Feasibility and Performance Analysis of Magnetohydrodynamic Control for Aerocapture at Neptune

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Introduction

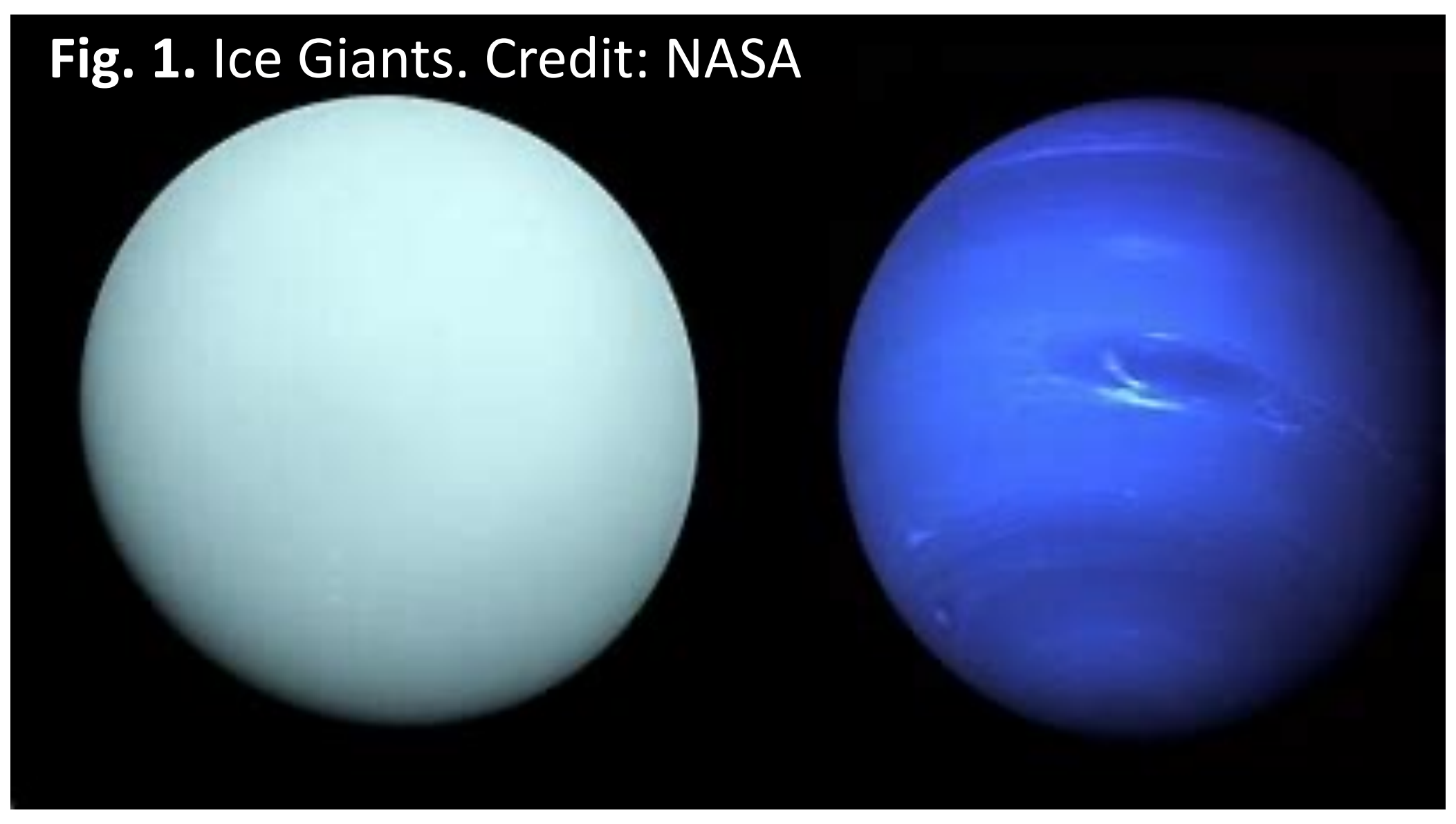
Fig. 1. Ice Giants. Credit: NASA

NASA's most recent Decadal Survey posed a mission to one of the Ice Giants as a top priority for flagship missions in the organization's future. However, orbital missions to these planets require high-cost orbit insertion maneuvers, and typical fully propulsive orbital maneuvers are infeasible due to the propellant mass cost. Atmospheric aerocapture has shown promise as an enabling alternative by utilizing the planet's atmosphere to decelerate and reduce propellant mass [1,2]. However, this control method requires a deep atmospheric pass and thus, a more robust thermal protection system (TPS), which reduces the potential mass savings. Magnetohydrodynamically controlled aerocapture serves as a potential alternative to reduce both propellant and TPS mass, enabling larger missions to the Ice Giants.

Mission Design

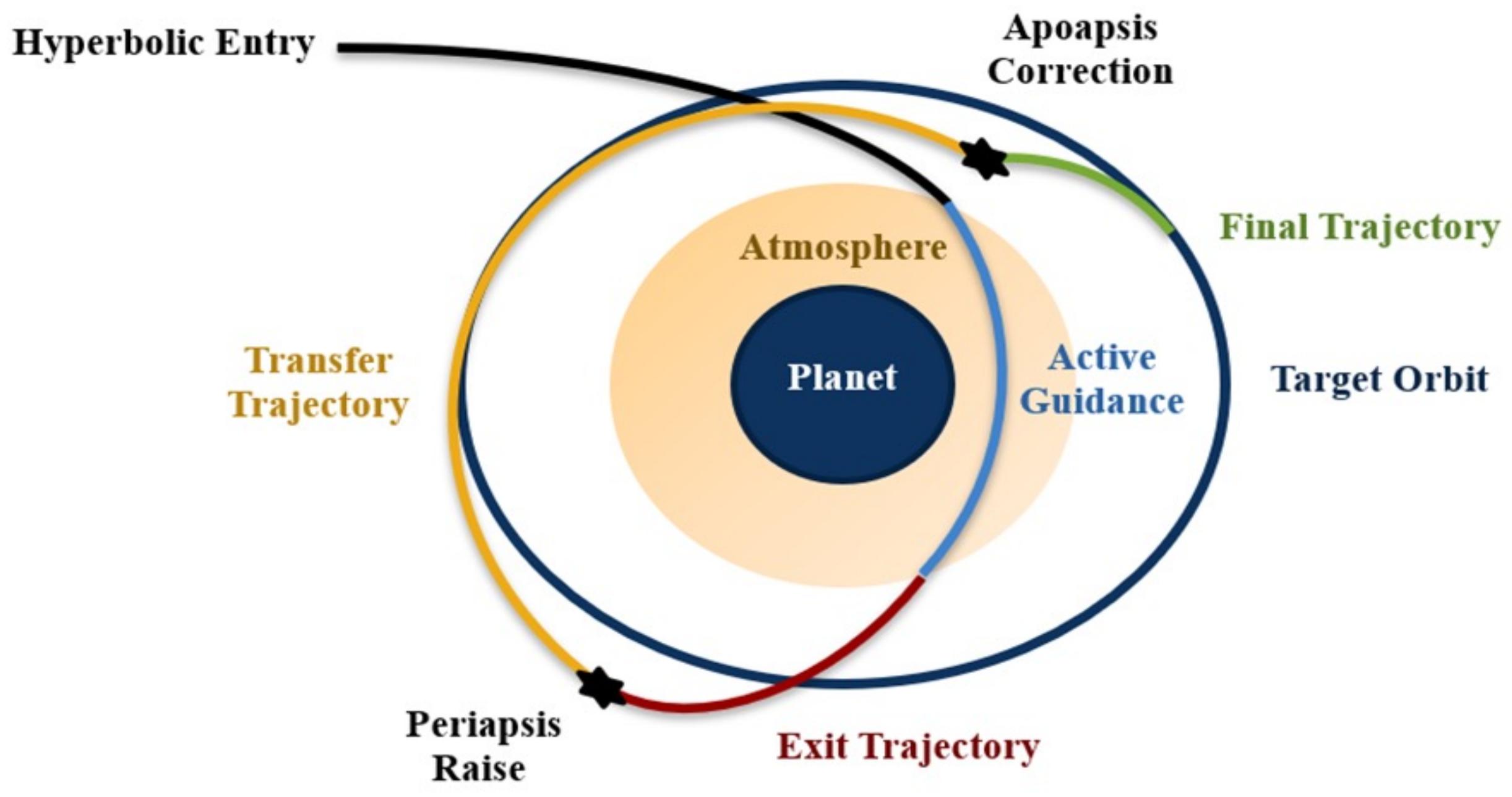

Fig. 2. Aerocapture concept of operation.

Aerocapture is the use of a planet's atmosphere to maneuver a spacecraft and capture into an orbit around that planet. As shown in Figure 2, during aerocapture, the spacecraft will enter hyperbolically into the atmosphere, begin its guidance to be put onto a trajectory towards some target parking orbit, and then finally perform a few corrective maneuvers to adjust for any inevitable uncertainties or perturbations. While these corrective maneuvers will require propulsive burns, these burns will require considerably less propellant mass than the burns that would have been required if aerocapture had not been applied. It is the goal of the controlled guidance during the atmospheric phase of the flight to minimize the required propellant for these corrective maneuvers while attaining the desired orbit.

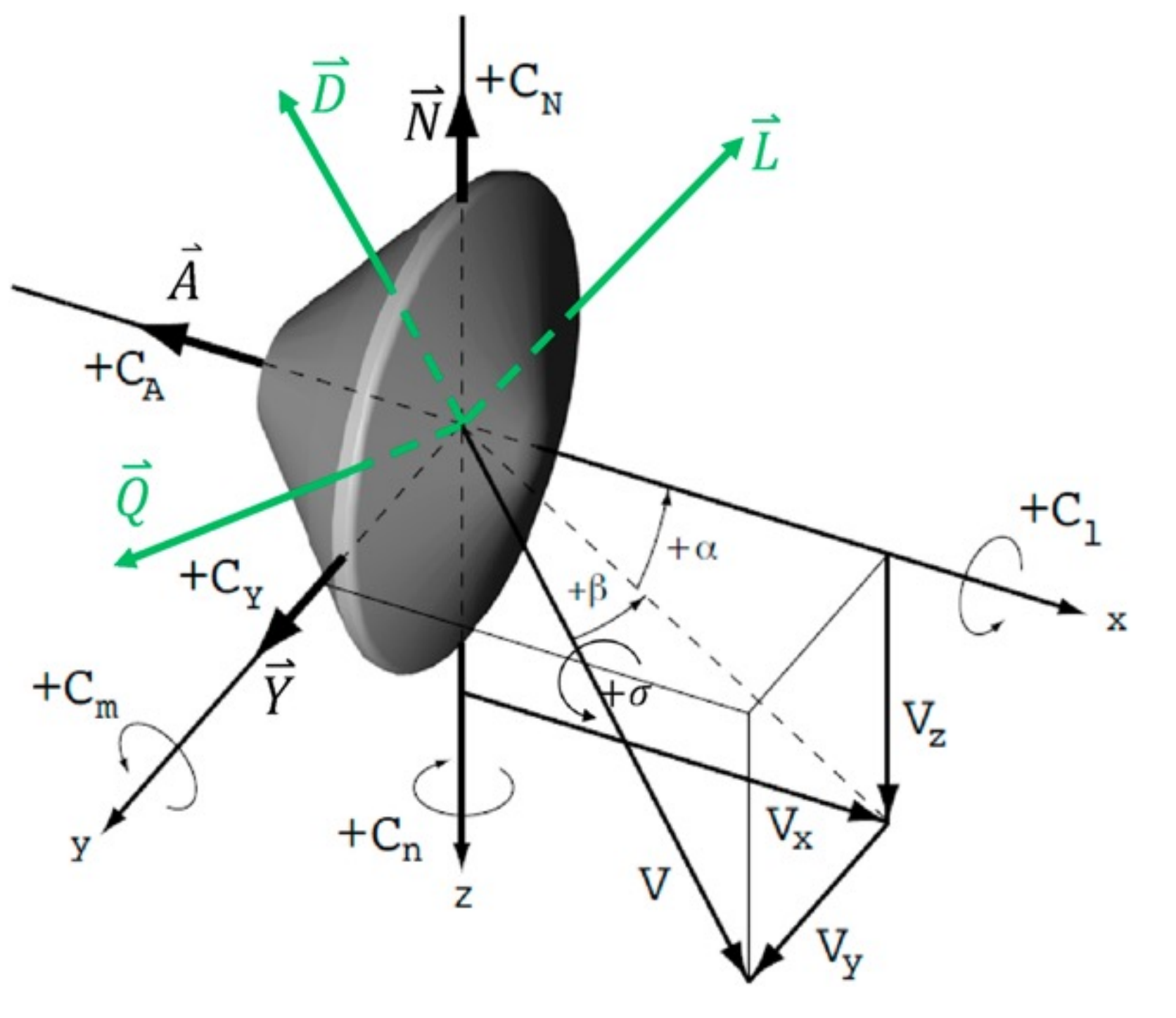

Fig. 3. Visualization of aerodynamic angles [3].

Atmospheric aerocapture is typically controlled by manipulating the aerodynamic angles and the subsequent forces on the spacecraft. These control methods are listed below:

- Direct force control (DFC) manipulates the angle of attack, α, and side slip angle, β, to directly control the lift and drag vectors to shape the spacecraft trajectory
- Bank angle modulation (BAM) actively adjusts the bank angle, σ, to roll the spacecraft and indirectly change the direction of the vehicle lift force.

Magnetohydrodynamic Control

Magnetohydrodynamic (MHD) control is theorized to have a unique advantage over its atmospheric counterparts because it can be activated much higher in the atmosphere, allowing for more control authority and less required TPS mass. It is important to note that this control assumes the magnetic field geometry is negligible and the atmospheric parameters between the spacecraft and the shock layer are constant. This serves as a sufficient estimate of the induced forces on the vehicle.

MHD-Induced Drag

$$F_{x,MHD} = -(1-K)\tilde{\sigma}u_2 B_z^2 A_{patch}\Delta$$

MHD-Induced Lift

$$F_{z,MHD} = (1-K)\tilde{\sigma}u_2 B_z B_x A_{patch}\Delta$$

K : Load factor
$\tilde{\sigma}$: Effective electrical conductivity
u_2 : Post-shock local velocity
B_x : Magnetic field x-component
B_z : Magnetic field z-component
A_{patch} : MHD patch area
Δ : Shock standoff distance

Hypersonic entry produces an ionized plasma surrounding the spacecraft that MHD can interact with and induce control forces through the following steps:

Electromagnets on-board the vehicle, each with current **I** — I_x, I_y, I_z
↓
A magnetic field of strength **B** is generated by each electromagnet — B_x, B_y, B_z
↓
The magnetic field interacts with the electrically conductive ($\tilde{\sigma}$) plasma — $\tilde{\sigma}$
↓
Lorentz force **F** is induced via Magnetohydrodynamic (MHD) interaction — F_x, F_y, F_z

The Lorentz force acts as an MHD-Control 'lift' and 'drag' force on the spacecraft.

Feasibility Analysis

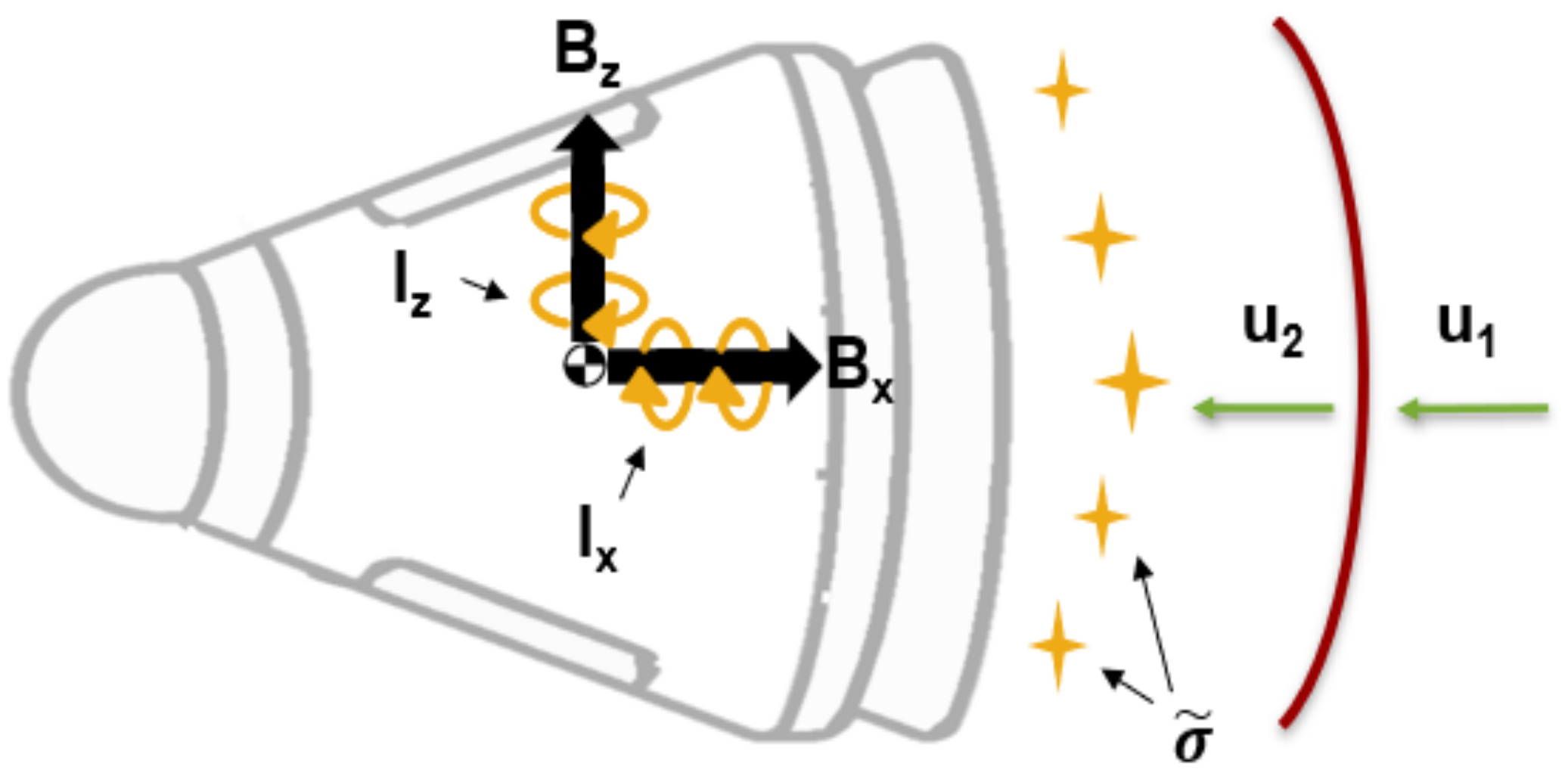

Fig. 4. Electromagnet configuration for MHD control.

With a fixed x- and z-axis electromagnet, the induced lift and drag forces on the spacecraft can be individually controlled by manipulating the current to each electromagnet. It is important to note that this configuration is placed at the center of gravity to isolate MHD control and uncouple its performance. Since these forces are a function of the magnetic field vectors, the goal of the electromagnet design is to maximize the magnetic field magnitude and electrical fusing time while minimizing the power and mass requirements. There is a wide range of possible designs; however, the point design chosen for this research for each electromagnet is shown in Table 1. Future work can optimize this design further.

Table 1. Electromagnet design parameters.

Design Parameter	Value
Coil Radius [m]	0.1
Material	Aluminum
Wire gauge [AWG]	6
Current [A]	130
Mass [kg]	**36.23**
Magnetic Field Strength [T]	**1.056**
Power Required [kW]	**22.084**
Fusing Time [s]	**1010.89**

Demonstrated feasibility

- Completely self-powering [4]
- Fusing time significantly more than typical guidance times with Monte Carlo dispersions

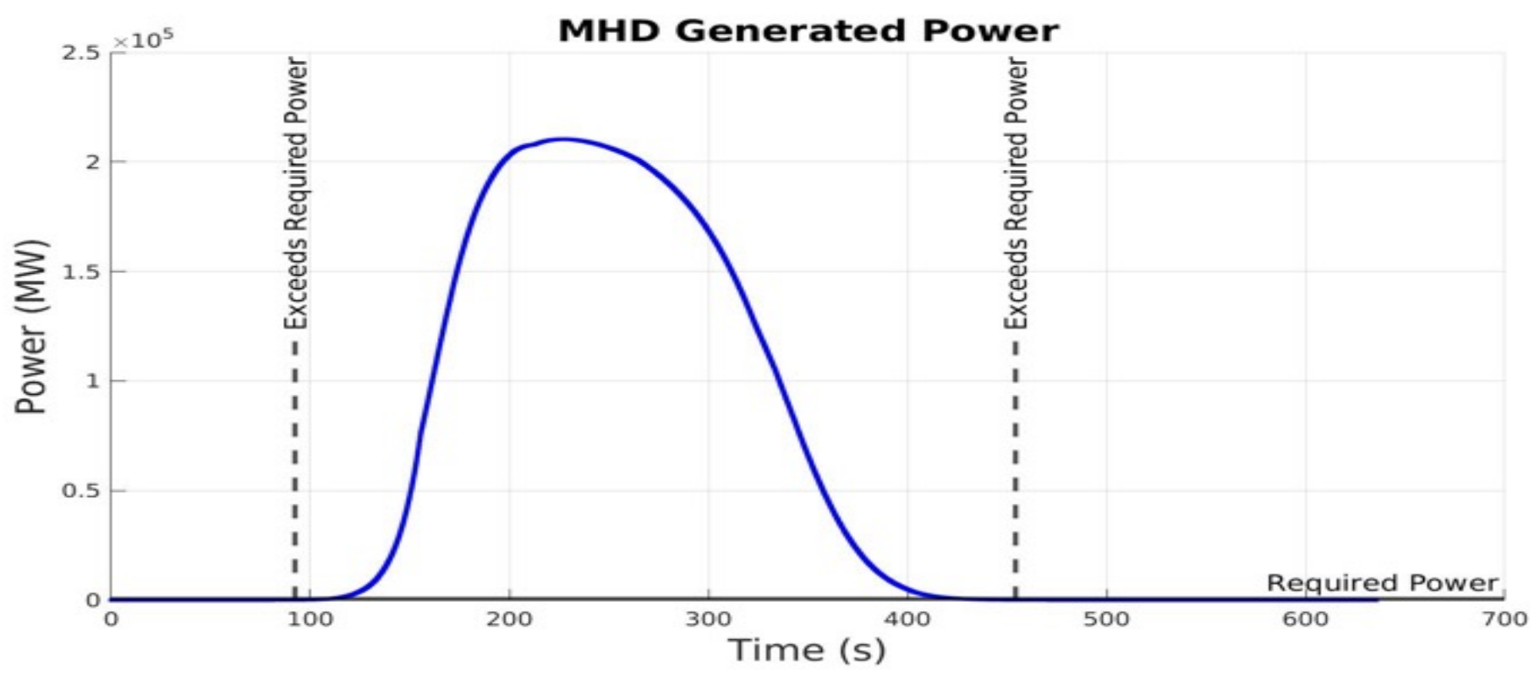

Fig. 5. Power generated through MHD interaction.

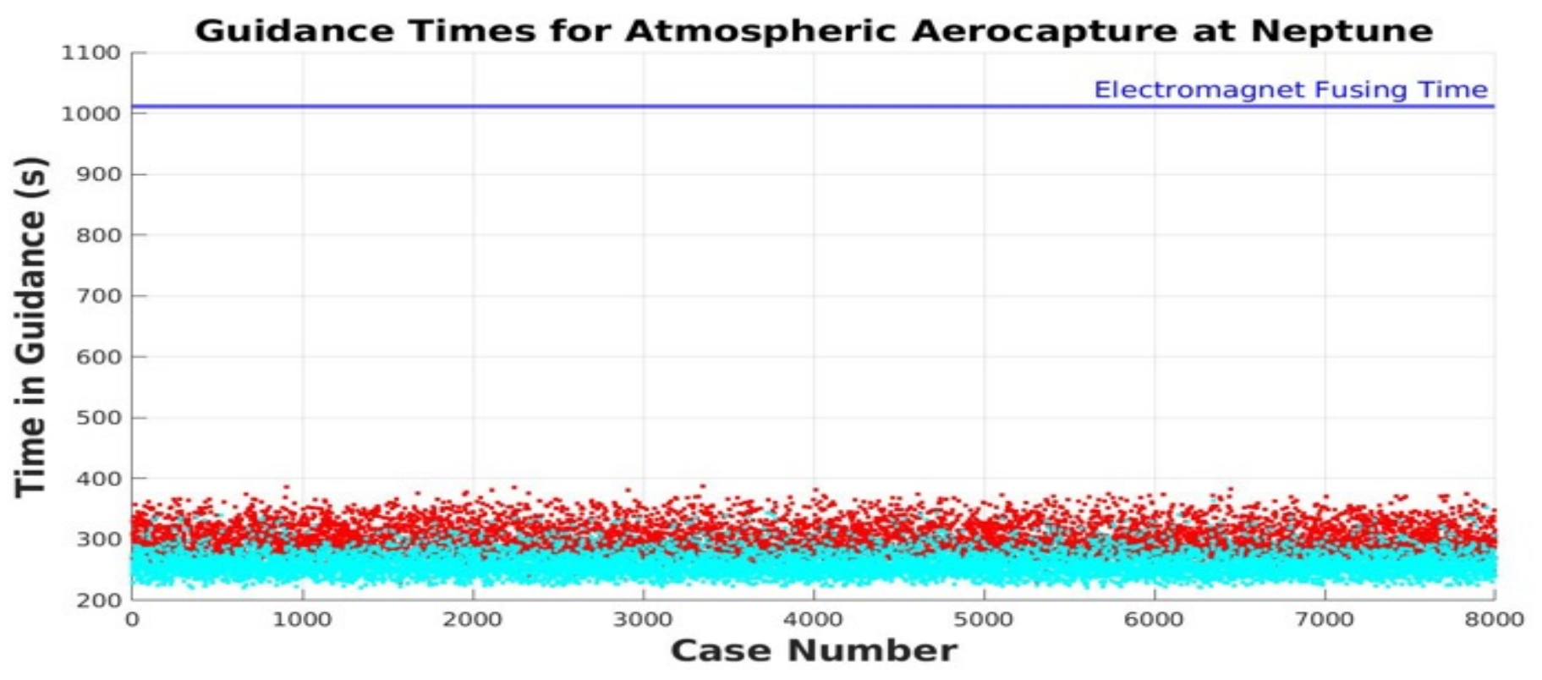

Fig. 6. Fusing time compared to typical atmospheric guidance times.

Simulating Aerocapture

Table 2. POST2 simulation vehicle and planetary model parameters.

Vehicle Mass [kg]	Vehicle Reference Area [m²]	Aerodynamic Model	Sutton-Graves Aeroheating Constant	Atmospheric Model	Gravitational Model
2,200	1.749	MSL Aerodatabase	6.719e-5	Neptune GRAM 2004	Oblate J2

Table 3. Neptune target orbit with Triton flybys.

Apoapsis Altitude [km]	Periapsis Altitude [km]	LAN (deg)	Inclination (deg)
430,000	3,986	330.829	153.547

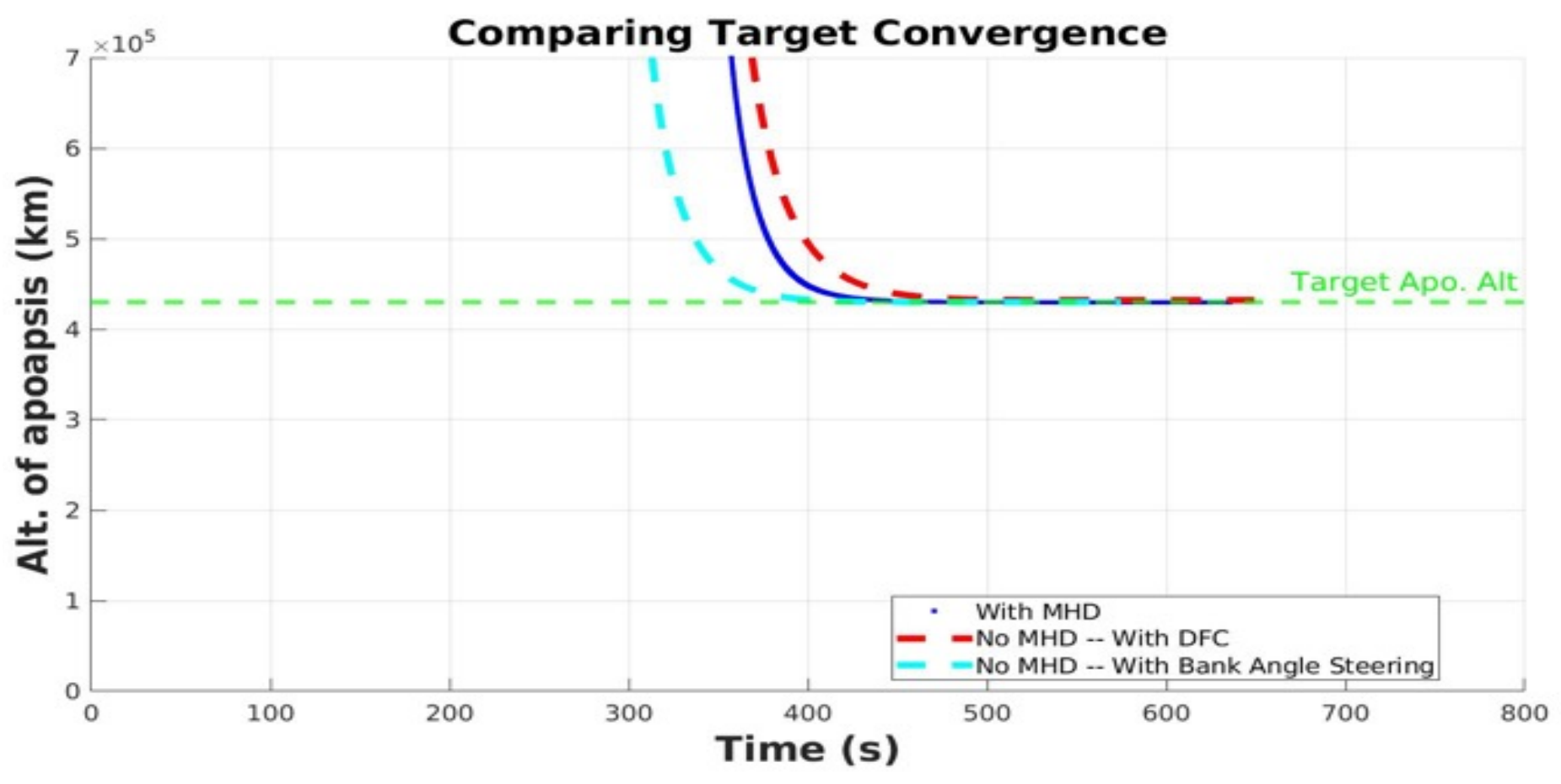

Fig. 7. Comparing convergence with target orbit.

To make a direct comparison, DFC, BAM, and MHD control were all modeled to the same target orbit under the same aerodynamic, aeroheating, atmospheric, and gravitational models. The simulations were all made in NASA Langley's high-fidelity 6DOF Program to Optimize Simulated Trajectories 2 (POST2) [5]. The atmospheric control methods utilized closed loop guidance using the Fully Numerical Predictor-corrector Aerocapture Guidance (FNPAG) algorithm whereas the MHD control method used open loop guidance under nominal conditions [6].

Results

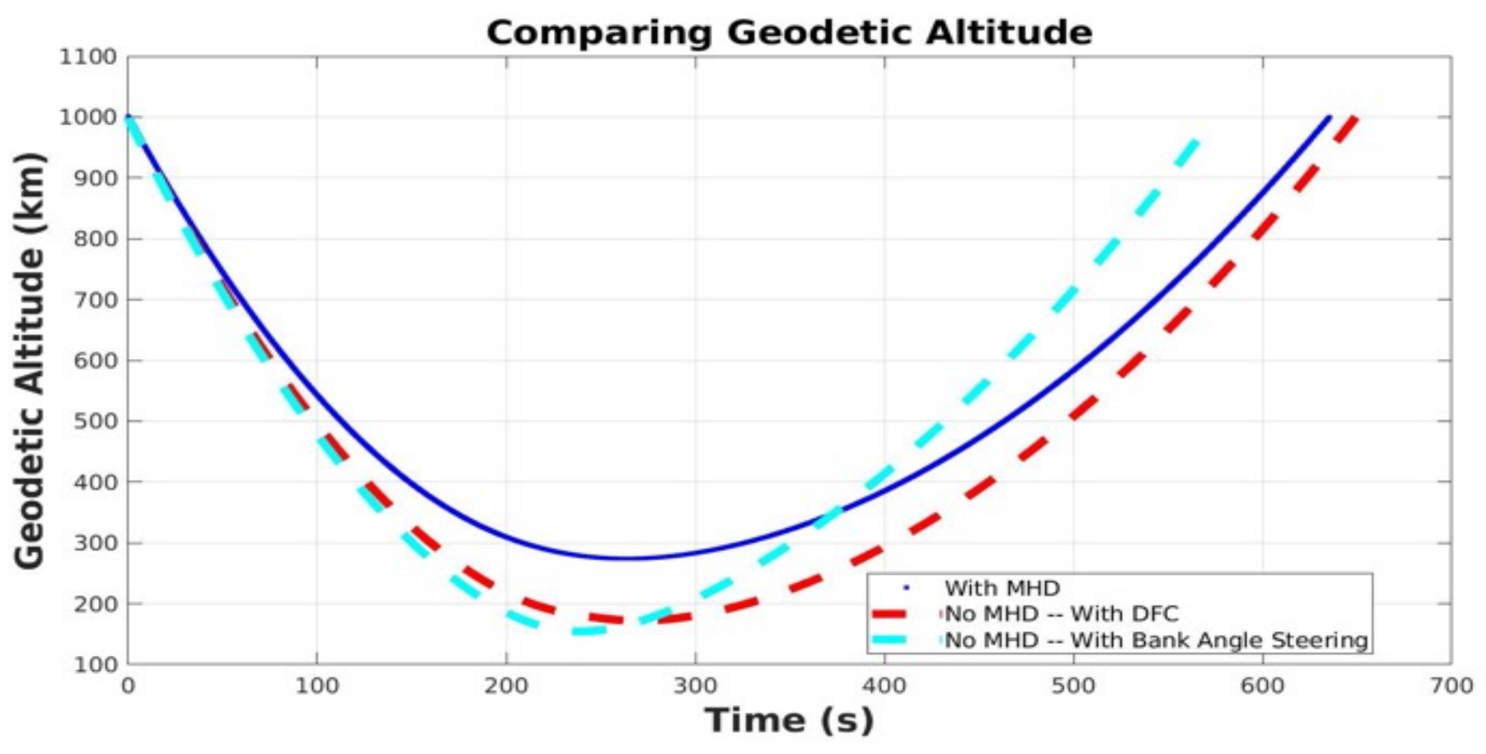

Fig. 8. Comparing geodetic altitude.

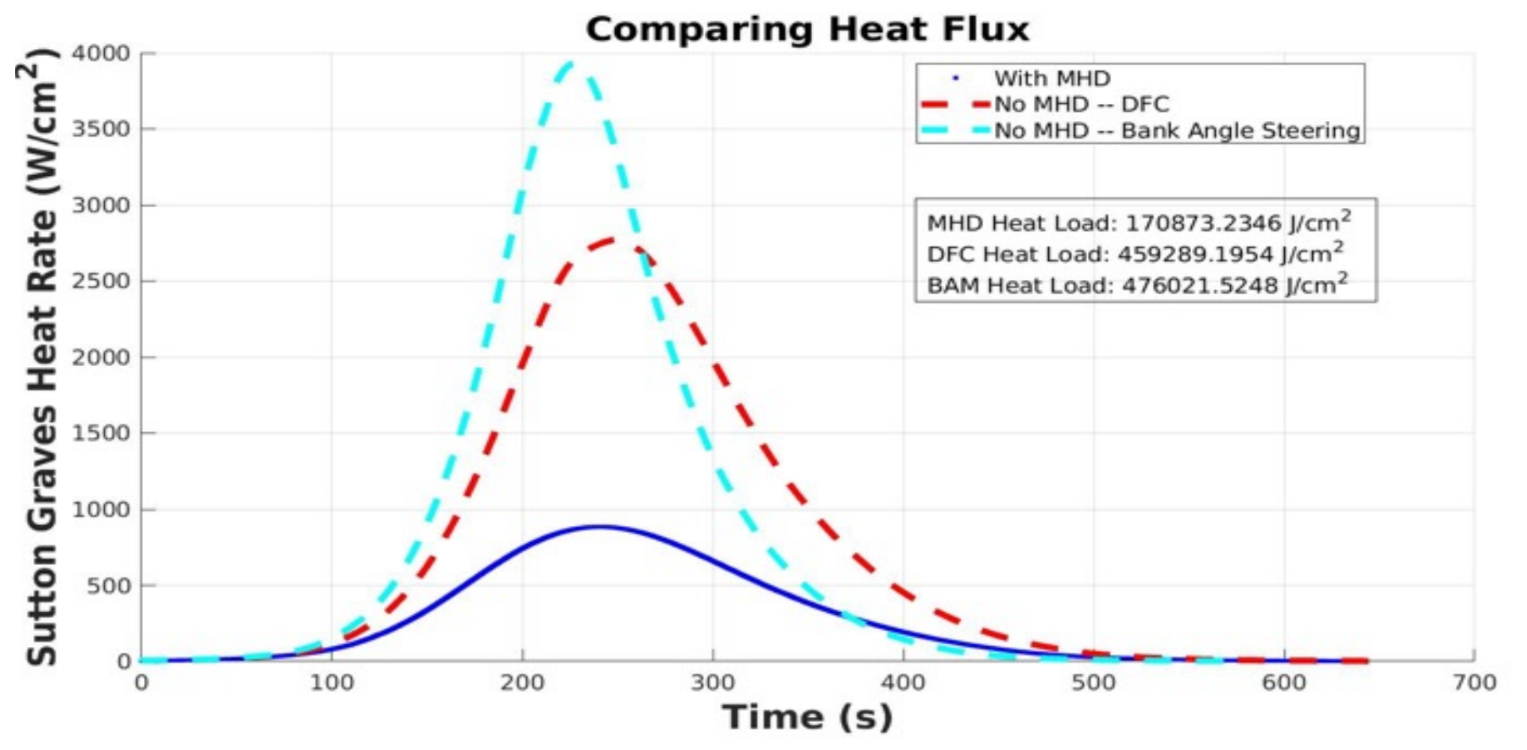

Fig. 9. Comparing heat fluxes and heat loads.

MHD control succeeded in capturing at a higher altitude which significantly reduced the experienced heat load on the vehicle compared to DFC and BAM. However, it is important to note that these results are for a nominal case tuned to a specific electromagnet configuration. Future results aim to broaden these results with off-nominal Monte Carlo case studies to allow for a more robust comparison.

References and Acknowledgements

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