Entry, Descent, and Landing Case Studies

- Entry, Descent, and Landing overview
- Case study: Mars EDL
- Case study: Mars Exploration Rovers
- Case study: Mars Science Laboratory

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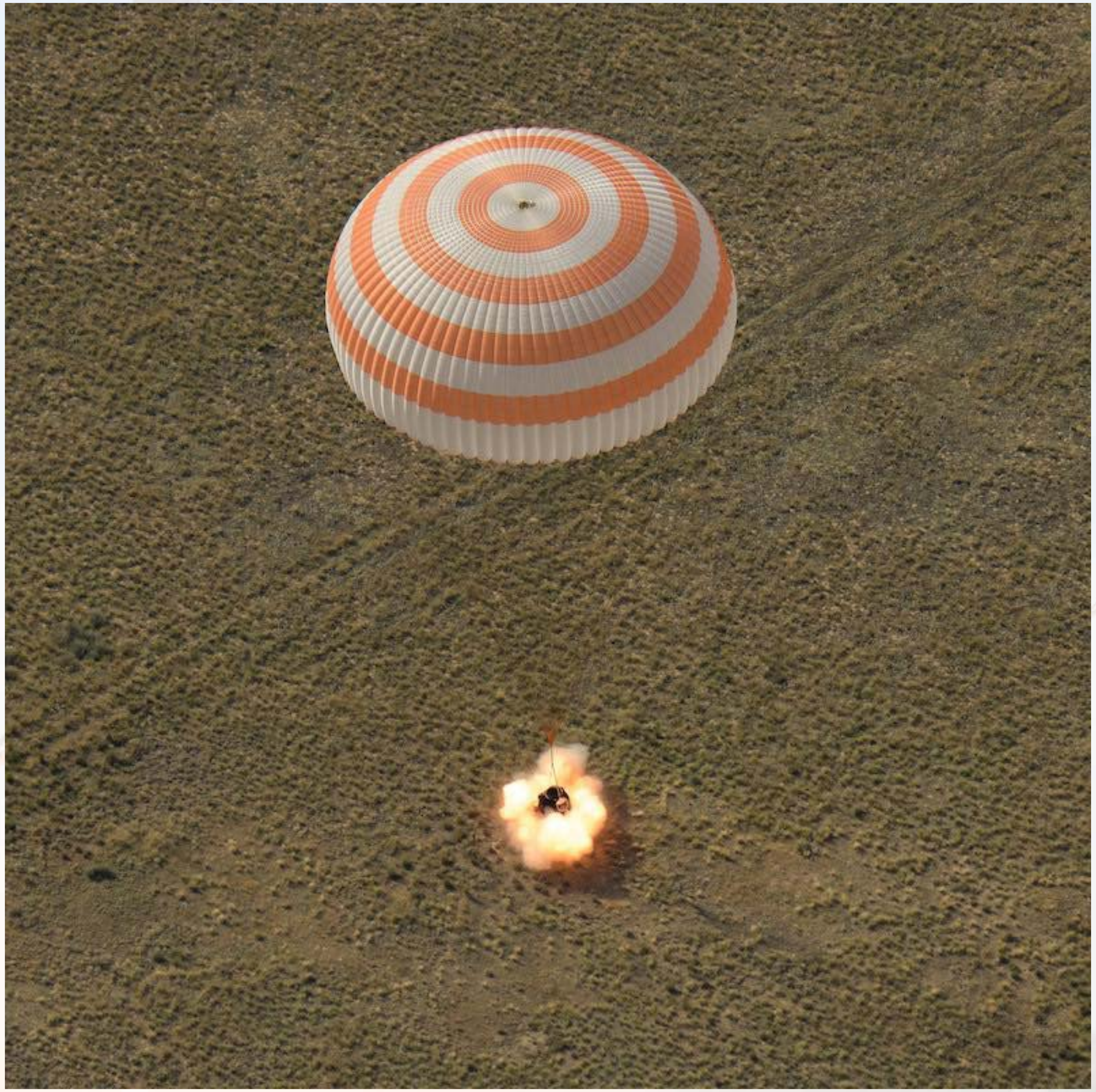
Apollo Landing

Dragon Landing

Soyuz Landing (Propulsive Decel)



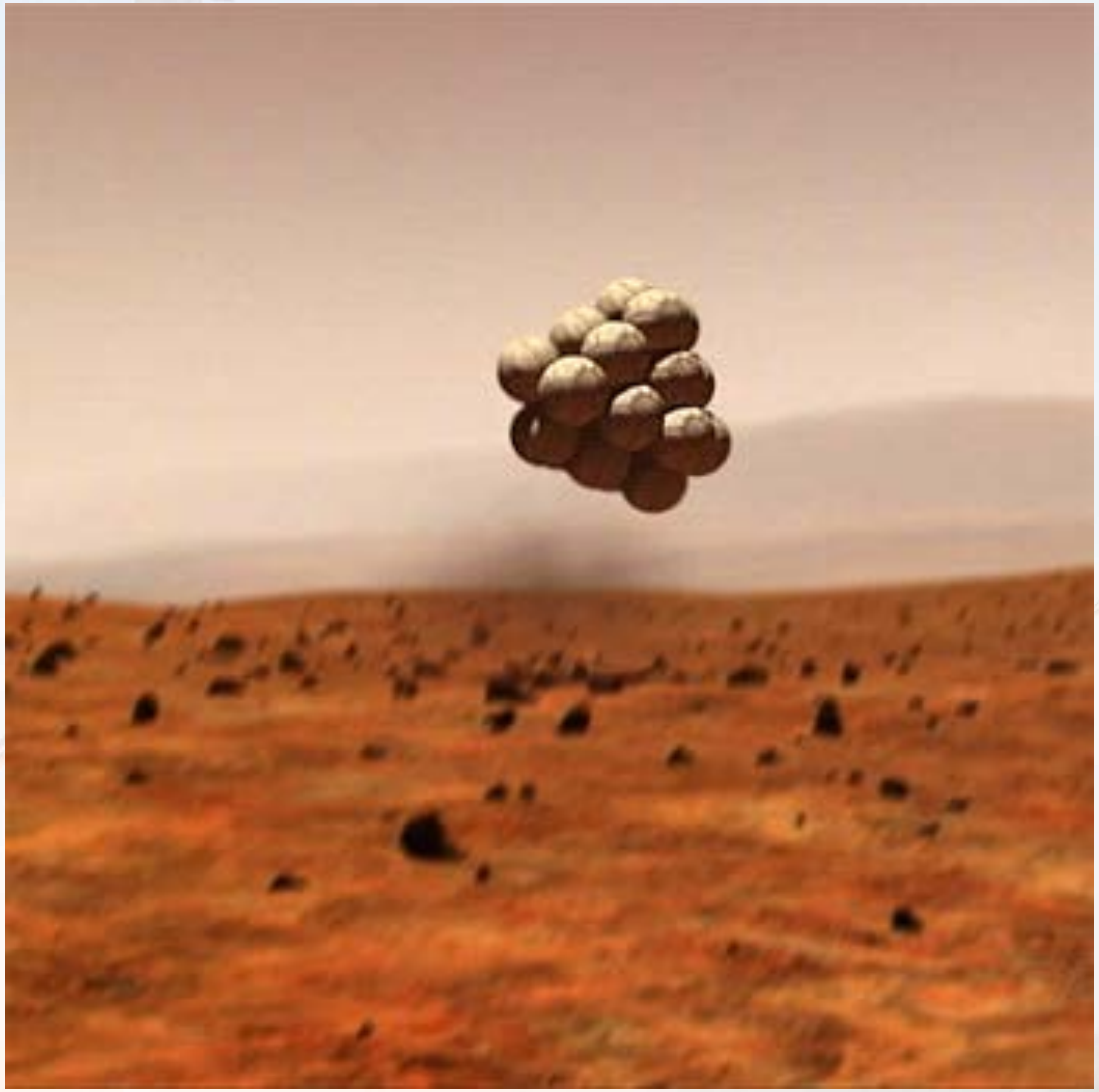
Starliner Landing (Air Bags)

Shuttle in Gliding Landing

New Shepard Landing (Blue Origin)

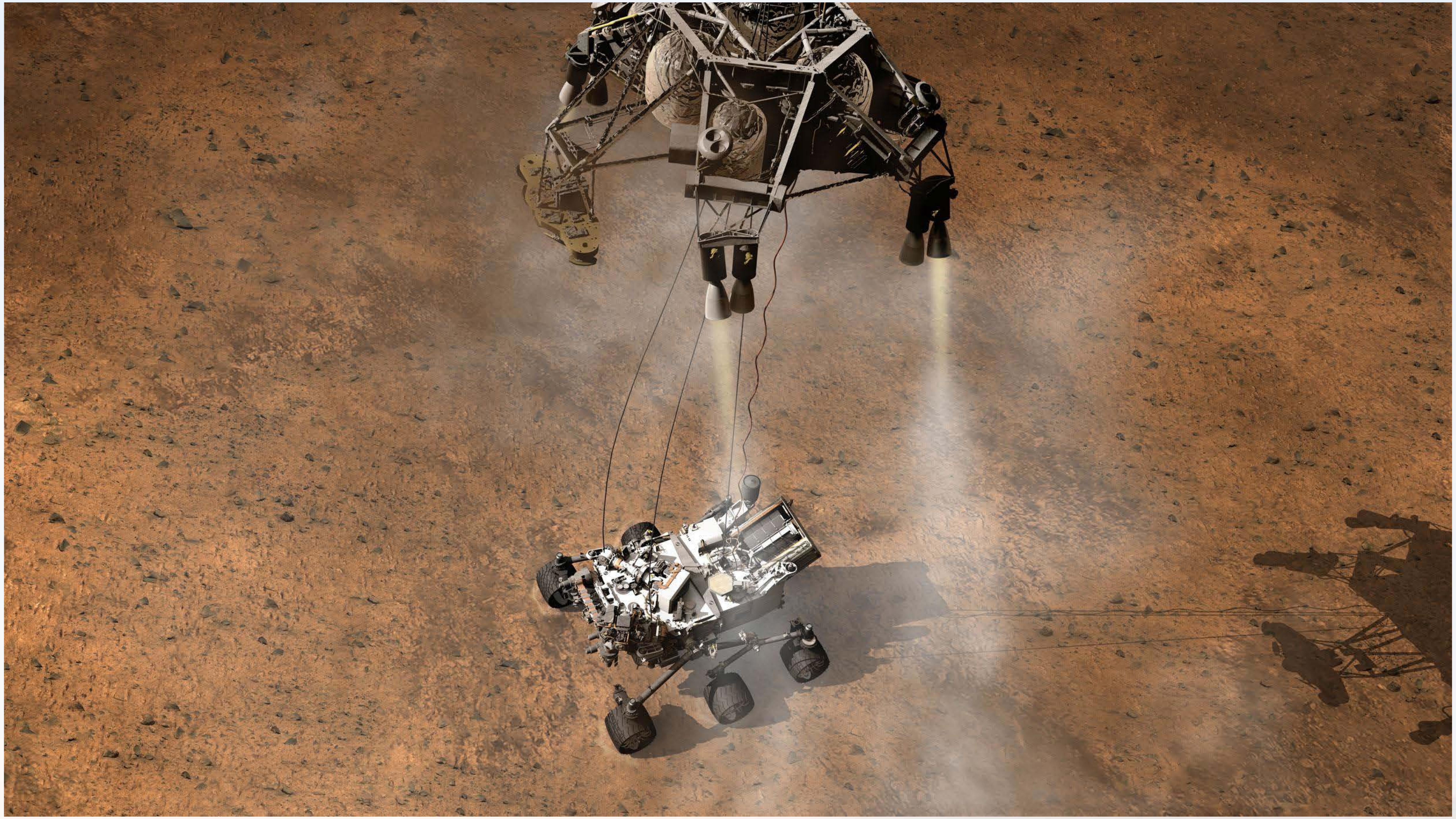
Falcon 9 First Stage Landing

Mars Pathfinder/MER Landing Bags



MER Mission Overview Video

MSL Skycrane Mars Landing System



Human Landing System (SpaceX)

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

Ron Sostaric
NASA Johnson Space Center
AIAA Senior Member

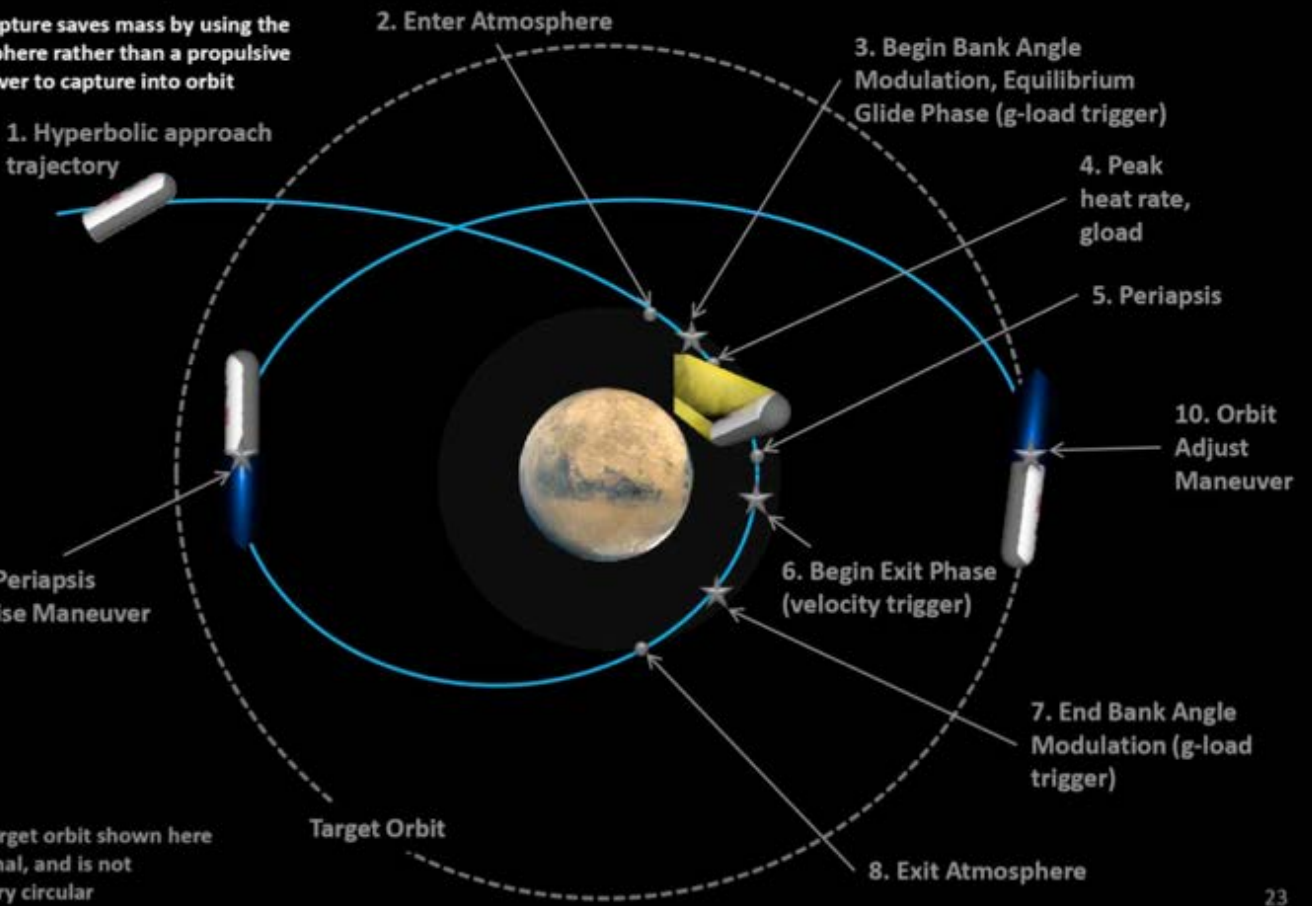
April 2010

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

Aerocapture saves mass by using the atmosphere rather than a propulsive maneuver to capture into orbit

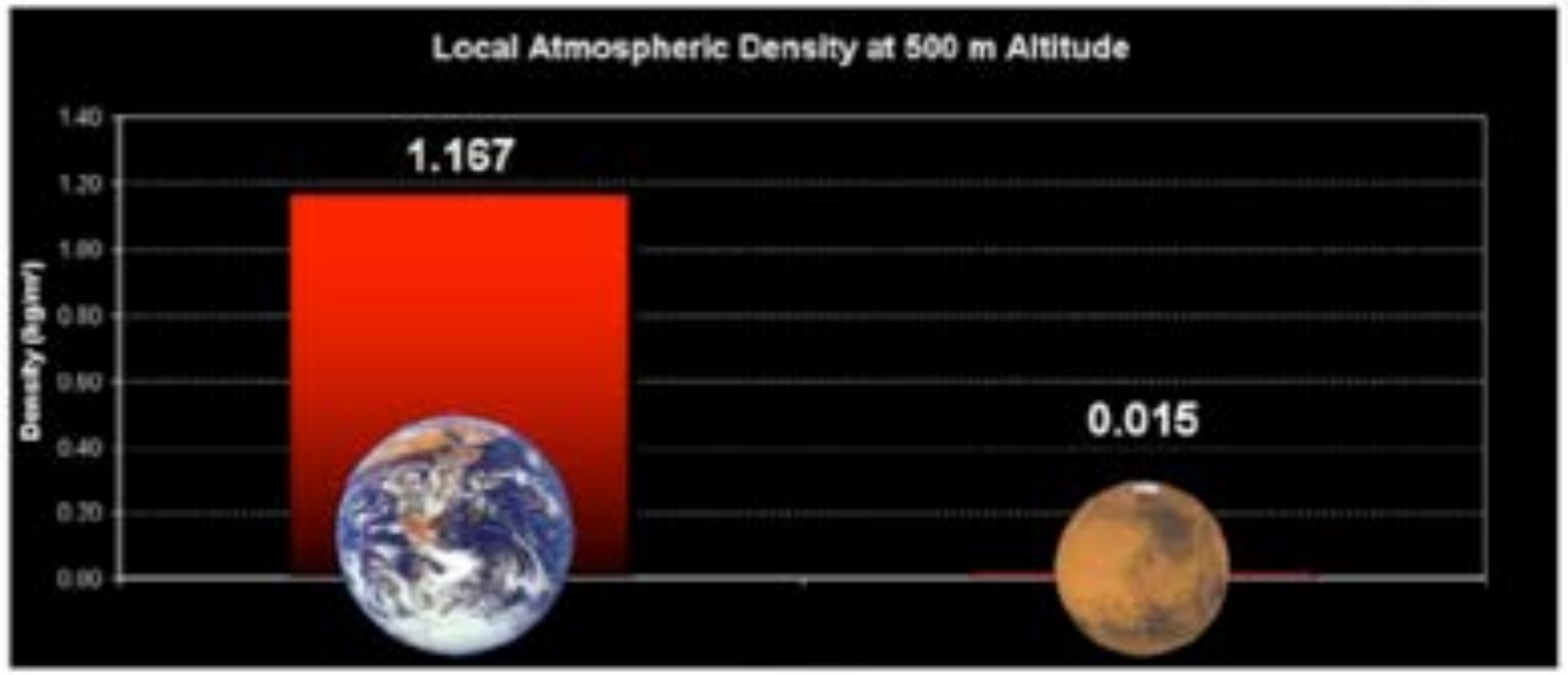


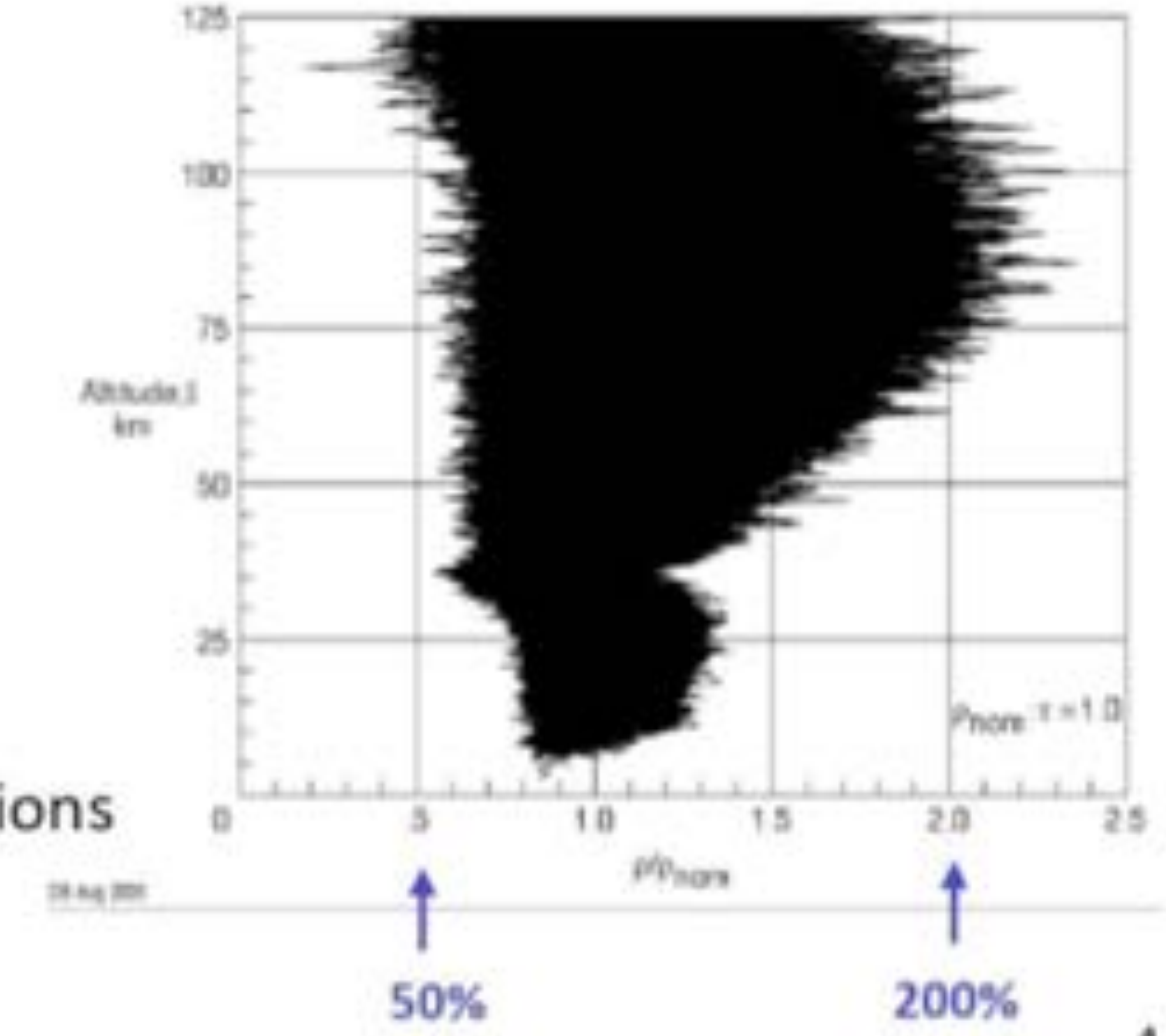
Note: target orbit shown here is notional, and is not necessary circular

Why is Mars EDL so difficult?

ATMOSPHERE:

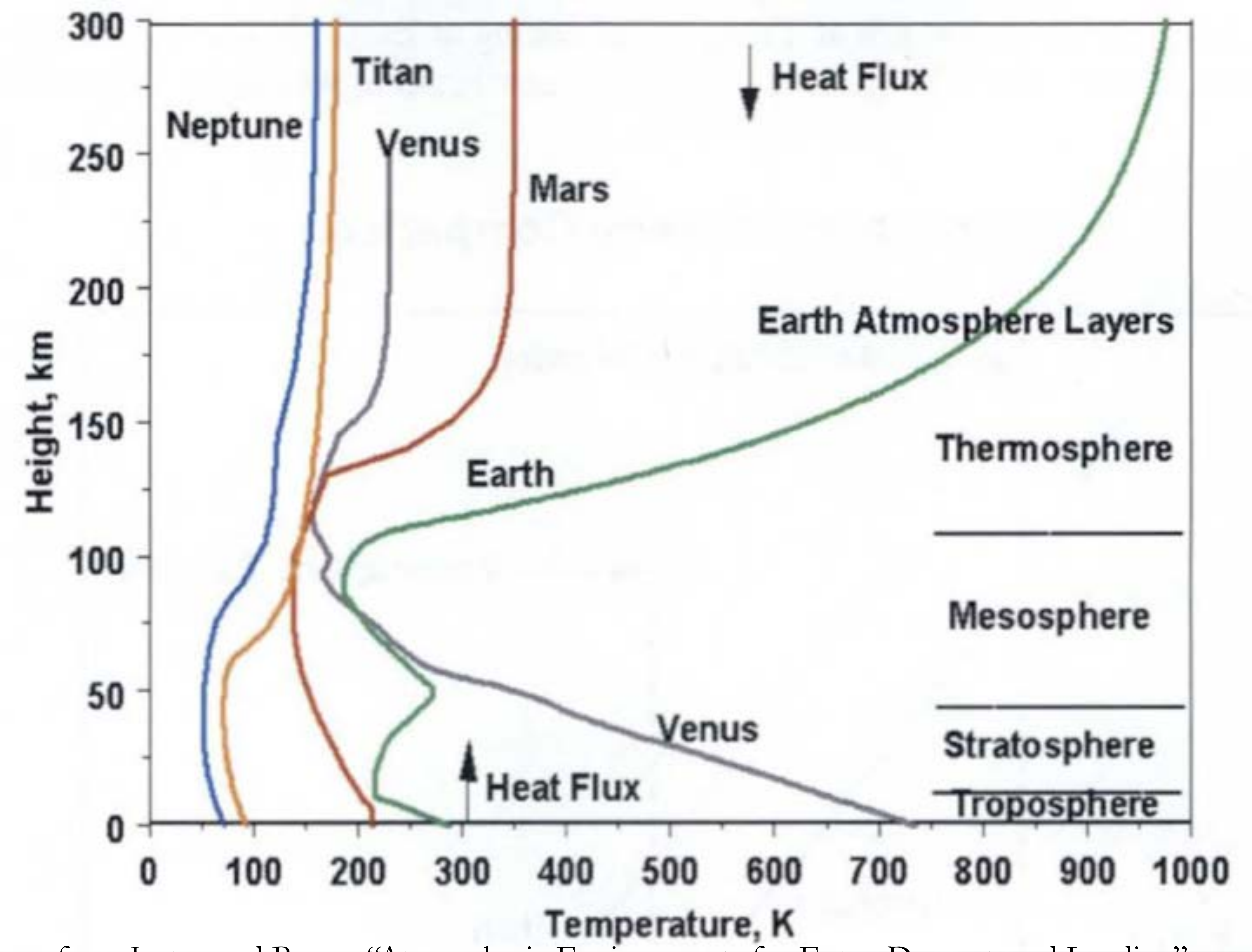
- Thin Martian atmosphere (surface density equivalent to Earth's at 30 km)
- Too little atmosphere to decelerate and land like we do at Earth
- Atmosphere is thick enough to create significant heating during entry





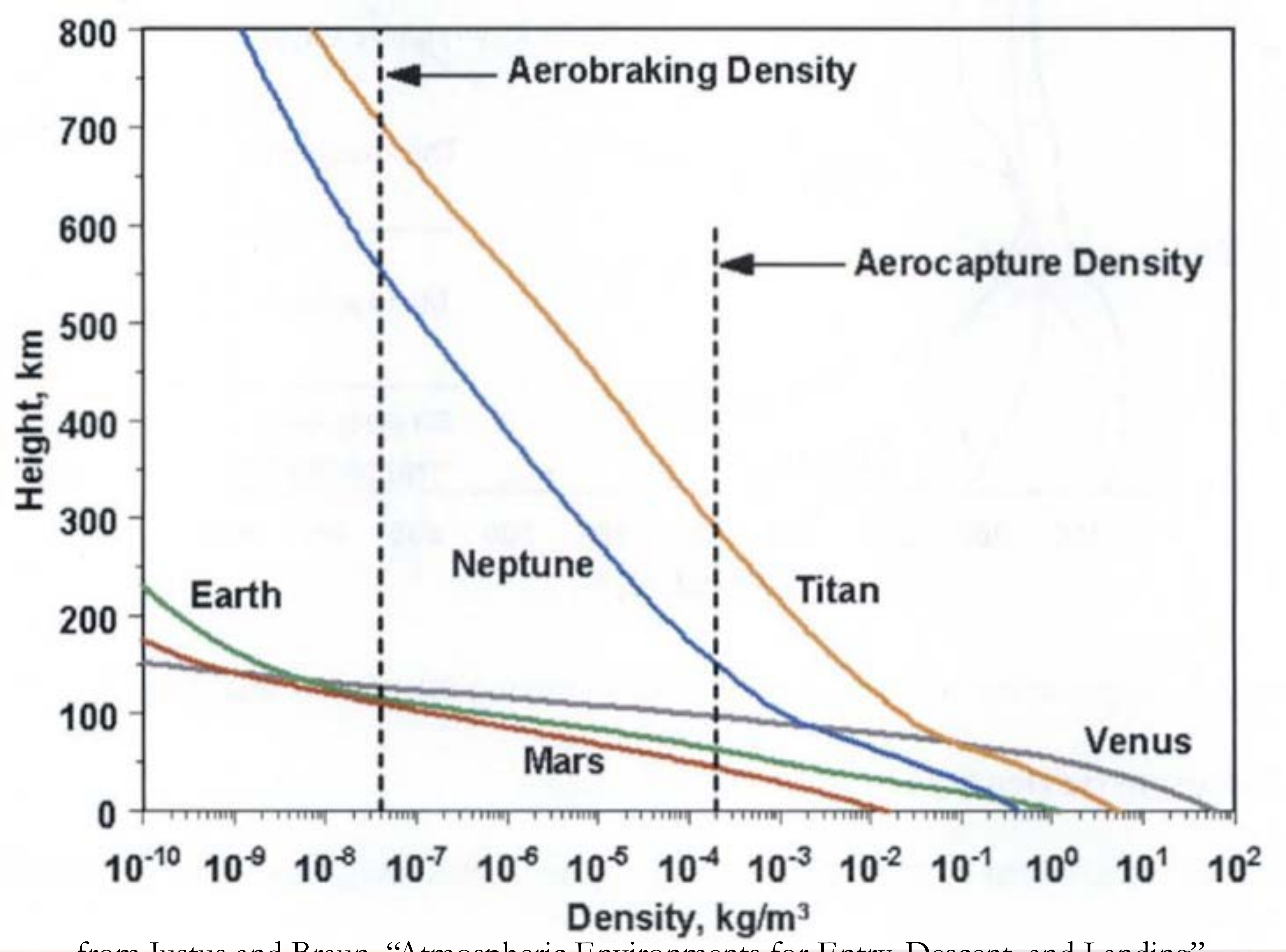
- Lack of understanding of the atmosphere:
  - Aerodynamics, aeroheating, winds, and density variations

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)

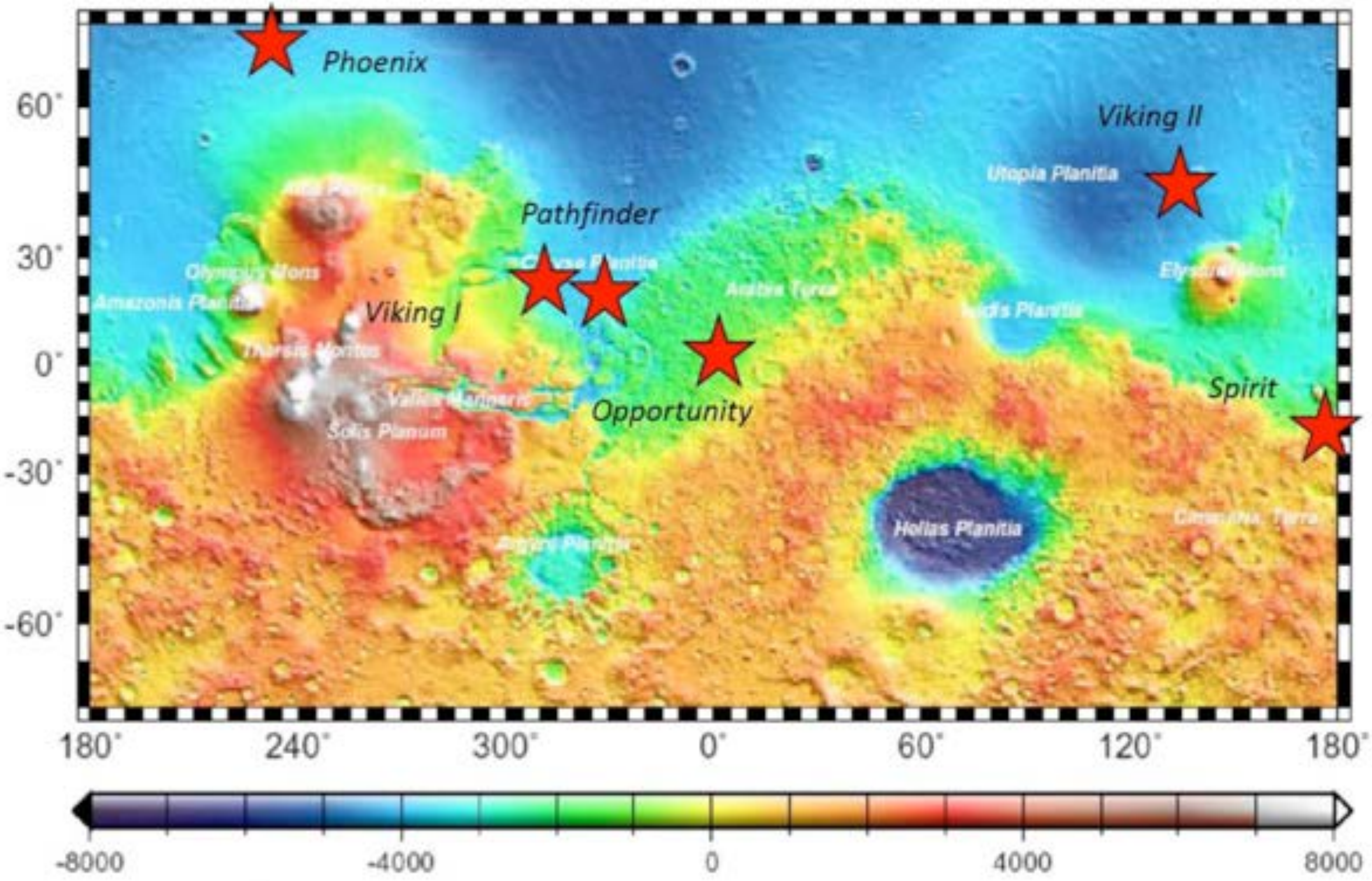
Mars Science Laboratory (MSL) '11 EDL Architecture:

- 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

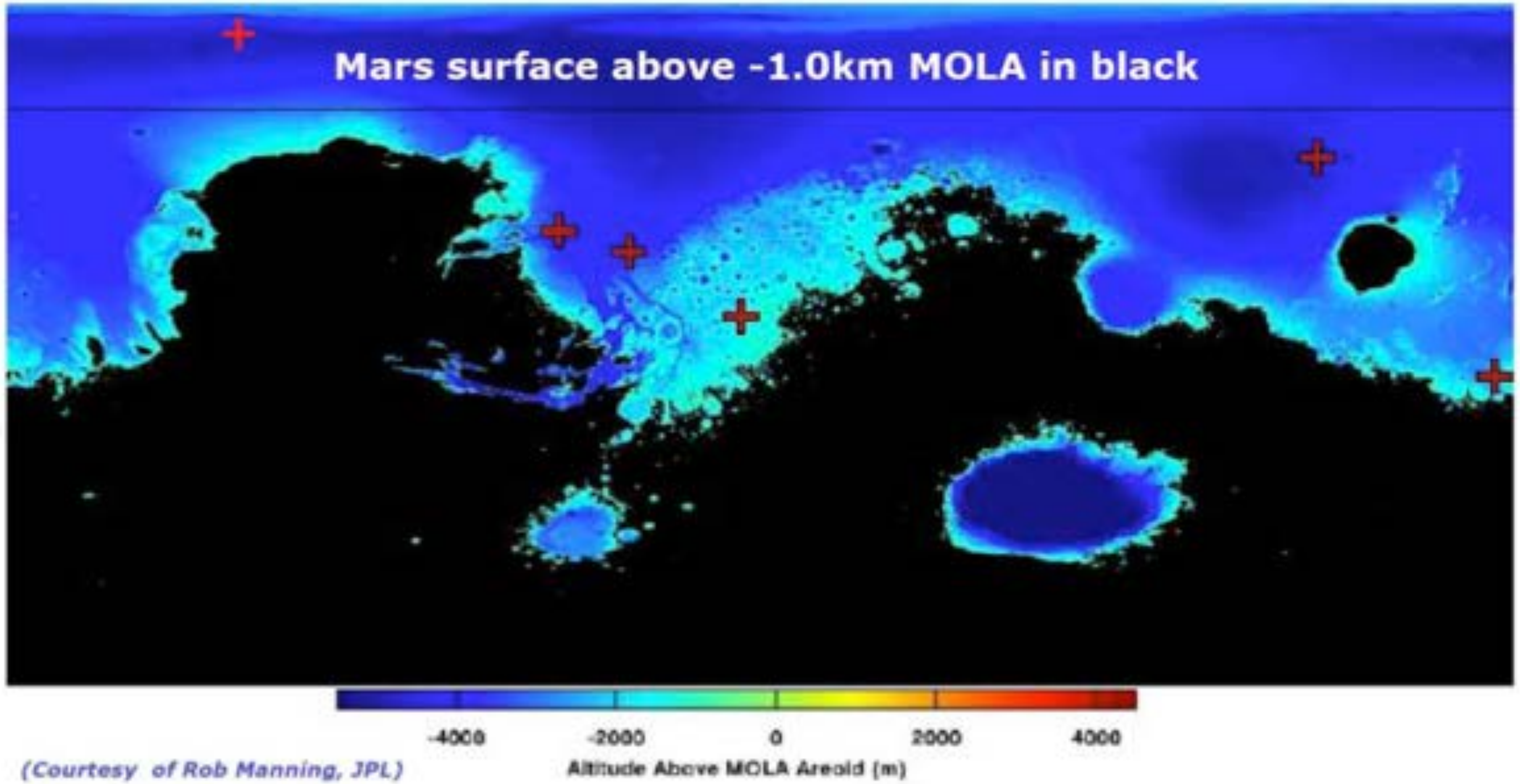
6 U.S. Mars Entry, Descent, and Landing Successes



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

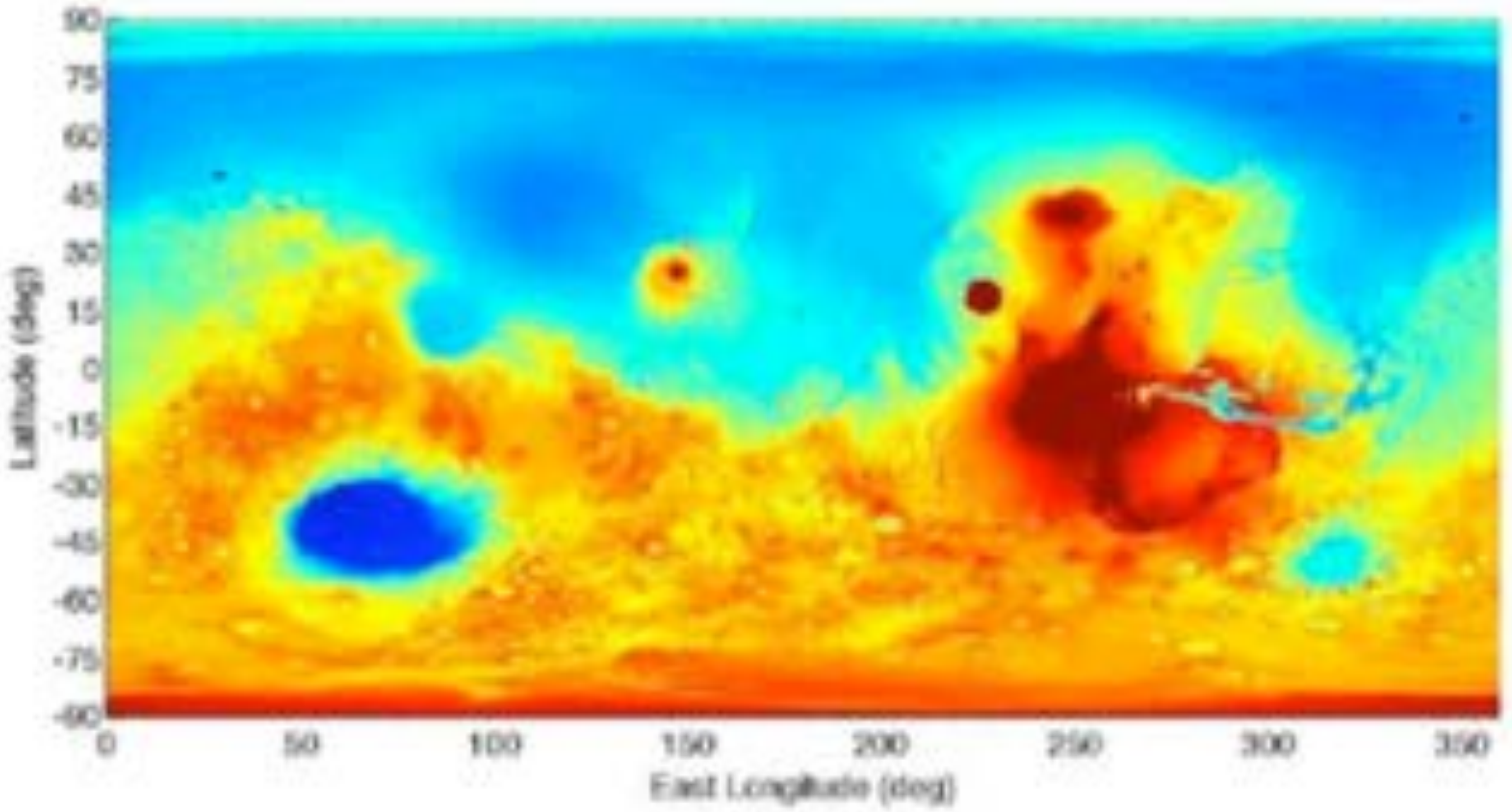
To date the southern hemisphere has been largely out of reach (approximately 50% of the planet surface remains inaccessible with current EDL technologies)



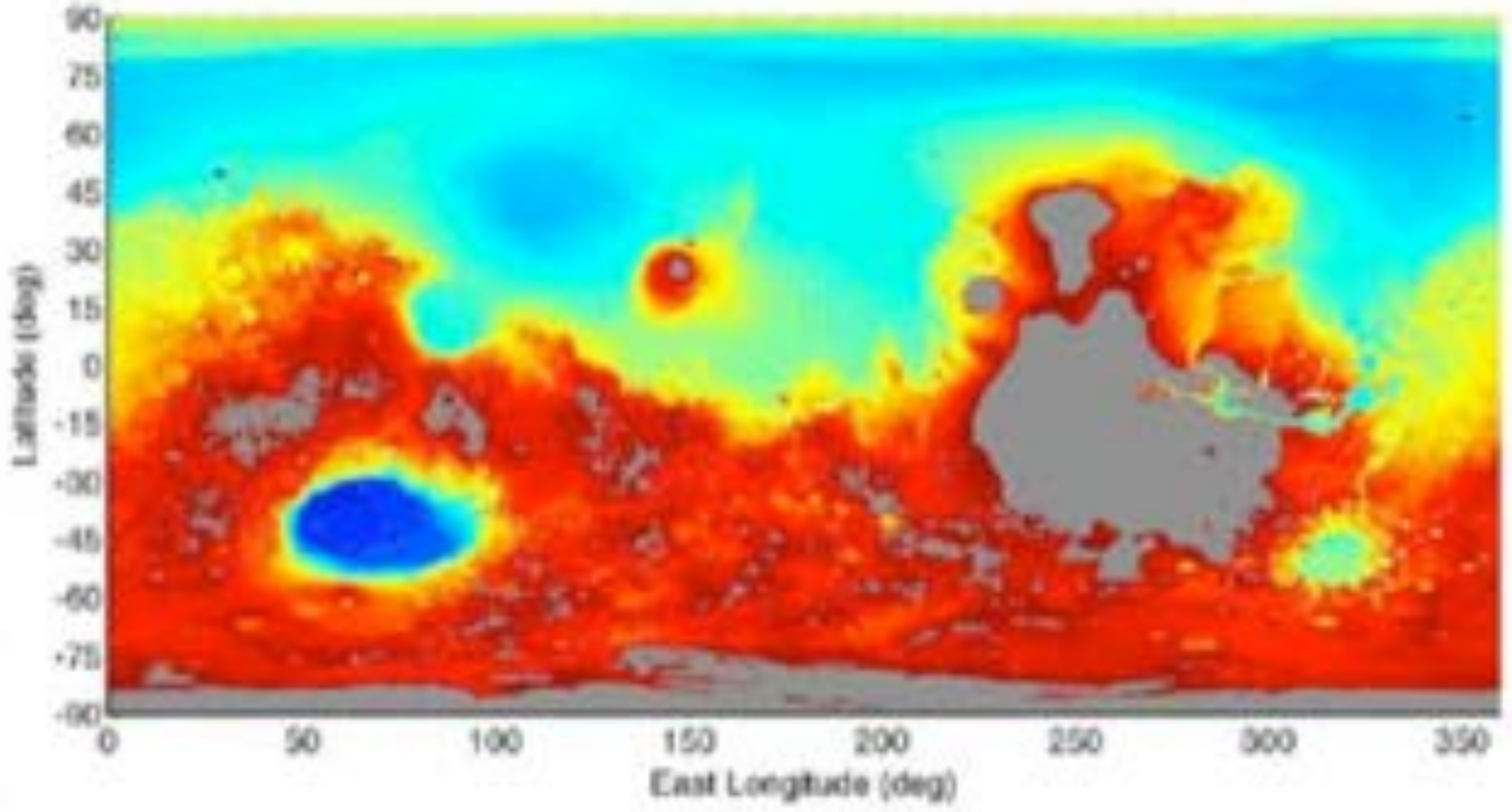
(Courtesy of Rob Manning, JPL)

Landing Site Elevation / Accessibility

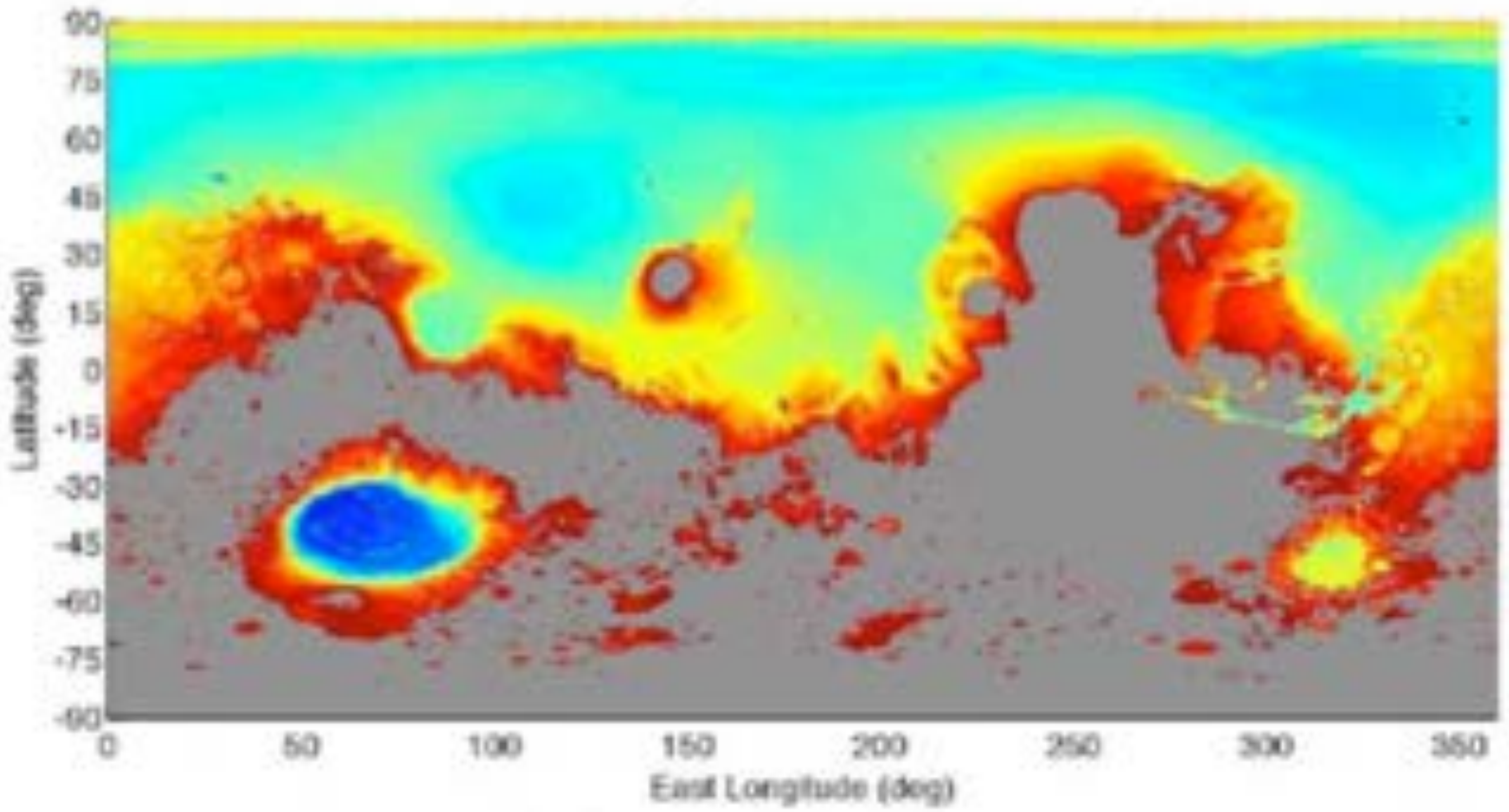
MOLA 1/4° Topographic Data



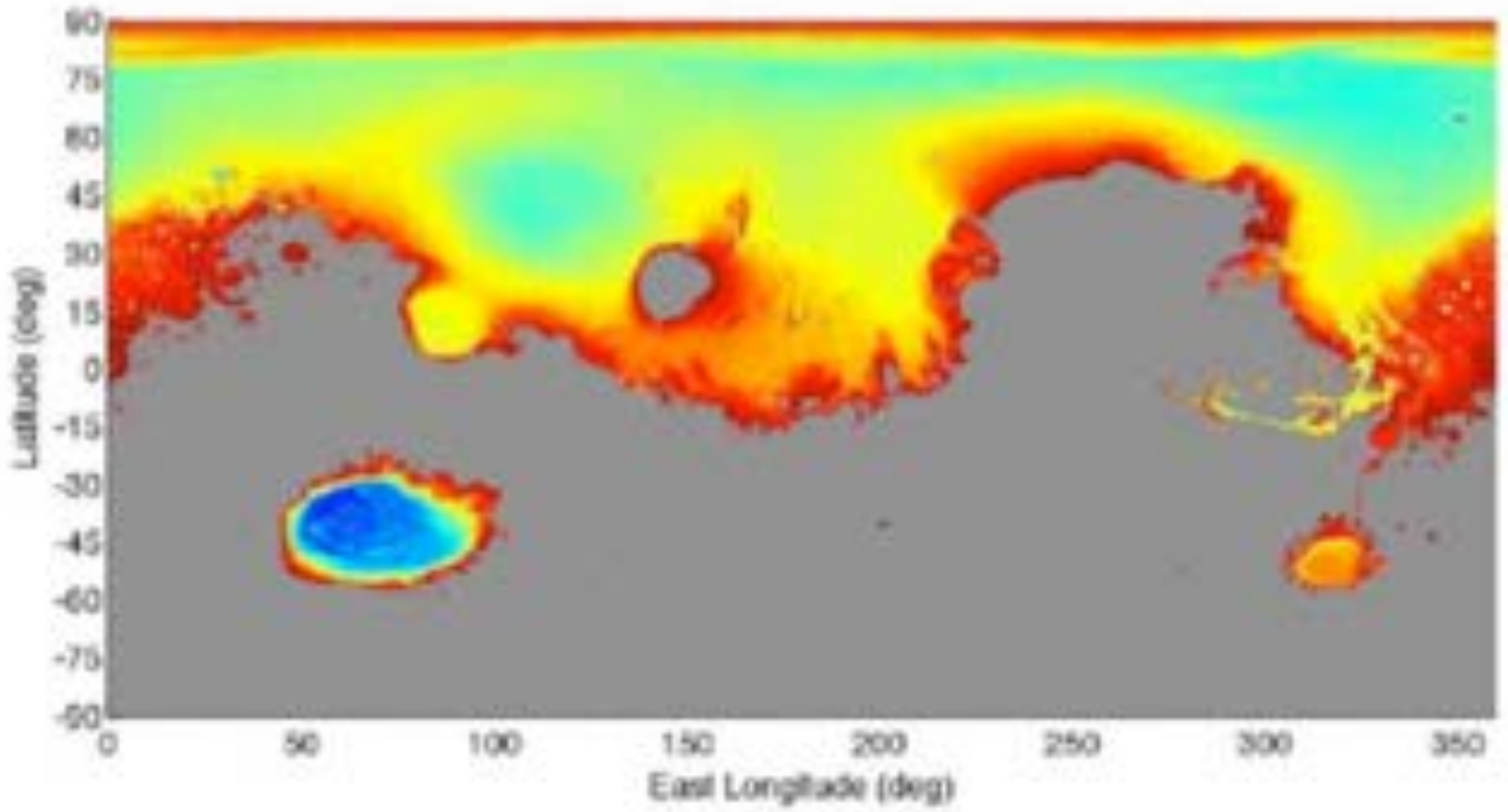
< 2.5 km (90% of Surface)



< 1.0 km (65% of Surface)

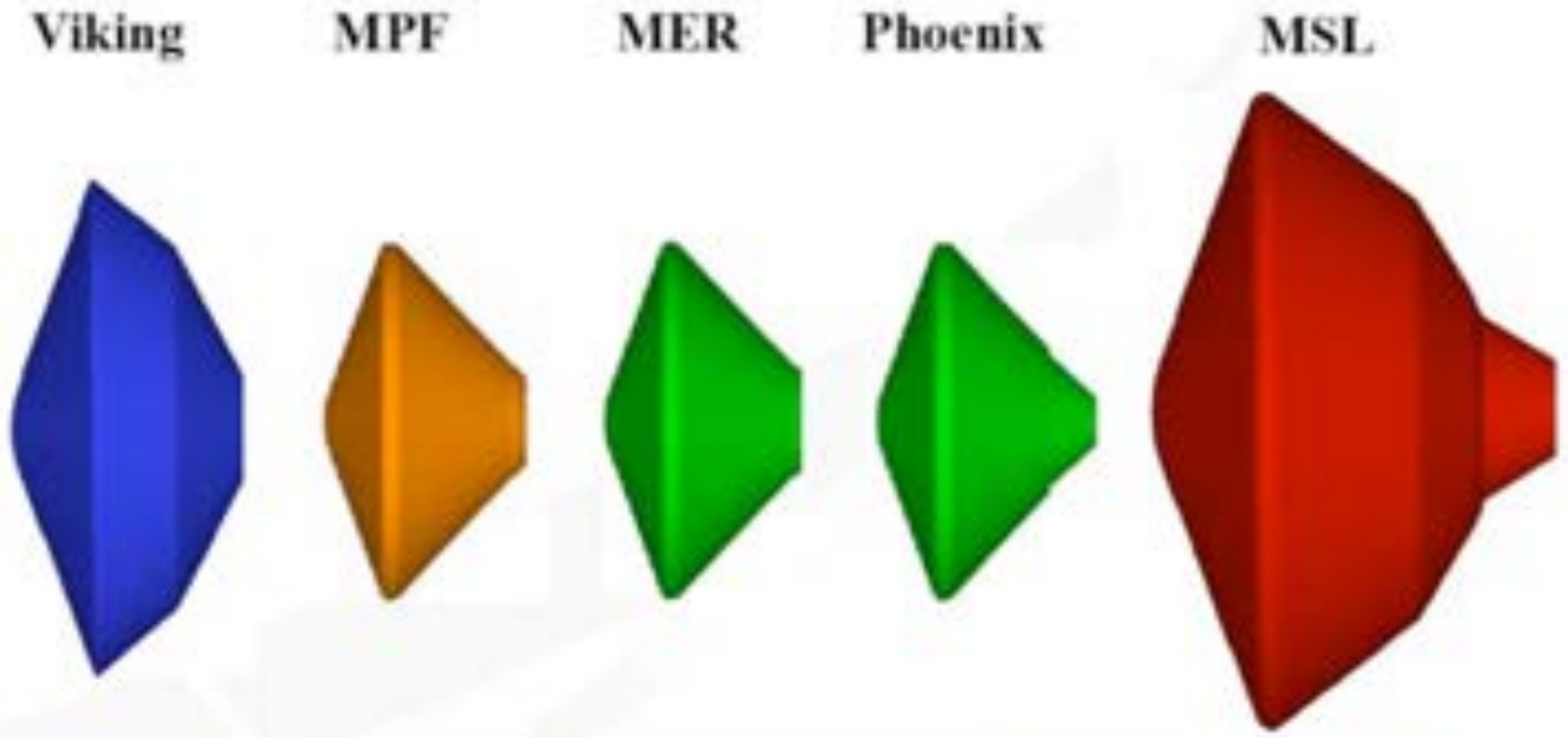


< -1.0 km (45% of Surface)



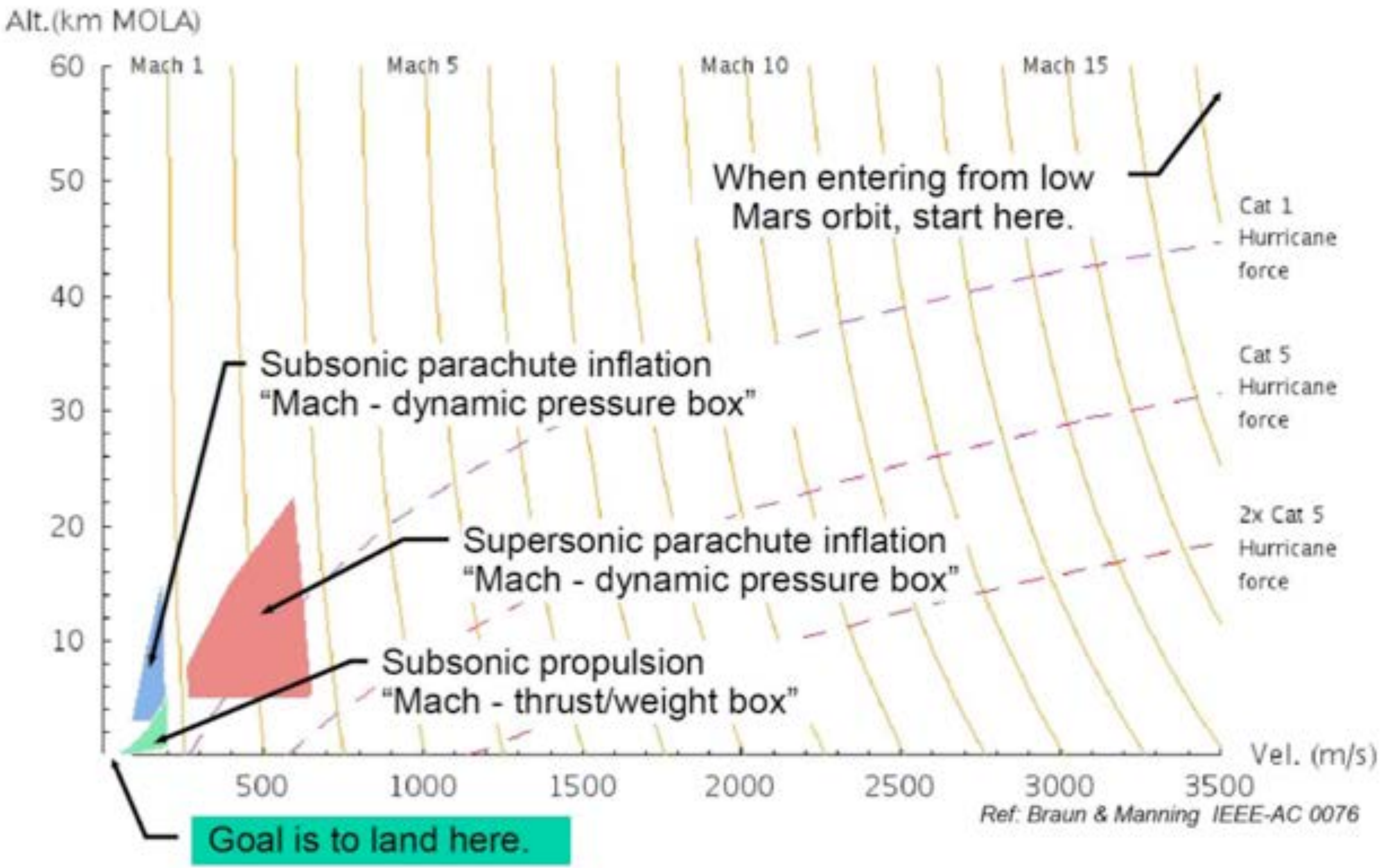
Mars Heritage Aeroshell - Mission Comparisons

<u>Core Viking Technologies</u>:
70° sphere-cone aeroshell



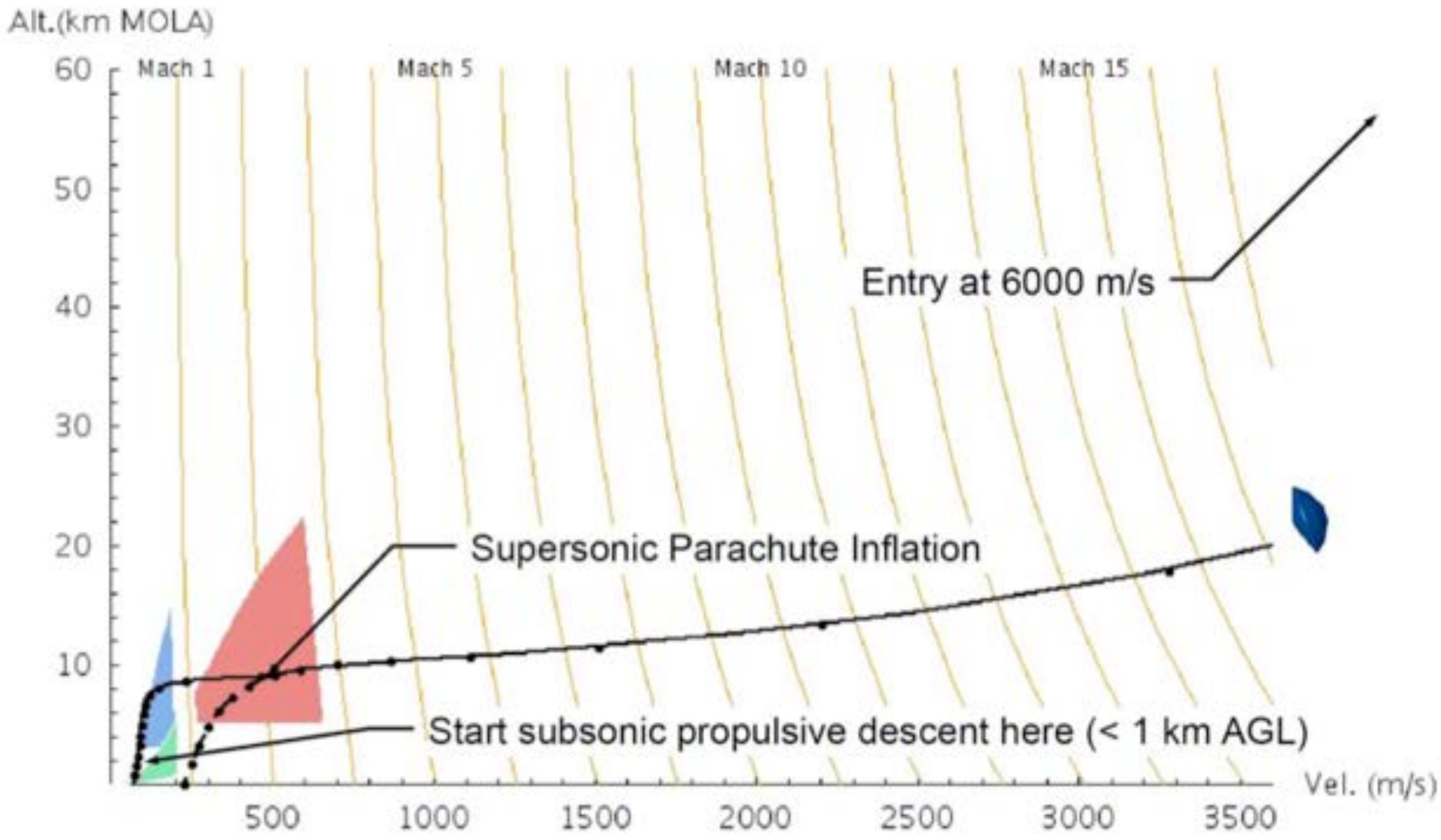
Parameter	Viking	MPF	MER	Phoenix	MSL
Entry Mass (kg) / Ballistic Coeff. (kg/m²)	980 / 66	585 / 63	836 / 90	603 / 65	3257 / 140
Lander/Rover Mass (kg)	612	11	173	64	850
Aeroshell Diameter (m)	3.5	2.65	2.65	2.65	4.5
Angle-of-Attack (deg) / L/D	11.1° / 0.18	0° / 0.0	0° / 0.0	0° / 0.0	-15.5° / 0.24
Peak Heatrate (W/cm²)	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

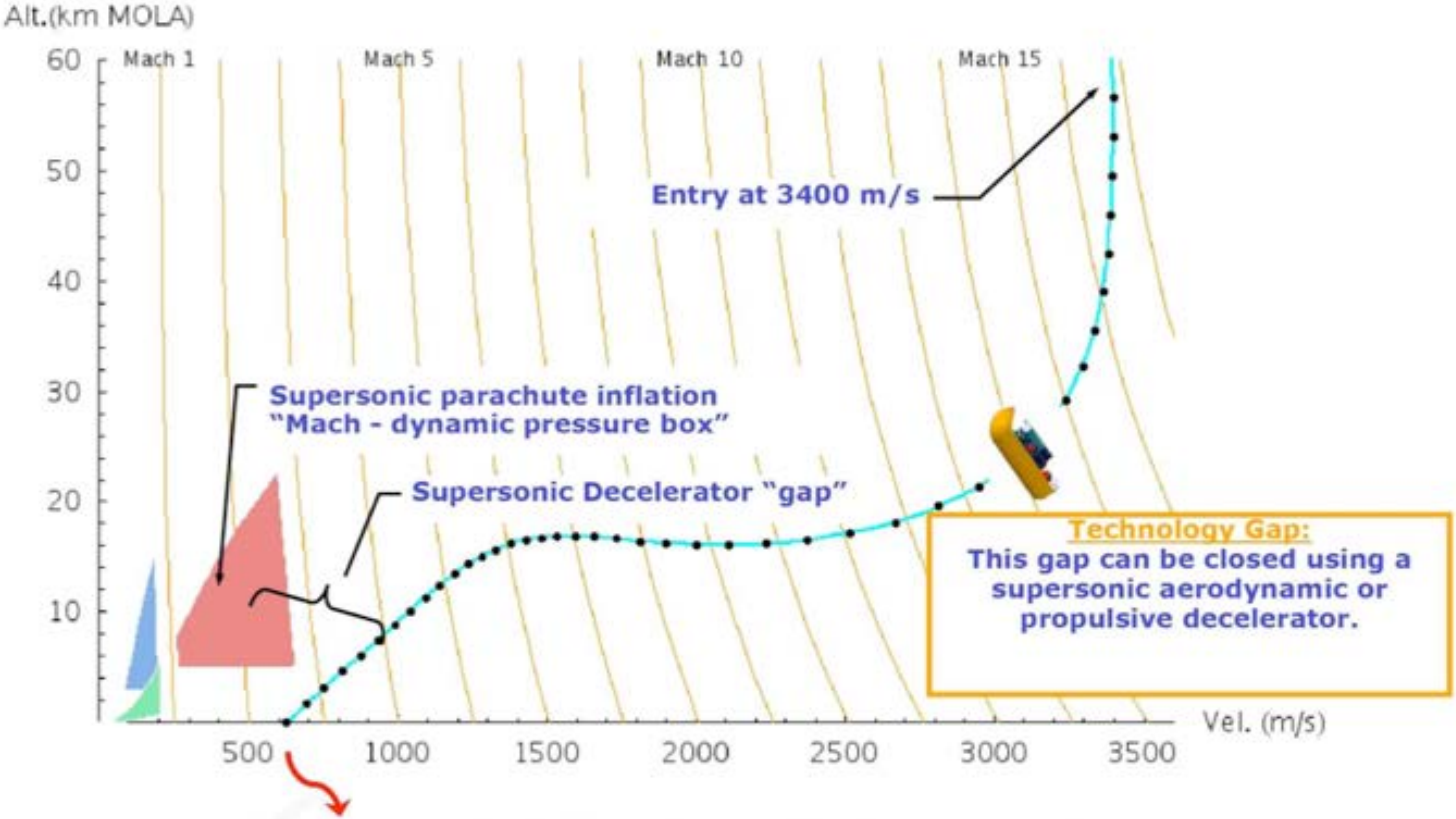


Ref: Braun & Manning IEEE-AC 0076

Robotic program: No gap so far ....



How would Humans Land?

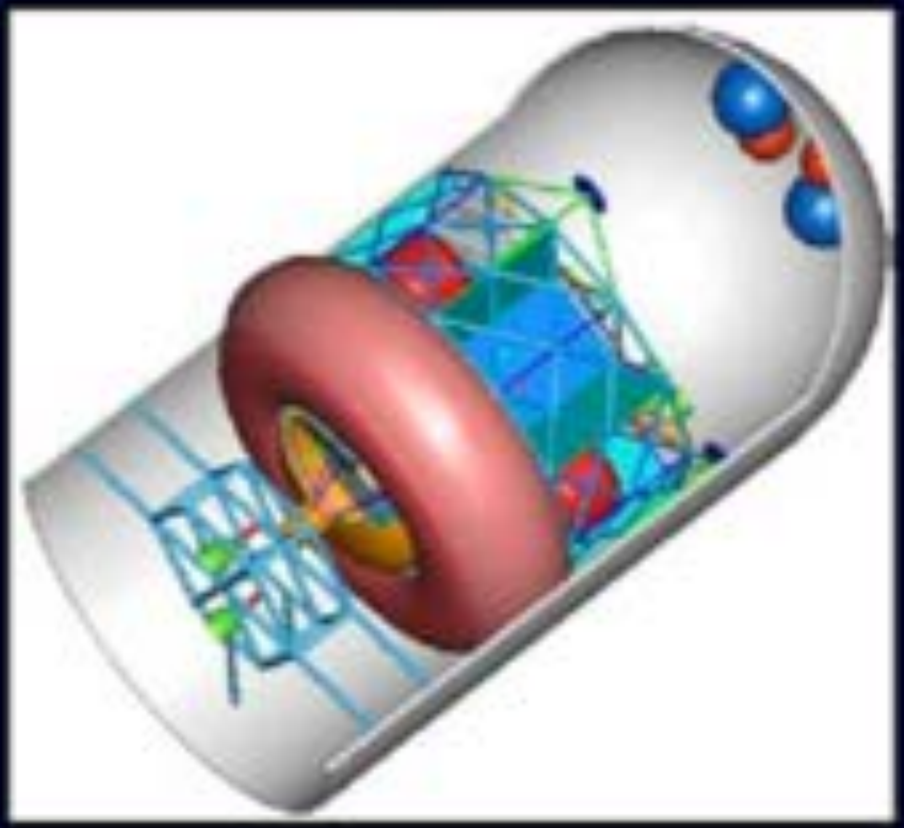


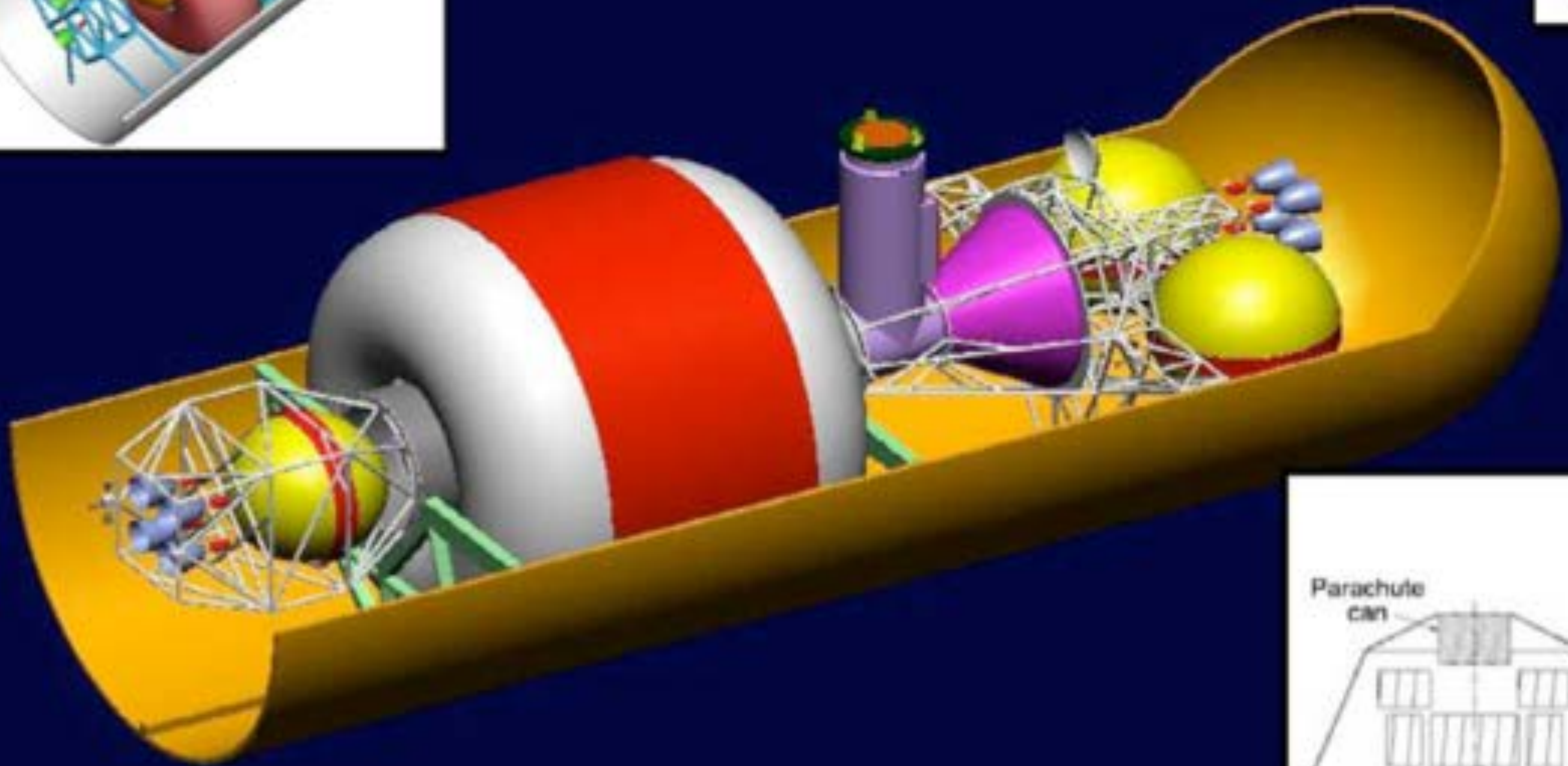
Without new technologies we have surface impact at Mach 2.5

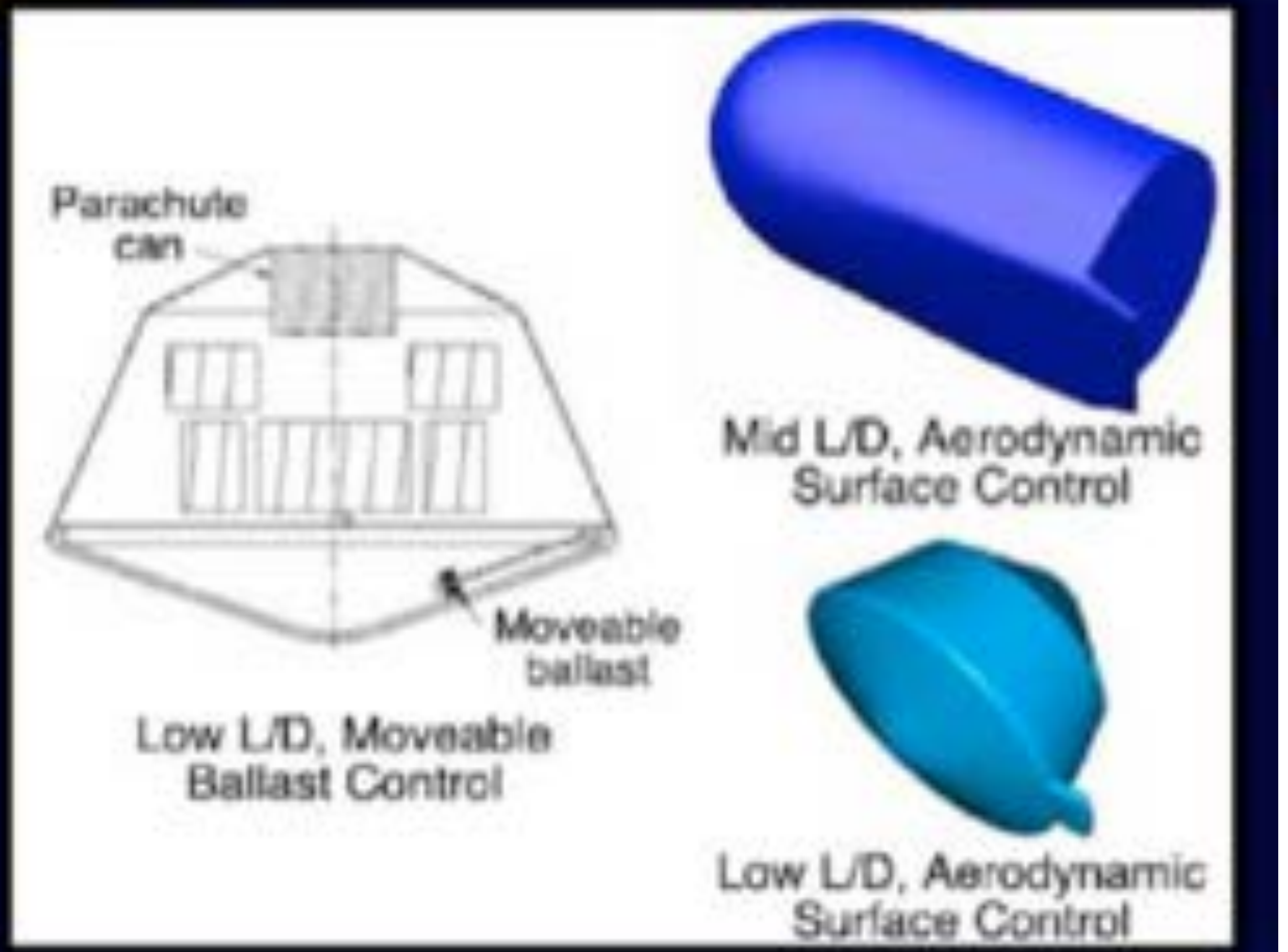
EDL Technology Development

- **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

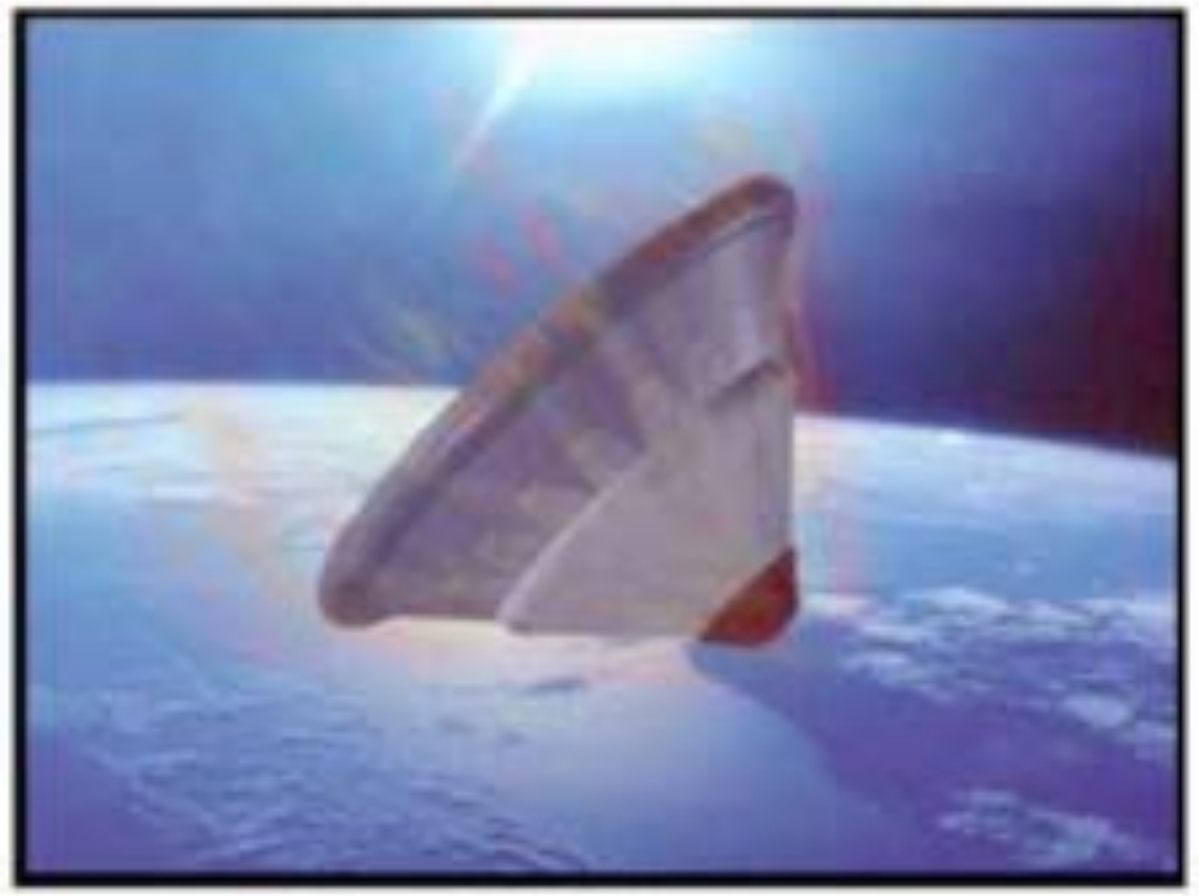
Rigid Aeroshells





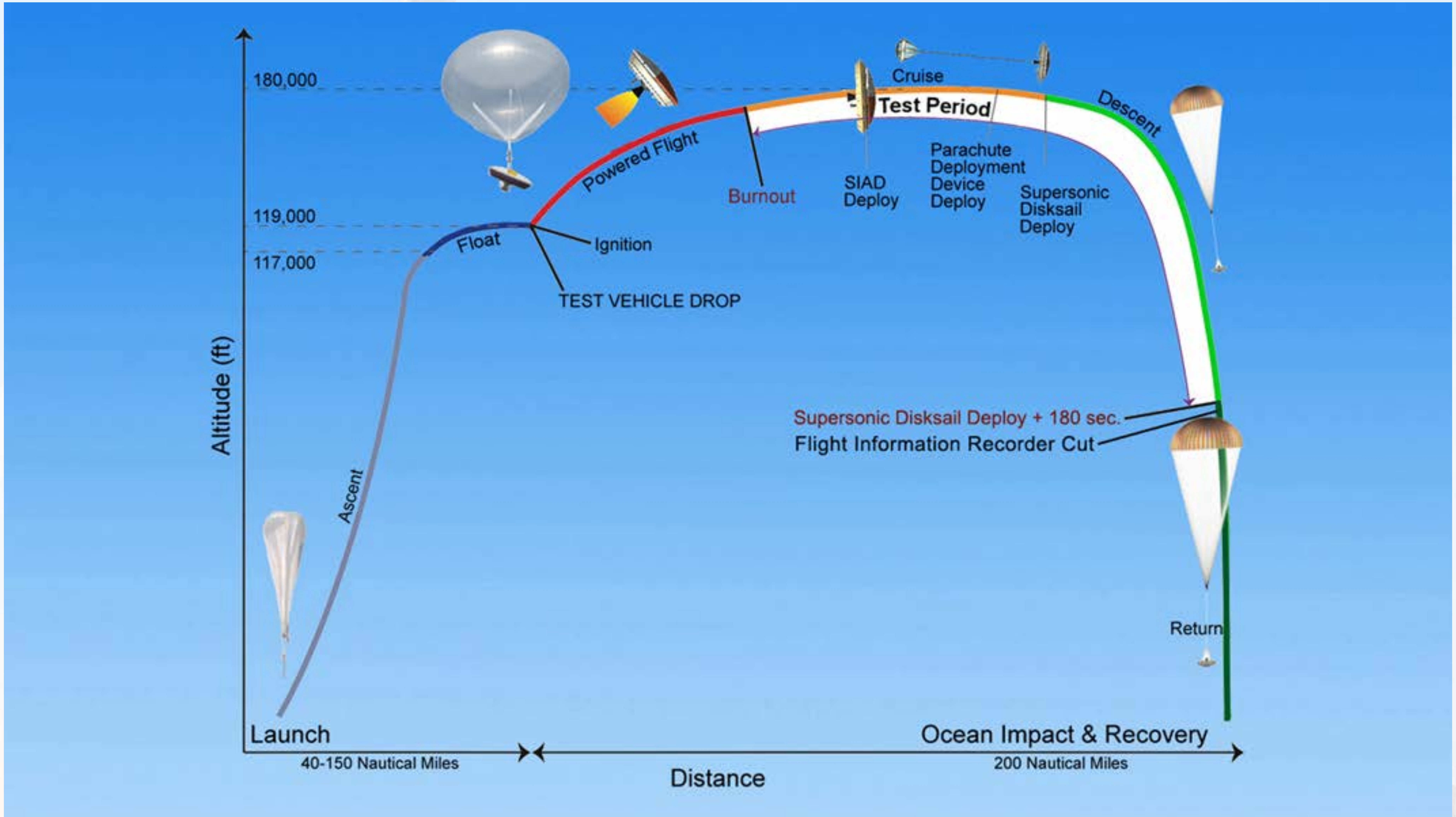


Inflatable Aerodynamic Decelerators

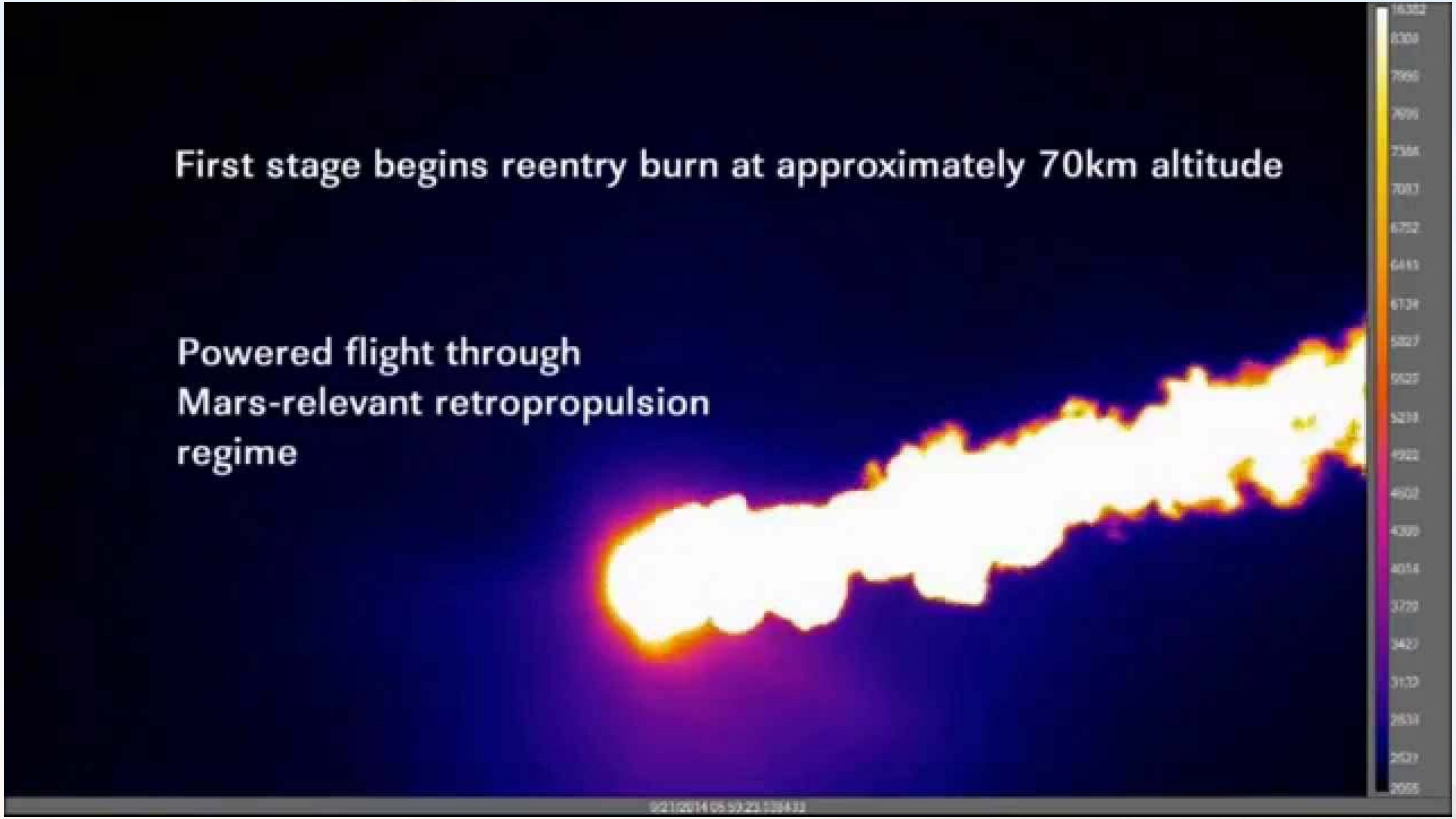


Low-Density Supersonic Decelerator

LDSD Flight Test Profile

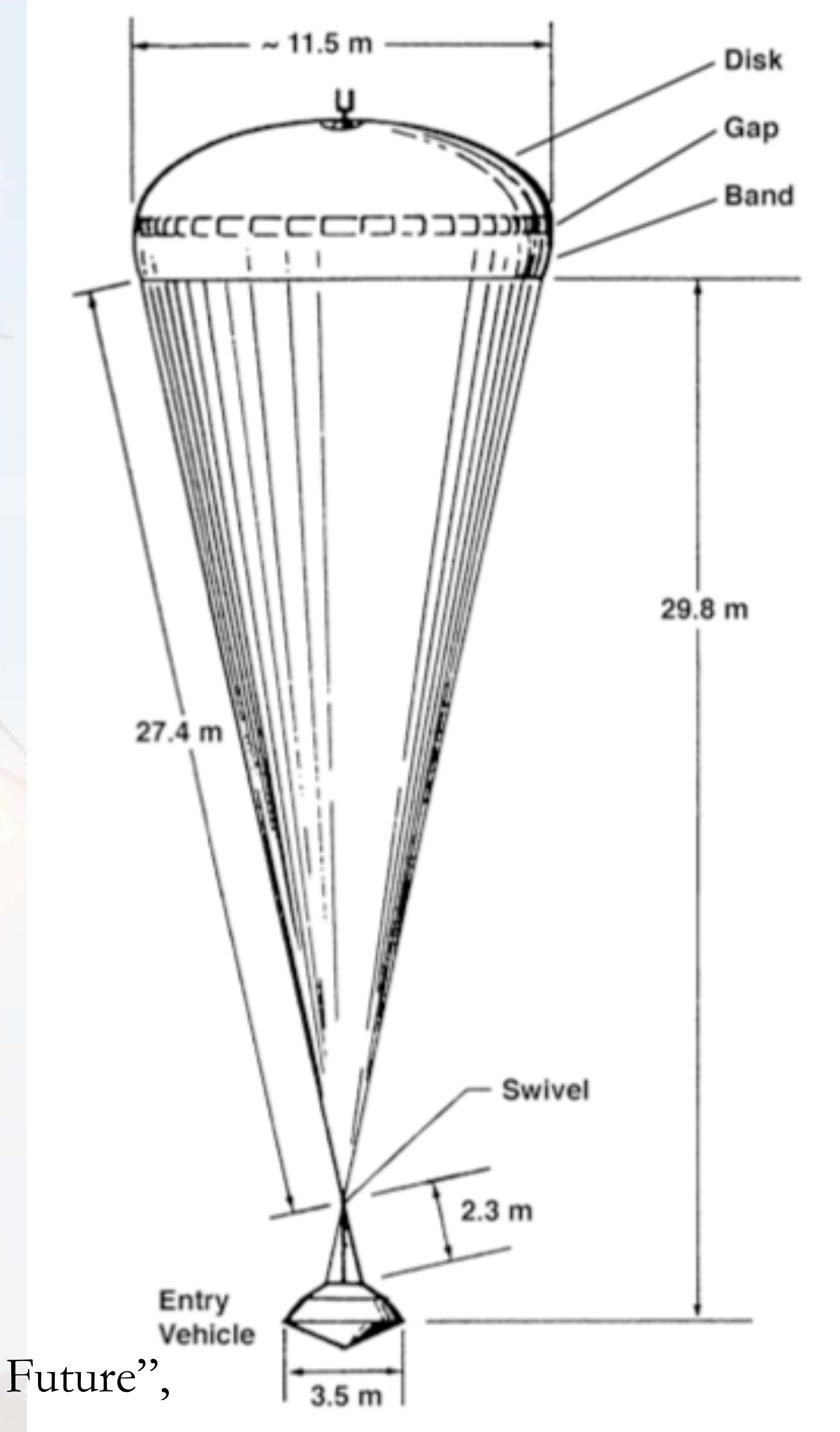


Supersonic Retropropulsion



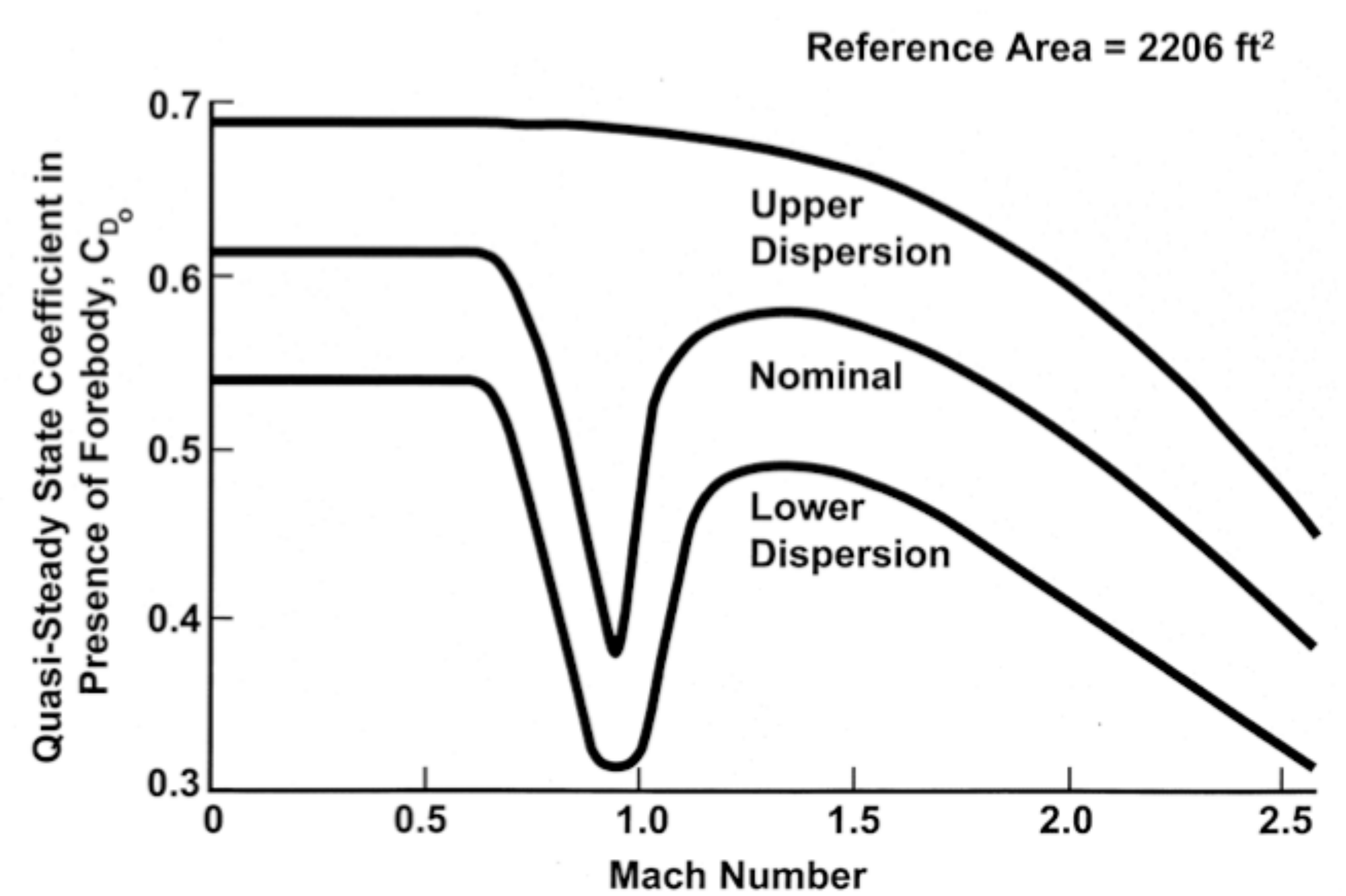
Viking Parachute Configuration

- "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 -

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

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

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

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

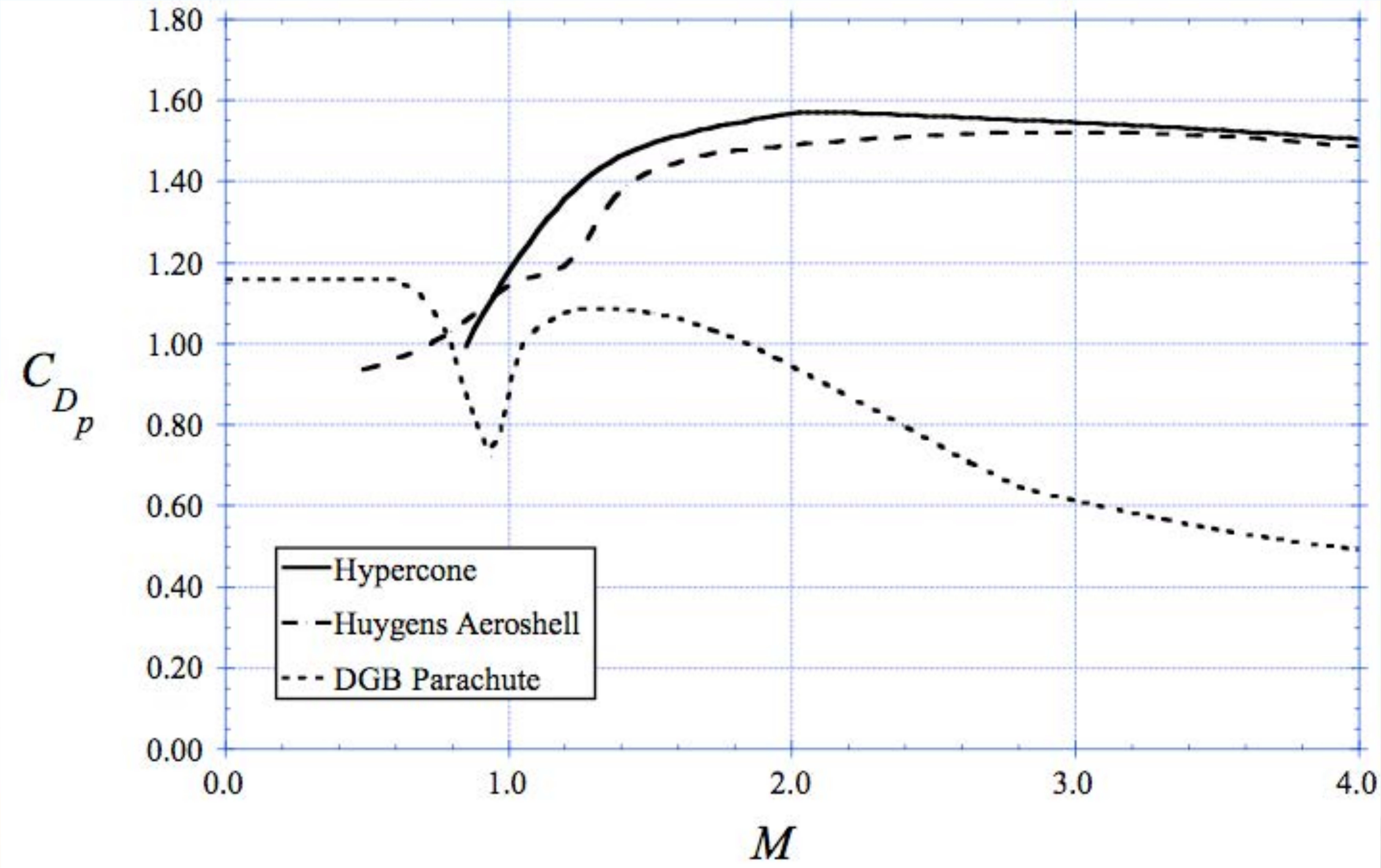
Viking Terminal Velocity Under Chute

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

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

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

Rigid and Inflatable Aeroshell vs. Chute



Low Ballistic Coefficient Hypersonic Decelerator Development Challenges

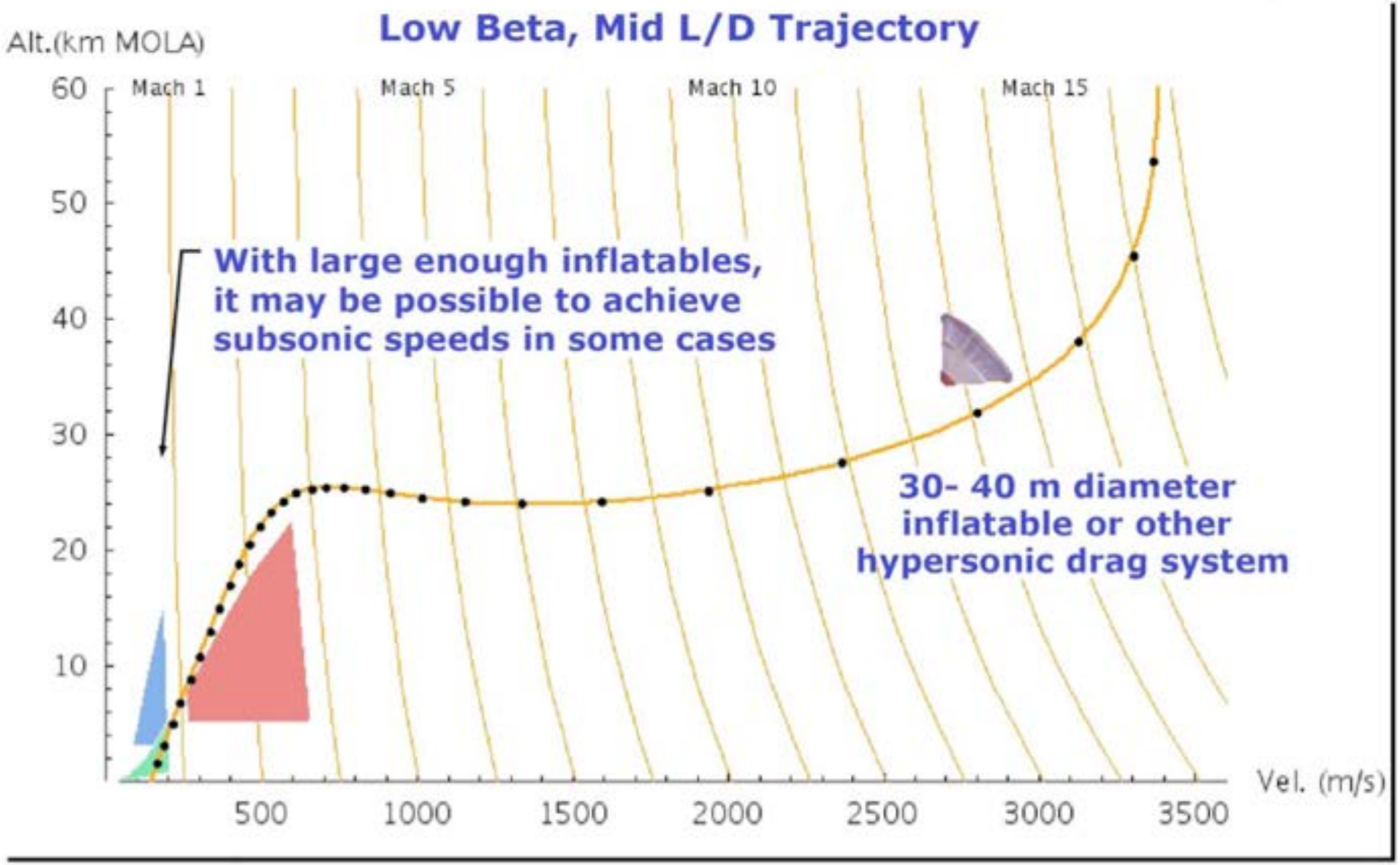
- **For 50-100 MT entry masses we need a 20-40 m diameter aeroshell.**
- **Large uncertainties (unknown-unknowns):**
  - Lift control (how to modulate drag) with large density uncertainties
  - Dynamic stability issues at supersonic and transonic conditions
  - Subsonic position correction
  - Subsonic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



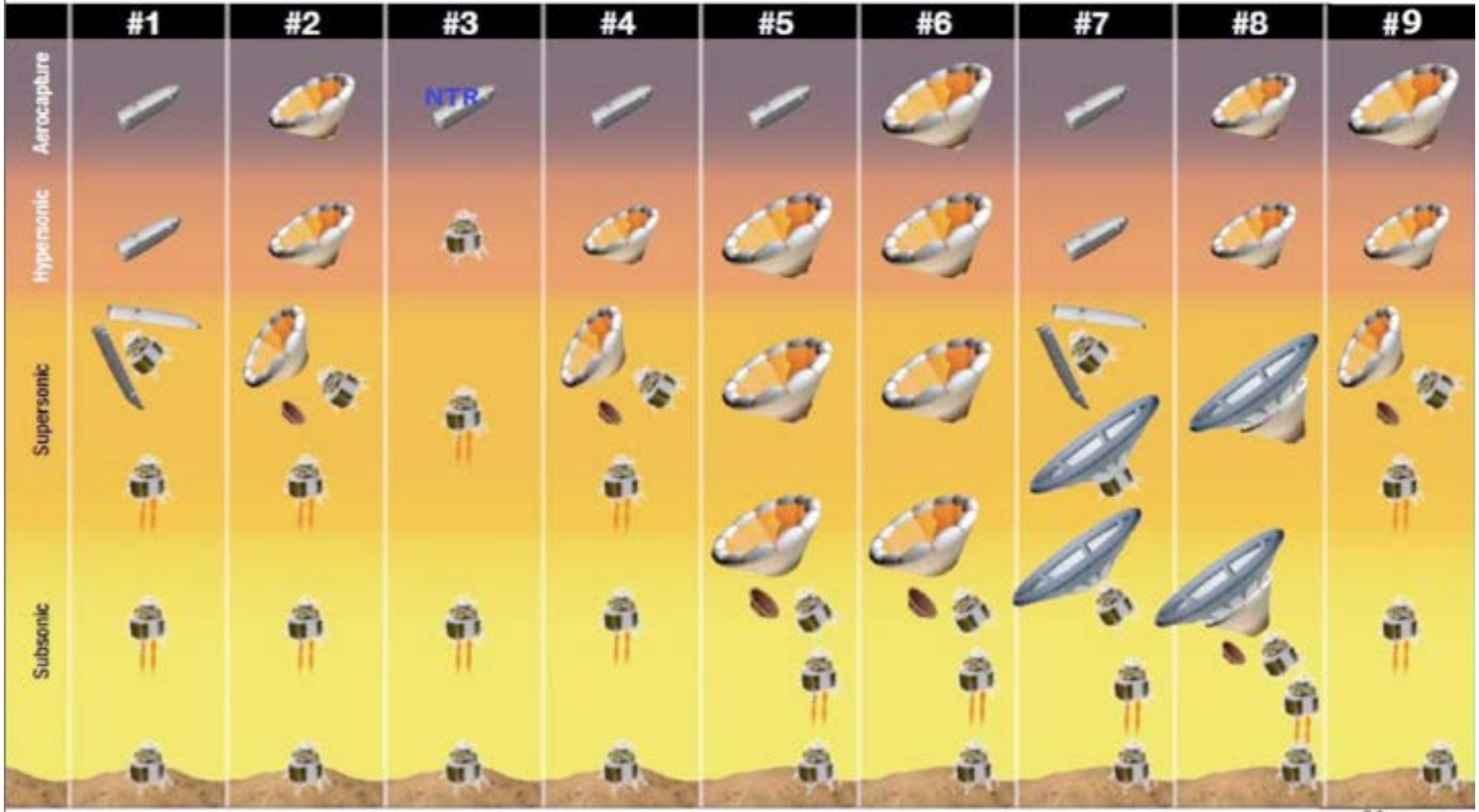
Supersonic Retro-Propulsion

- **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)

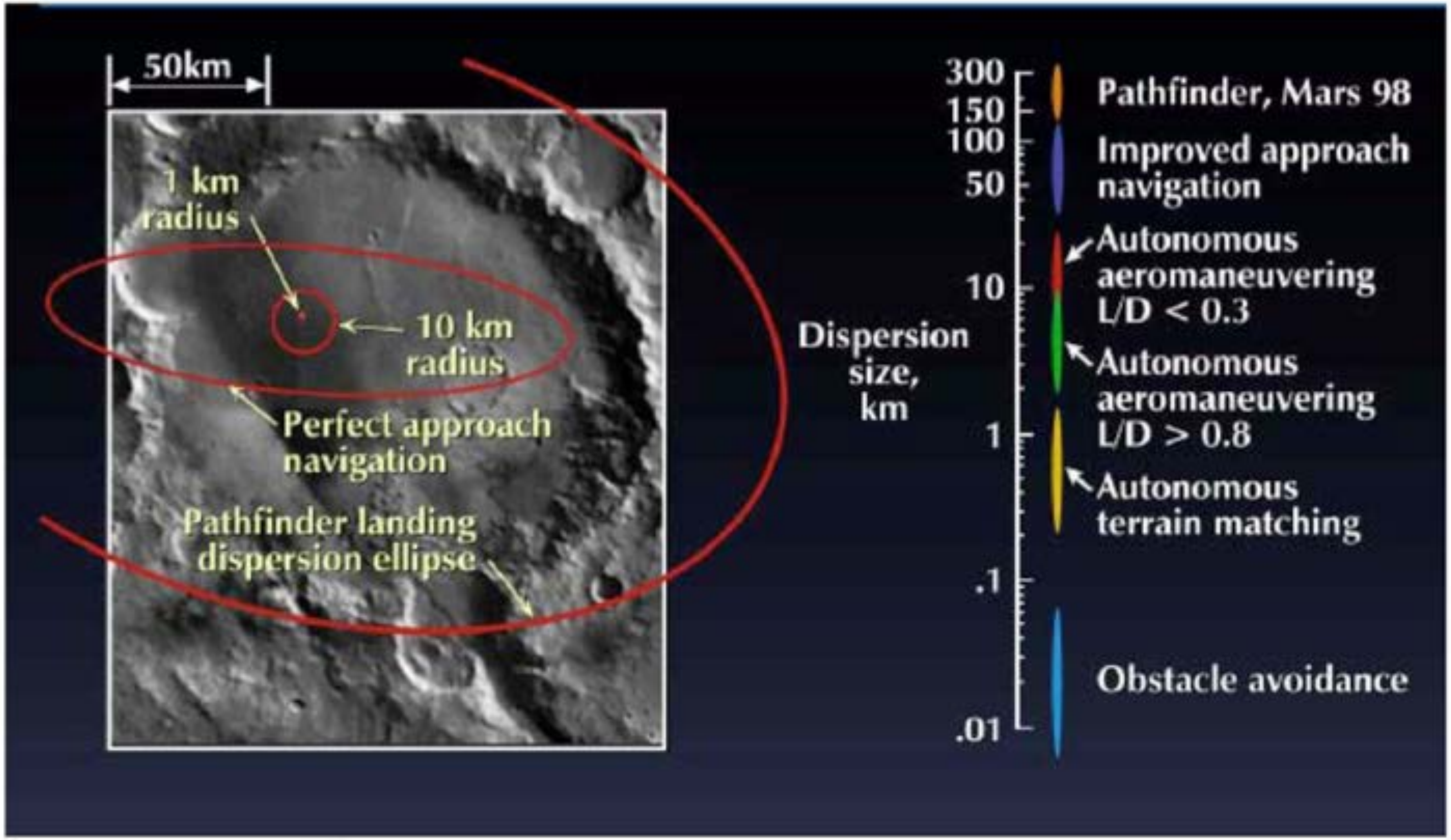
- **Disadvantages:**
  - Large propellant mass fractions
  - Aerodynamic stability of the vehicle plume and flow impingements
  - RCS / flow interactions
    - Aerodynamic / propulsion flow interactions
    - Plume / flow aeroheating
  - Surface contamination issues

Potential Exploration Architectures

Some possible combinations…

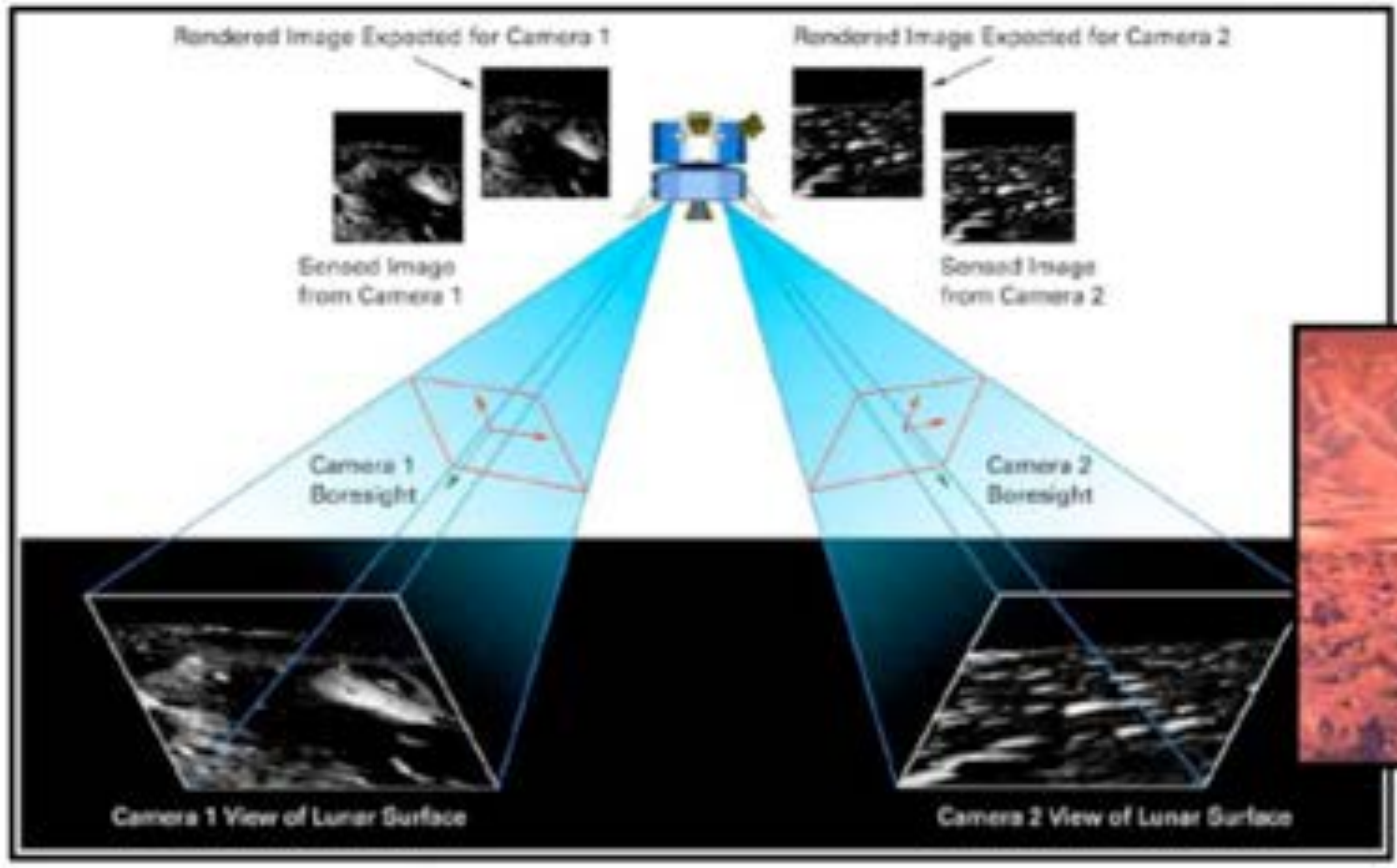


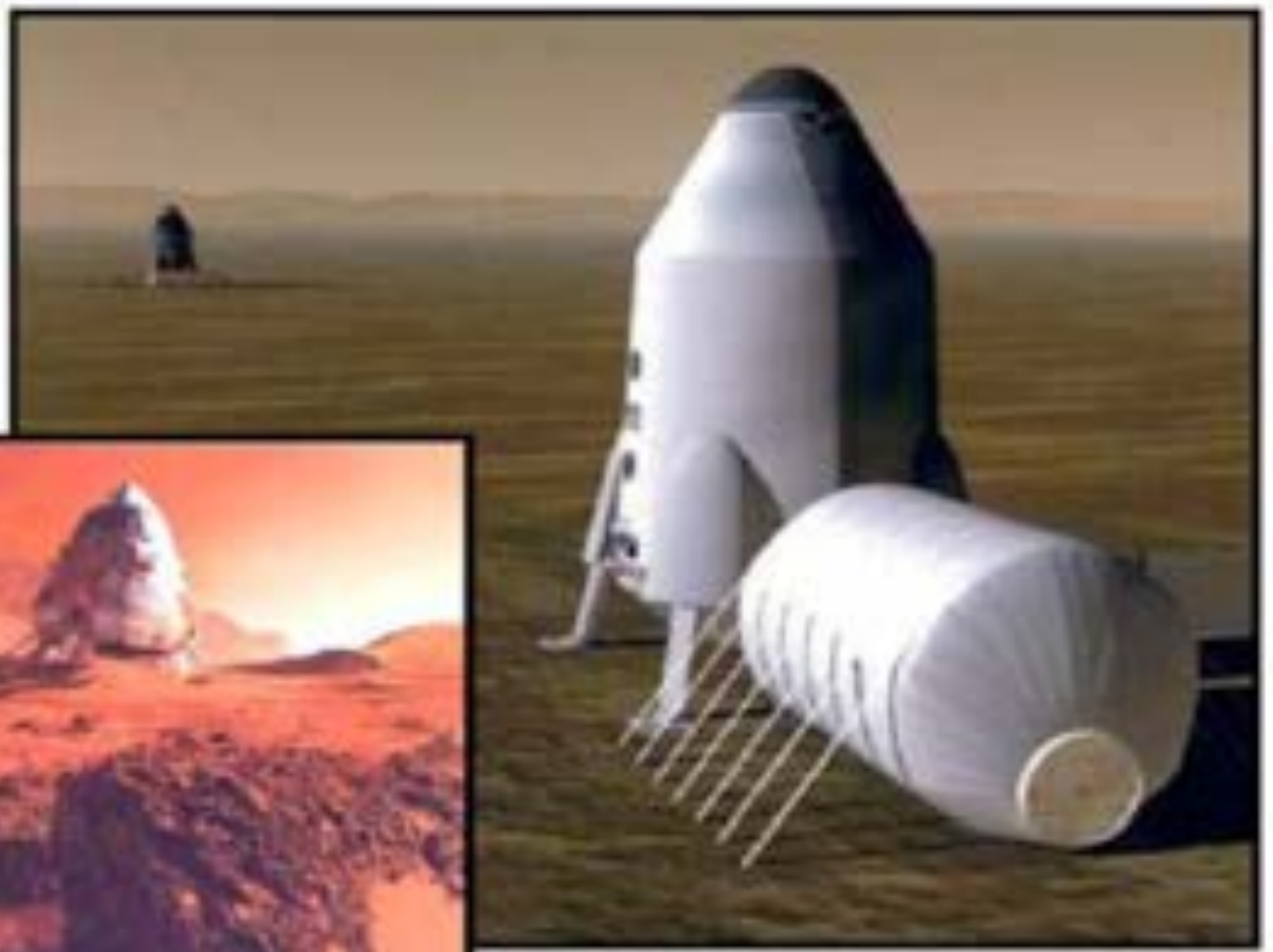
The Case for Precision Landing, Hazard Avoidance, and Pinpoint Landing



Precision Landing

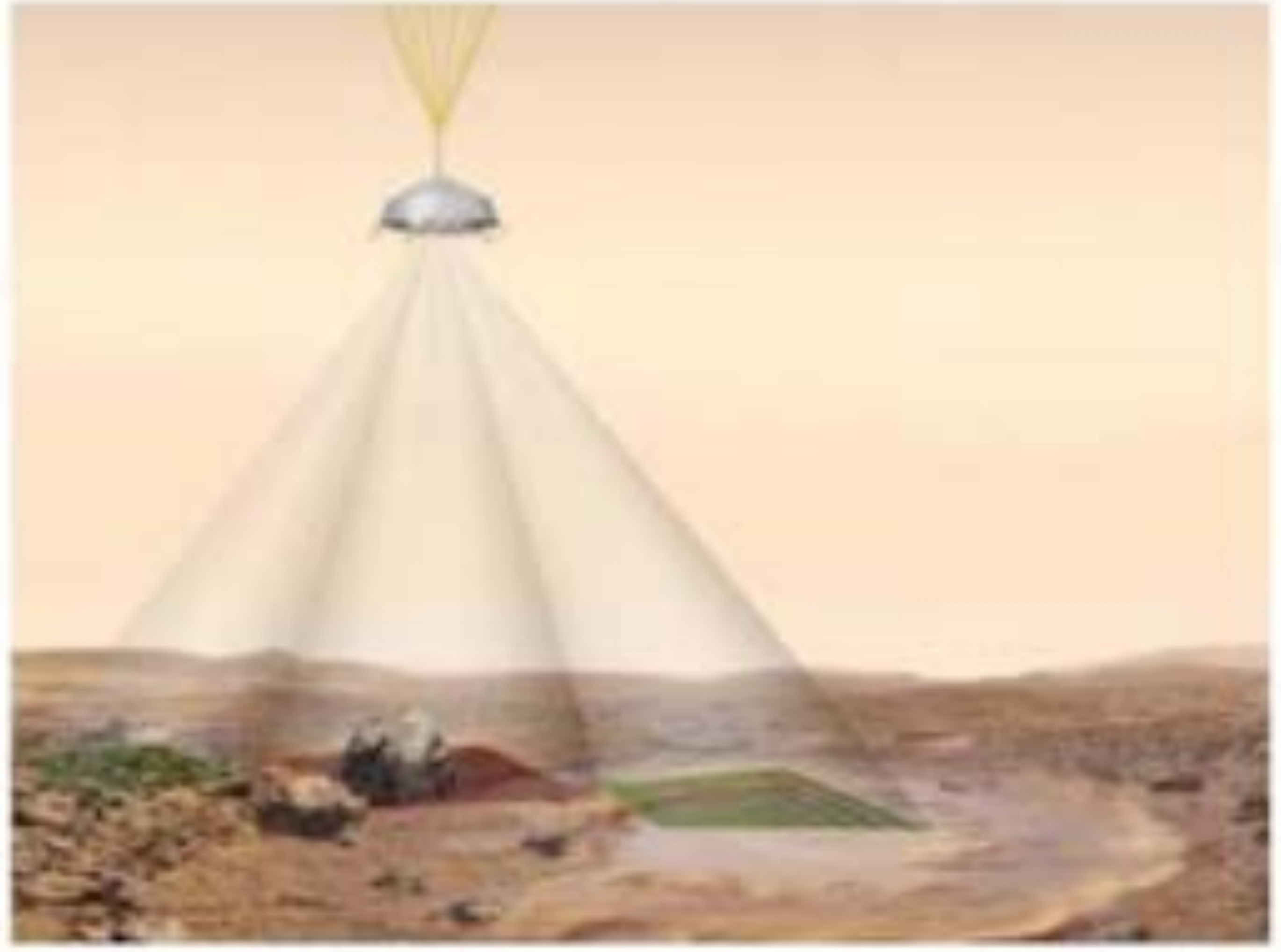
- Precision landing is the capability to land very accurately
- Requires very good knowledge of the vehicle state (navigation) at the right time, in addition to the ability to correct for state errors (guidance and control)
- A combination of sensors including star tracker, inertial measurement unit (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

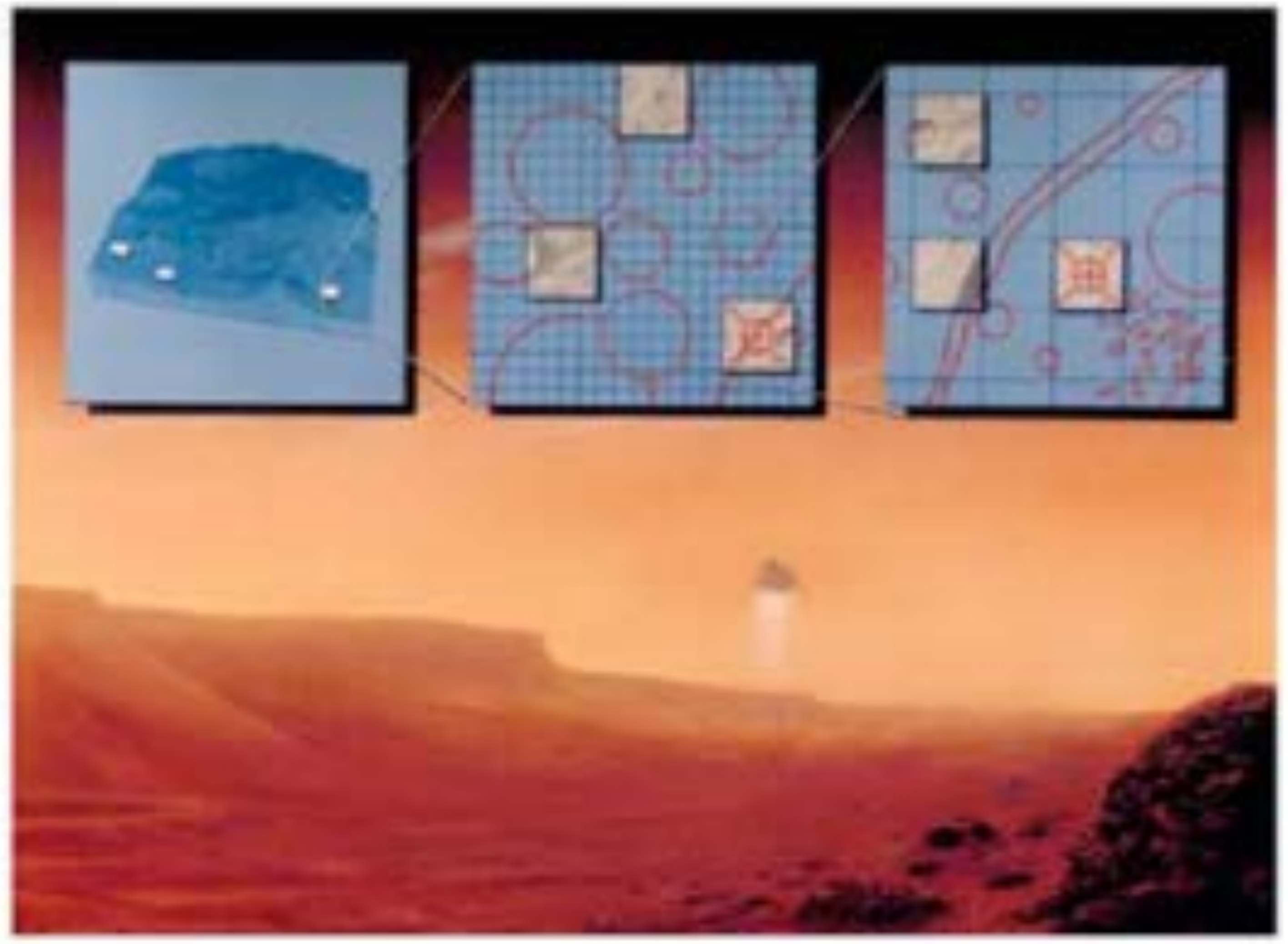




Hazard Detection and Avoidance (HDA)

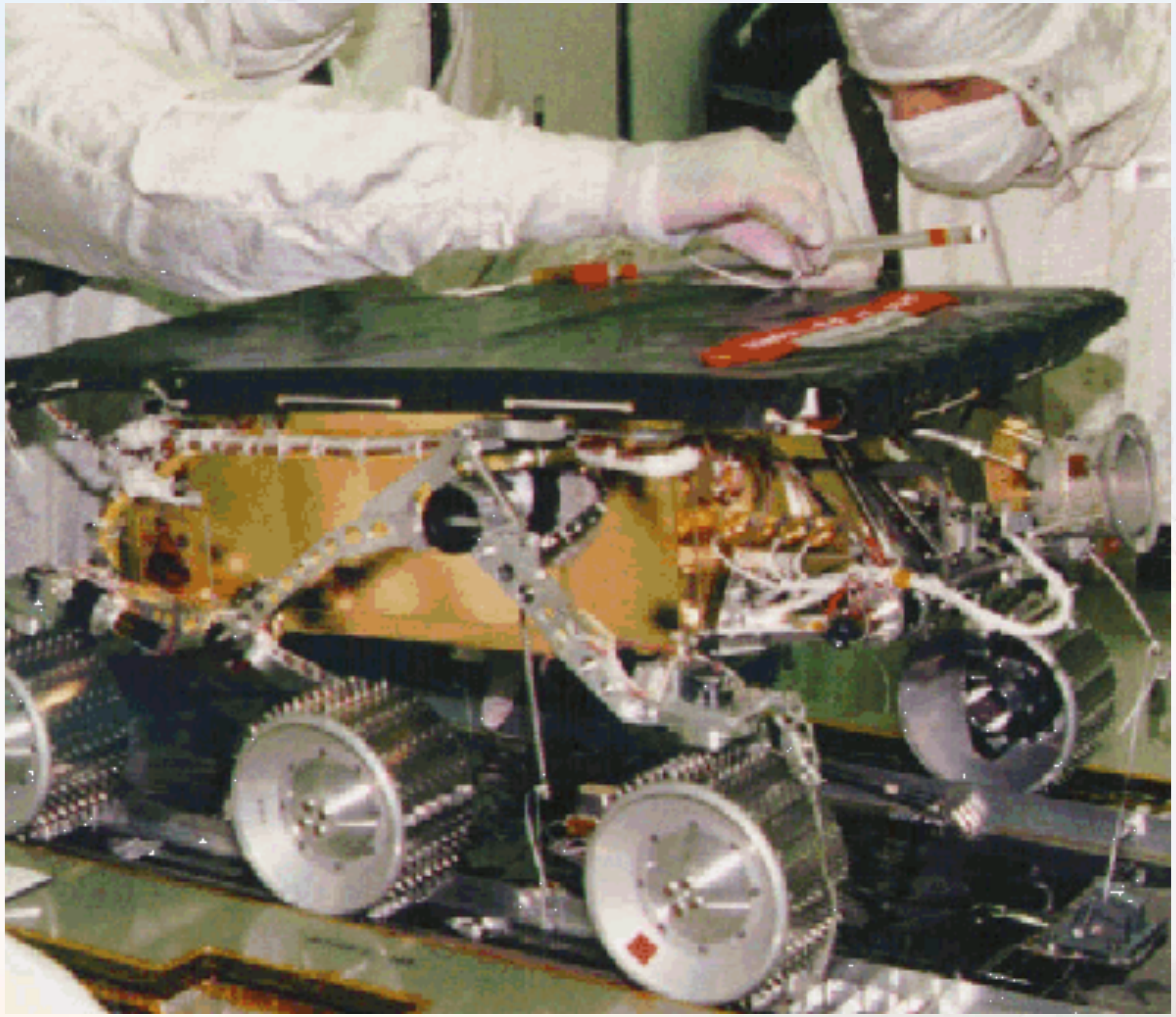
- HDA is the capability to detect and avoid hazards during the landing
- An onboard hazard map is developed real time during the descent using flash LIDAR
- The flash LIDAR returns a 3-D image of the landing area which contains higher resolution information of the landing area than currently possible 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



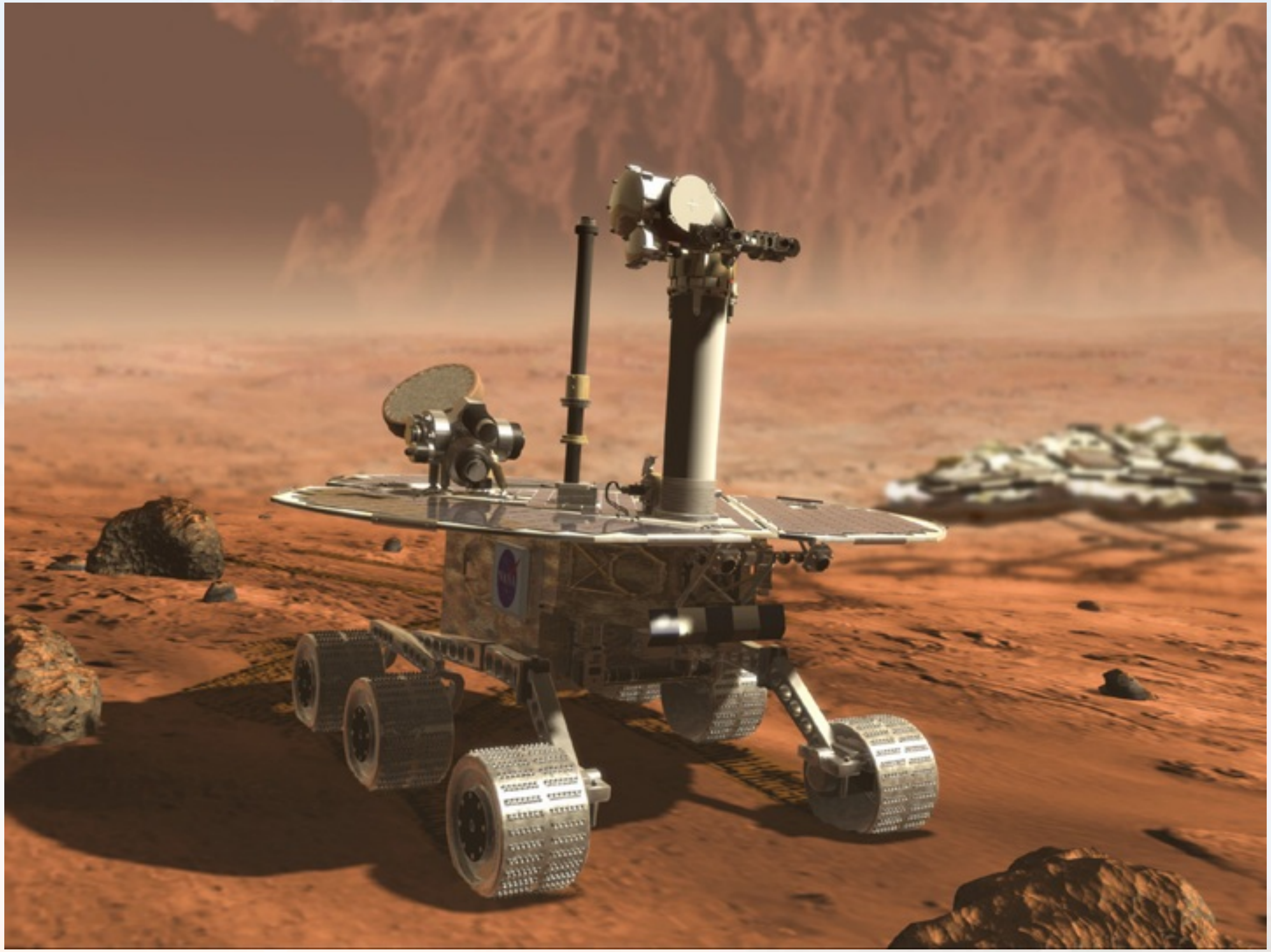


Viking Panoramas (1976)

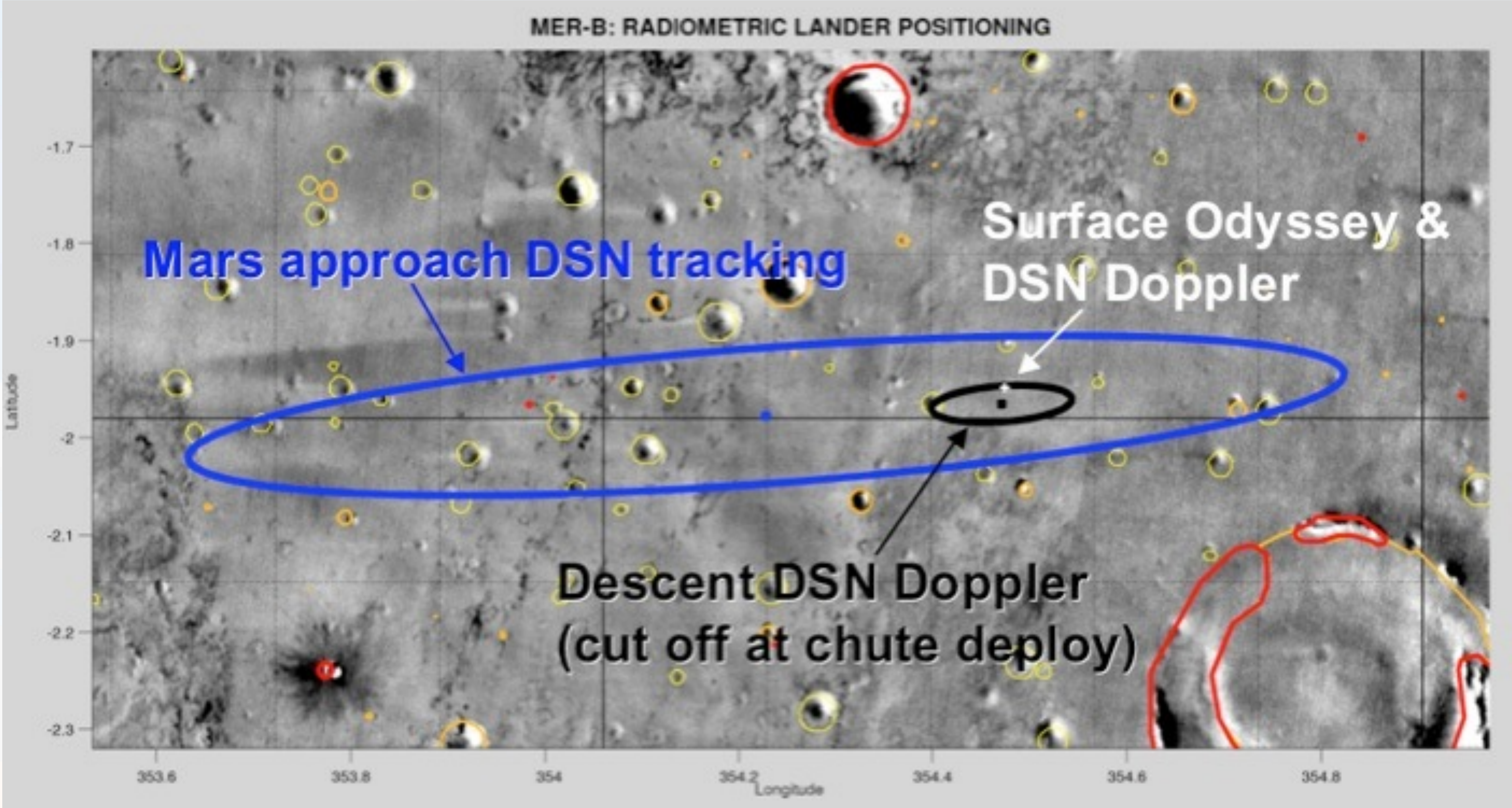
Mars Pathfinder Rover ("Sojourner")



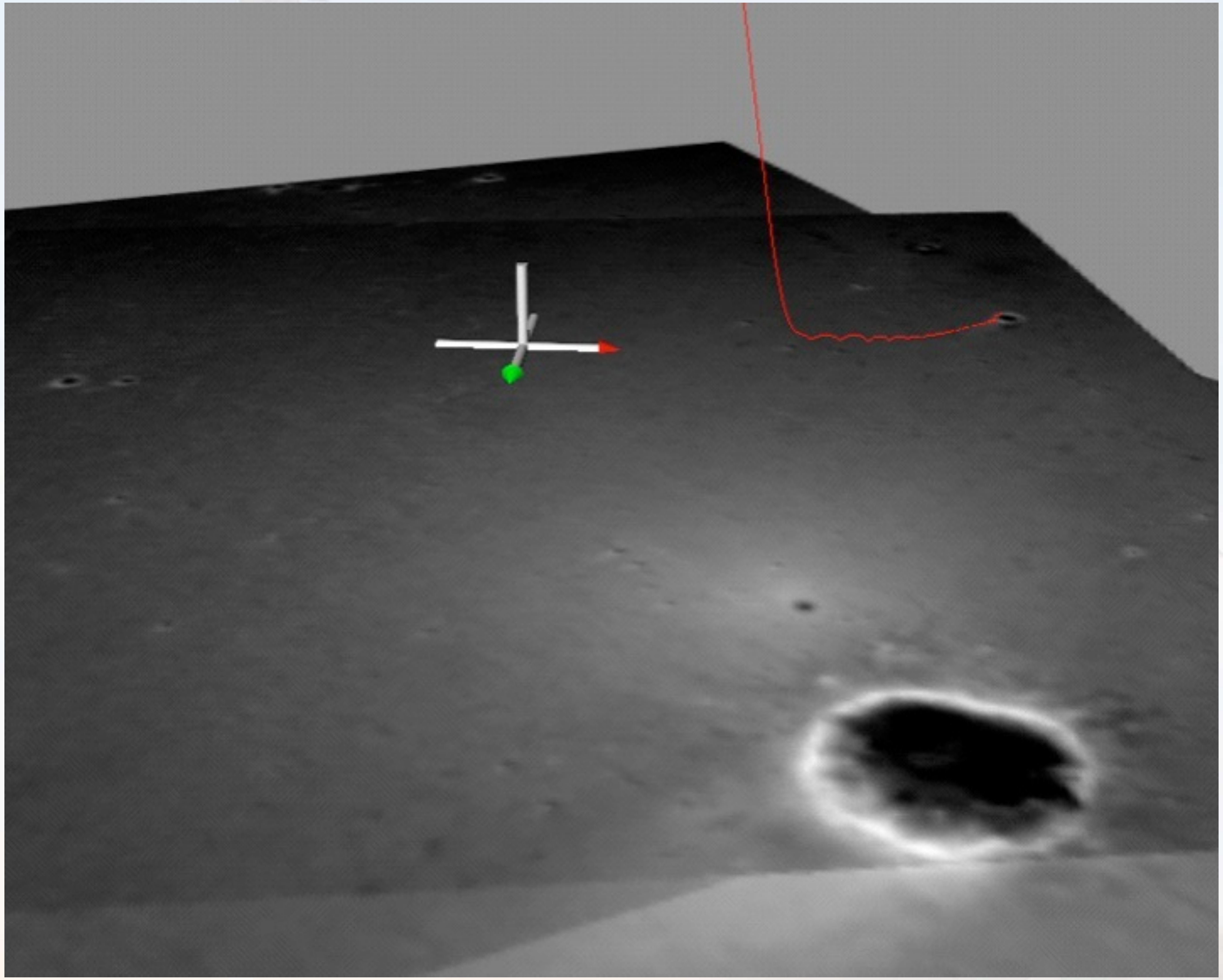
Mars Exploration Rover



Opportunity Landing Targeting

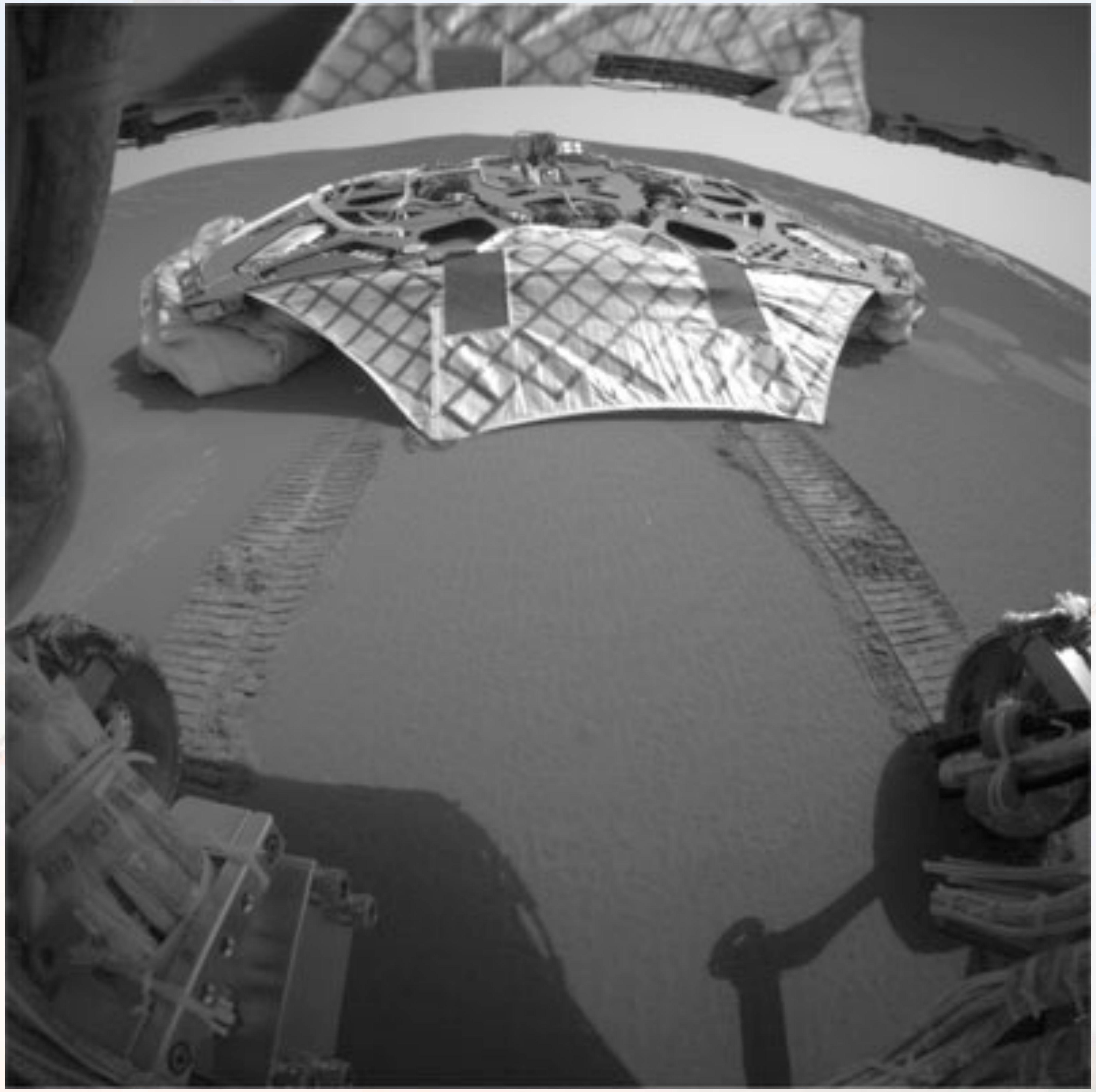


Sometimes the Bounces Go Your Way...

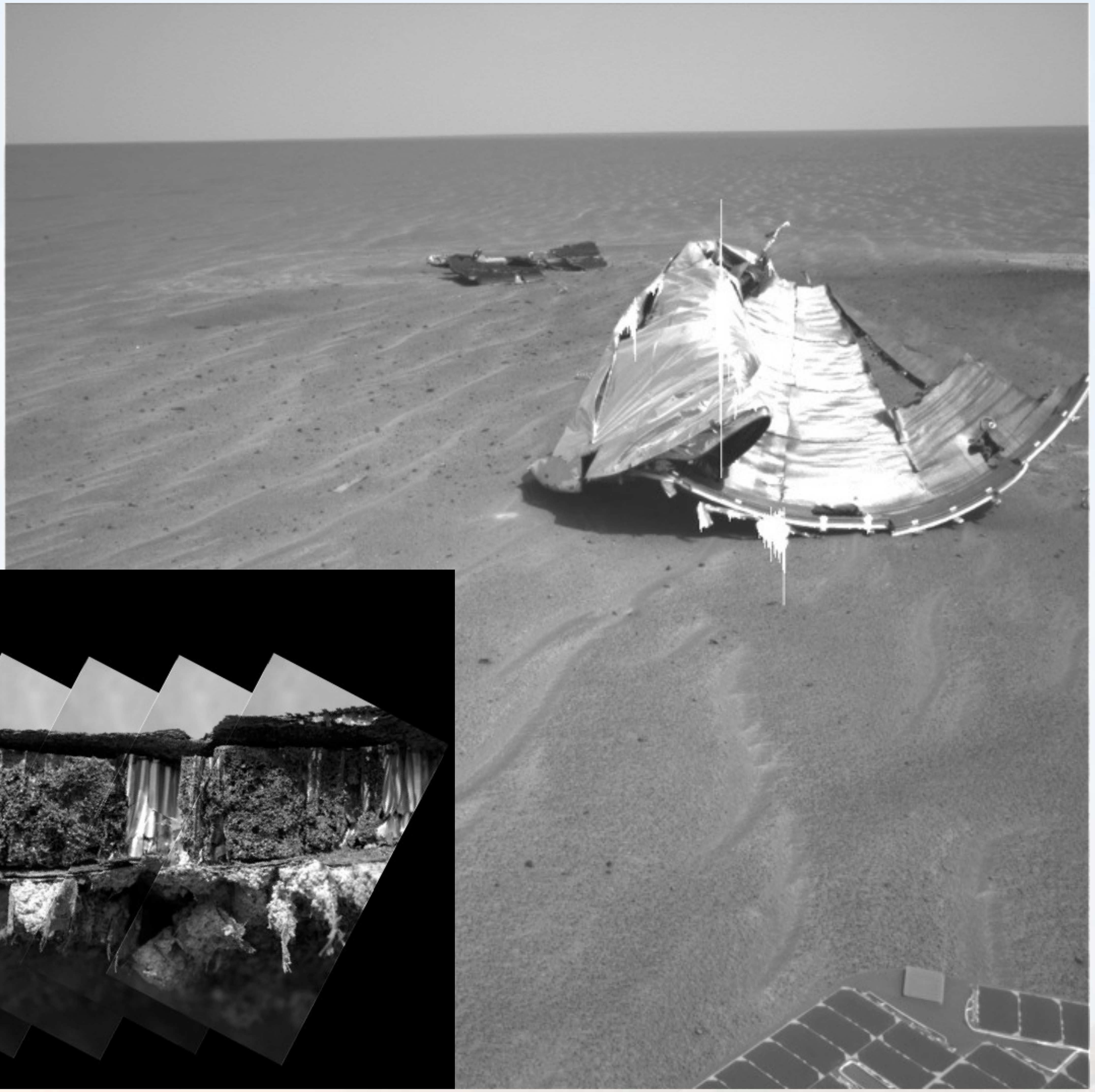


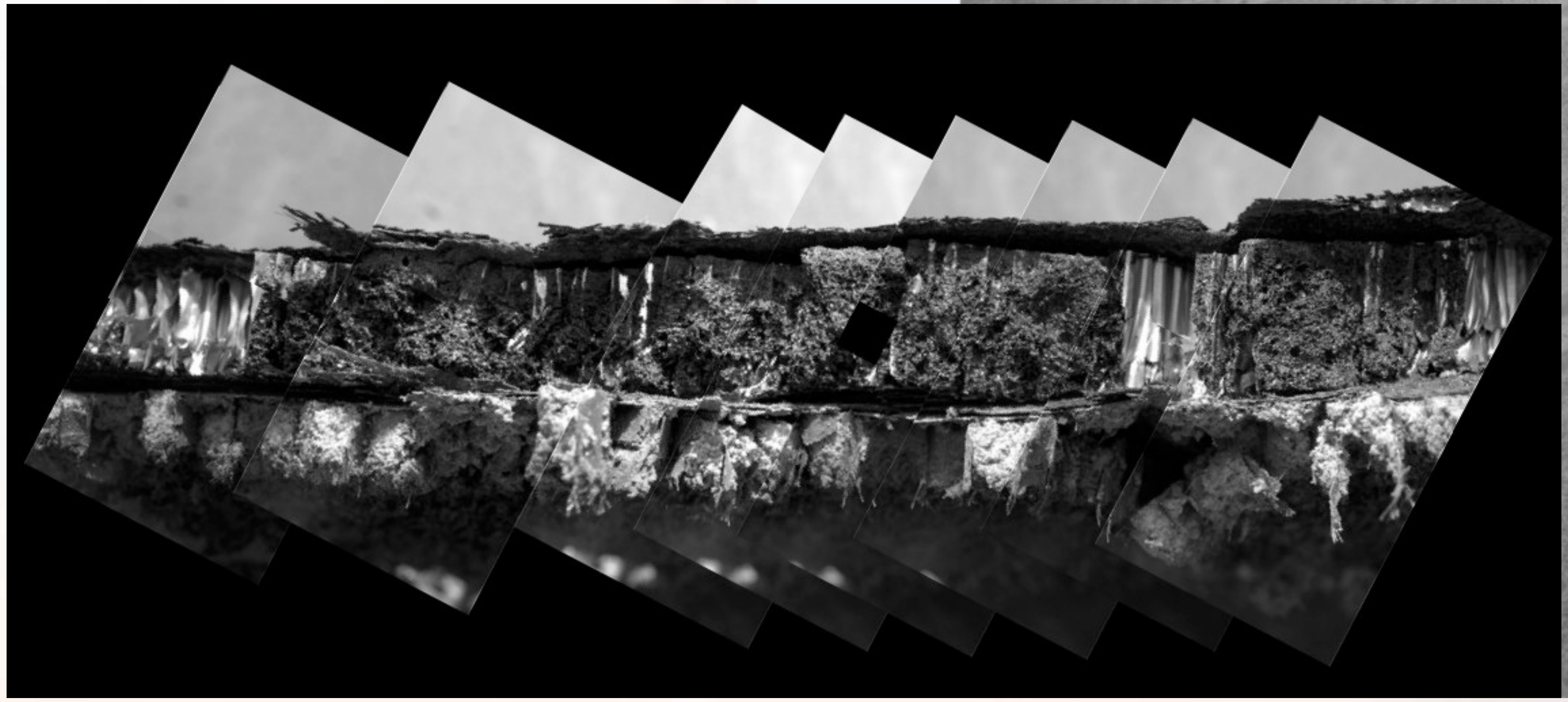
...Opportunity Scores a Hole in One

Spirit Lands in Gusev Crater

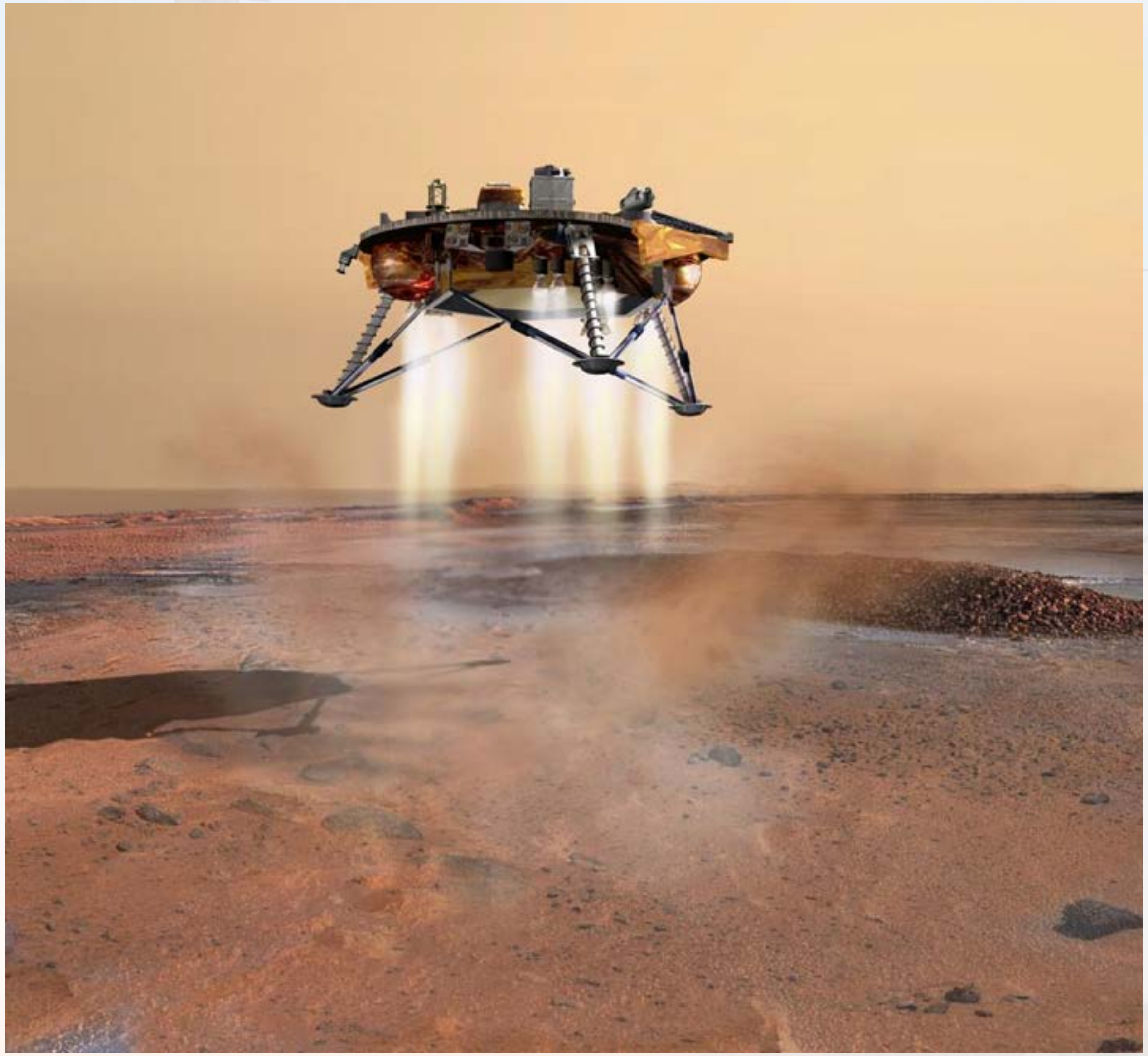


Odyssey Finds its Heat Shield...



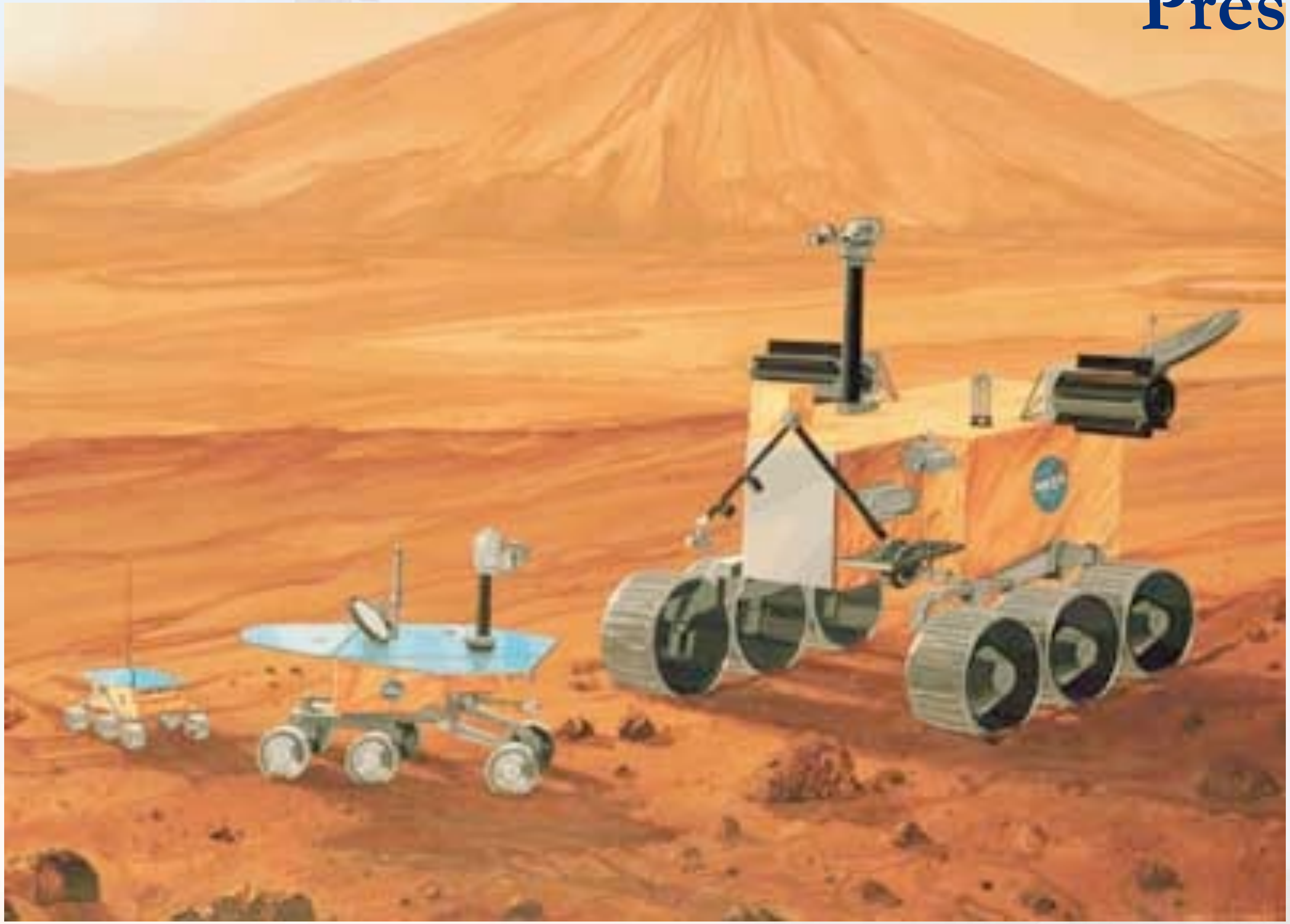


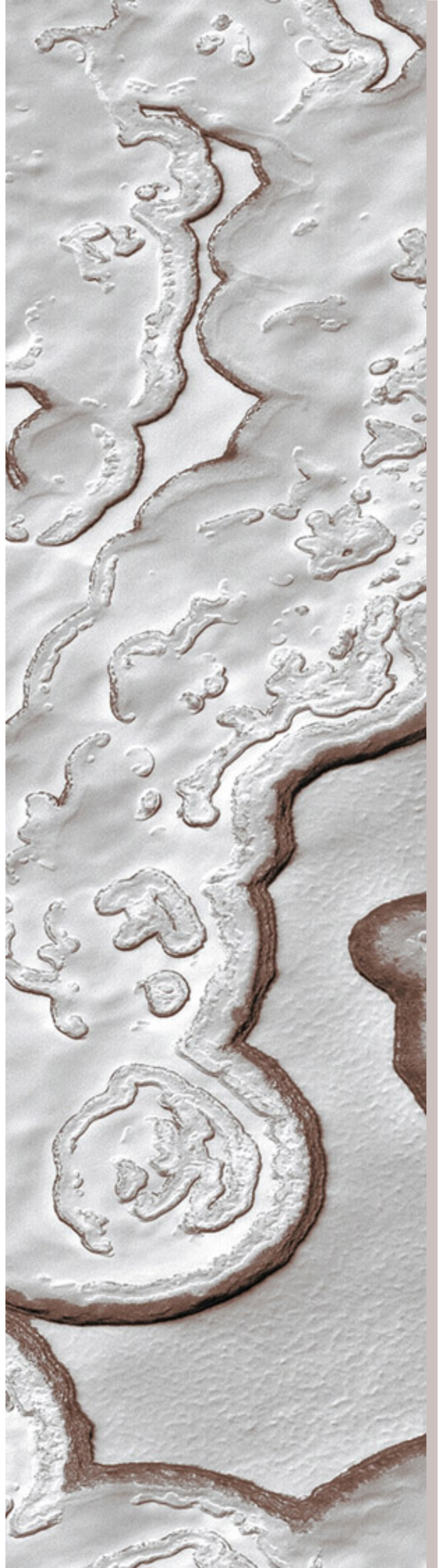
Mars Phoenix Lander Touchdown



Mars Rovers (Past, Present, Future)

Present





Mars Science Laboratory
Project Introduction

Richard Cook
Project Manager

December 7, 2005

Project Overview

Salient Features

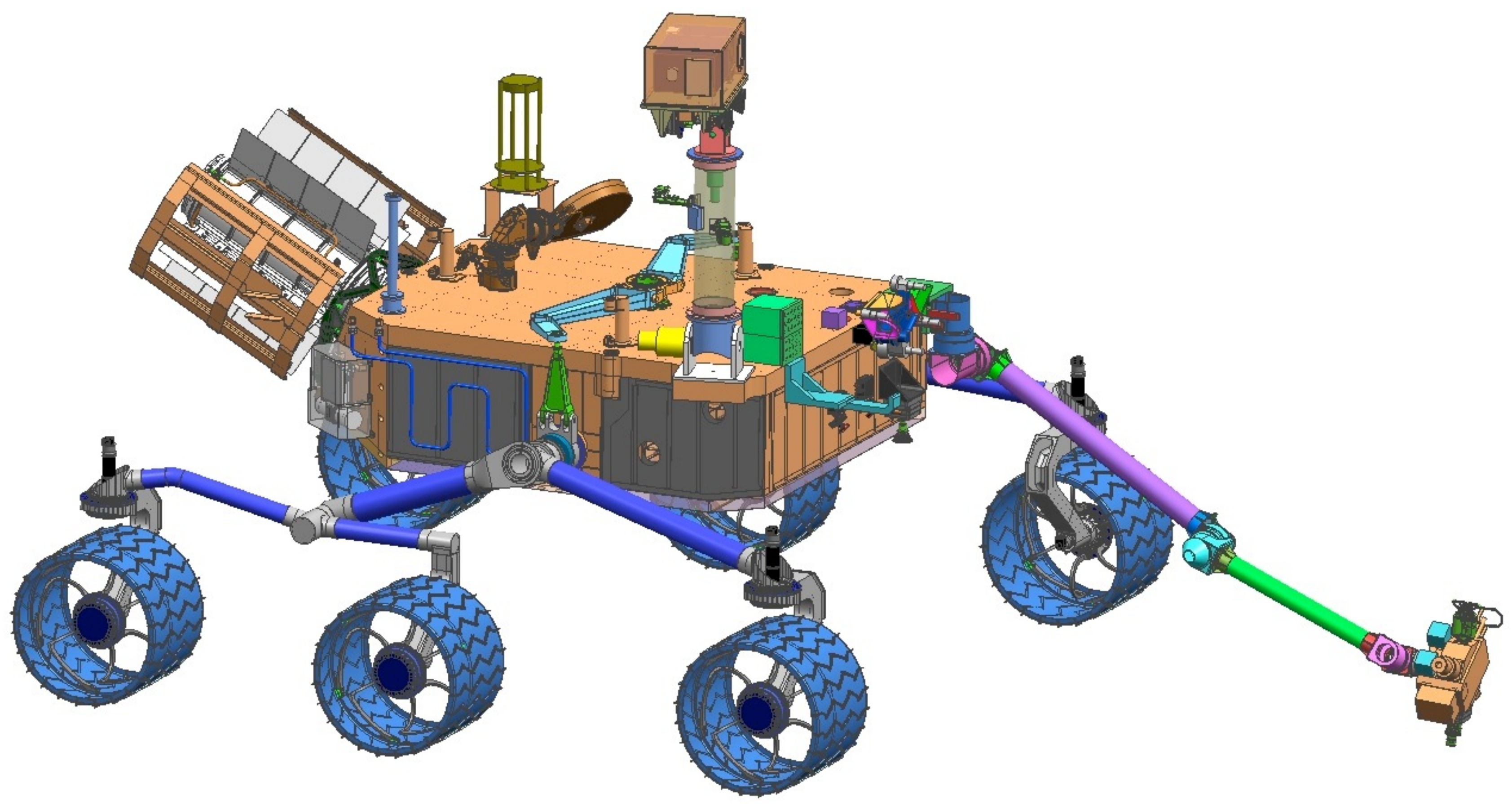
Mobile Science Laboratory

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



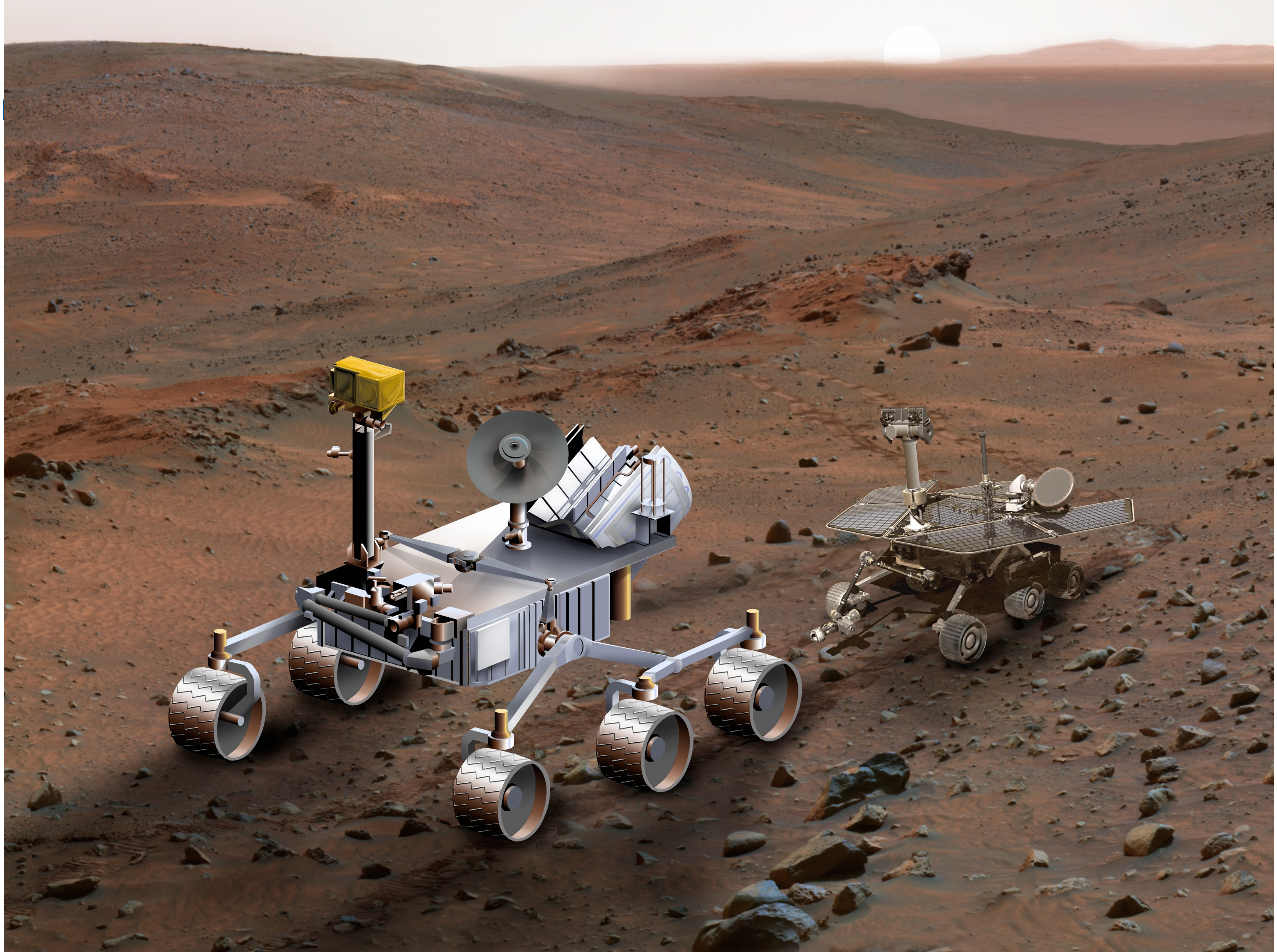
Science

Mission science will focus on Mars habitability

Next generation analytical laboratory science investigations

Remote sensing/contact investigations

Suite of Environmental Monitoring Instruments

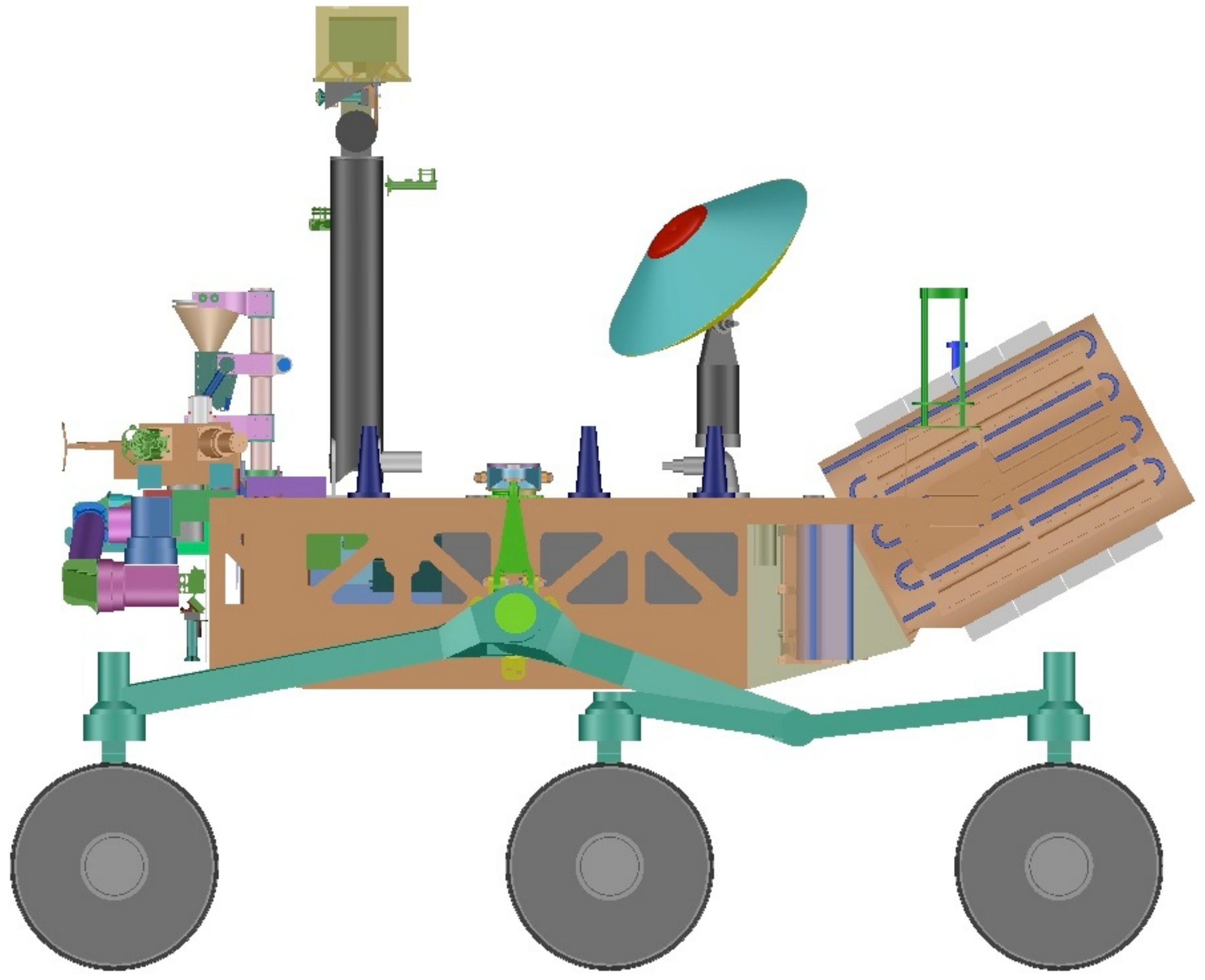


MSL-MER Comparison

	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

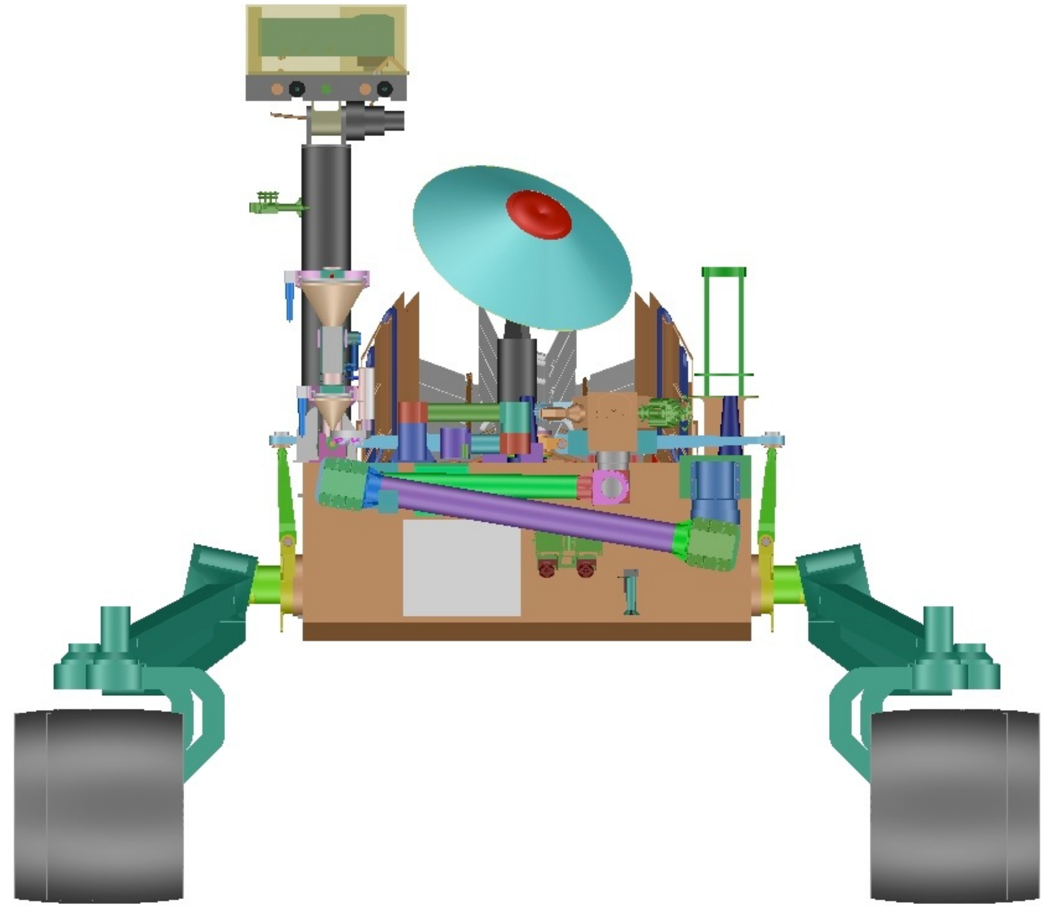
* - PreDecisional, RTG selection is contingent on NEPA/PD proces

MSL Rover Size Comparison

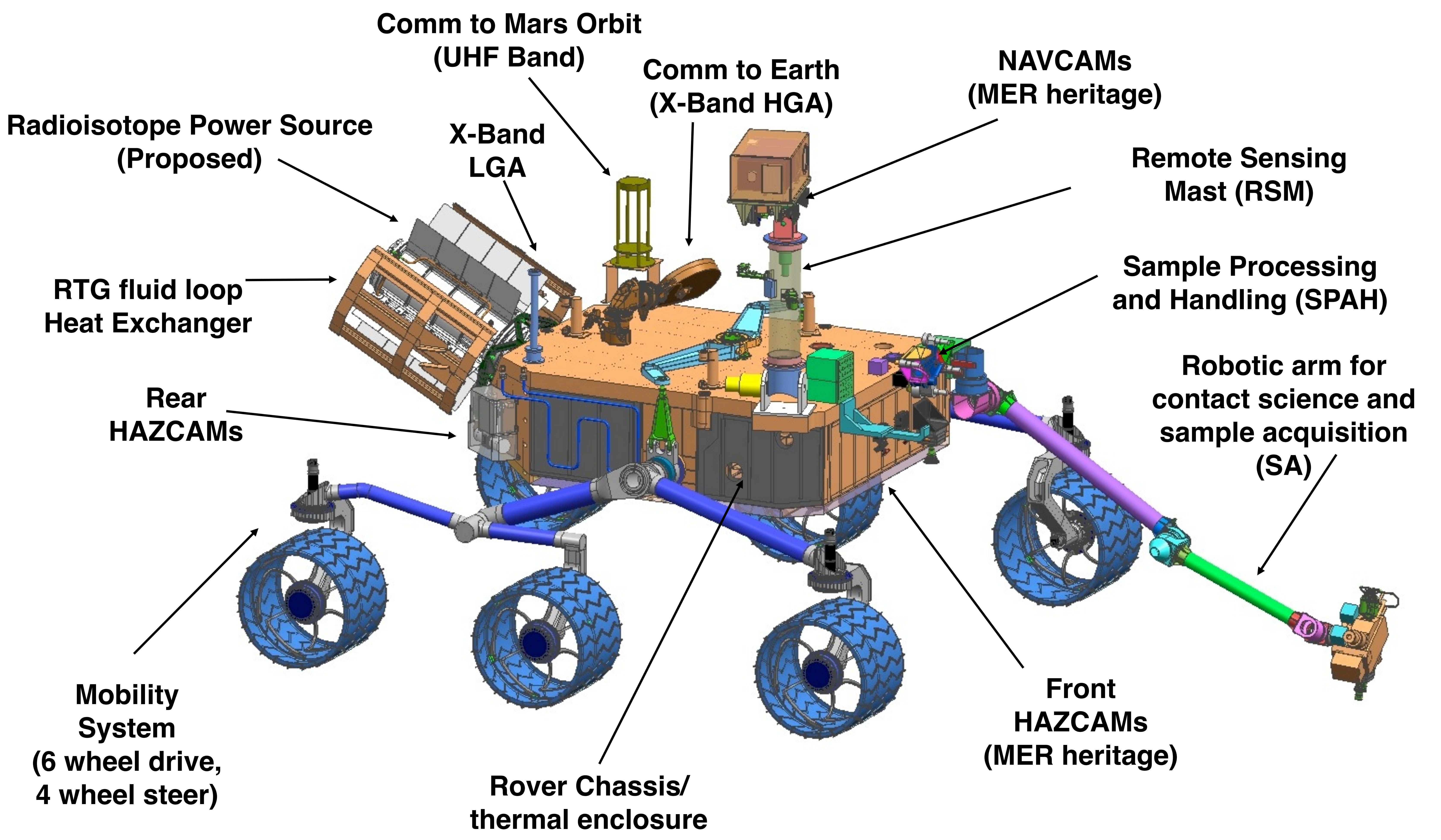


JPL 2009 MSL Rover

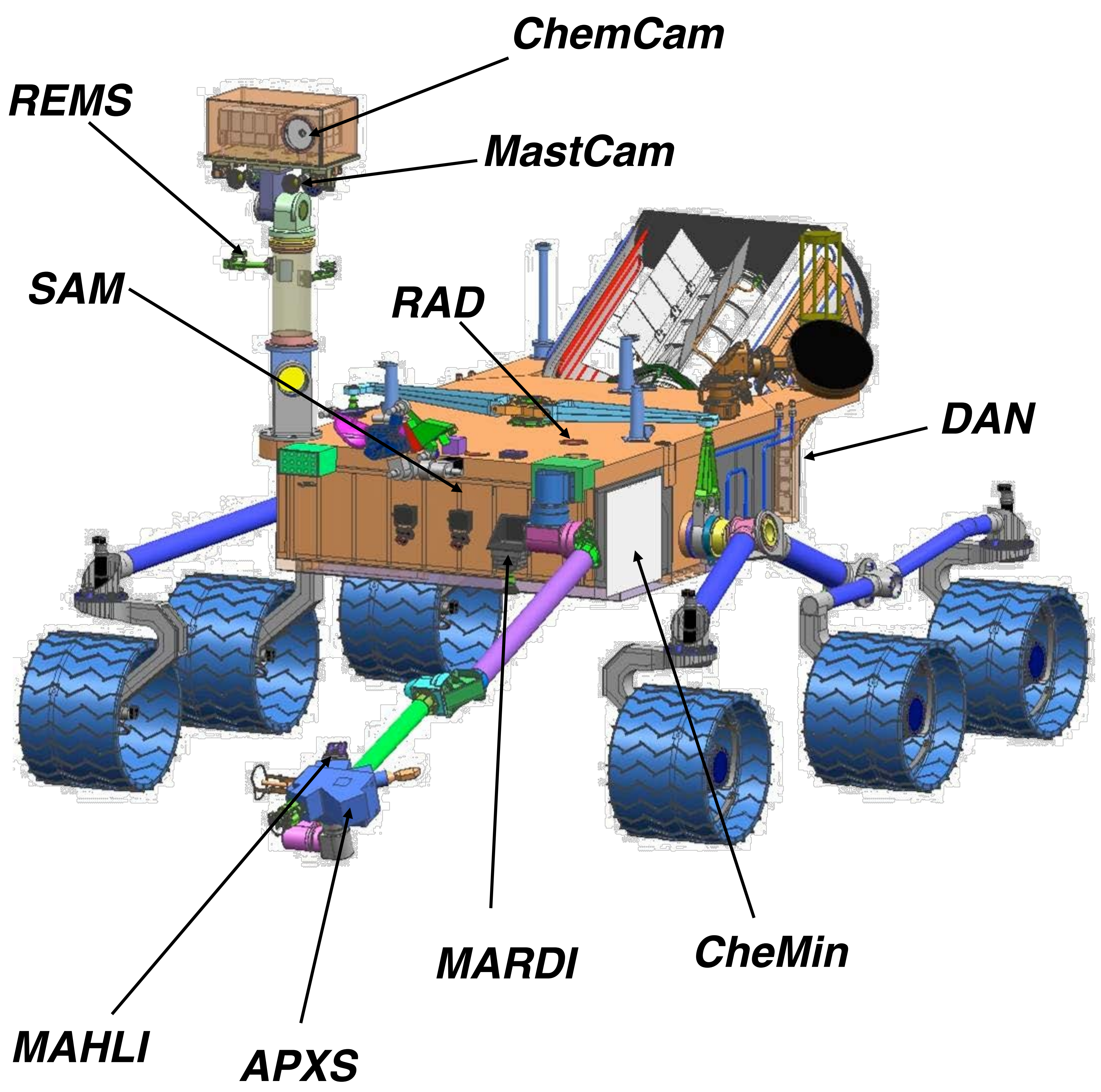
2005 MINI Cooper S



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

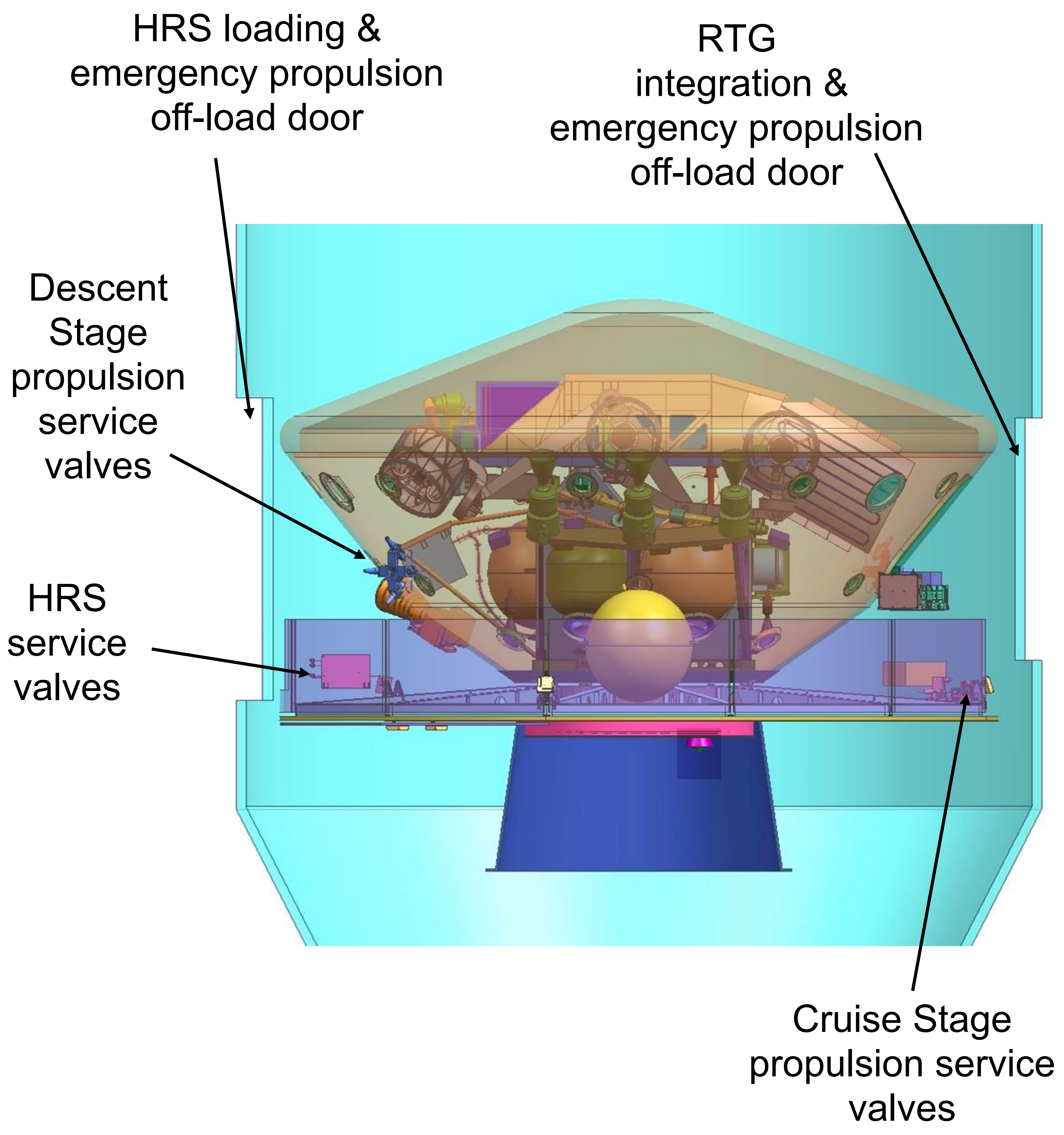
Presented at
Mars Science Laboratory PMSR
December 7-9, 2005

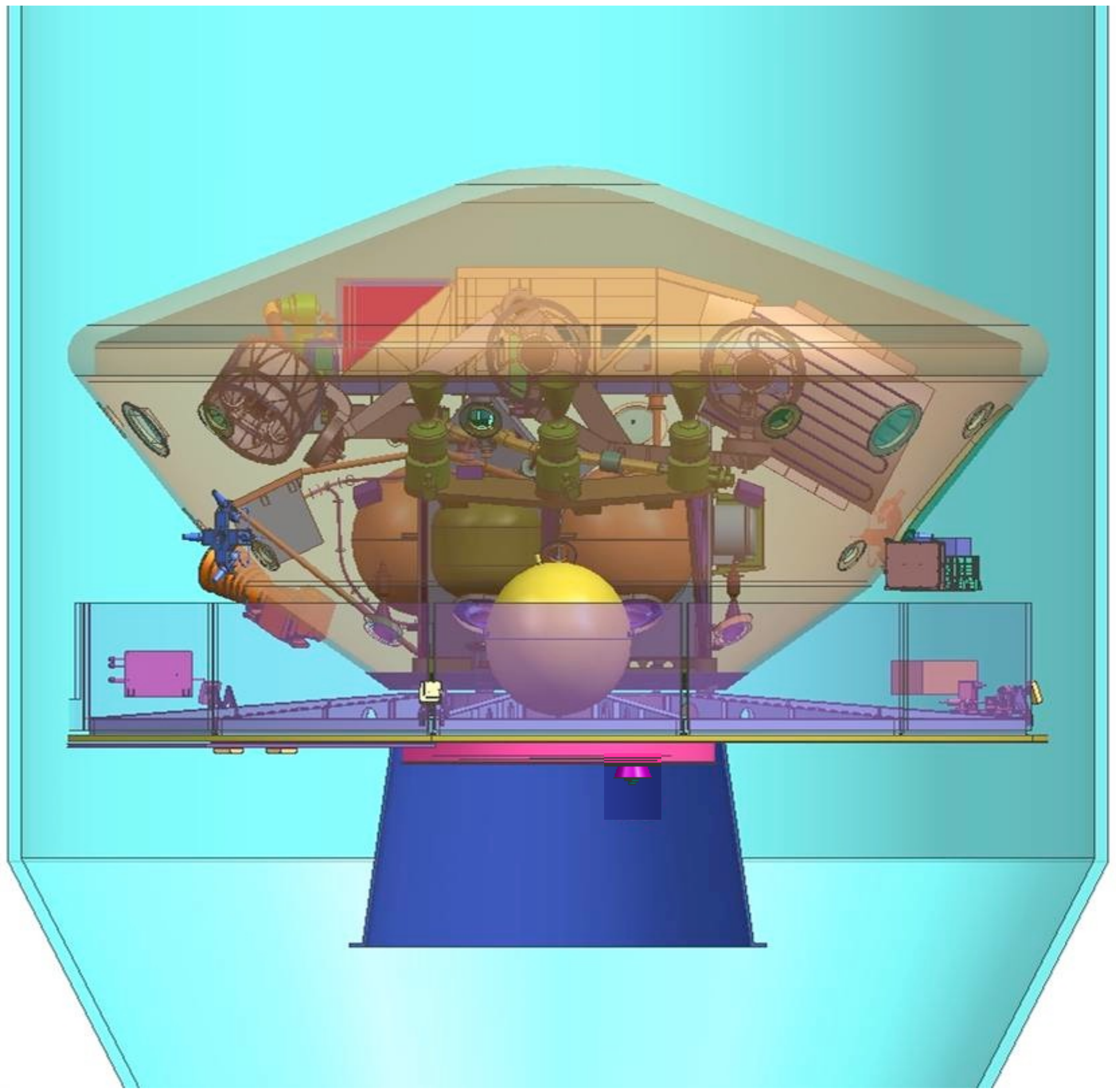
Christopher G. Salvo
Flight System Engineering Manager

PRE-DECISIONAL DRAFT: For Planning and Discussion Purposes Only

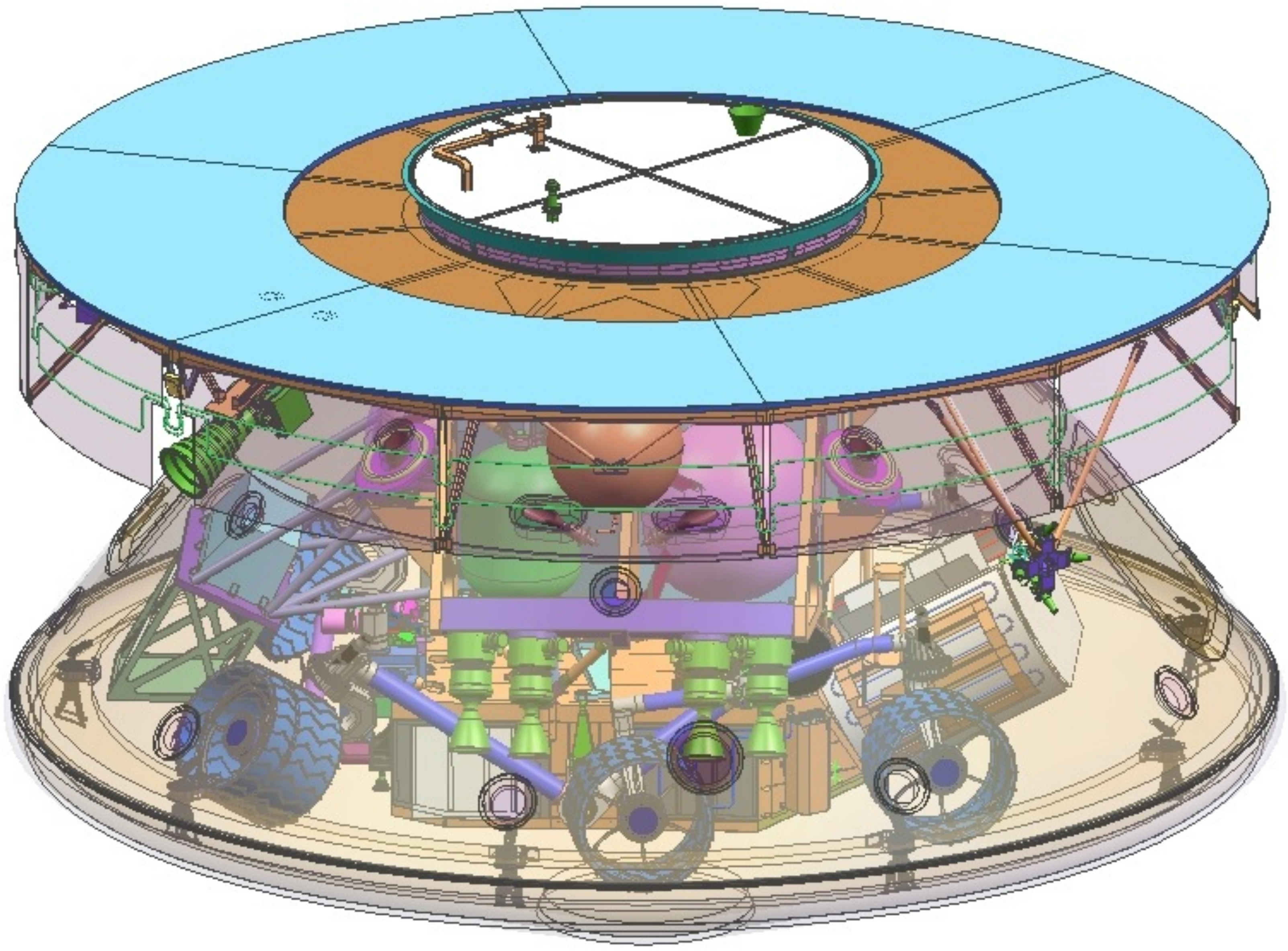
Launch Configuration

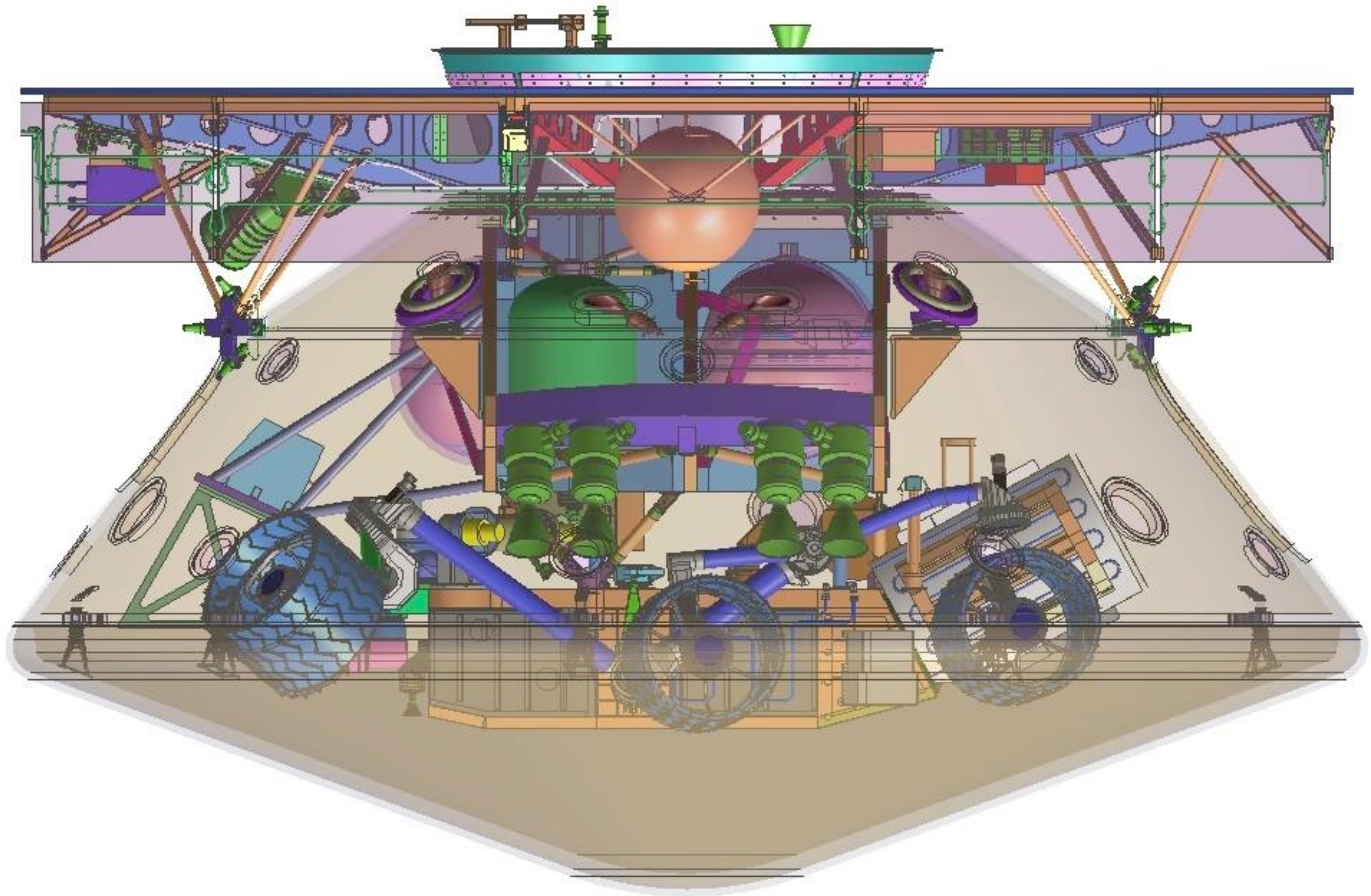
- 5m Fairing with 4.56 m internal envelope.
- 66” Payload interface to MSL Spacecraft.
- RTG integration access
- Heat Rejection System (HRS) loading access
- Emergency de-fueling access



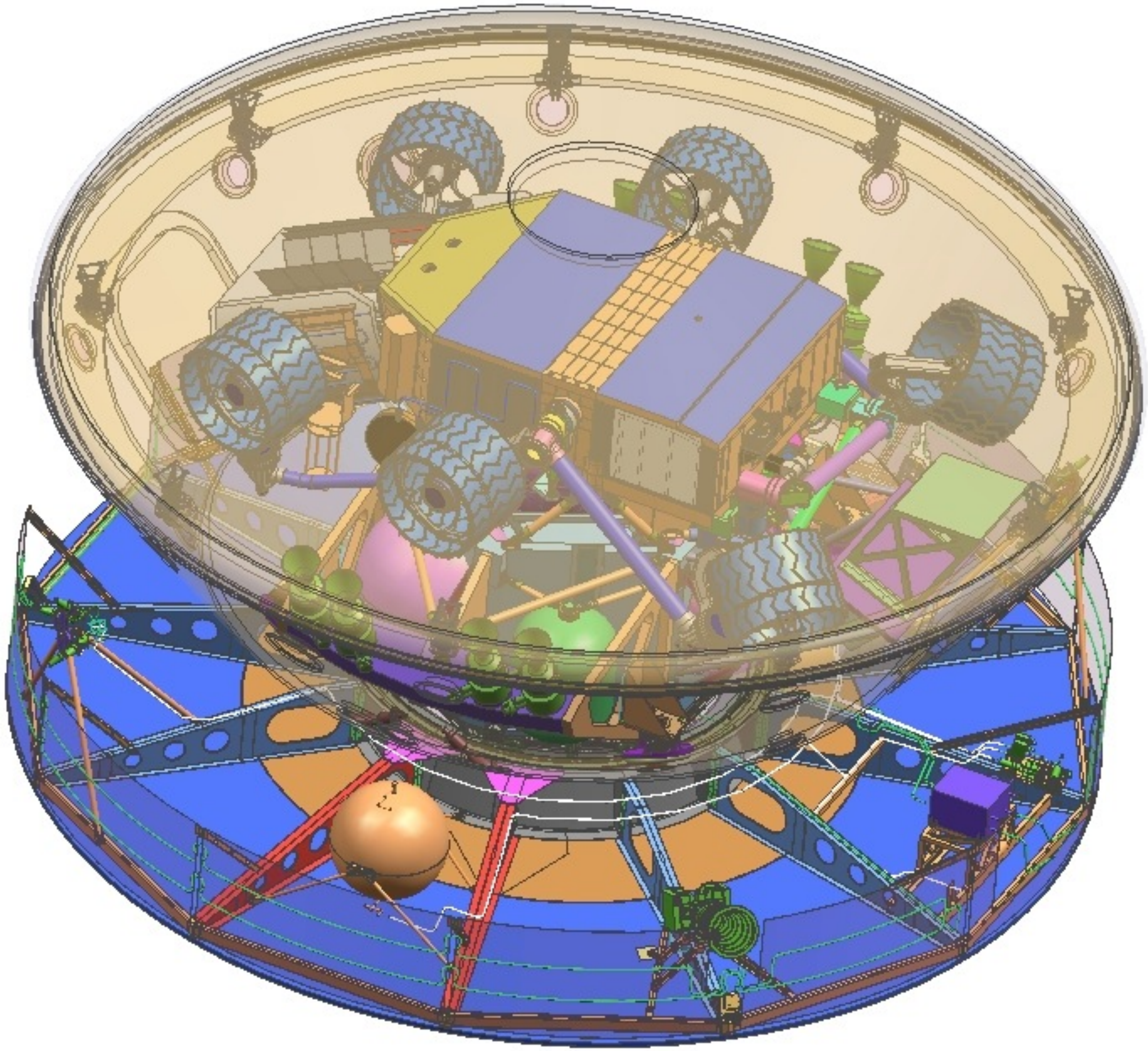


Cruise Configuration

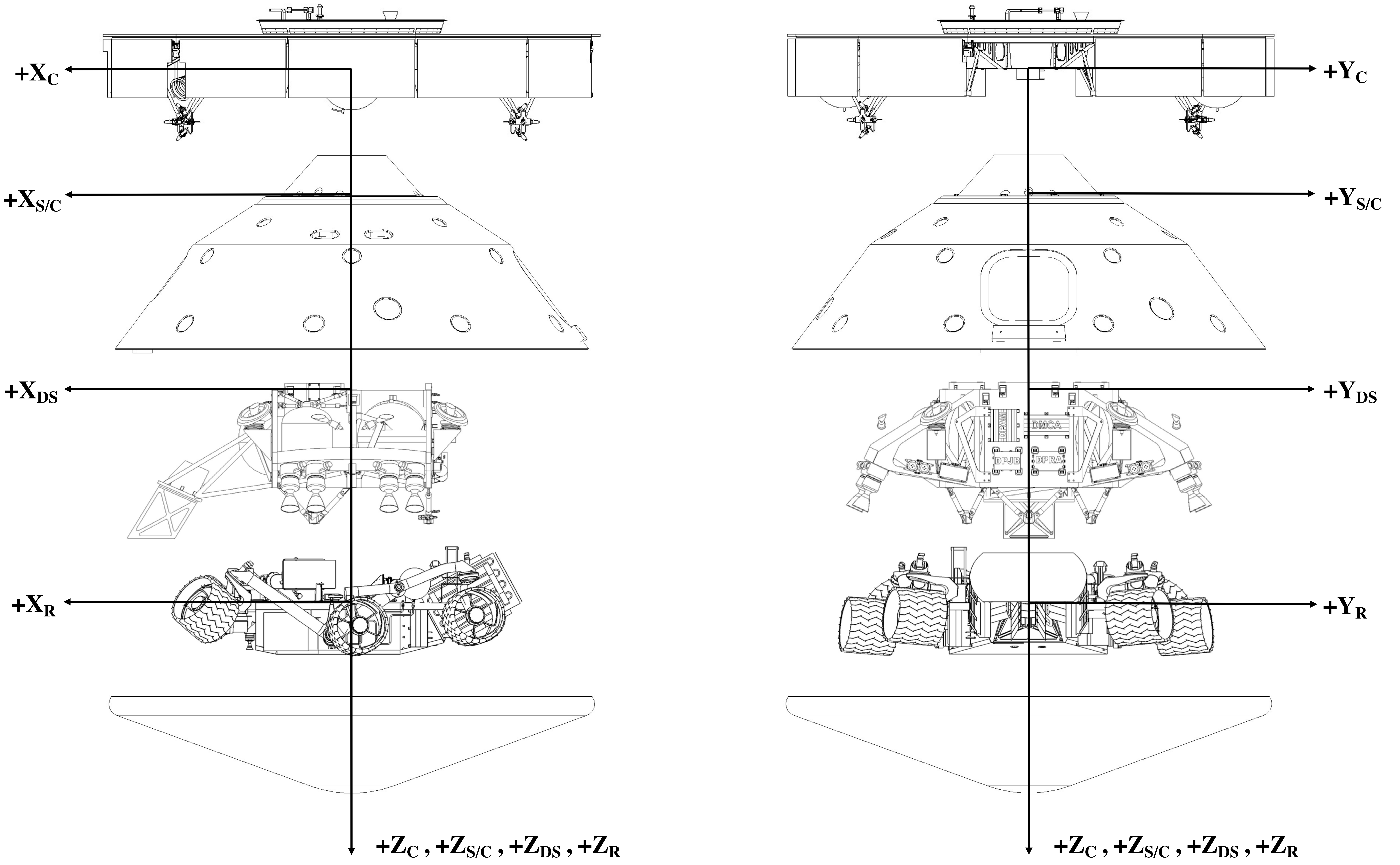




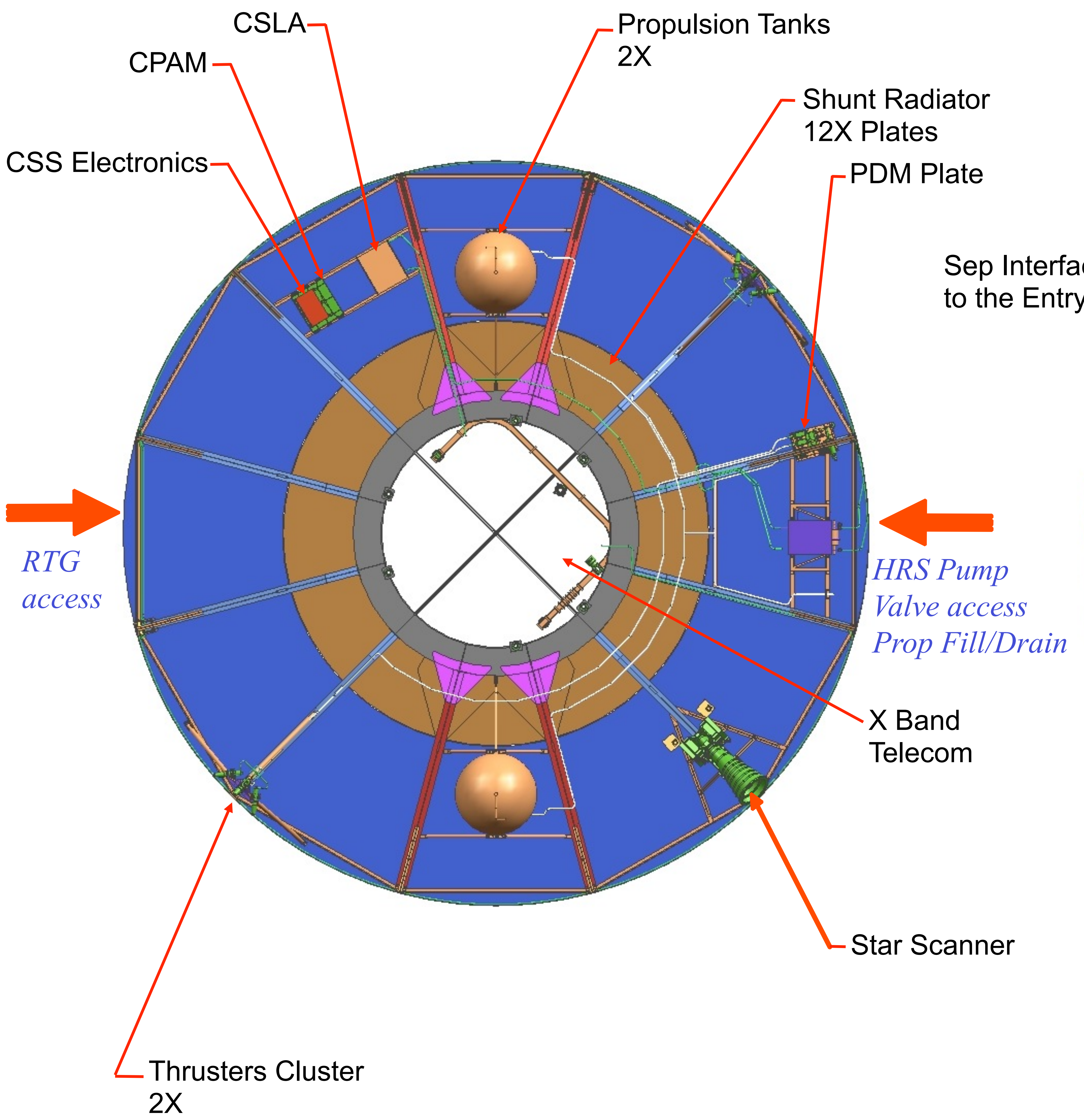
Cruise Configuration: Bottom View

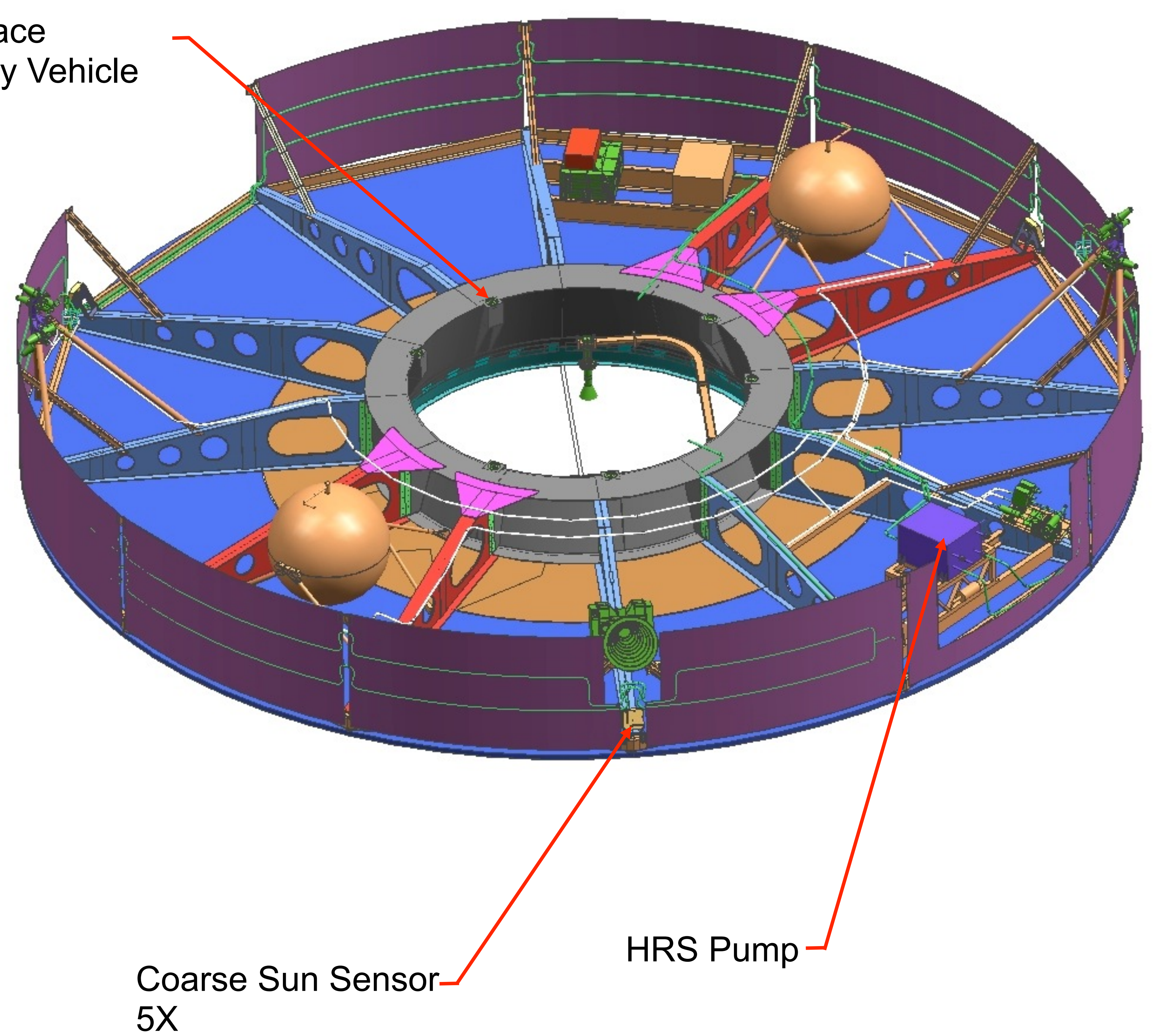


Comparison of Coordinate Systems

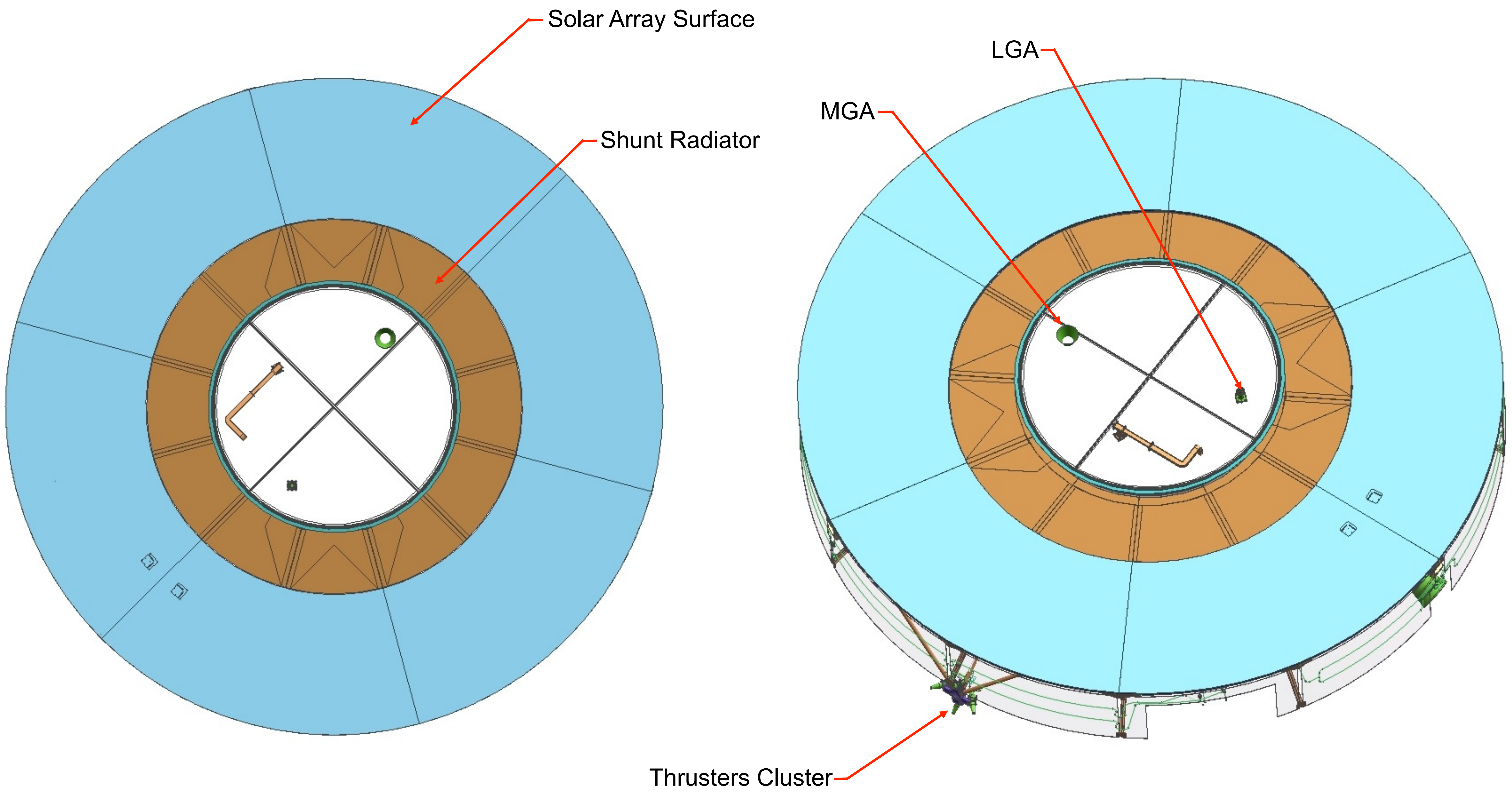


Cruise Stage Components Placement (1)

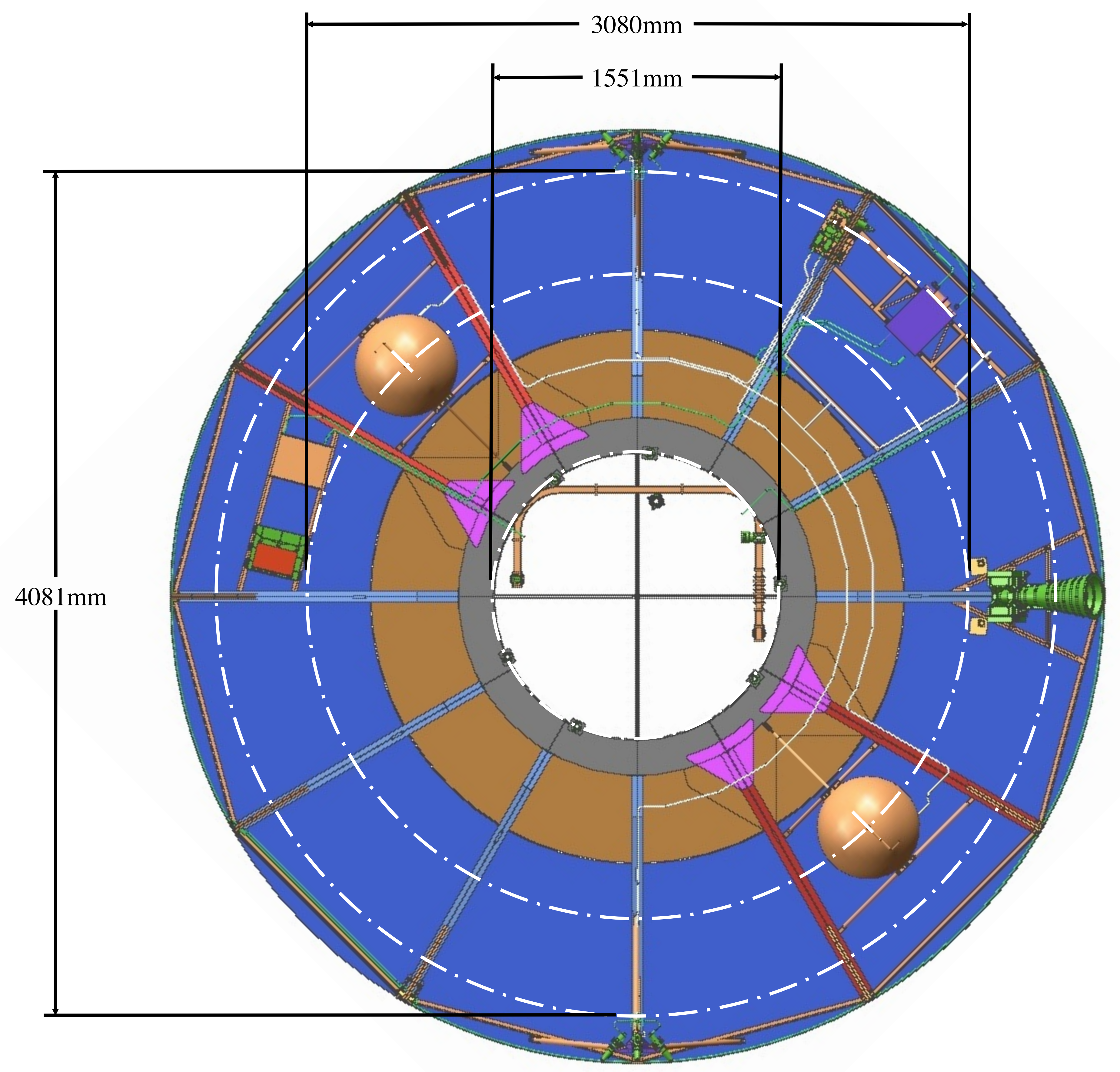


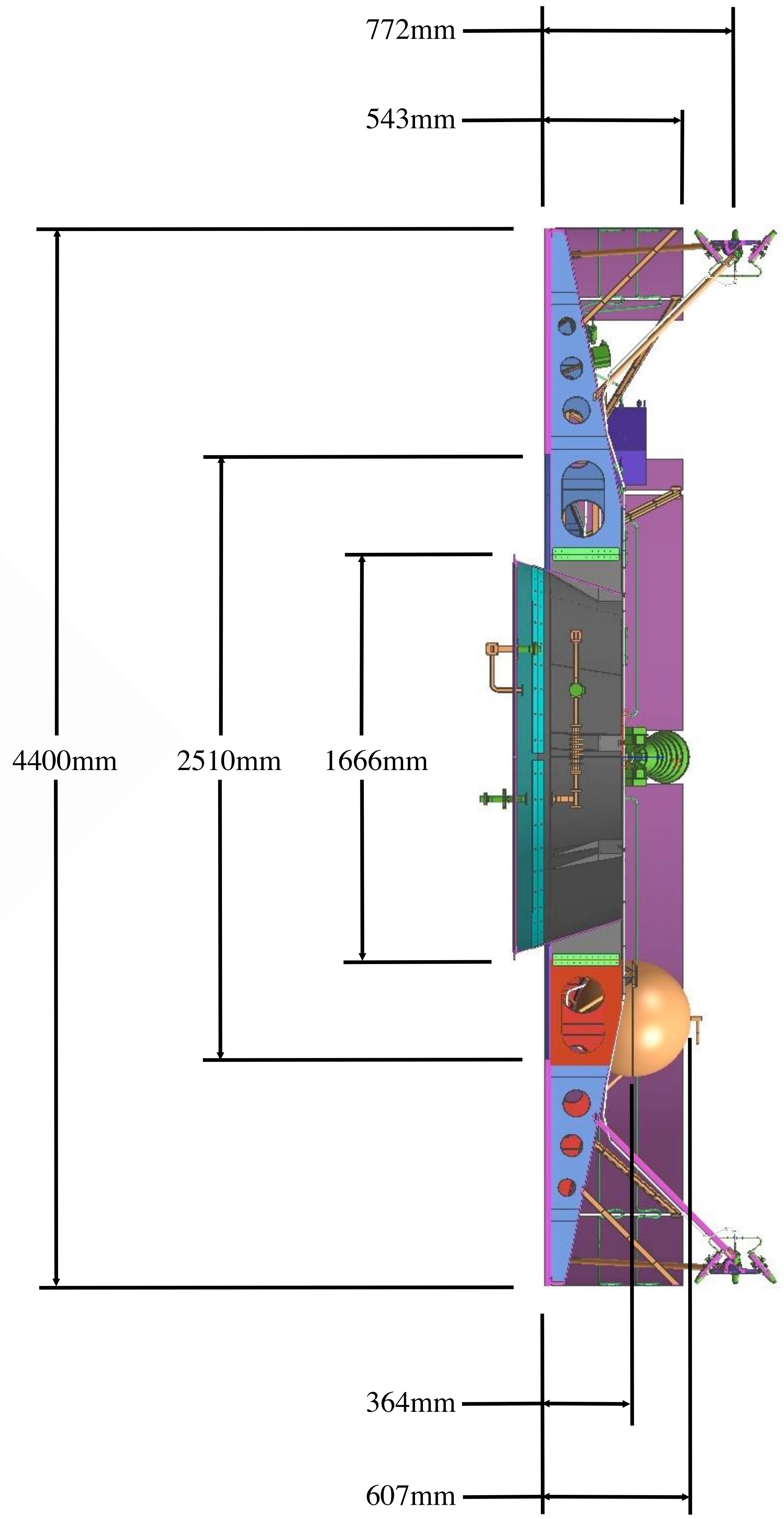


Cruise Stage Components Placement (2)

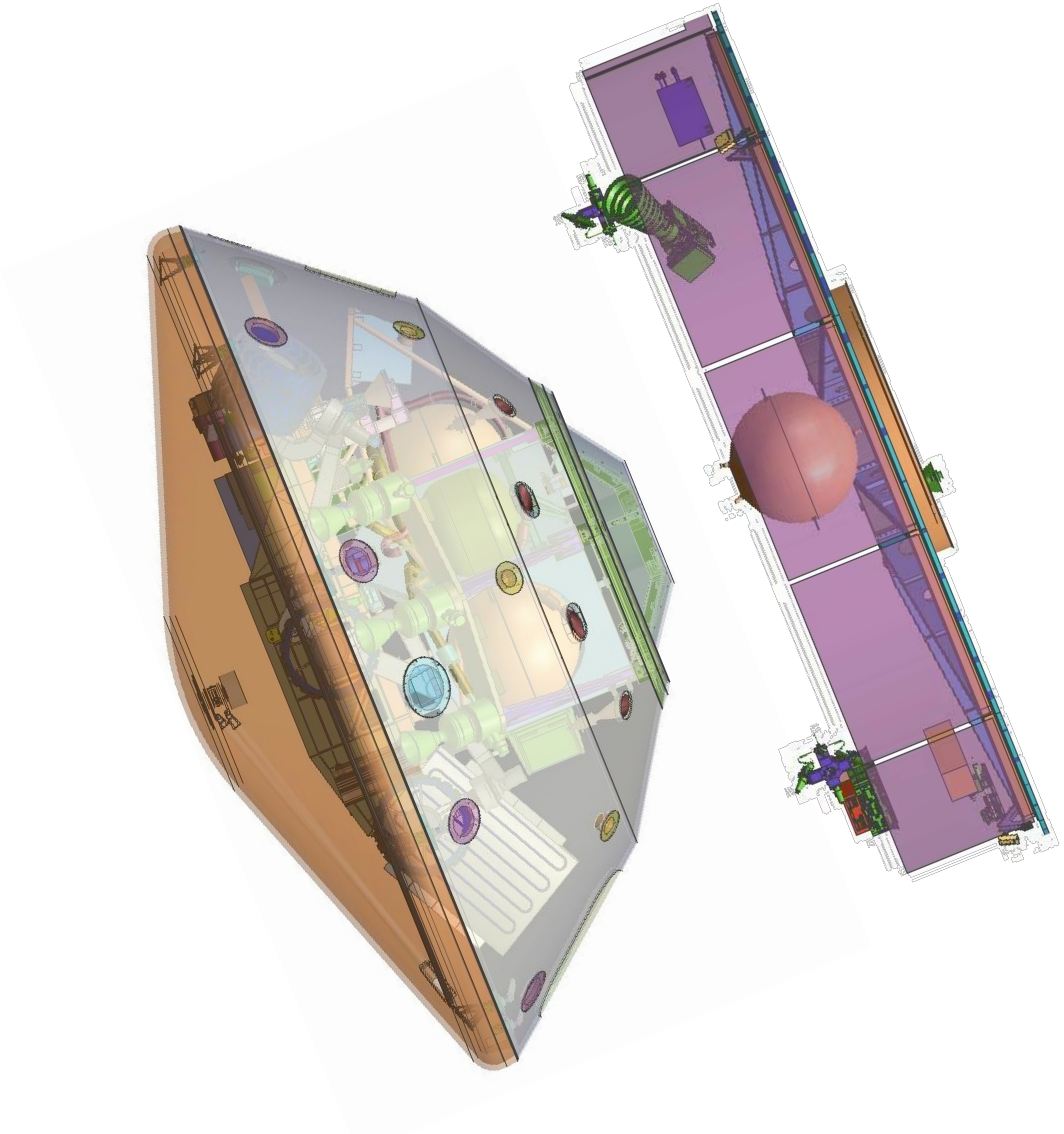


Cruise Stage Dimensions

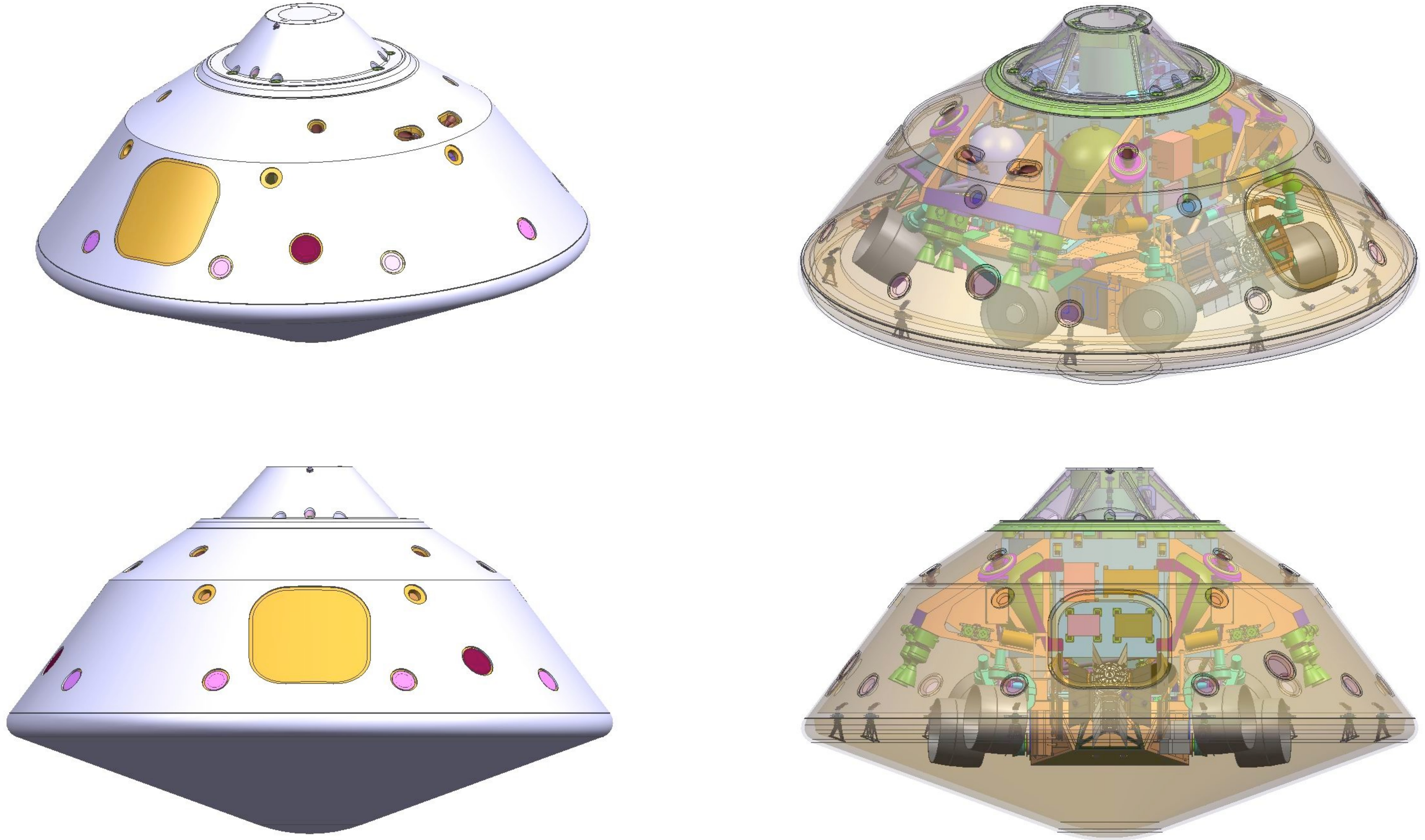




Cruise Stage Separation

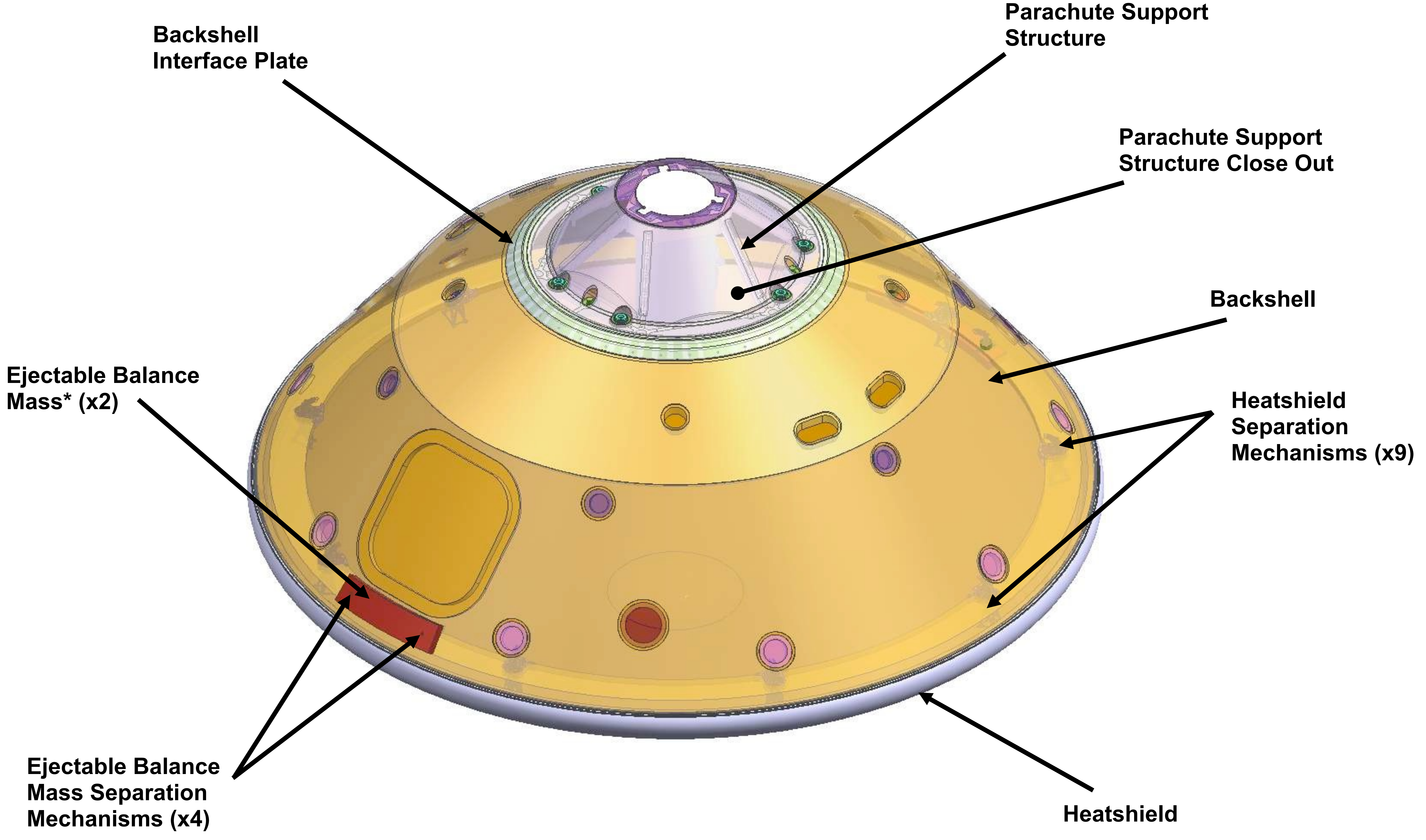


Entry Vehicle

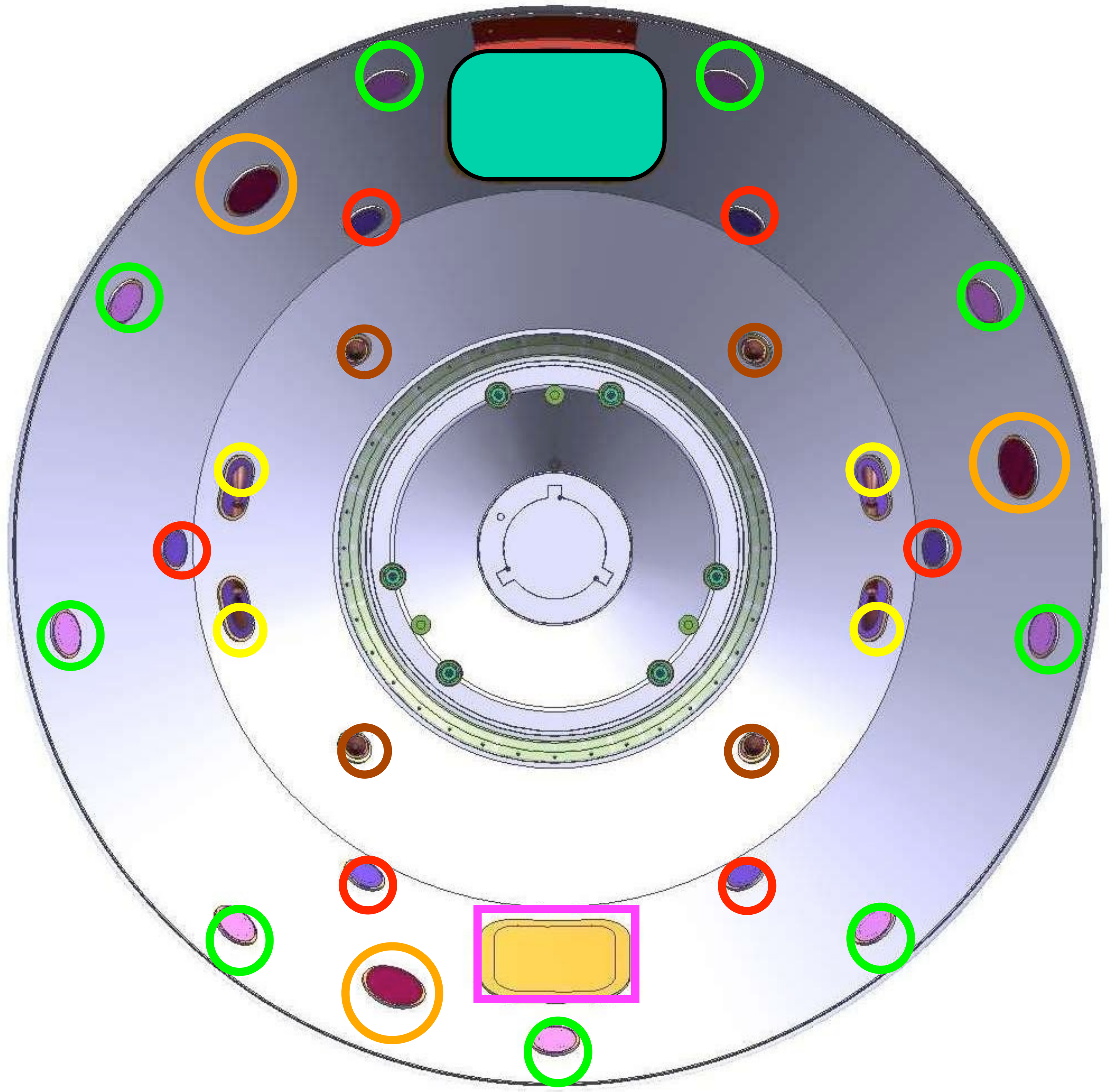


Aeroshell Overview

Aeroshell structure is shown transparent for clarity

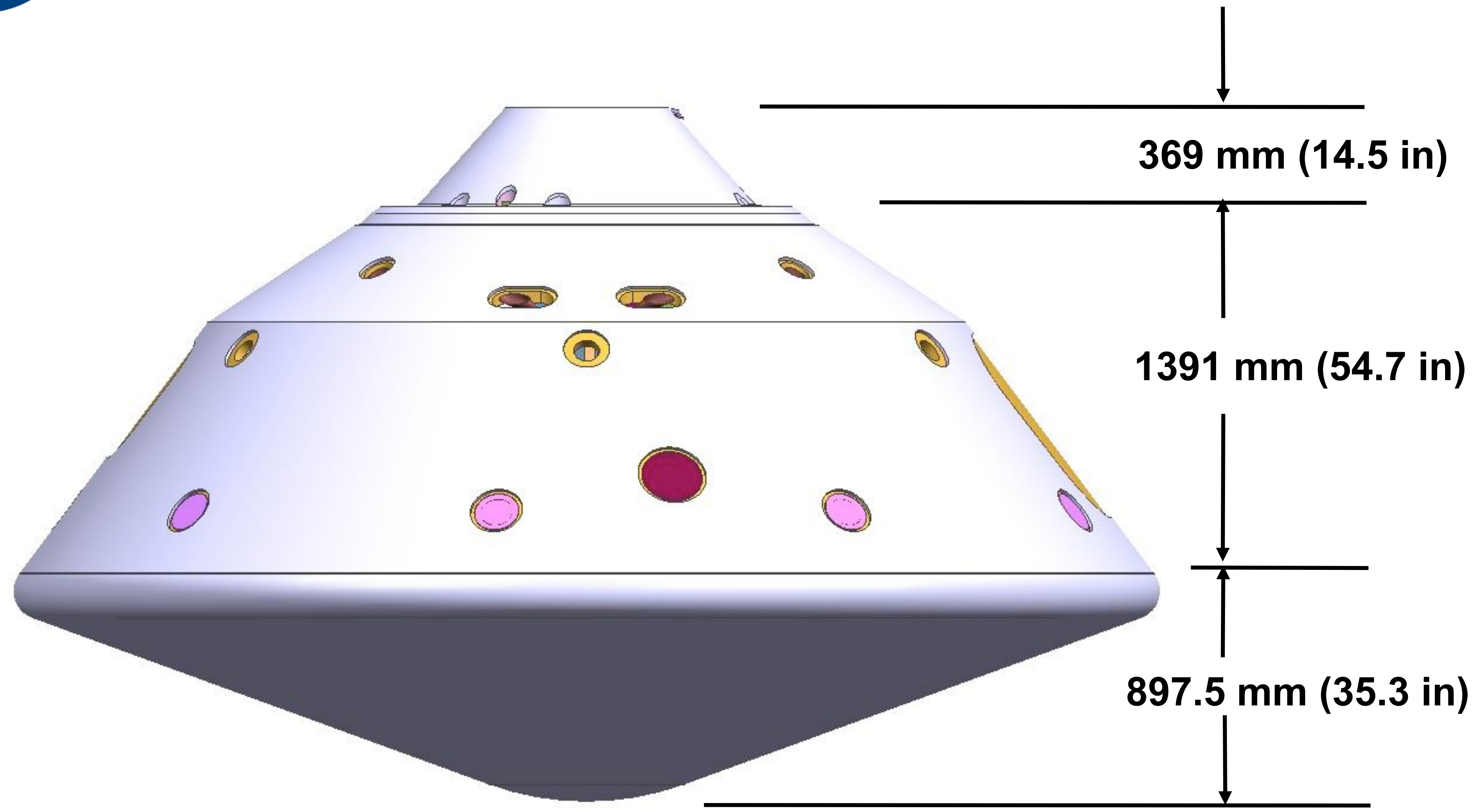


Aeroshell Features



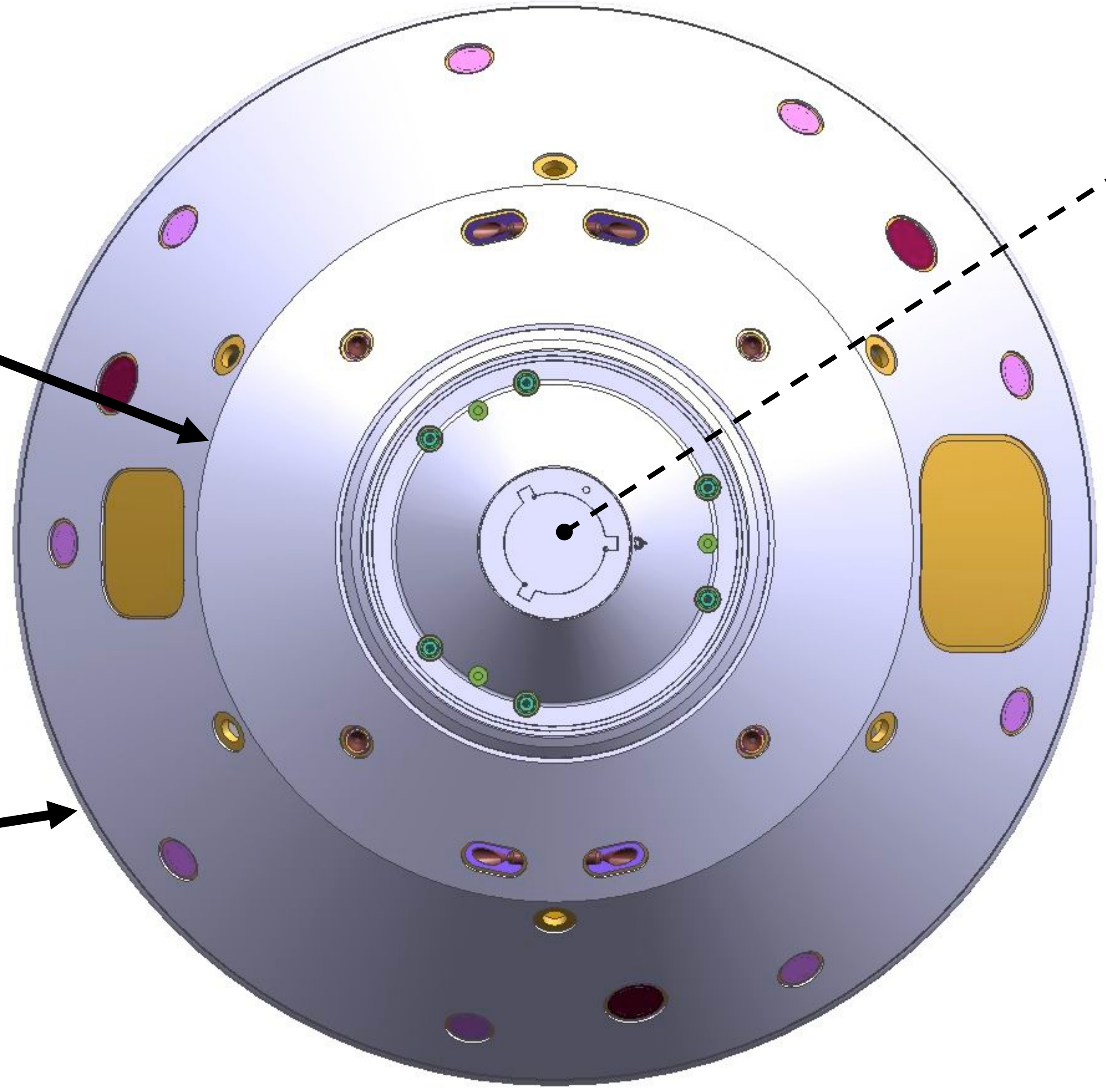
Backshell Penetration	Locator	Size (mm)
Heatshield Sep Fitting/ Balance Mass Covers		Ø 127
Upper Ring Balance Mass Covers		Ø 101.6
UHF Antennae Windows		Ø 190
RCS Windows, Roll Thrusters		80 x 205
RCS Windows, Pitch/ Yaw (Z)		Ø 120
Vent & Propulsion Access Door		450 x 450
RTG Access Door		750 x 750

Entry Vehicle Dimensions

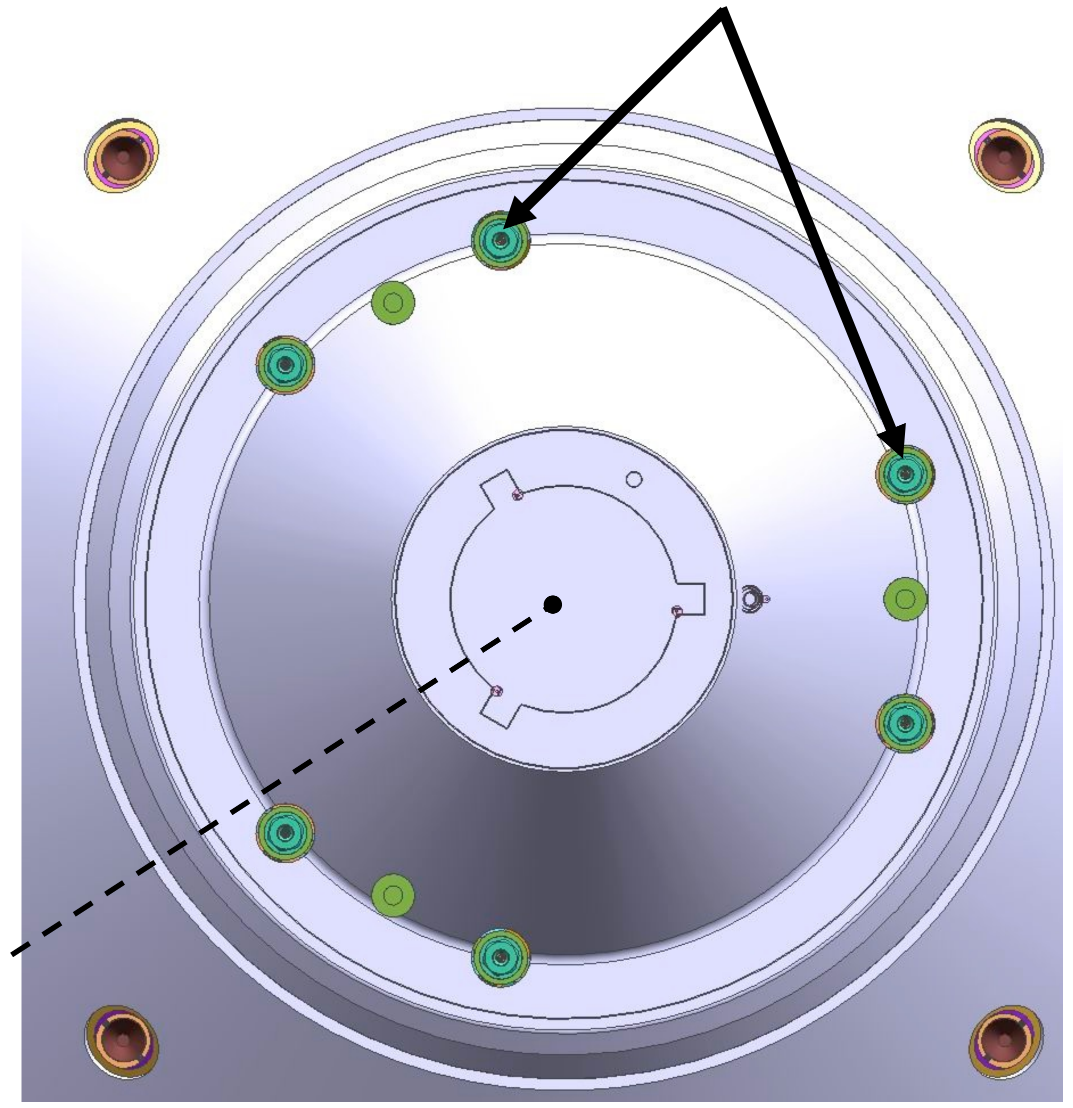


Ø 2975 mm (117.1 in)
Upper Cone "hip"

Ø 4500 mm (177.1 in)
OML-10b Configuration

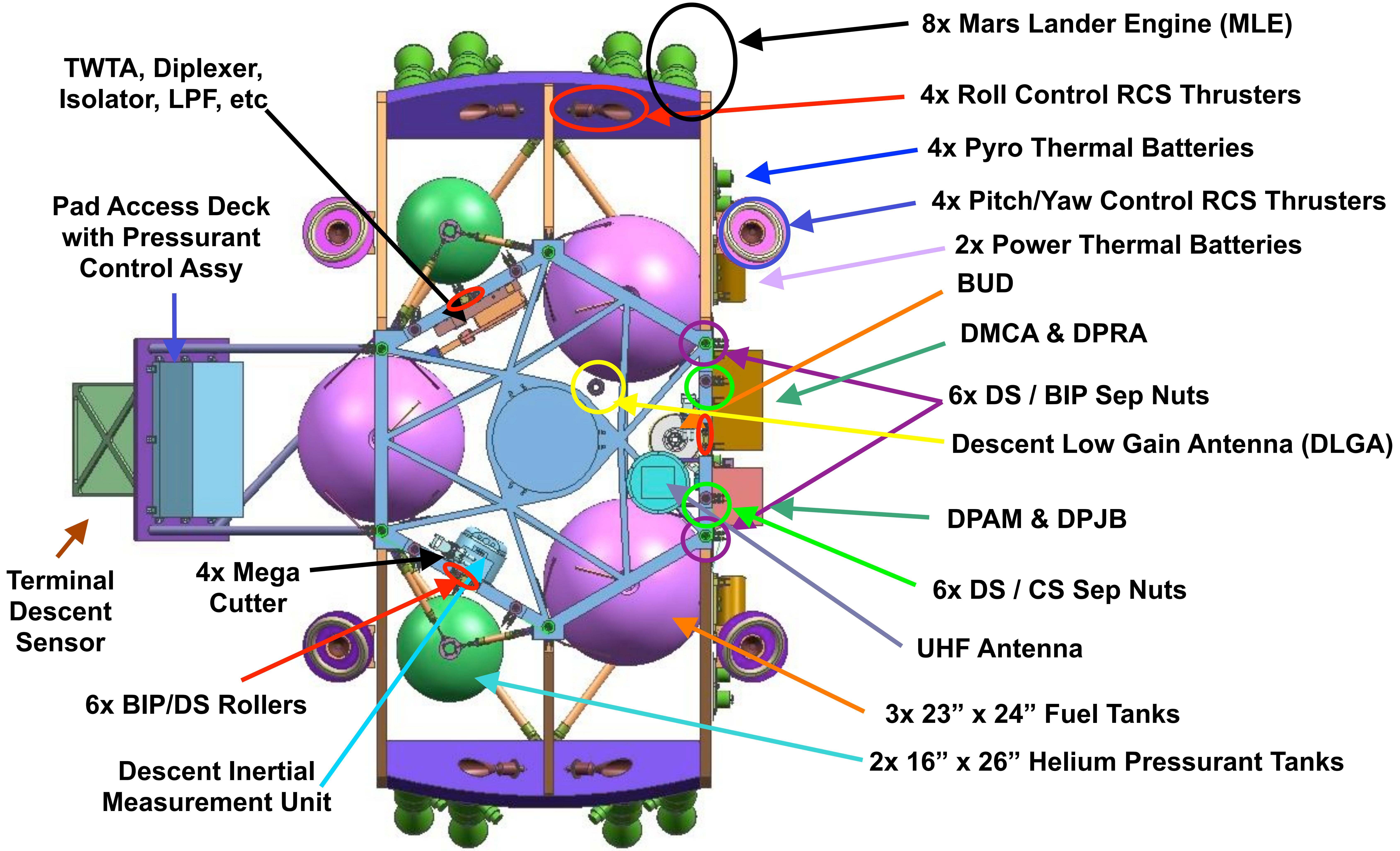


Cruise Stage Interface (x6)

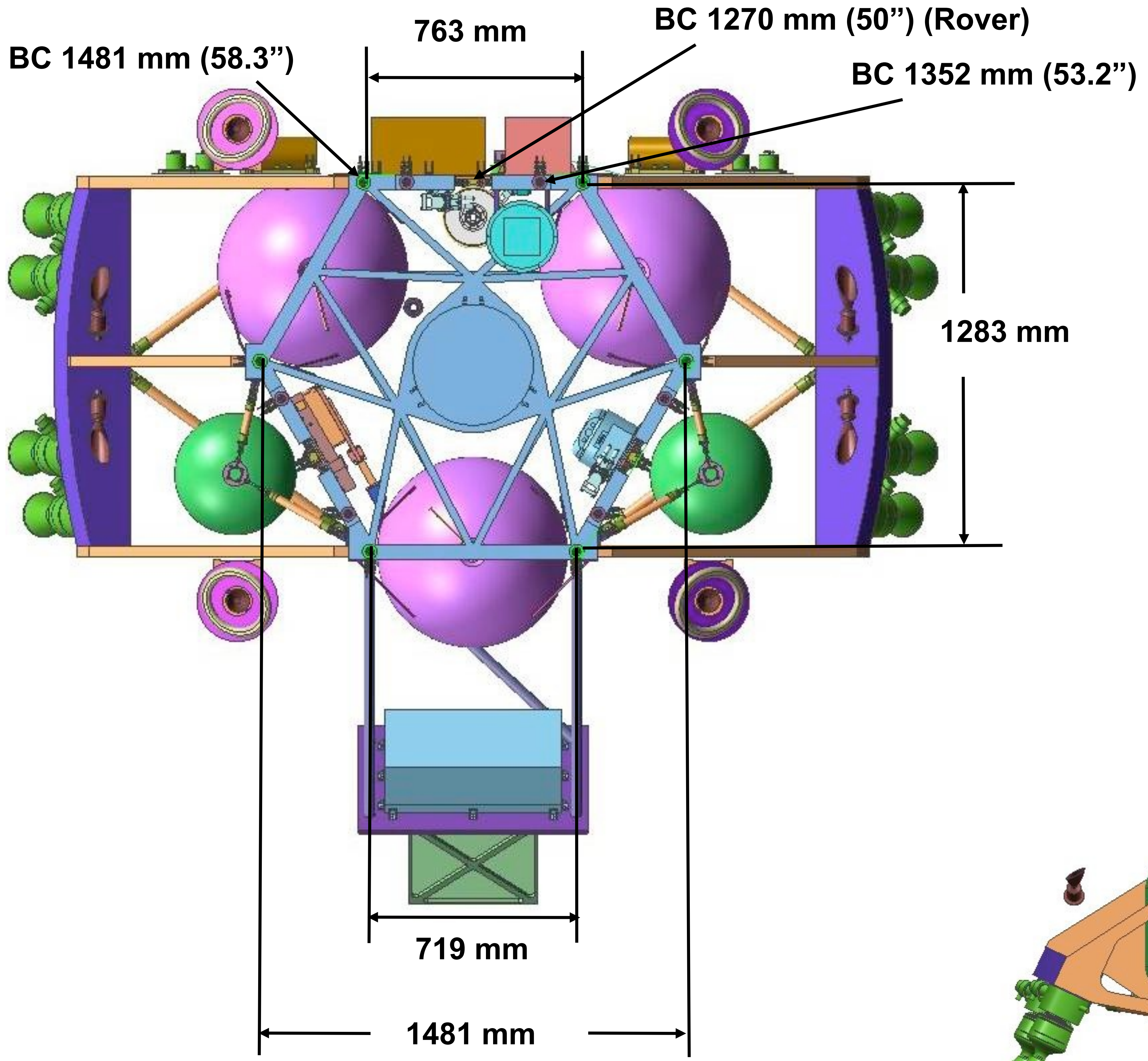


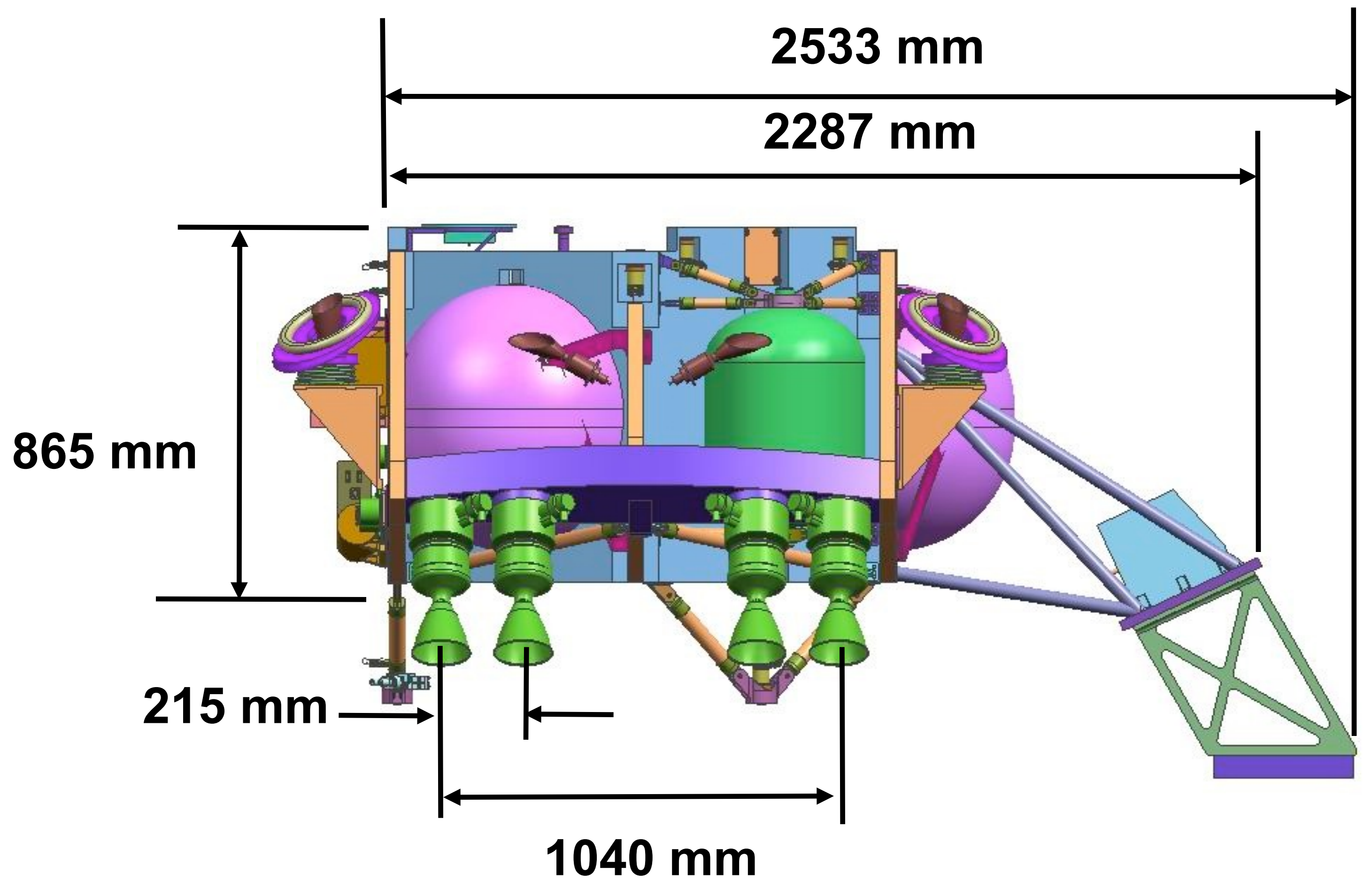
Parachute Support Structure (PSS) Close Out with TPS

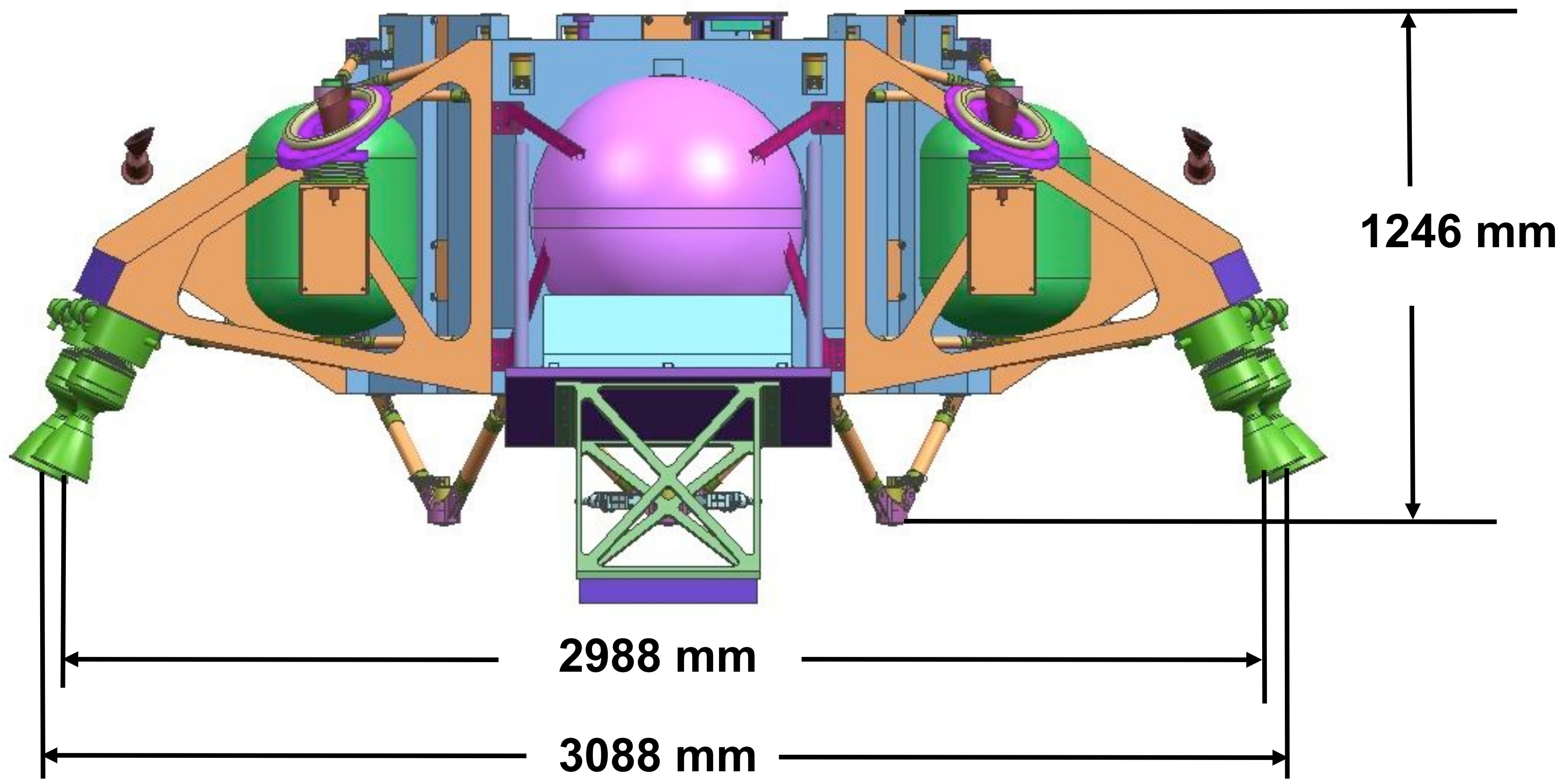
Descent Stage Components Placement



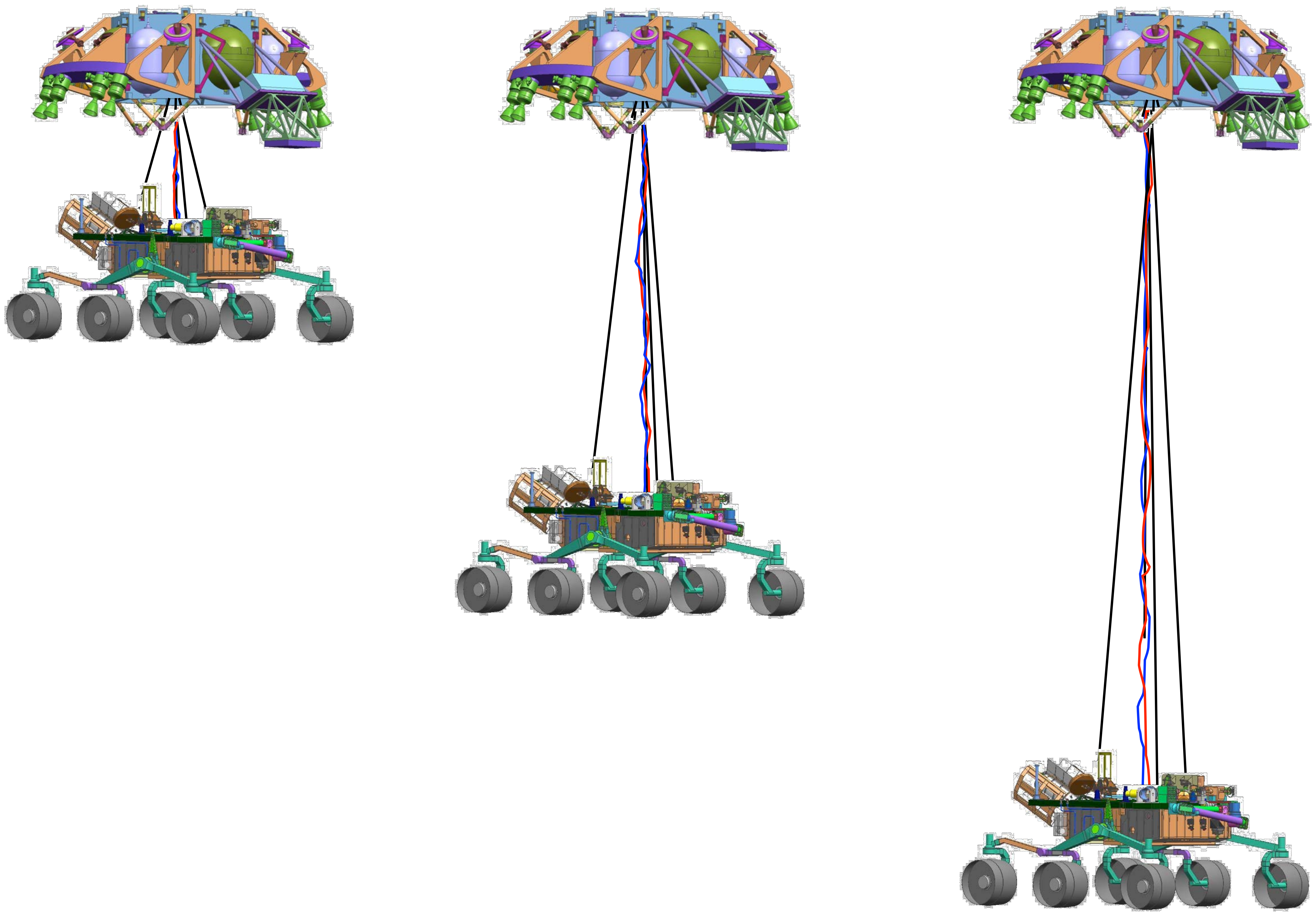
Descent Stage Dimensions



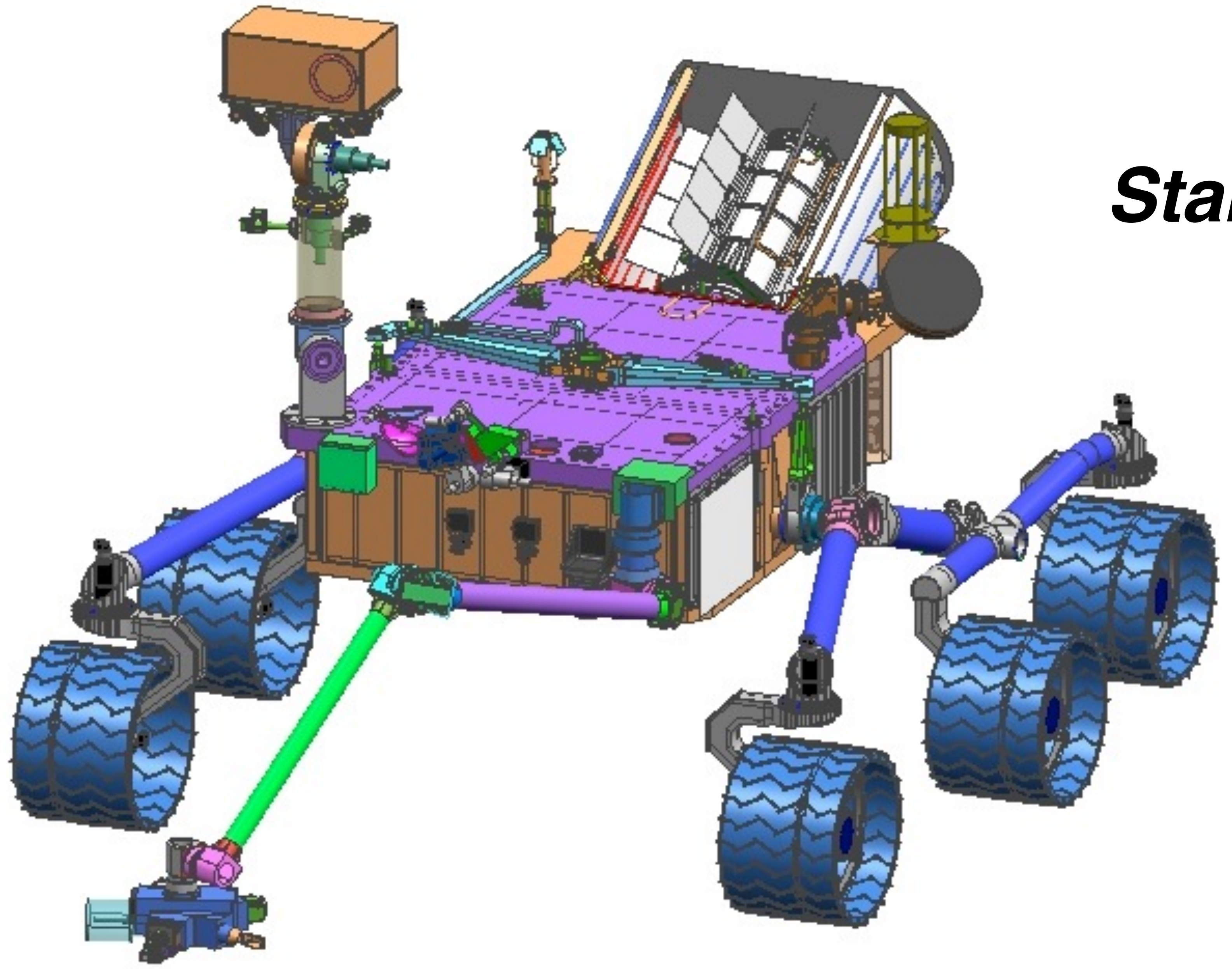




Rover Deployment - Touchdown Configuration

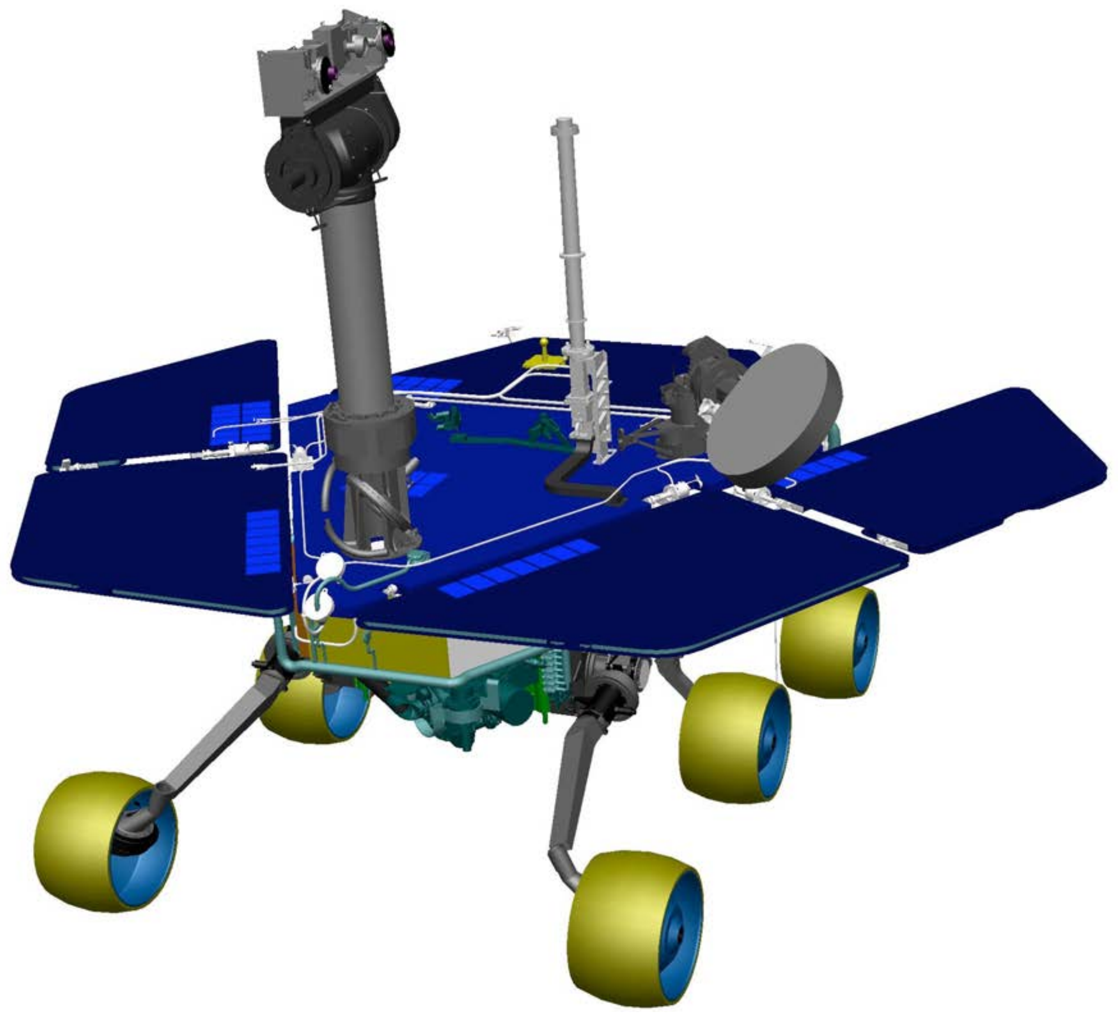


The Bigger Better Rover



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

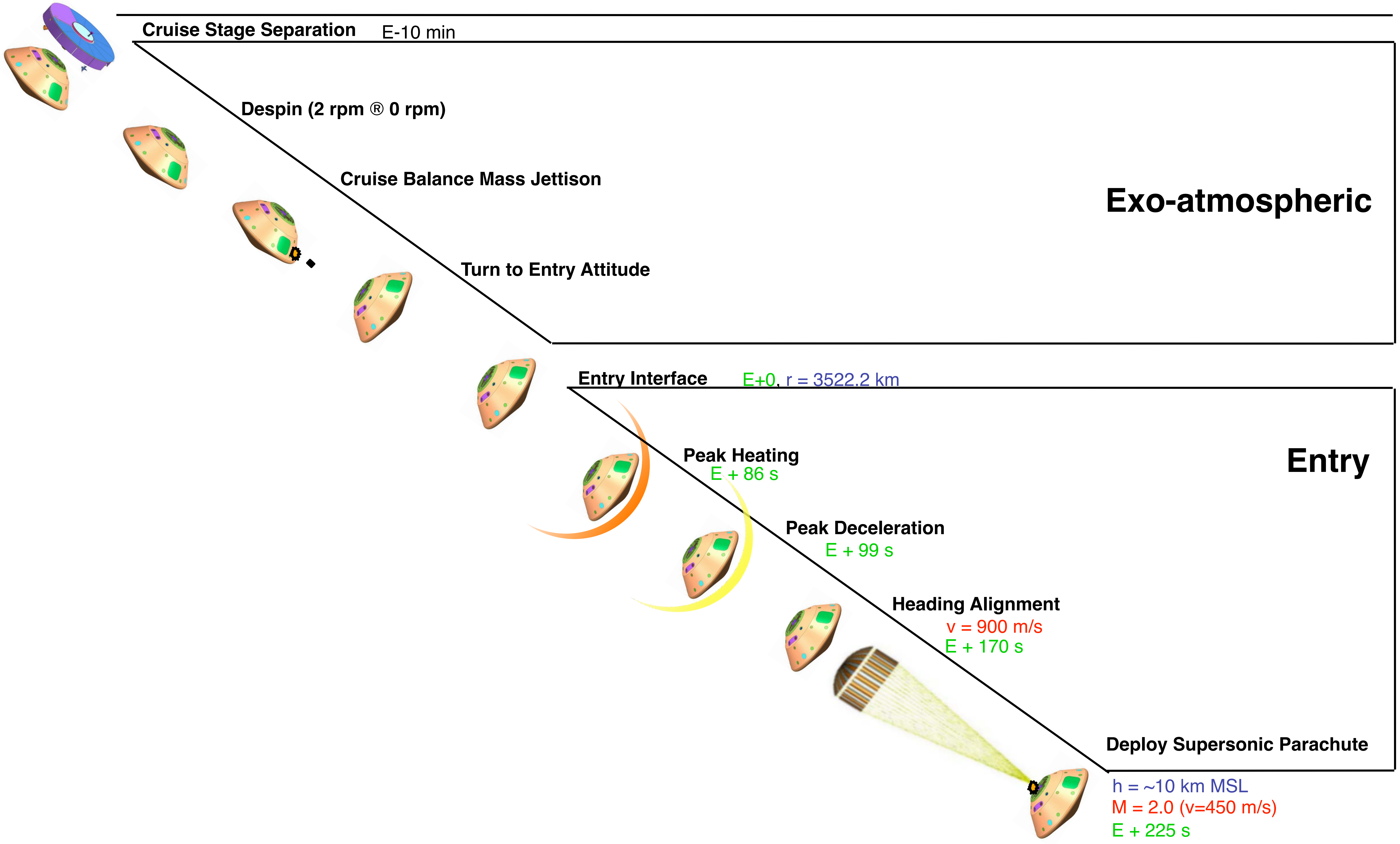
Key Driving EDL Requirements:

- 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

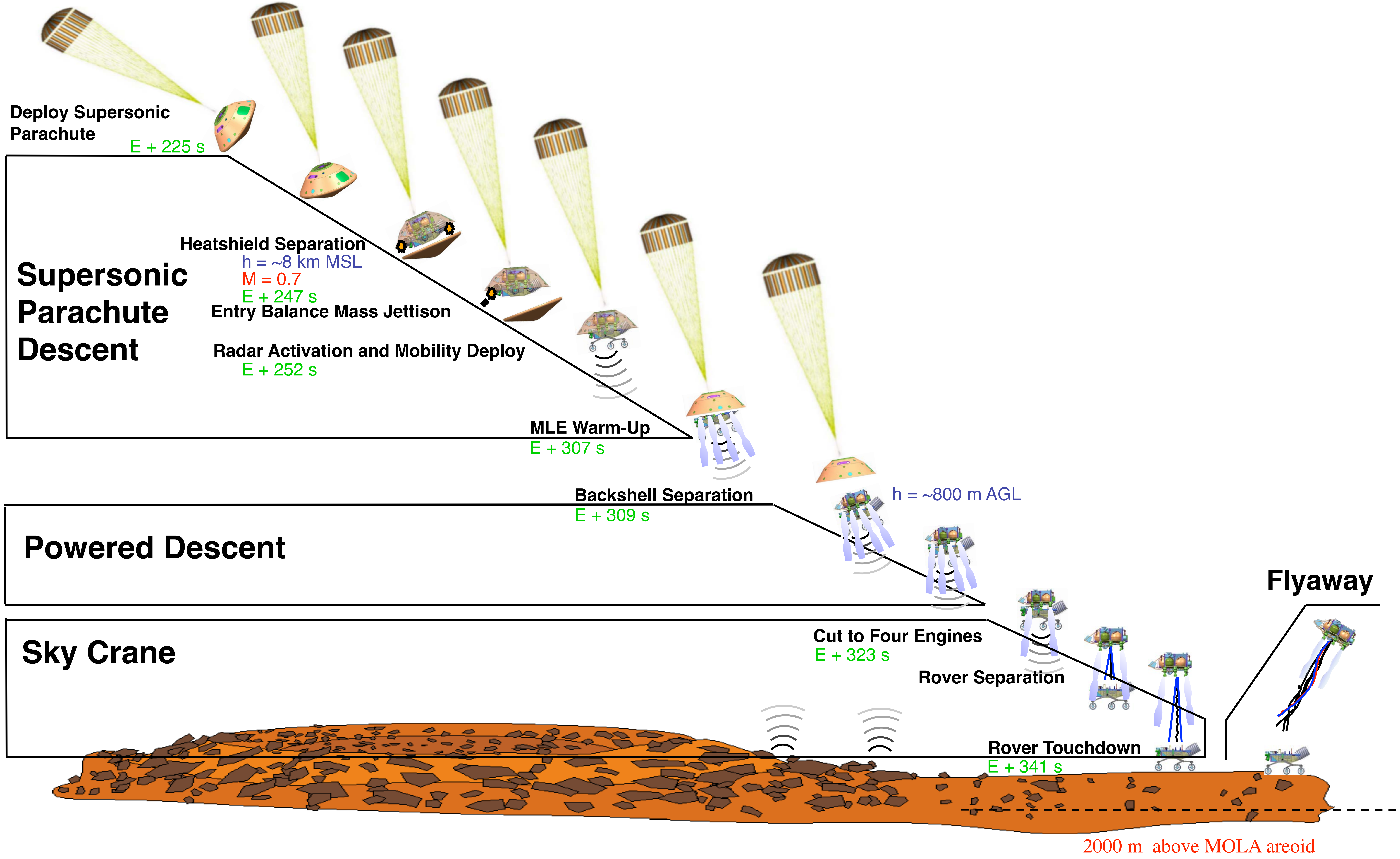
Detailed Requirements:

- See below

Event Timeline 1/2

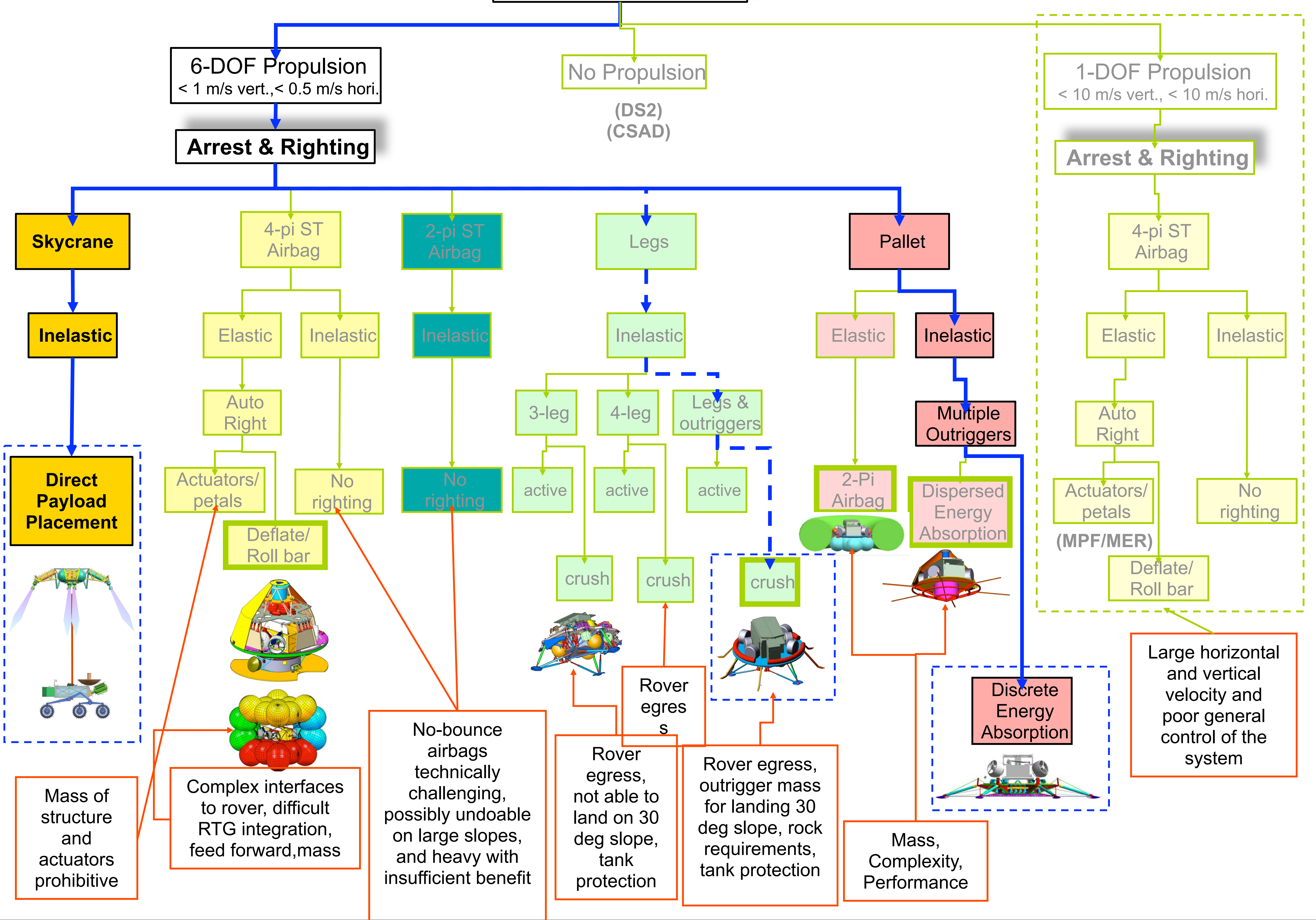


Event Timeline 2/2



EDL Design Comparison and Trades

Trade Coverage Example: Terminal Descent



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

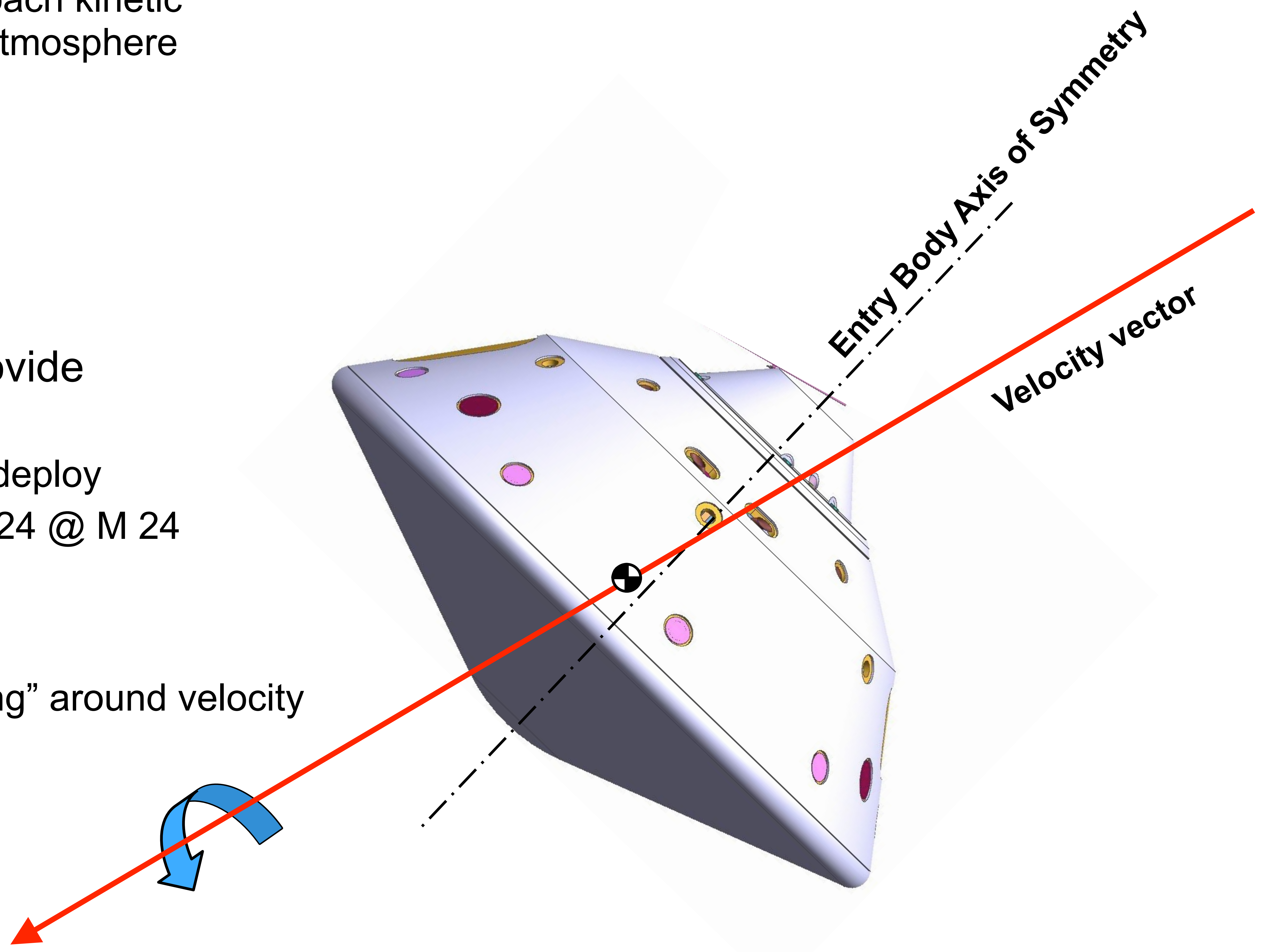
Guided Entry and TPS

Parachute Descent

Powered Descent/Sky Crane

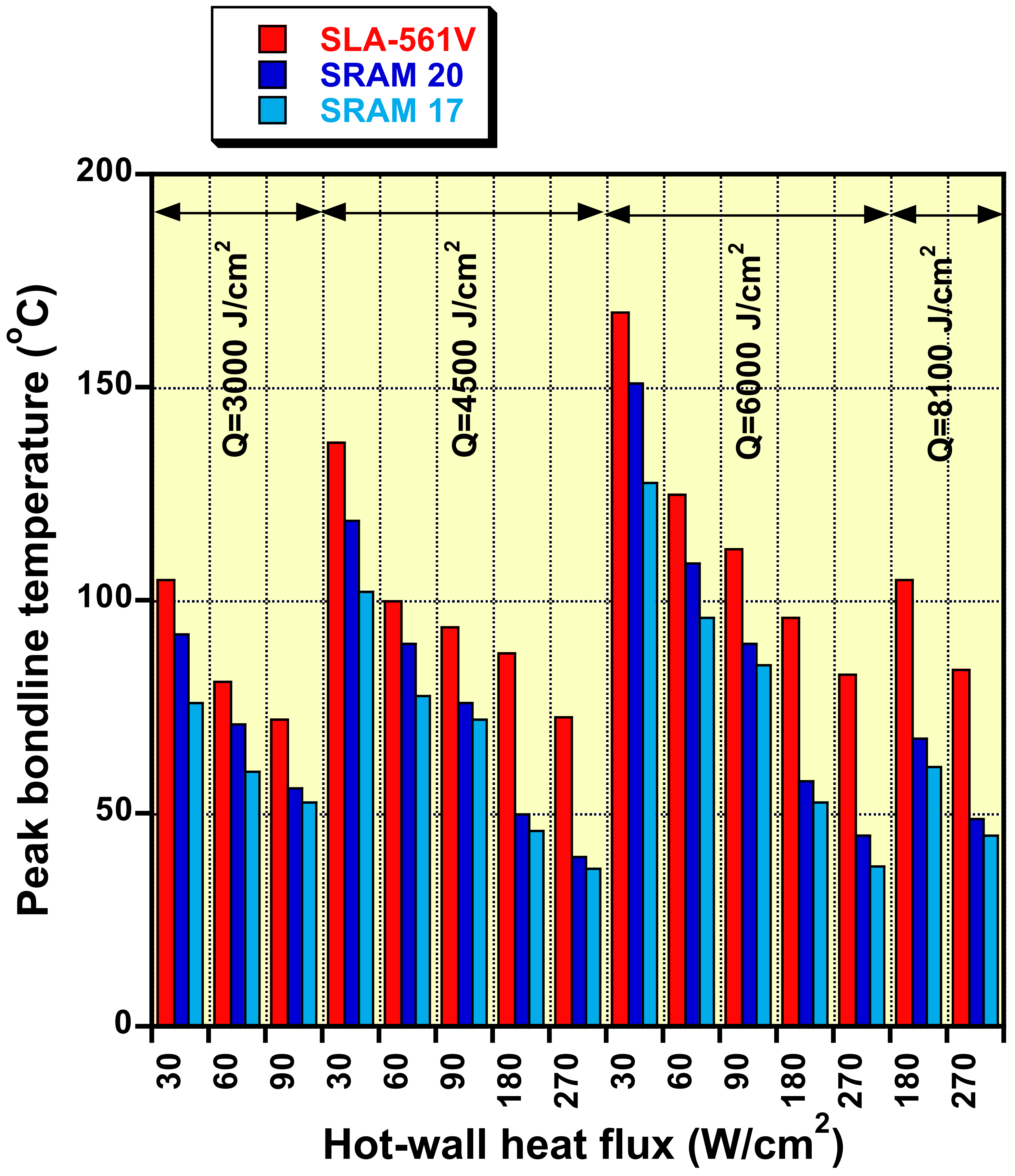
Entry: Aerodynamic Deceleration and Control

- 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

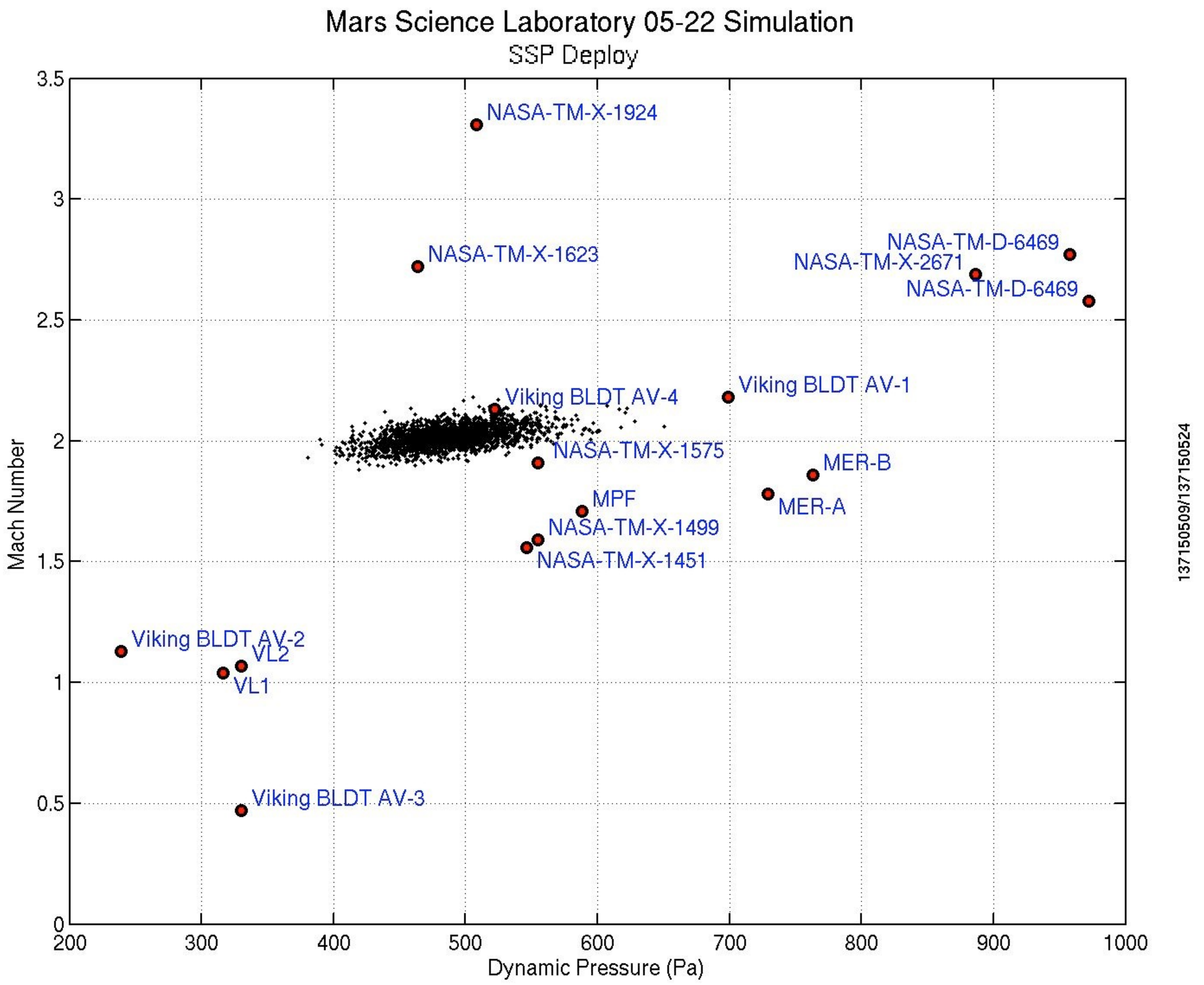
4 inch diameter samples
0.75 inches thick SRAM & SLA

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

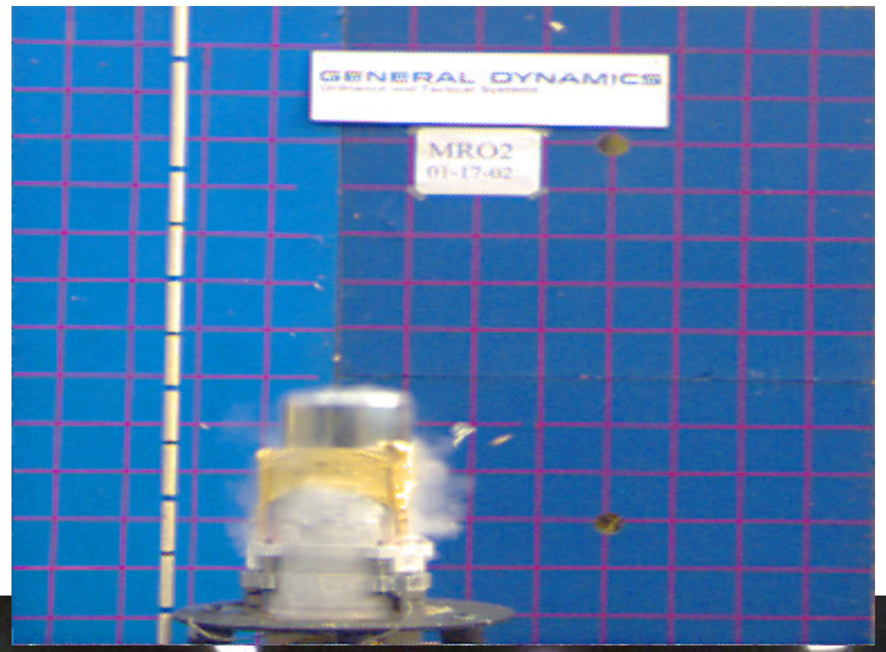
Parachute Deployment

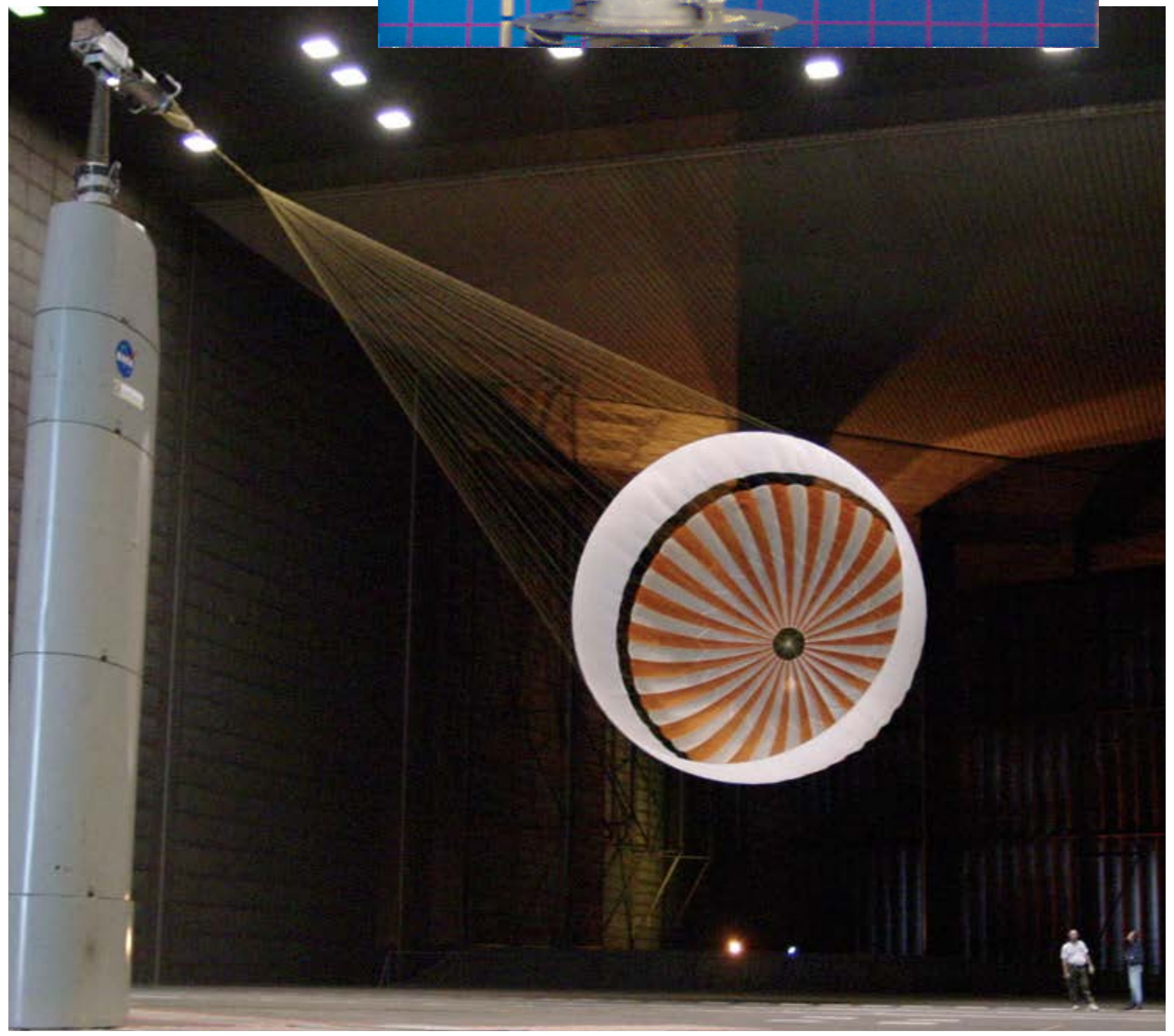


01-Dec-2005 MSL 05-22 40°S, 2 km Synthetic Terrain, +/- 0.5 know quat error dww-29

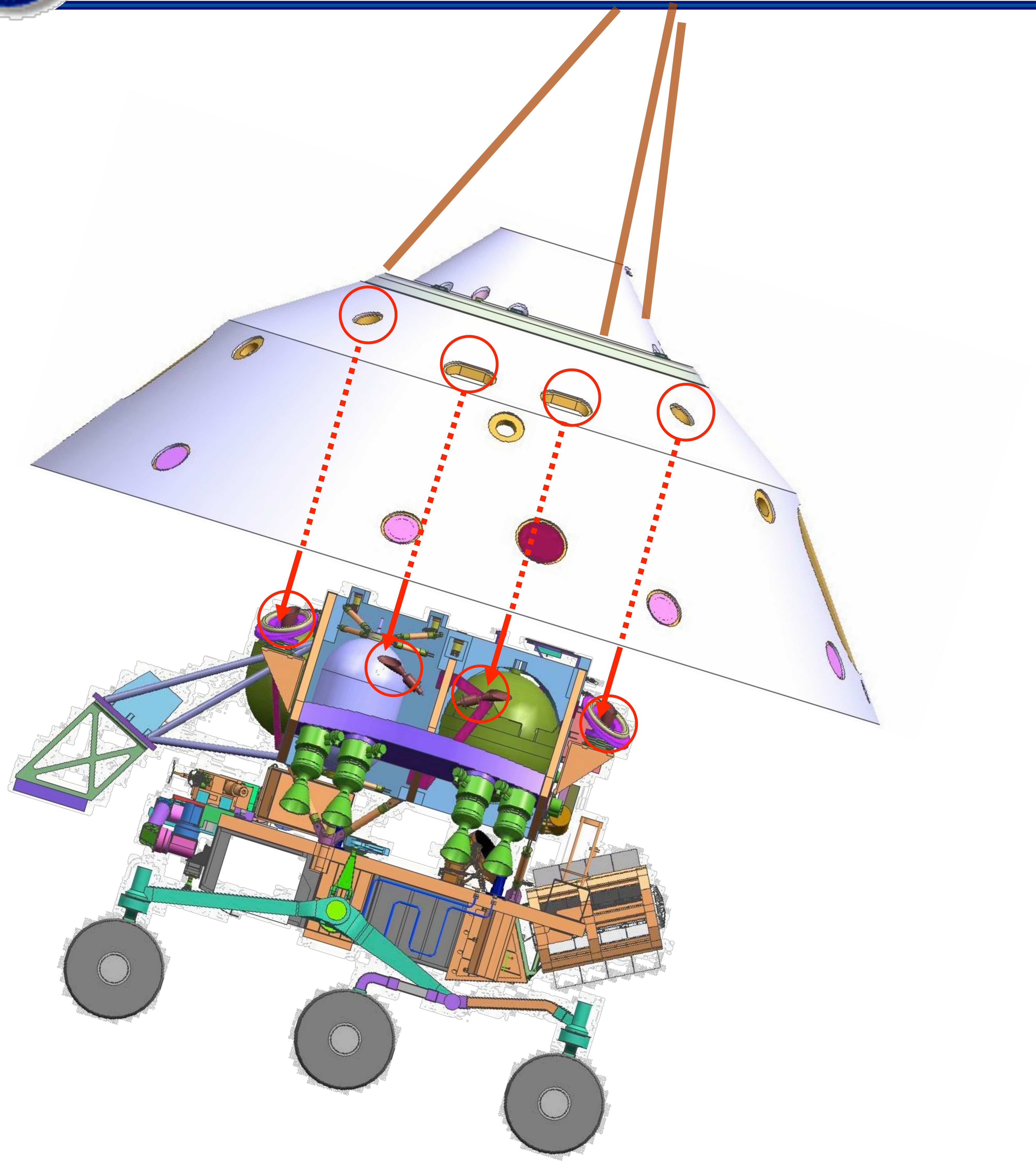
MSL Parachute System Qualification

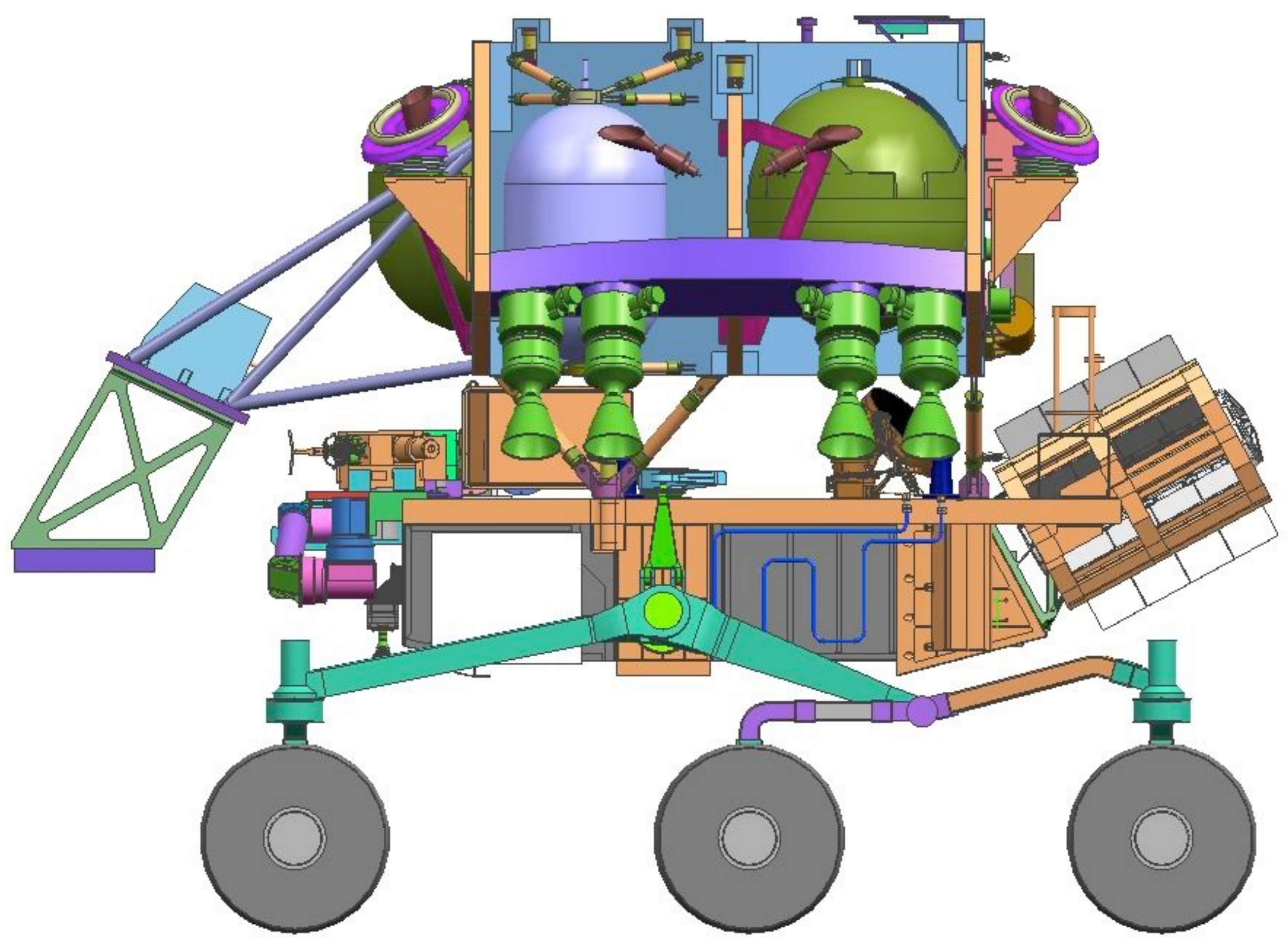
- Parachute Qualification requires validation of:
  - Deployment
  - Initial Inflation (Will it open?)
  - Inflation Strength (Will its structure survive inflation loads?)
  - Inflated Performance (Drag and Stability)
- MSL will make use of an augmented MER approach to qualification
  - Deployment: **Test**: 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

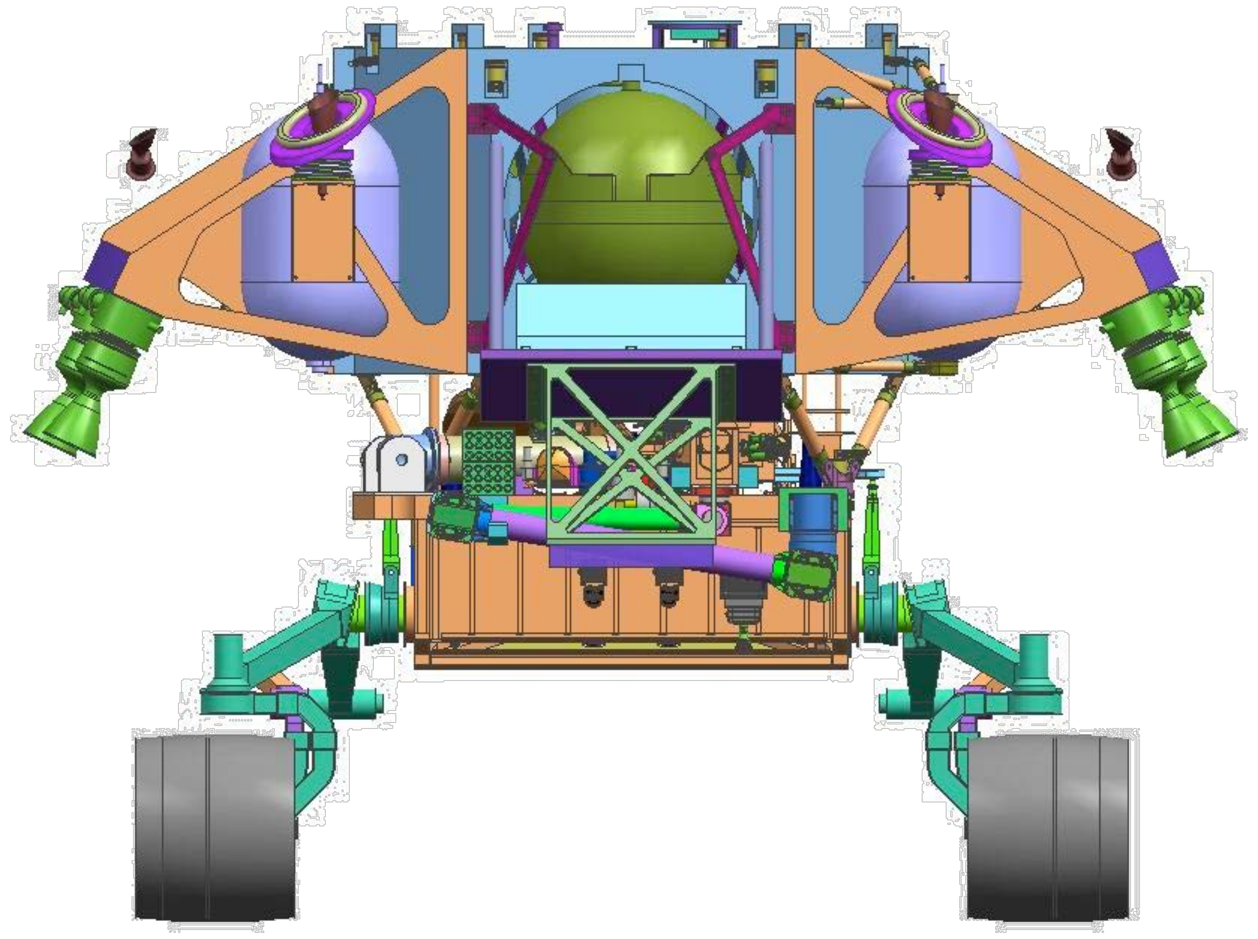




Powered Descent: Vehicle Configuration

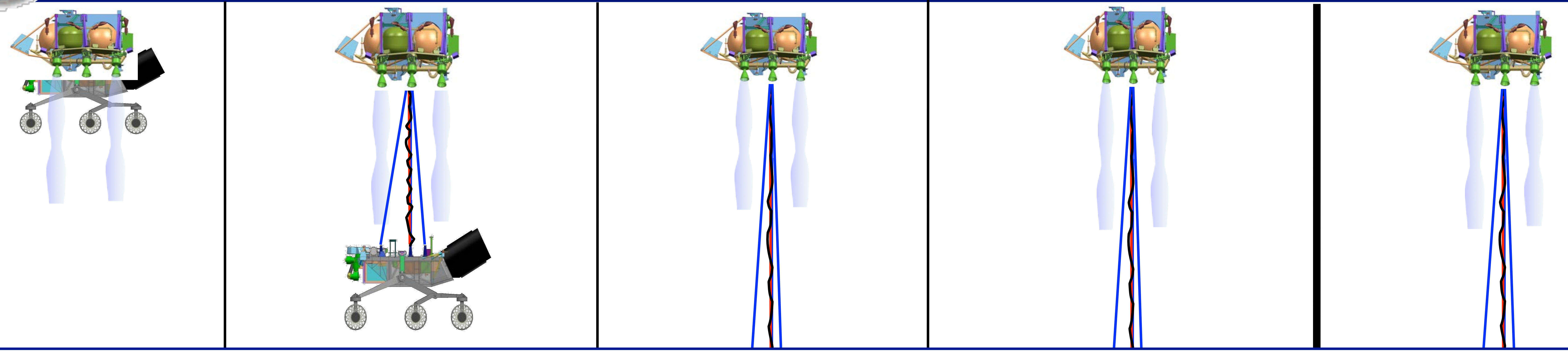




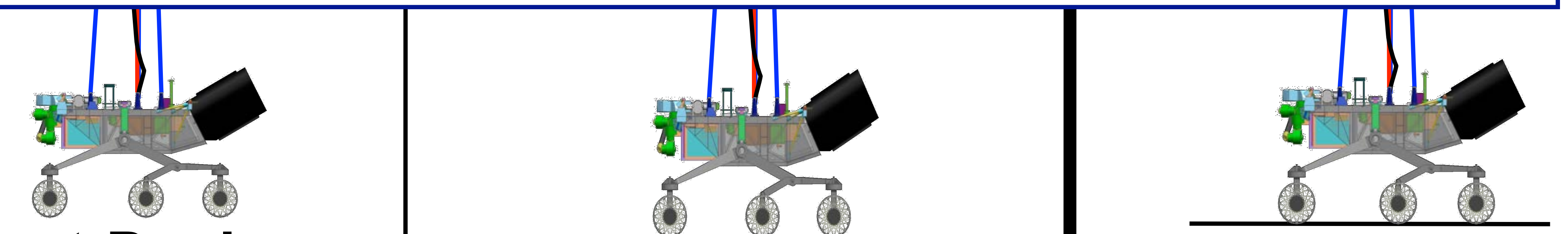


Sky Crane Maneuver Description

Mars Science Laboratory



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

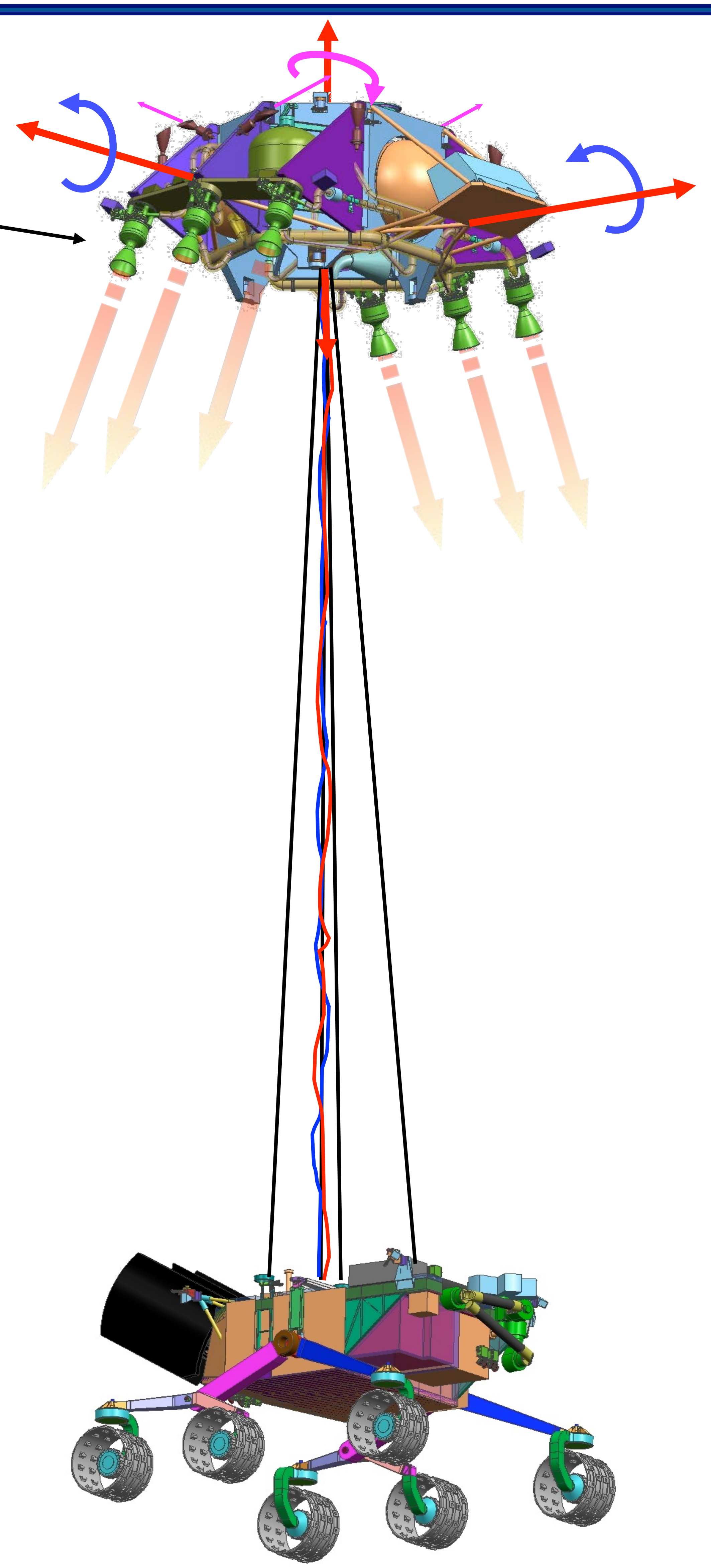
High Bandwidth Vertical Velocity Control
results in low and near constant D/S velocity

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

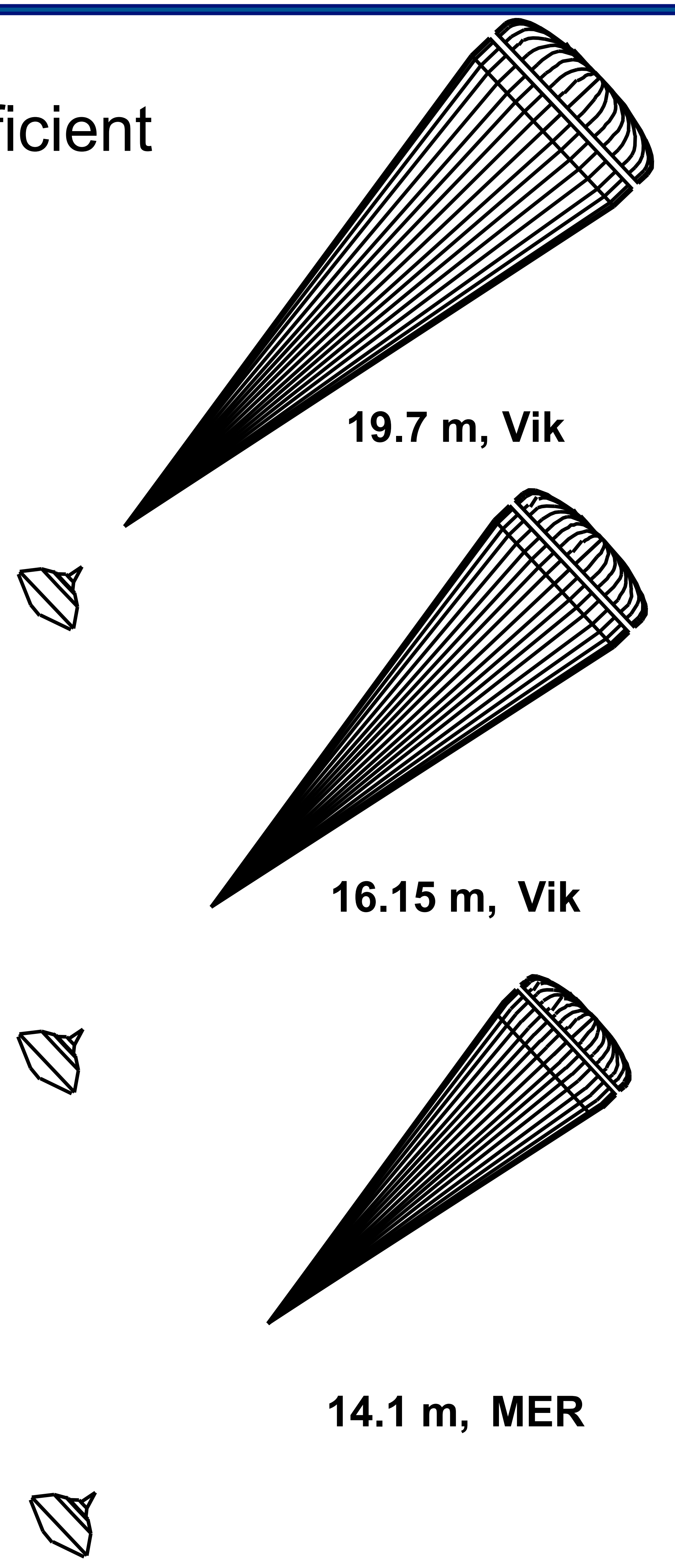
Rover Becomes the Touchdown System
Rover provides ground clearance, static stability, and terrain adaptation



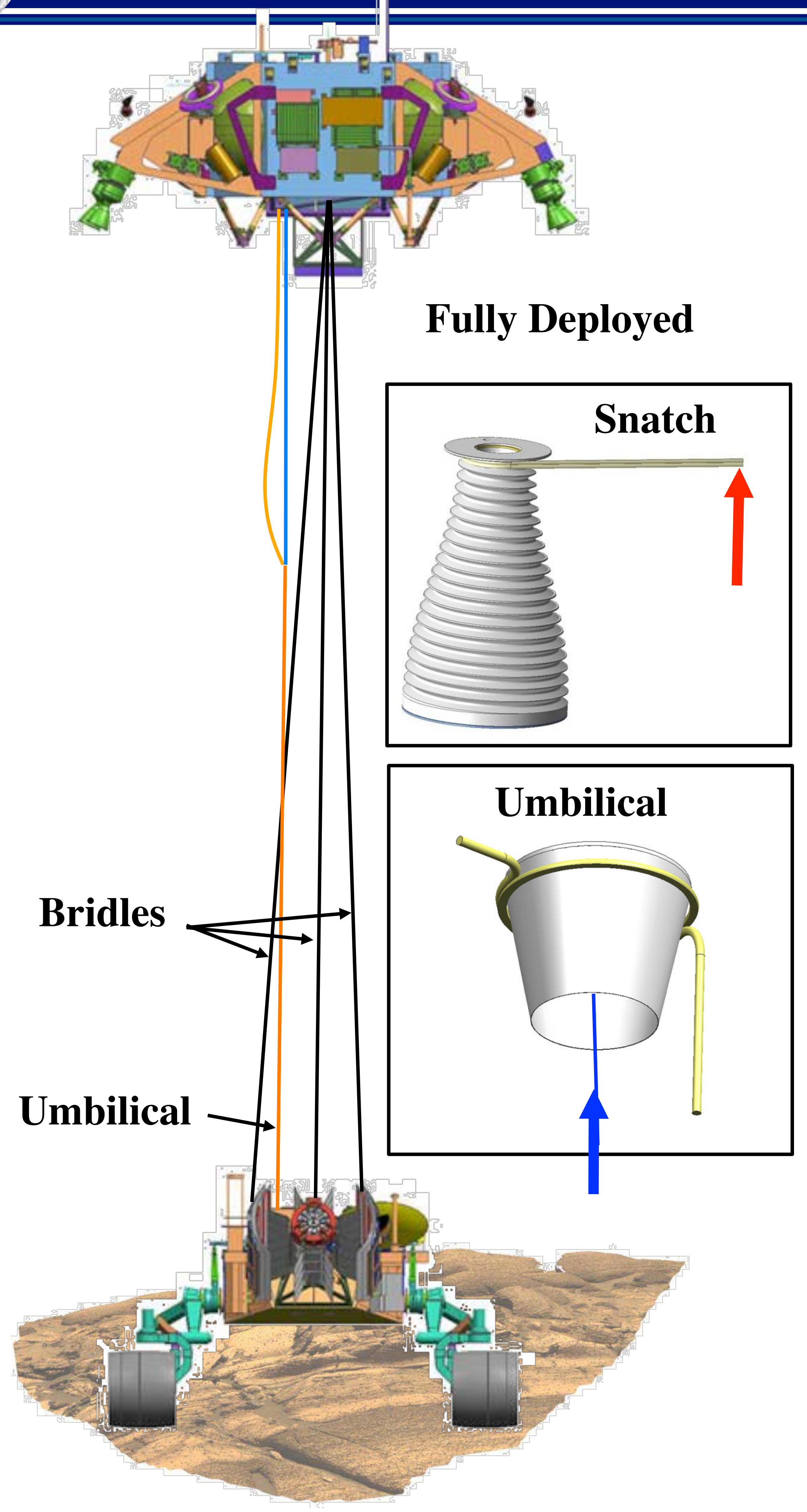
Mass Growth and Configuration

Comparison of mass growth and on-chute ballistic coefficient

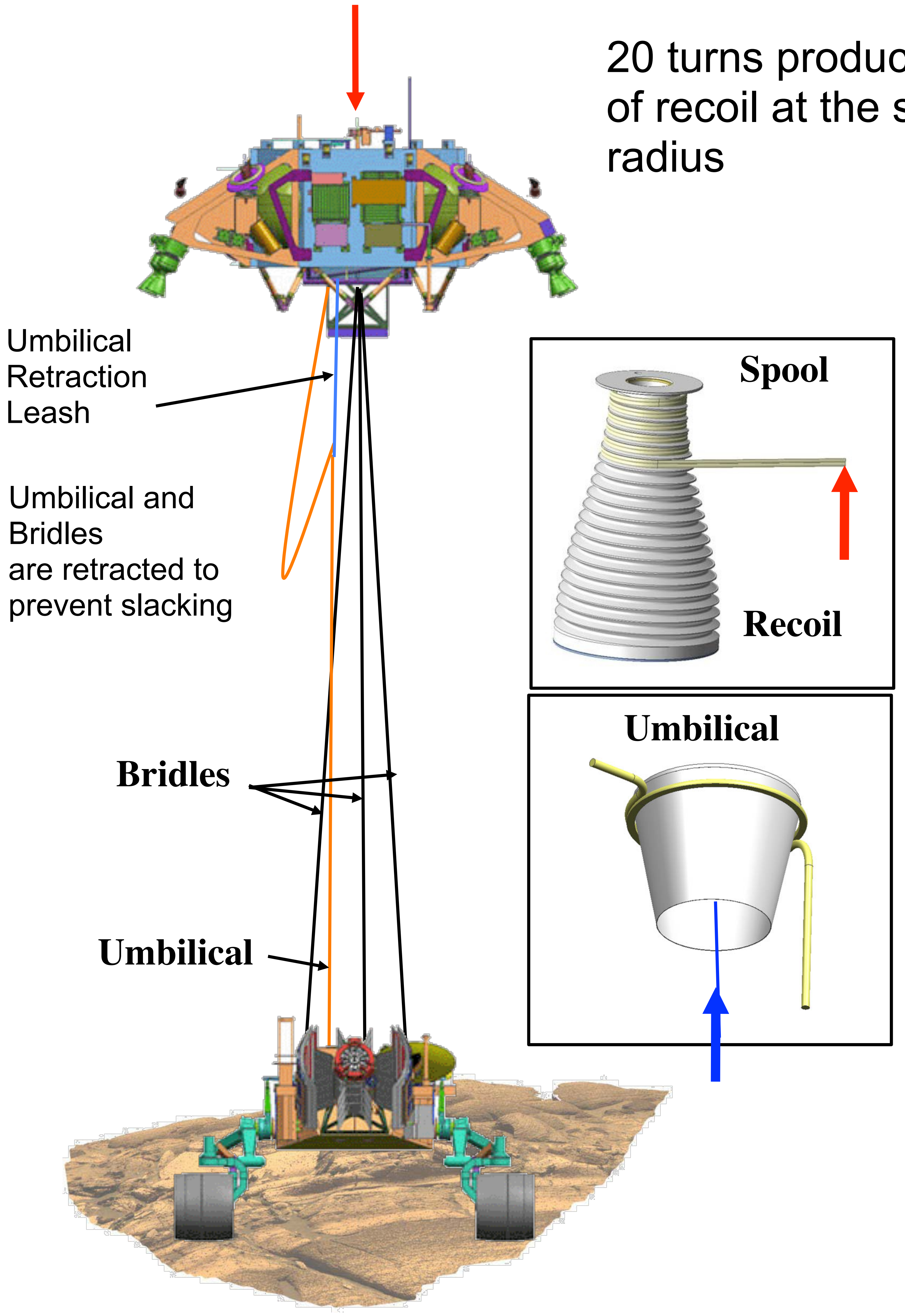
	Configuration	Rover/Entry Mass (kg)	Capsule/Chute Diameter Ratio (kg)	β on Chute (kg/m²)	Comments
Work-to-date	MSL MCR 10/03	900/2400	0.28	17.3	16.15 m Vik
Work-to-date	MSL M2 7/04	550/1883	0.23	13.6	16.15 m Vik
Work-to-date	MSL Costing 6/05	725/2705	0.28	19.5	16.15 m Vik
	Baseline	**755/2675**	**0.23**	**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**



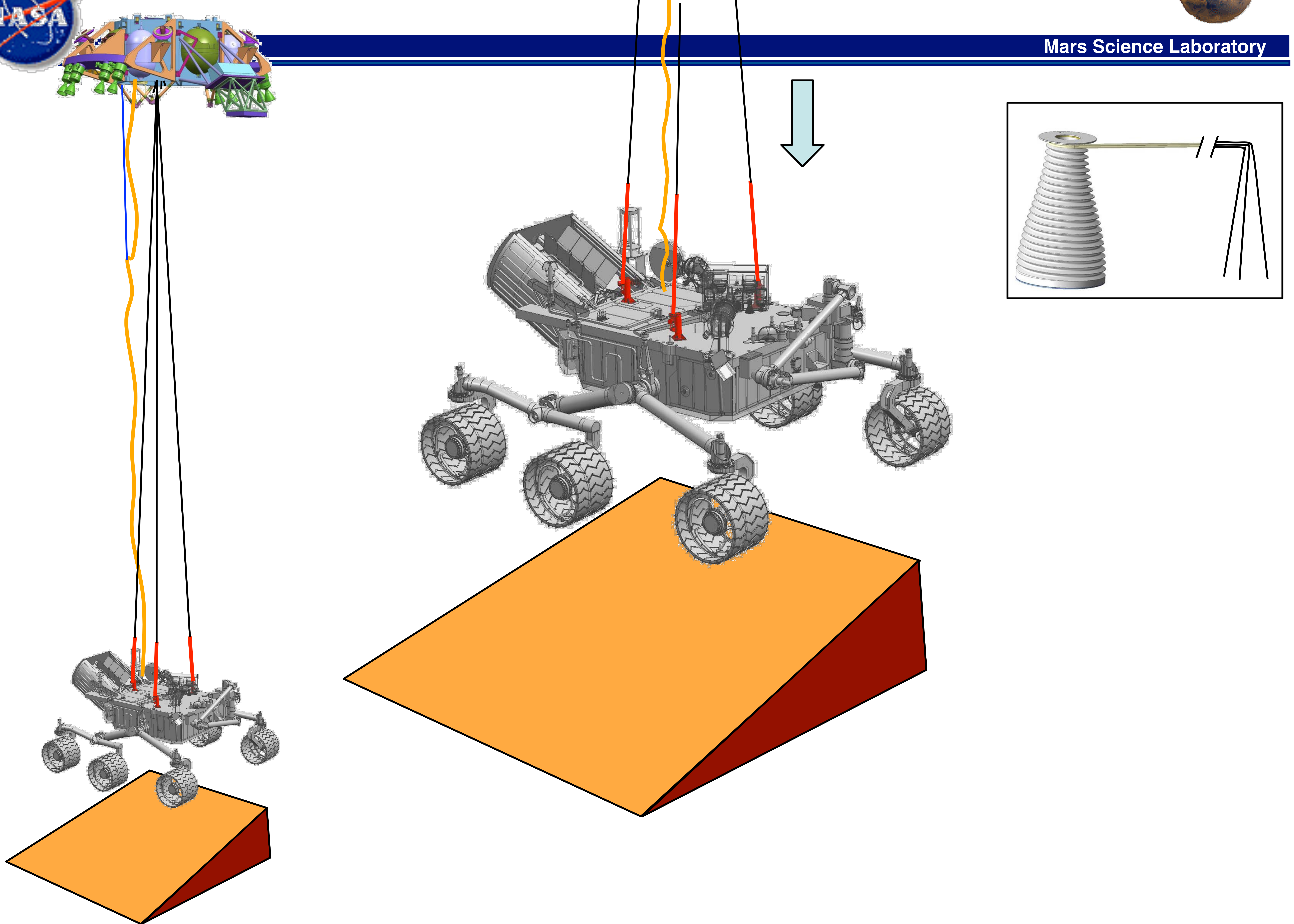
Uniform Slack Maintenance



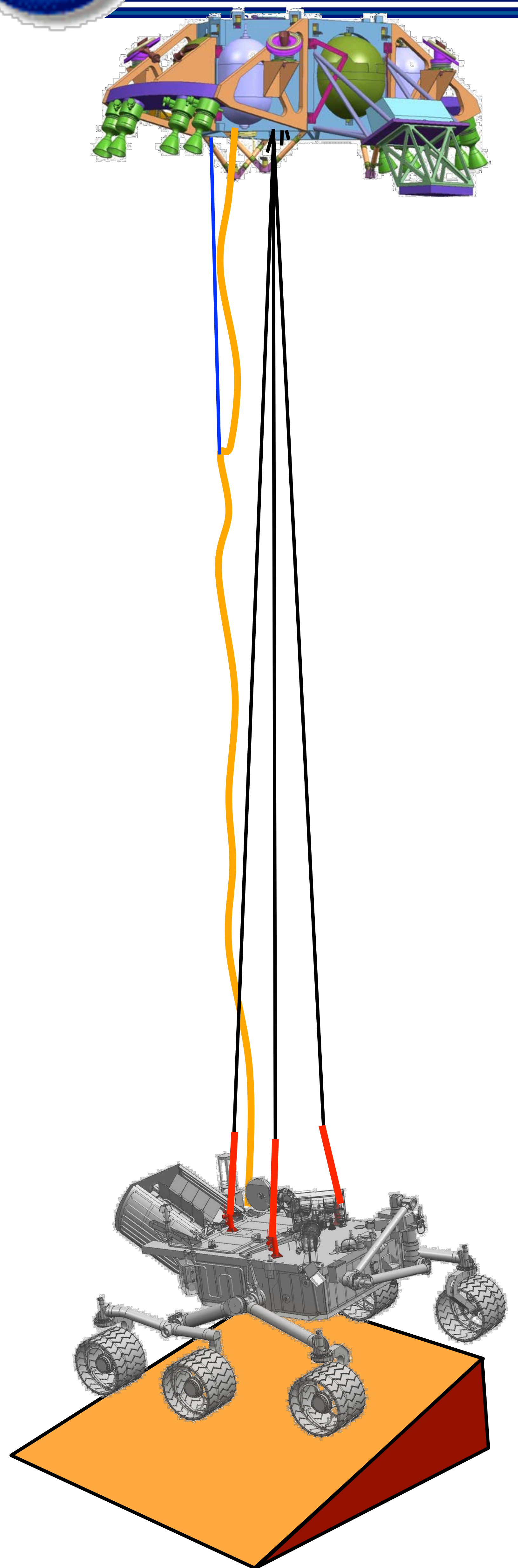
20 turns produces 4 m of recoil at the small radius

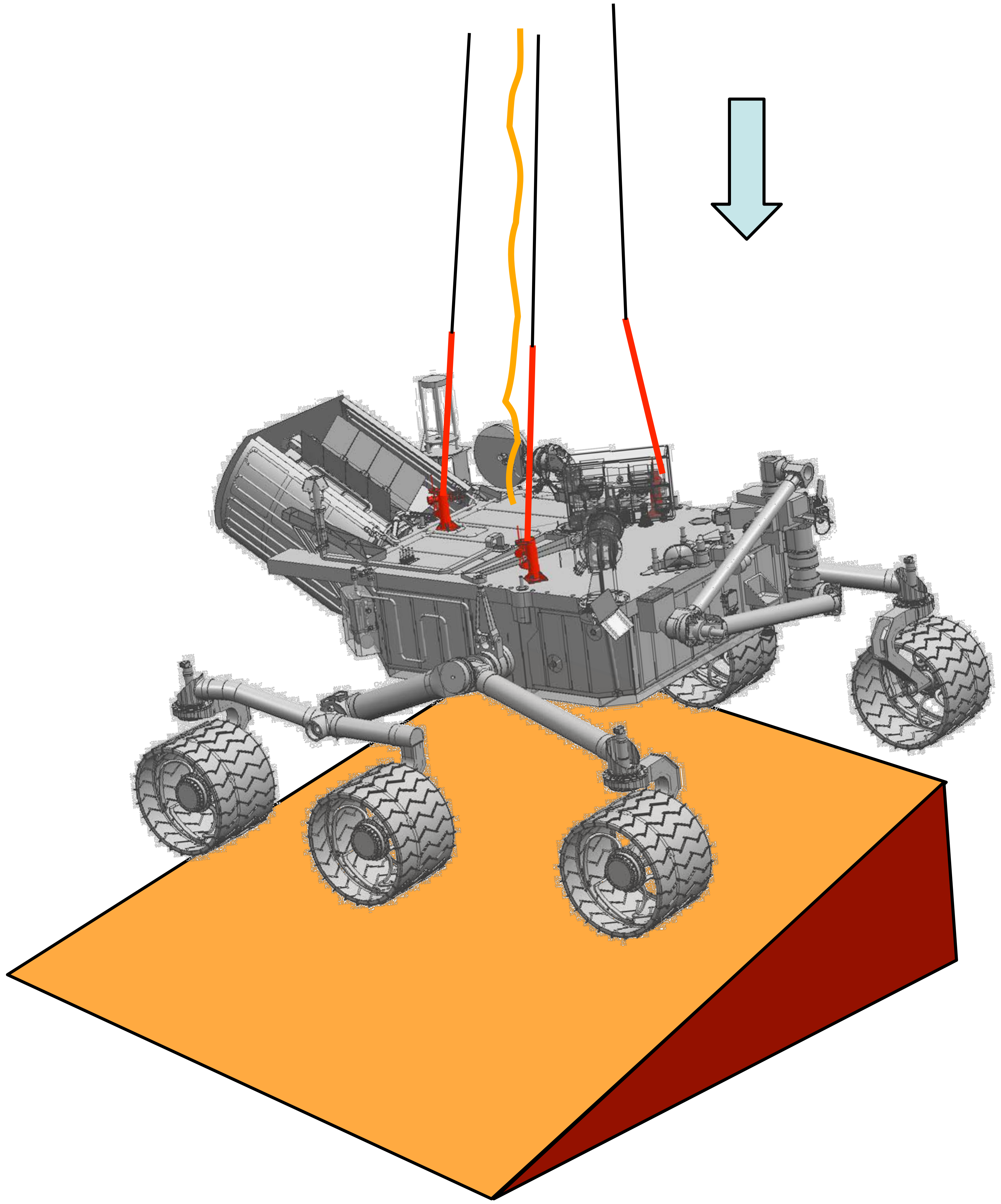


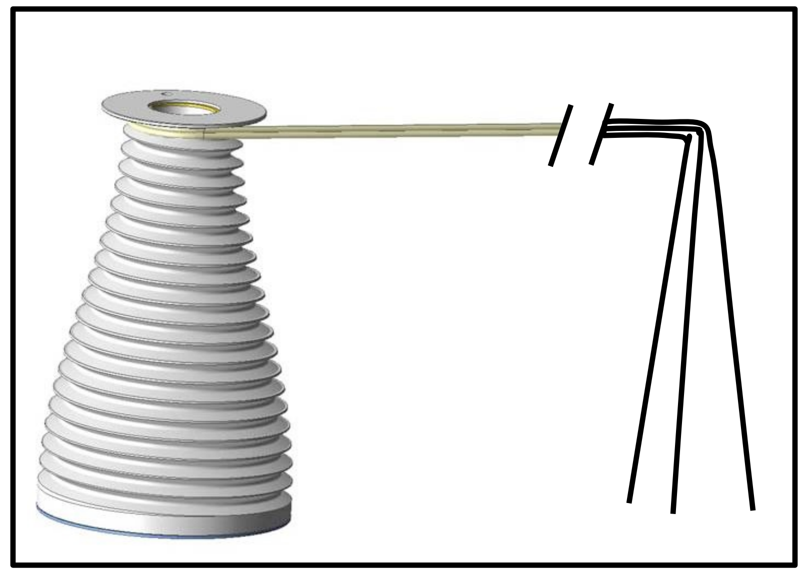
Pre-Touchdown



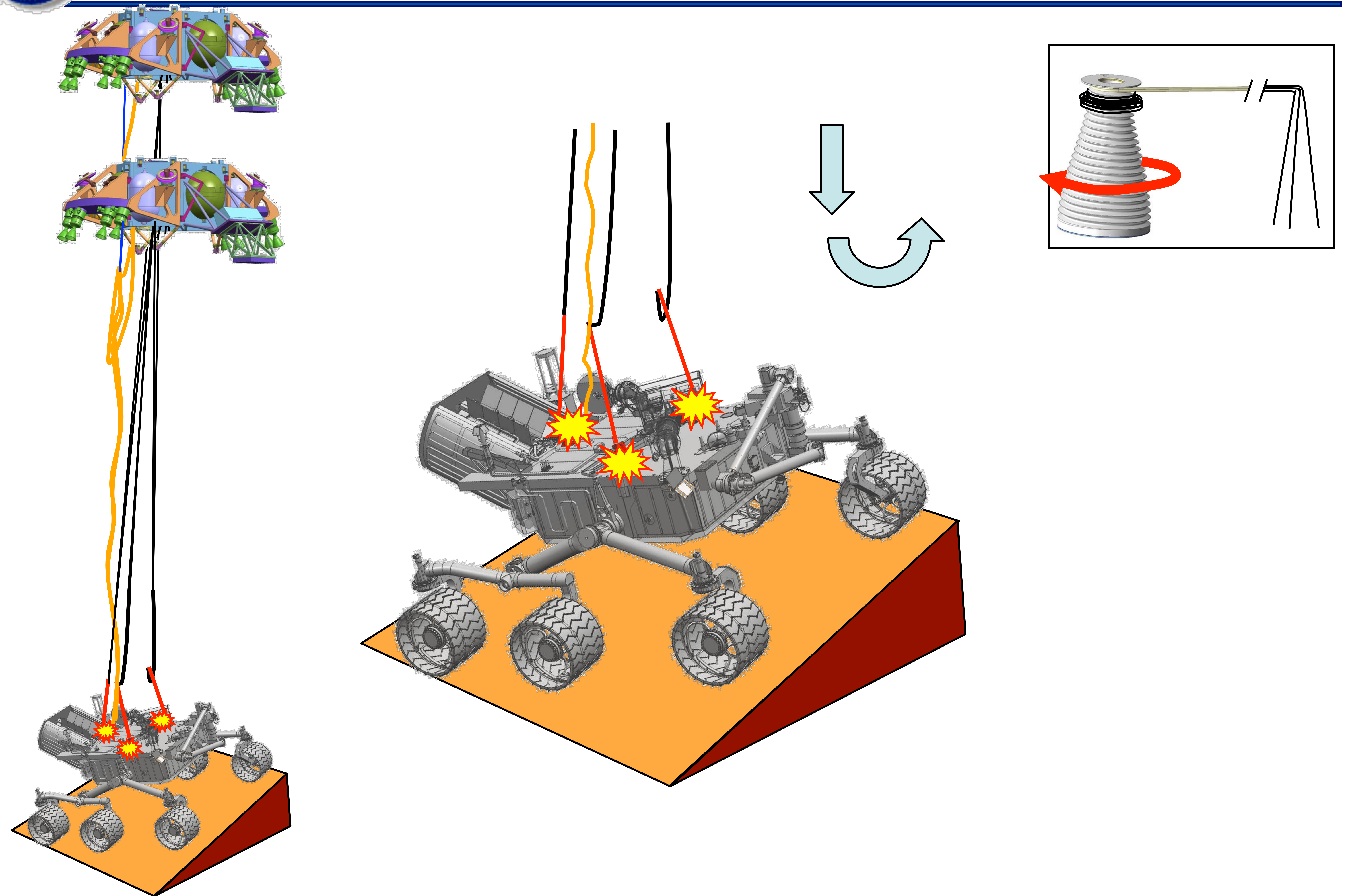
Initial Touchdown



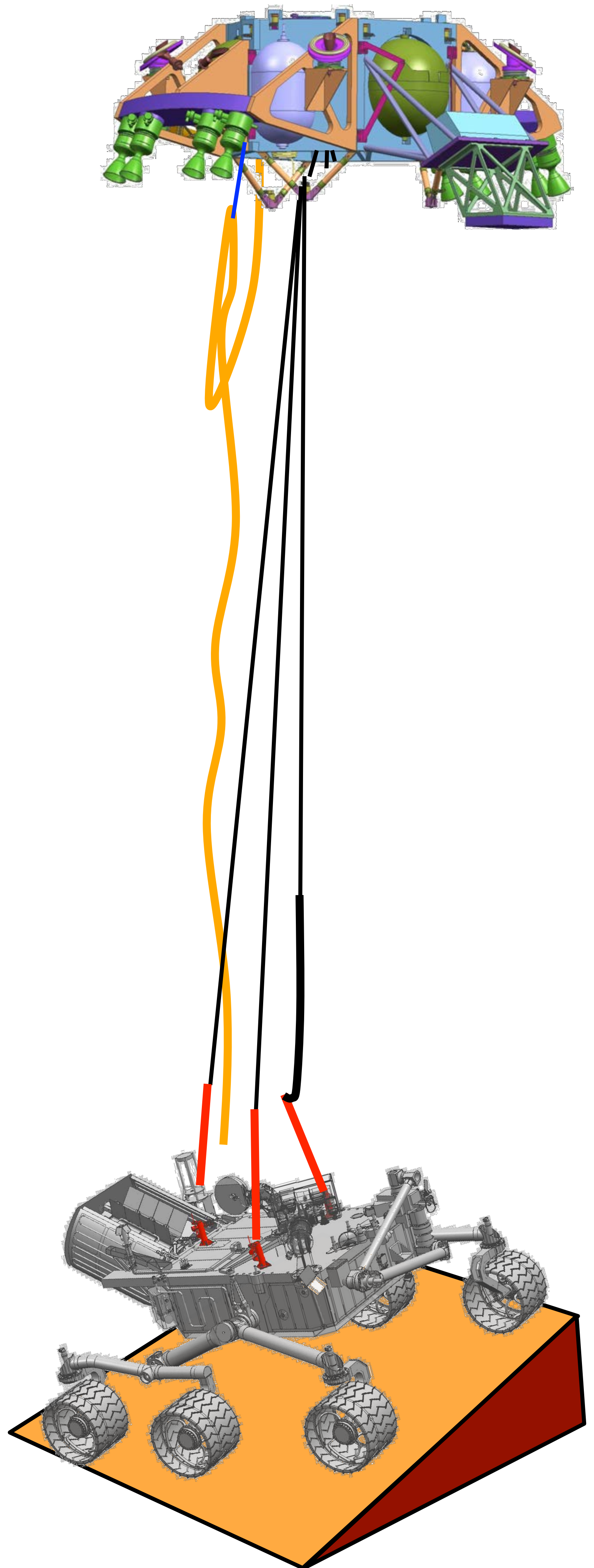


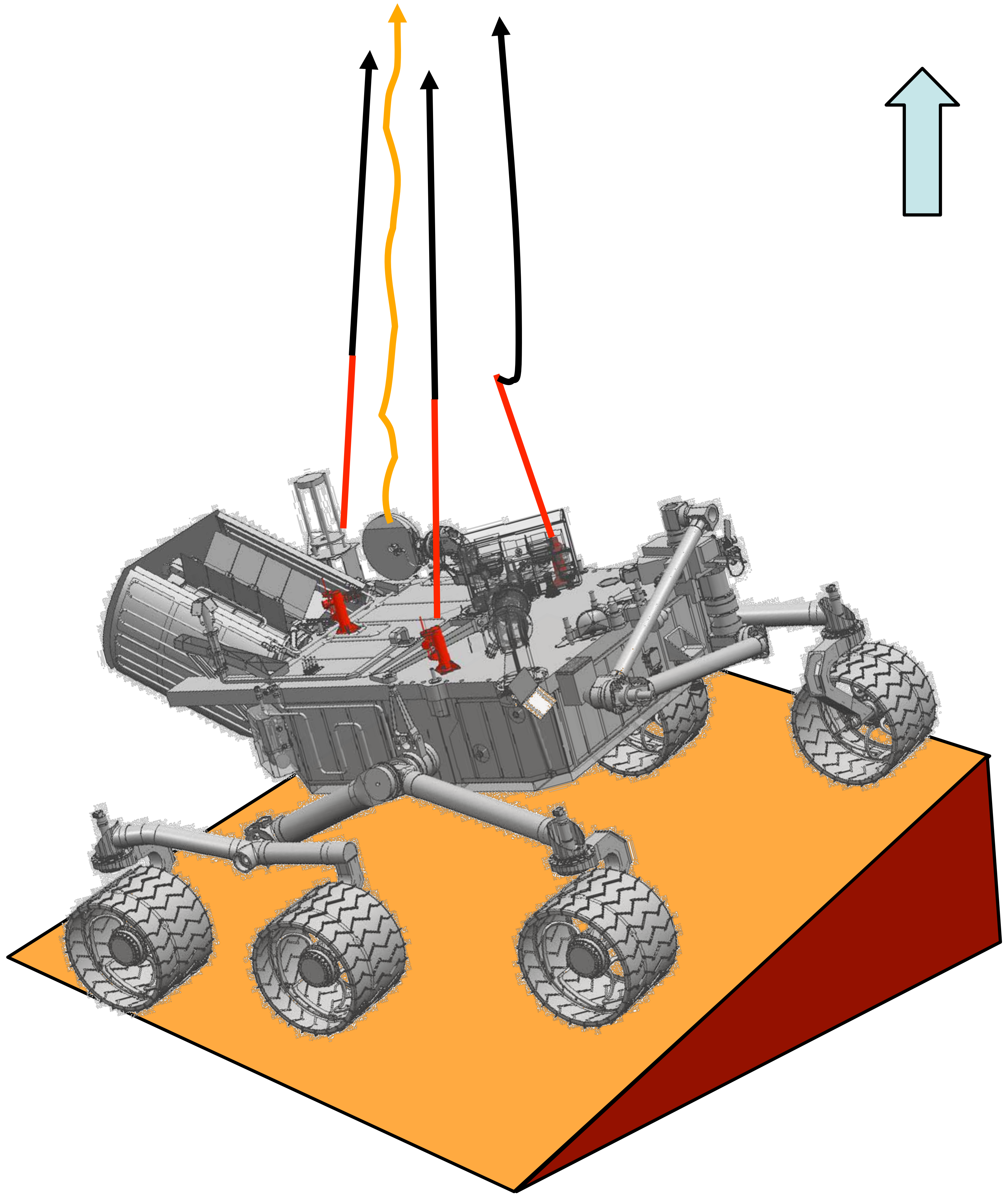


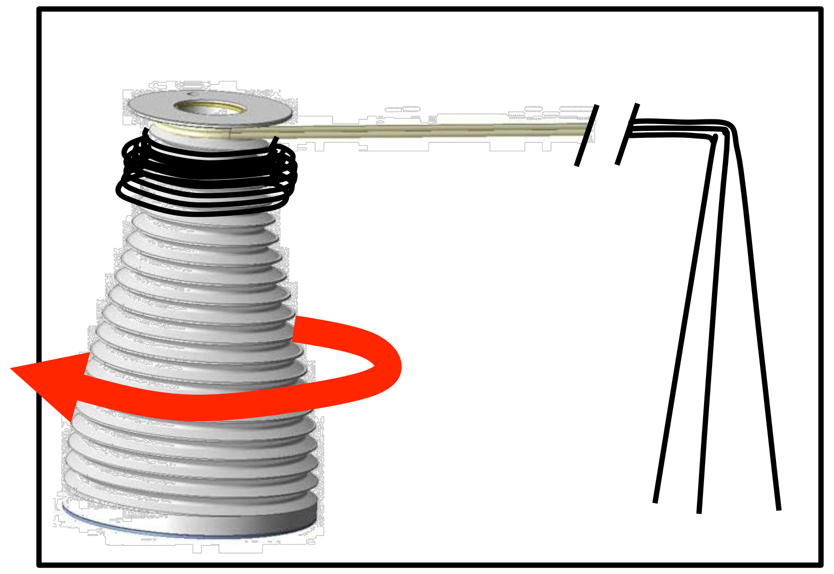
Complete Touchdown



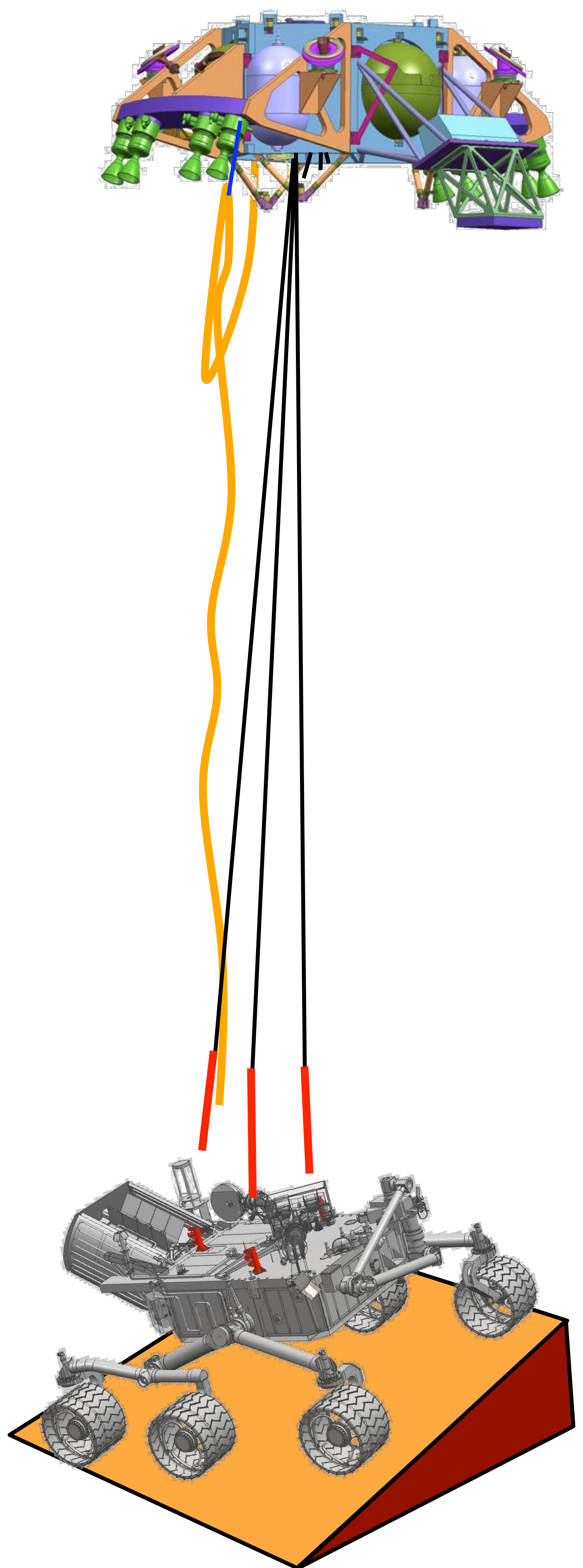
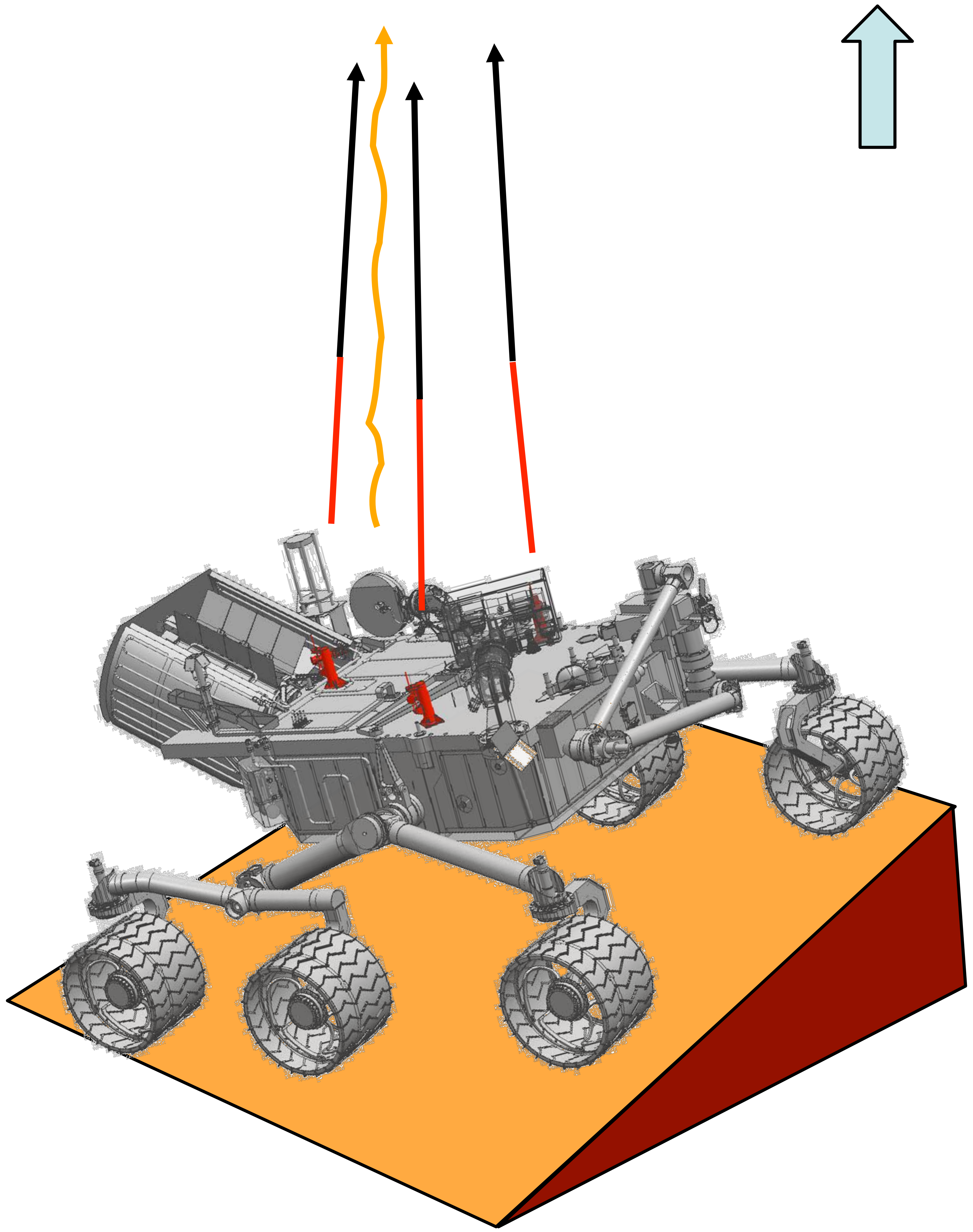
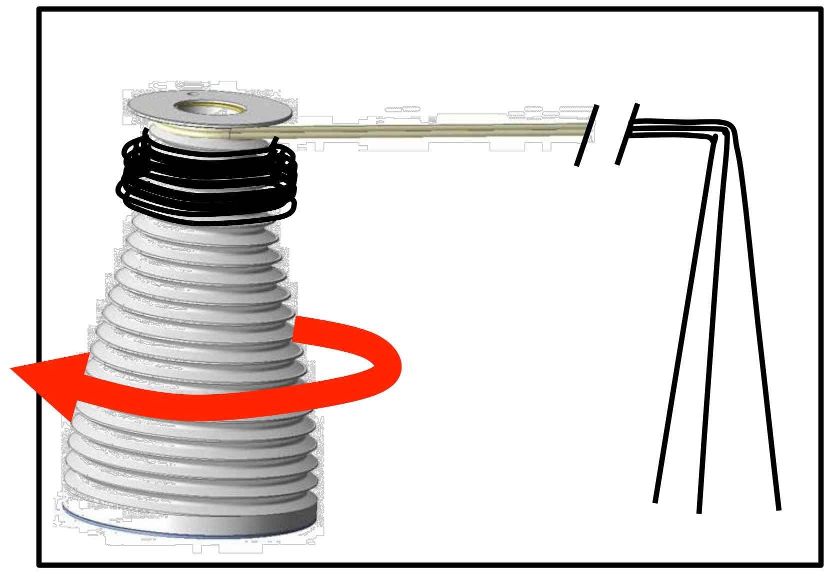
Bridle & Umbilical Initial Retraction



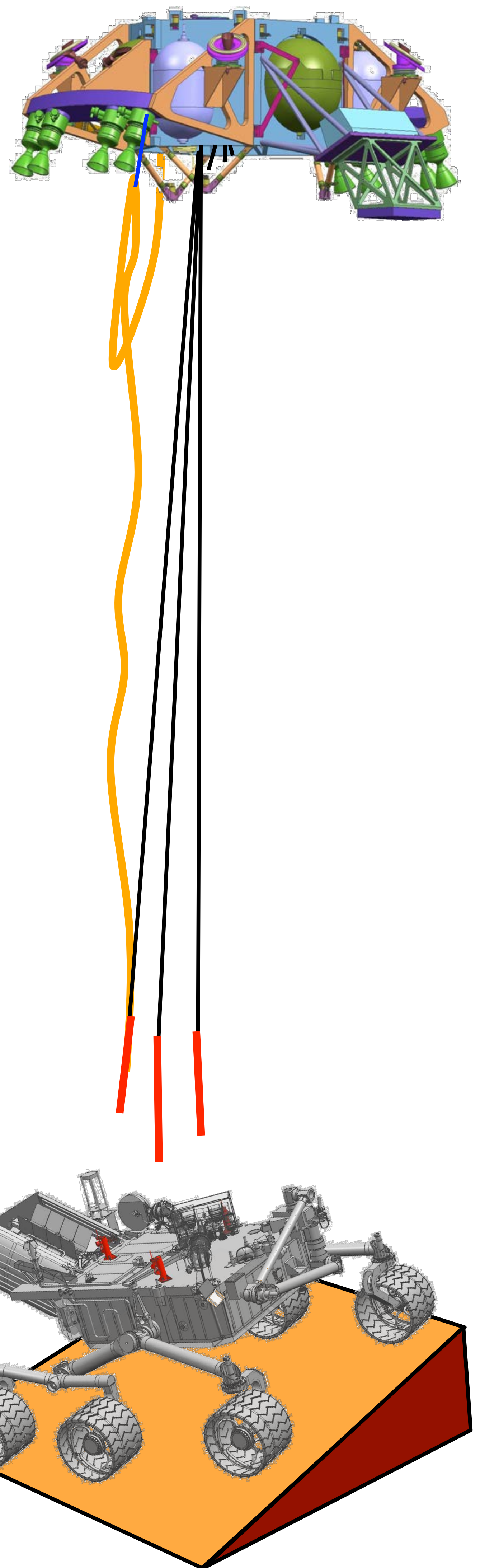


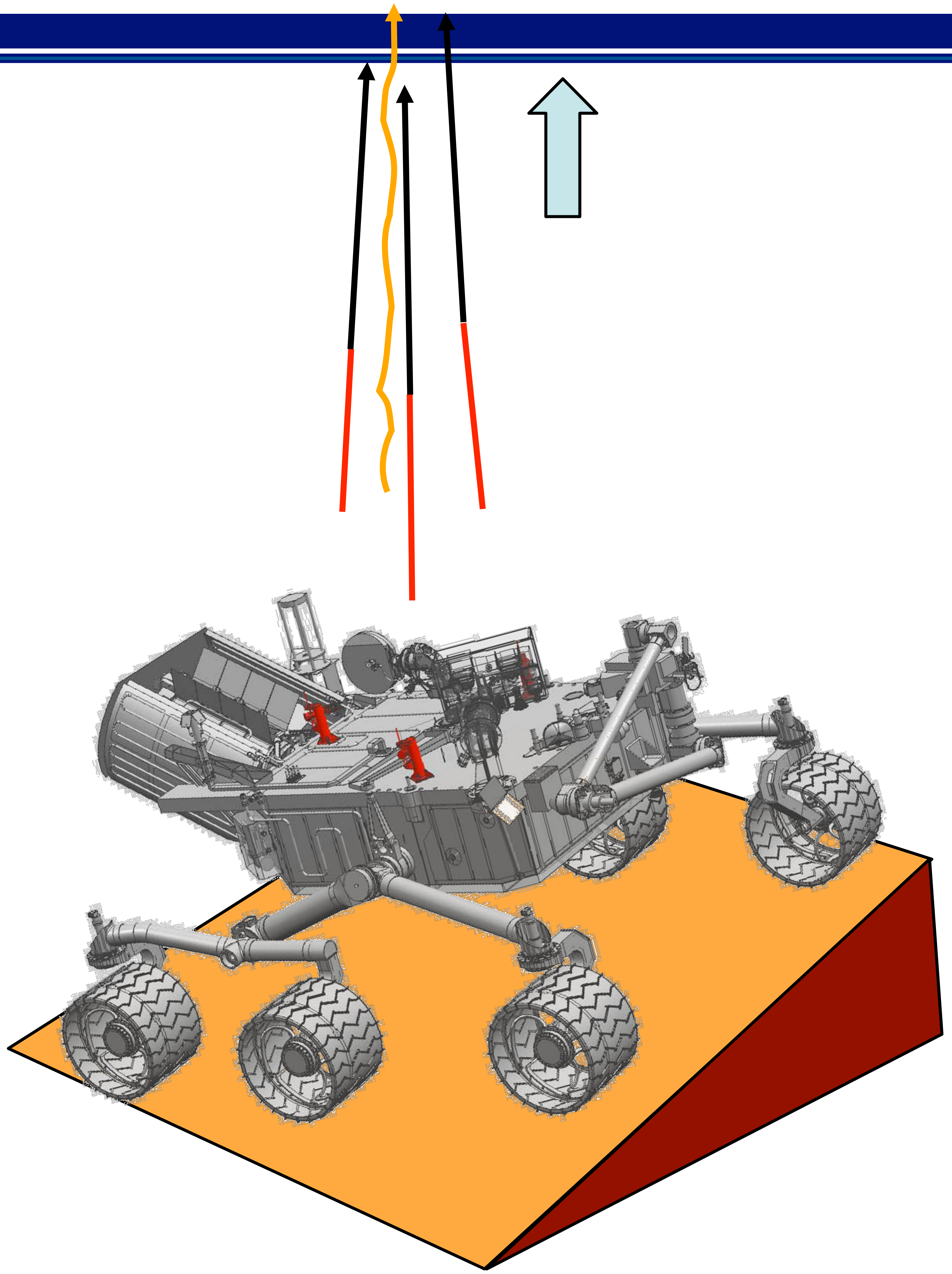


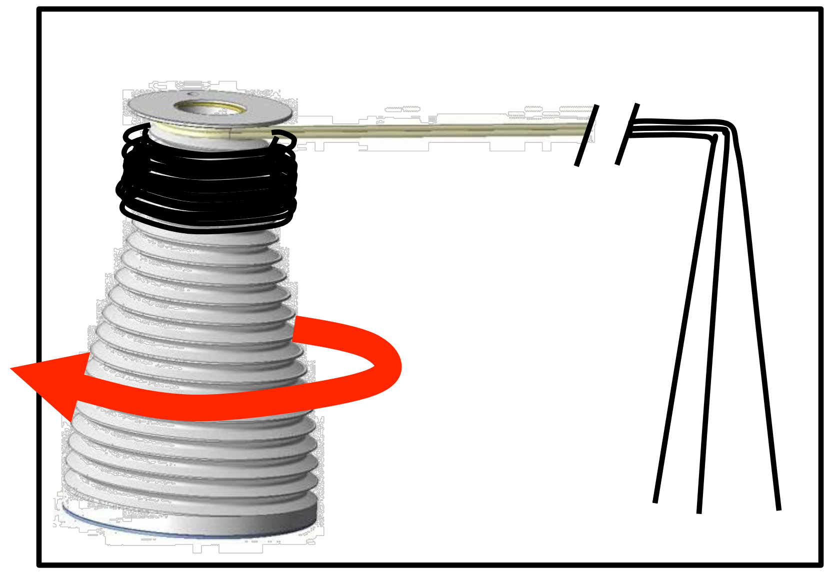
Bridle & Umbilical Complete Retraction

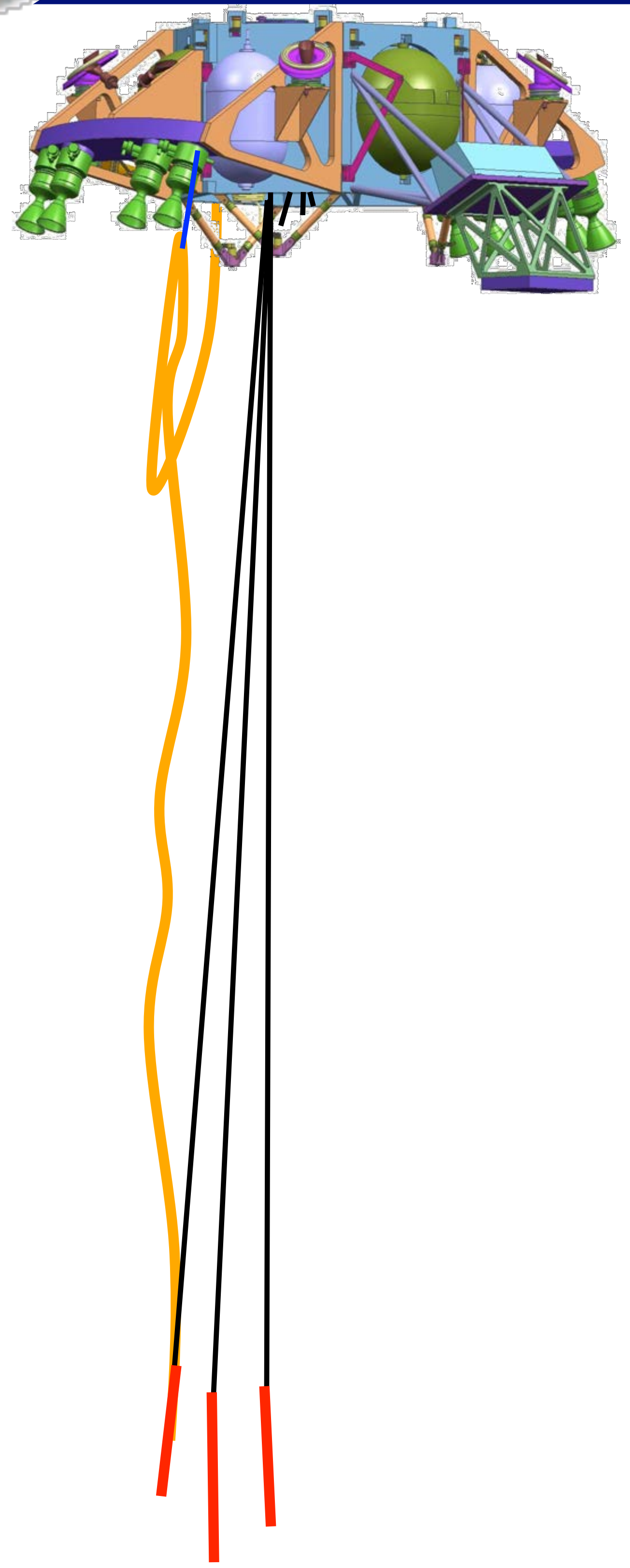
Fly Away

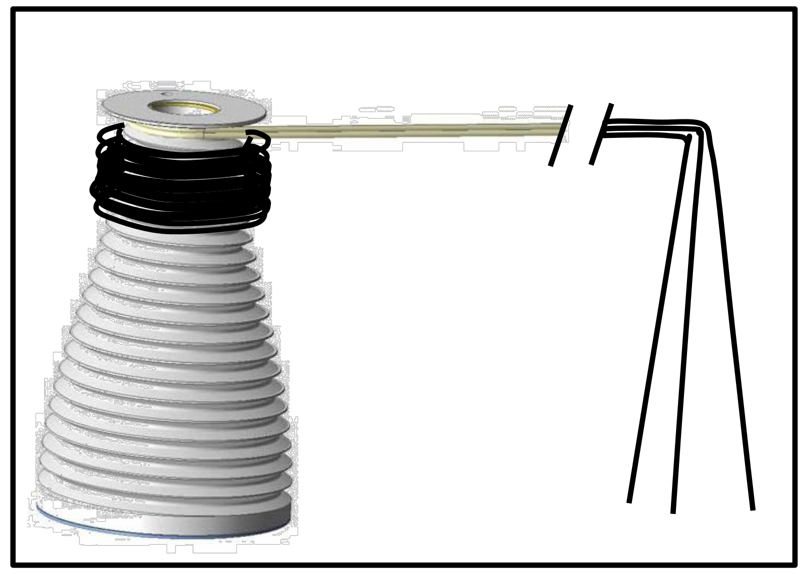


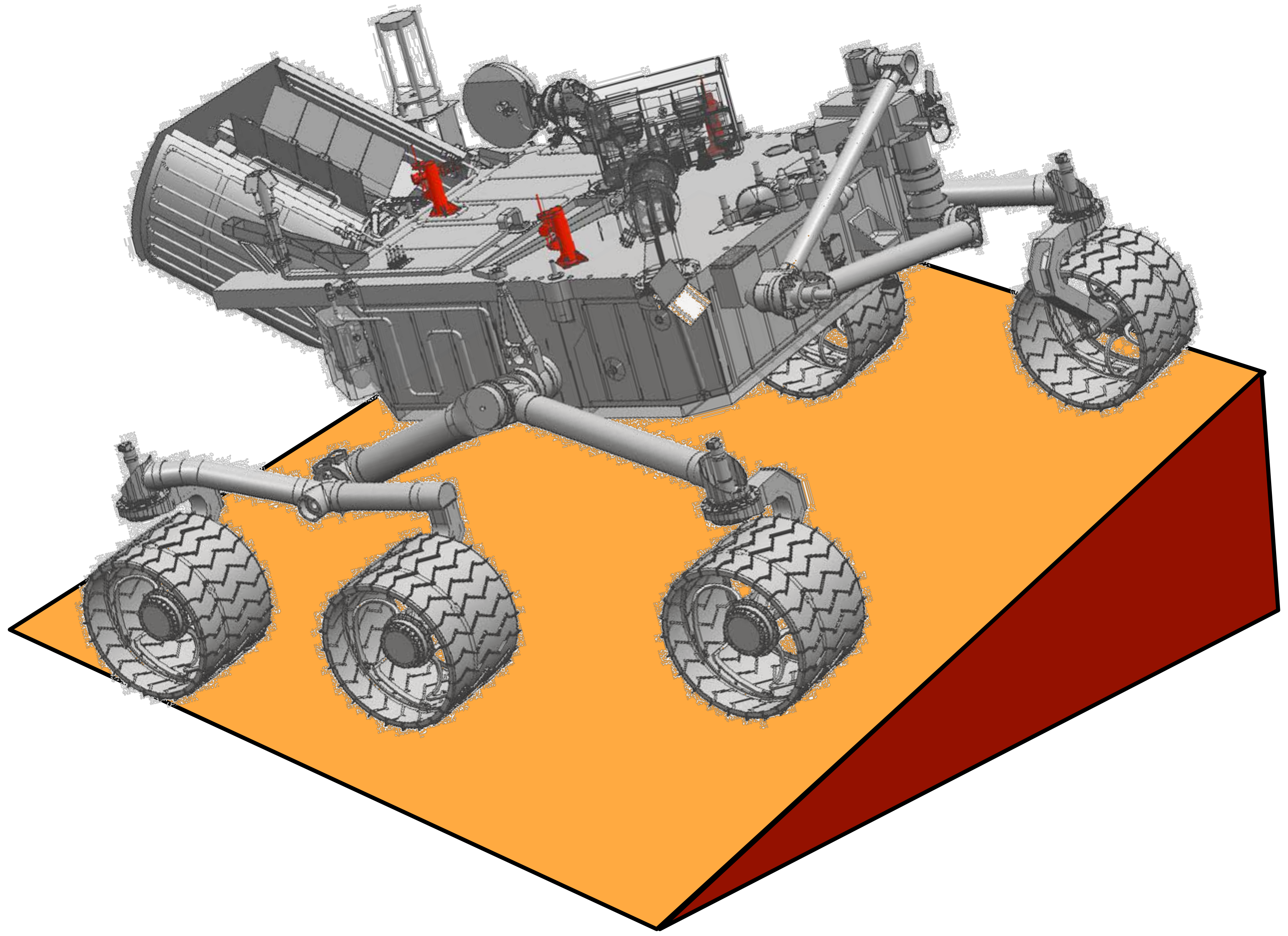


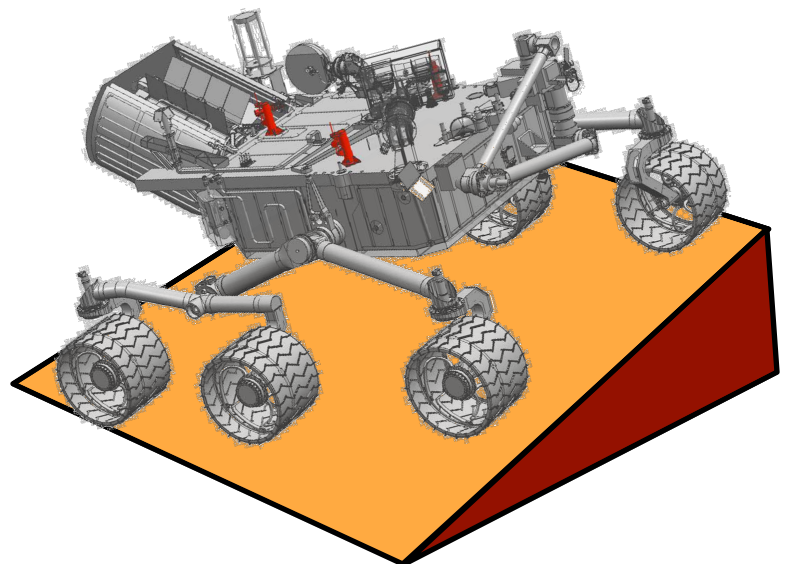


Fly Away



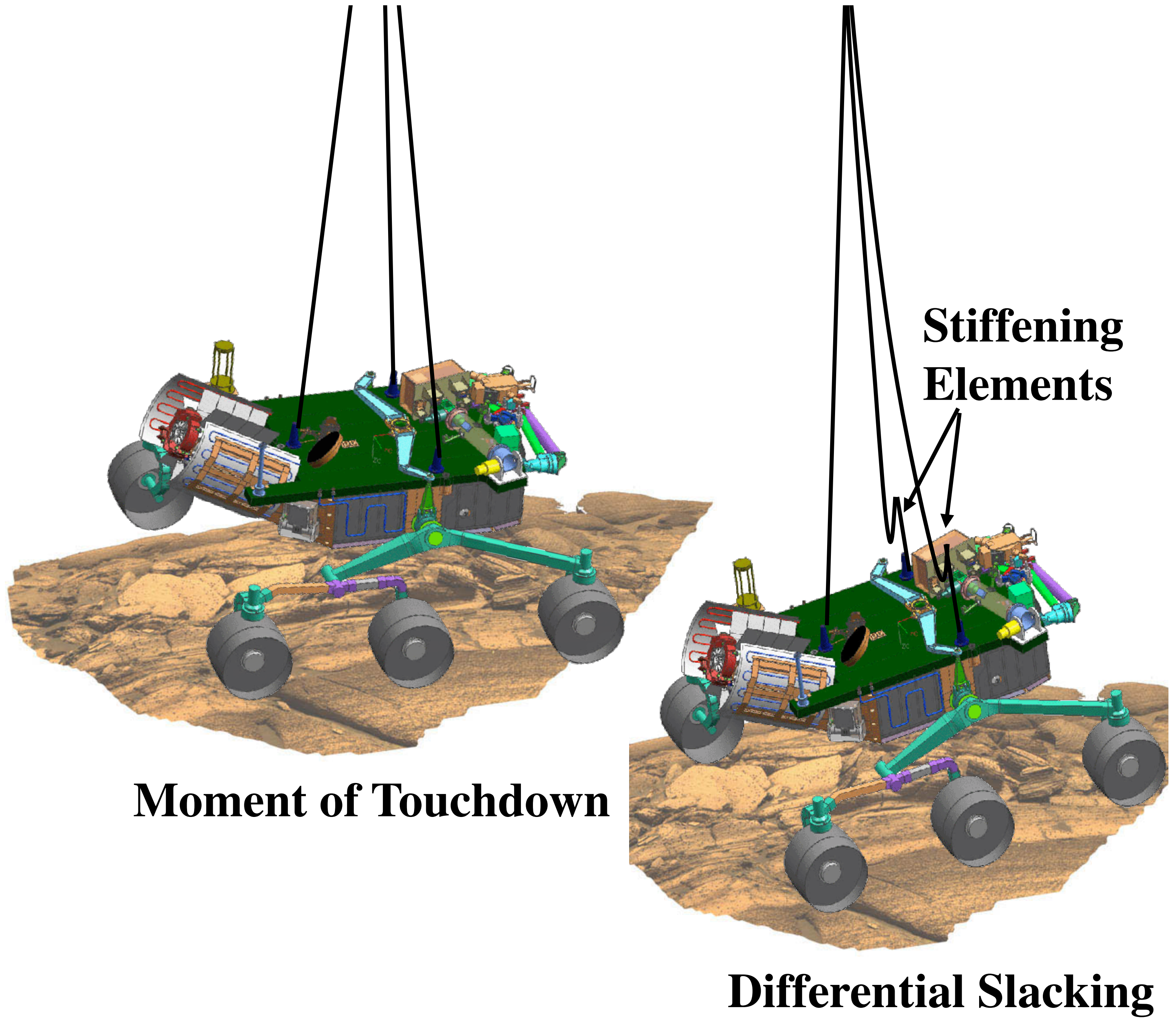


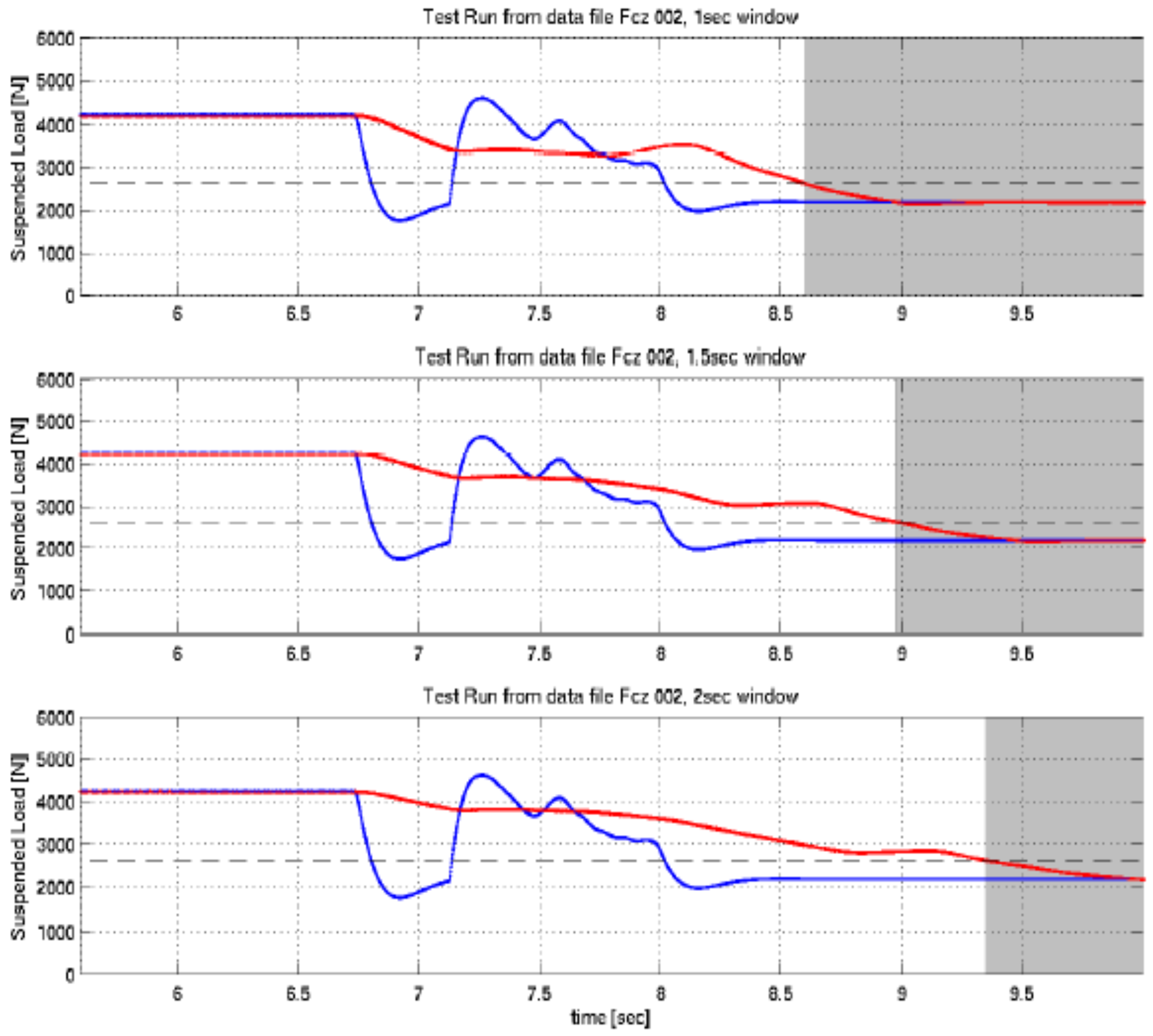




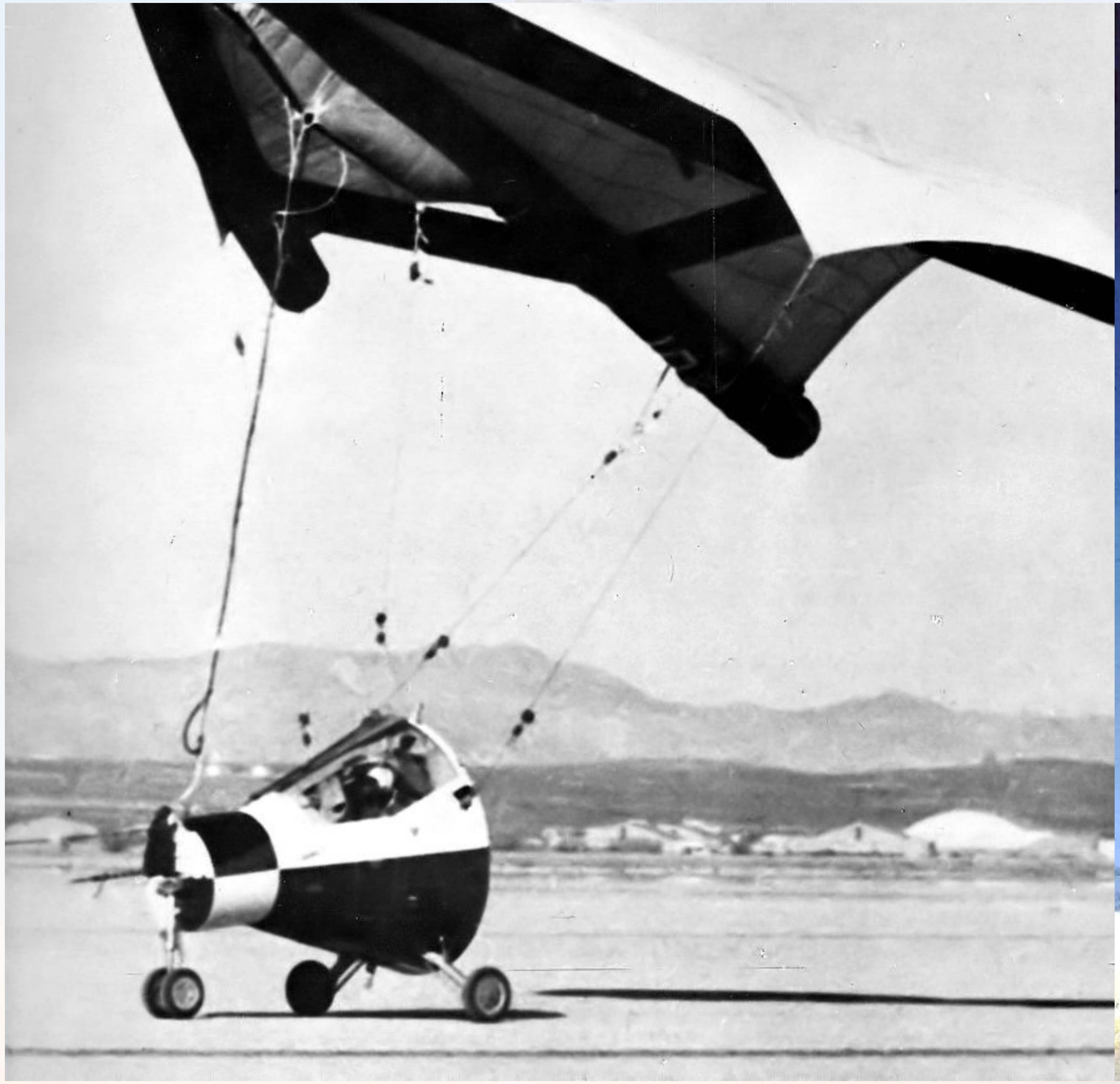
Sky Crane: Touchdown

- 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





Gemini Rogallo Wing Recovery



X-38 Parasail Landing System

SpaceX Propulsive Landing Tests

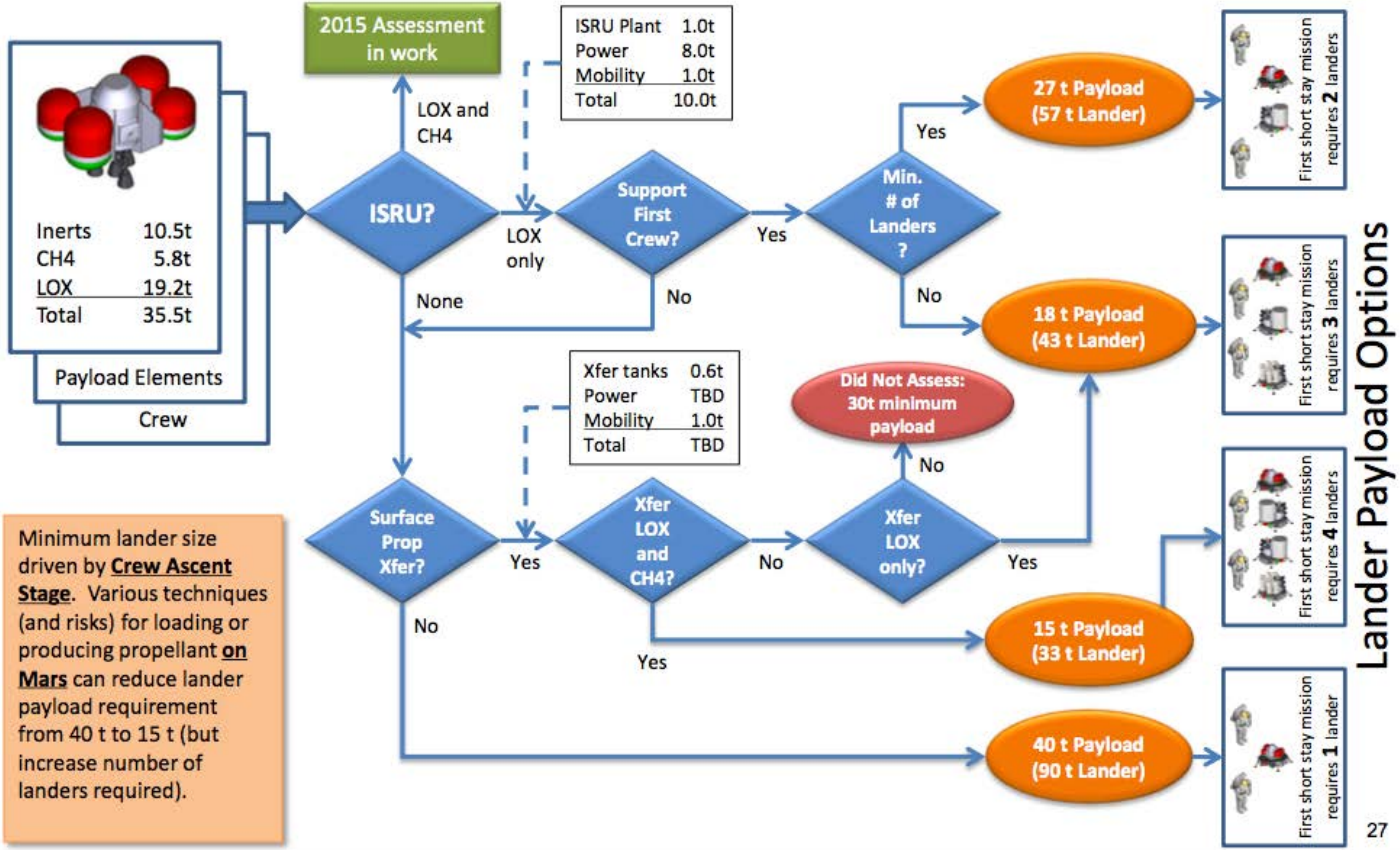
National Aeronautics and Space Administration

Evolvable Mars Campaign Overview to FISO Telecon

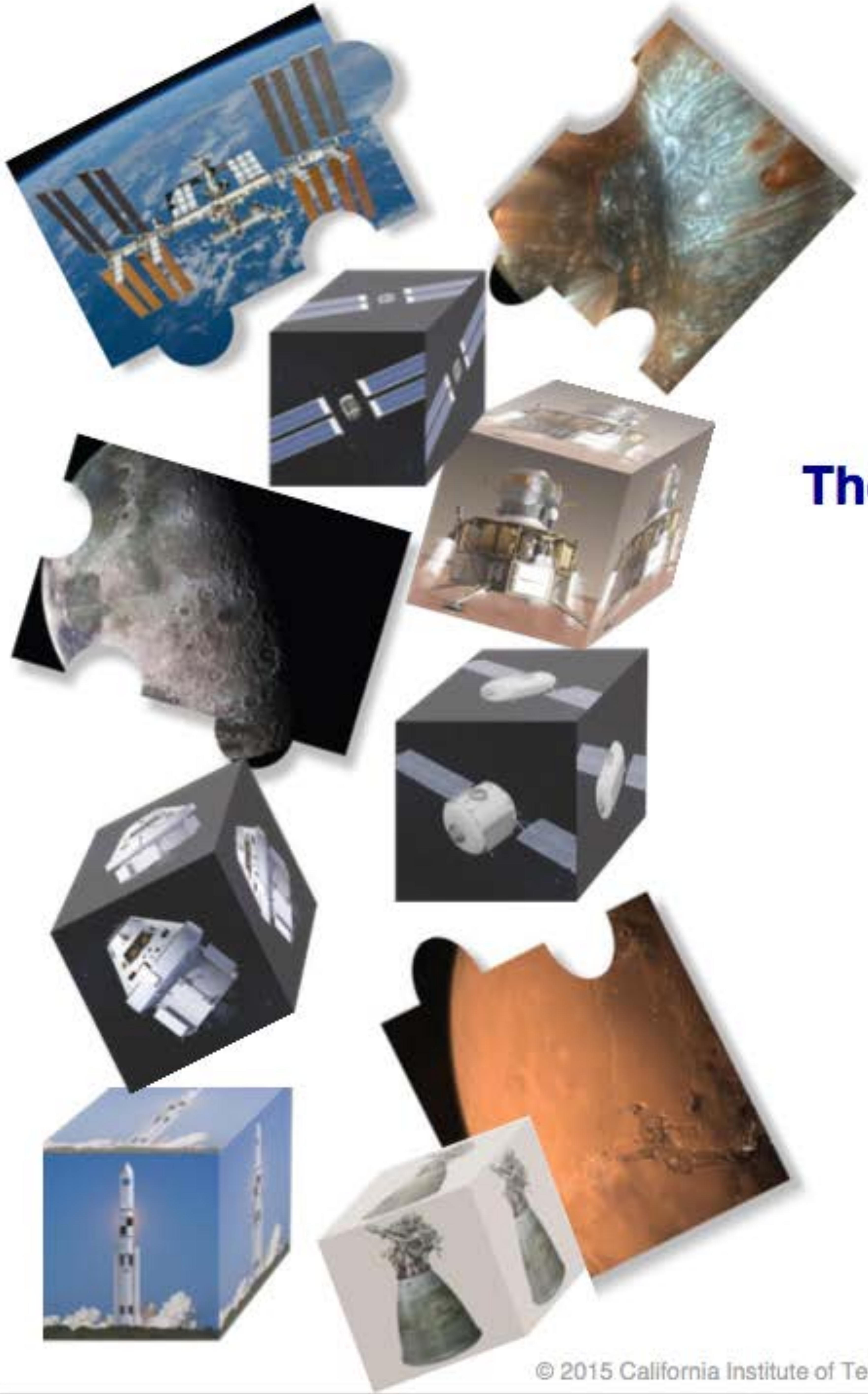
June 10, 2015

Douglas Craig
Strategic Analysis Manager
Advanced Exploration Systems
Human Exploration and Operations Mission Directorate
NASA HQ

Largest Indivisible Payload Element and Options for Size of the Lander



Minimum lander size driven by **Crew Ascent Stage**. Various techniques (and risks) for loading or producing propellant **on Mars** can reduce lander payload requirement from 40 t to 15 t (but increase number of landers required).



A Scenario for a Human Mission to Mars Orbit in the 2030s

Thoughts Toward an Executable Program

Fitting Together Puzzle Pieces & Building Blocks

Future In-Space Operations (FISO) Telecon
May 20, 2015

Hoppy Price*
John Baker*
Firouz Naderi*

*Jet Propulsion Laboratory
California Institute of Technology

H2M
Minimal Architecture

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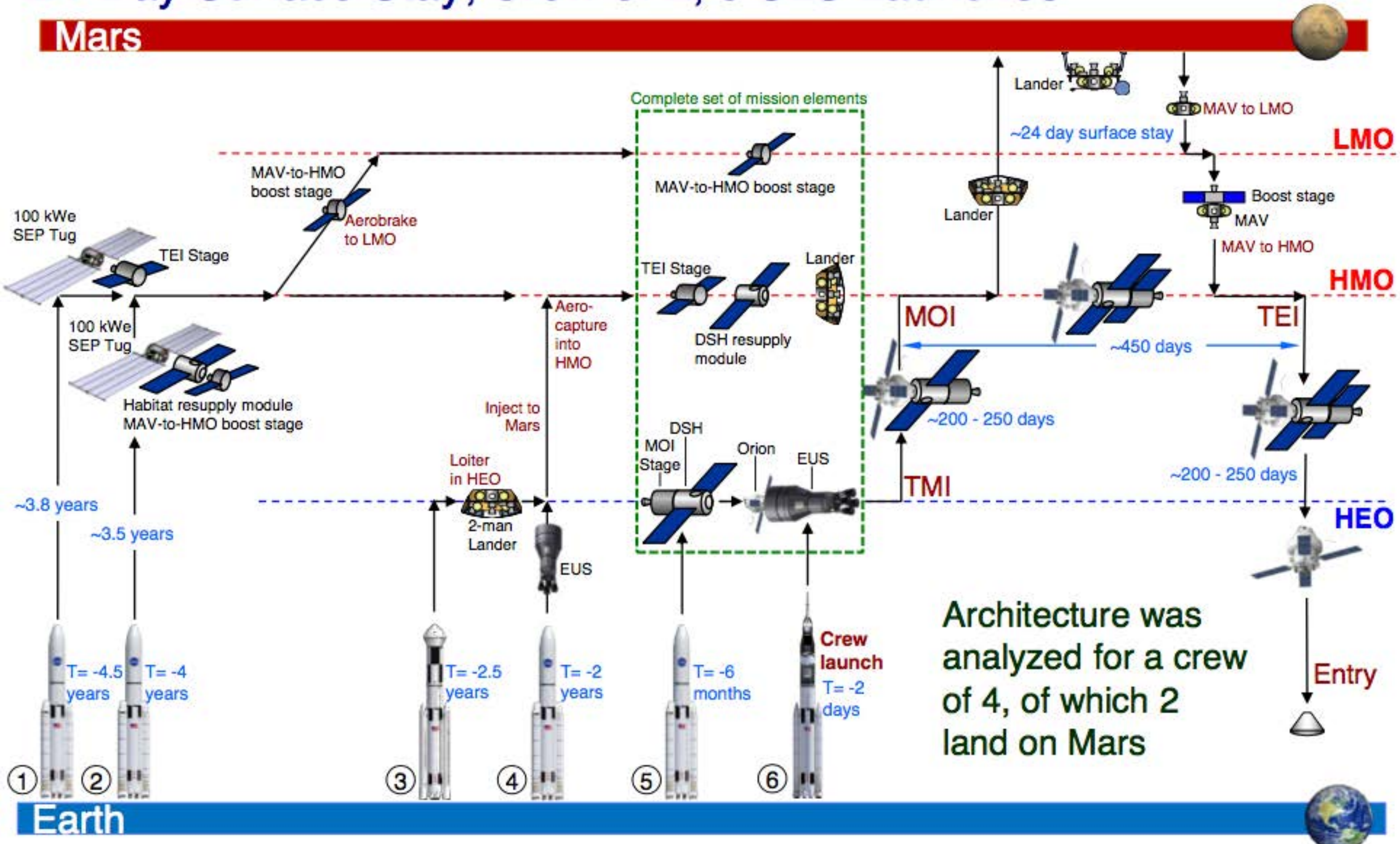
Short-stay Mars Lander Concept

Attributes of the Mission

- 23 t useful-landed-mass lander
  - Crew of 2 to the surface, 24-day stay
  - (Could support crew of 4 for 6 days)
- Architecture re-uses the Phobos approach for getting crew to HMO and back to Earth (already tested in 2033)
- The lander requires 2 additional SLS launches relative to Phobos mission, bringing total SLS launches to 6
- Lander sent to Mars with 2-SLS launch scenario and aero-captures into HMO to await crew arrival
- Lift off from Mars surface is achieved through a two-step ascent to High Mars Orbit (HMO)
  - MAV: Surface to Low Mars Orbit (LMO), then boosted to HMO
  - Minimizes the MAV propellant load to enable 23 t lander

Short-stay Surface Mission Concept

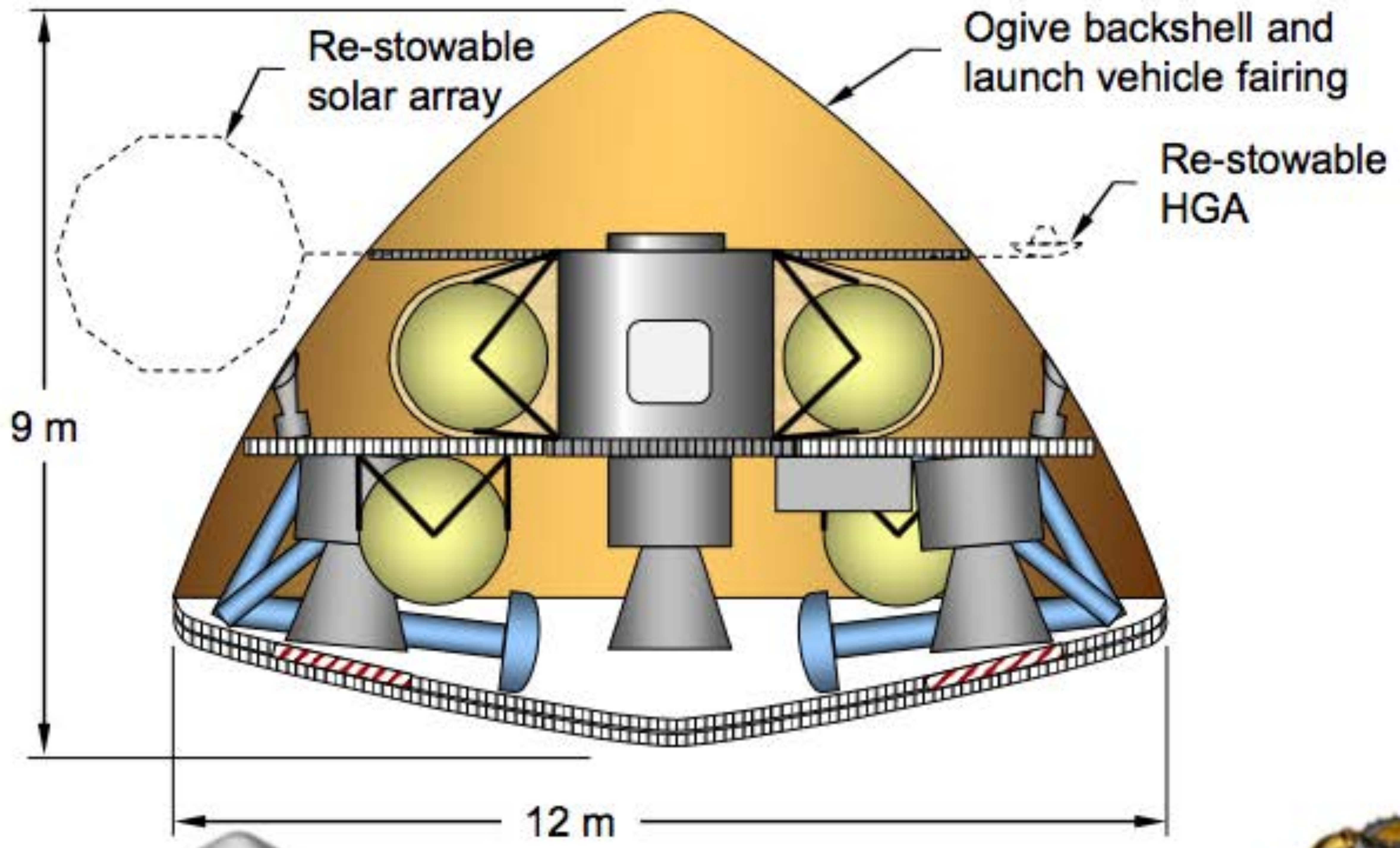
24-Day Surface Stay; Crew of 2; 6 SLS Launches

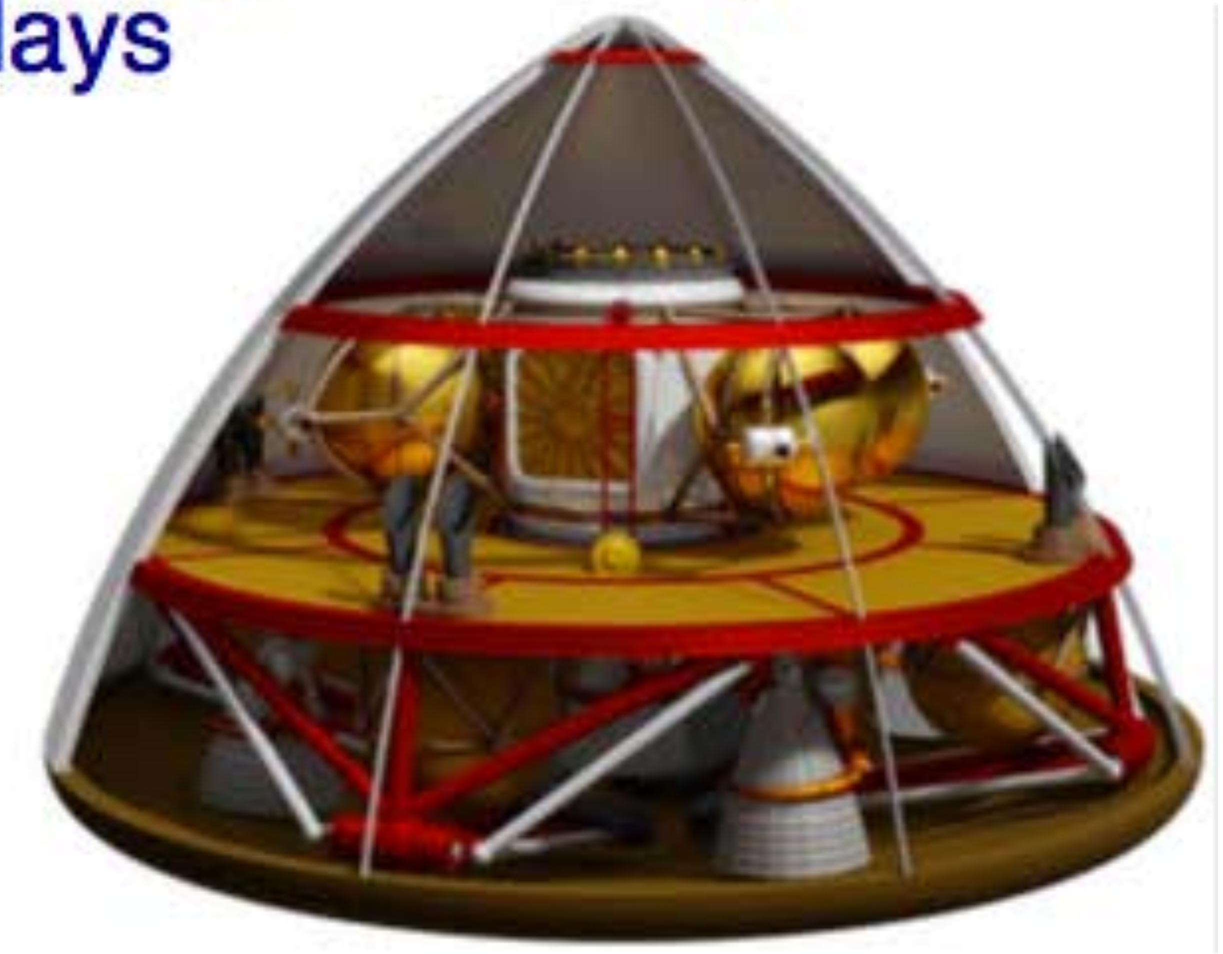


Architecture was analyzed for a crew of 4, of which 2 land on Mars

Descent/Ascent Vehicle (DAV)

Can support crew of 2 for 28 days, or crew of 4 for 6 days

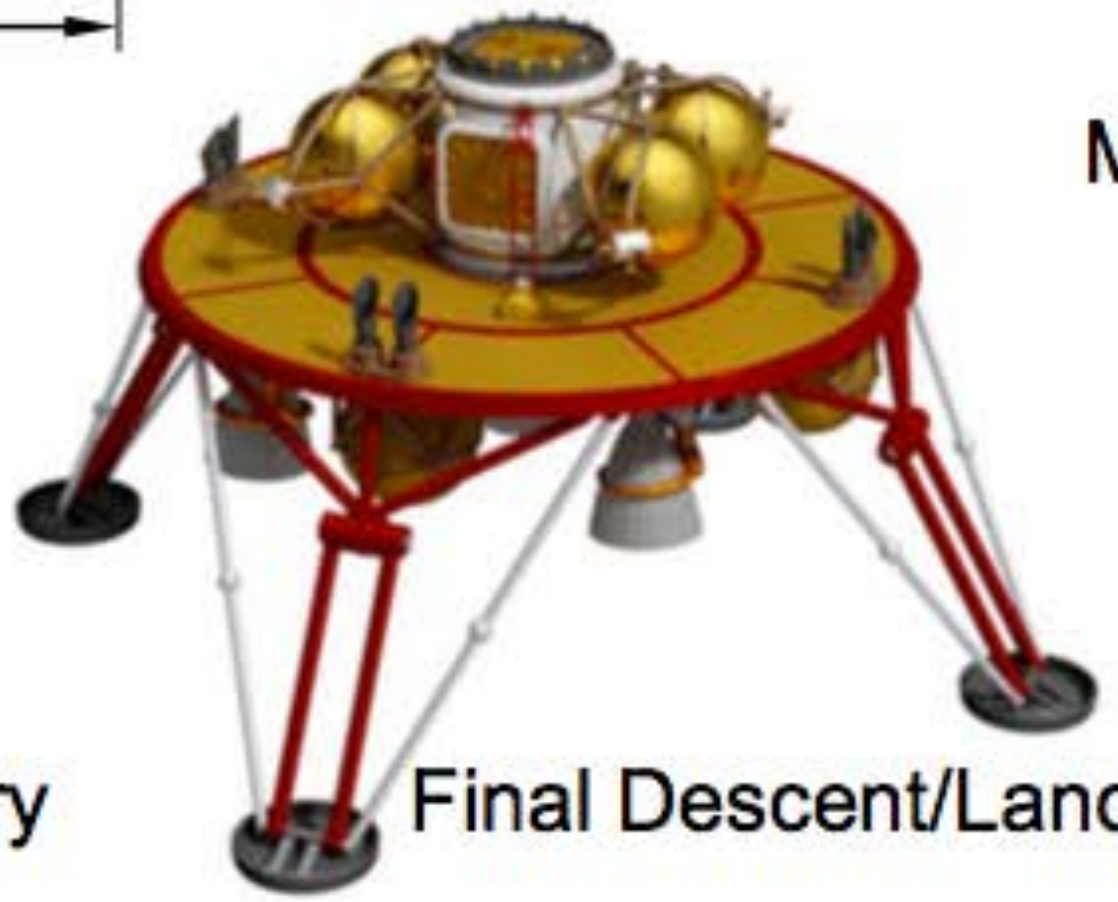




MAV Ascent

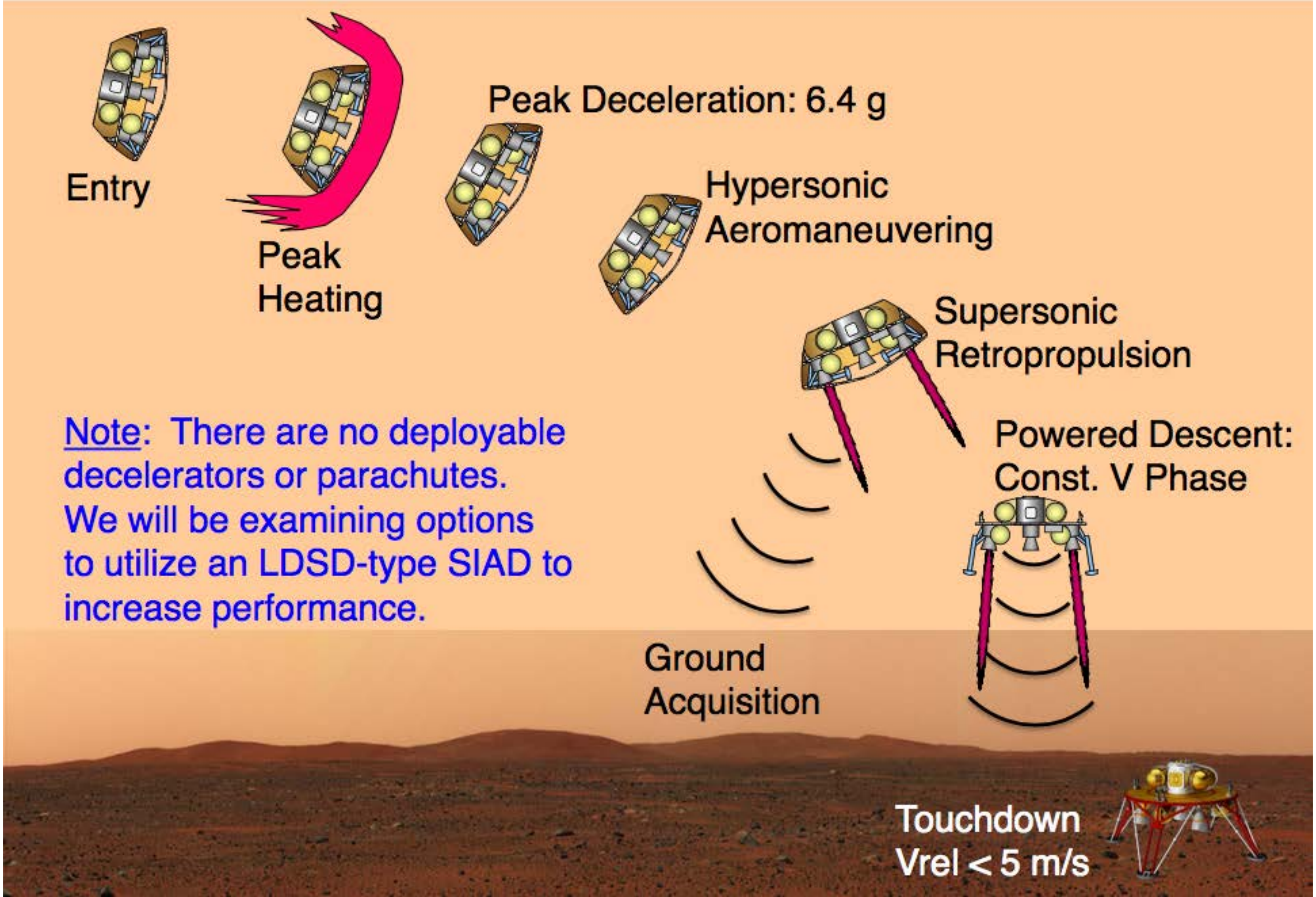
Launch

Cruise/Crew Transfer/Entry



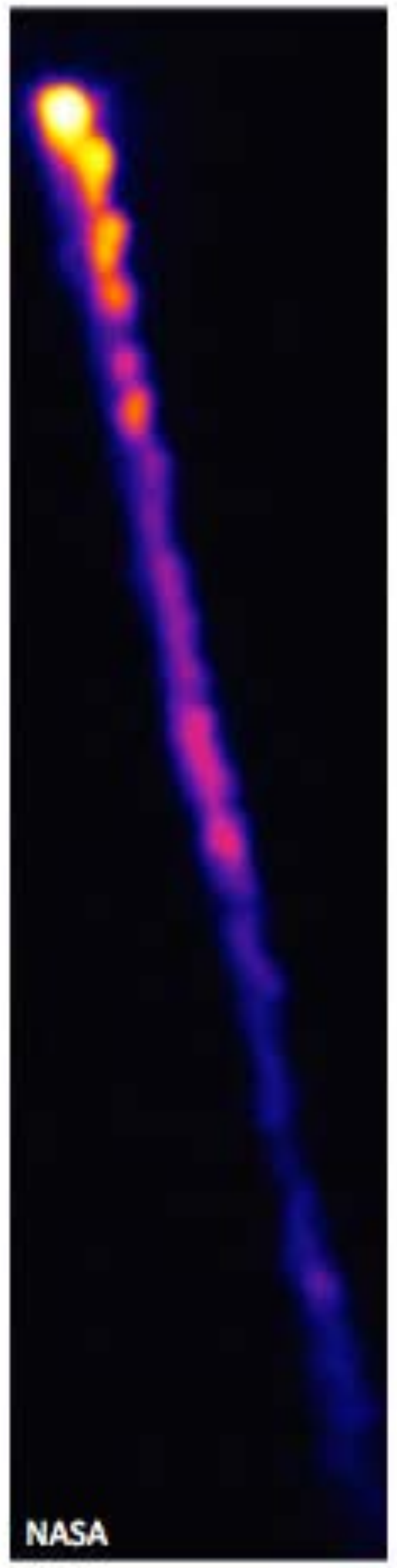
Final Descent/Landing

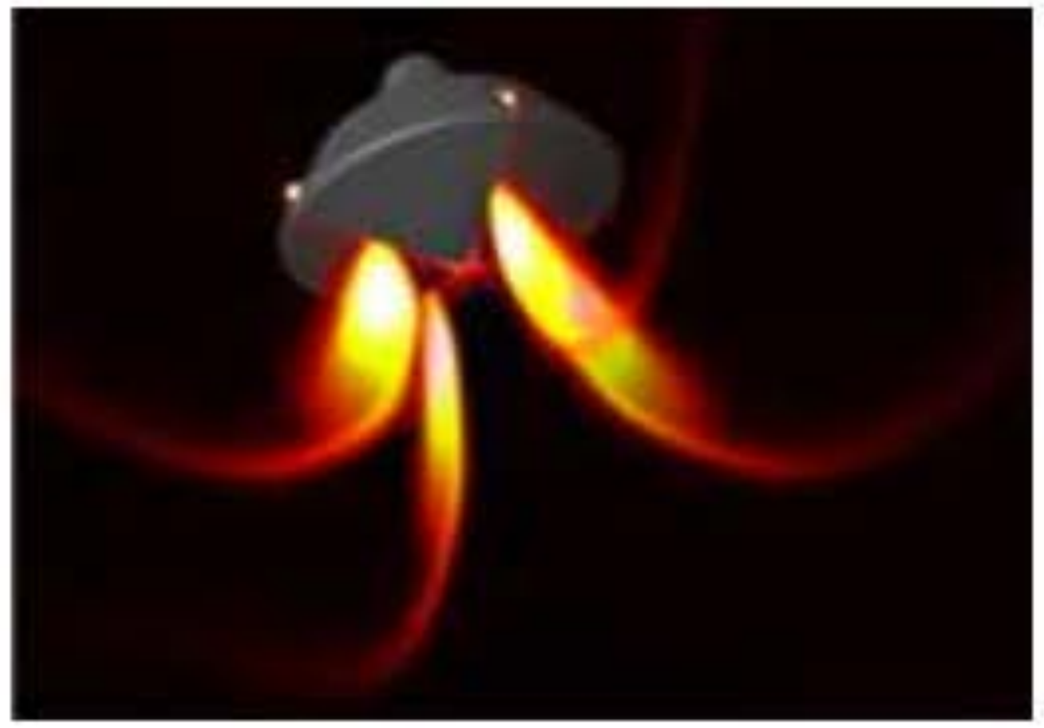
EDL Concept for Blunt Body Mars Lander



Supersonic Retro-Propulsion (SRP)

- Mars landers to date have used subsonic retro-propulsion
- Analyses have indicated the need for SRP for landing large payloads on Mars
- CFD analysis and wind tunnel tests have been performed, and now SRP data utilizing actual flight data has become available from Space X Falcon 9 stage recovery flights
  - 7 flights have been conducted with a portion of the flight regime being analogous to Mars atmospheric conditions





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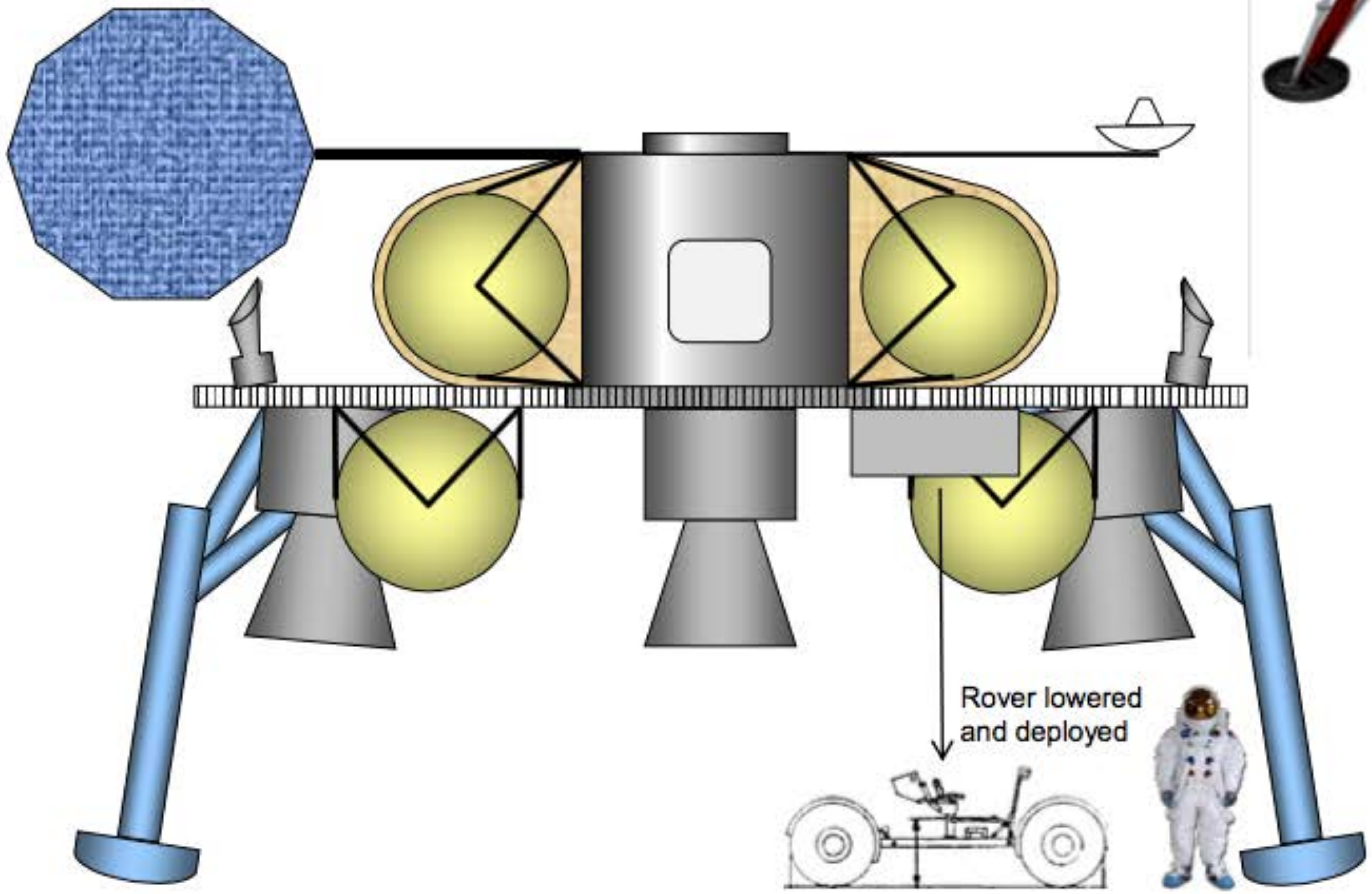
Landed Configuration



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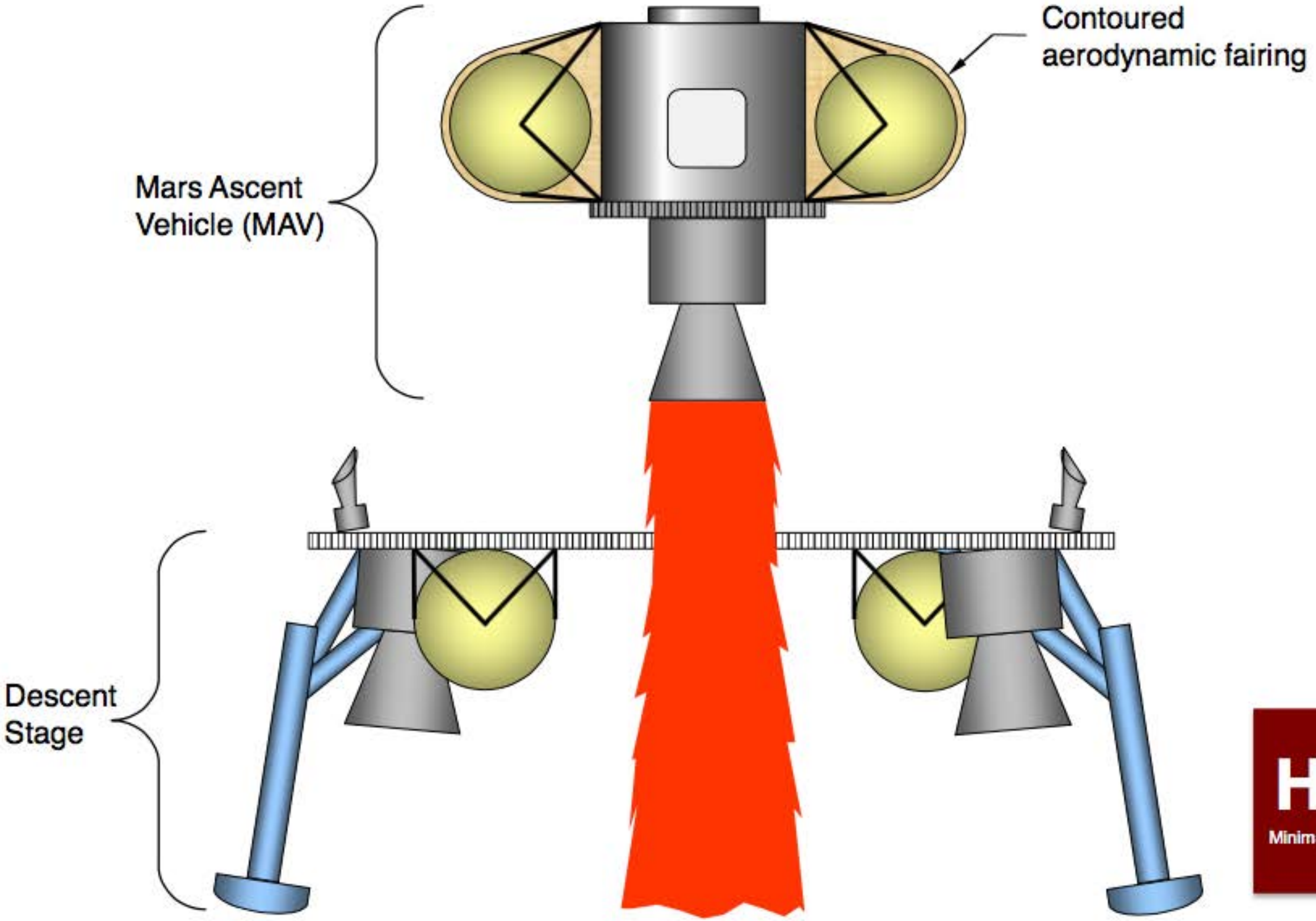
MAV Separation and Ascent



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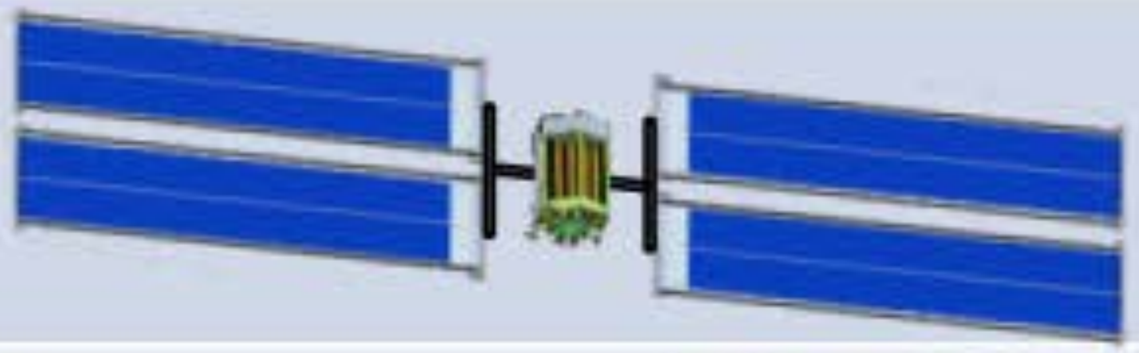
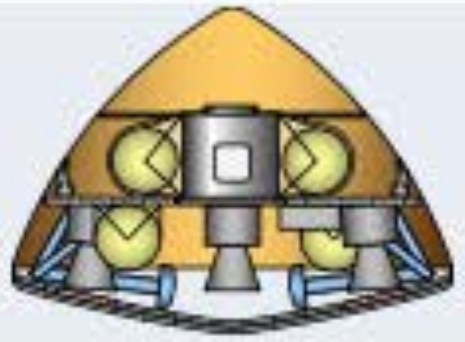
Vehicles to Enable Crewed Missions to Mars Surface (Short Stay)

Vehicles		# Vehicles per Mission
Orion		1
SLS		6
SEP Tug		2
Deep Space Habitat		2
In-Space Chemical Propulsion Stages		3
Mars Lander		1

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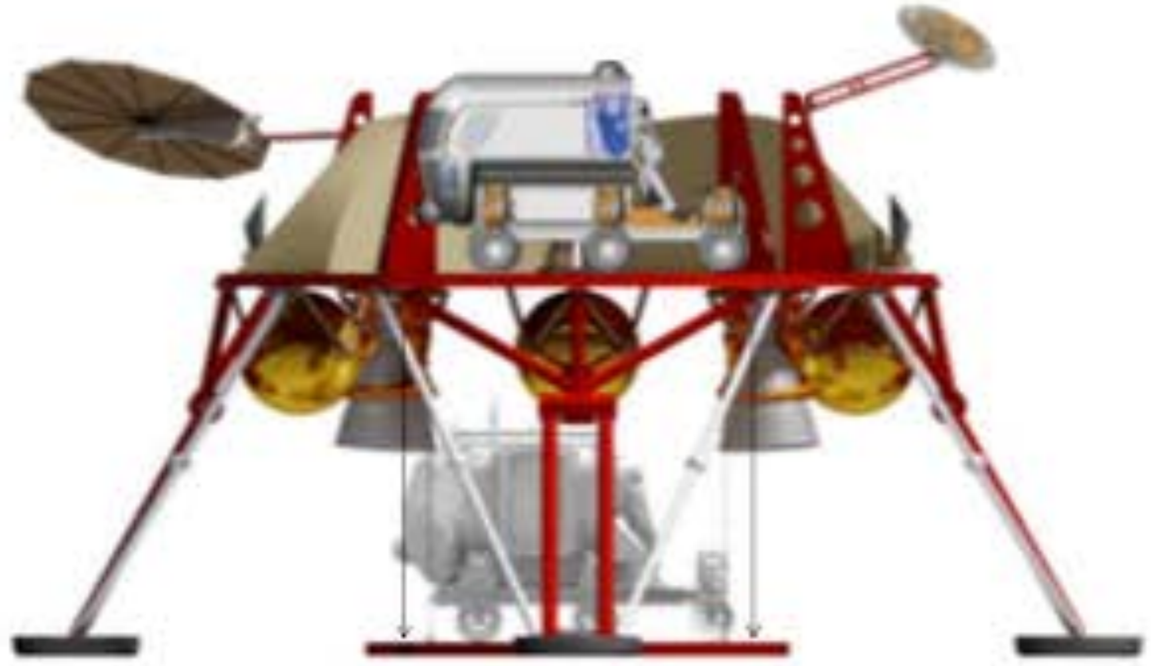
Toward a Permanent Presence

- Follow-on missions would have 1 year surface stays supported by a habitat and other supplies
  - Same descent stage design as crewed lander
  - Would support a landed crew of 4
  - Infrastructure would be built up on Mars to provide power, ISRU, food production, and increasing habitable volume
- The Mars program would evolve a reusable transportation architecture between Earth and Mars with an increased flight rate
- With an in-situ water source on Mars, a permanent presence with an Antarctica-type population could be achieved



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