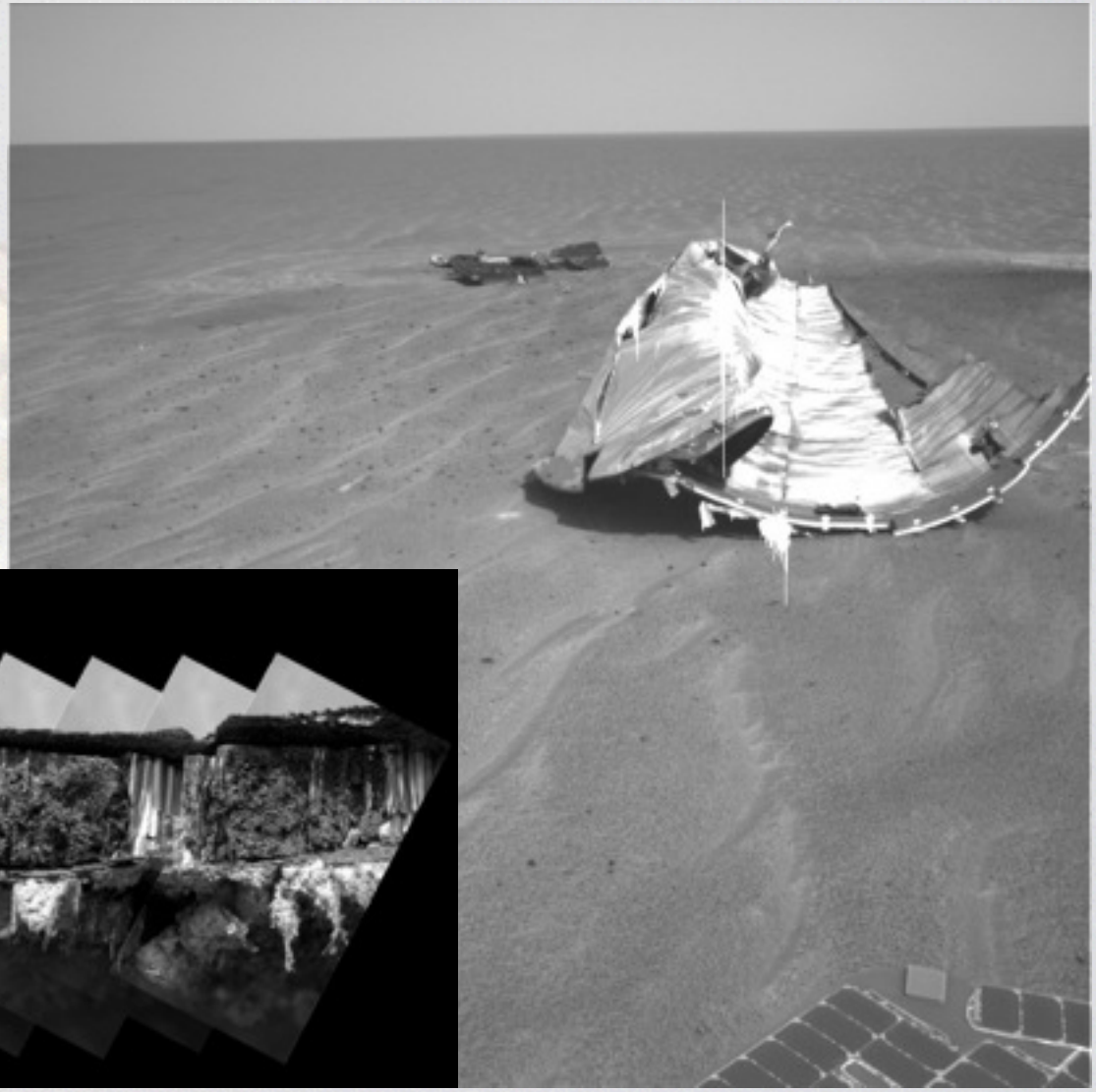
# ...Opportunity Scores a Hole in One

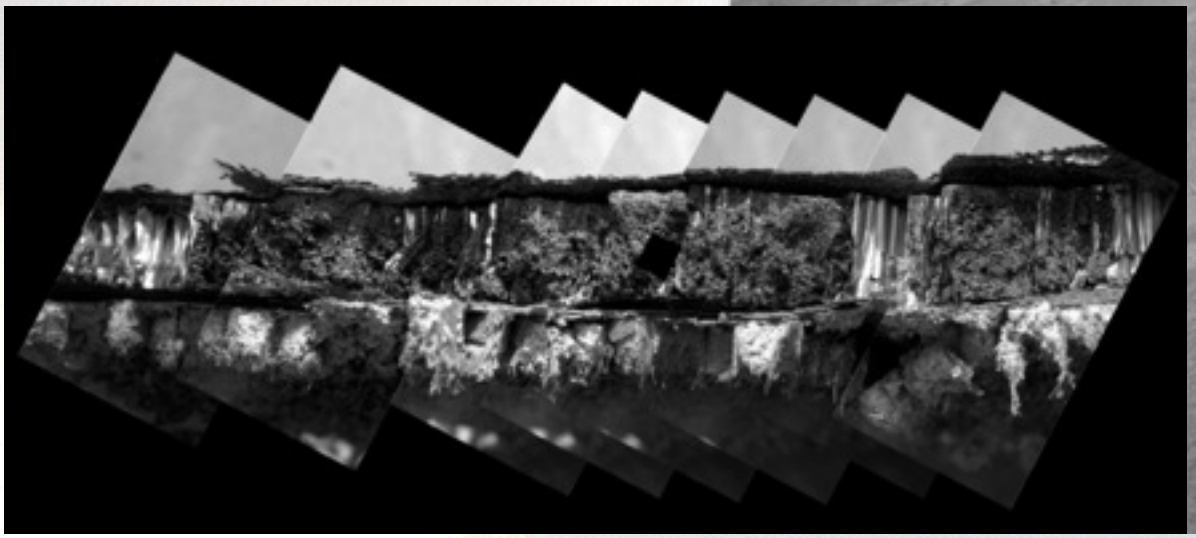


# Spirit Lands in Gusev Crater



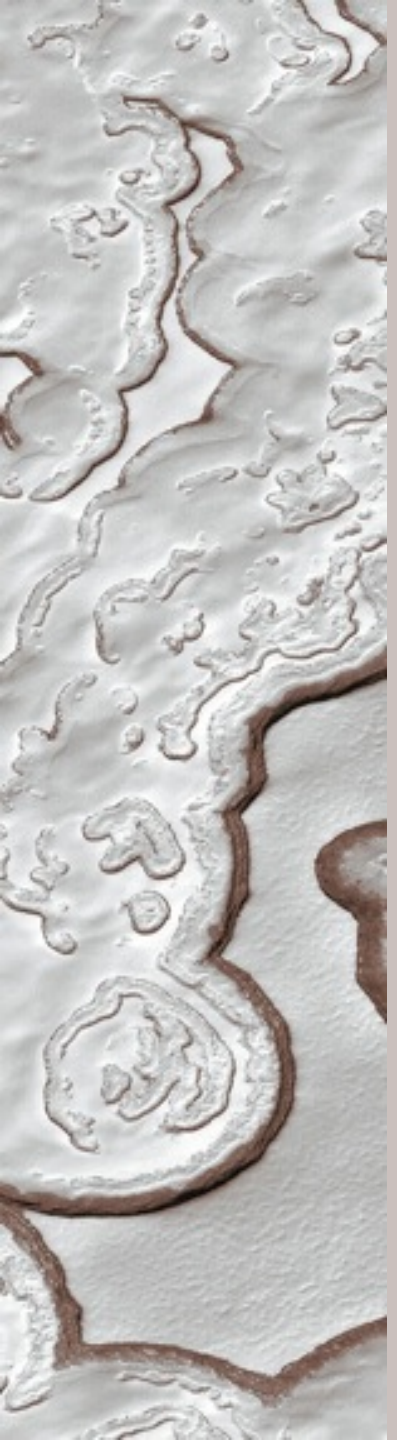
# Odyssey Finds its Heat Shield...





# Mars Phoenix Lander Touchdown

# Mars Rovers (Past, Present, ~~Future~~ Present)



# Mars Science Laboratory
# Project Introduction

Richard Cook
Project Manager

December 7, 2005

# Project Overview



***Salient Features***

***Mobile Science Laboratory***

***One Mars Year surface operational lifetime (669 sols/687 days)***

***Discovery Responsive over wide range of latitudes and altitudes***

***Controlled Propulsive Landing***

***Precision Landing via Guided Entry***

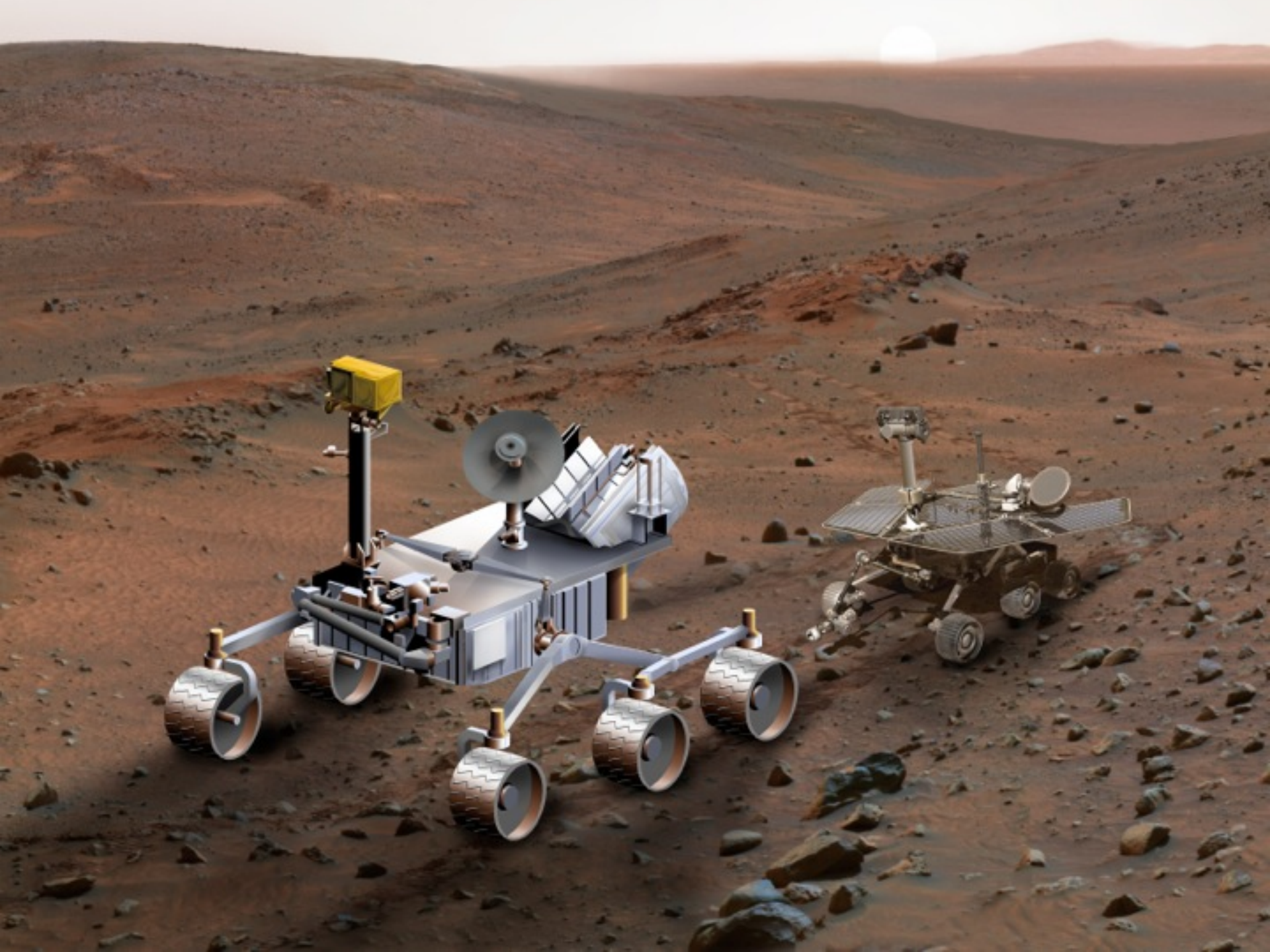
***Science***

***Mission science will focus on Mars habitability***

***Next generation analytical laboratory science investigations***

***Remote sensing/contact investigations***

***Suite of Environmental Monitoring Instruments***



# MSL-MER Comparison



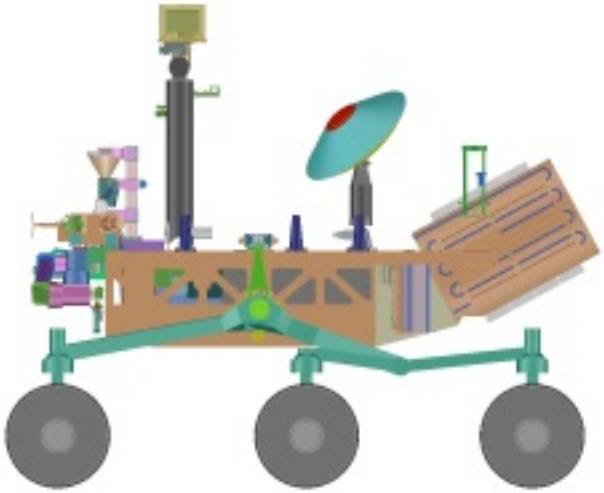
| | MSL | MER |
|---|---|---|
| LV/Launch Mass | Delta 4/Atlas V/3600 kg | Delta II/1050 kg |
| Design Mission Life | 1 yr cruise/2 yrs surface | 7m cruise/3 mo surface |
| Redundancy | Redundant Surface, Single String Cruise/EDL | Limited/Dual Mission |
| Payload | 10 instruments (75 kg) | 5 instrument (~9 kg) |
| Sample Acquisition | Arm + RAT + Corer + Scoop | Arm + RAT |
| Sample Processing | Rock Crusher | None |
| EDL System | Guided Entry/Skycrane | MPF Heritage/Airbags |
| Heatshield Diam | 4.5 m | 2.65 m |
| EDL Comm | UHF + Partial DTE or DTE | DTE + Partial UHF |
| Rover Mass | 775 kg (allocation) | 170 kg (actual) |
| Rover Range | >20 km | >5 km |
| Surface Power | RTG*/2500 Whr/sol | Solar/<900 Whr/sol |
| Surface Comm | X-band DTE + UHF | X-band DTE + UHF |



* - PreDecisional, RTG selection is contingent on NEPA/PD proces

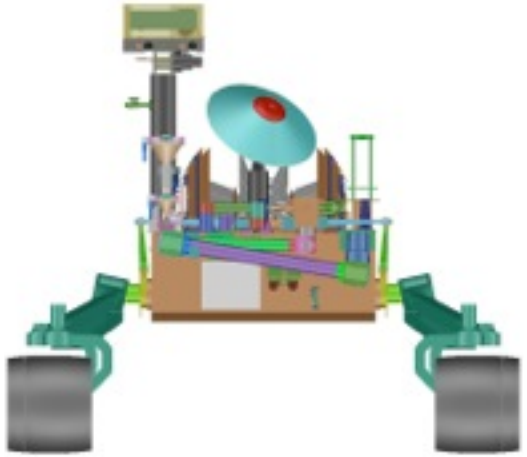
# MSL Rover Size Comparison





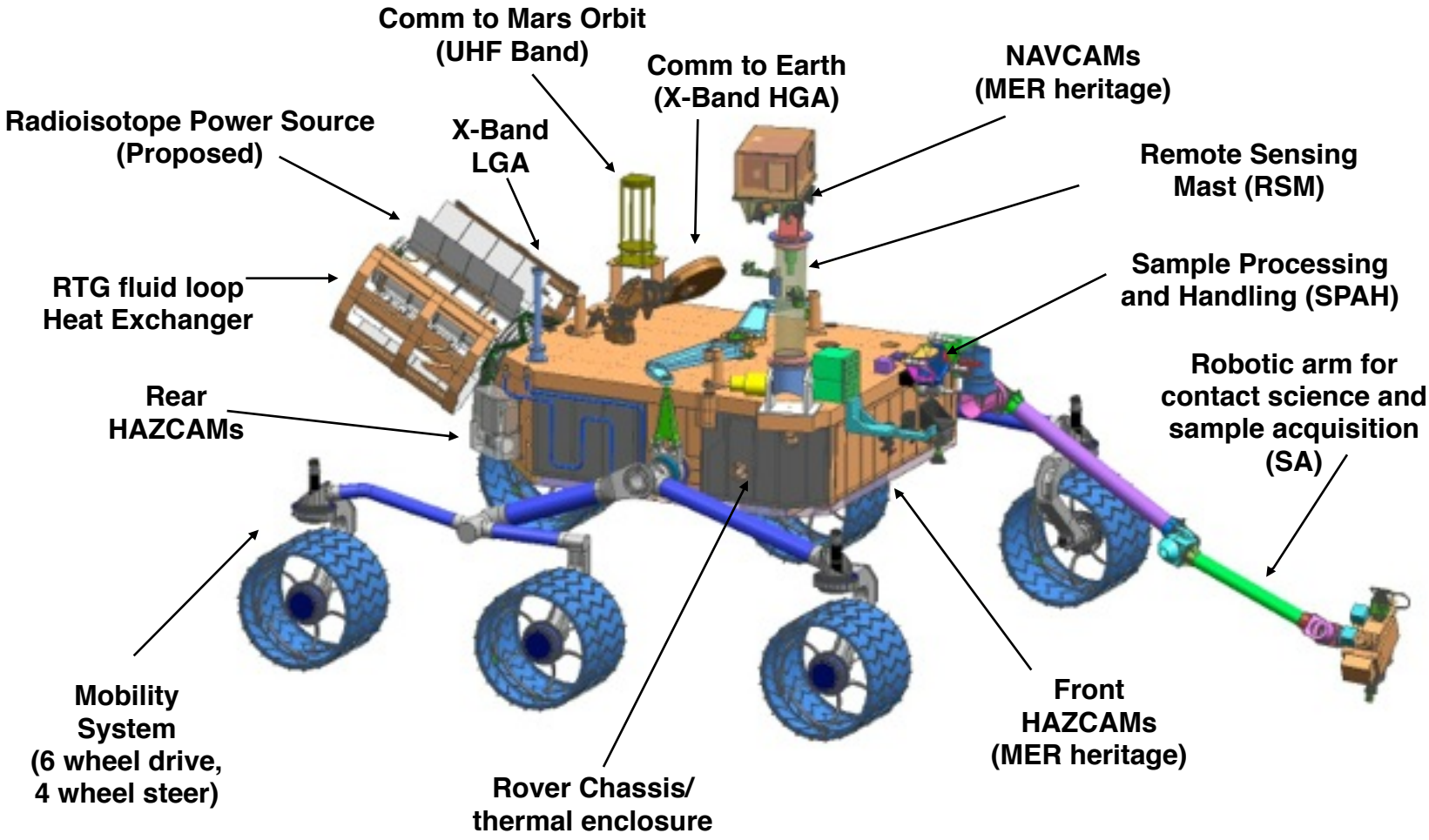
JPL 2009 MSL Rover

2005 MINI Cooper S



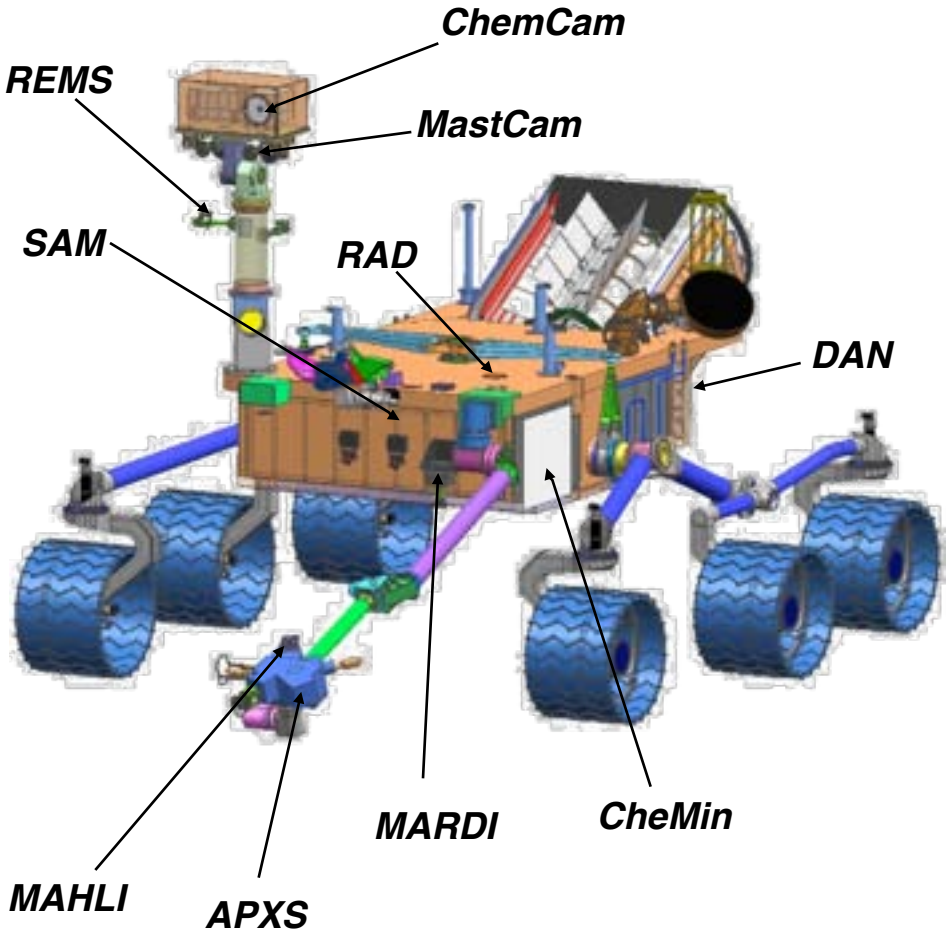
# Rover Engineering Capabilities





# MSL Payload






## Remote Sensing (Mast)

ChemCam – Laser Induced Breakdown Spectrometer
MastCam - Color Stereo Imager

## Contact Instruments (Arm)

MAHLI - Microscopic Imager
APXS - Proton/X-ray Backscatter Spectrometer

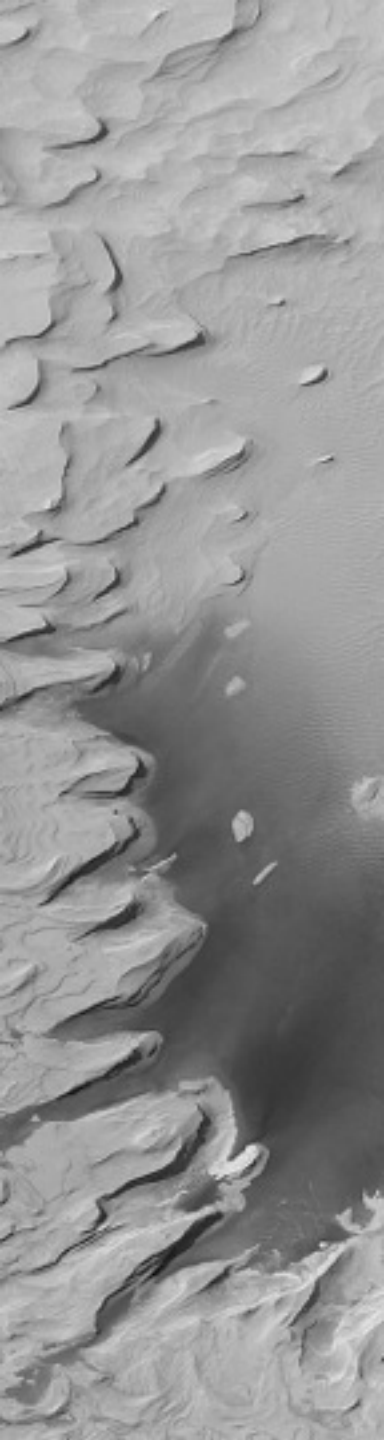
## Analytical Laboratory (Front Chassis)

SAM - Gas Chromatograph/Mass Spectrometer/ Tunable Laser Spectrometer
(Sample Composition / Organics Detection)

CheMin - X-ray Diffraction / Florescence
(Sample Mineralogy)

## Environmental Characterization (Body-mount)

MARDI - Descent Imager
REMS - Meteorological monitoring
RAD - Surface Radiation Flux Monitor
(future human health & safety)
DAN - Neutron Backscatter subsurface hydrogen (water/ice) detection



# Flight System Design Overview

Presented at
Mars Science Laboratory PMSR
December 7-9, 2005

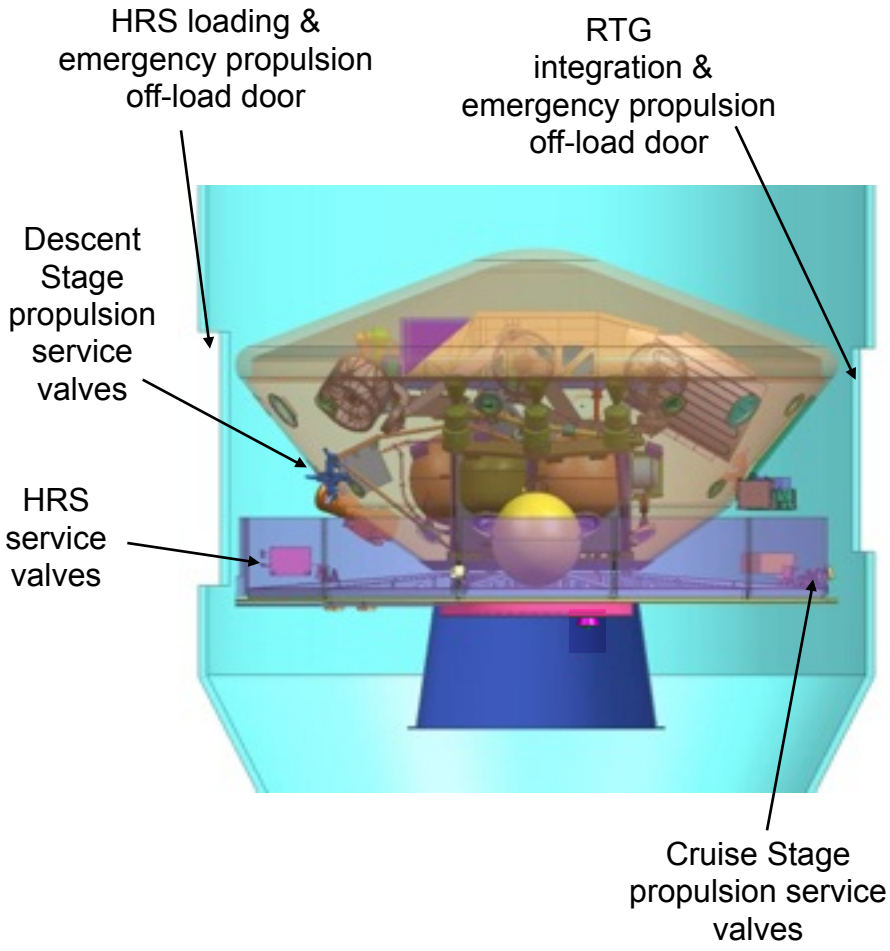
Christopher G. Salvo
Flight System Engineering Manager

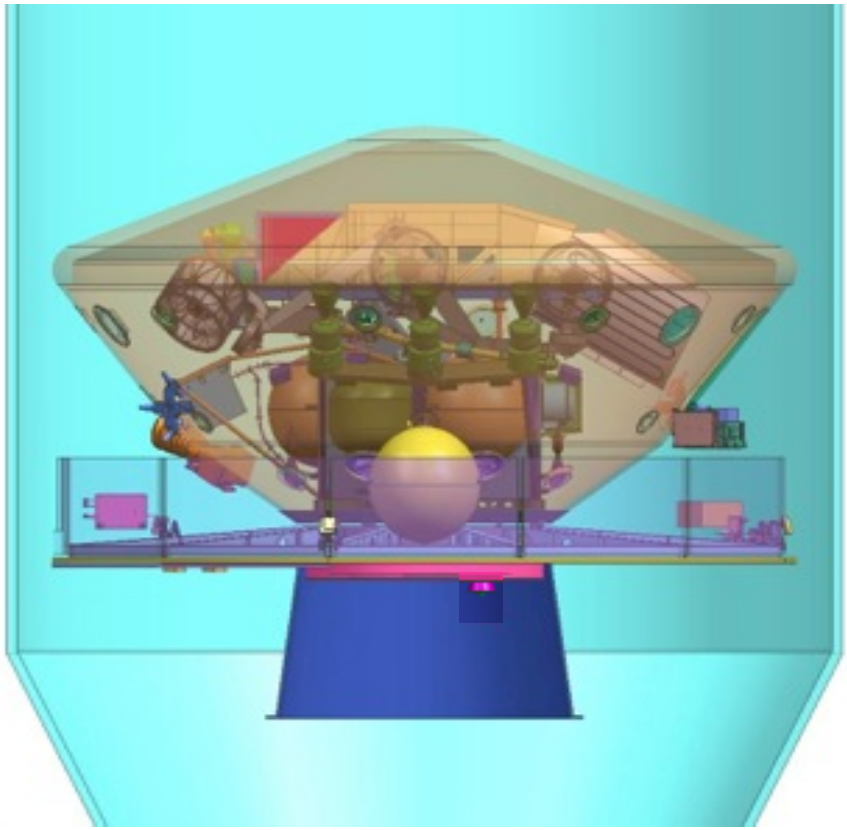
**PRE-DECISIONAL DRAFT: For Planning and Discussion Purposes Only**

# Launch Configuration



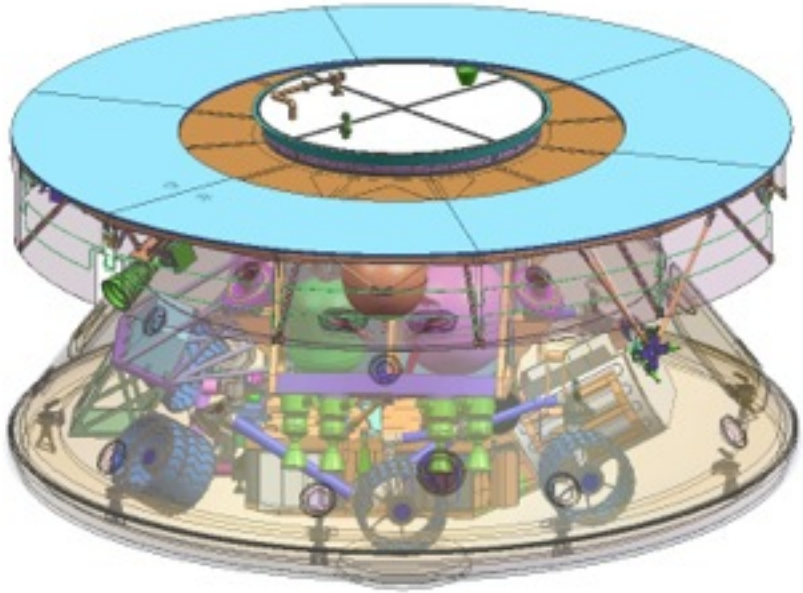
- 5m Fairing with 4.56 m internal envelope.
- 66” Payload interface to MSL Spacecraft.
- RTG integration access
- Heat Rejection System (HRS) loading access
- Emergency de-fueling access

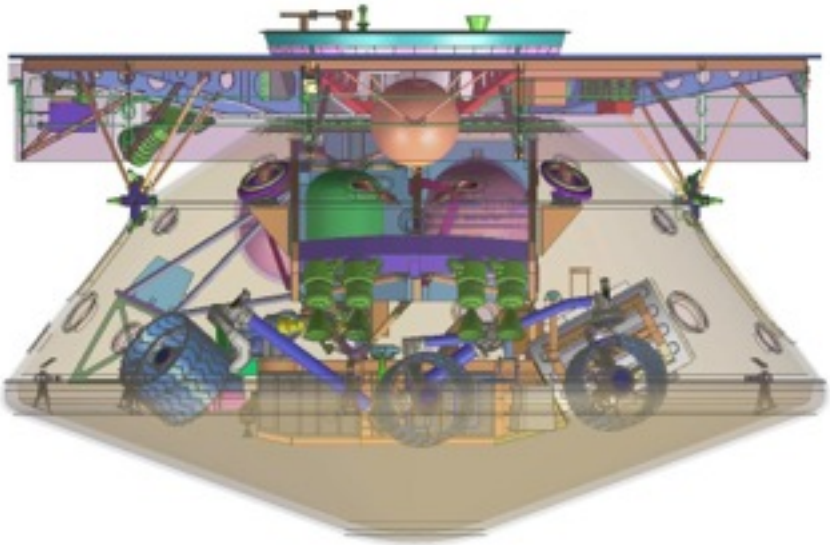


# Cruise Configuration

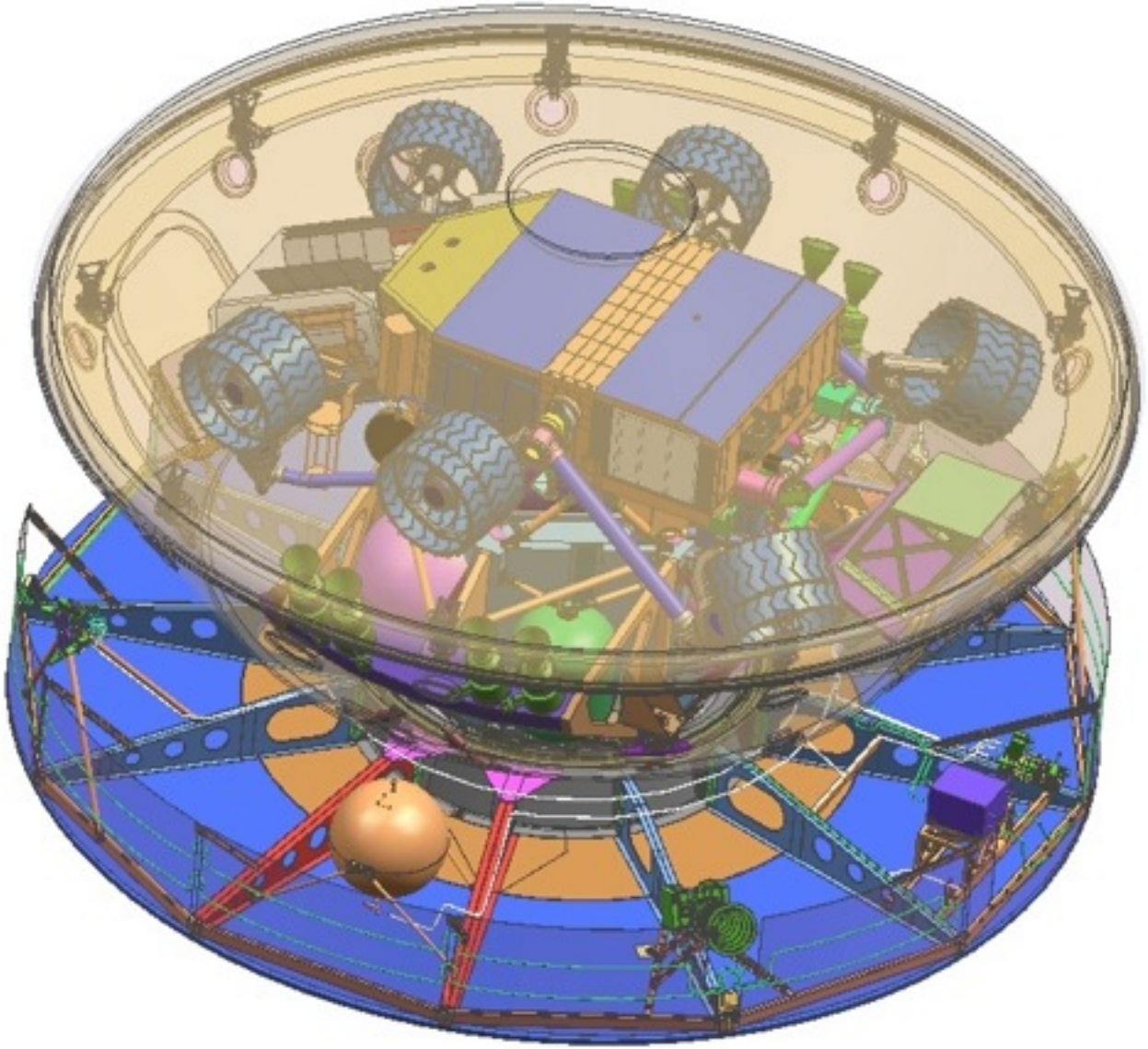






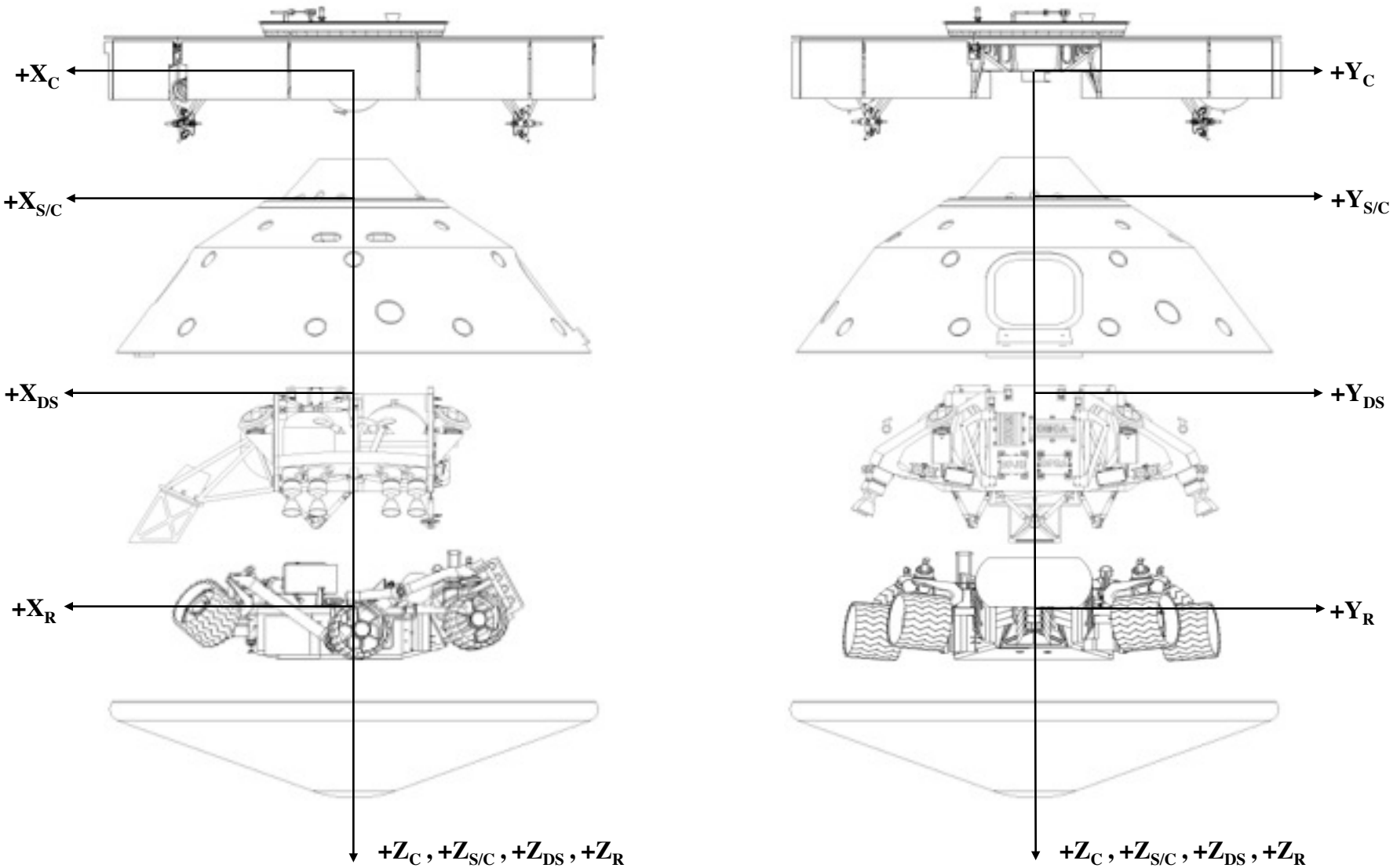
# Cruise Configuration: Bottom View





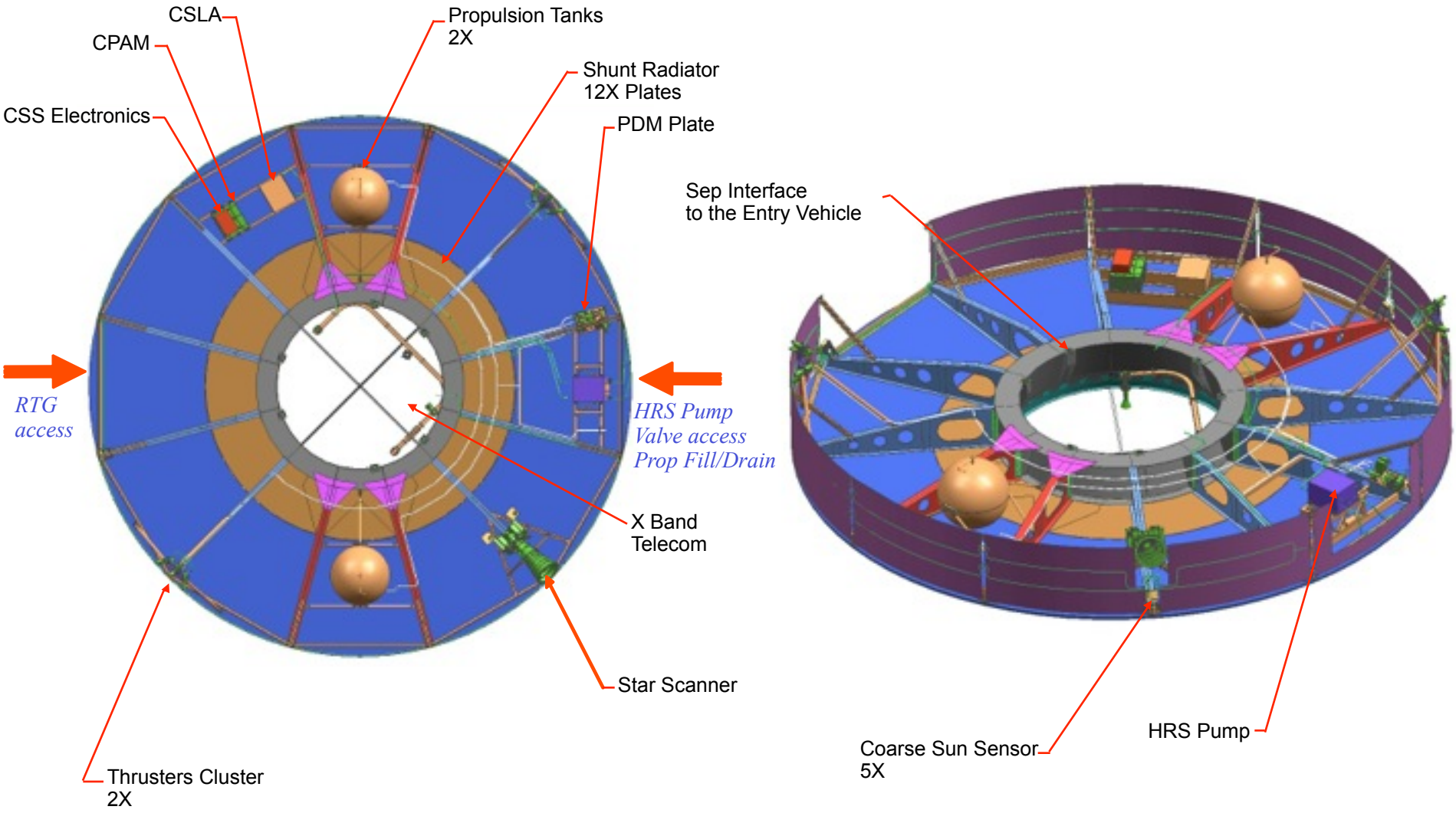
# Comparison of Coordinate Systems





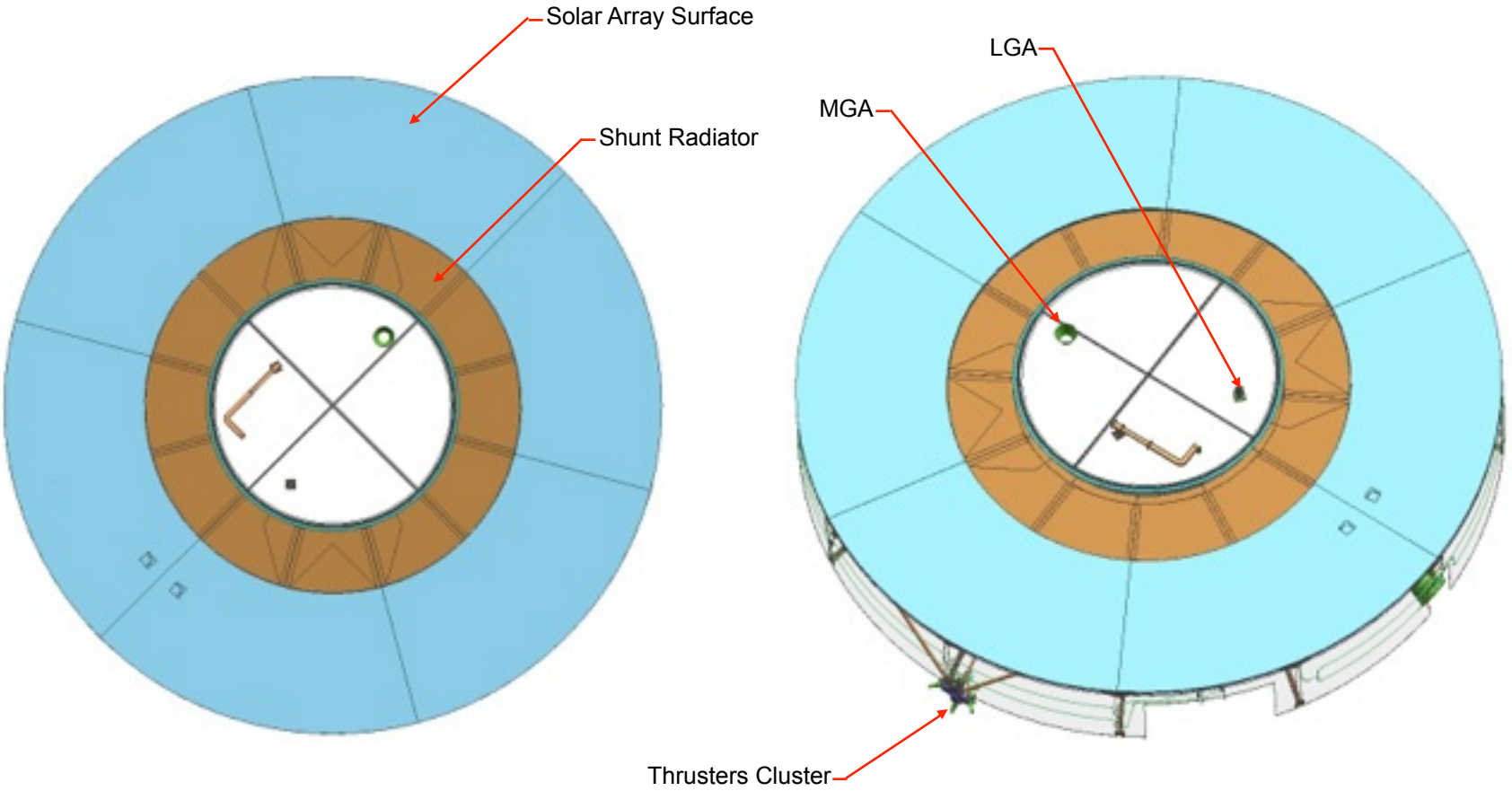
# Cruise Stage Components Placement (1)





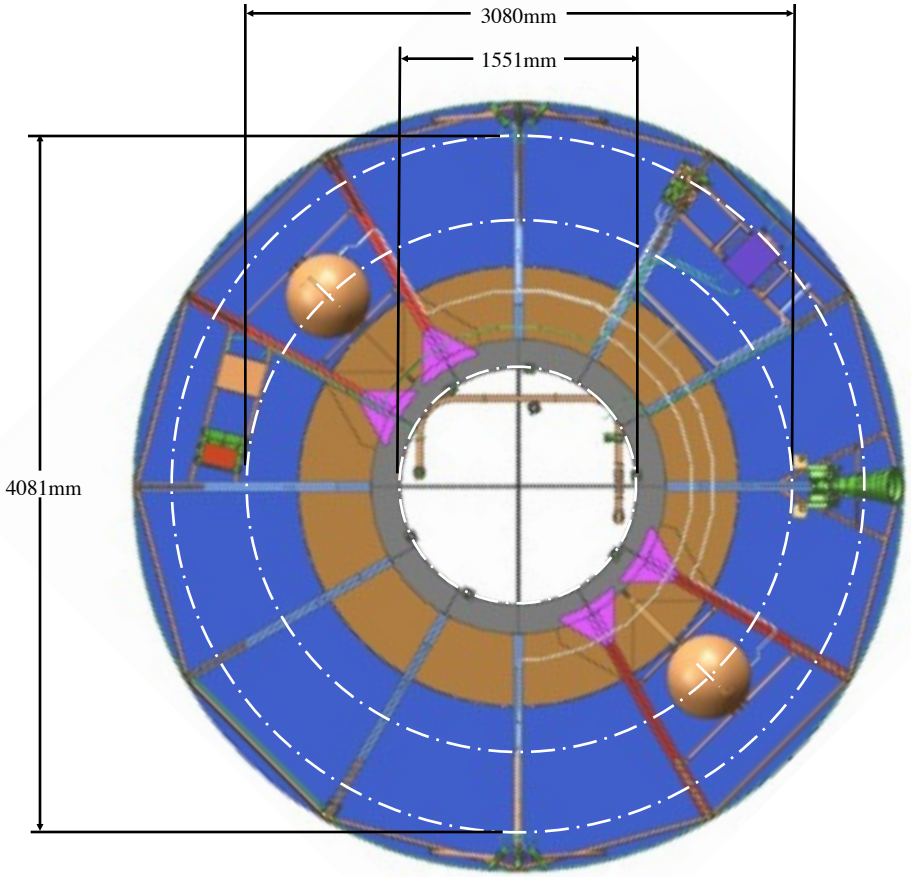
# Cruise Stage Components Placement (2)

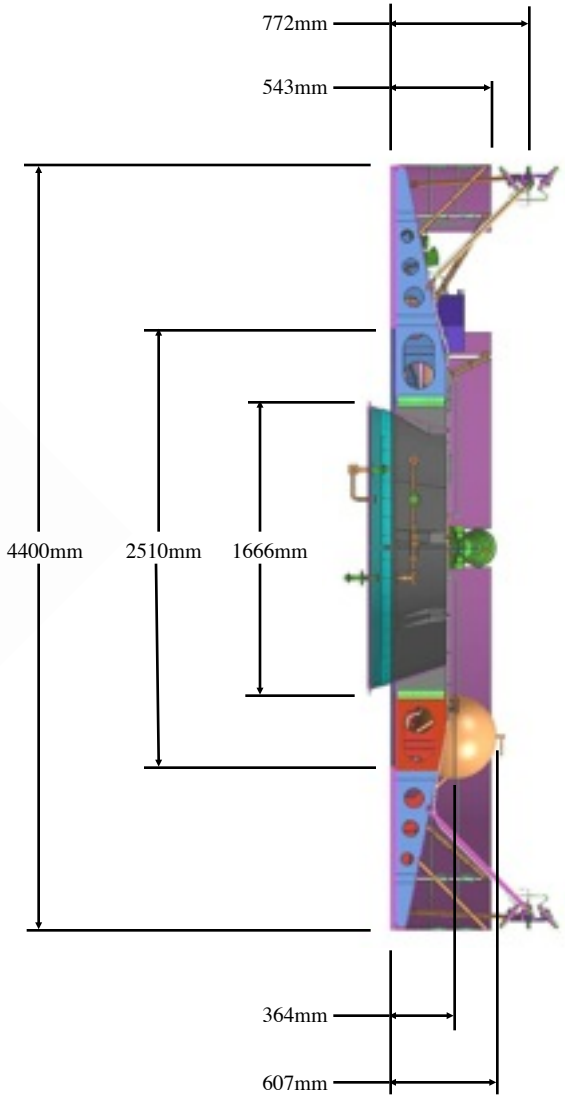




# Cruise Stage Dimensions

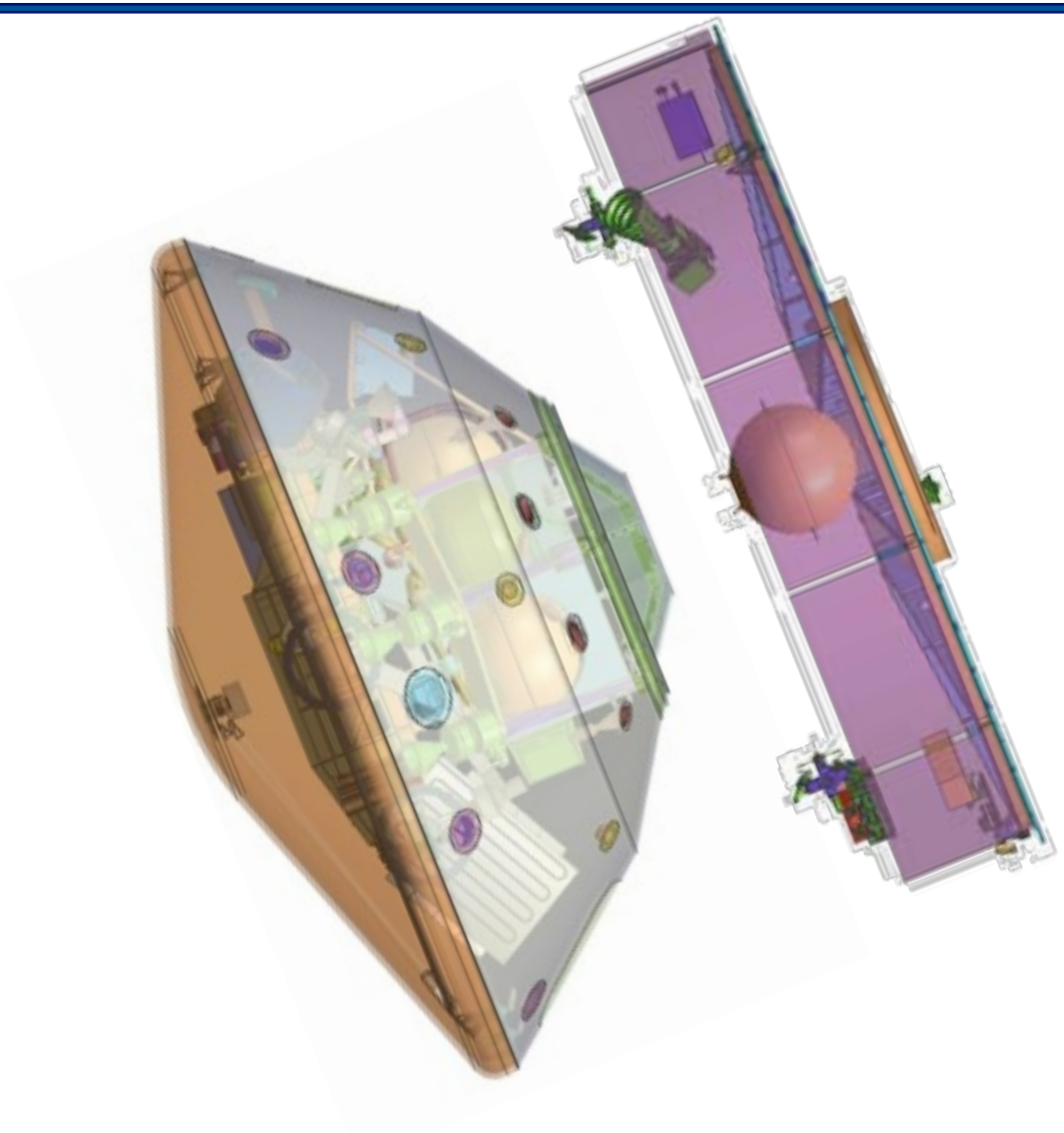




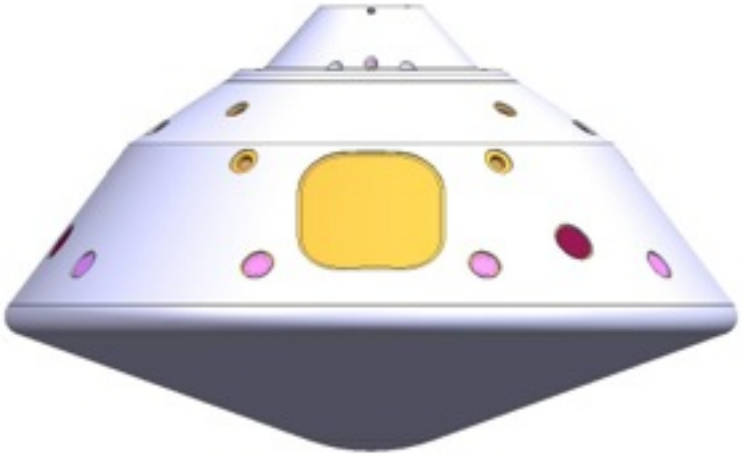



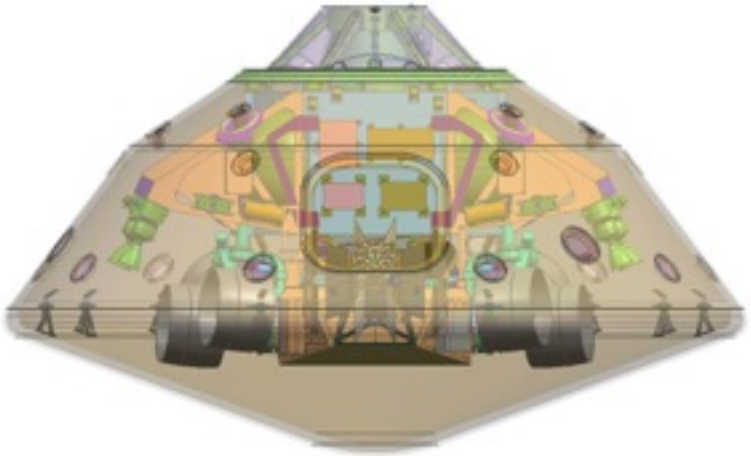
# Cruise Stage Separation





# Entry Vehicle

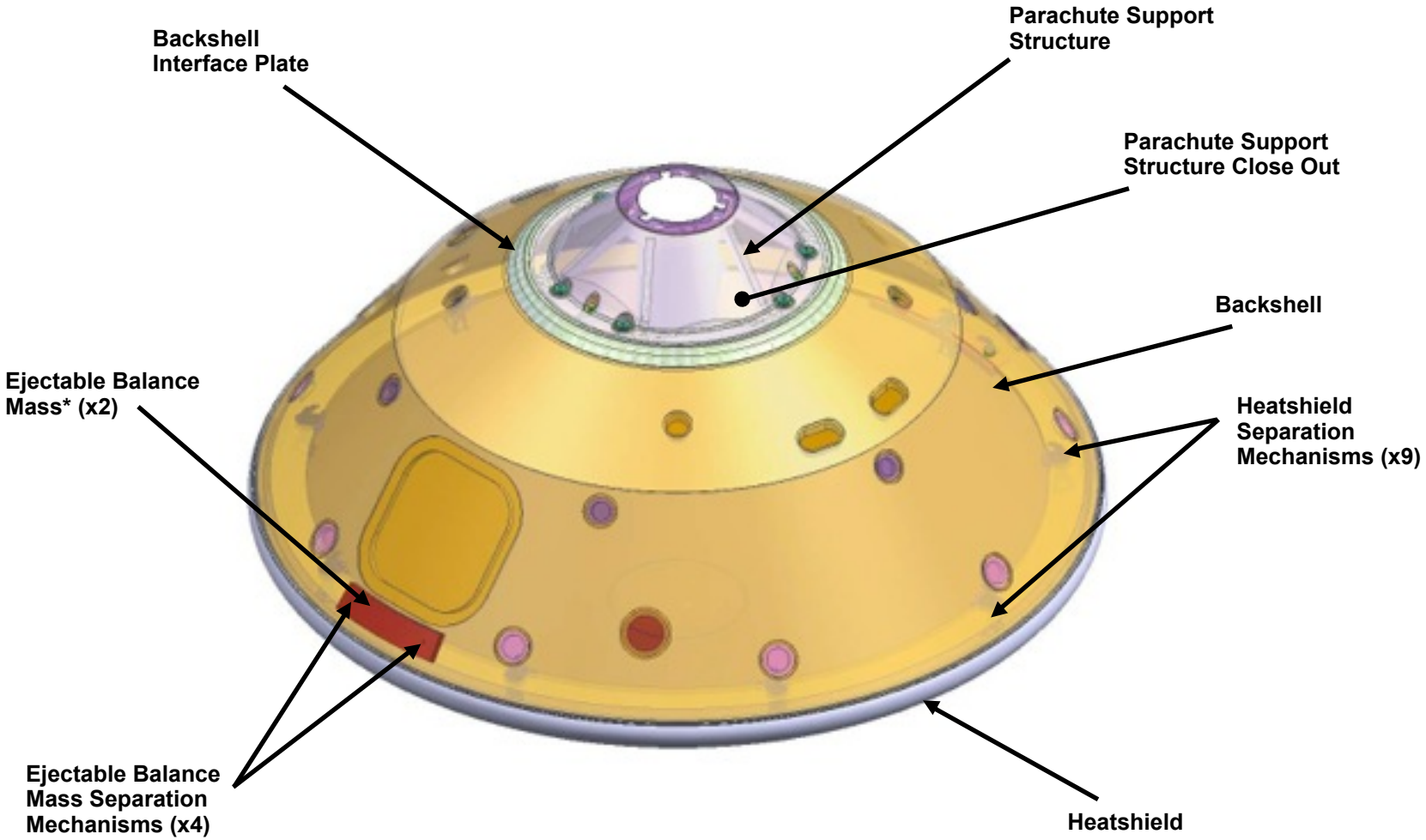




# Aeroshell Overview

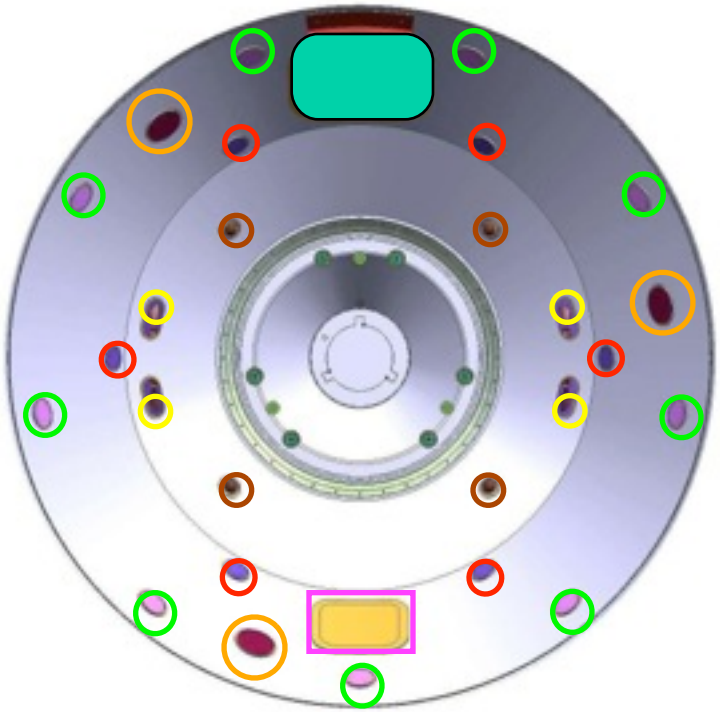


*Aeroshell structure is shown transparent for clarity*



# Aeroshell Features

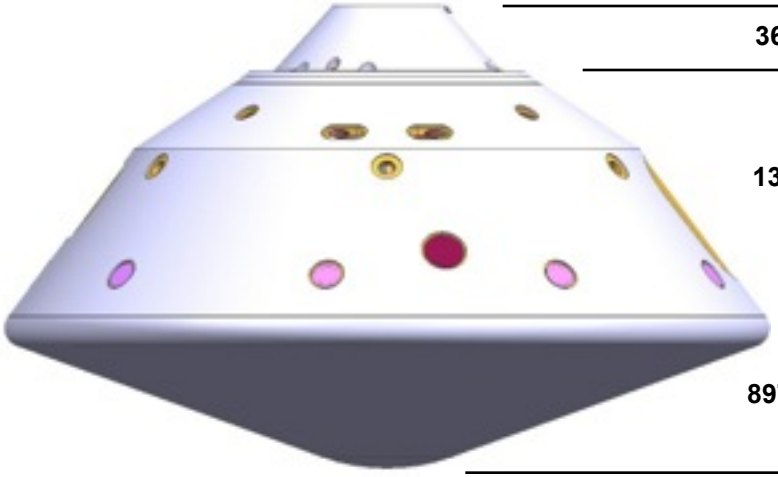


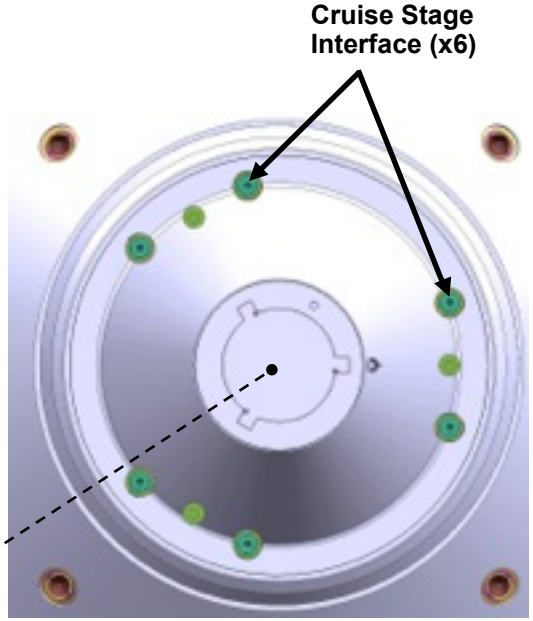


| Backshell Penetration | Locator | Size (mm) |
|---|---|---|
| Heatshield Sep Fitting/ Balance Mass Covers | | Ø 127 |
| Upper Ring Balance Mass Covers | | Ø 101.6 |
| UHF Antennae Windows | | Ø 190 |
| RCS Windows, Roll Thrusters | | 80 x 205 |
| RCS Windows, Pitch/ Yaw (Z) | | Ø 120 |
| Vent & Propulsion Access Door | | 450 x 450 |
| RTG Access Door | | 750 x 750 |

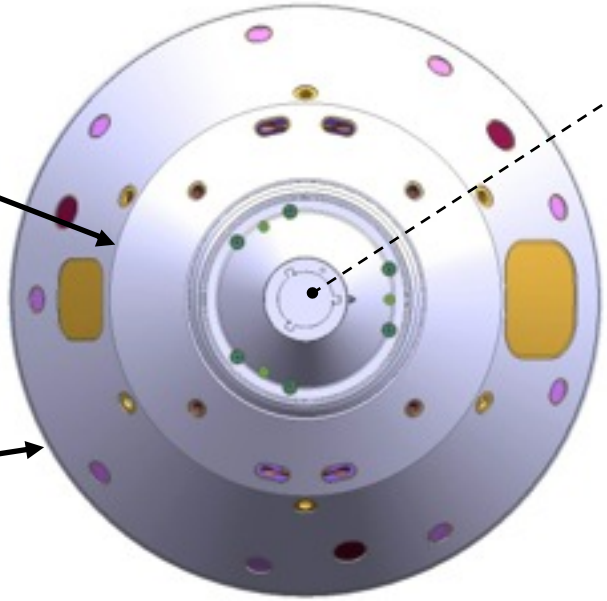
# Entry Vehicle Dimensions





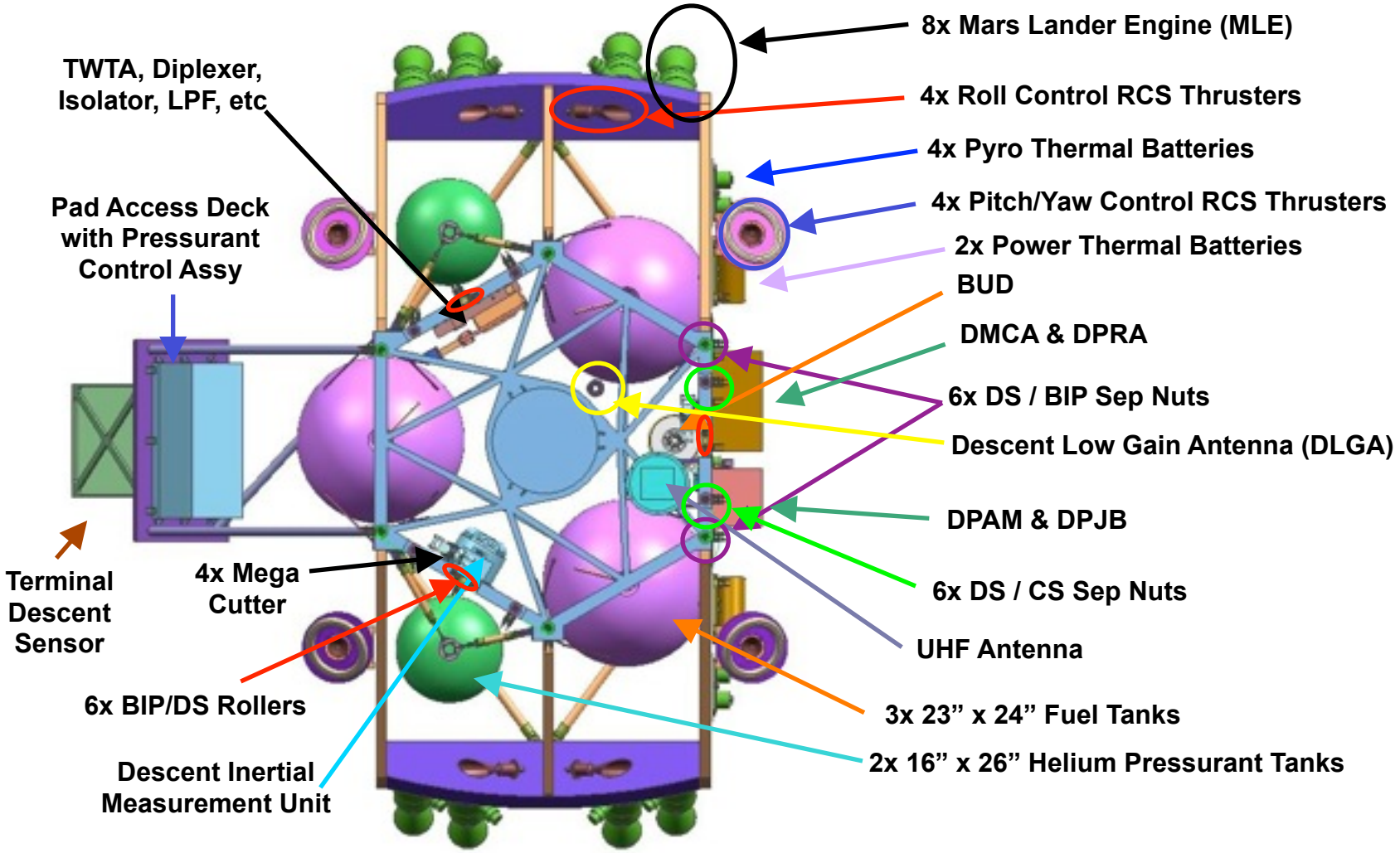




Parachute Support Structure
(PSS) Close Out with TPS



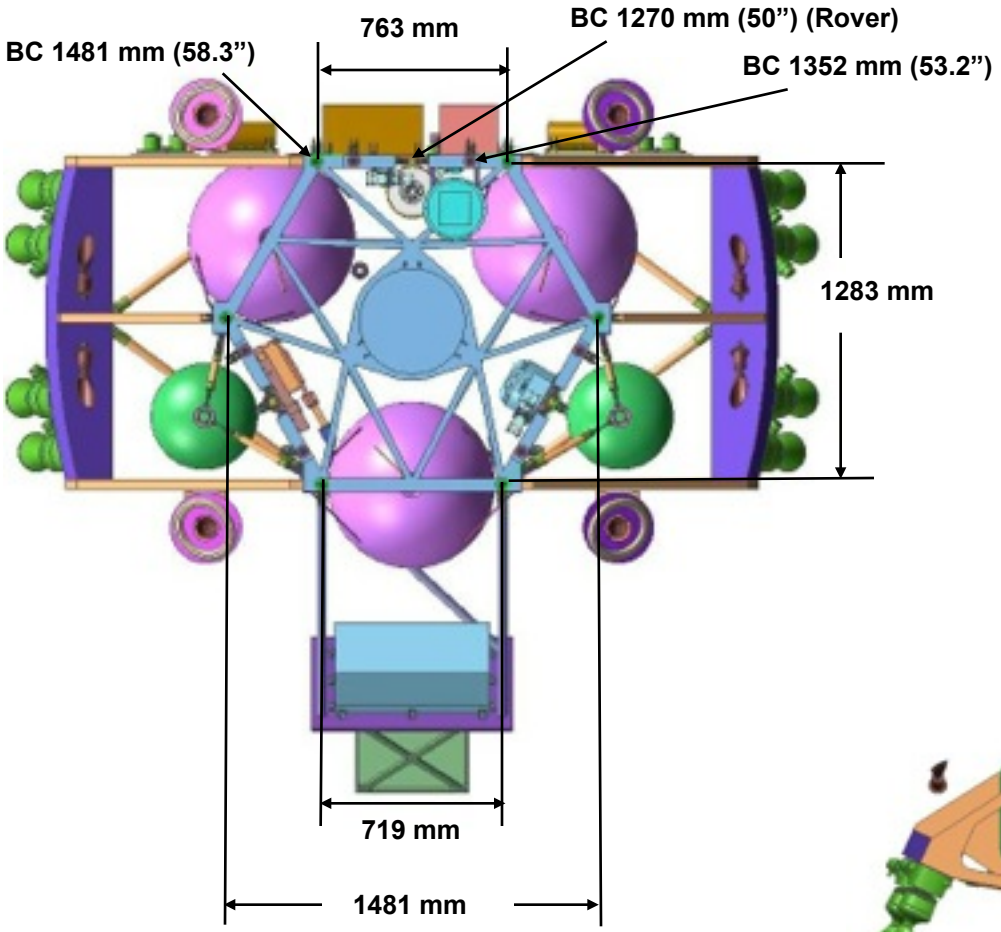
# Descent Stage Components Placement

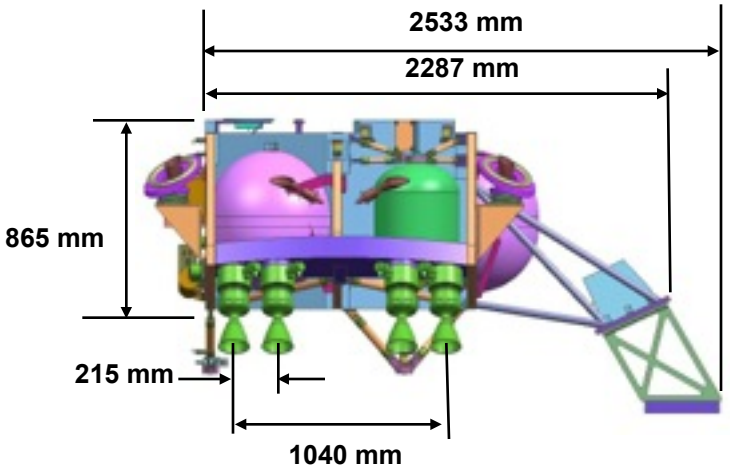


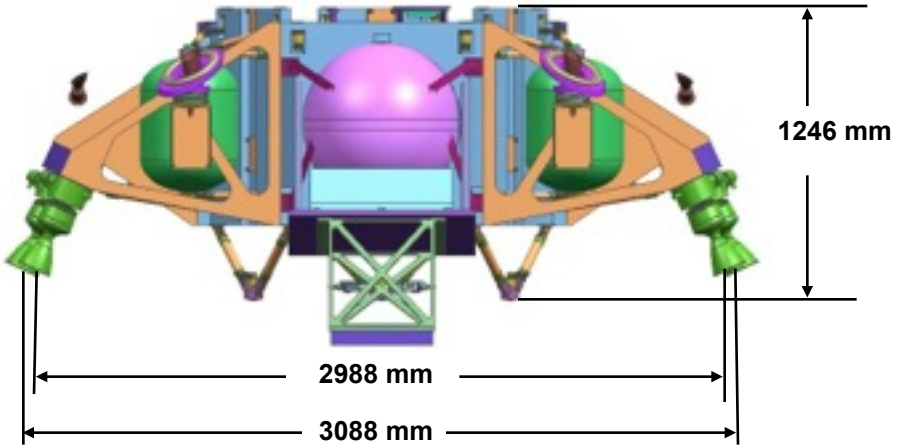


# Descent Stage Dimensions



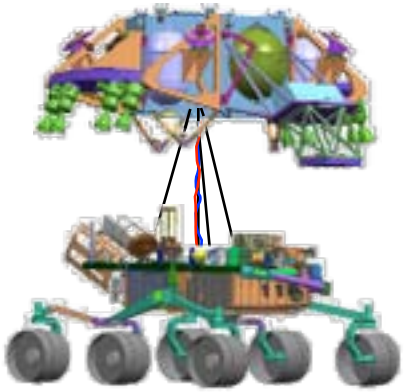


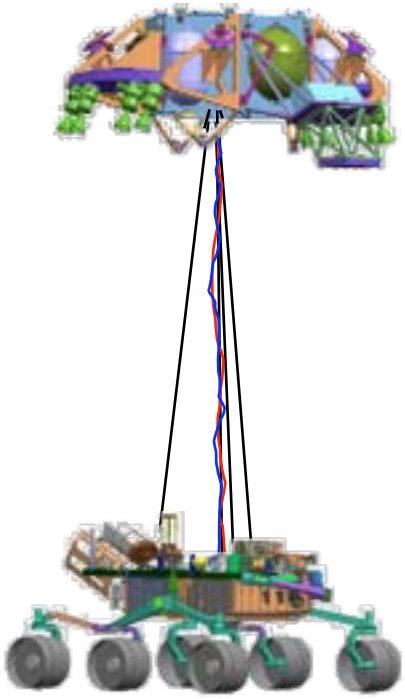



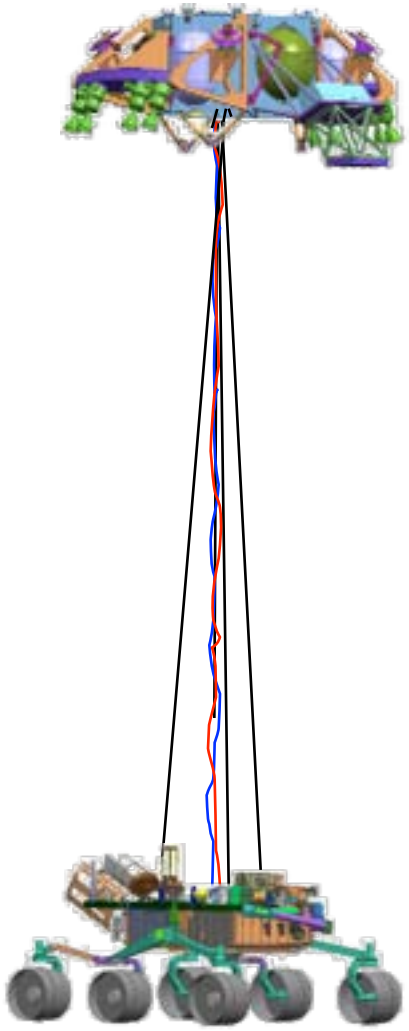



# Rover Deployment - Touchdown Configuration



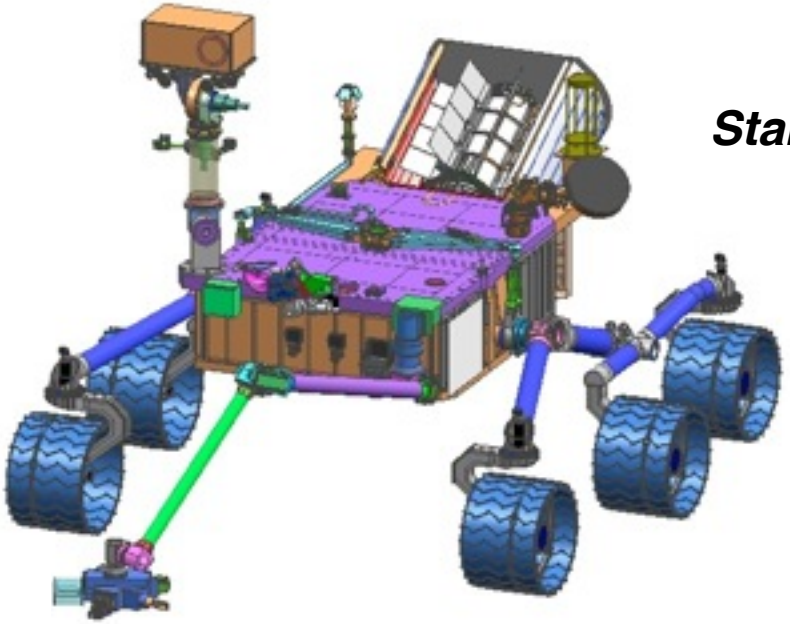






# The Bigger Better Rover

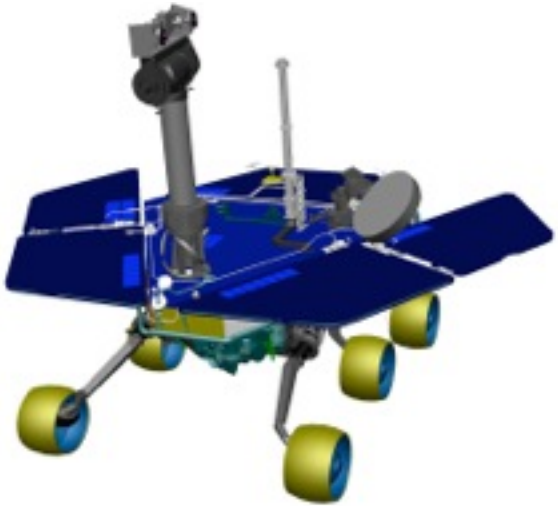




***Mars Science Laboratory - 2009***

***NASA Standard Astronaut***

***Mars Exploration Rover - 2003***



***Mars Pathfinder Sojourner Rover - 1996***

# *Mars Science Laboratory Project*
# *Project Mission System Review*

## *Entry, Descent and Landing*

Adam Steltzner
Flight System Engineering Manager
Entry, Descent and Landing

# EDL Driving Requirements

**Key Driving EDL Requirements:**

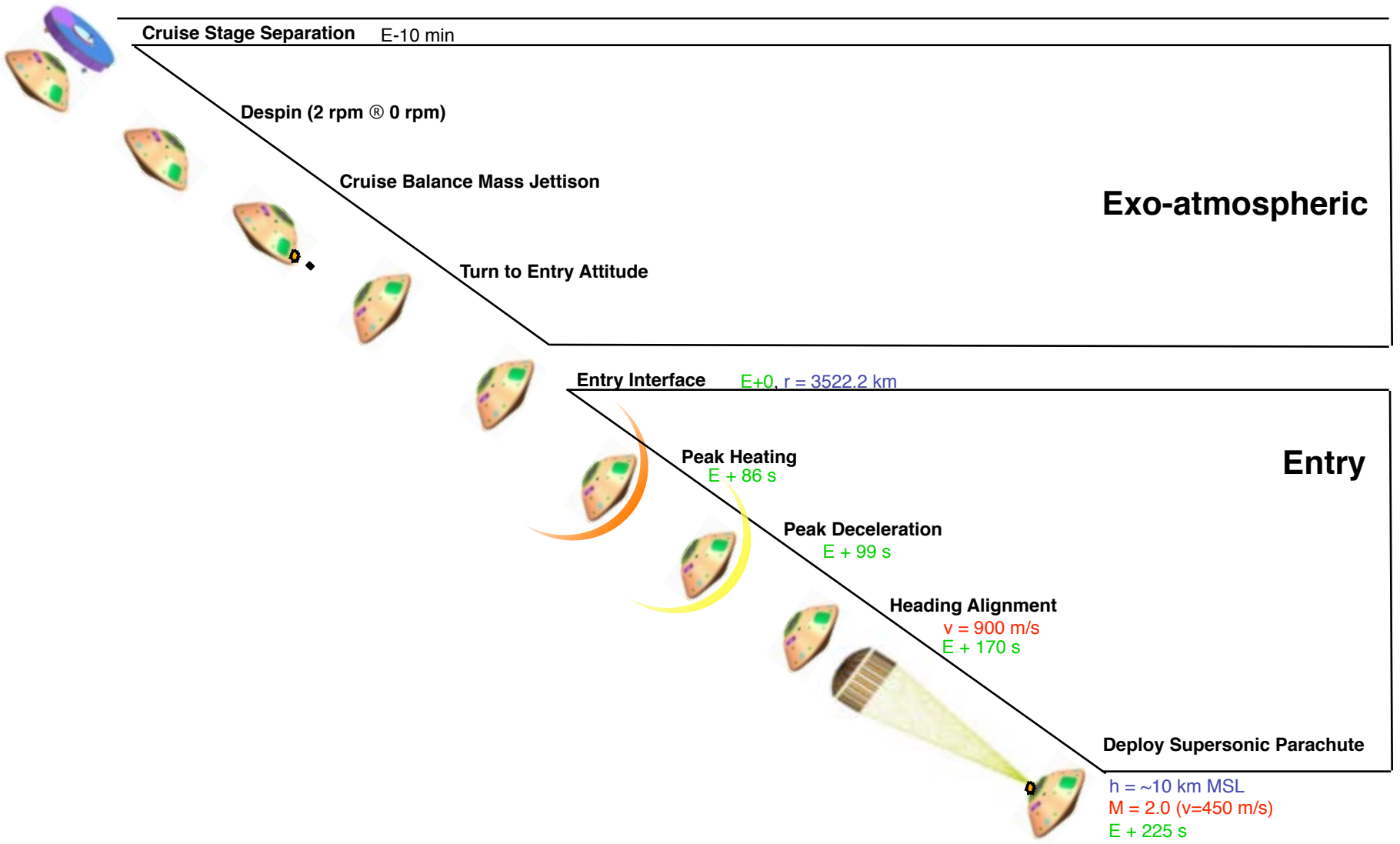
- Deliver 775 kg rover
  - Eliminates the use of airbag landing system due to interfaces, egress and mass scaling of airbags
- 2.0 km MOLA or greater altitude
  - Results in lifting element of entry design, ballistic entry will not meet performance
- Landing with a maximum error of 10 km from the targeted point
  - Results in guided entry to fly-out atmospheric and vehicle uncertainties

**Detailed Requirements:**

  - See below

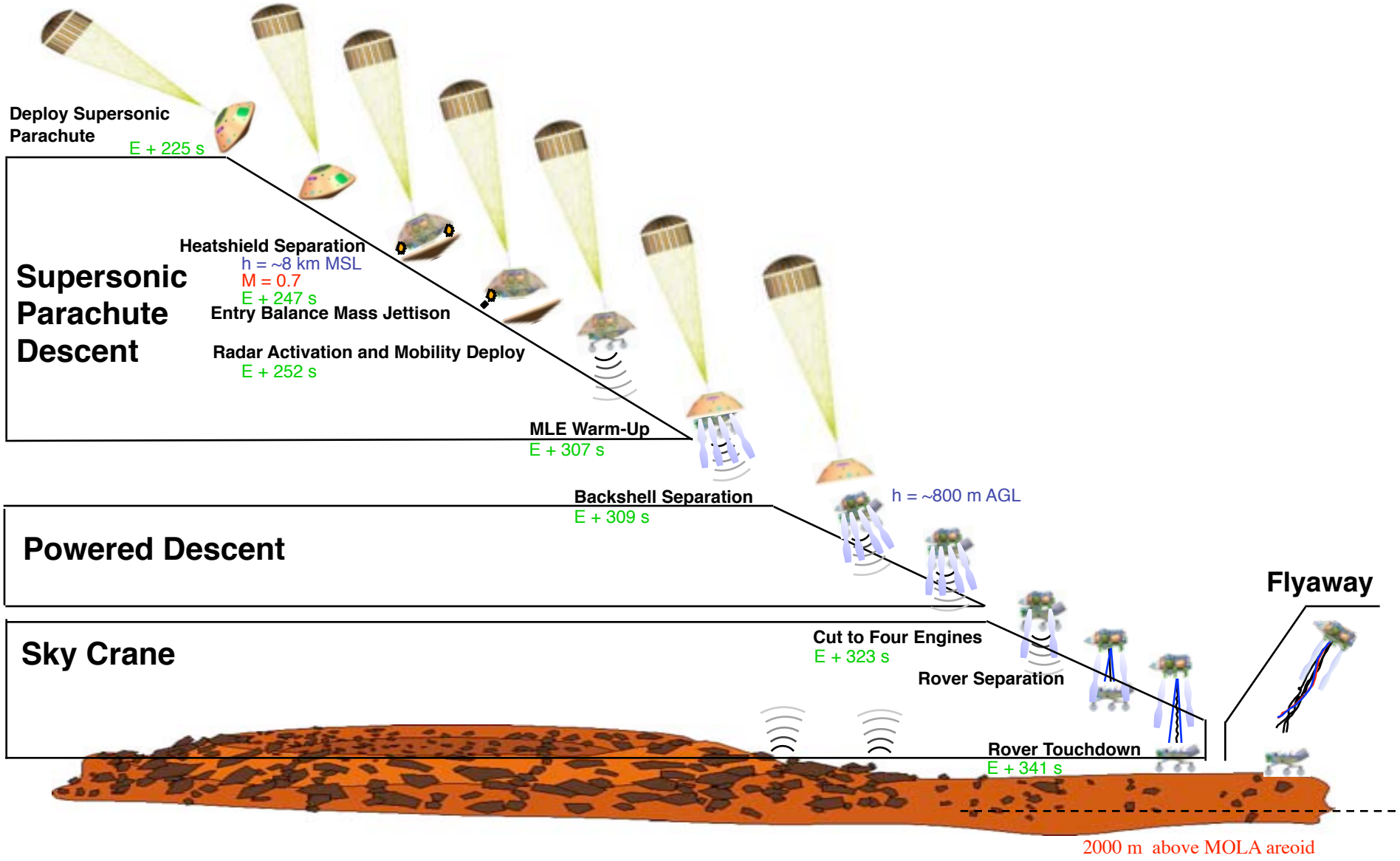
# Event Timeline 1/2





# Event Timeline 2/2



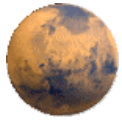


# *EDL Design Comparison and Trades*

# Trade Coverage Example: Terminal Descent

- 6-DOF Propulsion (< 1 m/s vert.,< 0.5 m/s hori.)
  - Arrest & Righting
    - Skycrane
      - Inelastic
        - Direct Payload Placement
          - Mass of structure and actuators prohibitive
    - 4-pi ST Airbag
      - Elastic
        - Auto Right
          - Actuators/ petals
            - Deflate/ Roll bar
              - Complex interfaces to rover, difficult RTG integration, feed forward,mass
          - No righting
            - No-bounce airbags technically challenging, possibly undoable on large slopes, and heavy with insufficient benefit
      - Inelastic
        - Deflate/ Roll bar
          - Complex interfaces to rover, difficult RTG integration, feed forward,mass
    - 2-pi ST Airbag
      - Inelastic
        - No righting
          - No-bounce airbags technically challenging, possibly undoable on large slopes, and heavy with insufficient benefit
    - Legs
      - Inelastic
        - 3-leg
          - active
            - crush
              - Rover egress, not able to land on 30 deg slope, tank protection
        - 4-leg
          - active
            - crush
              - Rover egress
        - Legs & outriggers
          - active
            - crush
              - Rover egress, outrigger mass for landing 30 deg slope, rock requirements, tank protection
    - Pallet
      - Elastic
        - 2-Pi Airbag
          - Mass, Complexity, Performance
      - Inelastic
        - Multiple Outriggers
          - Dispersed Energy Absorption
            - Mass, Complexity, Performance
        - Discrete Energy Absorption
          - Mass, Complexity, Performance
- No Propulsion
  - (DS2)
  - (CSAD)
- 1-DOF Propulsion (< 10 m/s vert., < 10 m/s hori.)
  - Arrest & Righting
    - 4-pi ST Airbag
      - Elastic
        - Auto Right
          - Actuators/ petals
            - (MPF/MER)
            - Deflate/ Roll bar
              - Large horizontal and vertical velocity and poor general control of the system
      - Inelastic
        - No righting
          - No-bounce airbags technically challenging, possibly undoable on large slopes, and heavy with insufficient benefit

# MSL EDL Design Table





| | Viking | MPF | MER | Phoenix | MSL |
|---|---|---|---|---|---|
| EFPA (deg) | -16.99 | -13.8 | -11.5 | -12.5 | -15.2 |
| Entry Velocity, Inertial (km/s) | 4.61 | 7.26 | 5.5 | 5.5 | 5.3-6.0 |
| Landing Sol, (Ls) | 97 | 143 | 330 | 90 | 120 -150 |
| Heatshield Geometry | 70 sphere-cone | 70 sphere-cone | 70 sphere-cone | 70 sphere-cone | 70 sphere-cone |
| Heatshield Diameter (m) | 3.5 | 2.65 | 2.65 | 2.65 | 4.5 |
| Ballistic Coefficient (kg/m^2) | 63 | 62.3 | 88 | 71 | 121 |
| Entry Mass (kg) | 930 | 585 | 836 | 608 | 2804 |
| Control Method | Guided/Lift-up | Ballistic | Ballistic | Guided/Lift-up | Guided |
| L/D | 0.18 | 0 | 0 | 0.06 | 0.24 |
| Trim angle @ M=24 (deg) | -11 | 0 | 0 | -4 | -15.5 |
| Landing Ellipse Semi-Major Axis (km) | 100 | 75 | 60 | 90-125 | 10 |
| Peak Heating Rate (W/cm^2) | 21.02 | 106 | 44 | 58.7 | 140 - 155 (margined) |
| Integrated Heat Load (J/cm^2) | 1100 | 3865 | 3687 | 3245 | ~ 6000 (margined) |
| Heatshield TPS Material | SLA561-V | SLA561-V | SLA561-V | SLA561-V | SLA561-V (TBC) |
| Heatshield TPS Thickness (in) | 0.54 | 0.75 | 0.62 | 0.55 | 0.9 |
| Parachute Type | D-G-B | D-G-B | D-G-B | D-G-B | D-G-B |
| Parachute Cd @ | 0.677 | ~0.48 | ~0.48 | 0.677 | 0.677 |
| Parachute Diameter (m) | 16.15 | 12.4 | 14.1 | 11.5 | 19.7 |
| Parachute x/D | 8.5 | 9.4 | 9.8 | 9.5 | 9.5 |
| Touchdown Velocity (m/s) | 2.4 | 25 | 25 | 2.4 | 0.75 |
| Descent Propulsion | Throttled N2H4 | Solid | Solid | Pulsed N2H4 | Throttled N2H4 |
| Landing Site Elevation (km) | -3.5 | -1.5 | -1.3 | -3.5 | +2.0 |
| Landed Mass, Dry (kg) | 590 | 360 | 539 | 364 | 1541 |
| Mobile Mass (kg) | 0 | 11 | 173 | 0 | 775 |
| Usable Equipment (kg) | 244 | 92 | 173 | 167 | 775 |
| Payload Inst. and Accmd. (kg) | 92 | 6 | 9.3 | 55 | 140 |
| Usable/Entry Ratio (non-structure and propulsion for landers) | 26% | 16% | 21% | 27% | 28% |

# *EDL Design Topic Areas*

## *Guided Entry and TPS*

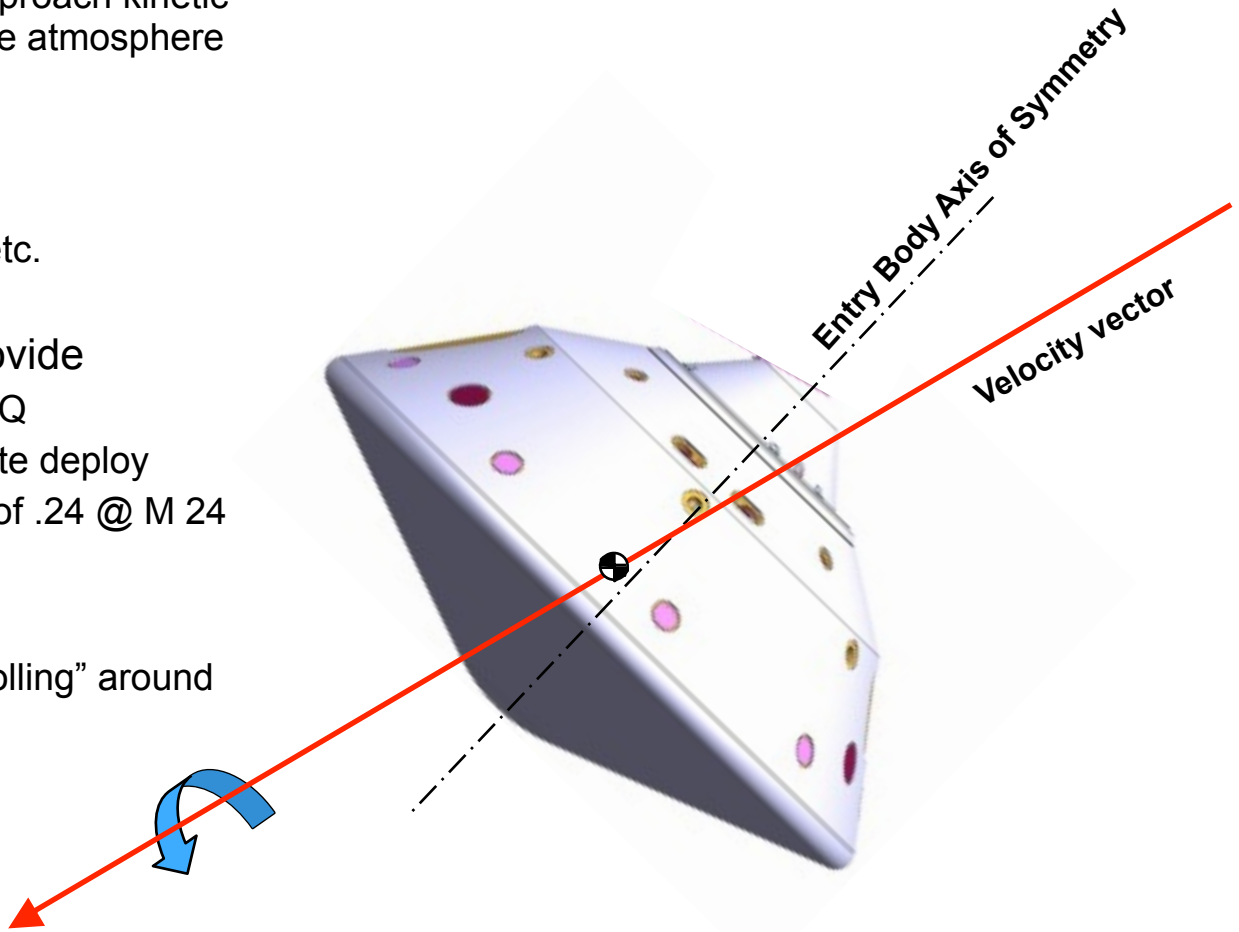
## *Parachute Descent*

## *Powered Descent/Sky Crane*

# Entry: Aerodynamic Deceleration and Control



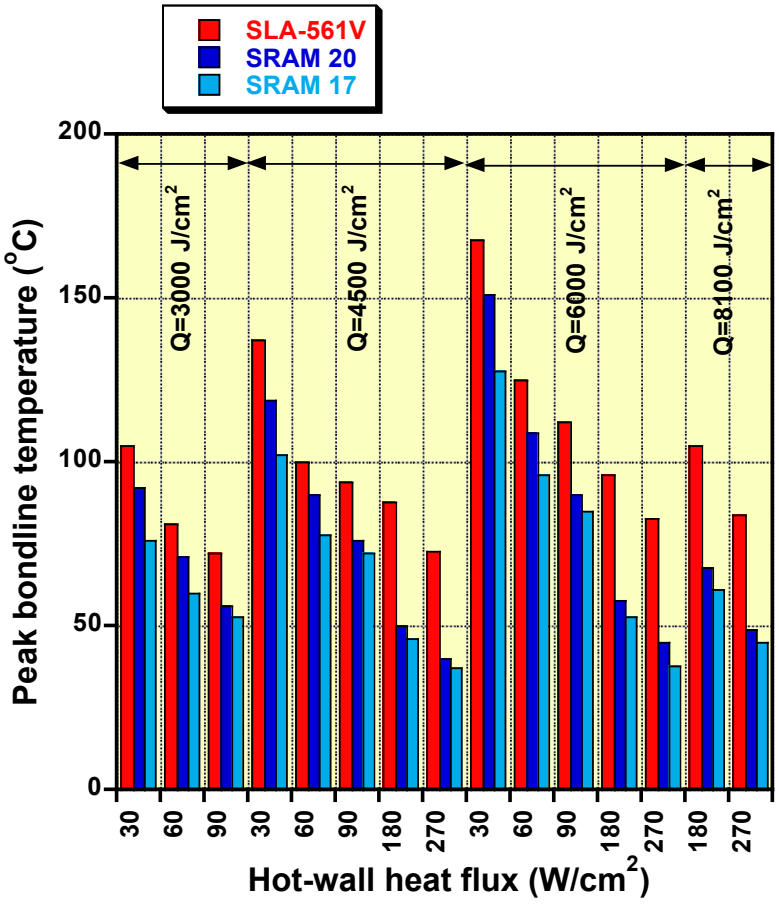
- Primary decelerator is entry body drag
  - Approximately 99% of approach kinetic energy is dissipated to the atmosphere
- Lifting entry configuration
  - Viking, Phoenix(?)
  - Shuttle, Apollo, Gemini, etc.
- CM offset calculated to provide
  - ~15 degree AOA @ max Q
  - ~19 deg AOA @ parachute deploy
  - Produces a nominal L/D of .24 @ M 24
- Apollo Guidance Algorithm
  - Guidance achieved by “rolling” around velocity vector
    - Apollo, Viking



# Entry: Thermal Protection

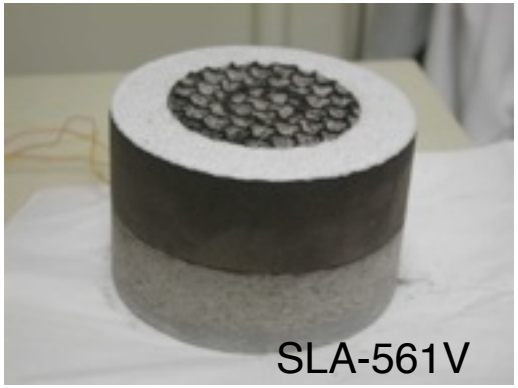


- Heritage SLA 561-V material has demonstrated performance in MSL flight regime
  - Test conducted at NASA Ames have shown SLA and other materials can meet the heat rate and heat load requirements of MSL




***Post-test photo: 180 W/cm²/6000 J/cm²***

4 inch diameter samples
0.75 inches thick SRAM & SLA




With SIRCA collar
Total diameter 4 inches

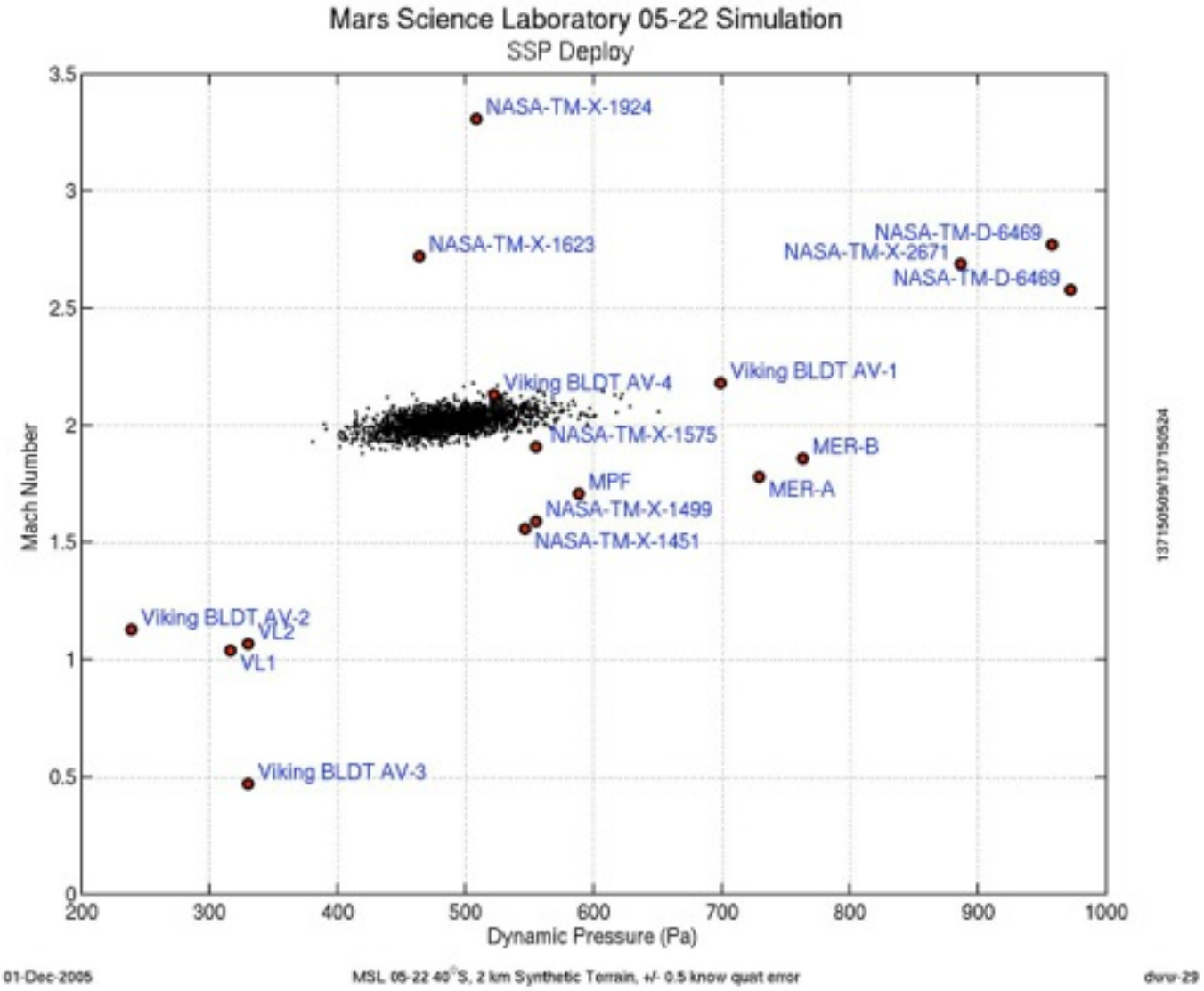
# Parachute Descent



- Secondary decelerator is Parachute drag
  - Approximately 95% of remaining Kinetic energy is dissipated to the atmosphere
- Viking configuration parachute
  - Larger diameter (19.7 m vs 16.1 m)
  - Modern materials (kevlar vs. polyester)
- Deployment conditions
  - Mach number < 2.15 (Viking)
  - Dynamic Pressure < 850 Pa (MER)
  - Deployment AoA @ deploy < 15 deg. (Viking)
- Parachute scaled to closely match Viking test post deployment flight conditions
  - Area ratios
  - On chute ballistic coefficient
  - Area oscillations matched

# Parachute Deployment

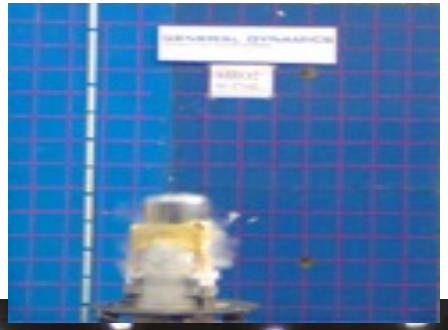




# MSL Parachute System Qualification

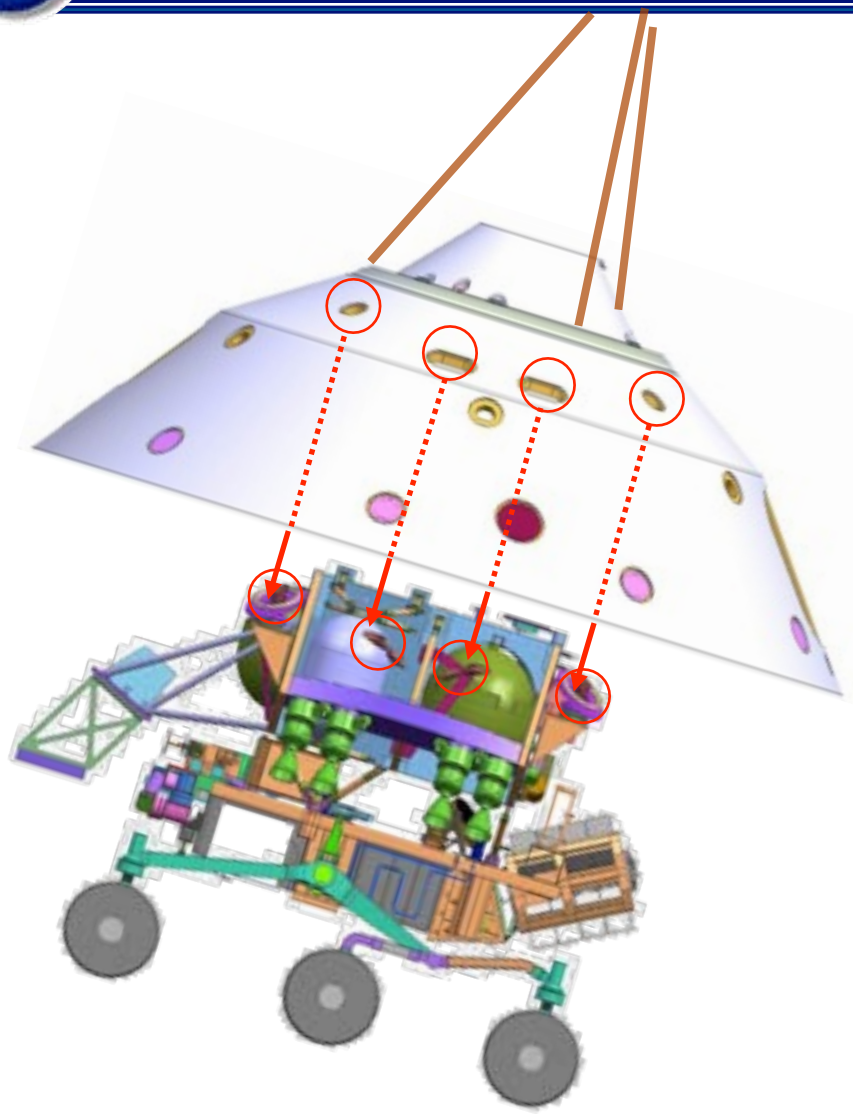


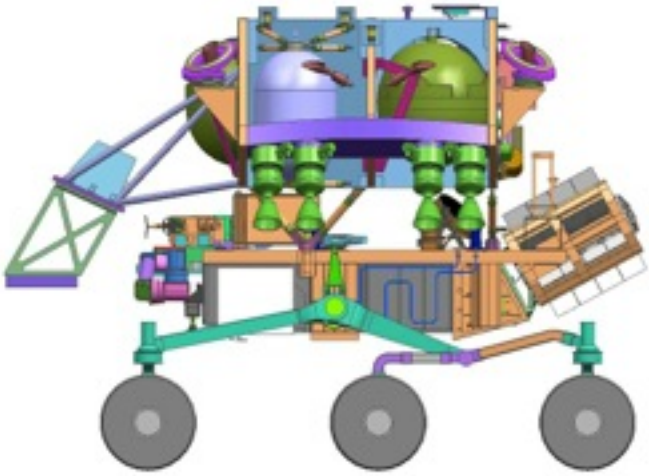
- Parachute Qualification requires validation of:
  - Deployment
  - Initial Inflation (Will it open?)
  - Inflation Strength (Will its structure survive inflation loads?)
  - Inflated Performance (Drag and Stability)
- MSL will make use of an augmented MER approach to qualification
  - Deployment: **Test**: Ground-based Mortar Firing tests of MSL system
  - Initial Inflation: **Heritage argument** by similarity to existing Mars flight and Earth high altitude test data (See *MSL Parachute Qualification Review Package*)
  - Inflation Strength: **Test**: Subsonic, full-scale windtunnel strength test of MSL system, augmented to include cyclic loading to cover the possibility of area oscillation in supersonic conditions
  - Inflated Performance: **Existing Data**: Viking and MER windtunnel data in conjunction with Viking, MPF, and MER flight data
- Parachute qualification program review results will be discussed later

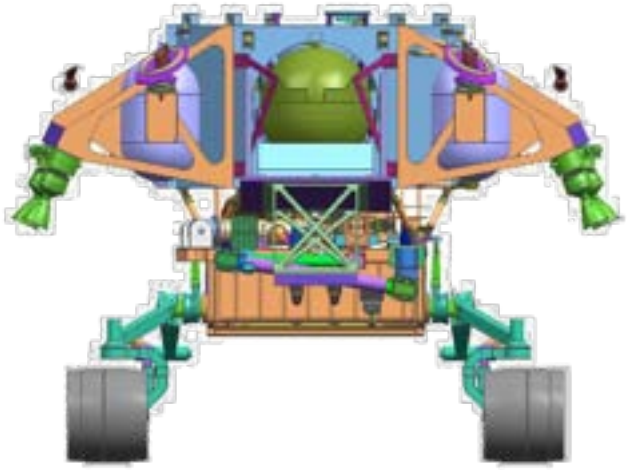


# Powered Descent: Vehicle Configuration

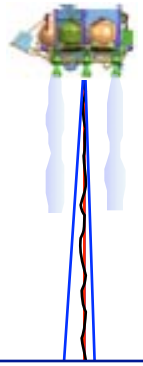
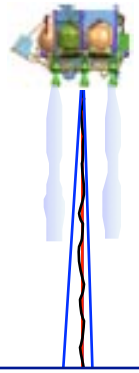




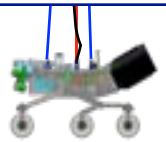
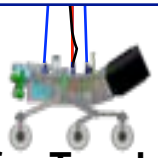
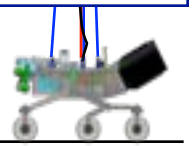




# Sky Crane Maneuver Description

***Descent Stage commanded to follow Reference Trajectory: $V_{Vertical} = 0.75$ m/sec & $V_{Horizontal} = 0.0$ m/sec***

## One-Body Phase

*Duration = ~2 sec*

Purpose:
Damp throttle-down transients

Entry State: h = 19.5 m
Exit State: h = 18 m

Event on entry:
"Shut-down" 4 (of 8) MLE's (to < 1% of total)

## Deployment Phase

*Duration = ~6 sec*

Purpose:
Rover/DS separation

Entry State: h = 18 m
Exit State: h = 13.5 m

Events on entry:
- Stop TDS altimetry
- Change controller gains
- Fire rover deployment pyros

## Post-Deploy Settling Phase

*Duration = ~2 sec*

Purpose:
Damp separation transients

Entry State: h = 13.5 m
Exit State: h = 12 m

Event on entry:

## Ready for Touchdown Phase

*Duration = 0-8 sec*

Purpose:
Wait for touchdown

Entry State: h = 12 m
Exit State: h = 9 m

Event on entry:
- Enable touchdown logic

Exit Condition:
- Rover off-loaded for persistent time

## Touchdown Phase

*Duration < 2 sec*

Note:
Touchdown K.E. ~ 450 J
Traverse K.E. ~ 800 J

# Sky Crane System Architecture



**Two-Body Architecture**
Decouples descent stage control from touchdown event and allows persistent touchdown signature

**Prop and GNC Away from Surface**
Closed loop during the touchdown event

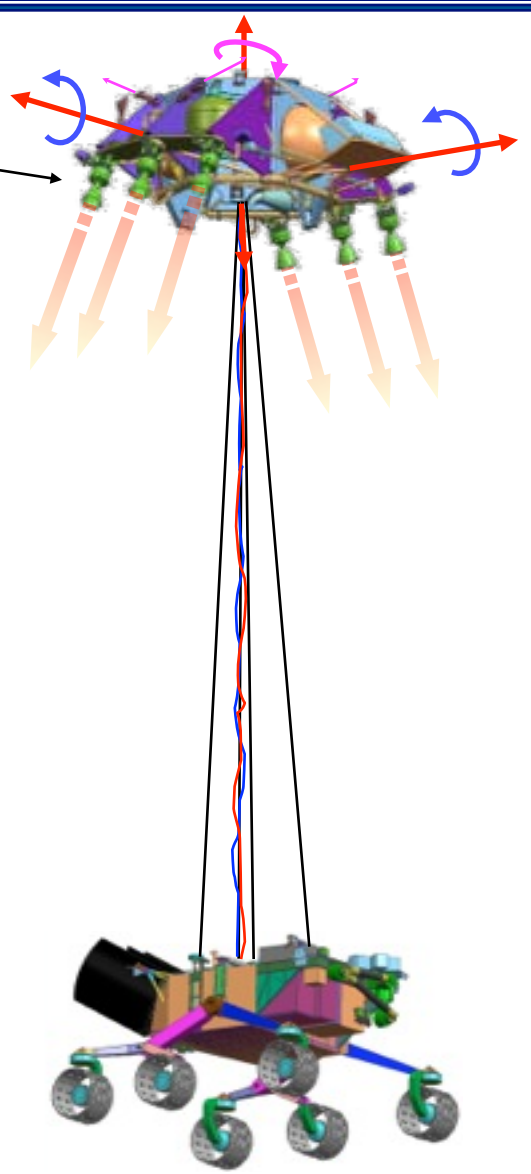
**High Bandwidth Vertical Velocity Control**
results in low and near constant D/S velocity

**Higher Stability**
Persistence of tethering during touchdown improves landing stability on rough terrain

**Lower Loads**
Low velocities
allows rover landing loads to be similar to the rovers driving loads

**System Design**
High stability and low landing loads mean:
- Separate TD system not required
- Egress system not required

**Rover Becomes the Touchdown System**
Rover provides ground clearance, static stability, and terrain adaptation

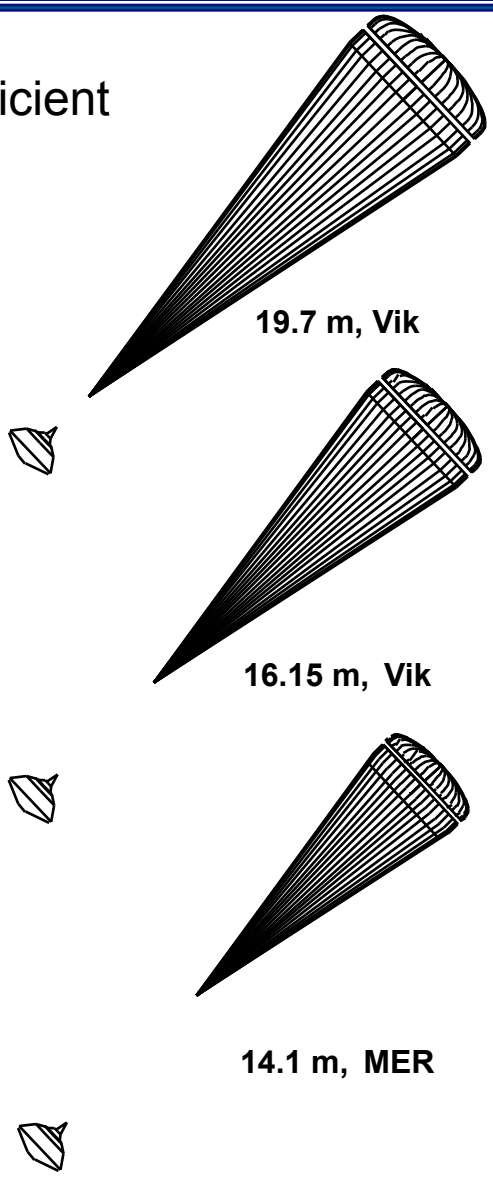


# Mass Growth and Configuration



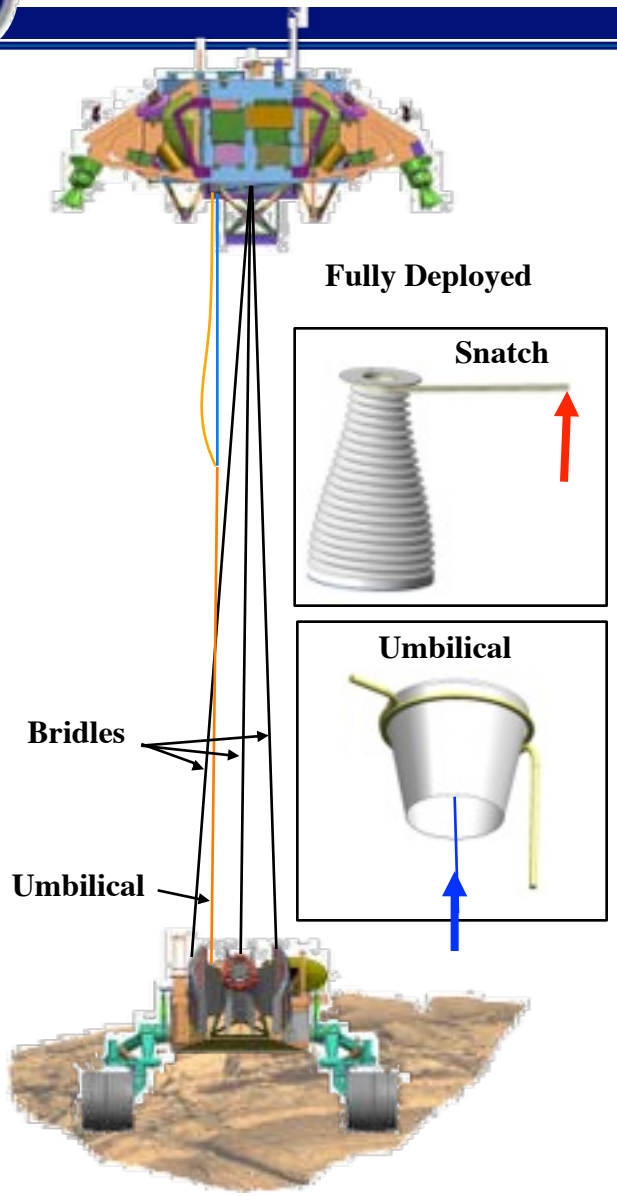
Comparison of mass growth and on-chute ballistic coefficient

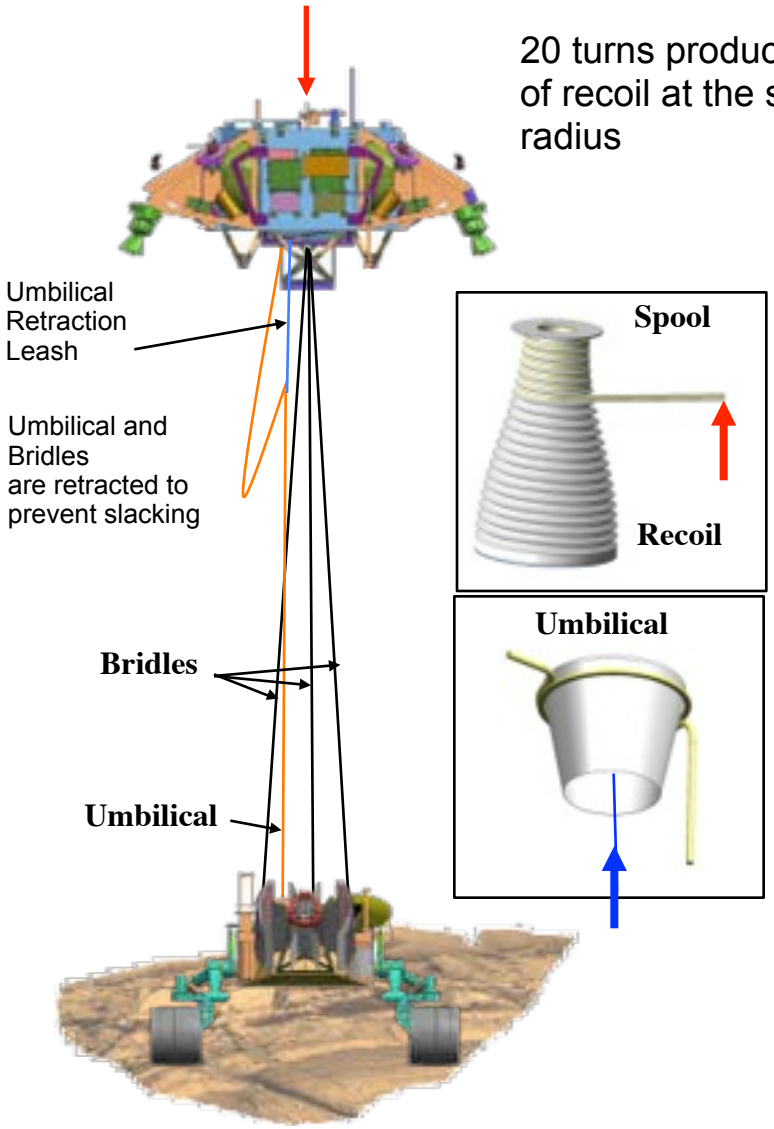
| | Configuration | Rover/ Entry Mass (kg) | Capsule/Chute Diameter Ratio (kg) | β on Chute (kg/m | Comments |
|---|---|---|---|---|---|
| Work-to-date | MSL MCR 10/03 | 900/2400 | 0.28 | 17.3 | 16.15 m Vik |
| | MSL M2 7/04 | 550/1883 | 0.23 | 13.6 | 16.15 m Vik |
| | MSL Costing 6/05 | 725/2705 | 0.28 | 19.5 | 16.15 m Vik |
| | ***Baseline*** | **755/2675** | **0.23** | **13** | **19.7 m Vik** |
| | **MSL w/MER chute** | **755/2675** | **0.36** | **28.7** | **14.1 m MER** |
| | **Viking** | **NA/1168** | **0.22** | **8.42** | **16.15 m Vik** |
| | **MER** | **174/845** | **0.22** | **12.4** | **14.1 m MER** |



# Uniform Slack Maintenance



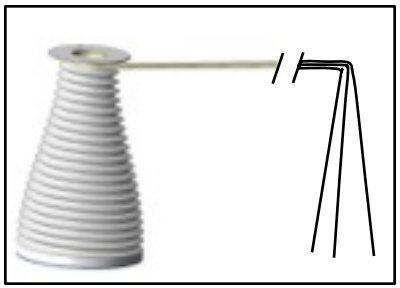



20 turns produces 4 m of recoil at the small radius

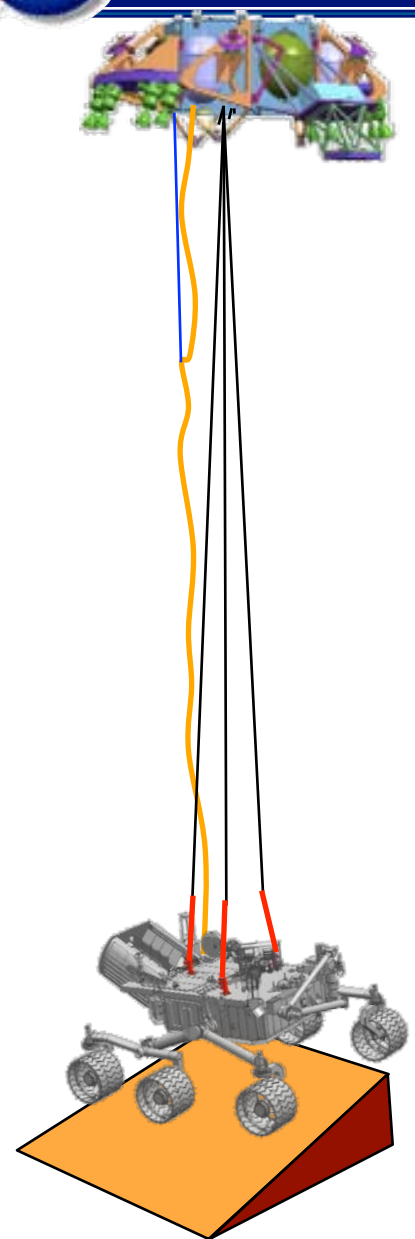
# Pre-Touchdown

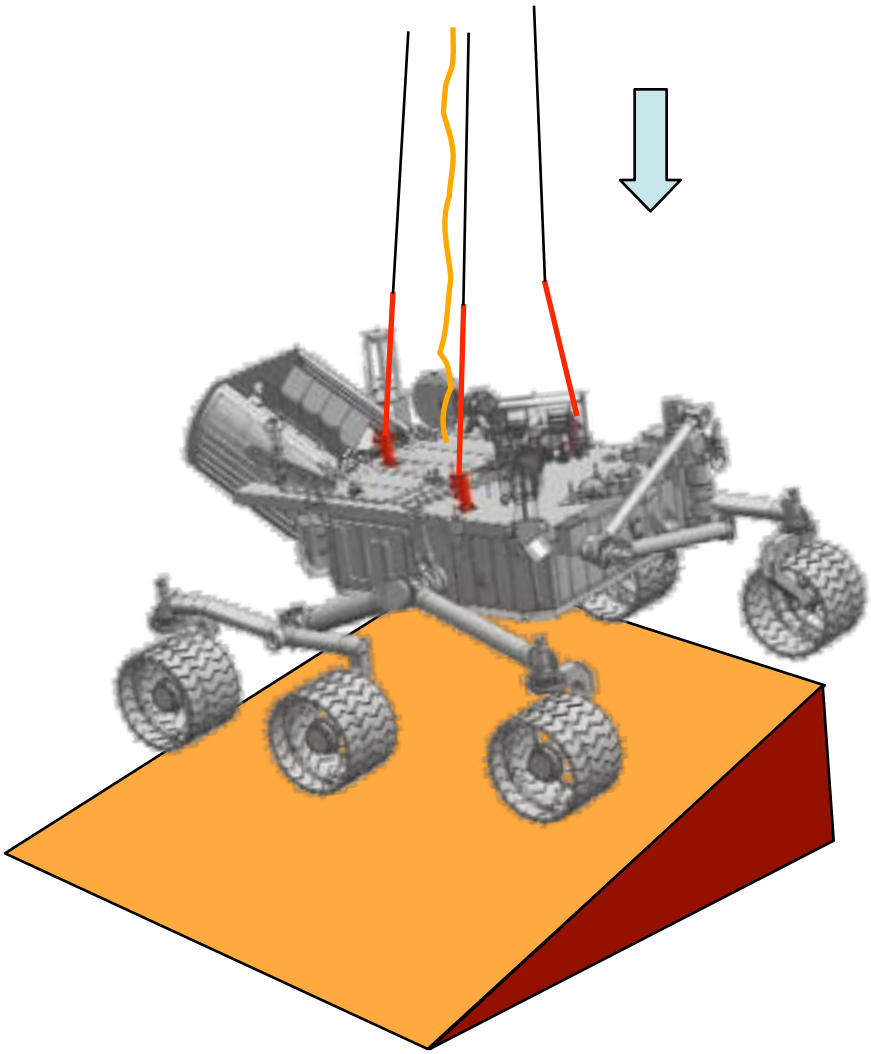


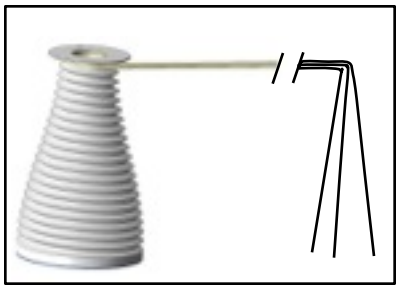


# Initial Touchdown



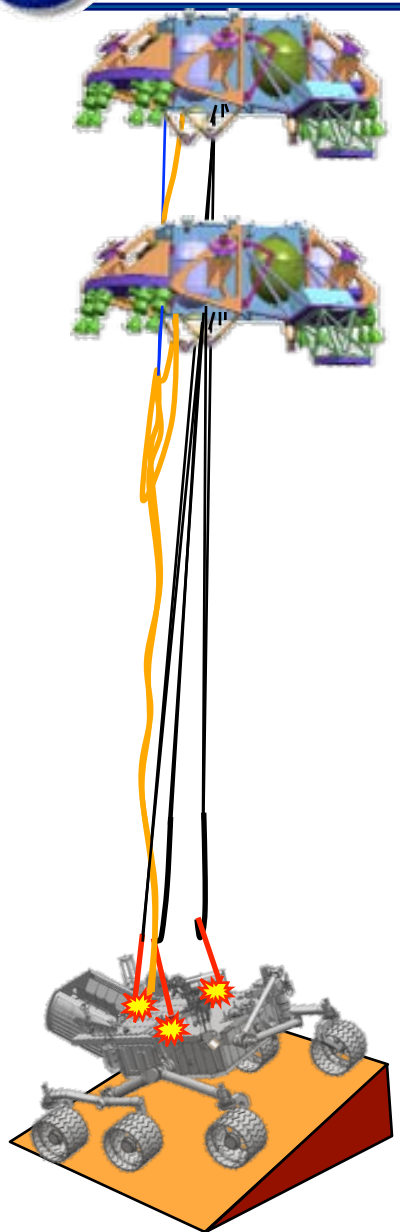


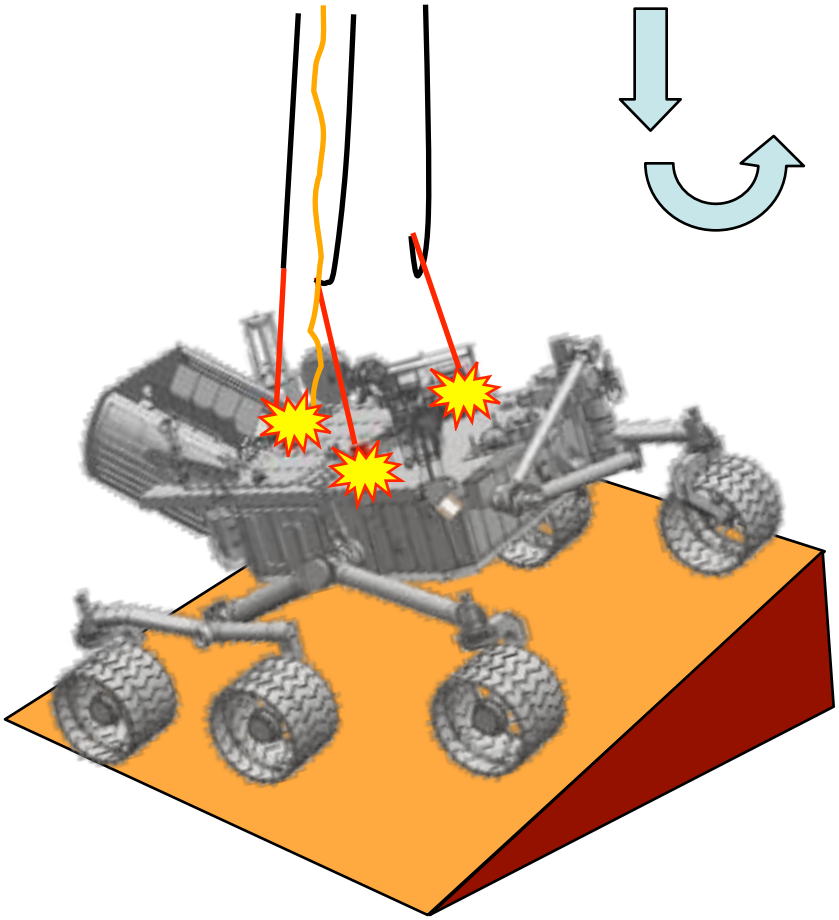


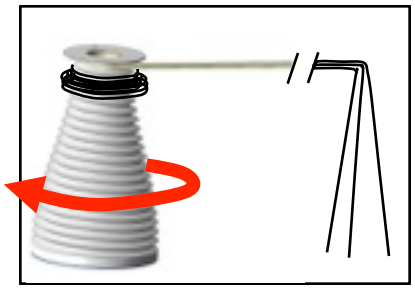


# Complete Touchdown



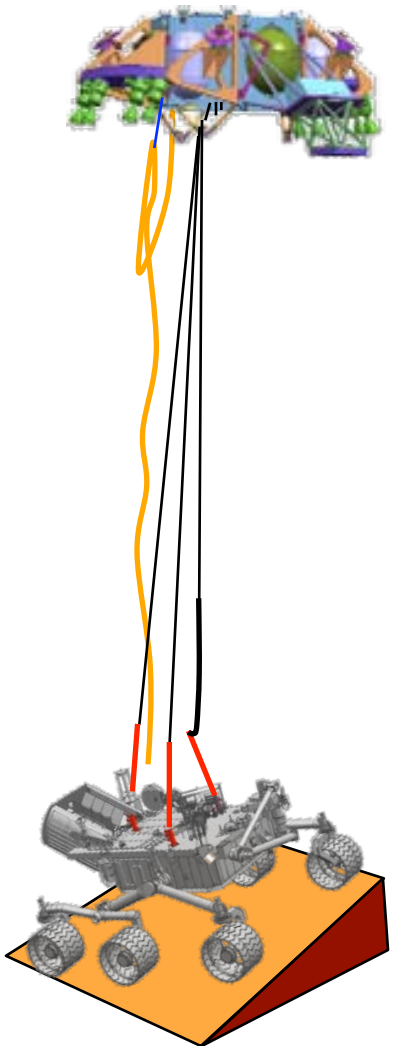


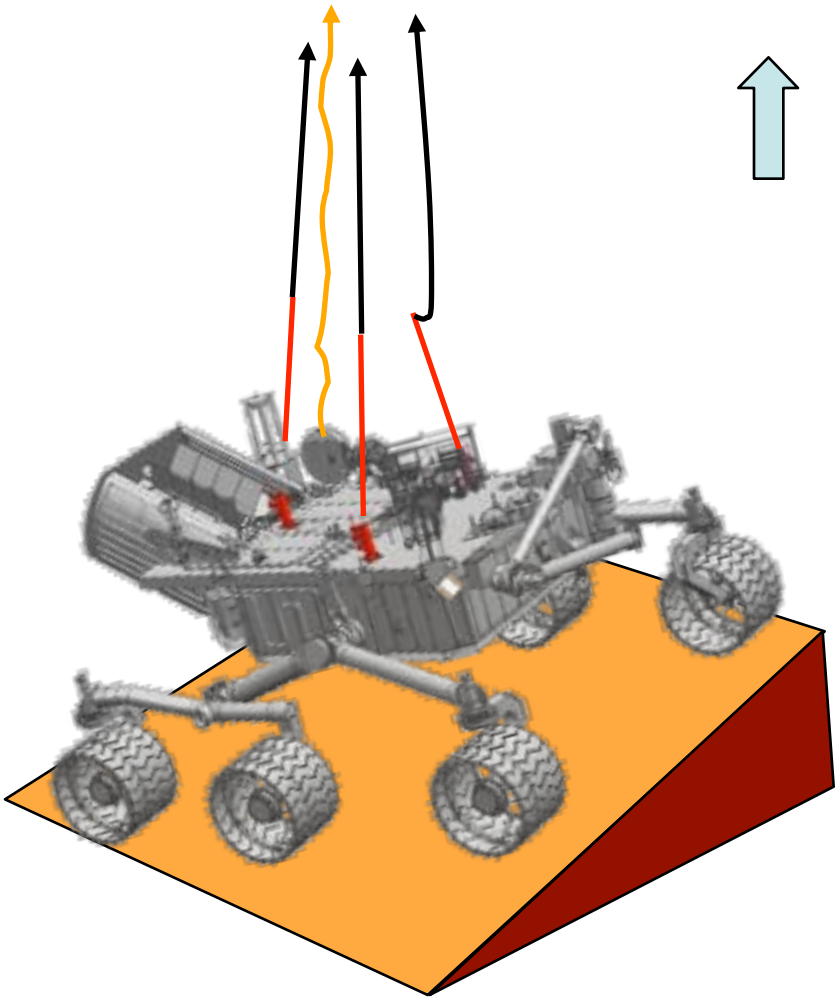


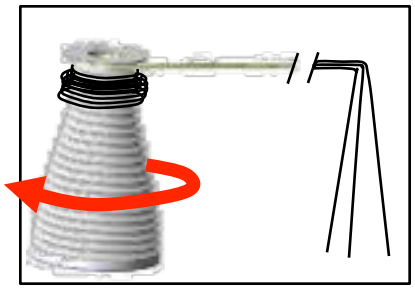


# Bridle & Umbilical Initial Retraction



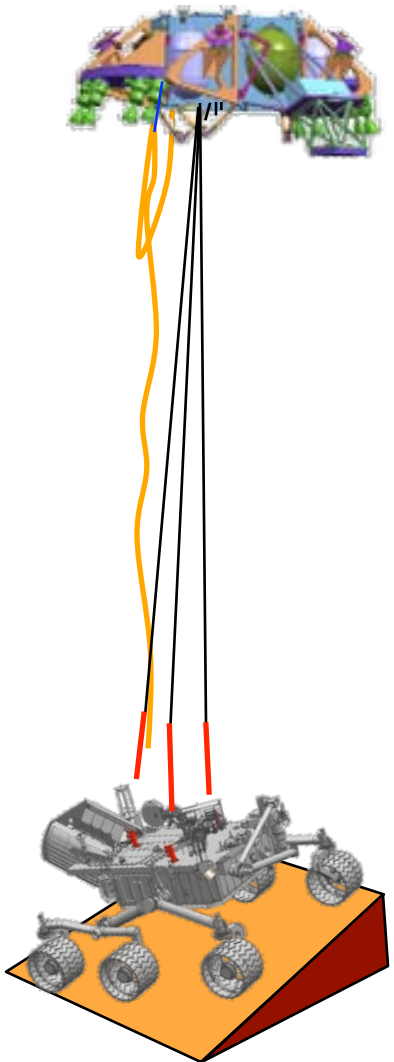


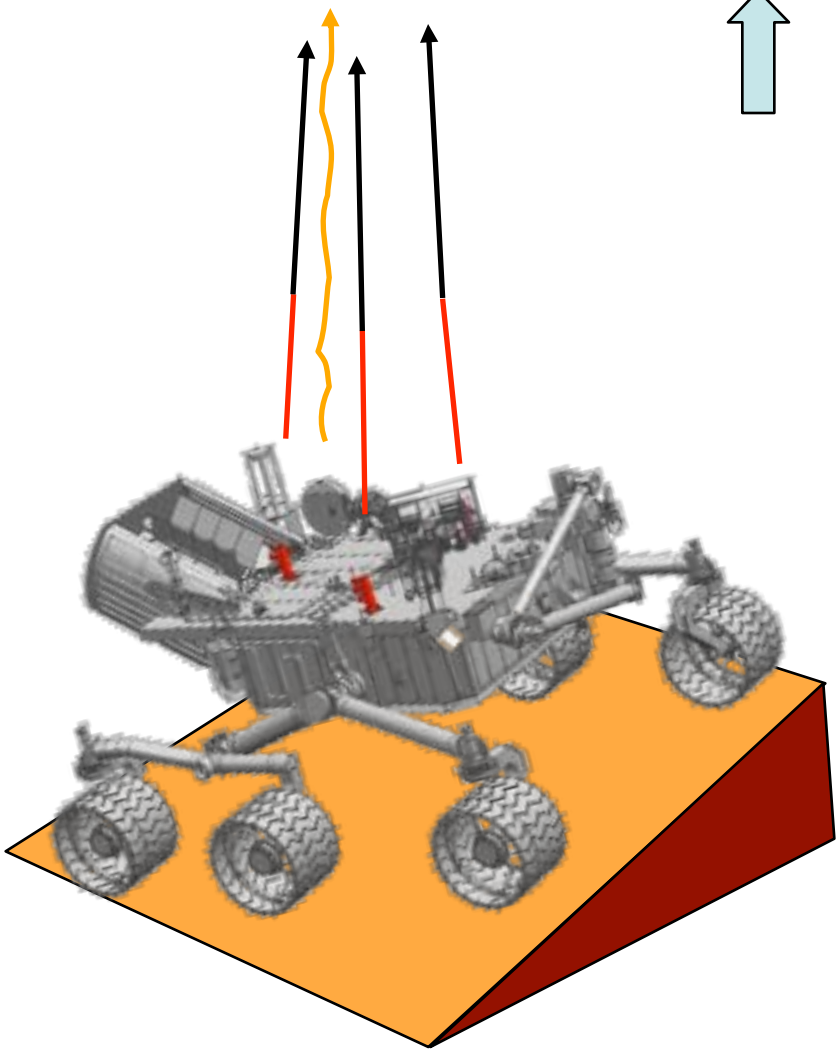


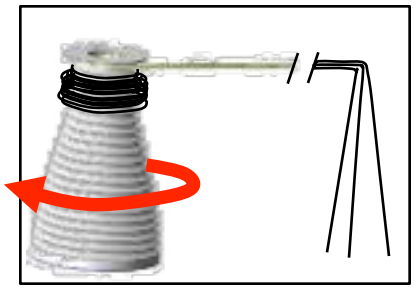


# Bridle & Umbilical Complete Retraction



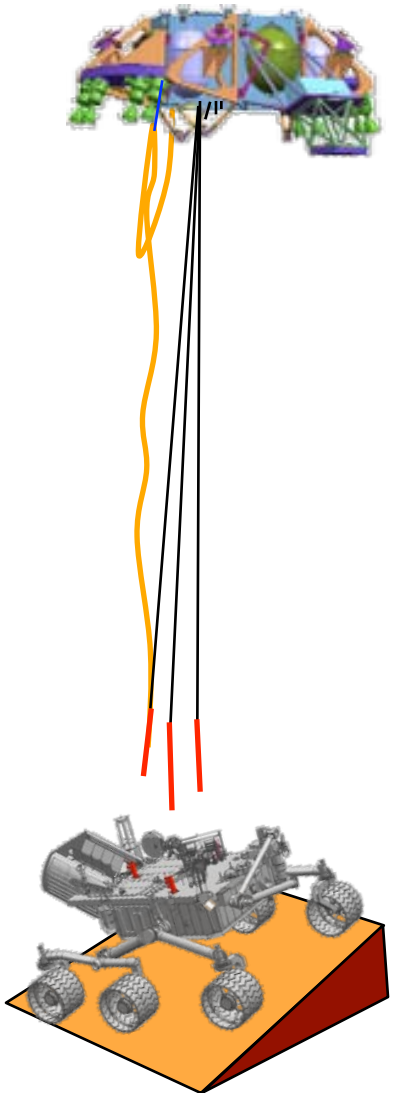


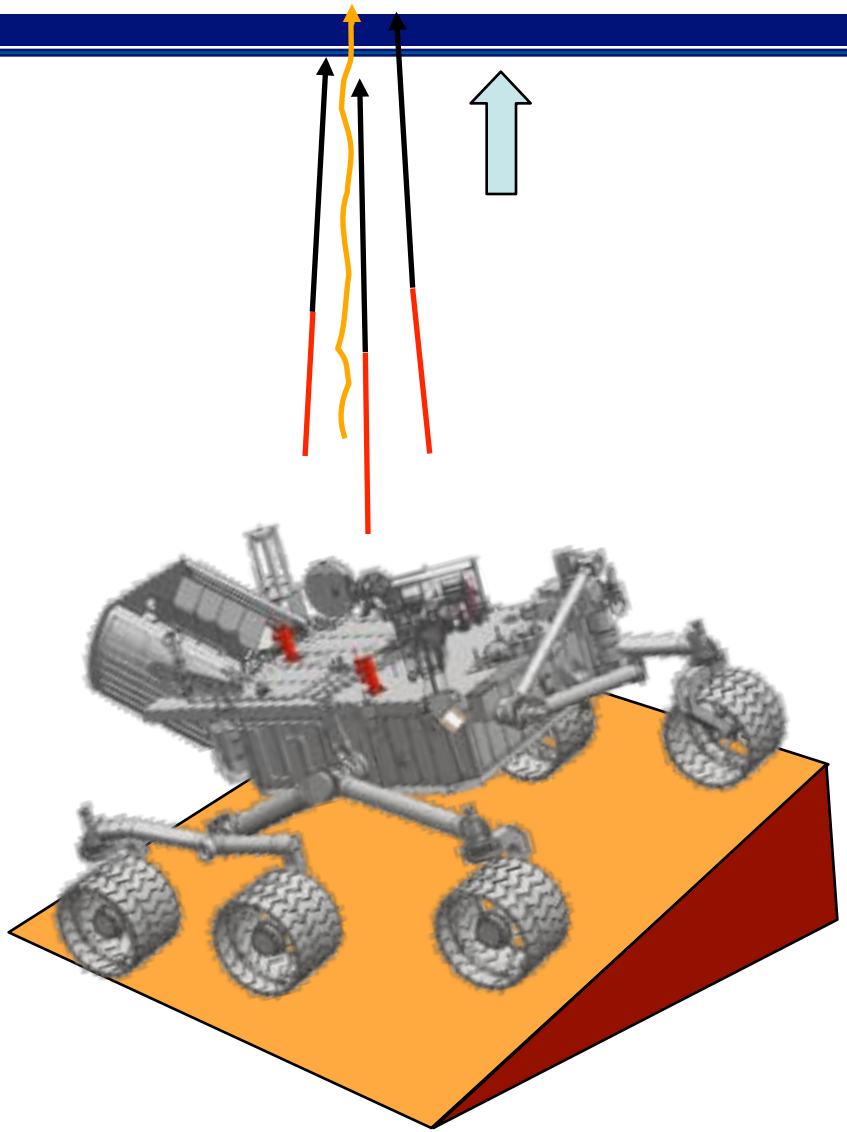


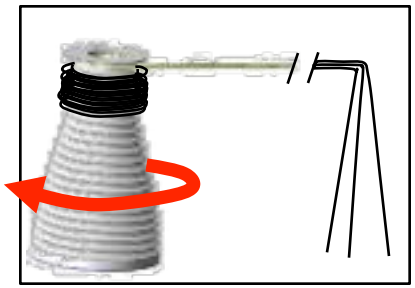


# Fly Away



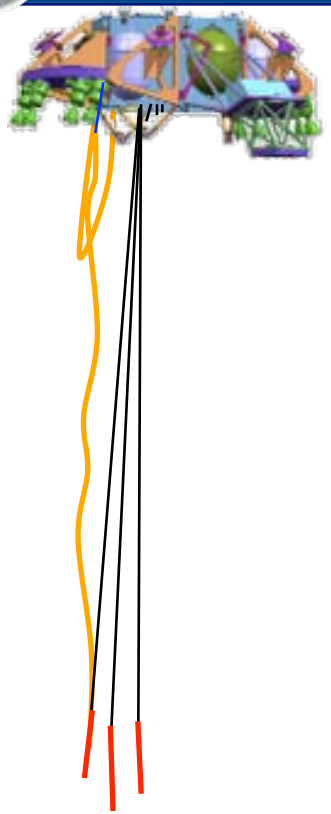


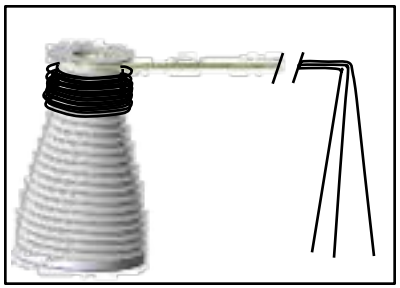


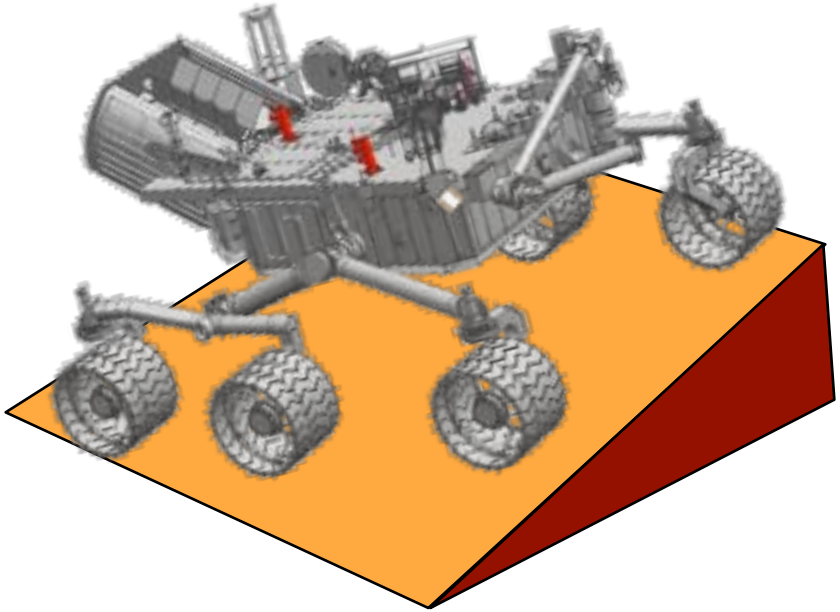


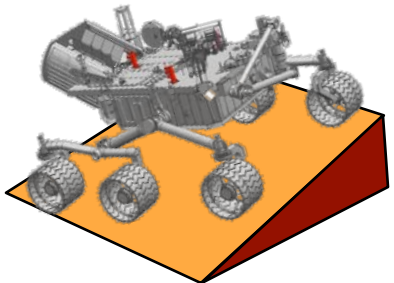
# Fly Away









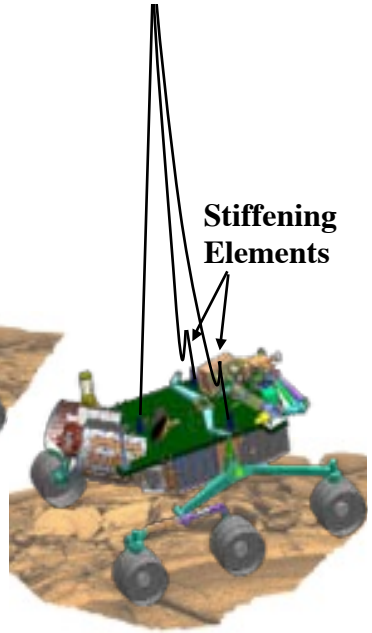


# Sky Crane: Touchdown

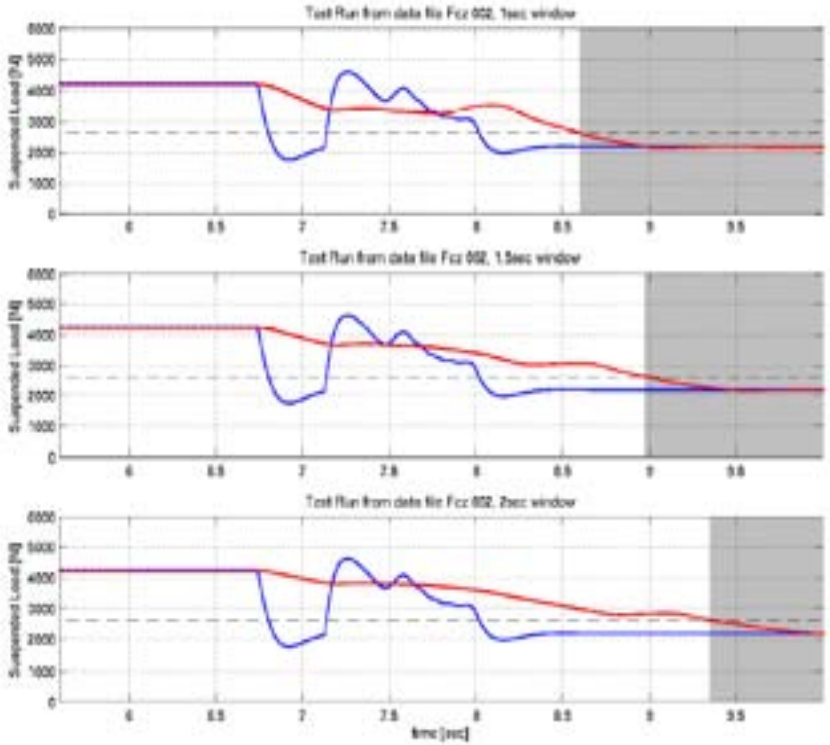


- Touchdown is triggered from the ***post-touchdown state*** NOT the touchdown event
  - Design allows 1-2 seconds of persistence
- Slack is managed within bridle system
  - Descent stage can continue downward for 2-3 meters

Moment of Touchdown




Differential Slacking



# Gemini Rogallo Wing Recovery

# X-38 Parasail Landing System

# SpaceX Propulsive Landing Tests