Aerocapture Technology for Venus Missions from SmallSat to Flagship

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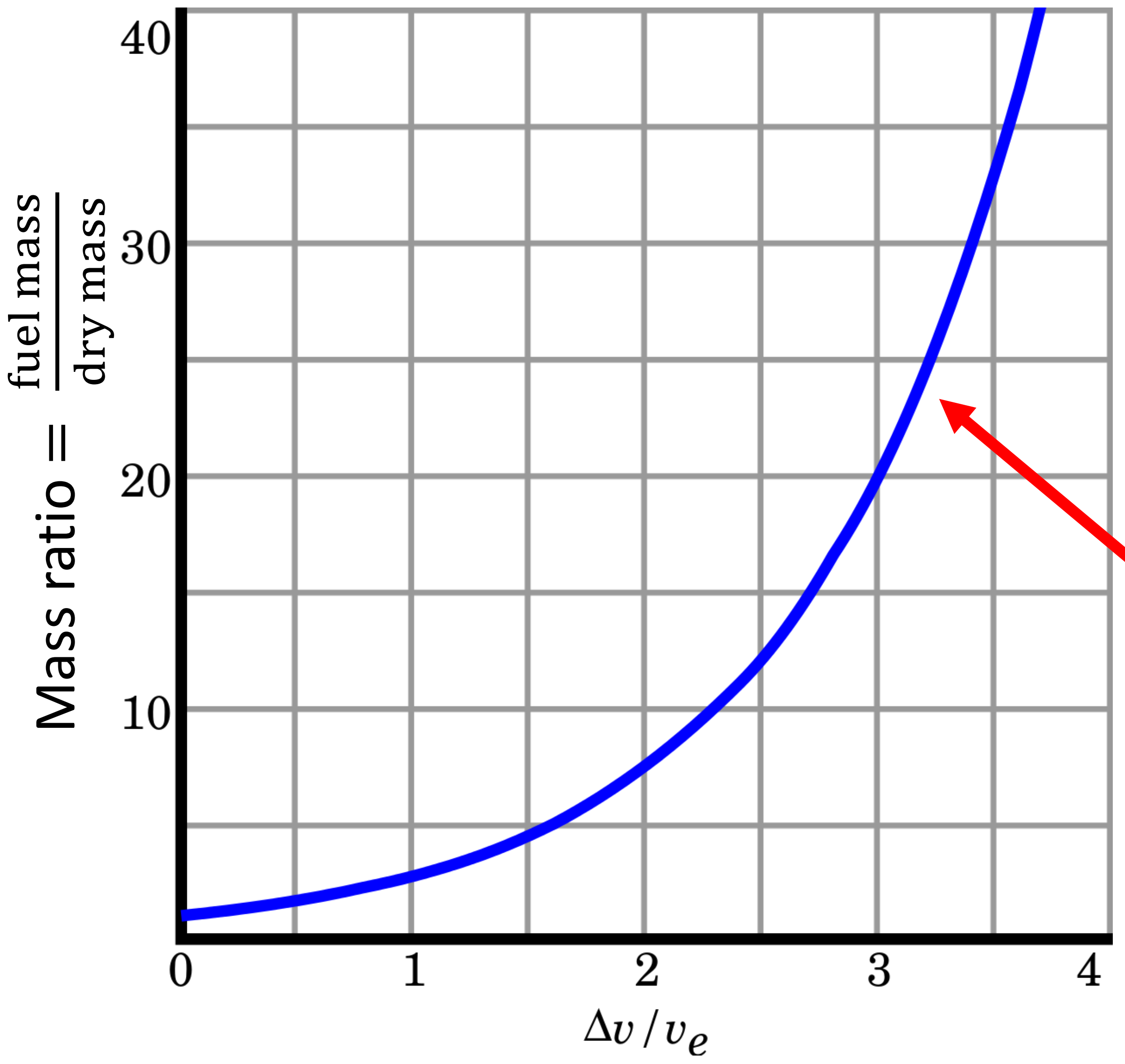
with contributions from a large team at NASA JPL, NASA Ames, and NASA Langley

Presentation to the Decadal Survey Venus Panel

July 14, 2021

The Rocket Equation

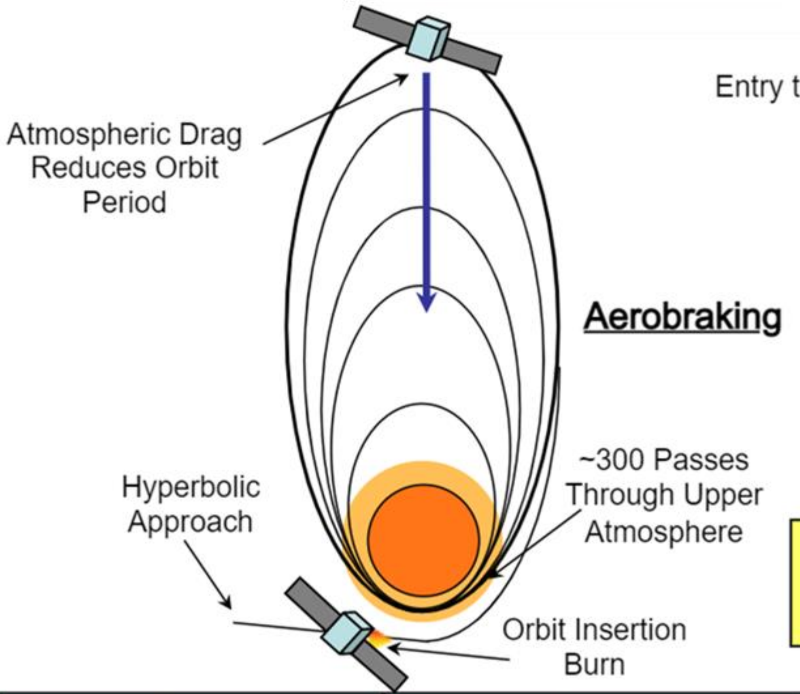


$$\Delta v = v_e \ln \frac{m_o}{m_f}$$

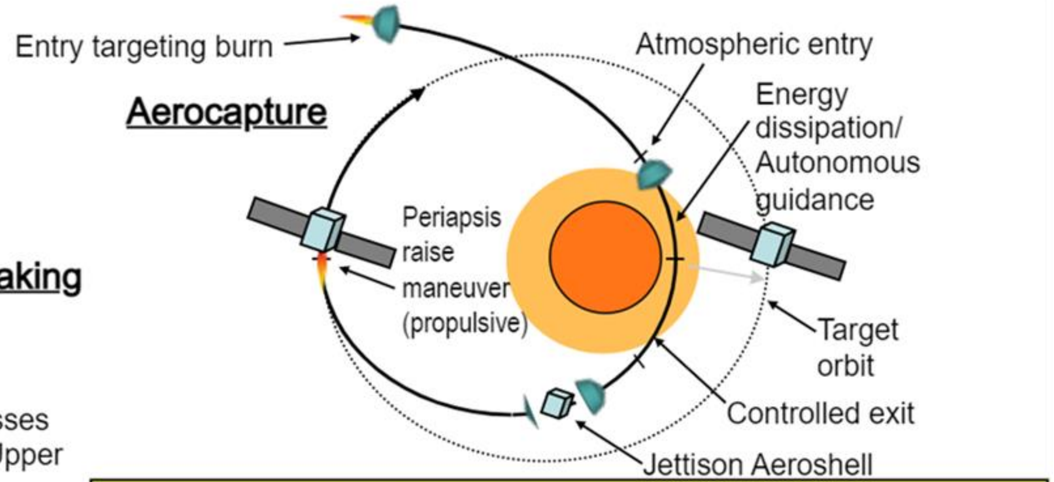
Large changes of velocity require large amounts of propellant! What if we could change this?

Aerobraking vs Aerocapture

Aerobraking was successfully demonstrated on Magellan and Venus Express. It will be used as part of the upcoming VERITAS mission.



Pros	Cons
Little spacecraft design impact	Still need ~1/2 propulsive fuel load
Gradual adjustments; can pause and resume as needed (with fuel)	Hundreds of passes = more chance of failure
Operators make decisions	Months to start science
	Operational distance limited by light time (lag)
	At mercy of highly variable upper atmosphere



Aerocapture: A vehicle uses active control to autonomously guide itself to an atmospheric exit target, establishing a final, low orbit about a body in a single atmospheric pass.

Pros	Cons
Uses very little fuel--significant mass savings for larger vehicles	Needs protective aeroshell
Establishes orbit quickly (single pass)	One-shot maneuver; no turning back, much like a lander
Has high heritage in prior hypersonic entry vehicles	Fully dependent on flight software
Flies in mid-atmosphere where dispersions are lower	
Adaptive guidance adjusts to day-of-entry conditions	
Fully autonomous so not distance-limited	

This presentation will focus on aerocapture.

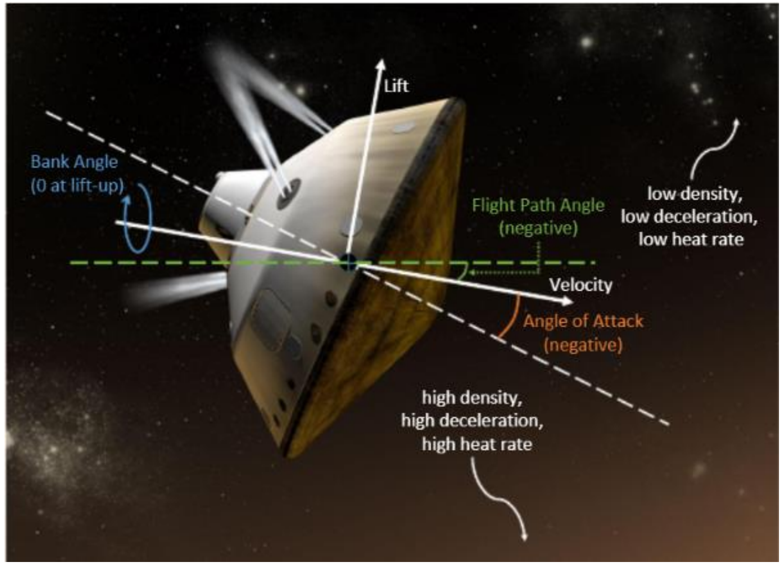
Credit: Michelle Munk & Thomas Spilker, 6th International Planetary Probe Workshop

Aerocapture Flight Control Approaches

To overcome navigation and atmospheric uncertainties in order to achieve a desired target orbit, a form of flight control is needed during the aerocapture pass through the atmosphere

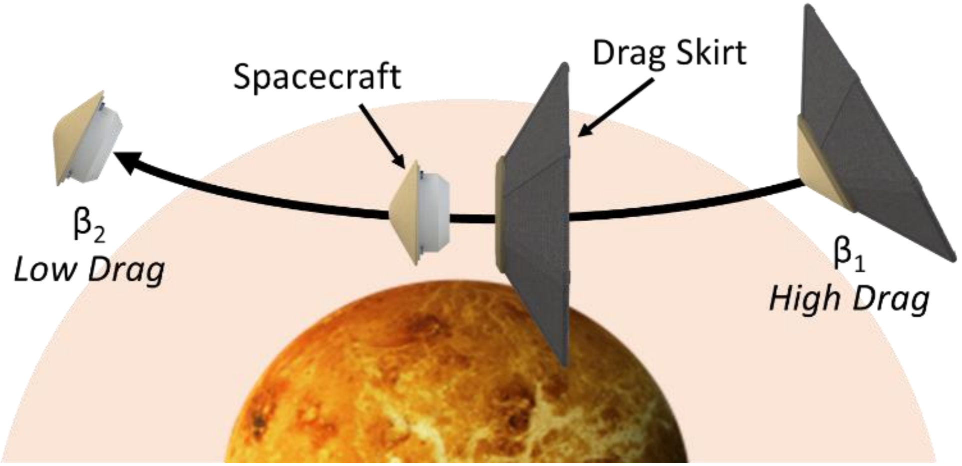
Heritage control method demonstrated on MSL and M2020

Lift Modulation



By banking the spacecraft, the lift vector is rotated to target higher or lower atmospheric densities and control the amount of delta-V and target a specific orbit

Drag Modulation



By modulating the time that a drag skirt is jettisoned from the spacecraft, the system can receive more or less delta-V and target a specific orbit

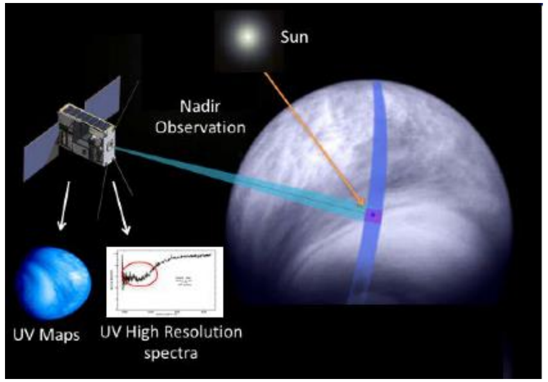
Focus of recent technology development, particularly to enable SmallSat orbiters

Venus SmallSat Orbiter Mission Concepts

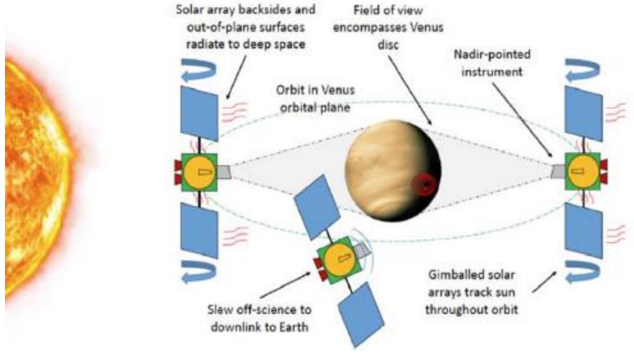
There is compelling science that can be done at Venus with SmallSats

PSDS3

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



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



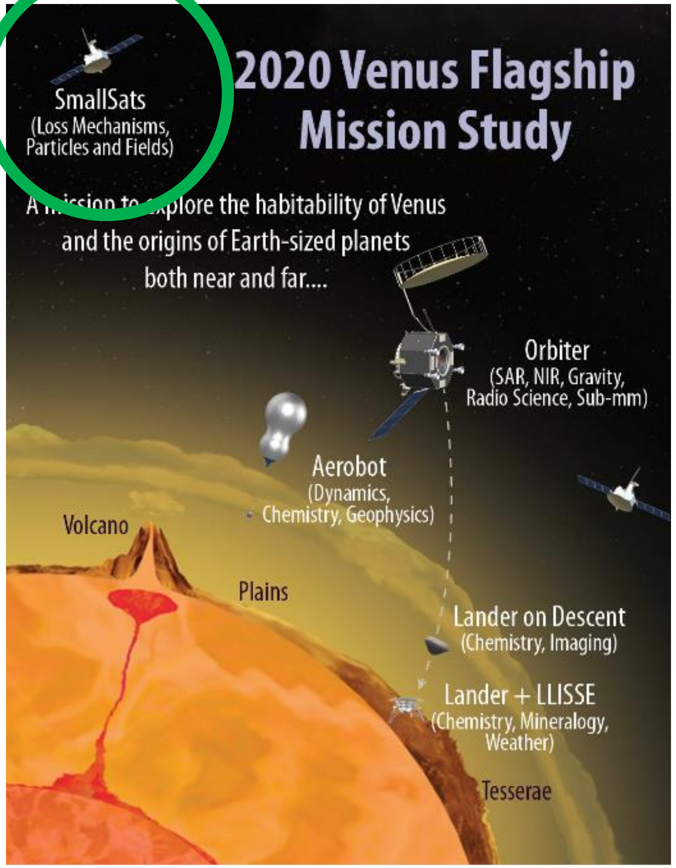
Venus Bridge

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

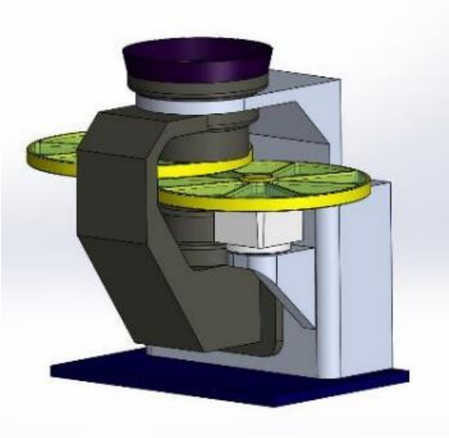
2020 Pre-Decadal Study

PI: Martha Gilmore, Wesleyan University

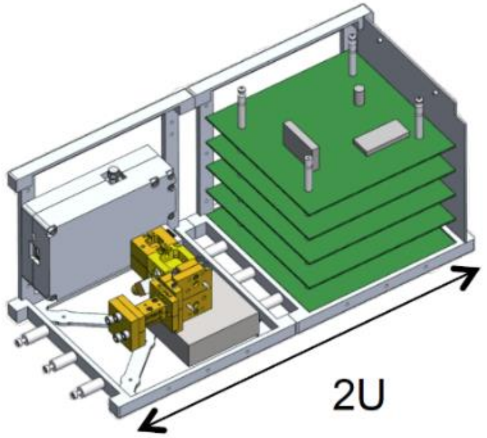


SmallSats: An Expanding Planetary Science Opportunity

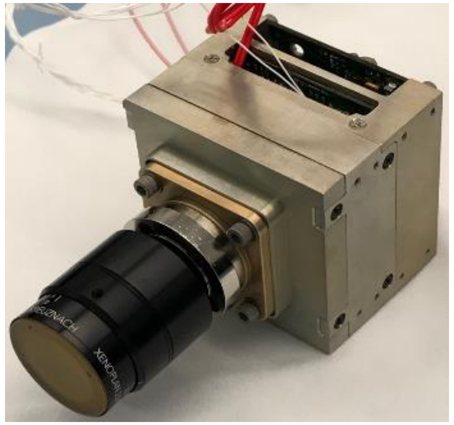
Technology development has enabled many small instruments



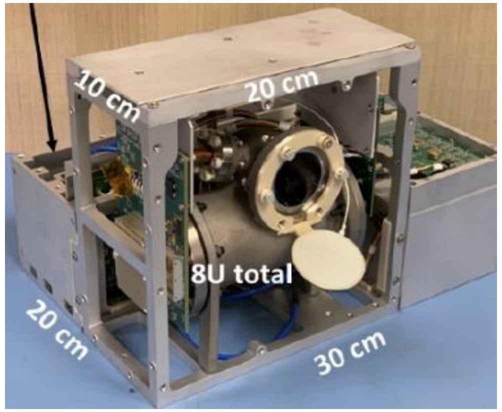
Compact IR imager (1.5U)



Compact Sub-mm spectrometer (2U)

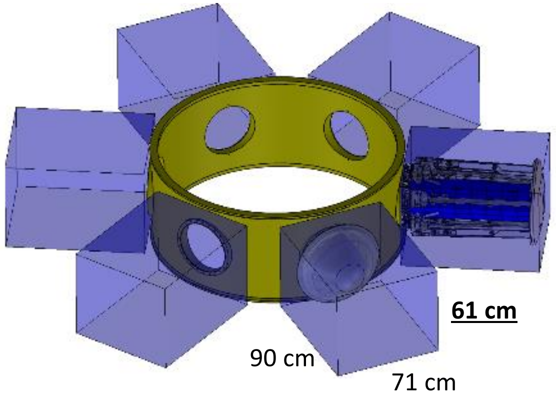


Compact visible camera (1U)



Compact Mass Spectrometer (4U)

Rideshare launch opportunities provide access to space



EELV Secondary Payload Adapter (ESPA)

- Provides ride to Earth escape, GTO, or cislunar space
- Used on Atlas V, Delta IV, Falcon 9, and Falcon Heavy

"We're not going to ask whether we need it. You have to convince us that we don't need it."

— *Thomas Zurbuchen, NASA associate administrator for science, pledging the U.S. space agency to purchase a secondary payload adapter whenever it buys a launch vehicle for a science mission.*

Reaching Orbit as a Secondary Payload

Secondary payload mass and volume constraints create unique challenges for SmallSat orbiters

1. The secondary payload launch opportunity and target orbit will require a certain orbit insertion delta-V

Launching with a mission going directly to Venus…

VERITAS

…versus a mission performing a flyby…

DRAGONFLY

…has significant differences in the required delta-V for orbit insertion

For SmallSats, flexibility to different launch opportunities is key

2. The mission must “close” within mass, power, and time constraints

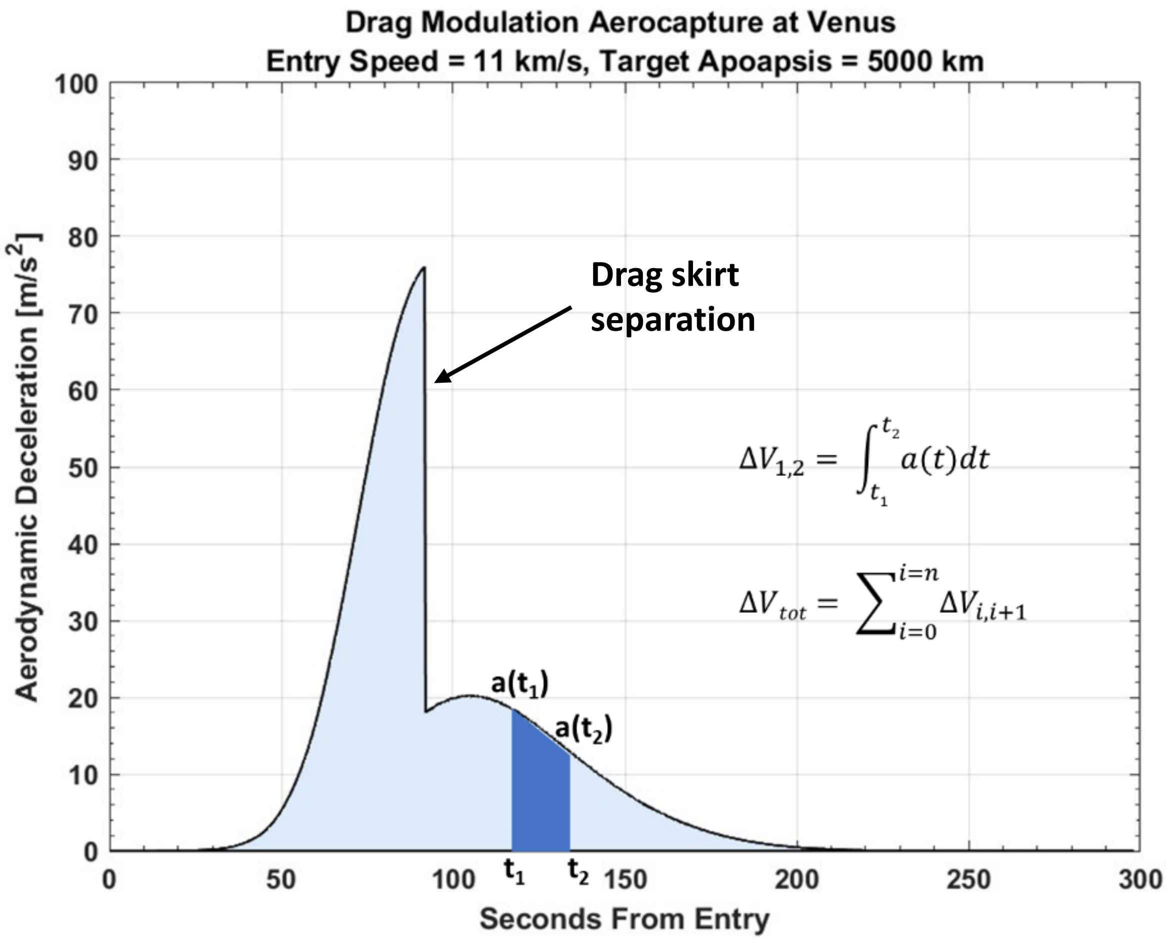
	Orbit insertion delta-V at Venus		**Propellant mass fraction required with 300s Isp chemical propulsion**	
Primary Mission	**5,000 km elliptical orbit**	**35,000 km elliptical orbit**	**5,000 km elliptical orbit**	**35,000 km elliptical orbit**
Venus Direct	2.8 km/s	1.5 km/s	61%	40%
Venus Flyby	4.5 km/s	3 km/s	78%	64%

Comparing aerocapture and solar electric propulsion

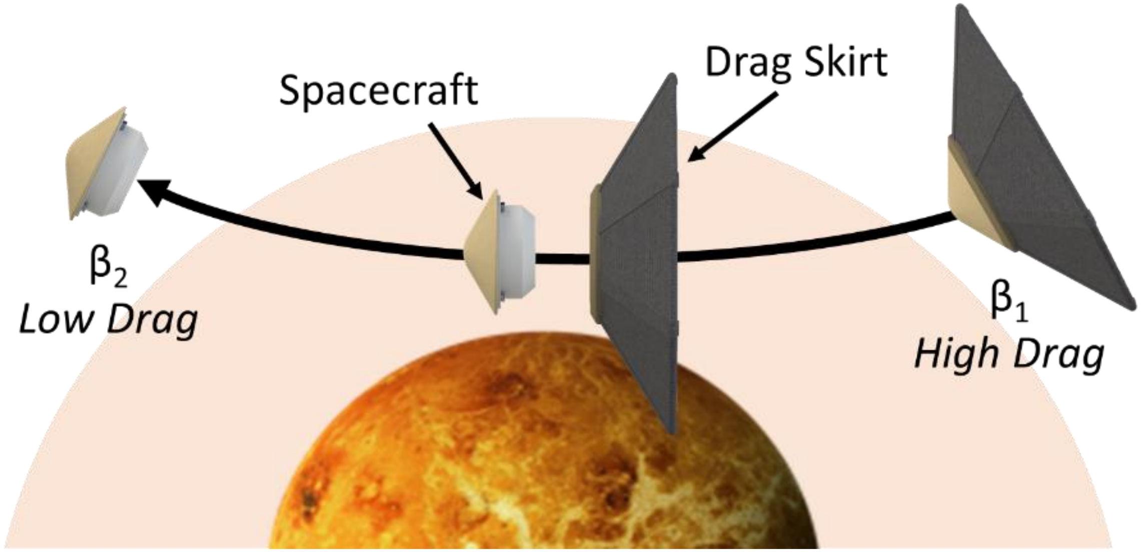
Orbit Insertion Method	**Aerocapture**	**Solar Electric Propulsion**
Cruise Time	0.5 – 1 year	3 – 4 years
Required Power	< 100 W	> 800 W
Launch Mass	100 – 150 kg	200 – 500 kg

Drag modulated aerocapture is the fastest, most efficient way for SmallSats to reach orbit as secondary payloads

Drag Modulation Flight Control



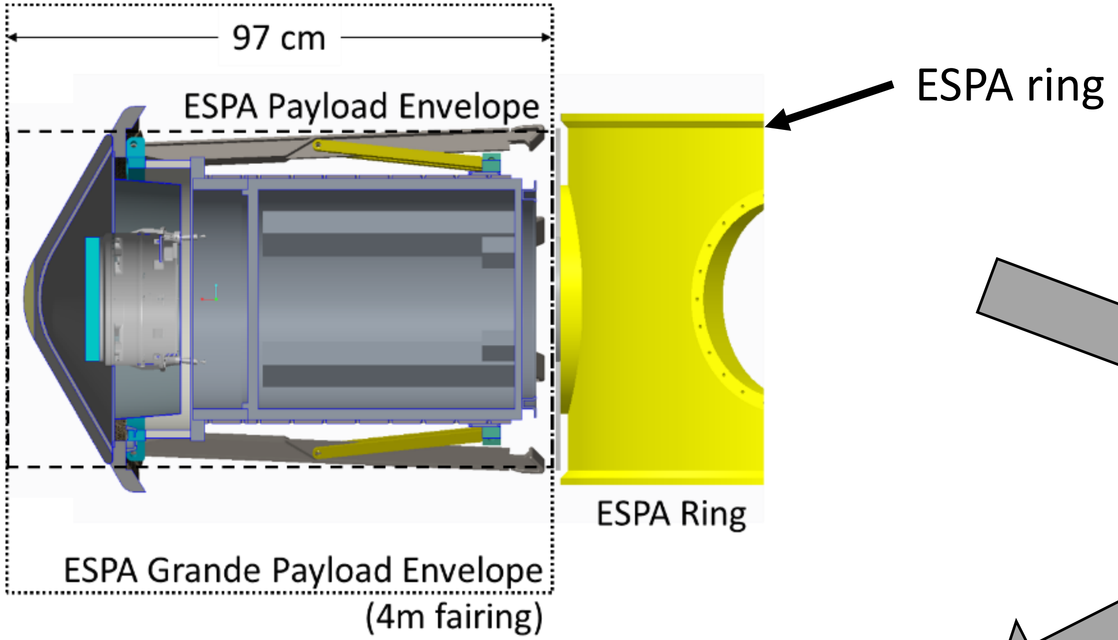
To overcome navigation and atmospheric uncertainties, a form of flight control is needed during the aerocapture pass through the atmosphere



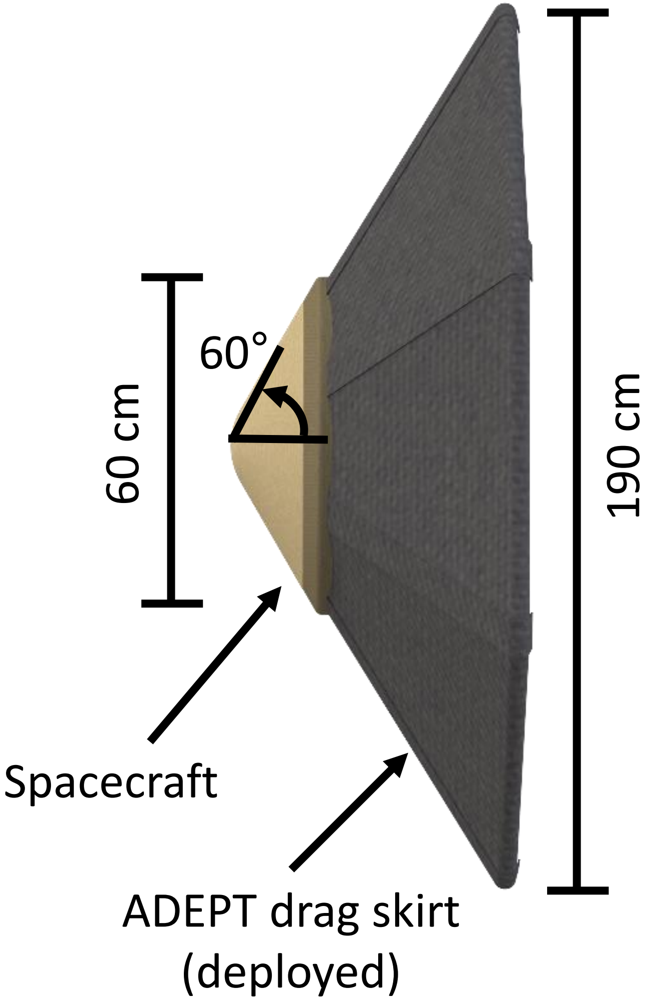
By modulating the time that a drag skirt is jettisoned from the spacecraft, the system can receive more or less delta-V and target a specific orbit

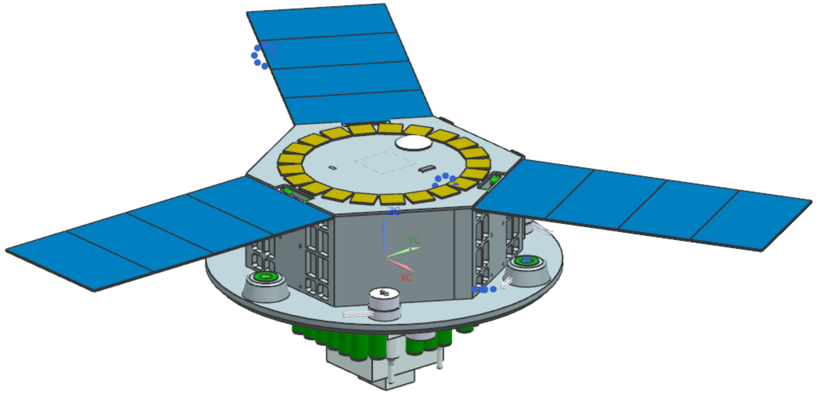
SmallSat Drag Modulation Aerocapture

Stowed in ESPA volume for launch



Deployed for cruise & entry

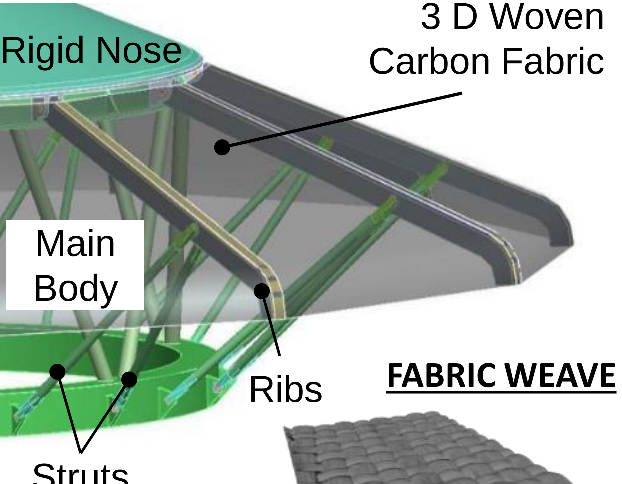




Spacecraft remains in orbit for science mission

ADEPT Deployable Drag Skirt

Ethiraj Venkatapathy will cover ADEPT and other entry system technologies in his presentation

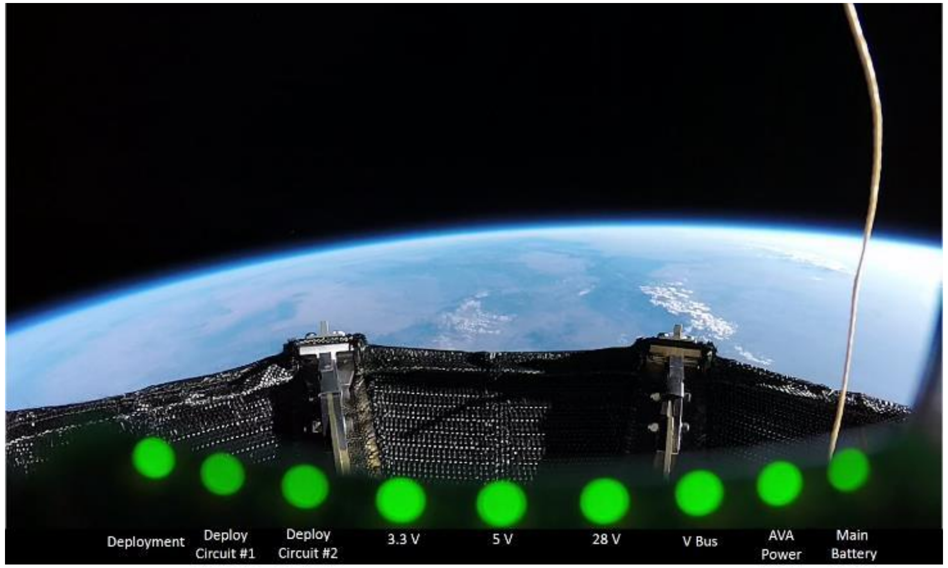


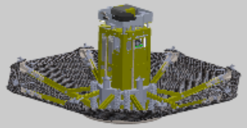
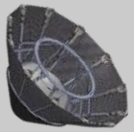
FABRIC WEAVE

2 m Deployment Prototype

Electrically driven actuators achieve high fabric pre-tension

Successful Flight Test of 70 cm SR-1 Demonstrator

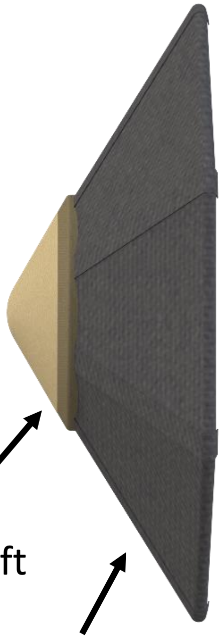


ADEPT Designs	SmallSat Class		Discovery or New Frontiers Class	Flagship Class
Design Concepts	SR-1 	Aft Drag Skirt 	ADEPT VITaL 	Human Mars 
Diameter Range	**< 3 m**		**6-10 m**	**>16 m**

Small → Large Missions

SmallSat Aerocapture

60 cm



190 cm

Spacecraft

ADEPT drag skirt (deployed)

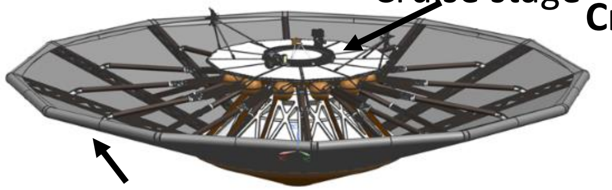
Mission Study for a Large Aerocapture System (JPL & ARC – 2019)

Folded Drag Skirt

Launch

Stowed system fits in 5m launch vehicle fairing

Cruise stage

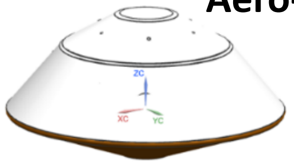


Cruise

12m drag skirt

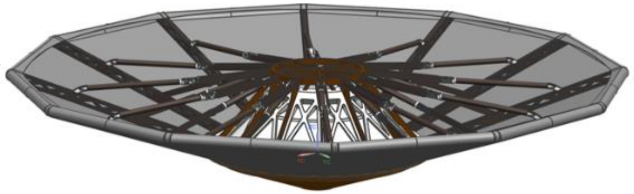
Deployed Drag Skirt

Aero-exit

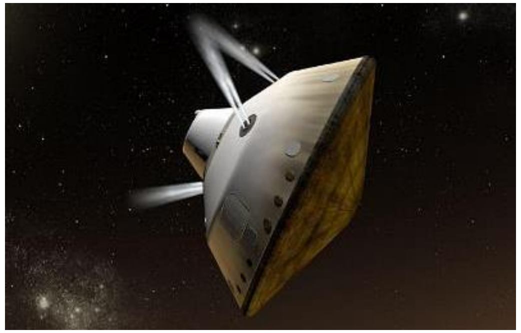


4m, 70 deg aeroshell

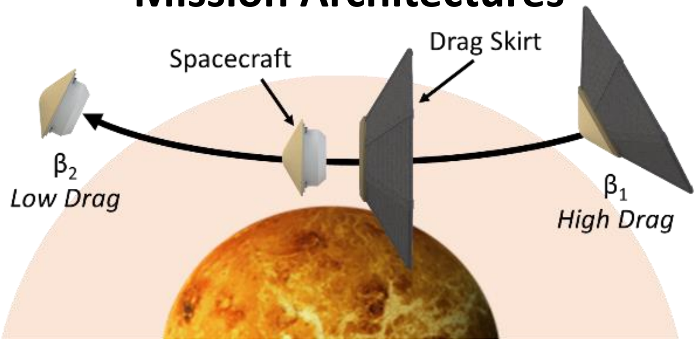
Aero-entry



Lift Modulation Mission Architectures



Drag Modulation Mission Architectures

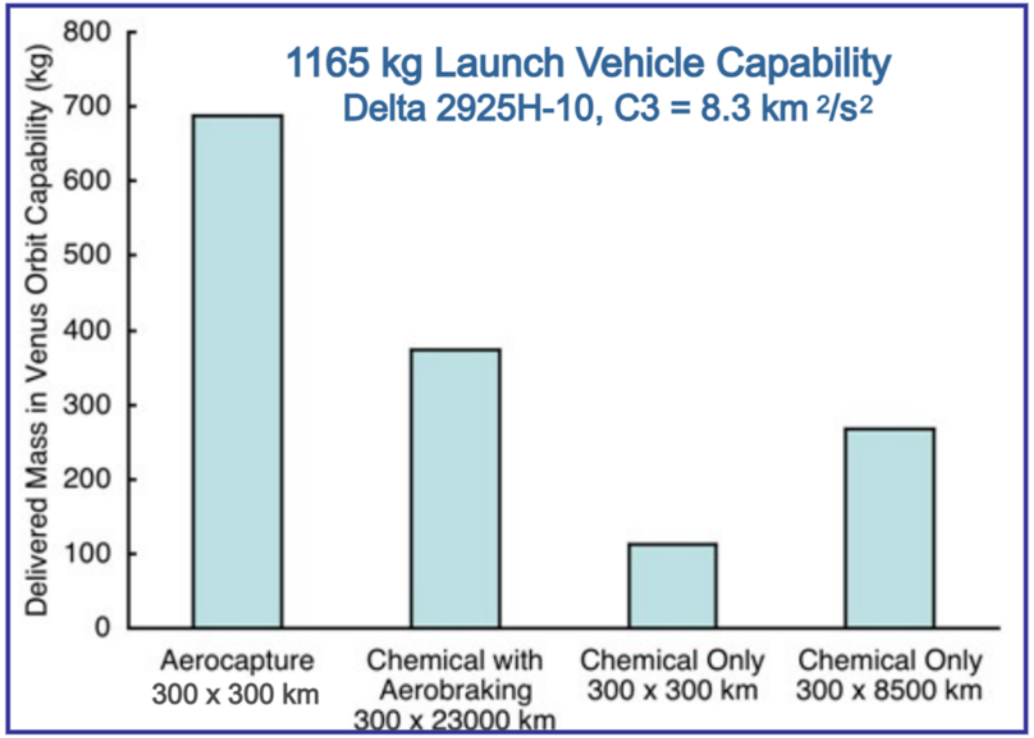


SmallSat aerocapture lays the groundwork for future larger missions of multiple types, while accomplishing meaningful, cost effective science

Benefits to Larger Missions

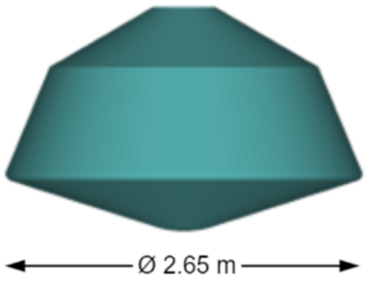
- **For larger Venus missions, the principal benefit of aerocapture is greater delivered mass to orbit**
  - Potential to open up new mission architectures with multiple flight elements in a single launch (i.e. orbiter and in-situ elements)
  - Alternatively, instead of bringing more mass, greater mass efficiency can be used to lower the total flight system mass and use a smaller launch vehicle
- **There are many opportunities for aerocapture and future missions should consider this a rich trade space to explore**

<u>One study highlighting the increased mass efficiency of a Venus aerocapture orbiter</u>



Mass savings will scale up for Flagship-class mission

Venus Orbiter
(OML Design Only)



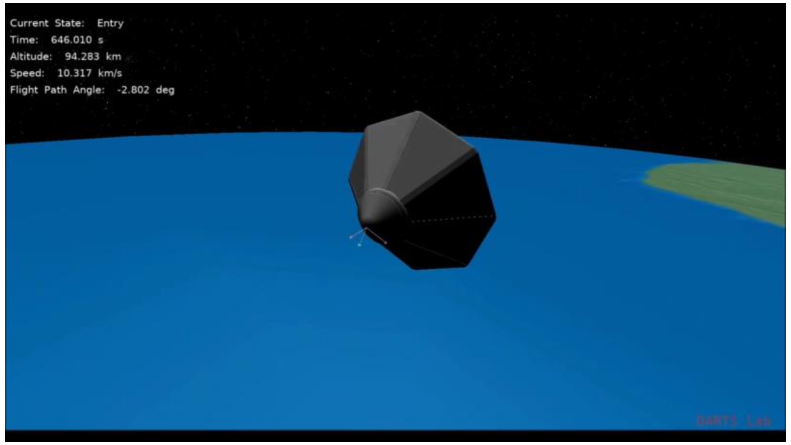
Into 300 x 300 km Venus orbit w/constant launch vehicle, Aerocapture delivers:
- **1.8x more mass** into orbit than aerobraking
- **6.2x more mass** into orbit than all chemical

Reference: Lockwood et al, "Systems Analysis for a Venus Aerocapture Mission", NASA TM 2006-214291, April 2006

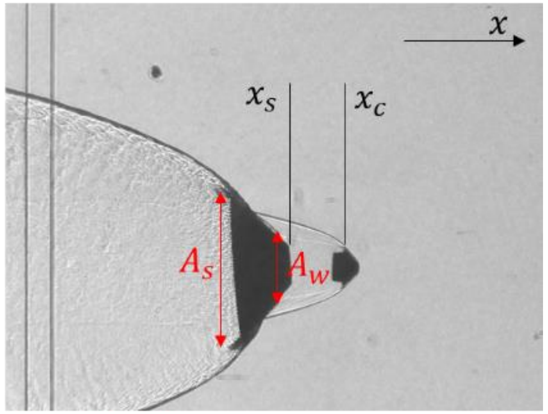
Credit: Michelle Munk & Thomas Spilker, 6th International Planetary Probe Workshop

Aerocapture Tech Development Progress

Many years of development progress has advanced aerocapture for use in Venus missions



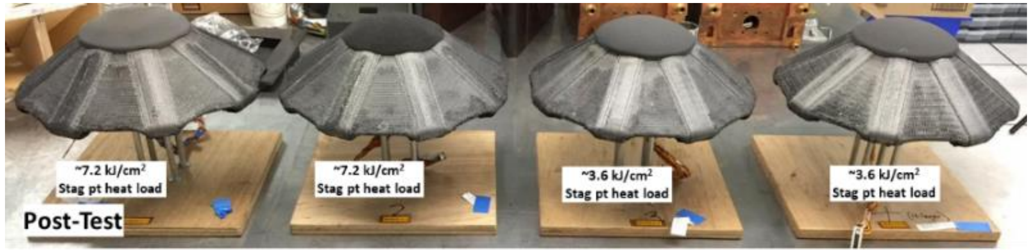
6-DOF simulation toolset provides capability to model the aerocapture maneuver



$$F_c = C_{D,c} A_c q_\infty$$

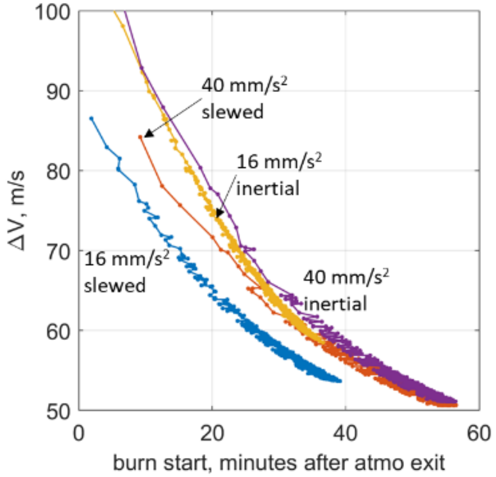
$$F_s = C_{D,s}(A_s - A_w) q_\infty + C_{D,s} A_w k q_\infty$$

JPL and ARC performed 8 sub-scale ballistic range shots at Mach 10, giving valuable test data to inform modeling efforts

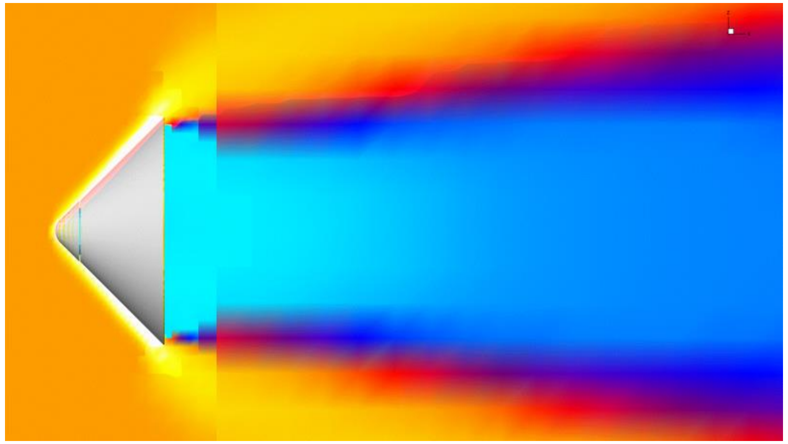


ARC performed arcjet testing of flexible carbon fabric at Mars relevant conditions

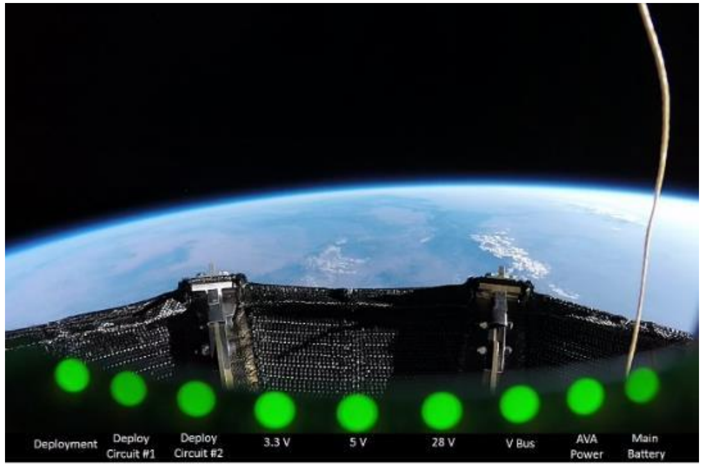
ADEPT vacuum bag and subsonic wind tunnel tests to assess shape change and possibility of flutter



Investigated post-aerocapture PRM delta-v and operations requirements

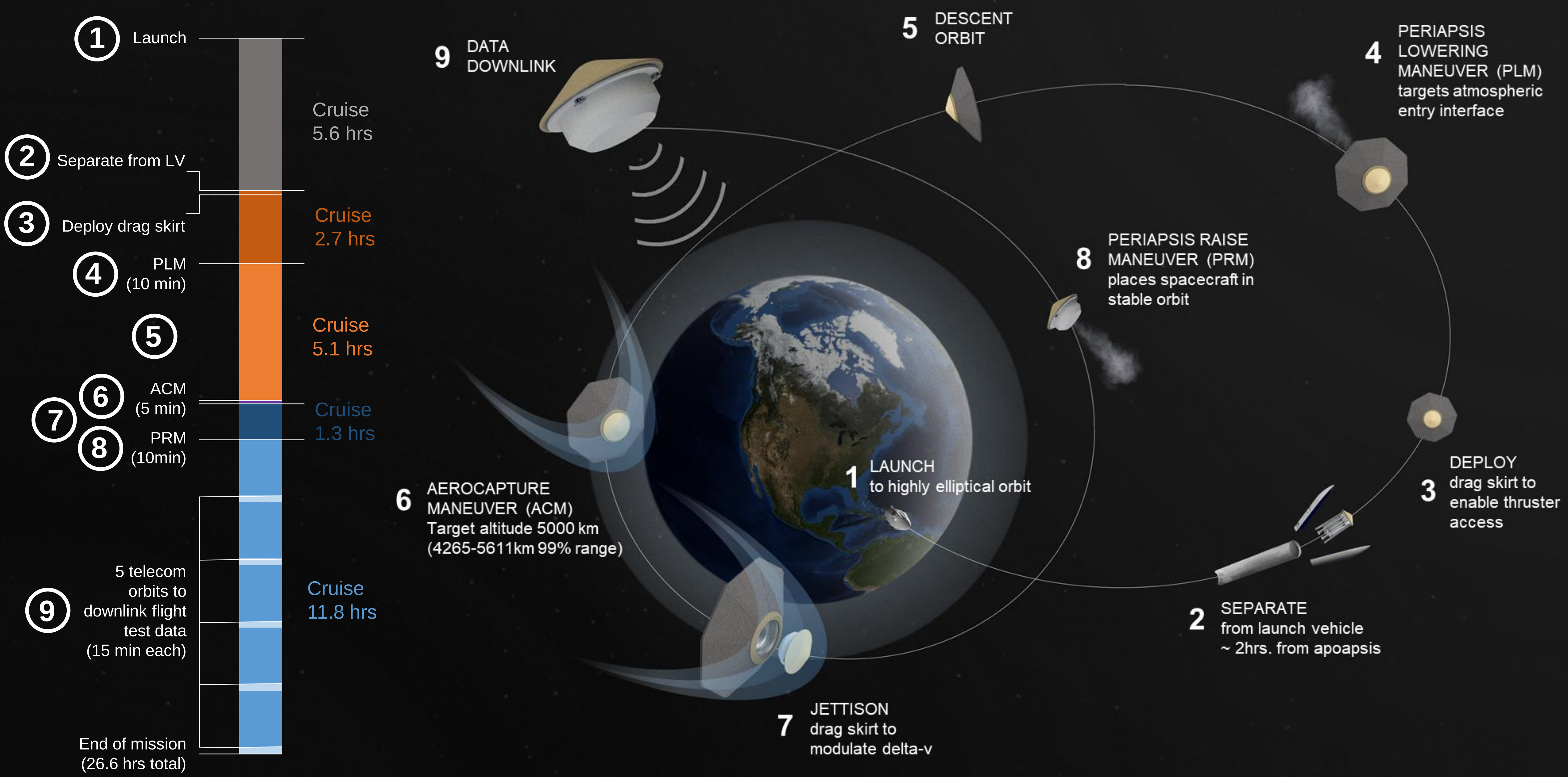


Cart3D CFD simulations at Venus flight conditions



ARC successfully flew a 70 cm diameter ADEPT skirt on a suborbital sounding rocket

Aerocapture Earth Flight Test



Aerocapture Decadal Whitepaper

WHITE PAPER FOR THE
PLANETARY SCIENCE AND ASTROBIOLOGY DECADAL SURVEY, 2023 - 2032

Enabling and Enhancing Science Exploration Across the Solar System: Aerocapture Technology for SmallSat to Flagship Missions

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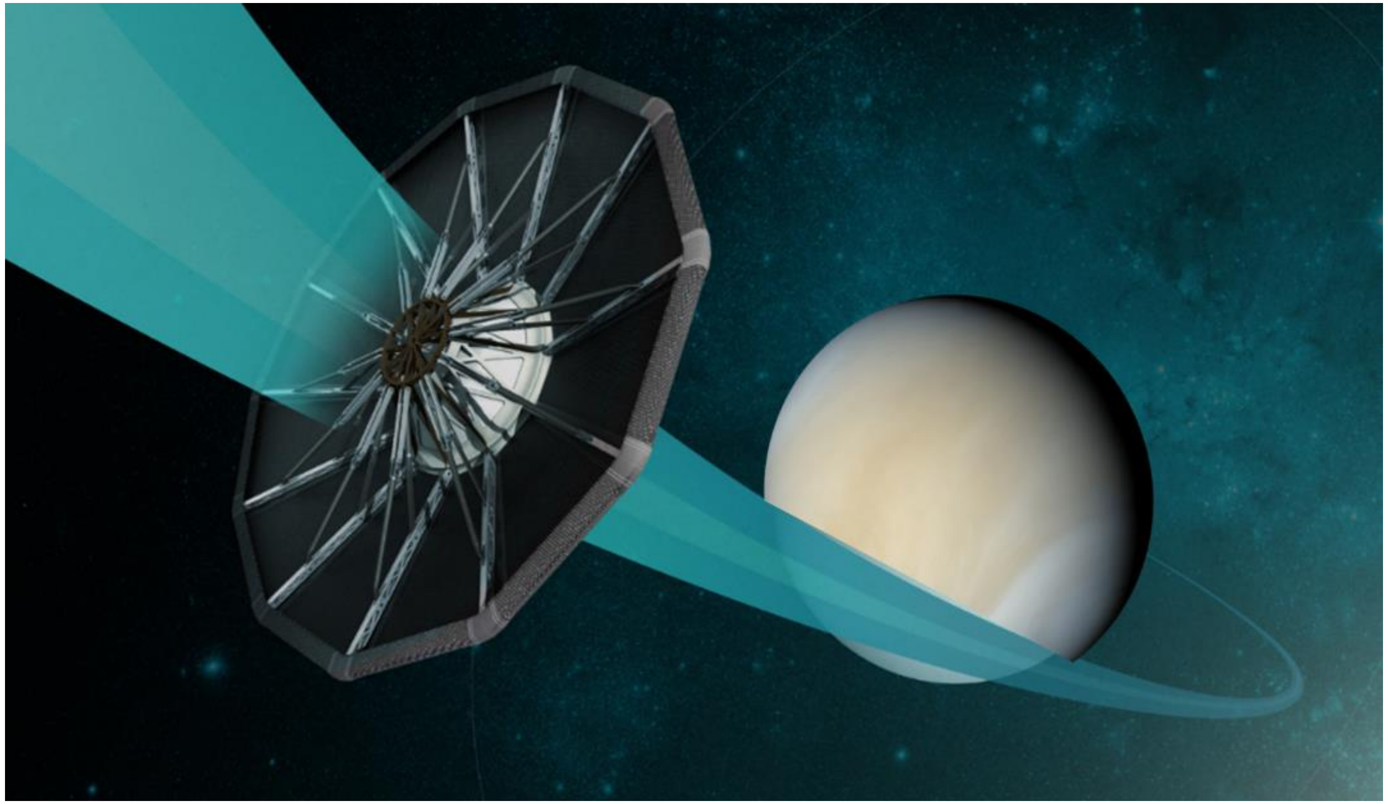

Summary and Recommendations

- Aerocapture uses the drag from a single pass through the atmosphere to slow down and enter orbit, rather than a large burn from a propulsion system.
- Aerocapture can enable greater payload mass to Venus, open up new mission architectures with multiple flight elements, or allow the use of smaller launch vehicles.
- Recent research and technology development of drag modulated aerocapture has identified that this could be an enabling technology to allow SmallSats to enter orbit at Venus, especially as secondary payloads taking advantage of rideshares on larger missions.
- Continuing to develop aerocapture technologies, with the next step being a SmallSat Earth Flight Test, will have a positive impact on Venus exploration with multiple classes of missions in the coming decades.

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