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Hypersonic Inflatable Aerodynamic Decelerator Earth-Based Applications

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AIAA SciTech Forum, Orlando FL
Jan. 6-10, 2025

Why HIAD?

- Hypersonic Inflatable Aerodynamic Decelerator (HIAD)
- Entry vehicle performance affected by ballistic coefficient (β)
- Typical entry capsules are limited to fairing diameter of the launch vehicle
- Deployable entry vehicles, like HIAD, can expand to larger diameters after separation

$$\beta = \frac{m}{C_D * S_{ref}}$$

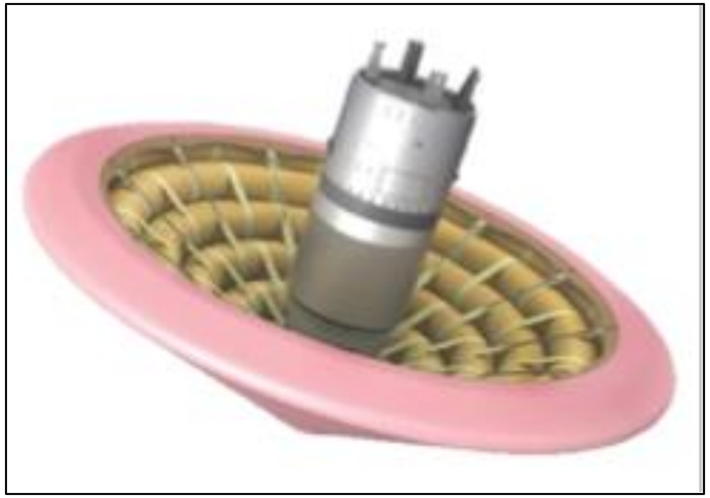
m = mass
C_D= drag coefficient
S_{ref} = area

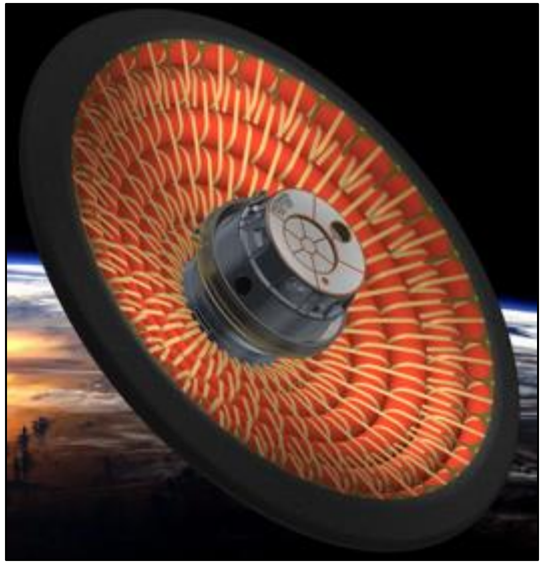
Credit: NASA

Credit: NASA

Past HIAD Flights

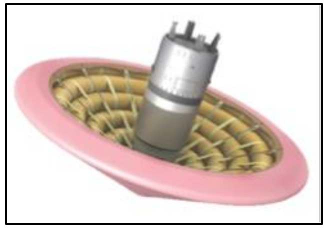

IRVE II

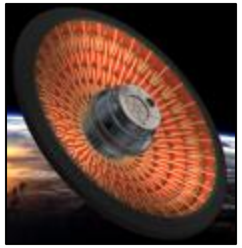

IRVE 3


LOFTID

IRVE = Inflatable Reentry Vehicle Experiment
LOFTID = Low-Earth Orbit Flight Test of an Inflatable Decelerator

Past HIAD Flights





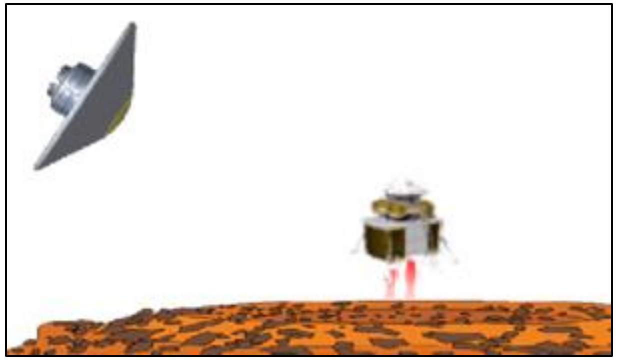
Parameters	IRVE-II	IRVE-3	LOFTID
Year of Test	2009	2012	2022
Diameter (m)	2.9	3	6
Nose Radius (m)	0.387	0.191	1.71
Sphere-cone Angle (deg)	60	60	70
Entry Mass (kg)	125	281	1100
Ballistic Coefficient (kg/m^2)	13.6	29.2	24.7
Planet-Relative Entry Velocity (km/s)	1.6	2.7	8
Peak Heat Flux (W/cm^2)	2.2	15	40
Thermal Protection System	Gen-1	Gen-1	Gen-2

Can successful HIAD test flights be leveraged for new entry applications?

Outline

- Past and Current Application Studies
- Models and Assumptions
- Aerocapture Results
- Low Earth Orbit Return Results
- Suborbital Flight Results
- Summary

Past Applications Studied



Scenario	Details	Entry Velocity (km/s)	Entry Mass (t)	HIAD Diameter (m)	Ballistic Coefficient (kg/m²)
Launch Asset Recovery	2nd Stage Recovery	7.7	4	5	140
Launch Asset Recovery	1st Stage Recovery	3.5	22	10	200
Mars Aerocapture	Aerocapture 500 km circular orbit, L/D=0.2	7.4	10.5	9	141
Mars Aerocapture	Aerocapture 500 km circular orbit, L/D=0.2	9.5	14	26	23
Mars Southern Highlands	HIAD to supersonic/subsonic retro-propulsion	5.8	4	10	37.8
Mars Southern Highlands	HIAD to subsonic retro-propulsion	5.8	4	15	17
Hybrid Lunar Return	Hybrid Lunar return, direct entry	11	10.8	18	33
Mars Fast Transit	400 km circular orbit capture at Earth, L/D=0.2	12	7	21	17.5
Mars Fast Transit	400 km circular orbit capture at Earth, L/D=0.2	12	14	27	20
L2 to Low-Earth orbit Transfer	Hybrid L2 to Low-Earth orbit aerocapture, L/D=0.2	11.5	11.5	23	24

Credit: AIAA 2013-1389

Earth-Based Applications

- Past mission studies emphasized human missions to and from Moon and Mars
- Past mission studies had high mass systems, large diameters
- Current paper’s focus on Earth-Based, commercial applications
  - Aerocapture and orbit change
  - Low Earth Orbit (LEO) return
  - Suborbital flight (e.g. recovery of launch assets)

Earth-Based Applications

Altitude vs. Velocity

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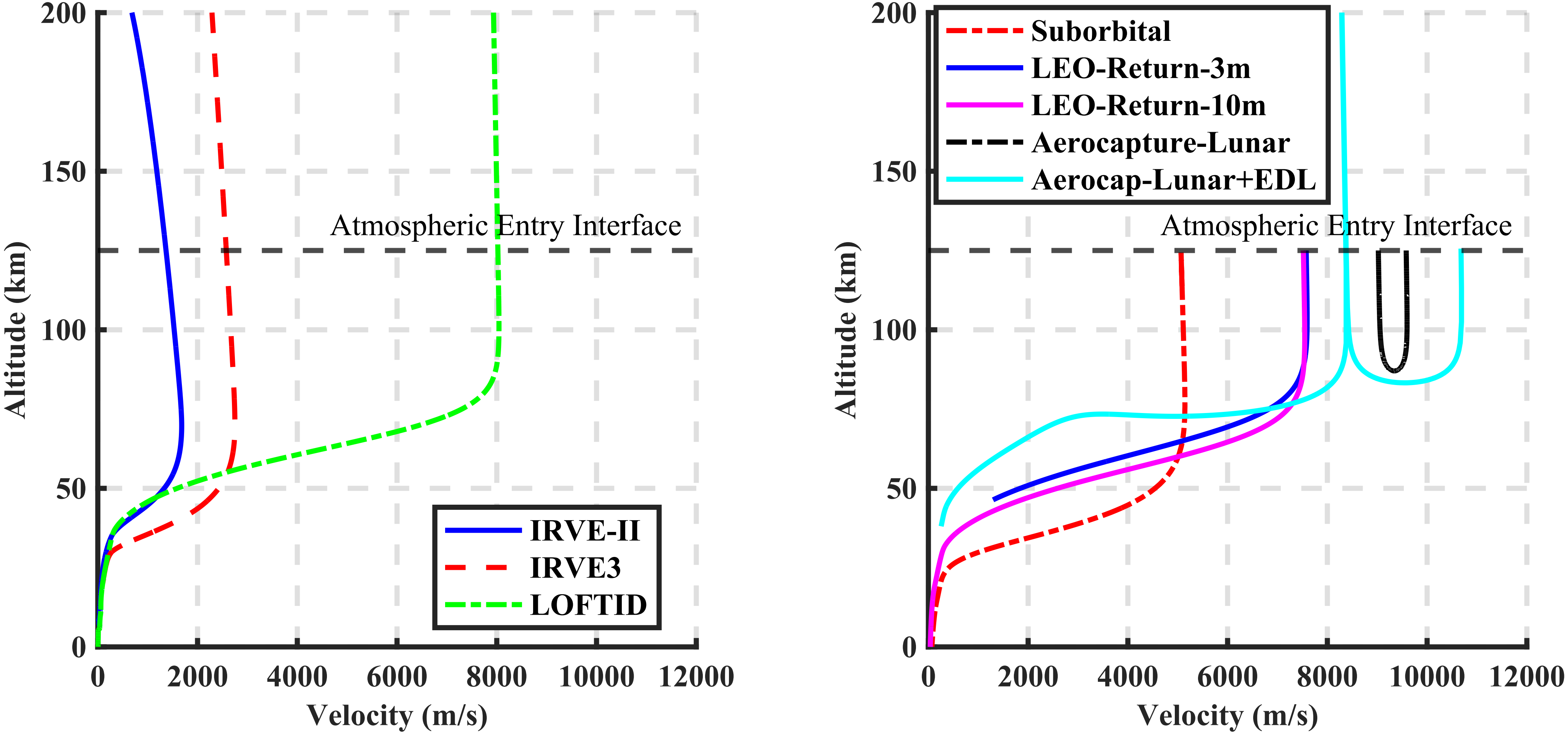
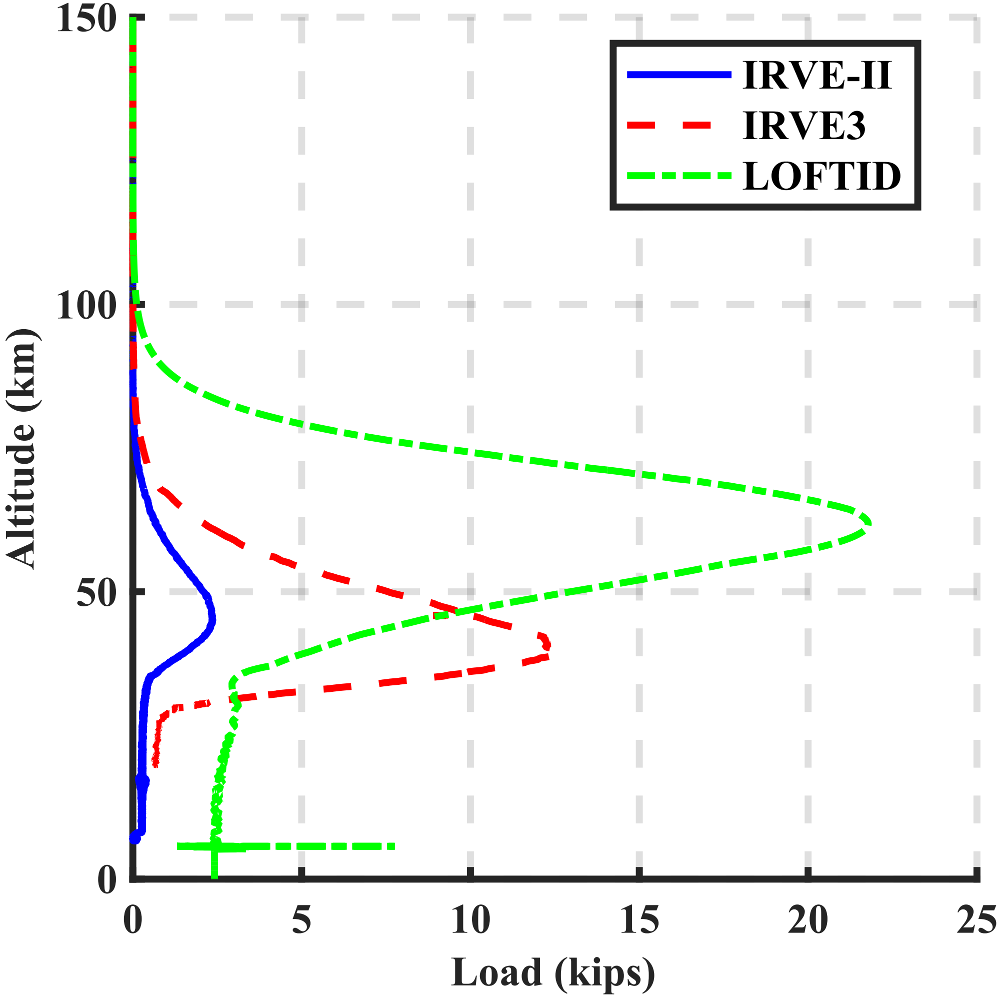
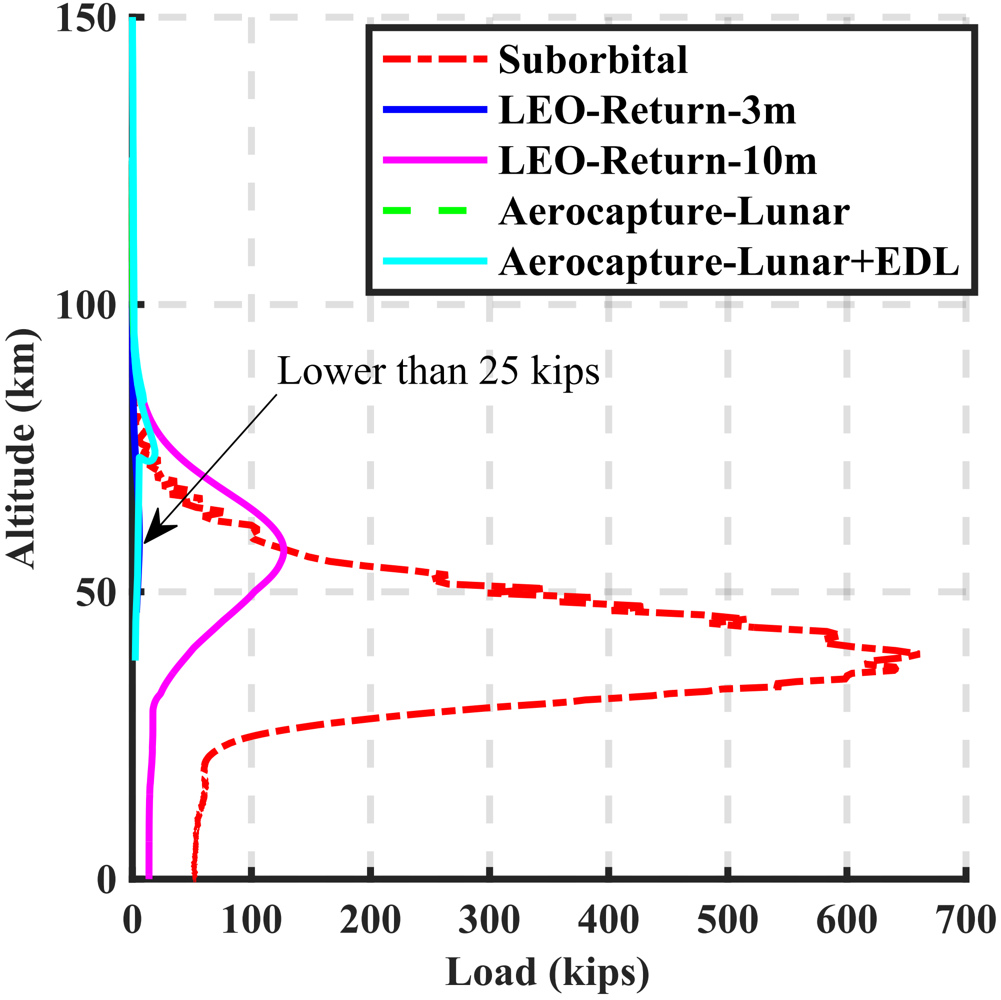


Earth-Based Applications

Loads (kilo pounds or kips)





Earth-Based Applications

Loads (kilo pounds or kips)

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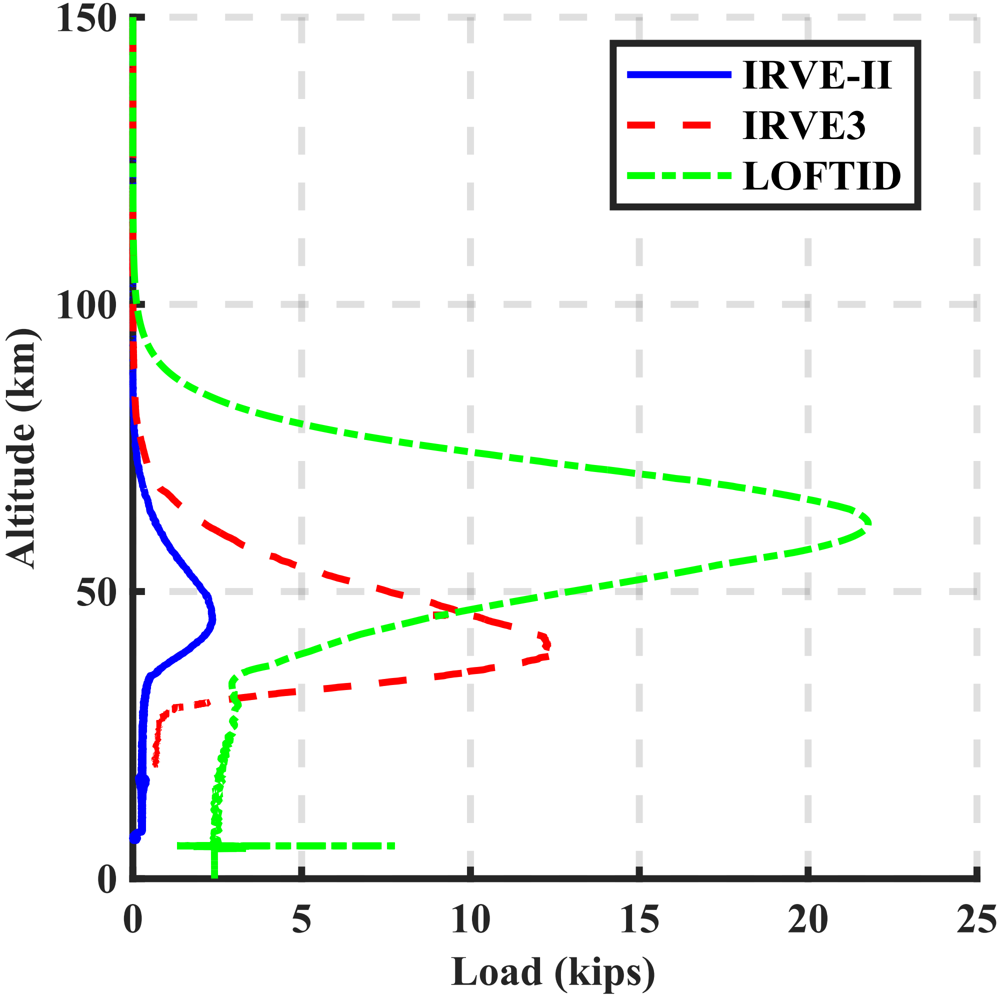
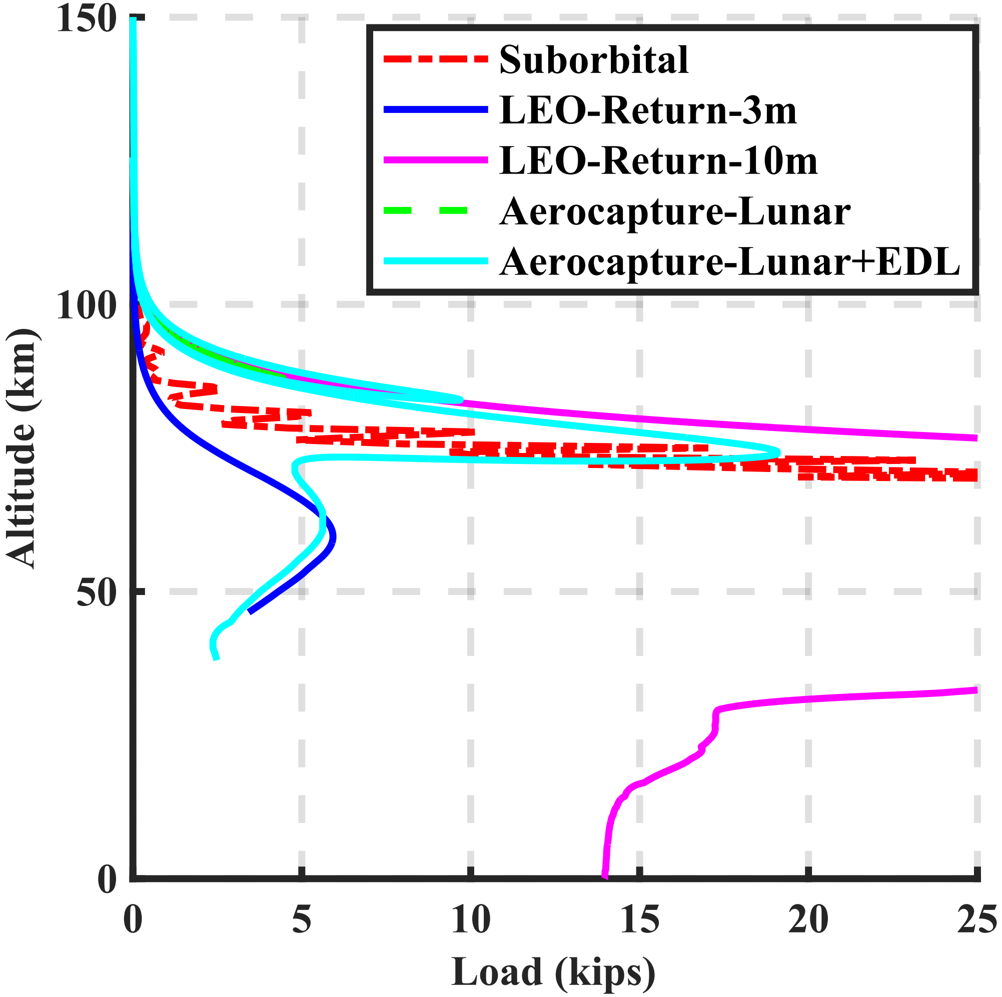




Earth-Based Applications

Heat Flux

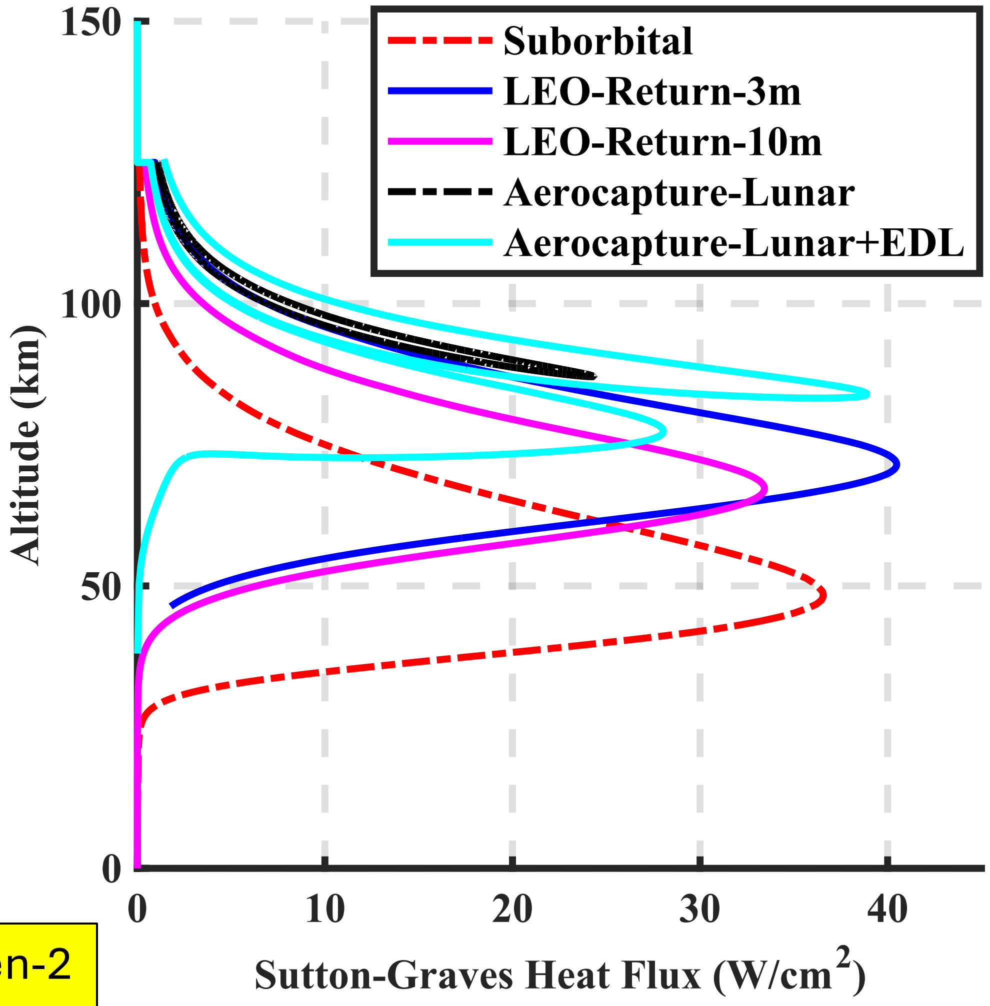
Parameters	IRVE-II	IRVE-3	LOFTID
Peak Heat Flux (W/cm^2)	2.2	15	40
Thermal Protection System	Gen-1	Gen-1	Gen-2

Plots of heating as a function of trajectory not available for past HIAD flights

Gen-1 – Nextel – High heat flux ~ 30 W/cm^2
Gen-2 – Silicon-Carbide – High heat flux ~ 50 W/cm^2
(eye towards Mars applications)

Sutton-Graves Indicator = Cold-wall, convective, non-margined heating indicator

Earth-Based applications are in the ballpark of Gen-1 and Gen-2 Thermal Protection System capabilities



Models and Assumptions

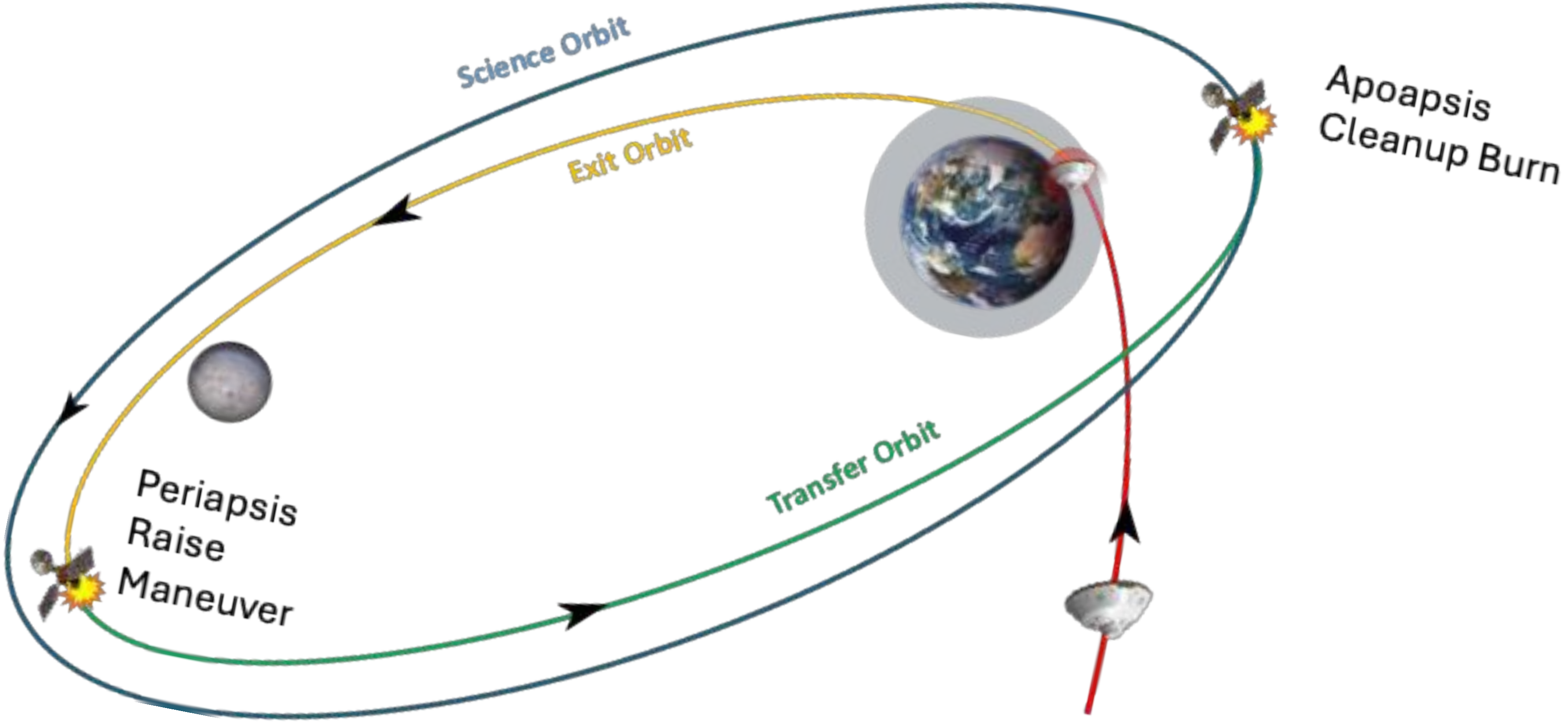
- Simulation based on Program to Optimize Simulated Trajectories II (POST2)
- Assumptions
  - All results are based on 3 degree-of-freedom (3DOF) analysis
  - No closed-loop Guidance, Navigation, and Control (GNC)
  - Vehicles modeled as rigid bodies at the center of mass. Significant flexible dynamics within the HIAD have not been observed in ground or flight tests to date. The rigid body assumption, even for a deployable like HIAD, for the most part seems to be a good assumption to predict flight mechanics performance
  - HIAD is assumed to be inflated
  - Parachute modeling for the recovery system was ignored
  - Future applications of the HIAD to similar scenarios may have different initial conditions, but the trends covered in the paper would be useful for mission designers during planning

Models and Assumptions

- Aerodynamics
  - LOFTID: 70 deg sphere-cone
  - High-Energy Atmospheric Reentry Test (HEART): 45, 60, 70 sphere-cone
  - Vulcan Engine Recovery Aeroshell (VERA): 65 deg sphere-cone
- Aeroheating
  - Sutton-Graves Indicator for heat flux
  - Integrated heat load = integration of heat flux
- Atmosphere
  - Earth GRAM 2010
  - GRAM Suite (2021+)

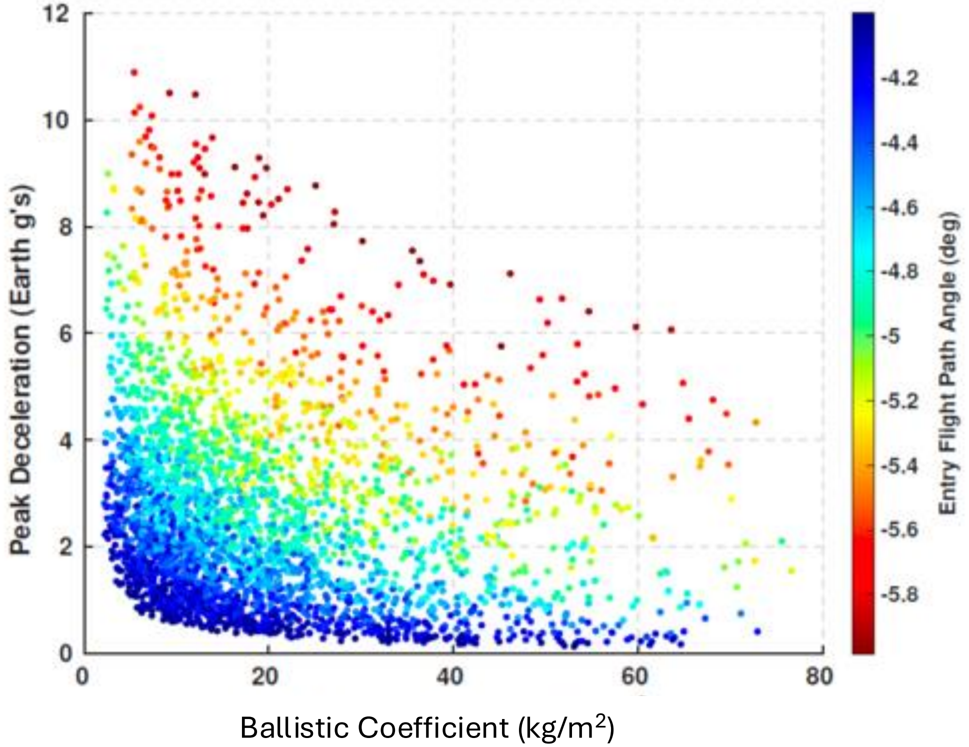
$$\underset{\text{Heat Flux}}{q} = \overset{\text{Sutton-Graves Constant}}{C_{SG}} * \sqrt{\underset{\text{Density}}{\rho_\infty} * \overset{\text{Nose Radius}}{r_n}} * \underset{\text{Velocity}}{V_\infty^3}$$

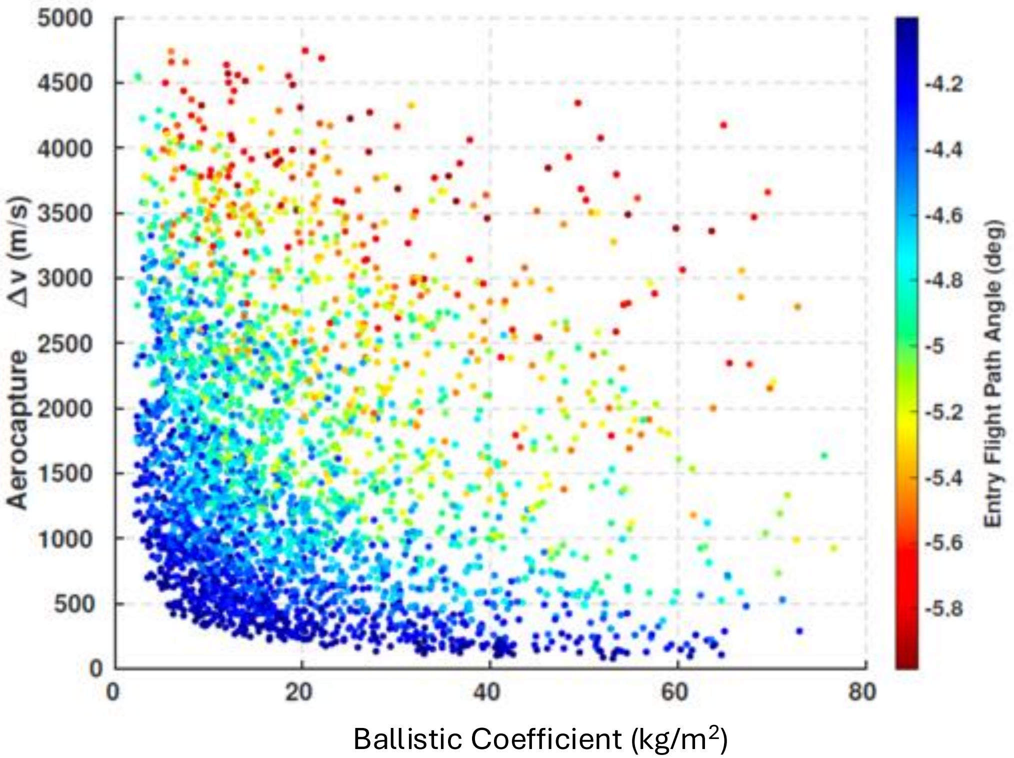
Aerocapture Results



- Aerocapture – orbital insertion maneuver using aerodynamic forces

Aerocapture Results



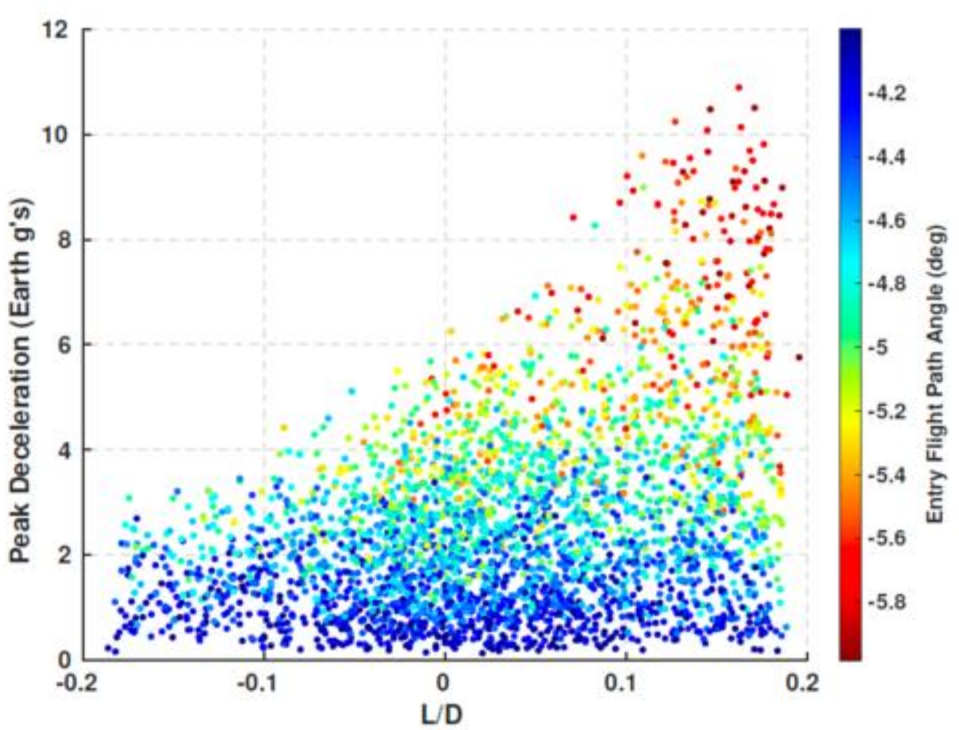


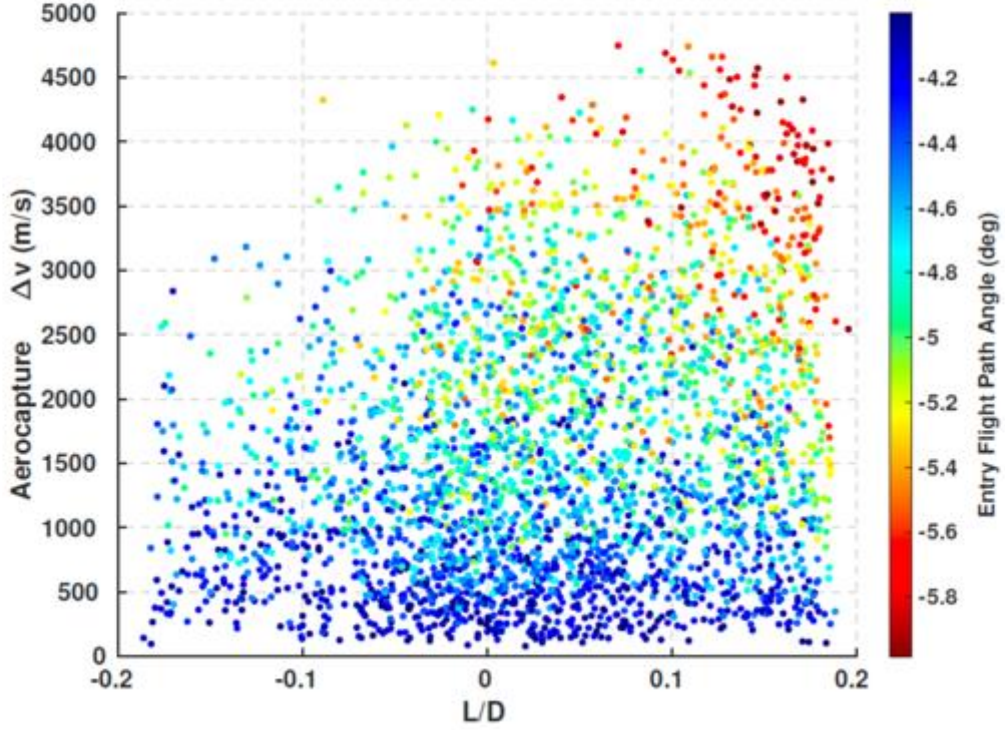
Energy dissipated during aerocapture

- Aerocapture – orbital insertion maneuver using aerodynamic forces
- Peak deceleration reduced with lower ballistic coefficient and shallower flight path angle
- Energy dissipation stronger function of flight path angle

Aerocapture Results

Lift-over-drag ratio (L/D) is fixed for each instance of trajectory





Energy dissipated during aerocapture

- Aerocapture – orbital insertion maneuver using aerodynamic forces
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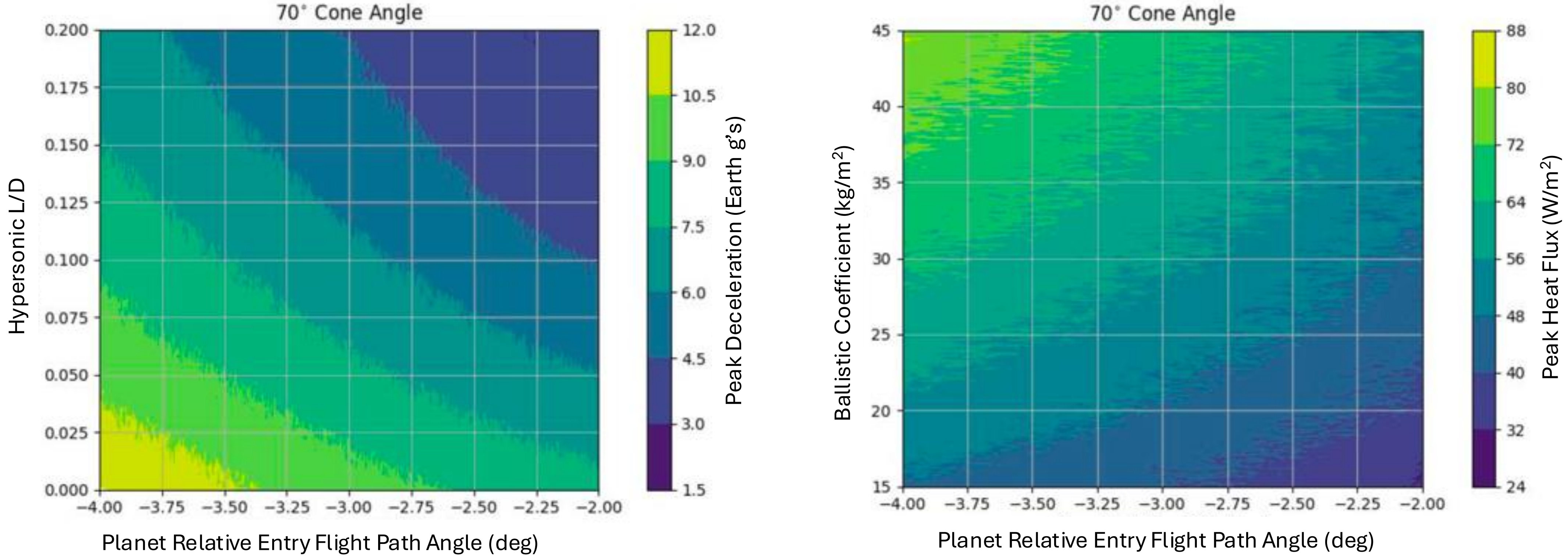
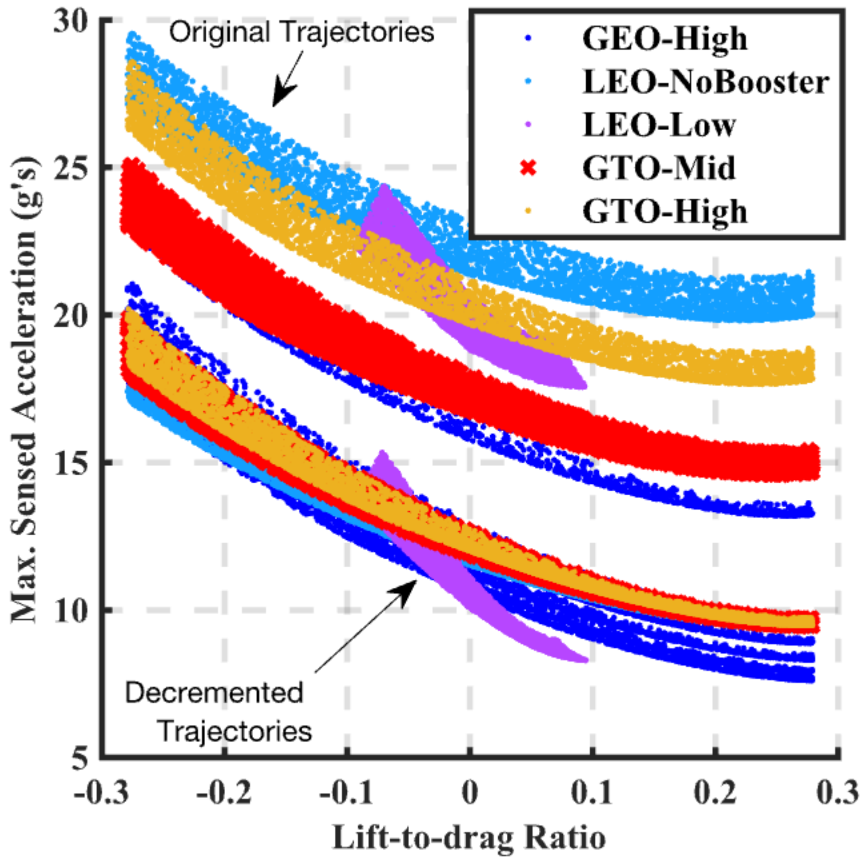
Low Earth Orbit Return Results

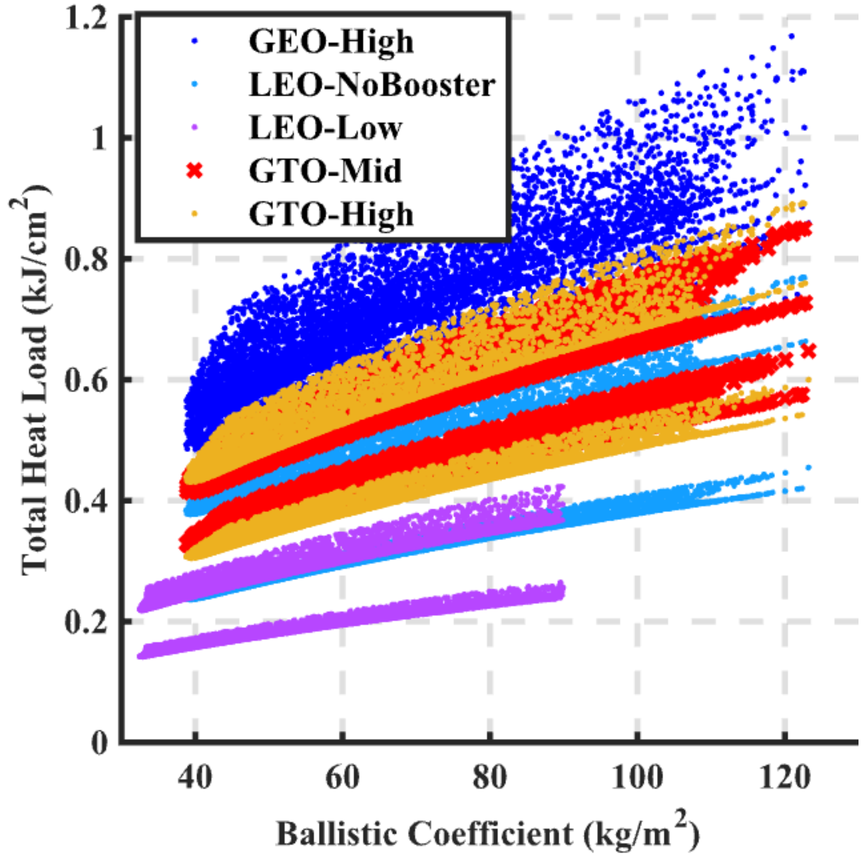
- Multiple design space explored:
  - Small HIAD (< 3 m diameter)
  - Large HIAD (3+ m diameter)
- Small L/D ratio (~0.1) can have a sizeable effect on peak deceleration and heat flux

Small HIAD Results



Suborbital Flight Results



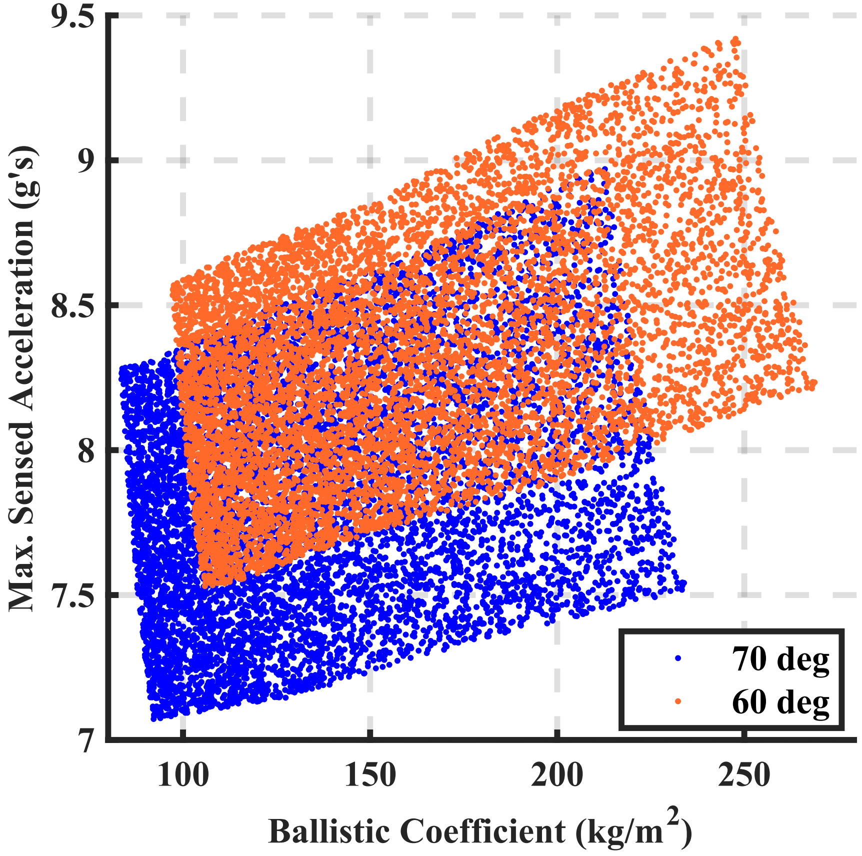


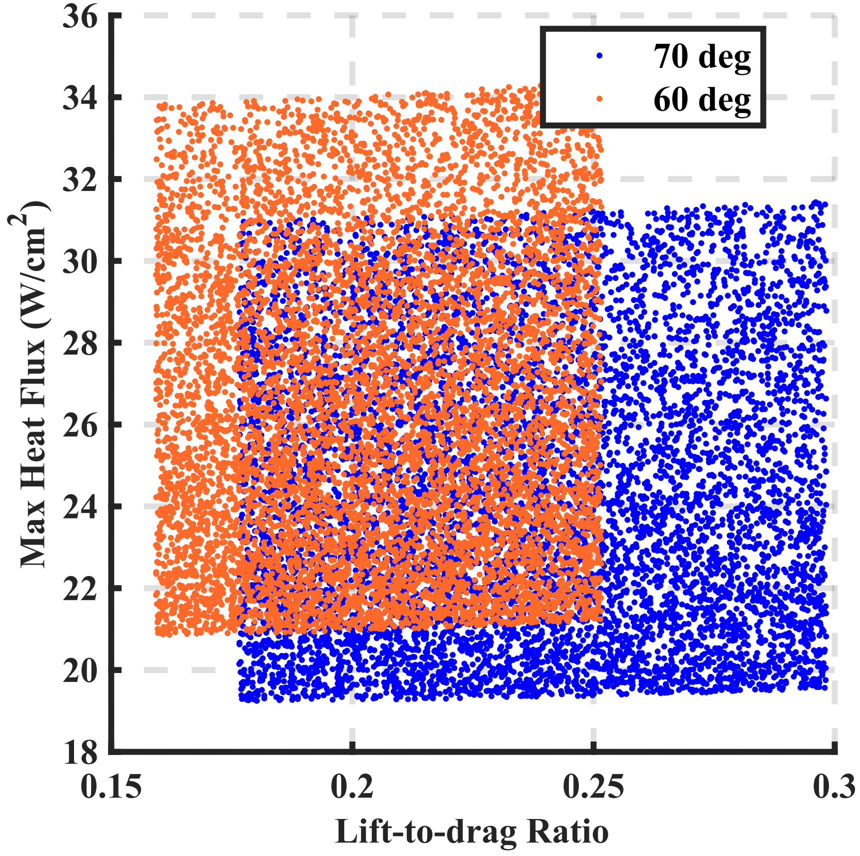
GTO = geosynchronous transfer orbit
LEO = Low Earth Orbit
GEO = Geosynchronous orbit

Decremented trajectories = extra burn before HIAD separation to create shallower flight path angle

- Several launch vehicle configurations studied for asset recovery
- Original trajectory design (with steeper initial flight path angles) led to high deceleration and heat loads
- Decremented trajectories with shallower flight path angles showed lower loads, but at potential costs to launch vehicle performance to shallow out the trajectories

Suborbital Flight Results





- Trade space in different geometries also explored
- Higher drag at high altitudes achieved with 70 deg. sphere-cone. Preferred choice based on these metrics

Summary

- HIAD technology can be enabling for many planetary and Earth-Based applications
- Recent success of LOFTID provides flight data and proven HIAD technology for many commercial applications, such as aerocapture, low Earth orbit return, and suborbital flights
- Paper showed the feasible design space for many scenarios, such as lunar return, low Earth orbit down mass, and recovery of launch vehicle assets
- Mission designers can evaluate the applicability of HIAD for their applications from the performance tabulated in this paper

Acknowledgements

- Brian Hollis, Ashley Korzun, and Hisham Shehata for aerodynamics and aeroheating results
- Neil Cheatwood (HIAD Principal Investigator) and John DiNonno (HIAD Chief Engineer)

Questions