



Overview and Status of Entry, Descent, and Landing at NASA

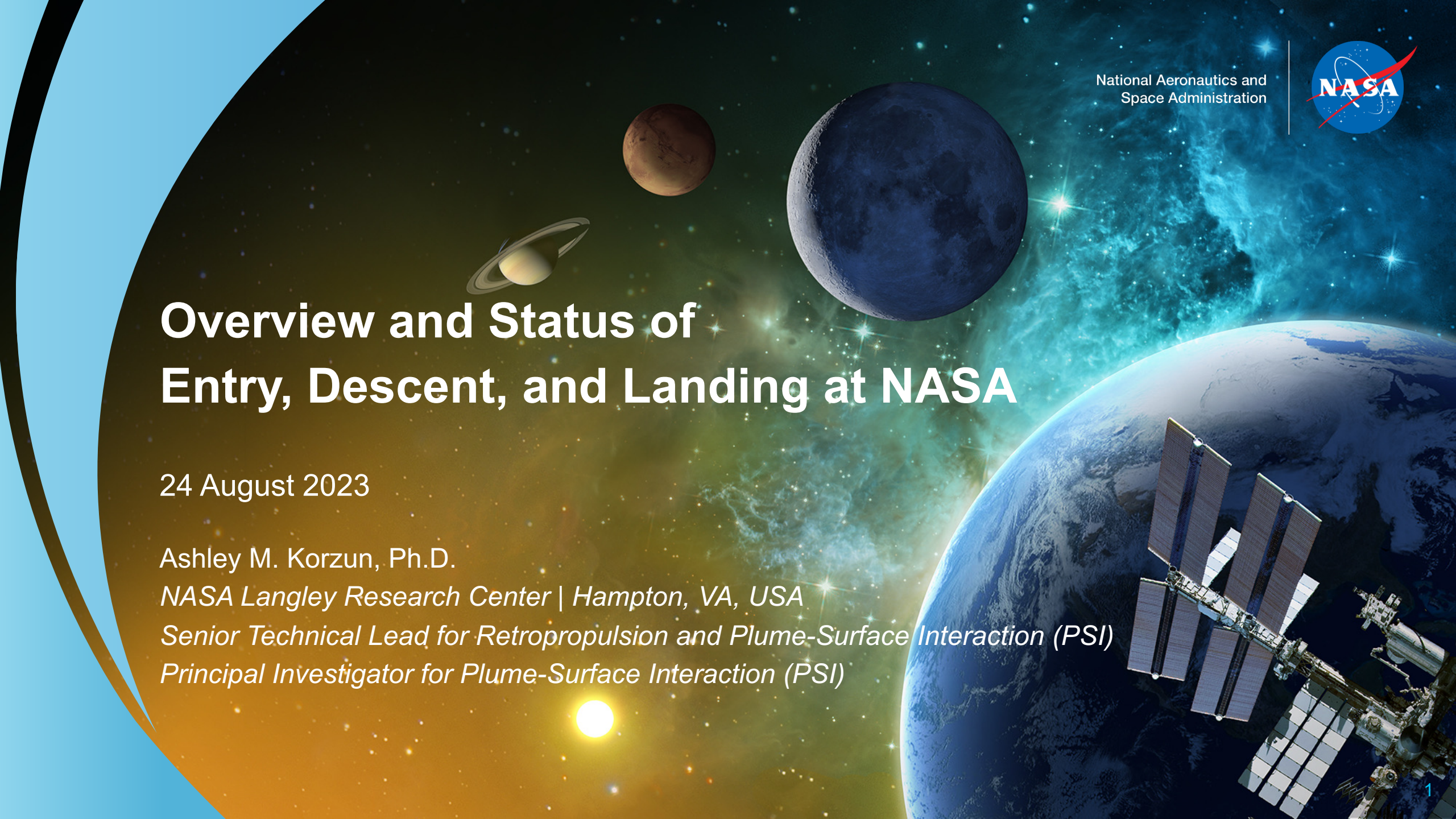
24 August 2023

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Senior Technical Lead for Retropropulsion and Plume-Surface Interaction (PSI)

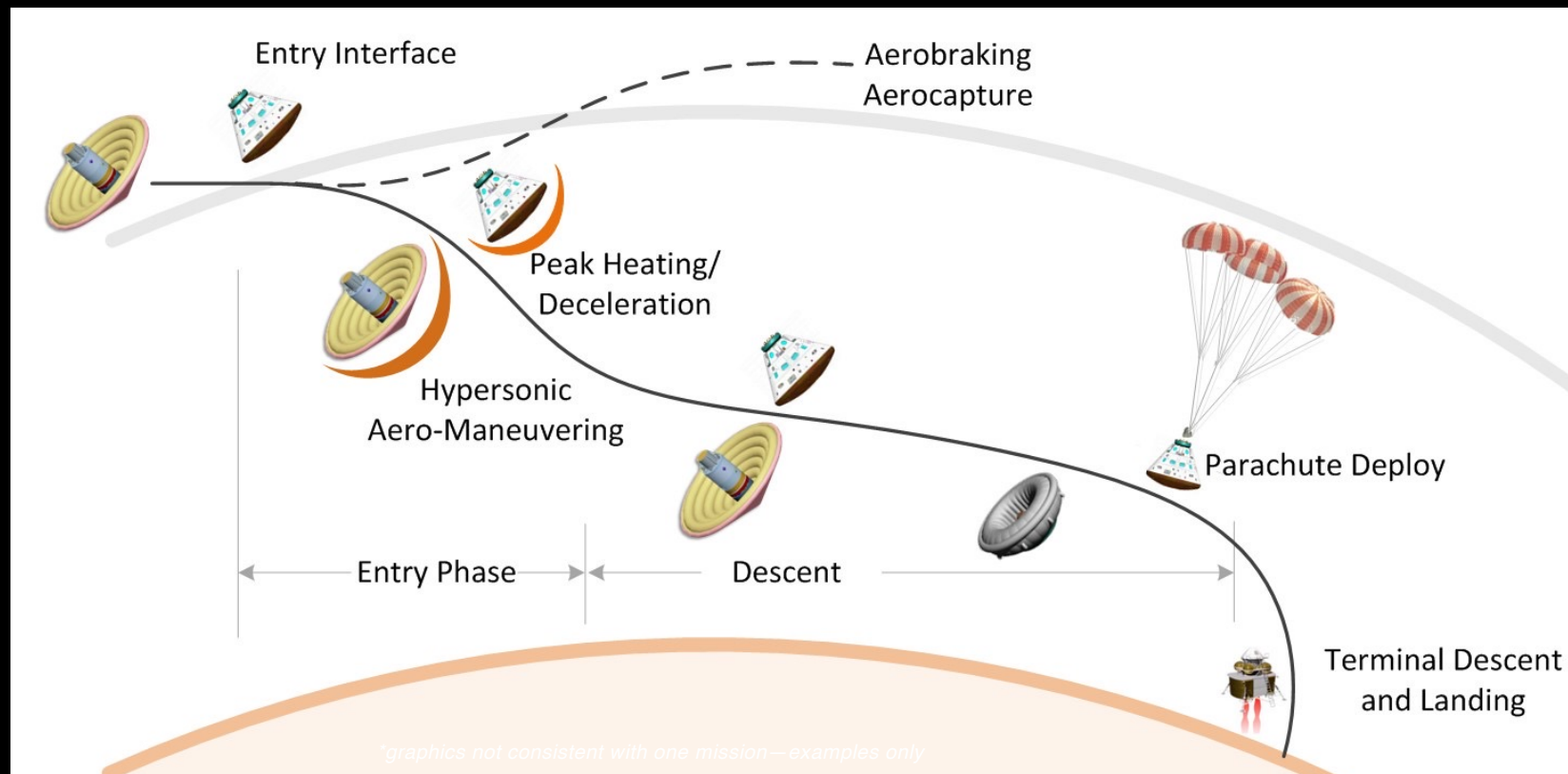
Principal Investigator for Plume-Surface Interaction (PSI)



Entry, Descent, and Landing (EDL)



Decelerating, approaching, connecting, or touching down on any body with significant gravity, with or without atmosphere





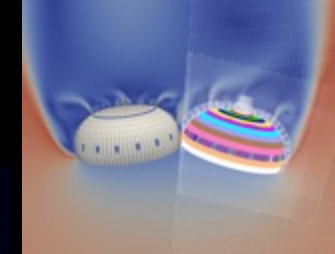
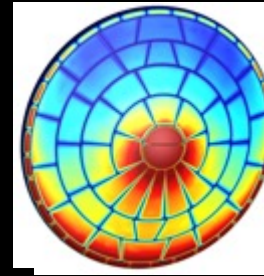
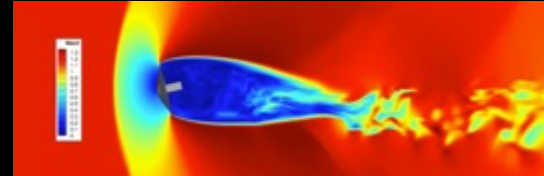
Outline

- EDL sub-capabilities
- NASA STMD strategic technology framework
- Planetary Science Decadal Survey priorities
- EDL Missions: current and future
 - DAVINCI
 - Mars Sample Return
 - Dragonfly
 - Ice Giants
 - Artemis Human Landing System
 - Human Mars Exploration

EDL Sub-Capabilities

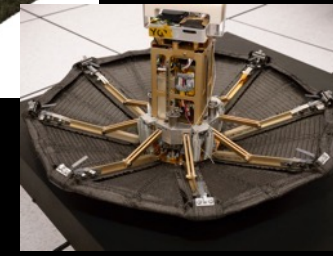
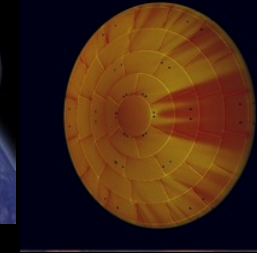
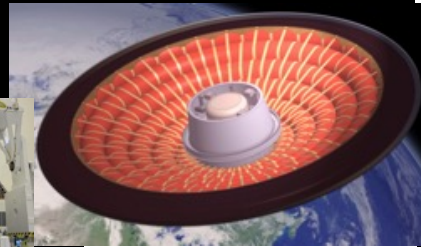
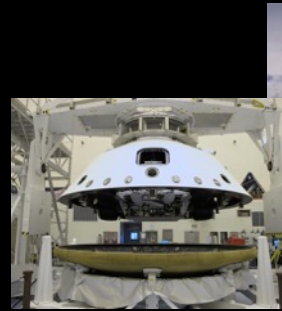
Analytical /
Discipline

- 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



**Propulsion discipline related less directly than others*

NASA STMD Strategic Technology Framework



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

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

Planetary Science Decadal Survey



	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*	<i>Unclear. Precision landing/hazard avoidance?</i>
	Europa Lander*	<i>Hazard detection and avoidance</i>
	Mercury Lander*	<i>Unclear. Precision landing/hazard avoidance?</i>
	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)*

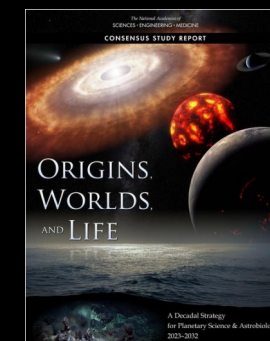
New Frontiers 6

- 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)*

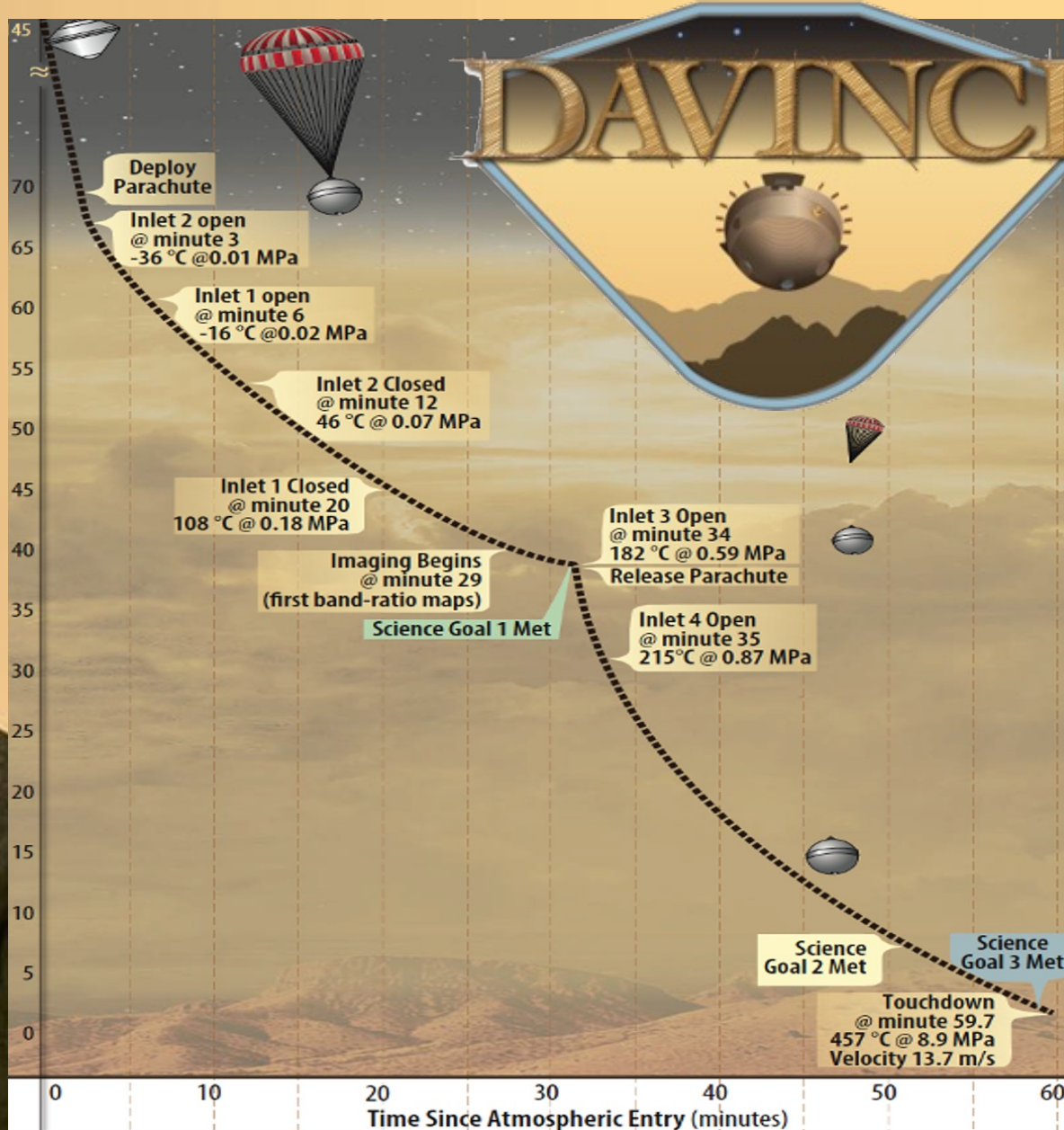
New Frontiers 7

- New Frontiers 6 list, plus
- Triton Ocean World Surveyor

* = mission involves EDL



Venus: DAVINCI

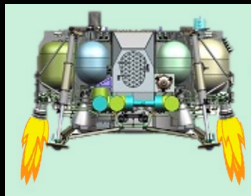
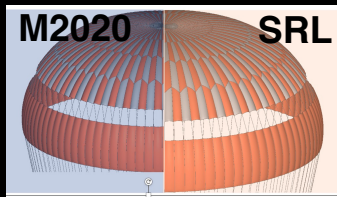
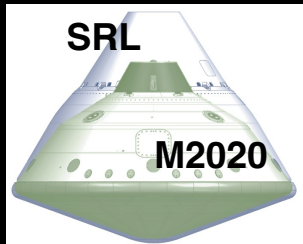


- Launch: June 2029
- Probe Mission: June 2031
- Entry probe similar to Pioneer Venus with larger diameter 45° sphere-cone forebody and flatter backshell
- Thermal protection system materials draw heritage from Genesis sample return and Mars EDL missions
- Parachute ConOps draw heritage from Mars missions
- Zephyr descent sphere differs in geometry from Pioneer Venus Large Probe

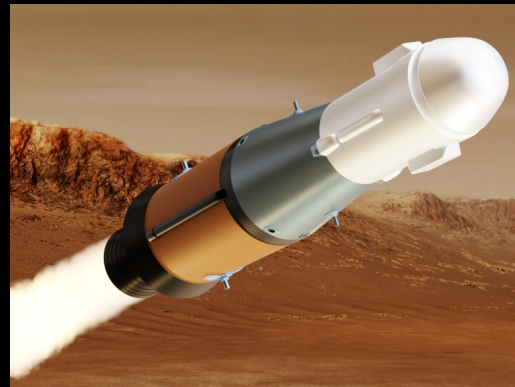


Mars Sample Return (Planned)

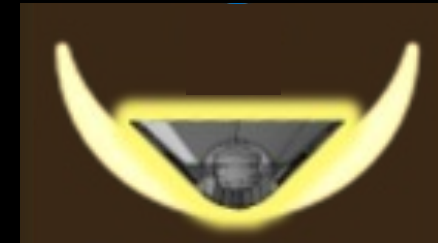
Sample Retrieval Lander (SRL)



Mars Ascent Vehicle (MAV)



Earth Entry System (EES)



Artist's Concepts

The decision to implement Mars Sample Return will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.

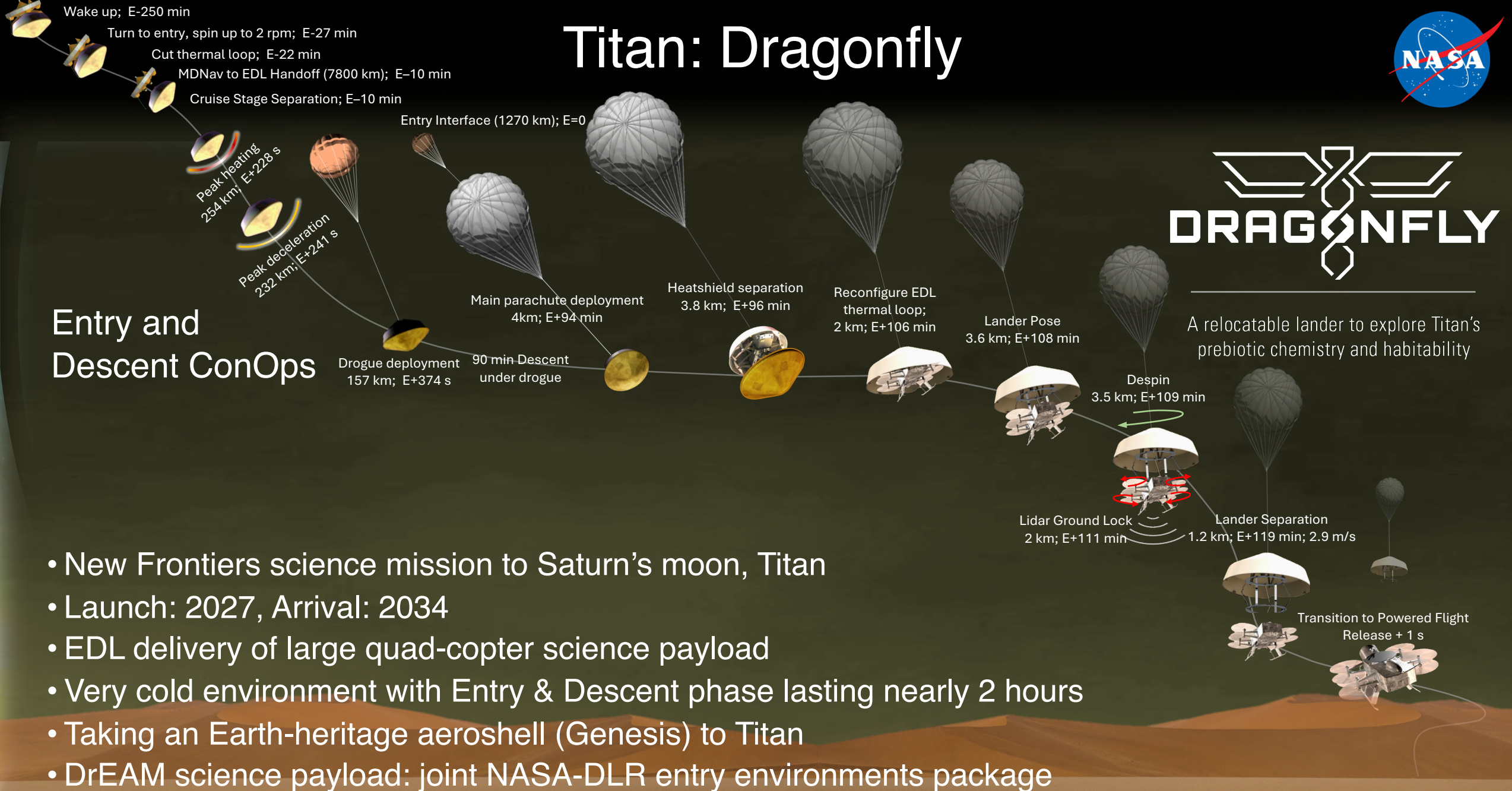


Titan: Dragonfly



A relocatable lander to explore Titan's prebiotic chemistry and habitability

Entry and Descent ConOps



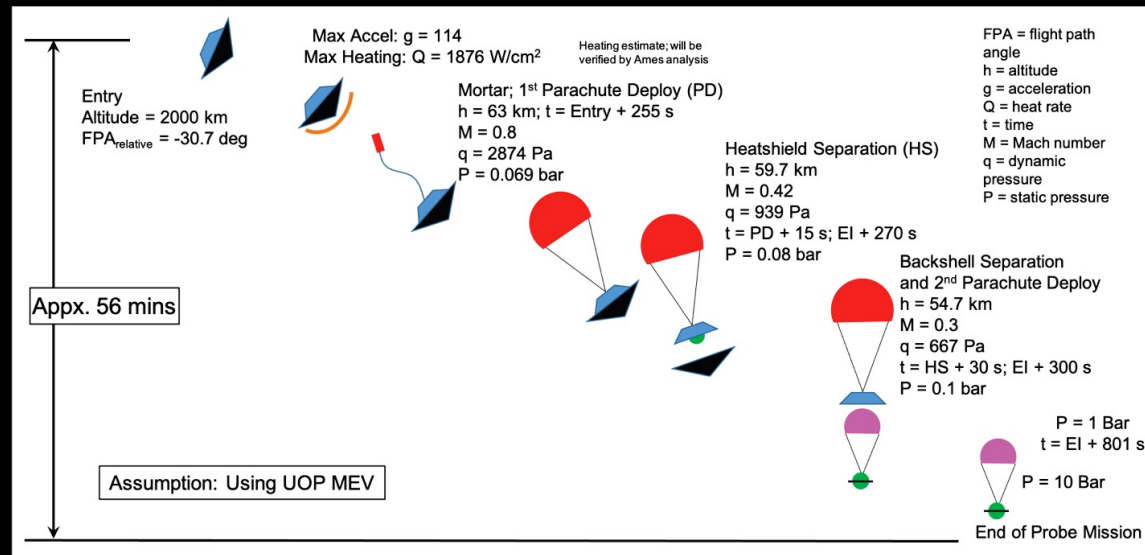
- New Frontiers science mission to Saturn's moon, Titan
- Launch: 2027, Arrival: 2034
- EDL delivery of large quad-copter science payload
- Very cold environment with Entry & Descent phase lasting nearly 2 hours
- Taking an Earth-heritage aeroshell (Genesis) to Titan
- DrEAM science payload: joint NASA-DLR entry environments package



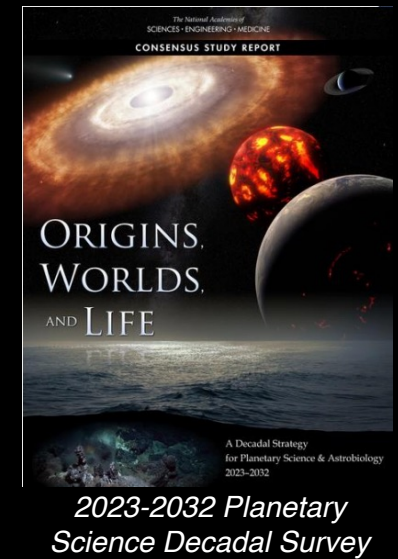
Uranus Orbiter Probe (UOP)

“The committee prioritizes the Uranus Orbiter and Probe (UOP) as the highest-priority new Flagship mission for initiation in the decade 2023-2032.”

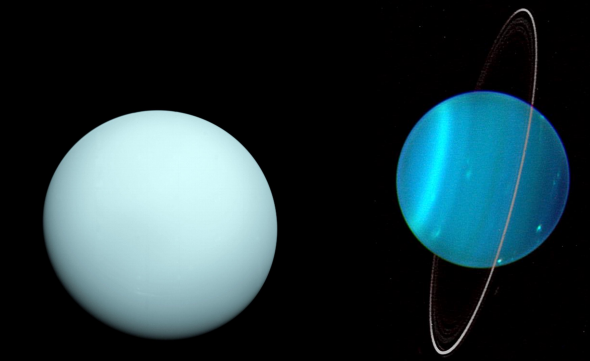
- Committee on the Planetary Science and Astrobiology Decadal Survey



Probe Trajectory Concept of Operations (Pensado et al., IPPW-2022)



- Requires in-situ atmospheric probe to meet science objectives
- Optimal launch opportunities in 2031 and 2032
- No new technologies required to enable but new technologies such as aerocapture are significantly mission-enhancing



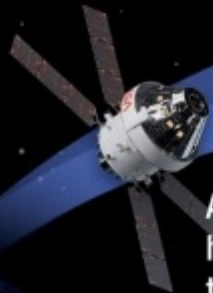
Uranus from Voyager 2

Uranus from Keck Observatory

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



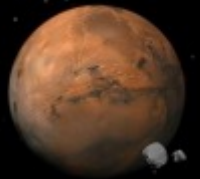
Artemis II: First humans to orbit the Moon and rendezvous in deep space in the 21st Century



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

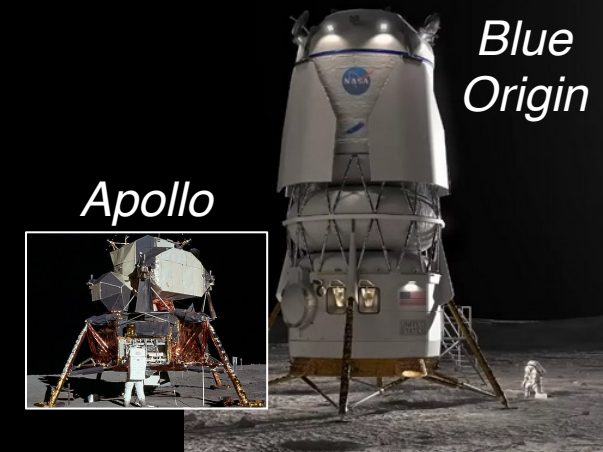
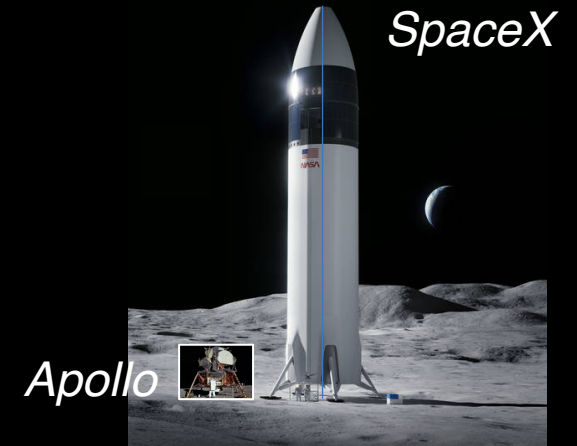
Uncrewed HLS Demonstration

Humans on the Moon - 21st Century
First crew expedition to the lunar surface

LUNAR SOUTH POLE TARGET SITE

HLS: Human Landing System

- When we return to the Moon, the vehicles and ConOps are very different from those used for Apollo
- Public-private partnership with two crewed landers:
 - SpaceX Starship
 - Blue Origin / National Team's Blue Moon
- Deorbit, Descent, and Landing (DDL) at the Moon is a valuable stepping stone to Mars
- Precise lunar landings will demonstrate integrated GN&C and complex multi-asset operations
- Lack of atmosphere on the Moon limits feed-forward of aerosciences and integrated EDL system performance capabilities to Mars
- Retropropulsion-induced environments will be challenging at the Moon and then very different at Mars, even with a similar vehicle



HLS Lander Concepts

Human Mars EDL: A Paradigm Shift

- Viking-heritage EDL systems cannot land the masses required for human Mars exploration
- Supersonic parachutes cannot be extended to high-mass EDL
- Precise Lunar landings require and will demonstrate integrated GN&C for the landing
- Lunar landings require prediction/knowledge of large-engine plume surface interaction (PSI) effects, but lunar PSI experience does not directly feed forward to Mars missions
- Robust guidance and control throughout entry and descent is required for safe, precise landing

	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 Low-L/D
Steady progression of “in family” EDL <i>Payloads up to ~1 t</i>								New EDL Paradigm <i>Payloads 20-30* t</i>

Land: Enable Lunar/Mars Global Access with ~ 20t Payloads to Support Human Missions



LUNAR CAPABILITIES (FEEDING FORWARD TO MARS)

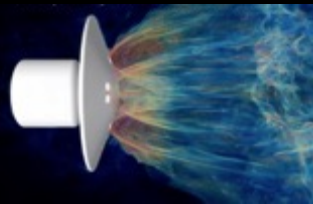
Precision Landing and Hazard Avoidance

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



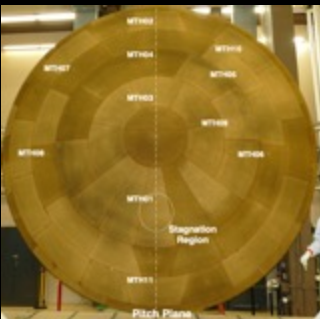
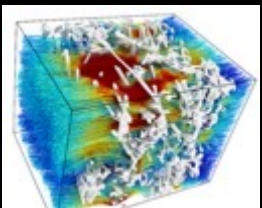
Retropropulsion

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



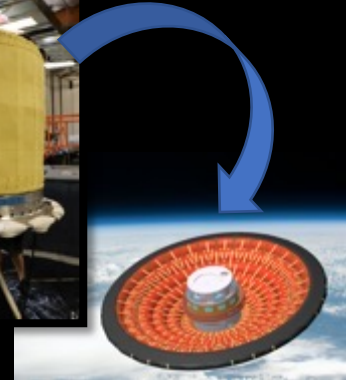
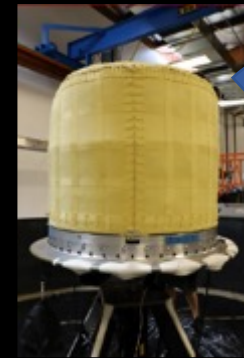
Foundational Modeling, Testing, Instrumentation, and Computing

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

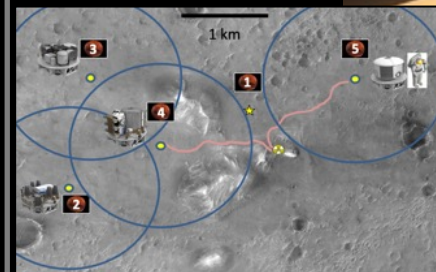


Earth Flight Tests, such as LOFTID



Assess Alternatives

Aggregate Assets



Human Mars EDL



Current/Recent Investments to Achieve 20t Landings



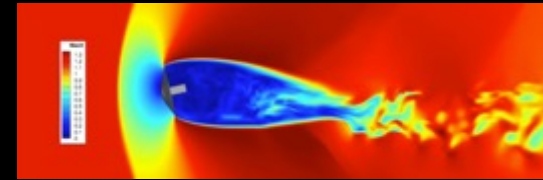
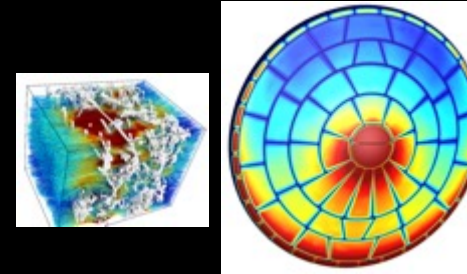
LOFTID

6m inflatable aeroshell test with United Launch Alliance (ULA) – 2022
Post-Flight Analysis in progress



*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)



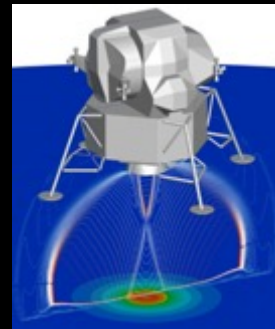
MEDLI-2 (complete)

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



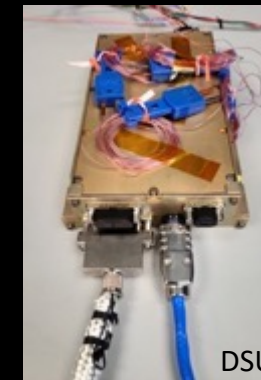
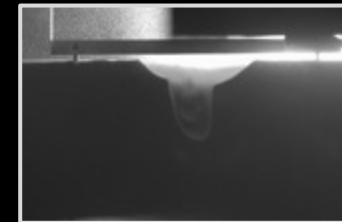
Descent Systems Study

Mid L/D configuration, HIAD and all SRP testing FY22/23



*Plume Surface Interaction (PSI) Mini-Suite

Flight instrument maturation to measure PSI phenomena



*SCALPSS 1.0 and 1.1

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



Camera

DSU

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

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)

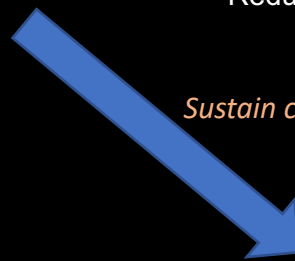
Vandenberg launch with JPSS-2. **HIAD experienced human Mars mission-relevant heating and g-load.**



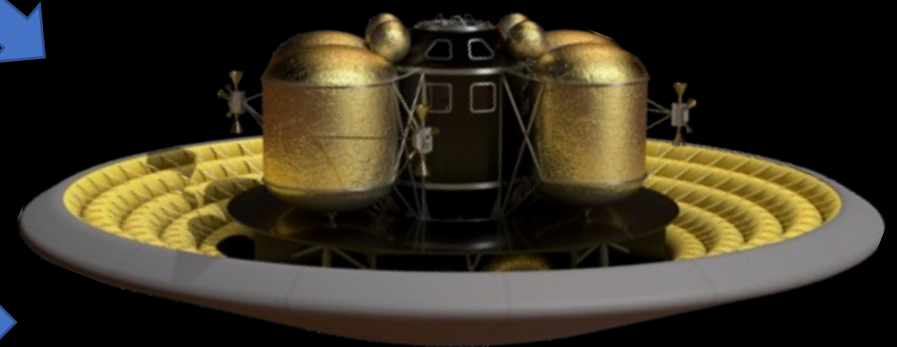
Commercial Rocket Engine Recovery (12 m) – 2024-25+

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



Sustain commercial base



Human Mars Lander (~18 m)

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

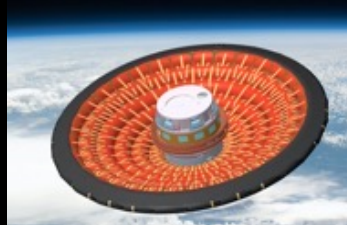
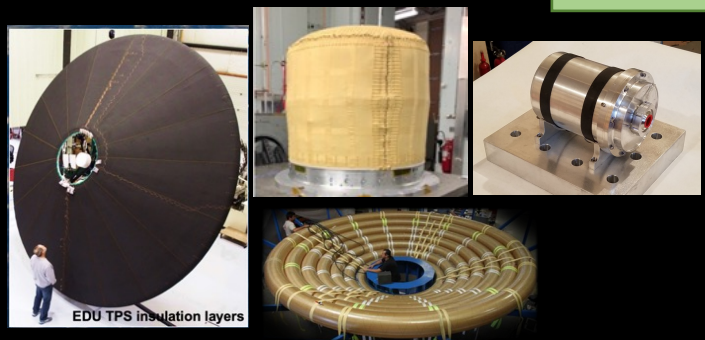
- Demonstrates closed-loop G&C and transition to propulsive deceleration
- Includes large-scale, mass-efficient structures



Ready for Mars infusion

Ground Scale-up Demonstration

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



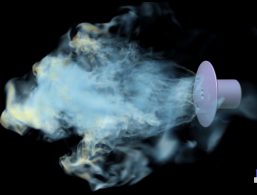
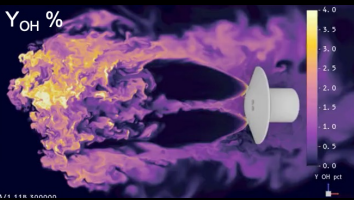
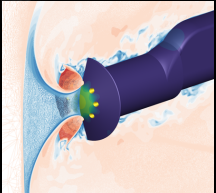
Green = currently funded; Yellow = not yet funded

Retropropulsion Advancement Approach



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

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

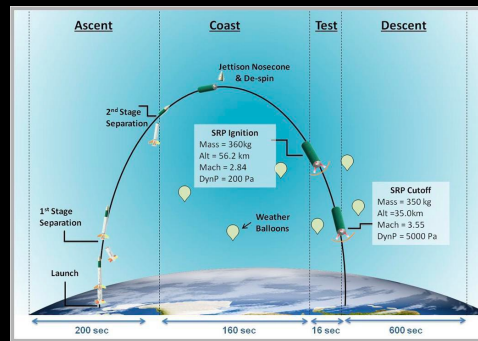
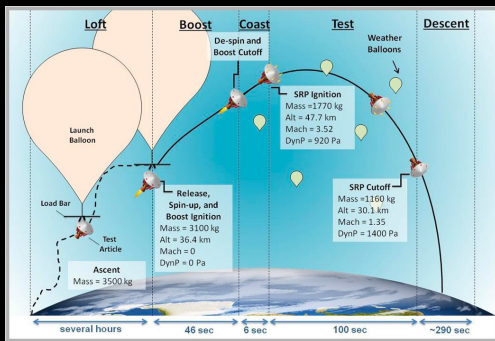


Wind Tunnel Testing with Combustion Engines (Glenn Supersonic and Transonic Tunnels)

- 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

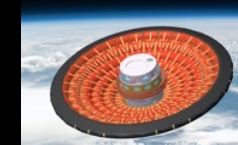
High-Altitude Suborbital Testing (~1m diameter scale)

- 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



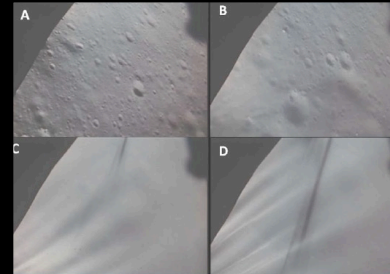
(see previous page)

Gradual increase in test fidelity retains flexibility and supports configuration decisions.
Rapid analysis of large datasets is key challenge – requires new tools, computing architectures

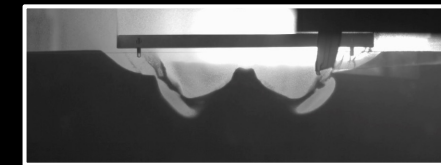
Plume Surface Interaction (PSI) Advancement Approach



The Challenge: Engine plumes of landing (and ascending) vehicles will disturb the surface below, potentially causing (1) cratering, (2) heating of the vehicle base and legs, 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 obscurations (Metzger, 2011)



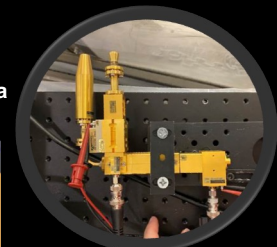
Physics-Focused Ground Test, annular crater in sand (2021)



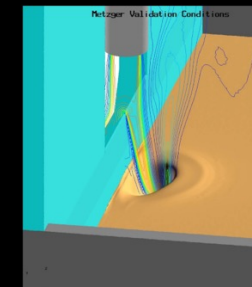
HLS PSI Ground Test Facility 60-ft Sphere at NASA LaRC



Crater Observation Camera



mm-Wave Doppler Radar



PSI Prediction Model

- **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 **and create dust that requires mitigation**
- Obscuration during PSI event may affect precision landing sensor performance/data, in high-thrust cases*

- Conduct vacuum ground tests with regolith/bedrock simulants to generate initial model validation data

- Small-scale, warm-gas tests varying simulants, vacuum levels (Moon and Mars), nozzle heights and mass flows
- “Scaled Flight Relevant” vacuum tests with simulants, combustion – more relevant to human-scale systems
- Limited vacuum facilities exist, to handle both regolith and combustion, at any scale

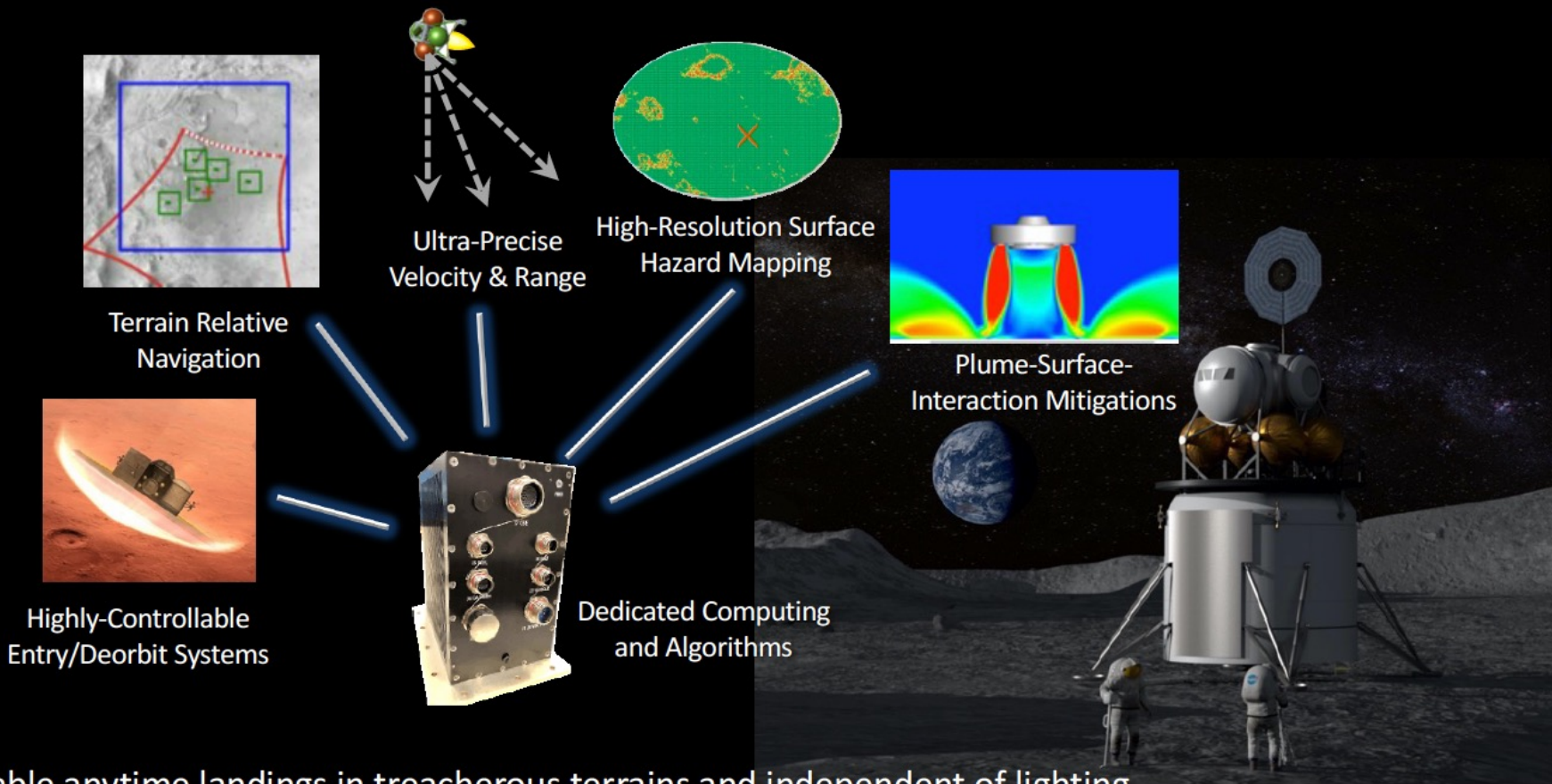
- Develop instrumentation to measure (1), (2), and (3) above

- Implement in ground tests to demonstrate instruments and measure relevant quantities for model validation
- Instrument CLPS landers (100's of lbf) for single and multiple PSI phenomena
- Instrument larger lunar and robotic Mars landers with low-SWaPc multi-sensor suites to obtain flight data

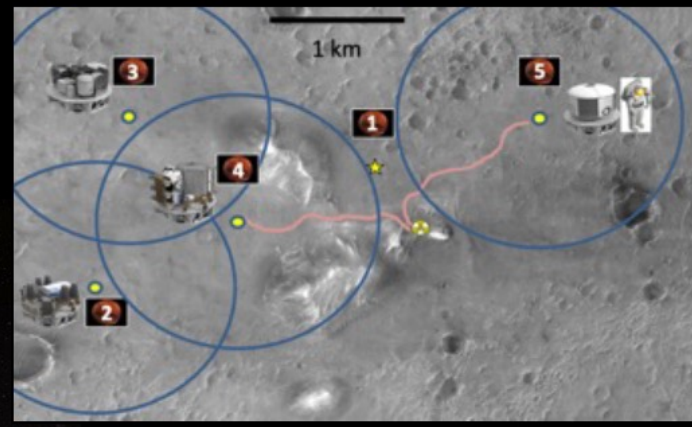


LAND: Technologies to Precisely Land Payloads and Avoid Landing Hazards

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



Summary

- EDL has always been and remains a core and critical capability at NASA
- We are going back to the Moon and continuing to challenge Mars...
All while continuing to enable in-situ science exploration across the Solar System
- EDL technology development is a major part of the portfolio, enabling science and human exploration goals that would otherwise be impossible



EXPLORE MOON *to* MARS

Questions?

