Status and Overview of Aerocapture Technology

Michelle M. Munk
Michelle.M.Munk@nasa.gov

NASA Entry, Descent and Landing System Capability Lead

Briefing to the Giant Planet Systems Panel
24 November 2020

Outline

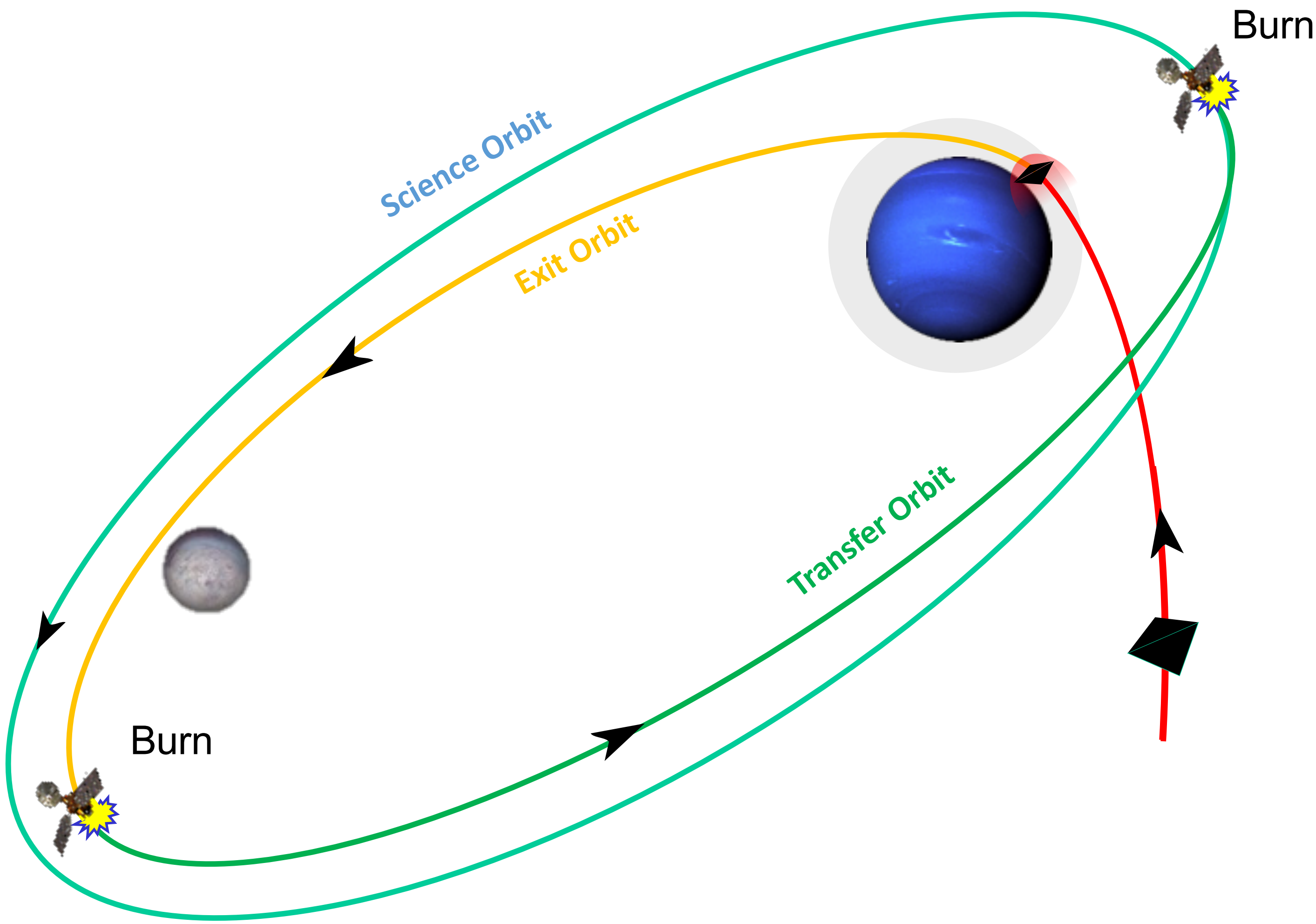
- ♦ Technology Definition/Benefit
- ♦ Technology Development Background/History
- ♦ Technology Studies/Work conducted for Giant Planet Applications
- ♦ Technology Readiness Summary for Giant Planets

Acknowledgements

The presenter wishes to acknowledge the following contributors to the content in this presentation:

- Soumyo Dutta, NASA-Langley Research Center
- Ethiraj Venkatapathy, NASA-Ames Research Center
- Michael Wright, NASA-Ames Research Center

What is Aerocapture?



Credit: Soumyo Dutta

Example Aerocapture Benefits for Science Missions

Mission - Science Orbit	Nominal Orbit Insertion ΔV, km/s	Best A/C Mass, kg	Best non-A/C Mass, kg	A/C % Increase	Launch Vehicle Savings?
Venus V1 - 300 km circ	4.6	5078	2834	79	Yes
Venus V2 - 8500 x 300 km	3.3	5078	3542	43	Yes
Mars M1 - 300 km circ	2.4	5232	4556	15	No
Mars M2 - ~1 Sol ellipse	1.2	5232	4983	5	No
Jupiter J1 - 2000 km circ	17.0	2262	<0	Infinite	Yes
Jupiter J2 - Callisto ellipse	1.4	2262	4628	-51	No
Saturn S1 - 120,000 km circ	8.0	494	<0	Infinite	Yes
Titan T1 - 1700 km circ	4.4	2630	691	280	Yes
Uranus U1 - Titania ellipse	4.5	1966	618	218	Yes
Neptune N1 - Triton ellipse	6.0	1680	180	832	Yes

Aerocapture can offer significant increases in delivered payload:

ENHANCING missions to Venus, Mars

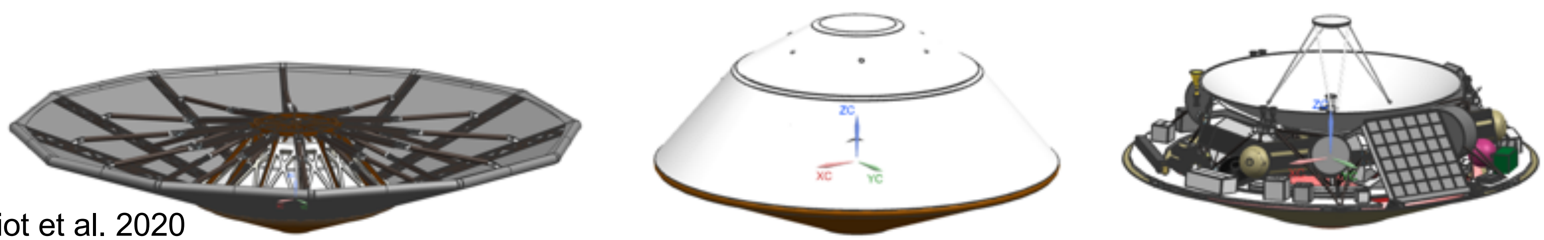
STRONGLY ENHANCING missions to Titan, and Uranus

ENABLING missions to Jupiter, Saturn, and Neptune

Ref.: Hall, J. L., Noca, M. A., and Bailey, R. W. "Cost-Benefit Analysis of the Aerocapture Mission Set," *Journal of Spacecraft and Rockets*, Vol. 42, No. 2, March-April 2005

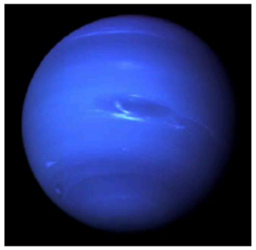
Aerocapture History, and Risk Perception

- **Aeroassist Flight Experiment (AFE) in 1980's was going to demonstrate components of aerocapture maneuver**
- **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 aerocaptured orbiter**
- **Aerocapture has been shown to be superior to aerobraking, the accepted aeroassist maneuver for orbit insertion, in 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, Exploration Flight Test-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 Ice Giant mission orbiters within aerocapture vehicles**

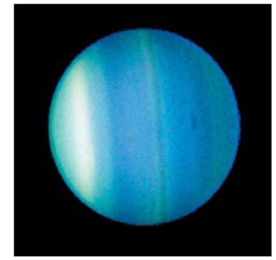


Credit: Elliot et al. 2020

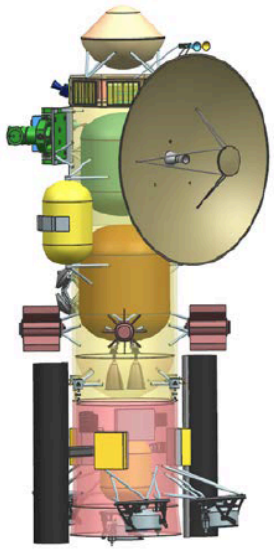
2017 Ice Giants Study Results



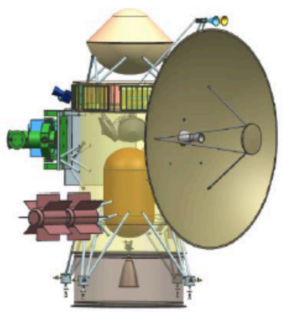
ICE Giants Study:Uranus & Neptune



Launch mass:7364 kg

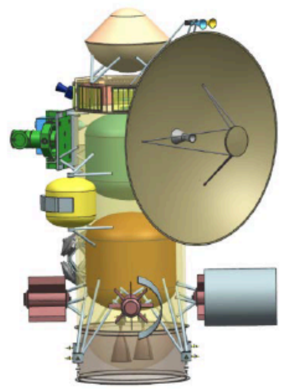


Neptune Orbiter with Probe, SEP, and 50 kg payload



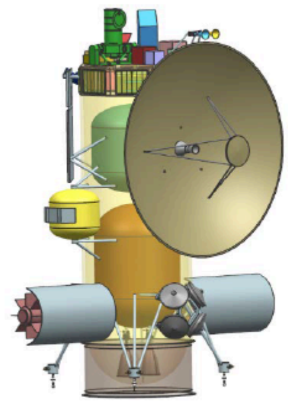
Launch mass: 1525 kg

Uranus Flyby with Probe and 50 kg payload



Launch mass: 4345 kg

Uranus Orbiter with Probe and 50 kg payload



Launch mass: 4718 kg

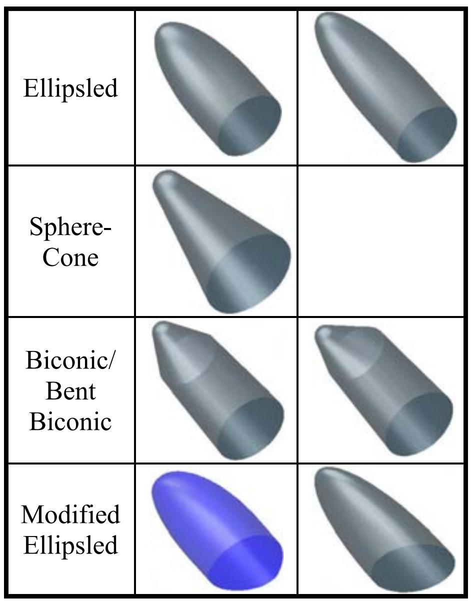
Uranus Orbiter with 150 kg payload

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."

NASA 2003 Study – Lockwood et al.

- **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 spend 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)



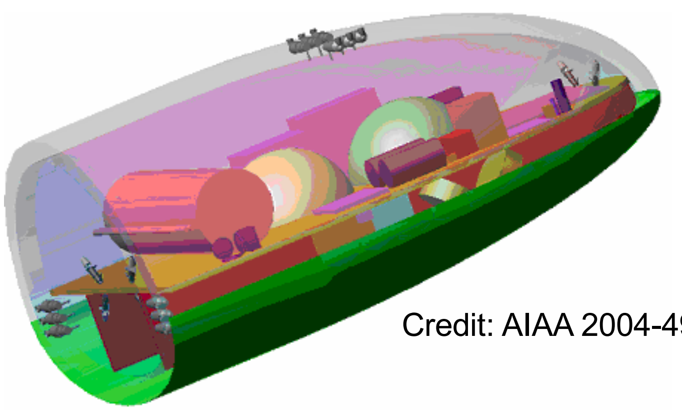
Needed a vehicle with L/D of 0.6-0.8

Credit: AIAA 2004-4953

- **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

2003 Neptune Aerocapture Point of Departure

Subsystem	Neptune
Atmosphere	Neptune-GRAM (2003) developed from Voyager, other observation - currently being updated
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.
System	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

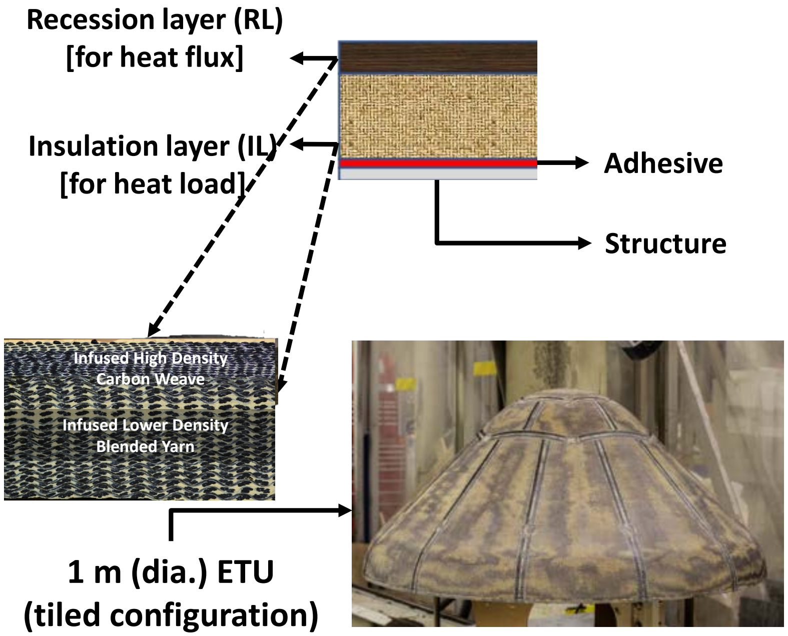
- **Uncertainty in aerocapture performance in the past has been levied largely in two areas [JSR 2005 Hall et al.]:**
  - Aerothermal Modeling and Thermal Protection System (TPS) materials
  - Guidance, Navigation, and Control strategies
- **Three capability developments have made aerocapture more feasible**
  1. New TPS materials have been developed, that 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

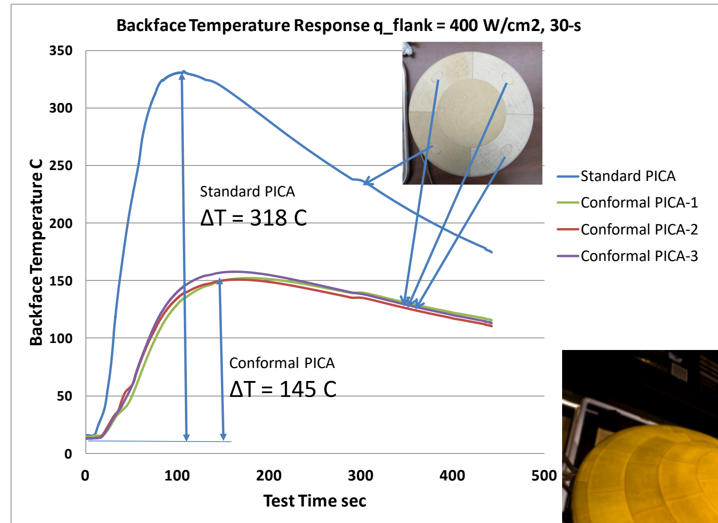
Capability 1.a. Improved Aerothermodynamics

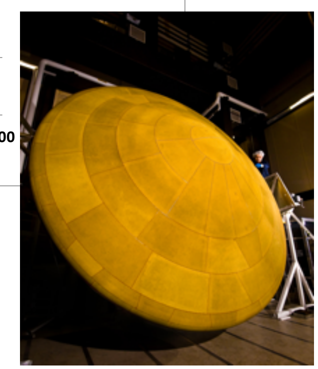
Sustained modeling investments since 2013 have advanced material response and aerothermal predictions, but there is still work to do:

- **Current aerothermal models for Giant Planets entry are based on methods validated for Mars and Earth entry**
- **Hydrogen/Helium (plus key impurities) atmospheres lead to higher uncertainty levels**
  - Behavior of atomic and molecular hydrogen (kinetics, nonequilibrium, transport, gas-surface interaction)
  - Importance of atmospheric impurities on shock layer radiation levels
    - E.g. preliminary evidence shows that methane could dramatically increase radiation levels at Neptune entry conditions
- **These uncertainties directly impact TPS selection and mass**
- **Approach: Proposed NASA/ESA "aerothermal convergence working group" to assess current models against available data, propose additional ground-based validation datasets**

Capability 1.b. Thermal Protection System







Heatshield for Extreme Entry Environment Technology (HEEET)

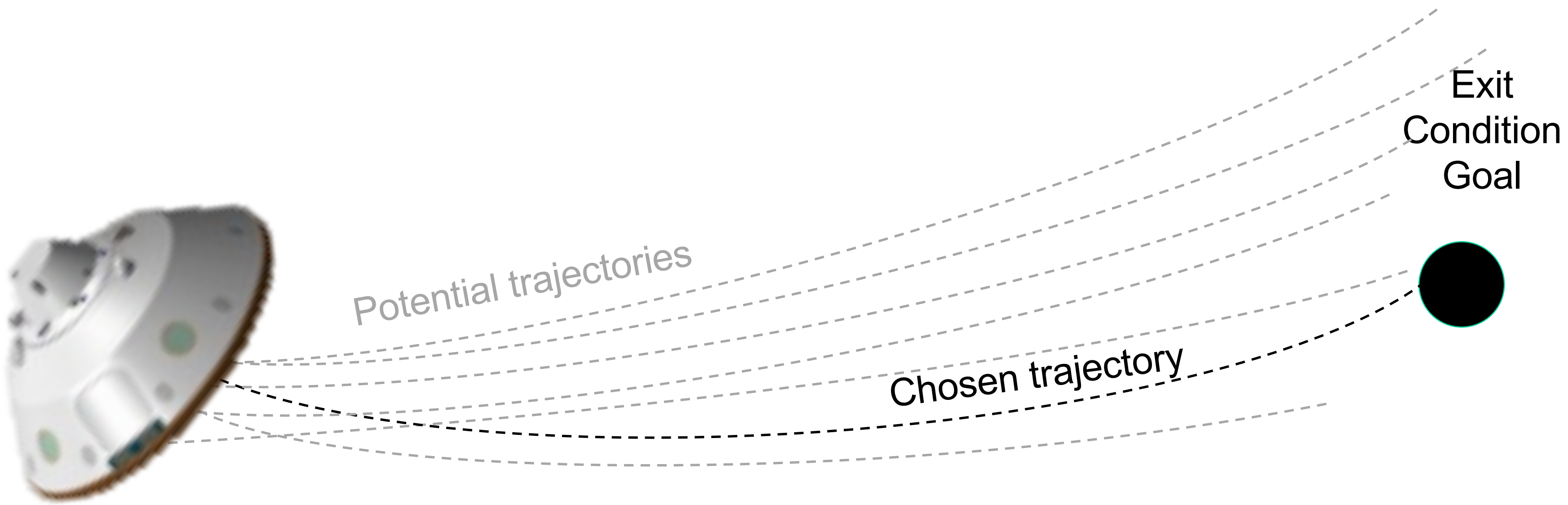
Phenolic Impregnated Carbon Ablator (PICA)

NASA-developed TPS are ready to support a Giant Planets mission in the next decade:

- HEEET is capable of withstanding extreme heat rates and loads, is at TRL 6 and is baselined for MSR EEV.
- PICA and Conformal-PICA are capable of moderate heating (above 1500 W/cm^2)—good for backshells, conical flanks.
- C-PICA is at TRL 4+ and can be matured in ~ 2 years; twice as mass efficient as PICA, 3x as strain tolerant

Capability 2.a. Guidance Methods

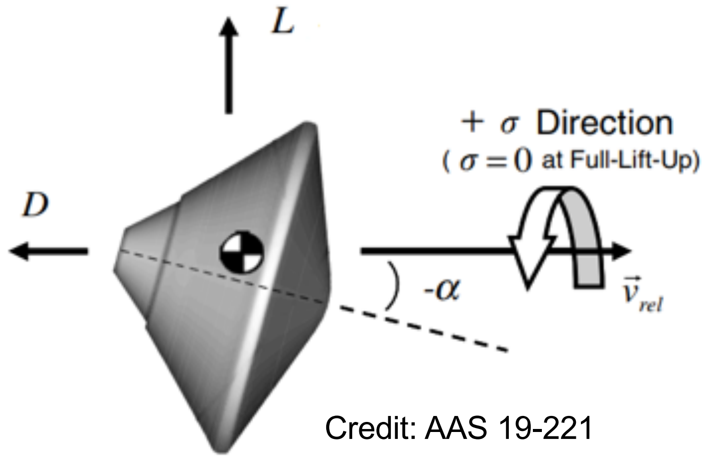
- **Analytic schemes**
  - Gains for guidance based on pre-generated reference profiles
  - Non-iterative and efficient code
- **Numerical predictor-corrector (NPC) schemes**
  - Numerically integrates equations of motion on-the-fly
  - Iterative code and adaptable to modern flight software
  - Can be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



Aeroshell Credit: AIAA 2017-0245

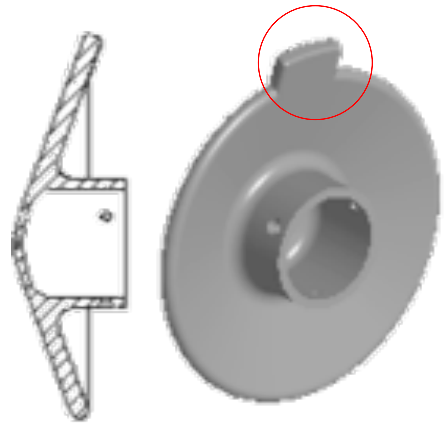
Capability 2.b. Control Mechanisms

Bank Angle Control

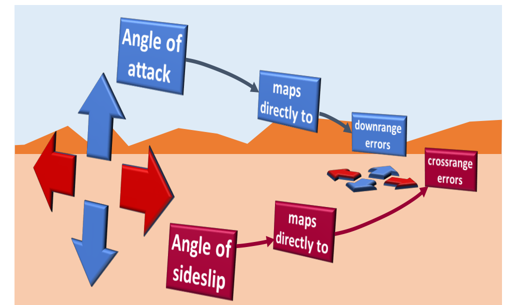


Credit: AAS 19-221

Direct Force Control

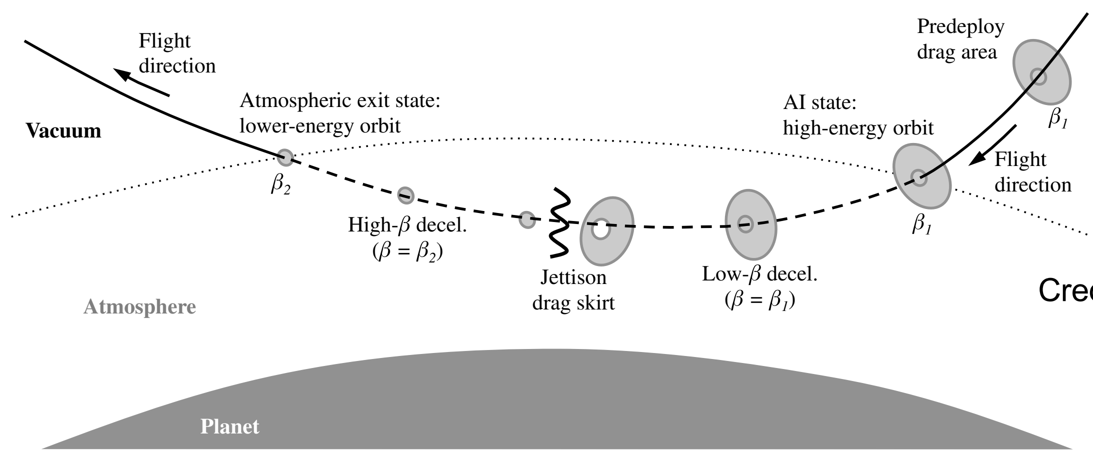


Credit: AIAA 2013-2809



Credit: AIAA 2019-0663

Drag Modulation Control



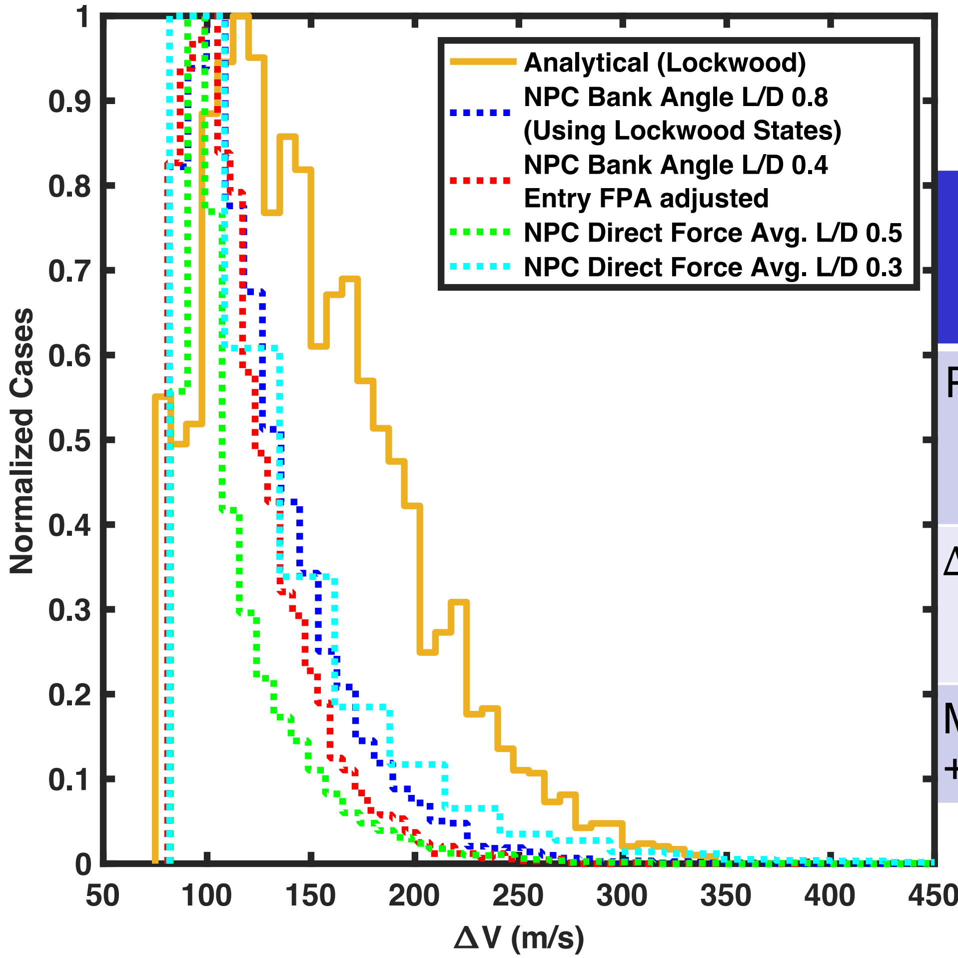
Credit: JSR 2014 Putnam et al.

Capability 3. Optical Navigation

- **Optical Navigation (OpNav) required for Ice Giant missions due to poor ephemeris knowledge of Uranus and Neptune**
  - 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

Recent Neptune Aerocapture Analysis Results

Combination of the two post-aerocapture burns



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

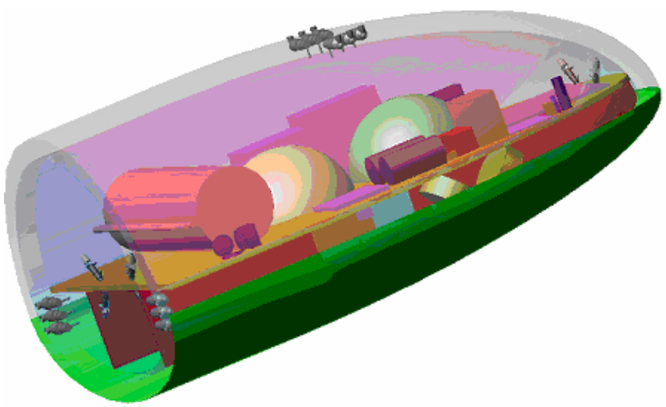
	Analytical	Numerical Predictor-Corrector	
Performance Metric	L/D = 0.8	Avg L/D = 0.5	Avg L/D = 0.3
ΔV: +3σ high	300 m/s (10% of all-prop ΔV)	212 m/s (7% of all-prop ΔV)	238 m/s (8% of all-prop ΔV)
Max Accel: +3σ high	20 g's	15 g's	11 g's

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

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

Which candidate vehicles are now feasible?

2003 Study Concept Vehicle



Credit: AIAA 2004-4953

Summary

- **Aerocapture is an aerodynamic maneuver where energy from interplanetary approach can be reduced in planetary atmosphere by almost 90%**
- **Aerocapture has been identified by several studies to be an enhancing technology for Ice Giants missions**
  - On-orbit mass can be increased by 40+%
  - May enable the inclusion of probes
  - Transit time can be decreased by >2-3 years
- **Existing blunt body aeroshells can be feasible for Ice Giants aerocapture with the help of capabilities that have been enhanced in the past 15 years**
  - Thermal Protection System materials
  - Numerical guidance schemes
  - Direct force control
  - Optical Navigation

Where Do We Go From Here?

- **Aerocapture can be confidently applied to missions.**
  - Less complex than EDL and incorporates robust design principles
- **The time is now, to advocate for Aerocapture development and use, to support Giant Planet exploration in the next decades.**
  - Technical: Generate technical data and publish results to establish benefits, requirements, and development needs
  - Cultural: Educate the broader community, have dialogues about risk, and advocate for technology maturation
- **Tangible steps that can be taken by the engineering and science communities, *together*:**
  - Ensure aerocapture discipline experts are invited to participate on mission concept teams, at the study outset
  - Use study results to devise development plans
  - Seek opportunities for risk reduction activities that would benefit multiple missions: Technology Demonstration Opportunities, SmallSat missions

Additional Notes

- **White papers submitted with focus on aerocapture as an enhancing technology for Ice Giants missions:**
  - Dutta, S., et al, "Aerocapture as an Option for Ice Giants Missions"
  - Venkatapathy, E., et al., "Thermal Protection System to Enable Ice Giant Aerocapture Mission for Delivering both an Orbiter and an *in situ* Probe"

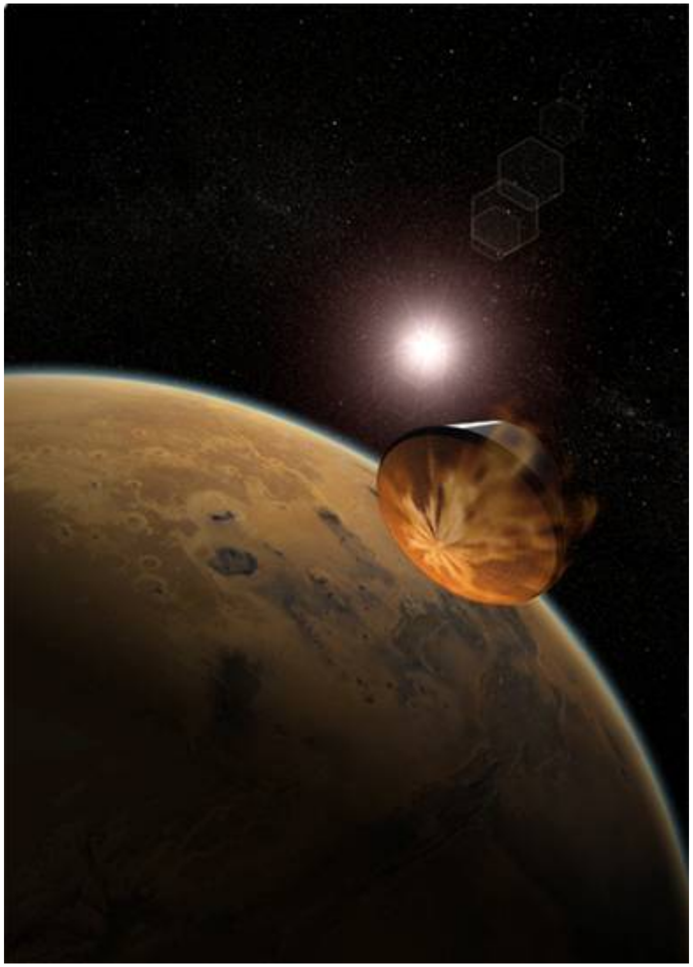
Additional Presentation Acknowledgements:

- Colleagues from NASA Langley Research Center, NASA Ames Research Center, Jet Propulsion Laboratory: A. Austin, S. Bhaskaran, A. Cassell, J. Cutts, R. Deshmukh, M. Lobbia, R. Lugo, A. Nelessen, R. Powell, B. Tackett, and P. Wercinski
- Material sourced from T. Spilker, A. Girija, S. Saikia, and C. Heidrich

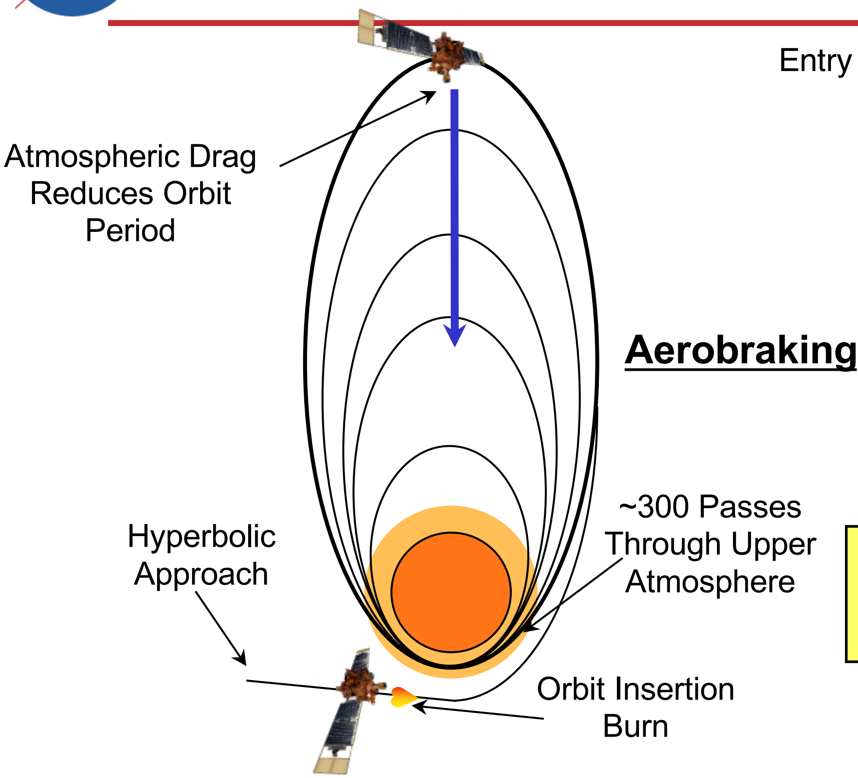
Thank you!

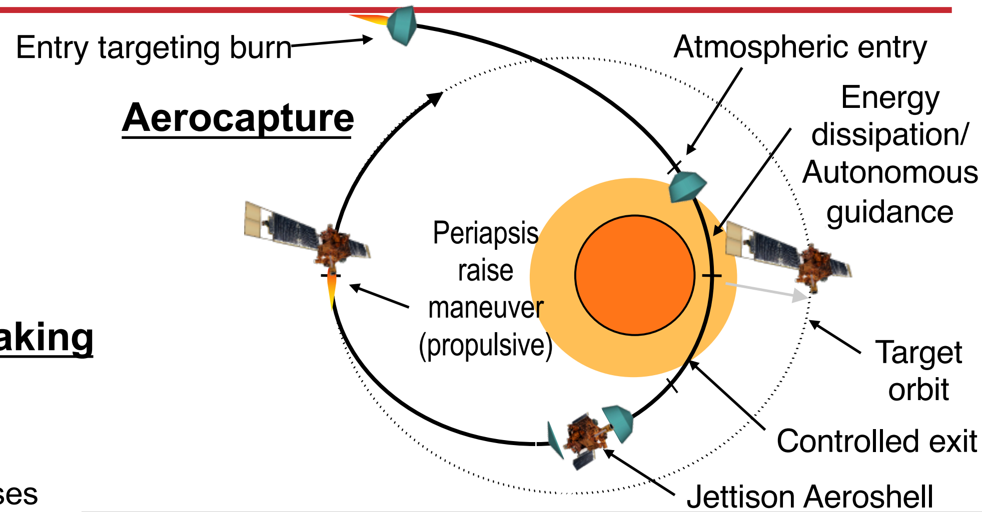
EDL Developments Lower Aerocapture Risk

- Investments over the past 15 years have helped **Narrow the Gaps** for Ice Giants missions
  - Mars Science Laboratory Hypersonic Guidance
  - Orion skip entry (Exploration Flight Test-1) builds on Apollo, Zond capabilities
  - 3D woven thermal protection systems (HEEET)
  - Aeroshell Sensors (MEDLI, EFT-1, MEDLI-2)
  - Arcjet radiative heating capability (NASA-Ames)
  - Aerothermal tools and methods
  - Early design work on mid-L/D vehicles and Direct Force Control (alpha modulation)
  - Atmosphere model upgrades
  - Deployable/Inflatable aeroshells (IRVE, LOFTID, ADEPT)



Aerobraking vs Aerocapture





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
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

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	