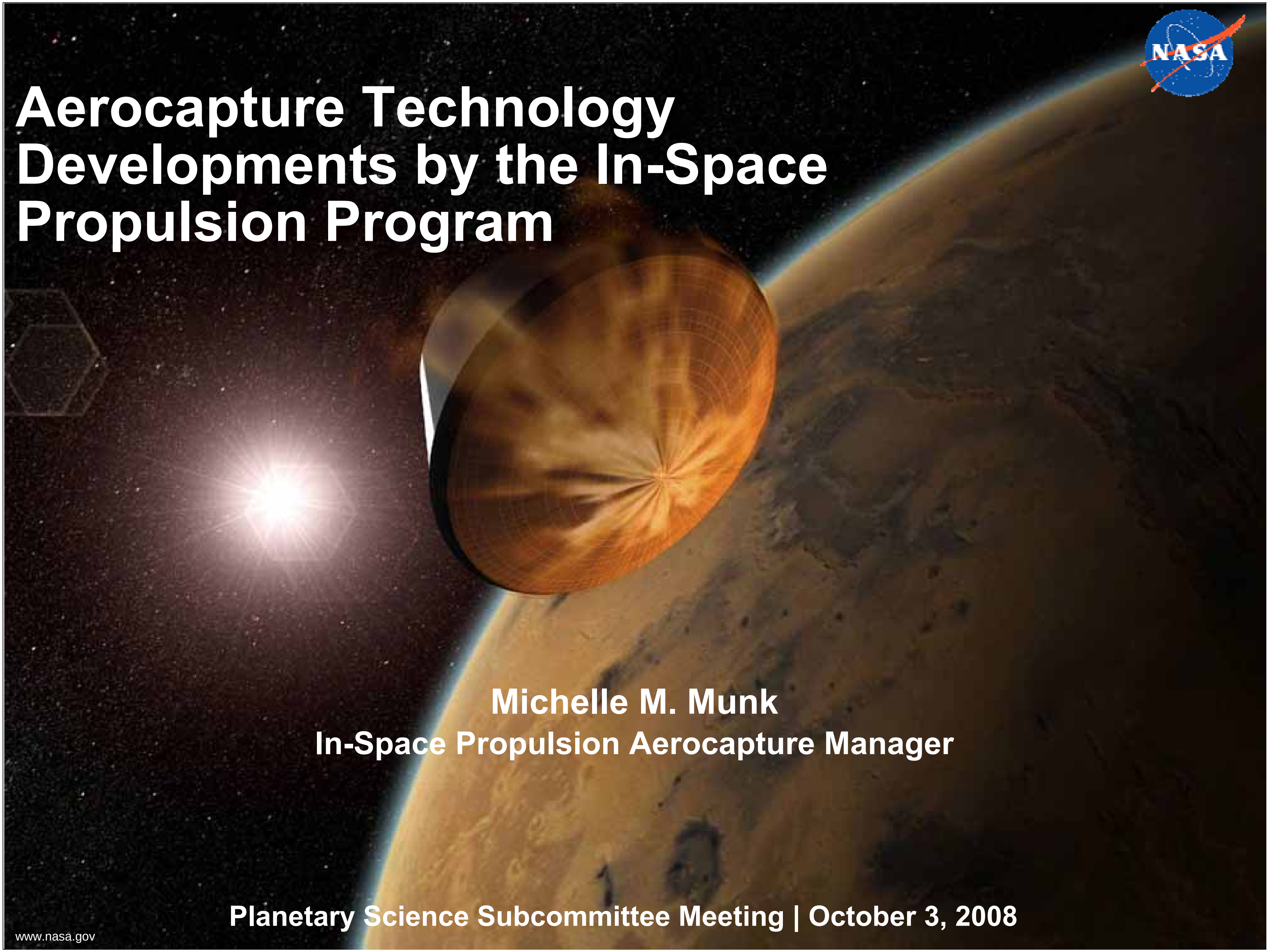


Aerocapture Technology Developments by the In-Space Propulsion Program

Michelle M. Munk
In-Space Propulsion Aerocapture Manager

Planetary Science Subcommittee Meeting | October 3, 2008

Outline

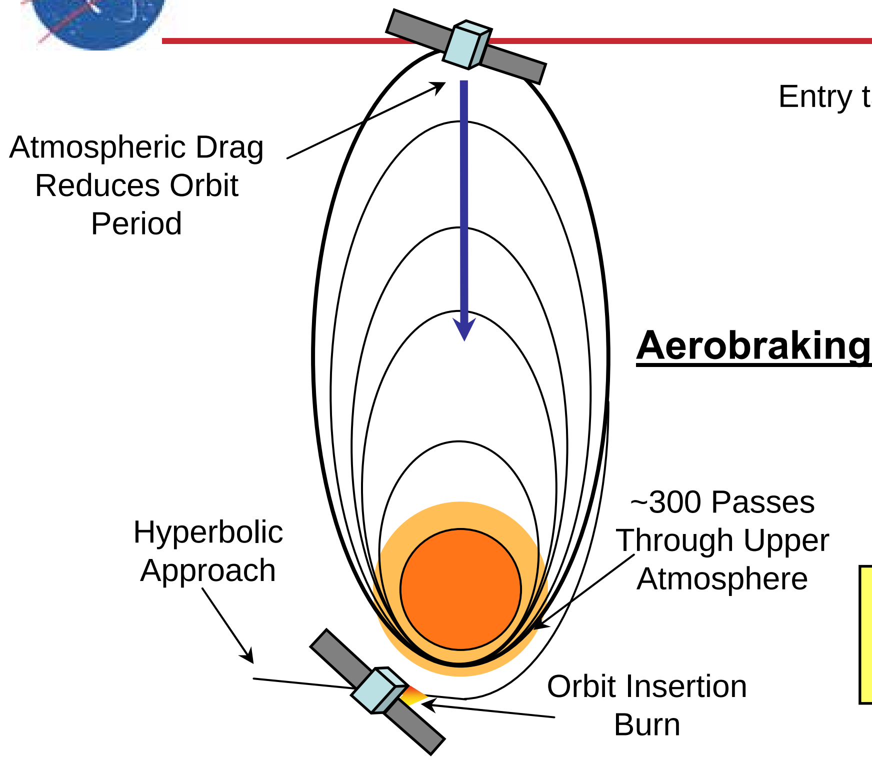
Introduction to Aerocapture

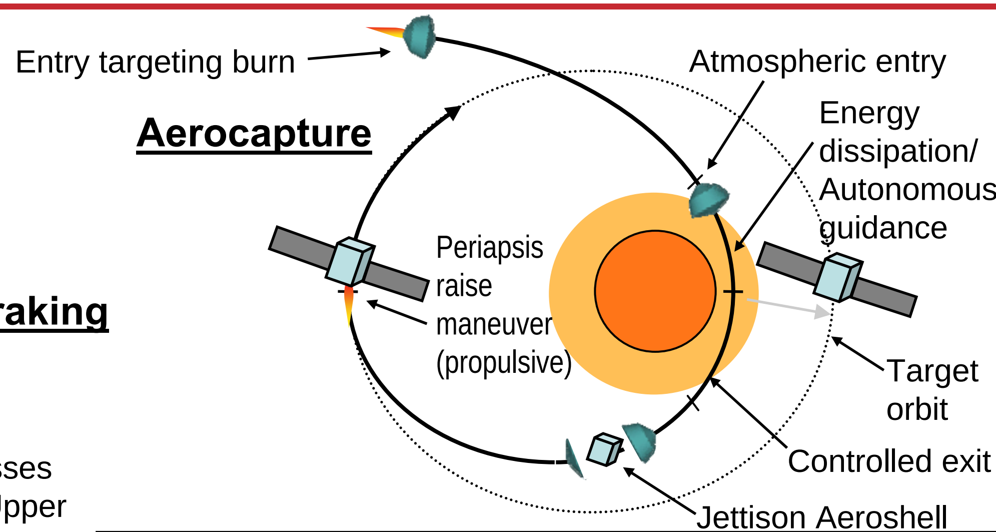
Application at Titan, Venus, and Neptune

Current Development Status

Next Steps

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	

Aerocapture Benefits for Robotic Missions

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

Aerocapture offers significant increase in delivered payload:

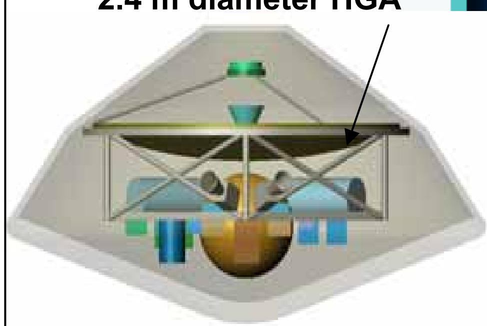
- **ENHANCING** missions to Venus, Mars
- **STRONGLY ENHANCING** to **ENABLING** missions to Titan, and Uranus
- **ENABLING** missions to Jupiter, Saturn, and Neptune

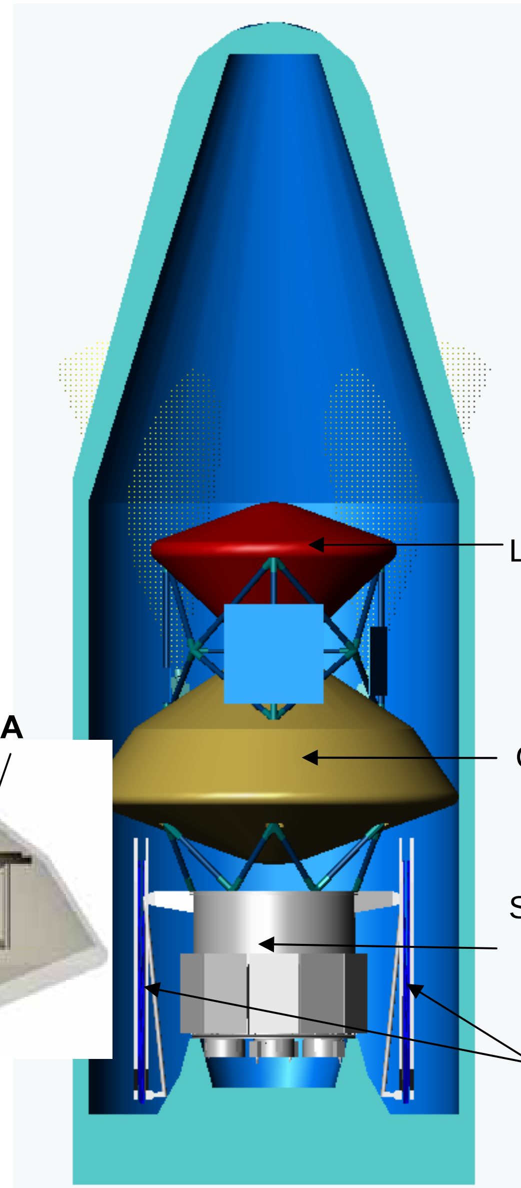
Ref.: Hall, J. L., Noca, M. A., and Bailey, R. W. "Cost-Benefit Analysis of the Aerocapture Mission Set," *Journal of Spacecraft and Rockets*, Vol. 42, No. 2, March-April 2005

Titan Aerocapture Reference Concept

Component	Mass (kg): Subsystem Rack-up: Current Best Estimate	% Contingency	Growth	System Allocation
Lander	***280.2***	***29.8%***	***363.8***	***400.0***
Orbiter/Lander Interface	**47.5**	**30.0%**	**61.8**	**61.8**
Orbiter	***883.6***	***24.2%***	***1097.7***	***1200.0***
Prop Mod/Orbiter Interface	**47.3**	**30.0%**	**61.4**	**61.4**
SEP Prop Module	***1084.0***	***21.4%***	***1316.5***	***1450.0***
Launch/Prop Mod Interface	**60.0**	**30.0%**	**78.0**	**78.0**
Stack Total	**2402.6**	**24.0%**	**2979.2**	**3251.2**
Launch Vehicle Capability	**3423**			
System Level Mass Margin	**29.8%**	(LV Cap - CBE) / LV Cap		
System Reserve	**13.0%**	(LV Cap - Growth) / LV Cap		

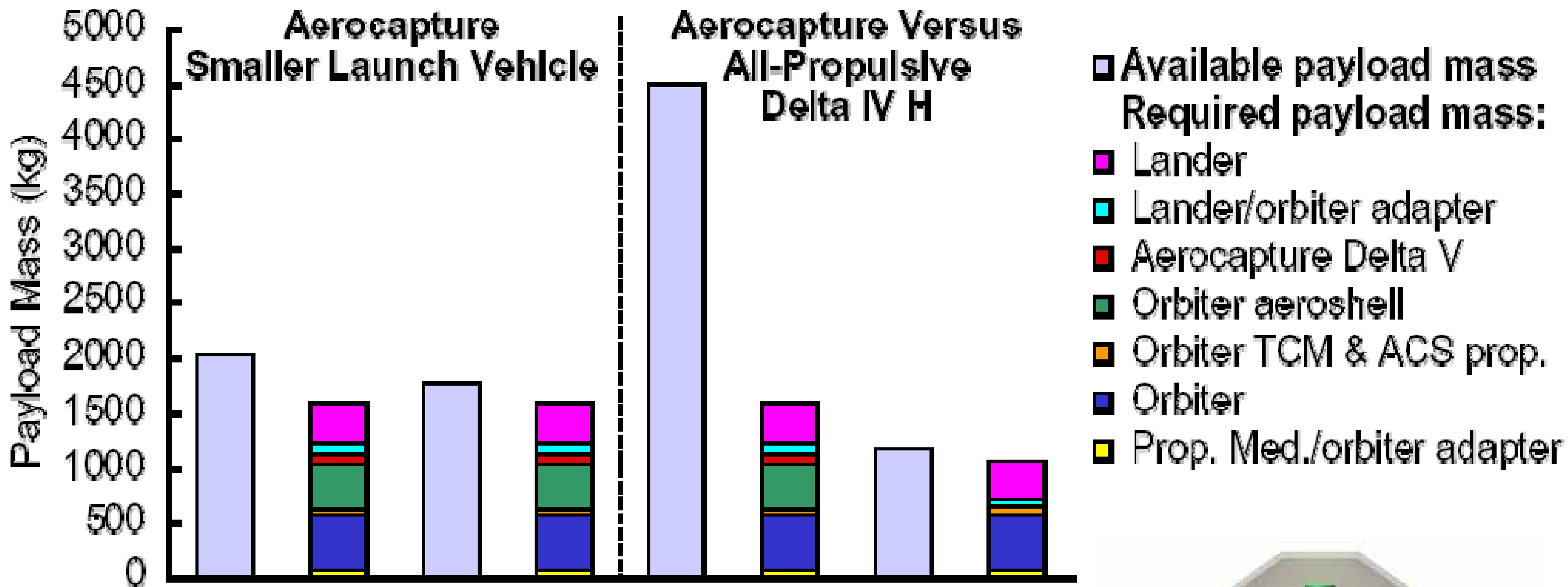
- "Titan Explorer"-type mission based on SSE Roadmap circa 2001
- Detailed analysis by multi-Center team of discipline experts (many papers)
- Delta 4450, SEP, EGA, aerocapture has 30% system level margin, >10% system reserve
- Aerocapture mass fraction = 39% of orbiter launch wet mass





Ref: "Aerocapture Systems Analysis for a Titan Mission", NASA TM 2006-214273, March 2006.

Titan Systems Definition Study Results



Launch Veh:	4450	4450	Delta IV H	Delta IV H
Gravity Assist:	EGA	VGA	EGA	VEEGA
Upper Stage:	SEP	SEP	SEP	Chem
Capture Type:	Aero	Aero	Aero	Chem
Trip Time:	6 yrs	6 yrs	6 yrs	12 yrs*
	Ref. concept			

* Includes 2-yr moon tour used to reduce propellant requirements for all propulsive capture

- 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

Aerocapture can be used with a chemical ballistic trajectory: Delta IV H, 7.1 year trip, EGA, 32% margin

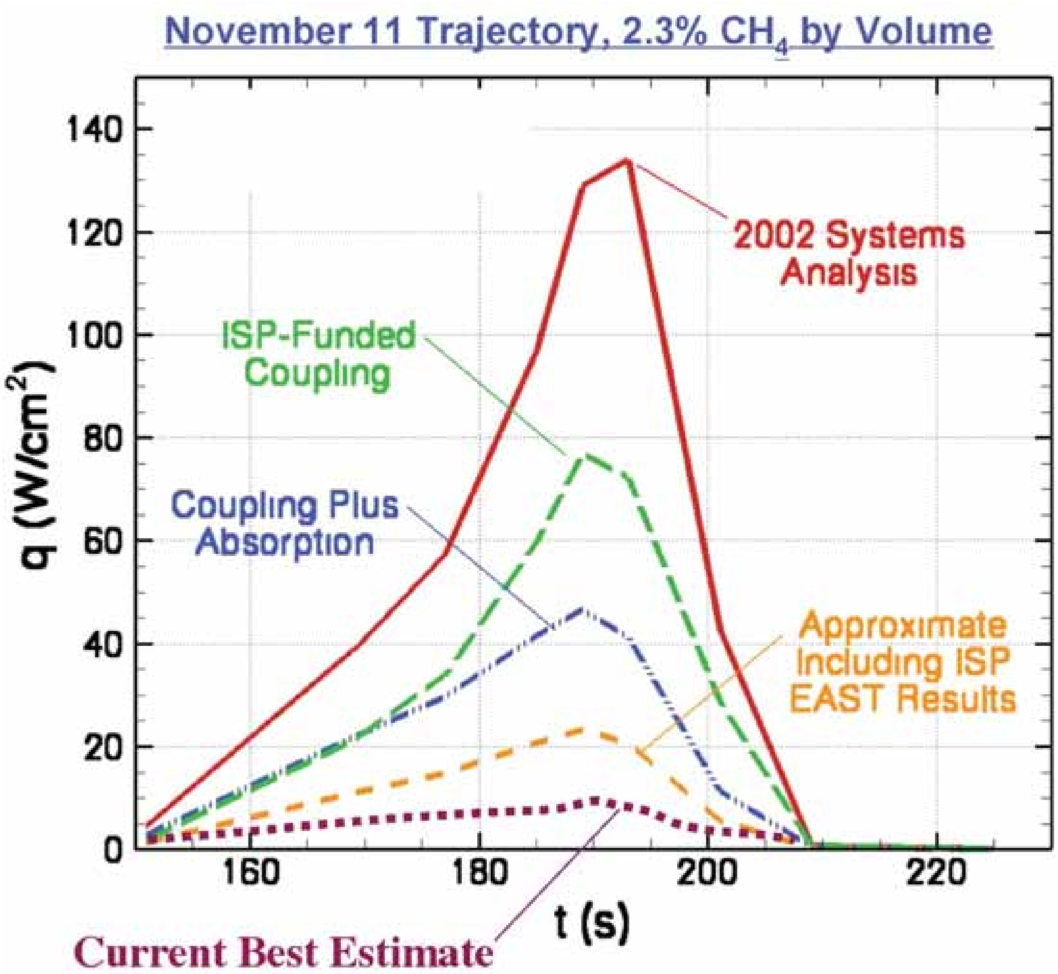
Titan Aerothermal Updates Since 2002 Study

Cassini-Huygens provided:

- Improved ephemeris data for reduced flight path angle uncertainty
- Improved atmospheric density measurement accuracy
- Improved atmospheric constituent data (less than 2% CH_4 vs 5% assumed in 2002 study)

Aerothermal modeling investments and testing provided improved aeroheating estimates and less critical need for TPS development

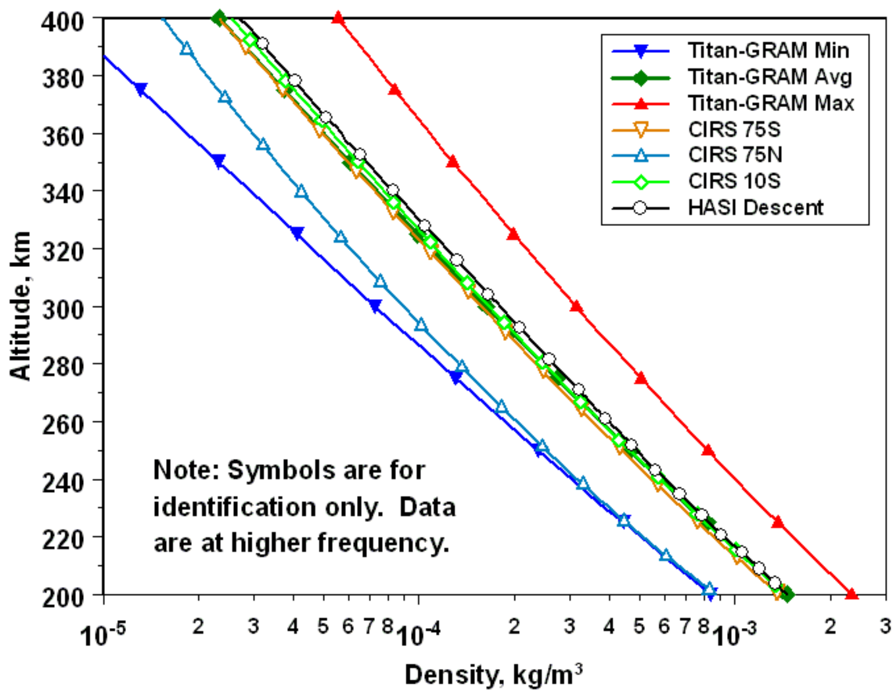
- Reduced heating estimates result in 75-100 kg less TPS mass than sized during the 2002 study (Laub and Chen, 2005)



Ref: Mike Wright

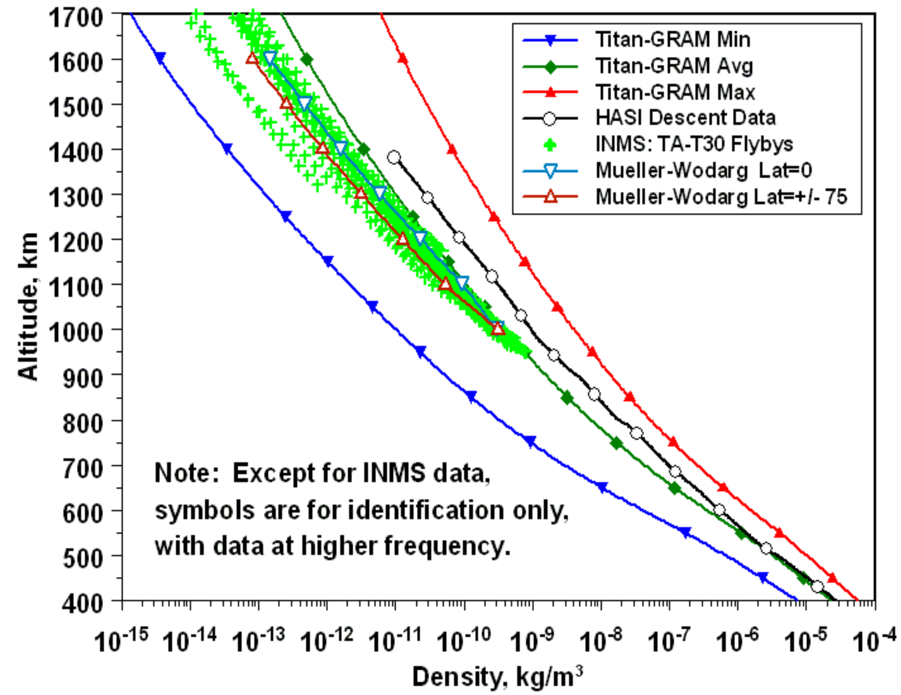
Titan-GRAM Model vs Cassini-Huygens Data

Titan Density: CIRS and HASI Data vs Titan-GRAM



Aerocapture Minimum Alt Range

Titan Density: INMS and HASI Data versus Titan-GRAM



Aerocapture to Orbit Alt Range

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

Ref.: Justh and Justus, "Comparisons of Huygens Entry Data and Titan Remote Sensing Observations with the Titan Global Reference Atmospheric Model (Titan-GRAM)"

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**

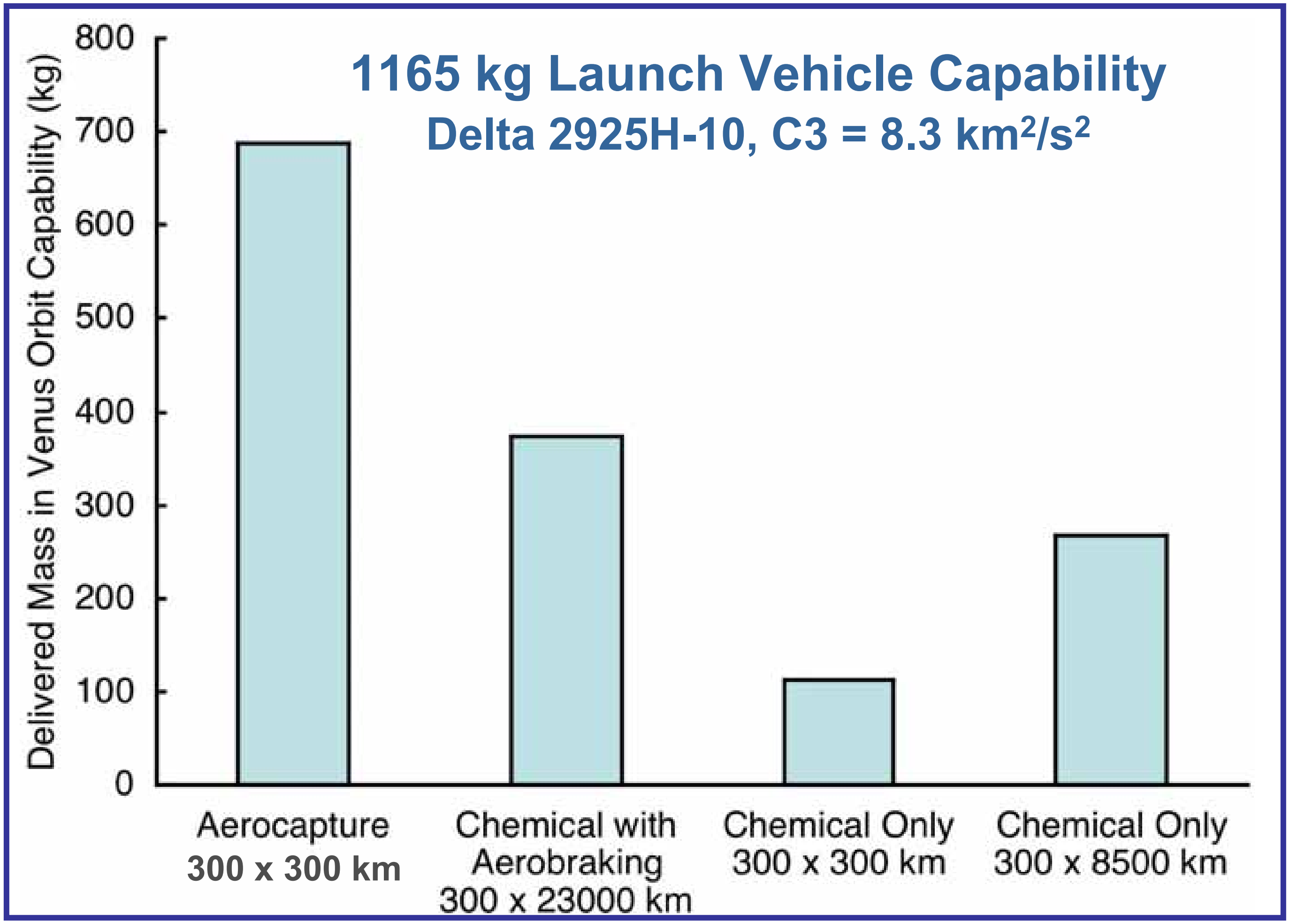
Mass properties/structures tool - systems analysis capability improvement, concept trades

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

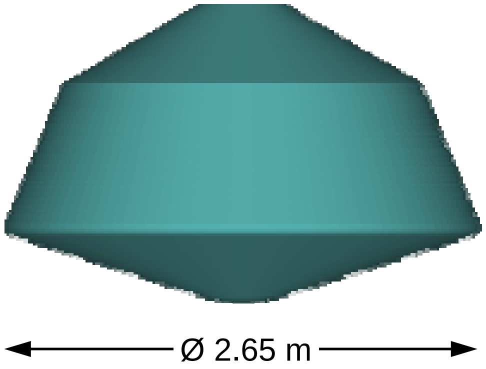
- MMRTG (JPL sponsored AO in proposal phase, First flight MSL)
- SEP engine (Glenn Research Center engine development complete in ‘10)
- Second Generation AEC-Able UltraFlex Solar Arrays (175 W/kg)
- ✓ Optical navigation to be demonstrated on MRO

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

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

Example Monte Carlo Simulation Results:
Venus Aerocapture

Venus Aerocapture Systems Analysis Study, 2004

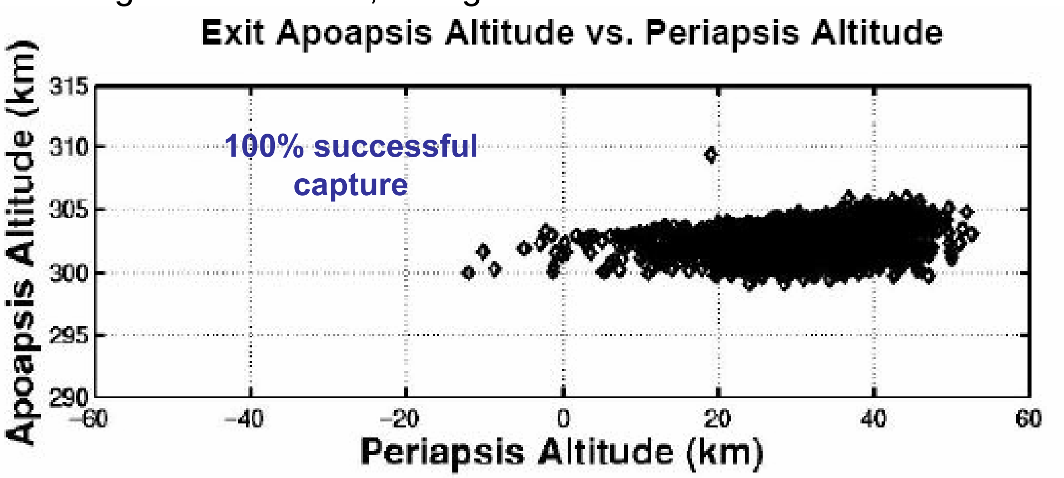
Vehicle L/D = 0.25, m/C_DA = 114 kg/m^2

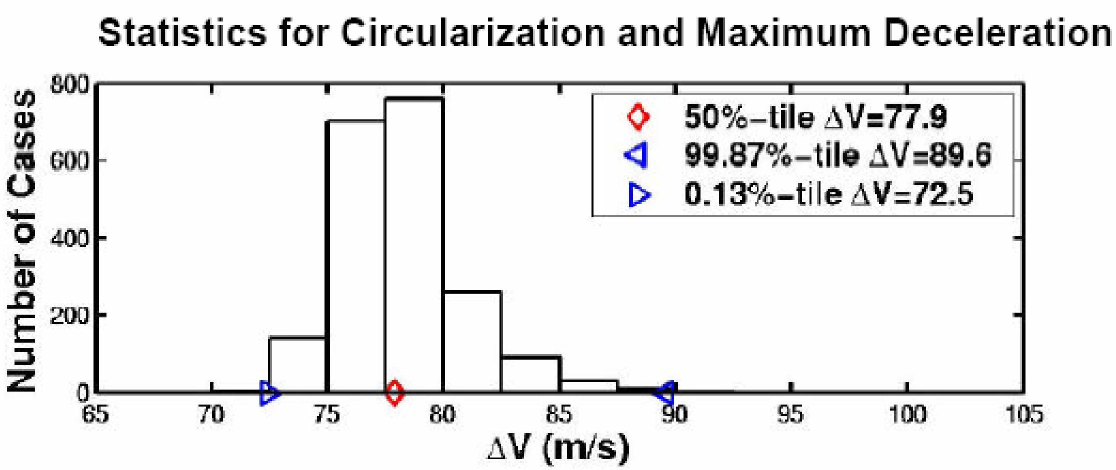
Target orbit: 300 km circ., polar

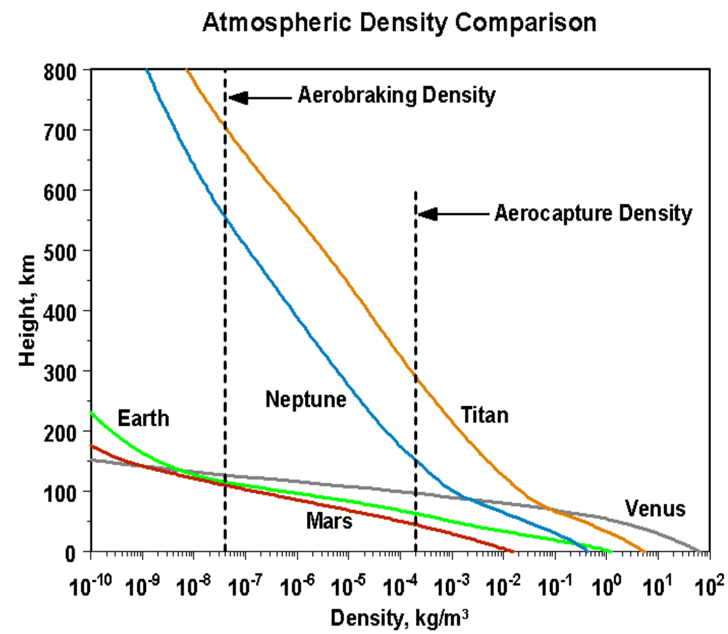
All-propulsive ΔV required for orbit insertion: 3975 m/s

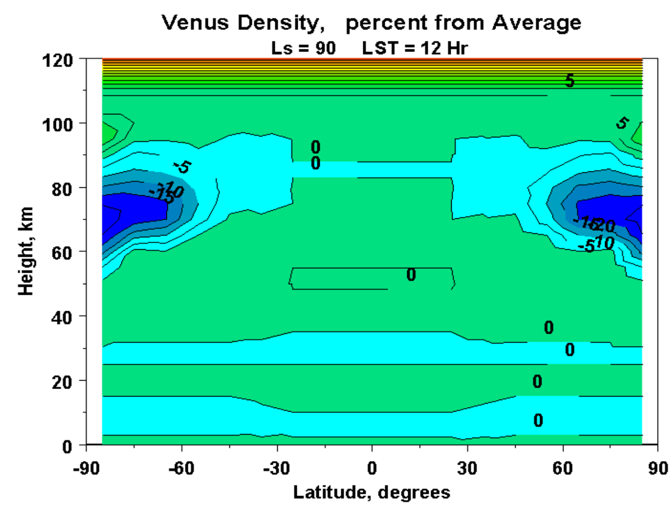
ΔV provided by aerocapture: 3885 m/s (97.7% of total)

30 deg/sec bank rate, 5 deg/sec^2 bank acceleration









1-sigma variations at 100 km = ~8%; 3σ = ~24%

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

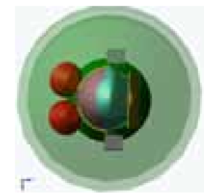
Neptune Orbiter Aerocapture Reference Concept

Launch Mass Summary

Component	Flight Units	Mass (kg): Subsystem Rack-up: Current Best Estimate	% Growth	Growth	Wet Allocation	Fuel Load	System Allocation minus Fuel Load	Dry Mass Margin
Orbiter Launch Dry Mass	**269**	**518.2**	**28.5%**	**666.0**	**1081.4**	**282.5**	**798.9**	**35.1%**
Aeroshell/TPS Dry Mass	**34**	**681.0**	**30.0%**	**885.2**	**885.3**	**0.0**	**885.3**	
Probes (2)	**2**	**159.3**	**30.0%**	**207.1**	**228.6**	**0.0**	**228.6**	**30.3%**
SEP Stage Dry Mass	**197**	**1133.8**	**29.7%**	**1469.7**	**2899.2**	**1154.5**	**1744.7**	**35.0%**
Launch/Prop Mod Interface	**1**	**49.0**	**30.0%**	**70.0**	**70.0**	**0.0**	**70.0**	
Stack Total	**503**	**2541.3**	**29.8%**	**3298.0**	**5164.5**	**1437.0**	**3727.5**	**31.8%**

35% Dry Margin Carried at Orbiter and SEP Level

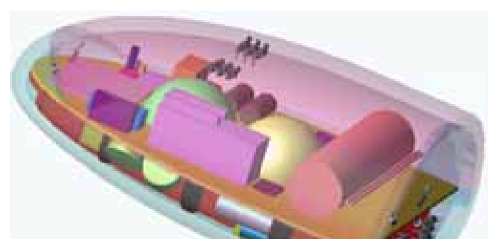
Launch Vehicle Capability	**5964**	
Unallocated Launch Reserve	**13.4%**	Unallocated Reserve / LV Cap
JPL System Dry Mass Margin	**31.8%**	(Dry Alloc - Dry CBE) / Dry Alloc
NASA Dry Mass Contingency	**29.8%**	(Dry Growth - Dry CBE) / Dry CBE (Measure of component maturity)
NASA Dry Mass Margin	**13.0%**	(Dry Alloc - Dry Growth) / Dry Growth (Measure of system maturity)



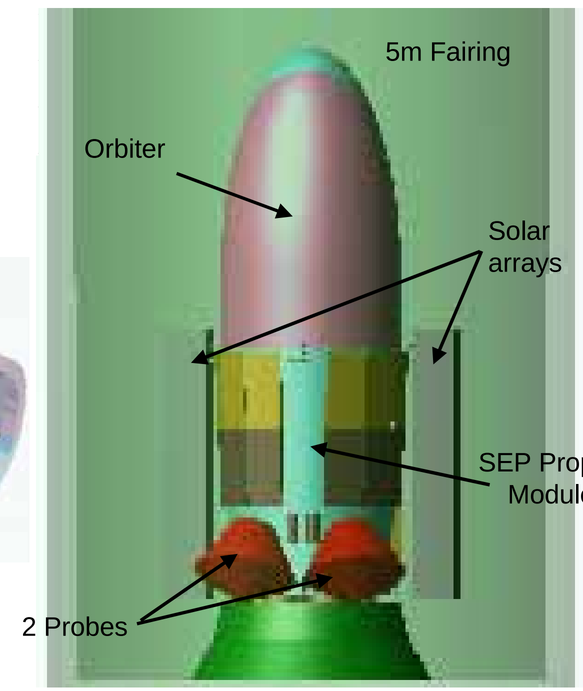
Delta IV H, 5m Fairing, 5964 kg, C3 = 18.44
31.8% System Dry Mass Margin; 13% Unallocated Launch Reserve (800 kg)
Mass margin provides opportunity for

- Third probe
- Increased aeroshell size for possible reduction in aeroheating rates/loads, TPS thickness requirements, surface recession

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

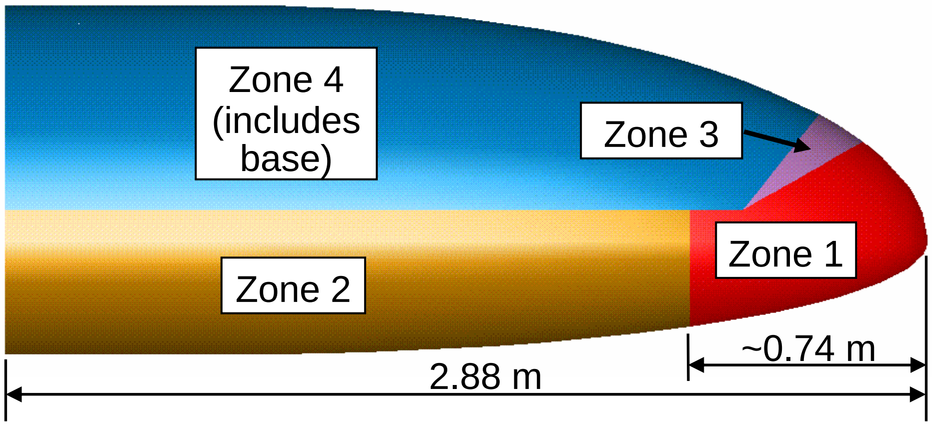


Orbiter
2.88 m Length Flattened Ellipsled Aeroshell

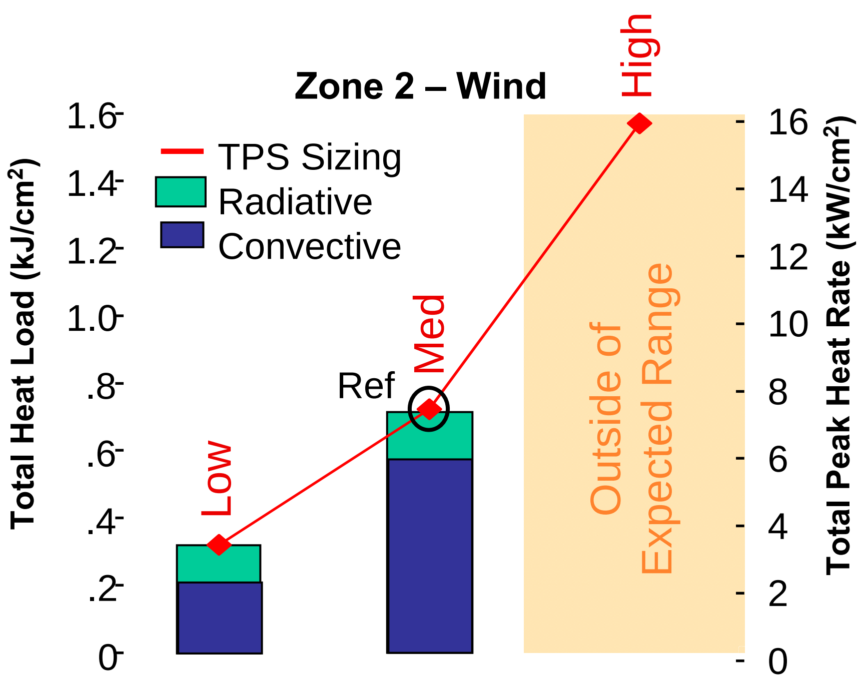


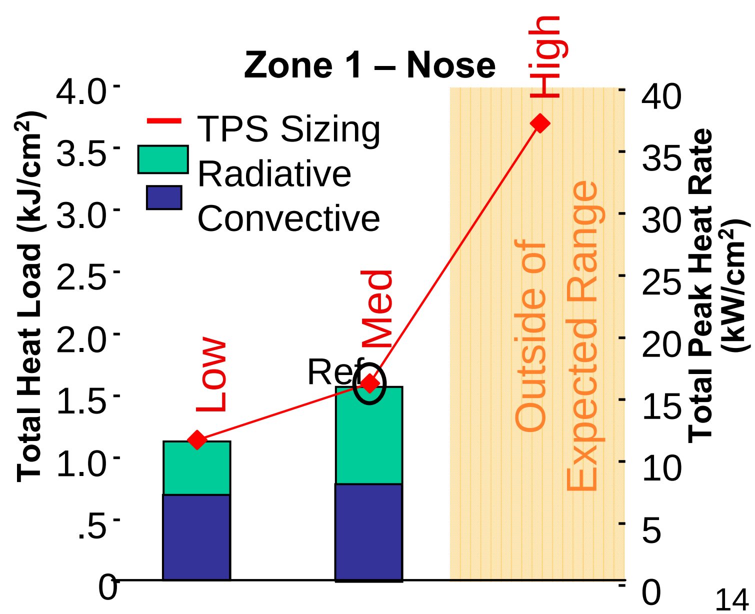
Reference: "Systems Analysis for a Neptune Aerocapture Mission", NASA TM 2006-214300, May 2006

Neptune Aeroheating Challenges



- Vehicle divided into 4 zones for TPS sizing. TPS selected/sized 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





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 - Accommodate 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

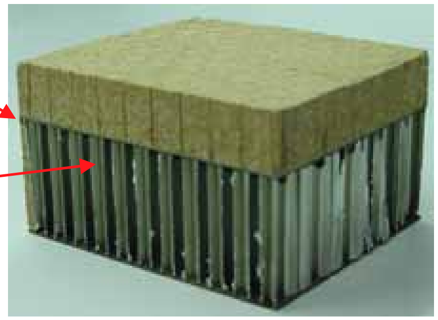
ISPT's Low-Risk Aeroshell Mass Improvements

Warm Structure System Model - based on MER, MPF, validated with testing

For environments up to 300 W/cm^2

HT-424 for adhesive

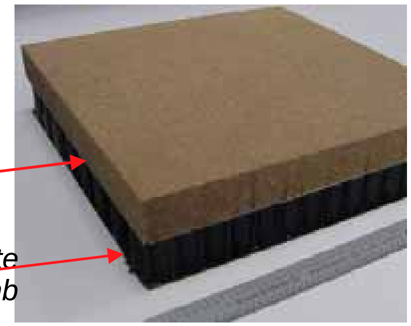
Aluminum honeycomb



MER SLA-561V System 250 deg C

Modified RS9 for adhesive

Graphite polycyanate honeycomb



Warm Structure SLA-561V System 316 deg C

14% Improvement

Areal Density = 2.07 lb/ft^2

Areal Density = 1.78 lb/ft^2

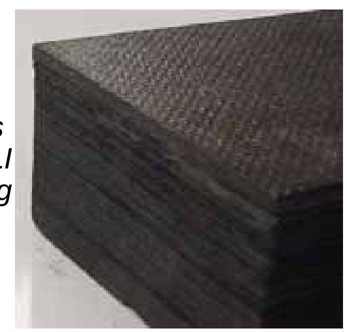
Hot Structure System Model - based on Genesis, validated with testing

For environments up to 700 W/cm^2

Final System included backup aluminum Honeycomb structure

Genesis Carbon-Carbon

Final System includes 11-layer MLI and high-temp coating



Hot Structure Carbon-Carbon/Calcarb

31% Improvement

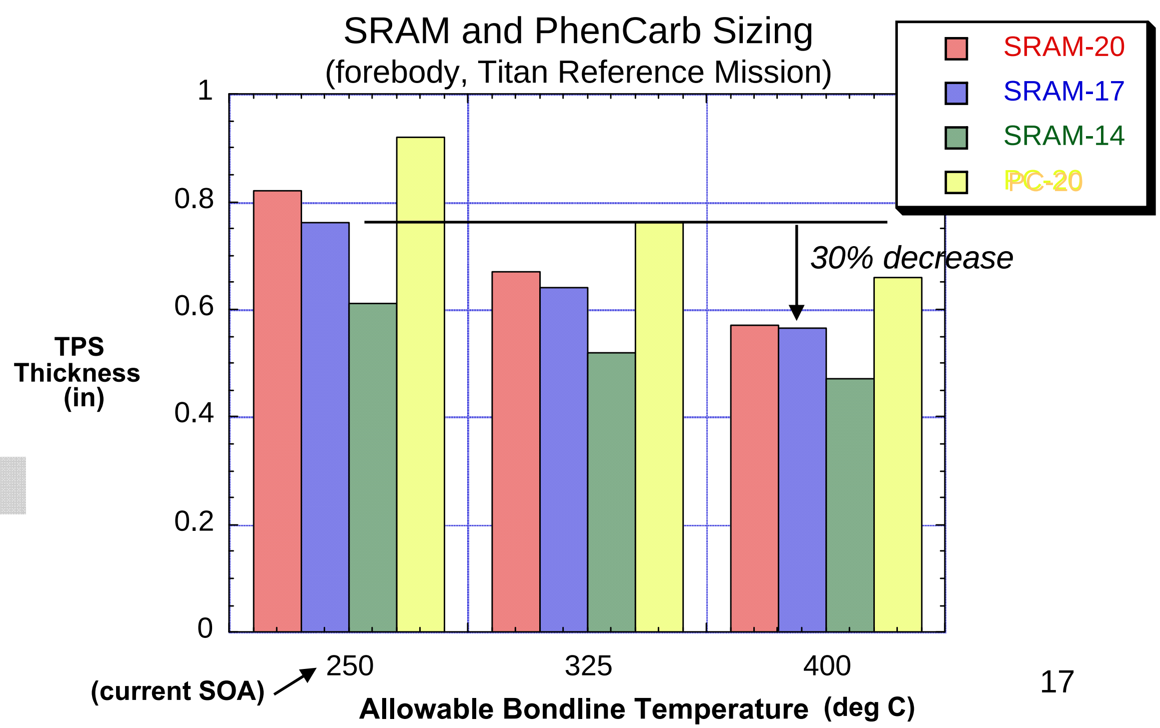
Areal Density = 3.65 lb/ft^2

Areal Density = 2.50 lb/ft^2

Higher Bondlines and Efficient Ablators Reduce Mass

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

1-m SRAM-20 aeroshell test at Solar Tower



Aerocapture Flight Validation Concept

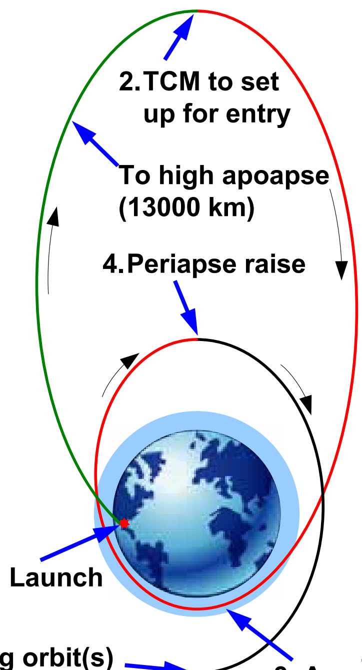
ST9 Vehicle Concept

Mission Parameters

Vehicle Type	60° sphere-cone aeroshell
Vehicle Mass (CBE)	148 kg, 1.2 m diameter
Access to space	Delta-II dual launch to 13000 km
Mission Duration	9.1 hours
Atmospheric Entry Speed	9.6 km/s
Atmospheric ΔV	1.7 km/s
Nominal Launch	June 2010
NMP ST9 Funding	$85 M
ISP ST9 Funding	$22 M

- 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

Mission Sequence



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**

Figure 6 – Posttest Sample 3540 with 18.0-Deg Seam

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
  - CO_2 EAST tests to verify shock chemistry

Aerocapture Technology Subsystem Readiness

Subsystem \ Destination	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 models agree within 35-300%	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. No known technology gaps.	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 tech gaps. ENABLING	Accomplishes 96.9% of ΔV to achieve Triton observ. orbit. ENABLING

Ready for Infusion | Some Investment Needed | Significant Investment Needed

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?**