

Analysis of a Bank Control Guidance for Aerocapture at Uranus

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We apply the Fully Numerical Predictor-corrector Aerocapture Guidance to capture a vehicle into orbit for a mission at Uranus. Using the Genesis flight mechanics simulation, we analyze both undispersed and dispersed trajectories in order to tune the guidance parameters. We then assess the performance of the guidance using Monte Carlo analyses. Properly accounting for the oblateness of Uranus within the guidance proves to be critical. We identify high-to-low density gradients as the cause of large target orbit misses. Intentionally targeting a steeper flight-path angle at entry interface mitigates the risk of exiting the atmosphere on a hyperbolic orbit. Finally, We deliver the guidance code and tuned parameters for integration into the Program to Optimize Simulated Trajectories II.

I. Nomenclature

γ	=	Flight-path angle
ΔV	=	Change in velocity
ϕ	=	Bank angle
ϕ_d	=	Lift down bank angle of the bang-bang bank angle profile used by the FNPAG predictor in phase 1
ρ	=	Atmospheric density
σ	=	Standard deviation
c_i	=	Coefficients of the density curve fit
h	=	Altitude
C_L	=	Lift coefficient
C_D	=	Drag coefficient
L/D	=	Lift-to-drag ratio

II. Introduction

MISSIONS to other planetary bodies can utilize fully-propulsive braking or an aero-assist maneuver to insert into a desired orbit. While fully-propulsive and aero-assist maneuvers such as aerobraking and skip entry have been demonstrated [1, 2], aerocapture remains an untested technology with a great deal of potential to save future missions time, mass, and cost [3]. Aerocapture is an orbital maneuver whereby the vehicle takes advantage of a planet's atmosphere to help reduce the amount of ΔV , or fuel, required to insert into a target orbit. Figure 1 illustrates the maneuver.

First the vehicle skims the atmosphere, reducing the hyperbolic arrival energy using aerodynamic forces. Following this atmospheric pass, the vehicle performs a periapsis raise maneuver followed by an apoapsis correction maneuver to

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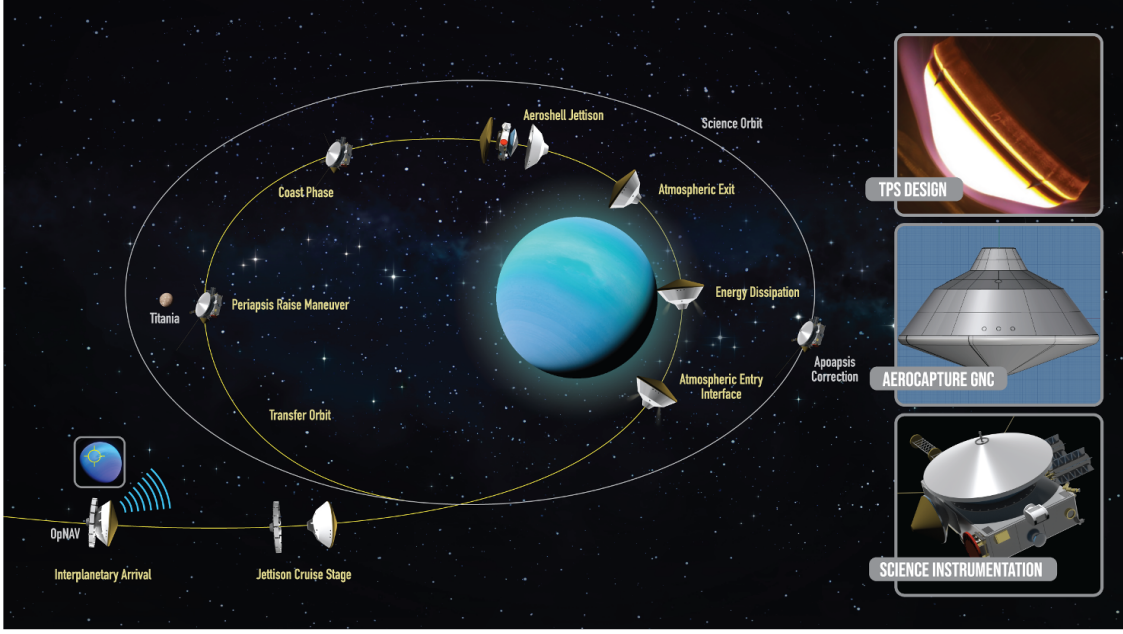


Fig. 1 Aerocapture concept of operations.

achieve the target orbit. While there have been many studies of aerocapture [4–8], there have been few with Uranus as the destination.

Recently, the National Academies Planetary Science and Astrobiology Decadal Survey of 2023-2032 identified Uranus as a top priority science destination [9]. Visiting Uranus has become a priority due to its unique atmospheric dynamics, axial tilt, and similarities to the most common of exoplanets discovered by the Kepler telescope [10]. However, Uranus has not been visited in over three decades. One of the biggest challenges in visiting the Ice Giants is the long transit times and high fuel required to perform a traditional, fully-propulsive orbit insertion. The more a vehicle allocates mass to fuel, the less mass is devoted to the science payload. While aerocapture could benefit many deep space missions, for distant destinations like Uranus, the effect of using aerocapture becomes even more impactful, with the potential to reduce the transit time by years. For these reasons, NASA is assessing the feasibility of performing aerocapture at Uranus, with the Ice Giants Aerocapture Project [11–13].

This paper details the application of aerocapture guidance to a Uranus orbiter mission, leveraging a method flown in previous guided reentry missions at Earth and Mars known as bank angle control [2, 14]. While other guidance methodologies and conceptual vehicle designs have been studied for missions to the Ice Giants, we chose to select the architecture and guidance approach most commonly flown to reduce potential risk and complexity should an aerocapture mission be selected over a fully propulsive orbit insertion [10]. In 2004, a team studied aerocapture at Neptune and found that an L/D of 0.8 was required for bank control to be feasible [8].

Our results here will show how guidance and navigation advances over the past two decades make aerocapture at the Ice Giants possible with much less L/D. Monte Carlo analysis will be discussed to quantify the mission’s sensitivities to uncertainty and guidance parameter selection. This paper will also expand upon unique Uranus considerations in guidance design such as its oblateness and atmospheric uncertainties. Finally, we will discuss how the Julia-based guidance from Genesis was integrated into the Program to Optimize Simulated Trajectories II (POST2) for the project’s runs for the record.

III. FNPAG Overview

This analysis uses the Fully Numerical Predictor-corrector Aerocapture Guidance (FNPAG) algorithm [15]. FNPAG is based on the optimal solution to the aerocapture problem using bank angle control, which dictates a bang-bang solution, where the vehicle first flies full lift up and then at some point switches to full lift down. The guidance consists of two phases. In the first phase, the predictor uses the profile shown in Figure 2, where ϕ_0 and ϕ_d are specified by the user. The corrector iterates to solve for the value of the switching time, t_s , such that the predicted radius of apoapsis is

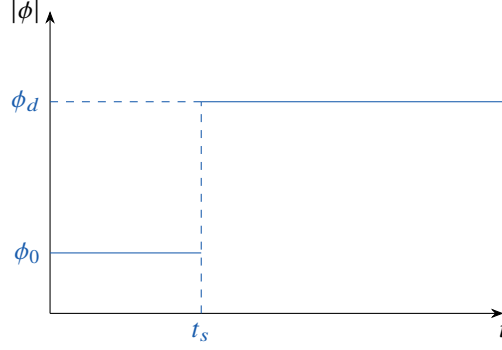


Fig. 2 Phase 1 of FNPAG uses a bang-bang bank profile in the predictor.

Table 1 The vehicle has a sphere-cone aeroshell with a low L/D and uses bank angle for control.

Property	Value
Ballistic Coefficient	180 kg/m ²
L/D	0.25
Max Bank Rate	15°/s
Max Bank Acceleration	5°/s ²

equal to the desired target. Once t_s is reached, the second phase begins, during which the predictor uses a constant bank angle command, and the corrector solves for the value of that command that achieves the radius of apoapsis target. For the lateral channel, FNPAG uses bank reversals to target a desired orbital plane.

FNPAG is a model-based guidance and does not require extensive tuning. It uses basic vehicle and environment parameters, such as the vehicle's mass and the planet's gravitational parameter, on-board models of the vehicle's aerodynamics and the planet's atmospheric density, and a small number of guidance-specific parameters.

We selected FNPAG for this Uranus mission because of its previous performance in studies for both small and large mass orbiters [6, 15–17]. The algorithm has also been shown to be robust to large uncertainties, an important consideration for planetary bodies with limited atmospheric data [9].

IV. Simulation Overview

Genesis was used to simulate open-loop and guided three-degree-of-freedom trajectories in order to tune FNPAG. Genesis is a generic, multi-vehicle, variable-degree-of-freedom flight mechanics simulation. It enables rapid mission design and is capable of modeling ascent, aerocapture, entry, descent, and landing trajectories around a single planetary body [18]. It is designed to be flexible and easily reconfigured for new vehicles. Genesis provides generic models for atmospheric properties, winds, aerodynamics, and propulsion. It can easily be extended with new environment, vehicle, or flight software models. Genesis can be used for a wide variety of analyses, ranging from optimizing a single trajectory to running a large Monte Carlo analysis in a High-Performance Computing (HPC) environment. It is a successor to the Flight Analysis and Simulation Tool (FAST) and consolidates and replaces a suite of legacy flight mechanics simulations used at JSC. It is implemented in the Julia programming language [19].

V. Simulation Configuration

The vehicle for this mission has a 70° sphere-cone aeroshell with a low lift-to-drag ratio (L/D). It continuously modulates the bank angle for control in the atmosphere. While the trajectory is only simulated in three degrees of freedom, the bank angle response is emulated by a phase-plane controller, with bank angle rate and acceleration limits selected to approximate the response in six degrees of freedom. The vehicle parameters are shown in Table 1. The target orbit is highly elliptical, and its parameters are given in Table 2. For this study, only the shape of the orbit is considered.

The simulation is initialized 10 minutes prior to Entry Interface (EI), but for our purposes the states at EI are more

Table 2 The aerocapture maneuver targets a highly elliptical orbit.

Target	Value
Altitude of Apoapsis	550 000 km
Altitude of Periapsis	4000 km

Table 3 The nominal conditions at entry interface.

State	Value
Radius	26 559 km
Longitude	100.7°
Planetocentric Latitude	−9.9°
Inertial Velocity	24.9 km/s
Planetocentric Inertial Flight-Path Angle	−11.1°
Planetocentric Inertial Azimuth	138.9°

relevant. The nominal states at EI are shown in Table 3. For Monte Carlo analyses, we disperse the initial state, mass, atmosphere, and aerodynamics, as summarized in Table 4.

The guidance team must synchronize the Genesis and POST2 simulations at the beginning of each design analysis cycle. The trajectory team delivers a comma-separated values (CSV) file of the relevant vehicle and environment model parameters. Genesis and POST2 have been configured to read this file to populate their respective inputs.

VI. Post-Aerocapture ΔV

After the atmospheric pass, some amount of ΔV is required to clean up the resulting orbit. This ΔV is one of the metrics by which we evaluate the performance of a trajectory. The concept of operations used depends on whether the vehicle exits the atmosphere on an elliptical or hyperbolic trajectory.

For this study, the ΔV does not include any burns to correct the orbital plane. The vehicle will perform a series of flybys of the Uranus system to gradually adjust the orbit to the final science orbit.

A. Nominal Concept of Operations

If the trajectory exits the atmosphere on an elliptical orbit, then a sequence of two impulsive maneuvers is used to achieve the desired orbit. First, after exiting the atmosphere, the vehicle coasts to apoapsis, at which point it performs a burn to raise the periapsis out of the atmosphere to the desired value. The vehicle then coasts to this new periapsis, at which point it performs a second burn to clean up any error in the apoapsis.

Table 4 Monte Carlo dispersions.

Variable	Dispersion
Initial Position	from entry state file
Initial Inertial Velocity	from entry state file
Mass	normal, $\sigma = 3.333 \%$
GRAM Random Seed	uniform, 1–30000
C_L Multiplier	uniform, $\sigma = 6.667 \%$
C_D Multiplier	uniform, $\sigma = 6.667 \%$

Table 5 The coefficients of the density fit used by guidance were tuned for the given entry states.

Coefficient	Value
c_1	4.29×10^7
c_2	4.09×10^4
c_3	-7.42×10^5
c_4	-1.71×10^2
c_5	2.51×10^3
c_6	2.12×10^{-1}
c_7	-2.40
c_8	2.80×10^{-5}
c_9	-1.46×10^{-3}

B. Hyperbolic Exit Concept of Operations

If the trajectory exits the atmosphere on a hyperbolic orbit, the concept of operations is more complicated, and there is no simple conic approximation. Instead, we used Copernicus [20] to calculate higher fidelity ΔV estimates. Copernicus is a generalized trajectory optimization tool primarily used for exo-atmospheric trajectory design applications. With a suite of built-in nonlinear solvers and optimizers, Copernicus allows users to efficiently define and solve constrained nonlinear optimization problems.

For hyperbolic cases, the final state at atmospheric exit was extracted from Genesis and used to seed the initial state in Copernicus simulations. A two-burn sequence was first proposed: the spacecraft would coast some short duration before initiating ΔV -1, it would then coast for a variable amount of time, then ΔV -2 would be executed. The objective function was to minimize the sum of the two ΔV magnitudes, the optimization variables were the ΔV vectors and the coast time between them, and the constraints were on the semi-major axis and eccentricity of the final orbit to match the size and shape of the target orbit. The rest of the orbital parameters were left unconstrained.

It was found that the optimal solution to the two-burn sequence placed ΔV -1 instantaneously after atmospheric exit (i.e., zero coast time), and ΔV -2 at the apoapsis point. Though this concept of operations effectively tries to mimic a Hohmann-like transfer, it is unable to as the atmospheric exit point (and therefore ΔV -1), occurs after passing periapsis. A 3-burn sequence was proposed to address this shortcoming in the 2-burn sequence. When optimized, ΔV -1 of the 3-burn sequence would subtract just enough energy to place the spacecraft in a highly eccentric orbit. ΔV -2 would again occur at apoapsis to raise periapsis altitude, and ΔV -3 would occur at the periapsis point to lower apoapsis to the target altitude. This concept of operations represents the theoretical lower bound on ΔV required for hyperbolic cases to capture into a target orbit with desired apoapsis and periapsis altitudes. The hyperbolic ΔV values shown in the results of this paper use this 3-burn sequence.

VII. FNPAG Tuning

The atmospheric density model has a large impact on performance and is typically the only guidance model that needs to be tuned. When given a new set of entry conditions, we propagate an open-loop, lift-up trajectory along the steep edge of the flight-path angle corridor and record the density profile. We then generate a curve fit to the log of the density as a function of altitude, as shown in Equation 1. By using a propagated trajectory, we attempt to incorporate latitude effects without making the curve fit depend explicitly on latitude. The density coefficients are shown in Table 5.

$$\ln \rho = \frac{c_1 + c_3 h + c_5 h^2 + c_7 h^3 + c_9 h^4}{1 + c_2 h + c_4 h^2 + c_6 h^3 + c_8 h^4} \quad (1)$$

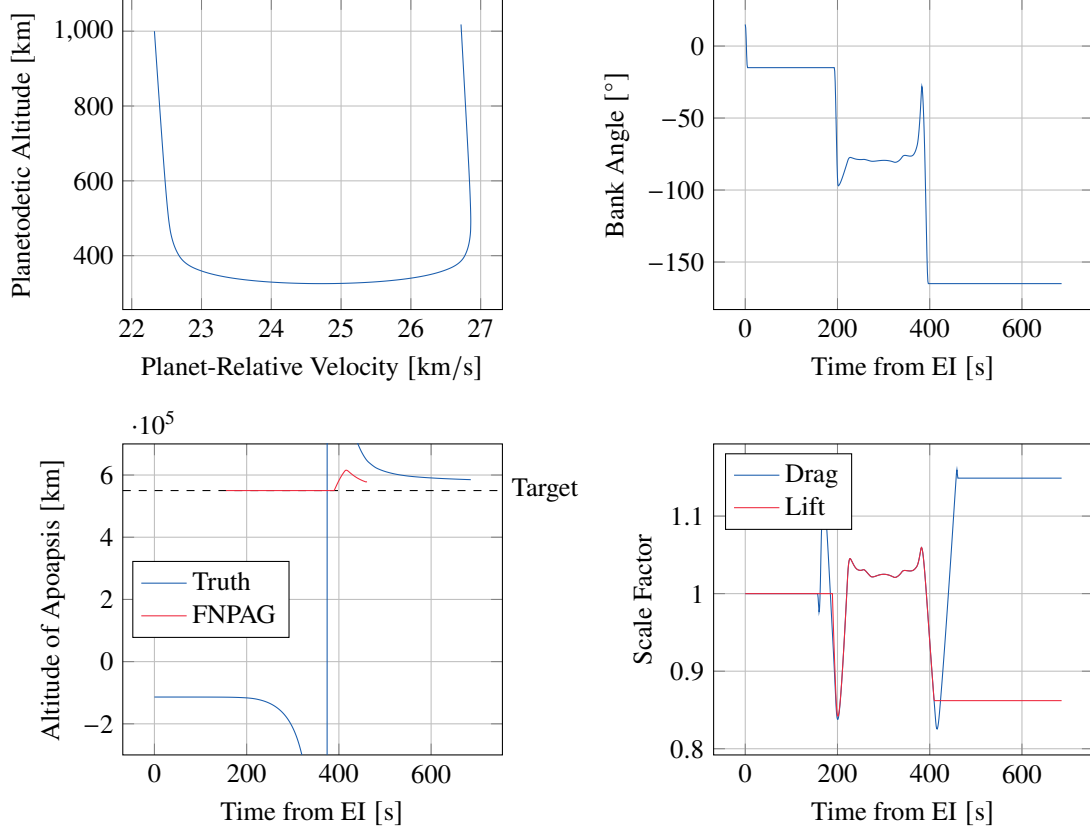


Fig. 3 An undispersed, guided trajectory showing the two-phase bank angle profile targeting a desired altitude of apoapsis.

VIII. Results

A. Undispersed

1. Open-Loop

We run open-loop cases to assess the flight-path angle corridor, which defines the range of flight-path angles within which the vehicle has enough control authority to reach its target. For a particular constant bank angle, we can iterate to find the flight-path angle at EI that results in the desired altitude of apoapsis at atmosphere exit. Flying full lift up corresponds to the steepest possible flight path angle. Flying full lift down corresponds to the shallowest possible flight-path angle. For this mission and vehicle, the flight path angle corridor at entry interface is from -11.36° to -10.81° .

2. Guided

Before we run a Monte Carlo analysis, we look at undispersed, guided cases, to ensure the guidance is properly configured and performing well. Figure 3 shows the results. The bank angle profile is typical for FNPAG: phase 1 of the guidance commands a bank angle of 15° , and then FNPAG switches to phase 2 at approximately 200 s. The final altitude of apoapsis being predicted by FNPAG tracks the target well for the majority of the trajectory. FNPAG's lift and drag estimators are adapting the on-board models as the vehicle flies through the atmosphere.

The late decrease in drag at 400 s, coupled with the loss of control authority as the vehicle pulls up out of the atmosphere, results in the commanded bank angle saturating full lift down. This is expected behavior.

3. Observation Regarding Planetary Oblateness

FNPEG's internal calculations use two versions of altitude. One version is simply the difference between the magnitude of the vehicle's position vector and the equatorial radius of the planet. The equations of motion in FNPEG are non-dimensionalized, and because lengths are non-dimensionalized by the equatorial radius of the planet, this altitude can be computed very easily as $r - 1$, where r is the non-dimensional magnitude of the vehicle's position.

The second version of altitude is the planetodetic altitude, which uses a bi-axial ellipsoid model of the planet's shape. Originally, planetodetic altitude was only used for computing the local atmospheric density.

Past FNPEG studies have focused on Earth, Venus, and Mars. Venus is nearly spherical, but Earth and Mars are somewhat oblate. However, the difference between their equatorial and polar radii are only about 20 km. Compared to the celestial bodies studied previously, Uranus is both more oblate and larger. The difference between the equatorial and polar radii is about 580 km, which is a significant portion of the EI altitude of 1000 km.

While running our initial undispersed cases for this study, we quickly realized that we needed to modify FNPEG. In particular, we were more careful to use the planetodetic altitude when computing events (e.g., atmosphere exit) in the predictor.

B. Dispersed

A 3,000-case Monte Carlo was performed to characterize the performance of FNPEG for this mission. Table 6 summarizes the statistics for the baseline Monte Carlo. There was a single case that exited on a hyperbolic trajectory. It is included in all of the statistics except the ΔV . The ΔV of the hyperbolic case was computed separately in Copernicus using the 3-burn sequence as described in Section VI.B and found to be 880 m/s. We will address these hyperbolic cases further in Section VIII.C.2.

Figure 4 shows scatter plots and histograms of the baseline Monte Carlo results. The vertical dashed lines show the steep and shallow flight-path angle corridor bounds. Note how the dispersed flight-path angle fills the entire corridor.

The first histogram plot shows the ΔV of the first post-aerocapture burn. This burn has a non-zero mean because it is raising the periapsis of the post-aerocapture orbit out of the atmosphere. The second histogram shows the ΔV of the second post-aerocapture burn. This burn corrects any apoapsis targeting error. Ideally, the guidance would hit the target perfectly, and this burn would not be necessary. But of course in practice the aerodynamic and atmospheric dispersions result in some apoapsis targeting error. The third histogram plot shows the total ΔV of the two post-aerocapture burns.

The first scatter plot shows the post-aerocapture altitude of apoapsis. The results cluster around the desired altitude of apoapsis across the dispersed range of flight-path angles, with a few outlier cases, especially on the shallow side.

The second scatter plot shows the duration of phase 1 of FNPEG, which is the phase when FNPEG commands lift up. As expected, near the shallow boundary, FNPEG immediately computes a switching time of 0 s because it must fly at a bank angle more lift down than ϕ_d in order to hit the target. Towards the steeper end of the corridor, FNPEG is able to utilize phase 1 and the optimal bang-bang structure.

The third scatter plot shows the total post-aerocapture ΔV . Outliers occur at both the shallow and steep edges of the corridor. Figure 5 explores the guidance performance of a representative outlier in more detail. Guidance activates at approximately 180 s. The estimators see that drag is about 25% higher than expected early on. FNPEG adapts to this and remains in phase 1, flying lift up. At approximately 300 s, the sensed drag and lift both decrease significantly, indicating a sudden drop in atmospheric density. Now that it anticipates less drag for the remainder of the trajectory, FNPEG switches to phase 2 and actually saturates at the maximum lift down bank angle command of $\pm 165^\circ$. The trajectory exits in a very elliptical orbit, with an altitude of apoapsis far greater than the desired value. This kind of high-to-low density gradient is a known difficulty for other guidance algorithms, such as skip-entry guidance.

C. Guidance Parameter Studies

1. Phase 2 Bank Angle

The ϕ_d guidance parameter allows the guidance team to trade performance and robustness. A trajectory with a more lift down value of ϕ_d will more closely mimic the optimal bang-bang bank angle profile, but it will retain less lift down margin to respond to atmospheric disturbances later in the trajectory.

We typically start with $\phi_d = 90^\circ$ and then perform Monte Carlo scans to see if a slightly more lift down value would be beneficial. In this case, with the dispersed flight-path angle at EI stretching across the entire flight-path angle corridor, we expected that a value of $\phi_d = 90^\circ$ would indeed be the best choice, as it maintains an equal amount of lift up and lift down margin. However, the results show that a more lift up bank angle is favorable. This is likely caused by the outlier

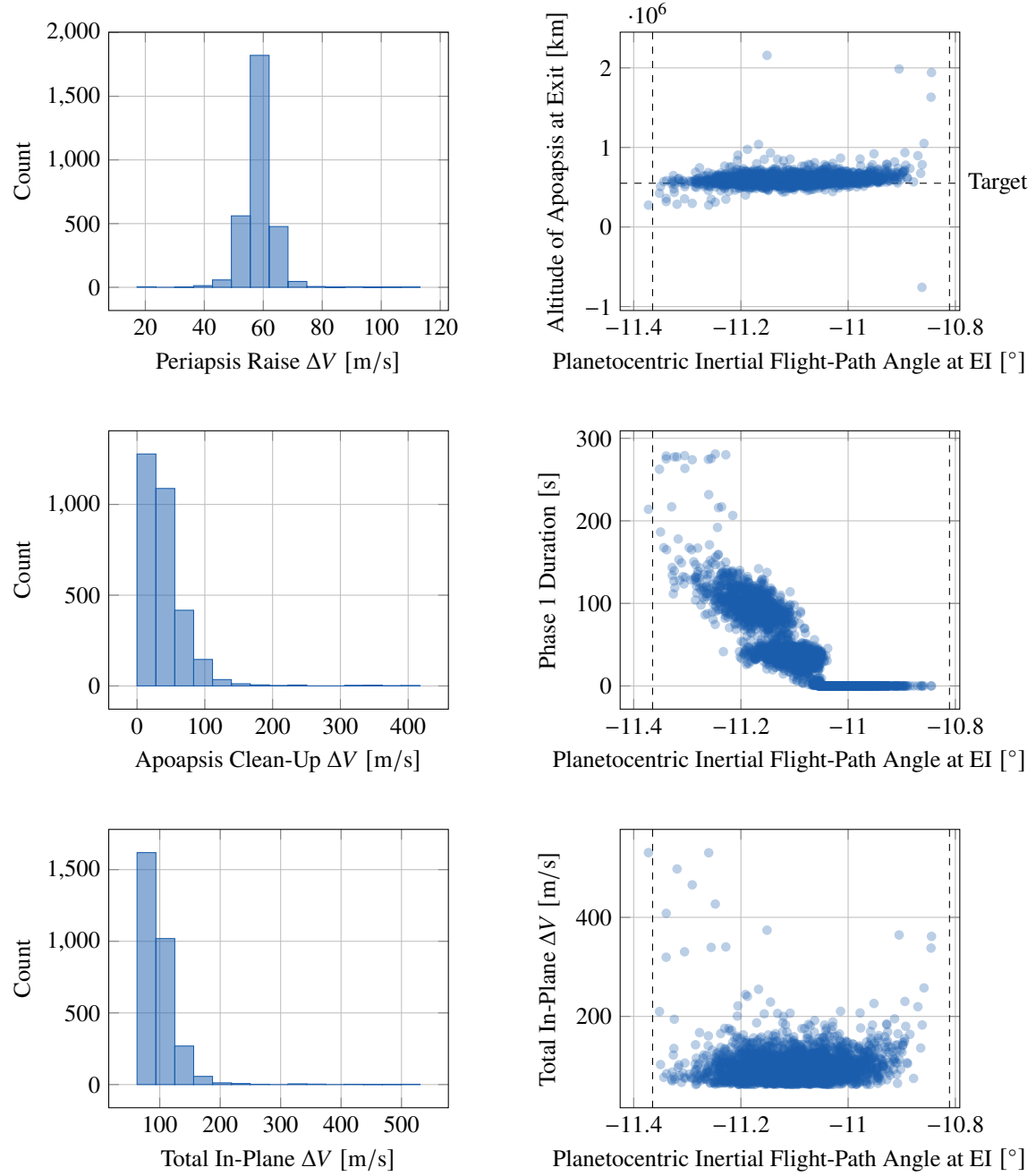
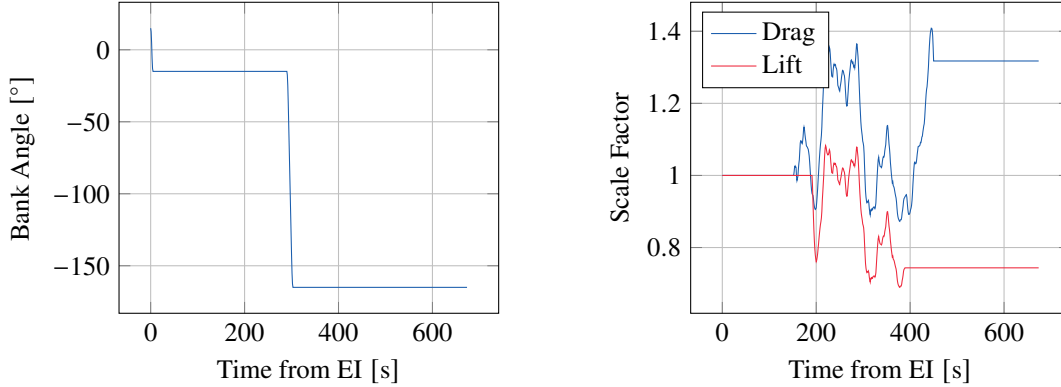


Fig. 4 Results of the baseline Monte Carlo.

Table 6 Statistical summary of the key performance parameters for the baseline Monte Carlo.

	Apoapsis Altitude [km]	Total In-Plane ΔV [m/s]	Peak Heat Rate [W/cm ²]	Peak G-Load [Earth g]
Minimum	-7.58×10^5	62.4	481	2.48
1%-ile	4.76×10^5	63.0	511	2.86
Mean	5.95×10^5	97.3	568	3.50
99%-ile	7.77×10^5	200	630	4.27
Maximum	2.16×10^6	531	674	4.90

**Fig. 5 Outlier cases tend to be caused by large changes in density.**

cases discussed above. By using a more lift up value of ϕ_d , the vehicle spends less time in the lift up configuration and preserves more lift down margin. The cases that experience high-to-low density gradients then have more capability to go lift down and reduce the final altitude of apoapsis.

2. Flight-Path Angle at Entry Interface

Another parameter that has a strong influence on aerocapture performance is the flight-path angle at entry interface, especially for this mission, where the dispersed flight-path angle provided by the interplanetary trajectory team spans the entire flight-path angle corridor. The baseline Monte Carlo results in Section VIII.B showed that one case out of 3,000 exited the atmosphere on a hyperbolic trajectory. This case's dispersed flight-path angle was very close to the shallow flight-path angle corridor boundary. As a reminder, the ΔV required to complete the capture of this case propulsively was 880 m/s.

By applying an additive bias to the flight-path angle at entry interface, we can approximate the effect of re-targeting

Table 7 Results of a scan on ϕ_d .

ϕ_d [°]	# Hyperbolic	99%-ile Total In-Plane ΔV [m/s]	99%-ile Peak Heat Rate [W/cm ²]	99%-ile Peak G-Load [Earth g]
70	1	195	638	4.42
80	1	193	635	4.34
90	1	200	630	4.27
100	1	218	624	4.20
110	1	258	623	4.19

Table 8 Results of a scan on flight-path angle at entry interface.

$\Delta\gamma$ [°]	# Hyperbolic	99%-ile Total In-Plane ΔV [m/s]	99%-ile Peak Heat Rate [W/cm ²]	99%-ile Peak G-Load [Earth g]
0.05	16	200	623	4.12
0.025	6	194	627	4.18
0.0	1	200	630	4.27
-0.025	0	208	636	4.35
-0.05	0	309	643	4.53

the arrival at Uranus. The results of this scan are shown in Table 8. The hyperbolic cases are excluded from the ΔV statistics but are included in the peak heat rate and peak sensed acceleration statistics.

As expected, a shallower mean flight-path angle results in more cases exiting the atmosphere on hyperbolic trajectories. By biasing the flight-path angles by only 0.025°, we see 6 cases that are hyperbolic. The ΔV required to complete the capture of these cases propulsively ranges from 546 to 1490 m/s.

A slightly steeper mean flight-path angle is able to completely eliminate the hyperbolic cases, with a small increase in ΔV , peak heat rate, and peak sensed acceleration. Some of the dispersed flight-path angles are then steeper than the steep flight-path angle corridor boundary, which simply means they capture into an elliptical orbit with an apoapsis below the desired value and require additional ΔV to boost back up to the desired orbit. None of the cases capture for entry.

IX. FNPAG Integration in POST2

The version of FNPAG used for this analysis was implemented in Julia. This was simple to use within Genesis, which is also implemented in Julia. However, the runs for the record for this project are performed using POST2, which is written in C. Rather than re-implement FNPAG in C, the team desired to call the Julia version directly.

It is straightforward to use the `PackageCompiler.jl` package to compile the FNPAG Julia code into a shared library with a C API. Internally, the guidance is still being run by Julia, but the C API makes it easy to incorporate into other tools like POST2.

In addition to the shared library, the guidance team delivers a CSV file containing the tuned guidance parameters and a time history file containing all of the guidance inputs and outputs for a unit test case. The POST2 team exercises their FNPAG interface with the unit test case and matches the outputs within a tight tolerance, giving the team confidence that the guidance has been integrated correctly in POST2.

X. Conclusion

The application of a numeric predictor-corrector, bank control guidance for aerocapture at Uranus has been presented. Nominal and Monte Carlo results indicate that bank angle control is capable of performing aerocapture at Uranus using a low-L/D aeroshell. Guidance parameter studies identify potential trade offs between performance and robustness. In particular, targeting the entry conditions steeper than the baseline can prevent cases from exiting the atmosphere on hyperbolic trajectories. The Julia implementation of the FNPAG algorithm is compiled into a shared library for integration into POST2.

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