EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

LAND: Entry, Descent, and Landing to Enable Planetary Science Missions

NASA Space Technology Mission Directorate

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

EDIT Log

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

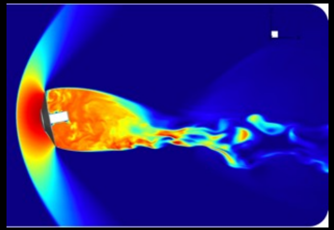
- P3 – added “low cost pulsed hydrazine propulsion” to Phoenix and “tiled PICA” to MSL (LM)
- P3 – changed color of Orion to black since Artemis-1 is in the books.
- P4 – added “Improvements in cost, mass and reliability remain attractive” to TPS bullet (ORNL).
- P4 – added “scalability” to above edit (LM)
- P7 – added “standalone and” to SSC aerocapture bullet (JPL)
- P9 – added “and can be verified with existing facilities” to TPS bulled (JPL)
- P9 – added “Aerocapture has broad benefits for multiple destinations and spacecraft scales” (JPL)
- P9 – added “or inner planet” to the demonstration bullet (Space-X)
- P11 – added fluid structure interactions (JPL)
- P12 – added “compact PLHA” to SSC bullet and “to facilitate adoption in future small spacecraft missions” to A/C bullet (JPL)
- P12 – added “and broaden data use from commercial flights” to performance validation (Space-X)
- P12 – added “3MDCP” to TPS (LM)

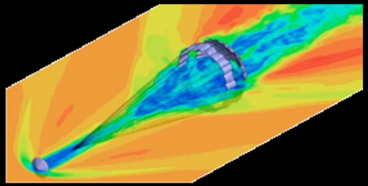
LAND: Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies

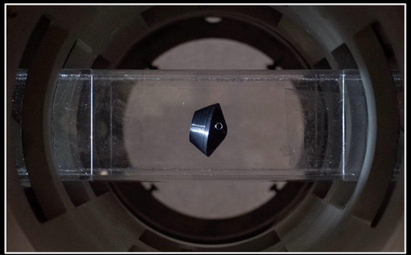
Developing atmospheric entry technology to enhance and enable small spacecraft to Flagship-class missions across the solar system

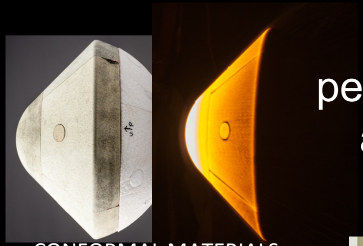
Entry Systems Modeling & Testing

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


"DESKTOP WIND TUNNEL"


PARACHUTE MODELING


MAGNETIC SUSPENSION WIND TUNNEL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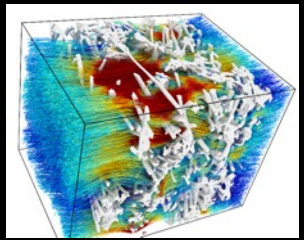
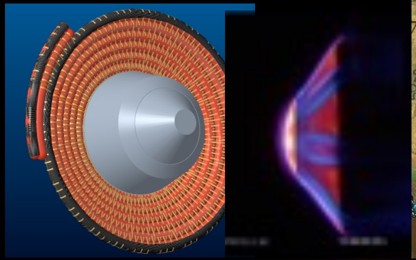

IN-DEPTH MATERIAL RESPONSE

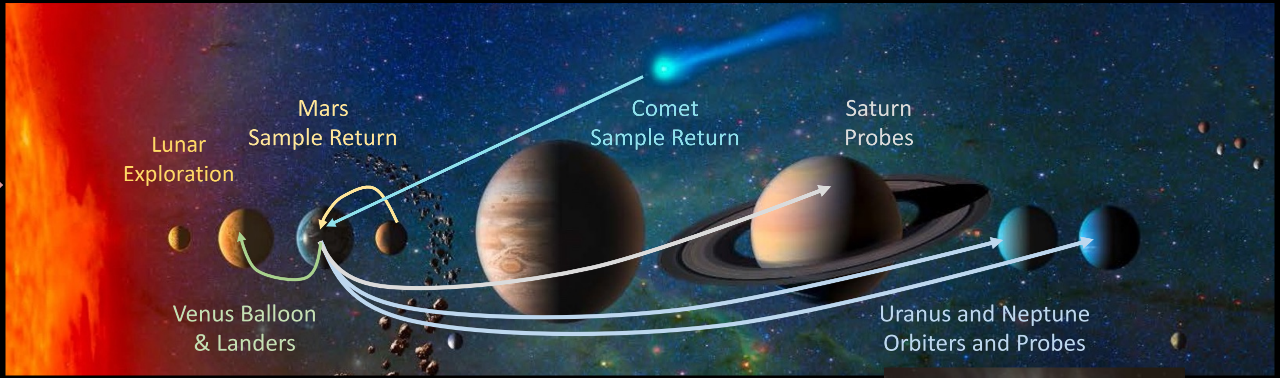

DEPLOYABLE DECELERATORS

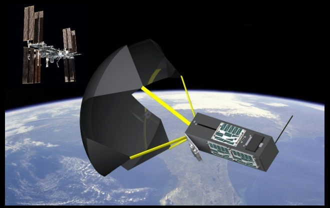

3D WOVEN HEATSHIELDS

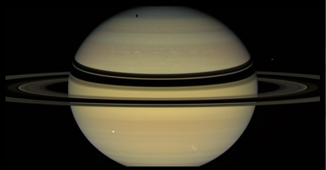
to enable

Hardware Development

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




PRECISION DEORBIT

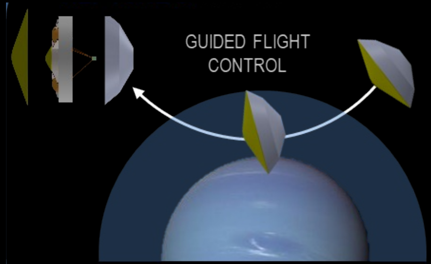

SATURN PROBE


TITAN PINPOINT LANDING

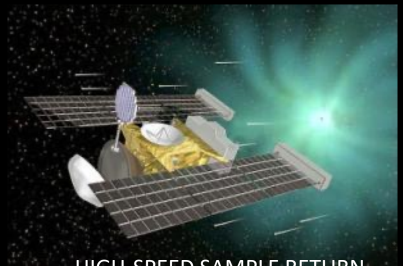

MARS SAMPLE RETURN

Increasing Science Return, Decreasing Risk, Cost, and Schedule


ICY MOON PRECISE LANDING



ICE GIANT AEROCAPTURE

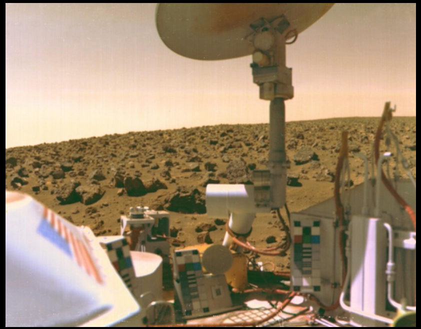

HIGH-SPEED SAMPLE RETURN

Not all activities depicted are currently funded or approved. Depicts "notional future" to guide technology vision.

State-of-the-Art: EDL for Planetary Science Missions

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 no longer available)
Galileo	Jupiter	1995	Carbon Phenolic TPS, ablation sensor (SOA no longer available)
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	Low-cost pulsed hydrazine propulsion
MSL	Mars	2012	Hypersonic guidance, Sky-crane, MEDLI, tiled PICA
InSight	Mars	2018	Viking-style pallet lander (no new features)
Mars2020	Mars	2021	TRN, EDL cameras, MEDLI2
Artemis-1	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
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
- Conservativism used to minimize risk (to accommodate large uncertainties), but also limits performance

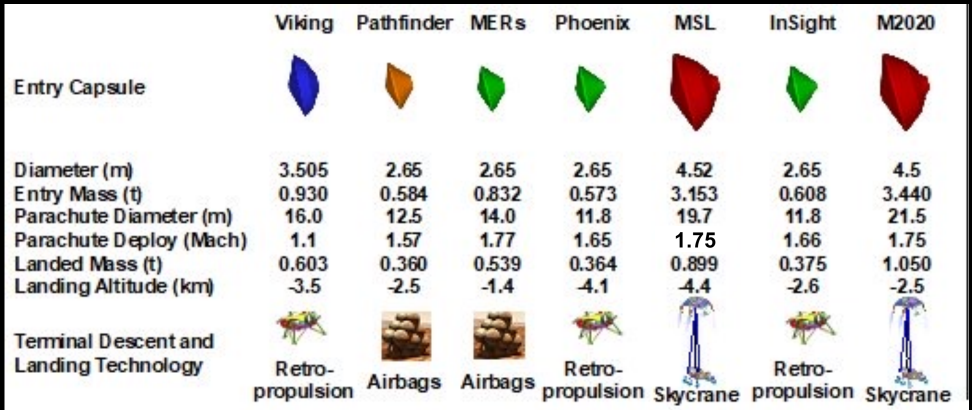


Viking 2

Galileo

Stardust

Mars Program



	Viking	Pathfinder	MERs	Phoenix	MSL	InSight	M2020
Entry Capsule							
Diameter (m)	3.505	2.65	2.65	2.65	4.52	2.65	4.5
Entry Mass (t)	0.930	0.584	0.832	0.573	3.153	0.608	3.440
Parachute Diameter (m)	16.0	12.5	14.0	11.8	19.7	11.8	21.5
Parachute Deploy (Mach)	1.1	1.57	1.77	1.65	1.75	1.66	1.75
Landed Mass (t)	0.603	0.360	0.539	0.364	0.899	0.375	1.050
Landing Altitude (km)	-3.5	-2.5	-1.4	-4.1	-4.4	-2.6	-2.5
Terminal Descent and Landing Technology	Retro-propulsion	Airbags	Airbags	Retro-propulsion	Skycrane	Retro-propulsion	Skycrane

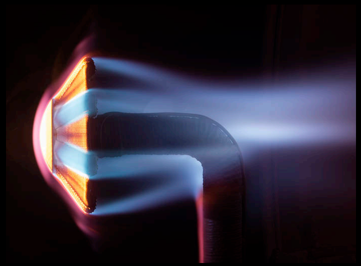
Purple = Future EDL, in development

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. Improvements in cost, mass, scalability and reliability remain attractive

HEEET

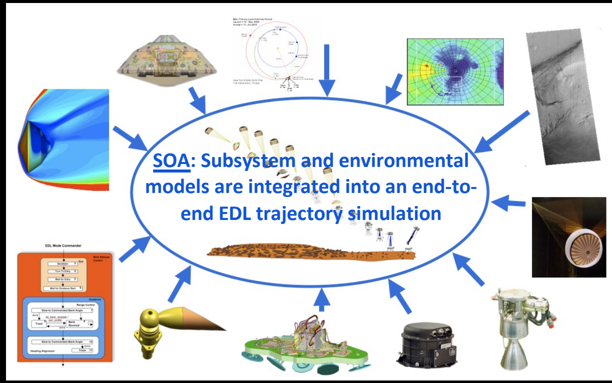


ADEPT/Spiderweave

PICA

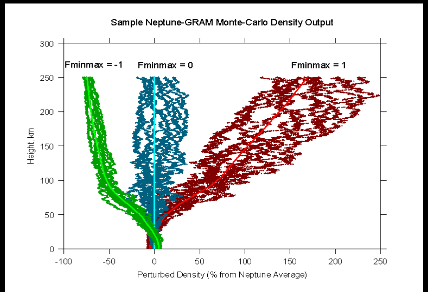
GN&C Modeling

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



Atmosphere Models

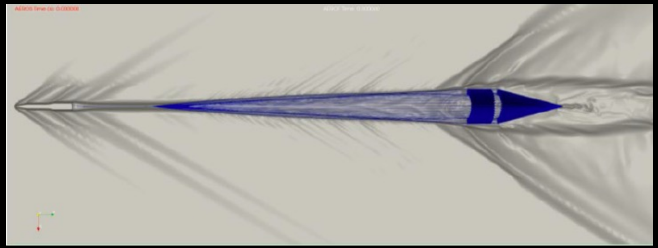
- GRAM update for PSD destinations of interest nearing completion; New data inclusion forthcoming



Parachutes

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

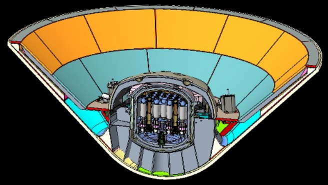
M2020 Parachute



Aero/FS Simulation of ASPIRE

Architecture/System

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



EES

ADEPT

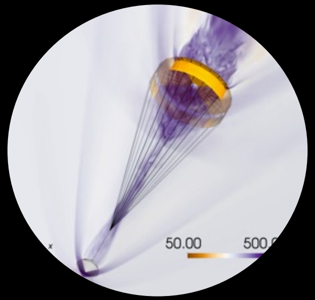
HIAD (LOFTID)

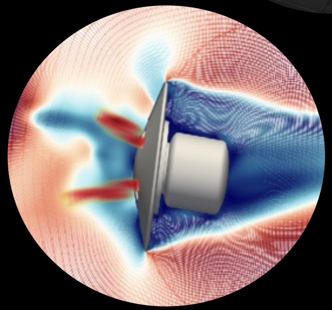
SRP Simulation

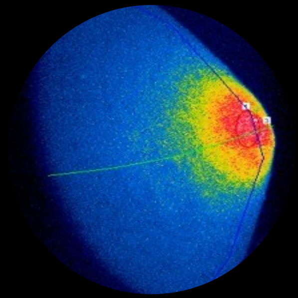
EDL Modeling and Simulation is Critical to Planetary Science

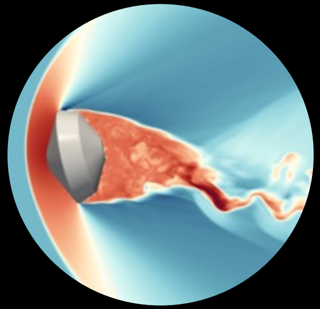
Planetary entries cannot be practically tested end-to-end on Earth; flight performance assessment and certification RELIES on robust EDL Modeling and Simulation capabilities.

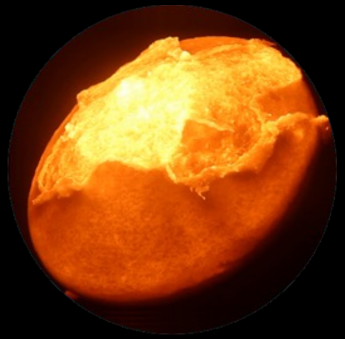
- **Models, particularly in aerosciences and material response, have largely undefined uncertainty levels for many problems (limited validation)**
  - Without well-defined uncertainty levels, it is difficult to assess system risk and to trade risk with other subsystems, leading to increased schedule 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.

Context: Mission Priorities from the 2022 Planetary Decadal Survey

List of Missions that Include 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*	*Precision landing/hazard avoidance?*
	Europa Lander*	*Hazard detection and avoidance*
	Mercury Lander*	*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

**Missions potentially involving EDL*

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

High-Priority Gaps and Current STMD/SMD Investments

There are 26 identified gaps mapped to the "Planetary EDL" outcome. Highest-priority gaps, as ranked by the EDL System Capability Leadership:

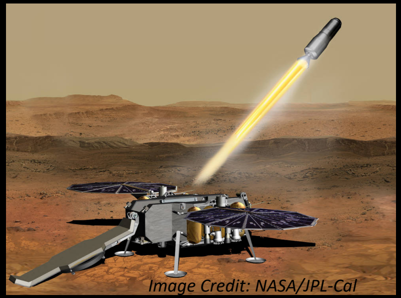
Current/Recent STMD Investments	
▪ Entry Systems Modeling (ESM) Project* ▪ ACCESS STRI (5 yrs, $15M) ▪ ECF and ESI Awards: Modeling, Chutes ▪ Plume Surface Interaction (PSI) Project ▪ Global Reference Atmospheric Models*	**Modeling & Simulation (includes UQ across the breadth of models)** ▪ Validated Aerothermodynamic Prediction for Robotic Mission EDL ▪ Thermal Protection System Performance Modeling & Optimization for Robotic Missions ▪ Validated Static/Dynamic Aerodynamics Prediction from Supersonic to low Subsonic Speed ▪ Validated Wake Models, Including Reaction Control Thruster Effects ▪ Atmospheric Model Development
▪ SPLICE† ▪ MEDLI and MEDLI2 Flight Instruments* ▪ DrEAM Flight Instrumentation* ▪ Parachute Sensors (ECI, SBIR) ▪ SCALPSS*, SCALPSS 1.1 (for PSI)	**Performance Validation** ▪ Integrated, Multi-Function Precision Landing Sensors for Robotic Missions† ▪ EDL Flight Vehicle (Aeroshell) Flight Performance Data for Robotic Missions ▪ Flight Instrumentation to Acquire Parachute Performance Data ▪ Planetary Aerothermodynamics Test Facility
▪ Entry Systems Modeling (ESM) Project* ▪ ACCESS STRI ▪ 3-D Woven TPS (HEEET, 3MDCP) ▪ Multiple SBIR awards	**EDL Hardware Technologies** ▪ High-Reliability Earth Entry Vehicles for Robotic Missions ▪ Supersonic Parachute Systems and Modeling
▪ Exo-Brake ▪ Additively-Manufactured TPS (ECI) ▪ Deployable Decelerators (HIAD, ADEPT)	**Enabling Small Spacecraft Missions** ▪ Small Spacecraft EDL ▪ Small Spacecraft Aerocapture (standalone and with feed forward to Ice Giant missions)

†NOTE: Precision Landing Technologies apply to several missions and are found in the "Land within 50 m" Outcome package.

*Funded/Co-funded by Science Mission Directorate

Enabling the Mars Sample Return Mission

EDL Challenges



Sample Retrieval Lander (SRL)

- Heaviest Mars payload to date
- Required volume may lead to new aerodynamics
- Largest supersonic parachute ever flown
- Precise landing needed, to efficiently recover cache
- Pallet-style lander will see increased PSI effects

Earth Entry System (EES)

- Category V payload → high reliability requirements against containment loss on entry or impact
- Capsule released 3 days before entry (MMOD risk)
- Extreme mass constraints (round trip multiplier)
- G-sensitive core samples

Forward Plan/Approach

For the Sample Retrieval Lander (SRL):

- Continue investments in Entry Systems Modeling (ESM) and ACCESS to reduce uncertainties in aerodynamics and aerothermodynamics, integrate material response, quantify risk, reduce entry system mass. Infuse tools and methods to mission.
- Test materials and sensors, continue parachute modeling advances through ESI, ECI projects, and ESM. Collaborate with ASPIRE2 to gather flight data. Infuse models to mission.
- Develop and commercialize precision landing and hazard detection sensors to infuse as needed. *(see Land - 50 m)*
- Conduct Mars-relevant ground tests and advance PSI models. Apply models to mission; quantify uncertainty/risk.
- **Gather flight data through MEDLI3 and EDL cameras to validate predictions and inform future missions.*

For the Earth Entry System (EES):

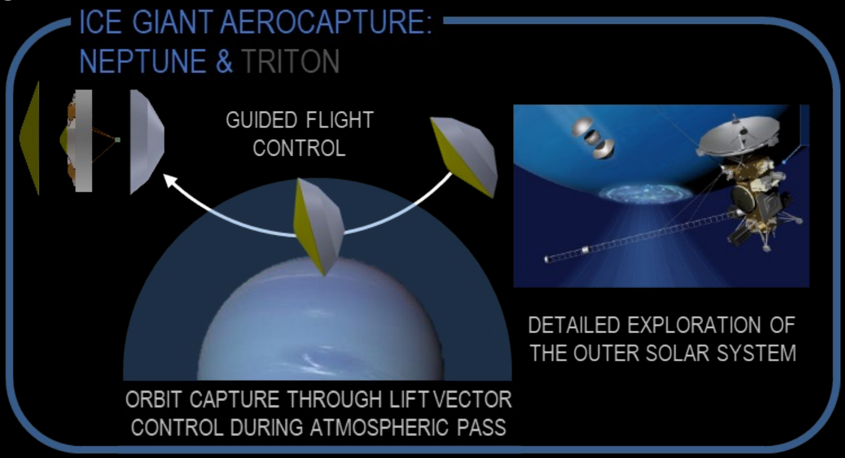
- Continue investments in Entry Systems Modeling (ESM) and ACCESS to reduce uncertainties in aerodynamics and aerothermodynamics, quantify risk, reduce entry system mass. Infuse tools and methods to mission.
- Use 3MDCP TPS material for efficient insulation, robust heat tolerance, and MMOD resilience. Infuse characterization and modeling tools to mission.

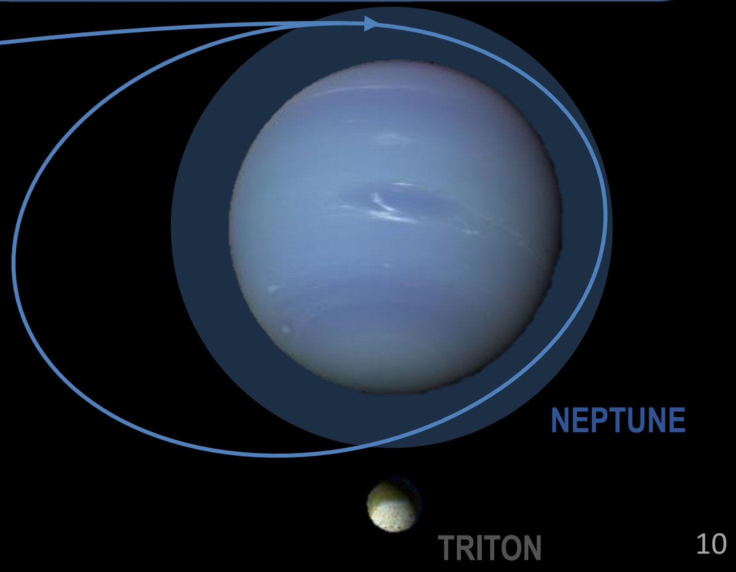
Orange = summary of infusion path

**Does not enable MSR, but inclusion on largest-ever SRL will inform and feed forward to future large-scale missions (see LAND 20 t package)*

Benefits of Aerocapture for Ice Giant Missions

- Missions to Uranus and Neptune are mass-constrained and have cruise times of several years
- An orbiter can AEROCAPTURE and use the planet's atmosphere to remove up to 95% of its arrival velocity, drastically reducing the propellant requirements, shortening the trip time, and/or allowing additional science (such as one or more probes) to be included in the mission.
  - Aerocapture has broad benefits for multiple destinations and spacecraft scales
- Aerocapture has never been performed but employs validated entry system design methods and leverages hypersonic guidance and control demonstrated by Apollo, Orion, MSL, and Mars 2020.
- 3-D woven TPS systems (TRL6) are well-suited for Uranus and Neptune entry speeds (>=29 km/s) and high heat loads of long atmospheric passes and can be verified with existing facilities
- An Earth (or inner planet) based aerocapture demonstration will reduce perceived risk and mature guidance and control methods required for Triton observations and/or Uranus aerocapture

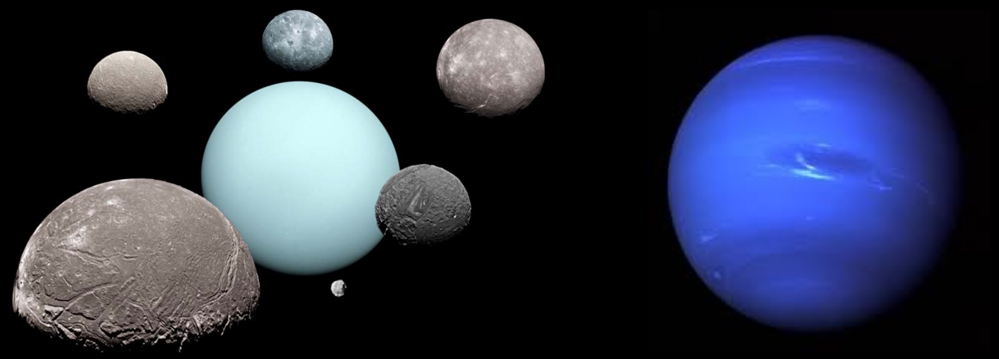




Enabling Aerocapture for Ice Giant Missions

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

Enabling Probes for Outer Planet Missions

Challenges

- High entry speed leads to high heat rates
- High pressure during entry and descent
- Aerothermodynamic uncertainties result from H_2/He atmosphere
- Aerodynamic stability characteristics
- Atmospheric uncertainties are significant
- Parachute deployments in different atmospheres; long descent phases
- **Uranus:** Precision approach/maneuvering needed to avoid rings

Forward Plan/Approach

- Pursue focused H_2/He investments and parachute fluid-structure interaction modeling in Entry Systems Modeling (ESM), ESI, and ECI; 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 and maintain atmospheric models, including Saturn-GRAM, Uranus-GRAM and Neptune-GRAM
- Use HEEET or 3MDCP TPS material for efficient insulation, robust heat tolerance. Infuse characterization and modeling tools to mission.
- Gather flight data through DrEAM and MEDLI3, and on DAVINCI, to validate predictions and inform future missions. Develop low-SWaPc instrumentation for Ice Giant entry systems.

Orange = summary of infusion path

Forward Plans to Close High-Priority Gaps

Gap Area	Near to Mid-Term Approach
Modeling & Simulation	• Continue investment in Entry Systems Modeling (ESM) project focusing on development and validation of integrated, higher-fidelity modeling capabilities to support next Decadal missions • Continue successful history of investments in Early Stage portfolio, including ECI, ESI/ECF, and ACCESS STRI • Complete and sustain upgrades to GRAM models for all relevant destinations • Initiate simulation retooling efforts to improve efficiency and take advantage of GPU-based and exascale computing architectures
Performance Validation	• Complete Mars 2020/MEDLI-2 post-flight analysis, including ESM deep dive • Implement DrEAM and DAVINCI instrumentation suites • Implement and conduct post-flight analysis from SCALPSS and SCALPSS 1.1 on CLPS; begin multi-sensor CLPS PSI suite • Begin development of MEDLI-3 for Mars Sample Return • Continue to support/improve Engineering Science Investigation (ESI) requirement on competed missions and broaden data use from commercial flights • Perform OSIRIS-REx airborne observation during Earth Return • Leverage SBIR/STTR for new sensor development, including for landing systems and parachutes • Advocate for new planetary aerothermodynamics facility as defined via ongoing HEAC study
EDL Hardware Technologies	• Maintain prior-developed (now SOA) TPS materials (e.g. PICA, HEEET, 3MDCP) to ensure capability for all classes of future missions • Continue development of Mars Sample Return Earth Entry System (EES) with a focus on overall reliability. Leverage ESM and ACCESS capabilities to better determine reliability of as-built system. • Push the state of the art for supersonic decelerators via a combined modeling and experimental validation effort. Leverage advanced modeling tools to better understand physics drivers. • Leverage SBIR, CIF, ECI, and other Early Stage investments
Enabling Small Spacecraft Missions	• Conduct an aerocapture flight test to facilitate adoption in future missions and with direct applicability to Ice Giants • Enable small spacecraft deorbit/EDL via compact, low-SWAPc deorbit/entry systems, compact precision landing / hazard avoidance and thermal protection materials development

Green = currently funded/planned; Yellow = not yet funded

Acronyms

- ADEPT – Adaptable, Deployable Entry and Placement Technology
- CLPS – Commercial Lunar Payload Services
- CFD – Computational Fluid Dynamics
- CORAL – Centaur Orbiter and Lander
- CSSR – Comet Surface Sample Return
- DrEAM – Dragonfly Entry Atmospheric Measurements
- ECF – Early Career Faculty
- EDL – Entry, Descent and Landing
- EES – Earth Entry System (specifically, that for Mars Sample Return)
- EMF – Enceladus Multiple Flyby
- ESI – Early Stage Innovation
- FEM – Finite Element Model
- FS – Fluid/Structural
- GN&C – Guidance, Navigation and Control
- GPU – Graphical Processor Unit
- GRAM – Global Reference Atmospheric Models
- HEAC – Hypersonic Environment Aerothermal Capability
- HEEET – Heatshield for Extreme Entry Environment Technology
- HIAD – Hypersonic Inflatable Aerodynamic Decelerator
- LGN – Lunar Geophysical Network
- LOFTID – Low Earth Orbit Flight Test of an Inflatable Decelerator
- MEDLI2 – Mars Entry, Descent and Landing Instrumentation (2)
- MSR – Mars Sample Return
- PICA – Phenolic Impregnated Carbon Ablator
- PSD – Planetary Science Division
- PSI – Plume Surface Interaction
- SBIR – Small Business Innovation Research
- SCALPSS – Stereo Cameras for Lunar Plume Surface Studies
- SOA – State of the Art
- SPLICE – Safe, Precise Landing Integrated Capabilities Evolution
- SRL – Sample Retrieval Lander (specifically for Mars Sample Return)
- SRP – Supersonic Retropropulsion
- STRI – Space Technology Research Institute
- SWAPc – Size, Weight, Power and Cost
- TPS – Thermal Protection System
- TRN – Terrain Relative Navigation
- VISE – Venus In Situ Explorer
- 3MDCP – 3-Dimensional Carbon Phenolic