

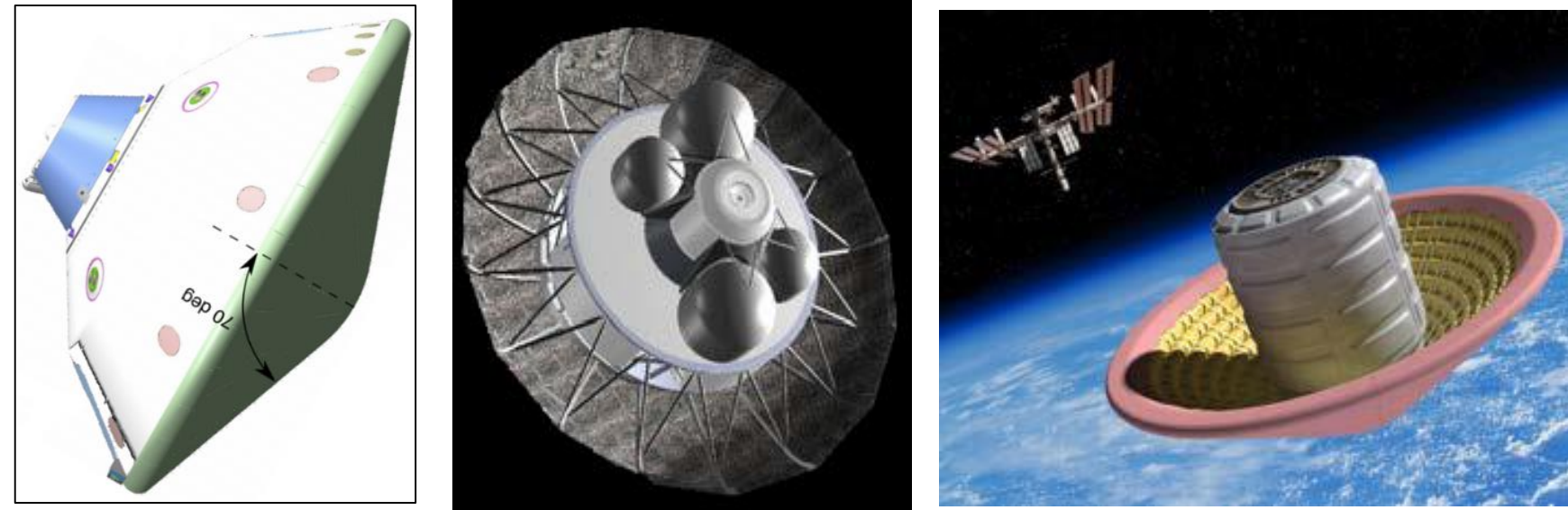
Abstract

A wide body of research is focused on aerocapture to facilitate orbital insertion. The aerocapture maneuver consists of a single pass through a target planet's upper atmosphere to reduce kinetic energy through aerodynamic forces. Upon atmospheric exit, the vehicle flies a Keplerian orbit to apoapsis where a series of small correction burns are performed. Studies of aerocapture at Neptune have confirmed significant mass savings over fully-propulsive methods. However, aerocapture requires active guidance during the atmospheric phase of flight and often requires large control margin that cannot be provided by typical entry vehicles with low lift-to-drag ratios. The goal of this study is to apply modern predictor-corrector guidance algorithms to enable the use of low lift-to-drag vehicle concepts for aerocapture at Neptune.

Motivation

Neptune Exploration

- NASA Planetary Decadal Survey 2013-2022 classified the ice giants as “the great remaining unknowns in the solar system”
- Program calls for flagship Neptune orbiter/probe
- Current state-of-the-art propulsive orbital insertion is prohibitive if not infeasible
- Concept studies found high L/D requirements, necessitating new vehicle design
- Modern aerocapture GNC methods may alleviate vehicle design constraints



Aerocapture

- Single-pass aeroassist maneuver using a planet's atmosphere to dissipate energy
- Essentially “free” orbit insertion ΔV
- Provides in-plane (a, e) and lateral (i, Ω) orbit targeting
- Estimated 43% increase in delivered mass to orbit over fully-propulsive [1]

Baseline Concept

The baseline of comparison in this research is a mission concept from a multi-center NASA study of Neptune aerocapture by Lockwood. [2]

Neptune-Triton Orbiter

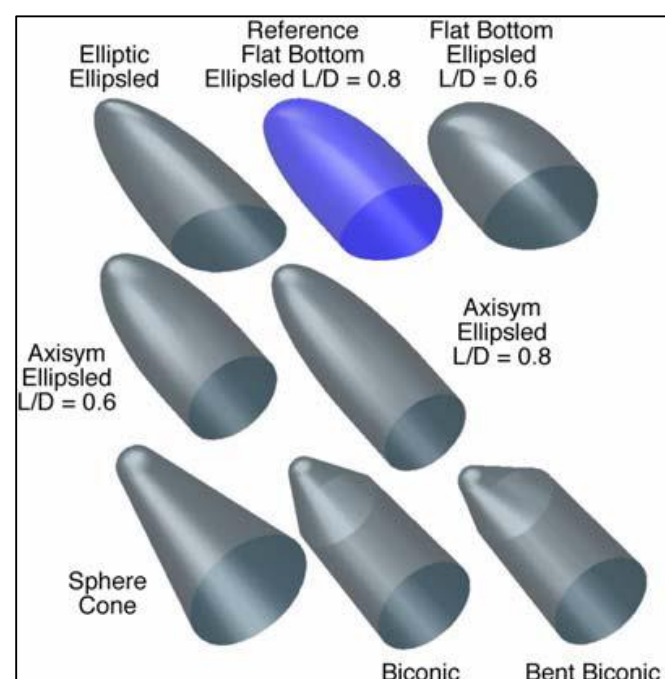
- 430,000 by 3,986 km elliptic science orbit
- 157 deg retrograde to allow Triton fly-bys

Vehicle Configuration

- Flat-bottom ellipsed OML
- Ballistic coefficient 895 kg/m²
- Lift-to-drag (L/D) of 0.8
- HYPAS guidance

Neptune Atmosphere

- Neptune GRAM 2004
- 80% H₂, 19% He, 1% CH₄
- $0.6 \leq F_{minmax} \leq 0.93$

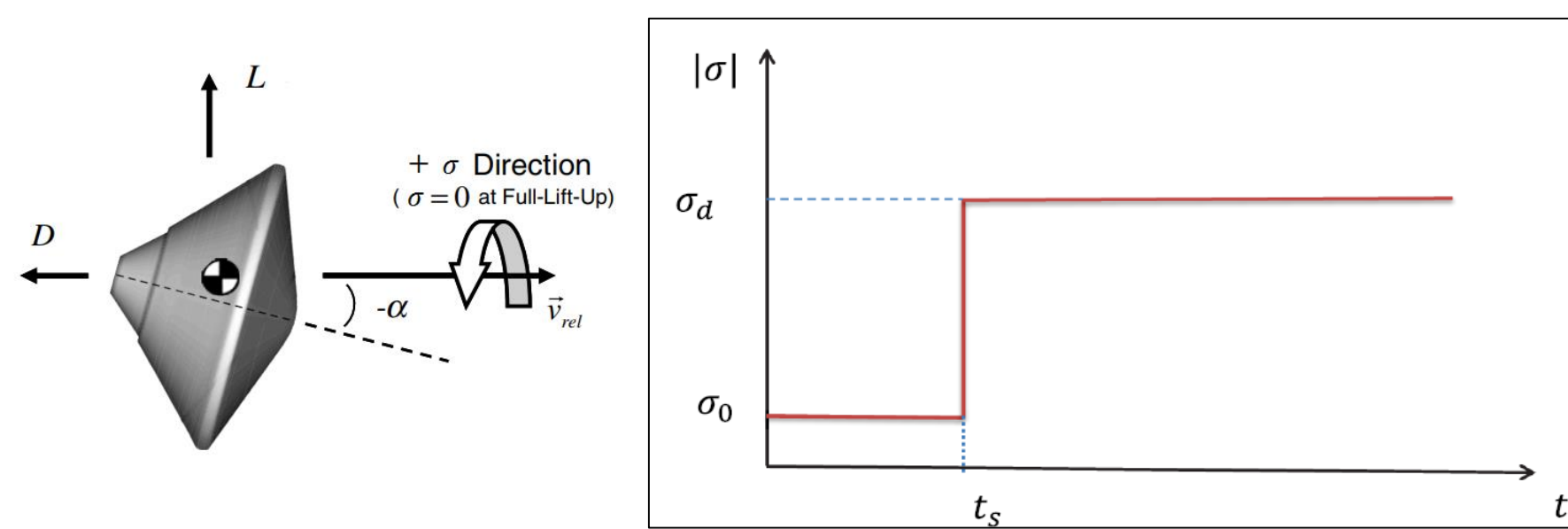


Aerocapture Guidance

This study utilized an optimal predictor-corrector algorithm called Fully Numerical Predictor-corrector Aerocapture Guidance (FNPAG). [3,4]

FNPAG

- Numerically propagates the EOM from vehicle's current state each guidance cycle
- Based on “bang-bang” optimal control solution
- Two-phase guidance strategy
 - Phase 1: switching time t_s is found
 - Phase 2: constant bank angle profile is found to minimize post-atmosphere ΔV
- Cross-range errors (inclination only) controlled by periodic bank reversals
- No reference trajectory requirement
- Robust to large trajectory dispersions

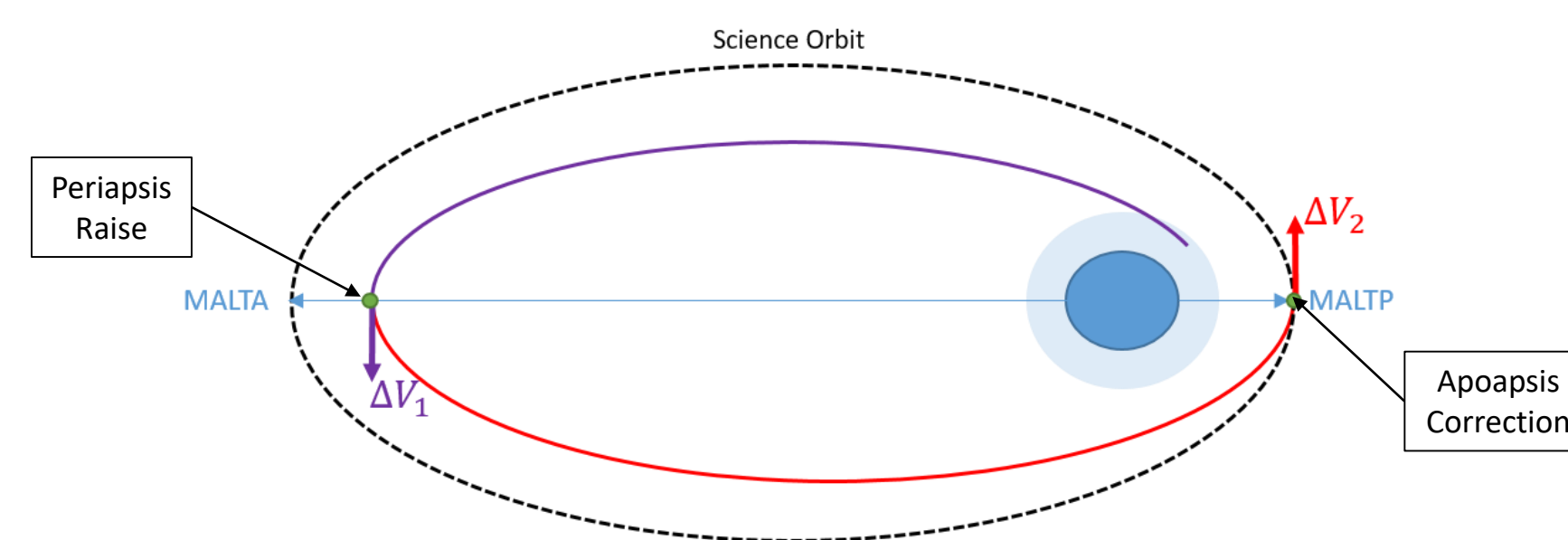


Final Orbit Insertion

Upon exiting the Neptunian atmosphere, the vehicle performs a series of orbital correction burns. A three-burn strategy was implemented in this study.

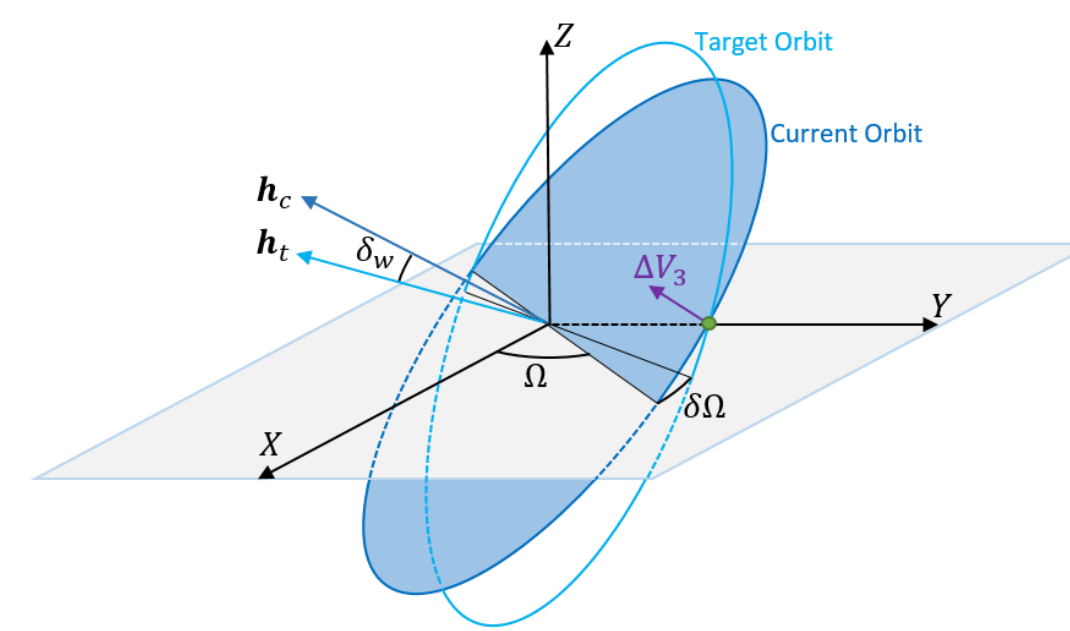
In-Plane Correction

- Periapsis (MALTP) and apoapsis (MALTA) altitude
 - Periapsis set by aerocapture altitude (~150 km)
 - Requires large ΔV (~80 m/s)



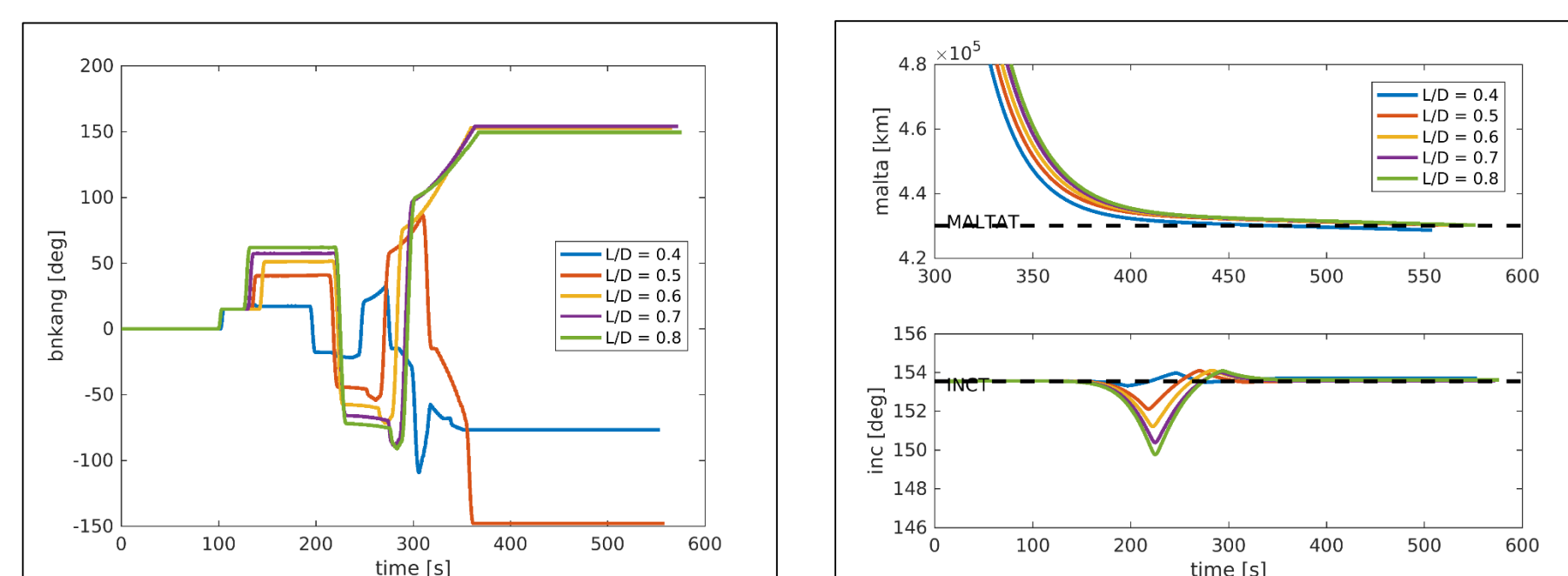
Lateral Correction

- Inclination (INC) and ascending node (LAN) angles



FNPAG Performance

POST2 was the primary simulation tool in this study. FNPAG was implemented and tested over a range of L/D. A bank rate limiter (20 deg/s, 5 deg/s²) was enforced to model bank angle dynamics.



Method	ΔV_1 (m/s)	ΔV_2	ΔV_3	Total $ \Delta V $
Three-burn	85.2	18.0	15.9	122

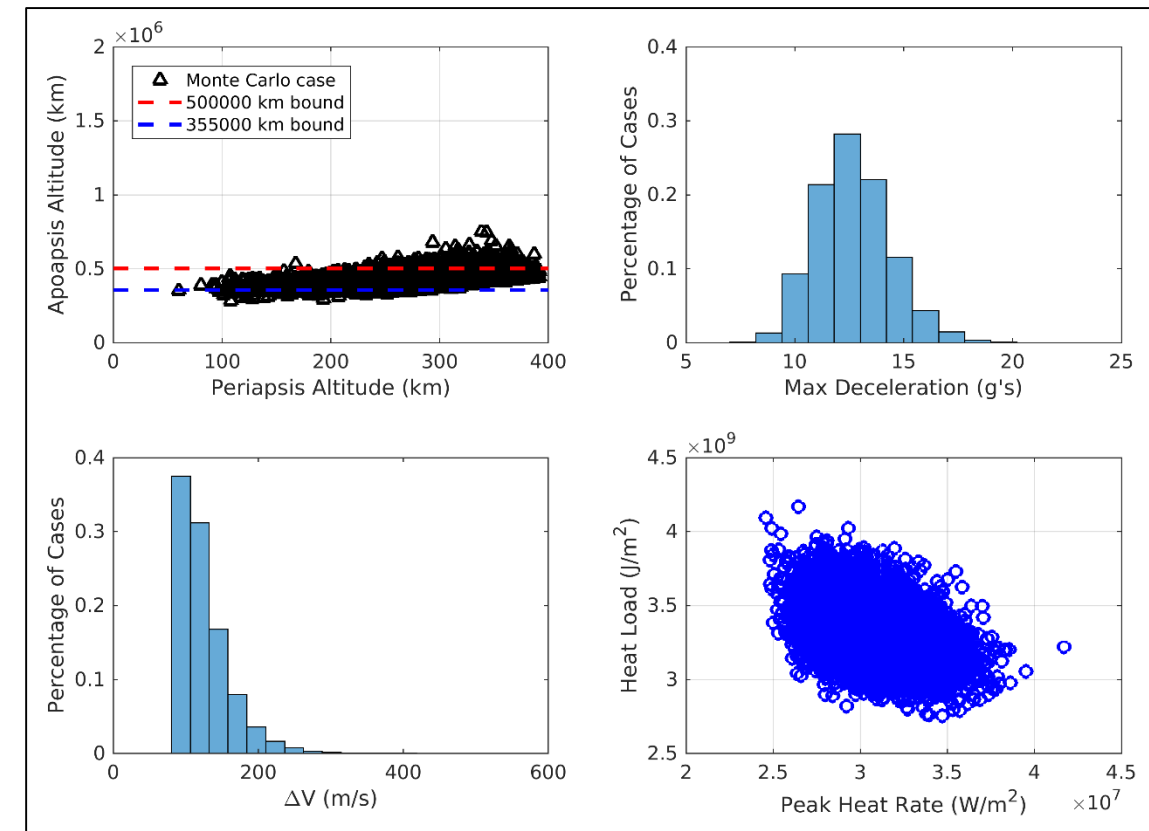
Table 1. FNPAG performance using baseline Lockwood entry conditions.

Monte Carlo Study

Two 8,000 run Monte Carlo studies were performed to test the efficacy of FNPAG at Neptune under dispersed vehicle and environment uncertainties.

Reference Case

- L/D = 0.8

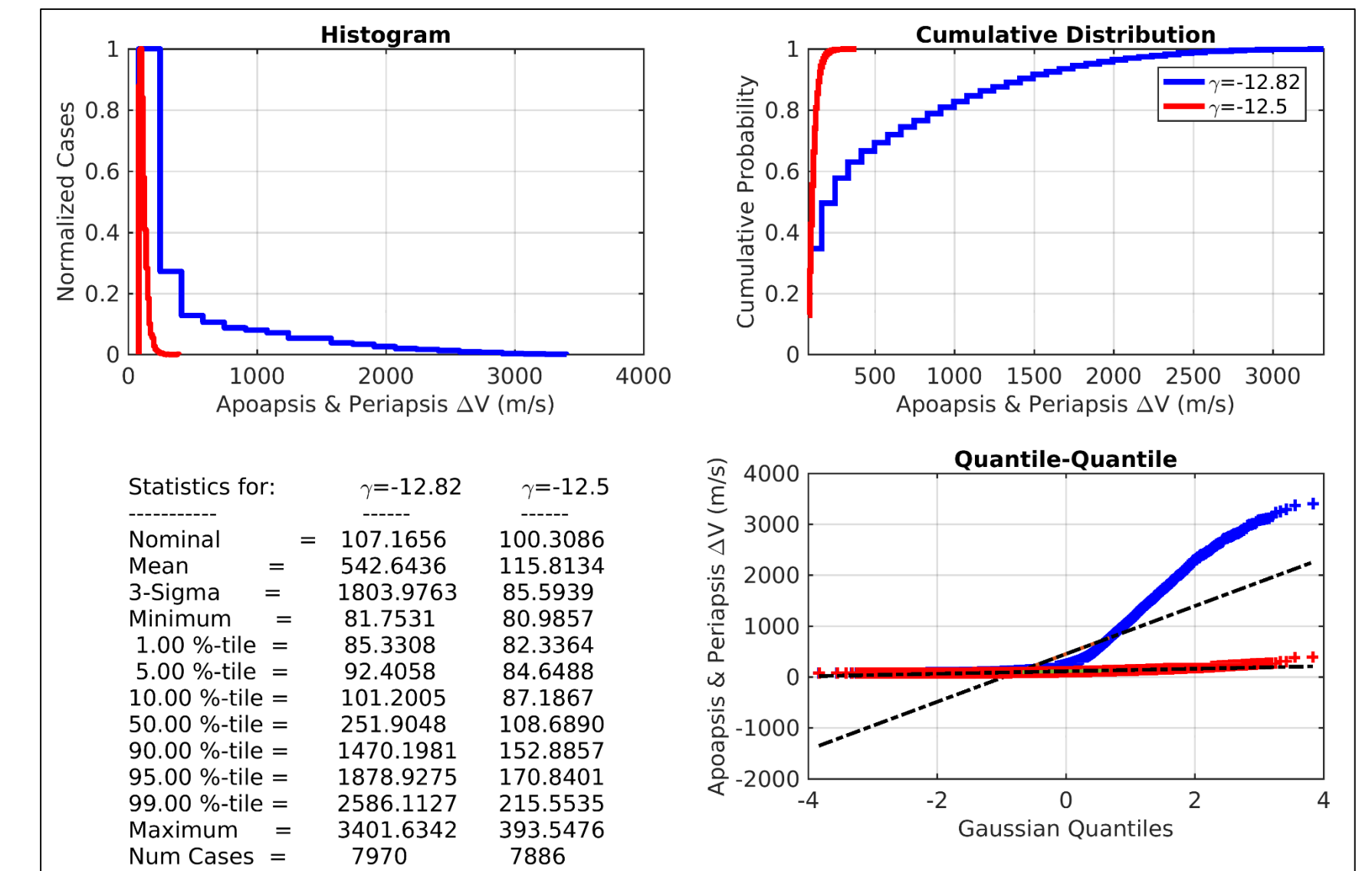


	HYPAS	FNPAG
Apoapsis Altitude - 3 σ high, low	12.85e+05, 3.25e+05 km	5.46e+05, 3.13e+05 km
ΔV - 3 σ high	456 m/s	210 m/s
Max g's	20 g's	20 g's
Heat Rate - 3 σ high	3.13e+07 W/m ²	3.55e+07 W/m ²
Heat Load - 3 σ high	2.94e+09 J/m ²	3.86e+09 J/m ²

Table 2. FNPAG and HYPAS performance comparison.

Reduced-Lift Case

- L/D = 0.4



Flight-path angle	Failed Cases	Percent Captured
-12.82 deg	30	99.6 %
-12.5 deg	114	98.6 %

Table 3. FNPAG performance for reduced-lift (L/D = 0.4) Monte Carlo runs.

- Capture criteria based on final orbit energy (failed if $E > 0$ or $E < E_{circ}$)
- Shallower nominal entry flight-path angle resulted in higher targeting accuracy
- FNPAG robust to large dispersions in vehicle and environment parameters

Conclusions / Future Work

Conclusions

- Significant reduction in targeting errors and ΔV with FNPAG compared to HYPAS
- Enables low L/D (~0.4) vehicles to achieve aerocapture at Neptune
- May eliminate need for new vehicle, enable use of heritage flight systems
- On-board computational power for FNPAG is feasible with modern flight computers
- Significant cost savings over fully-propulsive orbit insertion

Future Work

- Further reduce L/D constraints with shallower entry flight-path angles
- Include ascending node error in FNPAG lateral targeting
- Generalize FNPAG to direct force control

References

- [1] Wercinski P. F. (2002) AIAA 4812. [2] Lockwood, M. K. (2004) AIAA, p. 4951. [3] Lu P. (2015) JGCD, 38, p. 553-565. [4] Webb K. (2017) AIAA, p. 1900.

Acknowledgements

This work is funded through a NASA Space Technology Research Fellowship. The authors extend their gratitude to Dr. P. Lu for his work developing FNPAG.