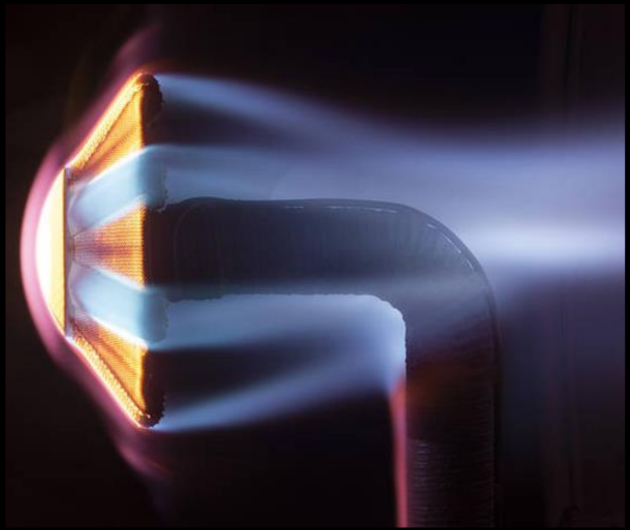
Deployable Entry Vehicles for Future Science and Exploration Missions



Credit: CIRA/ASI

Alan Cassell
Entry Systems & Technology Division
NASA Ames Research Center

Outline

A WHITE PAPER for the
PLANETARY SCIENCES DECADAL SURVEY, 2023-2032

Deployable Entry Vehicles for Future Science and Exploration Missions

Primary Author:
Alan Cassell[1]
Entry Systems and Technology Division
NASA Ames Research Center
Phone: 650-604-2325
Email: Alan.M.Cassell@nasa.gov

Co-Authors:
Neil Cheatwood[2]
Steven Hughes[2]
Cole Kazemba[1]
Greg Swanson[1]

Endorsers:
Gerald Lebeau[3]
Michelle Munk[2]
Ethiraj Venkatapathy[1]
Paul Wercinski[1]
Michael Wright[1]

[1] NASA Ames Research Center
[2] NASA Langley Research Center
[3] NASA Johnson Space Center

Cassell, A. et al Planetary Science and Astrobiology Decadal Survey 2023-2032 white paper e-id. 387; Bulletin of the American Astronomical Society, Vol. 53, Issue 4, e-id. 387 (2021)

- Deployable Entry Vehicles Overview
- Recent NASA Development Activities
- Mission Applications & Mission Concepts
- Technology Investments & Mission Infusion
- Summary

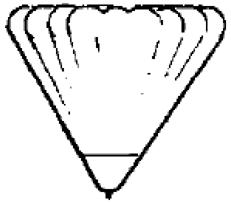
Deployable Entry Vehicles- Inflatable

SELECT HISTORICAL TECHNOLOGIES & CONCEPTS

SELECT RECENT DEVELOPMENT ACTIVITIES

Goodyear Aerospace

Cone

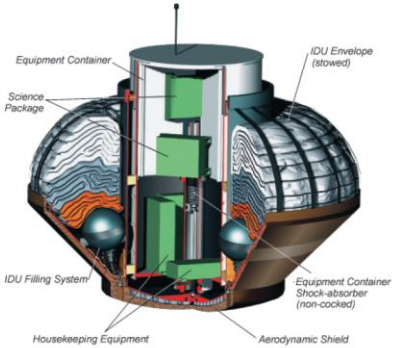


Tension Shell

Ballute

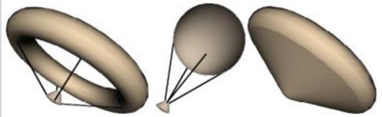
ERA
1960s
OBJECTIVES
Deployable aerodynamic decelerator assessment for M 1-25 flows.
ENTITIES
Goodyear Aerospace/NASA
STATUS
Report concluded significant development of analytical methods for aero and aerothermal predictions and materials needed.

IRDT

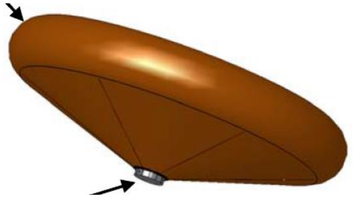


ERA
1990s
OBJECTIVES
Technology demonstration of inflatable reentry vehicle for LEO return & Mars surface networks.
ENTITIES
Lavochkin/ESA/ISTC/Astrium
STATUS/COMMENTS
First demonstration of an inflatable entry vehicle to return payload from LEO, including LV upper stages.

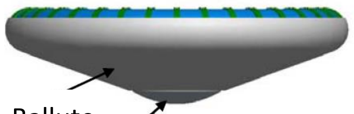
Ultra Lightweight Ballutes



Ballute



Payload



Ballute

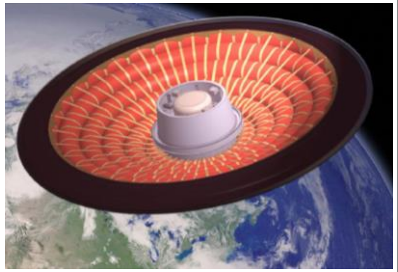
CEV

ERA
2000s
OBJECTIVES
Concept maturation studies to utilize inflatable entry vehicles for science and exploration.
ENTITIES
NASA/JPL/Ball/Ga Tech/ILC Dover
STATUS/COMMENTS
Systems analysis and testing concluded technology feasible for use in numerous entry applications.

HIAD

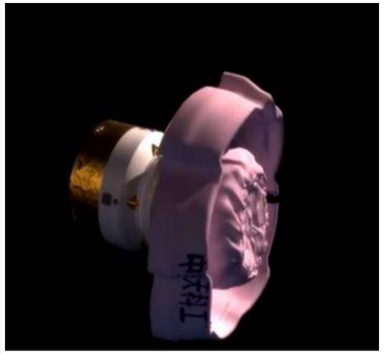
IRVE-3

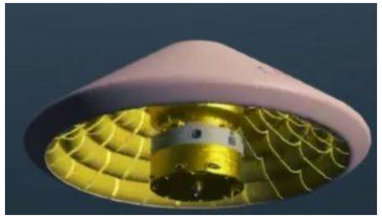
LOFTID



ERA
2000-present
OBJECTIVES
Develop system technologies for LEO, robotic missions and Human Mars exploration.
ENTITIES
NASA & Industry Partners
STATUS/COMMENTS
Extensive ground and flight demonstrations. LOFTID 6 m dia LEO entry mission scheduled for 2022.

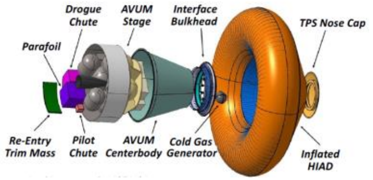
CMSA





ERA
2014-present
OBJECTIVES
Develop cargo return capability from Chinese Space Station.
ENTITIES
Chinese Manned Space Agency
STATUS/COMMENTS
2020 LEO entry technology demonstration not successful. Details not available. Current status unknown.

EFESTO

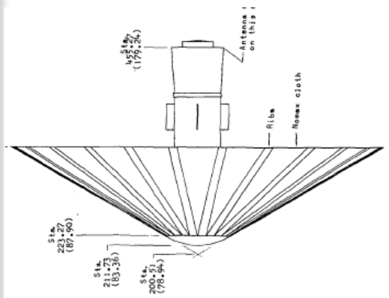


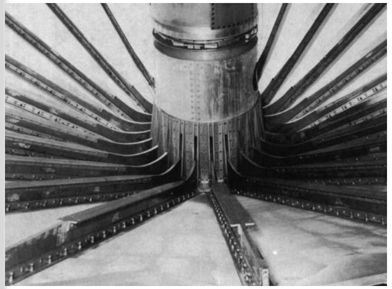
ERA
2018-present
OBJECTIVES
Develop inflatable heat shield technology for future re-entry vehicles.
ENTITIES
European Industry Partners
STATUS/COMMENTS
Technology maturation continues towards applications for LEO return and future robotic Mars missions.

Deployable Entry Vehicles- Mechanical

SELECT HISTORICAL TECHNOLOGIES & CONCEPTS

SPED



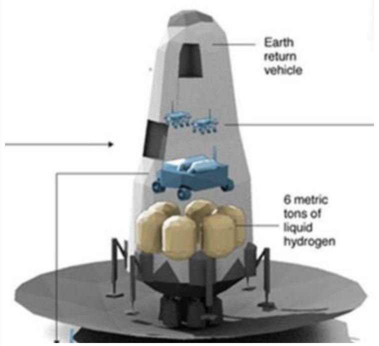


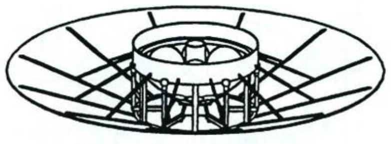
ERA
1970s
OBJECTIVES
Utilize SPED to mimic blunt body entry vehicle for parachute inflation dynamics.
ENTITIES
NASA
STATUS
Flight testing method established for simulated Mars parachute inflation conditions to mature Mars Viking program.

PARASHIELD

ERA
1990s
OBJECTIVES
Develop ultra low ballistic coefficient entry vehicle technology.
ENTITIES
MIT/U. Of Maryland
STATUS/COMMENTS
Unsuccessful demonstration due to Launch Vehicle failure.

Mars Direct

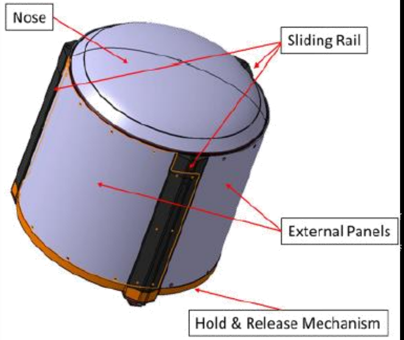


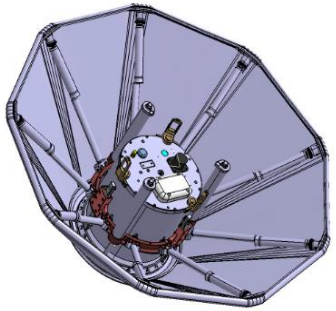


ERA
1990s
OBJECTIVES
Mission architecture study for Human Mars exploration.
ENTITIES
Martin-Marietta
STATUS/COMMENTS
Multiple elements of the architecture were proposed including a mechanically deployable heat shield.

SELECT RECENT DEVELOPMENT ACTIVITIES

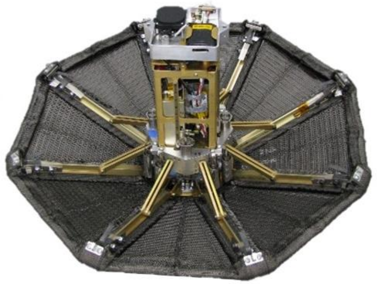
IRENE

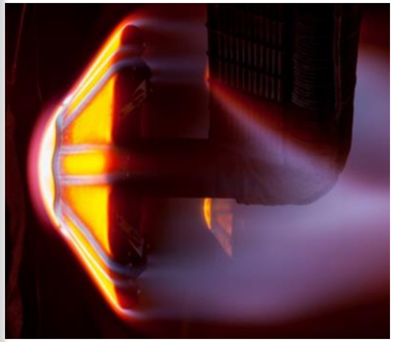




ERA
2008-present
OBJECTIVES
Develop mechanically deployable entry vehicle technology for payload return and delivery.
ENTITIES
ESA, CIRA, ASI, Industry & Academic partners
STATUS/COMMENTS
Sounding rocket flight test scheduled for 2022.

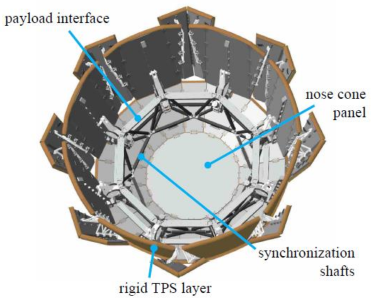
ADEPT





ERA
2011-present
OBJECTIVES
Develop mechanically deployable entry vehicle technology for payload return and delivery.
ENTITIES
NASA & industry partners
STATUS/COMMENTS
Sounding rocket flight test completed 2018, 3d weaving technologies explored for enhanced flexible TPS.

HATHOR



ERA
2016-present
OBJECTIVES
Develop rigid mechanically deployable entry vehicle technology for robotic Mars missions.
ENTITY
Imperial College London
STATUS/COMMENTS
Ground test campaign underway to mature technology.

Recent NASA Technology Development Activities

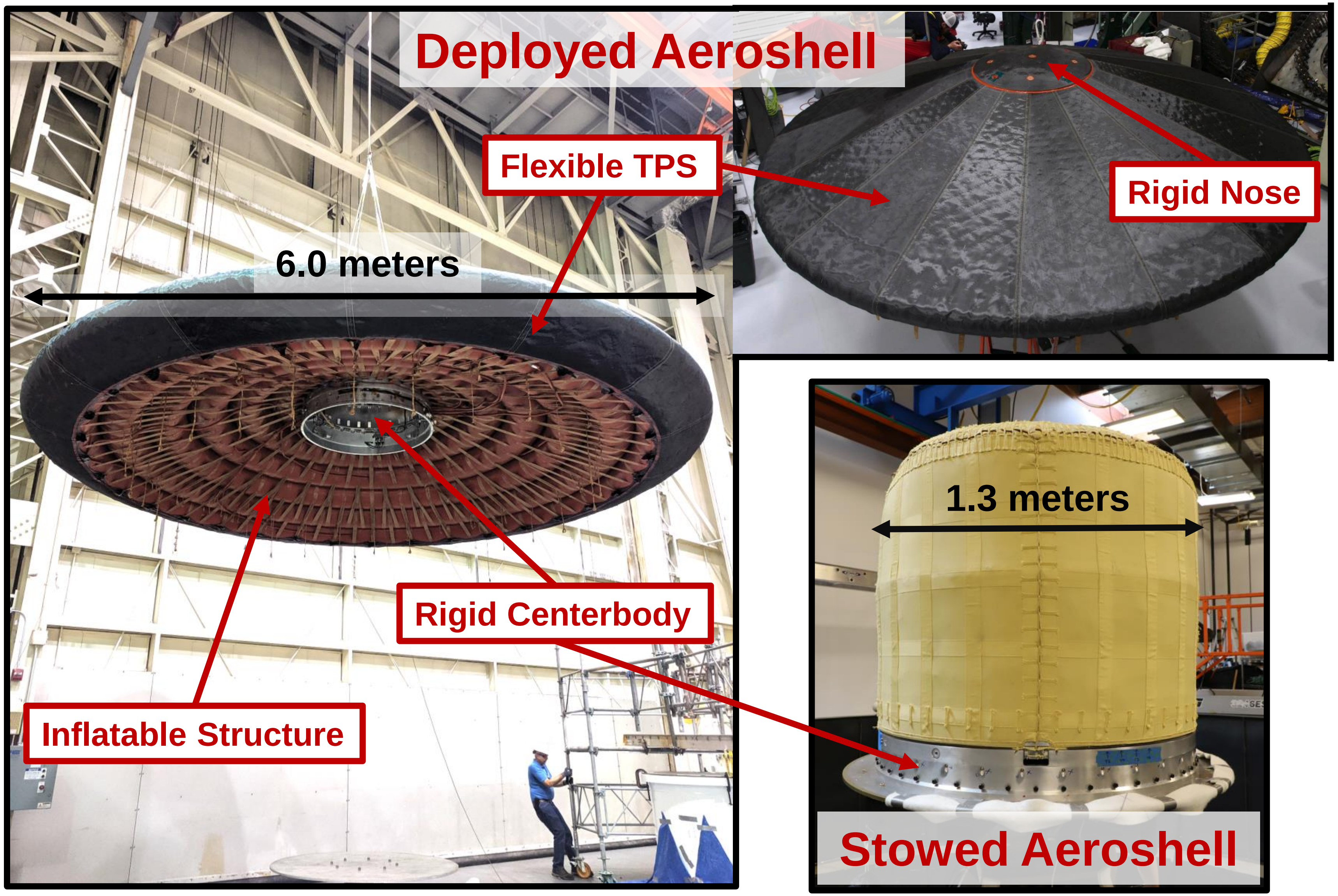
HIAD Recent Developments- LOFTID Orbital Flight Test

Low **E**arth **O**rbit **F**light **T**est of **I**nflatable **D**ecelerator (LOFTID) team is in final preparations for launch later this year as a secondary payload on the Joint Polar Satellite System-2 mission.

The technology demonstration is in partnership with United Launch Alliance.

Will be the largest diameter blunt body aeroshell ever flown.

ULA intends to use the technology at larger scale (~12 m) to recover Vulcan Launch Vehicle first stage propulsion module.



Recent Developments- LOFTID Orbital Flight Test

LOFTID flight test Concept of Operations:

Launch as secondary into Sun Synchronous Orbit from Vandenburg on Atlas V.

Centaur Upper stage performs deorbit burn, points, spins-up and releases 6 m HIAD.

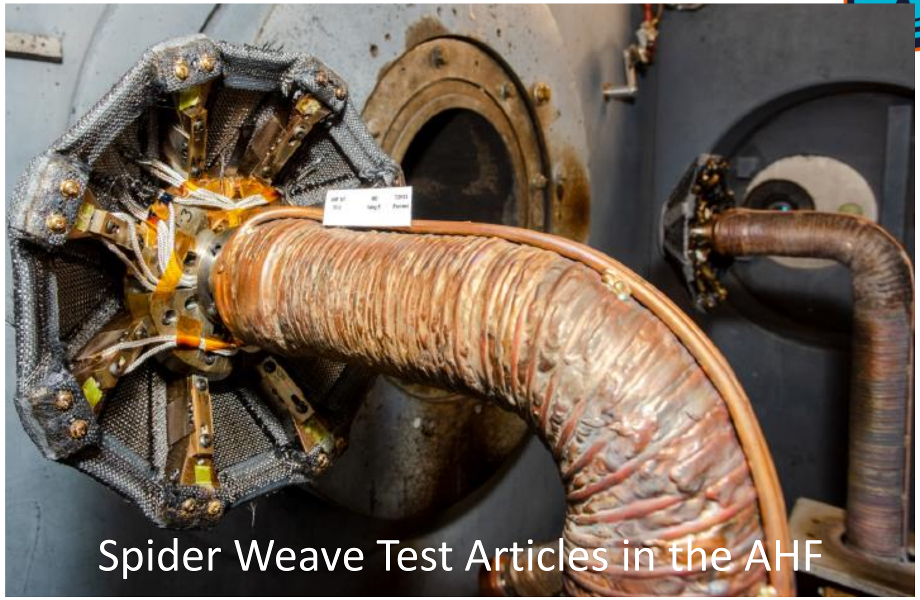
Critical data uplinked to satellite constellation.

Data recorder & Aeroshell recovered via ship off Pacific coast.

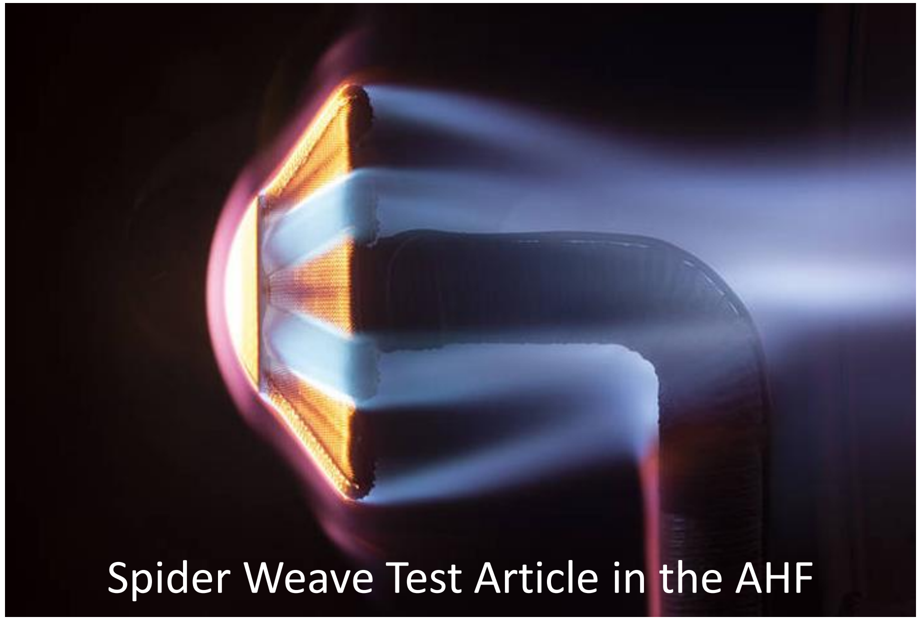
Recent Developments- ADEPT

NASA Ames has been working with Bally Ribbon Mills (BRM) for several years on the Adaptable Deployable Entry and Placement Technology (ADEPT).

- To date the ADEPT test articles have been made with 3D woven flat broad cloth which is cut and sewn into the desired shape.
- The stitched flexible aeroshell performance can be improved using advanced 3D weaving technologies.
- A new weaving process devised by BRM creates a folded tubular product that, when unfolded and trimmed, results in an octagonal pyramid net shape with continuous circumferential tows.
- Initial testing shows increased load carrying capability after relevant aerothermal environment testing.



Spider Weave Test Articles in the AHF

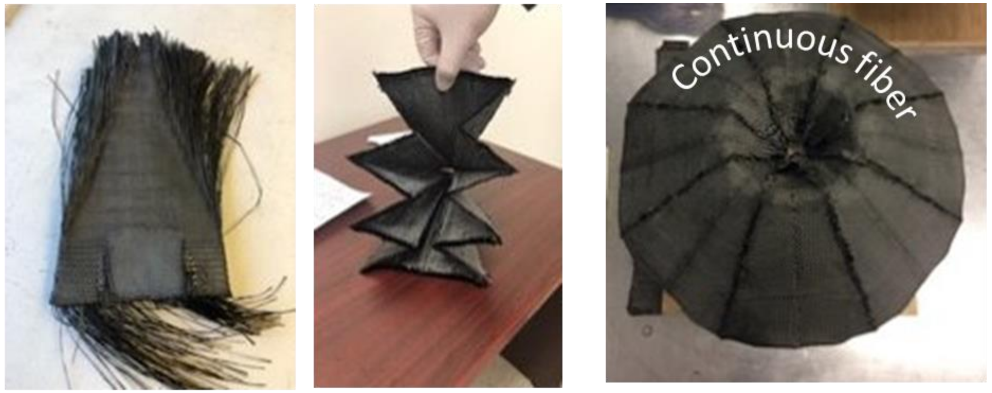


Spider Weave Test Article in the AHF

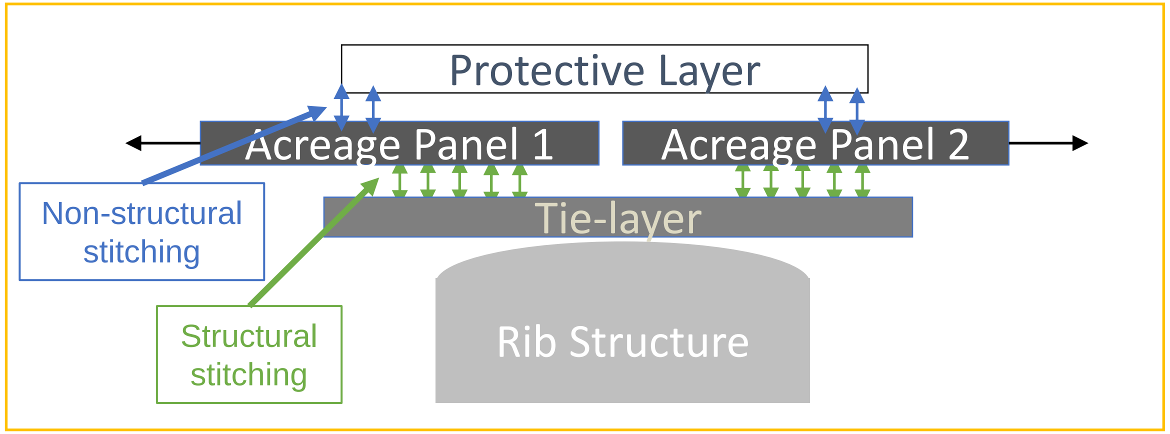
See J. Morgan et al “Arc-jet Testing of Continuously Woven Aeroshells – Spiderweave- for Adaptable Deployable Entry and Placement Technology, AIAA Aviation, 2022.

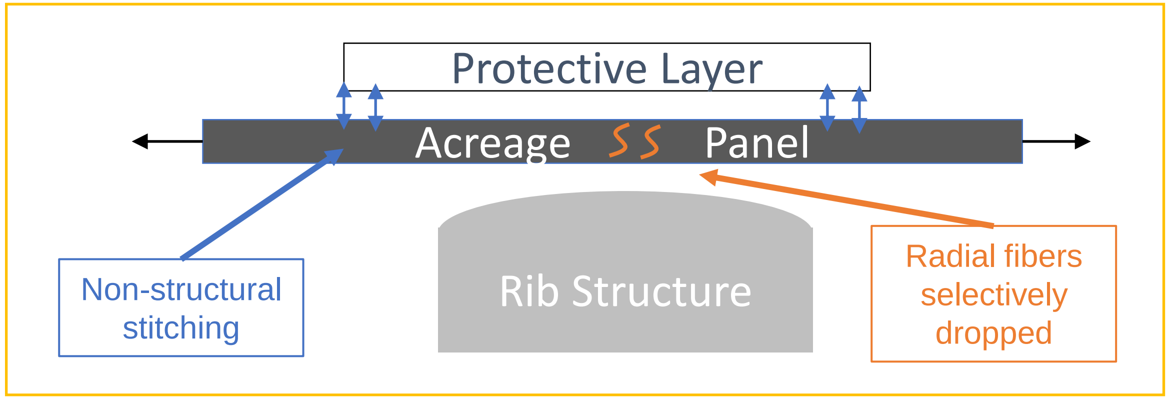
Recent Developments- ADEPT Stitched Joint vs Spiderweave

12-inch ADEPT Test Article



off the loom → trimmed → Installed for fit-check





- **<u>Stitched Joint</u>:** Individual, trapezoidal panels joined with underlying tie-layer using carbon thread
- **Pros:** Carbon thread sewing can combine any fabric
- **Cons:** Many pieces come together; stitching requires additional protection; load path not aligned with fibers

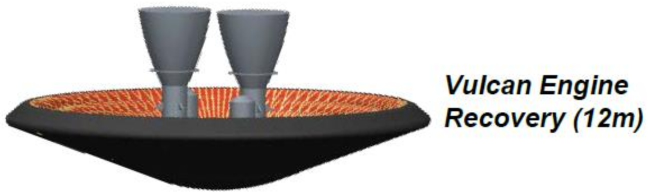
- **<u>Spiderweave</u>:** continuously woven, single-piece skirt
- **Pros:** Reduce assembly complexity and align load path with tows
- **Cons:** Weaving becomes difficult at relevant scales; dimensions are less controlled

Mission Applications & Mission Concept Development

Mission Applications- Earth

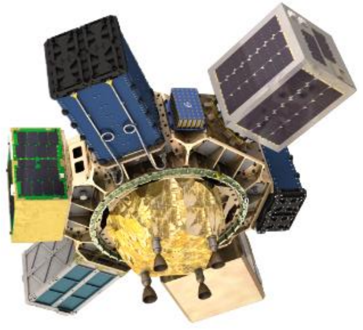
Launch Vehicle & On-Orbit Asset Recovery

First Stage Booster Module Recovery



Second Stage Recovery

Orbital Transfer Vehicle Recovery

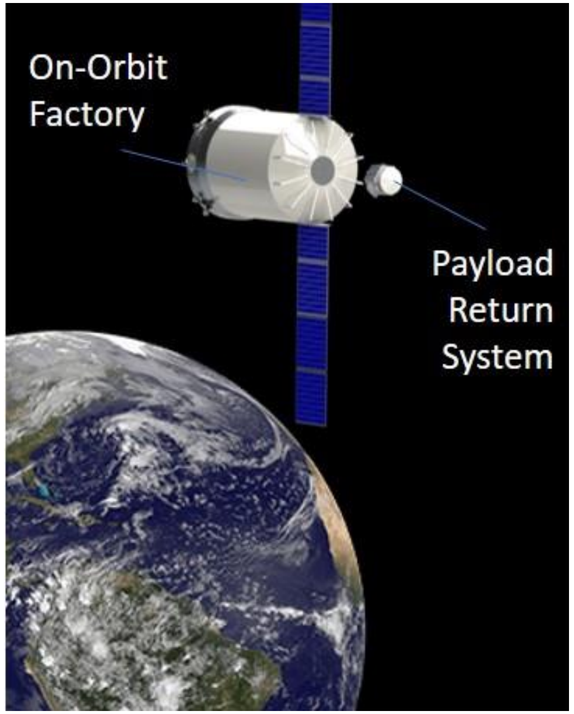


On-Orbit Manufacturing

Return of on-orbit manufactured goods produced in microgravity environment.

- Materials
- Pharmaceuticals
- Protein Crystals
- Additively manufactured goods

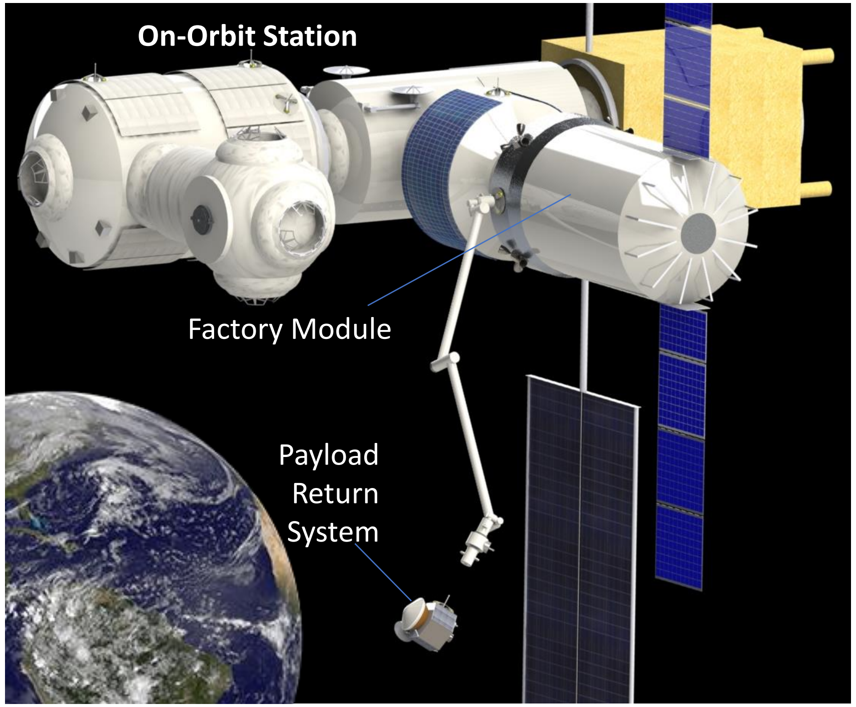
Largest market will likely be products returned to Earth.



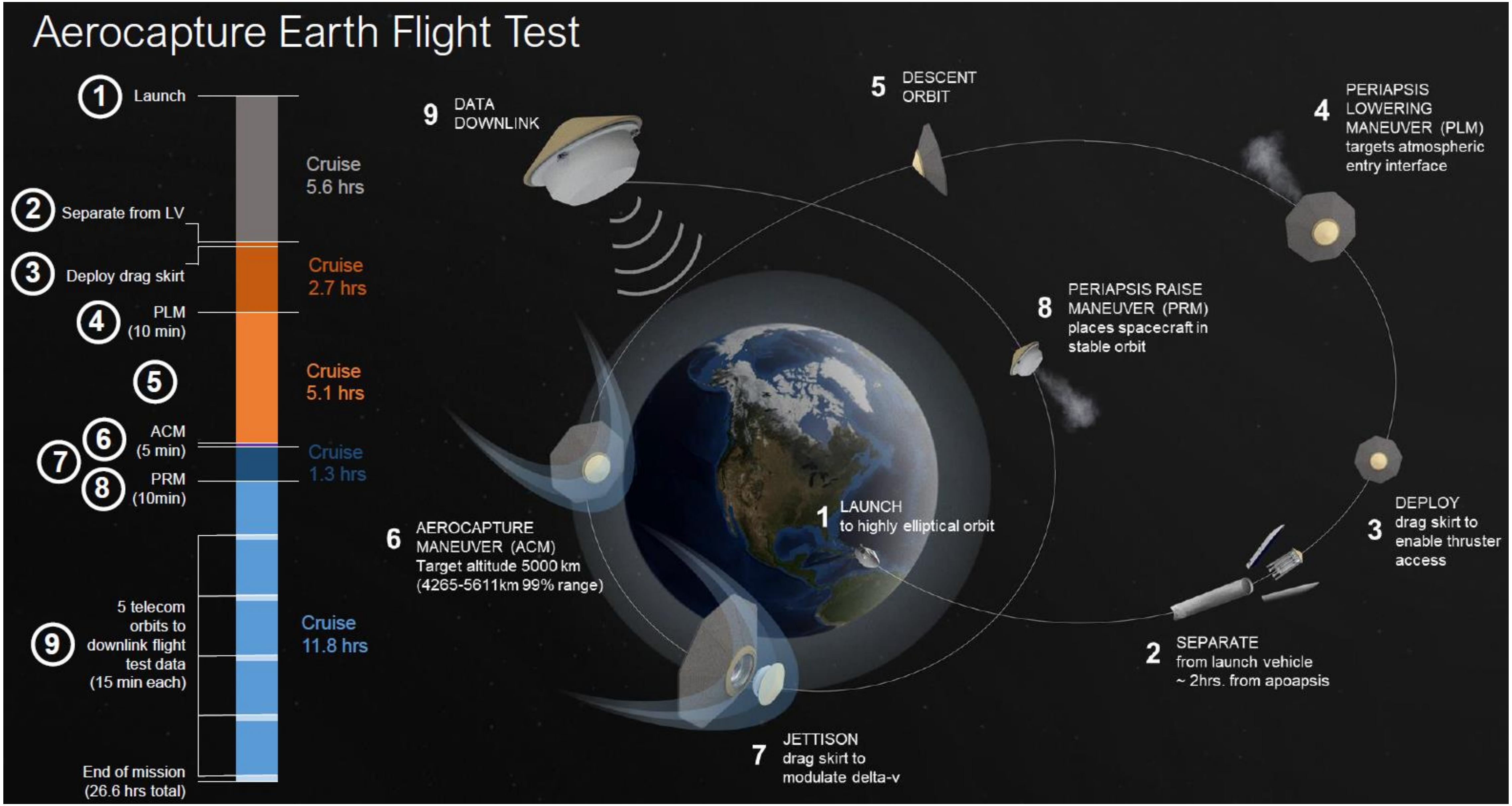
Commercial Research Stations

Return of on-orbit manufactured goods produced in microgravity environment.

- Reusable or partially reusable cargo return vehicles needed.
- DEVs with reuse capability should be explored.
- Precision targeting (guided) performance should be traded.

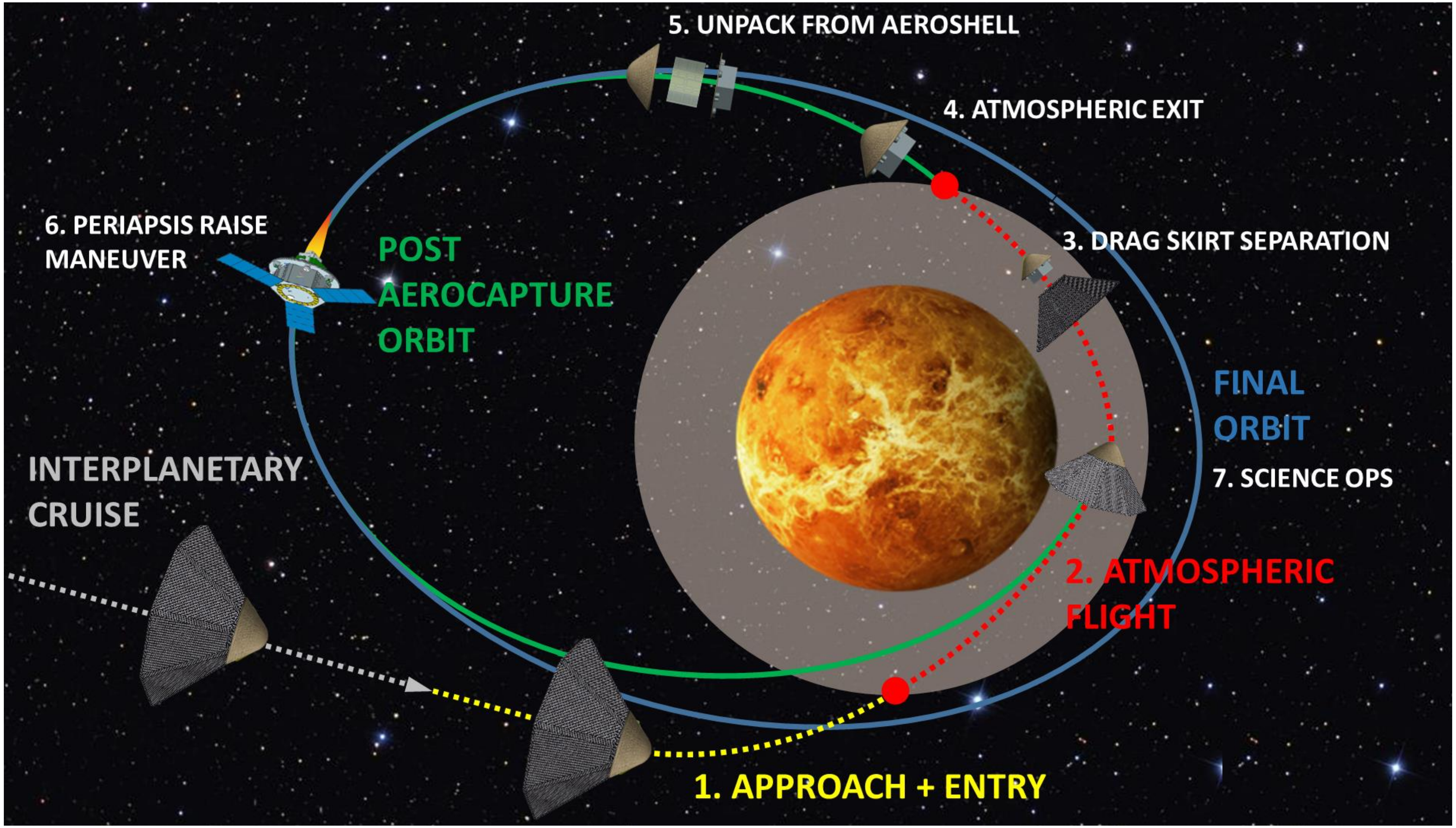


Drag Modulated Aerocapture Technology Demonstration Concept



Mission Applications- Venus Aerocapture

DRAG MODULATED AEROCAPTURE
FOR SMALL SPACECRAFT ORBIT INSERTION

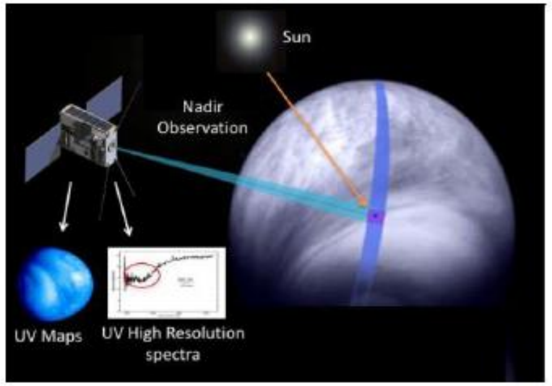


Mission Applications- Venus

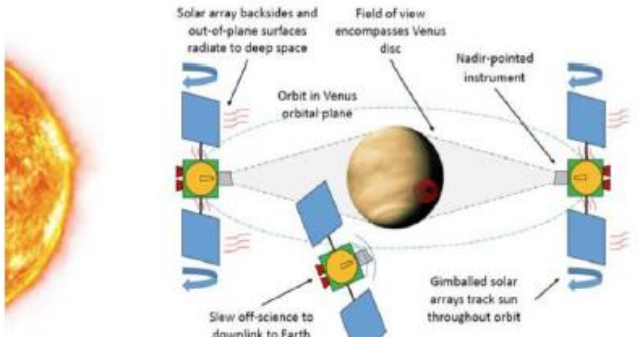
There is compelling science that can be done at Venus with SmallSats

PSDS3

CUVE (CubeSat UV Experiment)
PI: Valeria Cottini, University of Maryland



VAMOS (Venus Airglow Monitoring Orbiter for Seismicity)
PI: Attila Komjathy, JPL



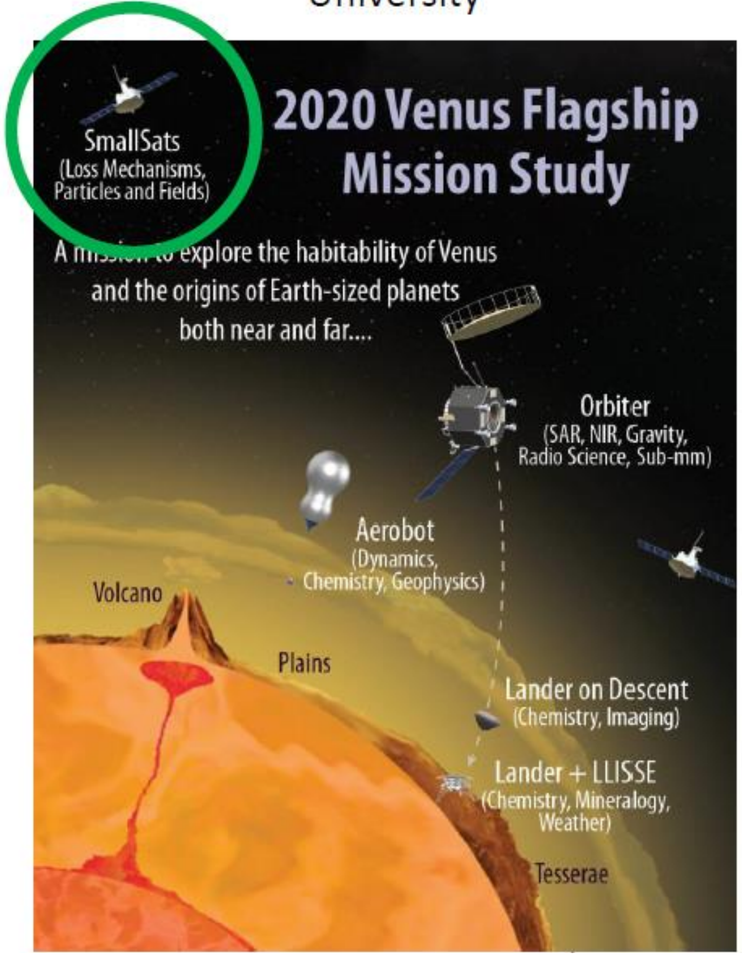
Venus Bridge

VEXAG
Venus Bridge Study

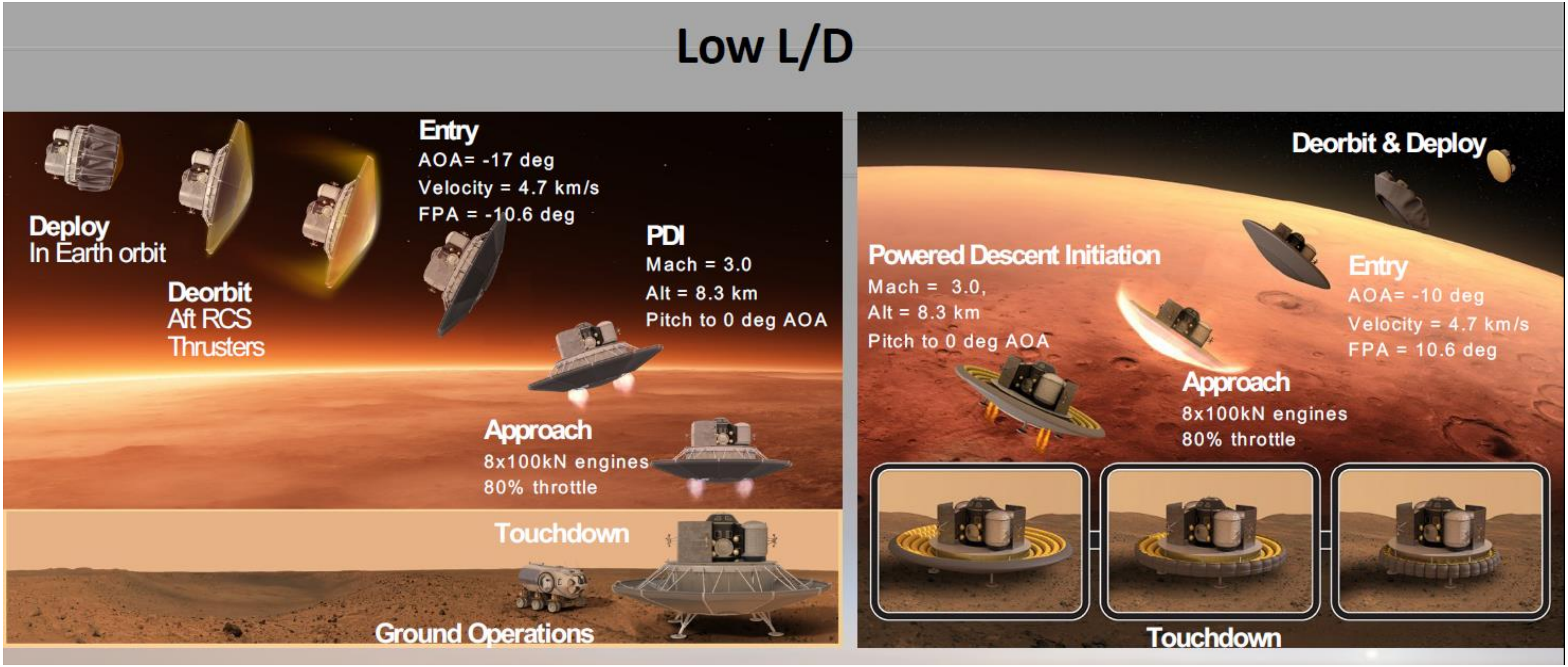
Principal Element	Variation	Purpose	VEXAG Science Goals, Object., & Investig. (GOI)	VEXAG Technology Plan	VEXAG Roadmap	Smallat Concepts PSDS3 Sel.
Science Orbiter with Telecom Relay	Surface (IR)	Surface composition & weathering. Does Venus have granites? Is there evidence of recent volcanism or past water?	II.A.4, II.B.1,2; III.A.2, 3; III.B.2.	Smallsat & cubesat assessment identified for next technol plan	Orbital Remote Sensing	VISM
	Atm (IR)	Middle circulation, planetary waves, airglow. How does the atm. circulate? Are there large quakes?	I.B.1,2,3; II.A.3,4.			VAMOS
	Atm (UV)	Upper circulation & composition. What is the origin of the UV absorber and energy balance of the atm.?	I.B.2; I.C.1,2,4.			CUVE
	Ionosphere	Ion escape & precipitation What is the current escape rate of the atmosphere?	I.A.2.			VISEN
Telecom relay greatly enhances data return and hence scientific value of in situ elements.				DSOC?		
Probe	Skimmer	Atmospheric sample below homopause. Isotopes of noble gases. What is the origin of the atmosphere?	I.A.1,2; II.A.2; III.A.1.	TPS	≈ Deep Probe	Cupid's Arrow
	Descender	Profile of atmospheric state and composition. How did the atmosphere form? What is the structure of the atmosphere?	I.A.1,2; I.B.1-3; I.C.4; II.A.2; III.A.1.4.	TPS	Deep Probe	DoVe VLAD
Aerial Platform	Balloon or Airplane	Global measurements of cloud-level circulation and composition. Investigate seismicity and interior. *Questions mirror probe and lander but global scale.*	I.A.1,2; 1.B.1,3; I.C.1-4; II.A.2,3; III.A.1, III.B.2,3.	TPS, Aerial Platforms	Sustained Aerial Platform	*V. Aerial Platforms Study Grp.*
Lander		Atmospheric & geophysical measurements. Imaging. What is the boundary-layer environment and origin of super-rotation? Is there seismic activity?	I.B.1,2; II.A.3; III.B.2-3.	TPS, HTE	"Long-Lived" Geophys. Lander	SAEVe VLAD

2020 Pre-Decadal Study

PI: Martha Gilmore, Wesleyan University

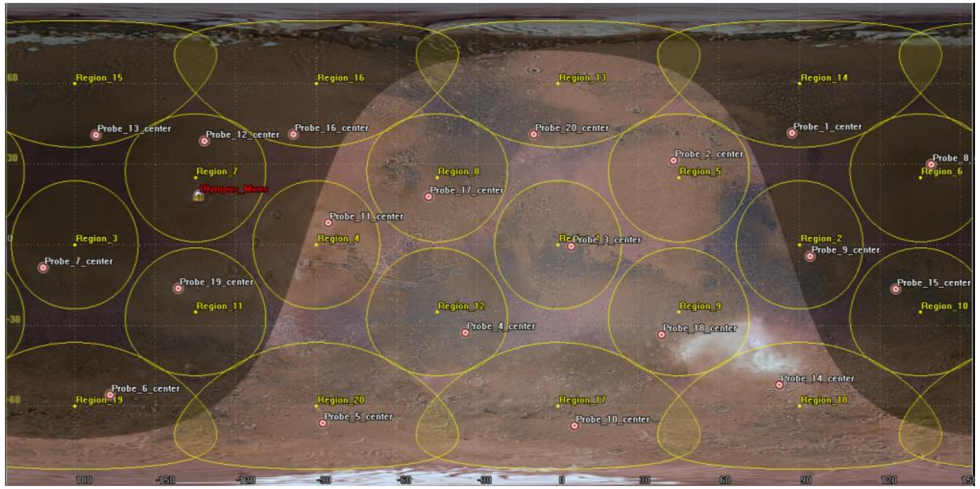


Mission Applications- Mars Human Exploration



Dwyer-Cianciolo, A. "CHANGING ENTRY, DESCENT, AND LANDING PARADIGMS FOR HUMAN MARS LANDER' International Planetary Probe Workshop, 2018.

Mission Applications- Mars Surface Networks

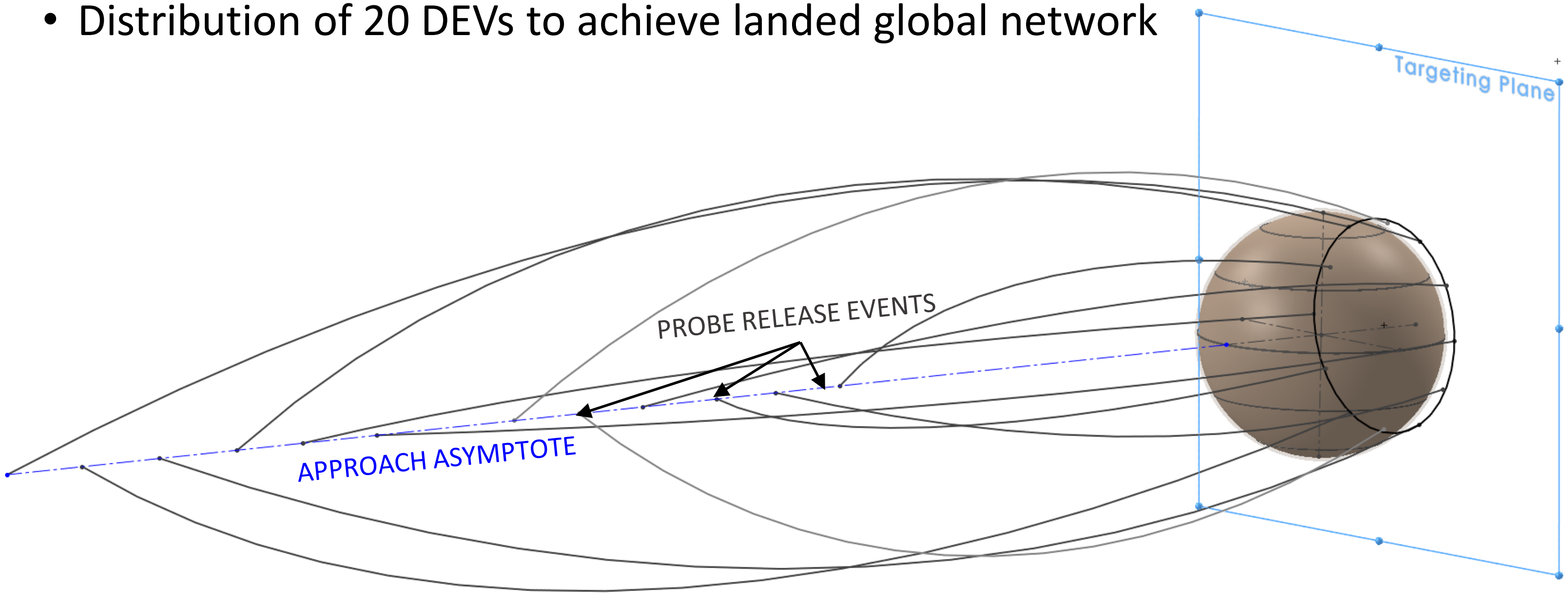


Distributed Surface Networks

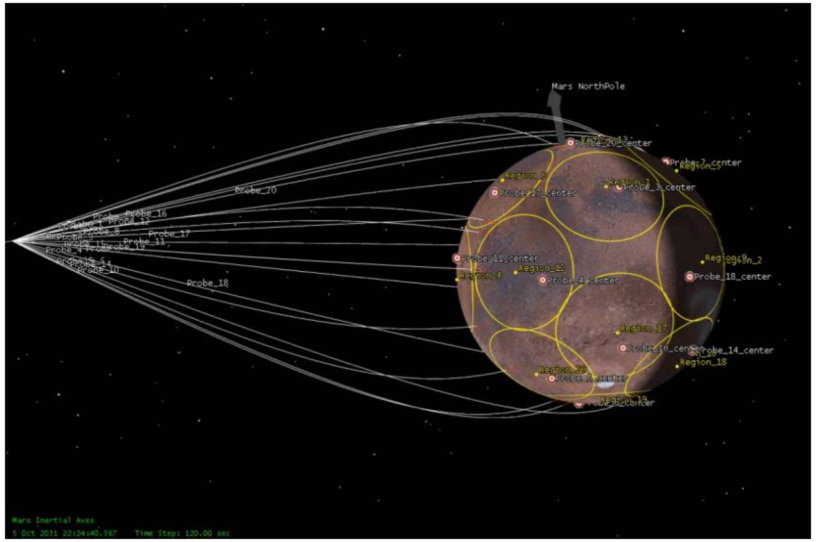
- Regional and global networks of small spacecraft-based landers/impactors
- DEVs could facilitate landing in difficult southern highlands terrain
- Regional networks for precursor Human Mars Missions

Deployment of Small Spacecraft Class Landers/Impactors on Approach

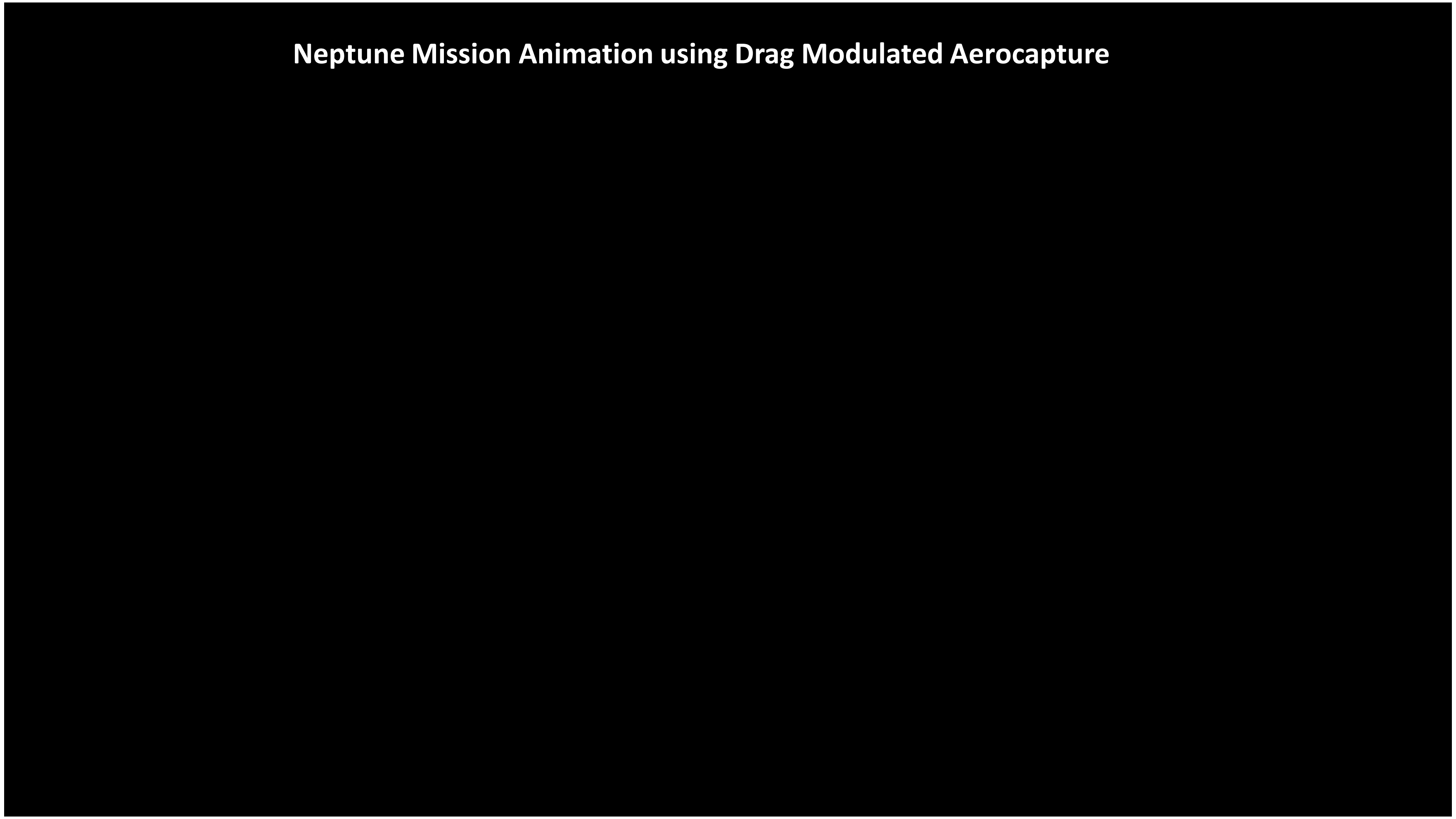
- Distribution of 20 DEVs to achieve landed global network



Mars Surface Network Animation



Mission Applications- Ice Giant Aerocapture

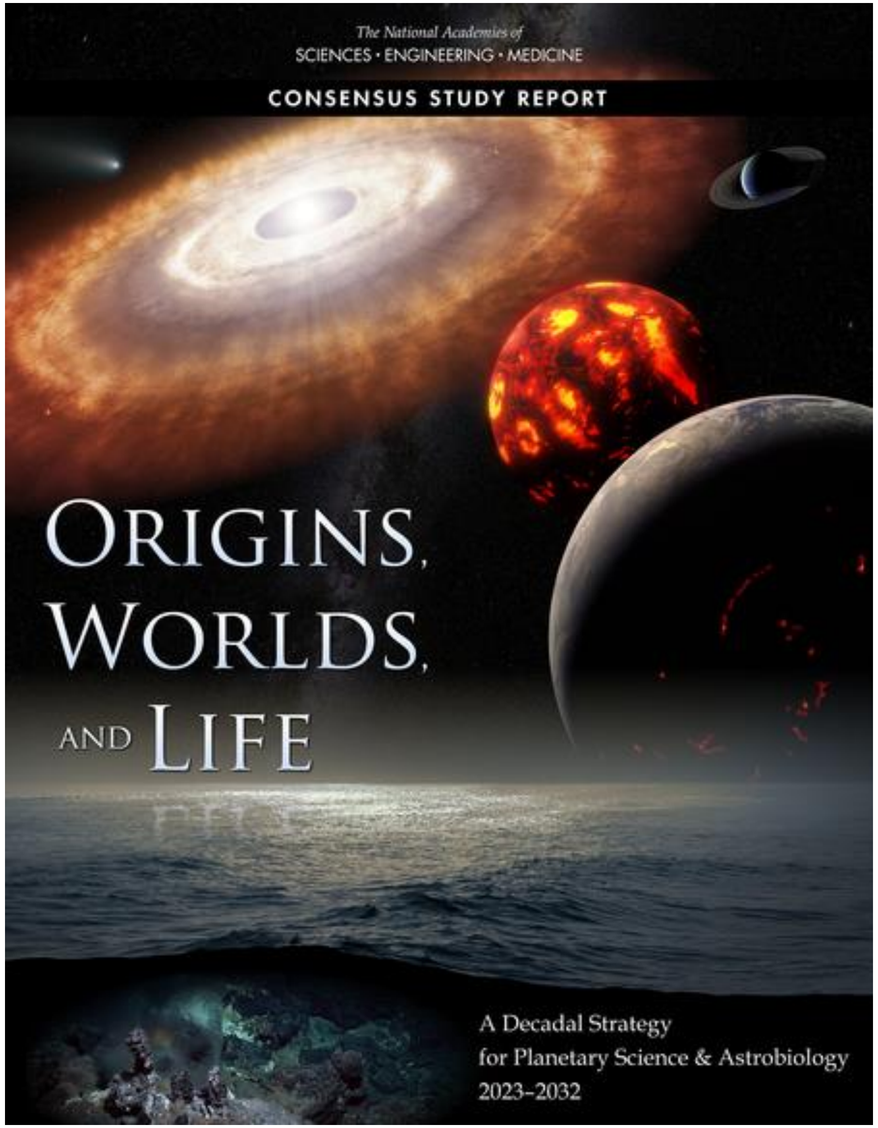


DEVs also have applicability in conventional Aerocapture operational scenarios.

John Elliot, TEMPEST Mission Concept Animation “Future exploration of the Ice Giants”, Royal Society, 2020

Technology Investments & Mission Infusion

DEV Technology Investment Recommendations



- Include HIAD technology in the Decadal Survey as an approach for landing large payloads for robotic- and human-class missions to Mars. Synergy with Mars robotic exploration should be considered within the context of the overall Solar System exploration strategy.
- Investigate DEVs for aerocapture-based orbit insertion missions to Venus, Titan and the Ice Giants. ADEPT is particularly attractive for small spacecraft class aerocapture missions for Venus, with potential feed forward to Ice Giant missions.
- Continue investments in high-temperature structures and flexible TPS to improve DEV aerothermodynamic, structural, and thermal protection performance capability.
- Invest in novel atmospheric entry control system technology development for guided DEVs to support missions requiring precision landing, such as human-class missions to Mars, and/or narrow entry corridors.
- Advocate for technology demonstration missions to be included as secondary payloads on future launch opportunities to advance DEV technology while also providing the opportunity for valuable science return.
- Engage with the DEV technology teams early during the mission concept development phase to understand DEV benefits and define achievable atmospheric entry envelope for that application space and mission benefits.

Planetary Science Decadal Survey Report Findings

FAR 2022

- NASA has invested considerable resources in the development of Thermal Protection Systems (TPS) like the Heatshield for Extreme Entry Environment Technology (HEEET), and the Phenolic-Impregnated Carbon Ablator (PICA). These TPS technologies are currently capable of operating over a wide range of entry conditions and are crucial for the landing of larger payloads on Mars and for enabling atmospheric probes on Venus, Saturn, Titan, Uranus, and Neptune. HEEET (currently at TRL 6 for certain conditions) was developed in the last decade, as the heritage carbon phenolic used for the Galileo entry probe is no longer available (Ellerby et al. 2020).
- Finding: NASA's investments in TPS technologies have enabled several landing missions and atmospheric probes in the past and together with current developments like HEEET stand to enable many future missions to multiple destinations.

- In addition to these enabling technologies there are also enhancing technologies and engineering developments that can also benefit from investments prior to a project start. NASA has invested considerable resources in the development of deployable aero-decelerators (e.g., HIAD, SIAD, and ADEPT) that have the potential to dramatically increase landed mass on future missions. These technologies, however, seem to fall ***into the second valley of death, i.e., too risky, and do not yet seem to being considered for future missions***.
- Finding: **NASA and the science community would benefit from studying how the maturing aero-decelerator technologies can be integrated into future missions to increase science value**.

Planetary Science Decadal Survey Report Findings

- Aerocapture is an orbital insertion technique which utilizes a single pass through a planetary atmosphere to dissipate enough orbital energy for planetary capture (Som Dutta, 2020). It can deliver large orbit insertion ΔVs with minimum fuel, resulting in significant reductions in transit time, and/or increases in science payload mass. Aerocapture can also enable planet orbit insertion of SmallSats, launched as secondary payloads, on targets like Venus and Mars (Alex Austin, 2020). Advances in atmospheric entry guidance and control techniques as demonstrated successfully by Curiosity and Perseverance on Mars and advances in autonomous optical navigation as demonstrated by the Deep Impact mission on comet Tempel 1, combined with the development of new thermal protections systems (TPS), like the Phenolic-Impregnated Carbon Ablator (PICA) used also by Curiosity and Perseverance and the Heatshield for Extreme Entry Environments Technology (HEEET) that will be used by the Mars Sample Return's Earth Entry Vehicle (EEV), make Aerocapture a technology ready for mission infusion. Because Aerocapture is not being proposed for use in missions, it is considered a "dormant" technology that is perceived as high risk in a mission competitive environment.

- Finding: **Aerocapture is a technology that is ready for infusion and that can enhance/enable a large set of missions, but that will require special incentives by NASA to be proposed and used in a science mission**.

DEV Community Advocacy & Collaboration

While technology demonstrations such as LOFTID, IRVE, IRDT, ADEPT SR-1 and IRENE advance the TRL, there is still not broad acceptance for implementing DEV technology in Science & Exploration missions.

How do we overcome the hurdles for DEVs be implemented in Science & Exploration missions?

- Seek opportunities to advance technology with commercial sector and other Government Agencies (near Earth)
  - Technology Transfer: HIAD technology transfer to United Launch Alliance.
  - Commercial Space Act or Interagency Agreements or other appropriate partnering arrangements.
  - Public/private partnerships (e.g.- UAE Hope Mission)

- Propose to programs with more tolerance for risk
  - NASA SIMPLEx (Small Innovative Missions for Planetary Exploration) is Class D.

- Seek opportunities for international collaborations
  - Secondary/rideshare opportunities, Small Spacecraft demonstrations/missions, missions of opportunity.
  - NASA SIMPLEx program encourages international collaborators and contributions.

Summary

Deployable Entry Vehicles are being developed across the globe. Small spacecraft class to large cargo class technologies are in various stages of development. Some technologies are ready or near ready for mission infusion.

Near Earth & cis-Lunar return applications will provide the most opportunities to mature DEV technology.

Inner Solar System robotic science applications are also promising, but there will be fewer opportunities for DEVs.

- Human Mars exploration is still
- Small spacecraft (e.g.- SIMPLEx) class missions provide a more risk tolerable implementation pathway.
- Particularly attractive small spacecraft class missions include surface lander networks and orbital constellations/swarms at Mars & Venus.

Partnership opportunities should be explored including public/private and international.

Encourage entire DEV community to continue advocacy through engagement with all stakeholders (public and private) at workshops, community meetings, and with policy makers.

Acknowledgements

HIAD- Neil Cheatwood, Steve Hughes, Greg Swanson, Cole Kazemba.

ADEPT- Paul Wercinski, Raj Venkatapathy, Brandon Smith, Bryan Yount, Owen Nishioka, Jonathan Morgan, Joseph Williams, Carl Kruger, Sergey Gorbunov, Tane Boghozian, Bally Ribbon Mills, Thin Red Line Aerospace.

ADEPT DMA & Ice Giant Aerocapture Mission Concepts: Alex Austin, John Elliott.

IRENE- Paolo Vernillo.

HATHOR- Lisa Peacocke, Danielle O'Driscoll, Michaela Gramola, Matthew Santer, Paul Bruce.