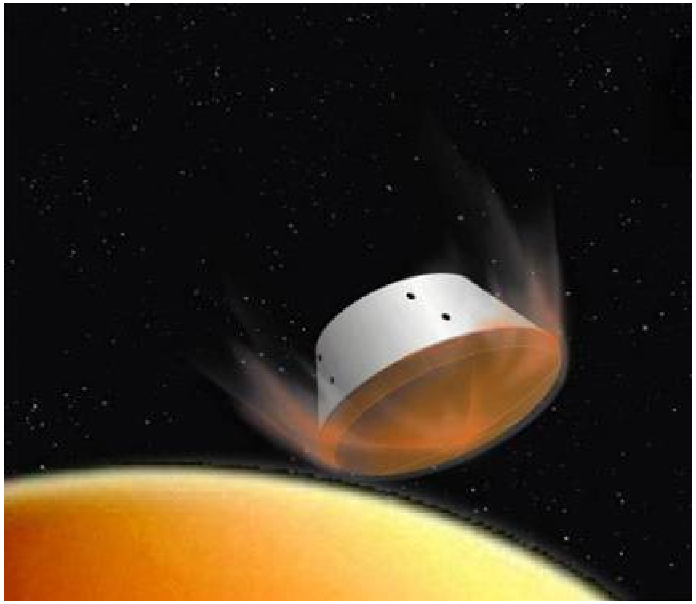
Aerocapture Summary
and
Risk Discussion



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Aerocapture Description

Aerocapture consists of:

- Hardware -- heatshield, reaction control system, avionics
- Software -- specialized guidance to steer vehicle to the correct exit state

The HARDWARE part has been done many times:

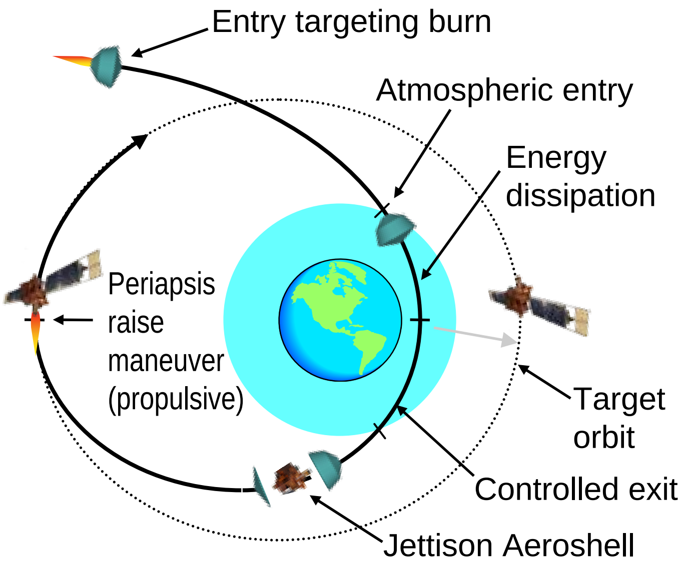
- Mercury, Gemini, Apollo, Viking, Pathfinder, MER, Space Shuttle, shroud jettisons,…
- (and many of these are hypersonic, guided vehicles)

The specific Aerocapture guidance algorithm has never been flown before, but has heritage in Apollo and Shuttle.

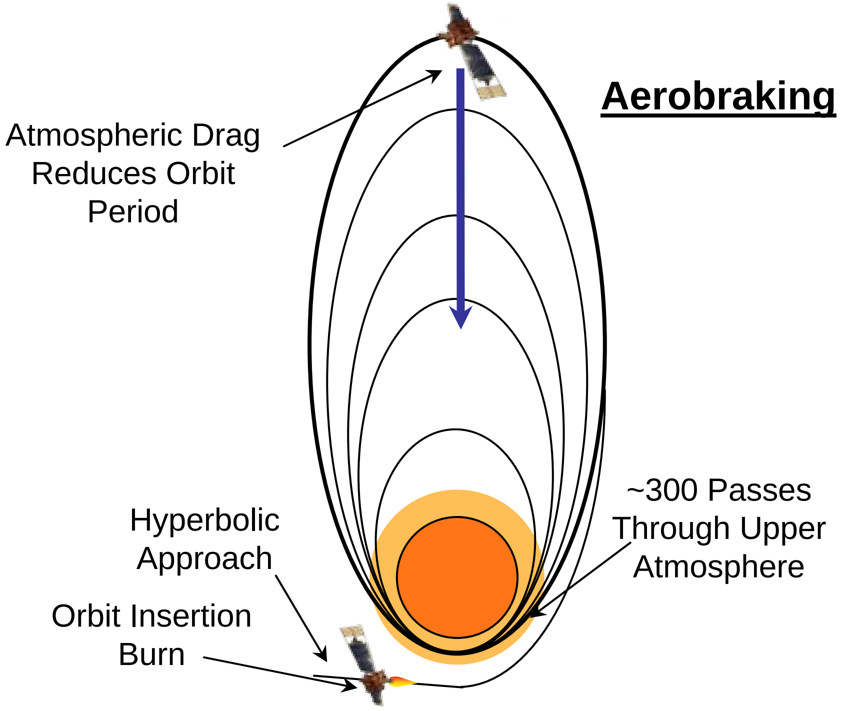
- Fully analytic
- Less than 400 lines of code

The portion of Aerocapture not previously demonstrated is the atmospheric exit

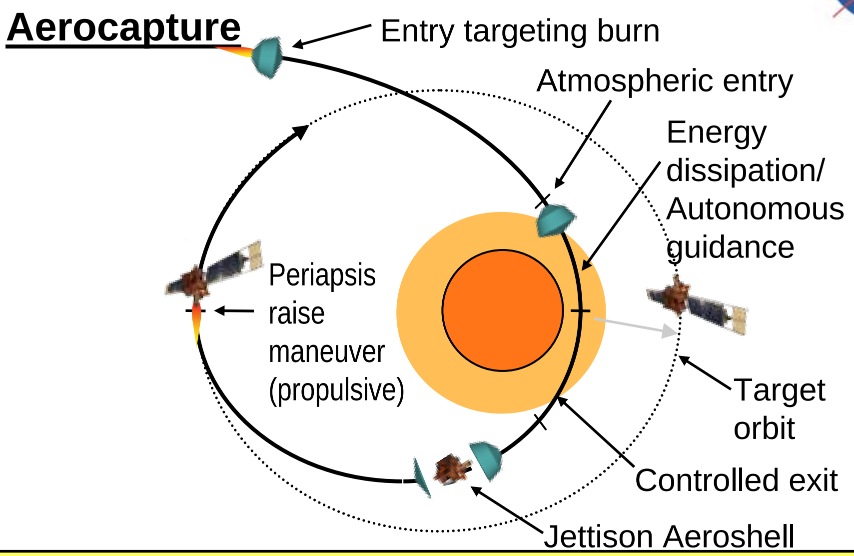
- A skip was human-rated for Apollo weather divert but never used
- Orion will skip to achieve an anytime return to the US Pacific coast



Aerocapture vs Aerobraking



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 bank angle 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

Parametric Analysis Results

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 Guidance

Aerodynamic drag provides the ΔV, while aerodynamic lift provides capability required to respond to dispersions

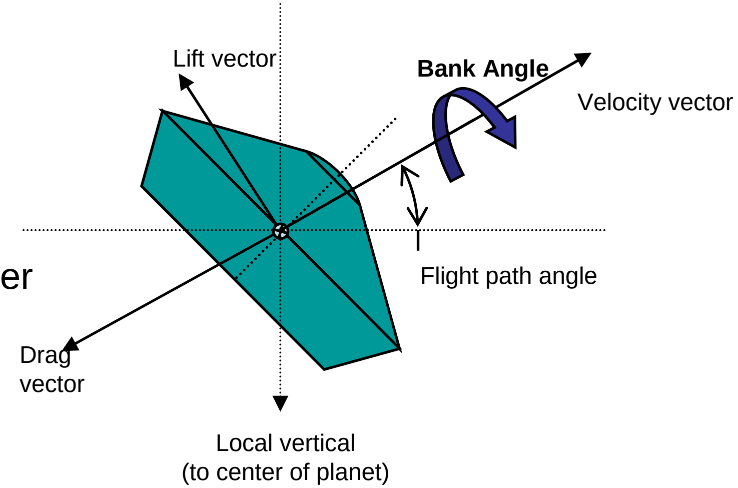
- When more drag is required → lift vector down pulls the vehicle deeper into the atmosphere where the density is higher
- When less drag is required → lift vector up to fly higher (lower density and drag)

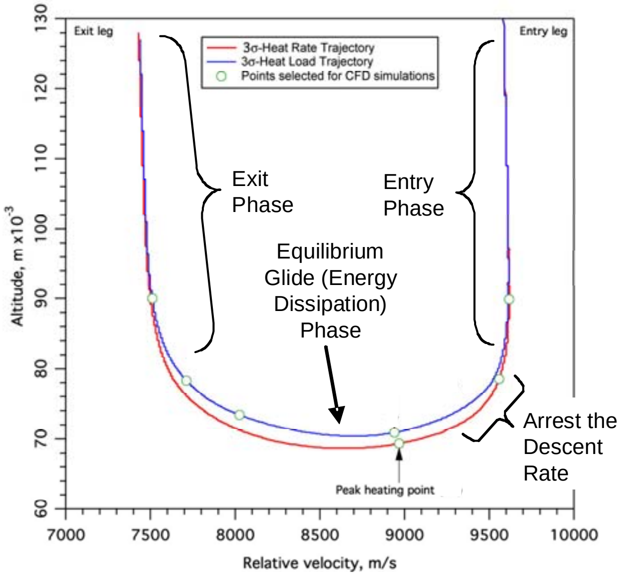
A fixed lift vector gets pointed in different directions by rotating the vehicle with thrusters about the velocity vector (bank angle modulation)

The guidance software works with the rest of the feedback control system (sensors, thrusters) to control the lift vector orientation as a function of time so as to precisely target the orbit upon exiting the atmosphere

The aerocapture trajectory consists of the following:

- Entry targeting – Atmospheric entry angle must be within an upper and lower bound (theoretical entry corridor)
- Arrest descent rate – Altitude rate goes from negative to zero
- Dissipate energy – Fly at nearly constant altitude to dissipate excess energy
- Exit atmosphere – Control altitude rate and velocity at atmospheric exit so as to achieve target orbit apoapsis
- Periapsis raise – Automated propulsive maneuver to raise periapsis so that vehicle does not reenter atmosphere





Aerocapture Risk

Why is there a perception that Aerocapture is risky?

- It is a mission-critical maneuver--but most are
- It utilizes atmospheres and there is a perception that we don't know the atmospheric density very well at other planetary bodies--but our knowledge is not as bad as perceived, it is improving, and aerocapture uses a portion of the atmosphere that is known better than that used in aerobraking
- Making an orbiter "look like a lander" does have impacts--but if designed in from the beginning, are a small price to pay, for the benefits

Why haven't we ever used Aerocapture before?

- At Mars, where we have *almost* used Aerocapture, the masses of the spacecraft we are capturing have been so small that the mass of fuel needed for capture is about the same as the mass of the aeroshell needed to protect the vehicle
- Aerobraking is now an accepted practice at Mars, and eliminates the need for about half of the fuel of a full propulsive capture--and that's been good enough (but becomes untenable at farther targets and with larger Mars payloads)
- Maneuvering a hypersonic vehicle (and flying at an angle of attack) has not been necessary (up until MSL) so that was just more of a challenge to deal with

Probabilistic Risk Assessment (PRA) comparing propulsive capture, aerobraking, and aerocapture at Mars:

- Aerocapture is slightly less reliable than propulsive capture
- Aerocapture is more reliable than aerobraking, primarily due to the duration and number of propulsion system operations

Aerocapture in Perspective

Aerocapture is *much less complex* than landing a vehicle on a surface

- Vehicle stays hypersonic--well-behaved aerodynamics
- No transitional or low-speed instabilities
- No critical events such as parachute deploy, or heatshield jettison in the presence of dynamic pressure
- Performance does not depend on local terrain, winds, or other near-surface phenomena

Aerocapture system is designed to tolerate perturbations

- Conservative estimates of variations are used in Monte Carlo analysis
- Thousands of simulations are run with validated tools to verify performance
- We ALWAYS design in margin, in the form of greater control authority (L/D) than is needed

The only part of Aerocapture that has not been proven is the atmospheric exit. If we consider that the "highest risk" part of the maneuver, what can result?

- The high heating and high dynamic pressure parts of the trajectory are over
- The uncertainty lies in the ability to achieve the target precisely if you hit a large density gradient, since control authority (aerodynamic force) is decreasing
- **Less-than-perfect targeting does not mean loss of vehicle, but rather results in some non-optimal final (science) orbit that requires more delta-V to adjust (i.e., a small mass penalty--tens of kg)**

Stardust Sample Return Capsule
TPS Comparison

Stardust SRC

0.827 m diameter, 46 kg

V_{entry} = 12.6 km/s

Max Heat Rate = 1200 W/cm^2

26%* mass Savings!

PICA Heatshield

Thickness: 2.29 in (5.82 cm)

Areal Density: 1.455 g/cm^2

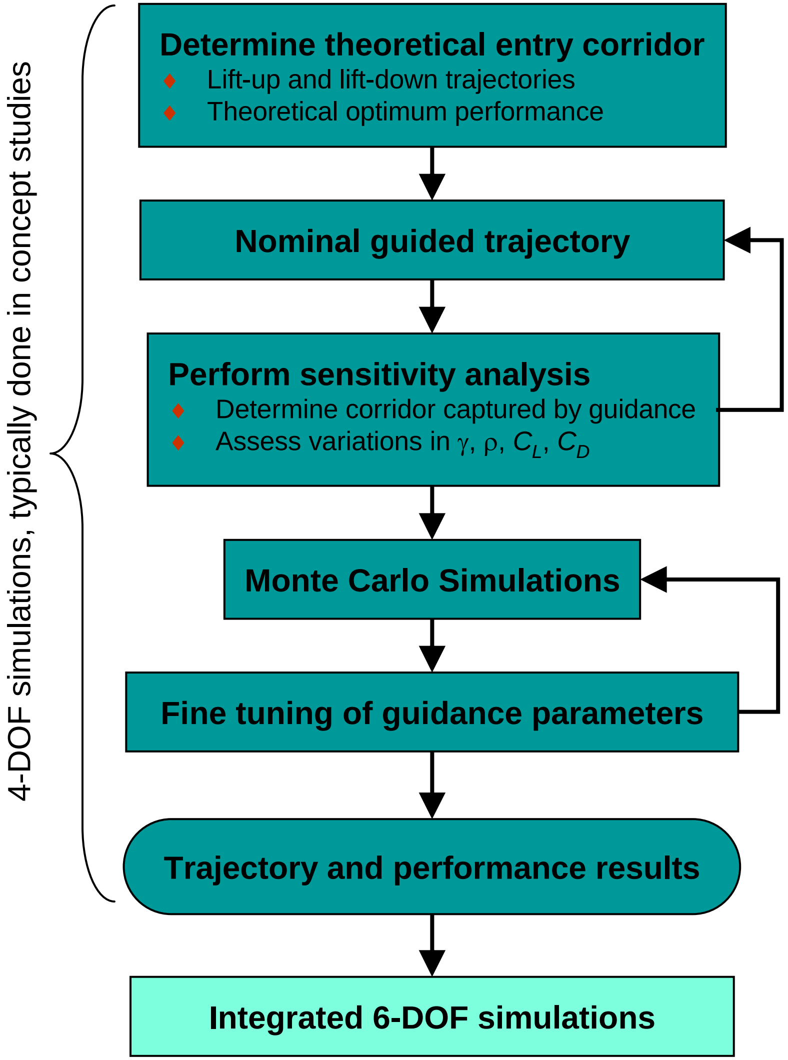
ISPT PhenCarb-28 Heatshield

Thickness: 0.95 in (2.41 cm)

Areal Density: 1.08 g/cm^2

*** The "gear ratio" for any mass returned to Earth is >5, so every kg counts**

Guidance Performance Has Been Rigorously Assessed at Multiple Destinations



4-DOF simulations, typically done in concept studies

Determine theoretical entry corridor
- Lift-up and lift-down trajectories
- Theoretical optimum performance

Nominal guided trajectory

Perform sensitivity analysis
- Determine corridor captured by guidance
- Assess variations in γ, ρ, C_L, C_D

Monte Carlo Simulations

Fine tuning of guidance parameters

Trajectory and performance results

Integrated 6-DOF simulations

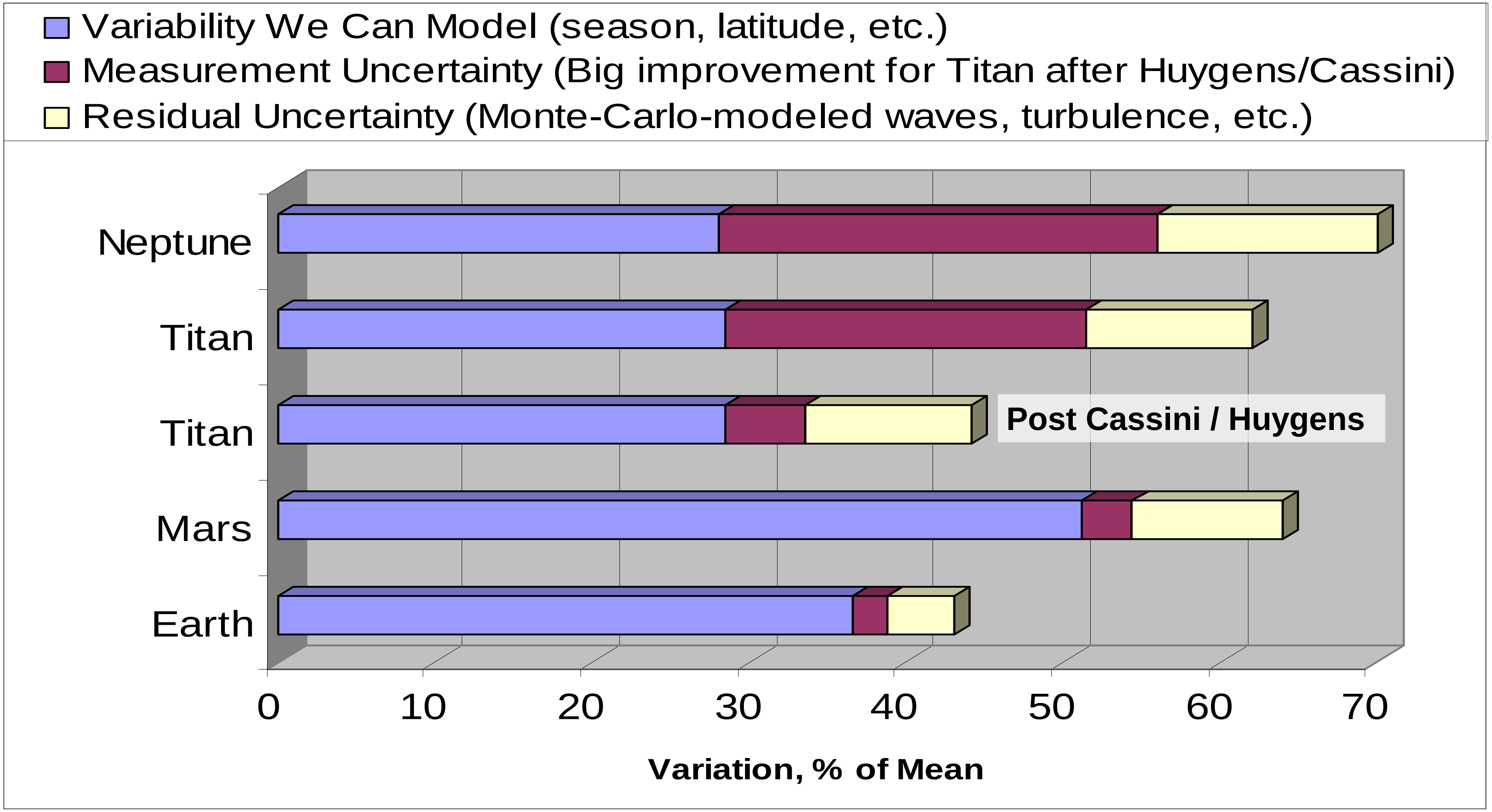
Completed guidance and aerocapture flight performance analysis process (shown in green) using 4-DOF simulations at the following destinations:

- **Mars**
- **Titan**
- **Neptune**
- **Venus**
- **Earth (ST9)**

During the ST9 Concept Definition Study, we went beyond what is typically done in Phase A by proceeding to 6-DOF simulation (normally not initiated until Phase B)

ISPT investing in TRL6 development of hardware-in-the-loop ground GN&C testbed -- completed end of 2009

Atmosphere: Uncertainties



- Variability plus Uncertainty at Titan already slightly less than at Mars
- Titan ~ same as Earth after Huygens reduces measurement uncertainty

Trajectory Simulations Include Realistic Atmosphere Models

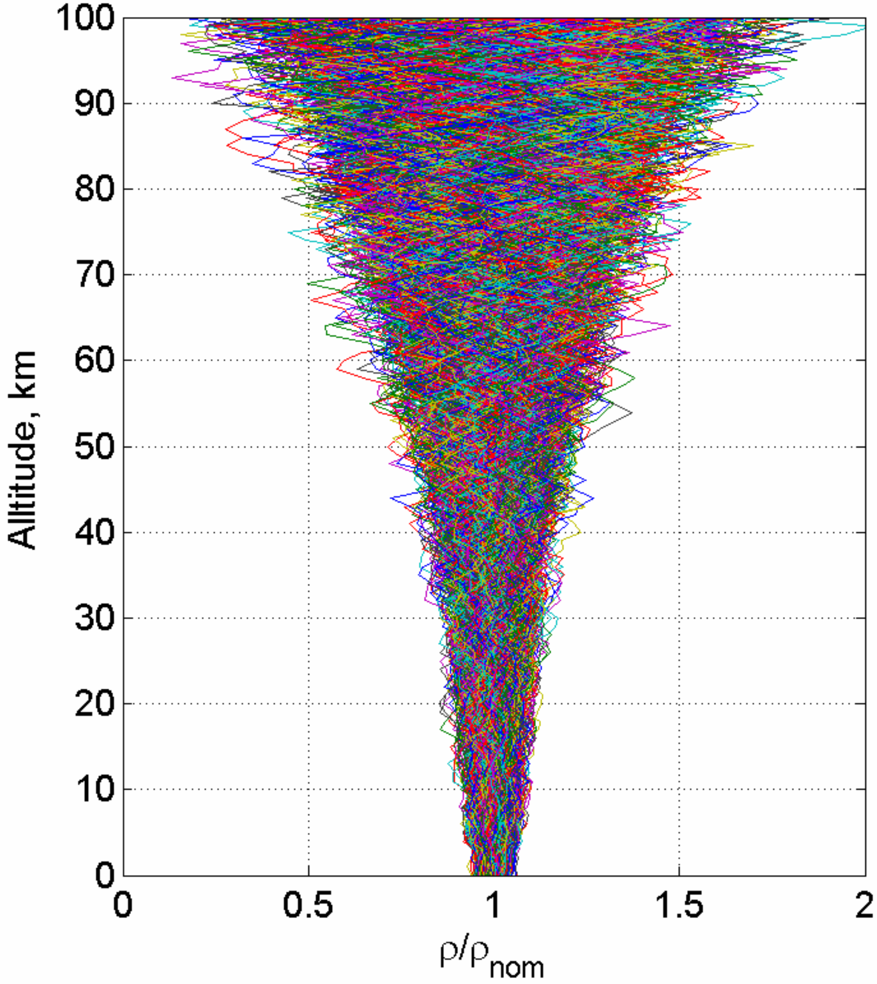
Global Reference Atmosphere Models (GRAM)

- Provides atmosphere parameters (density, pressure, temperature) vs. altitude, latitude, longitude, season, and time of day
- Earth GRAM used for Space Shuttle, Genesis, Stardust
- Mars GRAM used for Pathfinder, MER, MGS, Odyssey, MRO, MSL
- Titan, Neptune, Venus GRAM modeled using same approach as Mars GRAM
- Titan GRAM profiles recently validated against Cassini/Huygens measurements

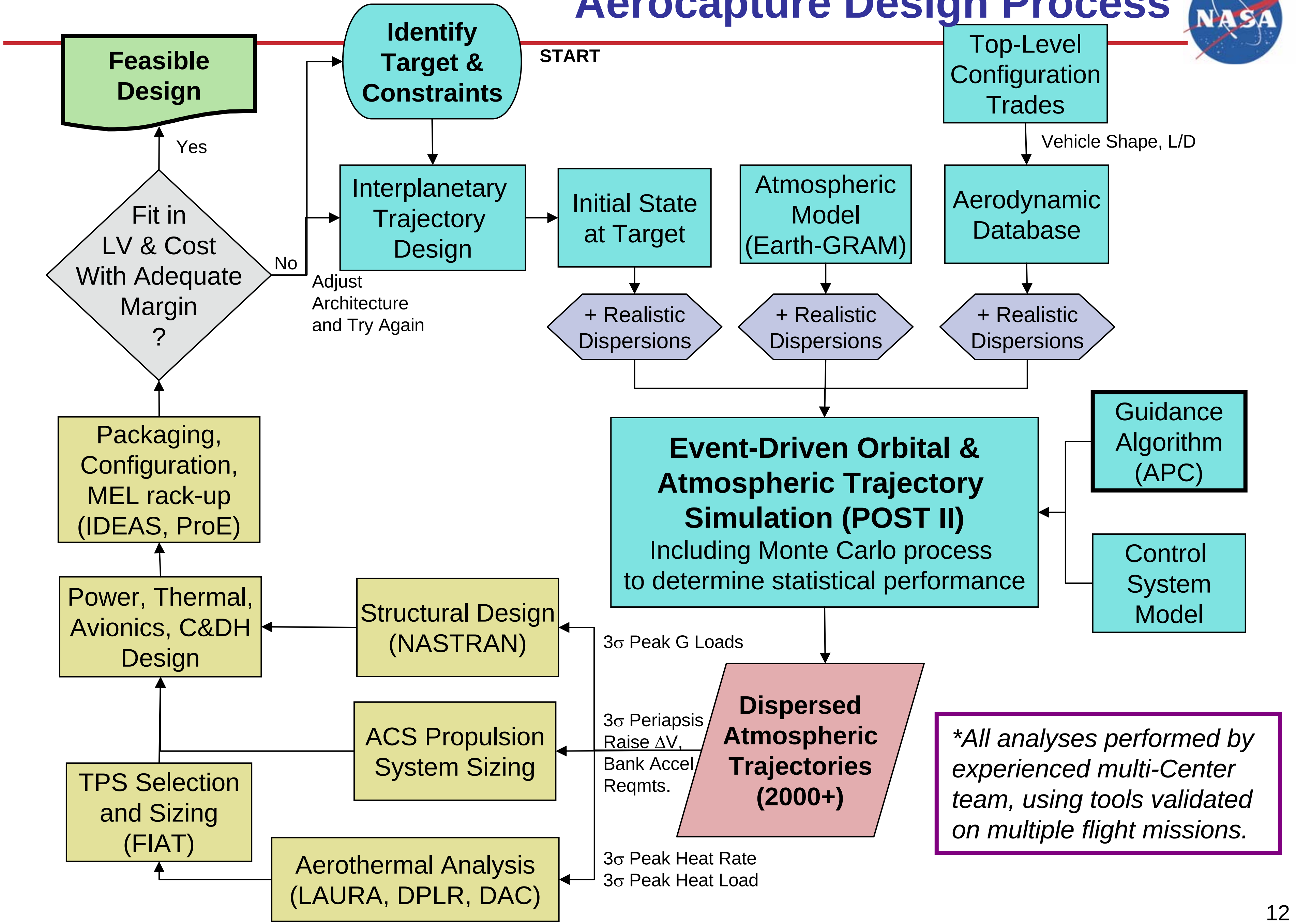
Models include variability and random perturbations for Monte Carlo trajectory analysis

- Includes uncertainties in current estimates derived from scientific measurements
- Includes perturbations based on models of dynamic processes

2000 Perturbed Density Profiles from Mars GRAM



Aerocapture Design Process



Identify Target & Constraints

START

Top-Level Configuration Trades

Vehicle Shape, L/D

Interplanetary Trajectory Design

Initial State at Target

Atmospheric Model (Earth-GRAM)

Aerodynamic Database

+ Realistic Dispersions

+ Realistic Dispersions

+ Realistic Dispersions

Event-Driven Orbital & Atmospheric Trajectory Simulation (POST II)
Including Monte Carlo process to determine statistical performance

Guidance Algorithm (APC)

Control System Model

Dispersed Atmospheric Trajectories (2000+)

3σ Peak G Loads

3σ Periapsis Raise ΔV, Bank Accel Reqmts.

3σ Peak Heat Rate
3σ Peak Heat Load

Structural Design (NASTRAN)

ACS Propulsion System Sizing

Aerothermal Analysis (LAURA, DPLR, DAC)

TPS Selection and Sizing (FIAT)

Power, Thermal, Avionics, C&DH Design

Packaging, Configuration, MEL rack-up (IDEAS, ProE)

Fit in LV & Cost With Adequate Margin ?

No

Adjust Architecture and Try Again

Yes

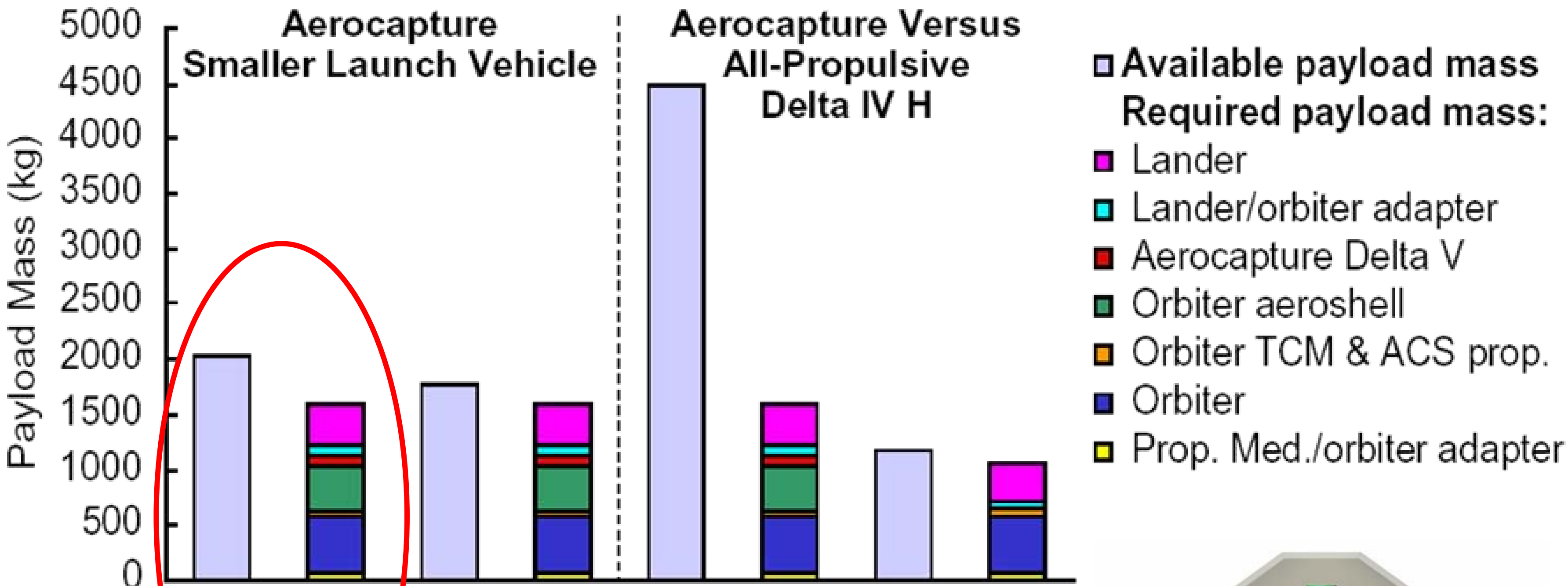
Feasible Design

**All analyses performed by experienced multi-Center team, using tools validated on multiple flight missions.*

Guidance Provides Features Required for a Robust Aerocapture Solution

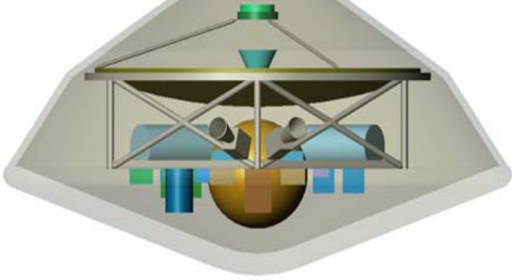
Feature	Algorithm Design
Tolerance to atmosphere density uncertainty, variability, and random perturbations	Sensed acceleration vector used to estimate density bias and scale height. Using a density filter, the on-board model of the atmosphere density is updated to accurately reflect the actual atmosphere.
Tolerance to variability in L/D	Sensed acceleration vector used to estimate L/D during flight and adjust bank angle command, compensating for sensitivity to L/D variability.
Tolerance to variability in ballistic coefficient	Variation in ballistic coefficient results in bias in measured density, which is automatically compensated for by density estimation filter.
Tolerance to variability in trim angle of attack	Variability in angle of attack results in variability in L/D and ballistic coefficient, which are handled as discussed above.
Tolerance to entry flight path angle delivery errors	Bank command before entry computed from estimated position in entry corridor. Algorithm captures nearly 100% of theoretical entry corridor.
Tolerance to IMU errors (altitude rate knowledge error)	Use of desired deceleration due to drag that is independent of altitude rate as a feedback control variable.
CPU load / execution time	Short, non-iterative sequence of computations provides fast, consistent, and predictable execution time.
Orbit altitude targeting	Generalized exit predictor logic enables flexibility in accurately targeting a large range of orbit altitudes.
Orbit plane targeting	Determining bank reversal direction using desired deceleration due to drag and altitude rate minimizes orbit plane error while maintaining orbit altitude targeting accuracy.
Flexibility	Variable duration of guidance phases fits wide range of mission parameters. Only 40 initialization parameters required to adjust to different mission conditions.
Extensibility	Guidance designed with separate, modular phases, with possible addition of new phases without affecting other phases. Angle-of-attack modulation can be incorporated with one new line of code.

Aerocapture for Titan Flagship - Systems Definition



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

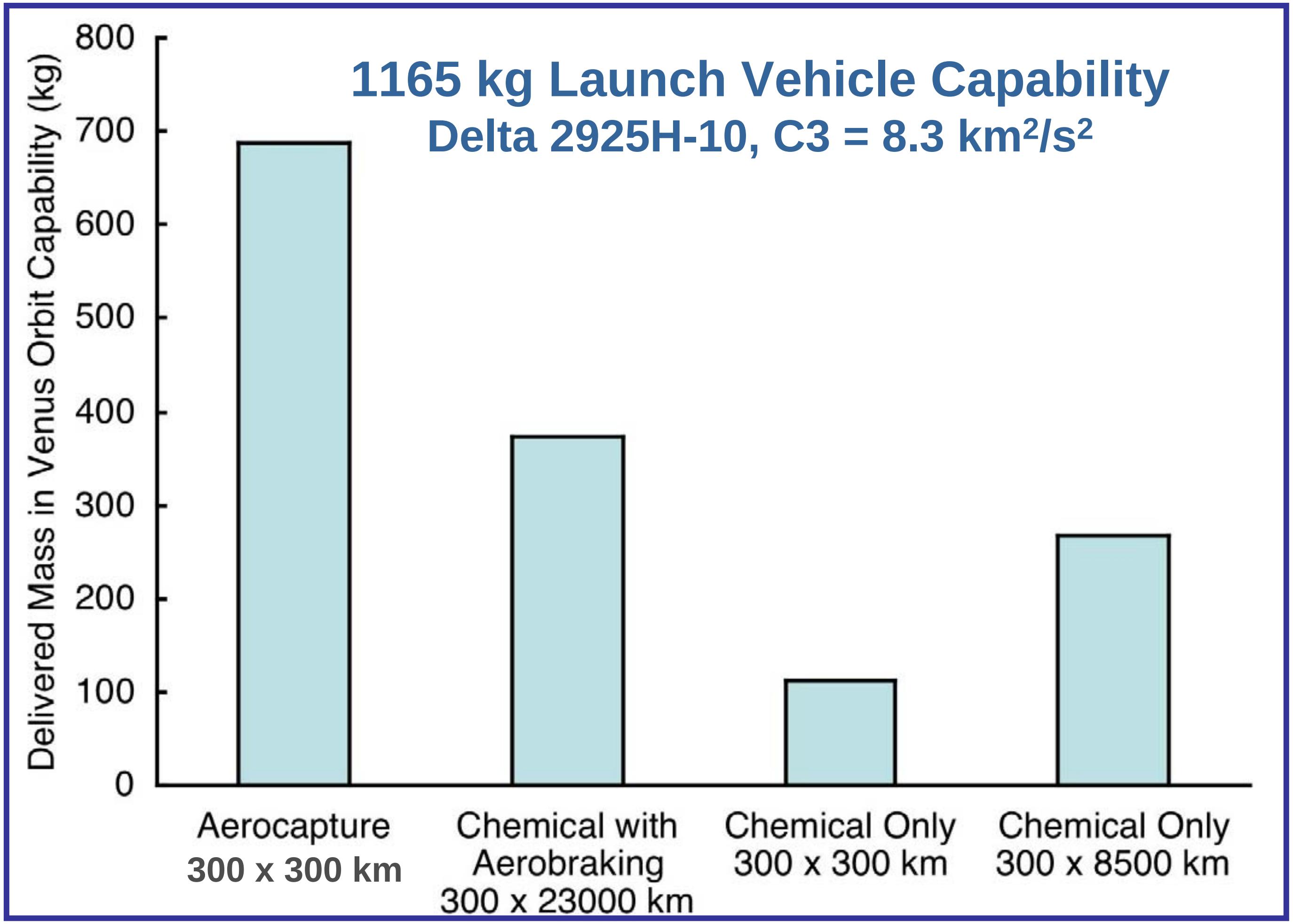


* Includes 2-yr moon tour used to reduce propellant requirements for all propulsive capture

- Aerocapture/SEP is **ENABLING** to **STRONGLY ENHANCING**, dependent on Titan mission reqts
- Aerocapture/SEP results in **~2.4x MORE PAYLOAD** at Titan compared to all-propulsive mission for same launch vehicle

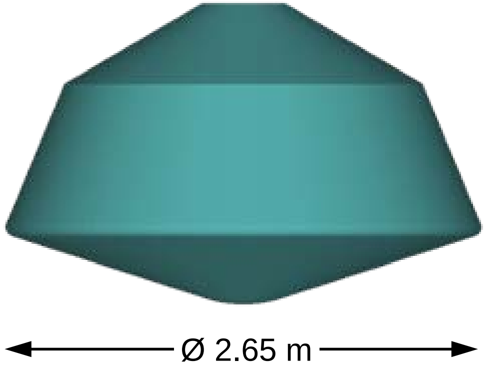
Aerocapture can be used with a chemical ballistic trajectory: Delta IV H, 7.1 year trip, EGA, 32% margin

Aerocapture Benefit for a Venus 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

Example Monte Carlo Simulation Results:
Venus Aerocapture

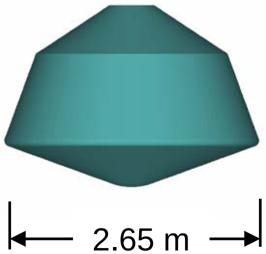
Venus Aerocapture Systems Analysis Study, 2004

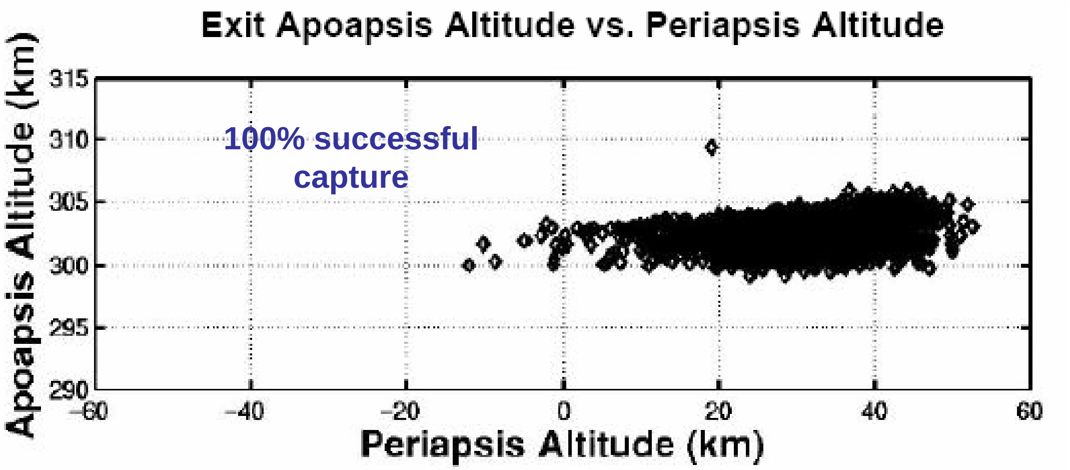
Vehicle L/D = 0.25, m/C_DA = 114 kg/m^2

Target orbit: 300 km circ., polar

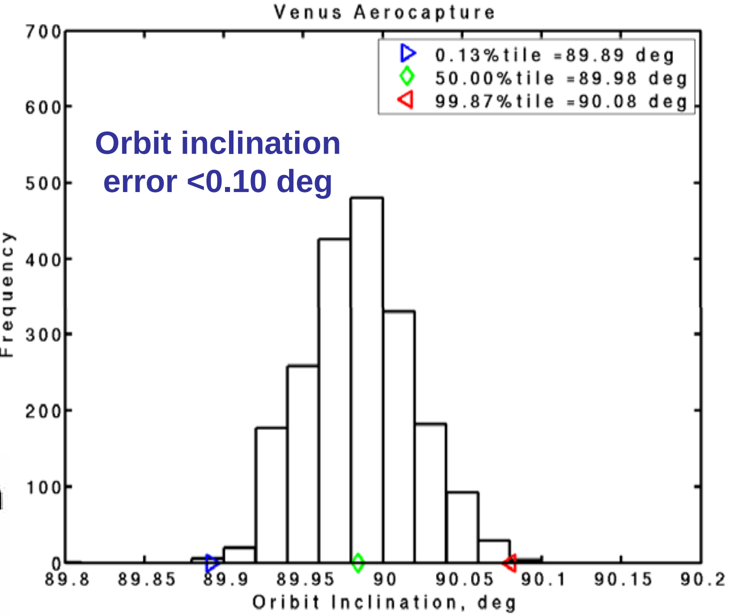
All-propulsive ΔV required for orbit insertion: 3975 m/s

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

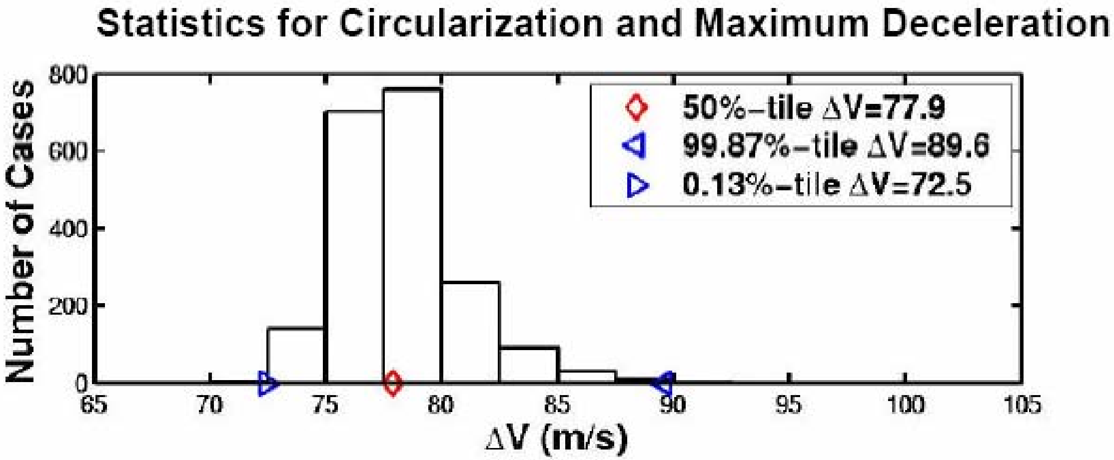




100% successful capture



Orbit inclination error <0.10 deg



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 **not** a high-risk maneuver:
  - Aerocapture is made of flight system elements that have **Strong Heritage** and firm computational basis
  - Aerocapture guidance is **simple and robust**
- ISPT investments have readied **Multiple Heatshield Components for Mission Infusion**
  - Multiple new charring ablators
  - Hot structure system
  - Alternative lightweight aeroshell supplier
- Use on a **New Frontiers** or **Discovery** mission will *immediately* open up multiple opportunities for use

Aerocapture Summary

Aerocapture has Heritage

- Aerocapture can be accomplished at Mars, Titan, Venus and Earth with a high-heritage blunt cone shape like that of existing planetary entry vehicles
- Aerocapture guidance is fully analytic, less than 400 lines of code, derived from Apollo and Shuttle entry guidance (and works at every destination)
- Hypersonic guided entry has been accomplished many times; the only part of aerocapture that has **not** been proven is the atmospheric exit, but skip entry is similar
  - Apollo human-rated a skip entry mode for weather divert but it was never executed
  - Orion will fly skip entry for anytime Lunar return to the US Pacific coast (flight test scheduled for ~2015)--using a numerical guidance of 1000's of lines

Aerocapture is Robust

- An aerocapture system is designed with performance margin to handle worst-case nav, aero, and atmospheric uncertainties. Conservative estimates of variations are used in Monte Carlos.
- Thousands of simulations are run with validated tools to verify performance; *guidance works even with worst-on-worst uncertainties*.
- Guidance allows vehicle to "fly out" density dispersions, which are modeled based on all available data for each planet/moon
- **Aerocapture is much simpler (and easier) than a planetary lander (single flight regime)**

Aerocapture is Not High Risk

- PRA Conducted by SAIC in 2005
- Compared propulsive capture, aerobraking, and aerocapture at Mars
- Results* showed that if the system reliability is normalized so that the reliability of propulsive capture = 1.0, then
  - Aerobraking reliability = 0.9841
  - Aerocapture reliability = 0.9941
- **Aerocapture has HIGHER RELIABILITY than aerobraking, to which we routinely entrust high-dollar missions.**

* Reference: T. Percy, E. Bright, A. Torres, "Assessing the Relative Risk of Aerocapture Using Probabilistic Risk Assessment," AIAA-2005-4107

Aerocapture Status/Next Steps

- ISPT will complete ground-based development to TRL6 by end of 2009
- Technically, a flight test of Aerocapture is not necessary before use at Titan, Mars, or Venus
- However, a flight validation would mitigate risk perception and immediately prove Aerocapture for multiple mission customers, for a relatively small up-front investment
- Continue to seek a near-term mission infusion or flight validation opportunity.
- Seek to infuse ISPT-developed thermal protection systems to fill gaps in current Agency choices.
- Advocate that heatshield sensors, some developed by ISPT to fly on MSL, be used on every entry vehicle to improve tools and future performance