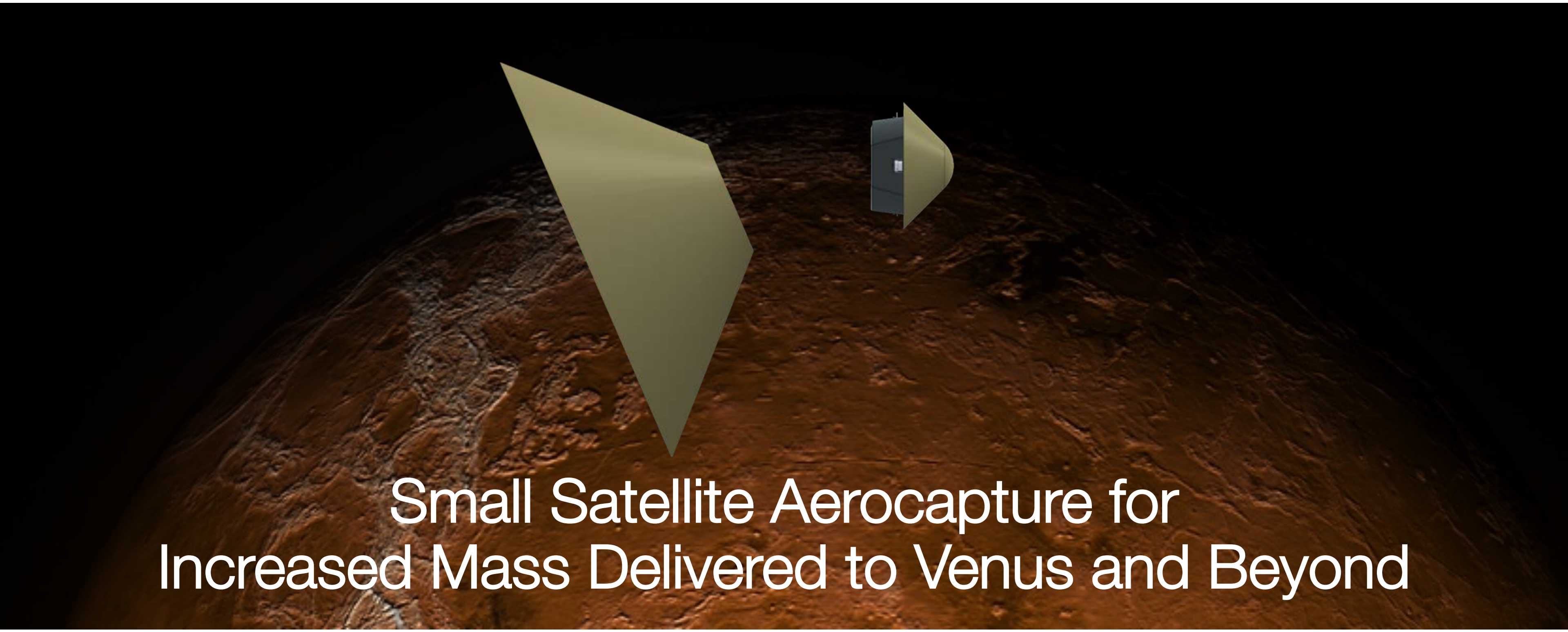


Small Satellite Aerocapture for Increased Mass Delivered to Venus and Beyond

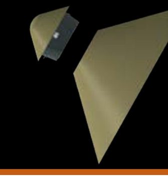
Adam Nelessen / Alex Austin / Joshua Ravich / Bill Strauss
NASA Jet Propulsion Laboratory

Ethiraj Venkatapathy / Robin Beck / Paul Wercinski / Mike Wilder / Gary Allen / Michael Aftomis
NASA Ames Research Center

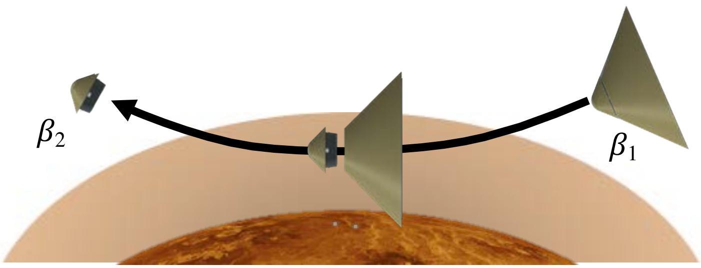
Robert Braun / Michael Werner / Evan Roelke
University of Colorado Boulder

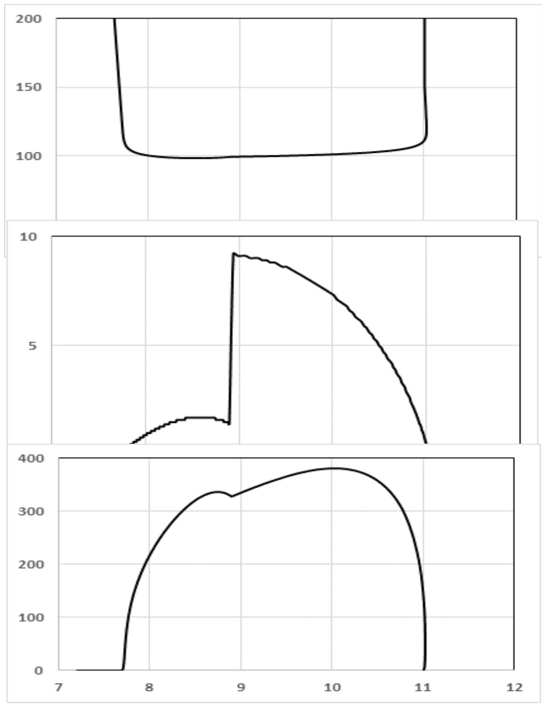
June 14, 2018

Overview



- A multi-organizational team is developing an aerocapture system for Small Satellites
  - Currently in year 1 of a 2-year effort
- Utilize drag modulation flight control to mitigate atmospheric & navigation uncertainties
  - Initially studied by Putnam and Braun in "Drag Modulation Flight Control System Options for Planetary Aerocapture"
  - Simplest form is the single event jettison
  - Ballistic coefficient ratio ($\beta 2/\beta 1$) provides control authority
- Study addresses key tall tent pole challenges
  1. Orbit targeting accuracy
  2. Thermal protection system feasibility
  3. Stability before, during, and after jettison event
- Technology development has so far been "mission-agnostic"
  - Pursue a notional flight system design and target orbit to demonstrate existence proof
  - Design and tools can be custom-tailored for a range of possible science missions

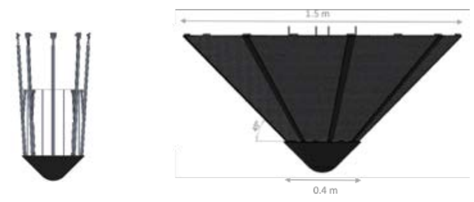




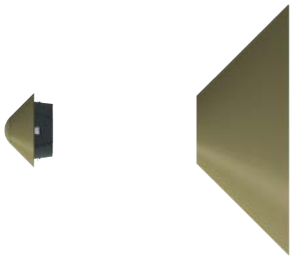
Mission Applicability

- Potential Destinations:
  - Venus
  - Earth
  - Mars
  - Titan
  - Ice Giants
- Vehicle Options:
  - Mechanical deployable drag skirt
  - Rigid drag skirt
- Delivery Schemes:
  - Dedicated launch & cruise
  - Delivery by host spacecraft

Mechanical deployable drag skirt



Rigid drag skirt



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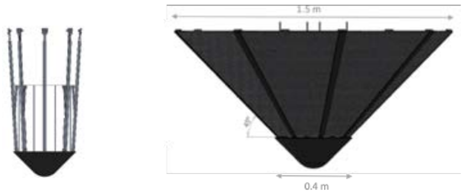
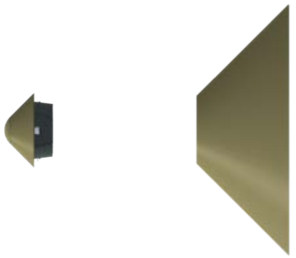
Mechanical deployable drag skirt



Rigid drag skirt



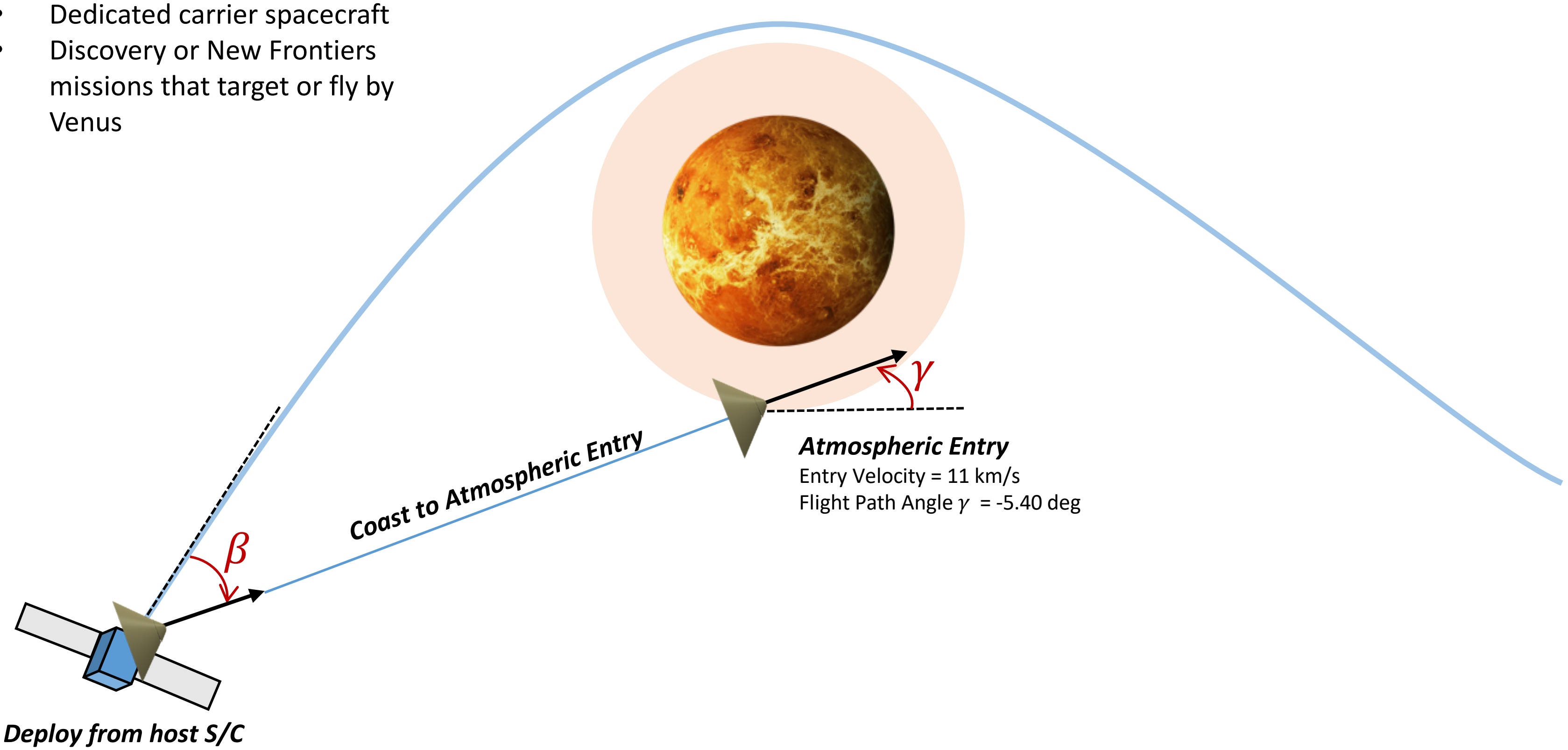
Initial Focus:

Chose Venus to bound the technology's capability. Can scale to "easier" destinations.
Chose rigid drag skirt and host spacecraft delivery to minimize system complexity.

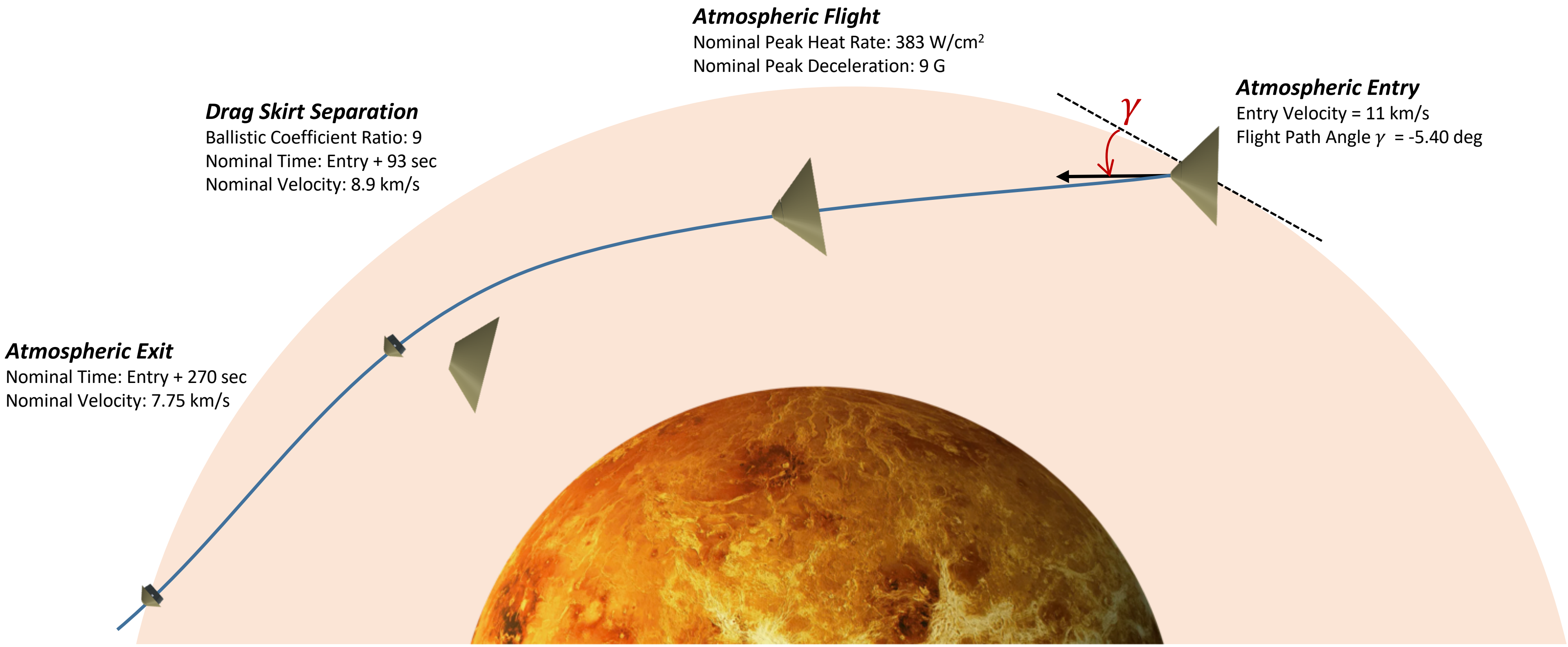
ConOps: Exo-Atmospheric

Potential Hosts:

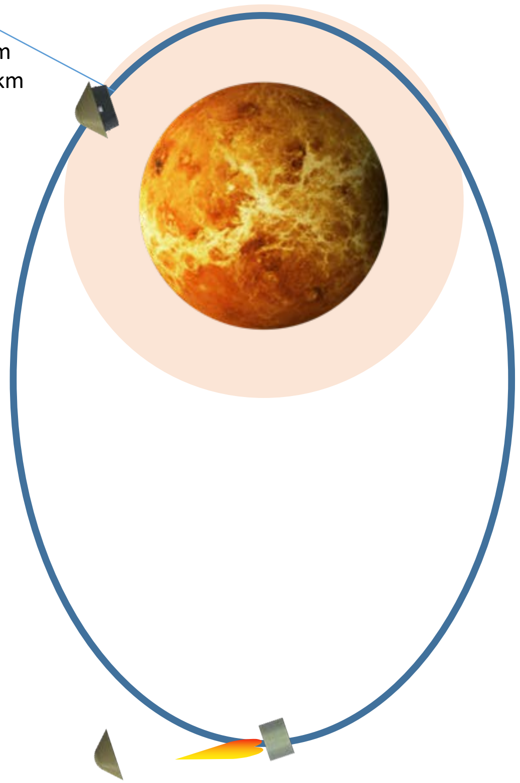
- Dedicated carrier spacecraft
- Discovery or New Frontiers missions that target or fly by Venus



ConOps: Atmospheric



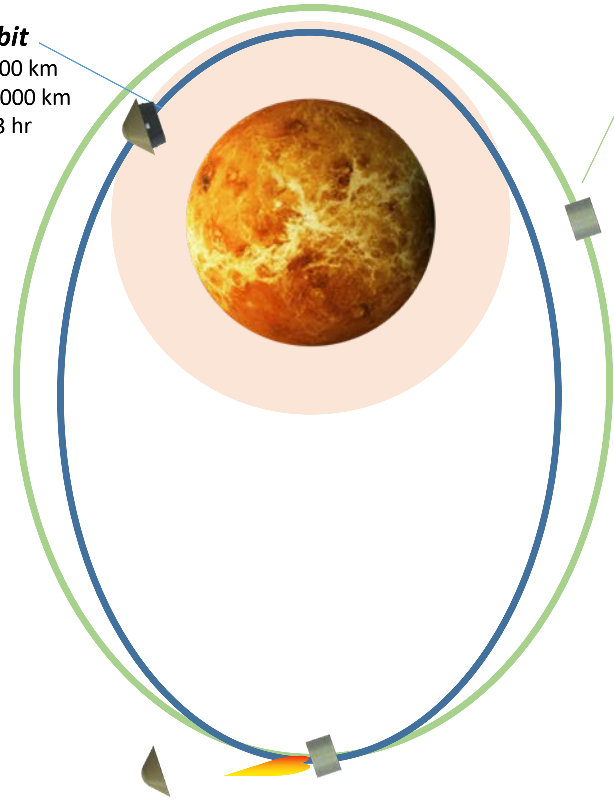
ConOps: Post-Aerocapture



ConOps: Post-Aerocapture

Initial Orbit
Periapsis: 100 km
Apoapsis: 2000 km
Period: 1.83 hr

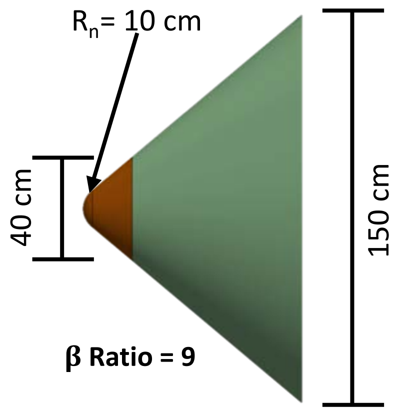
Final Orbit
Periapsis: 200 km
Apoapsis: 2000 km
Period: 1.85 hr



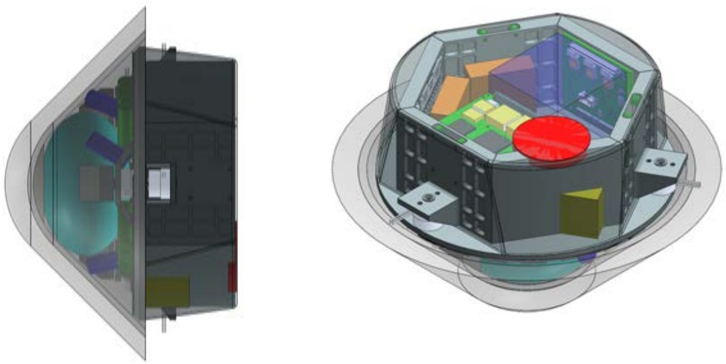
Drop Heat Shield +
Periapsis Raise Maneuver
Nominal Time: Atm. Exit + ½ Period
Trigger: Timer

Representative Flight System

Pre-Jettison Configuration



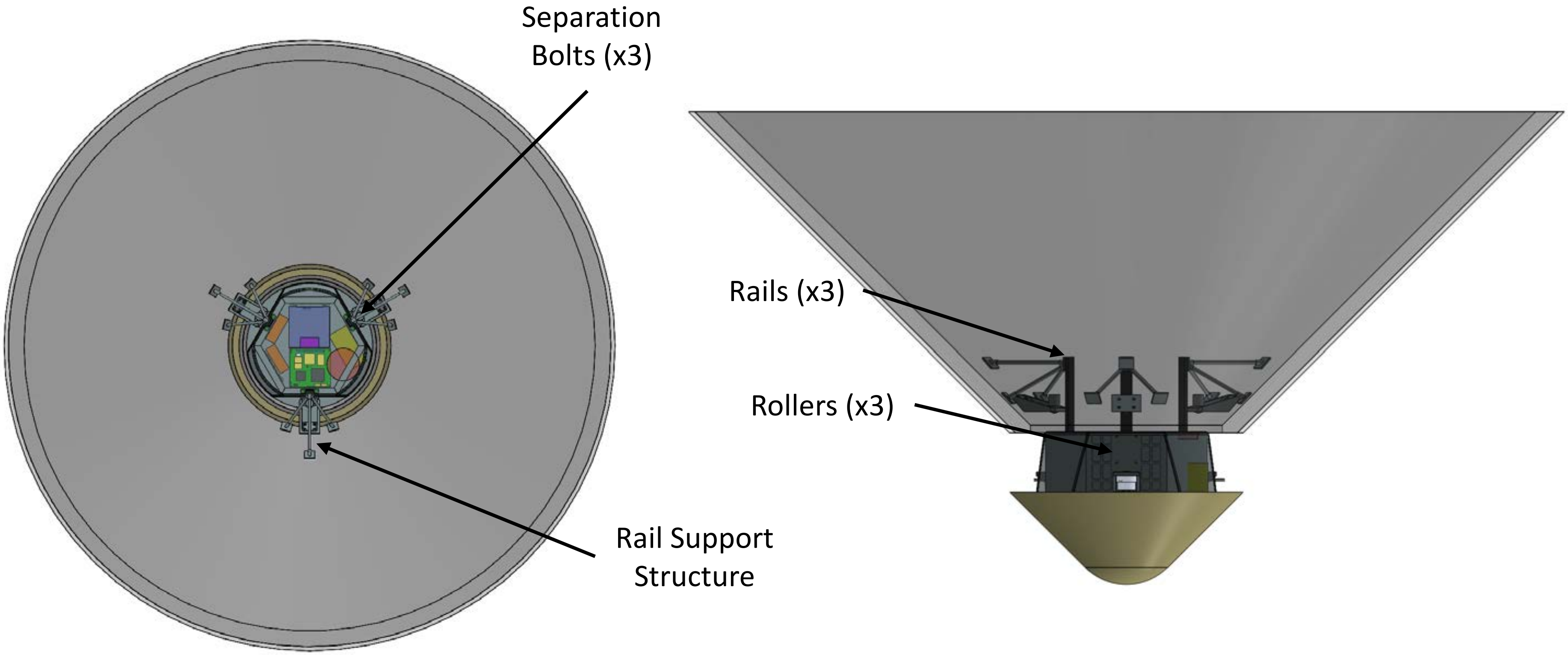
Delivered Flight System



Total Margined Mass = 69kg

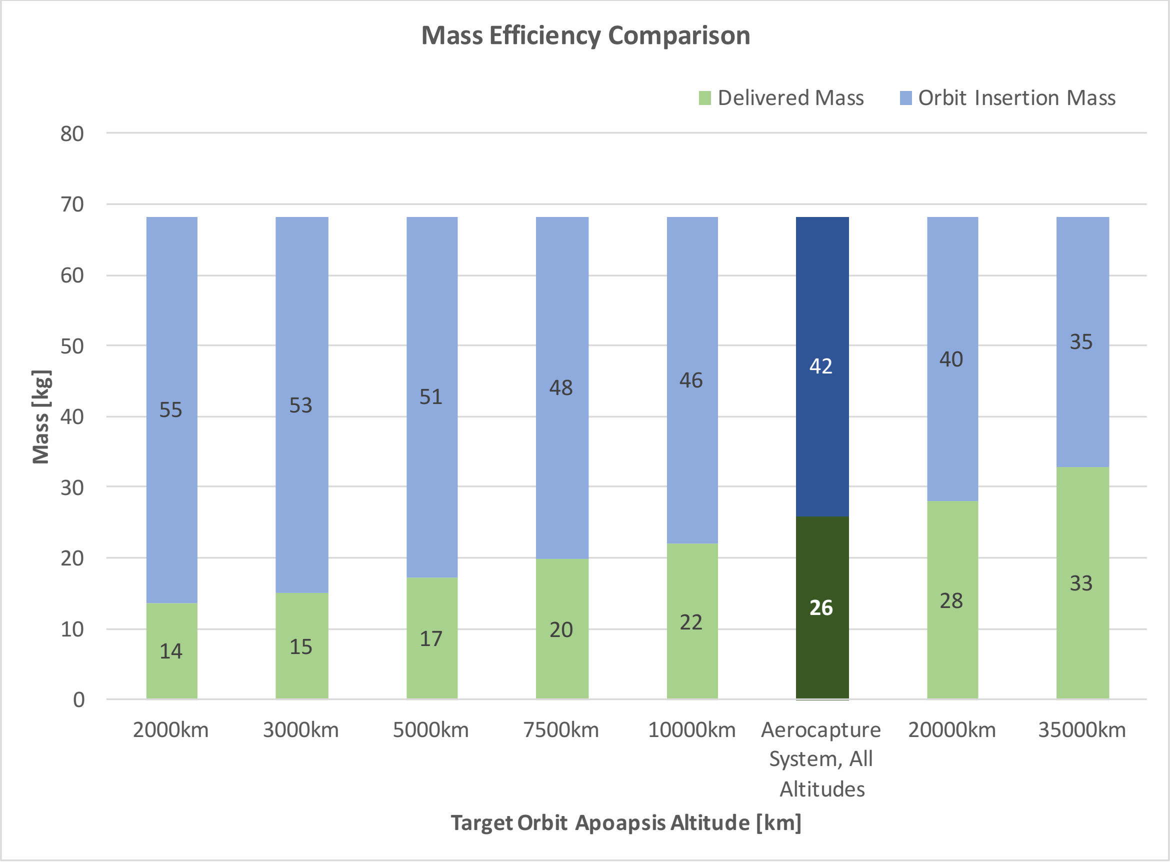
- Science Payload
  - ~1.5U available volume
- Telecom *(~2.5 kbps to 70m DSN)*
  - IRIS X-Band Radio
  - X-Band Patch Antenna
  - X-Band Circular Patch Array HGA
- ACS *(~10 arcsec pointing accuracy)*
  - BCT Star Tracker, Sun Sensors (x4), and Control Electronics
  - BCT Reaction Wheels (x3)
  - Sensonor IMU
- C&DH
  - JPL Sphinx Board
  - Pyro Control Board
- Thermal
  - Kapton Film Heaters
  - MLI
- Power *(~25 W with body mounted solar cells)*
  - Solar Arrays
  - Clyde Space EPS
  - 18650 Li-ion batteries (x11) (~180 Wh)
- Propulsion *(~70 m/s delta-V)*
  - 0.5 N Monoprop Thrusters (x4)
- Mechanical
  - Structure, TPS, Rails, Rollers, Separation Hardware

Drag Skirt Deployment System



- 3 separation bolts fire when triggered by the flight computer
- MSL-inspired rail & roller design reduces re-contact risk during drag skirt separation
- Drag skirt fabrication from MSL-style aluminum honeycomb with composite facesheets
- Heatshield made of solid carbon composite
- Backshell made of solid aluminum

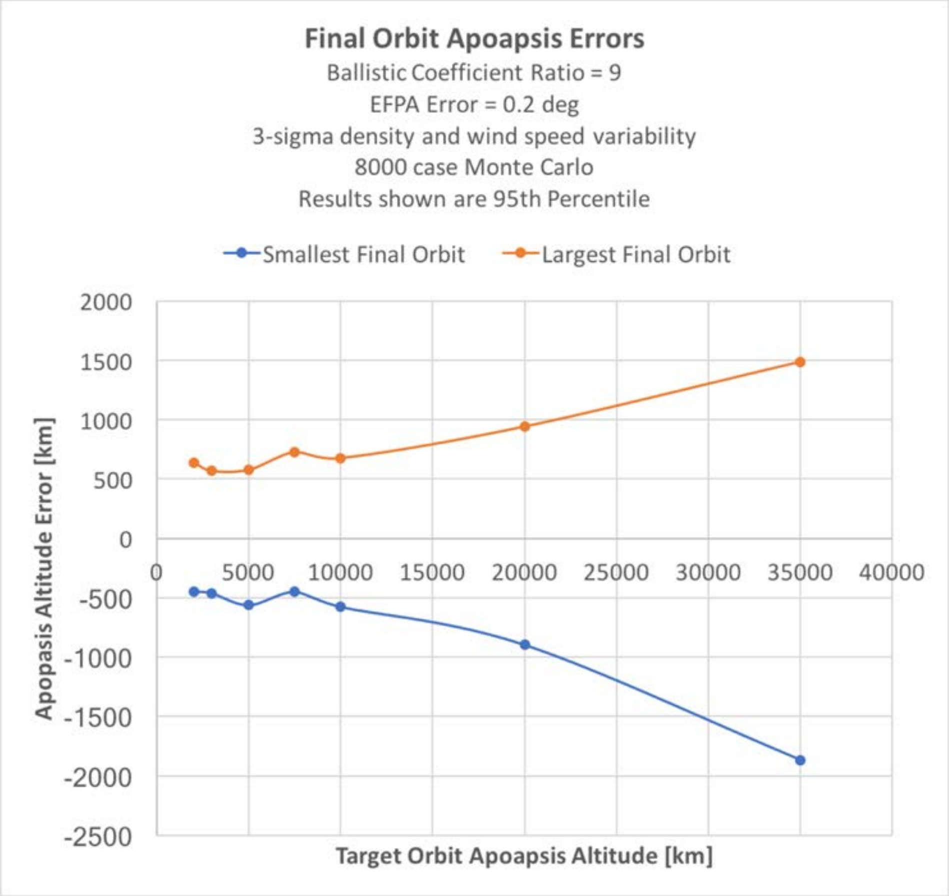
Mass Efficiency Comparison



- The aerocapture-based orbit insertion system can deliver up to 85% more useful mass to orbit than a propulsive system, depending on target orbit

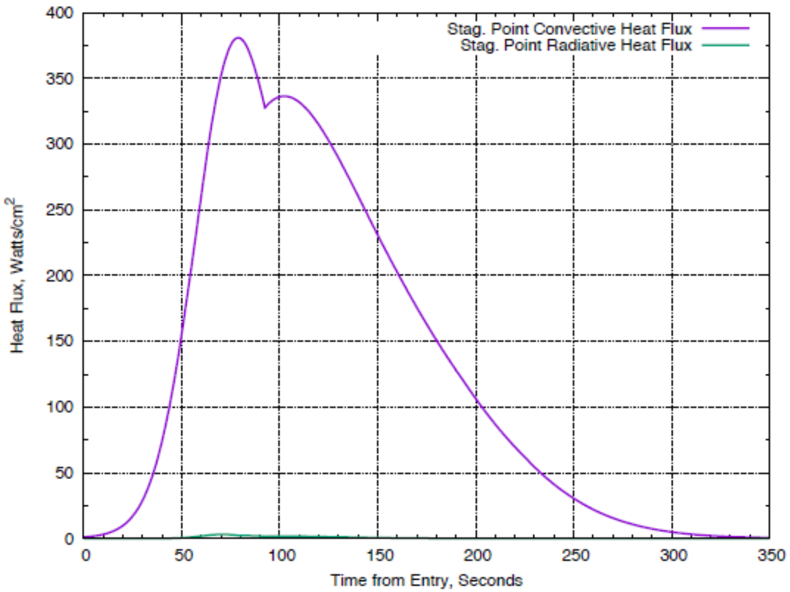
Orbit Delivery Accuracy

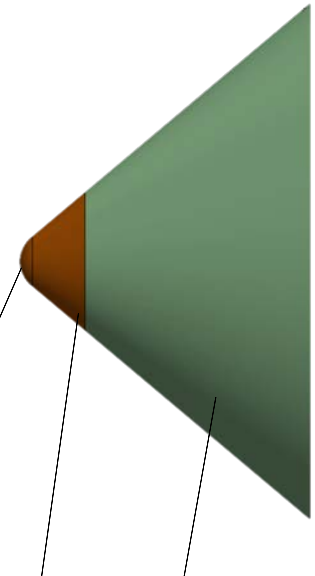
- 3DOF Monte Carlo runs in JPL's DSENDS trajectory tool used to assess orbit targeting accuracy
  - VenusGRAM atmospheric model with 3-sigma variability in density and wind speeds
- Options for improving orbit targeting accuracy are under investigation
  - Reduce EFPA error
  - Increase ballistic coefficient ratio
  - Improve G&C algorithm for drag skirt separation timing



Aerothermal & TPS

Stagnation Point Heating vs Time





	Nose	Flank (est)	Skirt (est)
Peak Heatflux (W/cm2)	383.3	191.65	191.65
Peak Heatload (J/cm2)	45179	22590	3840
Peak Pressure (Pa)	8800	4400	3650
C-PICA thickness (cm)	2.58	1.88	0.72
PICA thickness (cm)	4.125	3.51	1.11
C-PICA mass (kg)	0.13	0.80	4.56
PICA mass (kg)	0.20	1.45	6.83

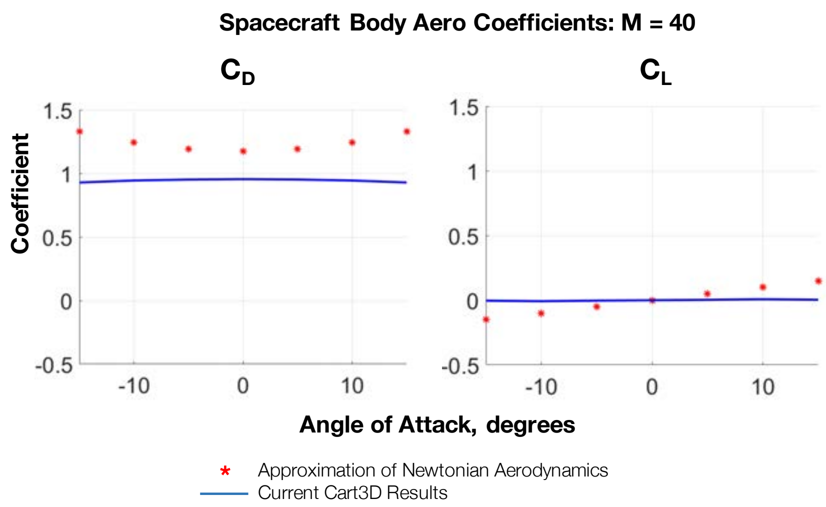
Total heat-shield only TPS mass for pre-and post-jettisoned bodies combined:

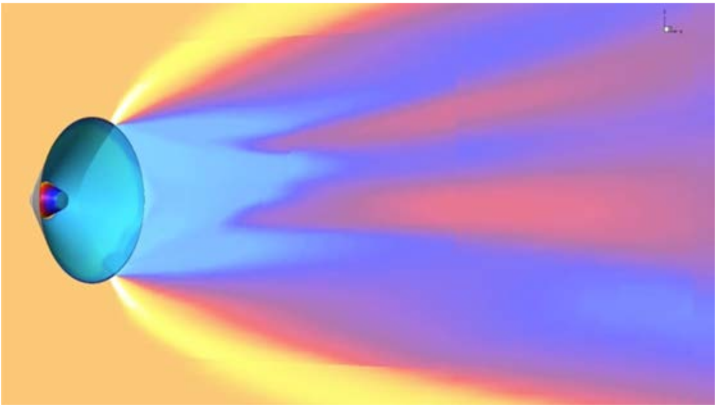
C-PICA 5.49 kg (**Un-margined** engineering estimate)

PICA 8.48 kg (**Un-margined** engineering estimate)

Aerodynamics

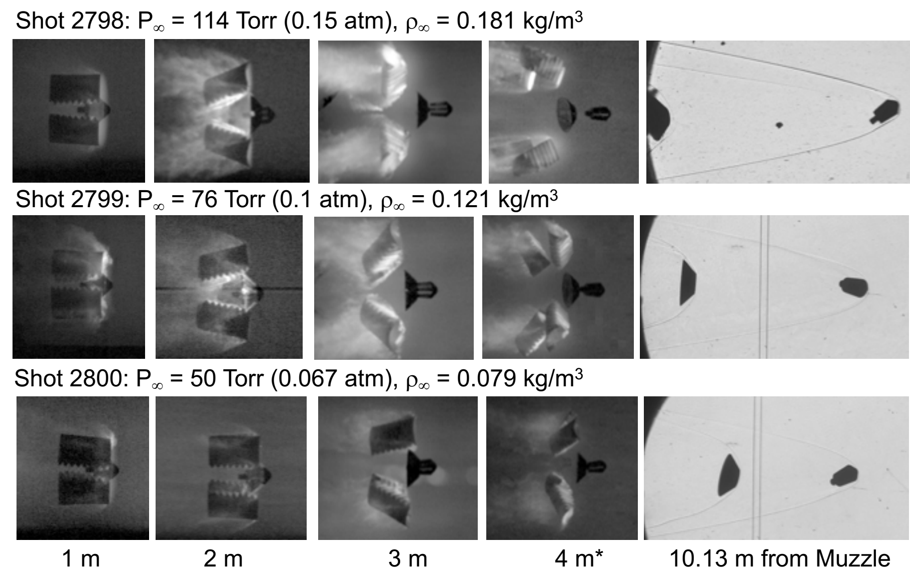
- CFD simulation development in Cart3D underway at CU Boulder
    - Currently troubleshooting coefficient errors vs. Newtonian aerodynamics
- Objectives
    - Analyze forces & moments during separation event
    - Generate 6DOF aerodynamic database

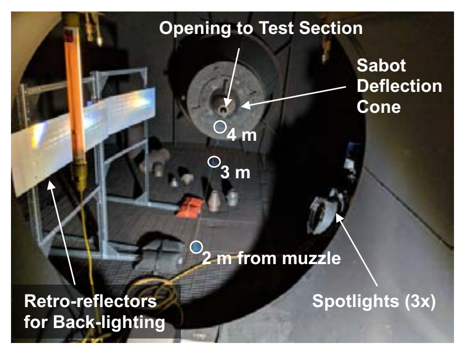




Ballistic Range Testing

- Ballistic range at NASA Ames has been modified to image the separation event
- Several exploratory test shots have been performed this year
- Ballistic range test articles based on final study design to be fabricated by end of FY18
- Multiple ballistic range shots planned for FY19





Conclusions and Future Work

This initiative addresses the following key challenges for drag modulation aerocapture at Venus:

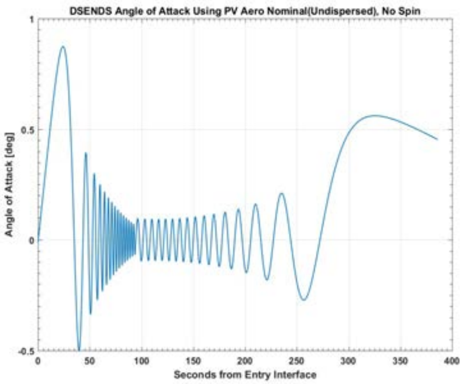
1. Orbit targeting accuracy
   - ✓ 3DOF Monte Carlo simulations of the maneuver
   - G&C algorithm improvements (Work to Go)

2. Thermal protection systems
   - ✓ Preliminary aerothermal assessment and TPS design
   - CFD detailed aerothermal assessment (In Progress)

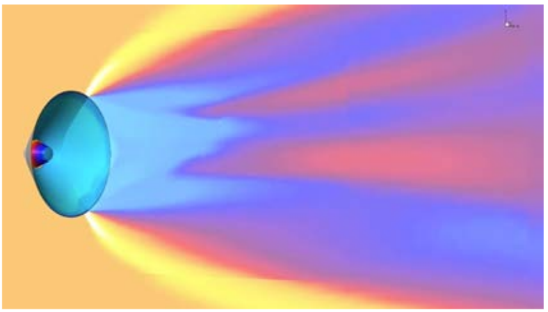
3. Stability before, during, and after jettison event
   - ✓ Preliminary 6 degree-of-freedom DSENDS simulations
   - CFD analysis of dynamics of drag skirt separation (In Progress)
   - CFD aerodynamic database generation (Work to Go)
   - Ballistic range testing (Work to Go)

- To improve mission accommodation options, investigating an ADEPT-based mechanical deployable drag skirt option

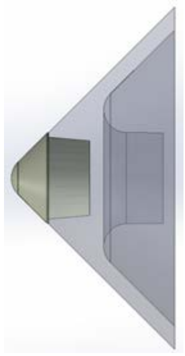
6DOF Trajectory Simulation



CFD Separation Analysis

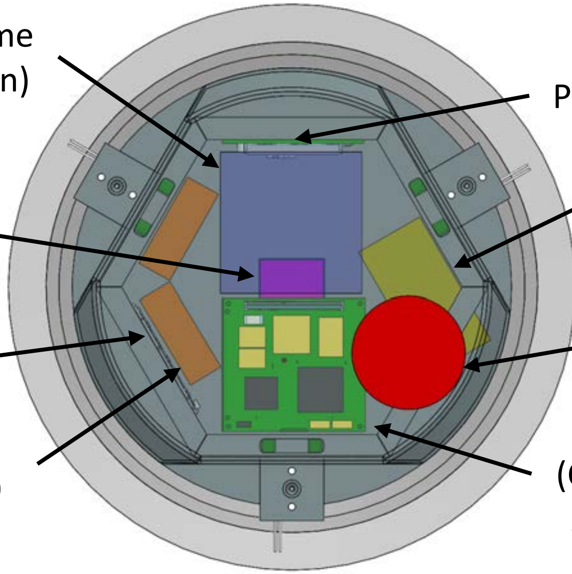


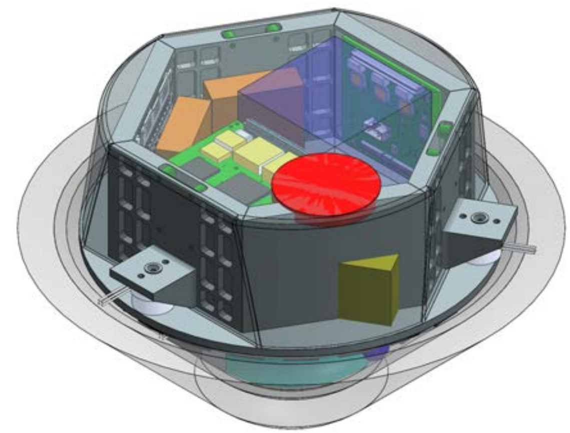
Ballistic Range Model Design

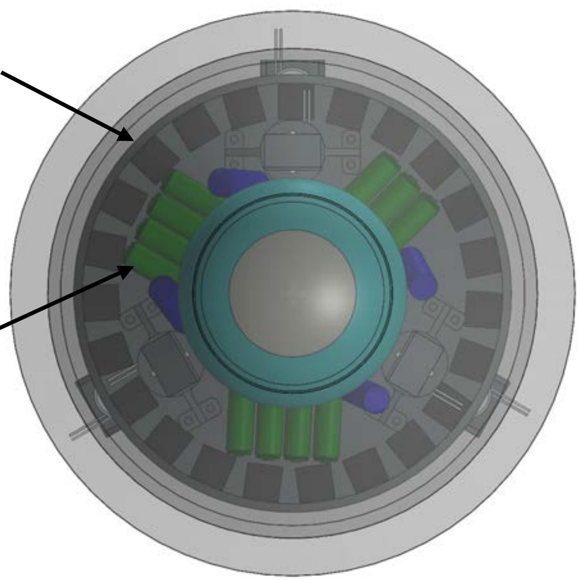


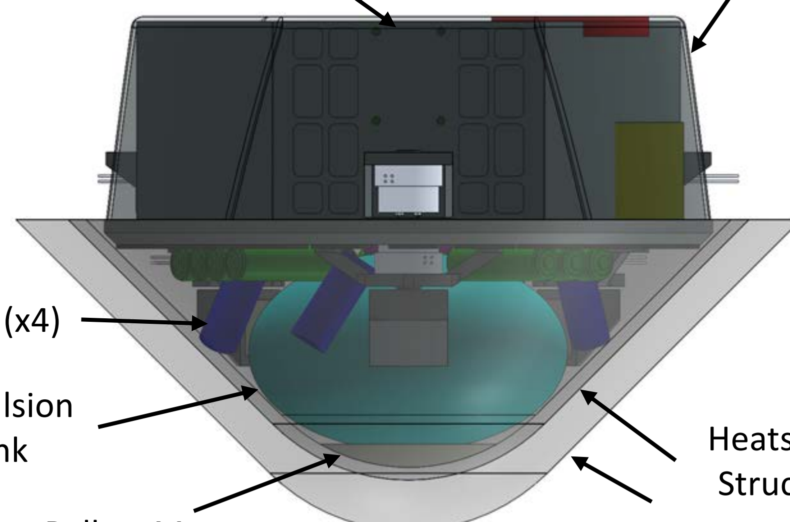
Thank you!

Internal Flight System Configuration





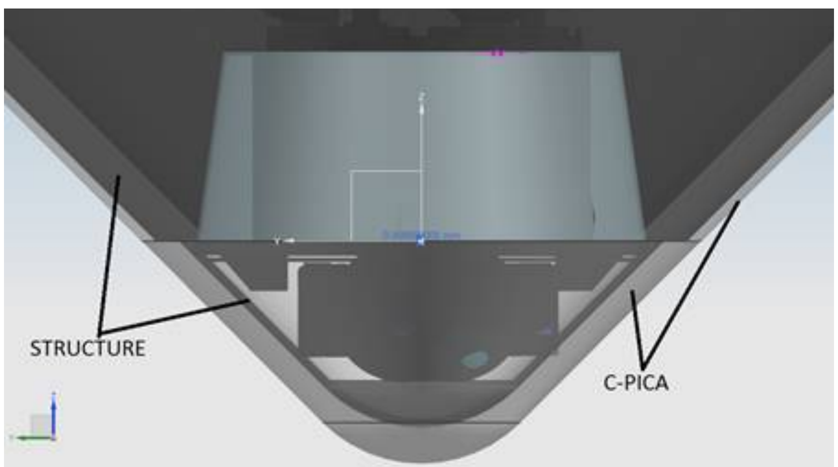




TPS Material Selection

- Available volume in the nose of the spacecraft is important
  - Give space for components to keep the CG forward
  - Give space for the propulsion system to perform the PRM
- Required PICA thickness results in too little space, but C-PICA is much more flexible.
- Rough calculation: Every 1 cm increase in the spacecraft diameter requires ~8 cm increase in the drag skirt diameter to maintain the same beta ratio.
- To remain as compatible as possible with hosts, growing the drag skirt is not desirable, therefore we choose C-PICA.

C-PICA TPS



PICA TPS