Atmospheric Delta-V

How I Learned to Stop Worrying and Love Aerocapture

Soumyo Dutta
NASA Langley Research Center, Hampton, VA
with contributions from numerous colleagues
at NASA Langley, NASA Ames, and NASA JPL

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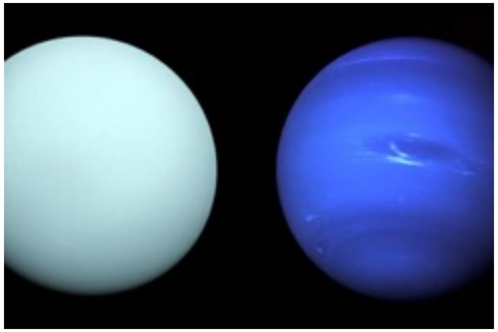
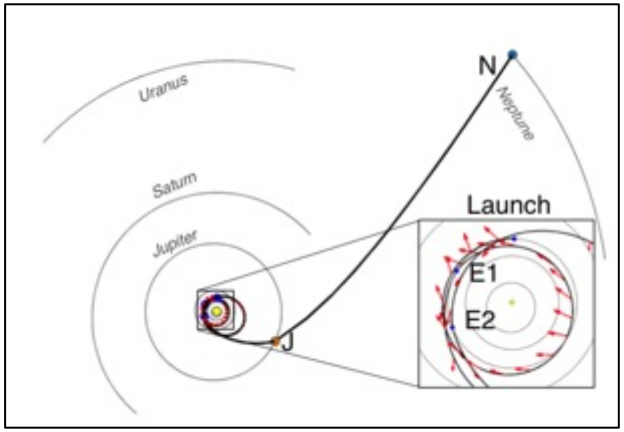
Motivation

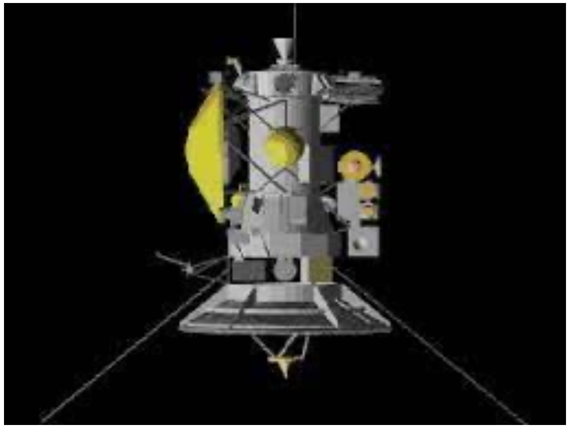
- Mission to the Ice Giants (Uranus and Neptune)
  - Direct mission to the planet (16 years) or with Jupiter Fly-by (14-15 years)
  - Orbital insertion maneuver: 1000+ m/s; propellant mass fraction is 55-70%



Credit: NASA



Credit: JAXA

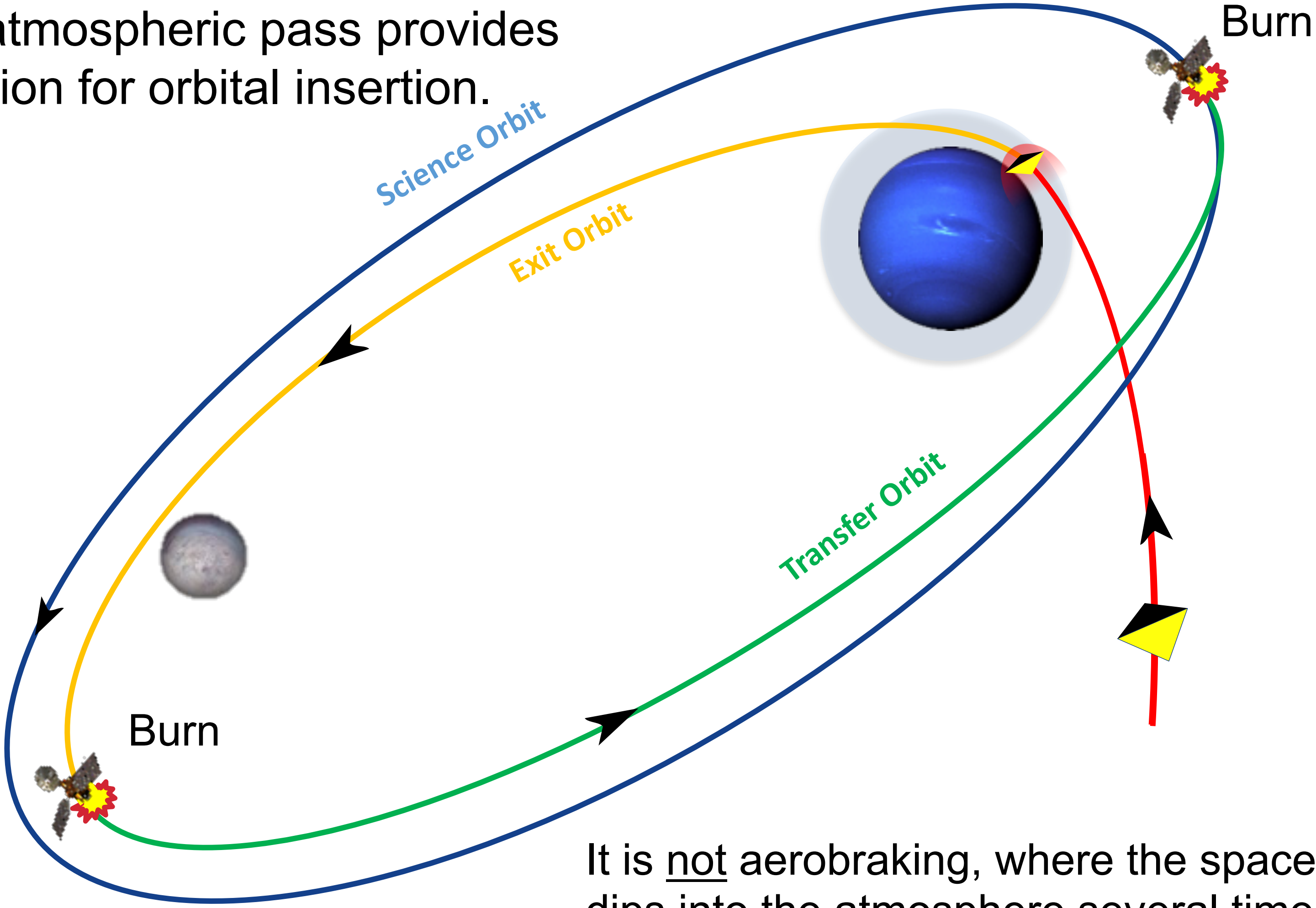


Credit: APL

- What if you could use the atmosphere of the planetary body to do most of the orbital insertion ΔV?
- What if the on-orbit mass could be increased by 40%?
- What if the interplanetary cruise duration could be cut by 2-5 years?

What is Aerocapture?

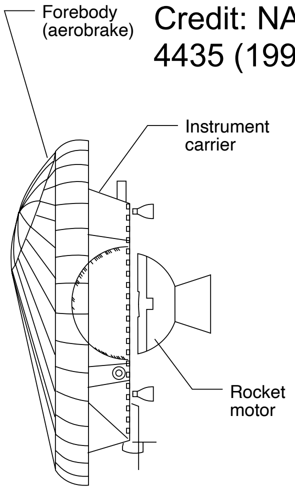
Orbital maneuver where the drag from a single atmospheric pass provides deceleration for orbital insertion.



It is not aerobraking, where the spacecraft dips into the atmosphere several times before the target orbit is reached.

Past Works

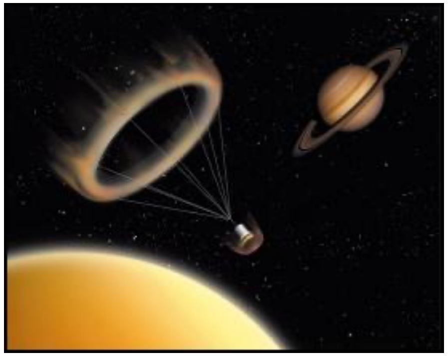
- Late 1960’s – Earth, Mars, and Venus orbit insertion studies
- Late 1980’s – Aeroassist Flight Experiment
- 2001 – Mars orbiter mission studies
- 2003-2005: Detailed systems analysis for aerocapture at Neptune, Titan, Venus, and Mars



Credit: NASA TM 4435 (1993)

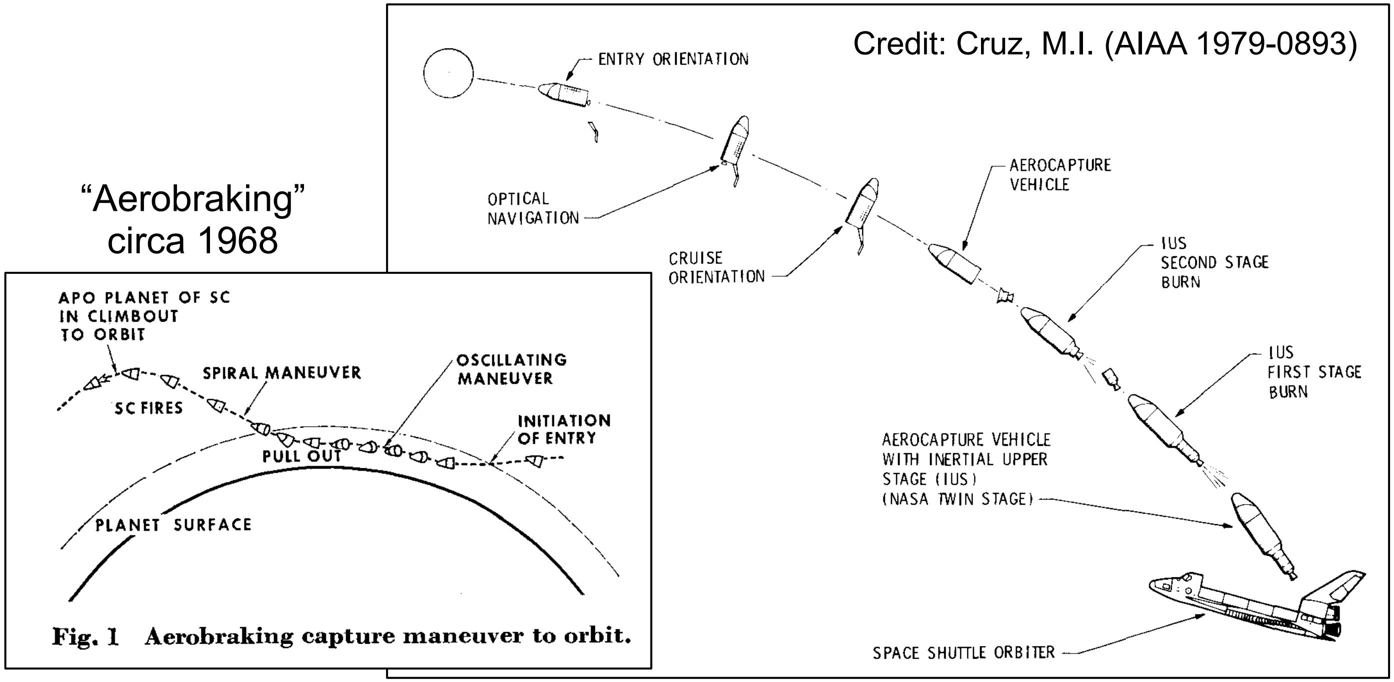
Aeroassist Flight Experiment (AFE)

Towed-Ballute Aerocapture



Credit: NASA

“Aerobraking” circa 1968

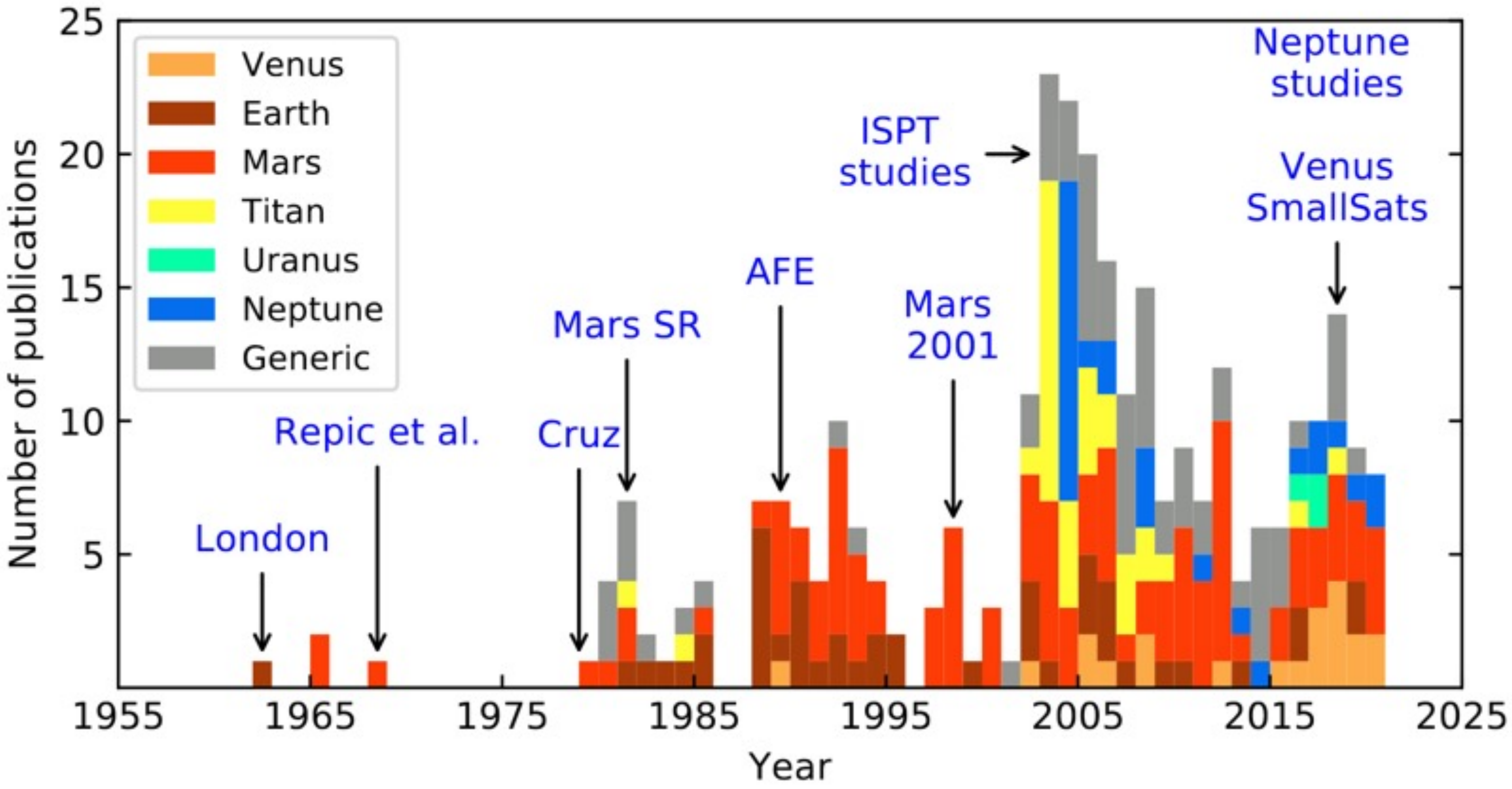


Credit: Cruz, M.I. (AIAA 1979-0893)

Fig. 1 Aerobraking capture maneuver to orbit.

Credit: Repic et al. (1968)

Past Works

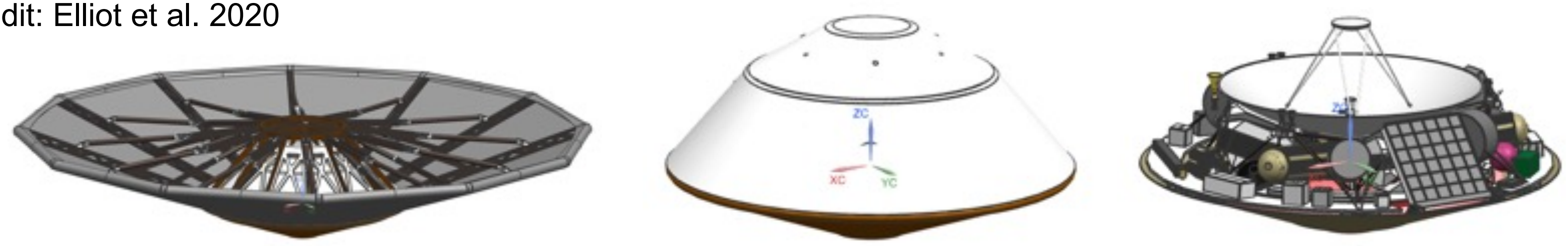


Credit: Girija, A.P. (2020)

Why has aerocapture not occurred in the past?

- Aeroassist Flight Experiment (AFE) was going to demonstrate components of aerocapture maneuver, but AFE was cancelled – not due to anything specific about aerocapture
- Aerocapture was initially the baseline for the Mars 2001 orbiter, but Mars Polar Lander and Climate Orbiter failures in 1999 (which did not involve aerocapture) led to lower risk posture for Mars missions
- Mars Sample Return in the early 2000’s had a CNES-led aerocapture element, but MSR in the early 2000’s was cancelled
- Aerocapture has been shown to be superior to aerobraking, the accepted aeroassist maneuver for orbital insertion, when using probabilistic risk assessment [Percy et al., AIAA 2005-4107]
- Perceived risk in aerocapture guidance and atmospheric/aerodynamic uncertainty
    - Aerocapture guidance schemes have been demonstrated under more constrained, stringent conditions by Mars Science Laboratory, EFT-1 etc.
        - EDL hypersonic guidance is precisely targeting a deploy condition
        - Aerocapture guidance only needs to get to a target energy state at exit and has capability of delta-V to clean up small errors
    - Aerocapture is staying within the hypersonic regime, unlike EDL which has staging events and aerodynamic instabilities in supersonic and subsonic phases
- Recent studies have shown packaging orbiters within aerocapture vehicles

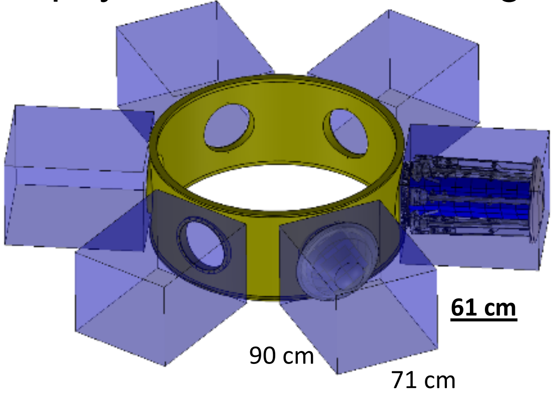
Credit: Elliot et al. 2020



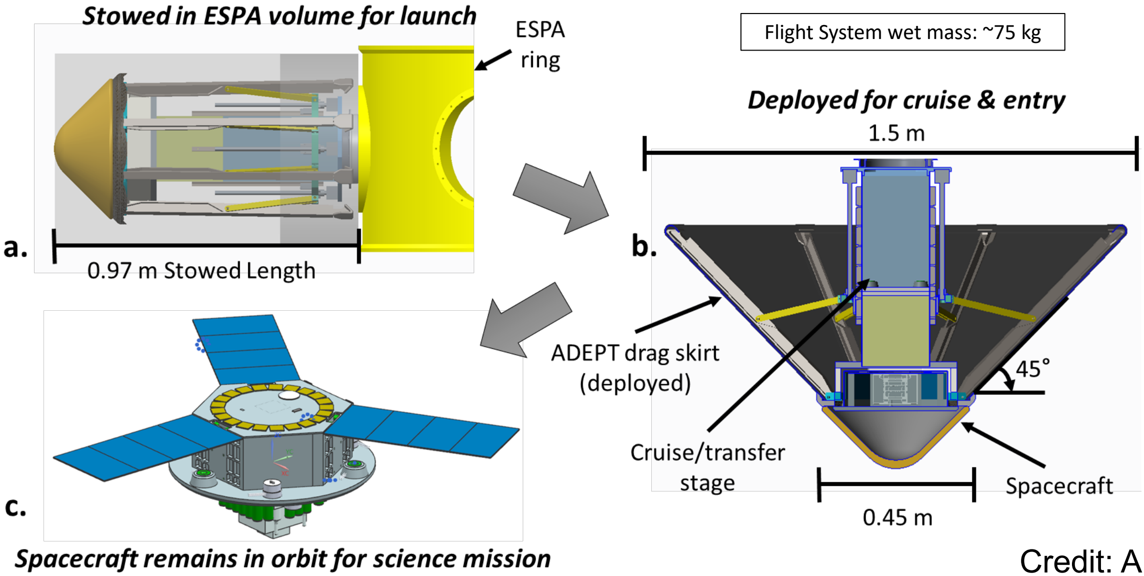
Mission Scenarios – Small Satellites Robotic Exploration

- Huge interest in SmallSat *planetary* missions since MarCO which did flybys of Mars in 2018
- ESPA Rings
  - Provides ride to Earth escape, GTO, or cislunar space
  - Used on Atlas V, Delta IV, Falcon 9, and Falcon Heavy
- Aerocapture provides the method to slow down and entry orbit without a large propellant or SEP module

SmallSat Aerocapture as a payload on an ESPA ring



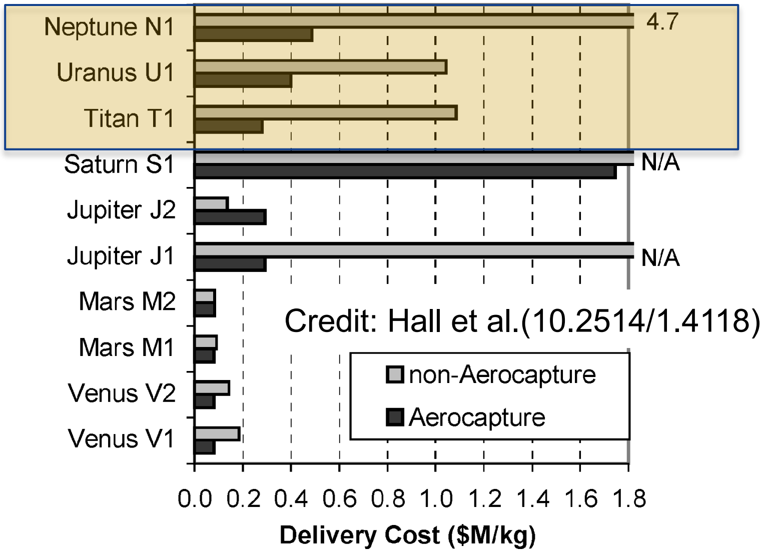
Credit: Austin et al. 2020



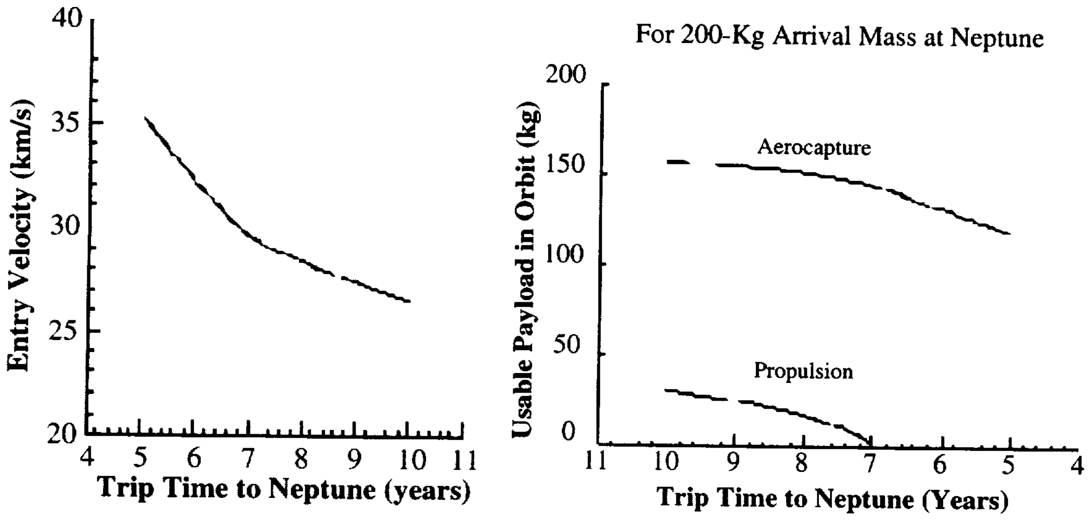
Credit: Austin et al. 2020

Mission Scenarios – Larger-scale Robotic Exploration such as the Ice Giants

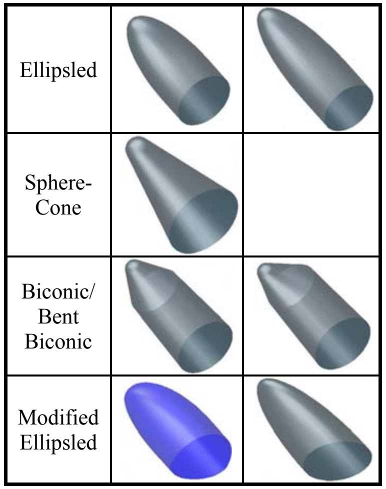
- For Outer Planet missions, orbit insertion maneuvers must deal with large ΔV (~1 km/s) and long interplanetary cruise duration
- Aerocapture can provide a large cost, mass, and time savings for Outer Planet missions
- Lockwood 2004 Study: 40% increase in on-orbit mass and 2-5 years reduction in trip time



Credit: Hall et al.(10.2514/1.4118)



Credit: NASA/TM-2002-211386



Needed a vehicle with L/D of 0.6-0.8

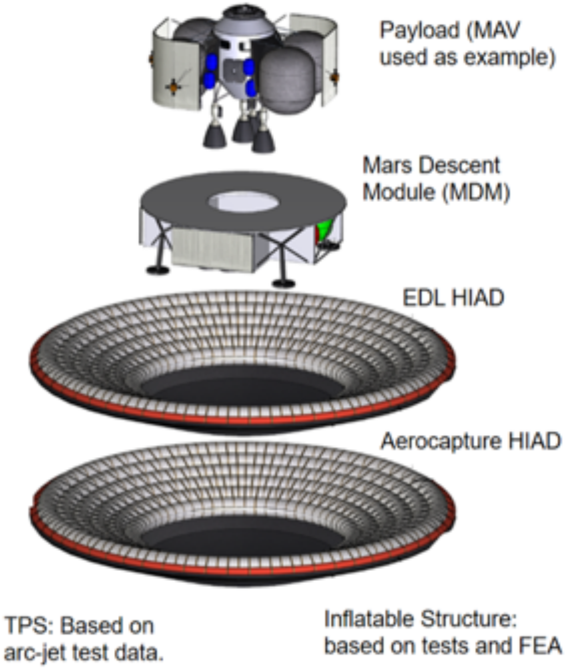
Credit: AIAA 2004-4953

Mission Scenarios – Human-scale Exploration

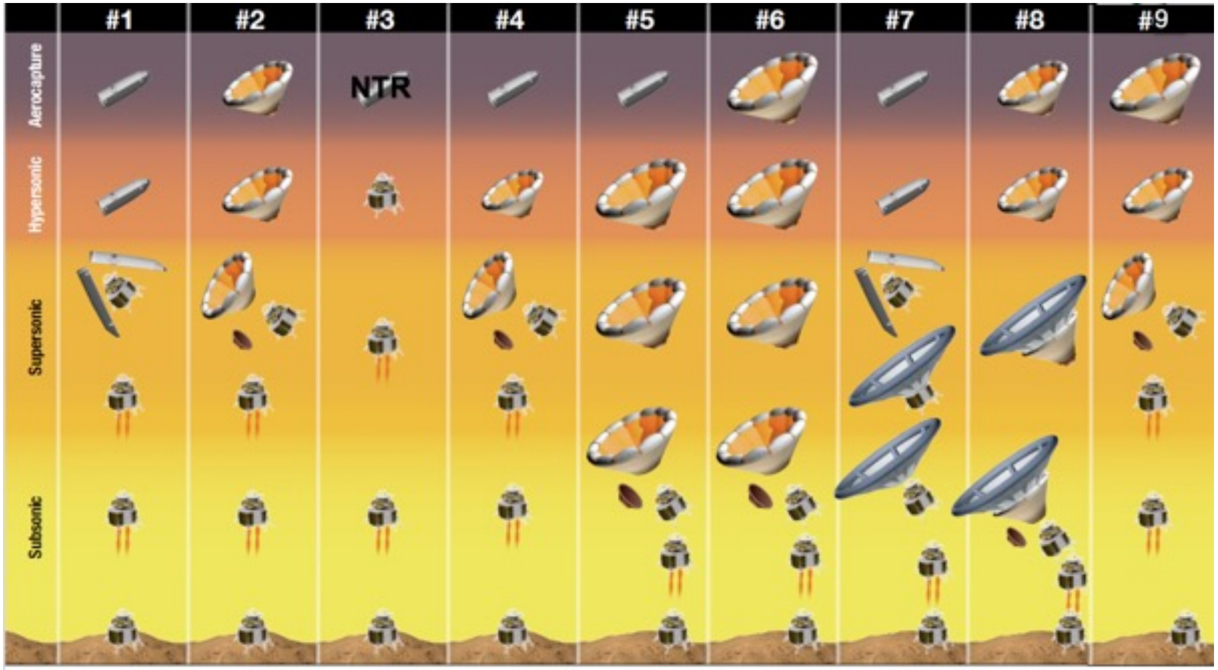
- Human-scale Mars missions – cargo or crew – has had aerocapture as a baseline concept in the past (EDLSA), but the current baseline does not have aerocapture
- Aerocapture can be conducted with mid L/D shape or a deployable like a HIAD

Credit: AIAA 2017-1898

Hypersonic Inflatable Aerodynamic Decelerator (HIAD)



Credit: JSR 2019 (DOI: 10.2514/1.A34483)

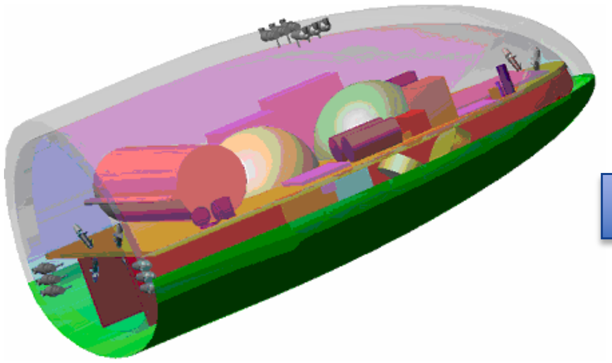


Credit: NASA/TM-2010-216720

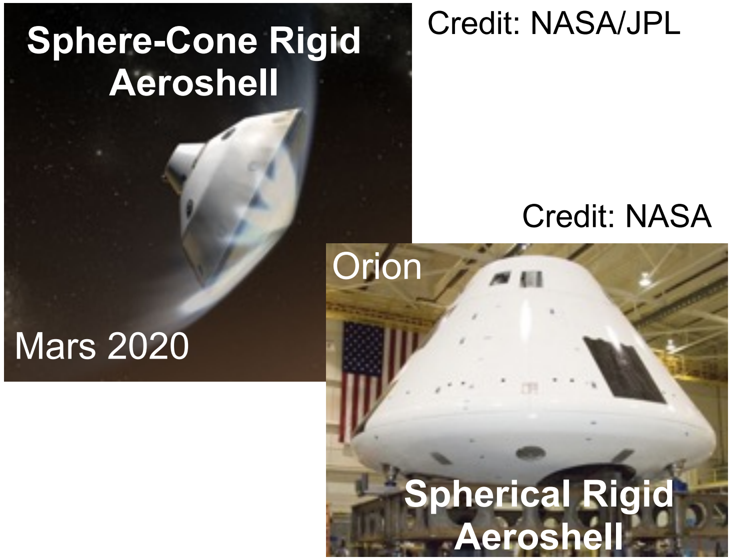
Enabling Capabilities

- Aerocapture design improvement in the last 15 years makes it easier to infuse into existing missions
- SmallSats: Development of deployable technologies, like HIAD and ADEPT, have made aerocapture for SmallSats feasible
- Human-scale aerocapture: Feasible due to improvements in deployable technology, mid L/D technology
- Larger-scale robotic missions: In the past, needed newer entry vehicle design or newer thermal protection system
  - Emerging capabilities make larger-scale robotic aerocapture missions feasible with existing, heritage entry-vehicle configurations

2003 Study Concept Vehicle



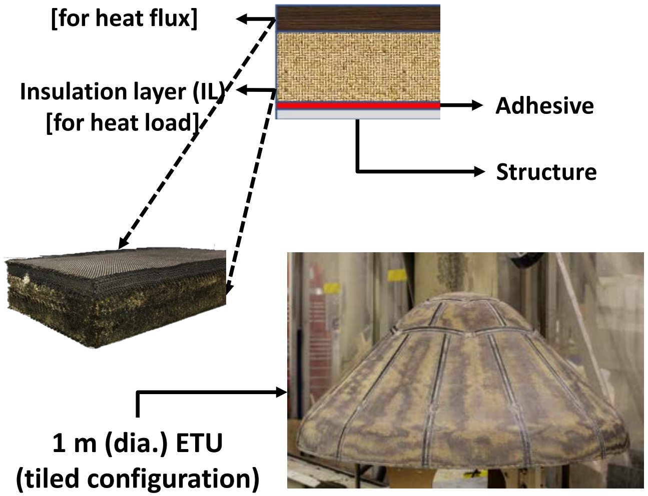
Credit: AIAA 2004-4953



Credit: NASA/JPL

Credit: NASA

Capability 1. Thermal Protection System



Credit: Venkatapathy et al. 2020

Heatshield for Extreme Entry Environment Technology (HEEET)

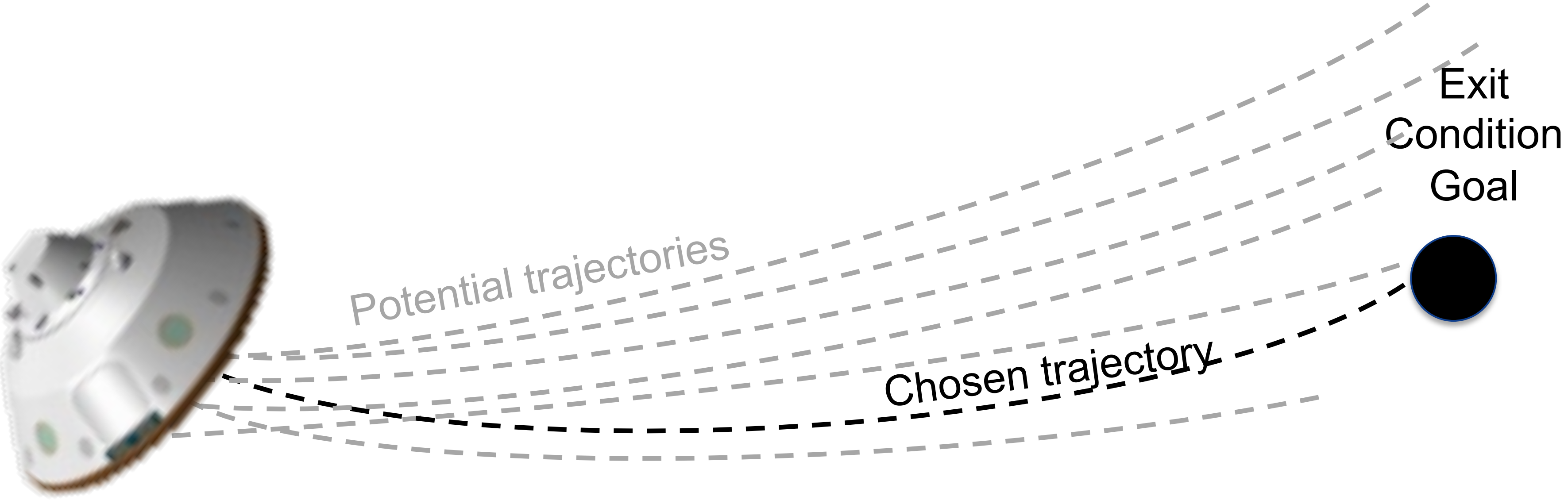

Credit: NASA

Phenolic Impregnated Carbon Ablator (PICA)

- Past studies identified need for high performance and lightweight thermal protection system material might be needed for missions for aerocapture at some planetary destinations where heat flux and stagnation pressure are higher
- Development and maturation of high performance HEEET and PICA have addressed those issues [Venkatapathy 2020 – Space Sci Review]

Capability 2.a. Guidance Methods

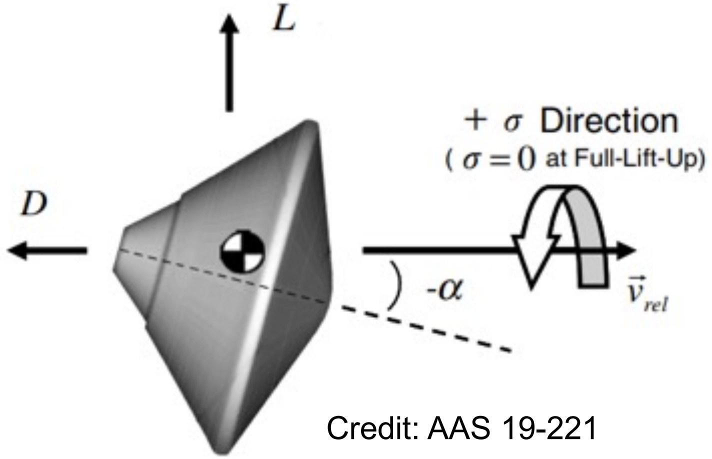
- Analytic schemes
  - Gains for guidance based on pre-generated reference profiles
  - Non-iterative and efficient code
- Numerical predictor-corrector (NPC) schemes
  - Numerically integrates equations of motion on-the-fly
  - Iterative code and adaptable to modern flight software
  - Can be robust to uncertainties in atmosphere and aerodynamics



Aeroshell Credit: AIAA 2017-0245

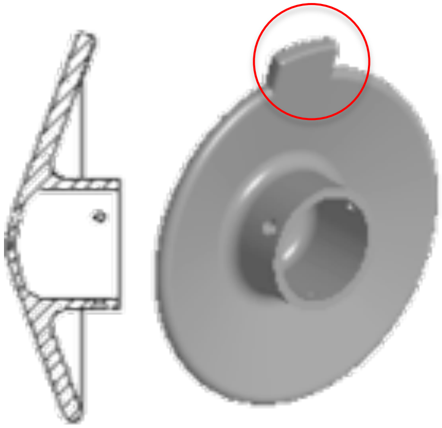
Capability 2.b. Control Mechanisms

Bank Angle Control

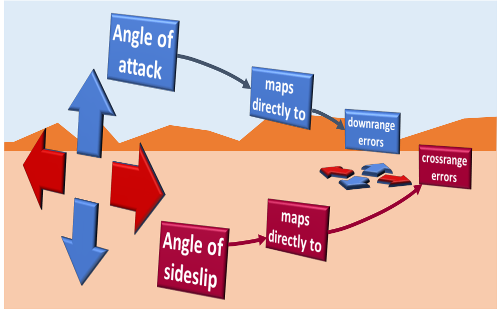


Credit: AAS 19-221

Direct Force Control

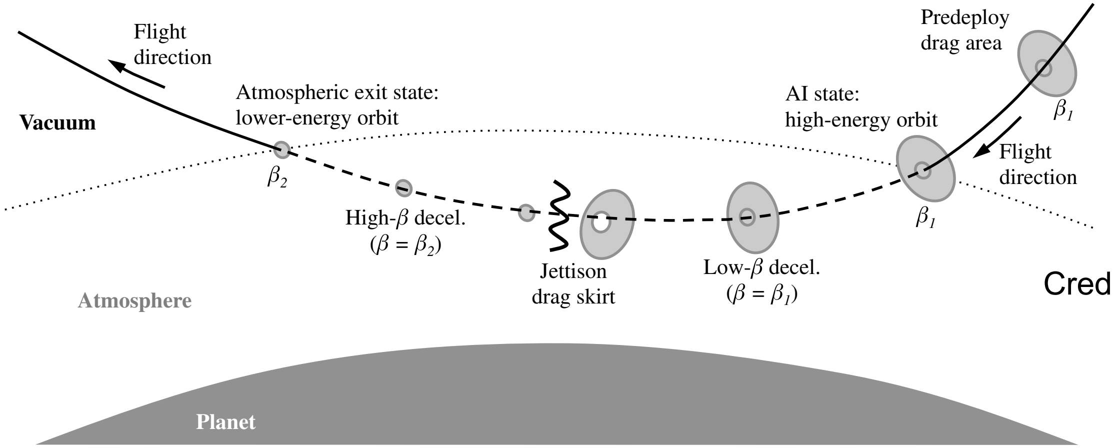


Credit: AIAA 2013-2809



Credit: AIAA 2019-0663

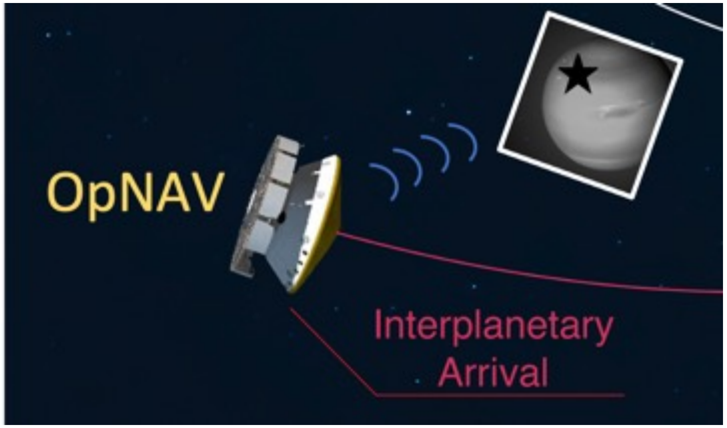
Drag Modulation Control



Credit: JSR 2014 Putnam et al.

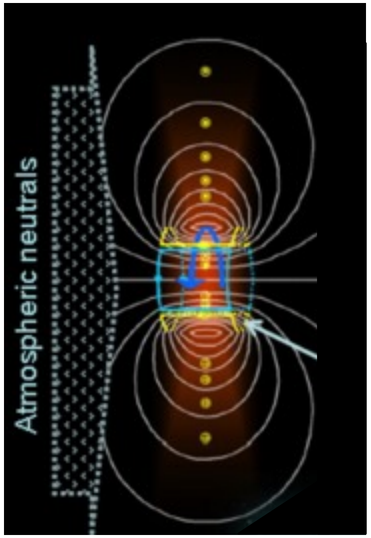
Capability 3. Optical Navigation

- Optical Navigation (OpNav) required for deep space missions due to poor ephemeris knowledge
  - Augments radiometric data from the Deep Space Network (DSN)
  - OpNav used on Voyager 2 flybys of Uranus and Neptune in the 1980s
- Standard OpNav uses ground processing of images. Turnaround time from receipt of data to uplinking control information (e.g., maneuvers, instrument pointing) can be many hours to days
  - Long round-trip light time (> 8 hours for Neptune)
  - Time for ground processing, sequence generation, etc.
- Recent advances in Onboard Autonomous Navigation (AutoNav) can dramatically improve navigation performance
  - Images processed, orbit determination, and maneuver computation all done onboard
  - Takes advantage of late-breaking navigation information to decrease target-relative ephemeris knowledge
  - Reduces turnaround time to minutes.

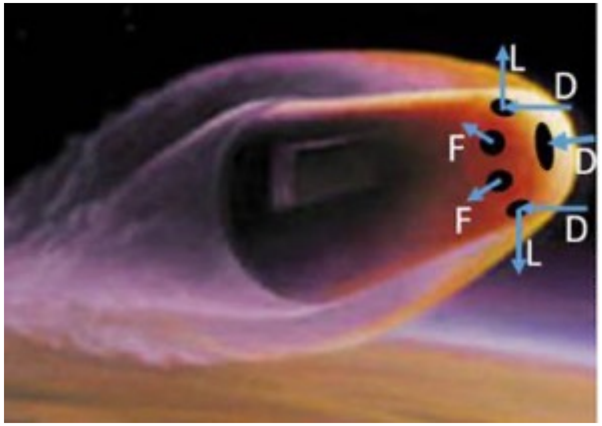


Aerocapture with Magnetohydrodynamics

- Lorentz Forces – forces exerted on a charged particle moving through an electrical and magnetic field
- Magnet placed near the nose of the vehicle will increase the bow shock stand-off distance, substantially decrease stagnation point heat flux [Moses et al. 2020]
- Magnets placed on the side of the vehicle nose will produce side forces for increasing lift [Moses et al. 2020]
- Control the Lorentz forces to shape the trajectory of the vehicle – drag to produce enough energy orbital insertion and modulate lift to move the vehicle into desired target orbit
- Maneuvers are at higher altitudes compared to traditional aerocapture



Credit: NASA



Credit: NASA

References

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Transition to Aerogravity Assist

Two Types of Aeroassist Maneuvers That Can Enable Mass Savings for Exploration Missions

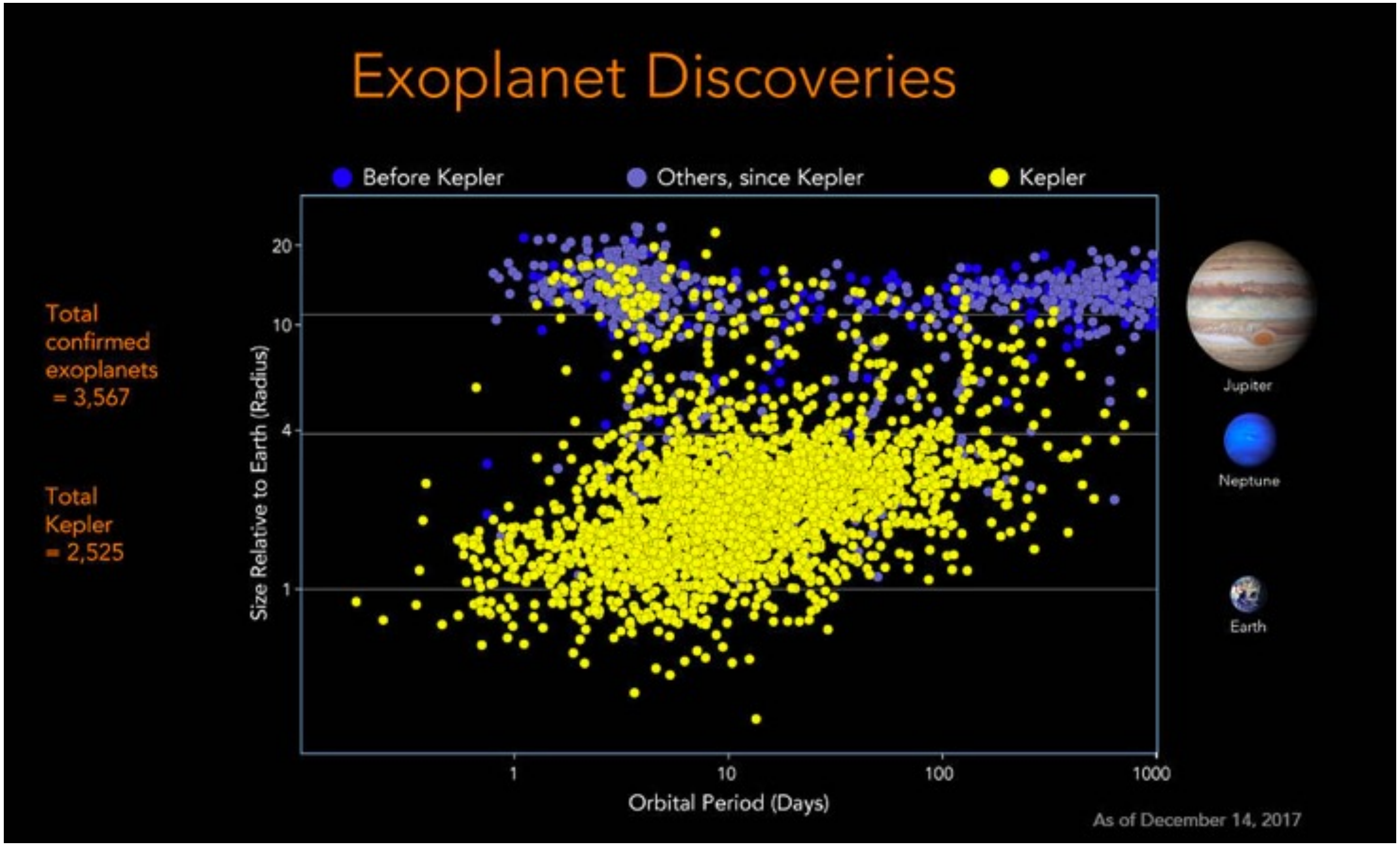
1. Aerocapture: Transition a spacecraft’s flight from a hyperbolic approach trajectory to an elliptical orbit about a target planet.
2. Aerogravity Assist: Transition a spacecraft’s flight from a hyperbolic approach trajectory to another one, heading toward a new destination.

Both maneuvers require Heat-Shielded Aeroshell and GNC for Atmospheric Flight

Back-up Slides

Why Ice Giants?

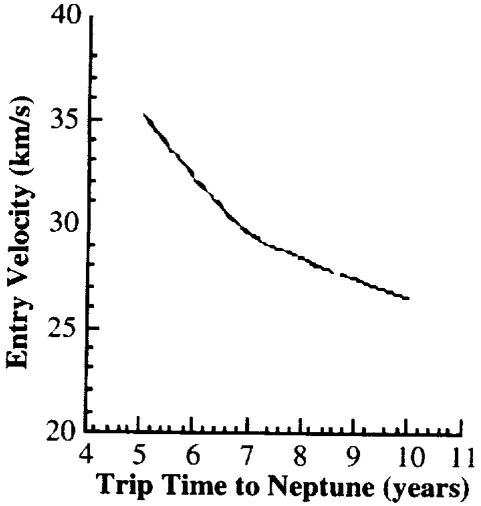
- Uranus and Neptune (Ice Giants) have only been visited by Voyager 2
- Uranus has interesting obliquity; Neptune has interesting moon: Triton
- Many exoplanets are Uranus/Neptune like

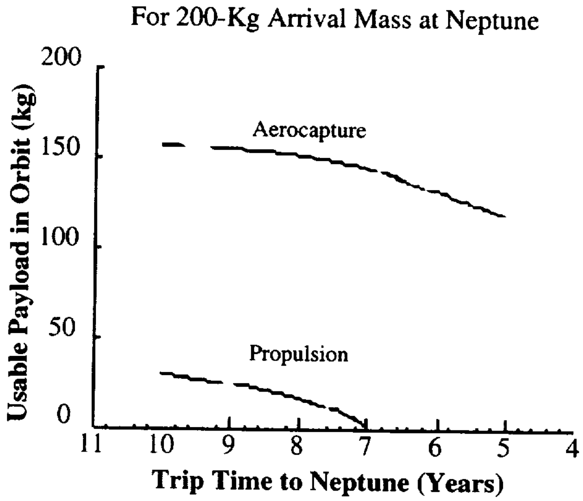


Credit: https://www.nasa.gov/image-feature/ames/exoplanet-discoveries

Aerocapture Studies about Ice Giants Missions

- NASA 2002 Study: Wercinski et al. (NASA/TM-2002-211386)
  - Showed increased on-orbit mass using aerocapture over all-propulsive options for a Neptune mission



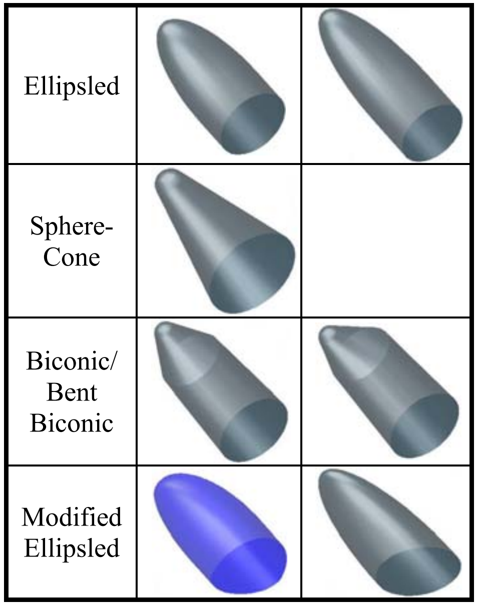

For 200-Kg Arrival Mass at Neptune

- NASA 2017 Study: Ice Giants Pre-Decadal Survey (D-100520)
  - “Aerocapture technology could enable trip times to be shortened, delivered mass to be increased or both.”
- JSR 2019 Article by Spilker et al.
  - “… a need for development of advanced aeroshells robust to ablation effects, though advanced flight control options might allow even Neptune aerocapture with the lower L/D [lift-to-drag] of a higher-heritage blunt-body aeroshell.”

NASA 2003 Study – Lockwood et al.. Study

- Studied Neptune capture and Triton fly-by orbit
  - Science orbit: 3896 km x 430,000 km
  - Orbiter (792 kg) and two separate Neptune entry probes
    - Orbiter would be two years in Neptune orbit
    - Visible imager, UV, IR, and thermal imaging spectrometer, ion and neutral mass spectrometer, magnetometer, charged-particle detector, plasma wave spectrometer, microwave radiometer, USO (radio occultations)

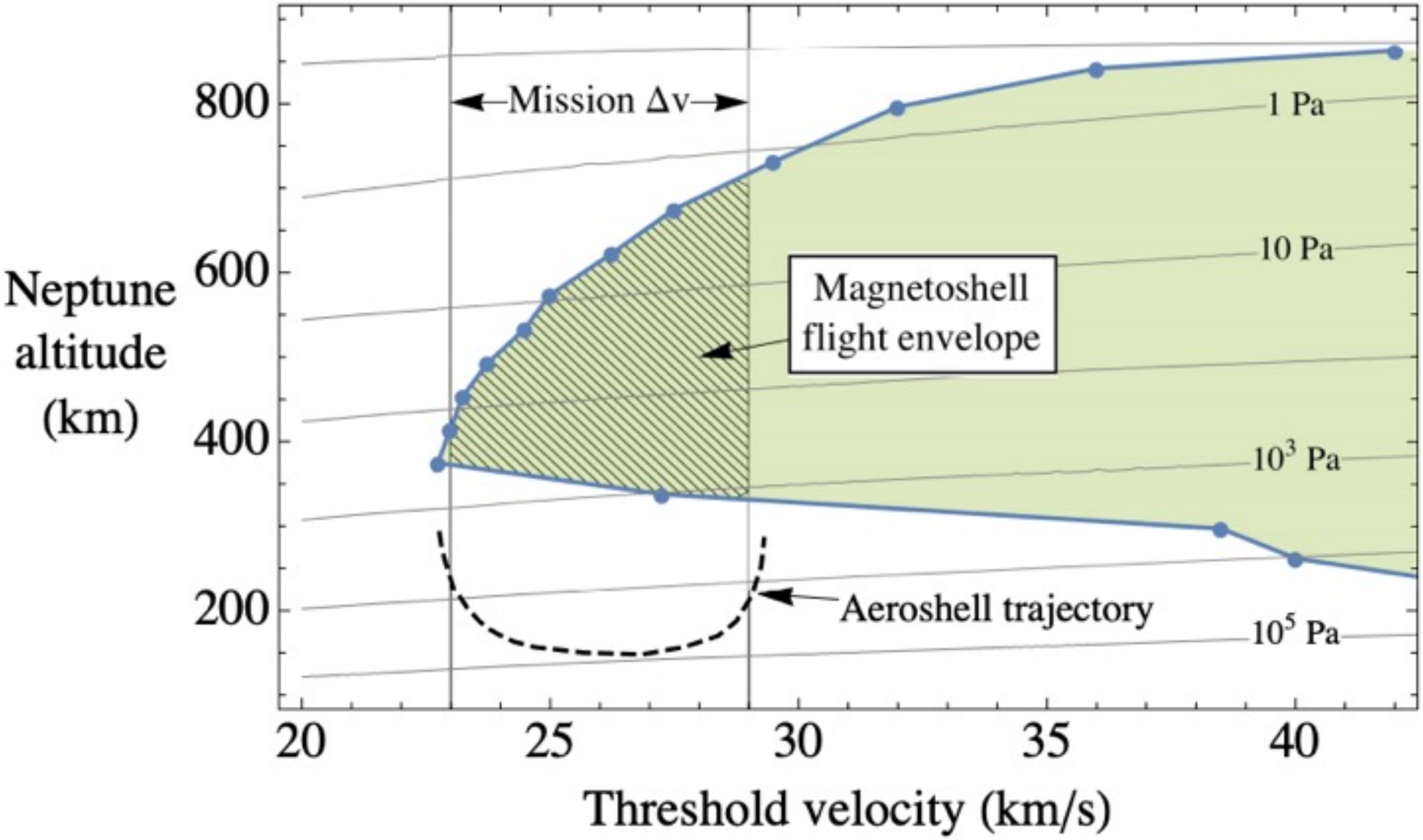
- Results of the study
  - 3-4 year trip time reduction compared to all-propulsive options (10 year trip vs. 14 year trip)
  - Aerocapture provided 40% more on-orbit mass compared to all-propulsive options (1614 kg vs. 1167 kg at zero-margin)
  - Needed development of a mid to high lift-to-drag (L/D) vehicle
  - Thermal Protection System environment challenging



Needed a vehicle with L/D of 0.6-0.8

Credit: AIAA 2004-4953

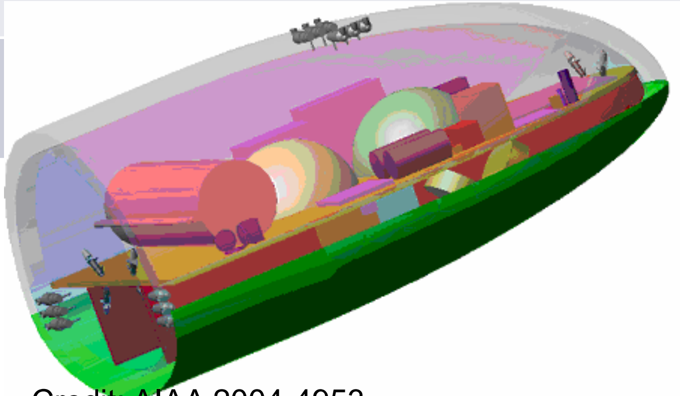
Drag-Modulated Plasma Aerocapture



Credit: IEPC-2019-202

Neptune Aerocapture Point of Departure

Subsystem	Neptune
Atmosphere	🟩 Neptune-GRAM (2003) developed from Voyager, other observation
Aerodynamics	🟨 New **shape**; aerodynamics to be established.
GN&C	🟩 APC algorithm with angle of attack control captures 95% of corridor.
Thermal Protection System	🟥 Zoned approach for mass efficiency. Needs more investment.
Structures	🟥 Complex **shape**, large scale. Extraction difficult.
Aerothermal	🟥 Conditions cannot be duplicated on Earth in existing facilities. More work on models needed.
	🟩 Aerodynamic drag accomplishes 96.9% of ΔV to achieve Triton observation orbit.



Credit: AIAA 2004-4953

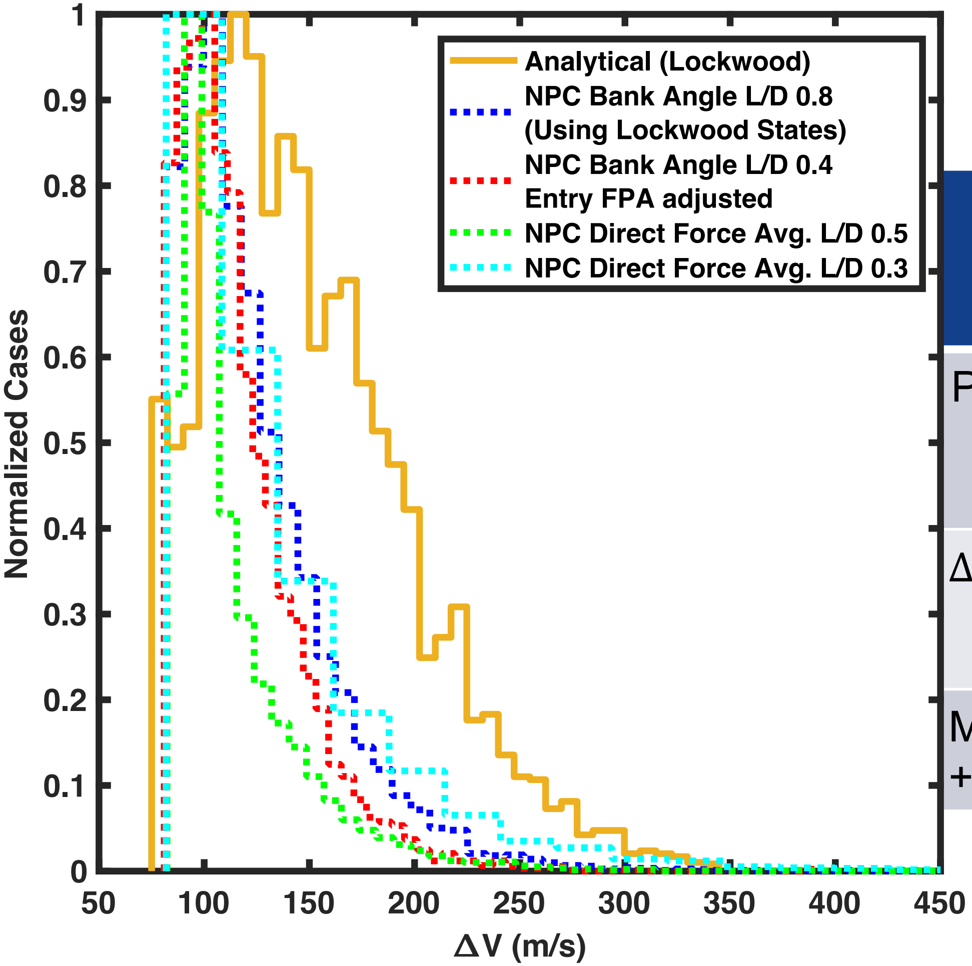
🟩 **Ready for Infusion** 🟨 **Some Investment Needed** 🟥 **Significant Investment Needed**

Capabilities Improved Since Earlier Studies

- Uncertainty in aerocapture performance in the past has been levied on two items [JSR 2005 Hall et al.]:
  - Guidance, Navigation, and Control strategies
  - Thermal Protection System (TPS)
- Three capability development have made aerocapture more feasible
  1. New TPS materials have been developed which meet requirements for Uranus and Neptune direct entries
  2. Guidance and control schemes have been developed that enable aerocapture under robust conditions with lower lift-to-drag heritage entry vehicles
  3. New optical navigation abilities improve vehicle state knowledge for Outer Planet missions

Recent Results

Combination of the two post-aerocapture burns



All-propulsive option: Total ΔV = 2871 m/s

	Analytical	Numerical Predictor-Corrector	
Performance Metric	L/D = 0.8	Avg L/D = 0.5	Avg L/D = 0.3
ΔV: +3σ high	300 m/s (10% of all-prop ΔV)	212 m/s (7% of all-prop ΔV)	238 m/s (8% of all-prop ΔV)
Max Accel: +3σ high	20 g's	15 g's	11 g's

NPC Results: AAS 19-221 and AAS 19-212

Heritage re-entry vehicles with lower L/D can be feasible for Ice Giant aerocapture with numerical guidance schemes and direct force control

Lockwood Study Concept

Credit: AIAA 2004-4951

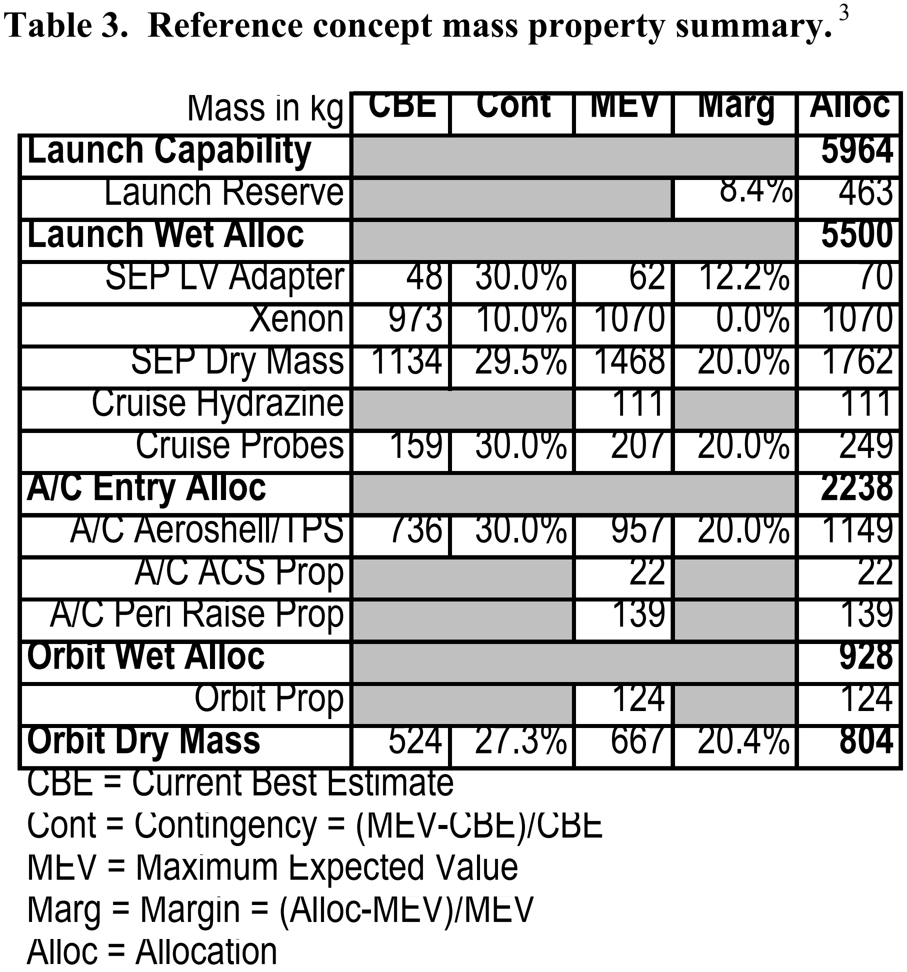


Table 3. Reference concept mass property summary.[3]

Mass in kg	CBE	Cont	MEV	Marg	Alloc
Launch Capability					**5964**
Launch Reserve				8.4%	463
Launch Wet Alloc					**5500**
SEP LV Adapter	48	30.0%	62	12.2%	70
Xenon	973	10.0%	1070	0.0%	1070
SEP Dry Mass	1134	29.5%	1468	20.0%	1762
Cruise Hydrazine			111		111
Cruise Probes	159	30.0%	207	20.0%	249
A/C Entry Alloc					**2238**
A/C Aeroshell/TPS	736	30.0%	957	20.0%	1149
A/C ACS Prop			22		22
A/C Peri Raise Prop			139		139
Orbit Wet Alloc					**928**
Orbit Prop			124		124
Orbit Dry Mass	524	27.3%	667	20.4%	**804**

CBE = Current Best Estimate
Cont = Contingency = (MEV-CBE)/CBE
MEV = Maximum Expected Value
Marg = Margin = (Alloc-MEV)/MEV
Alloc = Allocation

Aerocapture vs. Propulsive Comparison

Credit: AIAA 2004-4951

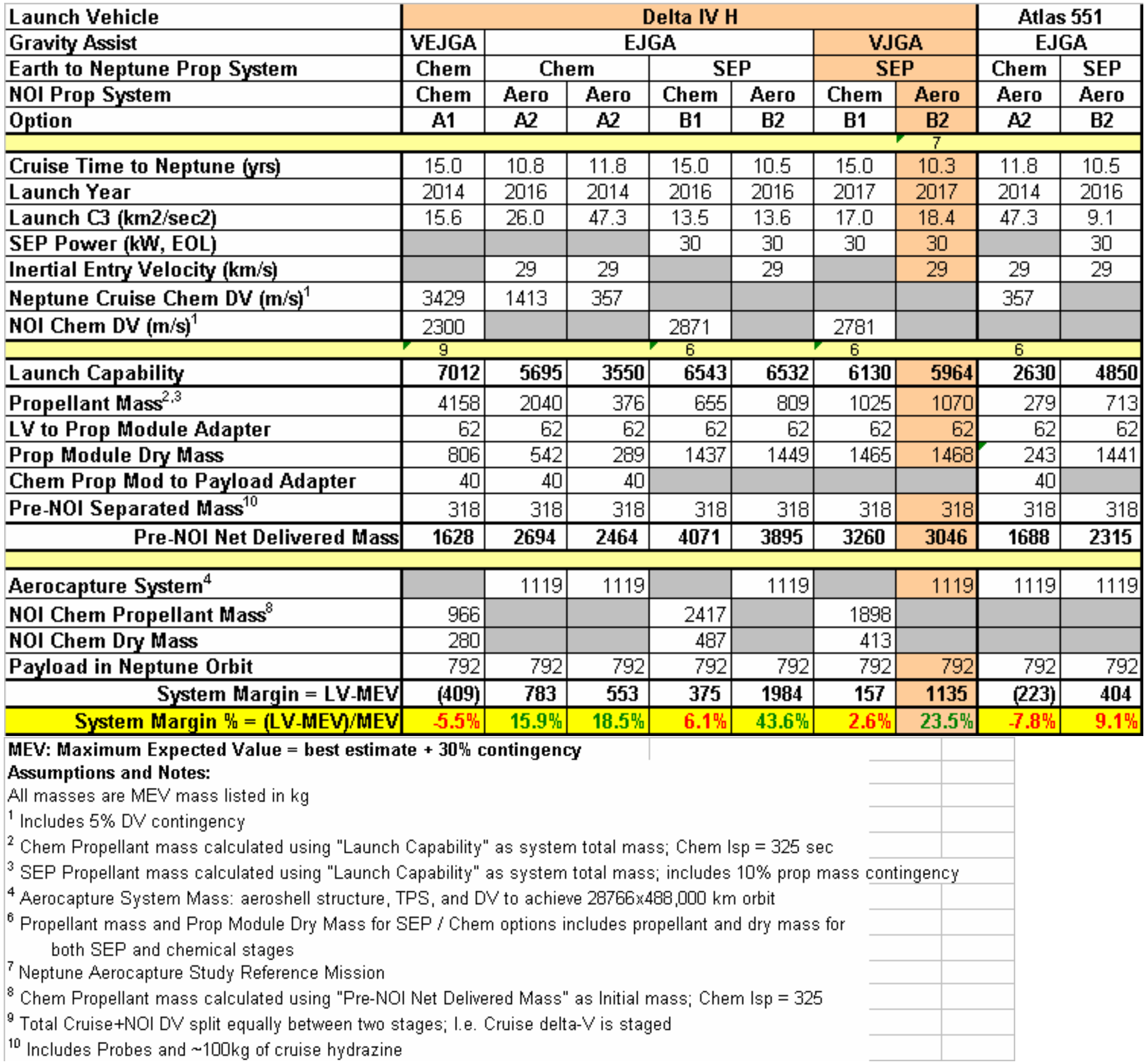


Table 4. Comparison to alternate mission concepts. [4]

Launch Vehicle	Delta IV H							Atlas 551	
Gravity Assist	VEJGA	EJGA				VJGA		EJGA	
Earth to Neptune Prop System	Chem	Chem		SEP		SEP		Chem	SEP
NOI Prop System	Chem	Aero	Aero	Chem	Aero	Chem	Aero	Aero	Aero
Option	A1	A2	A2	B1	B2	B1	B2	A2	B2
							7		
Cruise Time to Neptune (yrs)	15.0	10.8	11.8	15.0	10.5	15.0	10.3	11.8	10.5
Launch Year	2014	2016	2014	2016	2016	2017	2017	2014	2016
Launch C3 (km2/sec2)	15.6	26.0	47.3	13.5	13.6	17.0	18.4	47.3	9.1
SEP Power (kW, EOL)				30	30	30	30		30
Inertial Entry Velocity (km/s)		29	29		29		29	29	29
Neptune Cruise Chem DV (m/s)[1]	3429	1413	357					357	
NOI Chem DV (m/s)[1]	2300			2871		2781			
	9			6		6		6	
Launch Capability	**7012**	**5695**	**3550**	**6543**	**6532**	**6130**	**5964**	**2630**	**4850**
Propellant Mass[2,3]	4158	2040	376	655	809	1025	1070	279	713
LV to Prop Module Adapter	62	62	62	62	62	62	62	62	62
Prop Module Dry Mass	806	542	289	1437	1449	1465	1468	243	1441
Chem Prop Mod to Payload Adapter	40	40	40					40	
Pre-NOI Separated Mass[10]	318	318	318	318	318	318	318	318	318
Pre-NOI Net Delivered Mass	**1628**	**2694**	**2464**	**4071**	**3895**	**3260**	**3046**	**1688**	**2315**
Aerocapture System[4]		1119	1119		1119		1119	1119	1119
NOI Chem Propellant Mass[8]	966			2417		1898			
NOI Chem Dry Mass	280			487		413			
Payload in Neptune Orbit	792	792	792	792	792	792	792	792	792
System Margin = LV-MEV	**(409)**	**783**	**553**	**375**	**1984**	**157**	**1135**	**(223)**	**404**
System Margin % = (LV-MEV)/MEV	**-5.5%**	**15.9%**	**18.5%**	**6.1%**	**43.6%**	**2.6%**	**23.5%**	**-7.8%**	**9.1%**

MEV: Maximum Expected Value = best estimate + 30% contingency

Assumptions and Notes:

All masses are MEV mass listed in kg

[1] Includes 5% DV contingency

[2] Chem Propellant mass calculated using "Launch Capability" as system total mass; Chem Isp = 325 sec

[3] SEP Propellant mass calculated using "Launch Capability" as system total mass; includes 10% prop mass contingency

[4] Aerocapture System Mass: aeroshell structure, TPS, and DV to achieve 28766x488,000 km orbit

[6] Propellant mass and Prop Module Dry Mass for SEP / Chem options includes propellant and dry mass for both SEP and chemical stages

[7] Neptune Aerocapture Study Reference Mission

[8] Chem Propellant mass calculated using "Pre-NOI Net Delivered Mass" as Initial mass; Chem Isp = 325

[9] Total Cruise+NOI DV split equally between two stages; I.e. Cruise delta-V is staged

[10] Includes Probes and ~100kg of cruise hydrazine

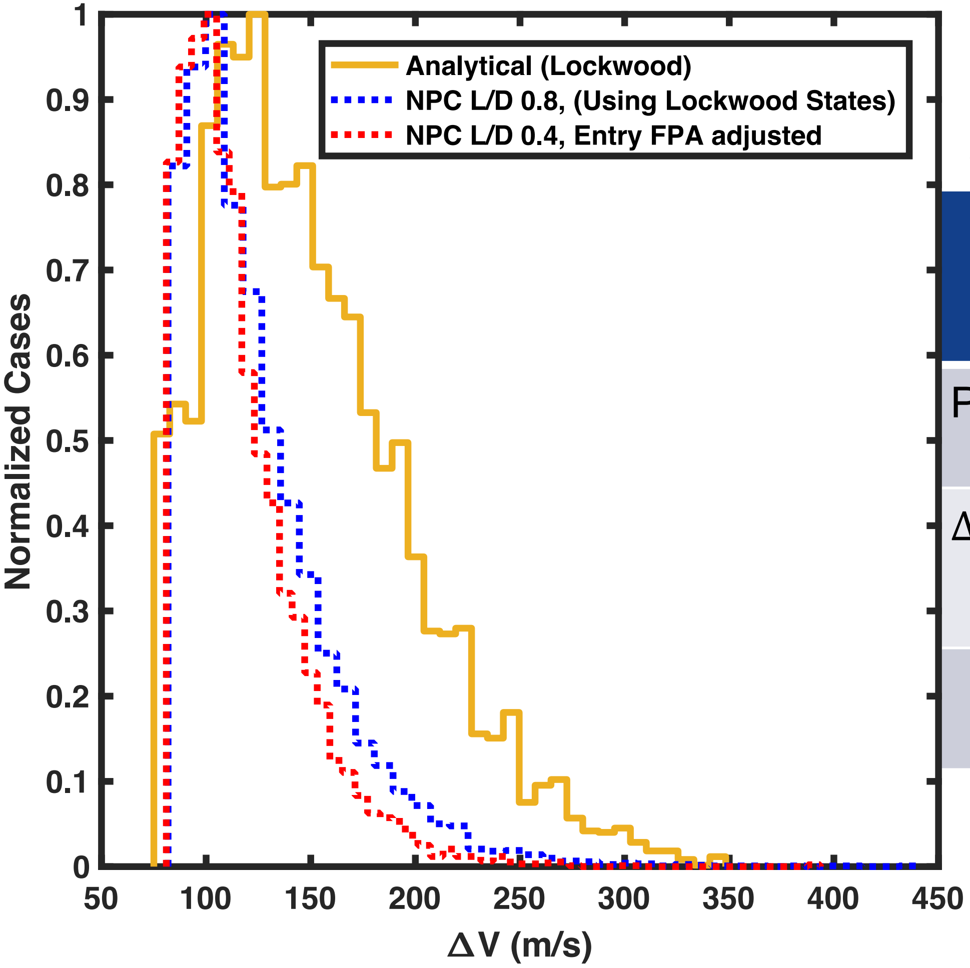
Aerocapture Subsystem Readiness (2010)

Destination **Subsystem**	**Venus**	**Earth**	**Mars**	**Titan**	**Neptune**
Atmosphere **Goal: Capture Physics**	Venus-GRAM (2004) based on world-wide VIRA.	Earth-GRAM (1974) validated by Space Shuttle	Mars-GRAM (1988) continuously updated with latest mission data.	Titan-GRAM (2002) based on Yelle atmosp. Accepted worldwide to be updated with Cassini-Huygens data	Neptune-GRAM (2003) developed from Voyager, other observations
Aerodynamics **Goal: Errors ≤ 2%**	Heritage shape, well understood aerodynamics C_A=±3%, C_N=±5%, α_{TRIM}=±2%	Heritage shape, well understood aerodynamics C_A=±3%, C_N=±5%, α_{TRIM}=±2%	Heritage shape, well understood aerodynamics C_A=±3%, C_N=±5%, α_{TRIM}=±2%	Heritage shape, well understood aerodynamics C_A=±3%, C_N=±5%, α_{TRIM}=±2%	New shape; aerodynamics to be established. C_A=±8%, C_N=±8%, α_{TRIM}=±10%
GN&C **Goal: Robust performance for 4-6 DOF simulations**	APC algorithm captures 96% of corridor	Small delivery errors. APC algorithm captures 97% of corridor	Small delivery errors using ΔDOR. APC algorithm captures 99% of corridor	Ephemeris accuracy improved by Cassini-Huygens. APC algorithm captures 98% of corridor	APC algorithm with α control captures 95% of corridor.
TPS **Goal: Reduce SOA by 30%+, expand TPS choices**	More testing needed on efficient mid-density TPS. Combined convective and radiative facility needed.	Technology ready for ST9. LMA hot structure ready for arrivals < 10.5 km/s.	ISPT investments have provided more materials ready for application to slow arrivals, and new ones for faster entries.	ISPT investments have provided more materials ready for application.	**Zoned approach for mass efficiency. Needs more investment.**
Structures **Goal: Reduce SOA mass by 25%**	High-temp systems will reduce mass by 31%.	High-temp systems will reduce mass by 14%-30%.	High-temp systems will reduce mass by 14%-30%.	High-temp systems will reduce mass by 14%-30%.	**Complex shape, large scale. Extraction difficult.**
Aerothermal **Goal: Models match within 15%**	Convective models match within 20% laminar, 45% with turbulence. Radiative models agree within 50%	Environment fairly well-known from Apollo, Shuttle. Models match within 15%	Convective models agree within 15%. Radiative: predict models will agree within 50% where radiation is a factor.	Convective models agree within 15%. Radiative no longer a concern.	**Conditions cannot be duplicated on Earth in existing facilities. More work on models needed.**
System **Goal: Robust performance with ready technology**	Accomplishes 97.7% of ΔV to achieve 300 x 300 km orbit.	Accomplishes 97.2% of ΔV to achieve 300 x 130 km orbit. **No known technology gaps.**	Accomplishes 97.8% of ΔV to achieve 1400 x 165 km orbit. **No known technology gaps.**	Accomplishes 95.8% of ΔV to achieve 1700 x 1700 km orbit. **No known technology gaps.**	Accomplishes 96.9% of ΔV to achieve Triton observ. orbit. **ENABLING**

🟩 **Ready for Infusion** 🟨 **Some Investment Needed** 🟥 **Significant Investment Needed**

Recent Results: Analytical vs. Numerical Predictor-Corrector

Combination of the two post-aerocapture burns



All-propulsive option: Total *Δ*V = 2871 m/s

	Analytical	Numerical Predictor-Corrector	
Performance Metric	L/D = 0.8	L/D = 0.8	L/D = 0.4
ΔV: +3σ high	300 m/s (10% of all-prop *Δ*V)	231 m/s (8% of all-prop *Δ*V)	200 m/s (7% of all-prop *Δ*V)
Max Accel: +3σ high	20 g's	20.5 g's	17.0 g's

NPC Results: AAS 19-221