National Aeronautics and Space Administration

Entry, Descent and Landing (EDL) “State of the Union”

Briefing to Summer Students and the NESC Academy

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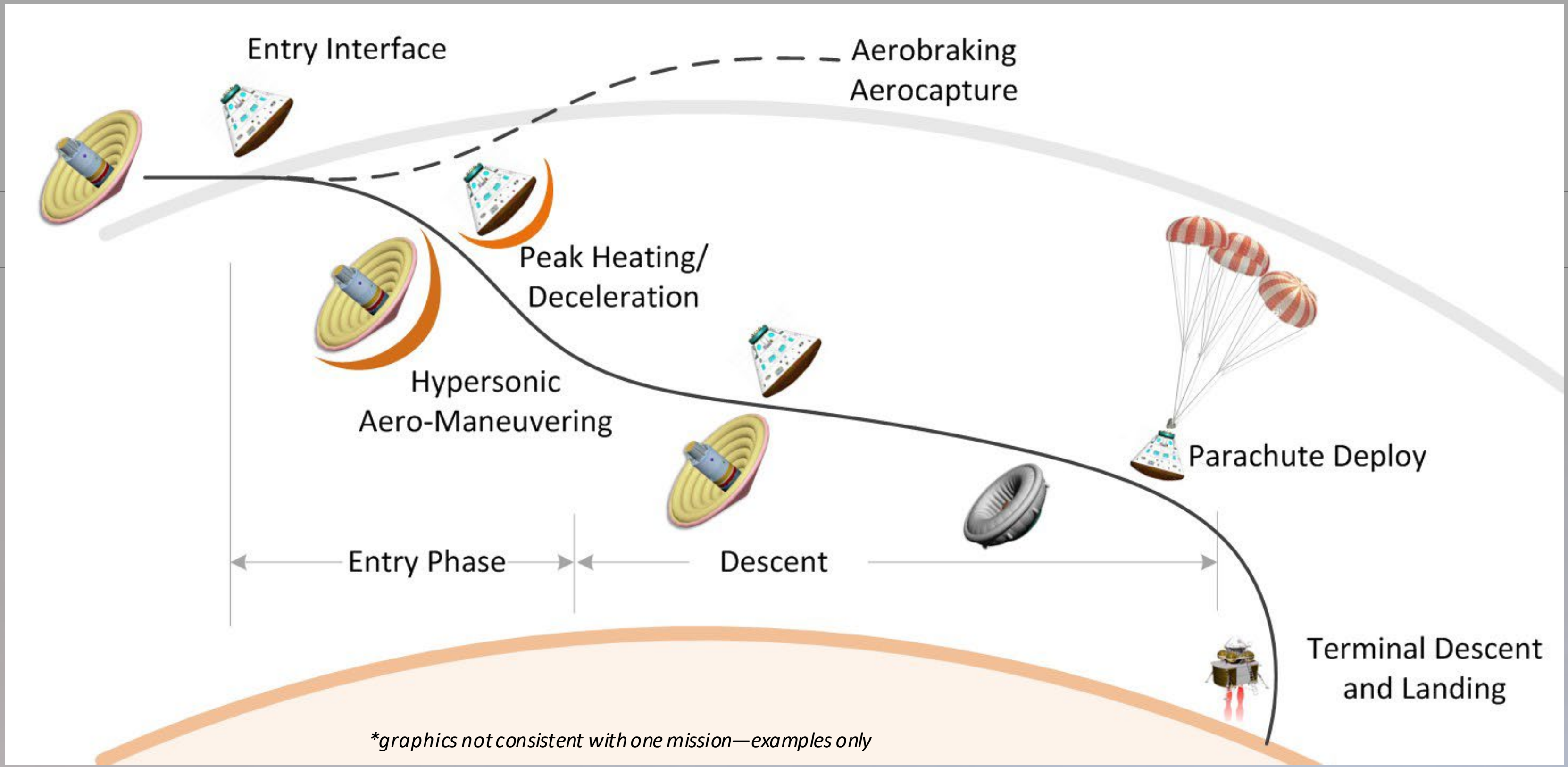
Outline

- **EDL Definition and Context**
- **Architectural Drivers**
- **STMD Strategic Framework**
- **Envisioned Future Priorities and Gaps**
  - Landing Heavy Payloads
  - Precision Landing and Hazard Avoidance
  - EDL at Science Destinations
- **Current Investments and Upcoming Missions**
- **Next Steps**

Entry, Descent and Landing (EDL)

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

EDL Sub-Capabilities

Analytical/ Discipline

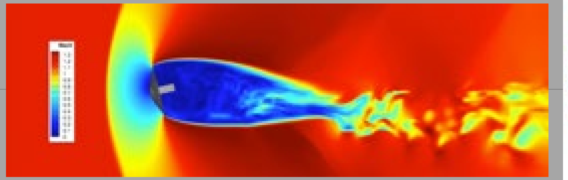
- Aerodynamics
- Aerothermodynamics
- Flight Dynamics/Design
- Thermal
- Modeling and Simulation
- *Plume Surface Interaction*

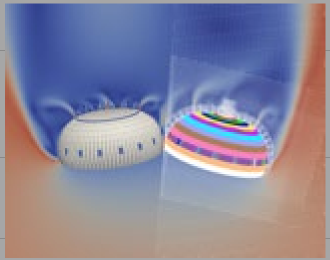
Hardware

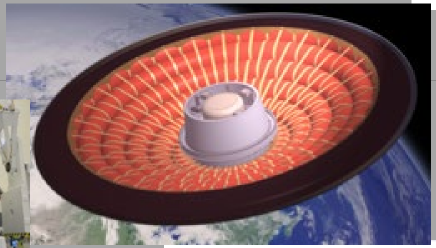
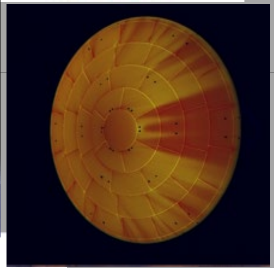
- Avionics
- GN&C
- Instrumentation
- Materials – High Temperature/TPS
- Mechanical Design
- *Propulsion**
- Structures
- Textiles

System Level

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

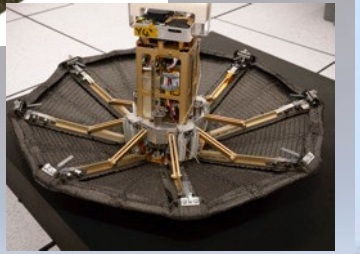
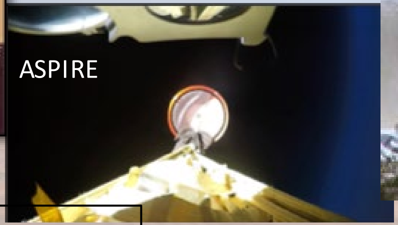






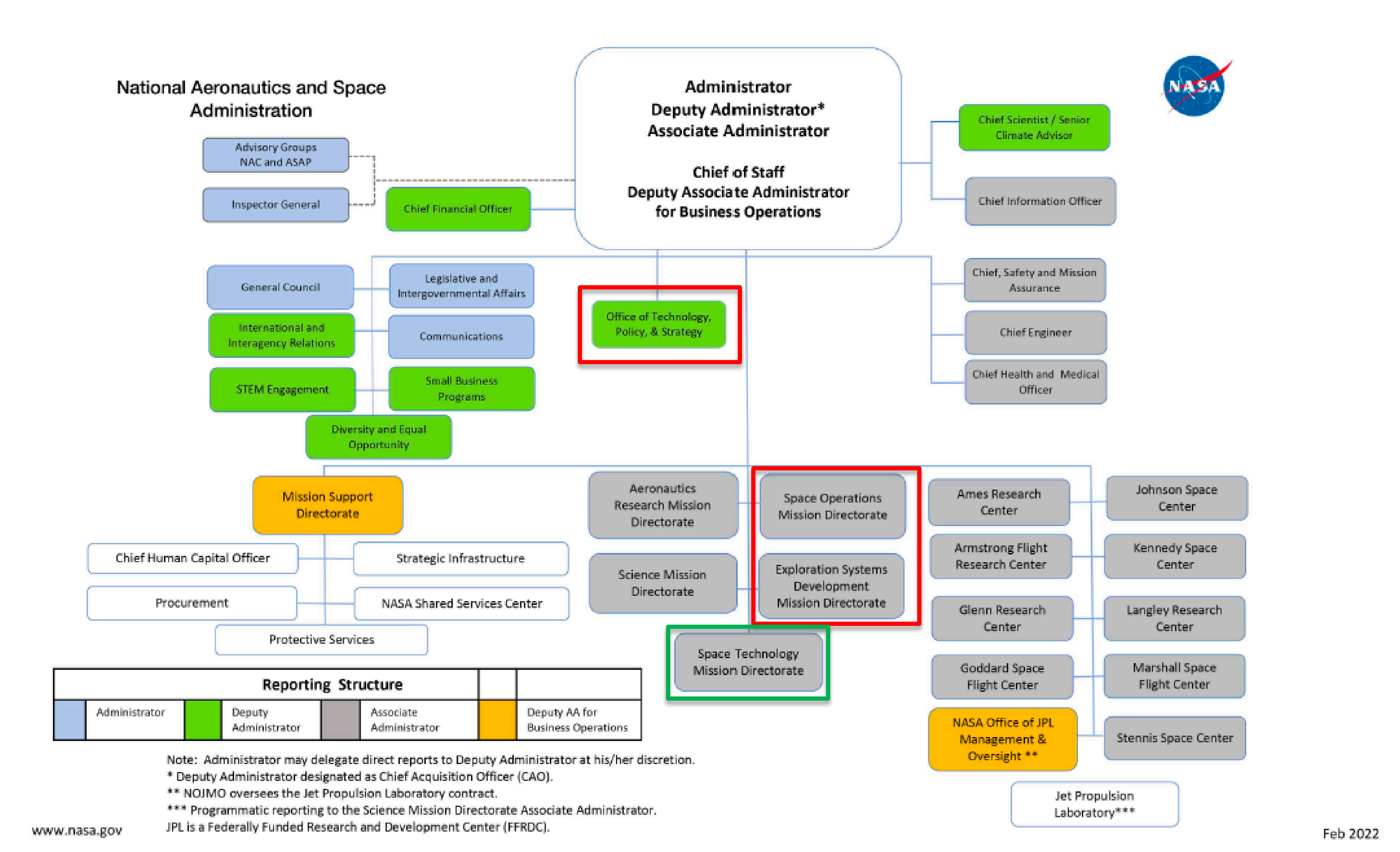


NASA Taxonomy: TX09

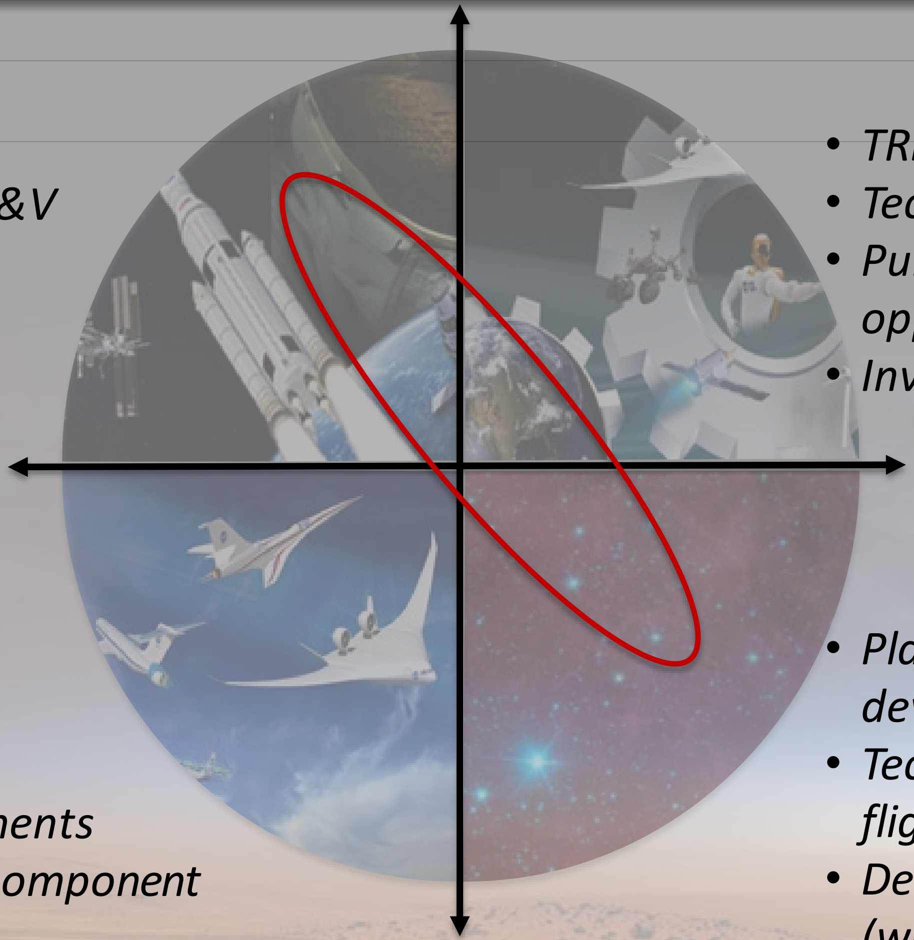
**Propulsion discipline related less directly than others*

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*

STMD

- *TRL 3-6+ investments to support other MDs*
- *Technology Demonstrations*
- *Public-Private Partnership, SBIR, academic opportunities*
- *Investment strategy definition*

ARMD

- *Hypersonics facility management*
- *Limited Hypersonics tool developments*
- *Supports expertise in several EDL component disciplines*

SMD

- *Planetary entry systems design, development, and ops*
- *Technology incentives and co-funding for flight infusion*
- *Development of Strategic Knowledge Gaps (with ESDMD)*

We Can Think About EDL in 3 Bins

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

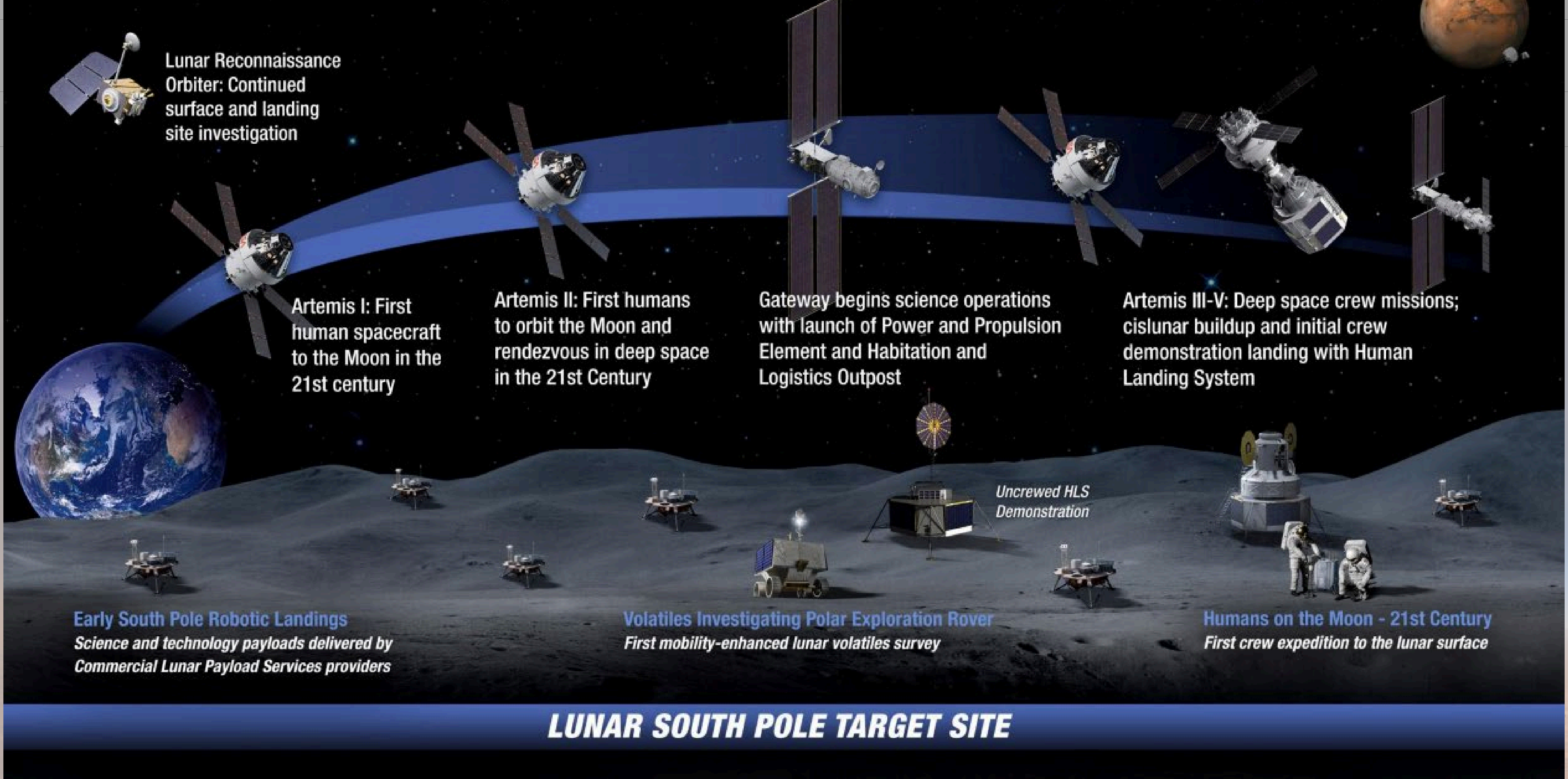
STMD Strategic Technology Framework

Lead	Thrusts	Outcomes	Primary Capabilities
	Transforming Space Missions		
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	**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

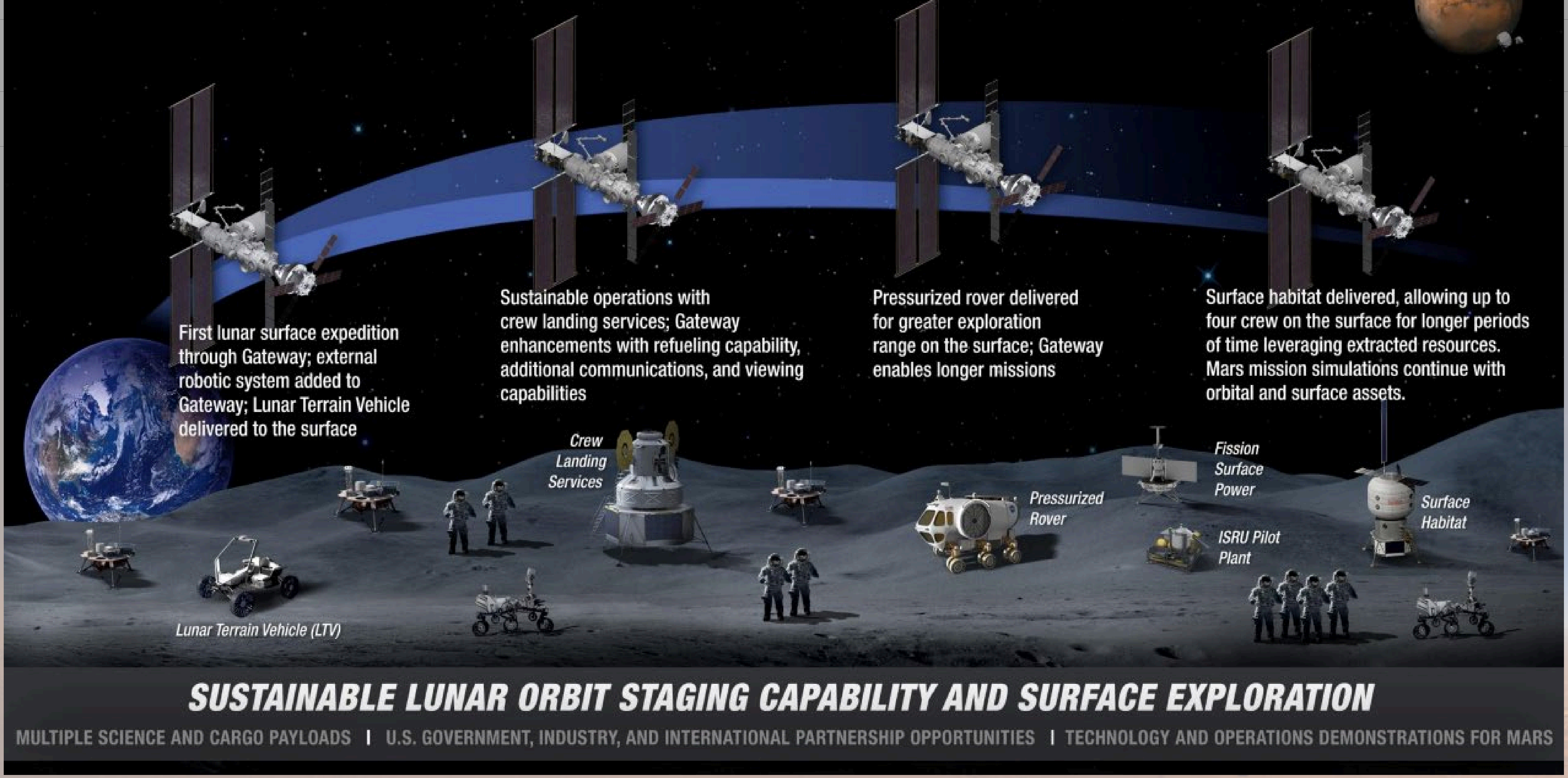
	Live
	Sustainable Living and Working Farther from Earth
		• Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities
		  • Sustainable power sources and other surface utilities to enable continuous lunar and Mars surface operations.
		  • Scalable 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

Artemis: Landing Humans On the Moon



Artemis Base Camp Buildup



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

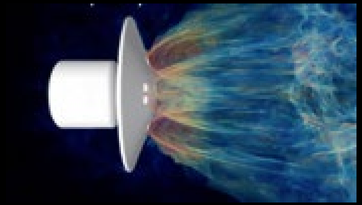
Lunar Capabilities (feeding forward to Mars)

Precision Landing and Hazard Avoidance

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

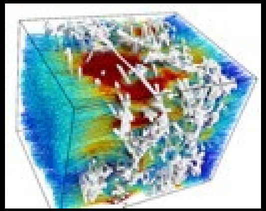
Retropropulsion

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

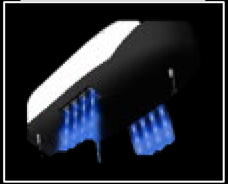
Measure EDL flight system performance and update/develop unique, critical simulations for EDL/DDL systems

Mars Capabilities

Large Scale Demonstrations

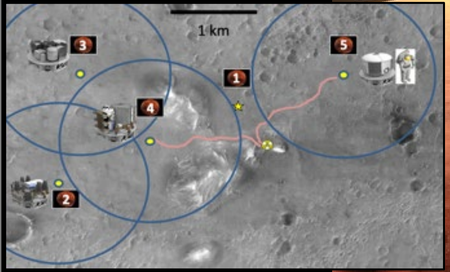
Large structures, including deployables, that can slow down a 20t payload in the thin Mars atmosphere

Earth Flight Tests, such as LOFTID



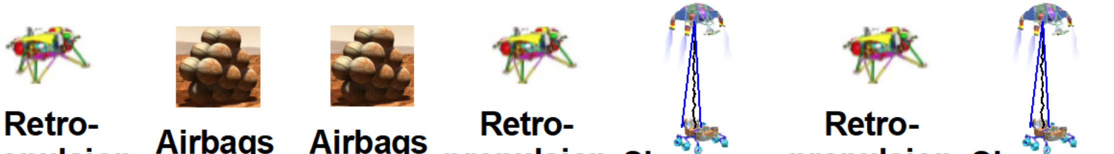
Assess Alternatives

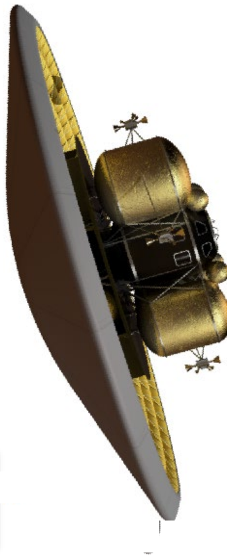
Aggregate Assets



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 *(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



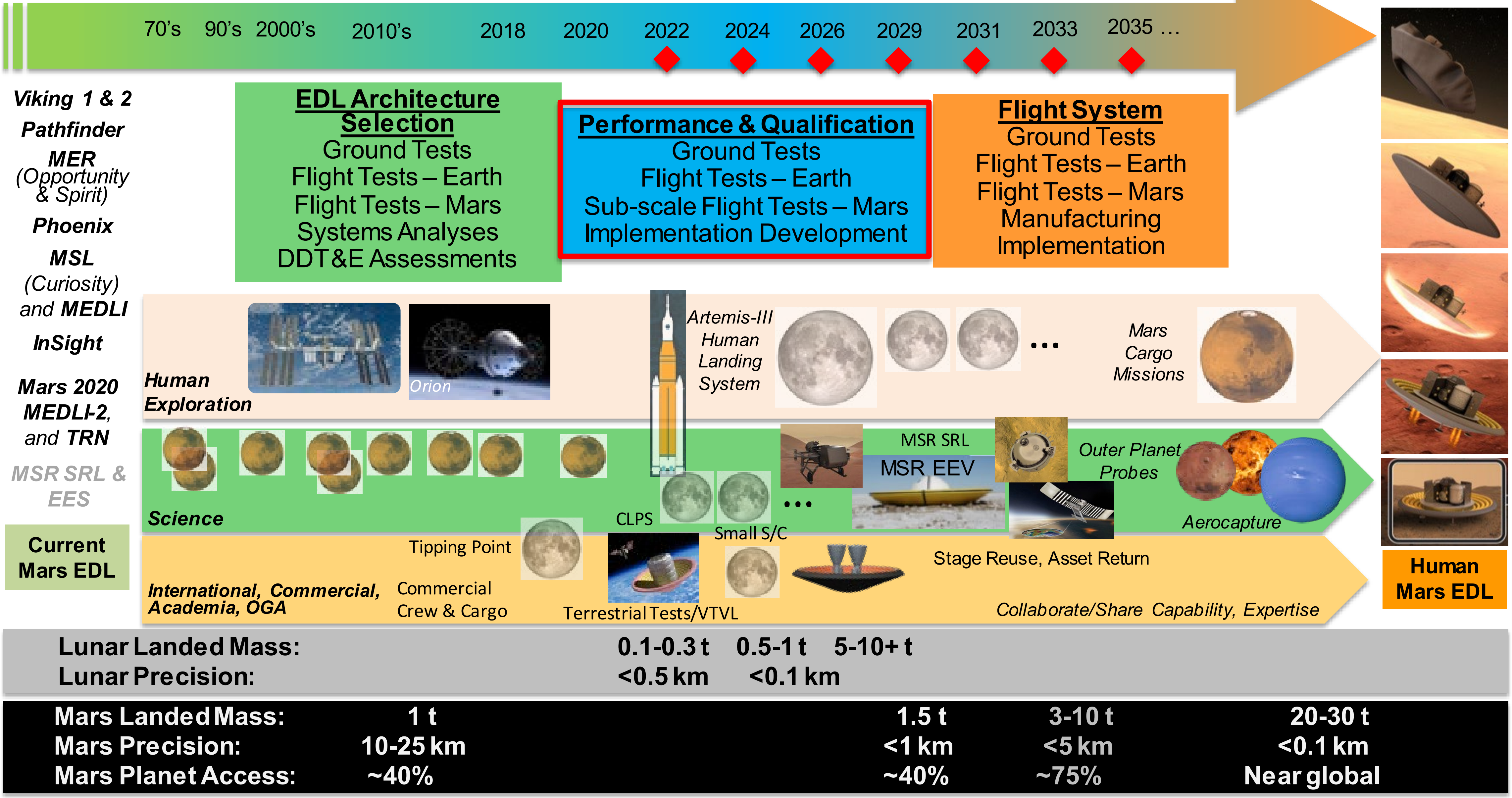
Steady progression of "in family" EDL → ***Payloads up to ~1 t***

New EDL Paradigm → ***Payloads 20-30* t***

*actual payload requirements differ with architecture assumptions

Mars EDL is a Long-Term Challenge

Leveraging Lunar Tech Demos and Missions

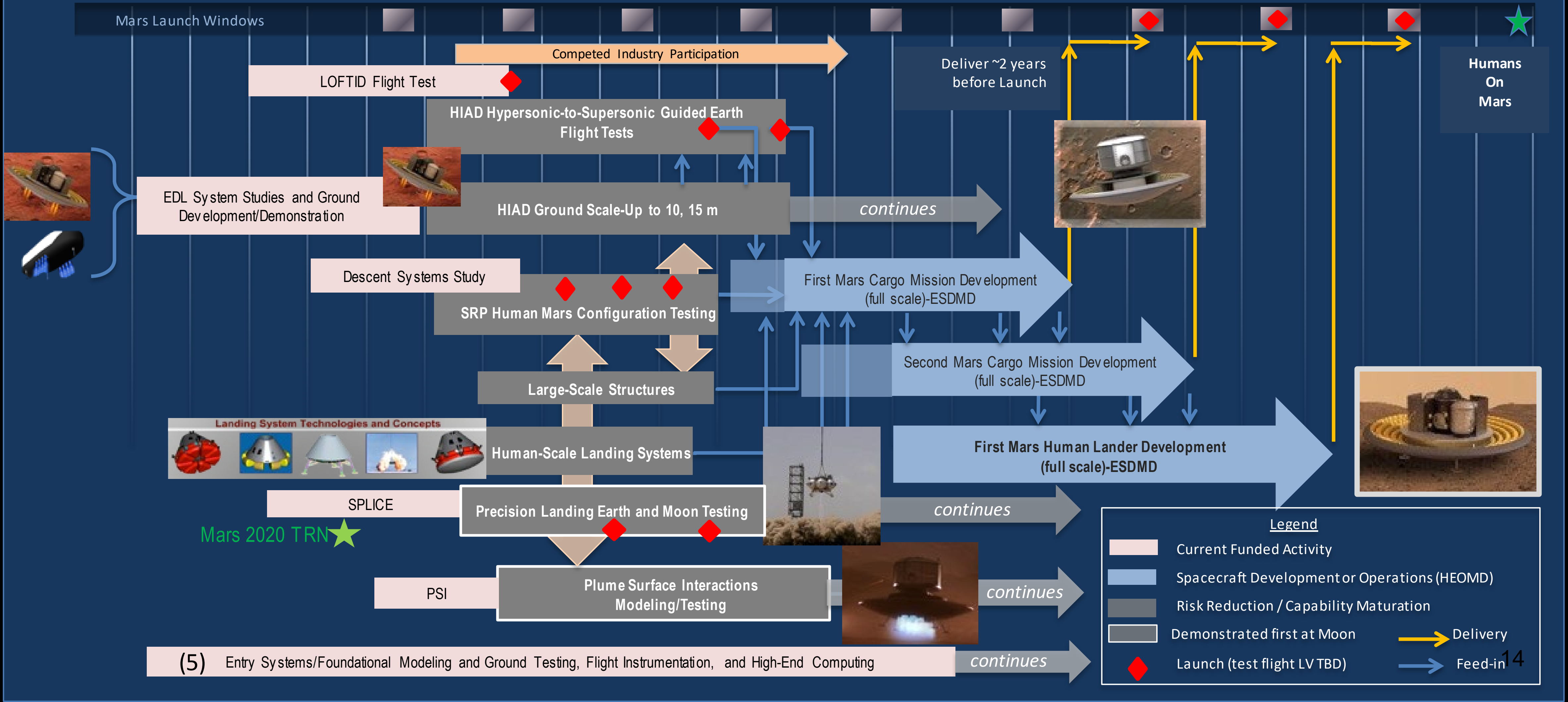


Mars Crew / Cargo Landers for 20t Payloads

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

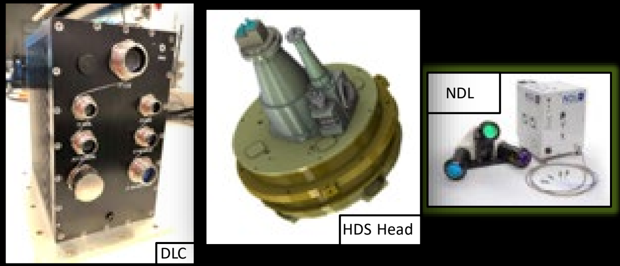
- *The large-scale Mars EDL system is comprised of multiple long-lead elements that all need to be matured in parallel.*
- *Flight tests of "E," "D," and "L" components occur at Earth. Precision Landing is demonstrated on the Moon. End-to-end Mars validation is performed computationally (as with current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

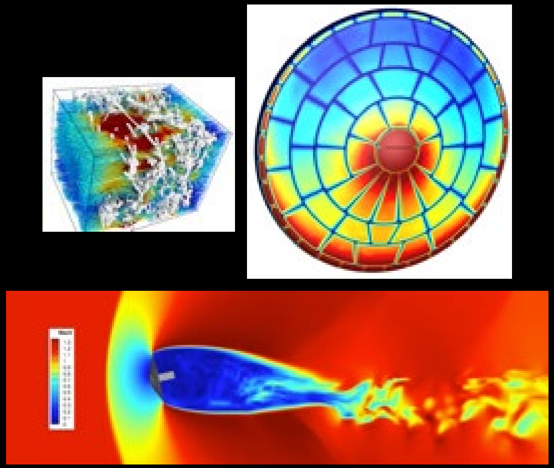


Current Investments to Achieve 20t Landings

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

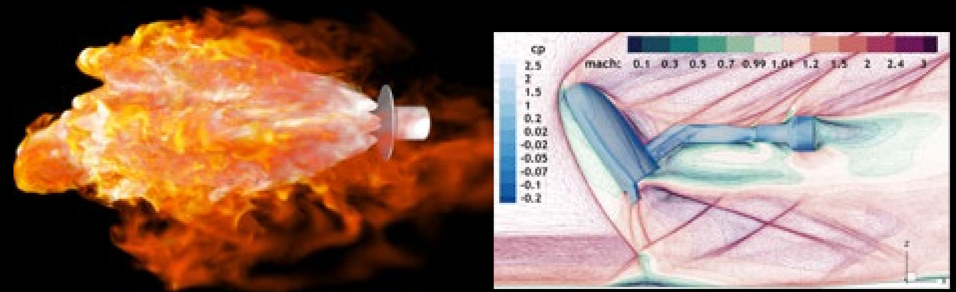


***SPLICE**
Precision Landing/Hazard Detection sensor, computing, and algorithm development, flight testing, and commercialization
(see "50 m" outcome)

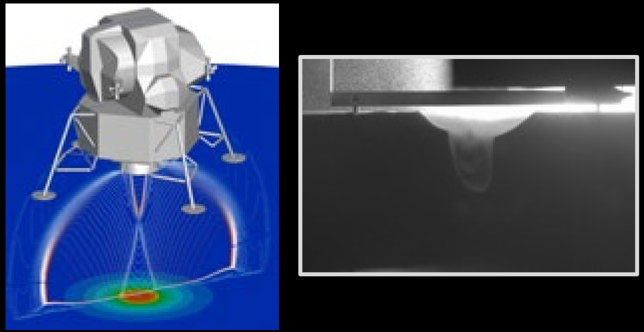


Entry Systems Modeling (ESM)
Advancing core capabilities and reducing mission risk through validation (Aerodynamics, Aerothermal, TPS, GN&C)

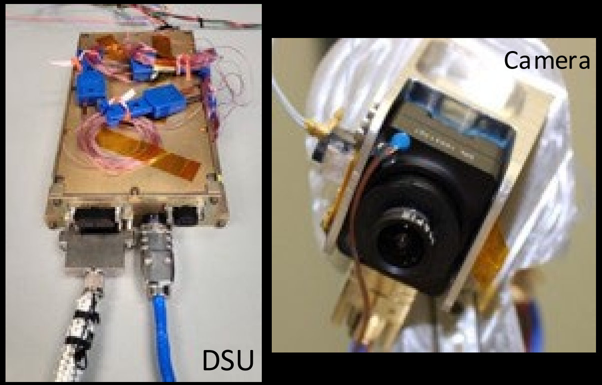
MEDLI2
Heating and pressure sensors on Mars 2020 aeroshell; provided aero/aerothermal model validation data (deep-dive data analysis in progress)



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



***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*

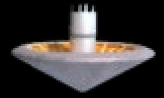
Highest-Priority Technology Gaps – Landing ~20t

- **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 (4)**
- **Entry Systems/Foundational Modeling and Testing, Instrumentation, and Computing (5)**
  - 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 "Land within 50 m" outcome and are therefore not included here. These are CRITICAL to implementing the Artemis architectures.*

Hypersonic Inflatable Aerodynamic Decelerator (HIAD)

Scale-Up and Flight-Testing Approach



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

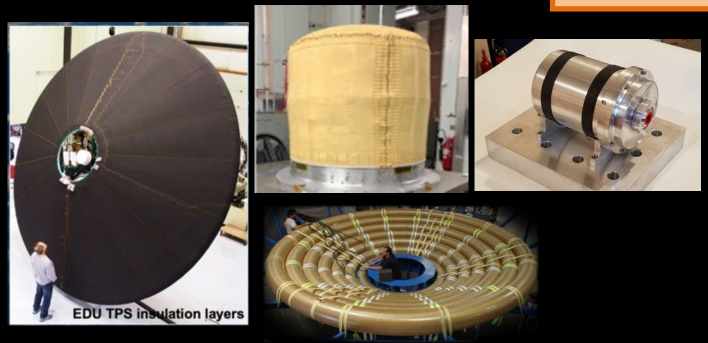
Established the aerodynamic performance and stability of inflatable heatshield approach

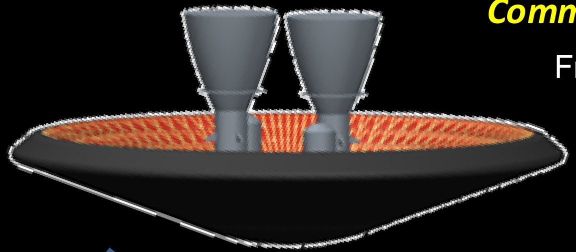
LOFTID Flight Test (6 m) – 2022 flight test in partnership with United Launch Alliance (ULA)

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

Human Mars Lander (~18 m)

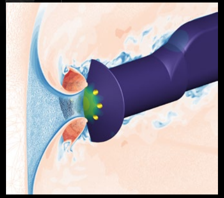
Guided HIAD, SRP Earth Flight Testing (10-15 m)

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

Ready for Mars infusion

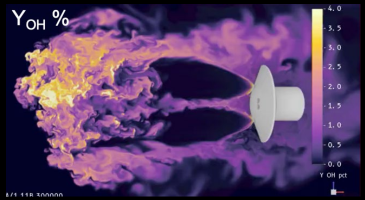
Green = currently funded; Yellow = not yet funded

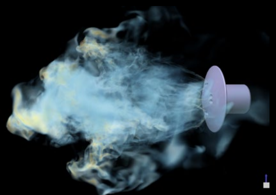
Retropropulsion Advancement Approach



Wind Tunnel Testing with Cold Gas Thrusters (Langley Unitary Plan Wind Tunnel – 2010, 2021-22) - SOA

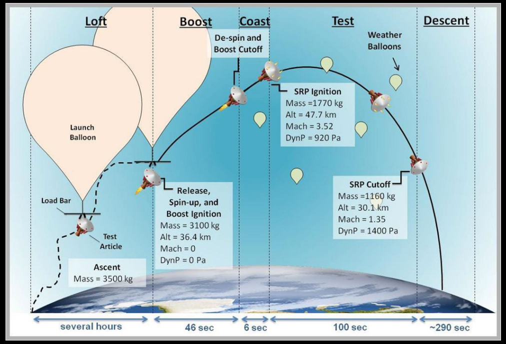
- Various nozzle configurations, uncertainty quantification, inert gas subscale validation data
- Establishes aerodynamic databases for simulations to assess performance of Mars EDL alternatives

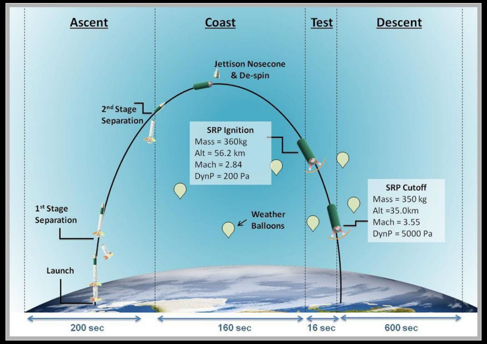




Wind Tunnel Testing with Combustion Engines (Glenn Supersonic and Transonic Tunnels)

- 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
- 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

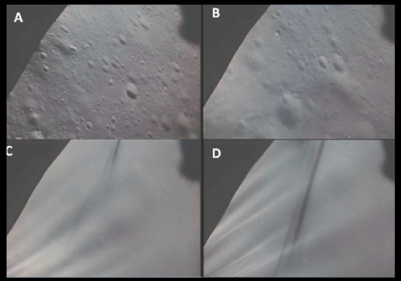
(see previous page)

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

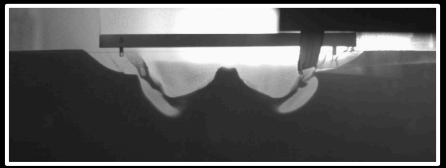
Rapid analysis of large datasets is key challenge – requires new tools, computing architectures

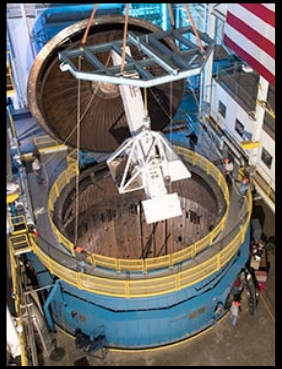
Plume Surface Interaction (PSI) Advancement Approach

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



Apollo 15 camera obscuration (Metzger, 2011)

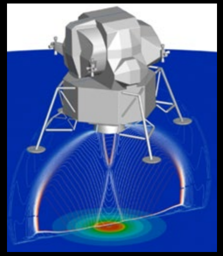

Physics-Focused Ground Test, annular crater in sand (2021)


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

- Mature predictive modeling capability, currently unvalidated
  - Complex, multi-physics problem requiring high-end computing resources to achieve required throughput
  - Key environment that will drive lander and surface asset design <u>**and create dust that requires mitigation**</u>
  - *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), (2), and (3) above**
  - 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

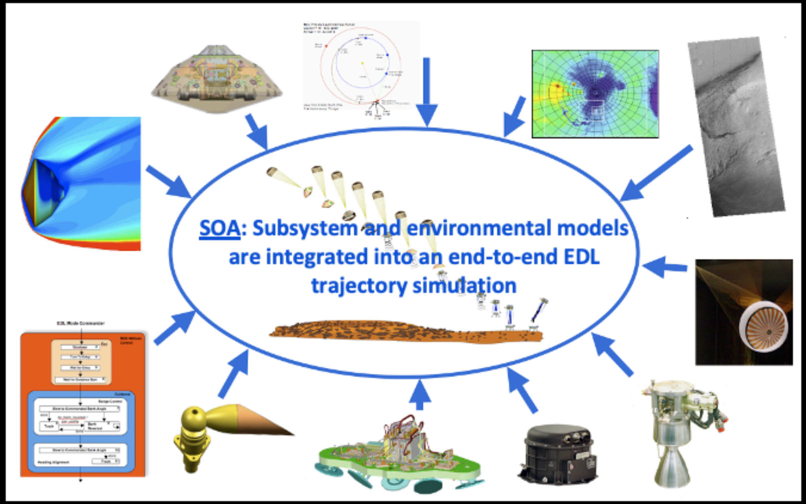

mm-Wave Doppler Radar


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



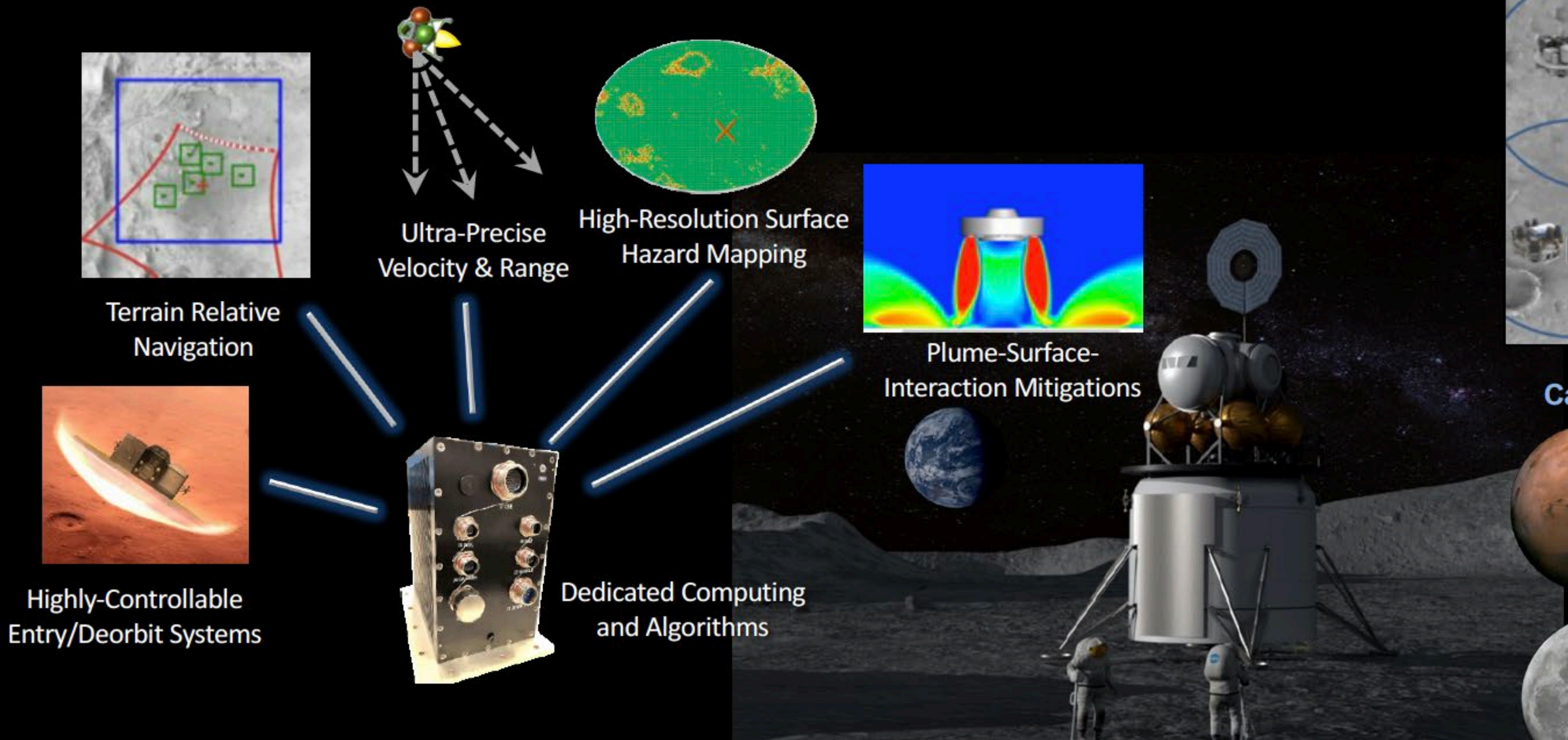
Advancement Approach (captured in gaps):

- 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

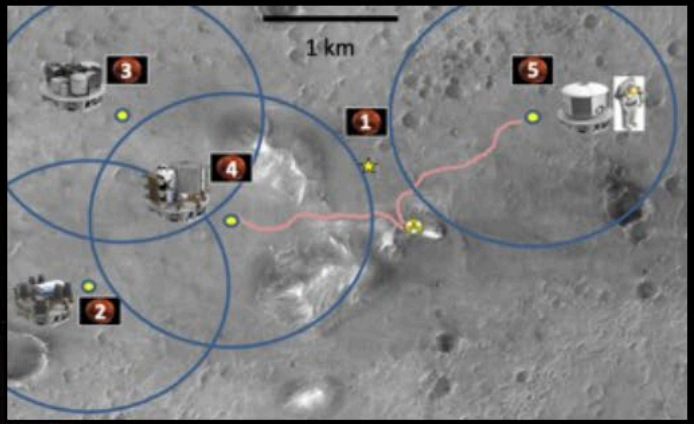
This content builds upon the Entry Systems Modeling project and a vibrant Early-Stage academic community. Progress requires a long-term, sustained commitment to foundational capabilities: tools, facilities, and high-end computing.

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

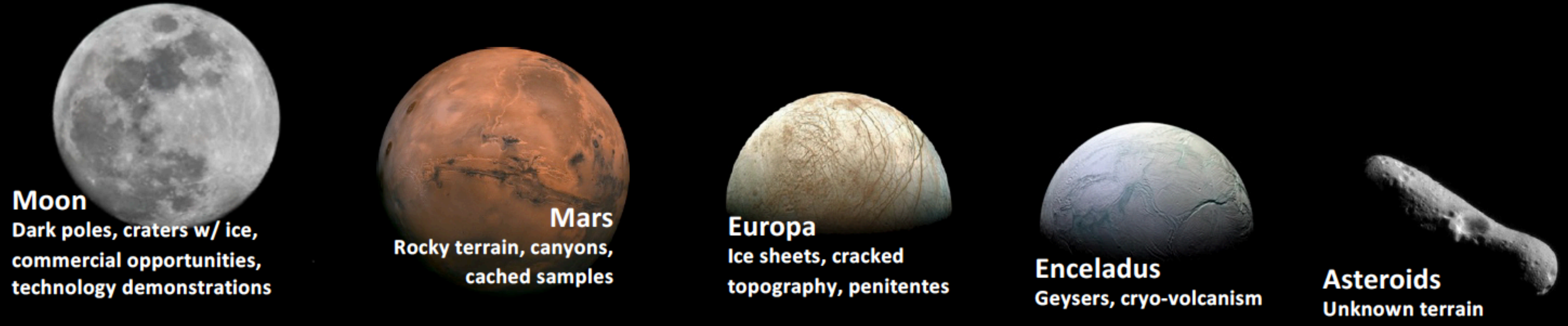
<u>Reduce operations time</u> for a rover or human to reach an interesting site

<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



Landing Precision: Summary and Logical Next Steps

Develop Technologies to Precisely Land Payloads and Avoid Landing Hazards

Current Investment | Maintain | Future Need

Summary of current approach

- SPLICE: developing sensors, computing and software for a baseline integrated capability for precise and safe landing
- LuNaMaps: developing and disseminating lunar mapping tools/processes for use by government and industry with lunar landing
- Europa Lander Concept Study: developing EDL technologies for the unique environment of Europa with potential for broader infusion
- Modeling and Architecture Studies: high-fidelity EDL simulations are continuing mission concept studies to evaluate highly-controllable EDL systems, model PSI, and assess PL&HA technologies that enable the closure of EDL gaps and the strategy evolution
- Commercialization: solicitations for public-private partnerships, SBIRs, Tipping Points, etc. are accelerating technology commercialization (spin off and spin in) plus infusion into CLPS missions and non-space applications (consider incentivizing certain EDL/PL&HA technologies for various mission classes)

What are the next steps?

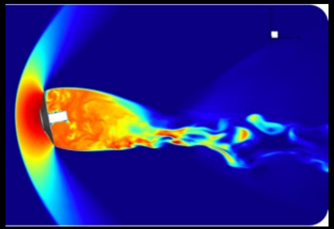
- Maintain concept studies, low-TRL investments, EDL-focused SBIR solicitations, academic awards, public-private partnerships, and commercialization to identify new technologies and evolve the development strategy
- Conduct planned demonstration tests to validate models, raise TRL, and mitigate infusion risks for EDL technologies
  - Conduct testing and then disseminate PSI-mitigation approaches for landing systems
  - Conduct a lunar demonstration of the SPLICE technologies being actively used (in closed loop) within a landing system
- Continue development toward future generations of EDL and Avionics Technologies
  - HPSC: continue development & commercialize → radiation-hard, multicore processing is critical to future envisioned missions
  - Europa Lidar: monitor advancement of systems for commercialization and broader-infusion prospects
  - Active TRN: develop lidar-based TRN for anytime, anywhere global access (e.g., EDL/DDL for dark/shadowed lunar regions)
  - Pursue multi-mode EDL/PL&HA sensors that further advance and miniaturize integrated capabilities

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

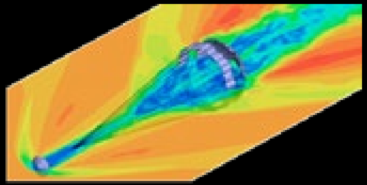
Developing atmospheric entry technology to enhance and enable small spacecraft to Flagship-class missions across the solar system

Entry Systems Modeling & Testing

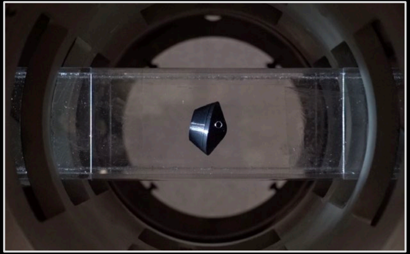
Reducing entry system mass and risk by developing advanced, validated models



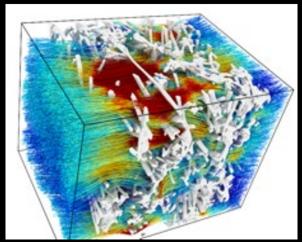
"DESKTOP WIND TUNNEL"



PARACHUTE MODELING



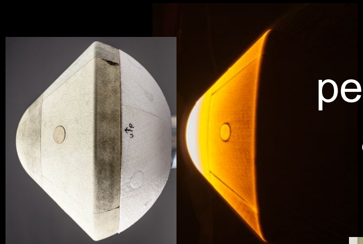
MAGNETIC SUSPENSION WIND TUNNEL



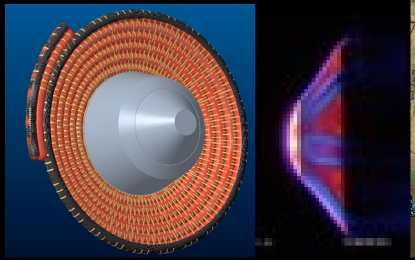
IN-DEPTH MATERIAL RESPONSE

Hardware Development

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



CONFORMAL MATERIALS

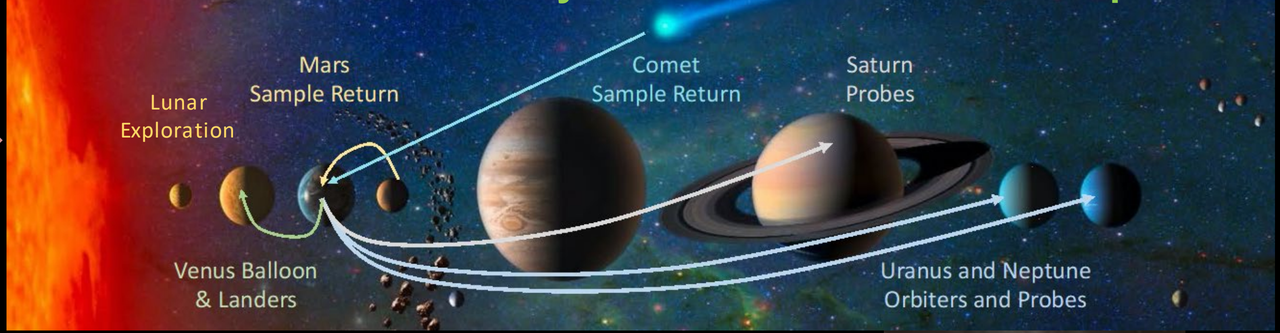


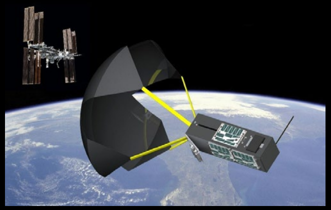
DEPLOYABLE DECELERATORS

3D WOVEN HEATSHIELDS

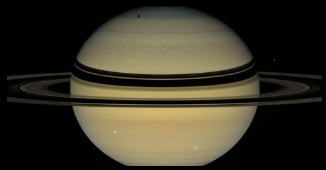
to enable

Missions Across the Solar System at Scales from Small Spacecraft to





PRECISION DEORBIT



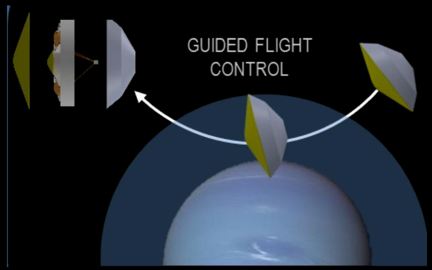
SATURN PROBE

TITAN PINPOINT LANDING

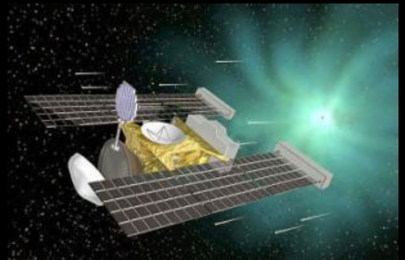
MARS SAMPLE RETURN

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

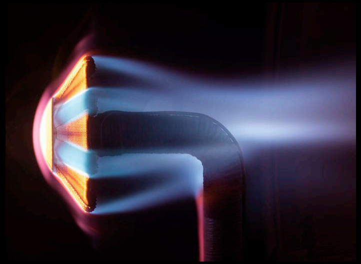
Reference: https://www.nationalacademies.org/our-work/planetary-science-and-astrobiology-decadal-survey-2023-2032

Planetary EDL Subsystem SOA

TPS

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

HEEET

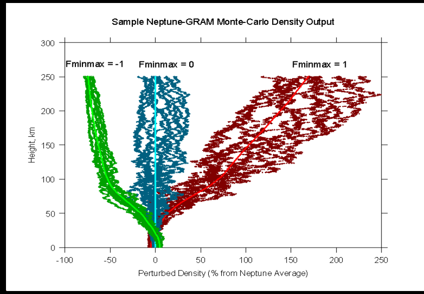


ADEPT/Spiderweave

PICA

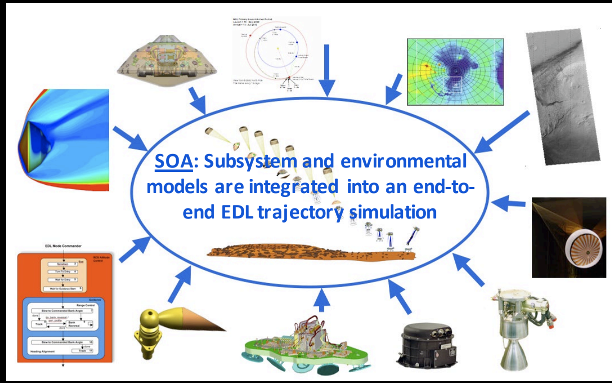
Atmosphere Models

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



GN&C Modeling

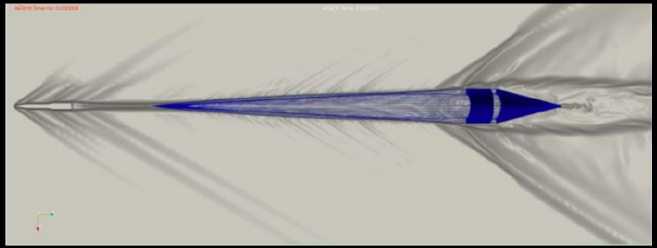
- Baseline models under development for expected planetary mission space; Quantified uncertainty forthcoming



Parachutes

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

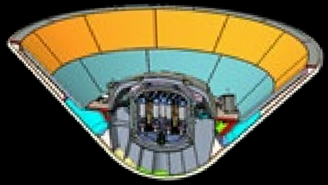
M2020 Parachute



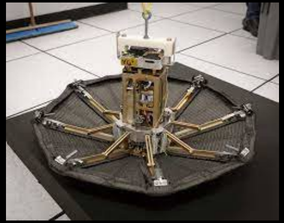
Aero/FS Simulation of ADEPT

Architecture/System

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



EES



ADEPT

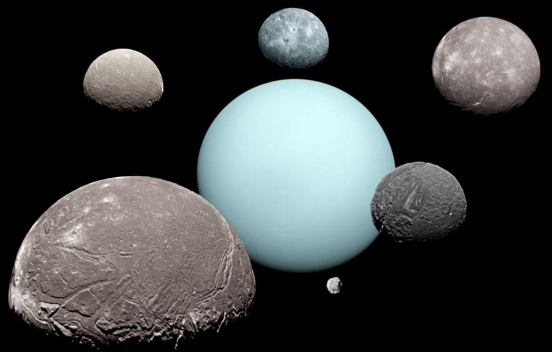
HIAD (LOFTID)

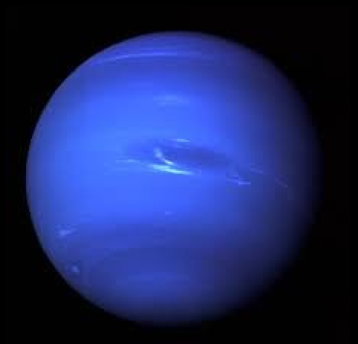
SRP Simulation

Enabling Aerocapture for Ice Giant Missions

Challenges

- **High entry speed leads to high heat rates**
- **Long atmospheric pass leads to high heat loads**
- **Aerothermodynamic uncertainties result from H_2/He atmosphere**
- **Atmospheric uncertainties are significant**
- **Uranus: Precision approach/maneuvering needed to avoid rings**
- **Neptune: High exit velocity required, for Triton observation orbit**





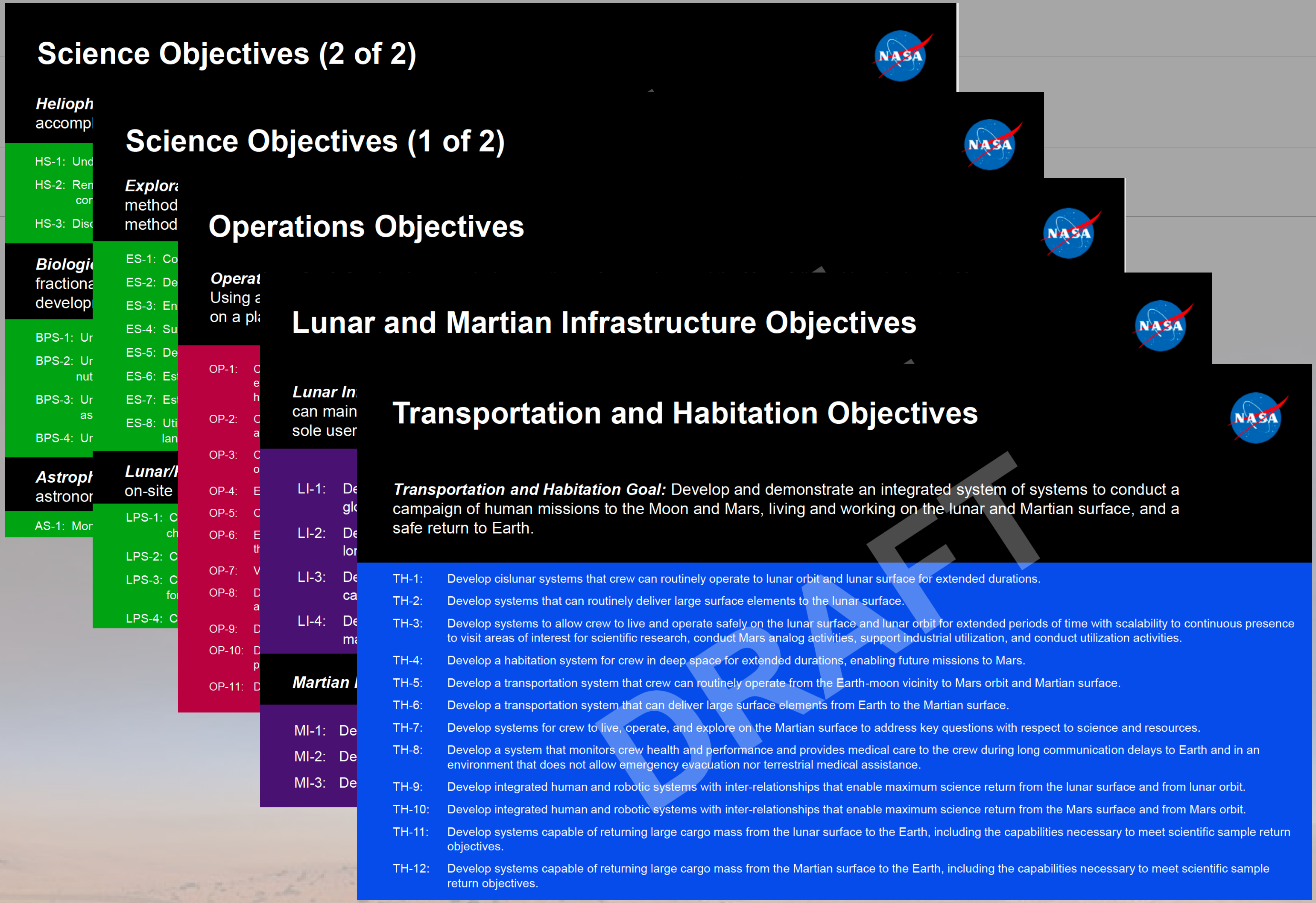
Forward Plan/Approach

- Pursue focused H_2/He investments in Entry Systems Modeling (ESM) and leverage ACCESS STRI to reduce uncertainties in aerodynamics and aerothermodynamics, integrate material response, quantify risk, reduce entry system mass. Infuse tools and methods to mission.
- Establish atmospheric models, including Uranus-GRAM and Neptune-GRAM
- Perform Earth demonstration of aerocapture, including applicable aerodynamic shape and guidance and control methods
- Use advanced TPS materials appropriate for efficient insulation, robust heat tolerance.
- Infuse characterization and modeling tools to mission.
- Gather flight data through DrEAM and MEDLI3 to validate predictions and inform future missions.
- Develop low-SWaPc instrumentation for Ice Giant entry systems.

Orange = summary of infusion path

NASA Moon-to-Mars Objectives (May 2022)

- 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

STMD Programs – Means to the End Goal

SBIR/STTR

Partnerships & Technology Transfer

- Technology Transfer
- Prizes and Challenges
- iTech

Early Stage Innovation

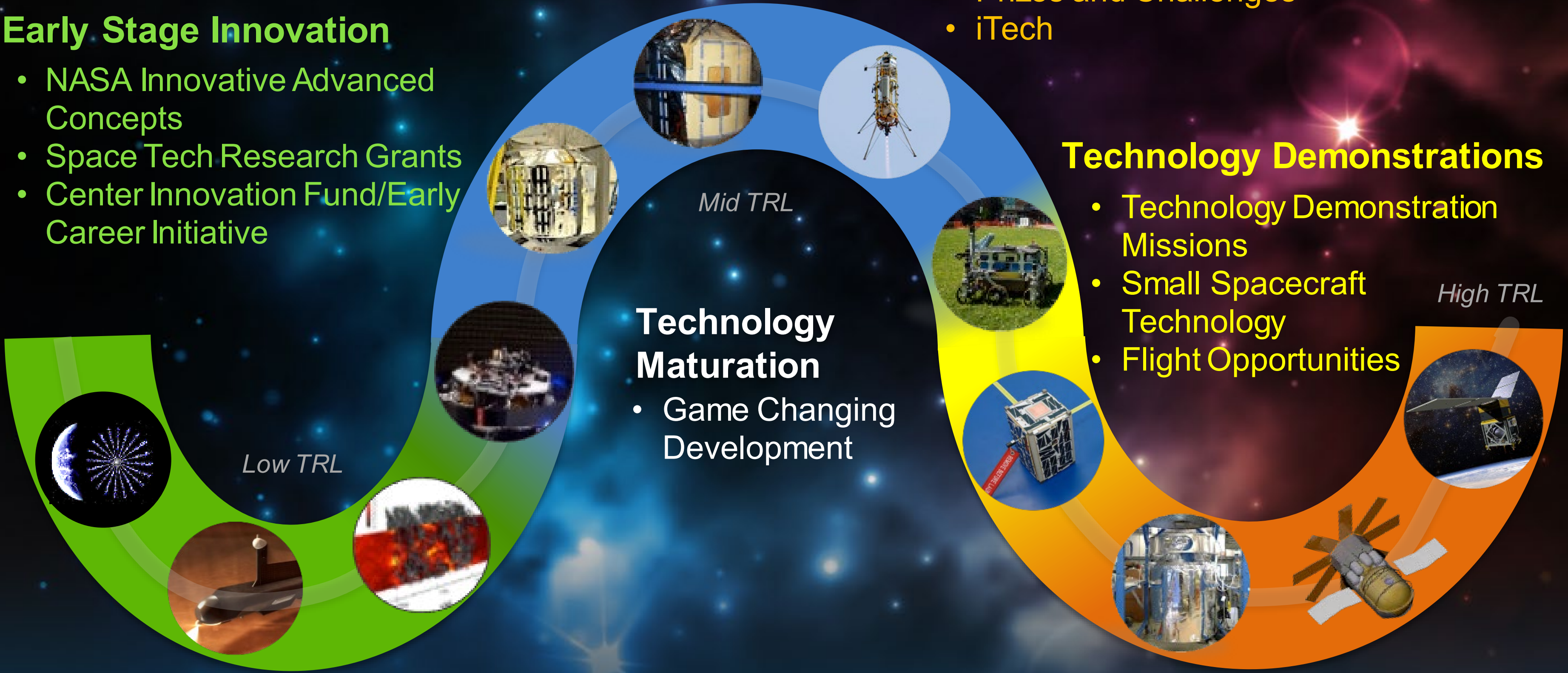
- NASA Innovative Advanced Concepts
- Space Tech Research Grants
- Center Innovation Fund/Early Career Initiative

Technology Demonstrations

- Technology Demonstration Missions
- Small Spacecraft Technology
- Flight Opportunities

Technology Maturation

- Game Changing Development



TECHNOLOGY PIPELINE

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 $1x10^{-6}$ 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

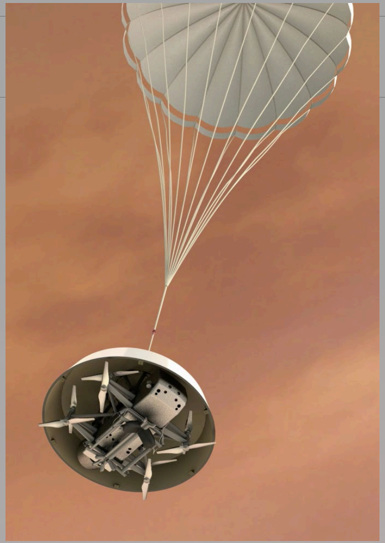
Summary

- EDL is a critical exploration function made of specialized disciplines and subsystem designs
- Our community is a critical part of NASA's upcoming lunar, Mars, science, and commercial partnership/economic growth objectives
- We have many ongoing missions in development, technology maturation efforts, and engagements with industry
- We are engaged in multi-Mission Directorate efforts to align objectives, architectures, and technology investments
- The future of EDL is bright, and we need the next generation of engineers, researchers and technologists to meet all of NASA's lofty exploration goals!

Thank you!

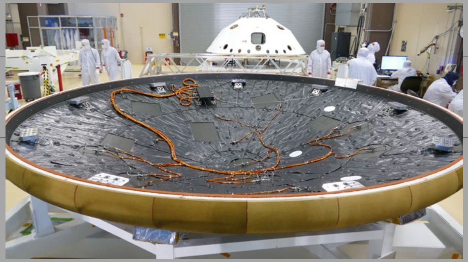
Recent/Current EDL Highlights/Activities

Dragonfly, Launch 2027
PDR Oct 2022
DrEAM Aeroshell Instrumentation



LOFTID Test, Launch Nov 2022
Largest blunt aeroshell

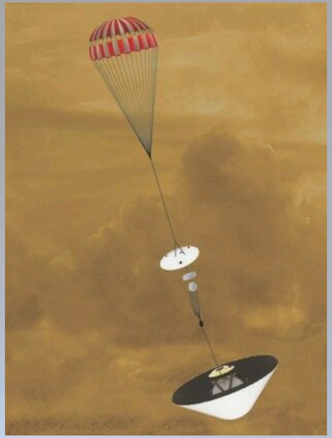
MEDLI2 on M2020
Deep Dive analysis underway



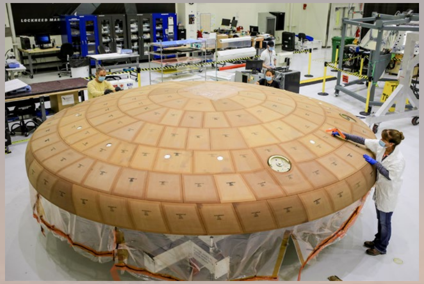
Mars 2020 - Perseverance
Landing 2/18/21. TRN First Use

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

VERITAS - Launch 2028
Aerobraking ESI

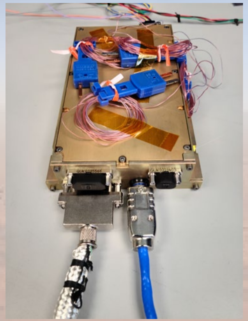


DAVINCI
Launch 2029
New TPS, Aeroshell Instrumentation

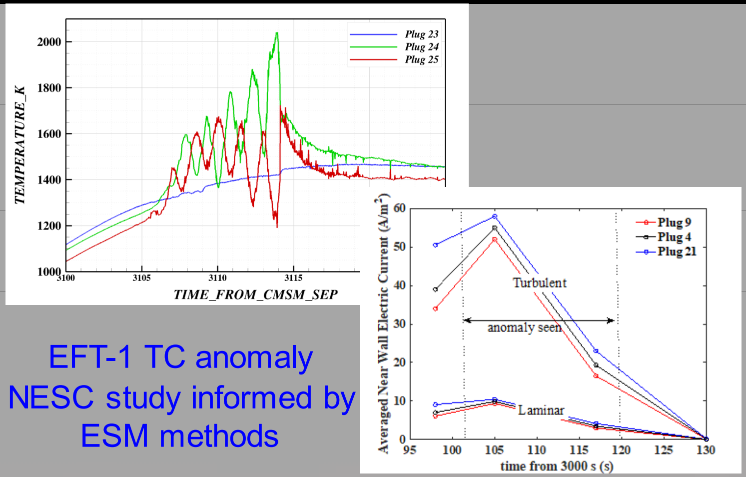


Artemis 1 – Ready to Fly!
NASA instrumentation
SCIFLI aerial imagery

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

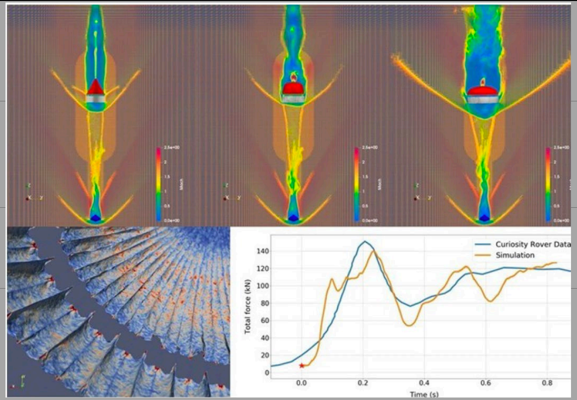


Recent EDL Highlights/Activities

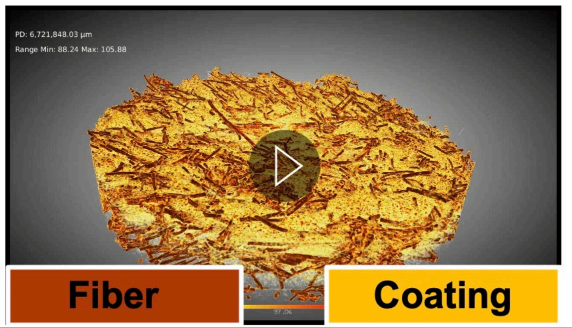


EFT-1 TC anomaly
NESC study informed by
ESM methods

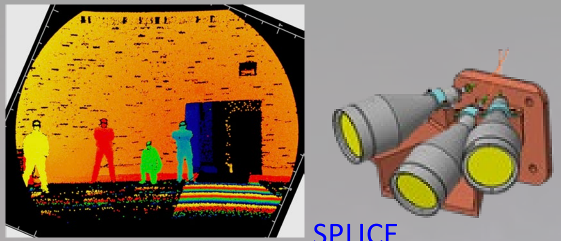
PSI – New Start in GCD
Active partnerships: STTR, SBIR, ESI



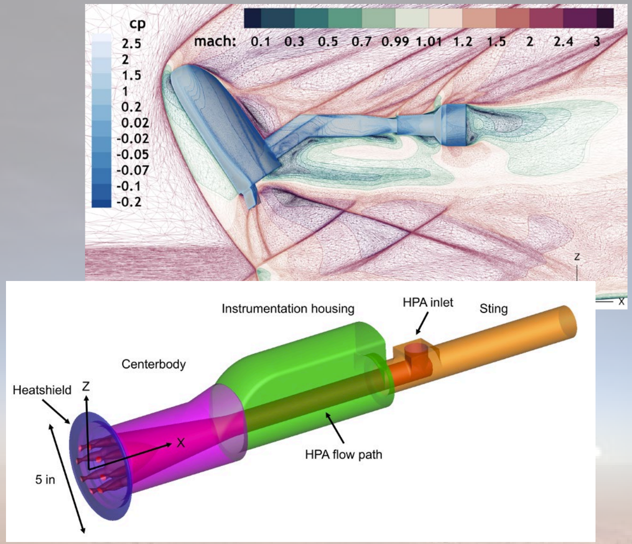
Parachute FSI
Partnership with ESM & STRG
New University Awards



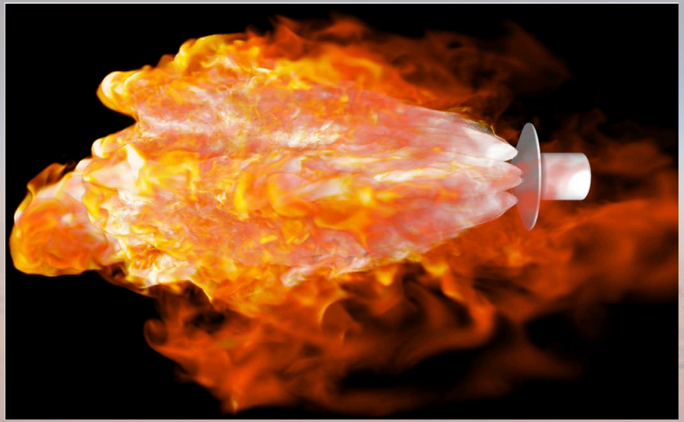
Entry Systems Modeling
Delivery of PICA-NuSil model
for MEDLI2



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



Descent Systems Study
Mid L/D testing complete
HIAD testing planned for FY21



Summit simulation of
Supersonic
Retropropulsion

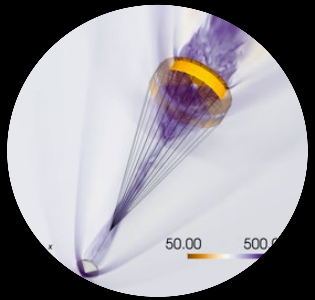
About Systems Capability

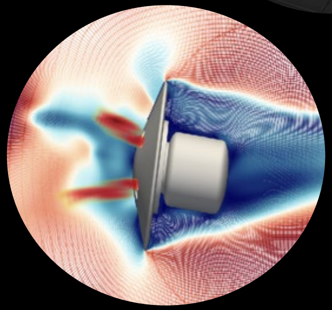
- **The 4 Mission Directorates have the dollars, and the Centers have the pool of people and facilities to implement the missions (a matrixed organization)**
- **It is important that the Agency maintain the talent and facilities it needs, for the future.**
  – There are some “special,” critical things that only NASA does, and that we do only once every several years—such as **entry, descent, and landing** on a planet
  – In addition, EDL is used by multiple Mission Directorates and multiple missions, so it’s difficult to pinpoint an “owner”
  – Systems Capability Teams (and Leads) were created to make sure these vital systems have advocacy and a long-term plan for sustainment (especially as leadership and/or direction changes)
- **The next generation of engineers is a vital part of that sustainment!**

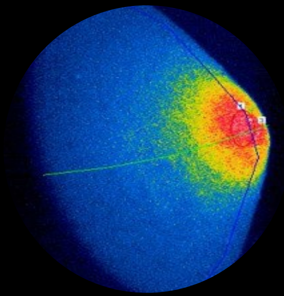
EDL Modeling and Simulation is Critical to Planetary Science

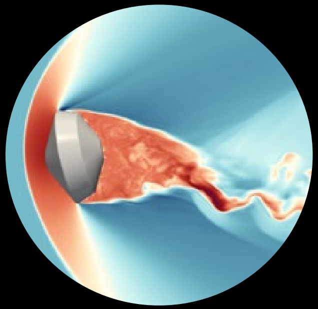
Planetary entries cannot be practically tested end-to-end on Earth; flight performance assessment and certification RELIES on robust EDL Modeling and Simulation capabilities.

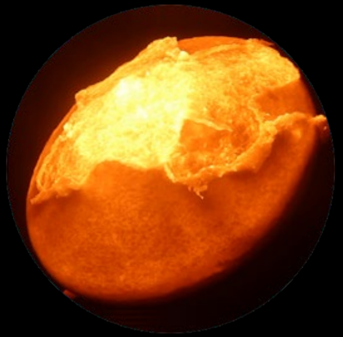
- **Models, particularly in aerosciences and material response, have largely undefined uncertainty levels for many problems (limited validation)**
  - Without well-defined uncertainty levels, it is difficult to assess system risk and to trade risk with other subsystems, leading to increased schedule 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 EDL Modeling and Simulation (M&S), *guided by mission challenges*, ensures that NASA is ready to execute the challenging planetary science missions of tomorrow.

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