



Aerocapture, Entry, Descent and Landing (AEDL) Overview

IPPW 2022 Short Course
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Outline



- **AEDL Definition and Context**
- **AEDL History and State-of-the-Art**
- **Architectural Drivers**
- **Technology Response to Drivers**
 - Landing Heavy Payloads
 - Precision Landing and Hazard Avoidance
 - EDL at Science Destinations
- **Current/Recent Investments and Activities**
- **Emerging Trends**
- **Summary**

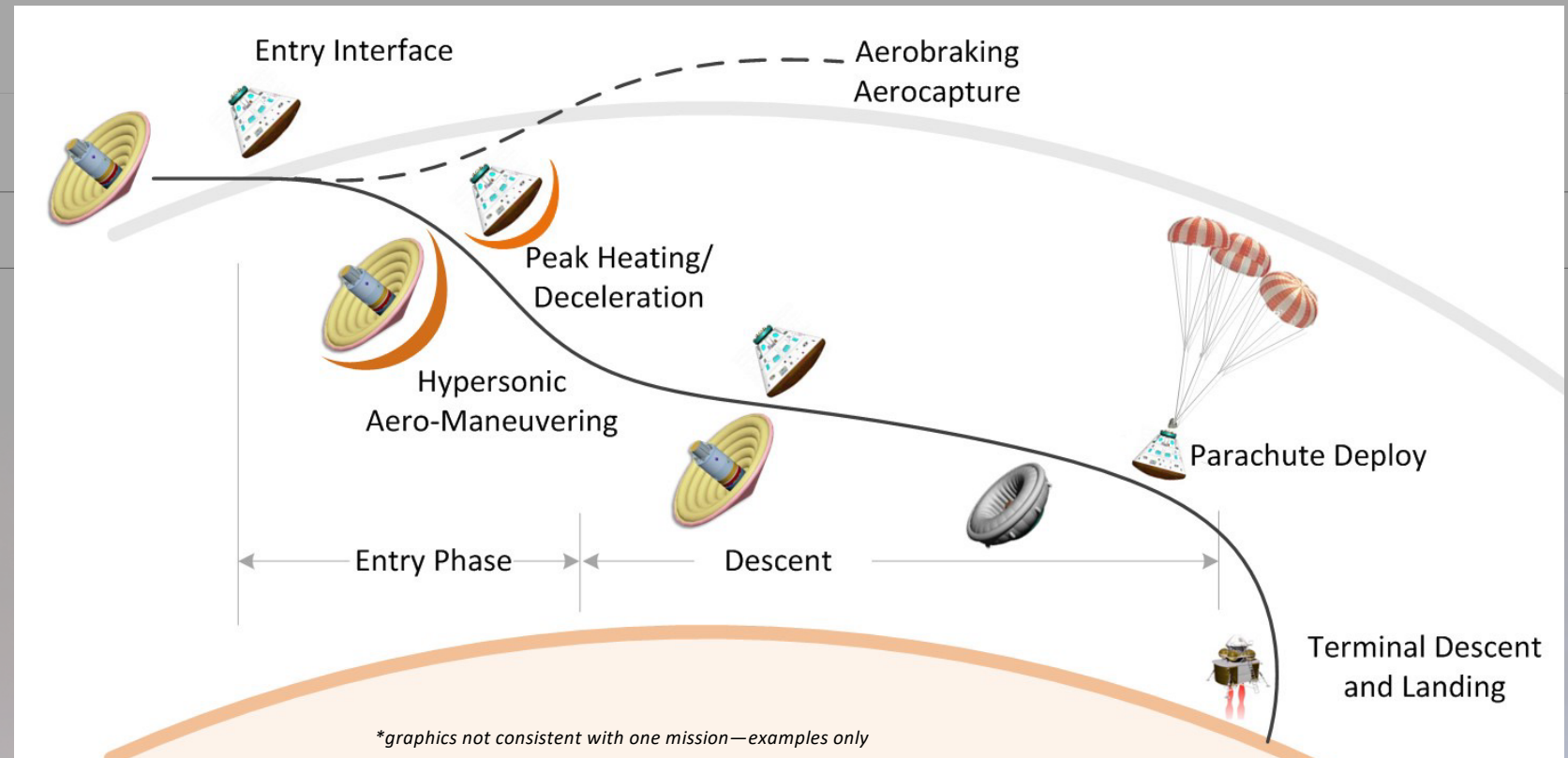


AEDL Definition and Context

Aeroassist, Entry, Descent and Landing (AEDL)

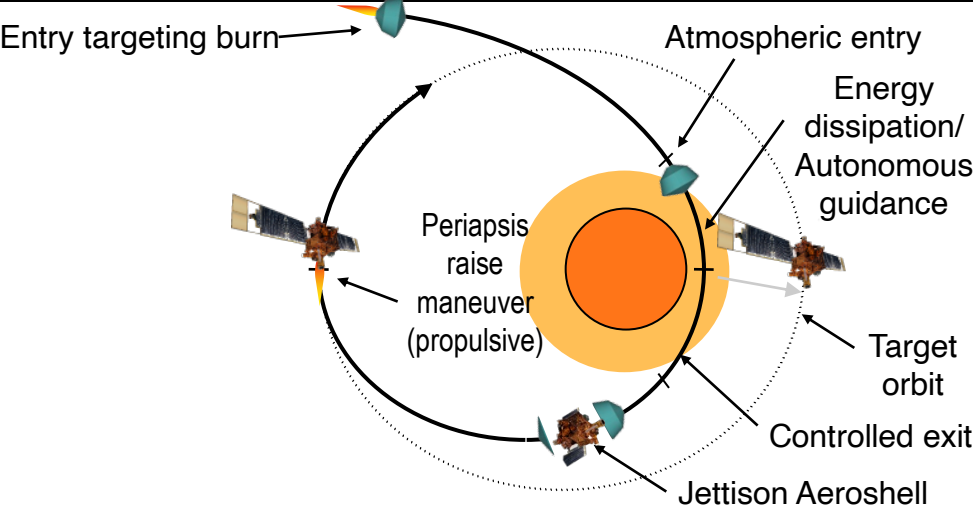
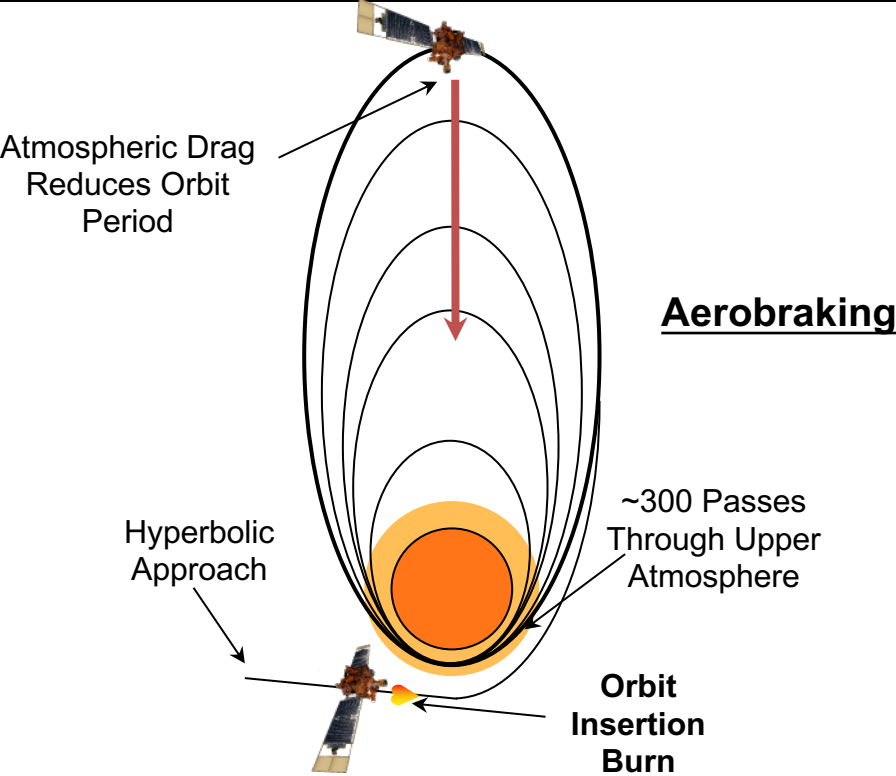


Slowing down, approaching, connecting or touching down on any body with significant gravity; with or without atmosphere.



- Three phases of flight
 - Entry – Hypersonic flight: Burn off energy; guide to the target
 - Descent – Supersonic flight: Deploy decelerators or turn on engines
 - Landing – Subsonic flight: Extend landing gear and/or throttle engines for touchdown

Aerobraking vs Aerocapture



Aerocapture: A vehicle uses active control to autonomously guide itself to an exit target, establishing a usable orbit about a body in a single atmospheric pass.

Pros	Cons
Little spacecraft design impact	Still need ~1/2 propulsive fuel load
Gradual adjustments; can pause and resume as needed (with fuel)	Hundreds of passes = more chance of failure
Operators make decisions	Months to start science
	Operational distance limited
	At mercy of highly variable upper atmosphere

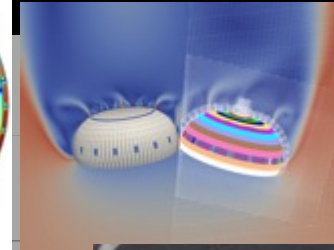
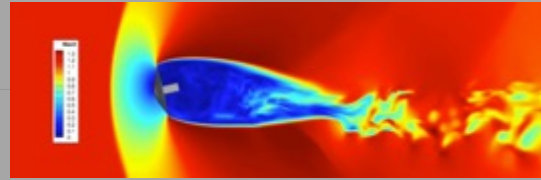
Pros	Cons
Uses very little fuel--significant mass savings for larger vehicles or high speed	Needs protective aeroshell
Establishes orbit quickly (single pass)	One-shot maneuver; no turning back, much like a lander
Has high heritage in prior hypersonic entry vehicles	Fully dependent on flight software
Flies in mid-atmosphere where dispersions are lower	
Adaptive guidance adjusts to day-of-entry conditions	
Fully autonomous so not distance-limited	

AEDL Sub-Capabilities



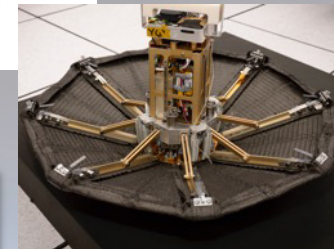
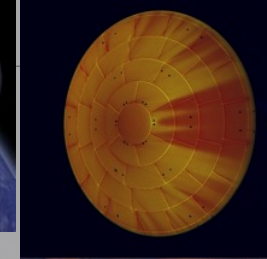
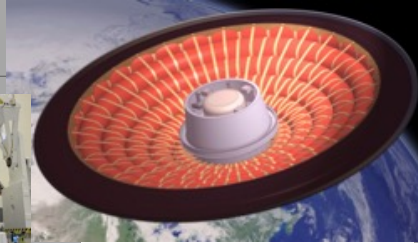
Analytical/ Discipline

- Aerodynamics
- Aerothermodynamics
- Flight Dynamics/Design
- Thermal
- Modeling and Simulation
- *Plume Surface Interaction*



Hardware

- Avionics
- GN&C
- Instrumentation
- Materials – High Temperature/TPS
- Mechanical Design
- *Propulsion**
- Structures
- Textiles



COBALT/Xodiac PL&HA Test
2017+ in Mojave, CA



System Level

- Software
- Mission Design & Analysis
- Systems Analysis
- Systems Integration

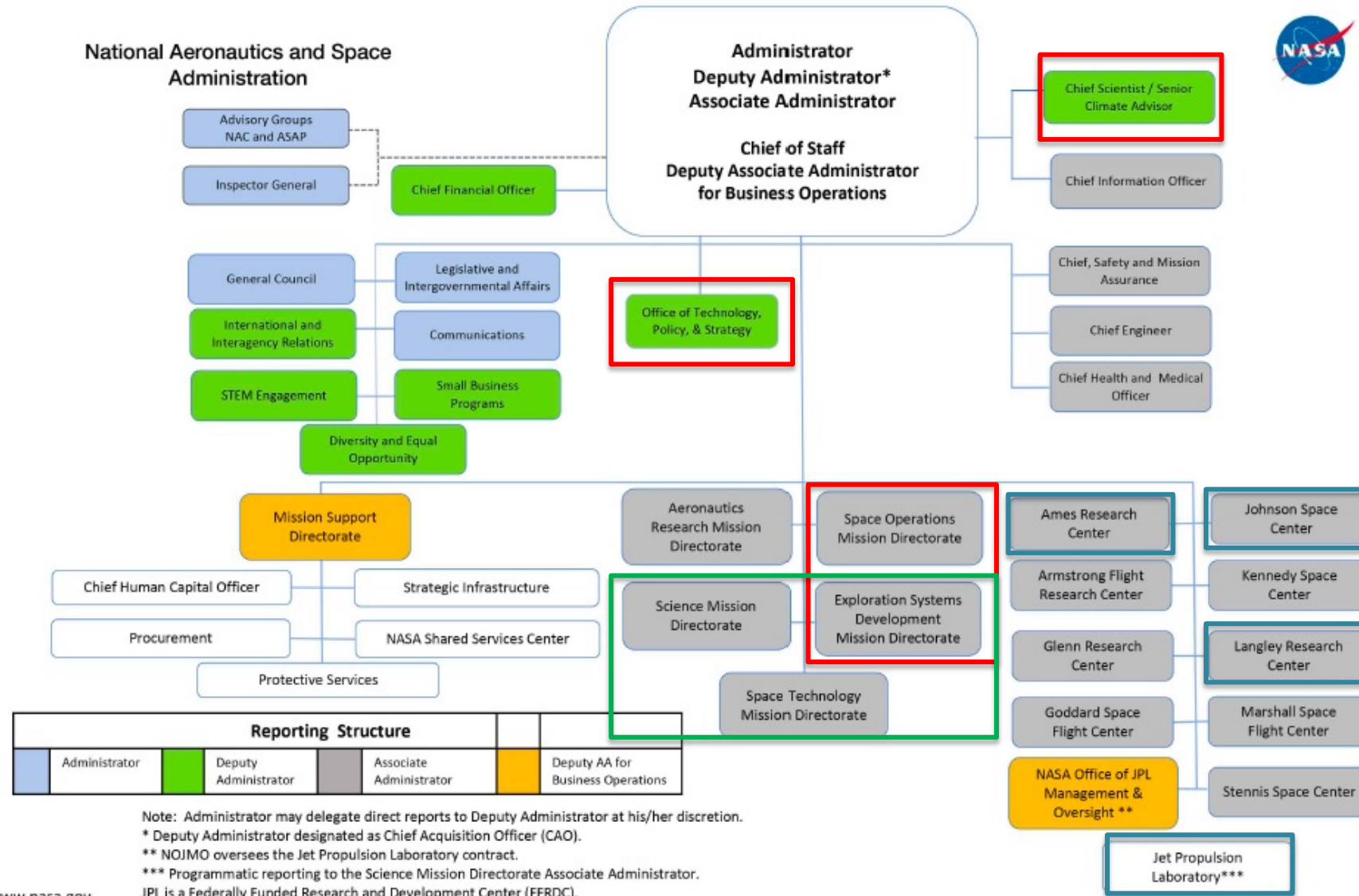


ASPIRE

NASA Taxonomy: TX09

**Propulsion discipline related less directly than others*

NASA Organizational Structure - Context



EDL Involvement by Mission Directorate



Relative Resources/Assets

ESDMD/SOMD

- Orion EDL system development
 - Commercial Crew/Cargo Resupply V&V
 - Human Landing System
 - Gateway/Lunar architecture studies
 - Human Mars architecture studies
-
- Hypersonics facility management
 - Limited Hypersonics tool developments
 - Supports expertise in several EDL component disciplines

STMD

- TRL 3-6+ investments to support other MDs
 - Technology Demonstrations
 - Public-Private Partnership, SBIR, academic opportunities (lower TRL)
 - Investment strategy definition and capability stewardship
-
- Planetary entry systems design, development, and ops
 - Technology incentives, demonstrations and co-funding for flight infusion
 - Accommodation of flight instrumentation

ARMD

SMD

Roughly 600 technical people support ~60-65 AEDL projects, across the Agency.

We Can Think About 3 Major AEDL Areas



- **Human Exploration (Directed and Commercially-Provided):**
 - ✓ Returning humans from Low Earth Orbit
 - Returning humans (and materials) from beyond LEO (Gateway, the Moon)
 - Landing humans and assets (precisely) on the Moon
 - Landing humans and assets (precisely) on Mars
- **Robotic Science (Competed and Directed):**
 - ✓ Mars: 9 successful landings, increasing in scale and performance
 - Rest of the Solar System: The Moon, Venus, Saturn, Titan, Neptune, Uranus, Europa, (Jupiter)
 - ✓ Earth Return of samples (potentially biological, or not)
- **Emerging/Commercial (*cost is key*):**
 - Small spacecraft: perform EDL or aerocapture at Earth or elsewhere
 - Interest in “asset” and on-demand return – rocket stages, goods/materials, etc.



History and State-of-the-Art

NASA's Mars Landing Missions



Photo Credit: NASA

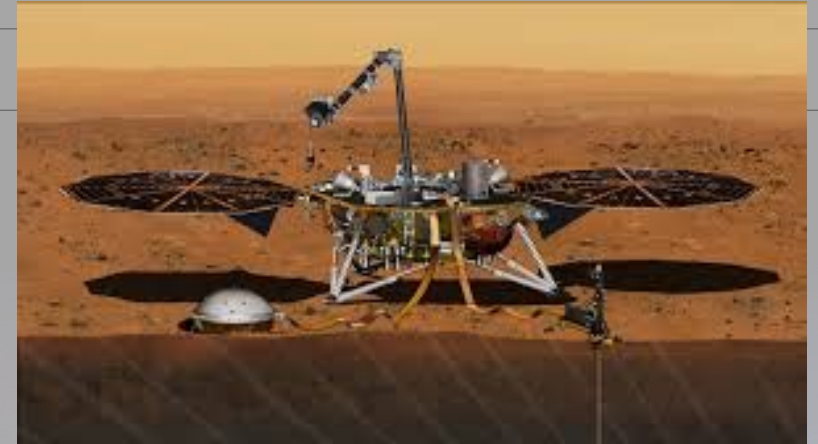
Viking 1 & 2
1976
(600 kg)



Spirit and Opportunity – 2004 (539 kg)



Phoenix – 2008 (364 kg)



InSight – 2018 (375 kg)



Pathfinder
1996
(360 kg)

Photo Credits: NASA/JPL-Caltech



Curiosity – 2012 (899 kg)



Mars 2020 – Perseverance (1,050 kg)

State-of-the-Art: NASA EDL Missions



Viking 2



Stardust



Galileo

Mission	Destination	EDL Date(s)	Capability Demonstrated/SOA Established
Apollo	Earth return	1967-1972	Packed Avcoat TPS, precision guidance
Viking	Mars	1976	Sphere-cone aeroshell, supersonic parachute, pallet
Pioneer Venus	Venus	1978	Carbon Phenolic TPS (SOA not available)
Galileo	Jupiter	1995	Carbon Phenolic TPS (SOA not available), ablation sensor
Pathfinder	Mars	1997	Landing Airbags
Genesis	Earth Return	2004	Carbon-Carbon TPS
MER	Mars	2004	Angular rate control
Stardust	Earth Return	2006	One-piece PICA TPS; fastest Earth entry
Phoenix	Mars	2007	Viking-style pallet lander (no new features)
MSL	Mars	2012	Hypersonic guidance, Sky-crane, MEDLI
InSight	Mars	2018	Viking-style pallet lander (no new features)
Mars2020	Mars	2021	TRN, EDL cameras, MEDLI2
Orion (11 km/s)	Earth return	2022	Block Avcoat TPS, precision guidance
OSIRIS-REx	Earth Return	2023	Stardust entry system (no new features)
MSR SRL	Mars	2028-2029	Highest Mars entry/landed mass, largest parachute
MSR-EES	Earth Return	2031	Class V reliability required; passive capsule w/3MDCP
DAVINCI	Venus	(2032)	Genesis-type aeroshell/TPS at Venus (Pioneer shape)
Dragonfly	Titan	2034	Titan EDL; thermal management over long descent

- EDL design & technologies are specialized for each destination/mission
- Newer missions tend to be more complex; push existing technologies to or beyond their limits
- Conservatism used to minimize risk (to accommodate large uncertainties), but also limits performance

Purple = Future EDL, in development



Architectural Drivers



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



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



Uncrewed HLS Demonstration



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.

Lunar Terrain Vehicle (LTV)

Crew Landing Services

Pressurized Rover

Fission Surface Power

ISRU Pilot Plant

Surface Habitat

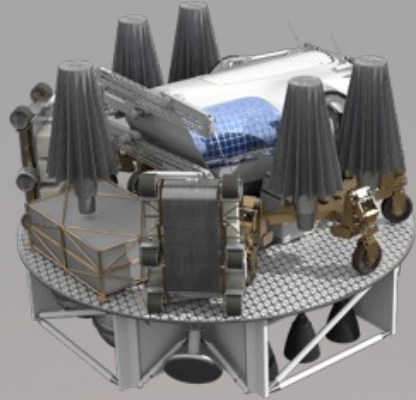
SUSTAINABLE LUNAR ORBIT STAGING CAPABILITY AND SURFACE EXPLORATION

MULTIPLE SCIENCE AND CARGO PAYLOADS | U.S. GOVERNMENT, INDUSTRY, AND INTERNATIONAL PARTNERSHIP OPPORTUNITIES | TECHNOLOGY AND OPERATIONS DEMONSTRATIONS FOR MARS

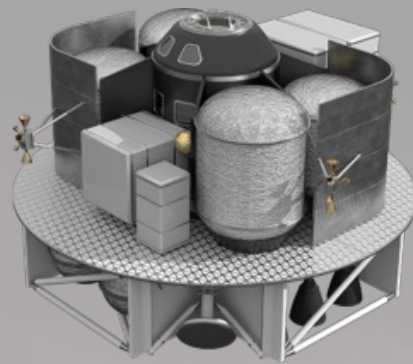
Human Mars Mission: Landing Multiple 2-Story Houses



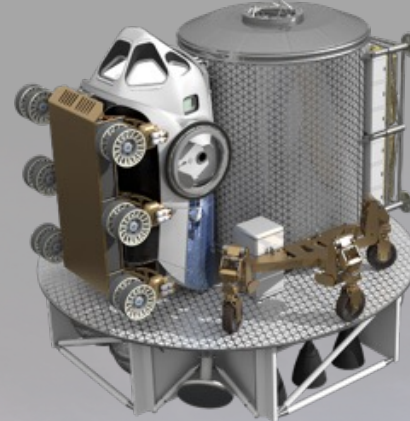
- Establishing sustained Human presence will require multiple landers
- NASA's Evolvable Mars Campaign identified a 4-lander manifest



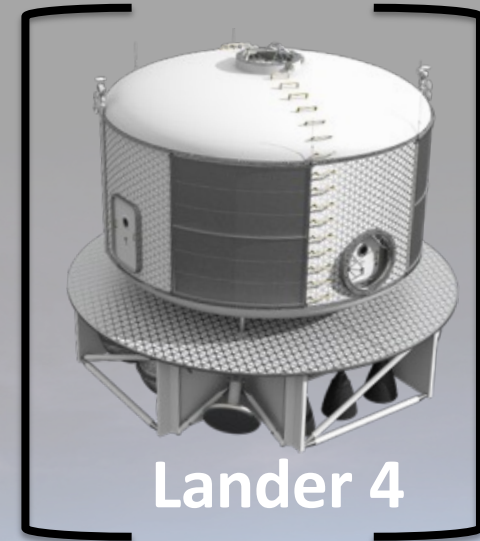
Lander 1



Lander 2



Lander 3



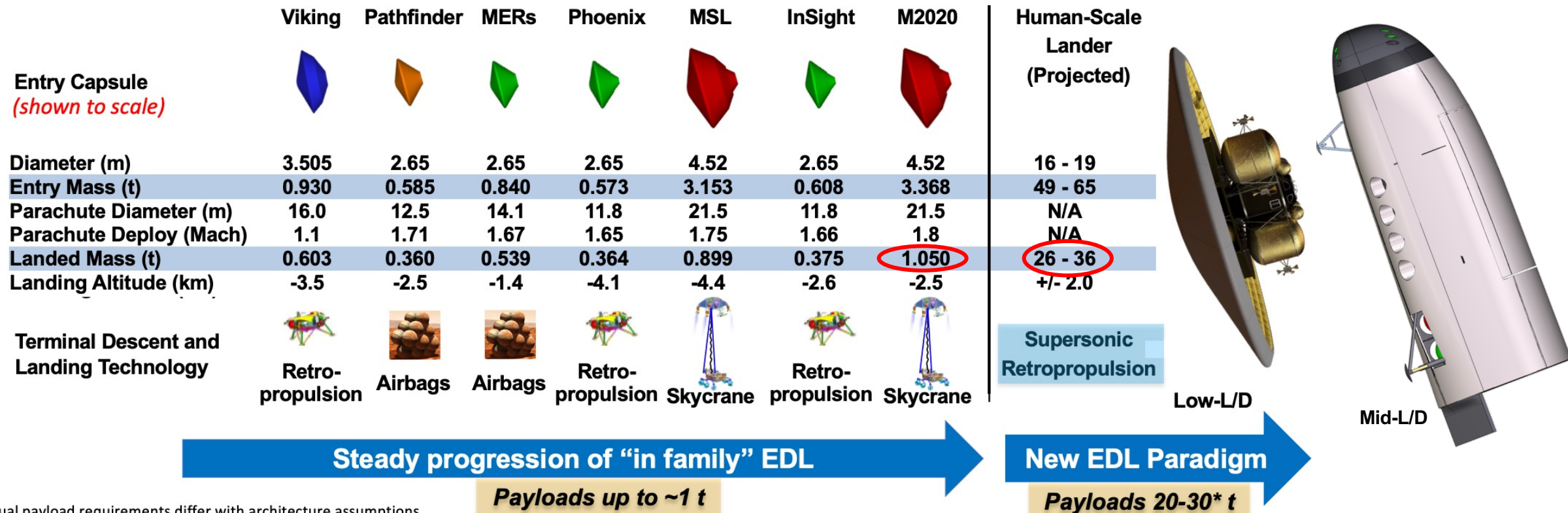
Lander 4

- Each payload is ~ 20t and must land within 50 m of a target
- Must remain 1 km from other landed assets to prevent damage

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”)



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*	Potential Aerocapture for orbiter; atmospheric modeling, aero/aerothermal modeling, mass-efficient entry system
	Enceladus Orbilander*	<i>Precision landing/hazard avoidance?</i>
	Europa Lander*	<i>Hazard detection and avoidance</i>
	Mercury Lander*	<i>Precision landing/hazard avoidance?</i>
	Neptune-Triton Odyssey	Aerocapture for orbiter (?); atmospheric modeling, aero/aerothermal modeling, mass-efficient entry system (if a probe is used)
	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>



Technology Response to Drivers

STMD Strategic Technology Framework Reflects AEDL Areas



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 Breaking news: LAND and EXPLORE are open for comment: NSPIRES - Solicitations Summary (nasaprs.com)	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

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)*

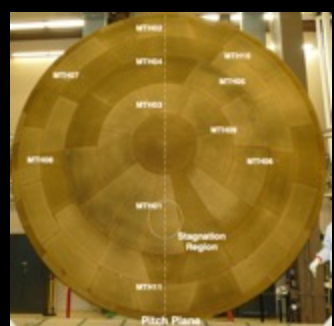
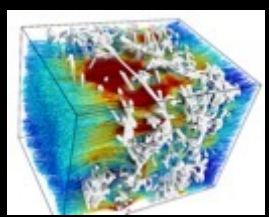
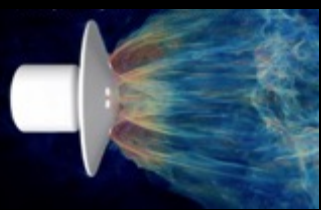


Plume Surface Interaction

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

Retropropulsion

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



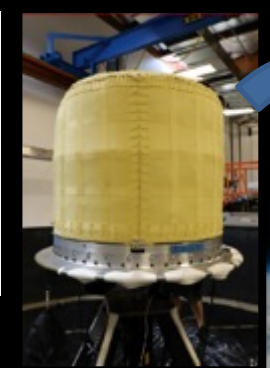
Foundational Modeling, Testing, Instrumentation, and Computing

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

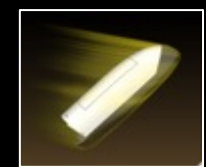
MARS CAPABILITIES

Large Scale Demonstrations

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

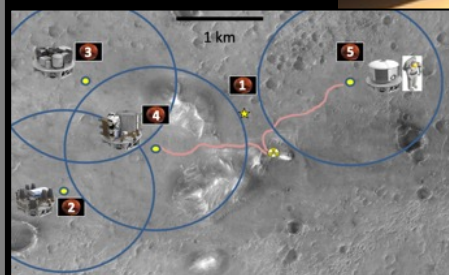


Earth Flight Tests, such as LOFTID



Assess Alternatives

Aggregate Assets



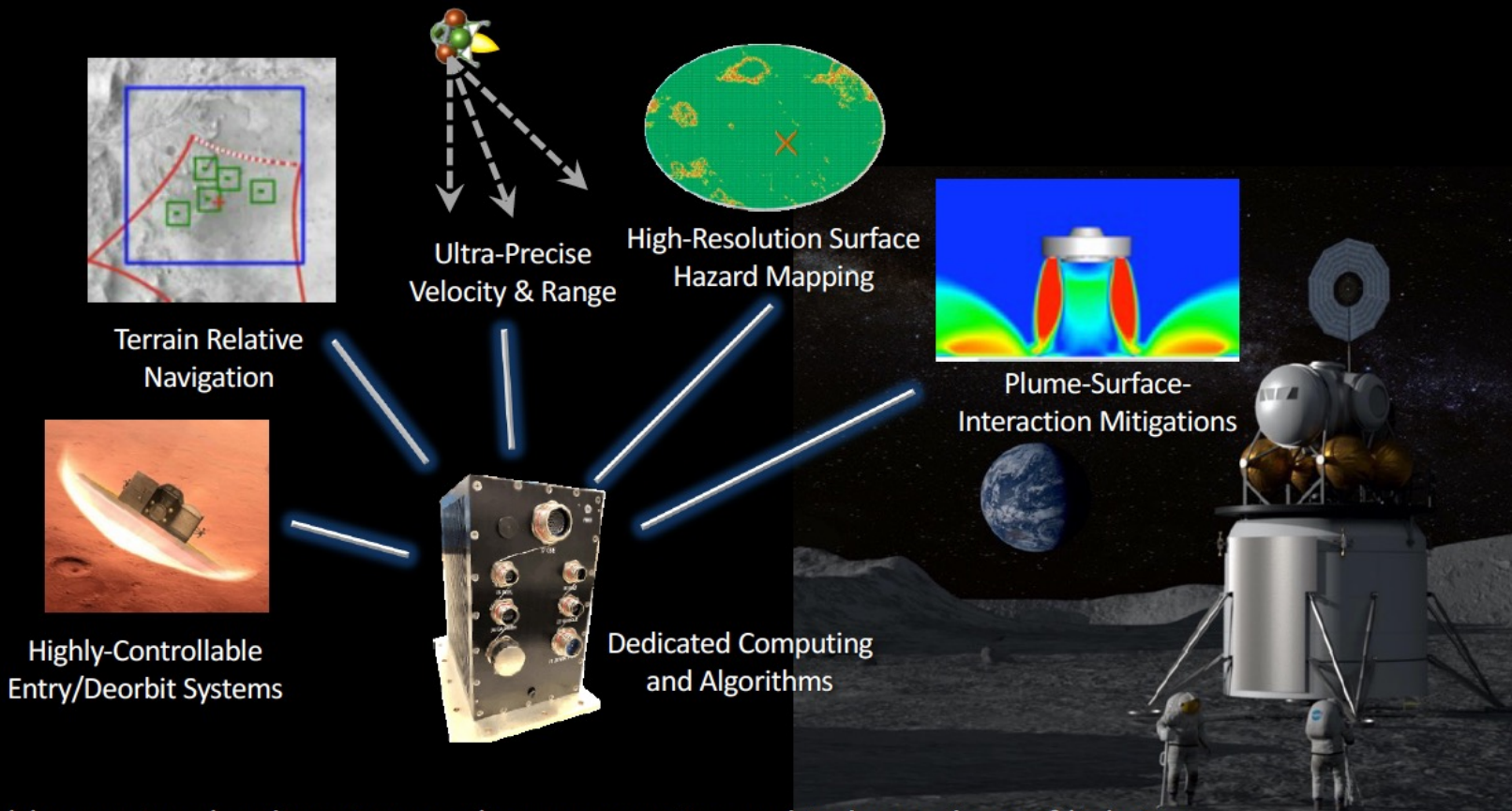
Human Mars EDL



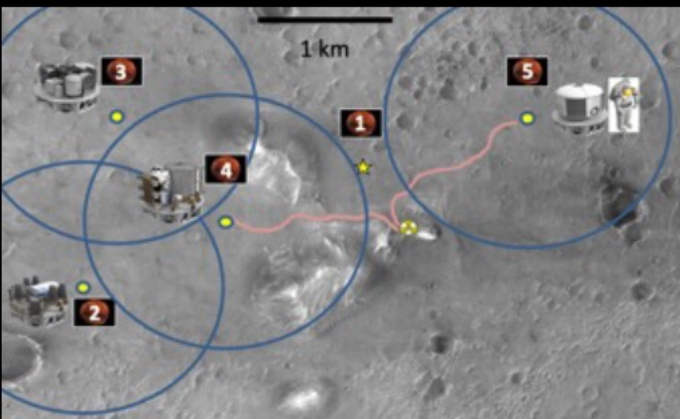


LAND: Technologies to Precisely Land Payloads and Avoid Landing Hazards

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



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

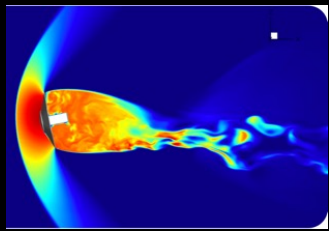
LAND: Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies



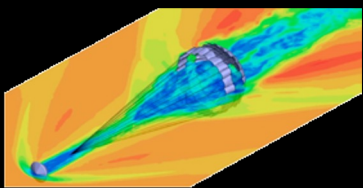
Developing atmospheric entry technology to enhance and enable small spacecraft to Flagship-class missions across the solar system

Entry Systems Modeling & Testing

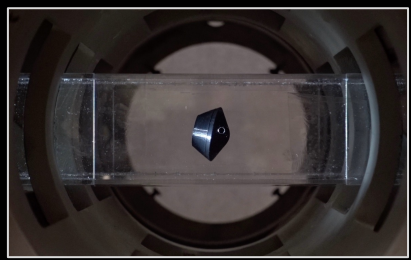
Reducing entry system mass and risk by developing advanced, validated models



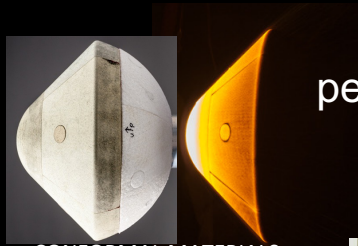
"DESKTOP WIND TUNNEL"



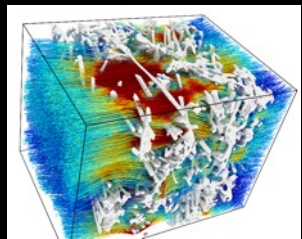
PARACHUTE MODELING



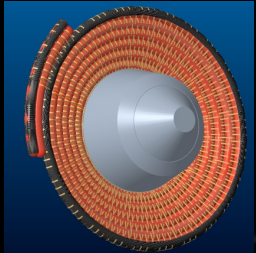
MAGNETIC SUSPENSION WIND TUNNEL



CONFORMAL MATERIALS



IN-DEPTH MATERIAL RESPONSE



DEPLOYABLE DECELERATORS

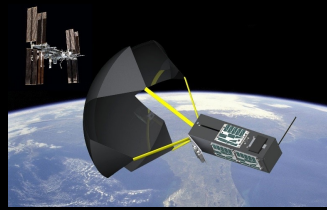
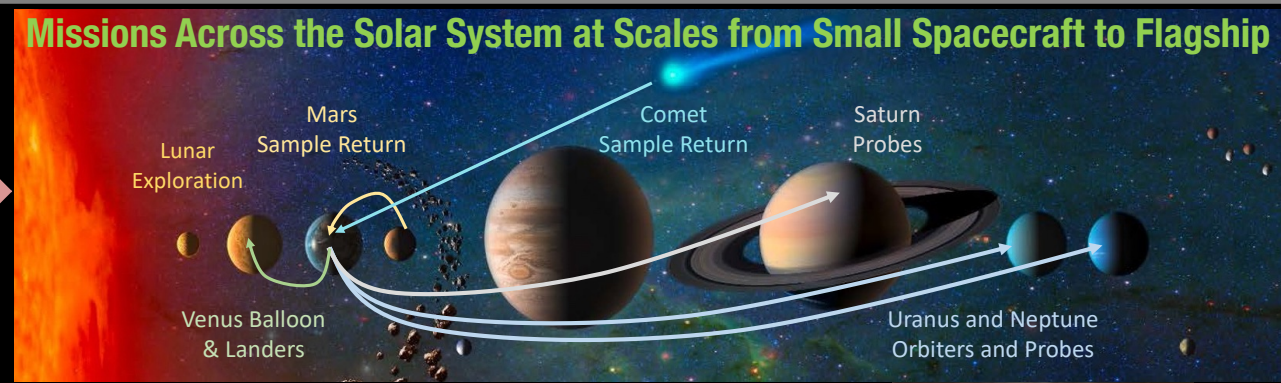


3D WOVEN HEATSHIELDS

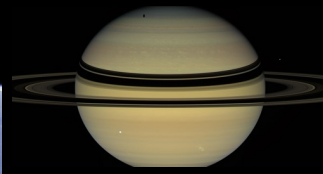
to enable

Hardware Development

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



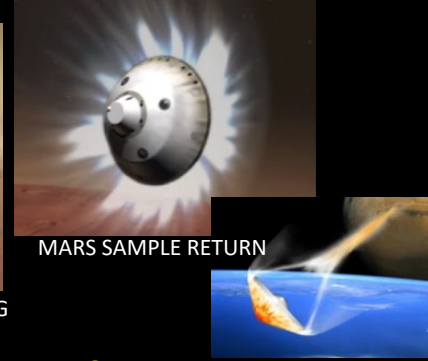
PRECISION DEORBIT



SATURN PROBE



TITAN PINPOINT LANDING

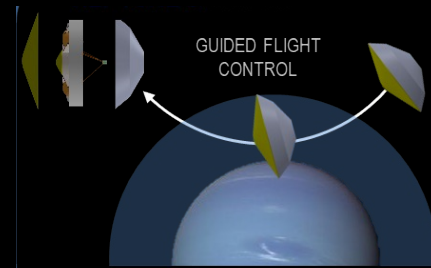


MARS SAMPLE RETURN

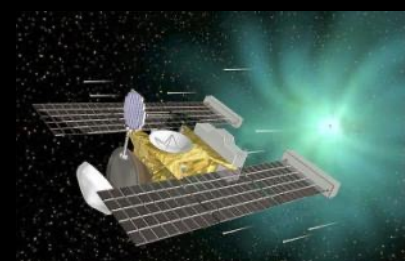
Increasing Science Return, Decreasing Risk, Cost, and Schedule



ICY MOON PRECISE LANDING



ICE GIANT AEROCAPTURE

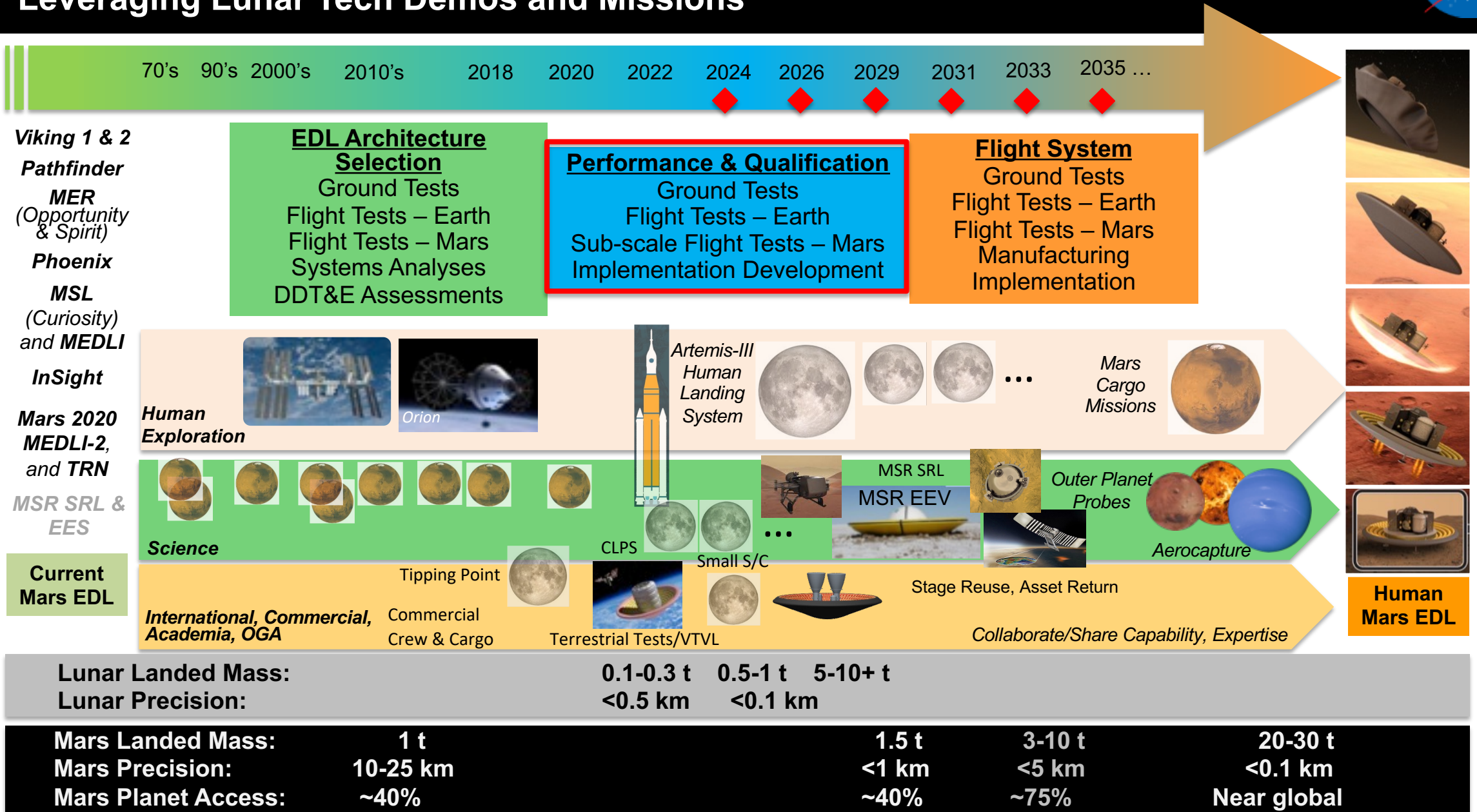


HIGH-SPEED SAMPLE RETURN

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

Mars EDL is a Long-Term Challenge

Leveraging Lunar Tech Demos and Missions



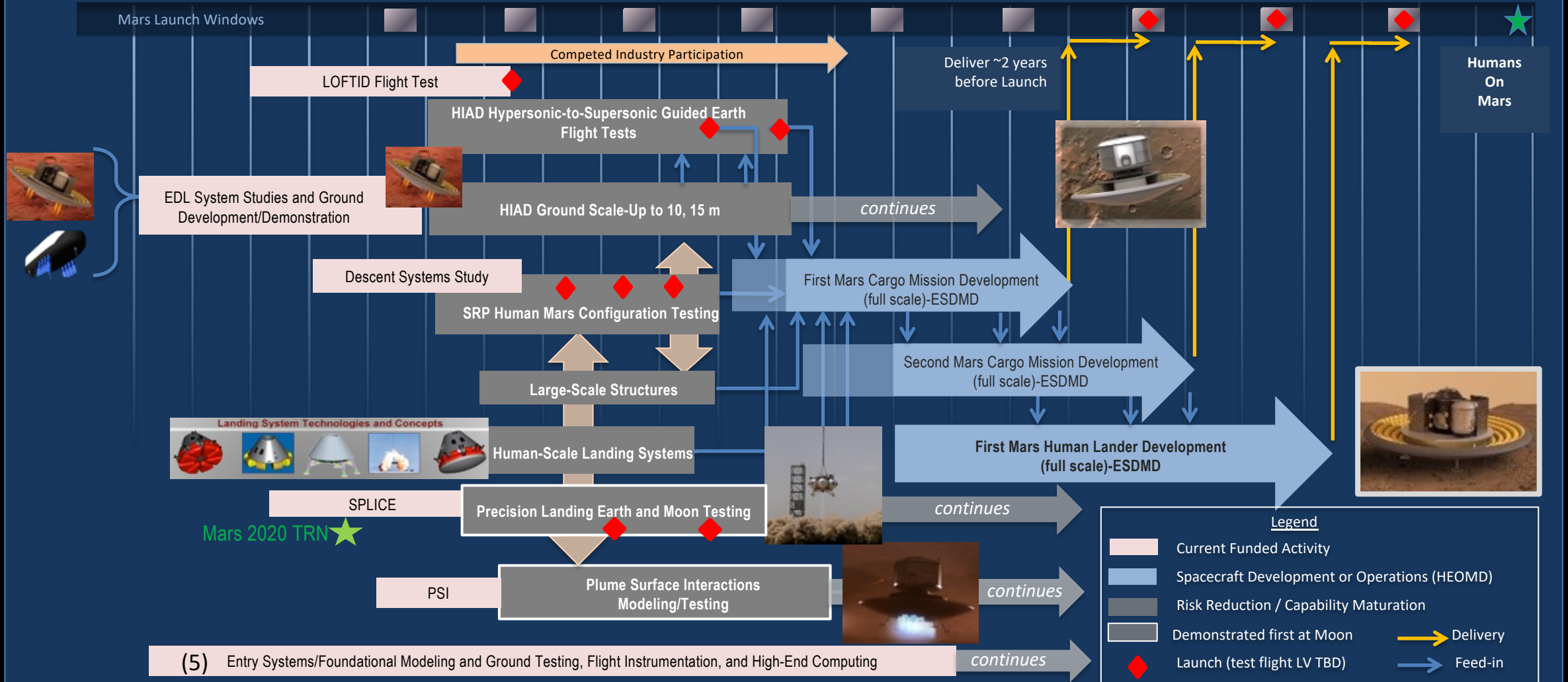
Mars Crew / Cargo Landers for 20t Payloads

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.





Current/Recent Investments/Activities

Current Investments to Achieve 20t Landings



LOFTID

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



DLC



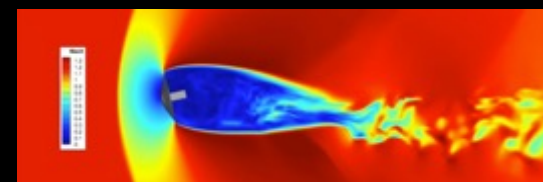
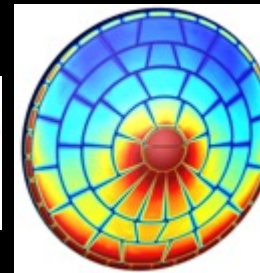
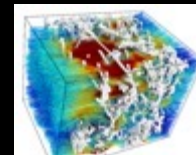
HDS Head



NDL

*SPLICE

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



Entry Systems Modeling (ESM)

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



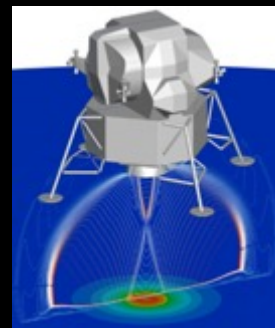
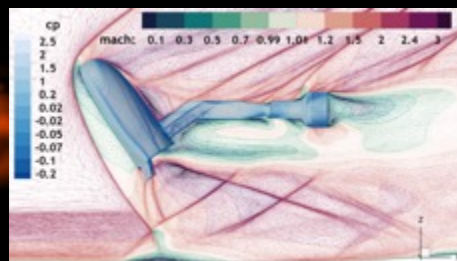
MEDLI2

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



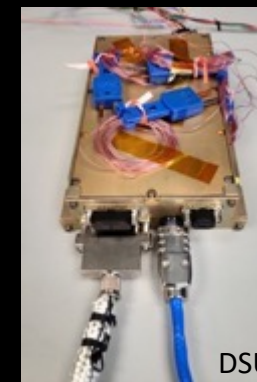
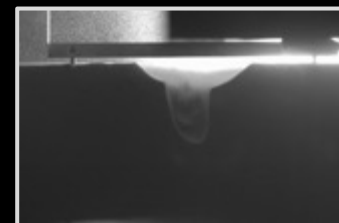
Descent Systems Study

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

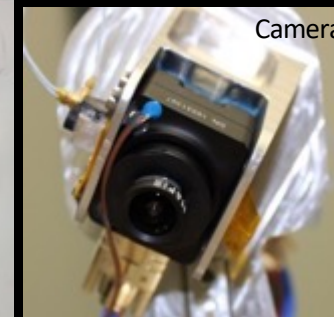


*Plume Surface Interaction (PSI)

Model Advancement and Validation through Ground Testing, Flight instrument maturation



DSU



Camera

*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

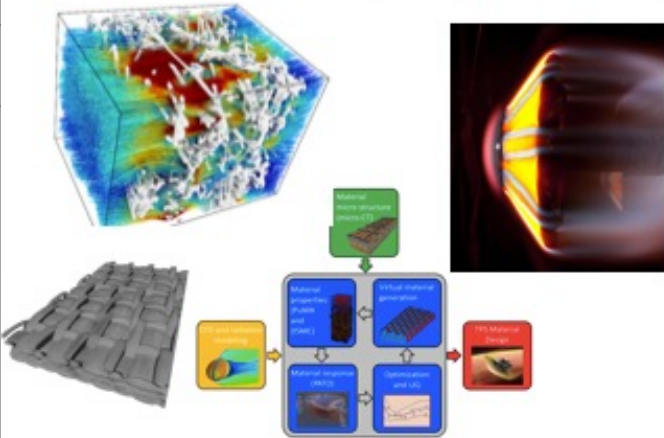
*Orange = Demonstration for Lunar missions in Near Term; Lunar-focused investments feed forward directly to Mars

Entry Systems Modeling (ESM) Portfolio



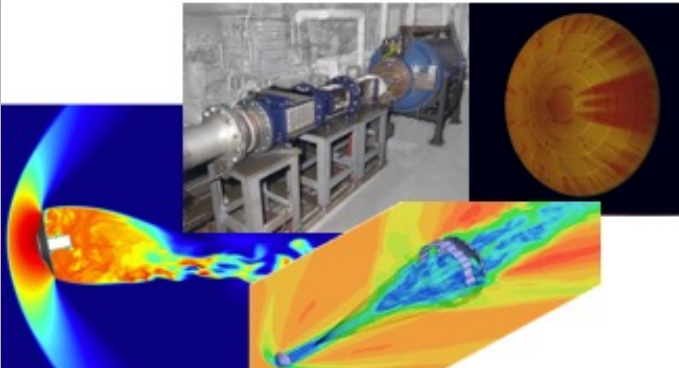
Predictive Materials Modeling

Advanced models for SMD materials; Micro- to engineering-scale analysis tools; Detailed material characterization; Computational design



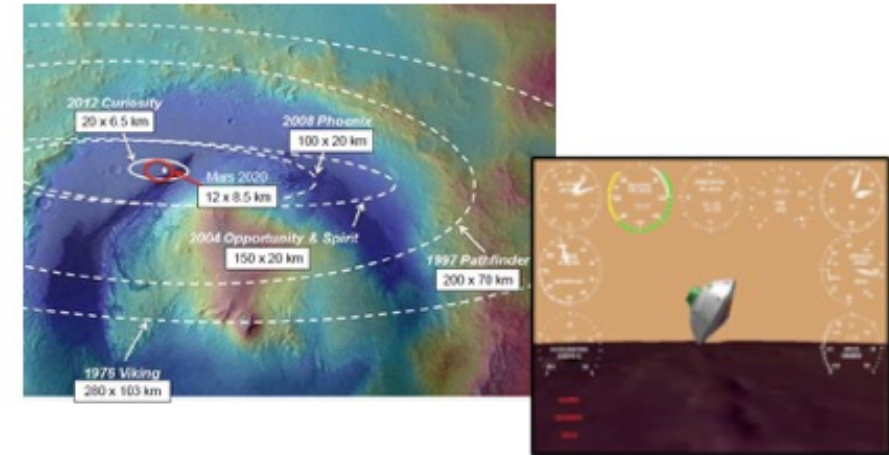
Aerosciences

Parachute dynamics; Free-flight CFD; Magnetic suspension wind tunnels; Experimental validation; Roughness, Advanced computational methods



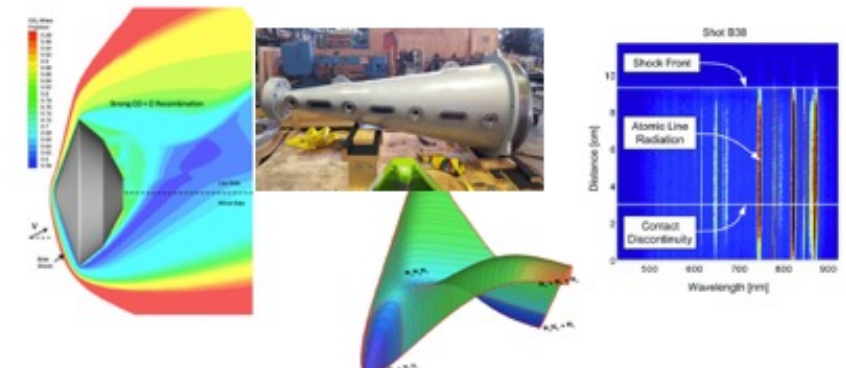
Guidance, Navigation, and Control

Entry guidance methods to enable precision landing of large robotic and human Mars missions



Shock Layer Kinetics and Radiation

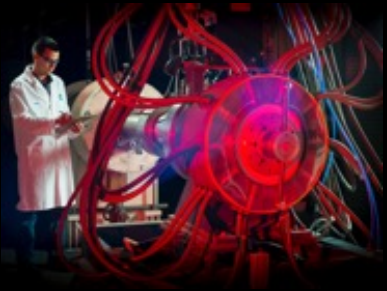
Heatshield and backshell radiation databases and models for all destinations of interest; High-fidelity coupled analysis tools



Model Validation: From Testing



Those robust AEDL Modeling and Simulation capabilities in turn RELY on ground testing, flight testing, and data return from missions for validation data or “truth.” This is a key area of international collaboration.



Shock Tubes and Ballistic Ranges



Sounding Rockets



VTVL Rockets



Arc Jets



Wind Tunnels



Landing Test Facility

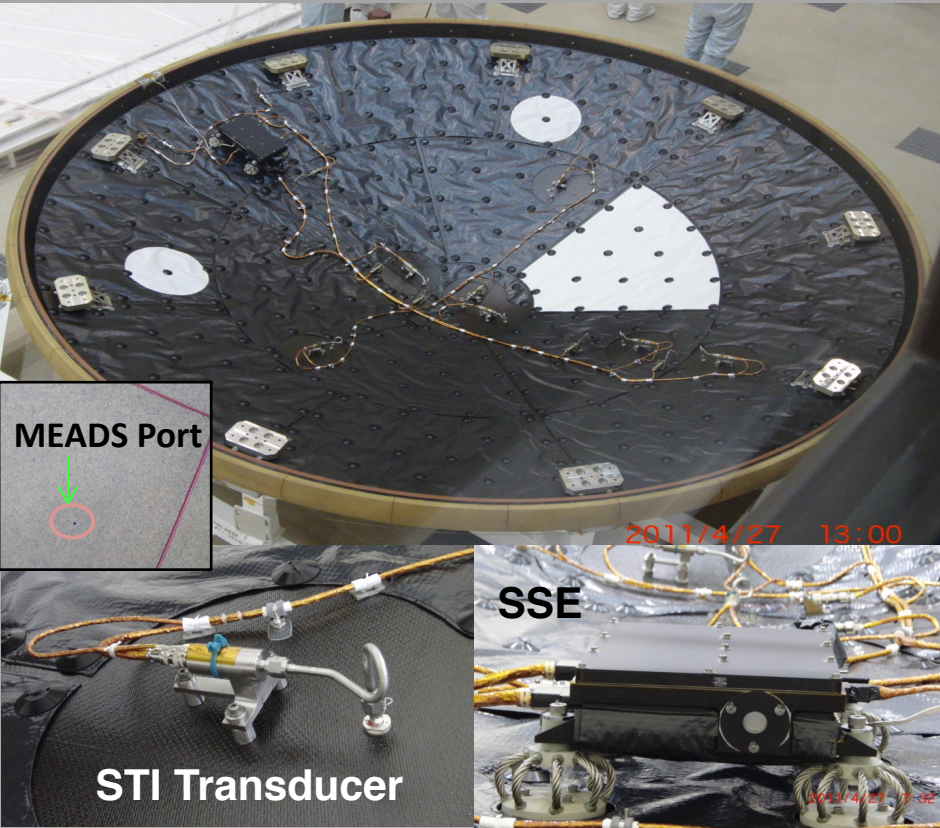


Balloons

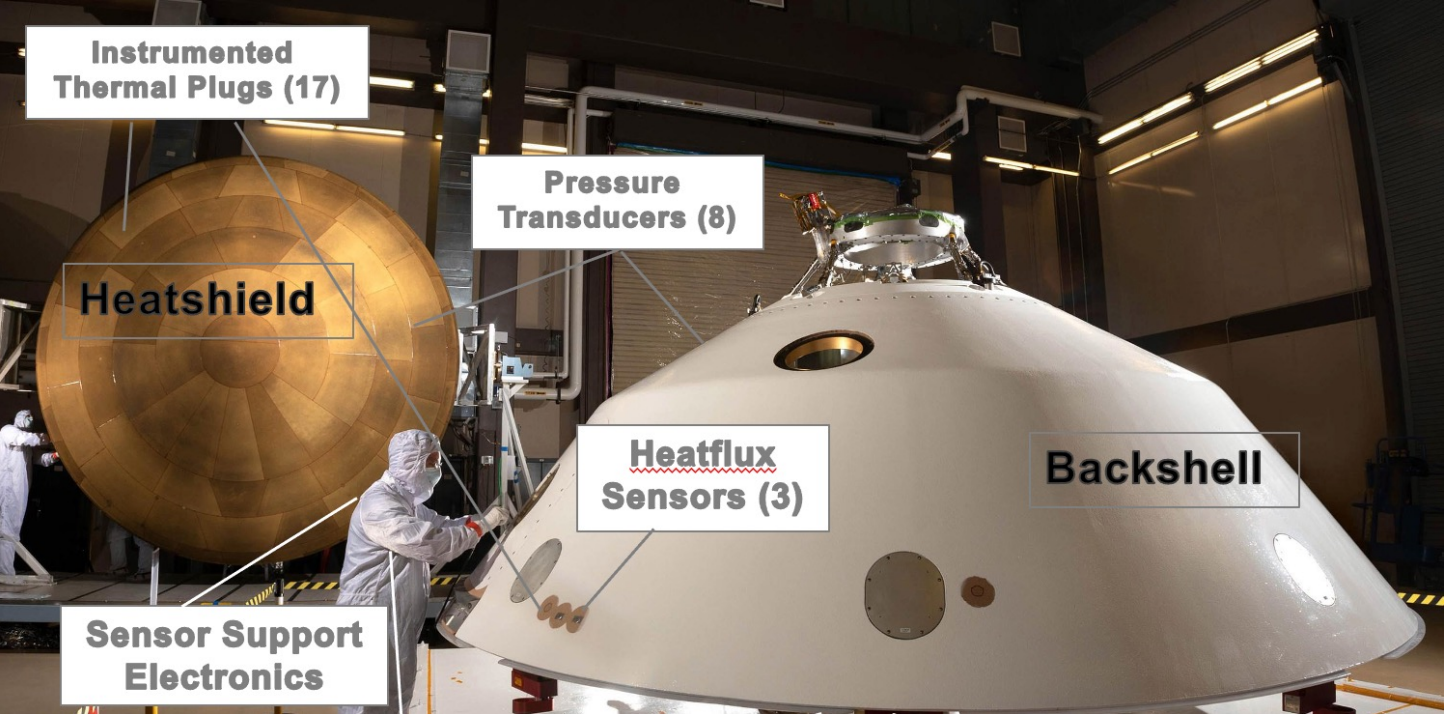
+ Airplanes, helicopters, etc!

The community uses a host of ground facilities and flight platforms to test various aspects of AEDL

Gathering In-Situ Data from Missions

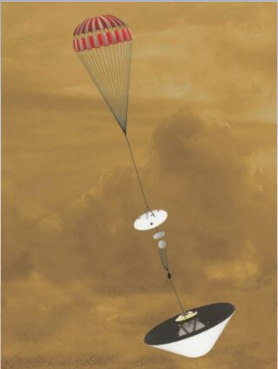


Mars Science Laboratory Instrumentation (MEDLI)

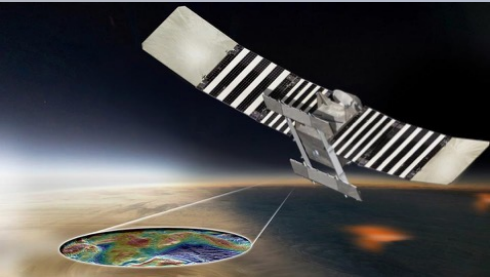


Mars 2020 Instrumentation (MEDLI-2)

Dragonfly Instrumentation (DrEAM)

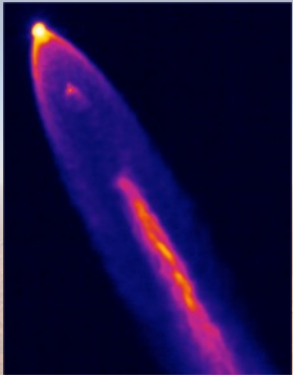


DAVINCI ESI



VERITAS ESI

Airborne Observation (SciFli)



Planetary EDL Subsystem SOA

Atmosphere Models



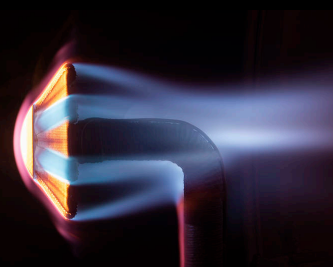
- GRAM update for PSD destinations of interest nearing completion; New data inclusion forthcoming

TPS

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



HEET



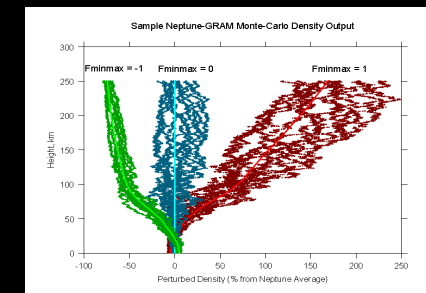
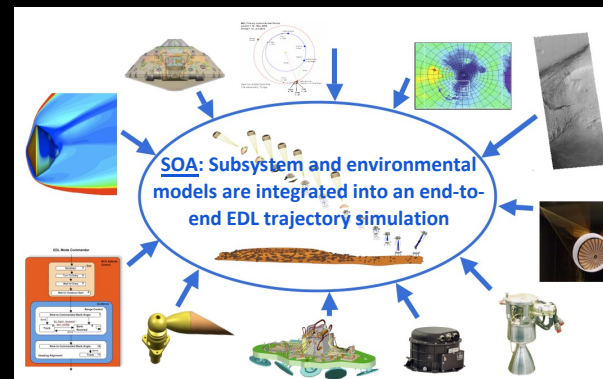
ADEPT/Spiderweave



PICA

GN&C Modeling

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

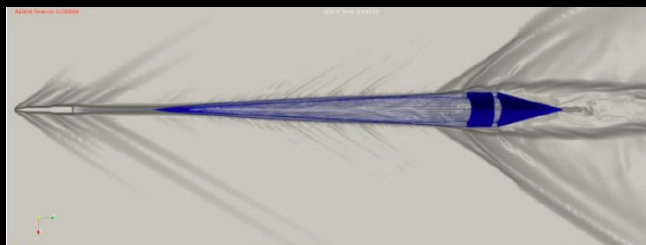


Parachutes

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



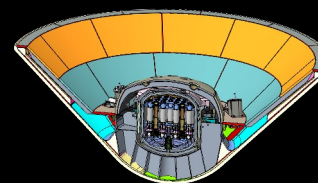
M2020 Parachute



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

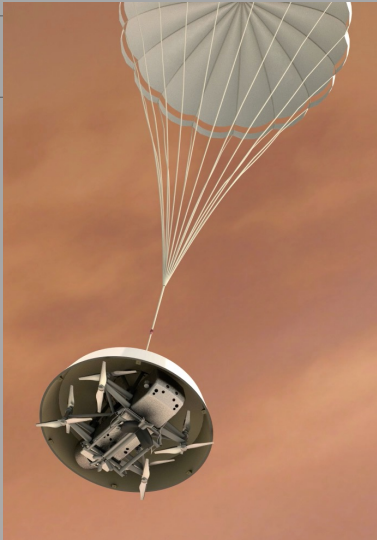
Recent/Current AEDL Highlights/Activities



Dragonfly, Launch 2027

PDR Oct 2022

DrEAM Aeroshell Instrumentation



LOFTID Test, Launch Nov 2022

Largest blunt aeroshell



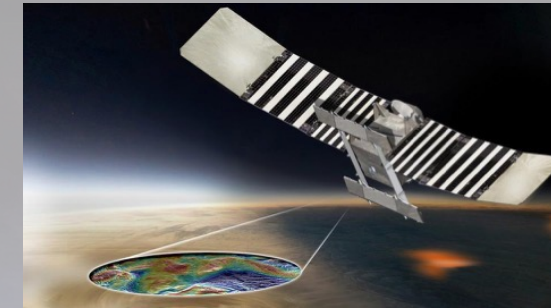
MEDLI2 on M2020
Deep Dive analysis underway



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



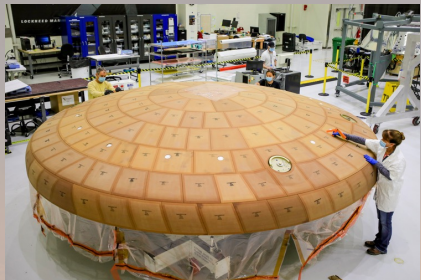
Mars Sample Retrieval Lander, Ascent Vehicle &
Earth Return Orbiter, Launch 2028
MSR EES using STMD-developed TPS



VERITAS - Launch 2028
Aerobraking ESI



DAVINCI
Launch 2029
New TPS, Aeroshell
strumentation

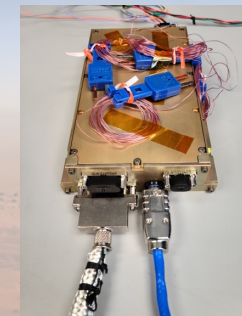


Artemis 1 – Ready to Fly!
NASA instrumentation
SCIFLI aerial imagery



Support to CCP

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



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**

- EDL Challenges:
- 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 late 2020's or early 2030's**

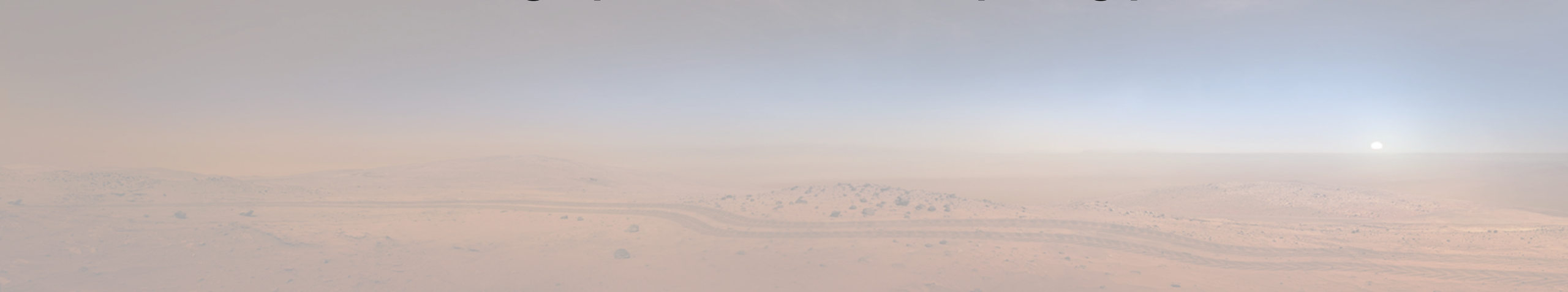
- EDL Challenges:
- Landing ~1500 kg precisely, next to samples that Mars 2020 caches
 - Landing a rocket on Mars and autonomously launching it
 - Returning the samples to Earth in a capsule with a very low probability of failure

- **Scientists want to go to Venus, Ice Giants, Ocean Worlds, and Outer Planets (& back)**
 - EDL Challenges: aerocapture, 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

Emerging Trends



- **Commercial space seeking to provide AEDL solutions**
- **Smallsats (in general, inexpensive missions) - more demand for interplanetary capability**
- **Use of AI/ML for greater autonomy and decision-making**
- **Higher demand for precision – will require facilities improvements**
- **Increased use of high-performance computing platforms**



Summary

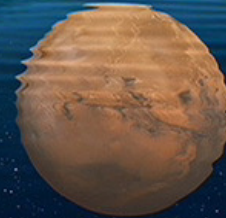


- AEDL is a critical exploration function made of specialized disciplines and subsystem designs
- Our community is a critical part of NASA's lunar, Mars, other science, and commercial partnership/economic growth objectives
- We have many ongoing missions in development, technology maturation efforts, and engagements with industry
- International and academic partnerships help advance foundational efforts through unique facilities and expertise.
- *The future of AEDL is bright, and we need the next generation of engineers, researchers and technologists to meet the world's exploration goals!*

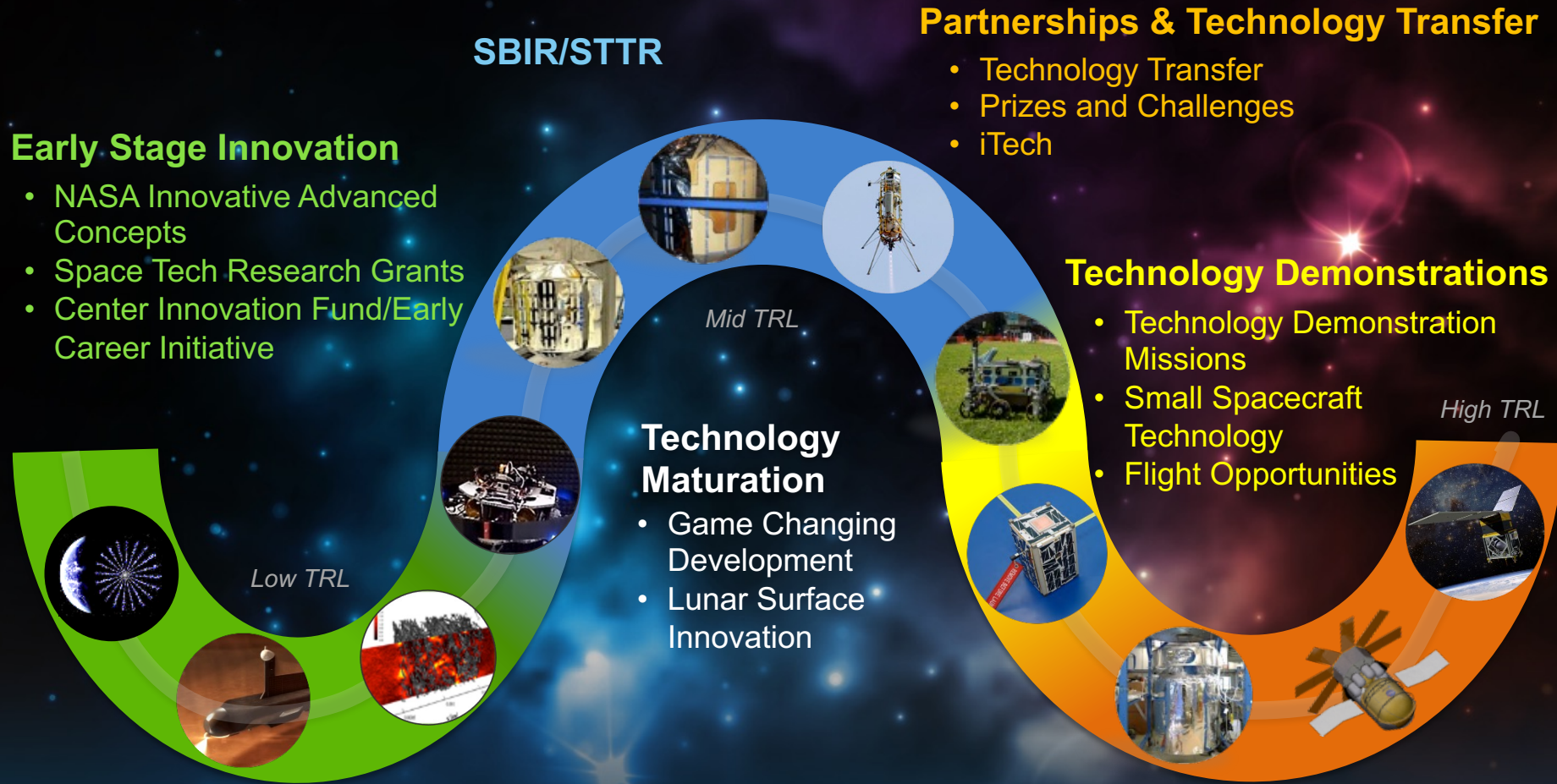


EXPLORE MOON_{to}MARS

Thank you!



STMD Programs – Means to the End Goal



TECHNOLOGY PIPELINE

Role of Modeling and Simulation in AEDL



Planetary entries cannot be practically tested end-to-end on Earth; flight performance assessment and certification RELIES on robust AEDL Modeling and Simulation capabilities.

➤ **Models, particularly in aerosciences and material response, have largely undefined uncertainty levels for many problems (limited validation)**

- Without well-defined uncertainty levels, it is difficult to assess system risk and to trade risk with other subsystems, leading to increased schedule and cost

➤ **Missions get more ambitious with time**

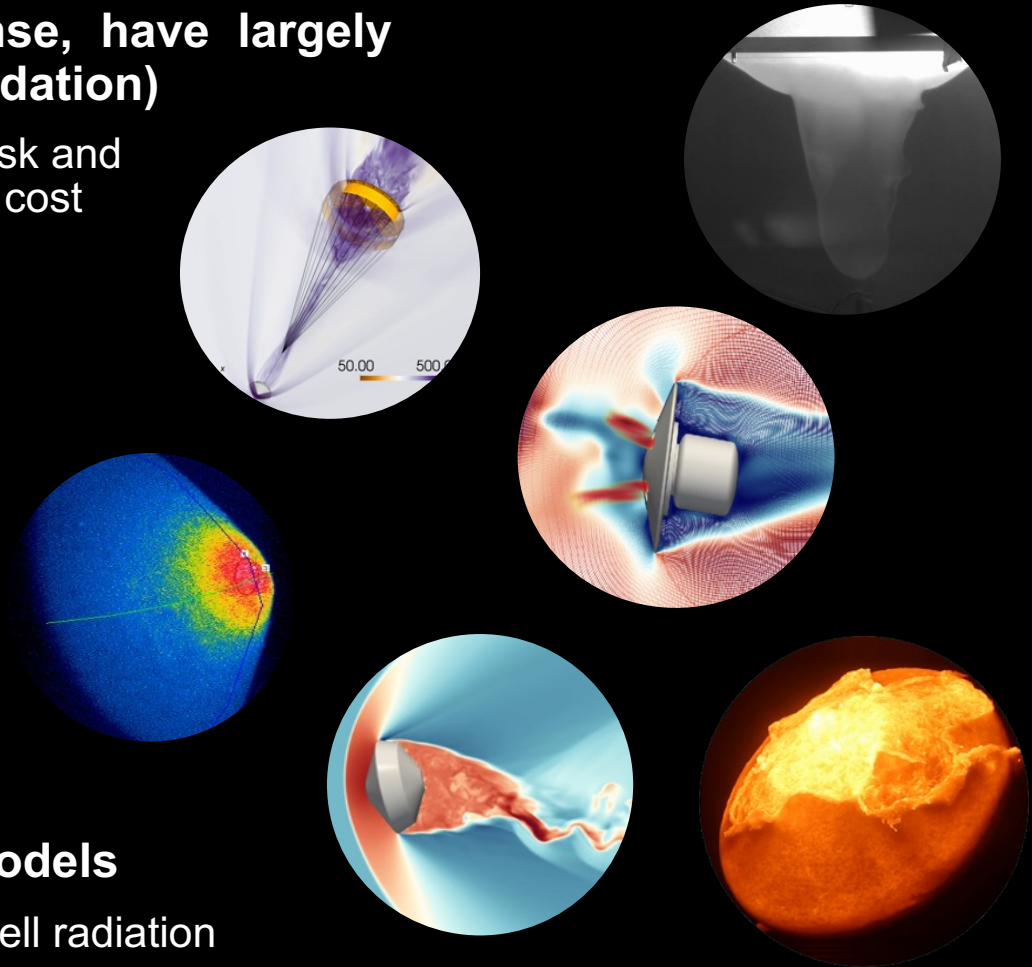
- Tighter mass and performance requirements
- More challenging EDL conditions requires that models evolve or the missions of tomorrow will remain out of our grasp

➤ **Even reflights benefit from improvement**

- Reflights are never truly reflights; changing system performance requires new analysis, introduces new constraints
- 'New physics' still rears its head in these disciplines

➤ **Some of the most challenging problems have the “worst” models**

- Parachute dynamics, separation dynamics, TPS failure modes, backshell radiation



Focused investment in development and validation of AEDL Modeling and Simulation (M&S), *guided by mission challenges*, ensures that NASA is ready to execute the challenging planetary science missions of tomorrow.

- [illegible]

- 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.

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**