Aerocapture Technology Developments by the In-Space Propulsion Program

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In-Space Propulsion Aerocapture Manager


Outline

Introduction to Aerocapture
Application at Titan, Venus, and Neptune
Current Development Status
Next Steps

Aerobraking vs Aerocapture

Atmospheric Drag Reduces Orbit Period

Hyperbolic Approach

Aerobraking

~300 Passes Through Upper Atmosphere

Entry targeting burn

Aerocapture

Atmospheric entry

Energy dissipation

Astromic entry

Controlled exit

Targeting Aeroshell

Periapsis raise maneuver (propulsive)

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.

Aerocapture Benefits for Robotic Missions

<table>
<thead>
<tr>
<th>Mission - Science Orbit</th>
<th>Nominal Orbit Insertion ΔV, km/s</th>
<th>Best A/C Mass, kg</th>
<th>Best non-A/C Mass, kg</th>
<th>A/C % Increase</th>
<th>Best non-A/C Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>Venus V1 - 300 km circ</td>
<td>4.6</td>
<td>5078</td>
<td>2834</td>
<td>79</td>
<td>All-SEP</td>
</tr>
<tr>
<td>Venus V2 - 8500 x 300 km</td>
<td>3.3</td>
<td>5078</td>
<td>3542</td>
<td>43</td>
<td>All-SEP</td>
</tr>
<tr>
<td>Mars M1 - 300 km circ</td>
<td>2.4</td>
<td>5232</td>
<td>4556</td>
<td>15</td>
<td>Aerobraking</td>
</tr>
<tr>
<td>Mars M2 - ~1 Sol ellipse</td>
<td>1.2</td>
<td>5232</td>
<td>4983</td>
<td>5</td>
<td>Chem370</td>
</tr>
<tr>
<td>Jupiter J1 - 2000 km circ</td>
<td>17.0</td>
<td>2262</td>
<td>&lt;0</td>
<td>Infinite</td>
<td>N/A</td>
</tr>
<tr>
<td>Jupiter J2 - Callisto ellipse</td>
<td>1.4</td>
<td>2262</td>
<td>4628</td>
<td>-51</td>
<td>Chem370</td>
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<tr>
<td>Saturn S1 - 120,000 km circ</td>
<td>8.0</td>
<td>494</td>
<td>&lt;0</td>
<td>Infinite</td>
<td>N/A</td>
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<tr>
<td>Titan T1 - 1700 km circ</td>
<td>4.4</td>
<td>2630</td>
<td>691</td>
<td>280</td>
<td>Chem370</td>
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<tr>
<td>Uranus U1 - Titania ellipse</td>
<td>4.5</td>
<td>1966</td>
<td>618</td>
<td>218</td>
<td>Chem370</td>
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<tr>
<td>Neptune N1 - Triton ellipse</td>
<td>6.0</td>
<td>1680</td>
<td>180</td>
<td>832</td>
<td>Chem370</td>
</tr>
</tbody>
</table>

Aerocapture offers significant increase in delivered payload:

ENHANCING missions to Venus, Mars
STRONGLY ENHANCING to ENABLING missions to Titan, and Uranus
ENABLING missions to Jupiter, Saturn, and Neptune

## Titan Aerocapture Reference Concept

<table>
<thead>
<tr>
<th>Component</th>
<th>Current Best Estimate (kg)</th>
<th>Mass Margin %</th>
<th>Contingency growth</th>
<th>System Allocation (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lander</td>
<td>280.2</td>
<td>29.8%</td>
<td>363.8</td>
<td>400.0</td>
</tr>
<tr>
<td>Orbital/Lander Interface</td>
<td>47.0</td>
<td>30.0%</td>
<td>61.9</td>
<td>61.9</td>
</tr>
<tr>
<td>Prop Motor/Lander Interface</td>
<td>68.3</td>
<td>30.0%</td>
<td>79.0</td>
<td>79.0</td>
</tr>
<tr>
<td>SEP Prop Module</td>
<td>1084.0</td>
<td>21.4%</td>
<td>1316.5</td>
<td>1450.0</td>
</tr>
<tr>
<td>Stack Total</td>
<td>2402.6</td>
<td>24.0%</td>
<td>2979.2</td>
<td>3251.2</td>
</tr>
<tr>
<td>Launch Vehicle Capability</td>
<td>3423</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**System Reserve**

- Titan Explorer-type mission based on SSE Roadmap circa 2001
- Detailed analysis by multi-Center team of discipline experts (many papers)
- Delta 4450, SEP, EGA, aerocapture has 30% system level margin, >10% system reserve
- Aerocapture mass fraction = 39% of orbiter launch wet mass

**Subsystem Rack-up**

- Mass (kg)
- Component
- Current Best Estimate
- Contingency Growth
- System Allocation
- System Reserve

**Titan Systems Definition Study Results**

- Available payload mass
- Required payload mass:
  - Lander
  - Lander/orbiter adapter
  - Aerocapture Delta V
  - Orbiter aeroshell
  - Orbiter TCM & ACS prop.
  - Orbiter
  - Prop. Mod/orbiter adapter

- Aerocapture/SEP is Enabling to Strongly Enhancing, dependent on Titan mission requirements
- Aerocapture/SEP results in ~2.4x more payload at Titan compared to all-propulsive mission for same launch vehicle

**Titan-GRAM Model vs Cassini-Huygens Data**

- Observations from HASI and INMS are well within Titan-GRAM max/min estimates

**Titan Aerothermal Updates Since 2002 Study**

- Cassini-Huygens provided:
  - Improved ephemeris data for reduced flight path angle uncertainty
  - Improved atmospheric density measurement accuracy
  - Improved atmospheric constituent data (less than 2% CH4 vs 5% assumed in 2002 study)

- Aerothermal modeling investments and testing provided improved aeroheating estimates and less critical need for TPS development
  - Reduced heating estimates result in 75-100 kg less TPS mass than sized during the 2002 study (Laub and Chen, 2005)

**Observations from HASI and INMS are well within Titan-GRAM max/min estimates**

**Ref.** Mike Wright

Titan Aerocapture Technologies - Ready!

Enabling Technologies - No new enabling technology required

Strongly Enhancing Technologies
- Aeroheating methods development, validation
  - Large uncertainties currently exist, improved prediction capability could result in reduced TPS mass
- TPS Material Testing
  - TPS materials proposed and other TPS options exist today, but are not tested against expected radiative heating at Titan
- Atmosphere Modeling

Enhancing Technologies
- Aeroshell lightweight structures - reduced aerocapture mass
- Guidance - Existing guidance algorithms have been demonstrated to provide acceptable performance, improvements could provide increased robustness
- Simulation - Huygens trajectory reconstruction, statistics and modeling upgrades
- Mass properties/structures tool - systems analysis capability improvement, concept trades
- Deployable high gain antennae – increased data return

The following technologies provide significant benefit to the mission but are already in a funded development cycle for TRL 6
- MMRTG (JPL sponsored AO in proposal phase, First flight MSL)
- SEP engine (Glenn Research Center engine development complete in 10)
- Second Generation AEC-Able UltraFlex Solar Arrays (175 W/kg)
- Optical navigation to be demonstrated on MRO

Example Monte Carlo Simulation Results: Venus Aerocapture

Venus Aerocapture Systems Analysis Study, 2004
Vehicle L/D = 0.25, mC/D = 114 kg/m²
Target orbit: 300 km circ., polar
All-propulsive ΔV required for orbit insertion: 3975 m/s
ΔV provided by aerocapture: 3885 m/s (97.7% of total)
30 deg/sec bank rate, 5 deg/sec² bank acceleration

Exit Apoapsis Altitude vs. Periapsis Altitude

Statistics for Circularization and Maximum Deceleration

1165 kg Launch Vehicle Capability
Delta 2925H-10, C₃ = 8.3 km/s²

Aerocapture Benefit for a Venus Mission

Mass savings will scale up for Flagship-class mission

Venus Orbiter (OML Design Only)

Into 300 x 300 km Venus orbit with same launch vehicle, Aerocapture delivers:
- 1.8x more mass into orbit than aerobraking
- 6.2x more mass into orbit than all chemical


Venus Aerocapture Technology - In Good Shape

- Aerocapture is feasible and robust at Venus with high heritage low L/D configuration
- 100% of Monte Carlo cases capture successfully
- TPS investments could enable more mass-efficient ablative, insulating TPS; accompanying aerothermal analysis investments would enable prediction of ablation, potential shape change
- Additional guidance work would increase robustness for small scale height of Venus atmosphere
- Mass savings will scale up for a Flagship-class mission, so Aerocapture provides a way to achieve the challenging science return that is desired
- Possible orbiter + lander/probe on 1 launch
Neptune Orbiter Aerocapture Reference Concept

Launch Mass Summary

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (kg)</th>
<th>Current Base</th>
<th>Dry Alloc</th>
<th>Dry Growth</th>
<th>Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbiter Launch Dry Mass</td>
<td>762</td>
<td>515.3</td>
<td>25.8%</td>
<td>555.8</td>
<td>35.1%</td>
</tr>
<tr>
<td>Acceleration/TPS Dry Mass</td>
<td>34</td>
<td>39.3</td>
<td>25.8%</td>
<td>38.3</td>
<td>35.1%</td>
</tr>
<tr>
<td>Probes</td>
<td>2</td>
<td>198.3</td>
<td>25.8%</td>
<td>207.3</td>
<td>35.1%</td>
</tr>
<tr>
<td>SEP Stage Dry Mass</td>
<td>197</td>
<td>1133.2</td>
<td>25.8%</td>
<td>1469.8</td>
<td>35.1%</td>
</tr>
<tr>
<td>Launching Rig Hardware</td>
<td>217</td>
<td>417.3</td>
<td>25.8%</td>
<td>514.6</td>
<td>35.1%</td>
</tr>
<tr>
<td>Total Black Mass</td>
<td>592</td>
<td>2541.3</td>
<td>25.8%</td>
<td>3298.0</td>
<td>35.1%</td>
</tr>
</tbody>
</table>

Launch Vehicle Capability 5964
Unallocated Reserve 13.4%
JPL System Dry Mass Margin 31.8%
NASA Dry Mass Margin 29.5%

Delta IV H, 5m Fairing, 5964 kg, C3 = 18.44
31.8% System Dry Mass Margin; 13%
Unallocated Launch Reserve (800 kg)

Mass margin provides opportunity for:
- Third probe
- Increased aeroshell size for possible reduction in aerothermodynamic design; TPS thickness requirements, surface recession

-57% aerocapture mass fraction (includes aerocapture propellant) ~48% structure/TPS mass fraction


Neptune Aerocapture Technologies - Need Work

Enabling Technologies
TPS Manufacturing
- TPS thicknesses are beyond current manufacturing experience for carbon phenolic for this shape/acreage

Aerothermodynamic methods and validation
- Aerothermodynamics characterized by high radiative and convective aeroheating, coupled convection/radiation/ablation, significant surface recession
- Coupled convection/radiation/ablation capability for three-dimensional flowfields
- Approach needed to determine and represent aerodynamics/uncertainties on resultant time varying path dependent shapes in aero database/simulation
- Testing facilities and methods

Strongly Enhancing Technologies
Guidance Algorithm - Existing guidance algorithms provide adequate performance; Improvements possible to determine ability to reduce heat loads for given heat rate; accommodate time varying, path dependent shape and ballistic coefficient change
Flight Control Algorithm - Accomodate shape change uncertainties
Atmosphere Modeling - Neptune General Circulation Model output to represent dynamic variability of atmosphere
Reduced Mass TPS - Lower mass TPS concepts, ex. Reduced density carbon phenolic
Alpha Modulation
Lower Mass and Power Science Instruments
Dual Stage MMRTGs
Deployable Ka-Band HGA

Neptune Aeroheating Challenges
- Vehicle divided into 4 zones for TPS sizing. TPS selected/size for max heating point in each zone.
- TPS interfaces will require a significant effort
- No facility exists for testing these heating levels
- Combination radiative and convective environment is analysis and testing challenge

ISPT’s Low-Risk Aeroshell Mass Improvements
Warm Structure System Model - based on MER, MPF, validated with testing
For environments up to 300 W/cm²

Areal Density = 2.07 lb/ft²
Areal Density = 1.78 lb/ft²

Hot Structure System Model - based on Genesis, validated with testing
For environments up to 700 W/cm²

Areal Density = 3.65 lb/ft²
Areal Density = 2.50 lb/ft²

Warm Structure System Model - based on GENESIS, validated with testing

MER SLA-561V System 250 deg C
Areal Density = 2.07 lb/ft²
Areal Density = 1.78 lb/ft²

Hot Structure System Model - based on GENESIS, validated with testing

Final System includes backup aluminum honeycomb structure
Areal Density = 3.65 lb/ft²
Areal Density = 2.50 lb/ft²
Higher Bondlines and Efficient Ablators Reduce Mass

<table>
<thead>
<tr>
<th>ARA Material</th>
<th>Density (g/cm²)</th>
<th>Heating Range (W/cm²)</th>
<th>New Missions</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyperlite-A</td>
<td>0.21</td>
<td>55 – 115</td>
<td>MPF-type</td>
<td>High Efficiency</td>
</tr>
<tr>
<td>SRAM-17</td>
<td>0.27</td>
<td>115 – 210</td>
<td>CEV, MSL</td>
<td>Robust Char</td>
</tr>
<tr>
<td>SRAM-20</td>
<td>0.32</td>
<td>140 – 260</td>
<td>CEV, MSL, RTF repair</td>
<td>Low Recession</td>
</tr>
<tr>
<td>PhenCarb-20</td>
<td>0.32</td>
<td>200 – 500</td>
<td>CEV, Titan</td>
<td>High Heating</td>
</tr>
<tr>
<td>PhenCarb-32</td>
<td>0.51</td>
<td>500 – 1,100</td>
<td>Venus, Neptune</td>
<td>Severe Heating</td>
</tr>
</tbody>
</table>

Aerocapture Flight Validation Concept

Mission Parameters

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>60° sphere-cone aeroshell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Mass (CBE)</td>
<td>148 kg, 1.2 m diameter</td>
</tr>
<tr>
<td>Access to space</td>
<td>1988 NPT dual launch to 13000 kr</td>
</tr>
<tr>
<td>Mission Duration</td>
<td>9.1 hours</td>
</tr>
<tr>
<td>Atmospheric Entry Speed</td>
<td>9.6 km/s</td>
</tr>
<tr>
<td>Nominal Launch</td>
<td>June 2019</td>
</tr>
<tr>
<td>NMP ST9 Funding</td>
<td>$85 M</td>
</tr>
<tr>
<td>ISP ST9 Funding</td>
<td>$22 M</td>
</tr>
</tbody>
</table>

Aerocapture System Technology for Planetary Missions was one of five competitors for NASA’s New Millennium Program Space Technology-9 mission (2006)

- The ST9 Aerocapture concept would have validated:
  - Aerocapture as a system technology for immediate use in future missions to Solar System destinations possessing significant atmospheres
  - The performance of the autonomous Aerocapture guidance system based on bank angle control
  - Efficient and robust new TPS for multiple applications
- Feedback on technology element readiness was very favorable
- ISPT’s recent maturation plans largely guided by work defined in this proposal

Current (and Final) ISPT Aerocapture Tasks (through FY09)

- Manufacture “large scale” (2.65-m) aeroshell
  - Advanced, high-temperature structure by ATK
  - SRAM-20 ablator applied using “modular” approach
  - Sensor/repair plugs included

Aerocapture Flight Validation Concept

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Current (and Final) ISPT Aerocapture Tasks (cont’d)

- Verify guidance software operation in “hardware-in-the-loop” ground testbed
  - Verify timing and control interfaces
- Perform Space Environmental Effects testing on promising materials for both rigid aeroshells and inflatable decelerators (TPS, structure, adhesive, sensors)
  - Impact
  - Space Radiation
  - Cold Soak
- Followed by arcjet testing
- Continue aerothermal modeling efforts
  - Spectrometer measurements of ablation products
  - Surface catalysis analysis
  - CO₂ EAST tests to verify shock chemistry
### Aerocapture Technology Subsystem Readiness

<table>
<thead>
<tr>
<th>Destination</th>
<th>Venus</th>
<th>Earth</th>
<th>Mars</th>
<th>Titan</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Atmosphere</strong></td>
<td><strong>Goal: Capture Physics</strong></td>
<td><strong>Goal: Readied for application</strong></td>
<td><strong>Goal: Readied for application</strong></td>
<td><strong>Goal: Developed from Voyager data</strong></td>
<td><strong>Goal: Readied for application</strong></td>
</tr>
<tr>
<td><strong>Aerodynamics</strong></td>
<td><strong>Goal: Error ≤ 2%</strong></td>
<td><strong>Goal: Combined convective and radiative facility needed</strong></td>
<td><strong>Goal: Models agree within 15%</strong></td>
<td><strong>Goal: Radiative models agree within 15%</strong></td>
<td><strong>Goal: Models agree within 10%</strong></td>
</tr>
<tr>
<td><strong>TPS</strong></td>
<td><strong>Goal: Reduce SDA by 20%</strong></td>
<td><strong>Technology ready for flight validation</strong></td>
<td><strong>SPT investments have provided more materials for application</strong></td>
<td><strong>SPT algorithm captures 95% of corridor</strong></td>
<td><strong>SPT algorithm captures 95% of corridor</strong></td>
</tr>
<tr>
<td><strong>Structures</strong></td>
<td><strong>Goal: Reducing mass by 20%</strong></td>
<td><strong>High-temp systems will reduce mass by 14% to 30%</strong></td>
<td><strong>High-temp systems will reduce mass by 14% to 30%</strong></td>
<td><strong>High-temp systems will reduce mass by 14% to 30%</strong></td>
<td><strong>High-temp systems will reduce mass by 14% to 30%</strong></td>
</tr>
<tr>
<td><strong>Aerothermal</strong></td>
<td><strong>Goal: Models match within 15%</strong></td>
<td><strong>Conductive models match within 20%</strong></td>
<td><strong>Conductive models agree within 15%</strong></td>
<td><strong>Conductive models agree within 15%</strong></td>
<td><strong>Conductive models agree within 10%</strong></td>
</tr>
<tr>
<td><strong>System</strong></td>
<td><strong>Goal: Robust performance with ready technology</strong></td>
<td><strong>Achieves 97% of mass by V to achieve 300 x 200 km orbit. No known technology gaps.</strong></td>
<td><strong>Achieves 97% of mass by V to achieve 300 x 130 km orbit. No known technology gaps.</strong></td>
<td><strong>Achieves 96.9% of mass by V to achieve 1700 x 1700 km orbit. No known technology gaps.</strong></td>
<td><strong>Achieves 96.9% of mass by V to achieve Triton orbit. No known technology gaps.</strong></td>
</tr>
</tbody>
</table>

### Aerocapture Development Summary

- Aerocapture is [Enabling or Strongly Enhancing](#) for many of the destinations in the Solar System, saving launch mass, trip time, and cost.
- Aerocapture is made of flight system elements that have [Strong Heritage](#) and firm computational basis.
- ISPT investments in modeling and test capabilities are [Benefiting Current NASA](#) projects.
- ISPT investments have readied [Multiple Heatshield Components for Mission Infusion](#):
  - 2 warm structure systems
  - Hot structure system
  - Multiple new charring ablators
  - Sensors
  - Aerothermal tools and methods

### What’s Next?

- Finish what we started within ISPT (shown in “Current Tasks”)
- Continue to support (likely only through advocacy) model improvements
  - Aerothermal and atmospheric
  - Gather validation data through flight tests; sensor development important (currently unfunded)
- Educate about mission benefits and advocate for use
  - Continue New Frontiers incentive discussions
  - Request involvement in Titan Flagship Study
- Is ISPT ground development + MSL hypersonic guidance + CEV skip entry = Aerocapture validation?
- Pursue TPS flight test or Aerocapture flight validation opportunity?
  - ARMD/ISPT partnership?
  - New Millennium Program restart?
- **Bottom line facing Aerocapture: Is flight validation NECESSARY?**

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![Image](https://via.placeholder.com/150)