EXPLORESPACE TECH

TECHNOLOGY DRIVES EXPLORATION

LAND: Enable Lunar/Mars Global Access and ~20t Payloads
NASA Space Technology Mission Directorate

STMD welcomes feedback on this presentation. Please visit https://techport.nasa.gov/framework/feedback
if you have any questions or comments regarding this presentation.

EDIT Log

(Page numbers are referred to original (without this slide))

- Cover – did not change, but recommend changing 20t to "25t+" (Troutman)
- Changed references to 20t to "25t+" throughout presentation (Troutman)
- P3 – added “Engine development” to Retropropulsion (Aerojet & LM)
- P9 – deleted MEDLI-3 from instrumentation and added to PSI (JPL)
- P11 – added “Engine development to meet performance requirements” to fourth step (Aerojet)
- P12 – added “including subsurface effects” to final bullet (Astrobiotic)
- P12 – added “transport and damage due to” in the 3 main areas top left (Metzger)
- P12 – added "sensor spoofing" to the main areas top left (Mueller)

Entry, Descent and Landing (EDL) Definition

- Process of delivering a vehicle from the top of an atmosphere to the surface and landing safely
- For bodies without an atmosphere, sequence referred to Deorbit, Descent and Landing (DDL)
- Three phases of atmospheric flight
  - Entry – Hypersonic flight: Decelerate, dissipate heat, guide to the target
  - Descent – Supersonic flight: Engage additional deceleration (parachutes/engines)
  - Landing – Subsonic flight: Sense the surface, expose landing hardware and reduce engine thrust for touchdown
- EDL is a critical mission phase, with extreme environments and complex dynamics, that cannot be fully tested end-to-end on Earth
- To date, all US Mars landings have utilized the same EDL technology developed for the Viking missions: rigid, 70˚ sphere-cone aeroshells and supersonic parachutes – suitable for < ~2t landed

Photo Credits: NASA/JPL-Caltech

LAND: Enable Lunar/Mars global access and ~25t+ payloads to support Mars human surface missions.

Developing landing capabilities that support unique requirements for both the Moon and Mars, to allow for landing greater payload capacity with greater accuracy

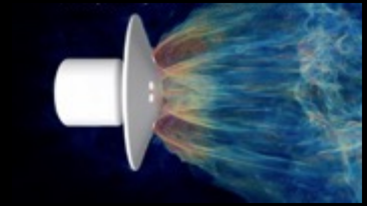
LUNAR CAPABILITIES (FEEDING FORWARD TO MARS)

Precision Landing and Hazard Avoidance

Safely and precisely land near science sites or pre-deployed assets *(see details in separate package)*

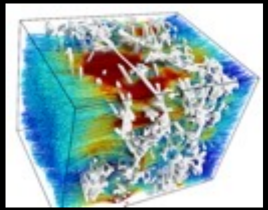
Retropropulsion

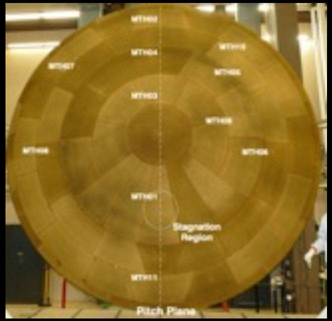
Understand flow physics and vehicle control through wind tunnel testing of Mars-relevant configurations; advance CFD and engine development



Plume Surface Interaction

Reduce risks to landers and nearby assets by understanding how engine plumes and surfaces behave





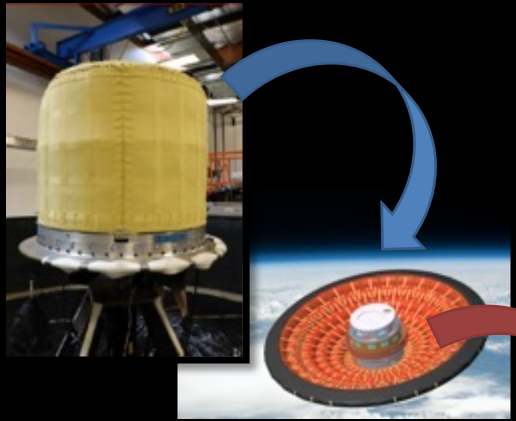
Foundational Modeling, Testing, Instrumentation, and Computing

Measure EDL flight system performance and update/develop unique, critical simulations for EDL/DDL systems

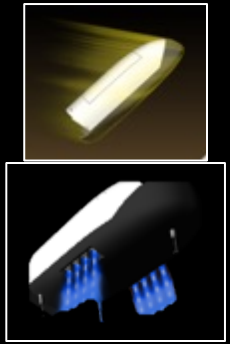
MARS CAPABILITIES

Large Scale Demonstrations

Large structures, including deployables, that can slow down a 25t+ payload in the thin Mars atmosphere

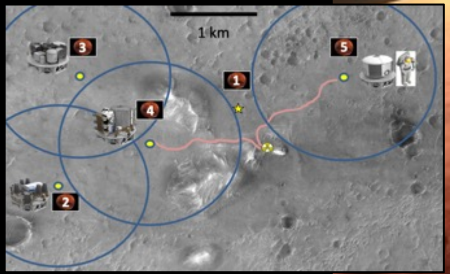


Earth Flight Tests, such as LOFTID



Assess Alternatives

Aggregate Assets

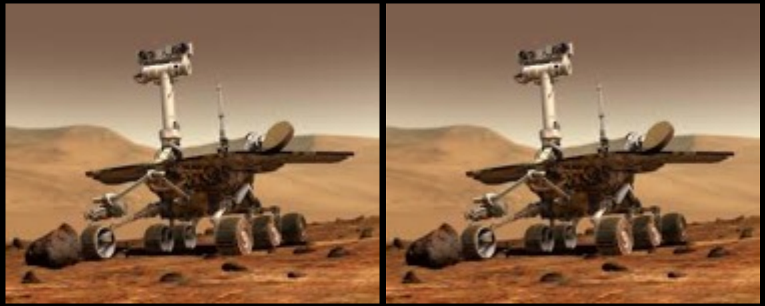


Human Mars EDL

NASA’s Mars Landing Missions – State-of-the-Art

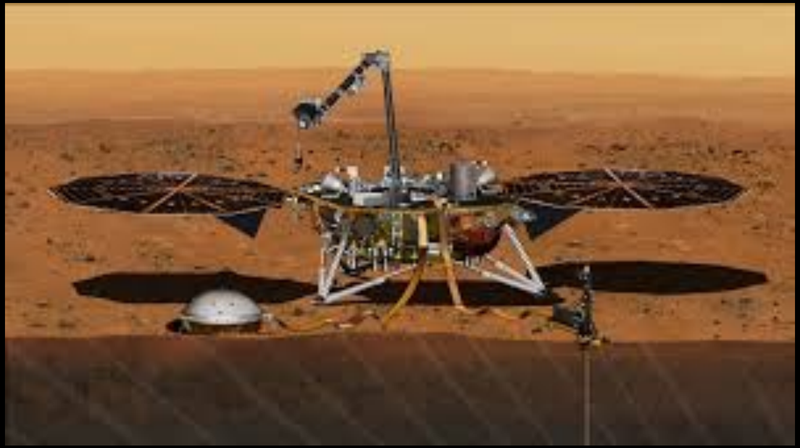
Photo Credit: NASA

Viking 1 & 2
1976
(600 kg)



Spirit and Opportunity – 2004 (539 kg)

Phoenix – 2008 (364 kg)



InSight – 2018 (375 kg)

Pathfinder
1996
(360 kg)

Curiosity – 2012 (899 kg)

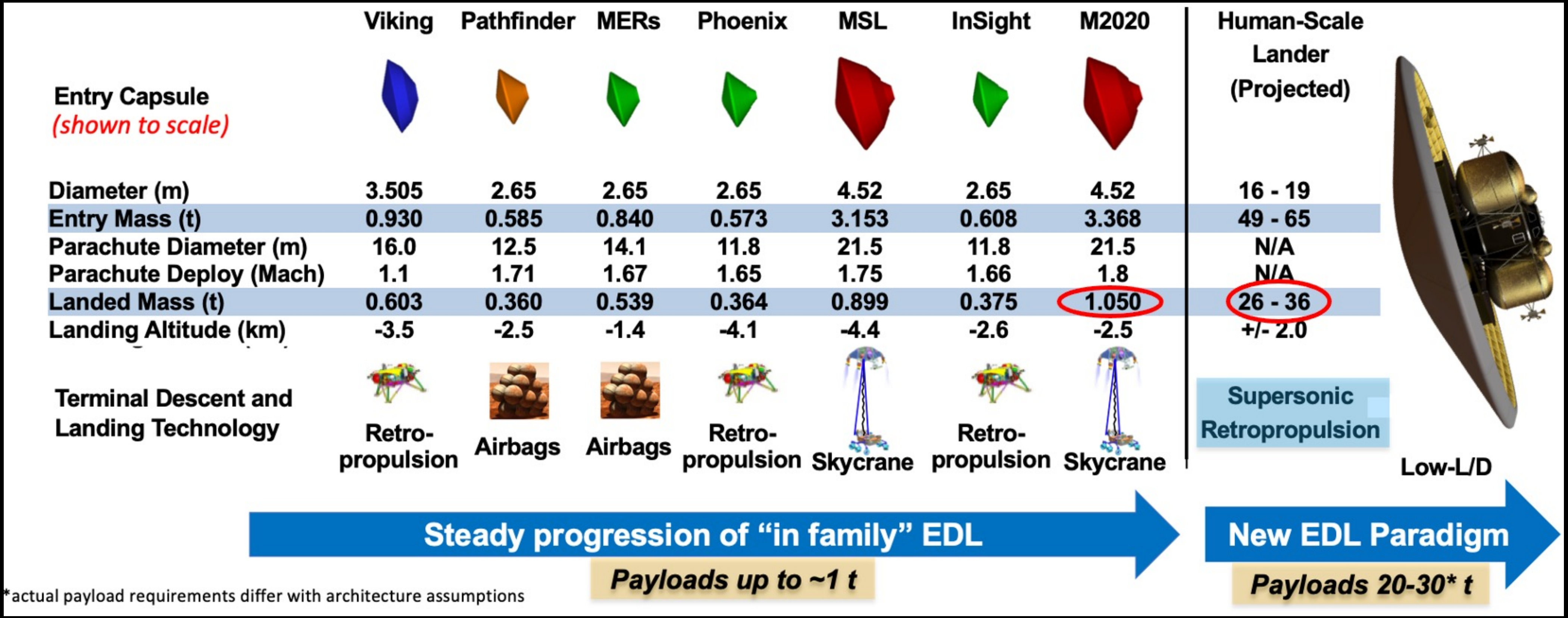
Mars 2020 – Perseverance (1,050 kg)

Artist Concept Credits:
NASA/JPL-Caltech

Landing 25t+ on Mars Requires A Leap in Scale and Capability

Represents a 20-30x increase over the SOA in delivered mass capability

- Viking-derived rigid sphere-cone aeroshells with cross sections that fit in a launch vehicle shroud are not large enough to decelerate heavy payloads in the thin Mars atmosphere – a larger entry system is needed (“E”)
- Supersonic parachutes cannot be used; high-speed propulsive descent is enabling (“D”)
- Precise Lunar landings require and will demonstrate integrated GN&C for the landing and prediction/knowledge of large-engine plume surface interaction (PSI) effects. Both feed forward to large Mars missions (“L”)
- Robust guidance and control throughout entry and descent is required for safe, precise landing (“EDL”)



	Viking	Pathfinder	MERs	Phoenix	MSL	InSight	M2020	Human-Scale Lander (Projected)
Entry Capsule *(shown to scale)*								
Diameter (m)	3.505	2.65	2.65	2.65	4.52	2.65	4.52	16 - 19
Entry Mass (t)	0.930	0.585	0.840	0.573	3.153	0.608	3.368	49 - 65
Parachute Diameter (m)	16.0	12.5	14.1	11.8	21.5	11.8	21.5	N/A
Parachute Deploy (Mach)	1.1	1.71	1.67	1.65	1.75	1.66	1.8	N/A
Landed Mass (t)	0.603	0.360	0.539	0.364	0.899	0.375	1.050	26 - 36
Landing Altitude (km)	-3.5	-2.5	-1.4	-4.1	-4.4	-2.6	-2.5	+/- 2.0
Terminal Descent and Landing Technology	Retro-propulsion	Airbags	Airbags	Retro-propulsion	Skycrane	Retro-propulsion	Skycrane	Supersonic Retropropulsion

Steady progression of “in family” EDL

Payloads up to ~1 t

New EDL Paradigm

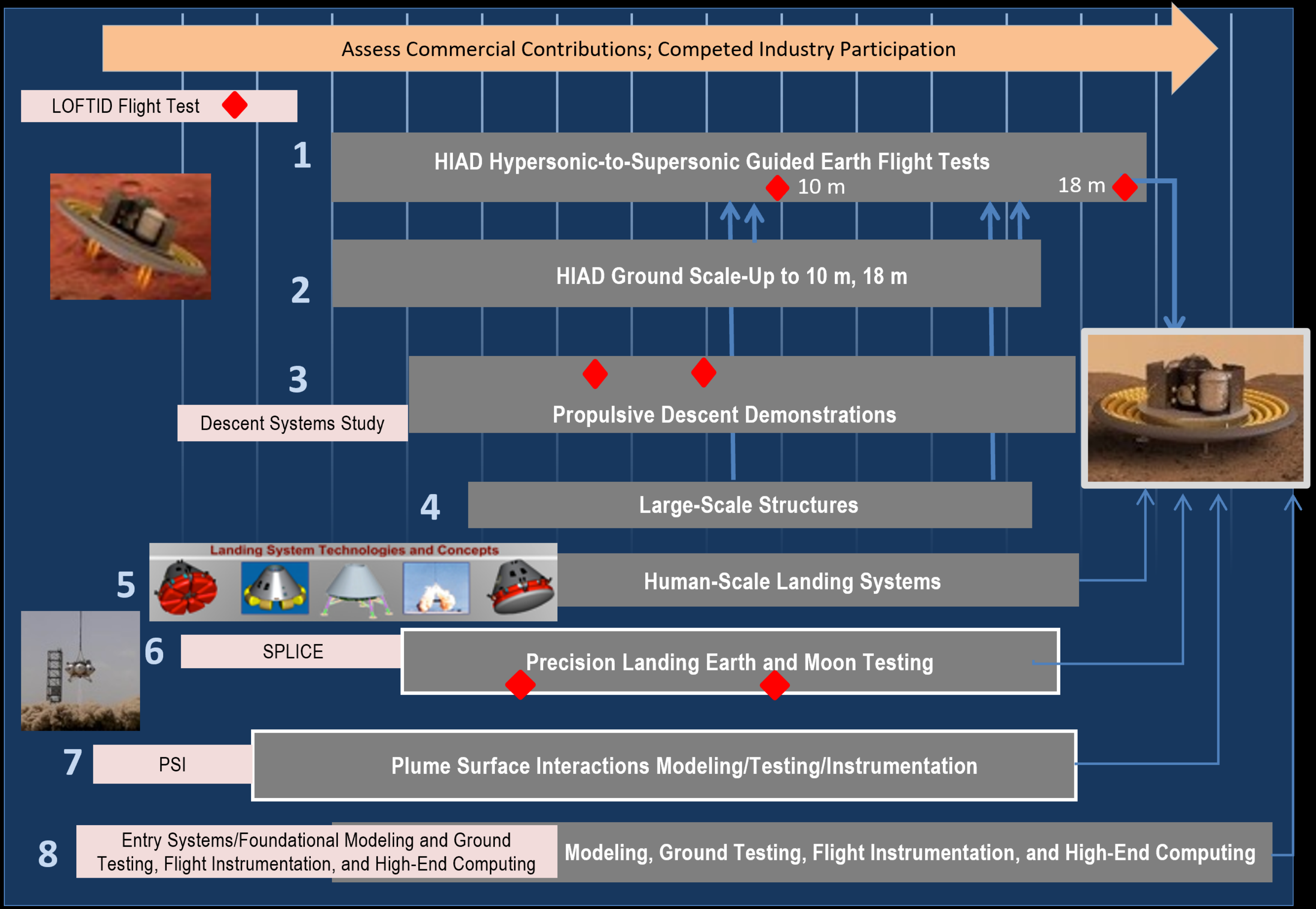
Payloads 20-30* t

*actual payload requirements differ with architecture assumptions

Mars Crew / Cargo Landers for 25t+ Payloads

Notional Development Plan (Current STMD Investments Noted in Pink Bars)

NOTE: Numbered items correspond to highest-priority gaps (see page 8). Activity duration and timing are success-oriented and require significant investment increases.



Assess Commercial Contributions; Competed Industry Participation

LOFTID Flight Test

1 HIAD Hypersonic-to-Supersonic Guided Earth Flight Tests
10 m
18 m

2 HIAD Ground Scale-Up to 10 m, 18 m

3 Descent Systems Study
Propulsive Descent Demonstrations

4 Large-Scale Structures

5 Landing System Technologies and Concepts
Human-Scale Landing Systems

6 SPLICE
Precision Landing Earth and Moon Testing

7 PSI
Plume Surface Interactions Modeling/Testing/Instrumentation

8 Entry Systems/Foundational Modeling and Ground Testing, Flight Instrumentation, and High-End Computing
Modeling, Ground Testing, Flight Instrumentation, and High-End Computing

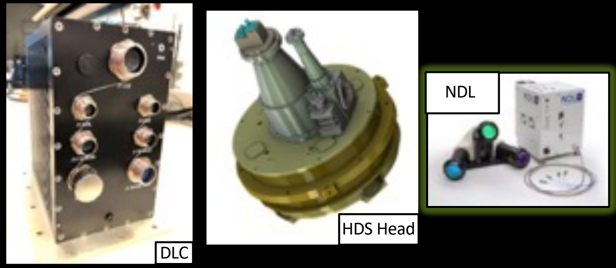
- *The large-scale Mars EDL system is comprised of multiple long-lead elements that all need to be matured in parallel.*
- *Flight tests of "E," "D," and "L" components occur at Earth. Precision Landing is demonstrated on the Moon. End-to-end Mars validation is performed computationally (as with current vehicles), and the Mars cargo missions serve as the system certification for humans.*

Legend

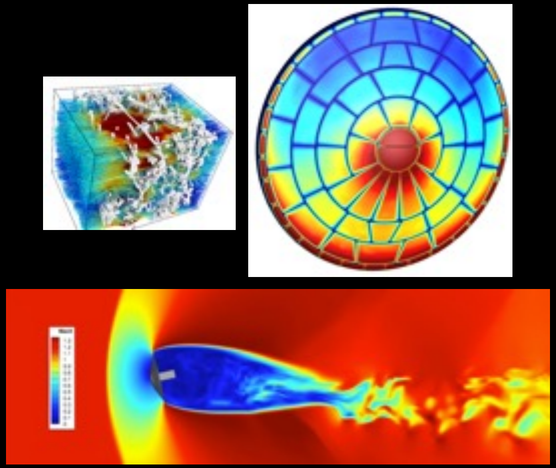
▭	Current Funded Activity
▬	Risk Reduction / Capability Maturation
▢	Demonstration/experience at Moon
▭	Commercial activity/leveraging
◆	Launch (test flight LVs TBD)
→	Feed-in

Current Investments to Achieve 25t+ Landings

LOFTID
6m inflatable aeroshell test with United Launch Alliance (ULA) - 2022

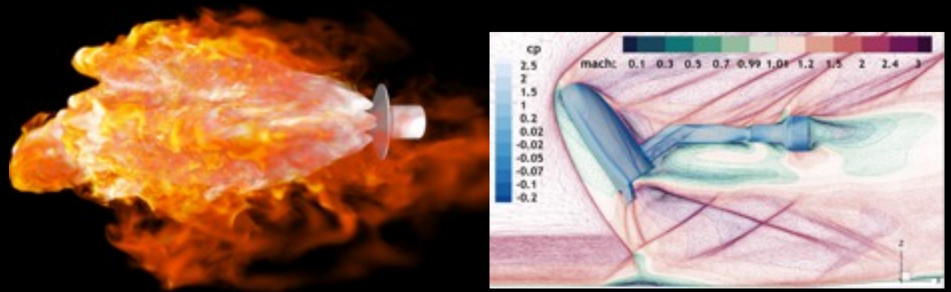


***SPLICE**
Precision Landing/Hazard Detection sensor, computing, and algorithm development, flight testing, and commercialization
(see separate package for "50 m" outcome)

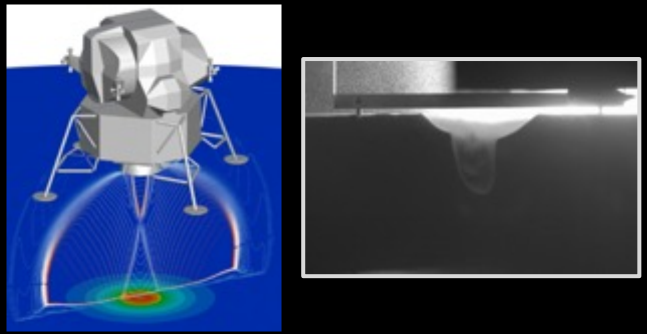


Entry Systems Modeling (ESM)
Advancing core capabilities and reducing mission risk through validation (Aerodynamics, Aerothermal, TPS, GN&C)

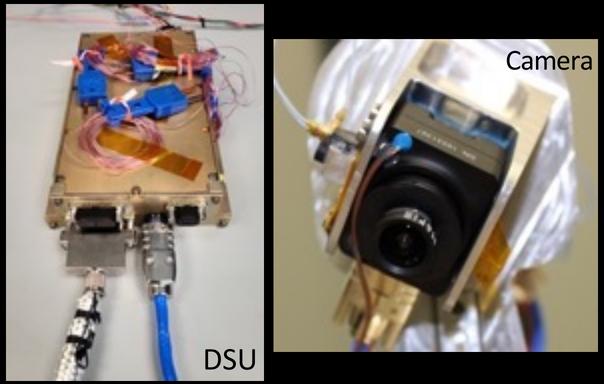
MEDLI2
Heating and pressure sensors on Mars 2020 aeroshell; provides aero/aerothermal model validation data (post-flight data analysis in progress)



Descent Systems Study
Mid L/D ground testing complete
HIAD and all SRP testing FY22-23



***Plume Surface Interaction (PSI)**
Model Advancement and Validation through Ground Testing, Flight instrument maturation



***SCALPSS**
Stereo Cameras to measure Plume Surface Interaction under CLPS landers; provides PSI model validation data

Early-Stage investments such as SBIR and academic efforts contribute to most projects shown

**Orange = Demonstration for Lunar missions in Near Term; Lunar-focused investments feed forward directly to Mars*

Highest-Priority Technology Gaps

There are 20 identified gaps mapped to the "Land 25t+" outcome. Below are the highest-priority gaps, as ranked by the EDL System Capability Leadership. The major bullets trace to the numbered grey bars on the schedule (page 6.)

- **Aeroshell (Hypersonic Deceleration) System (1)**
  - Flight Test Validation of Integrated High-Mass Mars Entry and Descent Architectures
  - Control Technologies for Exploration Class Inflatable Decelerator
  - Aeroshell/TPS Reliability Prediction
- **Ground Development and Scale-Up of Inflatable Decelerators and Large Structures (2)**
- **Retropropulsion (Supersonic Deceleration) System (3)**
  - Supersonic Retropropulsion (SRP) Modeling & Simulation
  - Supersonic Retropropulsion (SRP) Guidance, Navigation and Control
- **Validated Prediction of Plume-Surface Interaction (PSI) for Vehicles Landing on Mars (7)**
- **Entry Systems/Foundational Modeling and Testing, Instrumentation, and Computing (8)**
  - High-End Computing Capability for EDL Modeling
  - Multi-disciplinary / coupled EDL Performance Models
  - Validated Aerothermodynamic Prediction for Human Mars EDL
  - Thermal Protection System Performance Modeling & Optimization for Human Mars Exploration
  - EDL Flight Vehicle (Aeroshell) Flight Performance Data for Human Mars Entry and Earth Return
  - Low Cost EDL Flight Instrumentation Data Acquisition System
  - Planetary Aerothermodynamics Test Facility

**Note that all Precision Landing gaps are mapped to the "Precision Landing" outcome and are therefore not included here. These are CRITICAL to implementing the Artemis architectures. See the separate package on that outcome.*

Forward Plans to Close High-Priority Gaps

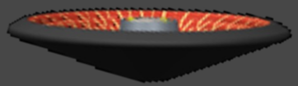
System/Area	Near- to Mid-Term Approach
Aeroshell (Hypersonic Deceleration) System (1), including Ground Development & Scale-Up, Large Structures (2) *(see graphic on following page)*	• **Complete current investments in LOFTID 6 m flight test, data analysis and dissemination. Assess alternate Mars architectures via analysis.** • Advance towards Commercial Rocket Stage Reuse capability (increased size, payload mass) – ground scale-up work must proceed in parallel to support this application, including materials, gas generators, and model advancement and validation • Formulate large-scale Earth flight tests through Pre-Phase A to establish objectives, estimate schedule and budget. Determine SRP requirements • Use LOFTID EDU to advance control strategies • Advance gas generator technology needed for large-scale systems, and materials with improved volume/handling characteristics (industry) • Perform large-scale Earth flight tests to demonstrate performance and functionality needed for human Mars mission implementation
Retropropulsion (Supersonic Deceleration) System (3) *(see graphic on following page)*	• **Complete current investments in Descent Systems Study wind tunnel testing and data analysis, including academic participation (ESI21)** • Initiate hot-fire wind tunnel testing at GRC to further characterize aerodynamic parametric data • Perform scaled (sounding rocket-based) Earth flight tests to validate in-flight performance • Integrate with large-scale decelerator Earth-based flight tests (if flight conditions can be met)
Plume Surface Interactions (PSI) (7) *(see graphic on following page)*	• **Complete foundational PSI ground testing and Early Stage investments to support improved prediction capability (SBIR, STRG)** • Instrument CLPS landers to gather Lunar validation data (SCALPSS, PSI Mini-Suite); also leverage data collected by lander providers, other P/Ls • Develop low-SWaPc flight instrumentation (in-house, SBIR, and other competitive opportunities) for larger-scale Lunar missions that will feed forward to Mars. Leverage Artemis landings. • Dedicated PSI data from future Mars robotic landers (MEDLI-3) to support improved understanding of landing environments and further gaps
Foundational Modeling, Testing, Instrumentation, and High-Performance Computing (8)	• **Continue investments in Entry Systems Modeling, focusing on development and validation of integrated, higher-fidelity modeling capabilities, including academic efforts (ACCESS STRI, ECF, ESI)** • Facilitate advanced computing implementation of key EDL models through code transfer, workforce development efforts, and OGA partnerships • Conduct ground facilities maintenance and construction as necessary to fill high-priority gaps • Instrument entry systems on future Mars robotic landers, invest in new sensors and low-cost DAS (SBIR), obtain data from Artemis I and II return
Precision Landing and Hazard Avoidance	• **Complete SPLICE for sensor and algorithm development and terrestrial testing; continue SBIR and FO use. Obtain NDL data from CLPS flights.** • Perform integrated CLPS lunar demonstration(s); commercialize for infusion to human and cargo landers • Implement and demonstrate integrated capabilities on future Mars robotic landers *See package dedicated to the LAND precision landing outcome, for more details*

NOTE: Large-Scale Structures and Human-Scale Landing Systems require initial in-house exploration followed by solicitations, when funding is available.

Hypersonic Inflatable Aerodynamic Decelerator (HIAD)
Scale-Up and Flight-Testing Approach

IRVE-3 (3 m) – 2012 successful flight test from Wallops Flight Facility - SOA

Established the aerodynamic performance and stability of inflatable heatshield approach

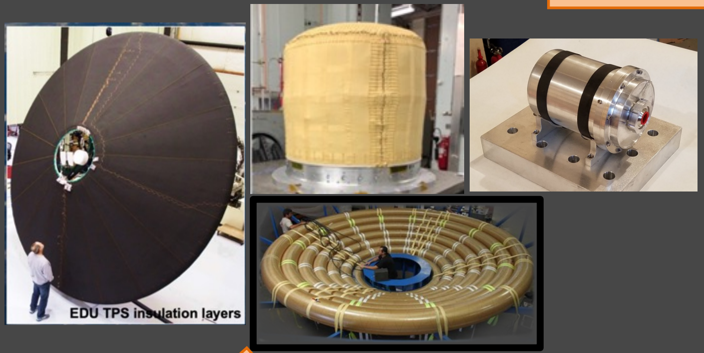


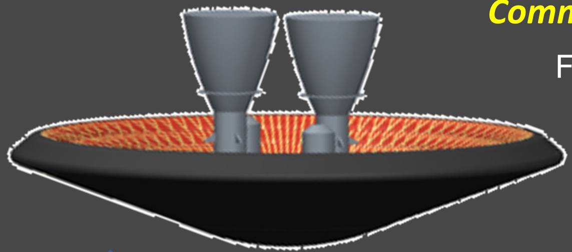
LOFTID Flight Test (6 m) – 2022 flight test in partnership with United Launch Alliance (ULA)

Vandenburg launch with JPSS-2. ***HIAD will experience human Mars mission-relevant heating and g-load.***

Ground Scale-up Demonstration

- Mass-efficient materials for structure and TPS
- Improved handling and packing density
- Gas generators: volume-enabling





Commercial Rocket Engine Recovery (12 m) – 2024-25+

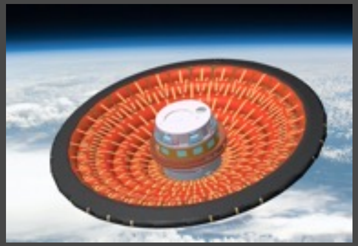
Frequent industry use will solidify HIAD technology

- Establish large-scale (12 m+) production
- Maintain specialized vendor base
- Return multiple sets of flight data for validation
- Reduce risk for human Mars mission implementation

Perform integrated demonstration

Sustain commercial base

Guided HIAD, SRP Earth Flight Testing (10-15 m)



- Demonstrates closed-loop G&C and transition to propulsive deceleration
- Includes large-scale, mass-efficient structures

Ready for Mars infusion

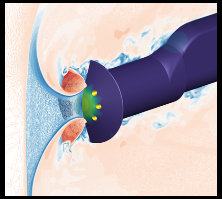
Human Mars Lander (~18 m)

Green = currently funded; Yellow = not yet funded

Retropropulsion Advancement Approach

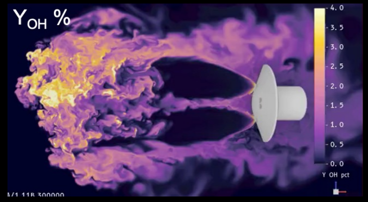
Commercial Demonstration of Supersonic Retropropulsion (SpaceX, high-altitude Earth stage return – 2013) - SOA

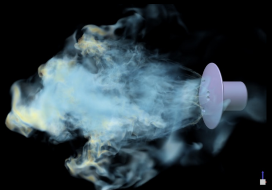
- Established viability of rocket engine restart in oncoming flow conditions. NASA received flight data for CFD assessment.
- Geometry/configuration dramatically different than NASA Mars EDL concepts, but general feasibility established.



Wind Tunnel Testing with Cold Gas Thrusters (Langley Unitary Plan Wind Tunnel – 2010, 2021-23) - SOA

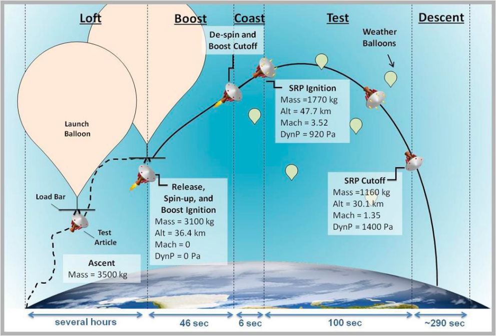
- Various nozzle/shape configurations, uncertainty quantification, inert gas subscale validation data
- Establishes aerodynamic databases for simulations to assess performance of Mars EDL alternatives

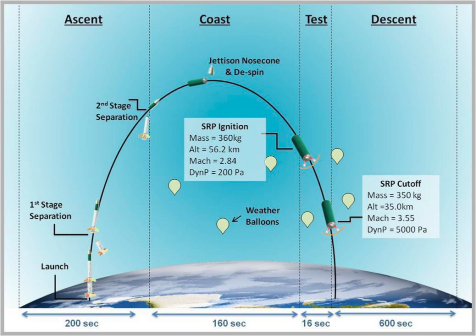




Wind Tunnel Testing with Combustion Engines (Glenn Supersonic and Transonic Tunnels)

- First hot-fire test with chemistry effects, hot-fire subscale validation data
- Establishes aerothermal environments, refines aerodynamics for iterative vehicle design; input to end-to-end flight dynamics simulations of 20 t Mars EDL





High-Altitude Suborbital Testing (~1m diameter scale)

- Series of tests at larger scale in Mars-relevant environment (density, Mach)
- Continuity in transitions across flight regimes, verifies stability
- Engine development to meet performance requirements
- Flight-relevant configurations, combustion, system integration

Integration with Hypersonic Decelerator, Transition Test

- Test transition from aerodynamic to propulsive deceleration at Mars-relevant conditions and configurations

(see previous page)

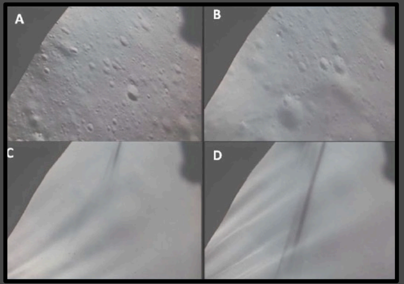
Gradual increase in test fidelity retains flexibility and supports configuration decisions.

Rapid analysis of large datasets is key challenge – requires new tools, computing architectures

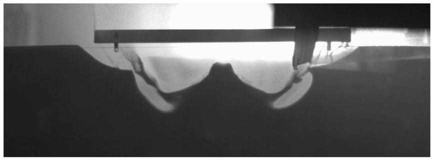
Plume Surface Interaction (PSI) Advancement Approach

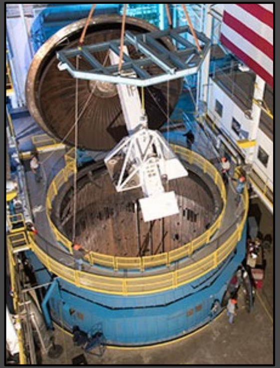
The Challenge: Engine plumes of landing (and ascending) vehicles will disturb the surface below, potentially causing (1) cratering, (2) heating of the vehicle base and legs, (3) high-speed ejecta transport and damage due to impacts on nearby surface assets, and (4) sensor spoofing. Little test or flight data exist to develop and validate predictive models.


MSL Skycrane Plume-Induced Surface Cratering



Apollo 15 camera obscuration (Metzger, 2011)


Physics-Focused Ground Test, annular crater in sand (2021)

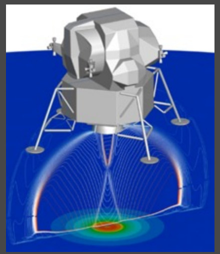

Large-Scale Ground Test, Armstrong Test Facility (OH)

Advancement Approach (captured in gaps):

- Mature & validate predictive modeling capability (goal is quantitative fidelity)
  - Complex, multi-physics problem requiring high-end computing resources to achieve required throughput
  - Key environment that will drive lander and surface asset design **and create dust that requires mitigation**
  - *Obscuration during PSI event may affect precision landing sensor performance/data, in high-thrust cases*
- Conduct vacuum ground tests with regolith/bedrock simulants to generate initial model validation data
  - Small-scale, warm-gas tests varying simulants, vacuum levels (Moon and Mars), nozzle heights and mass flows
  - Large-scale (1000 lb$_f$+) vacuum tests with simulants, combustion – more relevant to human-scale systems
  - *Limited vacuum facilities exist, to handle both regolith and combustion, at any scale*
- Develop instrumentation to measure (1-4) above, including subsurface effects
  - Implement in ground tests to demonstrate instruments and measure relevant quantities for model validation
  - Instrument CLPS landers (100's of lb$_f$) for single and multiple PSI phenomena
  - Instrument larger lunar and robotic Mars landers with low-SWaPc multi-sensor suites to obtain flight data


Crater Observation Camera

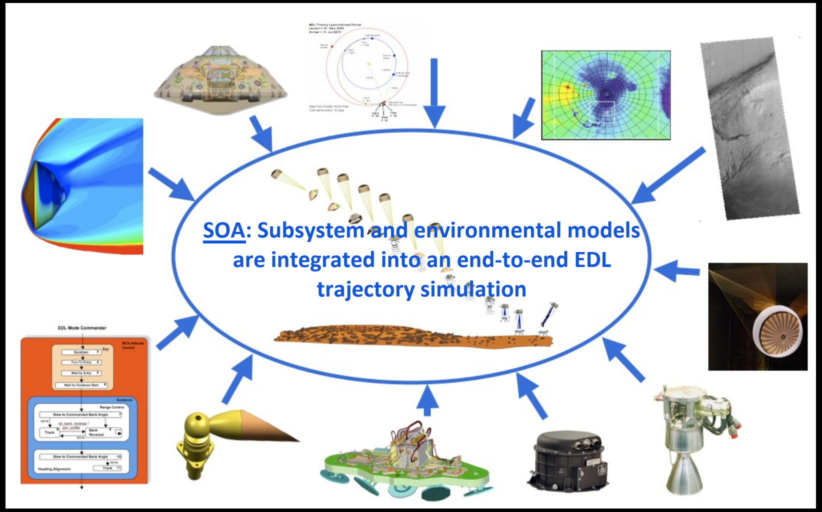

mm-Wave Doppler Radar


PSI Prediction Model

Green = currently funded; Green-Yellow = partially funded; Yellow = not yet funded

Modeling/Testing/Instrumentation Advancement Approach

- Planetary EDL/DDL cannot be practically tested end-to-end at Earth; system acceptance relies heavily on a combination of ground testing (wind tunnels, arcjets, ballistic ranges, drop tests, etc.) and computer modeling and simulation (CFD, material response, FEM, atmosphere, H/W and S/W, etc.)
  - Flight data has been historically sparse, for vehicles flying at planets other than Earth
  - Heatshield instrumentation on Mars Science Laboratory and Mars 2020 have helped validate models and improve design practices for future vehicles, but uncertainties still exist and risk tolerance will be lower, for human systems
- Aging and inadequate facilities, combined with high reliability requirements, create gaps in our ability to readily certify human-rated, large-scale planetary landers.
- Human-rated landing systems will require high-fidelity, closed-loop modeling and simulation, along with ground test and flight data with quantified uncertainties, gathered by precision instrumentation



<u>SOA</u>: Subsystem and environmental models are integrated into an end-to-end EDL trajectory simulation

<u>Advancement Approach (captured in gaps)</u>:

- Continue robust modeling capability within each subsystem development
- Develop coupled, multi-scale models for lander systems and environments, utilizing advanced computing architectures (GPU, exascale) to achieve schedule (requires new skills and tools)
- Ensure flight regime is adequately replicated in test facilities
- Develop and implement low-SWaPc instrumentation to gather critical model validation data from ground tests, flight tests, and EDL missions

This content builds upon the Entry Systems Modeling project and a vibrant Early-Stage academic community. Progress requires a long-term, sustained commitment to foundational capabilities: tools, facilities, and high-end computing.

Summary

- The EDL systems required for landing 25t+ payloads are significantly larger and different than those used in the past to land up to one tonne on Mars. A comprehensive set of ~20 high-priority gaps defines the needed near-term advancements.
- Human Mars architecture studies over the past 5 years indicate that a HIAD/SRP-based EDL system is most likely to be able to close the architecture *under the current Agency assumptions*. Alternative approaches must continue to be assessed as the space economy and available technologies evolve.
- Large-scale, human-rated EDL vehicles require maturing multiple systems in parallel, each with ground development and/or flight testing needed
- Landing-related technologies such as precision landing and hazard avoidance, and the prediction of plume-surface interactions, will heavily leverage development, testing, and implementation on lunar landers of increasing scales.
- Mars entry and descent technologies are long-pole developments that will remain untested by Artemis lunar missions. Given the Agency’s current lunar priority, major investments in these areas are few.
- The modeling and simulation used for end-to-end EDL certification will require significant modeling advances and computing efficiencies to achieve high reliability on the current manifested schedules.
- Ground and flight test will continue to be a foundation of EDL development. Modern instrumentation is critical, and new/upgraded test facilities will be required to secure this envisioned future.

Acronyms

- CLPS – Commercial Lunar Payload Services
- CFD – Computational Fluid Dynamics
- DDL – Deorbit, Descent and Landing
- ECF – Early Career Faculty
- EDL – Entry, Descent and Landing
- ESI – Early Stage Innovation
- FEM – Finite Element Model
- GN&C – Guidance, Navigation and Control
- GPU – Graphical Processor Unit
- HIAD – Hypersonic Inflatable Aerodynamic Decelerator
- H/W – hardware
- LOFTID – Low Earth Orbit Flight Test of an Inflatable Decelerator
- MEDLI2 – Mars Entry, Descent and Landing Instrumentation (2)
- PSI – Plume Surface Interaction
- SBIR – Small Business Innovation Research
- SCALPSS – Stereo Cameras for Lunar Plume Surface Studies
- SOA – State of the Art
- SPLICE – Safe, Precise Landing Integrated Capabilities Evolution
- SRP – Supersonic Retropropulsion
- STRI – Space Technology Research Institute
- S/W – software
- TPS – Thermal Protection System