

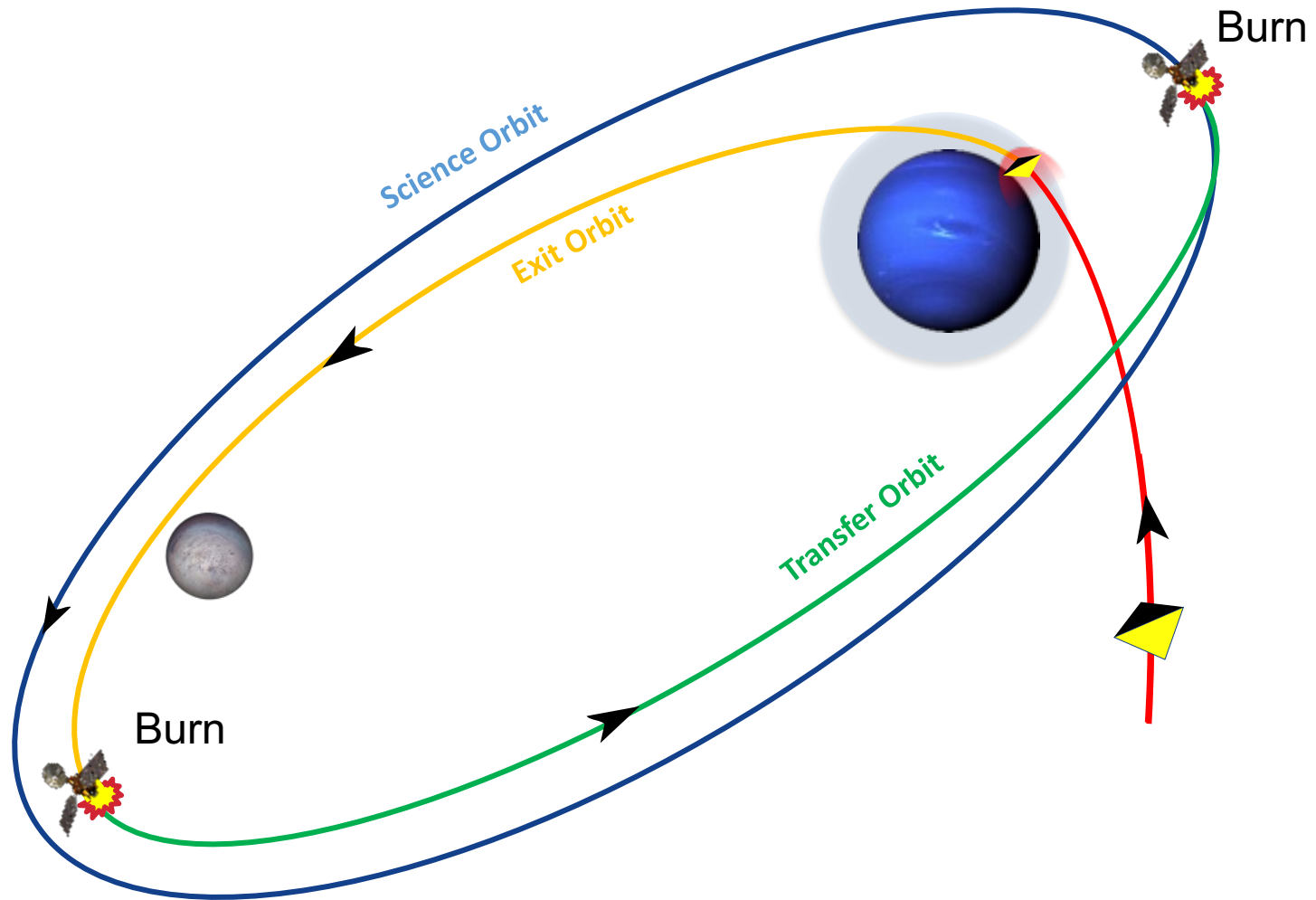
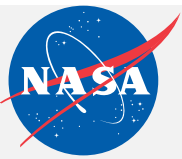
# **Enabling In-Situ Exploration of the Ice Giants Using Aerocapture**

**S. Dutta**

**NASA Langley Research Center, Hampton, VA, USA**

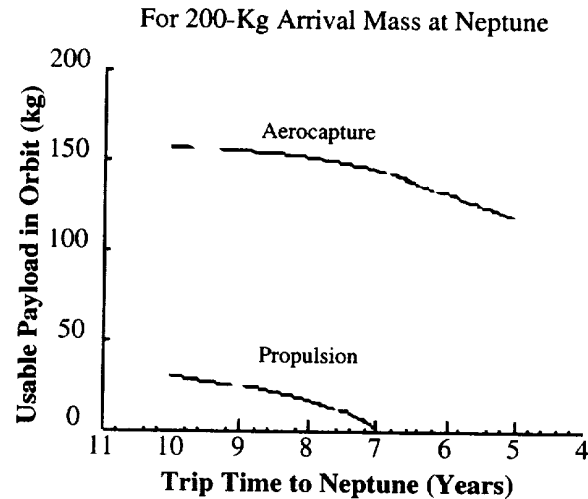
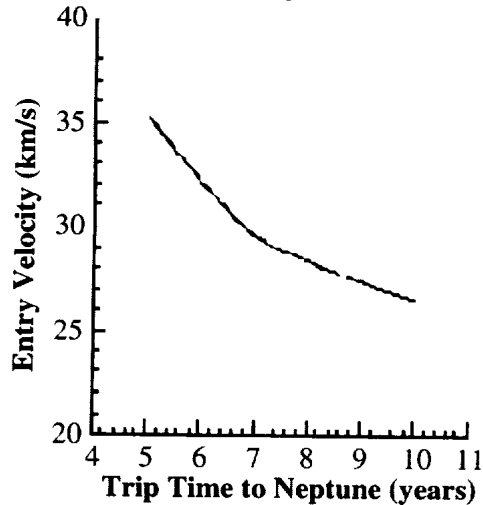
**Workshop on In Situ Exploration of the Giant Planets II  
Laurel, MD, USA, 12-14 July, 2022**

# What is Aerocapture?



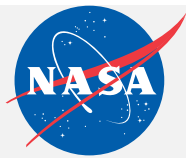
# Aerocapture Studies about Ice Giants Missions

- 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

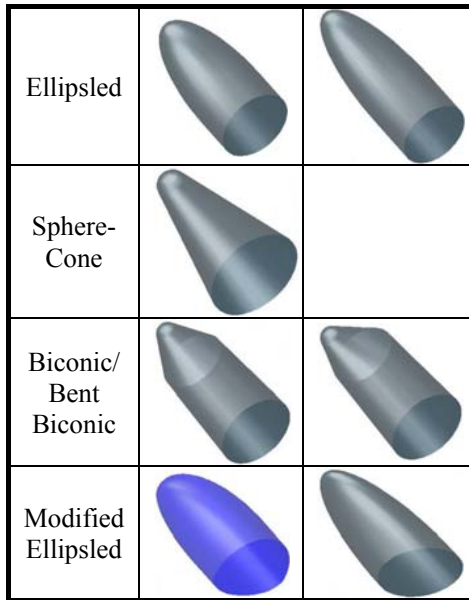


- NASA 2017 Study: Ice Giants Pre-Decadal Survey (D-100520)
  - “Aerocapture technology could enable trip times to be shortened, delivered mass to be increased or both.”
- JSR 2018 Article by Spilker et al.
  - “... a need for development of advanced aeroshells robust to ablation effects, though advanced 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)

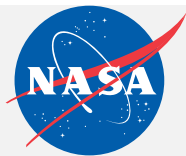


- Results of the study
  - 3-4 year trip time reduction compared to all-propulsive options (10 year trip vs. 14 year trip)
  - Aerocapture provided 40% more on-orbit mass compared to all-propulsive options (1614 kg vs. 1167 kg at zero-margin)
  - Needed development of a mid to high lift-to-drag (L/D)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

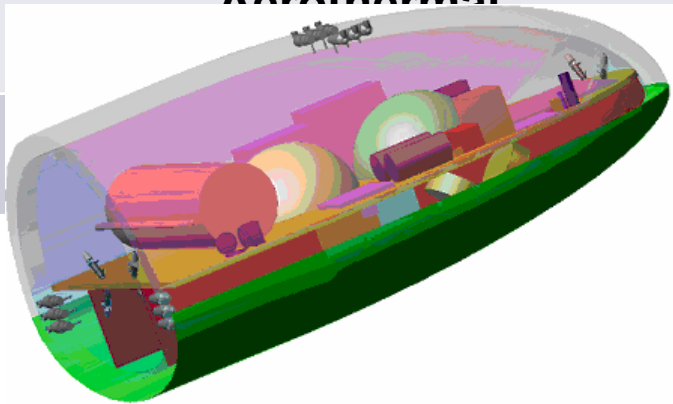
Needed a vehicle with L/D of 0.6-0.8

Credit: AIAA 2004-4953

# Neptune Aerocapture Point of Departure



Subsystem	Neptune
Atmosphere	Neptune-GRAM (2003) developed from Voyager, other observation
Aerodynamics	New <b>shape</b> ; 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 <b>shape</b> , 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 $\Delta V$ to achieve Triton observation orbit.



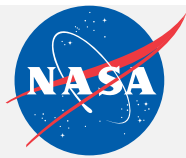
Credit: AIAA 2004-4953

Ready for Infusion

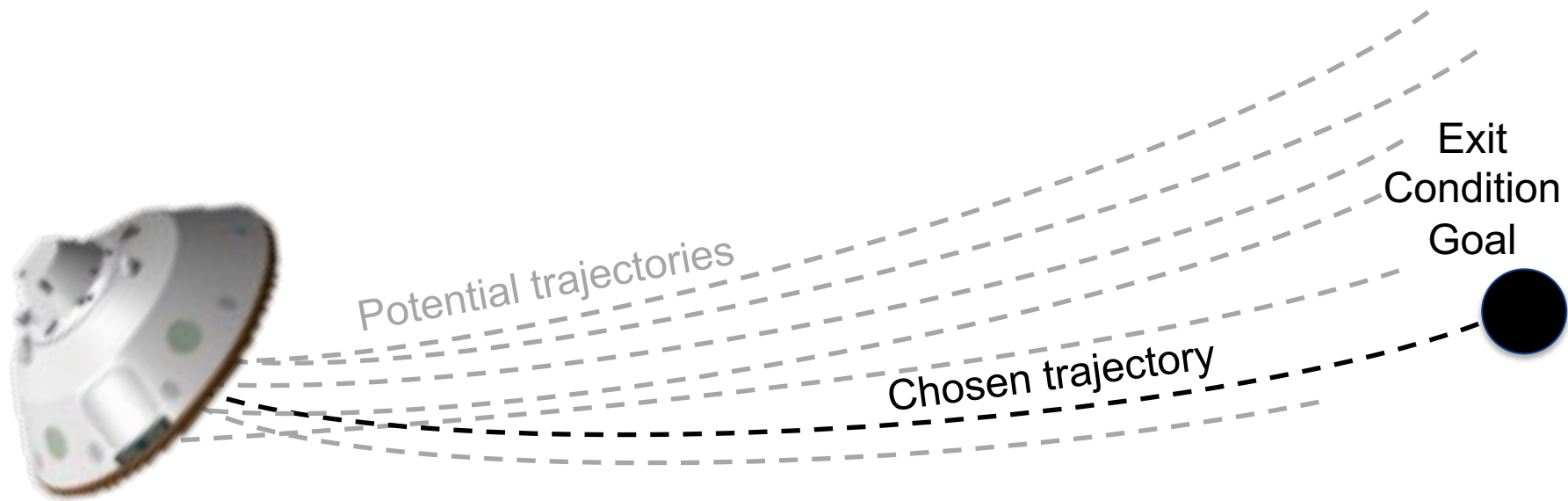
Some Investment Needed

Significant Investment Needed

# Recent Trends in Guidance Schemes

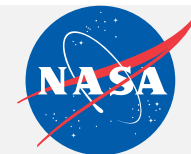


- Analytic schemes
  - Gains for guidance based on pre-generated reference profiles
  - Non-iterative and efficient code
- Numerical predictor-corrector (NPC) schemes
  - Numerically integrates equations of motion on-the-fly
  - Iterative code and adaptable to modern flight softwares
  - Can be robust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

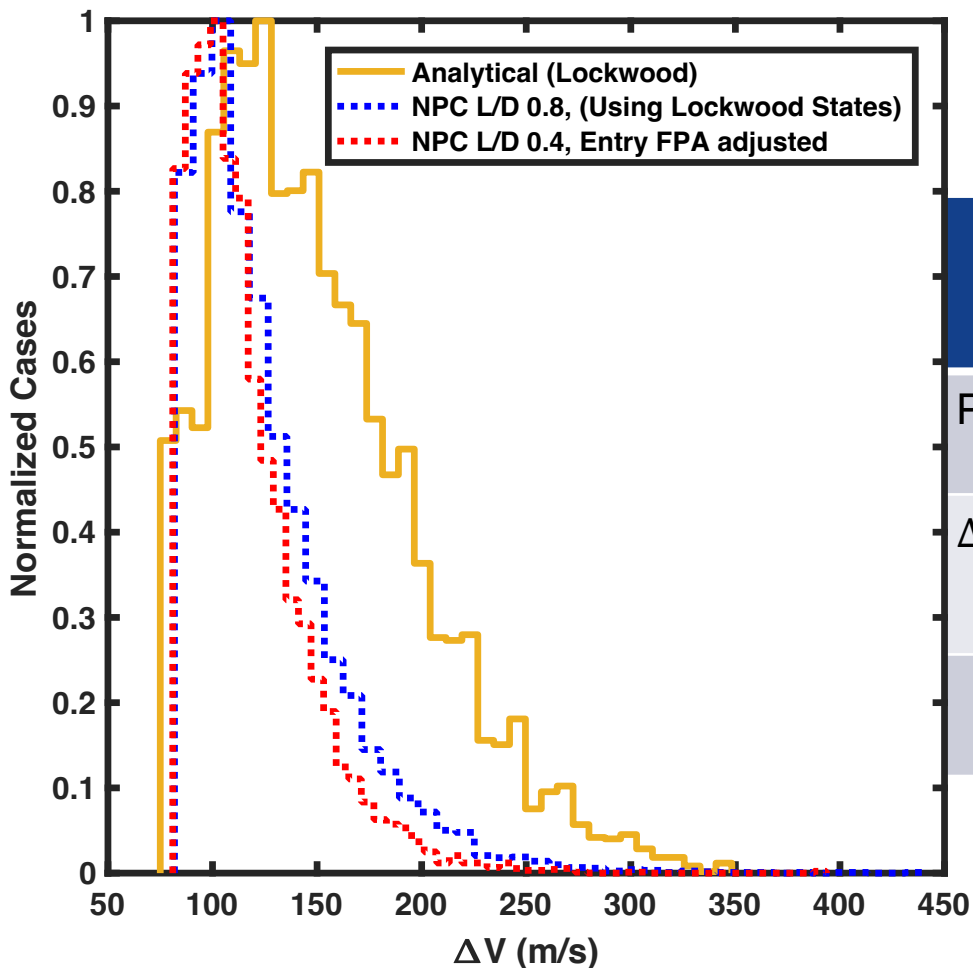


Aeroshell Credit: AIAA 2017-0245

# Recent Results: Analytical vs. Numerical Predictor-Corrector



Combination of the two post-aerocapture burns

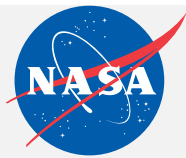


All-propulsive option: Total  $\Delta V = 2871$  m/s

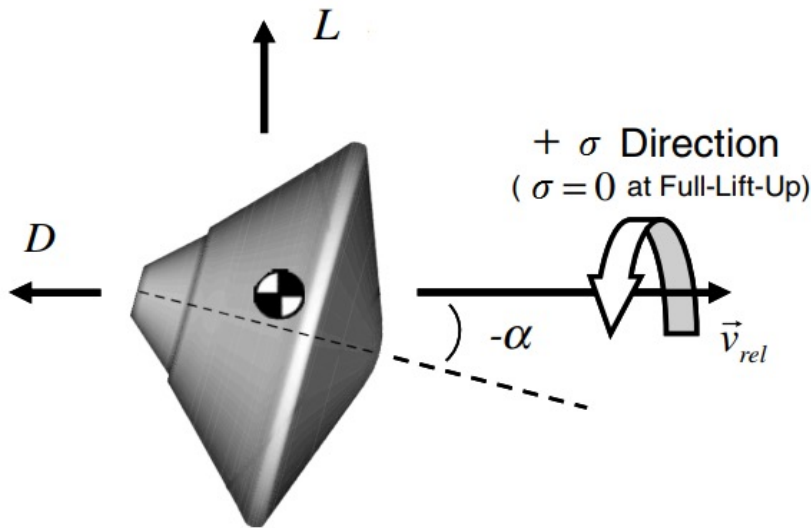
	Analytical	Numerical Predictor-Corrector	
Performance Metric	L/D = 0.8	L/D = 0.8	L/D = 0.4
$\Delta V$ : +3 $\sigma$ high	300 m/s (10% of all-prop $\Delta V$ )	231 m/s (8% of all-prop $\Delta V$ )	200 m/s (7% of all-prop $\Delta V$ )
Max Accel: +3 $\sigma$ high	20 g's	20.5 g's	17.0 g's

NPC Results: AAS 19-221

# Recent Results: Bank Angle Control vs. Direct Force Control

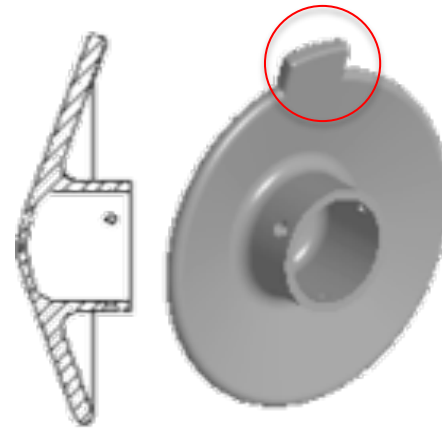


## Bank Angle Control

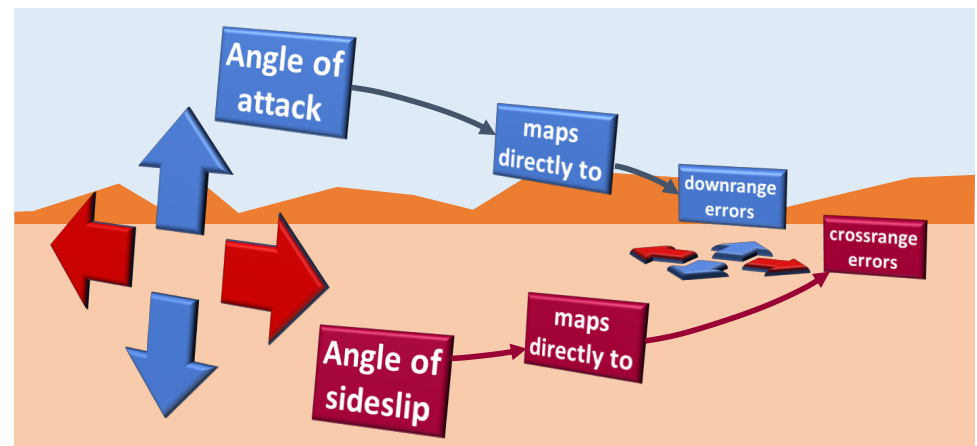


Credit: AAS 19-221

## Direct Force Control

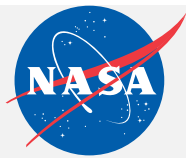


Credit: AIAA 2013-2809

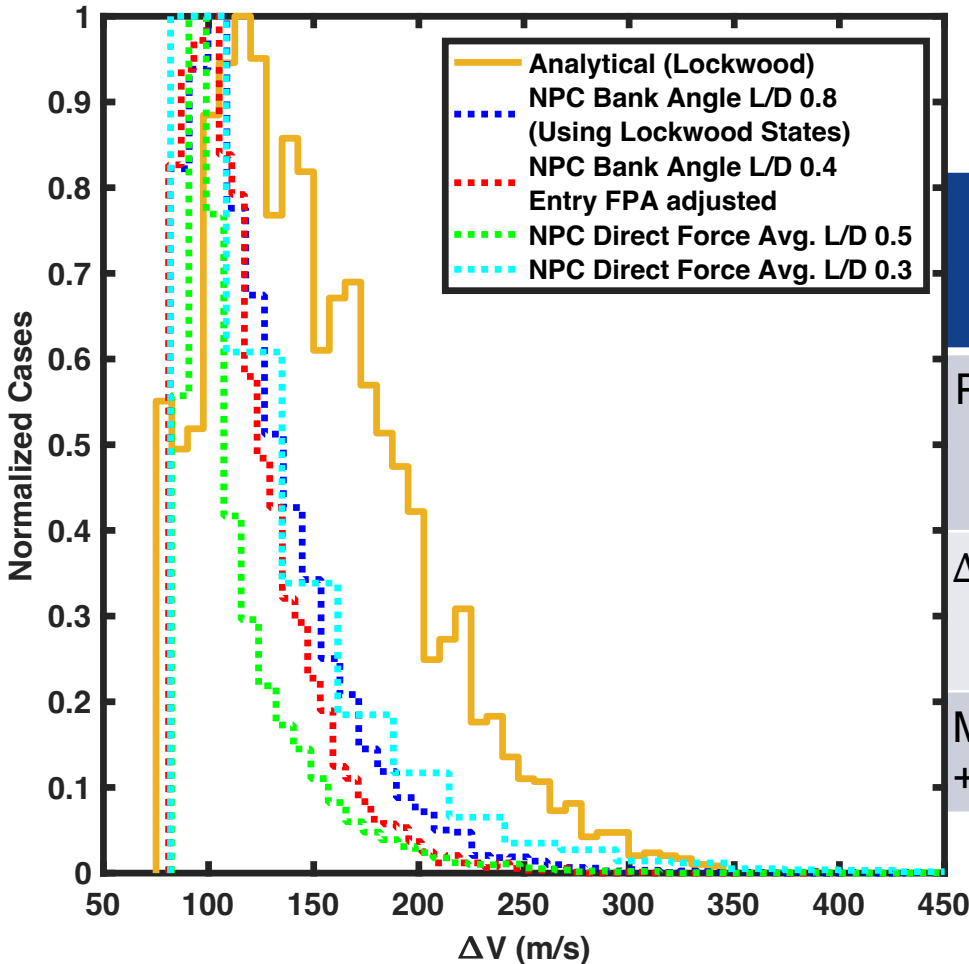


Credit: AIAA 2019-0663

# Recent Results: Bank Angle Control vs. Direct Force Control



Combination of the two post-aerocapture burns



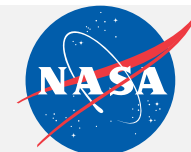
All-propulsive option: Total  $\Delta V = 2871$  m/s

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

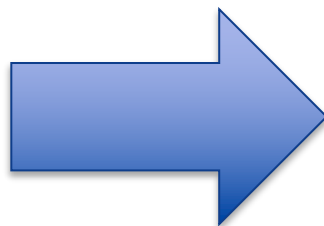
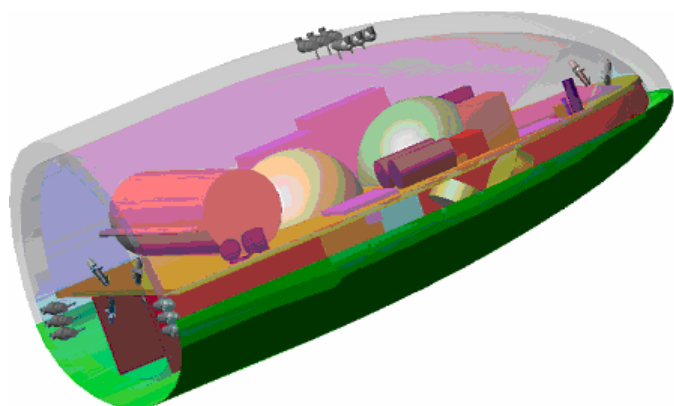
NPC Results: AAS 19-221 and AAS 19-212

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

# What is enabled?



2003 Study Concept Vehicle



Credit: AIAA 2004-4953

Sphere-Cone Rigid  
Aeroshell

2012 Mars  
Science  
Laboratory

Credit: NASA/JPL



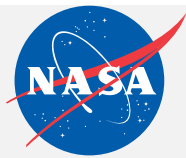
Orion

Credit: NASA

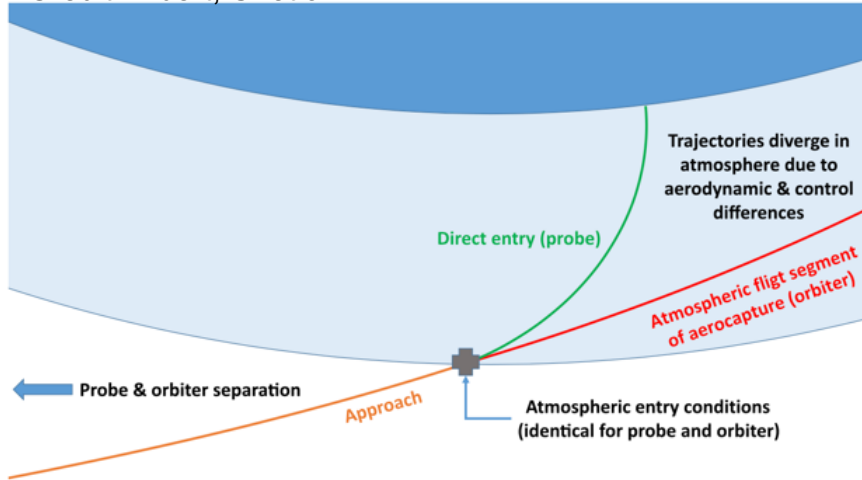
Spherical Rigid Aeroshell



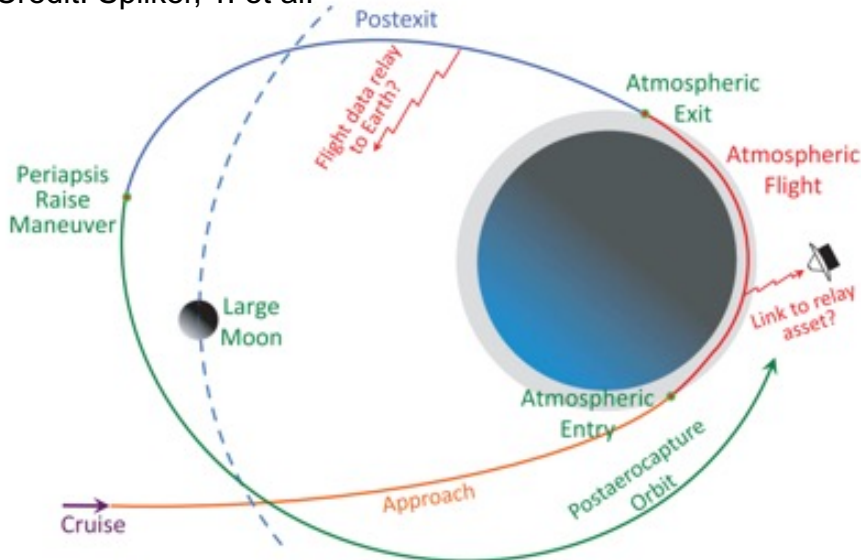
# Enable In-Situ Exploration



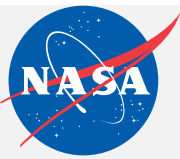
Credit: Albert, S. et al.



Credit: Spilker, T. et al.

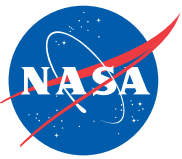


- Recent studies by Albert et al. show co-delivery of probe to planetary body during aerocapture maneuver
  - Can lead to more precise delivery of probes to scientifically interesting areas
  - Avoid issues like Galileo probe delivery
- Aerocapture maneuvers can target low altitude periapsis orbits more easily since the spacecraft has to be inside the atmosphere



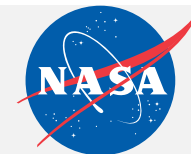
# Summary

- Aerocapture is an aerodynamic maneuver where energy from interplanetary approach can be reduced in planetary atmosphere by almost 90%
- For Neptune-Triton science orbits, aerocapture can increase on-orbit mass by 40% and reduce trip times by 3-4 years
- Aerocapture has been identified by several studies to be an enabling technology for Ice Giants missions
- Existing blunt body aeroshells can be enabled for Ice Giants aerocapture if accompanied with numerical guidance schemes along and newer control strategies



# Backup Slides

# Lockwood Study Concept



Credit: AIAA 2004-4951

**Table 3. Reference concept mass property summary.**<sup>3</sup>

Mass in kg	CBE	Cont	MEV	Marg	Alloc
<b>Launch Capability</b>					<b>5964</b>
Launch Reserve				8.4%	463
<b>Launch Wet Alloc</b>					<b>5500</b>
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
<b>A/C Entry Alloc</b>					<b>2238</b>
A/C Aeroshell/TPS	736	30.0%	957	20.0%	1149
A/C ACS Prop			22		22
A/C Peri Raise Prop			139		139
<b>Orbit Wet Alloc</b>					<b>928</b>
Orbit Prop			124		124
<b>Orbit Dry Mass</b>	524	27.3%	667	20.4%	<b>804</b>

CBE = Current Best Estimate

Cont = Contingency = (MEV-CBE)/CBE

MEV = Maximum Expected Value

Marg = Margin = (Alloc-MEV)/MEV

Alloc = Allocation

# Aerocapture vs. Propulsive Comparison

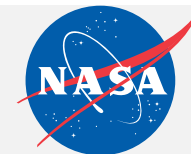


Table 4. Comparison to alternate mission concepts.<sup>4</sup>

Credit: AIAA 2004-4951

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

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

**Assumptions and Notes:**

All masses are MEV mass listed in kg

<sup>1</sup> Includes 5% DV contingency

<sup>2</sup> Chem Propellant mass calculated using "Launch Capability" as system total mass; Chem Isp = 325 sec

<sup>3</sup> SEP Propellant mass calculated using "Launch Capability" as system total mass; includes 10% prop mass contingency

<sup>4</sup> Aerocapture System Mass: aeroshell structure, TPS, and DV to achieve 28766x488,000 km orbit

<sup>6</sup> Propellant mass and Prop Module Dry Mass for SEP / Chem options includes propellant and dry mass for both SEP and chemical stages

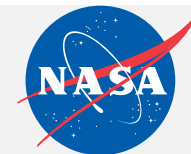
<sup>7</sup> Neptune Aerocapture Study Reference Mission

<sup>8</sup> Chem Propellant mass calculated using "Pre-NOI Net Delivered Mass" as Initial mass; Chem Isp = 325

<sup>9</sup> Total Cruise+NOI DV split equally between two stages; i.e. Cruise delta-V is staged

<sup>10</sup> Includes Probes and ~100kg of cruise hydrazine

# Aerocapture Subsystem Readiness (2010)



Destination Subsystem	Venus	Earth	Mars	Titan	Neptune
<b>Atmosphere</b> 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 atomp. Accepted worldwide to be updated with Cassini-Huygens data	Neptune-GRAM (2003) developed from Voyager, other observations
<b>Aerodynamics</b> Goal: Errors $\leq 2\%$	Heritage shape, well understood aerodynamics $C_A = \pm 3\%$ , $C_N = \pm 5\%$ , $\alpha_{TRIM} = \pm 2\%$	Heritage shape, well understood aerodynamics $C_A = \pm 3\%$ , $C_N = \pm 5\%$ , $\alpha_{TRIM} = \pm 2\%$	Heritage shape, well understood aerodynamics $C_A = \pm 3\%$ , $C_N = \pm 5\%$ , $\alpha_{TRIM} = \pm 2\%$	Heritage shape, well understood aerodynamics $C_A = \pm 3\%$ , $C_N = \pm 5\%$ , $\alpha_{TRIM} = \pm 2\%$	New shape; aerodynamics to be established. $C_A = \pm 8\%$ , $C_N = \pm 8\%$ , $\alpha_{TRIM} = \pm 10\%$
<b>GN&amp;C</b> 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 $\Delta DOR$ . APC algorithm captures 99% of corridor	Ephemeris accuracy improved by Cassini-Huygens. APC algorithm captures 98% of corridor	APC algorithm with $\alpha$ control captures 95% of corridor.
<b>TPS</b> 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.	<b>Zoned approach for mass efficiency. Needs more investment.</b>
<b>Structures</b> 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%.	<b>Complex shape, large scale. Extraction difficult.</b>
<b>Aerothermal</b> 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.	<b>Conditions cannot be duplicated on Earth in existing facilities. More work on models needed.</b>
<b>System</b> Goal: Robust performance with ready technology	Accomplishes 97.7% of $\Delta V$ to achieve 300 x 300 km orbit.	Accomplishes 97.2% of $\Delta V$ to achieve 300 x 130 km orbit. <b>No known technology gaps.</b>	Accomplishes 97.8% of $\Delta V$ to achieve 1400 x 165 km orbit. <b>No known technology gaps.</b>	Accomplishes 95.8% of $\Delta V$ to achieve 1700 x 1700 km orbit. <b>No known technology gaps.</b>	Accomplishes 96.9% of $\Delta V$ to achieve Triton observ. orbit. <b>ENABLING</b>

Ready for Infusion

Some Investment Needed

Significant Investment Needed