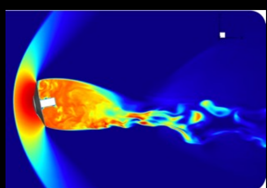
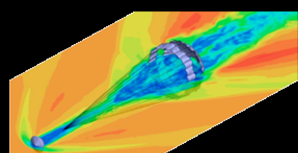
LAND: Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies

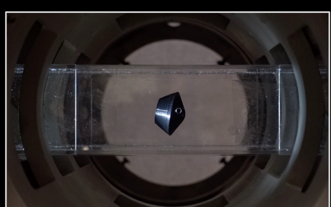
Developing atmospheric entry technology to enhance and enable small spacecraft to Flagship-class missions across the solar system

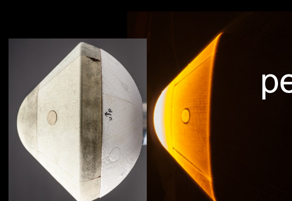
Entry Systems Modeling & Testing

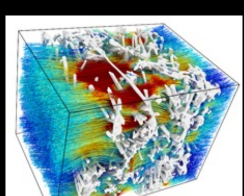
Reducing entry system mass and risk by developing advanced, validated models

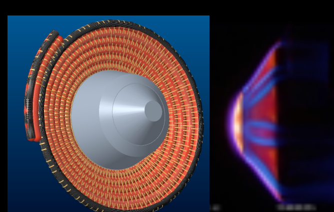

"DESKTOP WIND TUNNEL"


PARACHUTE MODELING


MAGNETIC SUSPENSION WIND TUNNEL


CONFORMAL MATERIALS


IN-DEPTH MATERIAL RESPONSE

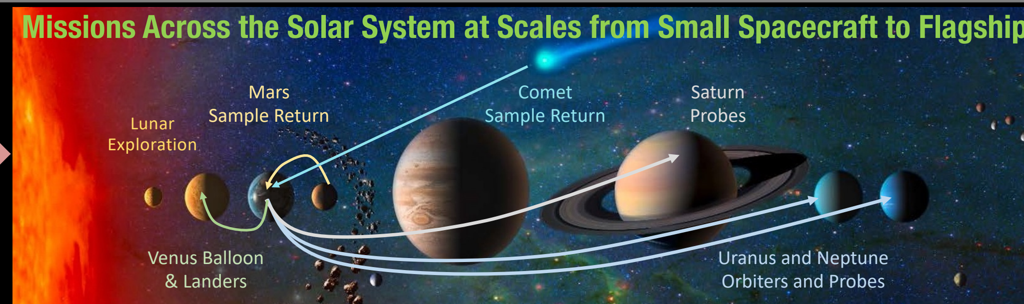

DEPLOYABLE DECELERATORS

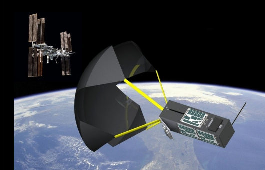

3D WOVEN HEATSHIELDS

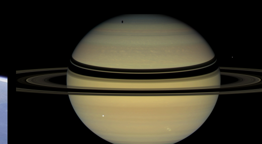
to enable

Hardware Development

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




PRECISION DEORBIT

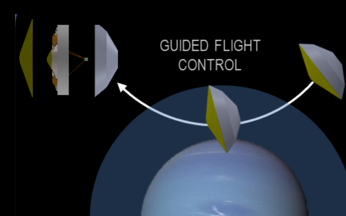

SATURN PROBE


TITAN PINPOINT LANDING

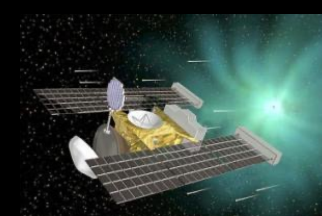

MARS SAMPLE RETURN

Increasing Science Return, Decreasing Risk, Cost, and Schedule


ICY MOON PRECISE LANDING



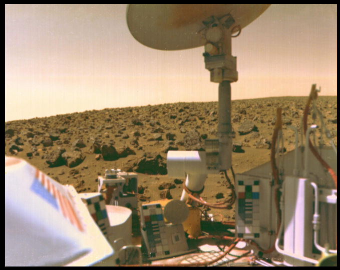
ICE GIANT AEROCAPTURE


HIGH-SPEED SAMPLE RETURN

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

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 now lost)
Galileo	Jupiter	1995	Carbon Phenolic TPS, ablation sensor (SOA now lost)
Pathfinder	Mars	1997	Landing Airbags
Genesis	Earth Return	2004	Carbon-Carbon TPS
MER	Mars	2004	Angular rate control
Stardust	Earth Return	2006	One-piece PICA TPS; fastest Earth entry
Phoenix	Mars	2007	Viking-style pallet lander (no new features)
MSL	Mars	2012	Hypersonic guidance, Sky-crane, MEDLI
InSight	Mars	2018	Viking-style pallet lander (no new features)
Mars2020	Mars	2021	TRN, EDL cameras, MEDLI2
Orion (11 km/s)	Earth return	*2022*	Block Avcoat TPS, precision guidance
OSIRIS-REx	Earth Return	2023	Stardust entry system (no new features)
MSR SRL	Mars	2028-2029	Highest Mars entry/landed mass, largest parachute
MSR-EES	Earth Return	2031	Class V reliability required; passive capsule w/3MDCP
DAVINCI	Venus	(2032)	Genesis-type aeroshell/TPS at Venus
Dragonfly	Titan	2034	Titan EDL; thermal management over long descent



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

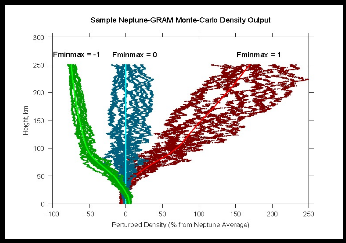
- EDL design & technologies are specialized for each destination/mission
- Newer missions tend to be more complex; push existing technologies to or beyond their limits
- Conservativism used to minimize risk (to accommodate large uncertainties), but also limits performance

Purple = Future EDL, in development

Planetary EDL Subsystem SOA

Atmosphere Models

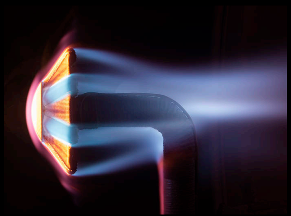
- GRAM update for PSD destinations of interest nearing completion; New data inclusion forthcoming



TPS

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

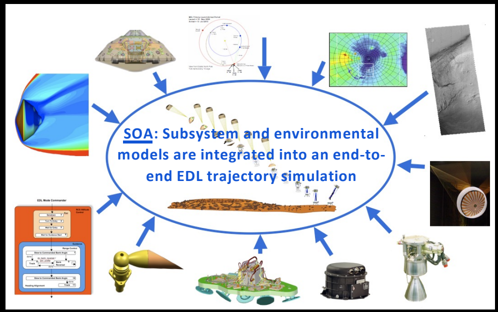

HEEET


ADEPT/Spiderweave


PICA

GN&C Modeling

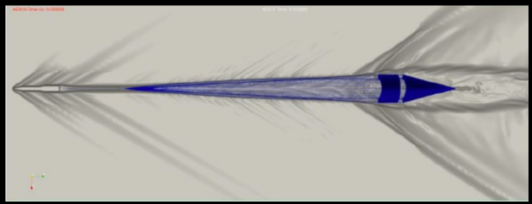
- Baseline models under development for expected planetary mission space; Quantified uncertainty forthcoming



Parachutes

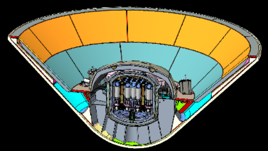
- Mars2020 flew largest supersonic chute to date; MSR plans even larger. Modeling SOA lags hardware/testing, but is under active development


M2020 Parachute


Aero/FS Simulation of ADEPT

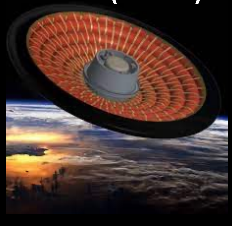
Architecture/System

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


EES


ADEPT

HIAD (LOFTID)

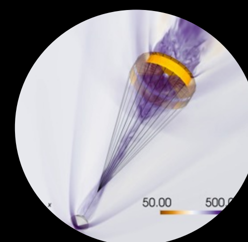


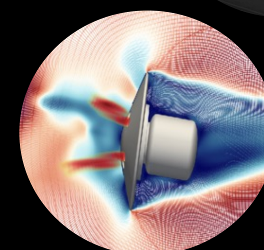
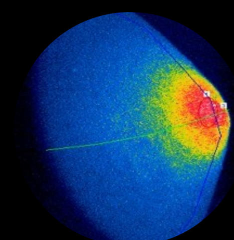
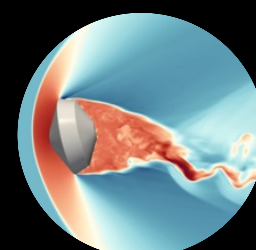
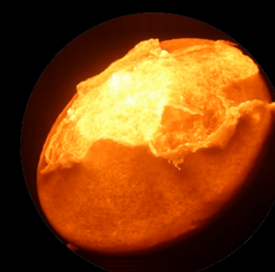

SRP Simulation

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 2013 Planetary Decadal Survey
List of Missions that Include Entry, Descent and/or Landing (EDL)

green = mission involves EDL

	2013 Planetary Decadal Survey Priority	Enabling/Enhancing EDL Capability Advancement
Flagship	Jupiter Europa Orbiter (JEO) + lander	Active hazard detection, radiation tolerance, very low SWaP
Flagship	Uranus Orbiter and Probe	Aerocapture for orbiter; atmospheric modeling, aero/aerothermal modeling, mass-efficient entry system
New Frontiers	Comet Surface Sample Return	Aerothermal modeling for high-velocity return
New Frontiers	Lunar South Pole-Aiken Basin Sample Return	Precision landing, mass-efficient entry system for cryo return
New Frontiers	Saturn Probe	Atmospheric modeling, aero/aerothermal modeling, mass-efficient entry system
New Frontiers	Venus in-Situ Explorer	Atmospheric modeling, aero/aerothermal modeling, mass-efficient entry system
New Frontiers	Lunar Geophysical Network	*No new tech needed, unless precise landings are required*
New Frontiers	Ocean Worlds	*No new tech needed (for Dragonfly implementation)*
Technology Development	Neptune Orbiter and Probe	Aerocapture for orbiter; mass-efficient entry system
Technology Development	Mars Sample Return Lander and Orbiter	Supersonic parachute modeling/risk reduction, PSI models
Technology Development	Titan Saturn System Mission	*No EDL*

Announced August 2021: New Frontiers list will stay constant, for the next Decadal Survey release in 2022, however, Flagship priorities may change

High-Priority Gaps and Current STMD/SMD Investments

Current/Recent STMD Investments	*There are 26 identified gaps mapped to the "Planetary EDL" outcome.* *Highest-priority gaps, as ranked by the EDL System Capability Leadership:*
▪ 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 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

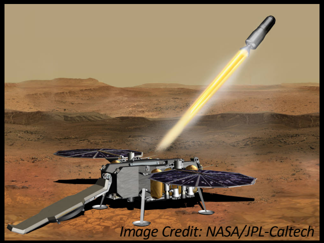


Image Credit: NASA/JPL-Caltech

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


Image Credit: NASA/LaRC

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

- 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.*

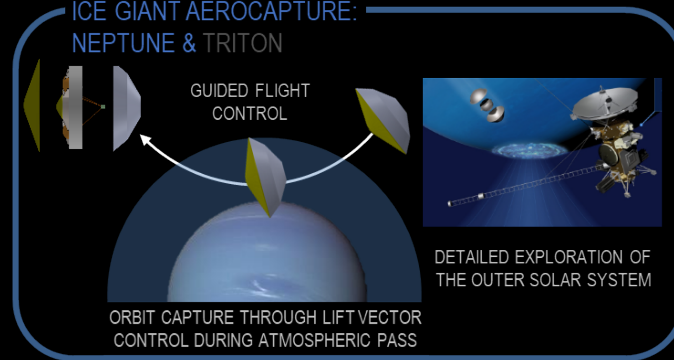
- Continue investments in Entry Systems Modeling (ESM) and ACCESS to reduce uncertainties in aerodynamics and aerothermodynamics, quantify risk, reduce entry system mass. Infuse tools and methods to mission.
- Use 3MDCP TPS material for efficient insulation, robust heat tolerance, and MMOD resilience.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

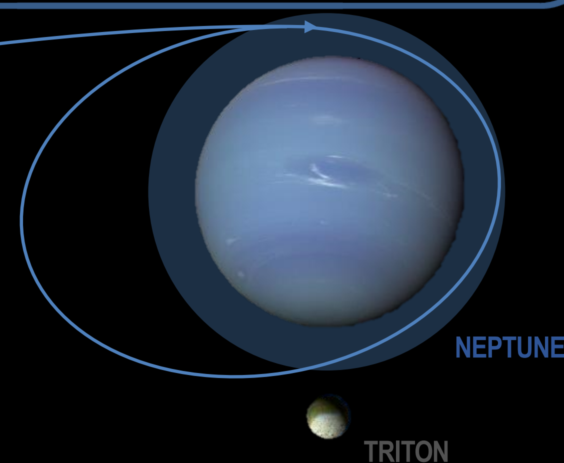
Orange = summary of infusion path

**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 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
- An Earth-based aerocapture demonstration will reduce perceived risk and mature guidance and control methods required for Triton observations and/or Uranus aerocapture





AEROCAPTURE PERFORMANCE BENEFITS:

INCREASED PAYLOAD MASS

INCREASED SCIENCE

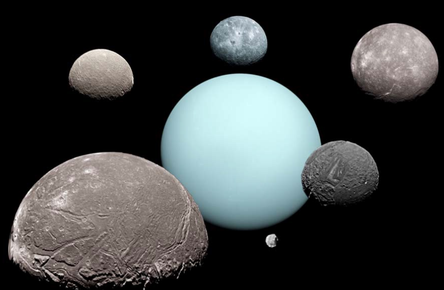
SHORTER TRIP TIMES

DECREASED OPERATIONS COST

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 parachutes 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 upcoming competed missions • 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) 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 with direct applicability to Ice Giants and retire technical and "perceived" risk of adoption • Enable small spacecraft deorbit/EDL via compact, low-SWAPc deorbit/entry systems 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
- DrEAM – Dragonfly Entry Atmospheric Measurements
- ECF – Early Career Faculty
- EDL – Entry, Descent and Landing
- EES - Earth Entry Sytem (specifically, that for Mars Sample Return)
- 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
- 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
- 3MDCP – 3-Dimensional Carbon Phenolic