Aerocapture Mission Concepts for Venus, Titan and Neptune

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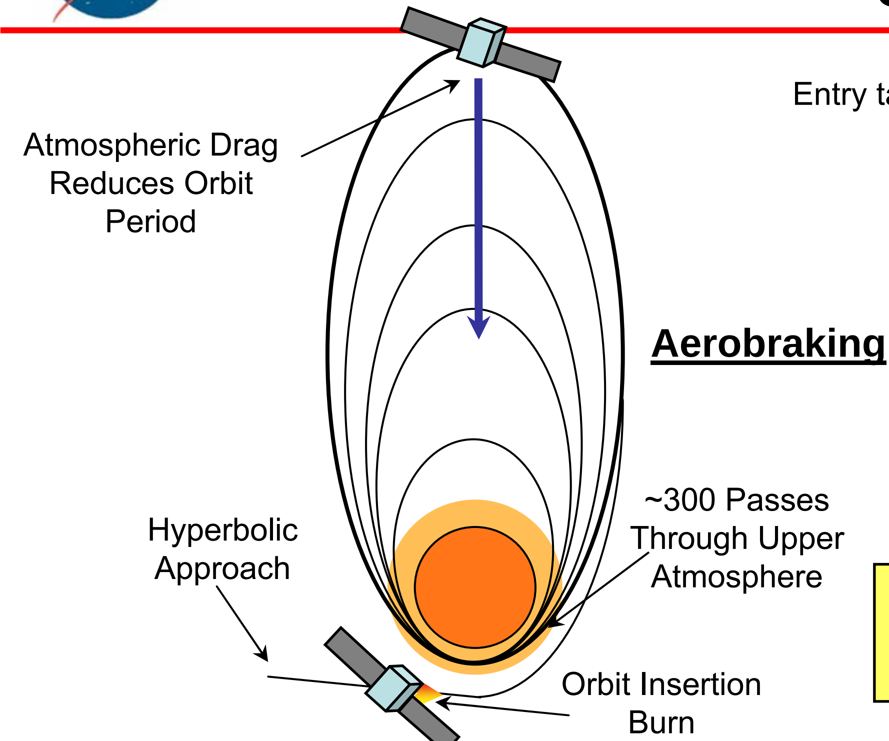
6th International Planetary Probe Workshop | Atlanta, GA | June 24, 2008

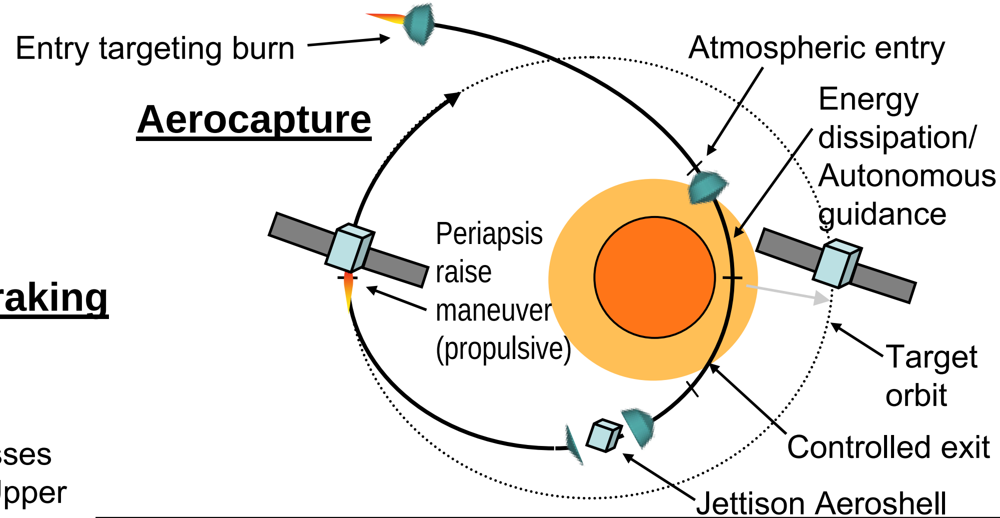
Motivation for this Talk

- Numerous Flagship and New Frontiers mission preparations are underway; cost is a big factor
- Detailed mission concept studies conducted by In-Space Propulsion Technology (ISPT) Program may be relevant:
  - Titan Explorer (2002)
  - Neptune Orbiter (2003)
  - Venus Discovery mission (2004)
- This presentation provides a review of those studies and a starting point for considering Aerocapture technology as a way to reduce mass and cost, to achieve the ambitious science returns currently desired

Aerobraking vs Aerocapture



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



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
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	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:

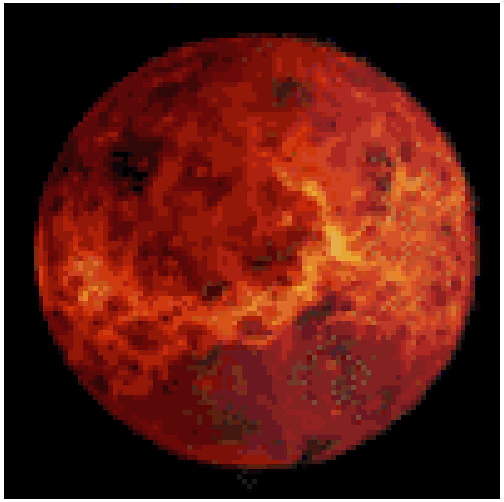
- **ENHANCING** missions to Venus, Mars
- **STRONGLY ENHANCING** to **ENABLING** missions to Titan, and Uranus
- **ENABLING** missions to Jupiter, Saturn, and Neptune

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

Aerocapture at Venus

Science at Venus

Very nearly Earth's twin -- why is it so different?



Science Areas of Interest

- Lithosphere (Crust & Interior)
  - Composition (elemental, mineralogy, isotopes)
  - Structure
  - Dynamics
- Atmosphere
  - Escape processes (evolution since formation)
  - Circulation
  - Composition & chemistry
    - Especially lower troposphere
- Surface & shallow subsurface
  - Interface between lithosphere & atmosphere
    - Lithosphere-atmosphere interactions
    - Clues to interior
  - Composition
  - Chemistry
  - Geology, geophysics
    - Any evidence for evolved crust?
      - Any granite at all?

Flagship mission study currently underway

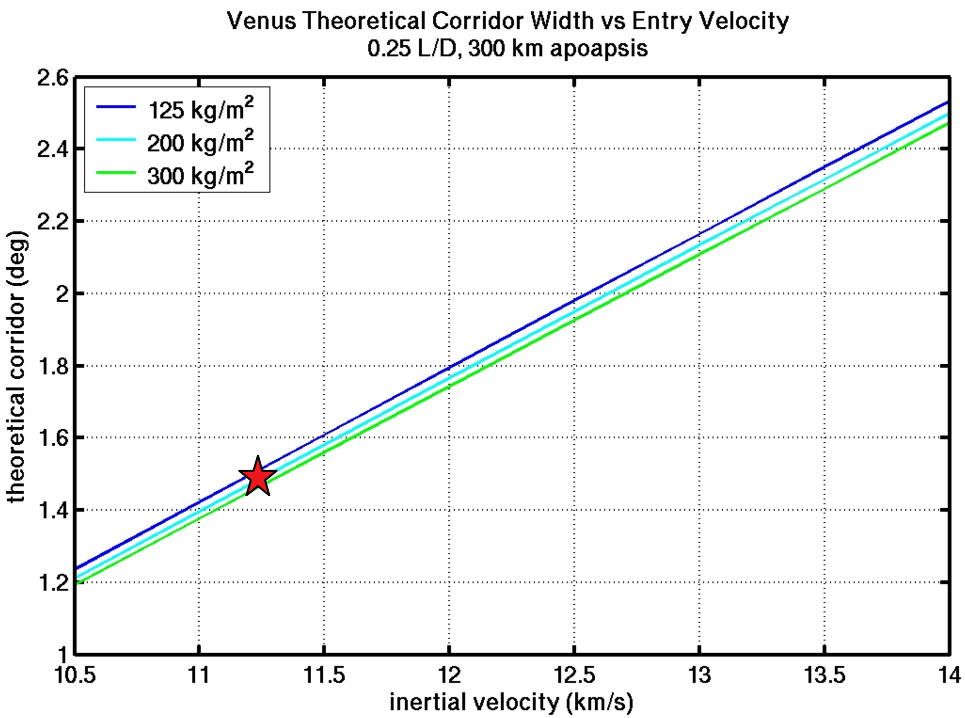
Candidate Mission Elements

- Orbiter
- Landers or rovers
- Aerial vehicles at various altitudes

Candidate Orbiter Science Instruments

- Imaging: multispectral IR
- Radar: altimetry, SAR, InSAR, GPR
- Radiometry: microwave-submm and/or IR
- Radio Science gravity
- Neutral & ion mass spectrometer
- Magnetometer
- Plasma

Venus Aerocapture Systems Study (2004)

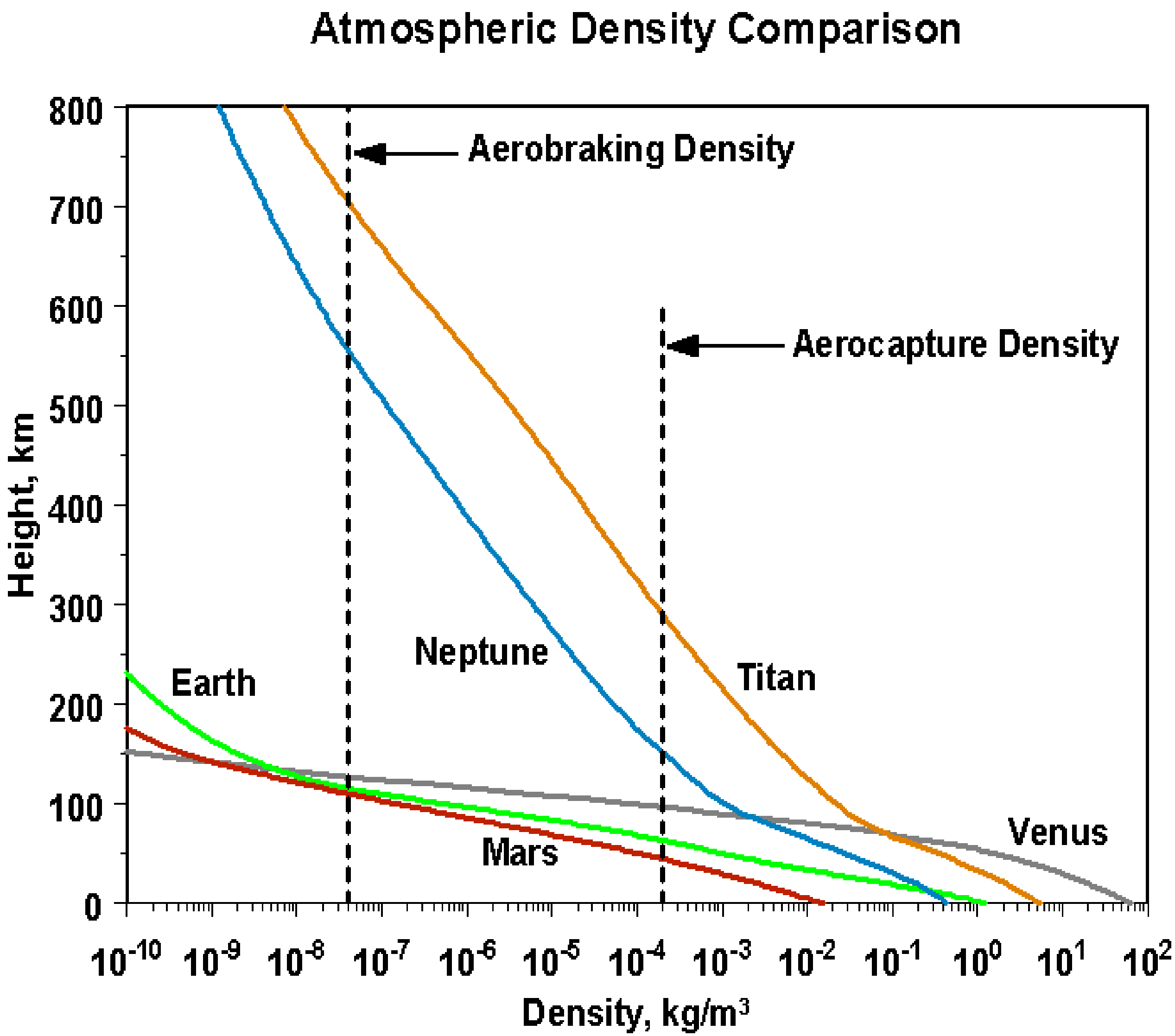


- **Entry vehicle characteristics**
  - 70º Sphere-Cone, L/D = 0.25
  - Entry Mass = 900 kg (initial allocation)
  - Diameter = 2.65 m
  - Ballistic Coeff, $m/(C_D A)$ = 114kg/m^2
- **Ballistic Coeff Performance Trade**
  - $m/(C_D A)$ = 228 kg/m^2

Spacecraft entry mass allocation = 1090kg corresponding $m/(C_D A)$ = 138kg/m^2

- Aerocapture into 300 km X 300 km polar orbit
- Atmospheric interface = 150 km altitude
- 11.25 km/sec inertial entry velocity, -6.12° entry flight path angle
- Autonomous guidance
- Small impulsive periapsis raise ΔV and apoapsis adjustment ΔV to attain science orbit calculated.

Atmospheric Density Variation with Height

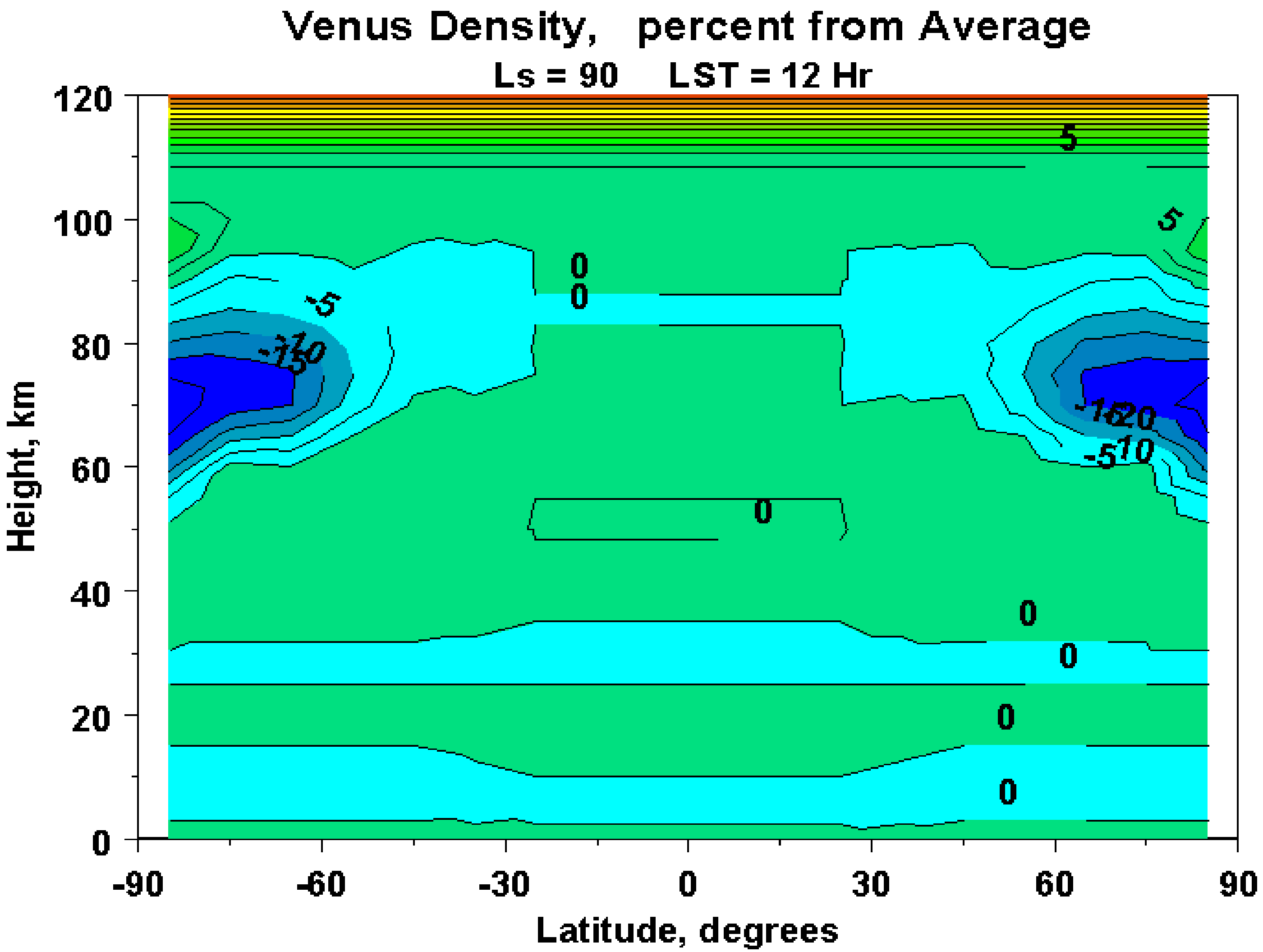


- Venus has Rapid Height Variation of Density
- Other Things Being Equal, This Leads To Smaller Entry Corridor Width

Ref.: J. Justus

Venus Atmospheric Density Variations
0-100 km vs Latitude

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



Ref.: J. Justus

Example Monte Carlo Simulation Results: Venus Aerocapture

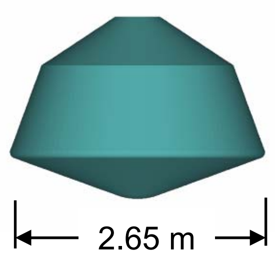
Venus Aerocapture Systems Analysis Study, 2004

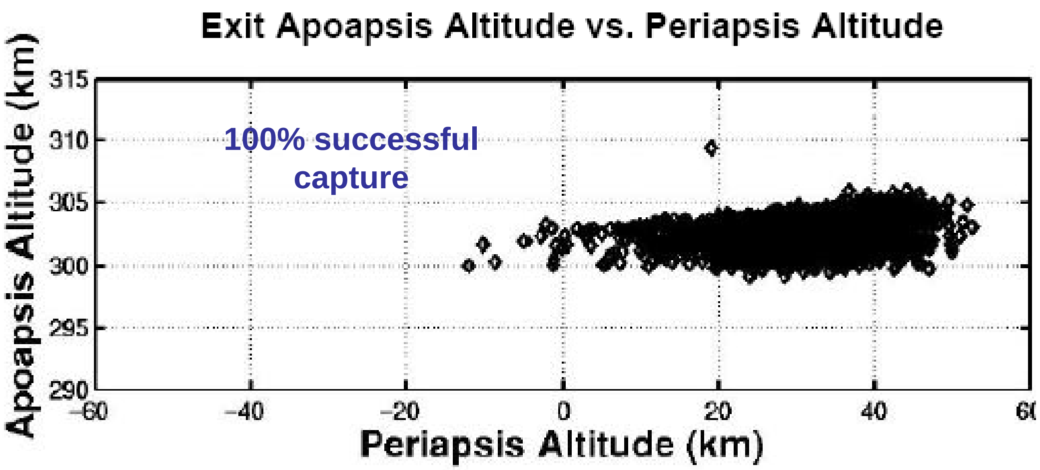
Vehicle L/D = 0.25, m/C_DA = 114 kg/m^2

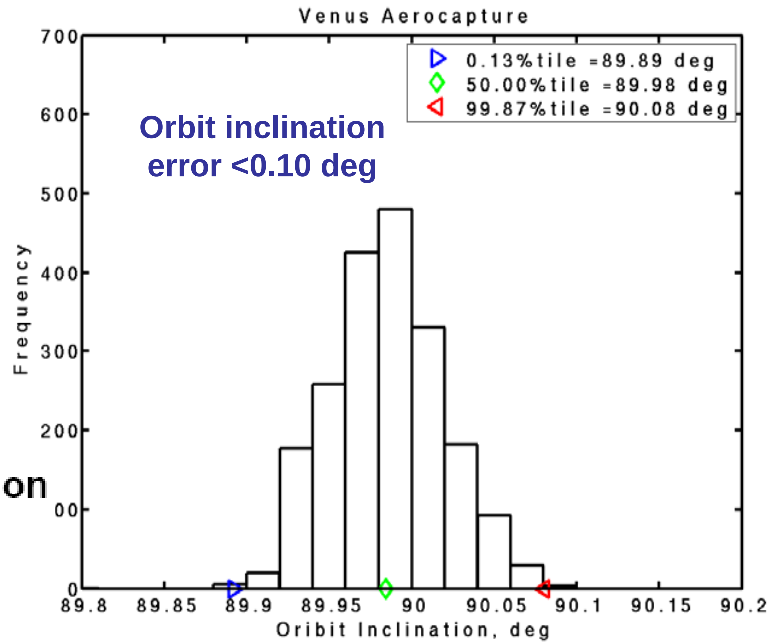
Target orbit: 300 km circ., polar

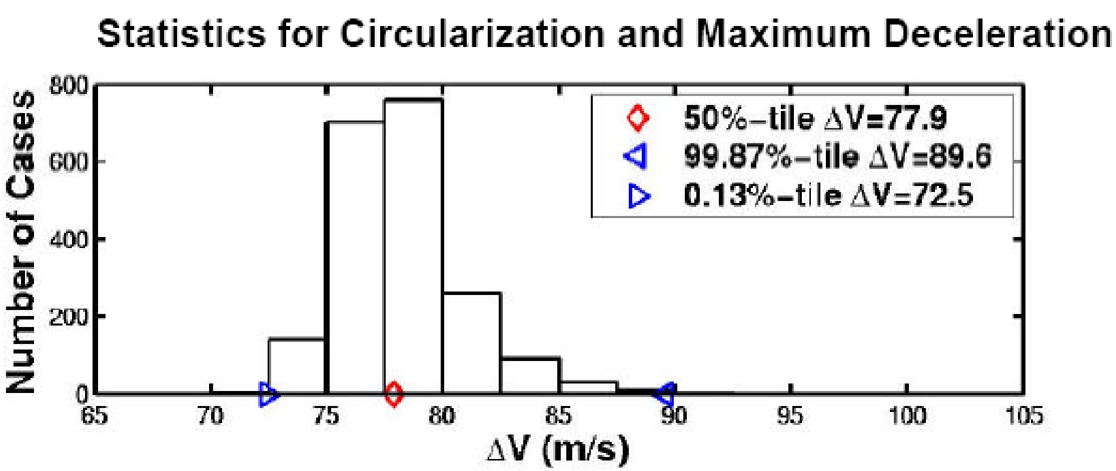
All-propulsive ΔV required for orbit insertion: 3975 m/s

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









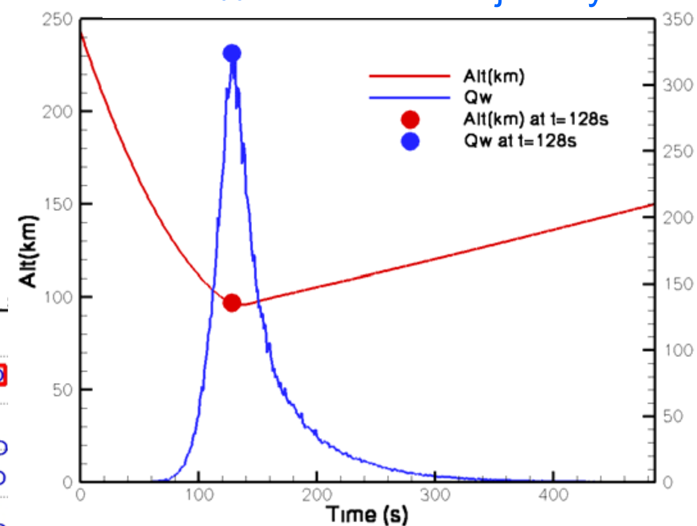
30 deg/sec bank rate

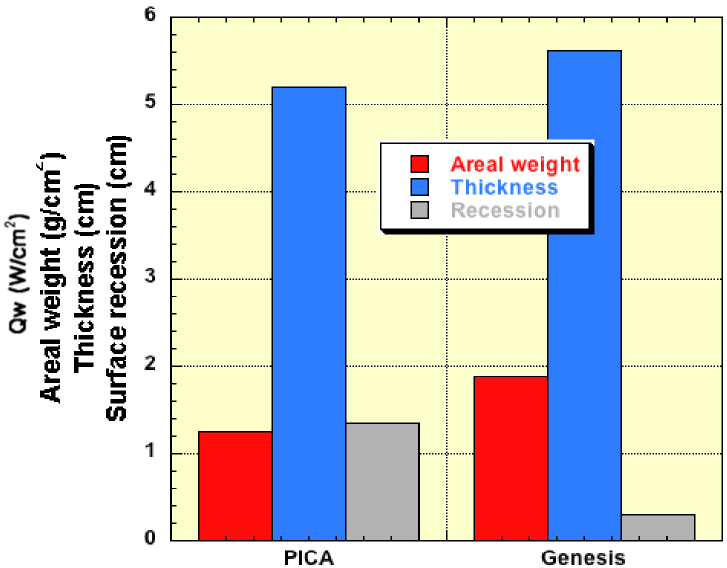
5 deg/sec2 bank acceleration

First-Look Aeroheating/TPS Sizing

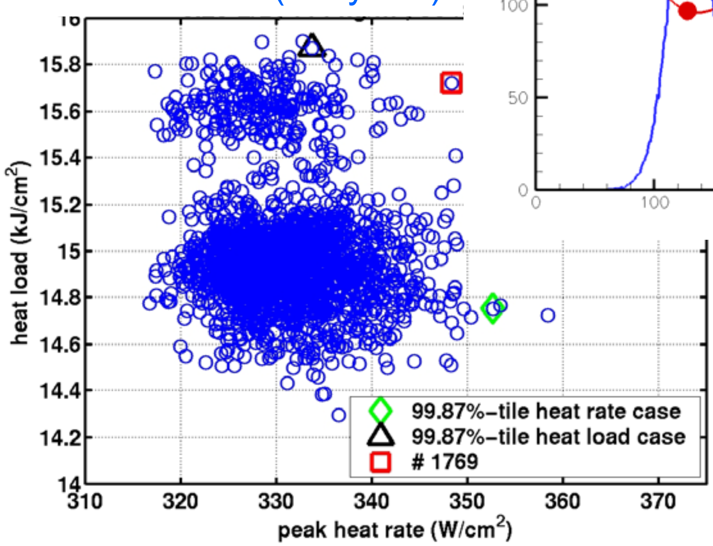
- Initial convective and radiative aeroheating results computed with LAURA/RADEQUIL and DPLR/NEQAIR at pk heating pt on 99.87% pk heat load M.C. trajectory; highest heating location on vehicle for radiative and convective; coupling estimate included
- Future work: aeroheating methods to reduce uncertainty in mass and shape change; TPS sizing of ARA PhenCarb, a potential non-tile option

99.87% Heat Load Trajectory





Monte Carlo (early ref.)

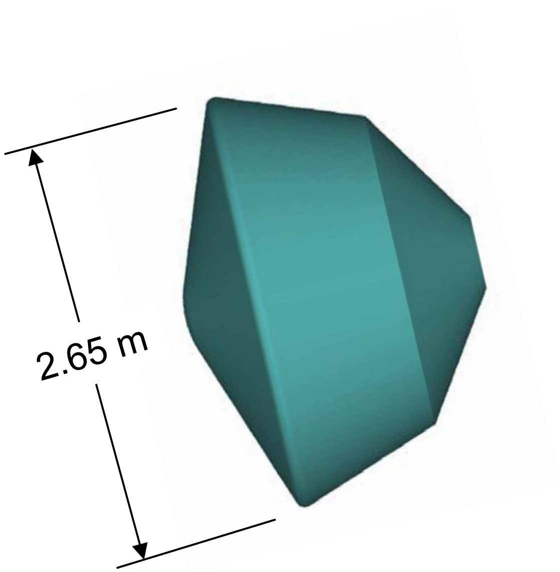


Material	Thickness (cm)	Recession (cm)	Areal Mass (g/cm2)	Total Mass (kg)
PICA	5.21	1.35	1.25	78.12
Genesis CC	5.61	0.30	1.88	117.50

Venus Orbiter Spacecraft Design

Top-level spacecraft design, mass, power analysis completed

- Delta 2925H-10 Launch Capability = 1165 kg
  - Cruise stage = 50 kg
  - Orbiter entry allocation = 1090 kg
    - Aerocapture system dry mass allocation = 350 kg (CBE = 243 kg)
    - Aeroshell Allocation (TPS + aeroshell structure) = 30% of wet launch mass capability
  - Mass margins are 20% or greater
- 1.4 m diameter high gain antenna packages in 2.65m 70deg sphere cone with biconic backshell (similar approach to Titan)



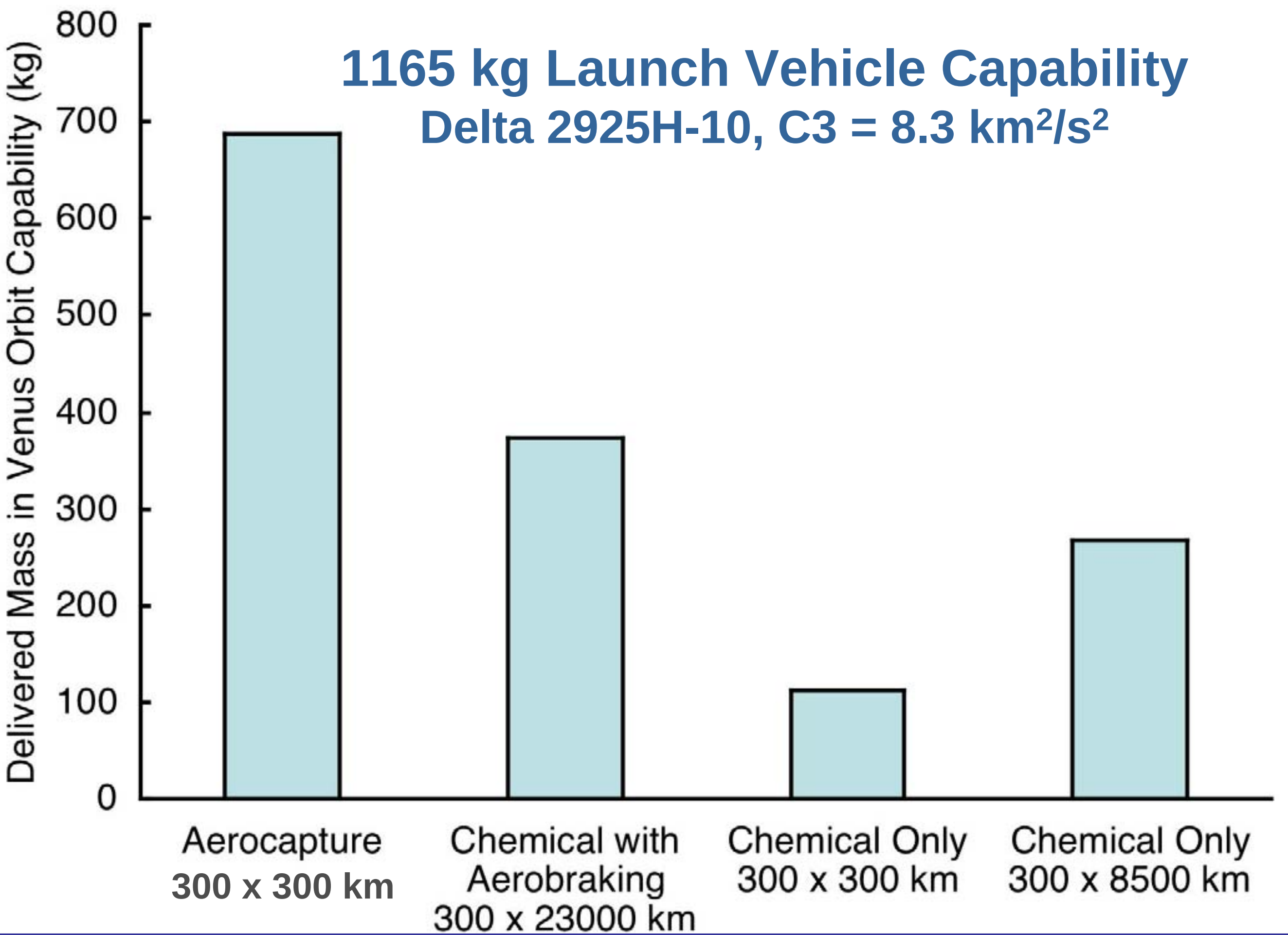
Alloc: Allocation
Cont: Contingency
CBE: Current Best Estimate

MEV: Max Expected Value
Cont = (MEV-CBE)/CBE
Margin = (Alloc-MEV)/MEV

		#	CBE	Cont	MEV	Alloc		
Launch Vehicle Capability						1165		
Propellant and Pressurant					**89.6**			
Hydrazine + Helium					**89.6**			
Cruise					27.3	50	m/s	JPL Margin
Aerocapture					50.9	99.2	m/s	
Orbit					8.8	10	m/s	
Residual & Pressurant	Tank				2.6		**Margin**	
Launch Dry Mass			**680.0**	**22.2%**	**831.2**	**1075.4**	**29.4%**	36.8%
Aerocapture System Dry Mass			**242.7**	**20.0%**	**291.3**	**349.5**	**20.0%**	30.6%
Spacecraft Dry Mass			**437.3**	**23.5%**	**540.0**	**725.9**	**34.4%**	39.8%
Instruments			**50.0**	**30.0%**	**65.0**			
Bus		121	**387.3**	**22.6%**	**475.0**			
Attitude Control		8	19.5	2.2%	19.9			
Command & Data		26	37.3	17.3%	43.8			
Power		5	46.5	17.0%	54.4			
Hydrazine Propulsion System		39	32.4	6.9%	34.6			
Structures & Mechan		1	140.0	30.0%	182.0			
Harness	31.00	1	31.0	30.0%	40.3			
X-Band Telecomm		40	20.6	6.5%	22.0			
Thermal		1	60.0	30.0%	78.0			

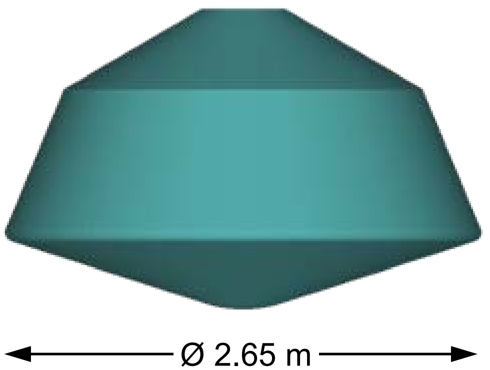
s/c dry mass allocation includes 50kg cruise stage

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 w/constant launch vehicle, Aerocapture delivers:
- **1.8x more mass** into orbit than aerobraking
- **6.2x more mass** into orbit than all chemical

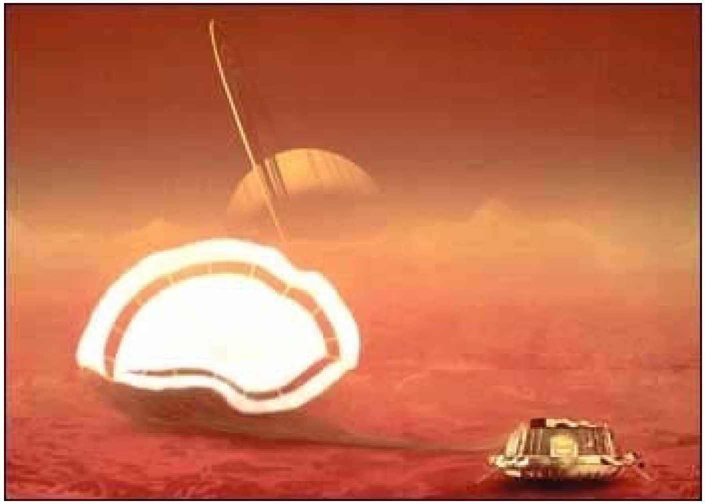
Reference: Lockwood et al, "Systems Analysis for a Venus Aerocapture Mission", NASA TM 2006-214291, April 2006

Venus Systems Analysis Conclusions

- Aerocapture performance 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
- Some additional guidance work would increase robustness for small scale height of Venus atmosphere
- For delivery into 300 x 300 km Venus orbit on same launch vehicle (Delta 2925H), aerocapture delivers
  - 1.8x more mass into orbit than aerobraking
  - 6.2x more mass into orbit than chemical only
- These 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

Aerocapture at Titan

Science at Titan



Cassini-Huygens Results -- "Lifting the Veil"

- Surprisingly Earthlike balance of evolutionary processes
- Methane cycle, analog to Earth's hydrologic cycle
- Aeolian & fluvial processes
- Rich organic environment
- Probable interior ocean -- communicates with surface?

Science Areas of Interest

- Lithosphere
  - Composition
  - Structure, evolutionary history
  - Dynamics: tidal effects, tectonism, (cryo)volcanism
  - Role & history of impacts
  - Resurfacing through erosion, sedimentation
    - Aeolian & fluvial
- Hydrospheres, surface & interior
  - Location (interior: depth to top & bottom)
  - Composition
  - Communication with surface?
- Atmosphere
  - Composition; outgassing & resupply from interior
  - Circulation, winds
  - Weather: clouds, rain (sometimes heavy), lightning
  - Loss processes
- Interactions among the above
- Evolution of organic compounds, in all venues
- External forcing: tidal effects, seasonal variations

Flagship mission study currently underway

Candidate Mission Elements

- Orbiter (long-duration)
- Landers
- Long-duration aerial vehicle(s) with altitude control
- Buoys / Boat / Submarine?

Candidate Orbiter Science Instruments

- Spectrometers: IR imaging, UV, submm
- Radar: altimetry, SAR, GPR
- Composition: GC, MS, or other for high-mol-mass organics
- Radio Science gravity
- Magnetometer
- Hi-energy plasma
- -> Driven to relatively high data rates

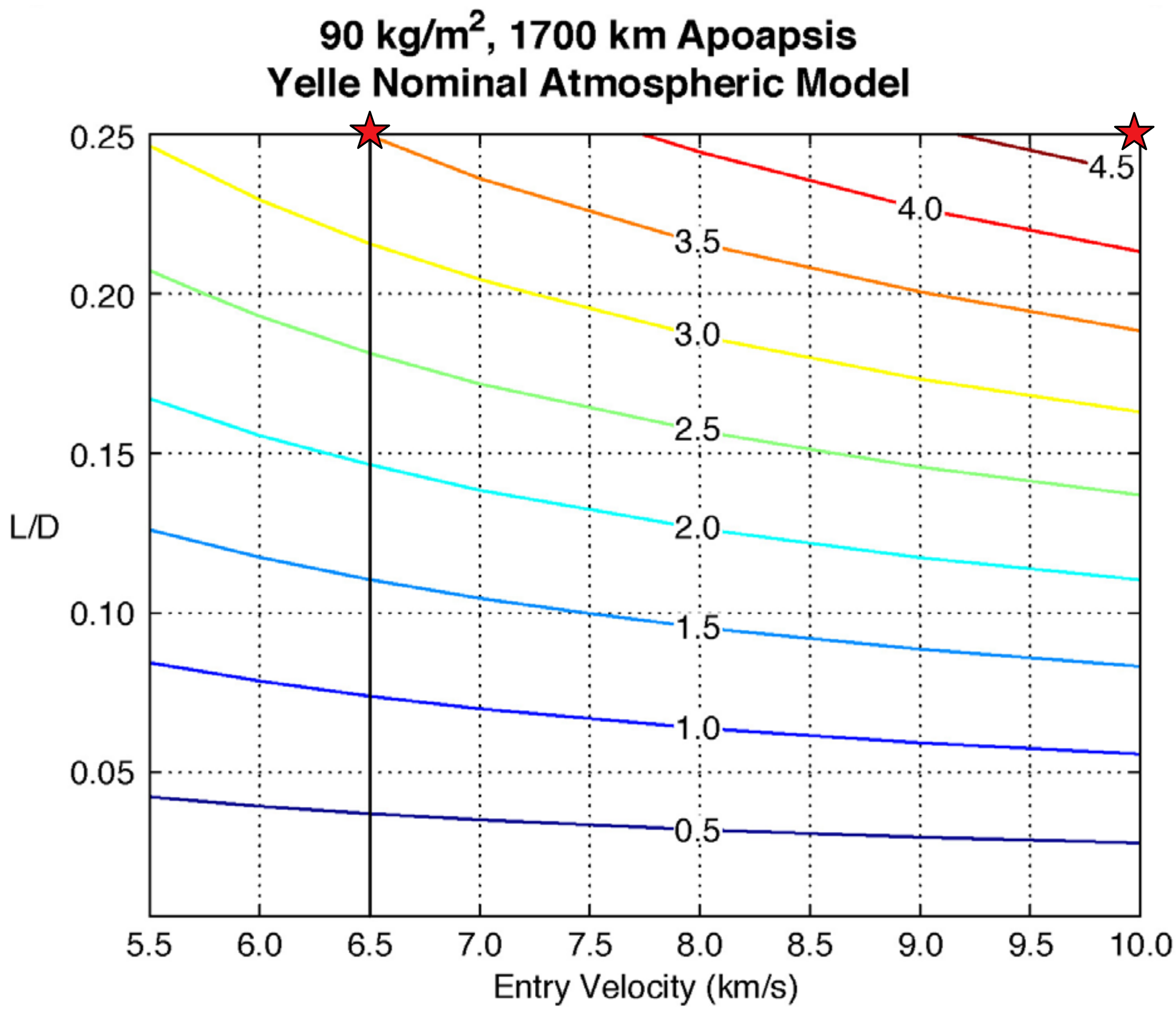
2002 Titan Reference Concept - Level 1 Objectives

- Orbiter and Lander delivery to Titan
  - Orbiter delivers Lander to Titan entry trajectory; Lander performs direct entry
  - Orbiter aerocaptures for Titan orbit insertion – near polar orbit
- 10 year total mission lifetime, includes
  - 3 year orbiter ops
    - Orbiter science instruments
      - Microwave spectrometer
      - SAR
      - Multispectral imager
      - USO
    - Relay for lander ops – 1 year
- Launch date = 2010; TRL 6 cutoff = 2006; compare performance with other launch opportunities
- Launch vehicle: Delta IV Medium, 4m fairing
- Cruise
  - SEP Propulsion Module (compare performance to chemical propulsion module)
- Utilize as much heritage HW as possible
- Class A mission; fully redundant design
- Lander is “black box”, 400 kg allocation

Ref: Lockwood, et al, “Aerocapture Systems Analysis for a Titan Mission”, NASA TM 2006-214273, March 2006

Low L/D Configuration for Titan Aerocapture

- L/D=.25 configuration provides
  - 3.5 deg theoretical corridor width with 6.5 km/sec entry velocity
  - 4.7 deg theoretical corridor width with 10 km/sec entry velocity
- 3.5 deg corridor width more than adequate to accommodate 3-sigma navigation delivery errors, atmosphere dispersions and aerodynamic uncertainties with 99.7% success
- High heritage low L/D sphere cone configuration selected



Contours denote theoretical corridor width

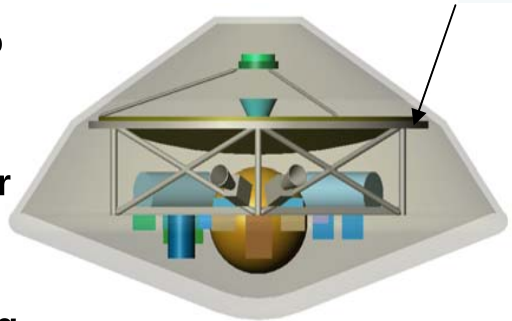
Ref: Lockwood, et al, "Aerocapture Systems Analysis for a Titan Mission", NASA TM 2006-214273, March 2006

Titan Aeroshell Aerocapture Reference Concept, Mass

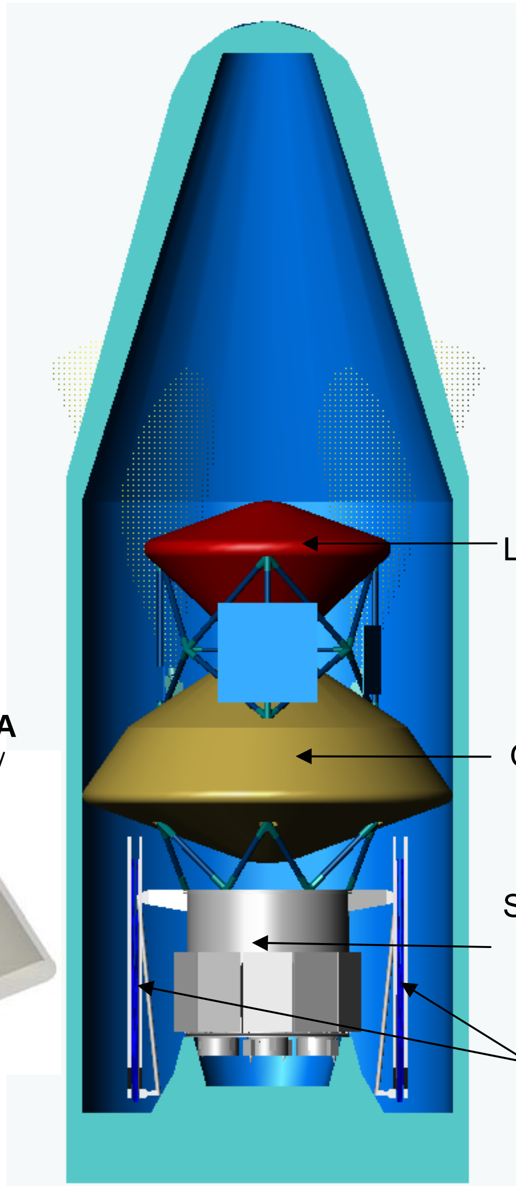
	Mass (kg)			
	Subsystem Rack-up			
Component	Current Best Estimate	% Contingency	Growth	System Allocation
Lander	***280.2***	***29.8%***	***363.8***	***400.0***
Orbiter/Lander Interface	**47.5**	**30.0%**	**61.8**	**61.8**
Orbiter	***883.6***	***24.2%***	***1097.7***	***1200.0***
Prop Mod/Orbiter Interface	**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		

- **Delta 4450, SEP, EGA, aerocapture has 30% system level margin, >10% system reserve**
- **Delta 4450, SEP, VGA, aerocapture has 6% system reserve, opportunity for improvement**
- **Aerocapture mass fraction = 39% of orbiter launch wet mass**
- **Aeroshell size, packaging efficiency governed by 2.4m diameter HGA packaging**
- **Results not possible without this level of detail in packaging, s/c design, structure, TPS**

2.4 m diameter HGA



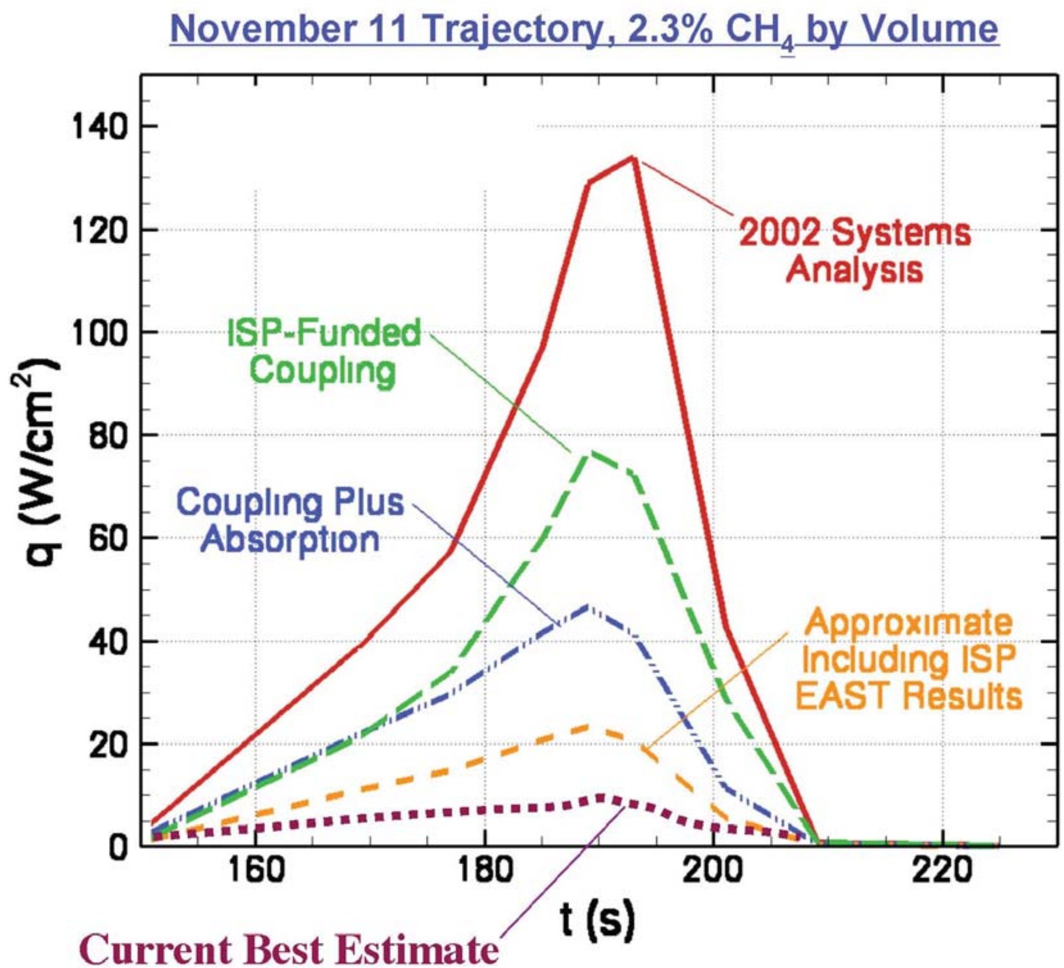
3.75 m diameter Aeroshell



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

Updates Since 2002

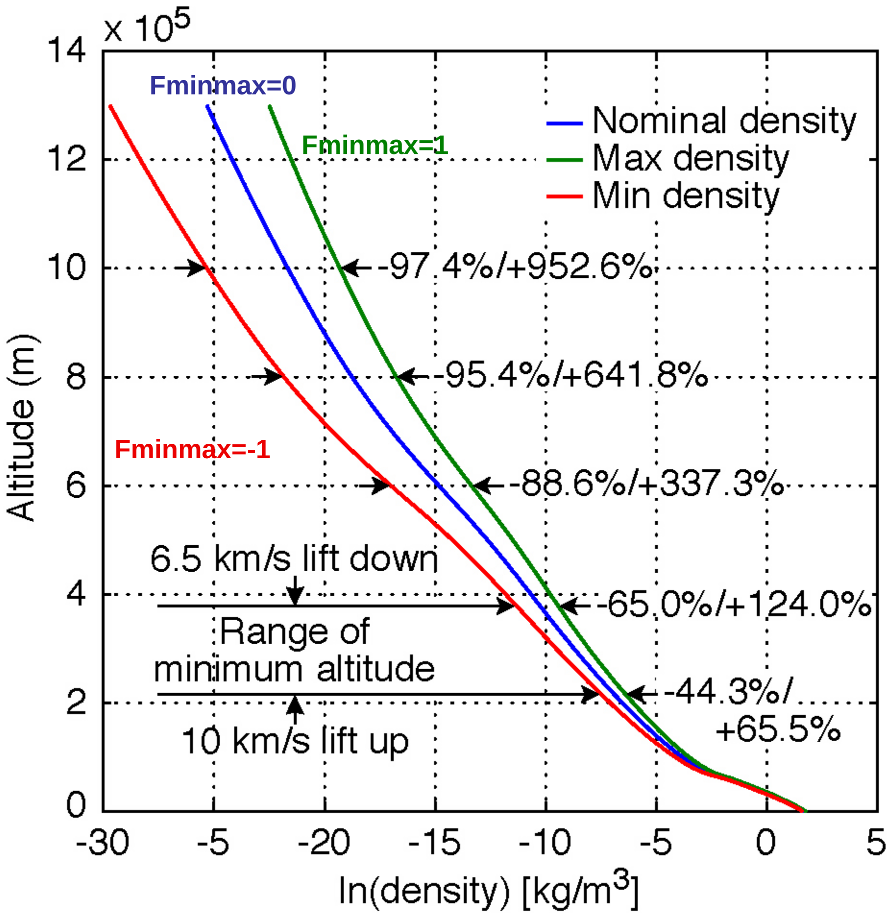
- Cassini-Huygens provided:
  - Improved ephemeris data for reduced flight path angle uncertainty
  - Improved atmospheric density measurement accuracy
  - Improved atmospheric constituent data (less than 2% CH_4 vs 5% assumed in 2002 study)
- Aerothermal modeling investments and testing provided improved 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)



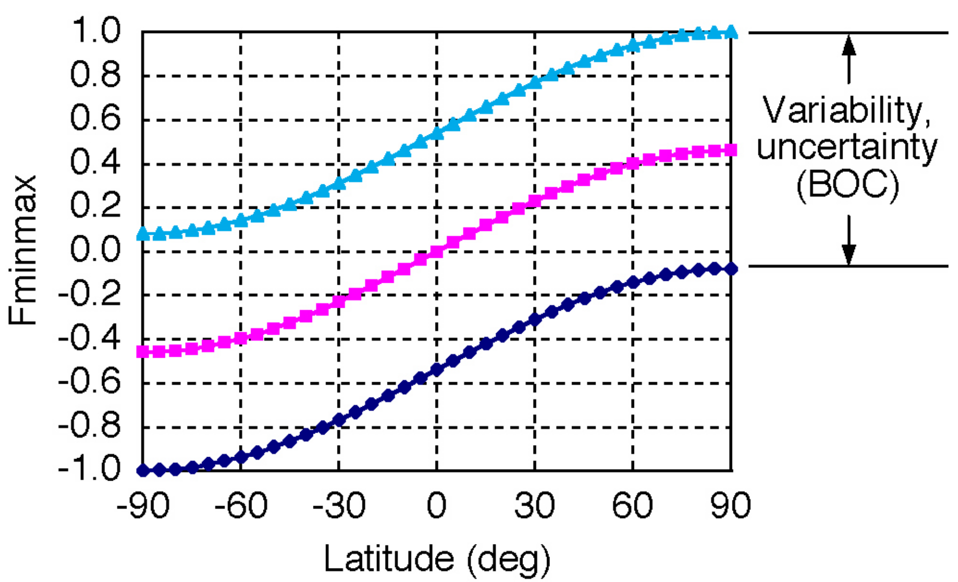
Ref: Mike Wright

Titan-GRAM Atmosphere Model

- Titan-GRAM includes model of:
  - Measurement uncertainties, residual uncertainties (turbulence, waves, etc)
  - Variation with latitude, altitude, time of day, season
  - Composition; maximum CH4 = 5% by volume for -1 ≤ FMINMAX ≤ 1
- Model fidelity required to assess mission feasibility, robustness



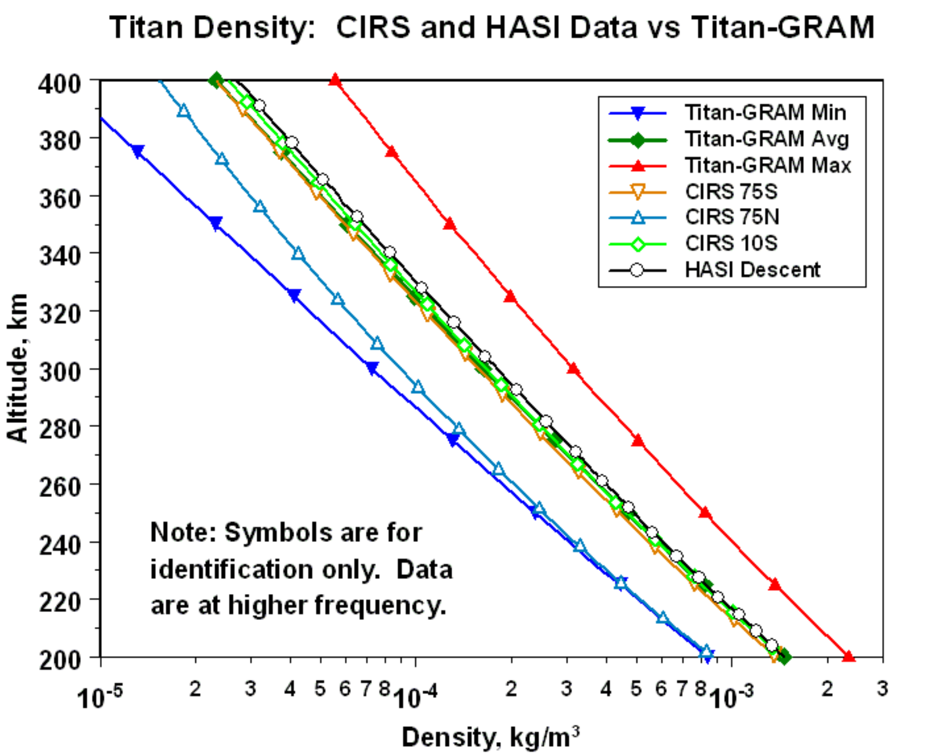
Atmosphere Variation at Aerocapture Altitude

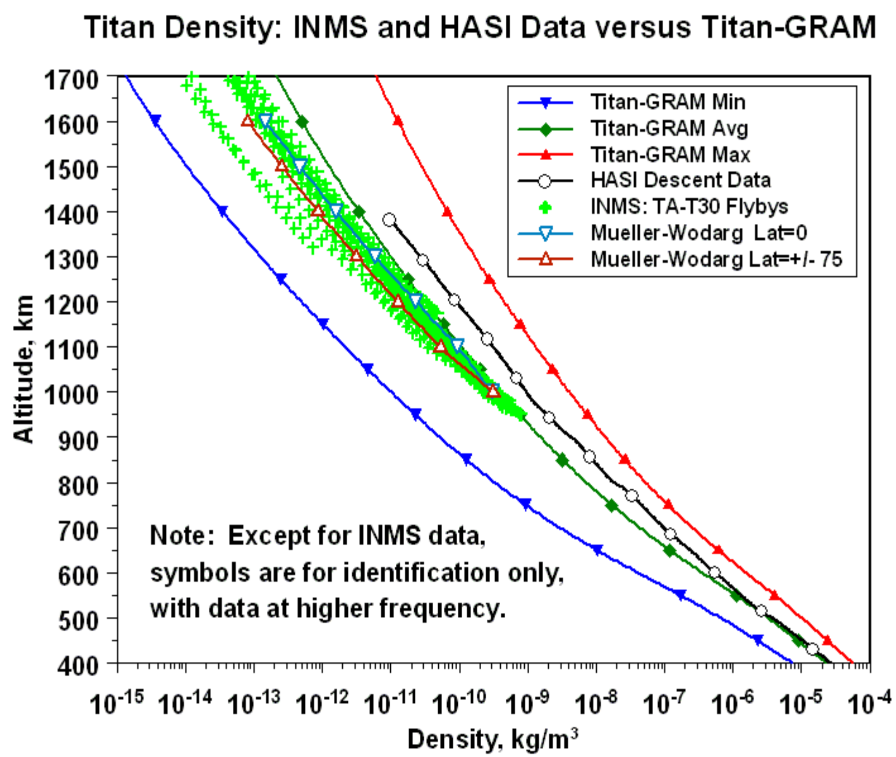


- Arrival date of current study results in maximum variation in density with latitude
- Cassini-Huygens data will reduce measurement uncertainty

Ref.: J. Justus

Titan-GRAM Model vs Cassini-Huygens Data

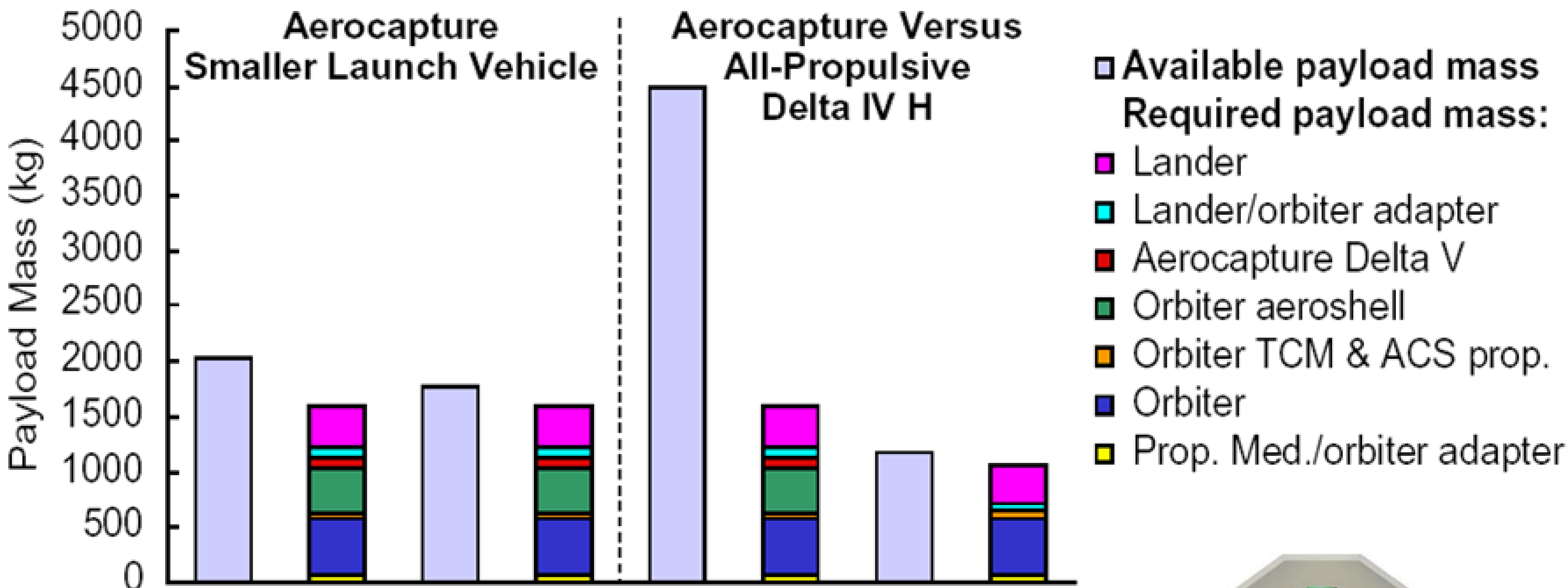




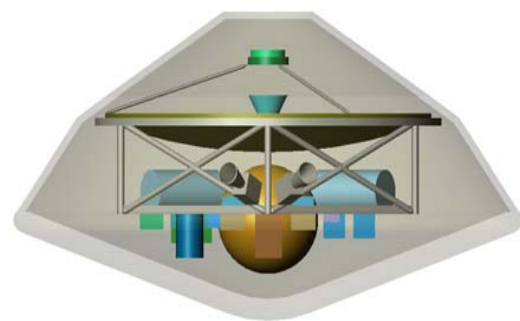
Observations from HASI and INMS are well within Titan-GRAM max/min estimates

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

Titan 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 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 Mars ’09)
- 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 in MRO

Ref.: M. K. Lockwood, et al.

Aerocapture at Neptune

Science at Neptune

Ice Giant (or Water Giant)

- Richer in heavier elements (e.g. water, ammonia)
- Mix of planet, magnetosphere, satellites, rings
- Triton might be a captured Kuiper Belt object

Science Areas of Interest

- Neptune
  - Composition (clues to origins)
  - Interior structure
  - Atmospheric dynamics: circulation, winds
  - Dynamo magnetic field
- Triton
  - Composition
  - Interior structure & activity
  - Surface morphology & activity, distribution of volatiles
  - Resurfacing processes
  - Orbital history
- Rings & small moons
  - Ring particle compositions & sizes
  - Ring dynamics
  - Moon composition, orbital history
- Magnetosphere
  - Structure
  - Interactions with solar wind, moons, rings
- Seasonal variations

Subject of recent NASA "Vision Missions" Program studies; long-term flagship mission priority

Candidate Mission Elements

- Orbiter
- Atmospheric entry probes (2 or more)
- Triton lander

Candidate Orbiter Science Instruments

- Cassini-like instrument suite
  - Needed for investigation of an entire planetary system
  - Relatively massive
- -> Driven to relatively high data rates

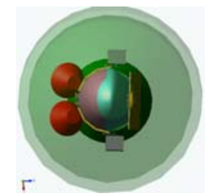
Neptune Orbiter Aerocapture Reference Concept

Launch Mass Summary

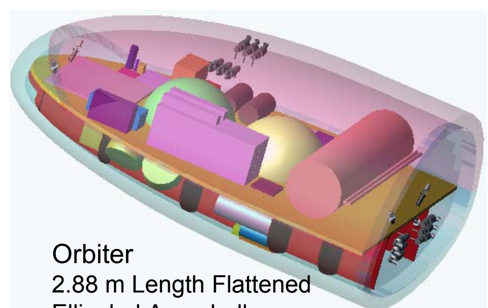
Component	Flight Units	Mass (kg) – Subsystem Rack-up: Current Best Estimate	% Growth	Growth	Wet Allocation	Fuel Load	System Allocation minus Fuel Load	Dry Mass Margin
Orbiter Launch Dry Mass	**269**	**518.2**	**28.5%**	**666.0**	**1081.4**	**282.5**	**798.9**	**35.1%**
Aeroshell/TPS Dry Mass	**34**	**681.0**	**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

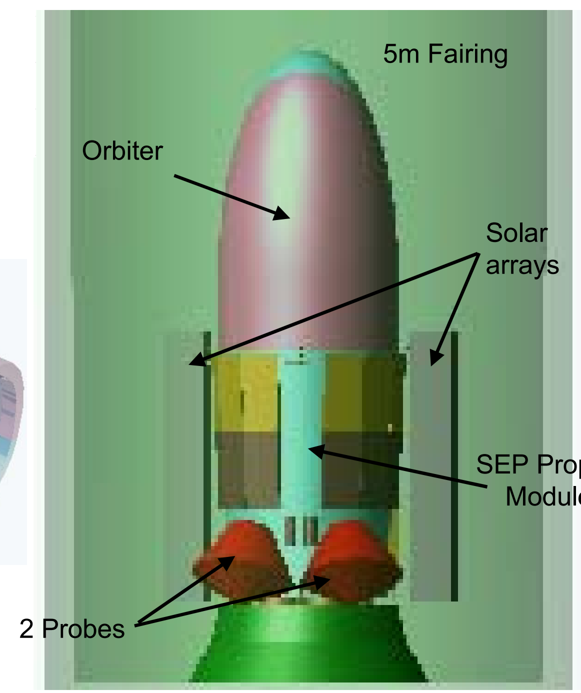
Launch Vehicle Capability	**5964**	
Unallocated Launch Reserve	**13.4%**	Unallocated Reserve / LV Cap
JPL System Dry Mass Margin	**31.8%**	(Dry Alloc - Dry CBE) / Dry Alloc
NASA Dry Mass Contingency	**29.8%**	(Dry Growth - Dry CBE) / Dry CBE (Measure of component maturity)
NASA Dry Mass Margin	**13.0%**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

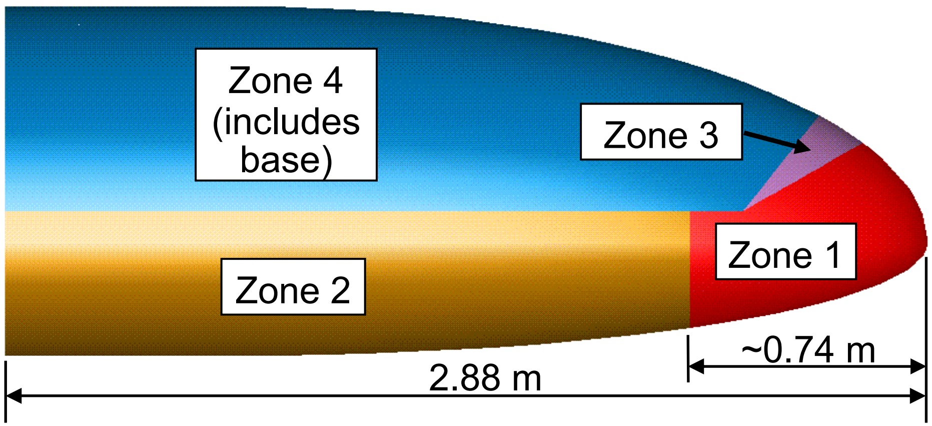


Orbiter
2.88 m Length Flattened Ellipsled Aeroshell

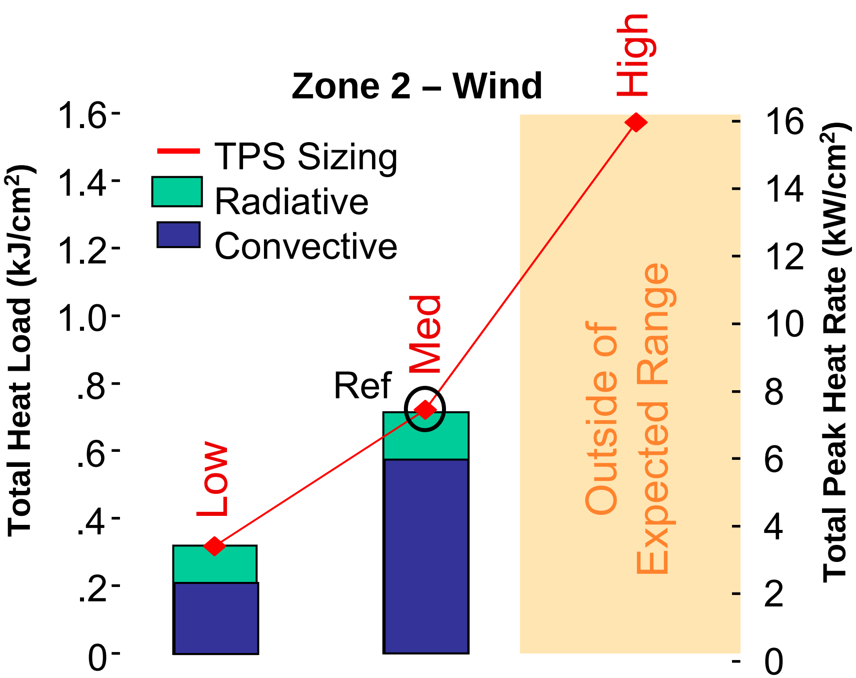


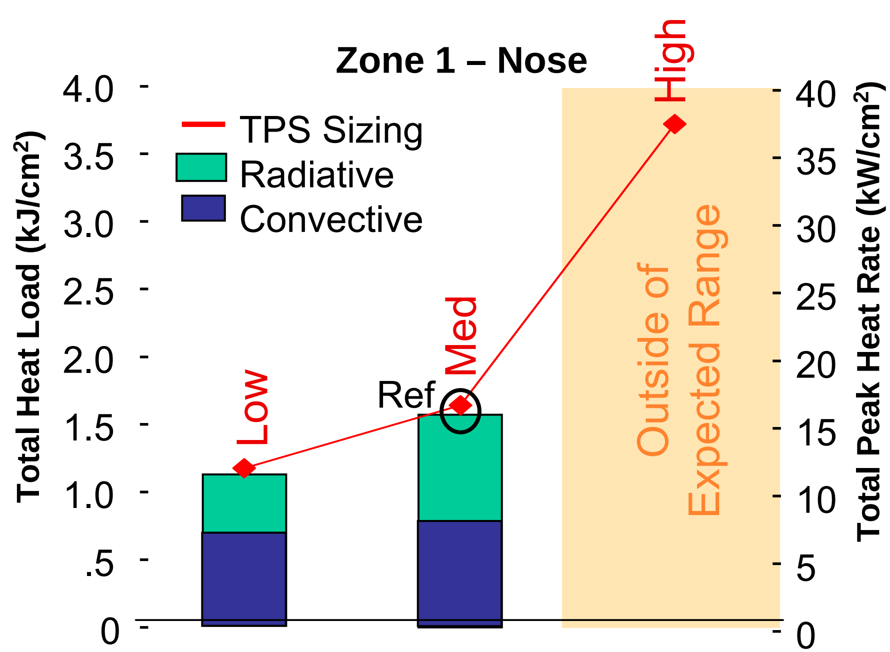
Ref.: M. K. Lockwood, et al.

Neptune Aeroheating Challenges



- Vehicle divided into 4 zones for TPS sizing. TPS selected/sized for max heating point in each zone.
- Heatshield (forebody) is defined by zone 1 + zone 2. Backshell (aftbody) is defined by zone 3 + zone 4. Post-aerocapture aeroshell separation occurs between the heatshield and backshell.
- “Low”, “Med”, and “High” aeroheating rates and loads along Monte Carlo trajectory #1647 shown. “Med” level of aeroheating utilized for TPS sizing for reference vehicle. After further aeroheating analyses, “High” is outside of expected range.





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

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

Conclusions

- Using Aerocapture can significantly increase the science return from Venus and Titan, and can enable a scientifically-viable mission to Neptune
- Aerocapture is ready to be applied to challenging missions at Titan, Venus, and with some more development, Neptune