Entry, Descent and Landing Technology Advancement

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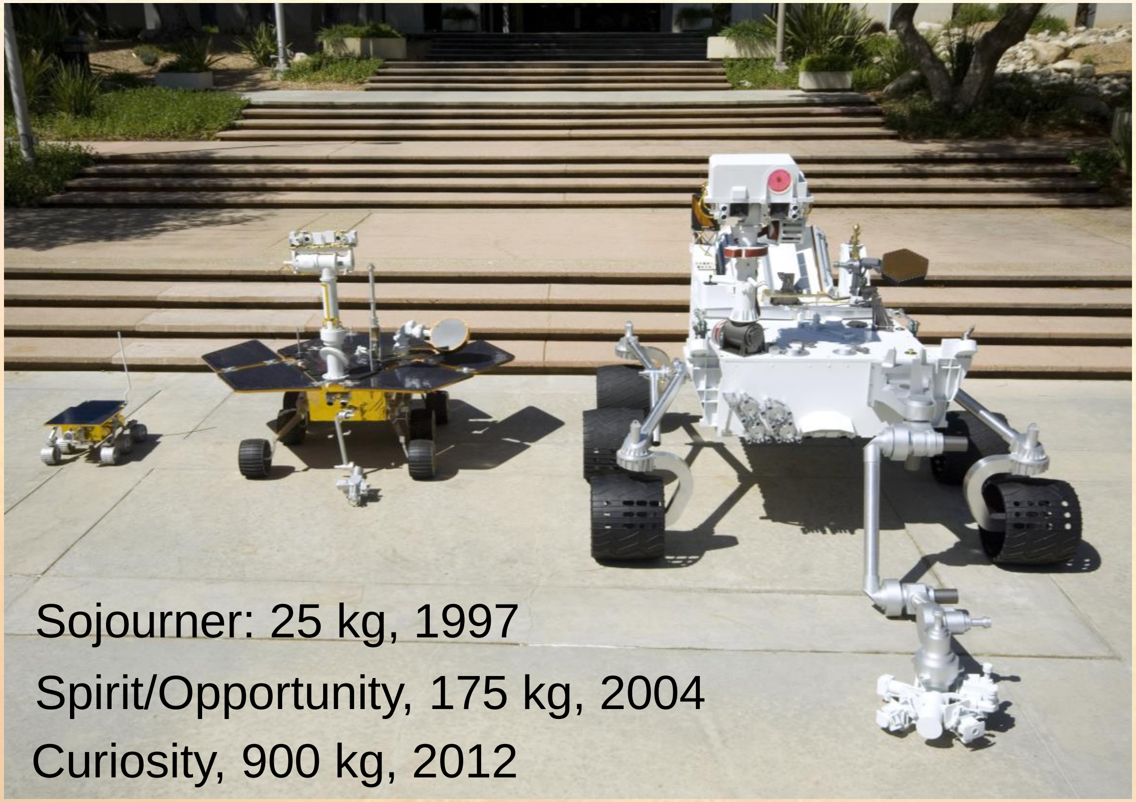
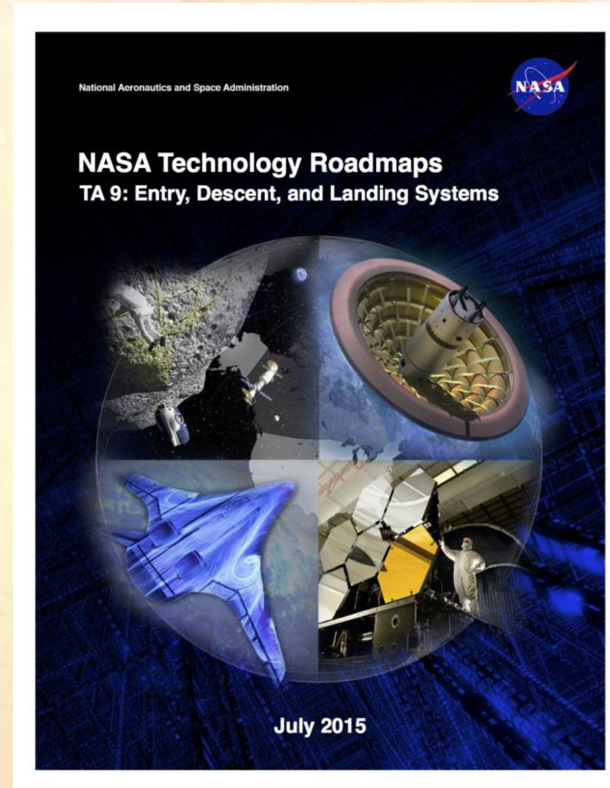
May 2, 2017

EDL Technology Investments Have Enabled Seven Increasingly-Complex Successful U.S. Landings on Mars





These missions & associated tech development have enabled growth of EDL community

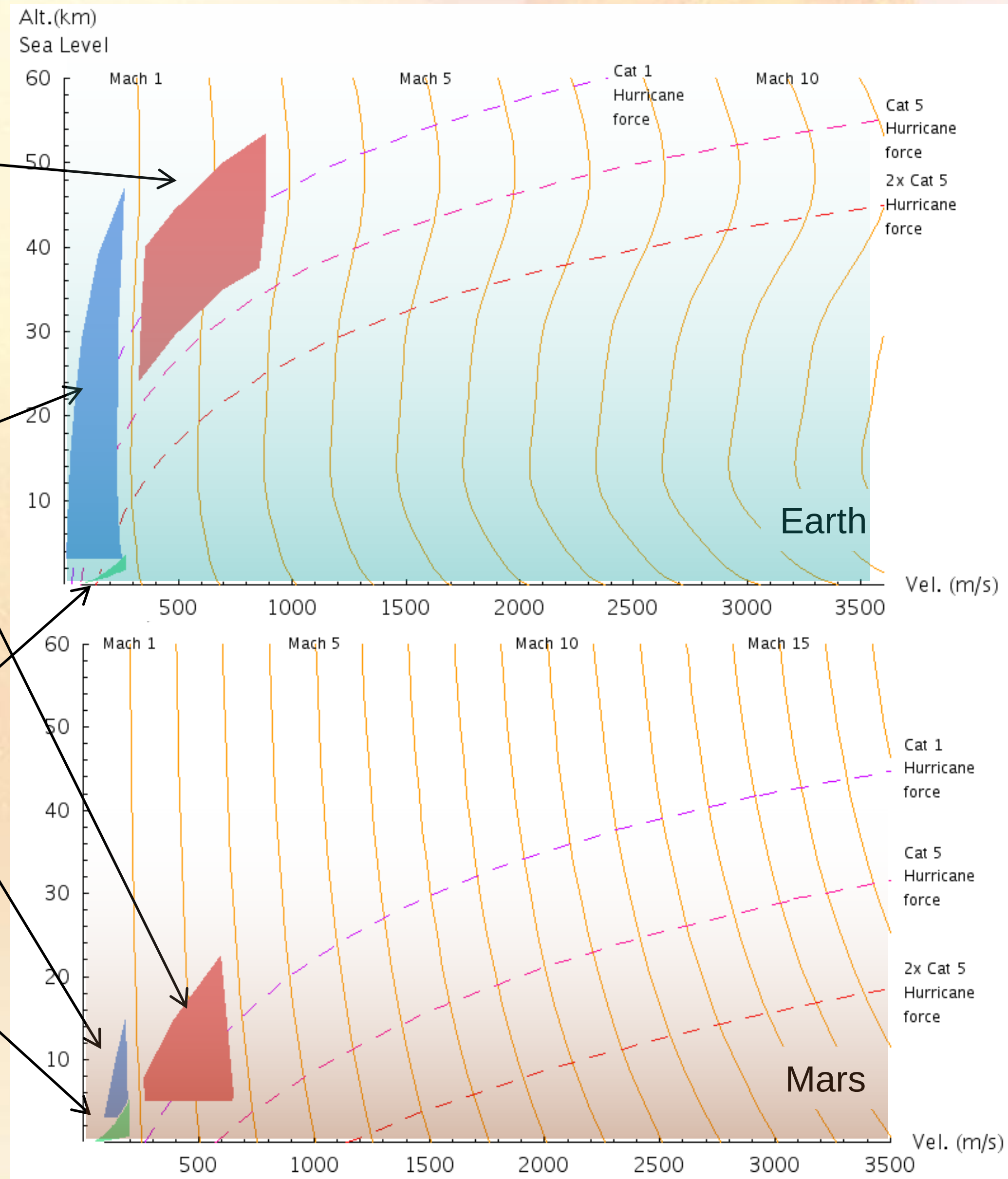
- 1992: For planetary missions, NASA couldn't spell EDL
- 2010: NASA included EDL as one of fourteen critical technologies domains
- 2017: Over 100 core technical community members primarily at NASA (Ames, JPL, JSC, and LaRC), LMSS, SpaceX, and academia; several hundred who touch EDL in some way; modest and challenged set of test facilities

EDL Phase Space: Another Way to View the Timeline and Deceleration Challenges of Landing on Mars

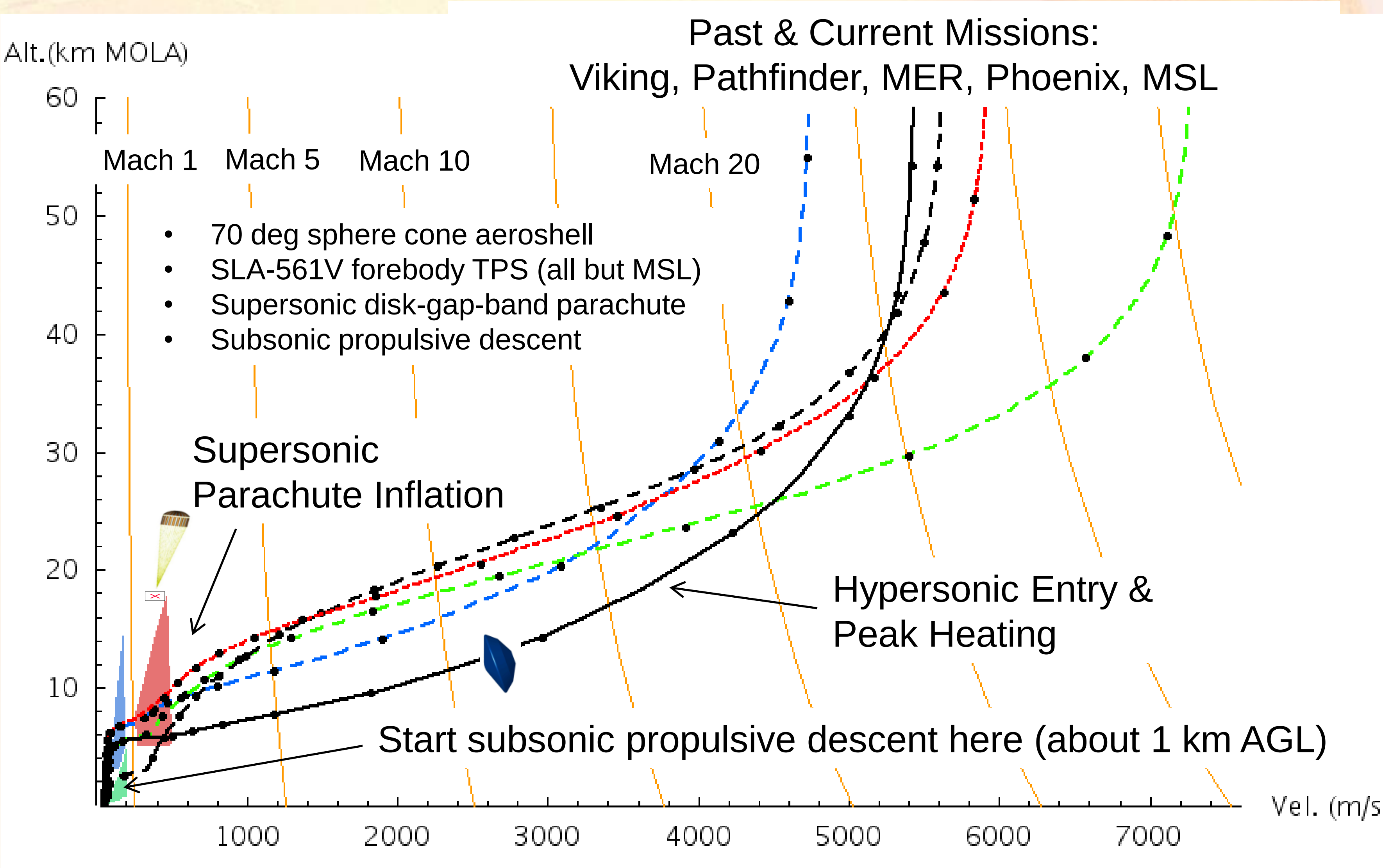
Supersonic parachute inflation Mach - dynamic pressure box (red region)

Subsonic parachute inflation "Mach - dynamic pressure box" (blue region)

Subsonic propulsion "Mach - thrust/weight - 3 g box" (green region)

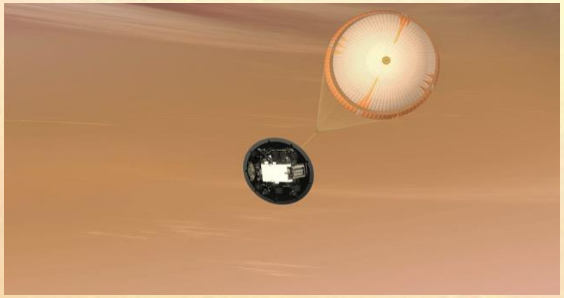


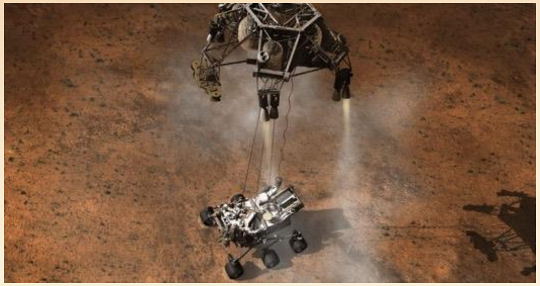
For Four Decades, We Have Built Upon and Evolved EDL Technology Initially Matured Prior to Viking



Note: Black dots are on 10 sec. centers.

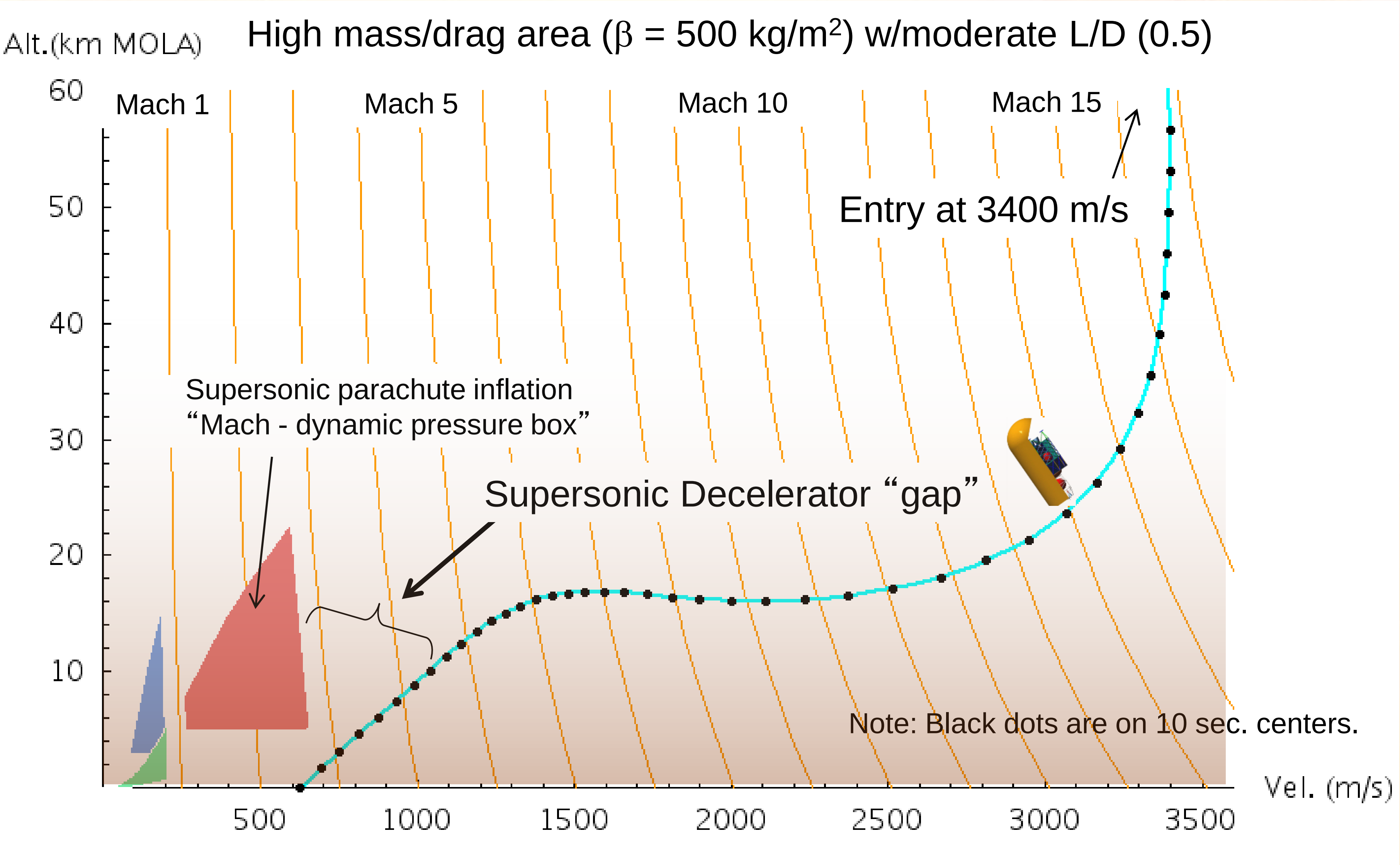
MSL EDL Stretched Viking-Era Technologies About As Far As Possible in Terms of Landed Mass





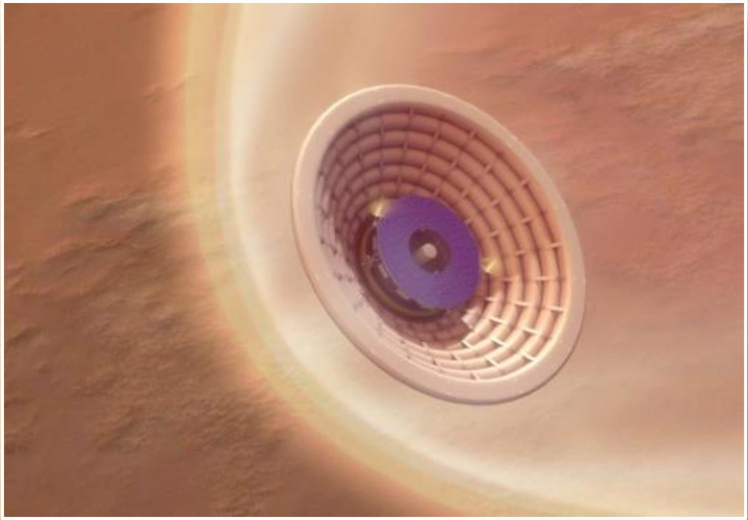
- **Sky-crane descent and landing architecture**
- **Largest entry mass (~3.7 t), payload mass (~1 t) and ballistic coefficient (145 kg/m^2) ever flown to Mars**
  - The largest aeroshell (4.5m diameter) ever flown
  - Highest aerothermodynamic environment ever designed for at Mars (margined at ~250 W/cm^2)
  - First Mars use of PICA TPS material
  - First hypersonic aeromaneuvering at Mars (atmospheric guidance with bank-angle control to adjust altitude and reduce landed footprint to ~20km)
  - Largest DGB parachute (21.5m diameter) ever flown
  - Highest chute deploy Mach number (2.2) ever designed for at Mars
  - First flight of new, high-capability radar system
  - First flight of new MLE

Unlike at Earth (Shuttle/Apollo experience), High Mass (β) Entry Systems Don't Close at Mars

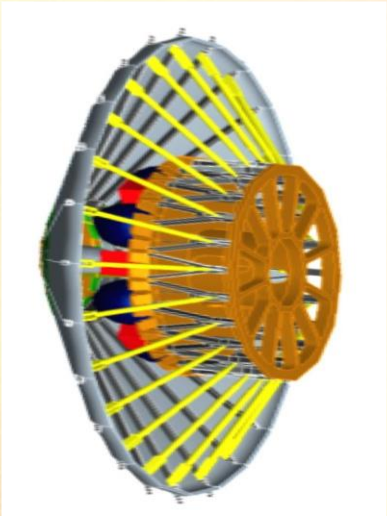


Braun, R.D. and Manning, R.M.; "Mars Entry, Descent and Landing Challenges," *Journal of Spacecraft and Rockets*, Vol. 44, No. 2, 2007.

EDL Technology Being Evaluated To Potentially Address This Performance Gap

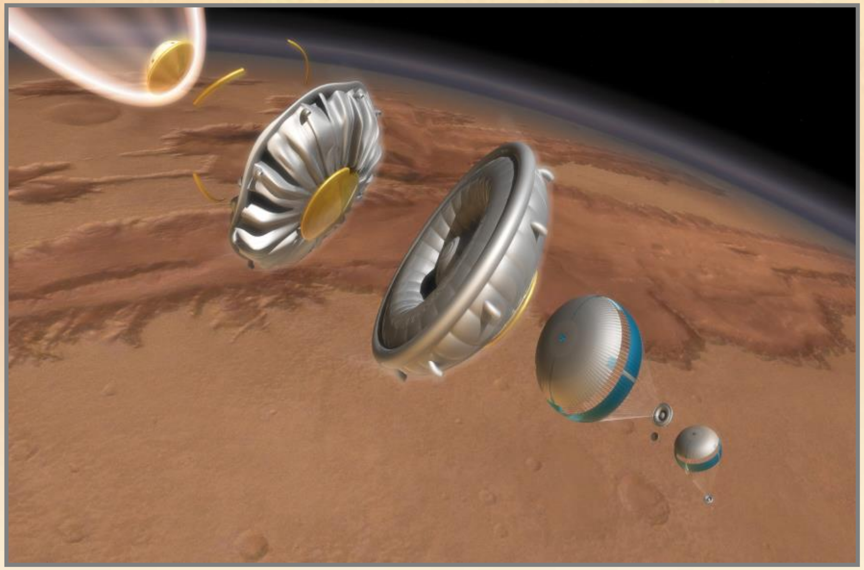


Hypersonic Inflatable Aerodynamic Decelerators

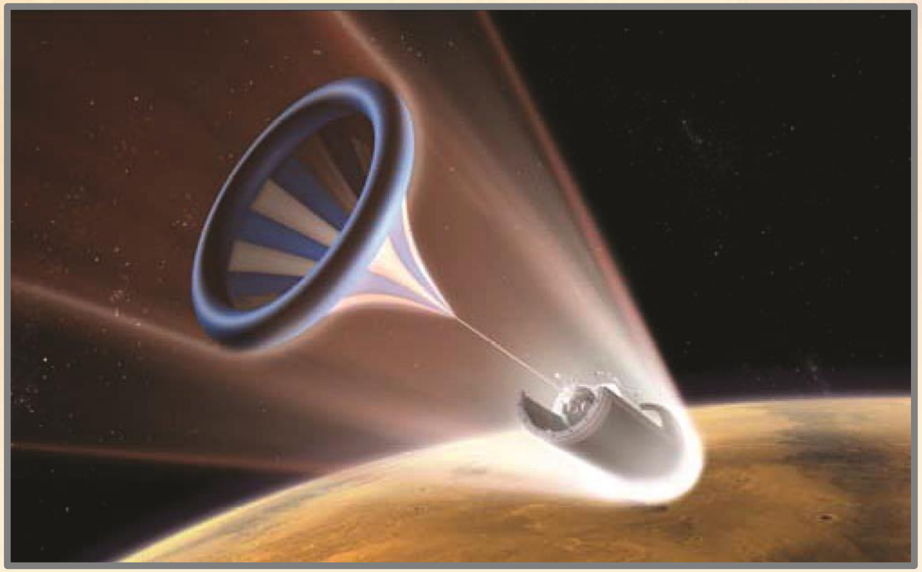


Deployable Entry Systems

Supersonic Retropropulsion Test

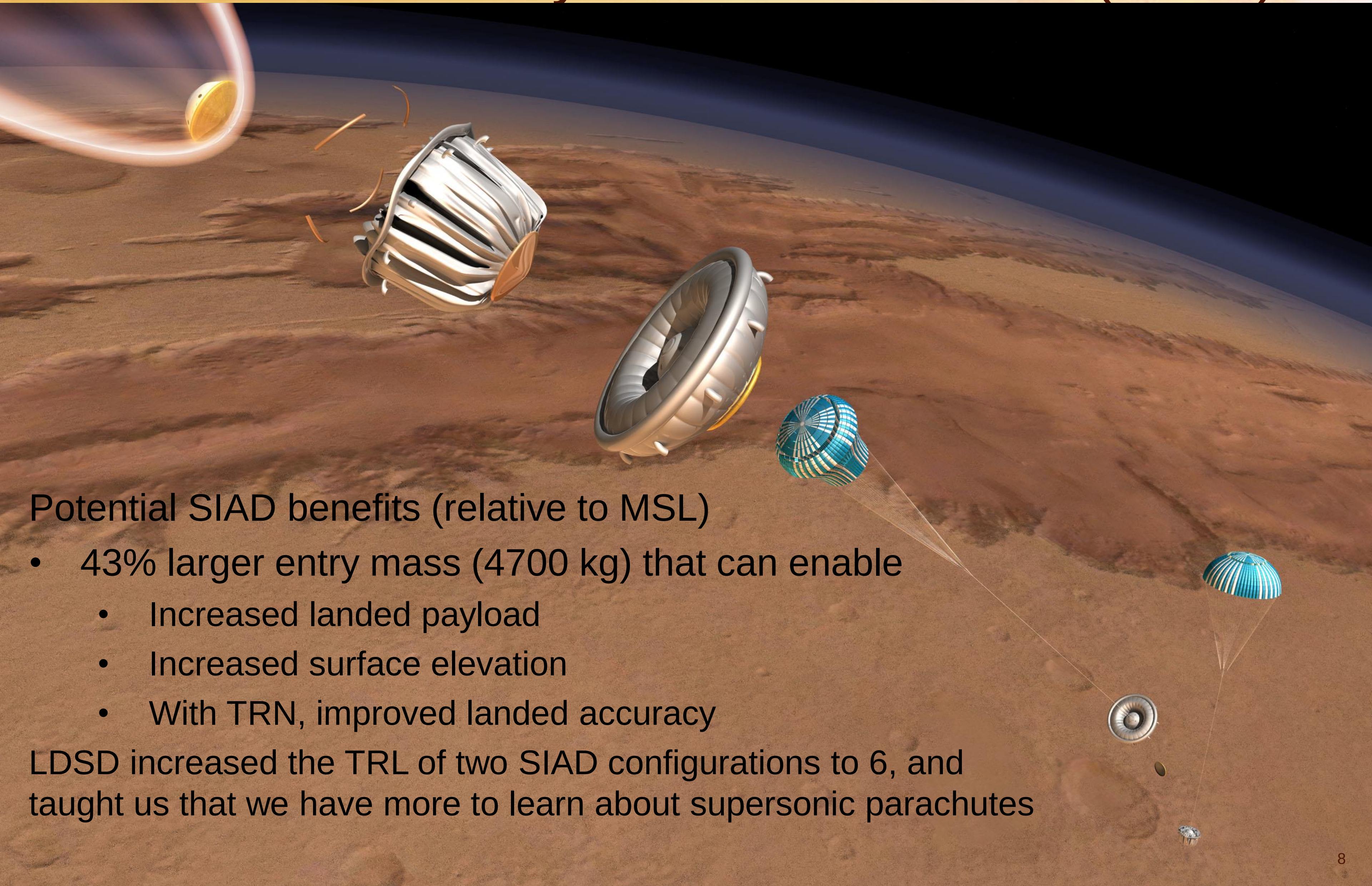


Supersonic Inflatable Aerodynamic Decelerators



Slender Body Entry Systems

EDL Sequence Employing a Supersonic Inflatable Aerodynamic Decelerator (SIAD)



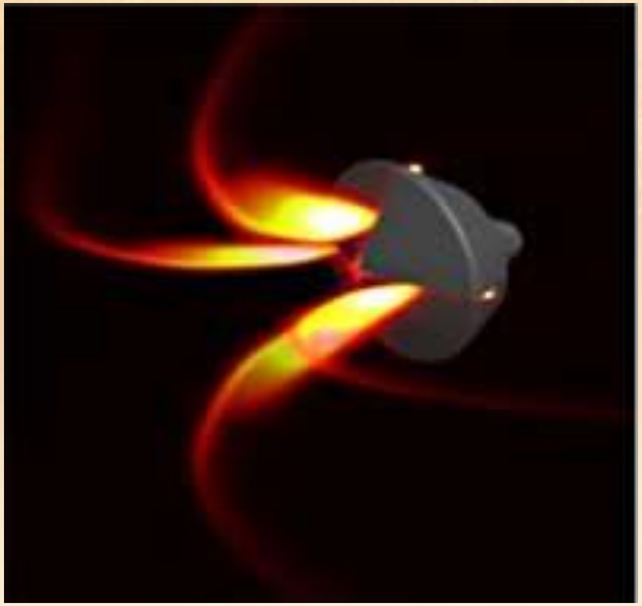
Potential SIAD benefits (relative to MSL)

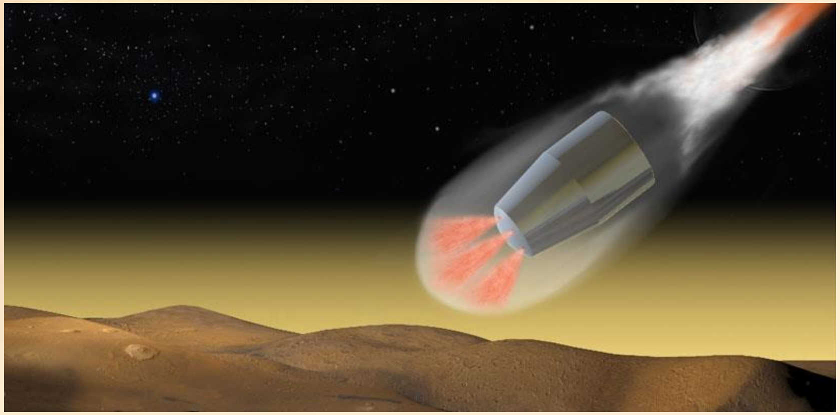
- 43% larger entry mass (4700 kg) that can enable
  - Increased landed payload
  - Increased surface elevation
  - With TRN, improved landed accuracy

LDSD increased the TRL of two SIAD configurations to 6, and taught us that we have more to learn about supersonic parachutes

Supersonic Retropropulsion (SRP)

- All previous U.S. Mars landers have used propulsion to decelerate subsonically as the surface is approached.
- Supersonic retropropulsion initially investigated experimentally in the 1960s and 1970s; technology development ceased when not baselined by Viking.
- Interest resurfaced in ~2005 when systems analyses demonstrated the potential benefits of SRP for landing large mass payloads on Mars.
- In 2013, a NASA effort to advance SRP technology was initiated; at this time, no rocket engine had ever been fired into an opposing supersonic freestream.

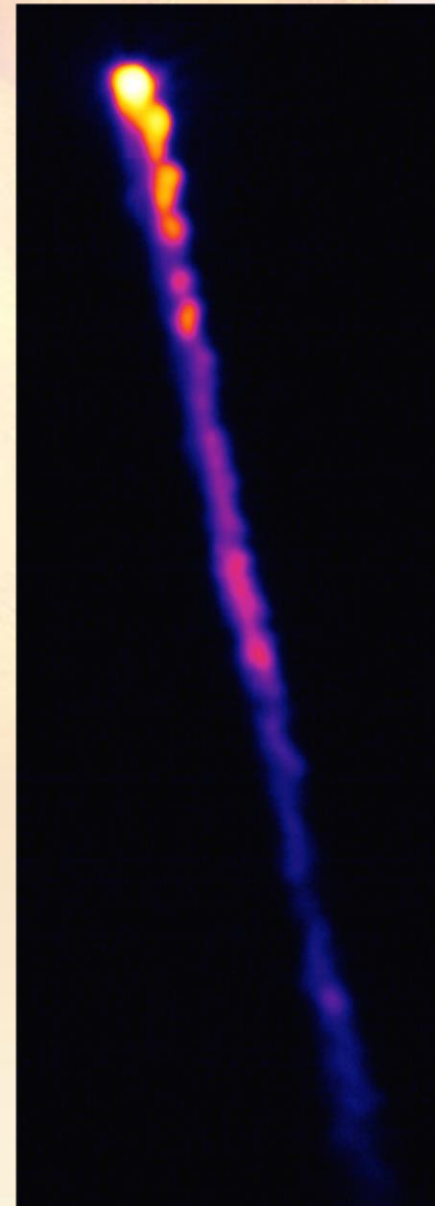




SpaceX Has Demonstrated Mars Supersonic Retropropulsion on Every First Stage Recovery Flight Since September 2013

Sept 29, 2013: SpaceX modulated first-stage reentry environment with supersonic retropropulsion for first time

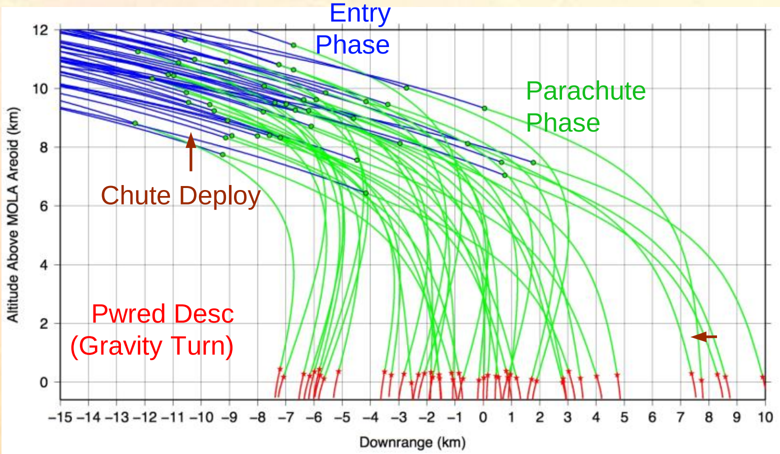
- This maneuver occurs at a high altitude in Earth's atmosphere in Mars-relevant conditions
- Space X has now successfully completed dozens of flights with a Mars-relevant SRP phase



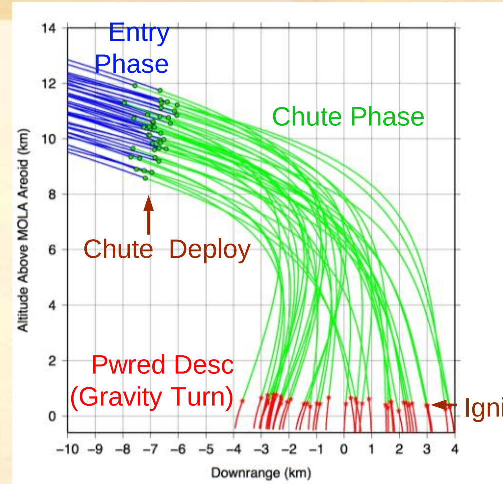
2014-2016: NASA, SpaceX and GT worked together to extract Mars-relevant insights from this unique data set

- Independent reconstruction of SRP phase of multiple first-stage recoveries showed no significant anomalies
- Several technical papers planned for AIAA Space 2017

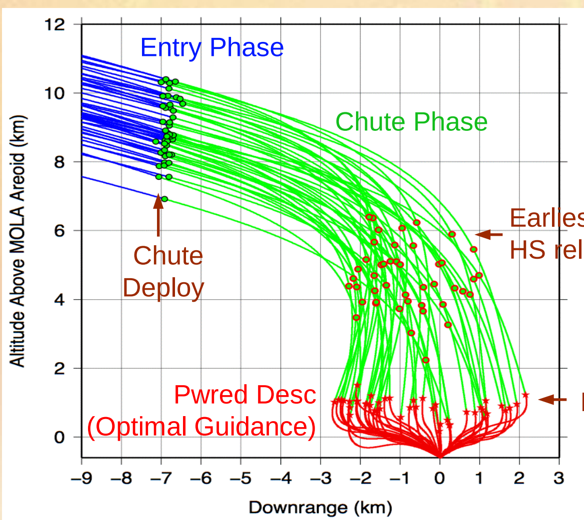
Landing Accuracy Technology Options



MSL ~**10km** from target



Improved chute deploy strategy + improved entry attitude knowledge **~3 - 4km** from target

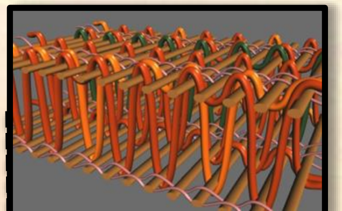


Add terrain-relative nav + powered descent guidance **≤~100m** from target (Mars 2020 anticipated performance)

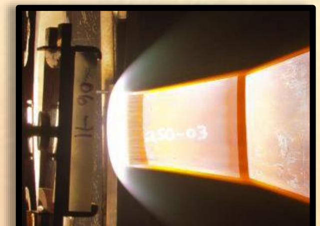
- Entry Guidance & Smart Chute applicable to Mars, Earth, Titan, Venus and other planetary bodies with an atmosphere
- TRN applicable to Mars, Europa, our Moon and other imaged planetary surfaces

Results courtesy A. Wolf, JPL

3D Woven Thermal Protection System (TPS) Development



Woven TPS CIF



Woven TPS GCT BAA

3D Woven Multifunctional Ablative TPS (3D-MAT)

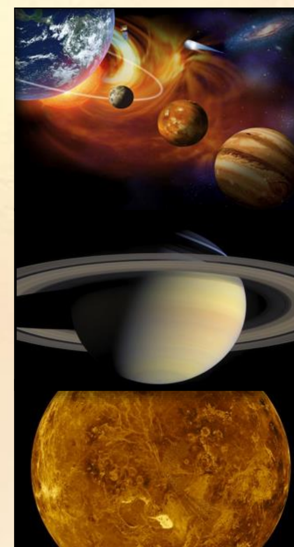
Enabling Orion with Lunar Capable Compression Pad

2018: Lunar

Heat-shield for Extreme Entry Environment Technology (HEEET)

Tech. Maturation to enable Venus, Saturn and outer planets missions

Discovery and NF-4 AO Incentivized



2020 - 2024

Robust heatshield for return of Mars samples

2024+

March 2011 | **Jan 2012** | **June 2012** | **Oct 2013** | **Sept 2018**

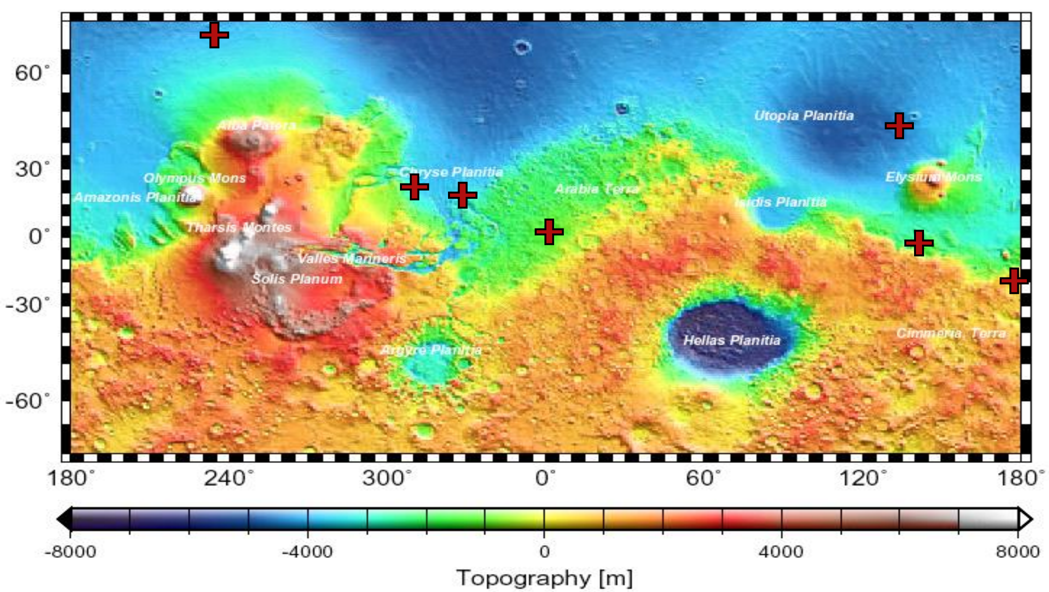
- Specific woven TPS solution baselined for the Orion compression pad for the lunar flight (EM-1)
- HEEET on track to achieve TRL 6 by FY19 for potential New Frontiers mission (launch in early 2020s).

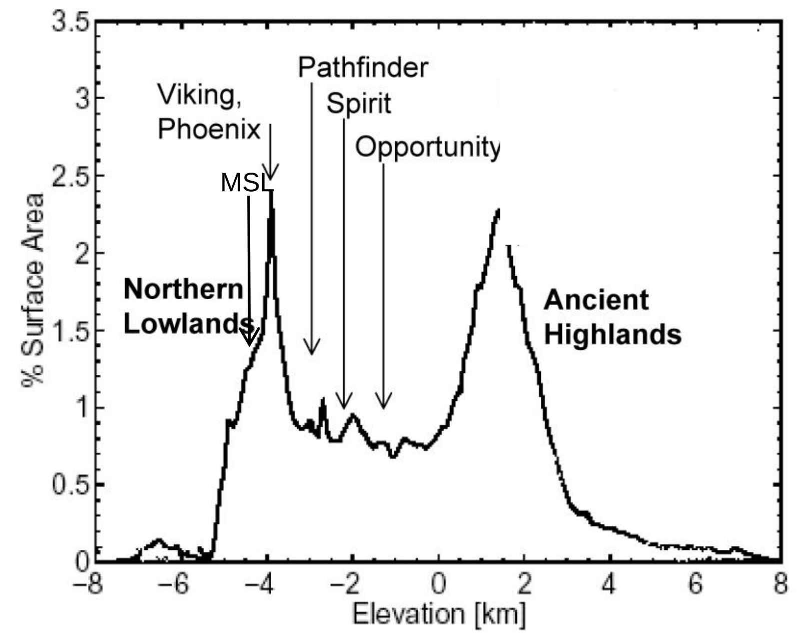
Summary

- EDL technology readiness
  - The EDL community has grown, innovated and made great strides evolving Viking-era technology for robotic missions.
  - Continued innovation in EDL technology is critical for future mission success
- Significant investment is required to achieve the Mars EDL capabilities required for high-mass robotic and human exploration missions. NASA is just beginning to invest the funds required.
  - Mars human exploration EDL systems will have little in common with current and next-decade robotic systems
- Promising technologies include:
  - Inflatable/deployable aerodynamic decelerators that greatly reduce β
  - Pinpoint landing technologies using terrain-relative navigation
  - Lightweight, flexible thermal protection systems
  - Supersonic retropropulsion
- These capabilities are also applicable to missions at other destinations (Titan, Venus) and are synergistic with the needs of industry and government organizations for a wide range of Earth applications.

Backup

Seven Successful U.S. Mars Landings

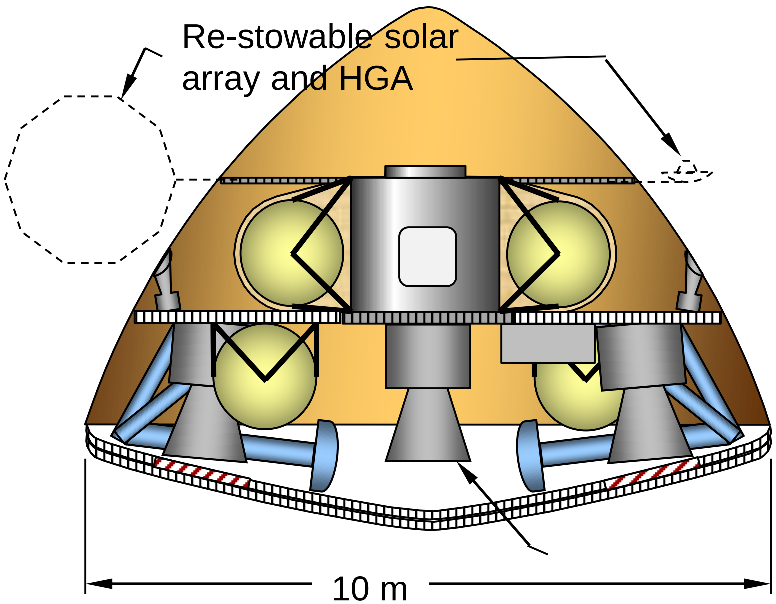


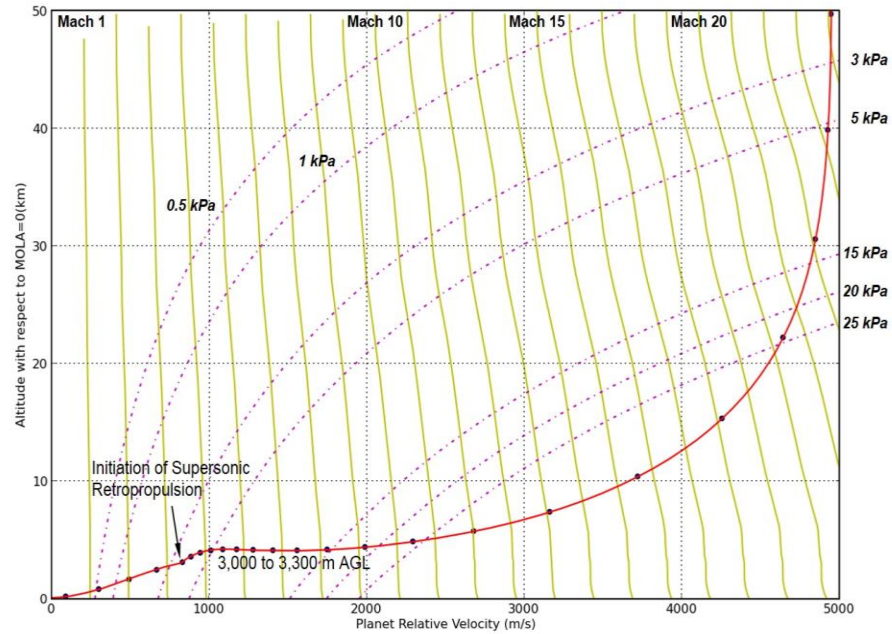


- For landed masses below 900 kg at surface elevations below -1.4 km (MOLA)
- For 4 decades, we have built upon & evolved EDL technology matured prior to Viking
  - SLA-561V forebody TPS (all but MSL)
  - 70 deg sphere cone aeroshell
  - Supersonic disk-gap-band parachute

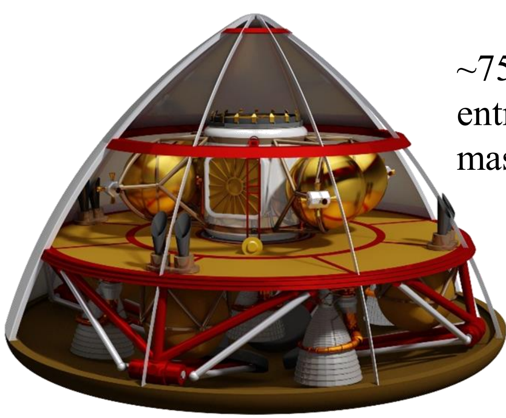
Human-Scale Blunt Body SRP System

Sized to support small crew for 2-4 weeks; other assets augment performance





Launch/Cruise/Entry



~75t entry mass

Descent/Landing

~28t landed mass

Ascent

Price, H.W.; Braun, R.D.; Manning, R.M.; and Sklyanski, E.; “A High-Heritage Blunt-Body Entry, Descent, and Landing Concept for Human Mars Exploration,” AIAA 2016-0219, 2016 AIAA Science and Technology Forum and Exposition, San Diego, CA, January 2016.

Landing Footprint Improvement