NASA’s Entry, Descent and Landing (EDL) Technology Portfolio

Michelle M. Munk
EDL Systems Capability Lead
NASA Space Technology Mission Directorate

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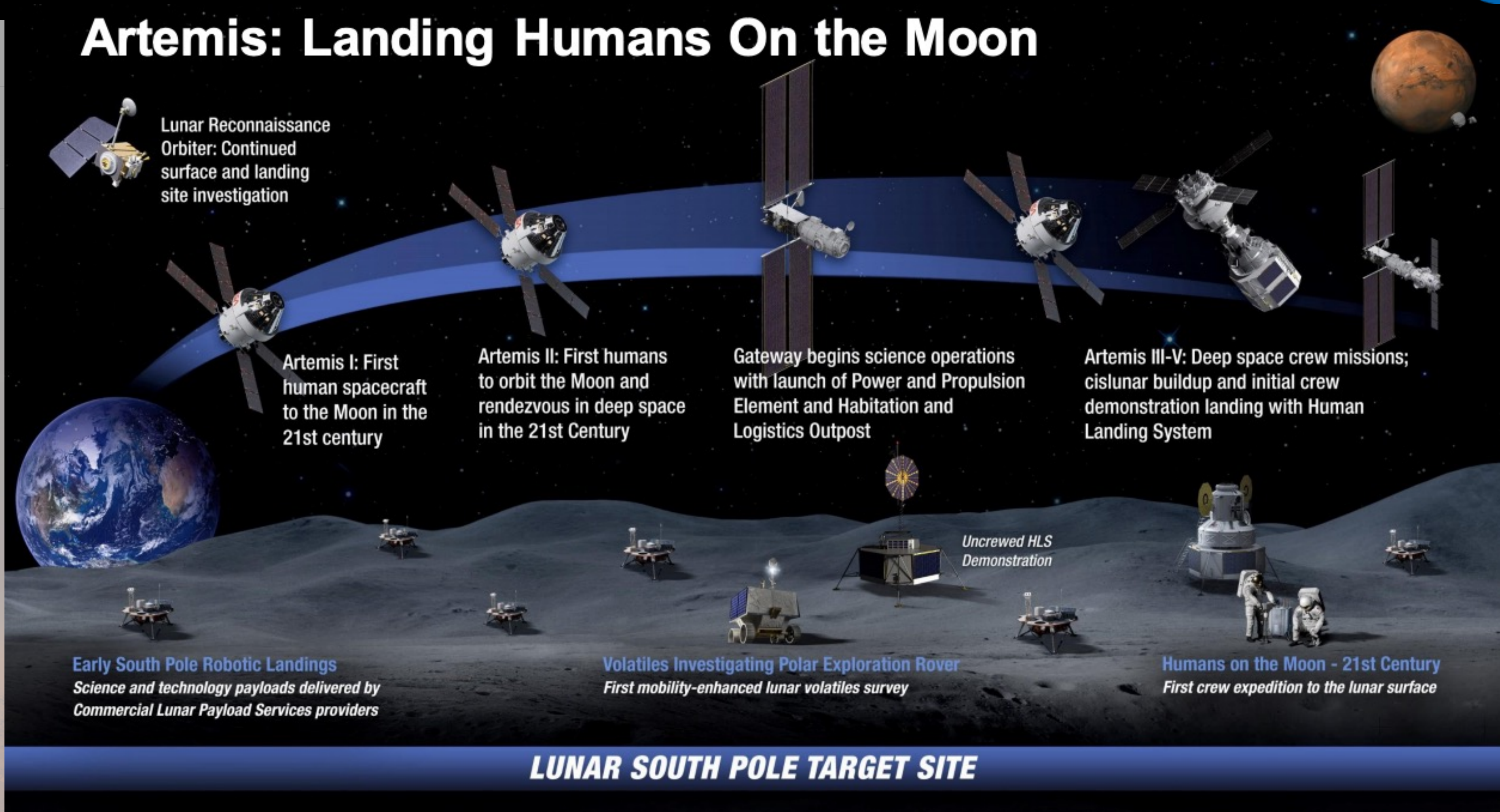
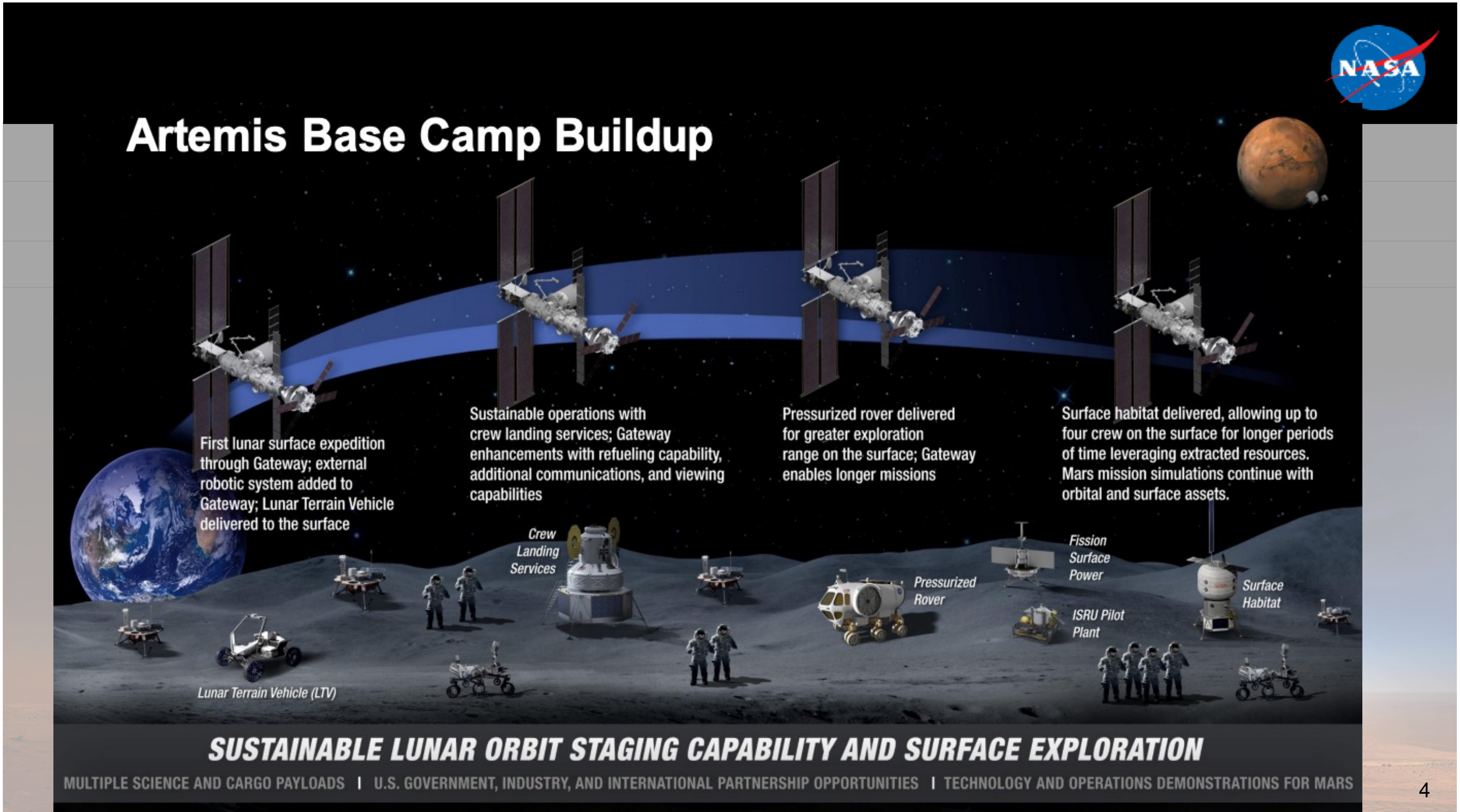
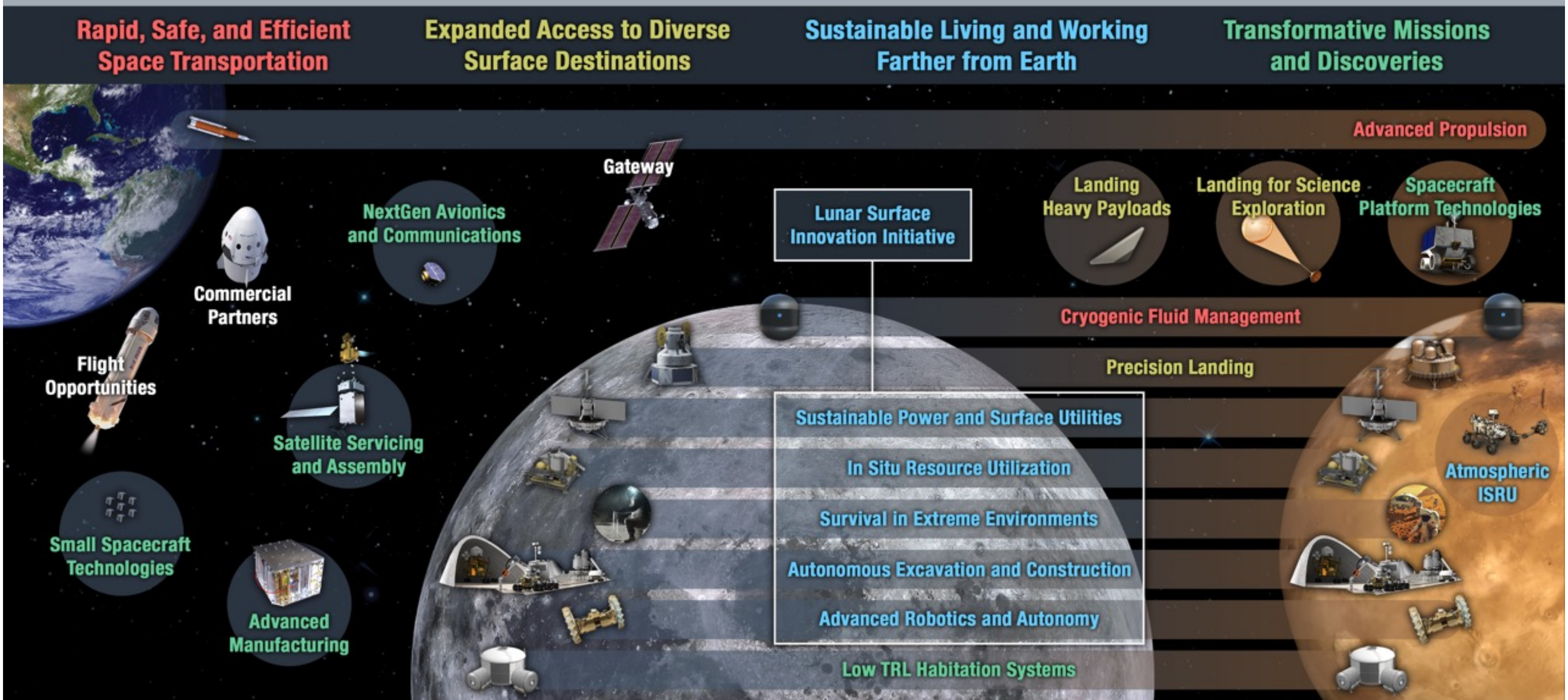
Outline

- Introduction to NASA Mission Goals
- NASA's Space Technology Mission Directorate Framework
- Process of Envisioned Future and Gap Definition
- Highlights of key technology projects
- Summary


Artemis: Landing Humans On the Moon
Lunar Reconnaissance Orbiter: Continued surface and landing site investigation
Artemis I: First human spacecraft to the Moon in the 21st century
Artemis II: First humans to orbit the Moon and rendezvous in deep space in the 21st Century
Gateway begins science operations with launch of Power and Propulsion Element and Habitation and Logistics Outpost
Artemis III-V: Deep space crew missions; cislunar buildup and initial crew demonstration landing with Human Landing System
Uncrewed HLS Demonstration
Early South Pole Robotic Landings
Science and technology payloads delivered by Commercial Lunar Payload Services providers
Volatiles Investigating Polar Exploration Rover
First mobility-enhanced lunar volatiles survey
Humans on the Moon - 21st Century
First crew expedition to the lunar surface
LUNAR SOUTH POLE TARGET SITE


Artemis Base Camp Buildup
First lunar surface expedition through Gateway; external robotic system added to Gateway; Lunar Terrain Vehicle delivered to the surface
Sustainable operations with crew landing services; Gateway enhancements with refueling capability, additional communications, and viewing capabilities
Pressurized rover delivered for greater exploration range on the surface; Gateway enables longer missions
Surface habitat delivered, allowing up to four crew on the surface for longer periods of time leveraging extracted resources. Mars mission simulations continue with orbital and surface assets.
Crew Landing Services
Fission Surface Power
Pressurized Rover
Surface Habitat
ISRU Pilot Plant
Lunar Terrain Vehicle (LTV)
SUSTAINABLE LUNAR ORBIT STAGING CAPABILITY AND SURFACE EXPLORATION
MULTIPLE SCIENCE AND CARGO PAYLOADS | U.S. GOVERNMENT, INDUSTRY, AND INTERNATIONAL PARTNERSHIP OPPORTUNITIES | TECHNOLOGY AND OPERATIONS DEMONSTRATIONS FOR MARS

NASA's Leadership in Space Technology



Technology Drives the Space Economy

STMD Strategic Technology Framework

Lead	Thrusts	Outcomes	Primary Capabilities
Ensuring American global leadership in Space Technology • Advance US space technology innovation and competitiveness in a global context • Encourage technology driven economic growth with an emphasis on the expanding space economy • Inspire and develop a diverse and powerful US aerospace technology community	***Transforming Space Missions***		
	Go Rapid, Safe, and Efficient Space Transportation	• Develop nuclear technologies enabling fast in-space transits. • Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications. • Develop advanced propulsion technologies that enable future science/exploration missions.	• Nuclear Systems • Cryogenic Fluid Management • Advanced Propulsion
	Land Expanded Access to Diverse Surface Destinations	• Enable Lunar/Mars global access with ~20t payloads to support human missions. • Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies. • Develop technologies to land payloads within 50 meters accuracy and avoid landing hazards.	• Entry, Descent, Landing, & Precision Landing

	Live
	Sustainable Living and Working Farther from Earth
		• Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities
		  • Sustainable power sources and other surface utilities to enable continuous lunar and Mars surface operations.
		  • Scalable ISRU production/utilization capabilities including sustainable commodities on the lunar & Mars surface.
		  • Technologies that enable surviving the extreme lunar and Mars environments.
		  • Autonomous excavation, construction & outfitting capabilities targeting landing pads/structures/habitable buildings utilizing in situ resources.
		• Enable long duration human exploration missions with Advanced Habitation System technologies. [Low TRL STMD; Mid-High TRL SOMD/ESDMD]
			• Advanced Power
			• In-Situ Resource Utilization
			• Advanced Thermal
			• Advanced Materials, Structures, & Construction
			• Advanced Habitation Systems

	Explore Transformative Missions and Discoveries	• Develop next generation high performance computing, communications, and navigation. • Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions. • Develop technologies supporting emerging space industries including: Satellite Servicing & Assembly, In Space/Surface Manufacturing, and Small Spacecraft technologies. • Develop vehicle platform technologies supporting new discoveries. • Develop technologies for science instrumentation supporting new discoveries. [Low TRL STMD/Mid-High TRL SMD. SMD funds mission specific instrumentation (TRL 1-9)] • Develop transformative technologies that enable future NASA or commercial missions and discoveries	• Advanced Avionics Systems • Advanced Communications & Navigation • Advanced Robotics • Autonomous Systems • Satellite Servicing & Assembly • Advanced Manufacturing • Small Spacecraft • Rendezvous, Proximity Operations & Capture • Sensor & Instrumentation

Human Mars Mission: Landing Multiple 2-Story Houses

- Establishing sustained Human presence will require multiple landers
- NASA's Evolvable Mars Campaign identified a 4-lander manifest

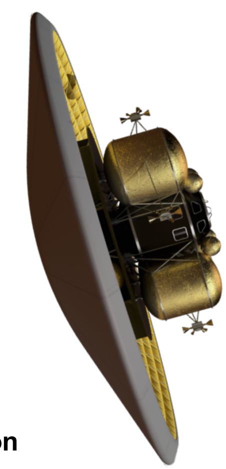
- Must land within 50 m of a target
- Must remain 1 km from other landed assets to prevent sand blasting

Requires orders of magnitude improvement on pinpoint landing capability

Human Mars EDL Capability Requires a Leap in Scale

- 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 (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
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 Mars EDL Paradigm

Payloads 20-30 t*

*actual payload requirements differ with architecture assumptions

LAND: Enable Lunar/Mars global access with ~20t payloads to support human missions

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

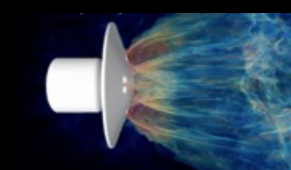
Lunar Capabilities (feeding forward to Mars)

Precision Landing and Hazard Avoidance

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

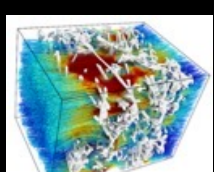
Retropropulsion

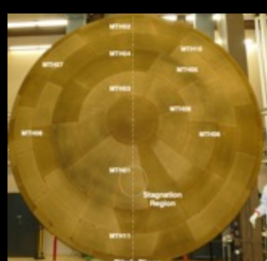
Understand flow physics and vehicle control through wind tunnel testing of Mars-relevant configurations; advance CFD modeling



Plume Surface Interaction

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





Foundational Modeling, Testing, Instrumentation, and Computing

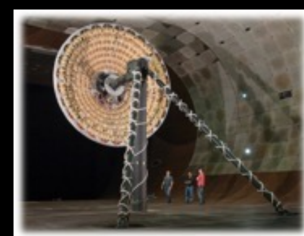
Measure EDL flight system performance and update/develop unique, critical simulations for EDL/DDL systems

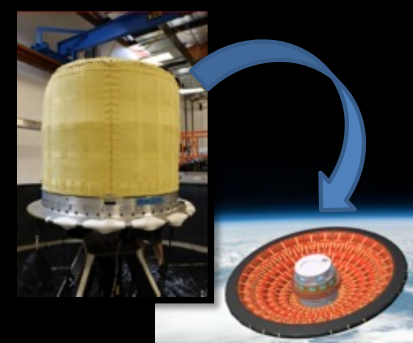
Mars Capabilities

Large Scale Demonstrations

Large structures, including deployables, that can slow down a 20t payload in the thin Mars atmosphere

Assess Alternatives





Earth Flight Tests, such as LOFTID

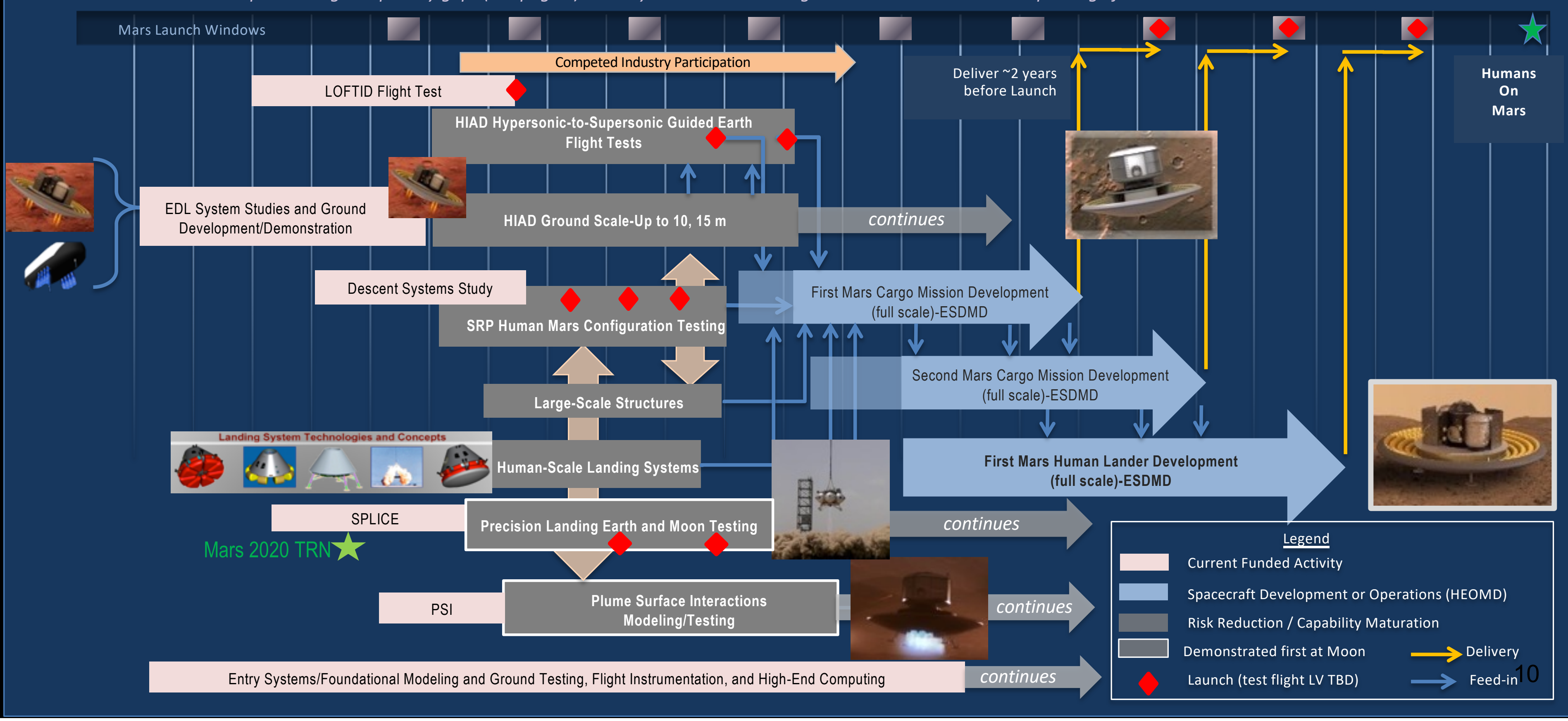
Aggregate Assets

Mars Crew / Cargo Landers for 20t Payloads

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

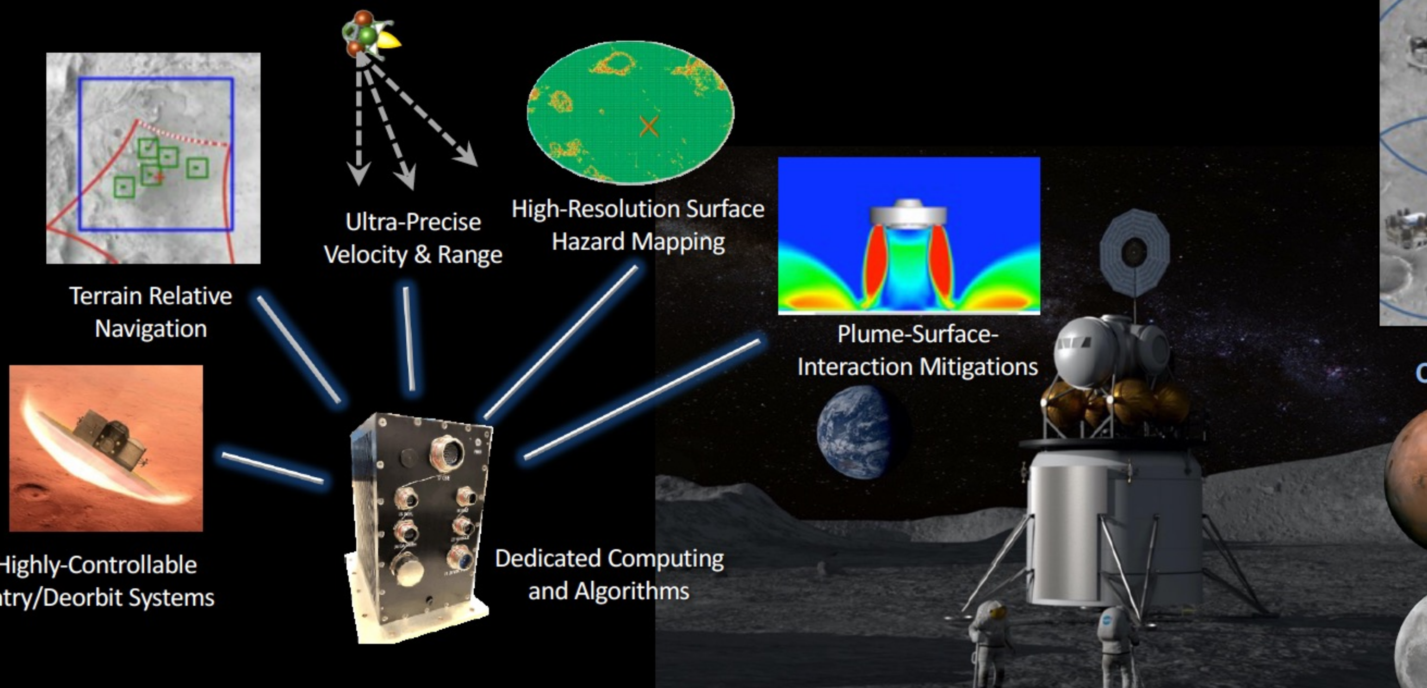
- *The large-scale Mars EDL system is comprised of multiple long-lead elements that all need to be matured in parallel.*
- *Flight tests of "E," "D," and "L" components occur at Earth. Precision Landing is demonstrated on the Moon. End-to-end Mars validation is performed computationally (as with current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

NOTE: Numbered items correspond to highest-priority gaps (see page 9). Activity duration and timing are success-oriented and require significant investment increases.

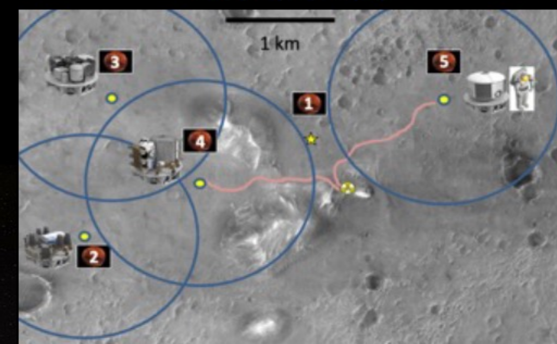


LAND: Technologies to Precisely Land Payloads and Avoid Landing Hazards

Developing entry, descent and landing technology to enhance and enable small spacecraft to Flagship-class missions across the solar system



Aggregated and Sustainable Sites on the Moon and Mars



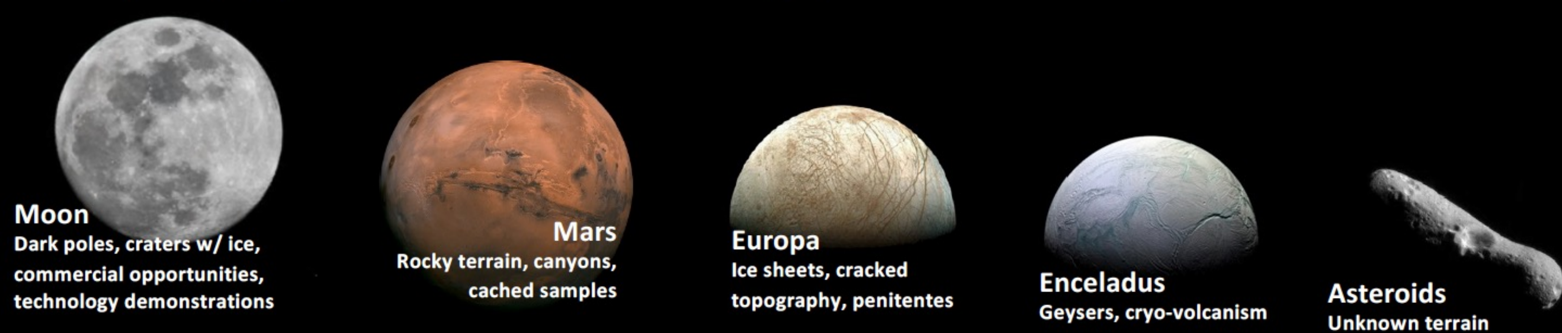
Capabilities evolvable for many solar-system destinations

<u>Enable</u> anytime landings in treacherous terrains and independent of lighting
<u>Reduce the risk</u> of the landing for human and robotic missions to many destinations
<u>Reduce operations time</u> for a rover or human to reach an interesting site
<u>Aggregate resources</u> in one surface region for missions requiring multiple landings

Landing Precision: Development Strategy

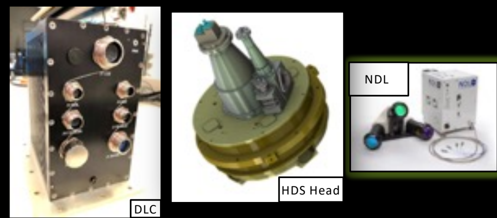
Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards

- **Overarching Goal**
  - Develop, infuse, and commercialize technologies applicable to robotic and human landers that become part of the future suite of off-the-shelf GN&C (Guidance/Navigation/Control) capabilities for precise safe landing
- **Overview of Approach**
  - Sustain an EDL/DDL knowledge base and simulation to capture near-term and future human and robotic mission needs and the evolving commercial and government PL&HA capabilities
  - Prioritize development and infusion of cross-cutting EDL/DDL systems, sensors, avionics, and algorithms applicable to human and robotic missions
  - Leverage multiple test paradigms (lab, flight, suborbital, space) to accelerate TRL advancement and infusion
  - Pursue technology transfer, public-private partnerships, commercial spin-offs and spin-ins to promote closure of EDL/DDL capability gaps and the transition-into/leveraging-of commercial off-the-shelf solutions

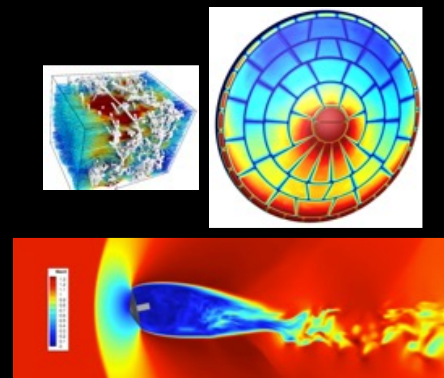


Current Investments to Achieve 20t Landings

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

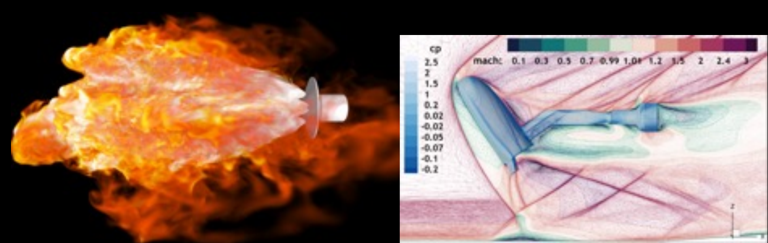


***SPLICE**
Precision Landing/Hazard Detection sensor, computing, and algorithm development, flight testing, and commercialization

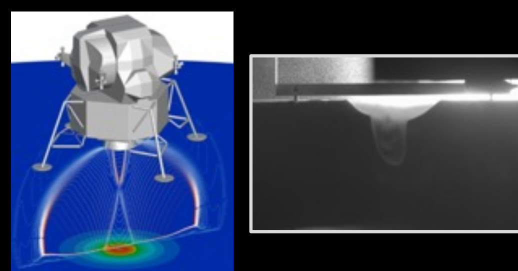


Entry Systems Modeling (ESM)
Advancing core capabilities and reducing mission risk through validation (Aerodynamics, Aerothermal, TPS, GN&C)

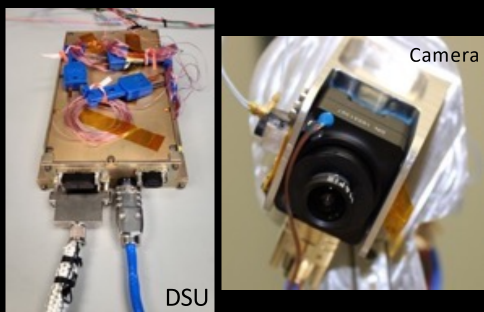
MEDLI2
Heating and pressure sensors on Mars 2020 aeroshell; provided aero/aerothermal model validation data (deep-dive data analysis in progress)



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



***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

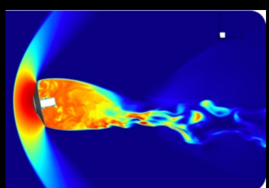
Early-Stage investments such as SBIR and academic efforts contribute to most projects shown
**Orange = Demonstration for Lunar missions in Near Term; Lunar-focused investments feed forward directly to Mars*

LAND: Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies

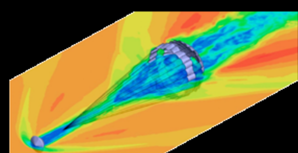
Developing atmospheric entry technology to enhance and enable small spacecraft to Flagship-class missions across the solar system

Entry Systems Modeling & Testing

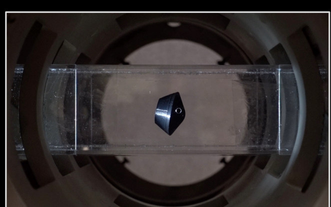
Reducing entry system mass and risk by developing advanced, validated models



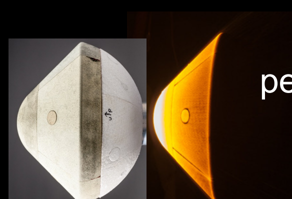
"DESKTOP WIND TUNNEL"



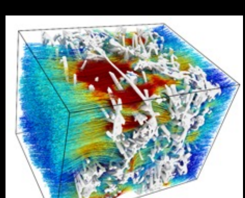
PARACHUTE MODELING



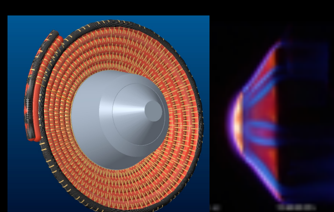
MAGNETIC SUSPENSION WIND TUNNEL



CONFORMAL MATERIALS



IN-DEPTH MATERIAL RESPONSE



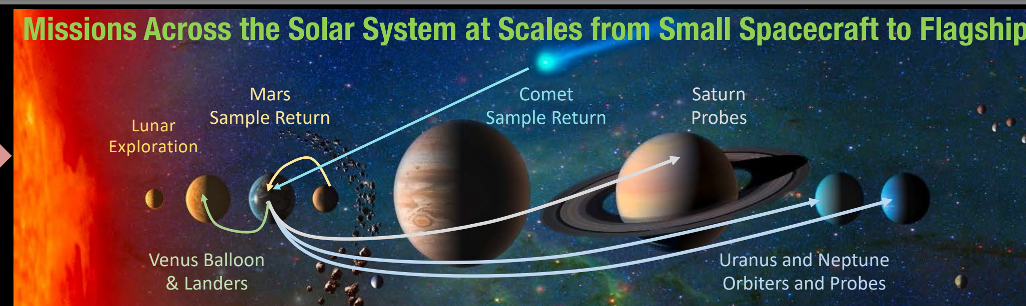
DEPLOYABLE DECELERATORS

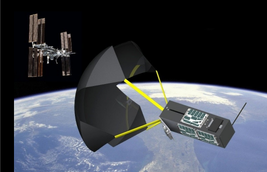
3D WOVEN HEATSHIELDS

to enable

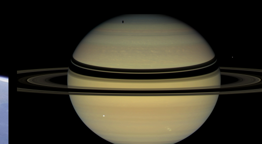
Hardware Development

Maturing new materials and systems to fill performance gaps and enable new missions





PRECISION DEORBIT



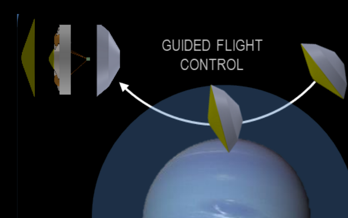
SATURN PROBE

TITAN PINPOINT LANDING

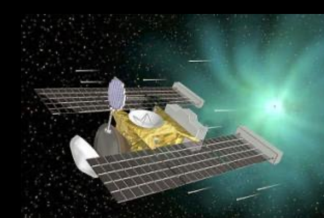
MARS SAMPLE RETURN

Increasing Science Return, Decreasing Risk, Cost, and Schedule

ICY MOON PRECISE LANDING



ICE GIANT AEROCAPTURE



HIGH-SPEED SAMPLE RETURN

All activities depicted not currently funded or approved. Depicts "notional future" to guide technology vision.

Mission Priorities from the 2022 Planetary Decadal Survey

List of Missions Includes Entry, Descent and/or Landing (EDL)

	2022 Decadal Survey Priority	Enabling/Enhancing EDL Capability Advancement
Flagship	Uranus Orbiter and Probe*	Aerocapture for orbiter; atmospheric modeling, aero/aerothermal modeling, mass-efficient entry system
	Enceladus Orbilander*	*Unclear. Precision landing/hazard avoidance?*
	Europa Lander*	*Hazard detection and avoidance*
	Mercury Lander*	*Unclear. Precision landing/hazard avoidance?*
	Neptune-Triton Odyssey	Aerocapture for orbiter (?); atmospheric modeling, aero/aerothermal modeling, mass-efficient entry system
	Venus Flagship*	Atmospheric modeling, aero/aerothermal modeling, mass-efficient entry system, precision landing?

New Frontiers 5 (2024 AO)

- Comet Surface Sample Return (CSSR)*
- Lunar South Pole-Aitken Basin Sample Return *
- Ocean Worlds (only Enceladus)
- Saturn Probe*
- Venus In Situ Explorer*
- Io Observer
- Lunar Geophysical Network (LGN)*

New Frontiers 6

- Centaur Orbiter and Lander (CORAL)*
- Ceres sample return*
- Comet surface sample return (CSSR)*
- Enceladus multiple flyby (EMF)
- Lunar Geophysical Network (LGN)*
- Saturn probe*
- Titan orbiter
- Venus In Situ Explorer (VISE)*

New Frontiers 7

New Frontiers 6 list, plus

- Triton Ocean World Surveyor

* = mission involves EDL

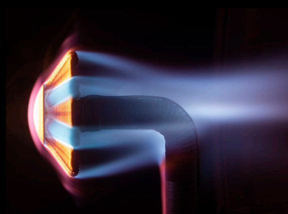
Reference: https://www.nationalacademies.org/our-work/planetary-science-and-astrobiology-decadal-survey-2023-2032

Planetary EDL Subsystem SOA/Activities

TPS

- Investments over the past ~15 years have produced materials that span the expected planetary mission space for the next 1-2 decades

HEEET

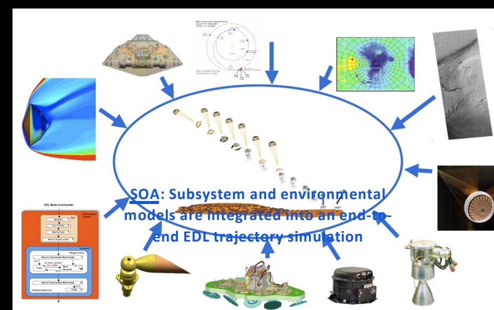


ADEPT/Spiderweave

PICA

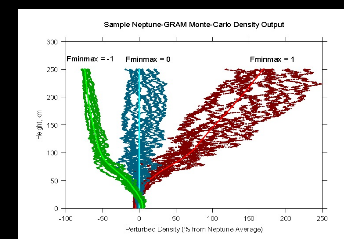
GN&C Modeling

- Baseline models under development for expected planetary mission space; Quantified uncertainty forthcoming



Atmosphere Models

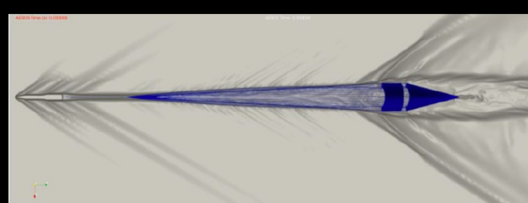
- GRAM update for PSD destinations of interest nearing completion; New data inclusion forthcoming



Parachutes

- Mars2020 flew largest supersonic chute to date; MSR plans even larger. Modeling SOA lags hardware/testing, but is under active development

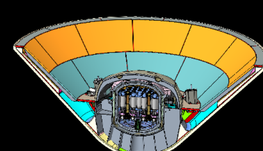
M2020 Parachute



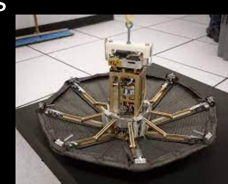
Aero/FS Simulation of ADEPT

Architecture/System

- EES designed for high reliability. ADEPT & HIAD provide scalability beyond rigid capsules, SRP provides extensibility beyond parachutes

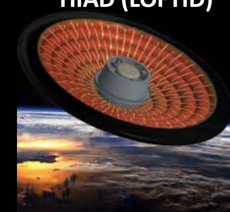


EES



ADEPT

HIAD (LOFTID)



SRP Simulation

EDL & Precision Landing Gaps

Lunar-Focused

- Land large payloads on the Moon
- Land within 50 m of desired site (develop sensors, algorithms)
- Establish consistent lunar maps
- Be able to predict Plume Surface Interaction (PSI)
- Obtain PSI flight data

Science Mission-Focused

- Design high-reliability EDL systems
- Develop EDL/Aerocapture capability for small spacecraft
- Perform aerocapture at ice giants
- Enable safe landing on Europa
- Develop technologies for large landers

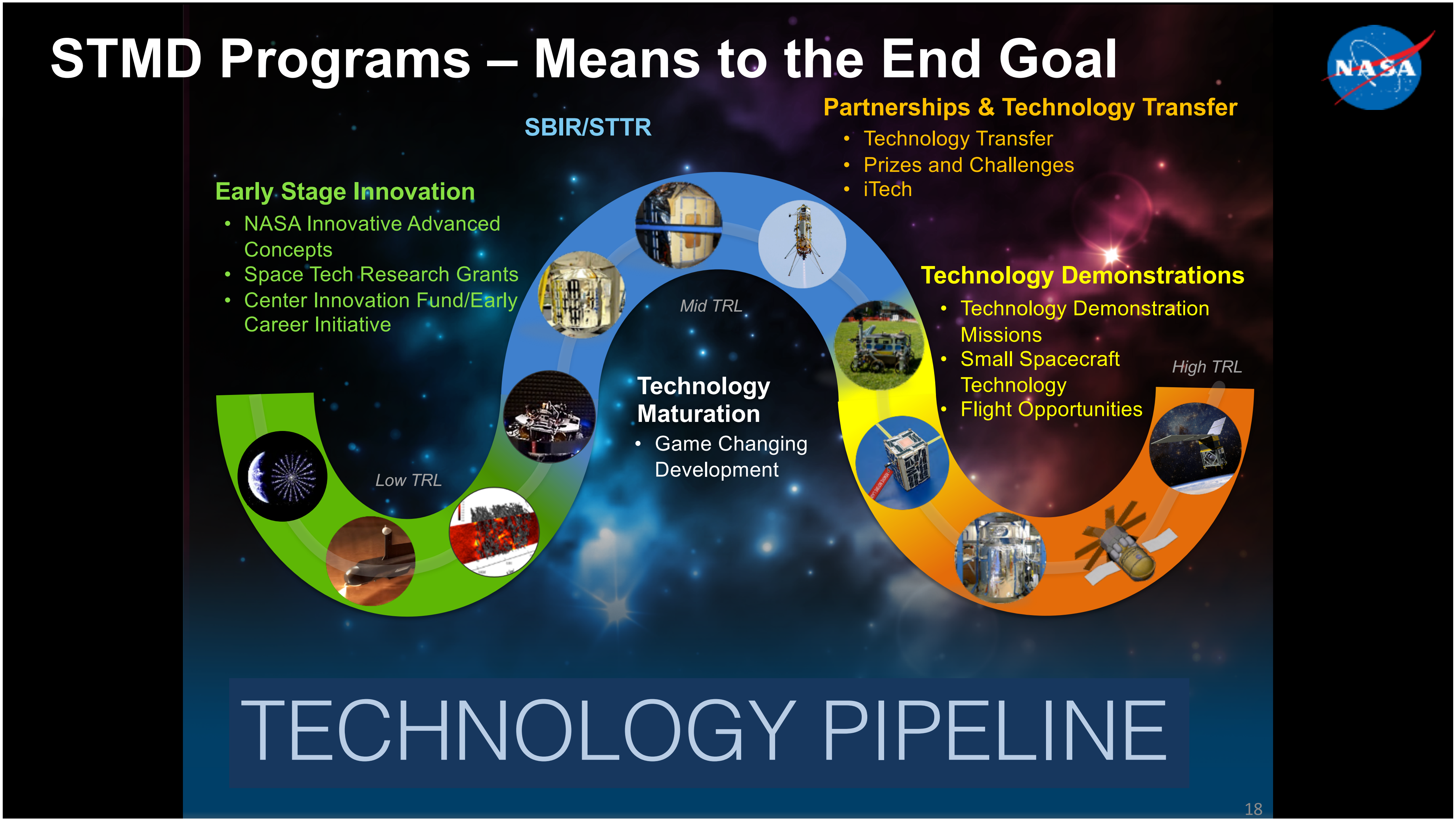
Mars-Focused

- Land 20+ t on Mars
- Land within 50 m of desired site
- Establish consistent Mars maps
- Be able to predict PSI
- Conduct flight tests of hypersonic entry system
- Conduct flight tests of retropropulsion system
- Scale up large rigid and inflatable structures
- Develop landing attenuation methods

Cross-Cutting

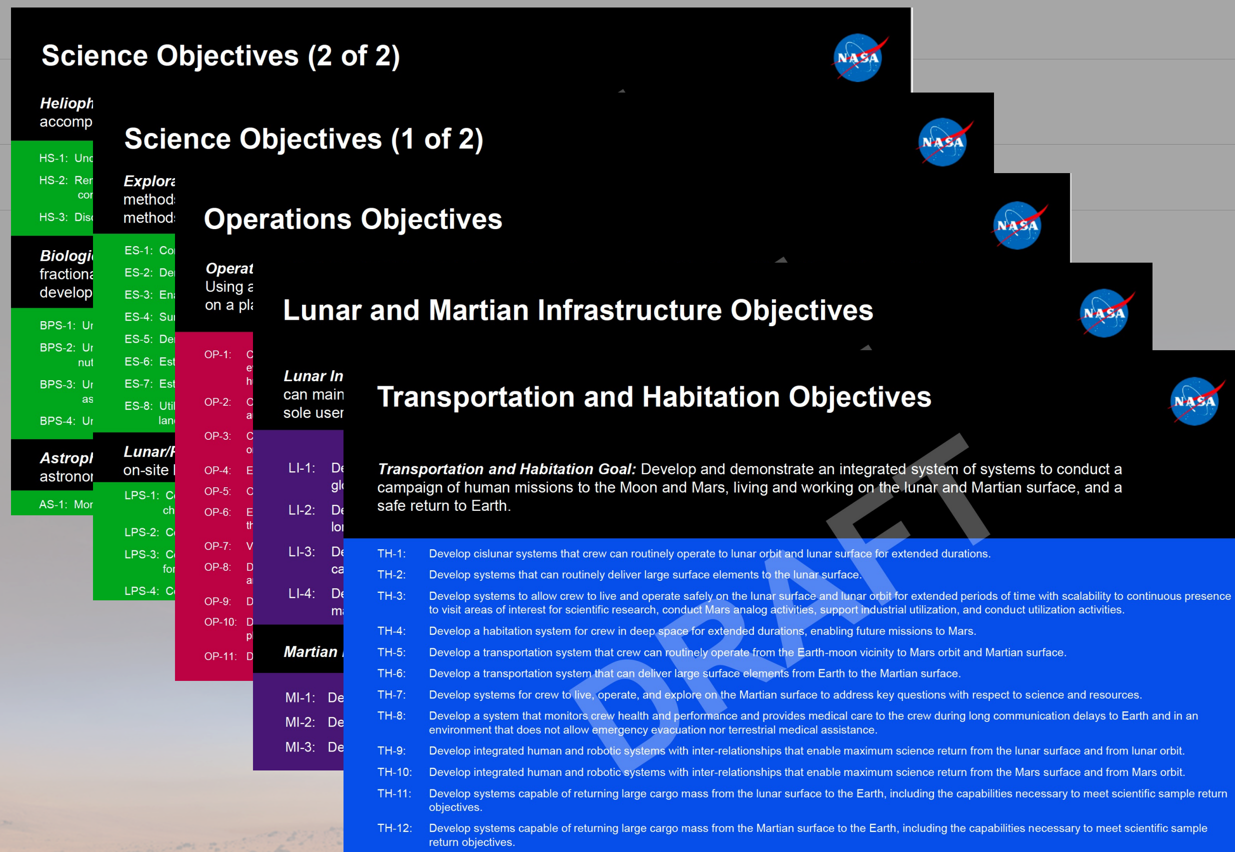
- Improve aerodynamic and aerothermal models
- Establish parachute modeling
- Advance multi-disciplinary, coupled tools
- Instrument EDL vehicles for lower SWaP-C
- Establish & access inexpensive flight test platforms
- Maintain and modernize unique facilities
- Modernize codes to GPU platforms; utilize high-end computing
- Advance flight mechanics/GN&C tools
- Mature TPS performance and reliability modeling

(summary representation of ~65 gaps, not verbatim)


STMD Programs – Means to the End Goal
NASA
SBIR/STTR
Partnerships & Technology Transfer
• Technology Transfer
• Prizes and Challenges
• iTech
Early Stage Innovation
• NASA Innovative Advanced Concepts
• Space Tech Research Grants
• Center Innovation Fund/Early Career Initiative
Mid TRL
Technology Demonstrations
• Technology Demonstration Missions
• Small Spacecraft Technology
• Flight Opportunities
High TRL
Technology Maturation
• Game Changing Development
Low TRL
TECHNOLOGY PIPELINE
18

Next Steps: NASA Moon-to-Mars (M2M) Objectives

- On May 17, NASA released 50 objectives for public comment (links to video/charts below)
- International comments are also being sought
- Result will be updated M2M objectives and updated architectures for lunar and Mars missions
- EDL technology gaps will be assessed against the updated architectures



- https://www.nasa.gov/press-release/update-nasa-seeks-comments-on-moon-to-mars-objectives-by-june-3
- https://www.nasa.gov/sites/default/files/atoms/files/moon-to-mars-objectives-.pdf

What's Next in EDL (2024-40)?

- **We will land precisely on the Moon, first with commercially-provided landers (small), then evolving to human-scale**
  - Lightweight, inexpensive sensors for precise landing (feeds to Mars); integration on commercial landers
  - Plume/surface/vehicle interactions near touchdown (feeds to Mars)
  - Integrated simulations for assessing landers and sensor suites (feeds to Mars)
- **Commercial efforts in EDL are growing: low-cost Earth return**
- **We want to return samples from Mars by the early 2030's**
  - Landing ~1500 kg precisely, next to samples that Mars 2020 caches
  - Landing a rocket on Mars and autonomously launching it
  - Returning the samples to Earth in a capsule with 1×10^{-6} probability of failure
- **Scientists want to go to Venus, Ice Giants, Ocean Worlds, and Outer Planets (& back)**
  - EDL Challenges: rugged terrain, unknown/thick atmospheres, high entry speeds
- **Scientists want to go to Mars more often**
  - EDL Challenges: cost, risk tolerance
- **We have the long-term goal of landing humans on Mars**
  - EDL Challenges: high mass, precise landing, risk posture for humans

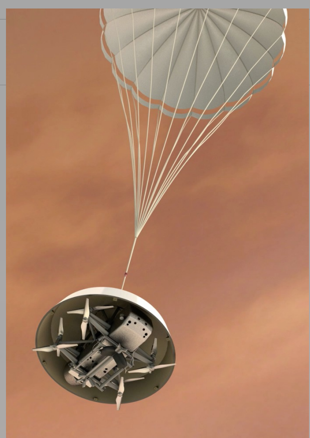
Summary

- EDL at NASA serves human exploration and science missions across the Solar System. EDL is a critical exploration function made of specialized disciplines and subsystem designs.
- There are many ongoing missions in development, technology maturation efforts, and engagements with industry
- We are participating in NASA-level efforts to align objectives, architectures, and identify gaps to guide technology investments
- We look forward to opportunities to collaborate with our international colleagues, to achieve these challenging missions


EXPLORE
MOON to MARS
Thank you!
NASA

Recent/Current EDL Highlights/Activities

Dragonfly, Launch 2027
PDR Oct 2022
DrEAM Aeroshell Instrumentation



LOFTID Test, Launch Nov 2022
Largest blunt aeroshell

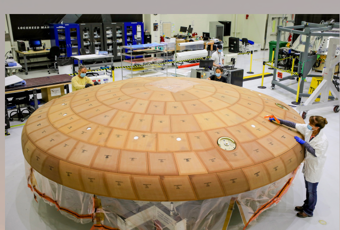
MEDLI2 on M2020
Deep Dive analysis underway

Mars 2020 - Perseverance
Landing 2/18/21. TRN First Use

Mars Sample Retrieval Lander, Ascent Vehicle &
Earth Return Orbiter, Launch 2028
MSR EES using STMD-developed TPS

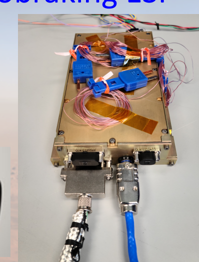
VERITAS - Launch 2028
Aerobraking ESI

DAVINCI
Launch 2029
New TPS, Aeroshell
Instrumentation

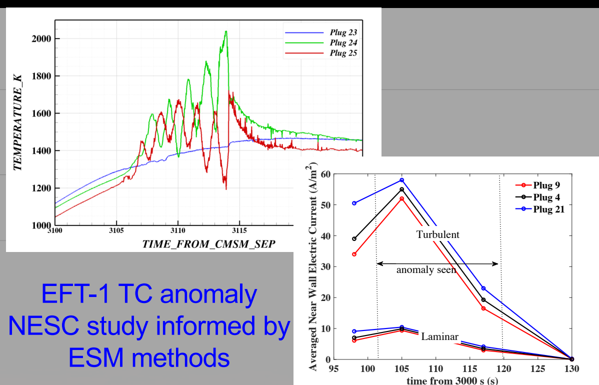


Artemis 1 – Ready to Fly!
NASA instrumentation
SCIFLI aerial imagery

SCALPSS
Delivered to IM for CLPS flight
in late 2022
Delivery to Firefly in Oct 2022

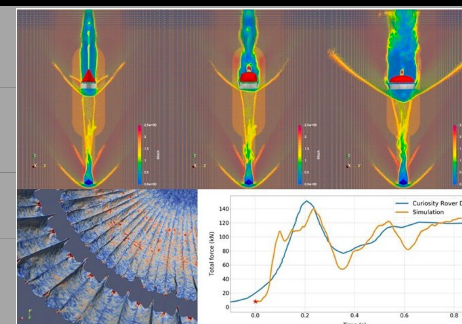


Recent EDL Highlights/Activities

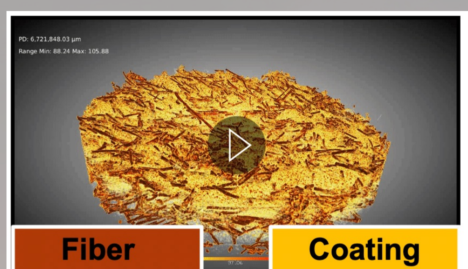


EFT-1 TC anomaly
NESC study informed by
ESM methods

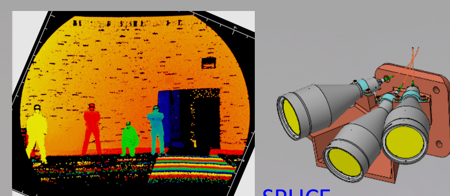
PSI – New Start in GCD
Active partnerships: STTR, SBIR, ESI



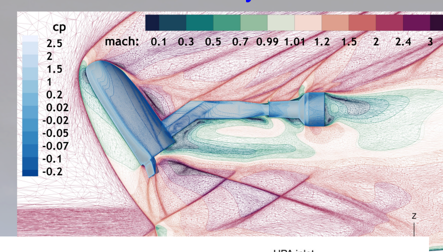
Parachute FSI
Partnership with ESM & STRG
New University Awards

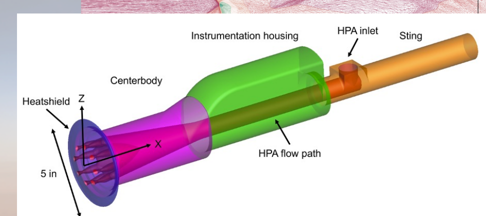


Entry Systems Modeling
Delivery of PICA-NuSil model
for MEDLI2



SPLICE
Multiple funded test flights
(Tipping Point, CLPS, FO)





Descent Systems Study
Mid L/D testing complete
HIAD testing planned for FY22

Summit simulation of
Supersonic
Retropropulsion

Acronyms

- ADEPT – Adaptable, Deployable Entry and Placement Technology
- DSS – Descent Systems Study
- ECLSS – Environmental Control and Life Support Systems
- ESM – Entry Systems Modeling
- HEEET – Heatshield for Extreme Entry Environment Technology
- HEOMD – Human Exploration and Operations Mission Directorate
- HIAD – Hypersonic Inflatable Aerodynamic Decelerator
- ISRU – In-Situ Resource Utilization
- LOFTID – LEO Flight Test of an Inflatable Decelerator
- NDL – Navigation Doppler LIDAR
- SMD – Science Mission Directorate
- SPLICE – Safe, Precise Landing Integrated Capabilities Evolution
- STMD – Space Technology Mission Directorate
- TRN – Terrain Relative Navigation
- TPS – Thermal Protection System