Feasibility and Performance Analysis of Magnetohydrodynamic Control for Aerocapture at Neptune

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August 3rd, 2022

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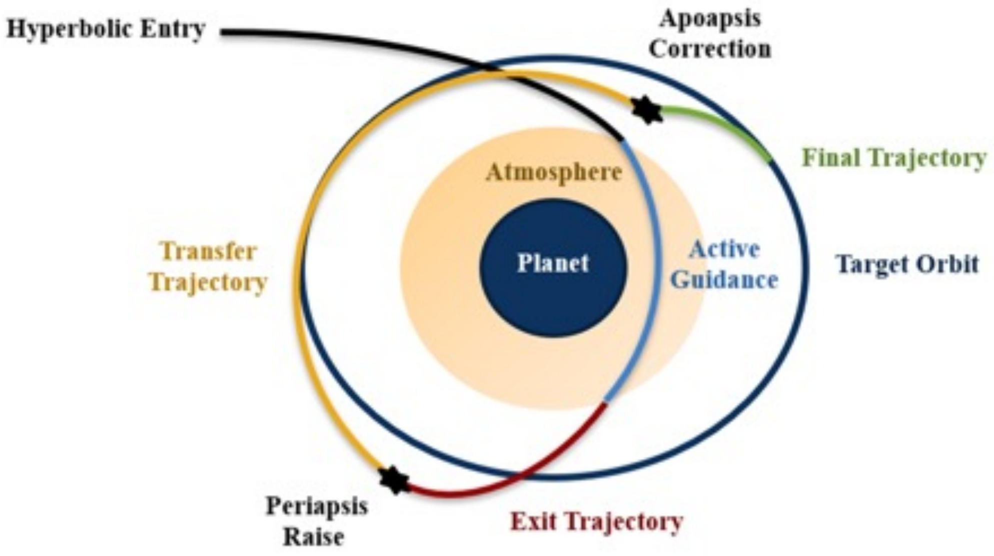
Background

- What is **aerocapture**?
  - Aerocapture is the use of a planet's atmosphere to slow down and transfer into an orbit around the planet
- Why use aerocapture?
  - Aerocapture reduces the ΔV required to reach a target orbit, which allows for less propellant and thus less mass
    - This is ideal and enabling for more massive missions or missions to outer planets
- **How is aerocapture applied?**



Motivation

- Atmospheric Aerocapture
  - Forms of control: **Direct force control (DFC)**, **bank angle modulation (BAM)**, and drag control
    - DFC adjusts both the angle of attack and the side slip angle to optimize towards some desired target orbit
    - BAM controls the bank angle to optimize the trajectory
      - Control authority changed indirectly by rolling and changing the vertical lift vector

- Simulating Atmospheric Aerocapture
  - Trajectories are simulated through the **Program to Optimize Simulated Trajectories II** (POST2) using the **Fully Numerical Predictor-corrector Aerocapture Guidance** (FNPAG) algorithm.
    - FNPAG is an advanced tool used to actively optimize aerocapture maneuvers

- **Limitation**
  - Atmospheric control requires robust thermal protection systems which increases spacecraft mass

Problem Statement

- Magnetohydrodynamic (MHD) control is theorized to have a unique advantage over its atmospheric counterpart because it can be activated much higher in the atmosphere.
  - **Higher atmospheric activation → Less required TPS mass → Farther and more massive missions!**

- This project serves to improve and justify last fall's MHD controlled aerocapture simulation in preparation for a NASA Innovative Advanced Concepts (NIAC) Phase II proposal and publication.

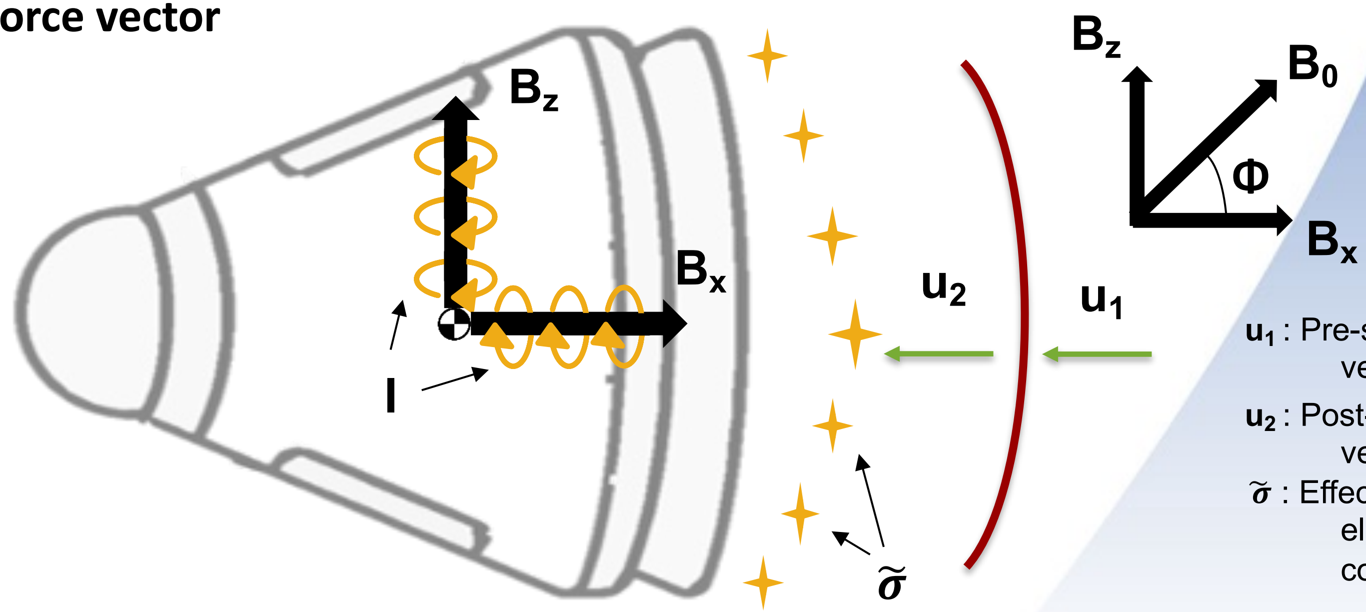
PHYSICAL DESIGN

Fundamentals of Magnetohydrodynamics

- **Hypersonic entry produces an ionized plasma surrounding the spacecraft**
- **The electromagnet configuration on the spacecraft interacts with the electrically conductive, *σ*, plasma to induce a Lorentz force (F_x, F_y, F_z)**
  - The Lorentz force essentially acts as a lift and drag force on the spacecraft
  - For the purposes of this research, the electromagnets are configured at the center of gravity to ensure ballistic entry and capture with solely MHD control
- **The current, *I*, can be increased or decreased to each electromagnet to change the magnetic field pitch angle (*Φ*), the corresponding magnetic field strength (B_x, B_y, B_z), and the resulting force vector**

$$F_x \propto -\tilde{\sigma} u_2 B_z^2$$

$$F_z \propto \tilde{\sigma} u_2 B_z B_x$$



u_1 : Pre-shock velocity

u_2 : Post-shock velocity

$\tilde{\sigma}$: Effective electrical conductivity

Electromagnet Design

Point design chosen for each electromagnet

- Wide range of designs are possible
- Aim to maximize magnetic field strength and electrical fusing time while minimizing mass and power
  - Electrical fusing time is the amount of time a wire can last before melting (under the assumption max current is running continuously)

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]	**1.508**
Power Required [kW]	**33.851**
Fusing Time [s]	**659.47**

Is this feasible?

Feasibility of Design

MHD Power Generation

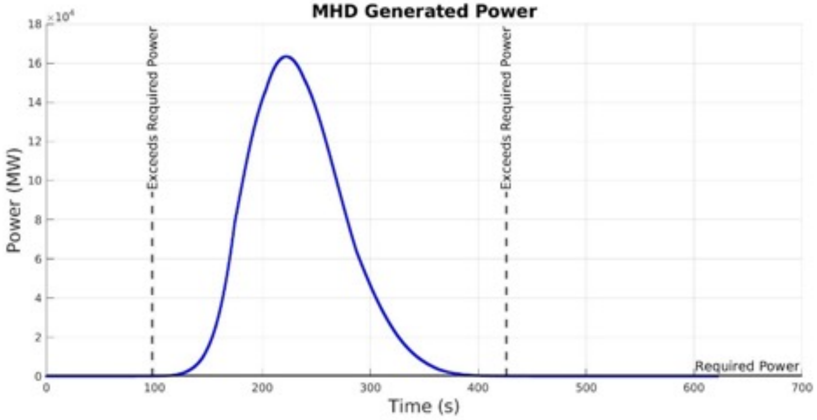
$$P_{MHD} = \frac{1}{4} * \tilde{\boldsymbol{\sigma}} * u_2^2 * B_0^2$$

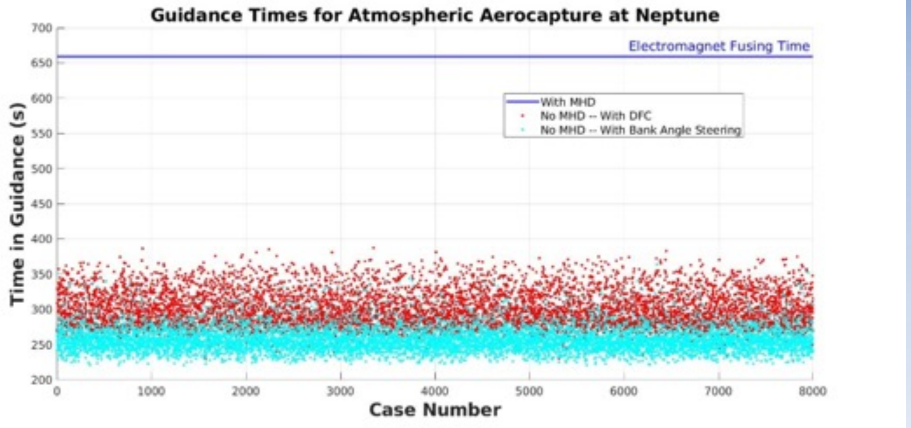
- $\tilde{\sigma}$ = Effective electrical conductivity
- u_2 = Post-shock local velocity
- B_0 = Magnetic field strength magnitude

Electromagnet Fusing Time

$$t_{fuse} = 63005.83347 \left(\frac{A_w}{I}\right)^2$$

- Onderdonk's constant for Al = 63005.83347
- A_w = 13.3 mm^2
- I = 130 A





Proven feasibility with large margins

SIMULATING AEROCAPTURE

Simulating MHD-Controlled Aerocapture

Aerodynamic Aerocapture vs. MHD-Controlled Aerocapture

- Both use NASA Langley's POST2 in order to create high fidelity trajectory simulations to Neptune
  - Neptune was chosen due to its need for mission-enabling mass savings as well as its relatively dense atmosphere compared to other gas giants
- Same target orbit
- Same vehicle configuration, aerodynamic model, and aeroheating model
- Same planetary gravitational and atmospheric models
- Aerodynamic case makes use of vehicle aerodynamic angles, but the MHD case ensures ballistic entry to prove MHD capabilities alone

Necessary requirements to get MHD-controlled aerocapture operational

- Electrical conductivity model
- MHD-induced Lorentz force model and integration

Electrical Conductivity Model

Electrical Conductivity

$$\sigma = \begin{cases} 3 * 10^5 \left(\frac{n_e}{n}\right), & \frac{n_e}{n} \le 10^{-3} \\ \boxed{2.147 * 10^{-3} (T_e)^{\frac{3}{2}}, \quad \frac{n_e}{n} > 10^{-3}} & \end{cases}$$

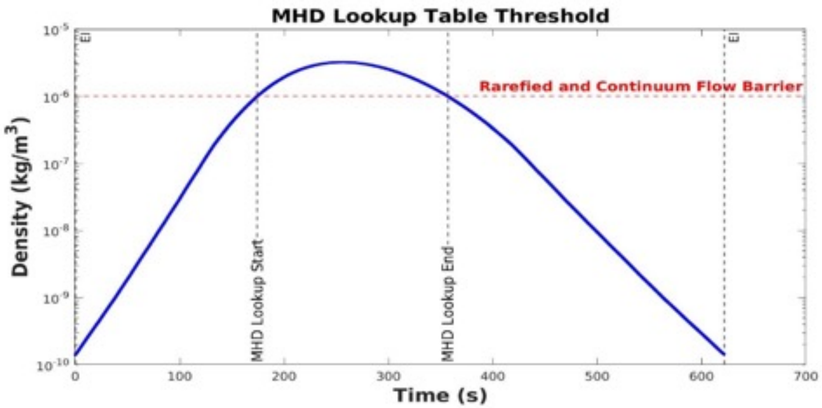
$\mathbf{n}$: Gas number density

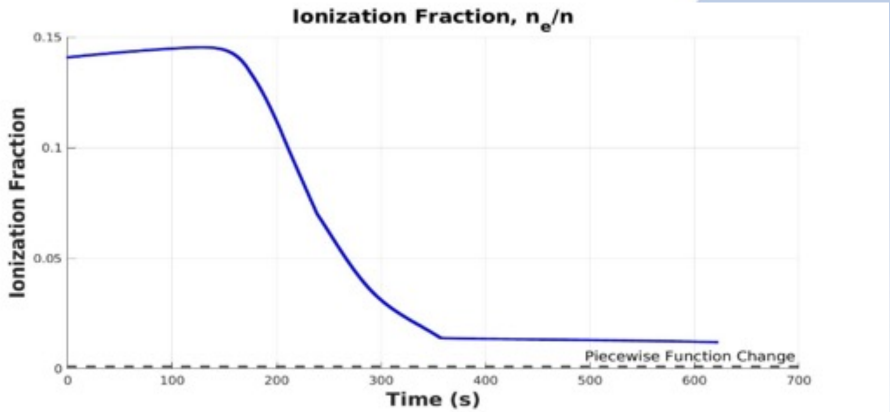
$\mathbf{n_e}$: Electron number density

$\mathbf{T_e}$: Electron temperature

The electron number density, gas number density, and electron temperatures are defined in a multivariable lookup table within the following bounds:

- 10^{-6} kg/m^3 < Atmospheric density < 10^{-3} kg/m^3
  - LAURA only provides values within the continuum flow regime
  - Values in the free-molecular or rarefied flow regime are logarithmically extrapolated
- 16 km/s < Atmospheric velocity < 32 km/s





Introducing Ion Slip

- **Ion slip occurs when the ions and electrons begin to slow down against the bulk neutral gas**
  - This is a common occurrence at larger velocities and is important to consider during hypersonic entry
  - Ion slip makes electron and ion behavior less uniform and reduces the performance of MHD control

$$\tilde{\sigma} = \frac{\sigma}{1 + \mu_i * \mu_e * \left|\overrightarrow{B_0}\right|^2}$$

$$\mu_i = \frac{1}{2} * \frac{2}{\left(N_n^{-1} * 2.2 * 10^{10} * (m_i * T)^{-0.5}\right)^{-1} + \left(14.3 * m_i^{-0.5} * T^{1.5} * N_i^{-1}\right)^{-1}}$$

$$\mu_e = \frac{1}{2} * \frac{2}{\left(N_n^{-1} * 3.74 * 10^{19} * e^{33.5*(\ln(T_e))^{-0.5}}\right)^{-1} + \left(N_i^{-1} * 9.5 * 10^{16} * T_e^{1.5} * (\ln(\Lambda))^{-1}\right)^{-1}}$$

- $\tilde{\sigma}$: Effective conductivity with ion slip
- ln(Λ) : Coulomb’s logarithm
- N_n : Neutral species number density

μ_i : Ion mobility

T_2 : Post-shock temperature

N_i : Ion number density

μ_e : Electron mobility

T_e : Electron temperature

m_i : Ion mass

Ion Slip Effects on Force

MHD-induced Lorentz Force Equations

$$\boldsymbol{F_X = -(1-K)\sigma u_2 B_z^2 A_{patch}}$$

$$\boldsymbol{F_Z = (1-K)\sigma u_2 B_z B_x A_{patch}}$$

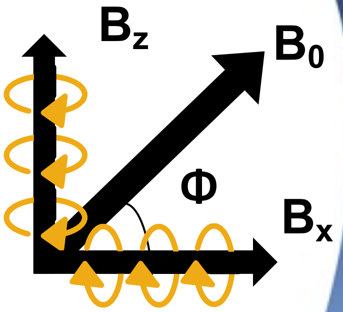
$$A_{patch} = \pi r_c^2$$

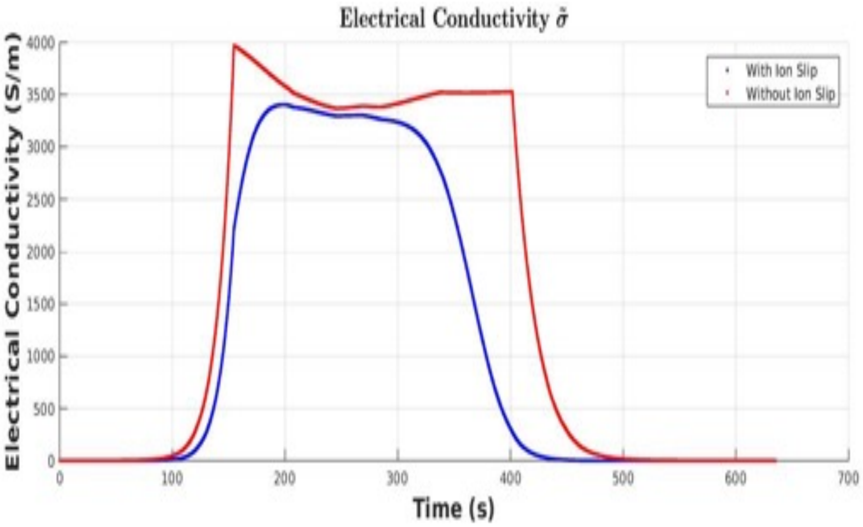
$$B_x = B_0 \cos(\phi)$$

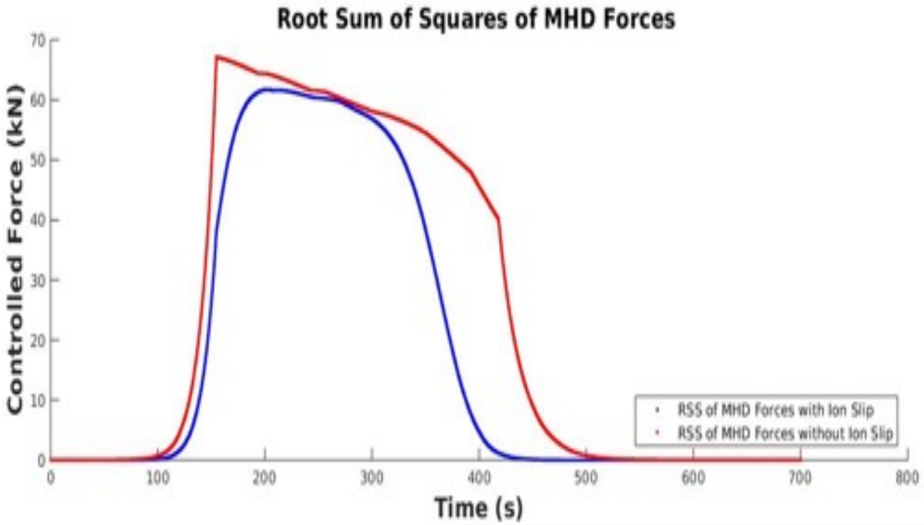
$$B_z = B_0 \sin(\phi)$$

$$B_0 = \frac{NI\mu_o}{2r_c}$$

K : Load factor
A_{patch} : MHD patch area
r_c : Coil radius
B_x : Magnetic field x-component
B_z : Magnetic field z-component
B_0 : Magnetic field magnitude
Φ : MHD pitch angle
N : Number of coils
μ_0 : Permeability of vacuum



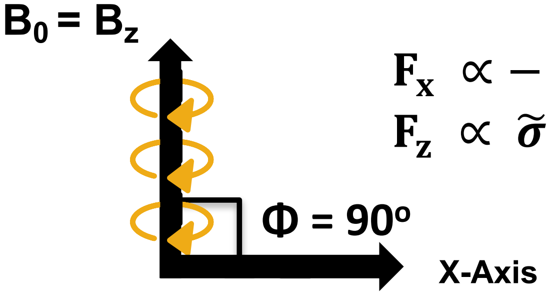




RESULTS

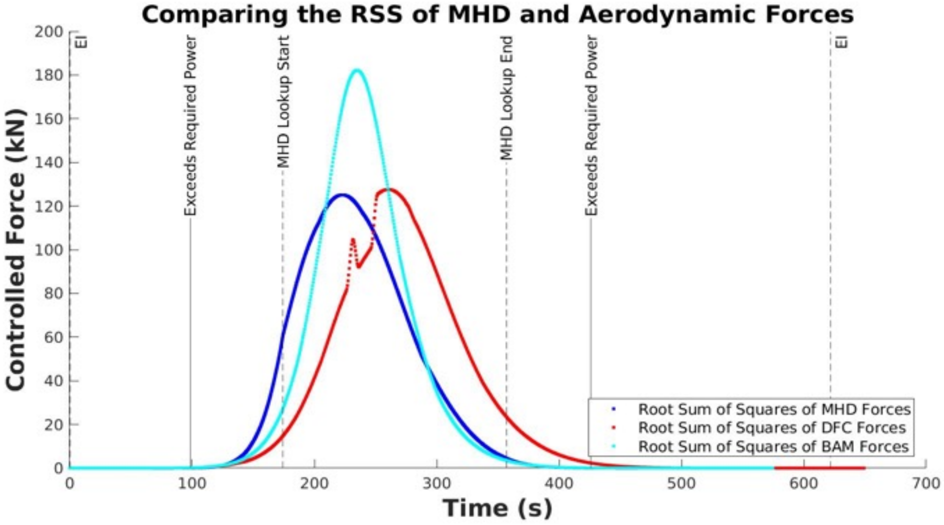
Nominal Open Loop Parameters

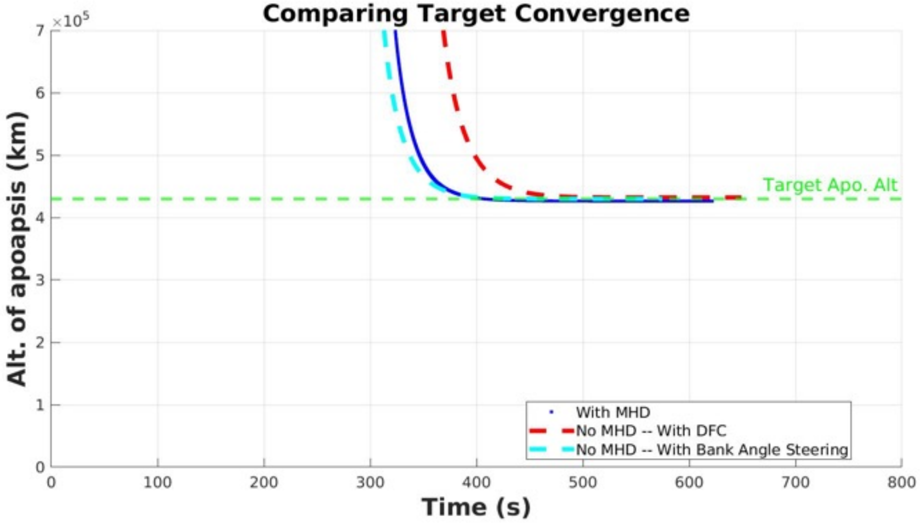
- **Set the MHD pitch angle to 90° maximize drag**
  - MHD Pitch Angle Φ: 90°
    - $I_z = 130$ A
    - $B_z = 1.306$ T



$$F_x \propto -\tilde{\sigma} u_2 B_z^2$$
$$F_z \propto \tilde{\sigma} u_2 B_z B_x$$

- **Ensured ballistic entry vehicle to isolate the effect of MHD forces**
  - Angle of attack: 0°
  - Side slip angle: 0°
  - Bank angle: 0°
  - C_L/C_D: 0


Comparing the RSS of MHD and Aerodynamic Forces


Comparing Target Convergence

Comparing Heat Loads

Shallower entry flight path angle

↓

Less deep atmospheric pass

↓

Significantly less heat load

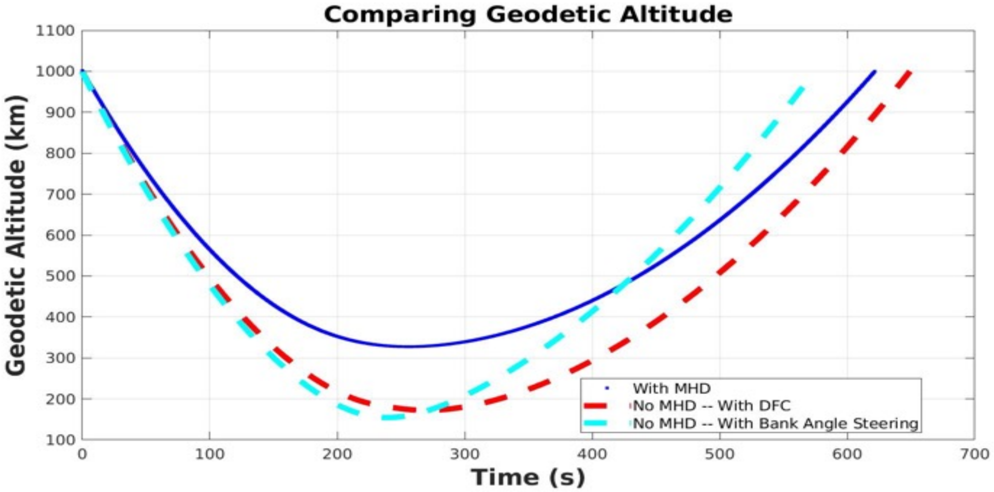
(~80% reduction)

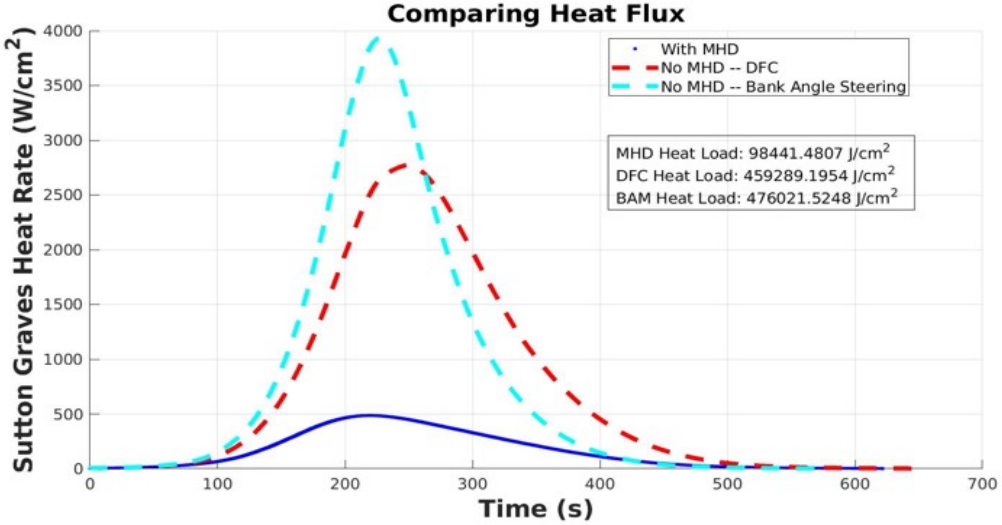
↓

Reduced required TPS mass

Note: These mass savings are not indicative of the order of magnitude of every MHD controlled aerocapture case. This is a nominal case tuned to a specific electromagnet configuration – entry flight path angle found to be sensitive to each configuration. Future work will aim to test off-nominal cases to allow for a more robust comparison

	DFC	BAM	MHD
Entry Flight Path Angle (°)	-12.3550	-12.6870	-11.0427





MHD Heat Load: 98441.4807 J/cm^2
DFC Heat Load: 459289.1954 J/cm^2
BAM Heat Load: 476021.5248 J/cm^2

Conclusions and Future Work

- **The current electromagnet configuration is feasible within a large margin for power and fusing time concerns**

- **Aerocapture with solely MHD control provides control authority on par with that of its atmospheric counterpart**

- **The nominal TPS mass savings when using MHD control show a potential for a unique advantage over atmospheric aerocapture**
    - These savings are extremely valuable for missions to outer planets and future manned flights

- **Ongoing effort to apply active closed-loop guidance throughout the spacecraft's flight and consider perturbations in off-nominal case studies.**

- **Future work can consider MHD control when the electromagnet configuration is not at the center of gravity and the magnetic field geometry is not uniform**

Acknowledgements

- Rohan Deshmukh for his help with implementing the guidance algorithms for each aerocapture simulation

- Sergey Macheret and Bernard Parent for their technical support with magnetohydrodynamics

Thank you!

BACKUP SLIDES

Target Orbit and Conditions

Neptune Target Orbit

- Chosen to allow for Titan flybys based on the 2004 Lockwood paper

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

Vehicle and Planetary Parameters Simulated

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