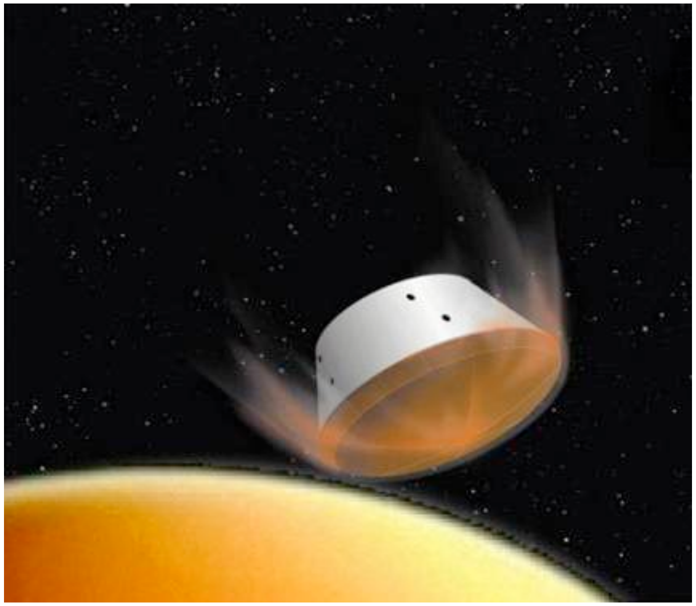
Aerocapture for Discovery Missions



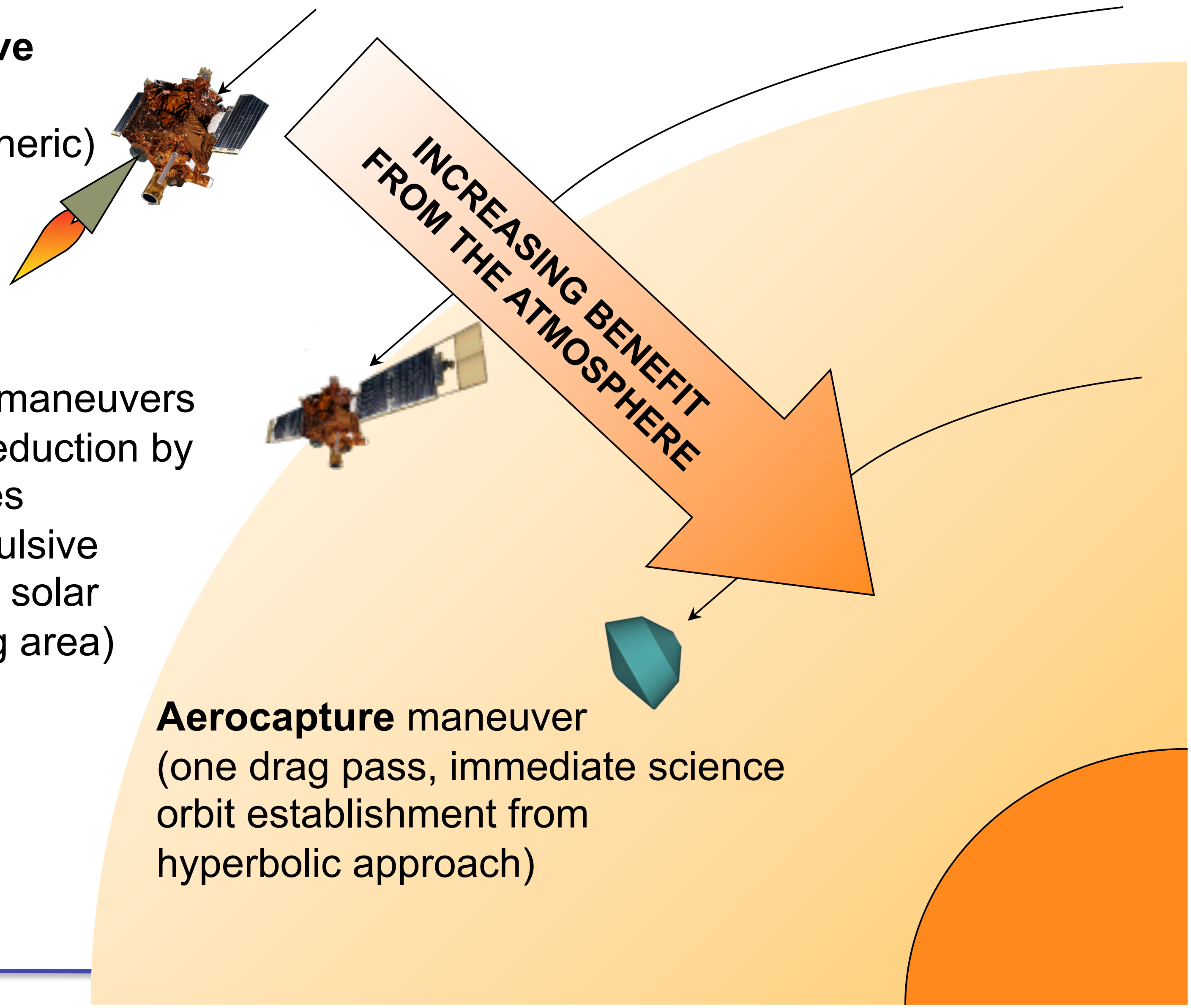
Briefing prepared for Discovery AO participants
June, 2010

Introduction

- NASA's Science Mission Directorate, through the In-Space Propulsion Technology (ISPT) Program, has been investing in Aerocapture technology since 2002.
- This package contains information to address the following:
  - What is Aerocapture?
  - What are the benefits of Aerocapture for planetary use?
  - Where is Aerocapture applicable?
  - What is the current state of Aerocapture?
  - What investments have been made to advance Aerocapture technology components?
  - What organizations have been involved in these advancements?

The Three Options for Orbit Capture

All-**Propulsive** maneuver (exo-atmospheric)

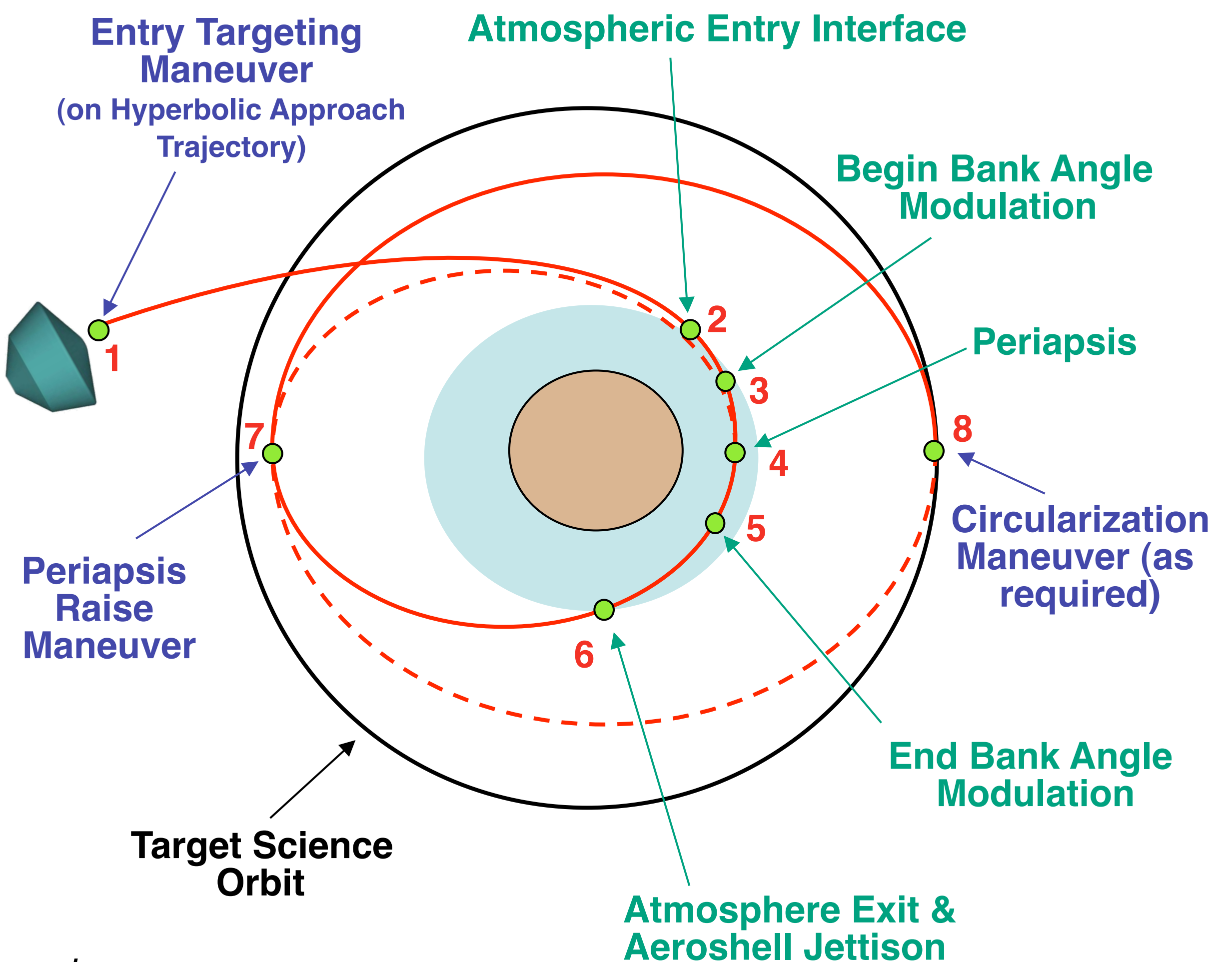


Aerobraking maneuvers (orbit period reduction by multiple passes following propulsive capture, using solar arrays for drag area)

Aerocapture maneuver (one drag pass, immediate science orbit establishment from hyperbolic approach)

Aerocapture Sequence

Aerocapture is accomplished with a single, autonomously-guided atmospheric pass:



Note: Not to scale

Aerocapture Elements

- **Aerocapture is an aerodynamic flight maneuver that occurs exclusively in the hypersonic flight regime.**

- **Aerocapture consists of:**
  - Hardware – heatshield and backshell, reaction control system, avionics
  - Software -- specialized guidance to steer vehicle to the correct exit state
- **Similar flight HARDWARE has been flown many times:**
  - Mercury, Gemini, Apollo, Viking, Pathfinder, MER, Phoenix, Space Shuttle, shroud jettison, etc.
  - Many of these are hypersonic, guided vehicles
- **The ISPT-matured Aerocapture guidance algorithm, HYPAS, has never been flown before, but has heritage in Apollo and Shuttle.**
  - Fully analytic, less than 400 lines of code
  - Has been used in thousands of high-fidelity Monte Carlo simulations and performs robustly at Mars, Venus, Titan, Neptune, and Earth
  - A HYPAS Hardware-in-the-Loop ground testbed completed in 2009
  - Close kin, Apollo guidance, is to be Mars flight-proven on MSL
- **The portion of Aerocapture not previously demonstrated is the atmospheric exit**
  - A skip was human-rated for Apollo weather divert but never used
  - Orion was designed to skip to achieve an anytime return to the US Pacific coast

Aerocapture Project Background

Since 2002, ISPT Aerocapture investments have been in 2 fundamental areas:

1. Systems analysis studies on the application of Aerocapture to representative science missions to Titan, Neptune, Venus and Mars
   - Conducted by multi-center NASA team with atmospheric flight systems discipline expertise:
     - Flight Dynamics
     - Guidance, Navigation and Control
     - Aerodynamics
     - Aerothermodynamics
     - Atmospheric Modeling
     - Thermal Protection Systems
     - Structures
     - Systems Integration
   - Included involvement from scientists to define mission requirements and constraints
2. Hardware development tasks competed through NRAs
   - Warm structures
   - Ablative TPS
   - Hot structures
   - Instrumentation
   - Guidance Algorithm development and hardware-in-the-loop simulation

ISPT Aerocapture Team Contact Information

- **NASA-Glenn Research Center** – Overall In-Space Propulsion Management and POC
  - David Anderson, Project Manager, 216-433-8709
- **Lockheed Martin Space Systems Co.** – warm and hot structure development
  - Bill Willcockson, Principal Investigator, 303-977-5094
- **Applied Research Associates, Inc.** – ablative thermal protection systems development
  - Bill Congdon, Principal Investigator, 303-699-7737
- **ATK/Composite Optics** – high-temperature structures
  - Mark Pryor, Principal Investigator, 858-621-7376
- **Ball Aerospace and Technologies Corp.** – guidance algorithm
  - Jim Masciarelli, Principal Investigator, 303-939-5146
- **NASA-Ames Research Center** – aeroshell thermal sensors and aerothermal models
  - Ed Martinez, Principal Investigator for Sensors, 650-604-2544
  - Mike Wright, Principal Investigator for Aerothermal, 650-604-4210

The State of Aerocapture

- **ISPT investments since 2002 have significantly improved:**
  - The understanding of Aerocapture system parameters and benefits to missions at Titan, Neptune, Venus, and Mars, through high-fidelity systems studies
  - The number of aeroshell and thermal protection system materials available for application to entry systems
  - The mass efficiency of state-of-the-art aeroshell and thermal protection systems
  - Computational tools and methods used to predict the aerothermodynamic environment during entry at Titan, Neptune, Mars and Venus
  - Awareness within the scientific communities of the benefits of Aerocapture to increase scientific return
- **Aerocapture is ready to be infused into planetary missions; the entry systems technical community has high confidence that it will be successful**
- **Aerocapture still carries with it a perceived risk (see next slide)**

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)**

A Word on 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 encountered during 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 <u>about half</u> 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 an extra challenge to deal with

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

- 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 required for aerobraking

Aerocapture Benefits and Applications

The Aerocapture Advantage

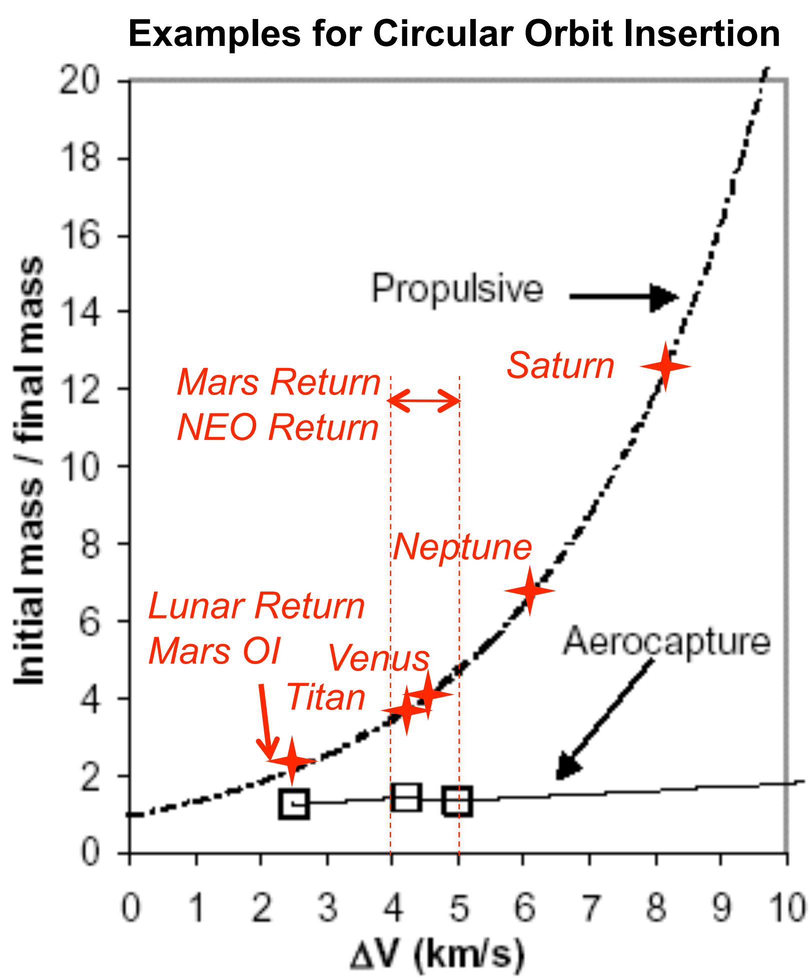
The ΔV necessary to slow from a hyperbolic approach trajectory to useful science orbit is

$$\Delta V = V_{phyp} - V_{circ}$$

The rocket equation shows why aerocapture is so advantageous, masswise:

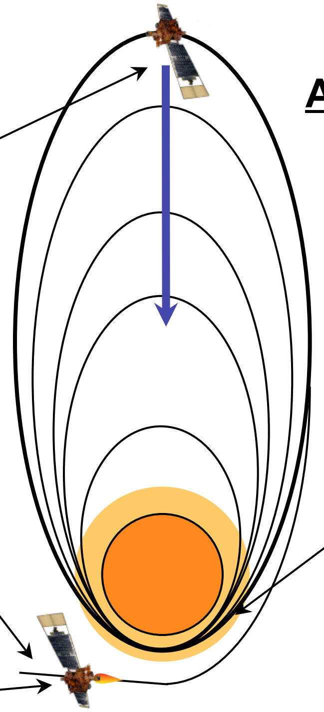
$$\frac{m_i}{m_f} = \exp\left(\frac{\Delta V}{I_{sp} g_0}\right)$$

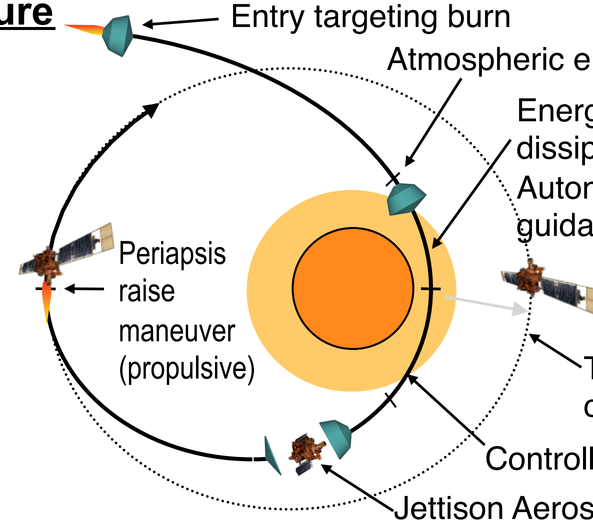
For a propulsive capture, the mass increases exponentially with the ΔV; for aerocapture, the mass of the aeroshell is linear with ΔV.



Aerocapture can provide a direct benefit of reduced launch mass or enable previously unattainable destinations

Aerocapture has Benefits Compared to Aerobraking





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
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

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 increases in delivered payload to most Solar System destinations with atmospheres

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

ISPT Systems Analysis Results

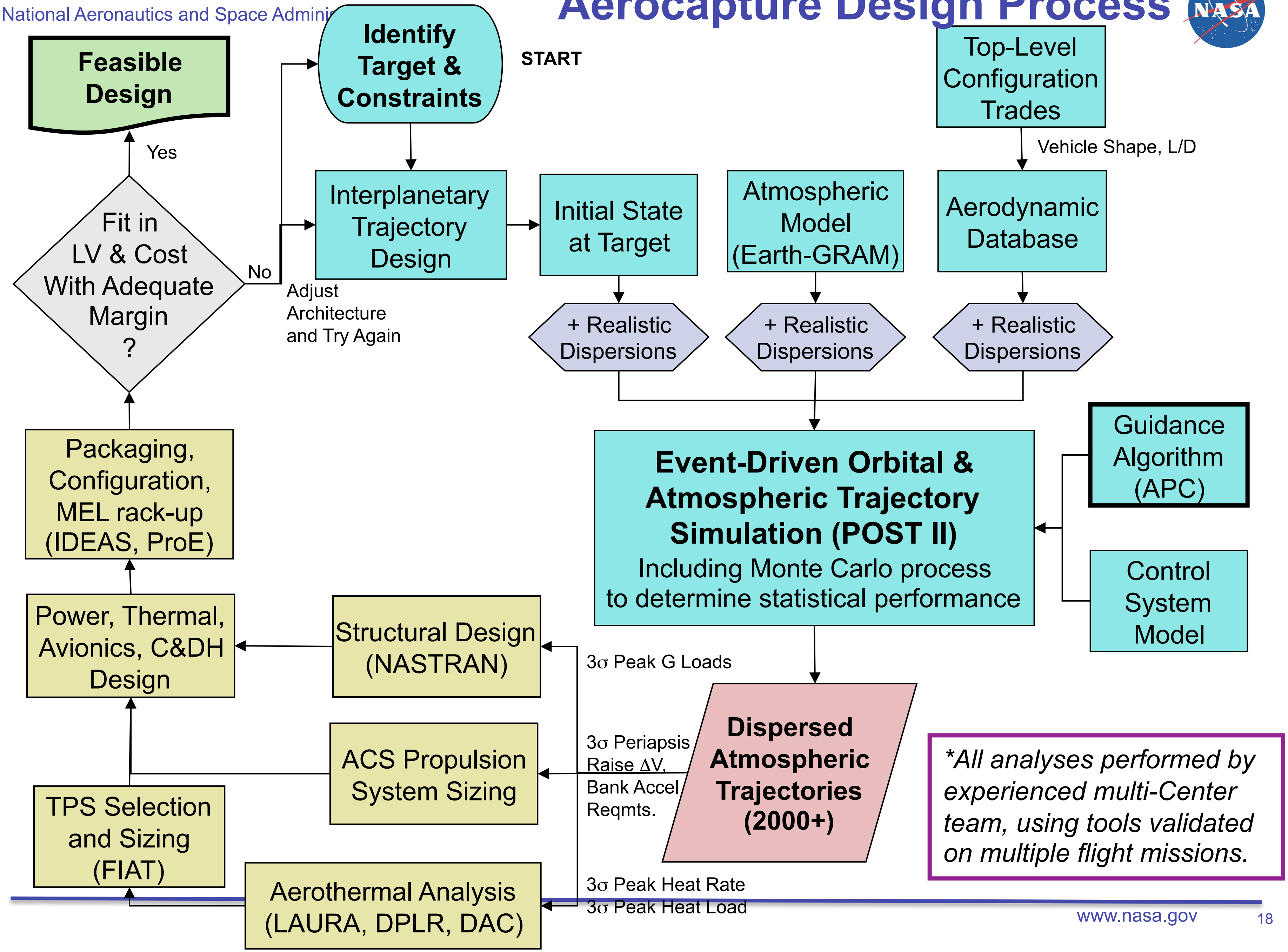
Target Mission	Significant Result
Titan Observer Flagship 1700 km circ orbit from 6.5 km/s, 3.75-m blunt, 70 deg sphere cone vehicle, L/D 0.25	Use of SEP and Aerocapture can save half of trip time (6 yrs) compared to chemical, enable drop from Delta IV-H to Atlas V. Benign environment, robust system performance within heritage hardware capabilities--**technology in-hand**.
Neptune Orbiter Flagship 350,000 km circ orbit from 29 km/s, slender, elliptical vehicle, L/D 0.8	Use of aerocapture is ENABLING – chemical mission cannot be launched within current capabilities. Delivered orbiter & 2 probes with 800+ kg margin on Delta IV-H. **Aerothermal and TPS challenges**.
Venus Discovery-Class Mission 300 km circ orbit from 11 km/s, 2.65-m blunt, 60 deg sphere cone vehicle, L/D 0.25	Use of aerocapture delivers 6 times more mass than chemical, allows use of a modest launch vehicle. Could enable orbiter and lander on 1 launch. Some **TPS testing needed** to minimize system mass.
Mars Large Orbiter Mission 500 km circ orbit from ~7 km/s, 4.75-m blunt, 70 deg sphere cone vehicle, L/D 0.25	Aerocapture enables short-stay Mars Sample Return, which could reduce overall cost. Good system performance; efficiencies gained by using **new ISPT TPS material**.

Aerocapture Subsystem Development Status

1. Simulation and Guidance Algorithm
2. Aeroshell Hardware
   - Warm structures
   - Hot structure

Simulation and Guidance Algorithm

Aerocapture Design Process



Aerocapture Guidance

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

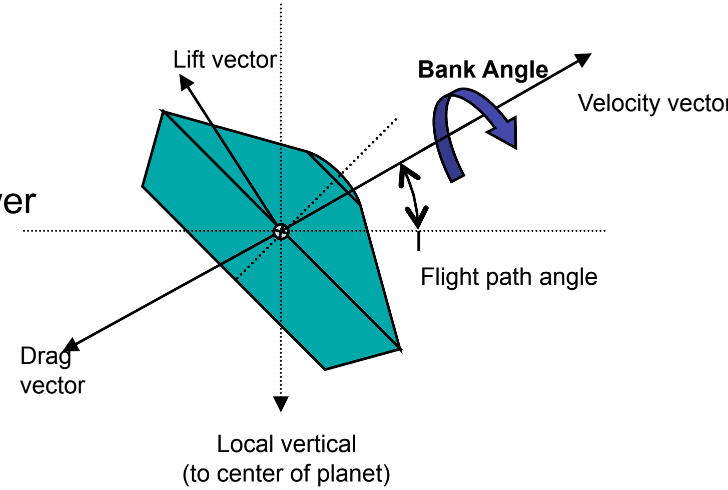
- When more drag is required → lift vector down pulls the vehicle deeper into the atmosphere where the density is higher
- When less drag is required → lift vector up to fly higher (lower density and drag)

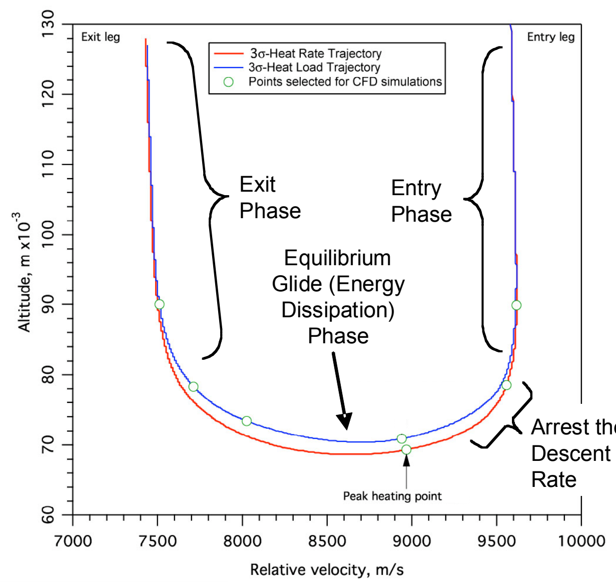
A fixed lift vector gets pointed in different directions by rotating the vehicle with thrusters about the velocity vector (bank angle modulation)

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

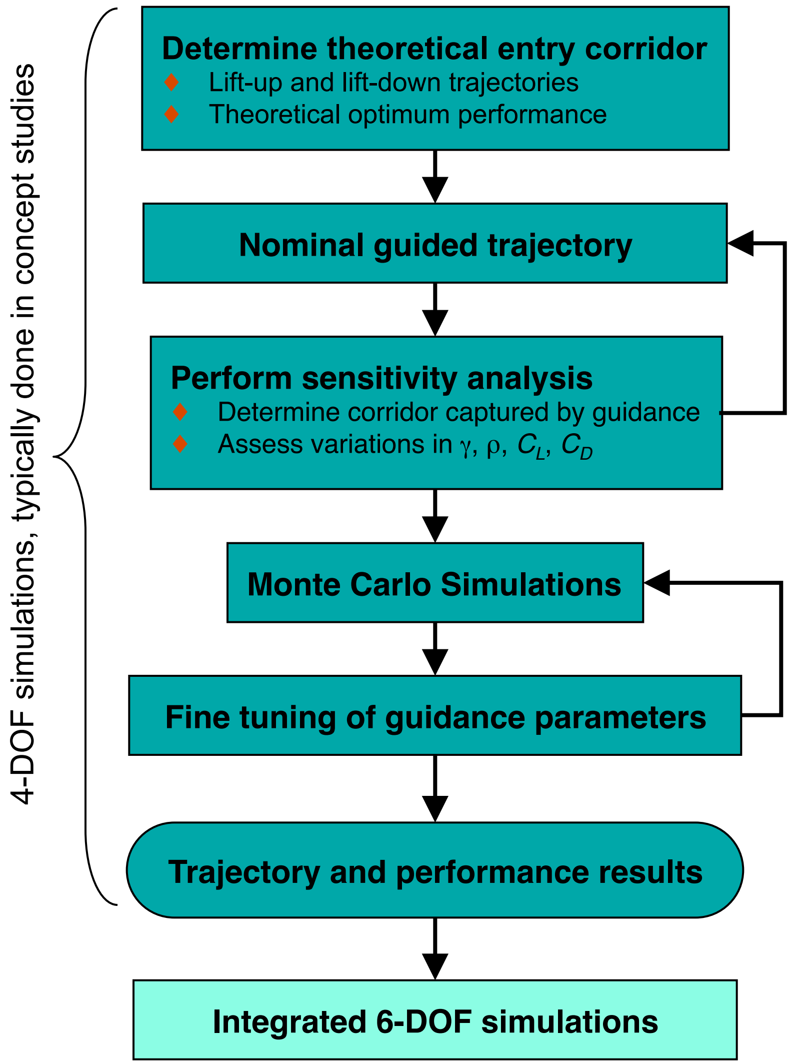
The aerocapture trajectory contains the following:

- 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





Guidance Performance Has Been Rigorously Assessed at Multiple Destinations



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)

Completed TRL6 development of hardware-in-the-loop ground GN&C testbed in 2009 at Ball Aerospace

Trajectory Simulations Include Realistic Global Reference Atmosphere Models

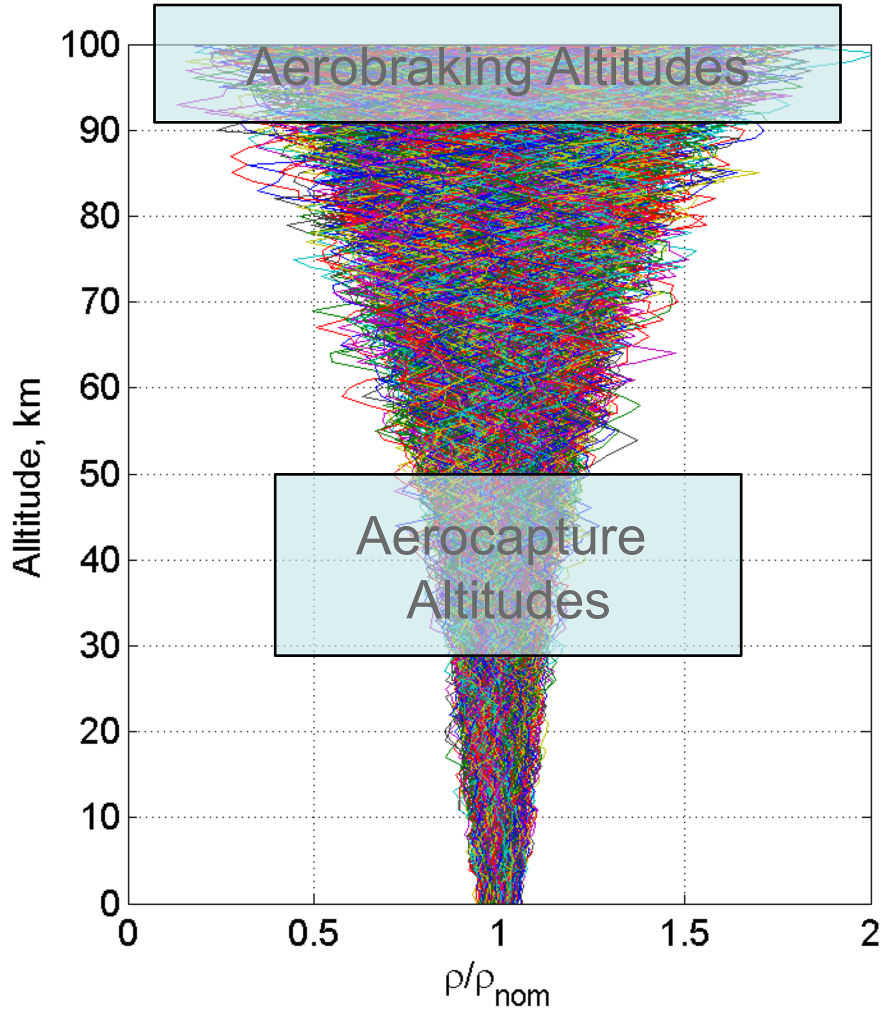
Global Reference Atmosphere Models (GRAM)

- 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 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

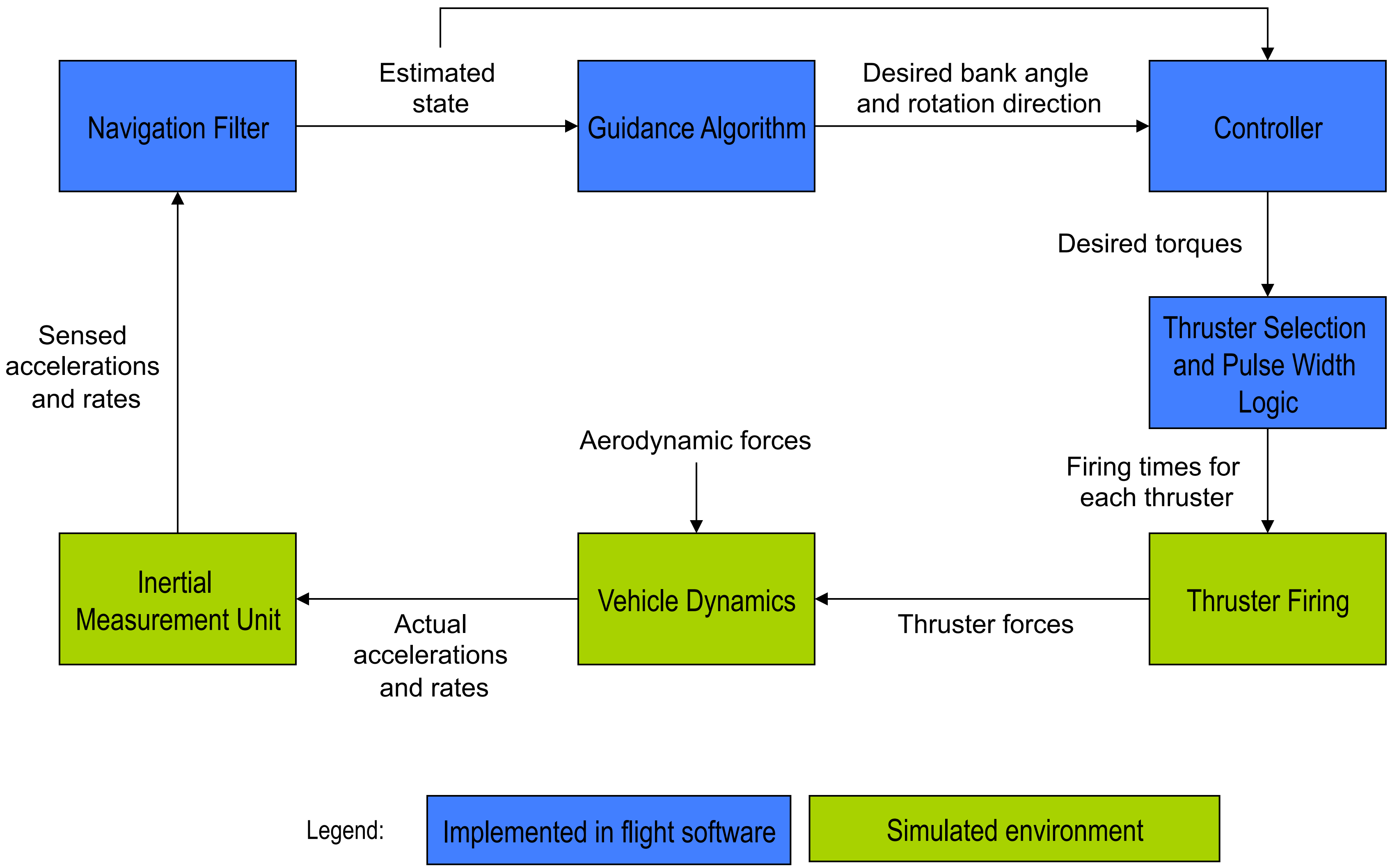
2000 Perturbed Density Profiles from Mars GRAM



Guidance Provides Features Required for a Robust Aerocapture Solution

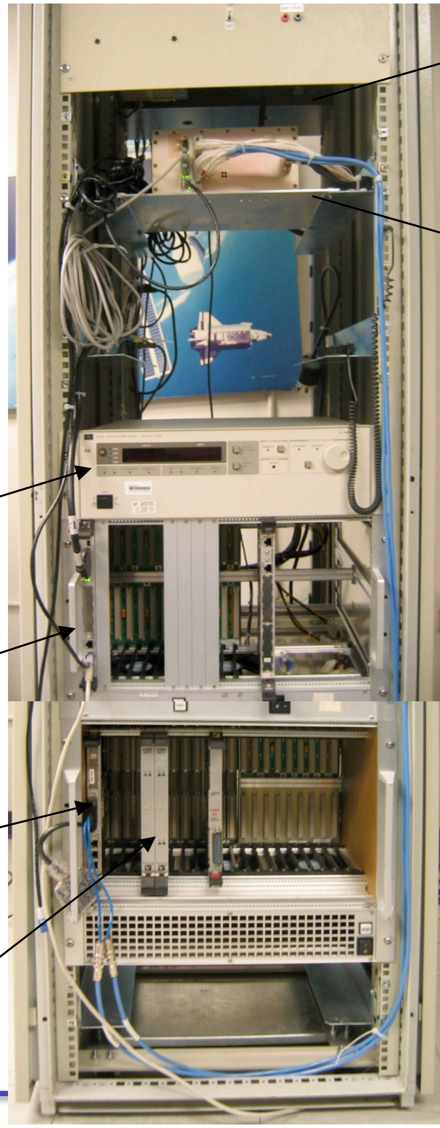
Feature	Algorithm Design
Tolerance to atmosphere density uncertainty, variability, and random perturbations	Sensed acceleration vector used to estimate density bias and scale height. Using a density filter, the on-board model of the atmosphere density is updated to accurately reflect the actual atmosphere.
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.

Ball Aerospace GN&C Testbed
Software Logic Flow



Aerocapture GN&C Test Bench Hardware

Uses flight computer suitable for a low-cost planetary spacecraft

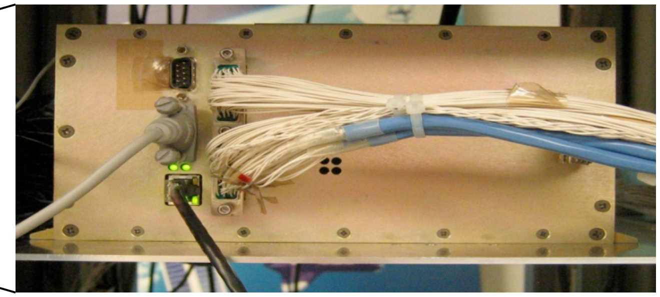


Power Supply

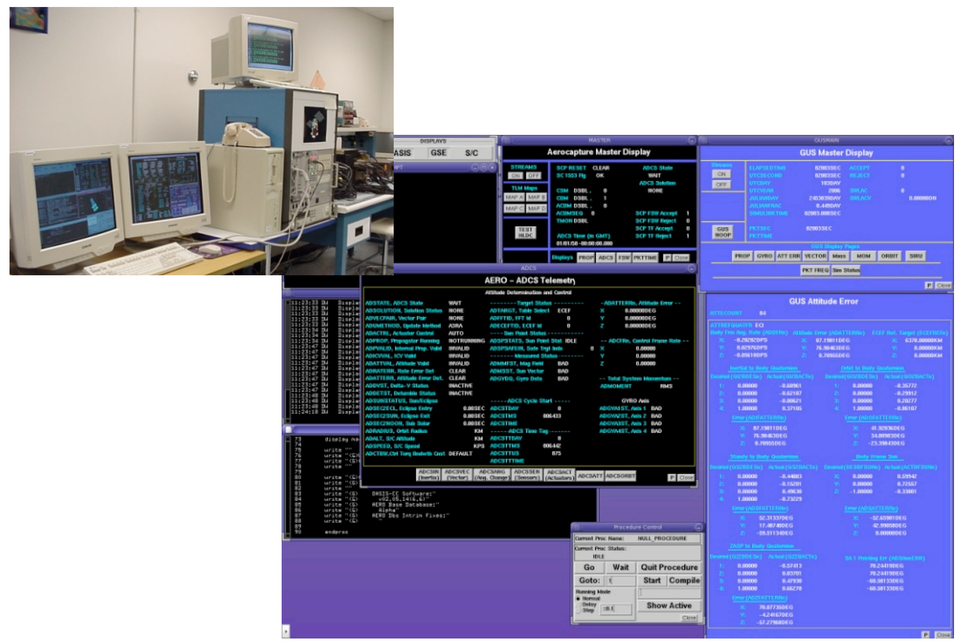
Command & Telemetry Processing

Main Simulation Processor

Simulation I/O Cards for IMU & Thrusters



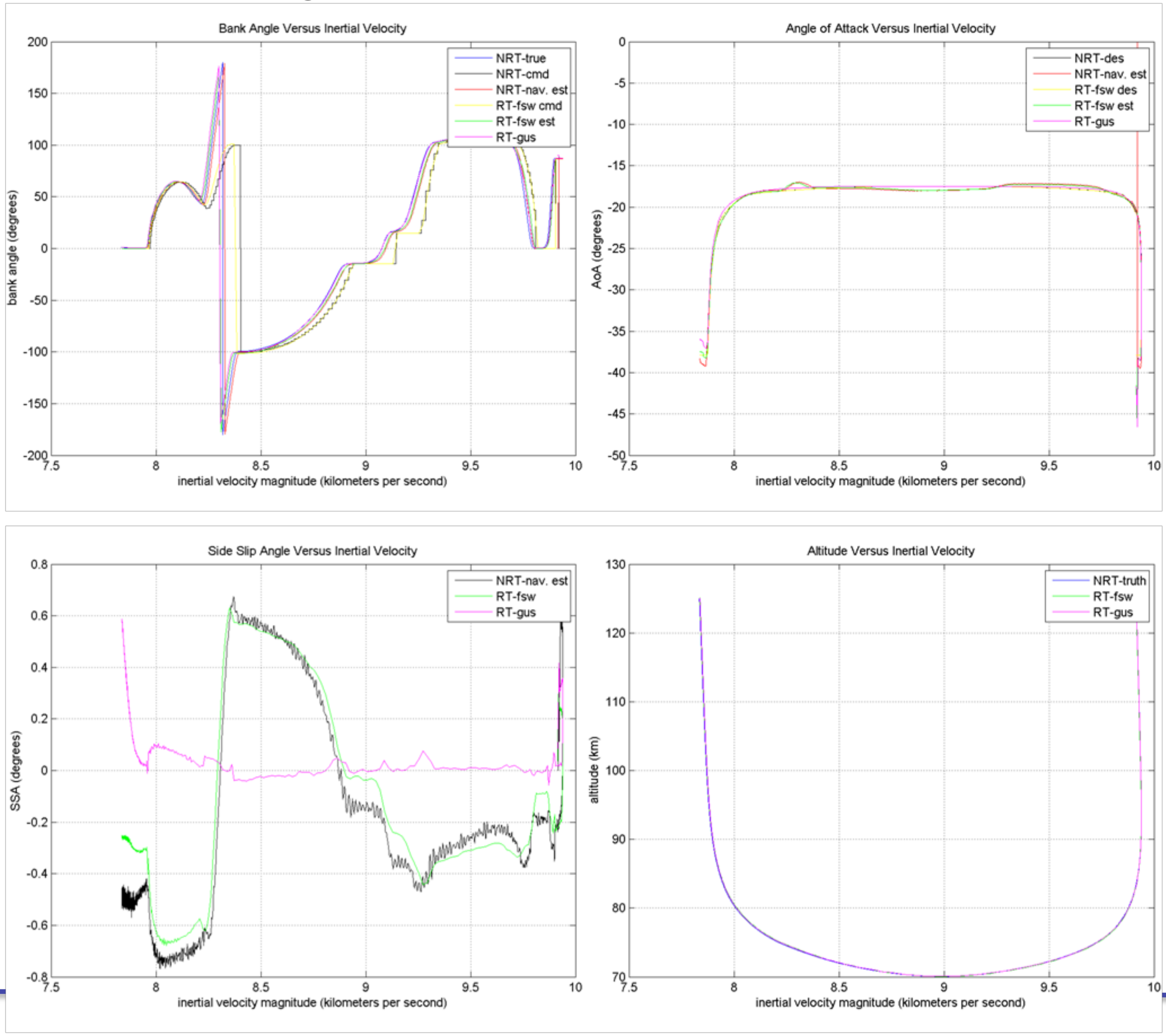
Spacecraft Computer with MOAB Card (Broad Reach Engineering)



Command & Telemetry Workstation

Simulation Results Agree
Real Time and Non-Real Time Simulations

GN&C flight software implementation is verified



Aerocapture Guidance Summary

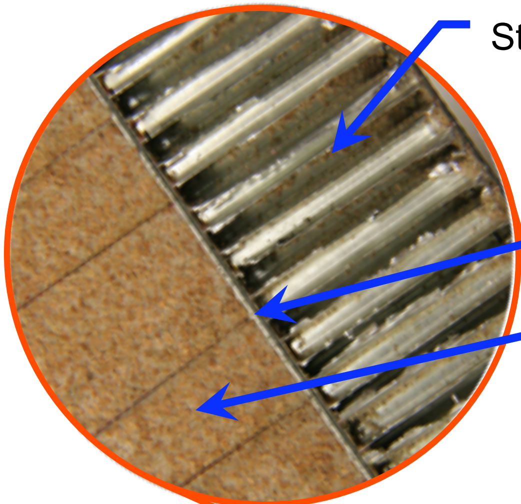
- Aerocapture guidance is simple, robust, and has demonstrated performance at Titan, Venus, Neptune, Mars, and Earth in high-fidelity, realistic simulations
- Algorithm has been coded into flight software
- GN&C system performance has been verified by Ball Aerospace in a hardware-in-the-loop ground testbed using a flight computer suitable for a planetary spacecraft
- The aerocapture guidance is judged to be at TRL6

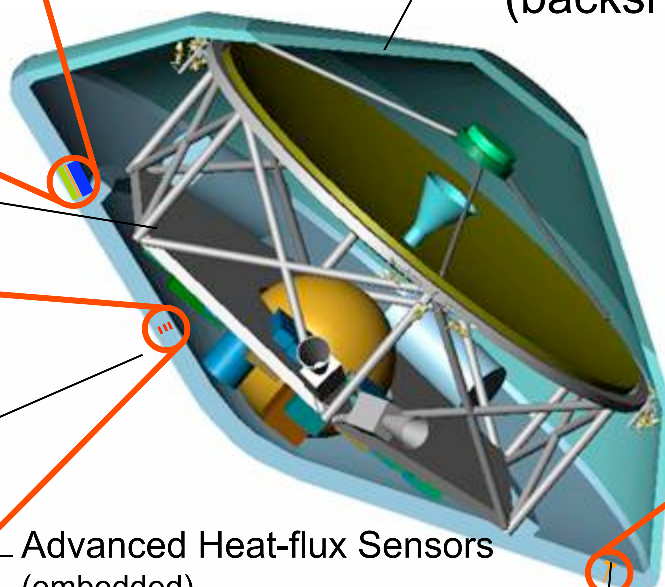
Aeroshell Hardware: Warm Structures

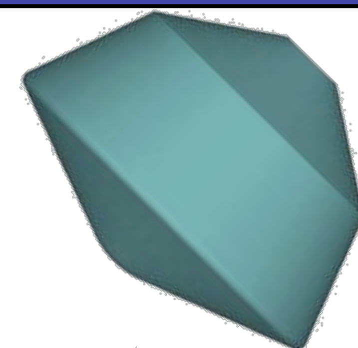
The Rigid Aeroshell System

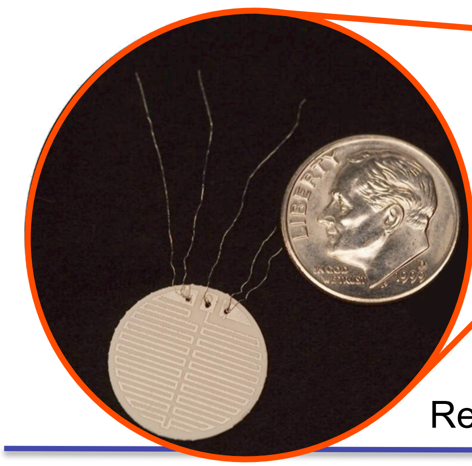
Components of the Rigid Aeroshell

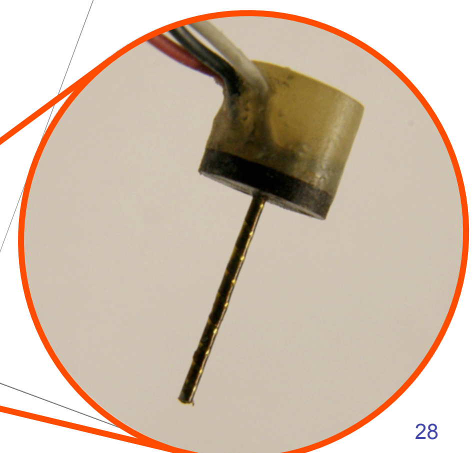
- Thermal Protection Systems
- Supporting Structures
- Bonding Agents/Adhesives
- Sensors (Thermal & Recession)











Introduction to ISPT-matured TPS

- **If a mission is not suited for Aerocapture, but needs thermal protection, ISPT-developed materials provide multiple solutions.**
  - Robust, efficient ablative TPS in densities suited for heating rates up over 1000 W/cm^2
  - Rib-stiffened Carbon-Carbon heatshields suited for up to 700 W/cm^2 (hot structure with internal insulation)
  - Alternate supplier for lightweight structural aeroshells (ATK/Composite Optics)
- **NASA has only 4 primary flight-proven TPS options**
  - Carbon phenolic (very dense, for severe heating; limited heritage raw material)
  - SLA-561V (used on every Mars lander to date; good for heat rates up to ~200 W/cm^2)
  - Shuttle tile (brittle, good for low heat rates of about 40 W/cm^2)
  - PICA (tiled over 1 m diameter, good for heat rates up to 1200 W/cm^2, may be challenging to install)
  - *Avcoat – remanufactured for Orion application; modern material not flown yet*
- **None of the flight-proven materials may be ideal for a particular mission, and there are large gaps between solutions**
- **ISPT-developed materials span the range of environments, and have been extensively tested**
  - Hundreds of arcjet tests
  - Up to 1-meter thermostructural test
  - Response models show good agreement with arcjet test data
- **A 2.65-meter aeroshell of robust ablator and lightweight structure is being manufactured with ISPT funding (by Applied Research Assoc. & ATK)**

Ablator Family Systems
by Applied Research Associates

The "family system" approach to TPS provides varying levels of robustness using the same constituents.

- No performance "cliffs"
- Predictable performance based on family traits
- Silicone, Reinforced Ablative Material (SRAM) and Phenolic Carbon (PhenCarb)

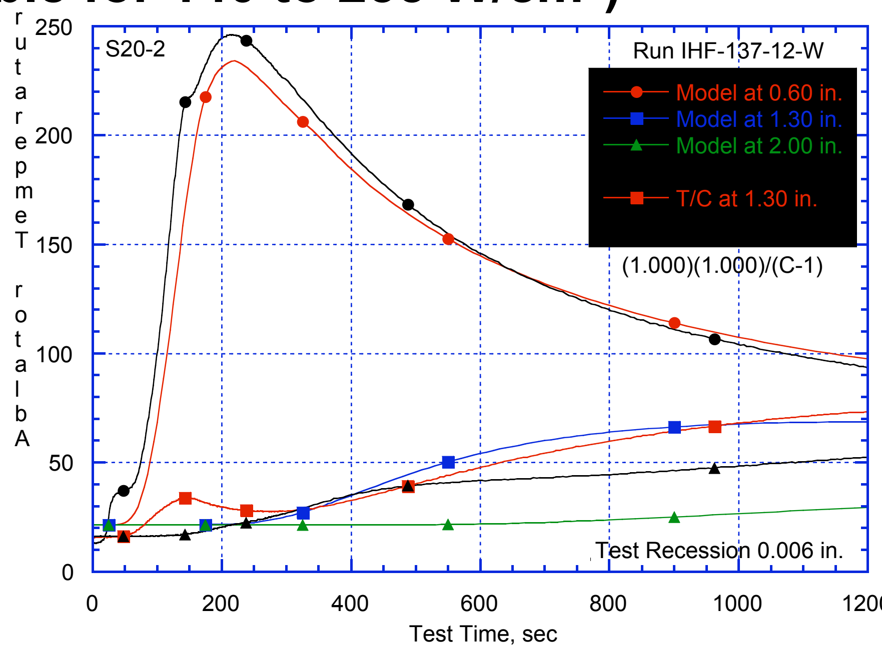
Ablator	Density	Resin System	Fillers	Heating Range	EDL Location	Abbrev.
SRAM-14	14 lb/ft^3	Silicone	Silica / others	57 to 142 W/cm^2	Forebody	S14
SRAM-17	17 lb/ft^3	Silicone	Silica / others	115 to 200 W/cm^2	Forebody	S17
SRAM-20	20 lb/ft^3	Silicone	Silica / others	140 to 255 W/cm^2	Forebody	S20
SRAM-24	24 lb/ft^3	Silicone	Silica / others	170 to 284 W/cm^2	Forebody	S20
PhenCarb-20	20 lb/ft^3	Phenolic	Carbon / others	227 to 568 W/cm^2	Forebody	P20
PhenCarb-24	24 lb/ft^3	Phenolic	Carbon / others	341 to 795 W/cm^2	Forebody	P24
PhenCarb-28	28 lb/ft^3	Phenolic	Carbon / others	455 to 1023 W/cm^2	Forebody	P28
PhenCarb-32	32 lb/ft^3	Phenolic	Carbon / others	568 to 1250 W/cm^2	Forebody	P32
Hyperlite-C	11 lb/ft^3	Silicone	Silica / others	11 to 34 W/cm^2	Backshell	S11
Hyperlite-B	12 lb/ft^3	Silicone	Silica / others	34 to 57 W/cm^2	Backshell	S12
Hyperlite-A	13 lb/ft^3	Silicone	Silica / others	57 to 114 W/cm^2	Backshell	S13

ARA Arcjet and Thermal Model Results

Typical Sample

SRAM-20 TPS, 20 lb/ft^3 (suitable for 140 to 255 W/cm^2)

114 W/cm^2 for 150 sec
Sample 1545

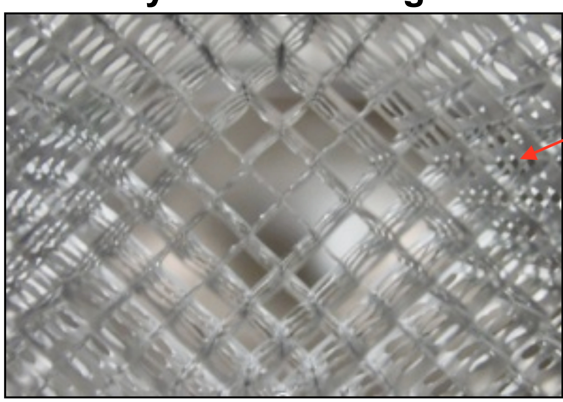


119 W/cm^2 for 125 sec
Thermal Model - Sample 3002

"Warm" Structure

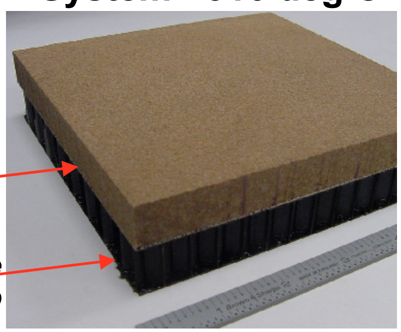
- A higher-temperature-capable aeroshell structure paired with an efficient ablator can decrease the aerocapture system mass by 10-25%.
  - Traditional aeroshell constructions use an Aluminum honeycomb core with composite facesheets
  - Limiting factor (250 deg C) is the honeycomb core and its adhesive; this bondline temperature limit drives TPS thickness
- **ISPT has matured warm structure technology through 2 vendors:**
  - ATK/Composite Optics – partnered with Applied Research Assoc. for TPS
    - Approach is light-weighted Titanium honeycomb and improved facesheets
  - Lockheed Martin Space Systems Co. – uses heritage SLA-561V TPS
    - Approach is graphite polycyanate core and improved facesheets

ATK: Lightweighted Titanium Core System - 400 deg C



System Areal Density = 4.2 kg/m²

LMA: Warm Structure/SLA-561V System - 316 deg C



Areal Density = 1.78 lb/ft²

14% Improvement over MER

Warm Structure Summary

- **The TPS developer Applied Research Associates is teamed with ATK/Composite Optics to develop a high-temperature aeroshell system that can meet a wide range of mission needs.**
  - A 2.65-meter aeroshell with 1.0” SRAM-20 TPS is being manufactured and instrumented as a manufacturing proof of concept.
  - Structure has been vacuum load tested to greater than aerocapture loads, with good correlation.
  - A 1-meter version of the 400-deg C capable system will be CT scanned before and after thermal radiation testing in the Fall of 2010, to determine and characterize the presence of defects or failures.
- **Lockheed Martin developed an improved structure to carry heritage SLA-561V TPS material.**
  - System bondline is 316 deg C, significantly greater than the traditional 250 deg C.
  - Numerous structural and thermal test established confidence in this construction method.
  - Low-risk, incremental improvement in aeroshell technology capability.

Aeroshell Hardware: Hot Structure

Lockheed Martin "Hot" Structure

- Lockheed Martin Space Systems Co., with support from Carbon-Carbon Advanced Technologies (C-CAT), developed an advanced carbon-carbon (ACC) heatshield insulated with Calcarb foam
  - Called a "hot structure" because the ACC is the vehicle outer mold line
  - Designed to be an improvement in efficiency, over the Genesis aeroshell
  - All system components underwent thermostructural testing to establish properties in relevant heating environment
- A 2-meter diameter, 70-degree sphere cone forebody aeroshell was built to demonstrate manufacturing and repair techniques
  - Article has co-cured ribs for stiffness – scalable to larger diameters
- The article was load tested to 1.1x Titan aerocapture aerodynamic loads and the article response was correlated to the finite element model within 10%
- Resulting system can be used up to ~300 W/cm^2 unsupported, up to ~700 W/cm^2 with supporting structure

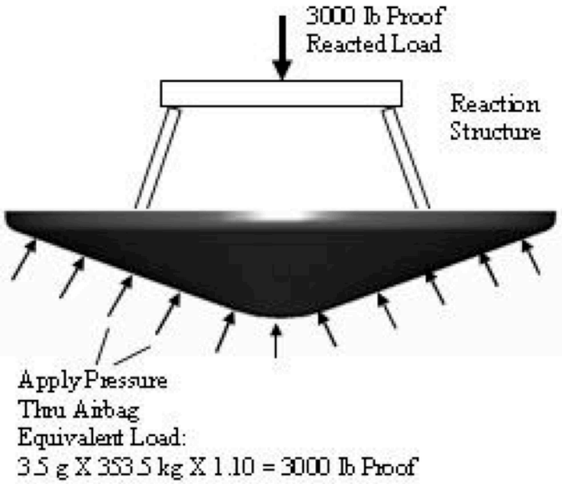
Hot Structure Component Testing

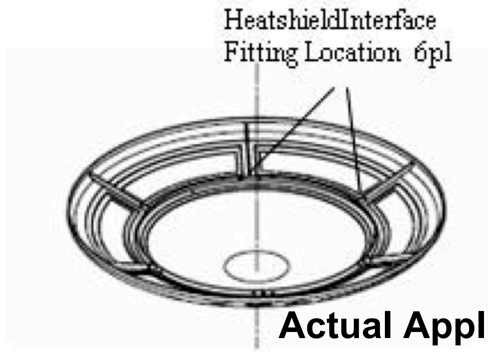
- T300 C-C heat treated ACC-6 laminates were mechanically tested for tension, in-plane shear, compression, interlaminar shear, and CTE, at temperature. Ambient temperature mechanical properties of C-C honeycomb and Calcarb CBCF foam have been determined.

T300 Heat Treated ACC-6 Mechanical Properties

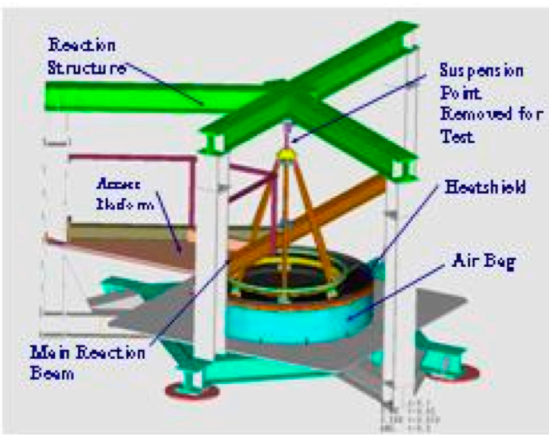
	Temperature Deg F	Modulus msi	Strength ksi
Tension	75	9.7	21.1
	3600	7.7	23.4
	4500	4.6	23.1
	5500	2.2	15.7
Compression	75	13.7	18.6
	3600	9.6	21.9
	4500	6.3	21.4
	5500	4.5	12.8
Interlaminar Shear	75	N/A	0.92
	3600	N/A	1.09
	4500	N/A	1.25
	5500	N/A	1.29

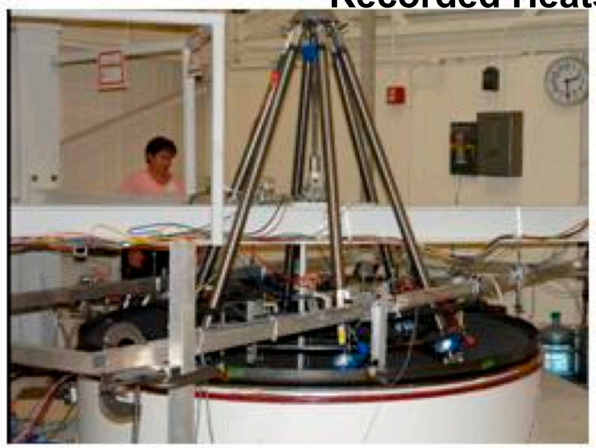
Hot Structure 2m Article Testing





Actual Applied Load: 3305 lb Proof
Required Applied Load: 3000 lb Proof
Additional Demonstrated Factor: 1.10
Recorded Heatshield Stress (Max): 1705 psi Proof





Proof Test Displacement vs FEM Values

Displacement Location	Value @ Proof (in)	FEM Predict (in)	% Correlation
Center	0.0245	0.0256	4.6
Rim	0.0368	0.0346	6.0
Ring	0.0236	0.0218	7.6

Hot Structure Summary

- **Lockheed Martin Space Systems developed a rib-stiffened C-C hot structure to improve upon the Genesis aeroshell implementation, using ACC-6 and Calcarb insulation**
- **Extensive structural and thermal testing performed on each component**
- **2-m diameter article verified manufacturing at scale and was load tested to representative aerocapture environments**
  - Co-cured stiffening ribs increase the system scalability
  - Structural performance matched finite element model
- **System is applicable in heating environments up to 300 W/cm^2 unsupported, up to 700 W/cm^2 with backing structure**

Aerocapture Technology Subsystem Readiness

Destination / Subsystem	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 no longer a concern.	**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.	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 technology gaps.**	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 **not** significantly riskier than other space maneuvers:
  - Aerocapture is made of flight system elements that have **Strong Heritage** and firm computational basis
  - Aerocapture guidance is **simple and robust, at TRL6**
- ISPT investments have readied **Multiple Heatshield Components for Mission Infusion**
  - Multiple new charring ablators
  - 2 warm structure aeroshell providers
  - Hot structure system
- Use on a **New Frontiers** or **Discovery** mission will *immediately* open up multiple opportunities for use