

Analysis of the Fully Numerical Predictor-corrector Aerocapture Guidance for an Earth-based Demonstration

Julia M. Briden¹ Daniel A. Matz²

NASA Johnson Space Center, Houston, TX, 77006, USA

Rohan G. Deshmukh³ Evan Roelke⁴ Soumyo Dutta⁵ Alejandro Pensado⁶

NASA Langley Research Center, Hampton, VA, 23666, USA

Sergio Sandoval⁷

NASA Johnson Space Center, Houston, TX, 77006, USA

Aerocapture serves as an enabling technology for time and propellant-efficient atmospheric planetary exploration. To progress this technology beyond simulation, guidance algorithms for aerocapture require maturation to flight-implementable code for future technology demonstrations. In this work, we expand the Fully Numerical Predictor-corrector Aerocapture Guidance (FNPAG) algorithm for use in an Earth-based aerocapture demonstration. In addition to longitudinal targeting, a lateral targeting strategy is chosen and assessed using a novel bank maneuver strategy selection algorithm developed in this work. Sensitivity analyses and implementation tradeoffs of FNPAG are explored for planned Geostationary Transfer Orbit (GTO) and lunar return mission designs.

I. Nomenclature

β	=	filter gain
χ	=	lateral error
γ	=	flight path angle
κ	=	estimator scale factor
λ	=	azimuth
μ	=	gravitational parameter of the planet
Ω	=	planet rotation rate
ρ	=	local atmospheric density
σ	=	bank angle
τ	=	time constant
a	=	acceleration
C_D	=	drag coefficient
C_L	=	lift coefficient
c	=	atmosphere model coefficients
g_0	=	gravitational acceleration at the equatorial radius
h	=	planetodetic altitude
K	=	lateral guidance parameter
M	=	maneuver strategy

¹Advanced Mission Design and GN&C Engineer, NASA Johnson Space Center (JETS II - Amentum), AIAA Member.

²Aerospace Engineer, NASA Johnson Space Center, Senior AIAA Member.

³Aerospace Engineer, NASA Langley Research Center, AIAA Member.

⁴Aerospace Engineer, NASA Langley Research Center (Analytical Mechanics Associates), AIAA Member.

⁵Aerospace Engineer, NASA Langley Research Center, AIAA Associate Fellow.

⁶Aerospace Engineer, NASA Langley Research Center (Analytical Mechanics Associates), Senior AIAA Member.

⁷Aerospace Engineer, NASA Johnson Space Center, AIAA Member.

n	=	desired number of bank reversals
R	=	rotation matrix
R_0	=	equatorial radius of the planet
t	=	time
X	=	state vector position component
Y	=	state vector position component
Z	=	state vector position component

II. Introduction

Aerocapture guidance computes commands for a successful orbital insertion maneuver that utilizes atmospheric aerodynamic forces to achieve a desired orbit. The advantages of aerocapture over traditional all-propulsive systems include reduced mission durations, higher payload mass allowances, and reduced propellant consumption [1], [2], [3], [4], [5], [6]. With the 2023 Planetary Decadal Survey identifying Ice Giants, Uranus and Neptune, as top flagship class destinations, aerocapture serves as an enabling technology for exploration and scientific discovery for atmospheric outer planets [7]. While aerocapture represents a promising exploration technology, it must first be demonstrated in a low-risk mission to advance technology readiness and validate simulated performance metrics. In this work, we develop and test a guidance algorithm for the aerocapture Earth demonstration design detailed in (Dutta et al., 2026) [8]. Fully Numerical Predictor-corrector Aerocapture Guidance (FNPAG) with bank angle control balances heritage, from bank-controlled Earth and Mars guided reentry missions, with the predictive capabilities of an onboard predictor-corrector [9], [10], [11]. The FNPAG algorithm iteratively solves for the optimal switching time and bank angle control policy using knowledge of the bang-bang solution profile. In this paper, we extend FNPAG to include the lateral targeting algorithm detailed in (Smith, 2016) [12]. Given a deterministic number of bank reversals and an allowable cross-range error, a geometrically contracting algorithm was formulated to reduce lateral error. Of significant interest is the extension of Smith’s lateral error algorithm from entry to the aerocapture guidance algorithm described in this work. From the analysis in this paper, several challenges were identified and addressed in our final algorithm; wedge angle-based lateral error exhibited bi-modal behaviors when paired with the FNPAG-derived control policy, a solution for lateral error edges cases needed to be formulated, and FNPAG exhibited a root-finding singularity resulting from ambiguity in the bank reversal rate. The developed guidance algorithm in this work utilizes inclination-based lateral targeting and solves for both the bank angle and the bank angle rate in the FNPAG corrector. Algorithmic parameters for the guidance algorithm are systematically selected from a series of Monte Carlo sensitivity analyses in the flight mechanics simulation software framework, Genesis [13]. Genesis is a new flight mechanics simulation developed by NASA in the Julia programming language and is available in the NASA software catalog [14].

III. Methods

A. Earth-based Aerocapture

In this work, we detail the guidance algorithm for the Earth aerocapture demonstration mission, Aerocapture to Reliably Reduce Inertial Velocity with Aerodynamics and Lift (ARRIVAL). The planned NASA mission includes a SmallSat-scale vehicle, with geostationary transfer orbit (GTO) and Lunar return mission design options [8]. For the GTO mission, the spacecraft will perform a periapsis lowering maneuver from an elliptic orbit about Earth and then release the aeroshell to target an atmospheric entry interface (EI) of 125 km in altitude. The Fully Numerical Predictor-corrector Aerocapture Guidance (FNPAG) guidance algorithm is used to actively target the desired orbit apoapsis altitude and inclination. After exiting the atmosphere, the SmallSat exists in an elliptic orbit within the Earth’s atmosphere. Similarly, a Lunar return trajectory departs from a Near Rectilinear Halo Orbit (NRHO), travels back to Earth, and following a cruise stage separation, performs the GTO mission concept of operations (CONOPS).

B. FNPAG Guidance

The FNPAG algorithm utilizes onboard models and online root finding to compute the bang-bang bank angle profile required to reach a desired apoapsis altitude. In addition to apoapsis altitude targeting, a lateral

channel is often adopted in FNPAG to target a specific wedge angle, using the lateral targeting logic in (Smith, 2016) [12]. In this work, we evaluate the choice of the wedge angle for lateral targeting and discover aerocapture edge cases, where lateral error does not decrease monotonically, causing solution divergence. We propose the use of the inclination angle for lateral targeting, with the new architecture detailed in this section.

The top-level flow of FNPAG is illustrated in Fig. 1, where the navigated state (the radius, longitude, declination, planet-relative velocity magnitude, planet-relative planetocentric flight path angle, and planet-relative planetocentric azimuth) is used to update the lift and drag estimators and the lift and drag estimates are used in the predictor and corrector. The guidance loop shown is called at a fixed rate by the flight software, with the bank angle profile from Fig. 2.

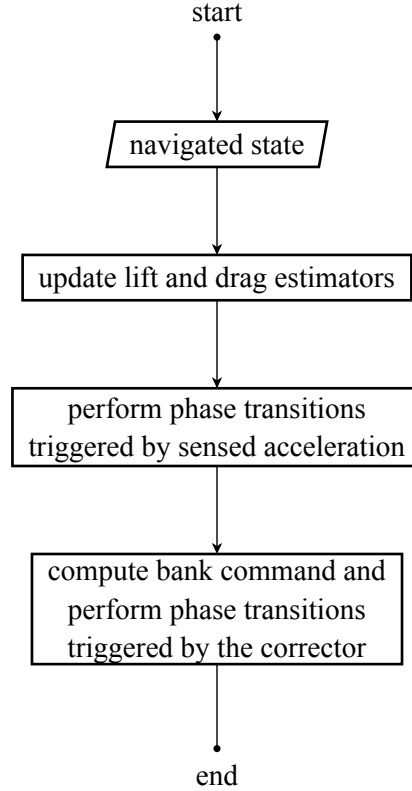


Fig. 1 Top-level FNPAG logic.

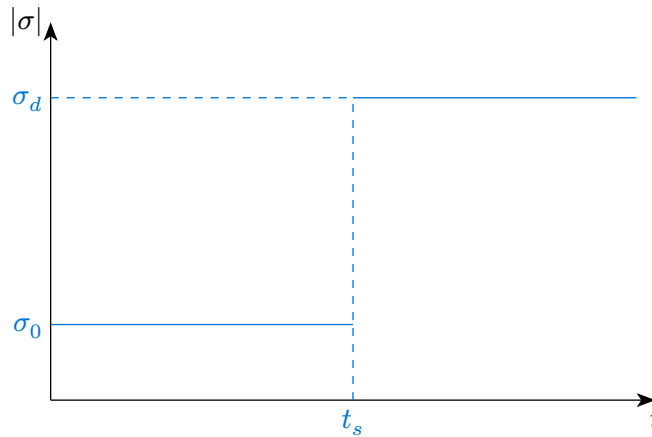


Fig. 2 FNPAG uses a bang-bang bank-angle profile during phase 1.

During pre-entry, the commanded bank angle is set to a user-defined value and the lateral logic is not active. Once a sensed acceleration threshold $a_{\text{threshold}}$ is met, the bank angle guidance algorithm initiates, consisting of two phases: 1) The predictor utilizes a bang-bang bank profile, (σ_0, σ_d) in Fig. 2, specified by the user,

and the corrector solves for the switching time, t_s , such that the predicted apoapsis altitude is equal to the desired target and 2) The predictor utilizes a constant bank angle profile and the corrector now solves for the bank command that achieves the desired target apoapsis altitude. phase 2 is triggered when the switching time, estimated in phase 1, is reached. Once both the flight path angle is positive and the sensed acceleration is below the threshold, phase 2 is exited and the last computed value is used as the bank angle command post-exit. Fig. 3 shows the transitions between the Pre-Entry, phase 1, phase 2, and Post-Exit guidance phases.

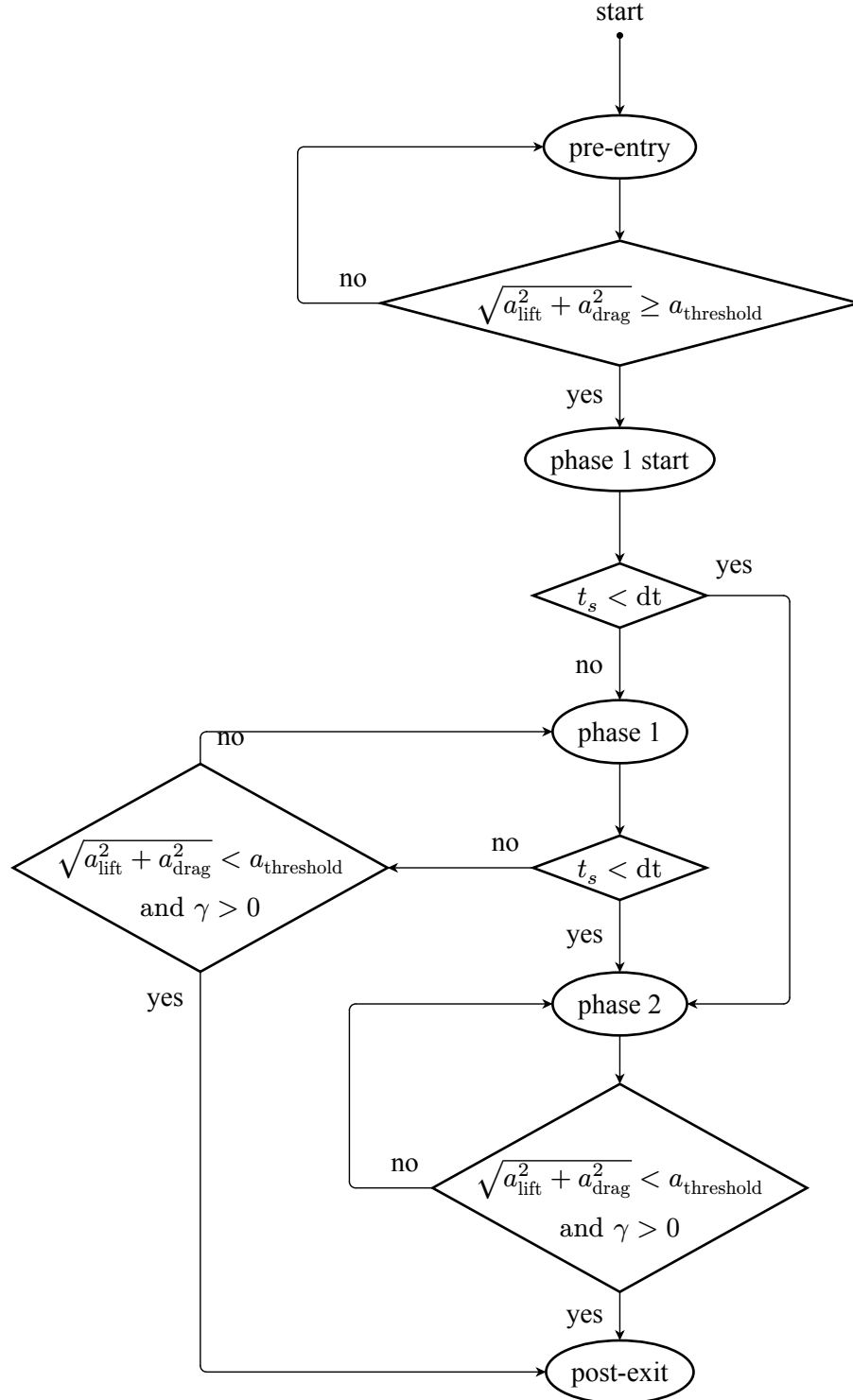


Fig. 3 FNPAG proceeds through several phases as the spacecraft flies through the atmosphere.

1) Lateral Logic:

In this work, a lateral logic algorithm, originally developed by [12] for entry guidance, was extended for this aerocapture guidance application. This logic is used in both phase 1 and phase 2 of FNPAG to determine if the vehicle should perform a bank reversal to hit the lateral target within a user-specified tolerance χ_f . Both the wedge angle and inclination angle are explored in this work for use as the lateral targeting parameter. The lateral parameter K is computed according to Eq. (1):

$$K = \left| \frac{\chi(t)}{\chi_f} \right|^{\frac{1}{n}} \quad (1)$$

where $\chi(t)$ is the current lateral error, χ_f is the desired final lateral error, and n is the desired number of bank reversals [12]. If K increases, apoapsis altitude error approaches the zero-bank reversal limiting case. While too small of a K may affect longitudinal channel performance, increasing K may result in a non-deterministic number of bank reversals.

2) Phase 1 Overview:

In phase 1 of the FNPAG guidance algorithm, the user-defined bank angle command σ_{cmd} is used by the targeting algorithm to compute the switching time to enter phase 2. If the switching time has already occurred, phase 2 is initiated. Otherwise, the switching time is chosen to be either the current bank angle-based switching time or the switching time after performing a bank reversal, based on the bank reversal lateral logic.

When then phase 1 targeting algorithm is called, Algorithm 1, the lift-up and lift-down solutions are computed and the associated switching time for either case is returned if the final apoapsis radius is predicted to be above or under the target. Otherwise, when the solution is between the targeting bounds, bisection search is used to determine the optimal switching time to enable the predicted trajectory to hit the apoapsis altitude target. The bisection search algorithm uses the bisection method and converges once a user-specified bank angle accuracy ε is reached. While the time complexity for the bisection search algorithm, used by the corrector, is $O(\log \frac{1}{\varepsilon})$, the corrector calls the predictor at each step, which also influences the time complexity.

Algorithm 1 Corrector

```

1: procedure corrector(predictor, below_bound, above_bound)
2:
3:   ▷ Run the predictor for the lift-up bound
4:
5:   lift_up_solution ← predictor(above_bound)
6:
7:   if is_below_target(lift_up_solution) then
8:
9:     return lift_up_solution
10:
11:   end
12:
13:   ▷ Run the predictor for the lift-down bound
14:
15:   lift_down_solution ← predictor(below_bound)
16:
17:   if !is_below_min_altitude(lift_down_solution) and is_above_target(lift_down_solution) then
18:
19:     return lift_down_solution
20:
21:   end
22:   ▷ Run bisection search to find the optimal solution to reach the desired radius of apoapsis
23:
24:   return bisection_search(predictor)
25:
26: end

```

The predictor steps through the trajectory's time history until either atmospheric exit, a high amount of energy loss, or reentry occurs. In the predictor algorithm, the Dormand-Prince 5(4) (DP5) integrator is used for each integration step until one of the exit conditions are reached. Dependant on the number of adaptive steps taken by the integrator, N_{steps} , the time complexity of the predictor is $O(N_{\text{steps}})$. Since each iteration

of the corrector calls the predictor, the full predictor-corrector time complexity is $O(N_{\text{steps}} \log \frac{1}{\epsilon})$, where the scaling is linear in the number of integration steps and logarithmic in the corrector tolerance.

3) Phase 2 Overview: In phase 2, the bank angle σ_{cmd} is now the optimization variable, rather than the switching time. When considering the vehicle's control, two different *maneuver strategies* could be used to reach the same commanded bank angle: a positive rate strategy and a negative rate strategy. The ShorterTimeStrategy selects the rate based on the direction that takes the shortest time to reach the desired bank angle. A new contribution of this work is the implementation of a targeting algorithm that optimizes over the maneuver strategy, as well as the commanded bank angle. If the initial bank angle σ_0 is between a user-defined minimum and maximum bound, the vehicle's state is considered as not currently completing a bank reversal. Otherwise, it is assumed that a bank reversal is currently occurring and the maneuver strategy is held fixed until the reversal is complete. While the fixed maneuver strategy targeting uses the bisection search-based corrector to solve for the commanded bank angle once, the phase2_targeting_choose_maneuver_strategy algorithm solves the targeting problem twice, once for each maneuver strategy.

Algorithm 2 iterates through the PositiveRateStrategy and NegativeRateStrategy options and computes the corrector-computed solution for each. If there are two solution roots, both bank angle commands approximately hit the apoapsis altitude target, then the solution that is closest to 90 degrees is used. Otherwise, the bank command and associated strategy are chosen from the solution that results in the lowest targeting error.

Algorithm 2 Phase 2 Targeting Choose Maneuver Strategy

```

1: procedure
2:   phase2_targeting_choose_maneuver_strategy(predictor, below_bound, above_bound)
3:    $\triangleright$  Compute the optimal bank commands for each maneuver strategy
4:   for (i, M) in enumerate(PositiveRateStrategy, NegativeRateStrategy) do
5:     solutions[i]  $\leftarrow$  corrector(predictor, M)
6:   end
7:    $\triangleright$  Determine if both solutions hit the apoapsis altitude target
8:   if distance_from_target(solutions)  $\approx$  0 then
9:      $\triangleright$  Choose the solution that has a bank command closest to 90 degrees
10:     $\sigma_{\text{cmd}}, M \leftarrow \text{argmin}(\text{angle\_error}(\text{solutions}, 90 \text{ deg}))$ 
11:  end
12:  else
13:     $\triangleright$  Choose the solution that is closest to hitting the target
14:     $\sigma_{\text{cmd}}, M \leftarrow \text{argmin}(\text{distance\_from\_target}(\text{solutions}))$ 
15:  end
16:  return  $\sigma_{\text{cmd}}, M$ 
17: end

```

The phase2_targeting_fixed_maneuver_strategy algorithm similarly runs the corrector, but only performs this step once for the input maneuver strategy. Note that both the fixed maneuver strategy and the choose maneuver strategy phase 2 targeting algorithms have the same time complexity, $O(N_{\text{steps}} \log \frac{1}{\epsilon})$, since the corrector is only run twice for choosing the maneuver strategy.

4) Lift and Drag Acceleration Estimators:

The lift and drag acceleration estimators compare the sensed lift or drag acceleration a_{sensed} and the onboard model of the lift or drag acceleration $a_{\text{threshold}}$ to determine a scale factor for the onboard model that aligns it with the sensed value. The scale factor is then passed through a first-order filter, to prevent the

bank command from trying to track higher frequency noise in the sensed acceleration. The two estimators have the same structure. The logic flow of an estimator is shown in Fig. 4.

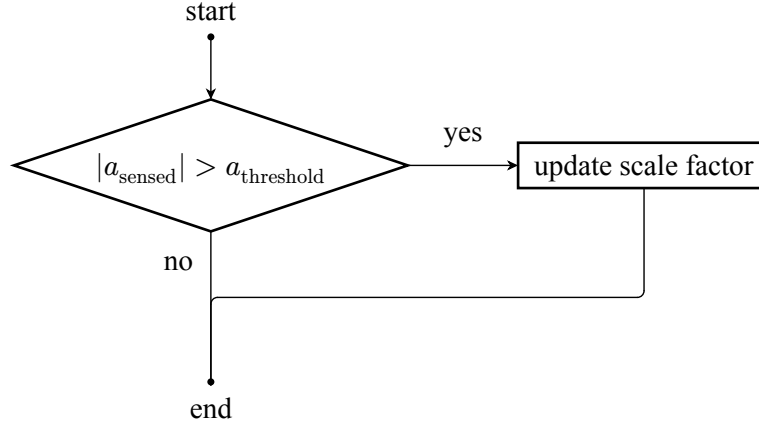


Fig. 4 Logic flow of an estimator

The scale factor $\kappa_{a,\text{unfiltered}}$ is

$$\kappa_{a,\text{unfiltered}} = \frac{|a_{\text{sensed}}|}{|a_{\text{modeled}}|}. \quad (2)$$

The first-order filter is of the form

$$\kappa_{a,i+1} = \beta \kappa_{a,i} + (1 - \beta) \kappa_{a,\text{unfiltered}}. \quad (3)$$

The filter gain, β , is computed as

$$\beta = \exp\left(-\frac{dt}{\tau}\right), \quad (4)$$

where dt is the change in time and τ is a user-defined filter time constant.

5) Planet Model:

The planet model includes a gravity model, surface model, and planet orientation. The gravity model is a simple J2 model. The user provides both the gravitational parameter, μ , and an unnormalized J2 coefficient, J2. The surface is modeled as a bi-axial ellipsoid. The user provides both the equatorial and polar radii. The planet orientation model only includes the rotation of the planet around its $+Z$ axis, R_Z . The planet orientation at the current time is provided to FNPAAG, and the predictor updates the planet rotation by a delta-rotation computed from the user-provided planet rotation rate, Ω , as

$$\Delta R = R_Z(\Omega \Delta t). \quad (5)$$

6) Atmosphere Model:

The atmosphere model computes the local atmospheric density as a function of planetodetic altitude. It is based on a curve fit of the form

$$\ln \rho = \frac{c_1 + c_3 h + c_5 h^2 + c_7 h^3 + c_9 h^4}{1 + c_2 h + c_4 h^2 + c_6 h^3 + c_8 h^4}, \quad (6)$$

where $c = [c_1, c_2, \dots, c_9]$ are coefficients and h is planetodetic altitude in units of km. For efficiency, it is actually computed using Horner's method as

$$\ln \rho = \frac{c_1 + h(c_3 + h(c_5 + h(c_7 + hc_9)))}{1 + h(c_2 + h(c_4 + h(c_6 + hc_8)))}. \quad (7)$$

7) Aerodynamics Model:

The aerodynamics model is a symmetric formulation in the missile frame. The user provides tables for the missile frame C_L and C_D as functions of α_t . The coefficients are linearly interpolated. The coefficients are rotated from the missile frame to the freestream-relative velocity frame in the equations of motion.

8) State Vector:

The state vector consists of the radius, longitude, declination, planet-relative velocity magnitude, planet-relative planetocentric flight path angle, and planet-relative planetocentric azimuth. The state vector

quantities are in the Planetocentric North East Down (PCNED) coordinate frame, illustrated in Fig. 38 and Fig. 39 in the Appendix.

The equations of motion assume a spherical planet shape. Only the atmosphere model uses an bi-axial ellipsoid planet model. Both dimensional and nondimensional representations of the state vector are used at various points throughout the algorithm. To nondimensionalize a state vector, the quantities are divided by the following reference scales:

$$\begin{aligned} \text{time scale} &= \sqrt{\frac{R_0}{g_0}}, \\ \text{length scale} &= R_0, \\ \text{velocity scale} &= \sqrt{R_0 g_0}, \\ \text{acceleration scale} &= g_0, \end{aligned} \tag{8}$$

where R_0 is the equatorial radius of the planet and g_0 is the gravitational acceleration at the equatorial radius, which can be computed as

$$g_0 = \frac{\mu}{R_0^2}, \tag{9}$$

where μ is the gravitational parameter of the planet. Angles are already nondimensional.

C. Genesis Guidance Simulation

The flight mechanics simulation software framework, Genesis [13], was utilized to simulate the Earth aerocapture mission designs. The simulation starts from Entry Interface (EI)-10 minutes and ends when the vehicle exits the atmosphere. In this section, we detail the models and assumptions used in the Genesis aerocapture simulation.

IV. Results

The FNPAG algorithm with inclination targeting was utilized in a Geostationary Transfer Orbit (GTO) mission design, implemented in the Genesis software framework, to assess the guidance performance for an Earth-based aerocapture demonstration. A sensitivity analysis was conducted for each FNPAG hyperparameter to assess the impact of guidance parameters selection on performance and to determine the best parameter selection for the GTO mission design. Table 1 details the vehicle parameters, entry parameters, and target parameters for the baseline GTO mission used in this work, where the atmospheric entry interface (AEI) point is defined as the state at 300 km geodetic altitude. For consistency and targeting purposes, the trajectory simulation is initialized at the point 10 minutes prior to EI (EI-10). See [15] for additional information on the vehicle and mission design, as well as Monte Carlo results for the lunar return mission designs.

Table 1 Vehicle and mission design parameters.

Parameter	AEI Value	EI Value
Mass	180 kg	
L/D	0.26	
Inertial Velocity	10.1 km/s	10.3 km/s
Geodetic Altitude	300 km	125 km
FPA	−9.91 deg	−5.06 deg
Inclination Target	28.5 deg	
Target Apoapsis Altitude	500 km	

The Earth simulation setup uses the Earth GRAM atmosphere model, with the MET Model as the Thermosphere model. All atmosphere parameters and Earth parameters for the Genesis simulations are shown in Table 2.

Table 2 Earth simulation settings.

Parameter	Value
Equatorial Radius	6378137 m
Polar Radius	6356752 m
J2	1.082E-3
Rotation Rate	7.292E-5 rad/s
Gravitational Constant	3.986E14 m ³ /s ²
Atmosphere Model	Earth GRAM Suite v2.1
Thermosphere Model	MET Model
Daily 10.7-cm flux	120 sfu
Mean 10.7-cm flux	120 sfu
Geomagnetic Index	16

The FNPAG parameters are defined in Table 3. Before phase 1, an initial bank angle of 0 degrees is commanded, then a phase 1 bank angle magnitude of 15 deg and a phase 2 bank angle of 90 degrees is used. The guidance and estimator rates are defined and a deterministic number of bank reversals is specified. Five reversals are chosen to ensure the desired lateral error tolerance of 0.1 deg is met.

Table 3 FNPAG parameters.

Parameter	Value
Initial Bank Angle Magnitude	0 deg
Phase 1 Bank Angle Magnitude	15 deg
Phase 2 Bank Angle Magnitude	90 deg
Guidance Rate	2 Hz
Guidance Trigger	0.1 G's
Estimator Time Constant	5 s
Lateral Error Tolerance	0.1 deg
Number of Bank Reversals	5

Fig. 5 and Fig. 6 show the nominal trajectory produced by guiding the spacecraft with FNPAG, using the default set of parameters and initial conditions. Five bank reversal are performed, with the first, fourth, and fifth reversals going through lift down and the other two reversals going through lift up. Around 50 seconds are spent in phase 1 before switching to phase 2 in the FNPAG algorithm. Additionally, the inclination angle error is decreasing at each timestep and flips sign when a reversal occurs. Lastly, the altitude of apoapsis is converging steadily to the 500 km target altitude.

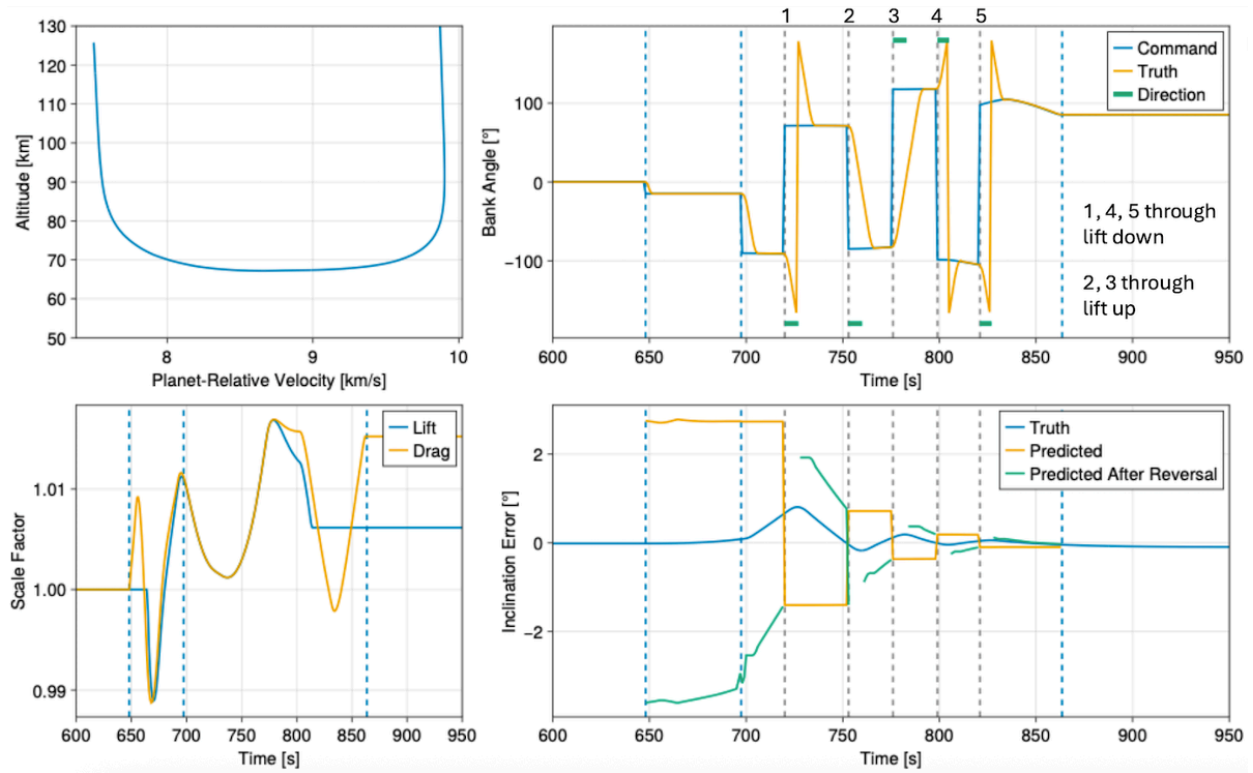


Fig. 5 Nominal results for the FNPAG algorithm for the GTO case.

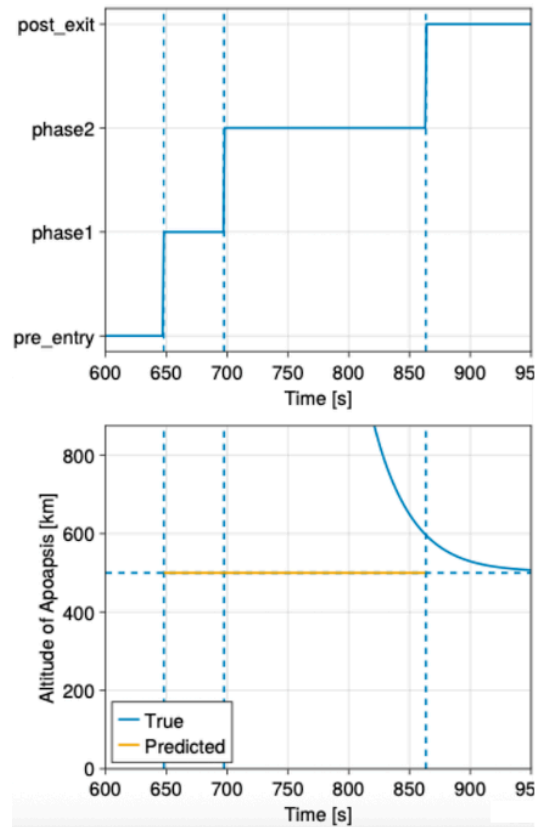


Fig. 6 Nominal results for the FNPAG algorithm for the GTO case.

A. Sensitivity Studies

Each analysis consists of 3000 Monte Carlo (MC) runs for the GTO case, with varying guidance parameters. The number of reversals, guidance rate, gravity trigger, estimator time constant, initial bank angle, and bank angle 2 parameters were changed over a set of MC runs to analyze the effect of each parameter. The 3σ , where σ is the distribution's standard deviation, parameter dispersion settings are shown in Table 4. The state, maneuver, aerodynamics, mass, and atmospheric density are perturbed using expected 3σ values for a real demonstration scenario.

Table 4 Monte Carlo dispersion settings.

Parameter	Dispersion (3σ)
Position	1 km
Velocity	0.2 m/s
Atmosphere	2.0
Maneuver Magnitude	$0.1 + 1\%$
Maneuver Direction	1 deg
Axial Aerodynamics Force Multiplier/Adder	1
Normal Aerodynamics Force Multiplier/Adder	1
Side Aerodynamics Force Multiplier/Adder	1
Mass Multiplier	$\pm 10\%$

1) Baseline:

The baseline Monte Carlo analysis uses the parameters and vehicle settings in Table 1, Table 2, and Table 3 with the dispersions specified in Table 4. The 3000 solutions are shown in the following figures. In Fig. 7, the 500 km uncorrected apoapsis altitude is actively targeted by the FNPAG algorithm, while the 0 km uncorrected periapsis altitude is a general reference for the desired final periapsis. Most of the 3000 solutions are within ± 50 km of the target apoapsis altitude and the few outliers represent density gradient cases that cannot be recovered by the FNPAG guidance algorithm.

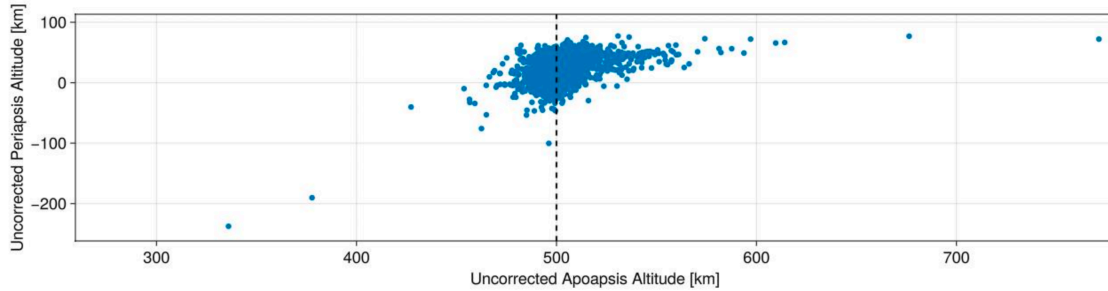


Fig. 7 Altitude targeting errors for the baseline GTO case.

Fig. 8 shows the tradeoff between phase 1 duration and the inertial flight path angle (FPA) at EI. As the magnitude of the entry FPA decreases, the phase 1 duration generally decreases. This behavior is expected since steeper FPAs result in shorter flight times and a quicker switch to phase 2, as an effect.

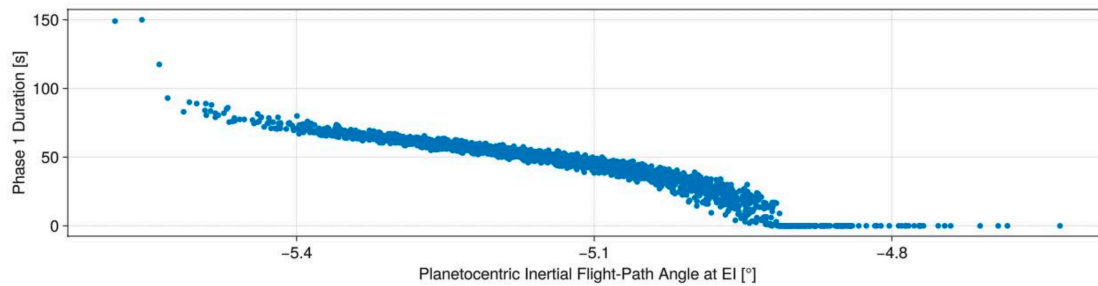


Fig. 8 Phase 1 duration vs. inertial flight path angle for the baseline GTO case.

The cumulative density functions (CDFs) in Fig. 9 show the CDFs for in-plane, periapsis raise, and apoapsis clean up delta V. Both the in-plane and apoapsis clean up delta Vs have most cases that are very close in value, where the CDF quickly reaches approximately 1. The periapsis raise delta V has a larger variation among runs, with most cases ranging from 125 m/s to 150 m/s.

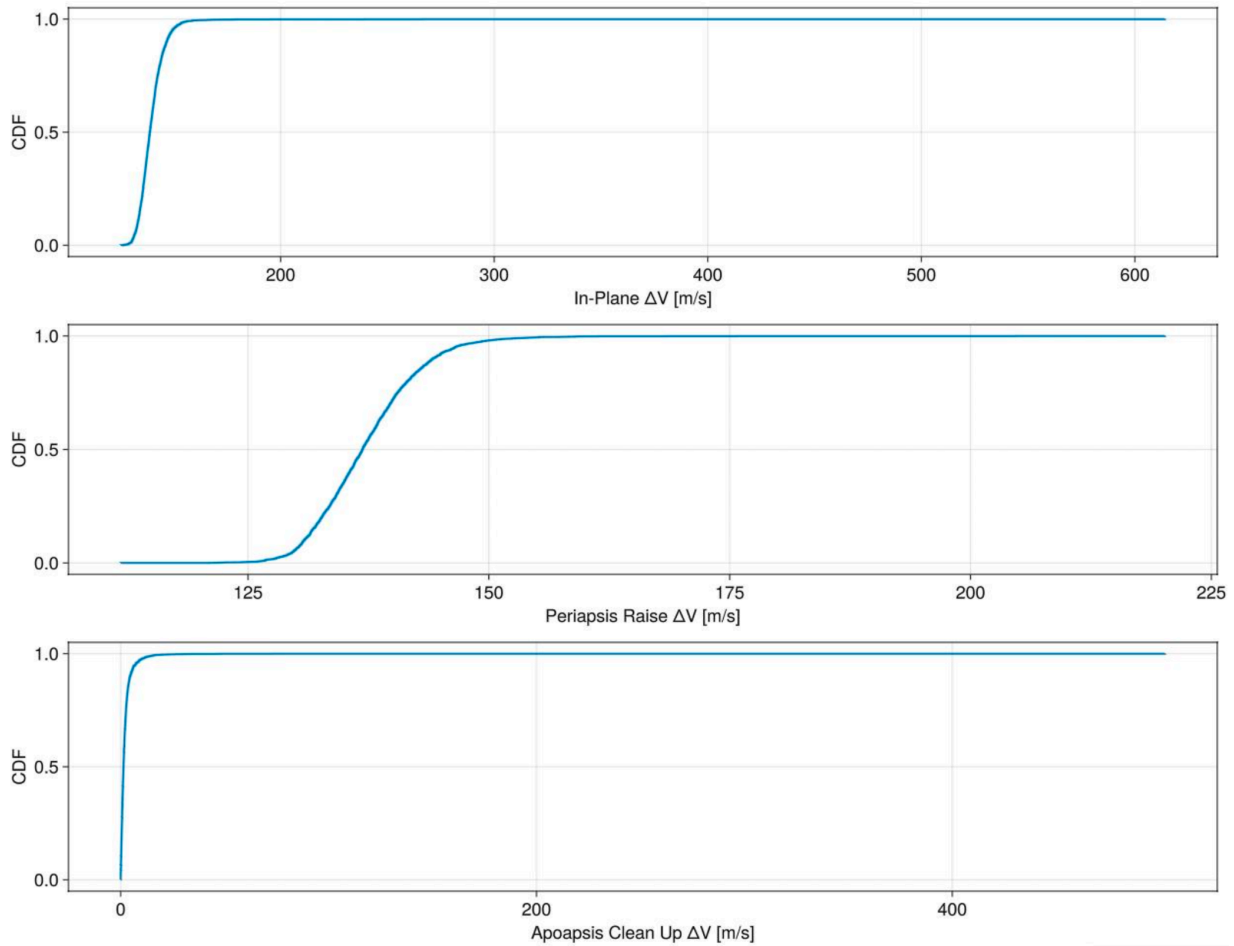


Fig. 9 Delta velocity, ΔV , cumulative density functions (CDFs) for the baseline GTO case.

Fig. 10 show how the in-plane delta V varies with entry FPA, periapsis altitude vs. the periapsis delta V, and apoapsis altitude vs. the apoapsis clean up delta V. The in-plane delta V spikes up when a high magnitude FPA is used and is relatively constant for the other entry FPAs. There is one outlier case where in-plane delta V is over 600 m/s at a low magnitude FPA. There is an approximately linear relationship between the periapsis raise delta V and the periapsis altitude reached at the end of the trajectory, as expected. Apoapsis clean up is similar, where the linear relationship switches when under or above the target apoapsis altitude. Since FNPAG is actively targeting the 500 km apoapsis, this is an expected result.

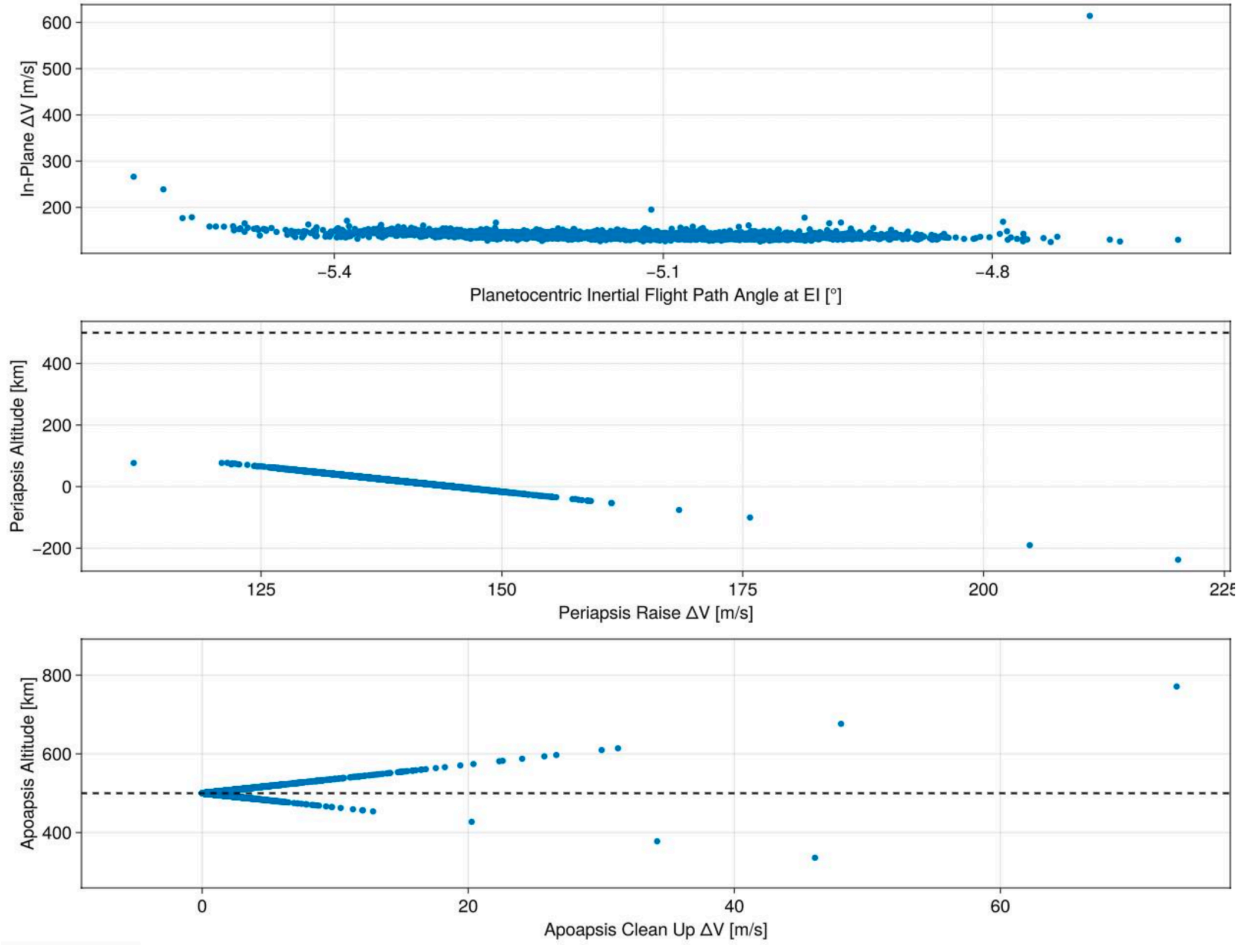


Fig. 10 Delta velocity, ΔV , plots for the baseline GTO case.

2) Number of Reversals:

To analyze the impact of the user-specified number of bank reversals on the guidance algorithm performance, the 3000 MC runs were completed for 0 reversals, 3 reversals, and 4 reversals, compared to the baseline case of 5 reversals. Eq. (1) shows that increasing the number of bank reversals decreases the lateral parameter K . In the 0 reversal case, the lateral logic is not used and only longitudinal targeting is considered by FNPAG. In Fig. 11, the 0 reversal case has the most accurate targeting, with the accuracy decreasing as the number of reversals decreases. This behavior is expected since performing reversals requires a balancing of longitudinal and lateral targeting, where the 0 reversal case is only targeting the apoapsis altitude. While the 3 and 4 reversal cases had a larger range of apoapsis altitude errors, the 5 reversal case has more apoapsis altitude error cases around 100 km greater than the apoapsis altitude target.

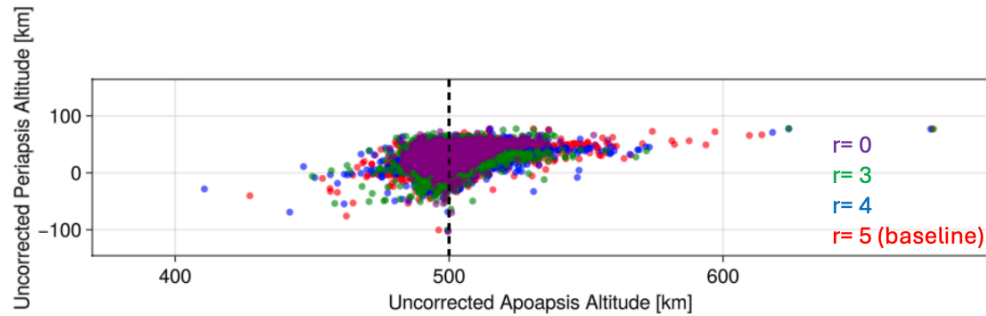


Fig. 11 Altitude targeting errors for the bank reversal cases.

In Fig. 12, it is evident that the the phase 1 duration does not significantly change based on the number of bank reversals. Since bank reversals only occur in phase 2 of the guidance algorithm, the phase 1 duration is not affected.

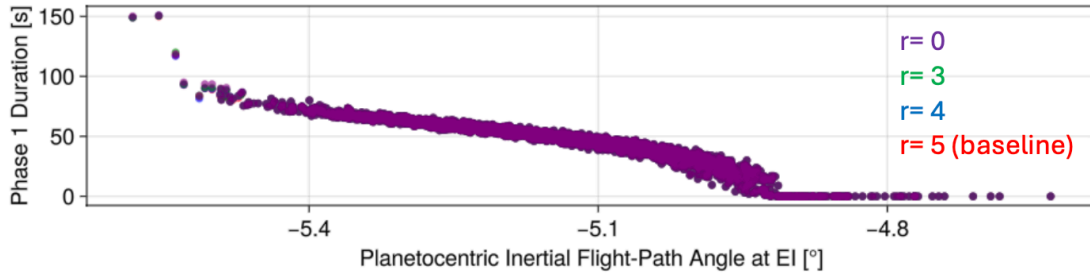


Fig. 12 Phase 1 duration vs. inertial flight path angle for the bank reversal cases.

The CDF delta V plots in Fig. 13 show that the 0 reversal case bounds the minimum in-plane, periapsis, and apoapsis clean up delta Vs. Interestingly, the 5 reversal case has more lower delta V for in-plane and periapsis raise delta V, when compared to the 3-4 reversal cases. This result reveals that prioritizing the lateral channel, with more bank reversals, can improve delta V over the trajectory.

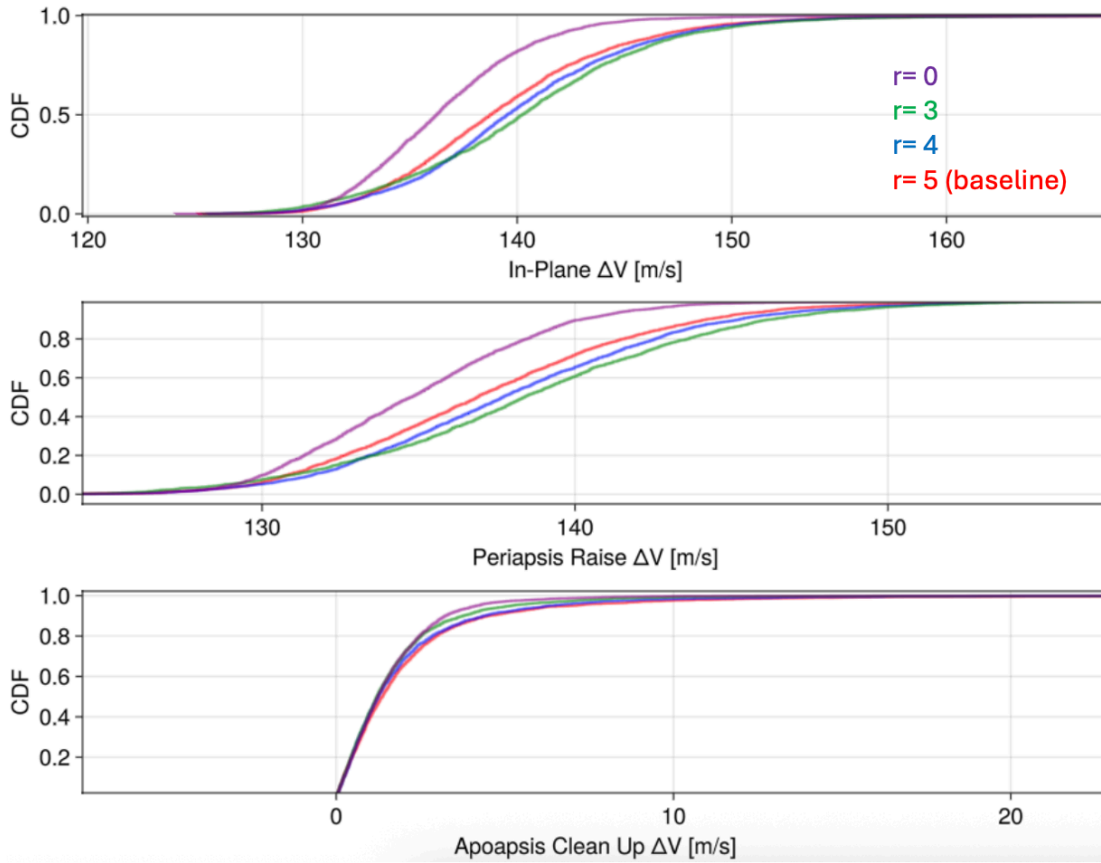


Fig. 13 Delta velocity, ΔV , cumulative density functions (CDFs) for the bank reversal cases.

In Fig. 14, a higher number of large in-plane delta V cases occur when the number of bank reversals is increased. These higher delta V cases are expected since performing bank reversals can result in in-plane errors which need corrections using delta V. In contrast, the outlier high periapsis raise delta V cases include the zero reversal case using slightly higher delta V, at low periapsis altitudes. Finally, the zero reversal case dominates for low apoapsis clean up delta V. The reversal cases have more outlier cases of higher apoapsis clean up delta Vs, as the targeted apoapsis altitude of 500 km is either overshoot or undershot.

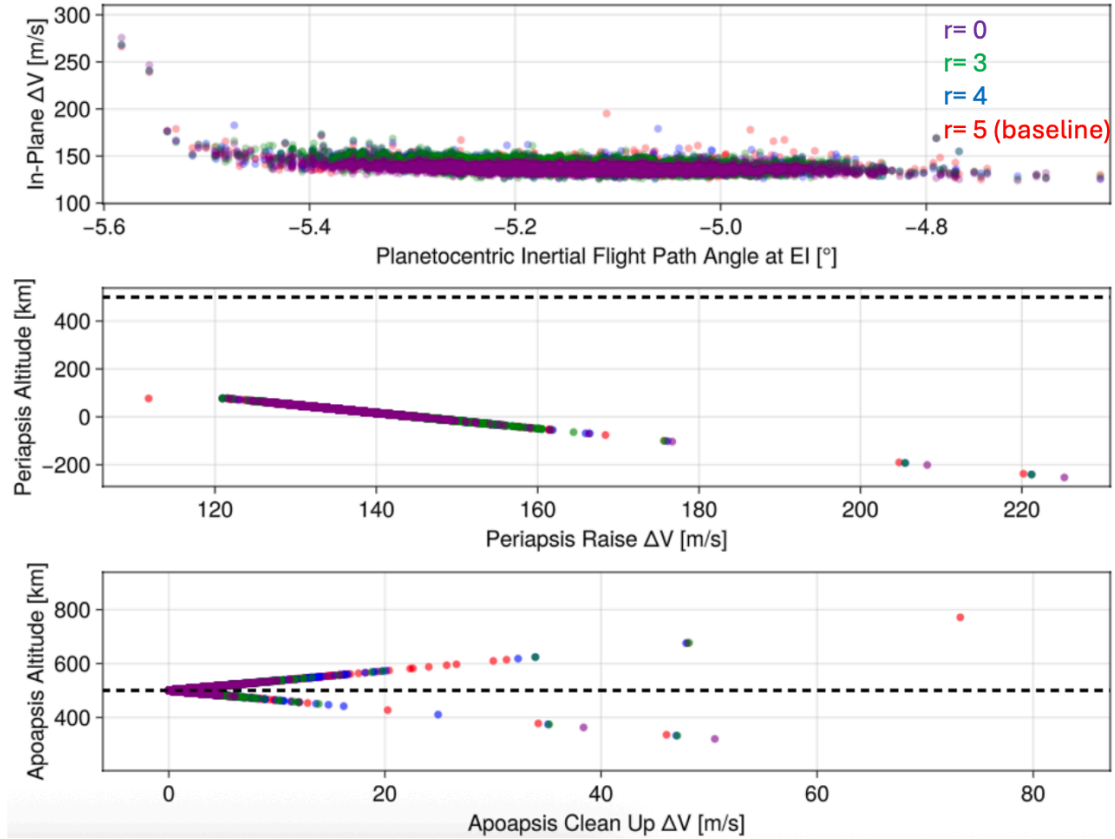


Fig. 14 Delta velocity, ΔV , plots for the bank reversal cases.

Table 5 shows the summary table for the total delta V and apoapsis altitude error. The zero reversal case has both the lowest delta V and the smallest apoapsis altitude error. As in the previous figures, the 5 reversal case has a lower mean delta V and the 99 percentile delta Vs are close for all reversal cases. Both the mean and 99 percentile apoapsis altitude errors increase monotonically as the number of bank reversals increases. When selecting the number of bank reversals parameter, there exists a tradeoff between lateral, or inclination, and longitudinal, or apoapsis altitude, targeting accuracy. Delta V, instead, is roughly constant, but could be reduced for a non-zero number of reversals, as the number of bank reversals increases.

Table 5 Delta V and apoapsis altitude error for the number of bank reversals.

Bank Reversals	Mean Delta V [m/s]	99%-tile Delta V [m/s]	Mean Apoapsis Altitude Error [km]	99%-tile Apoapsis Altitude Error [km]
0	136.7	149.0	5.858	26.78
3	140.5	157.3	6.376	34.46
4	140.2	155.9	7.265	46.97
5*	139.7	156.0	8.575	53.43

* Baseline value.

3) Guidance Rate:

Guidance rates of 1 Hz and 5 Hz were compared with the 2 Hz baseline guidance rate to assess the necessity of frequently calling the FNPAG guidance algorithm. In Fig. 15, increasing the frequency of calling guidance retracts some of the outlier large apoapsis altitude error cases. The 1 Hz guidance rate cases are the most concentrated around the apoapsis altitude target.

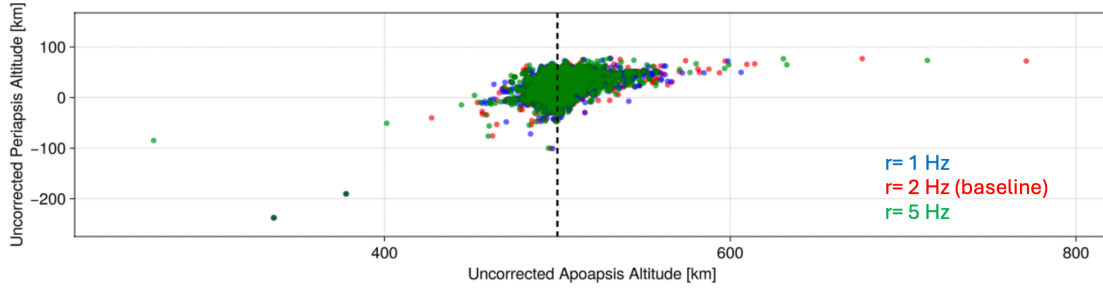


Fig. 15 Altitude targeting errors for the guidance rate cases

Similar to the bank reversal parameter, the guidance call rate does not affect the phase 1 duration since the duration of phase 1 does not depend on the rate at which guidance is called. All cases generally decrease in phase 1 duration as the planetocentric inertial FPA decreases in magnitude.

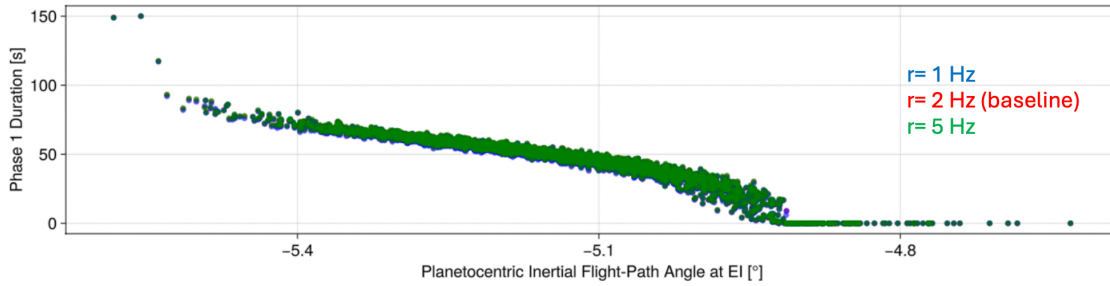


Fig. 16 Phase 1 duration vs. inertial flight path angle for the guidance rate cases.

From the CDFs in Fig. 17, the differences in delta V between each case are very slight. For the in-plane and periapsis raise delta V, the 5 Hz case results in the lowest delta V.

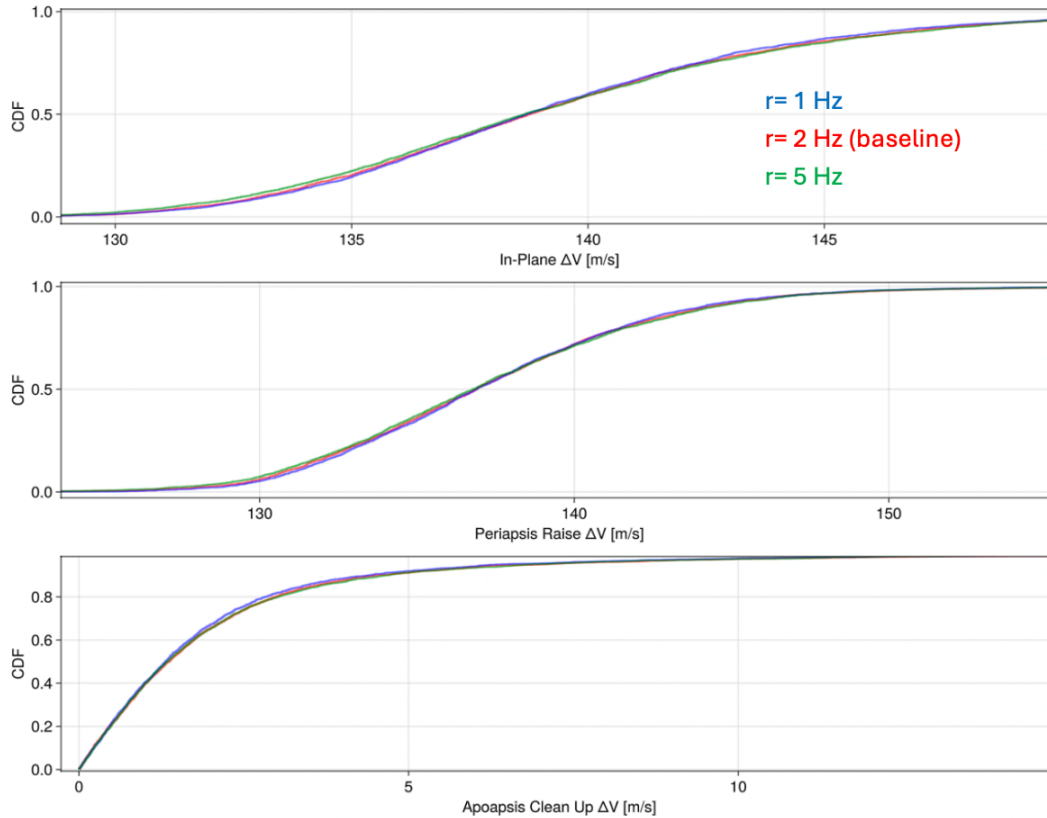


Fig. 17 Delta velocity, ΔV , cumulative density functions (CDFs) for the guidance rate cases.

In Fig. 18, the higher delta V outlier cases for the 2 Hz and 5 Hz guidance call rates are reduced when the guidance call rate is reduced to 1 Hz. At the lowest guidance call rate of 5 Hz, in-plane delta Vs can reach up to 400 m/s, which may put a fuel-limited mission more at risk.

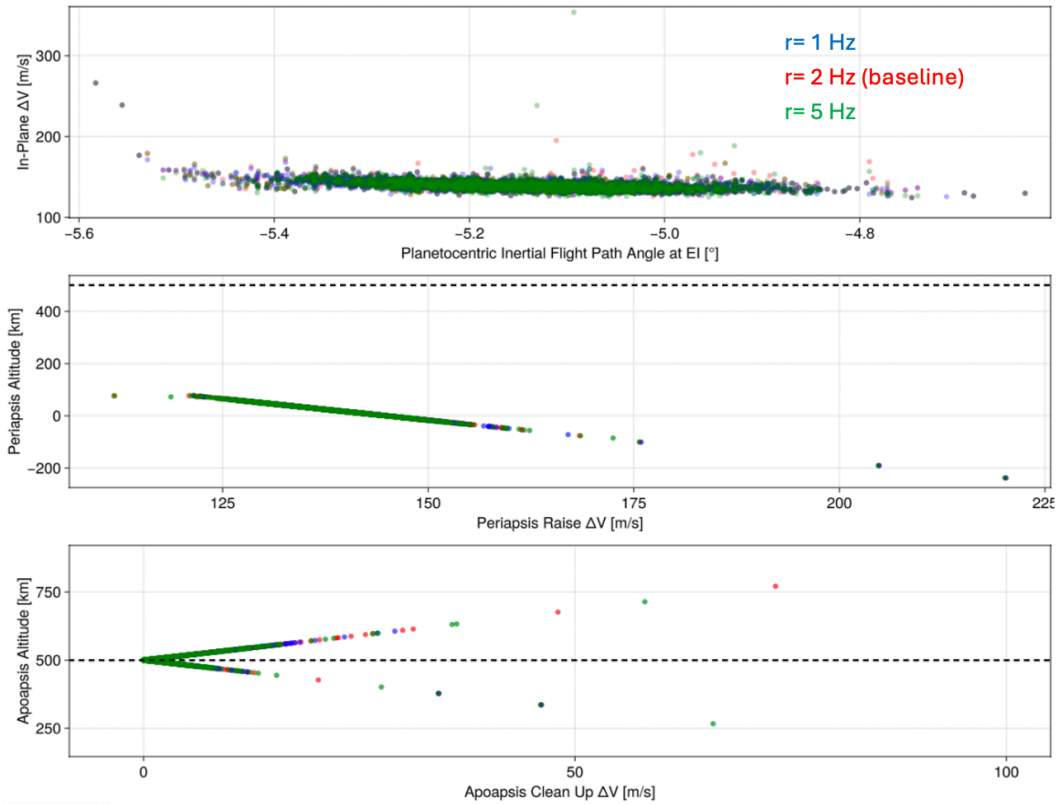


Fig. 18 Delta velocity, ΔV , plots for the guidance rate cases.

The delta V and apoapsis altitude targeting results are summarized in Table 6 for the guidance rate parameter. An additional case, 0.5 Hz, is included in the table to provide a wider bound of guidance rates. Even with the addition of the 0.5 Hz case, the 1 Hz guidance rate dominates in both delta V and apoapsis altitude error. The delta Vs are very close in value for all cases while the apoapsis altitude errors vary by more than 1 km. The lower apoapsis altitude errors for the 1 Hz case may indicate that calling FNPAG too frequently degrades targeting performance.

Table 6 Delta V and apoapsis altitude error for the guidance rate.

Guidance Rate [Hz]	Mean Delta V [m/s]	99%-tile Delta V [m/s]	Mean Apoapsis Altitude Error [km]	99%-tile Apoapsis Altitude Error [km]
0.5	139.4	155.2	7.579	48.35
1	139.4	155.1	7.386	47.59
2*	139.7	156.0	8.575	53.43
5	139.7	156.8	8.859	48.35

* Baseline value.

4) Gravity Trigger:

The gravity trigger was reduced to $0.01g_e$ and increased to $0.5g_e$, compared to the baseline of $0.1g_e$ to analyze the effect of altering the percentage of Earth's gravity to trigger the guidance algorithm. The gravity trigger sets the estimators' threshold, shown in Fig. 3 and Fig. 4. From the targeting errors in Fig. 19 increasing the gravity trigger threshold reduces the periapsis altitude corridor and increases the apoapsis altitude error. Outlier large apoapsis altitude error cases occur for each gravity load trigger.

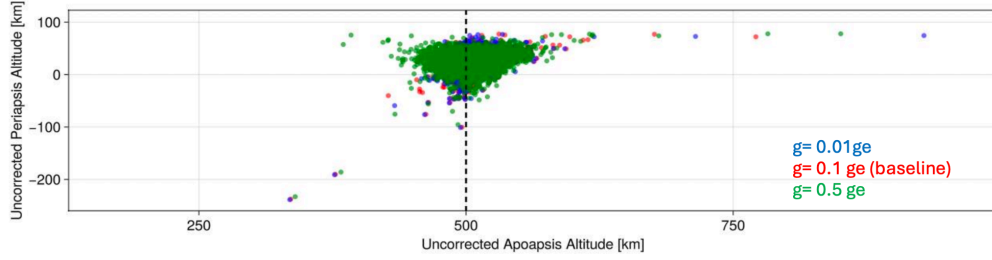


Fig. 19 Altitude targeting errors for the gravity rate trigger cases.

As expected, the phase 1 duration is directly dependant on the gravity load trigger. As the gravity load trigger increases, the phase 1 duration for varying inertial FPAs decreases. This result is expected since the pre-entry phase would last for longer if $a_{\text{threshold}}$ is increased. Once a FPA of about -4.9 deg is reached, all cases collapse to the skip phase 1 case. This transition happens at a higher magnitude FPA for the $0.5g_e$ case.

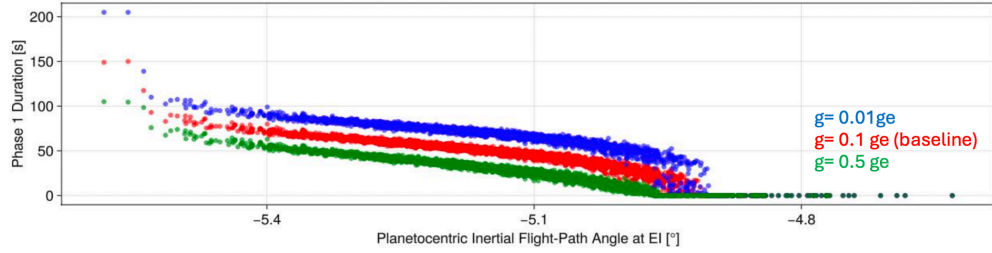


Fig. 20 Phase 1 duration vs. inertial flight path angle for the gravity rate trigger cases.

The gravity load trigger also significantly changes the delta V in Fig. 21. A smaller gravity trigger value reduces the in-plane, periapsis raise, and apoapsis clean up delta Vs, with the large gravity load trigger of $0.5g_e$ showing a significant increase in in-plane and apoapsis clean up delta Vs. Since the gravity load trigger affects the phase 1 and phase 2 durations, the predictor corrector process would be called for a longer or shorter time based on this parameter.

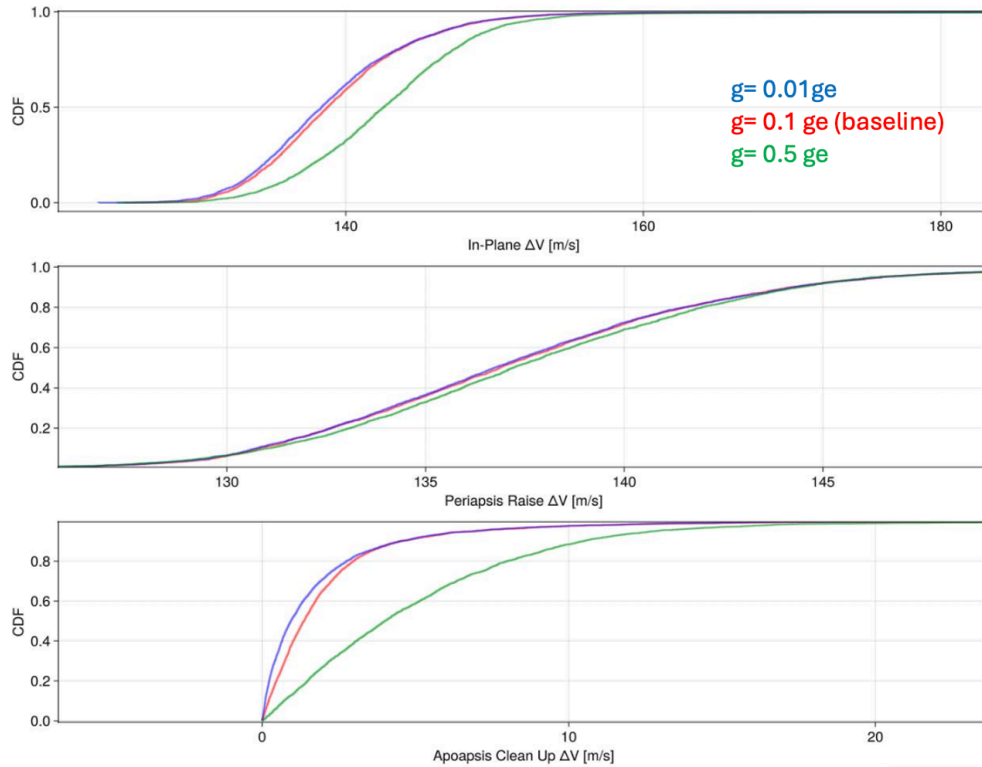


Fig. 21 Delta velocity, ΔV , cumulative density functions (CDFs) for the gravity rate trigger cases.

The delta velocities for the gravity rate trigger, in Fig. 22, are relatively close in value between all cases. The larger gravity load trigger has more large delta V outlier cases at low magnitude FPAs.

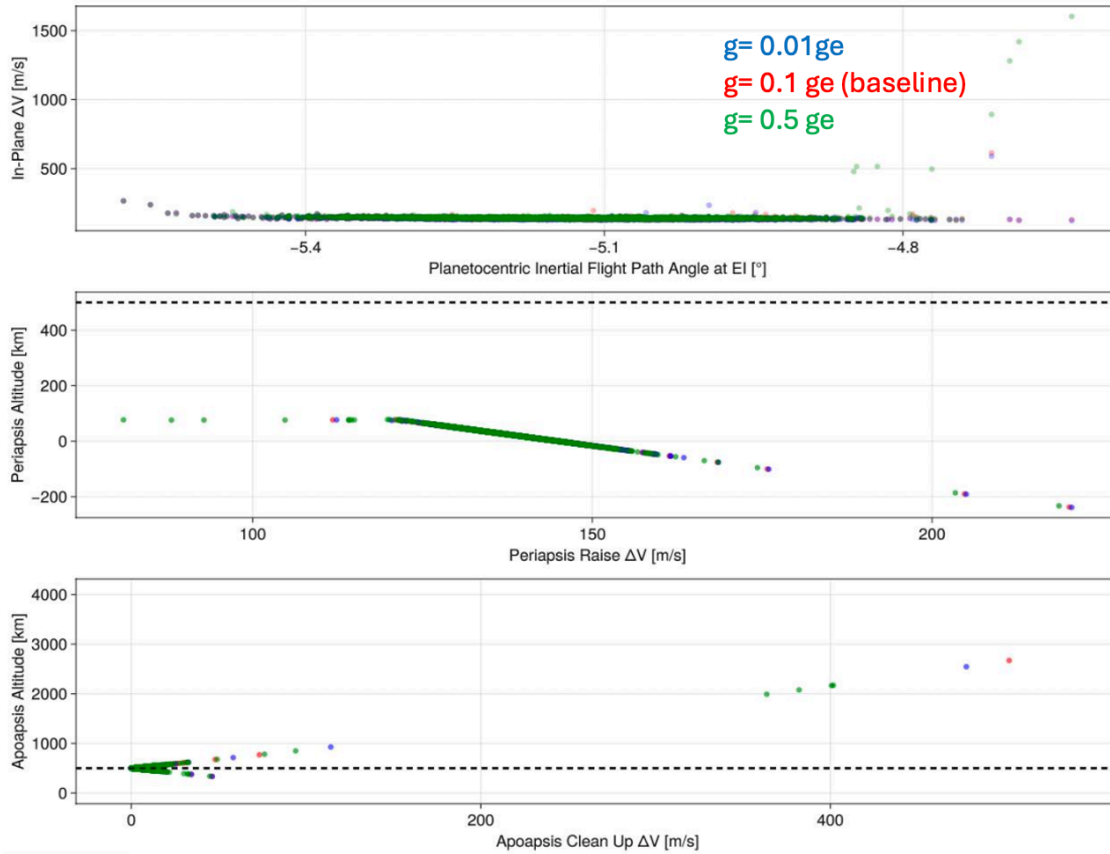


Fig. 22 Delta velocity, ΔV , plots for the gravity rate trigger cases.

In Table 7, the lowest gravity rate trigger, $0.01g_e$, has the smallest delta V and apoapsis altitude error. For triggers less than $0.1g_e$, there is not a significant effect on delta V, but apoapsis altitude error can change by more than a few kilometers. Overall, using too high of a gravity rate trigger can increase mean delta V and significantly increase the mean apoapsis altitude error, by over 20 km.

Table 7 Delta V and apoapsis altitude error for the gravity trigger.

Gravity Trigger	Mean Delta V [m/s]	99%-tile Delta V [m/s]	Mean Apoapsis Altitude Error [km]	99%-tile Apoapsis Altitude Error [km]
$0.01g_e$	139.3	155.5	7.607	47.97
$0.1g_e^*$	139.7	156.0	8.575	53.43
$0.5g_e$	144.7	159.1	30.37	72.67

* Baseline value.

5) Estimator Time Constant:

The time constant used for calling the estimator in FNPAG was adjusted from the 5 second baseline case to determine the effect on delta V and apoapsis altitude error. Eq. (4) shows this user-specified filter time constant, which is used to compute the filter gain β . Generally, increasing τ increases the gain for the filtered scale factor and subsequently decreases the gain for the unfiltered scale factor. In Fig. 23, outlier high apoapsis altitude errors exist for all time constant values, with more outliers existing for the 5 second baseline case.

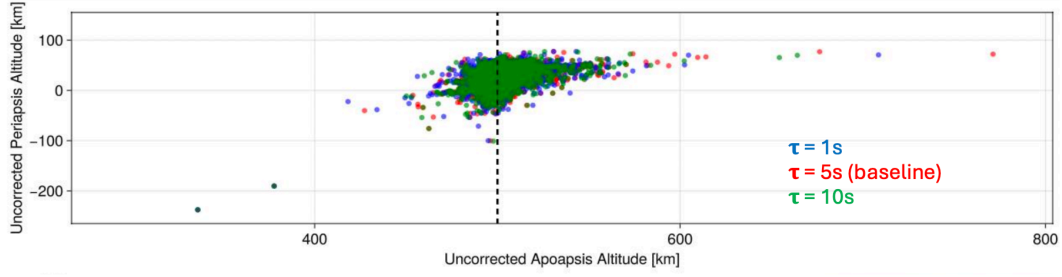


Fig. 23 Altitude targeting errors for the estimator time constant cases.

The phase 1 duration between cases roughly matches for all cases except for around the threshold of skipping phase 1, from Fig. 24. The larger time constants have a narrower range of phase 1 durations around the flight path angle of -5 deg.

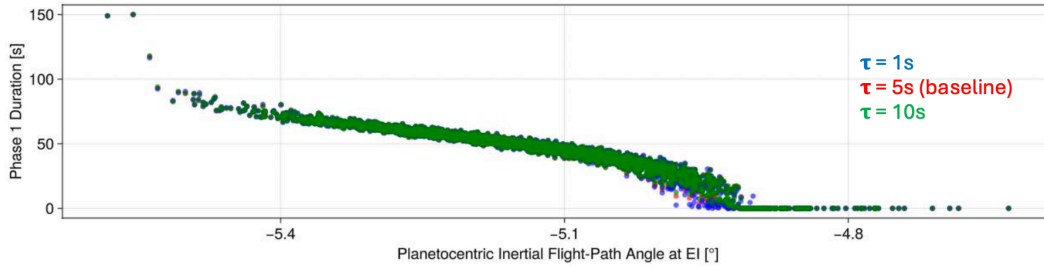


Fig. 24 Phase 1 duration vs. inertial flight path angle for the estimator time constant cases.

Similar to the previous figure, Fig. 25 shows that the delta Vs are all very close for varying estimator values. There is a slight reduction in delta V for smaller time constants.

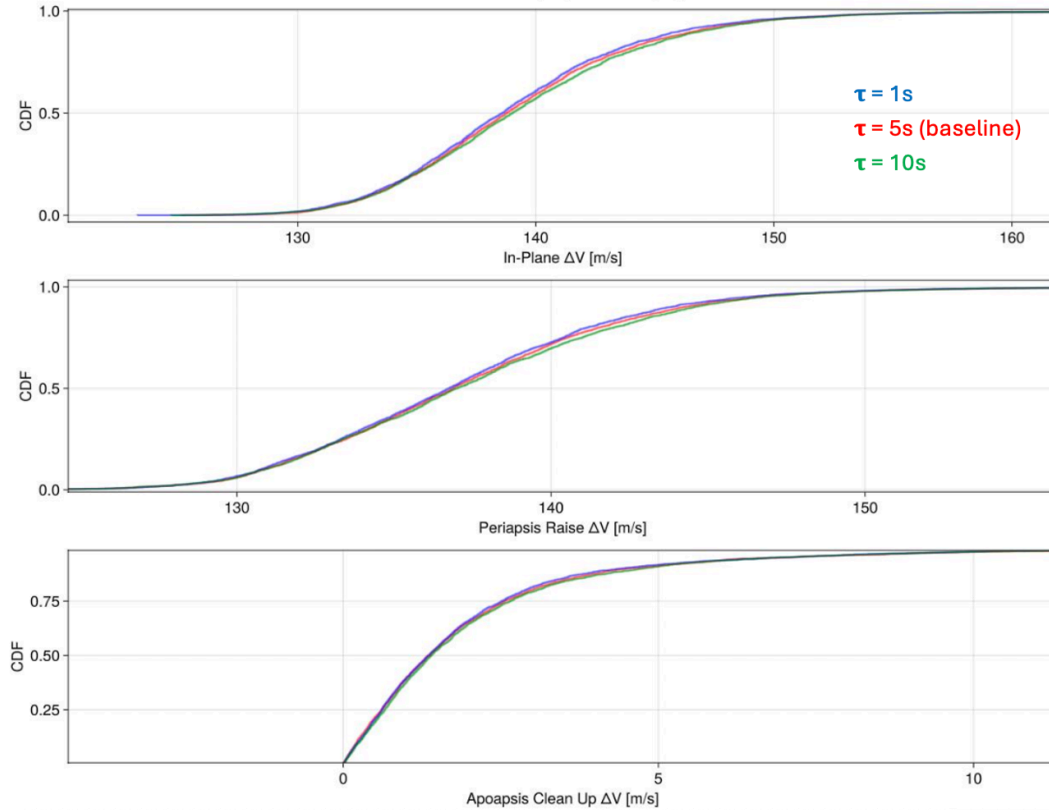


Fig. 25 Delta velocity, ΔV , cumulative density functions (CDFs) for the estimator time constant cases.

The outliers in Fig. 26 make up the largest differences between each estimator time constant. As in Fig. 23, the 5 second baseline case has a larger number of outlier high delta V values but some of the highest delta Vs include the 10 second and 1 second cases.

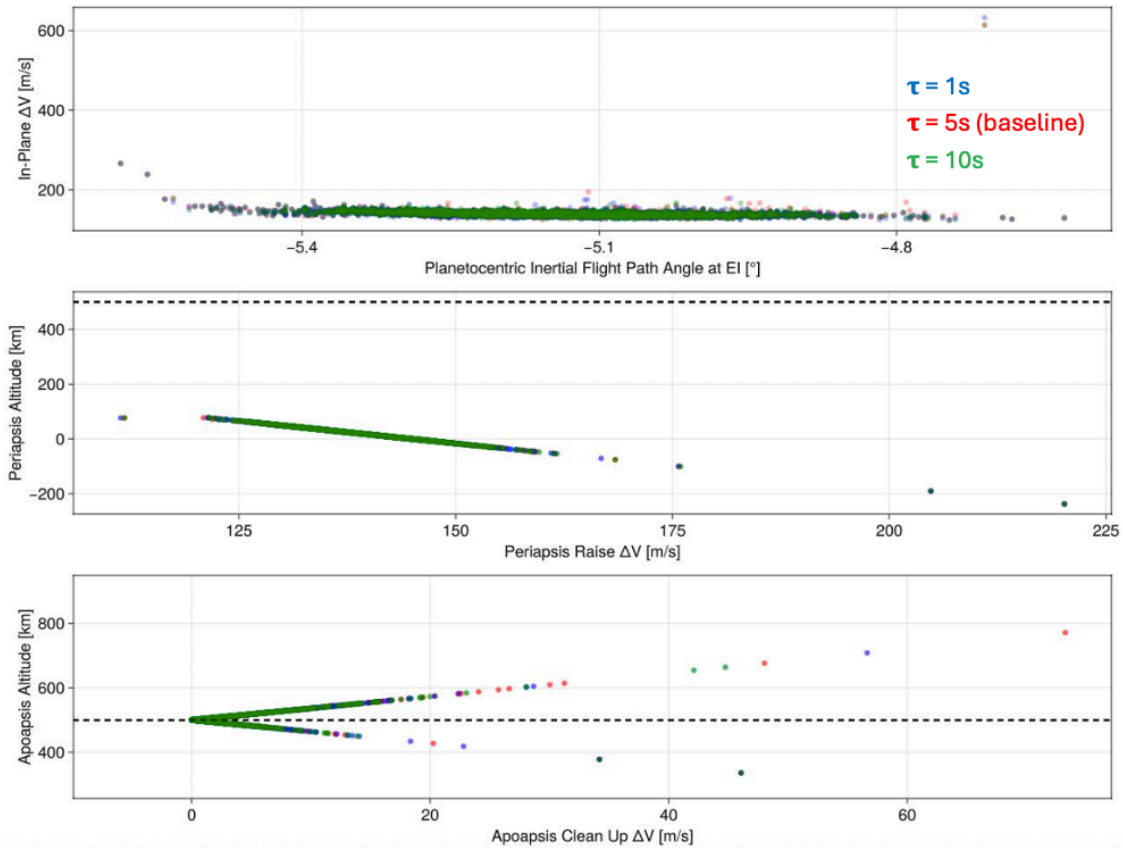


Fig. 26 Delta velocity, ΔV , plots for the estimator time constant cases.

From Table 8, the delta Vs for all cases are very close in value and the mean apoapsis altitude errors are less than 1 km. As seen in the previous figures, the 99 percentile errors for the 5 second case are slightly larger than the other cases. For the 1 second vs. the 10 second cases, there is a tradeoff of a low 99 percentile delta V for the 10 second time constant and a low 99 percentile apoapsis altitude error for the 1 second case.

Table 8 Delta V and apoapsis altitude error for the estimator time constant.

Estimator Time Constant [s]	Mean Delta V [m/s]	99%-tile Delta V [m/s]	Mean Apoapsis Altitude Error [km]	99%-tile Apoapsis Altitude Error [km]
1	139.4	156.6	8.332	48.41
5*	139.7	156.0	8.575	53.43
10	139.9	155.6	8.629	49.96

* Baseline value.

6) Initial Bank Angle:

The initial bank angle was varied to determine the sensitivity of the trajectory from this initial condition. This initial bank angle is the bank angle commanded during pre-entry, before phase 1 is reached. Based on Fig. 27, the outlier cases with high apoapsis altitude errors, that overshoot the apoapsis altitude target, primarily occur for the 0 deg case. The largest undershoot errors occur the most for the 165 deg case. Therefore, as expected, the edge cases can bias the trajectory towards overshooting or undershooting the longitudinal target.

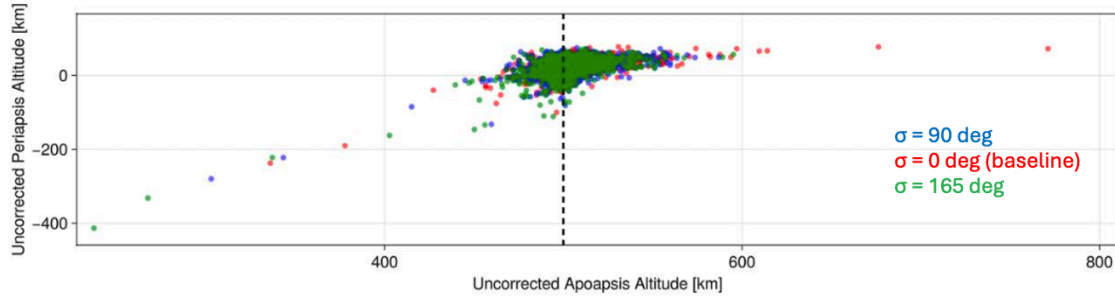


Fig. 27 Altitude targeting errors for the initial bank angle.

Changing the initial bank angle shifts the phase 1 duration vs. the inertial FPA up or down, and slightly left or right, in Fig. 28. A higher initial bank angle increases the phase 1 duration likely due to the high bank angle causing a more lofted trajectory, where the vehicle spends more time in phase 1.

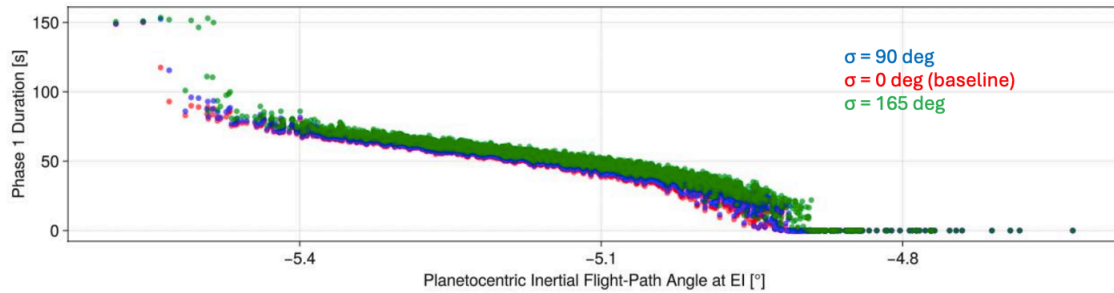


Fig. 28 Phase 1 duration vs. inertial flight path angle for the initial bank angle.

The delta V CDFs in Fig. 29 show the 165 deg case using the most delta V for the in-plane and periapsis raise, potentially due to a longer phase 1. Both the 0 deg and 90 deg cases are very close in delta V.

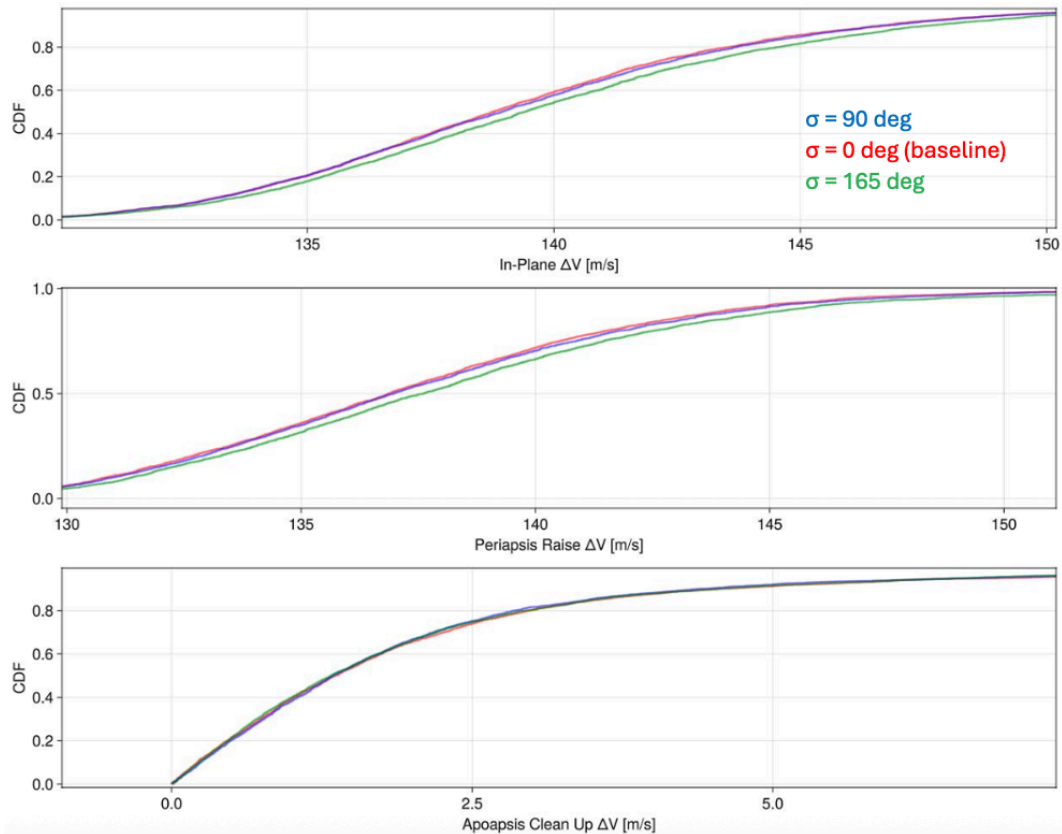


Fig. 29 Delta velocity, ΔV , cumulative density functions (CDFs) for the initial bank angle.

From Fig. 30, the 165 deg case uses more in-plane delta V for high magnitude FPAs and the 0 deg case has the largest in-plane delta V errors for low magnitude FPAs. Similar to Fig. 27, the 0 deg baseline case has the largest apoapsis clean up delta Vs for overshooting the target and the 165 deg case has the largest delta Vs for undershooting the target.

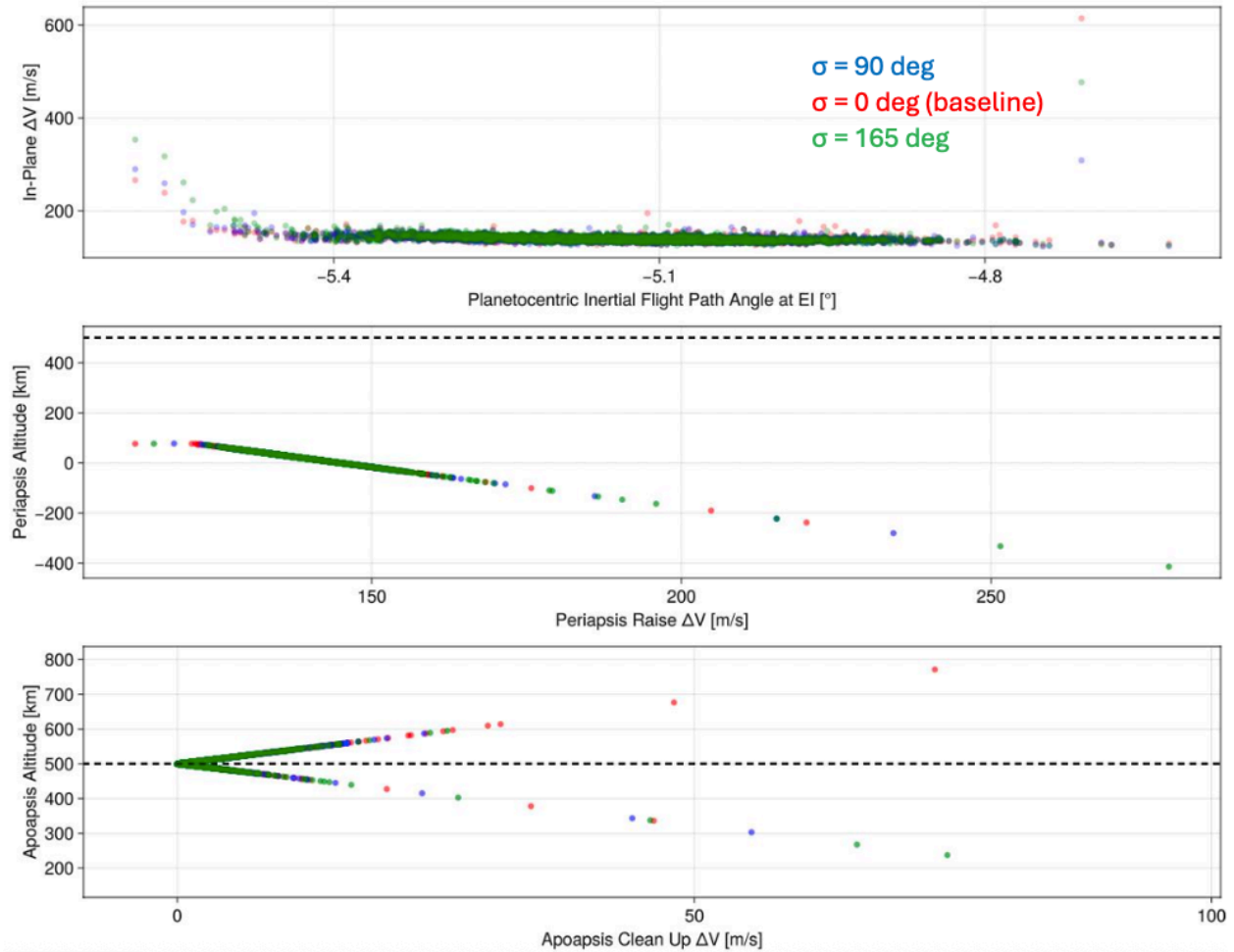


Fig. 30 Delta velocity, ΔV , plots for the initial bank angle.

The overall delta V and apoapsis altitude error metrics in Table 9 show the 0 deg case performing best for delta V, tying with the 90 deg case for mean delta V. Additionally, the 90 deg case has the lowest mean apoapsis altitude error and the 165 deg case has the lowest 99 percentile apoapsis altitude error.

Table 9 Delta V and apoapsis altitude error for the initial bank angle.

Initial Bank Angle [deg]	Mean Delta V [m/s]	99%-tile Delta V [m/s]	Mean Apoapsis Altitude Error [km]	99%-tile Apoapsis Altitude Error [km]
0*	139.7	156.0	8.575	53.43
90	139.7	156.2	7.731	46.81
165	140.5	161.0	8.041	43.90

* Baseline value.

7) Bank Angle 2:

The bank angle for phase 2 was varied to minimize delta V and the apoapsis altitude error. Adjusting the phase 2 bank angle significantly alters the apoapsis altitude error, contracting the overall error as bank angle 2 increases. Conversely, increasing bank angle 2 increases the number of outlier cases with large apoapsis altitude errors. These extreme cases may stem from operating at the edge of the corridor.

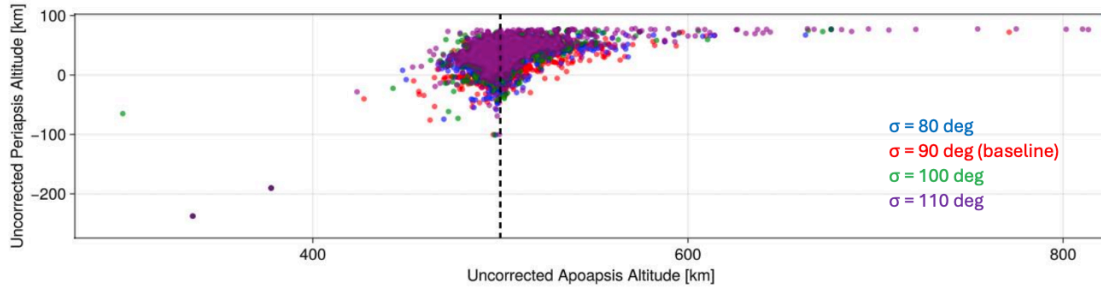


Fig. 31 Altitude targeting errors for the bank angle 2 cases.

From Fig. 32, as the phase 2 bank angle increases, the phase 1 duration increases and phase 1 is skipped at a lower magnitude FPA. This behavior is exaggerated at small phase 1 durations.

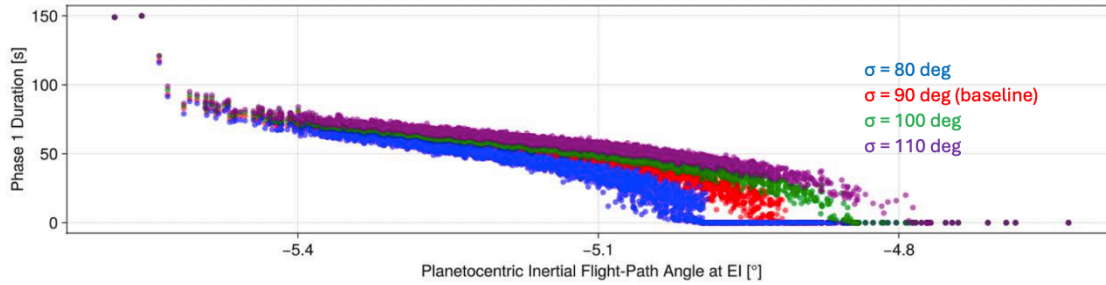


Fig. 32 Phase 1 duration vs. inertial flight path angle for the bank angle 2 cases.

The most significant delta V effect from the phase 2 bank angle is the periapsis raise delta V in Fig. 33. The 110 deg case uses the least delta V and the 90 deg case uses the most delta V.

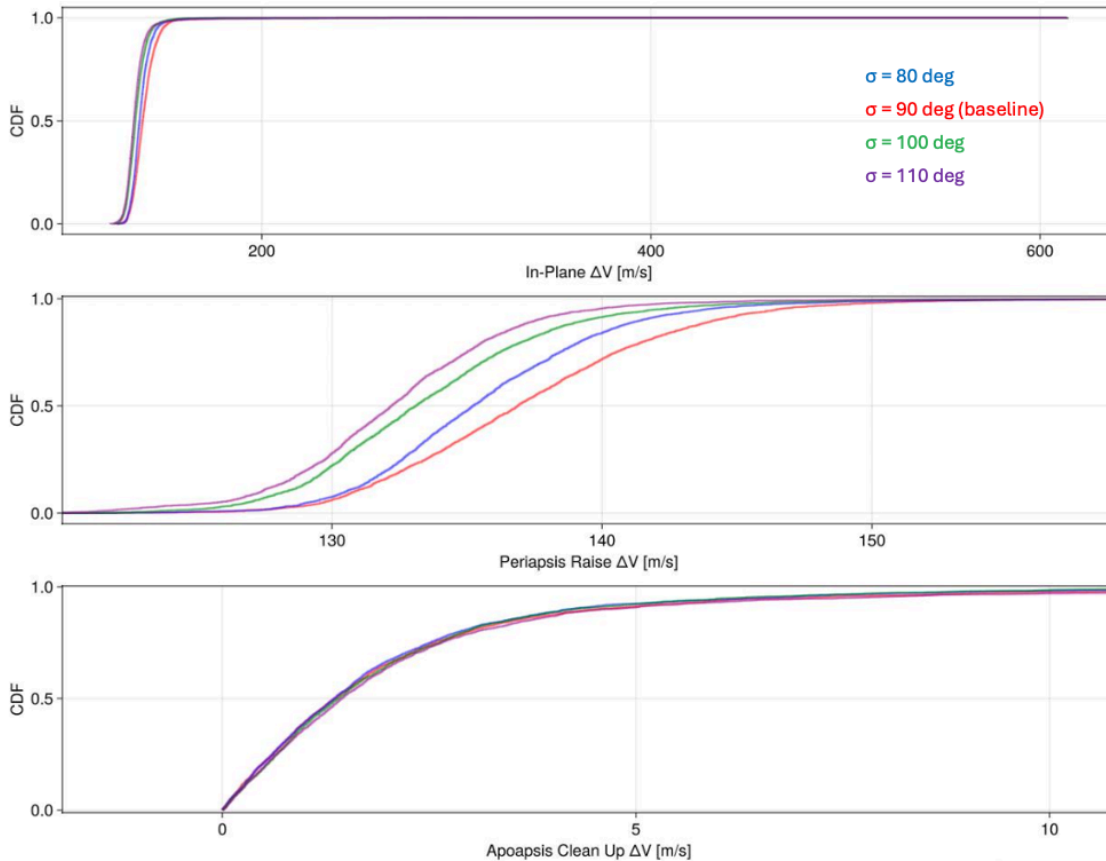


Fig. 33 Delta velocity, ΔV , cumulative density functions (CDFs) for the bank angle 2 cases.

In Fig. 34, the 110 deg case has the largest in-plane delta V values, some of which occur in the middle of the FPA corridor. There are similar outliers for the 110 deg case for the apoapsis clean up delta V. Therefore, there may exist a tradeoff for the bank angle 2 parameter for periapsis raise delta V and both the in-plane and apoapsis clean up delta Vs.

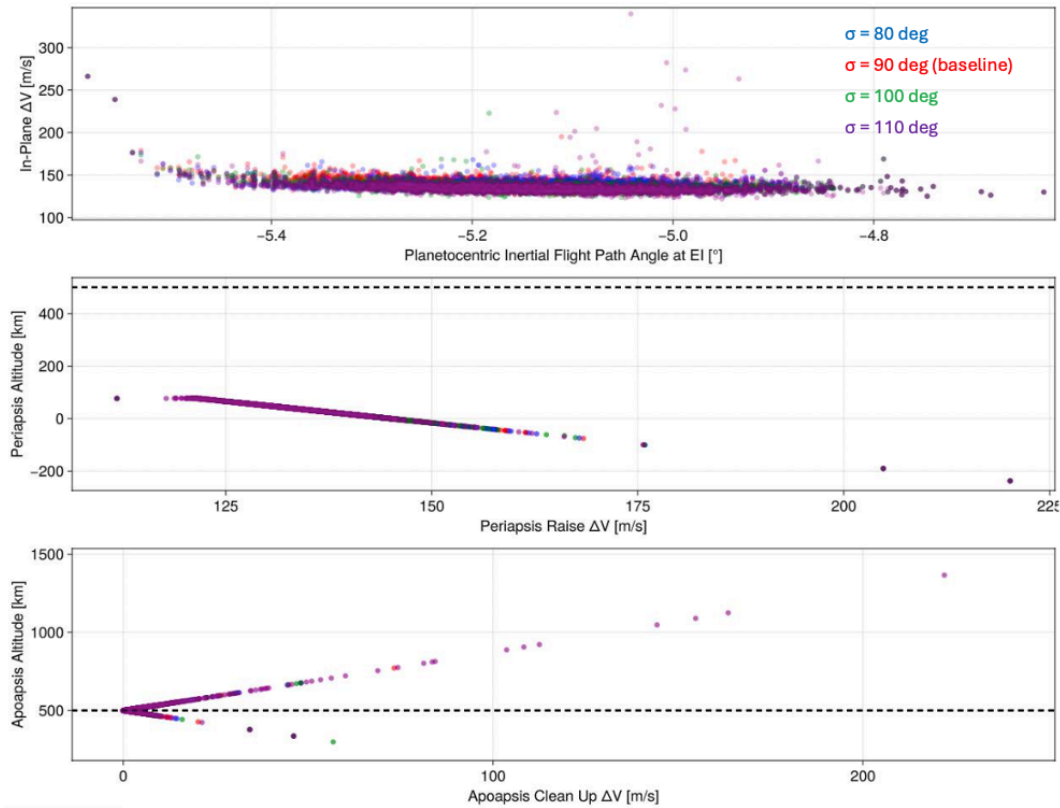


Fig. 34 Delta velocity, ΔV , plots for the bank angle 2 cases.

From Table 10, there exists a tradeoff between a high vs. low bank angle 2 magnitude and the delta V and apoapsis altitude errors. The 110 deg bank angle has the lowest mean delta V and the 80 deg bank angle has the lowest mean apoapsis altitude error. Notably, the 110 deg bank angle 2 has a very large 99 percentile apoapsis altitude error, matching the large set of outliers seen in Fig. 31.

Table 10 Delta V and apoapsis altitude error for bank angle 2.

Bank Angle 2 [deg]	Mean Delta V [m/s]	99%-tile Delta V [m/s]	Mean Apoapsis Altitude Error [km]	99%-tile Apoapsis Altitude Error [km]
80	138.1	154.9	8.195	48.76
90*	139.7	156.0	8.575	53.43
100	135.9	152.6	8.311	40.85
110	135.5	160.4	11.14	111.8

* Baseline value.

B. Lateral Targeting Analysis

1) Impact of the Lateral Parameter Choice:

While the entry implementation of [12] uses crossrange as the lateral target parameter, the aerocapture scenario requires a parameter that identifies the lateral orbit parameter. Previous literature has primarily used wedge angle as the lateral target [16], [17]. In this work, we have discovered instances of non-convergence for the lateral logic algorithm when the wedge angle is used. This issue stems from the wedge angle not being monotonic in decreasing error. Instead, we propose the use of inclination angle for lateral targeting,

which is monotonic in decreasing lateral error. Fig. 35 shows the difference in convergence between the wedge angle and the inclination angle-based lateral targeting.

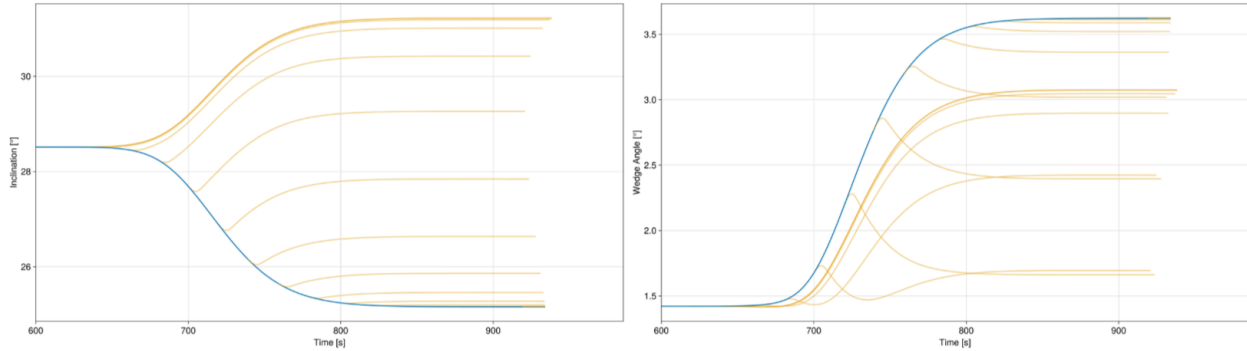


Fig. 35 Wedge angle error compared to inclination error for aerocapture.

Since the wedge angle implementation jumps across the zero degree case, convergence never occurs and the lateral logic algorithm stops before completing all n reversals. When the inclination angle is used instead, the error no longer exhibits jumps in behavior, guaranteeing the monotonic convergence of the lateral logic in Eq. (1).

2) Lateral Corridor Analysis:

Table 11 shows the computed lateral corridor by banking the vehicle at -90 degrees and at 90 degrees and taking the sum. Due to the Earth's rotation, the corridor for banking 90 deg vs. -90 deg is not equal. For the setup of the GTO case, banking -90 deg has a larger corridor by a little less than 1 degree. The 7.309 deg lateral corridor informs the targeting logic to ensure the desired lateral targeting error is reachable, given a set of initial conditions.

Table 11 Lateral Corridor for the GTO scenario.

Lateral Corridor [deg]	Bank -90 deg Inclination Change ($i_f - i_0$) [deg]	Bank 90 deg Inclination Change ($i_f - i_0$) [deg]
7.309	3.277	-4.031

3) Sensitivity Analysis:

Fig. 36 shows the estimated apoapsis altitude error CDF for five Monte Carlo runs, each with different lateral parameters, K . Larger K values represent higher inclination range capabilities for the vehicle, and subsequently, result in lower apoapsis altitude errors; results for these cases closely match the 0 bank reversal bounding case.

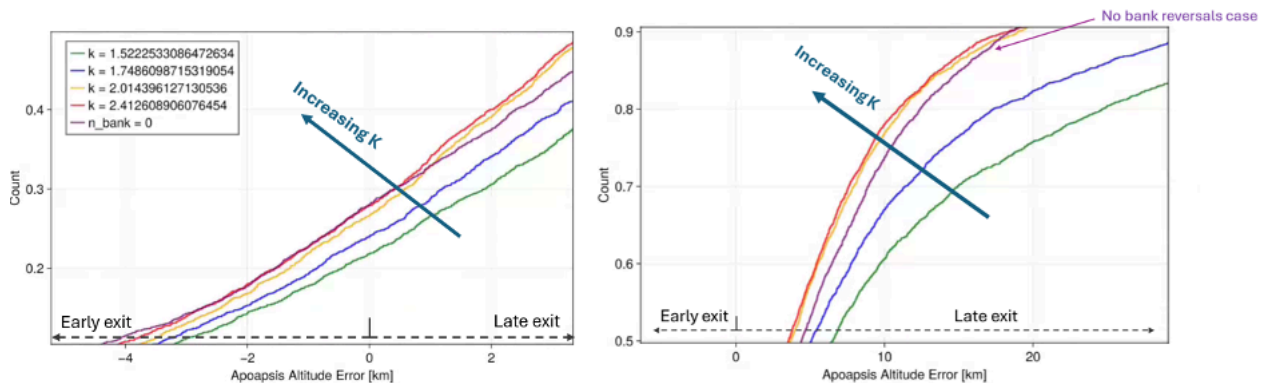


Fig. 36 Estimated CDF for apoapsis altitude error as a function of the lateral control parameter, K .

C. Bank Reversal Strategy Analysis

Fig. 37 shows the histogram of the maneuver strategies for 3 reversals, 4 reversals, and 5 reversals, where -1 indicates the reversal is through lift down and 1 indicates that the reversal is through lift up. The nominal

trajectory for the 5 reversal case is overlaid to show an example of the most frequently occurring maneuver strategy over time. The maneuver strategy sequence of reversing through lift down, reversing through lift up, and then reversing through lift down is the most frequently occurring strategy for the test cases of 3 through 5 reversals. Still, strategies that do not follow that policy do occur and require the additional root-finding procedure outlined in this work, Algorithm 2, to solve for the optimal strategy sequence.

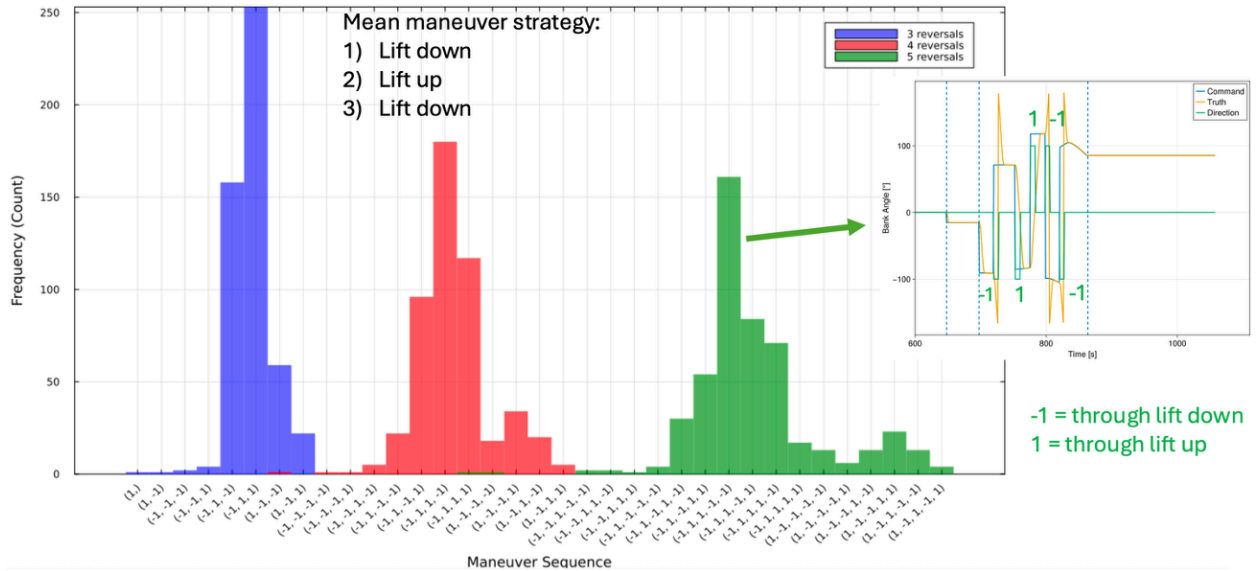


Fig. 37 Histogram of the maneuver strategies used for 500 FNPAG runs commanding between 3 and 5 reversals.

V. Conclusions

In this work, the FNPAG algorithm was augmented to include inclination-based lateral guidance, with a specified direction for each reversal. A set of sensitivity analyses were completed for the set of FNPAG hyperparameters and the lateral algorithm was evaluated for reachability and parameter choice. Overall, FNPAG performed well for the Geostationary Transfer Orbit case, reaching desired delta V ranges and hitting the apoapsis altitude target.

VI. Appendix

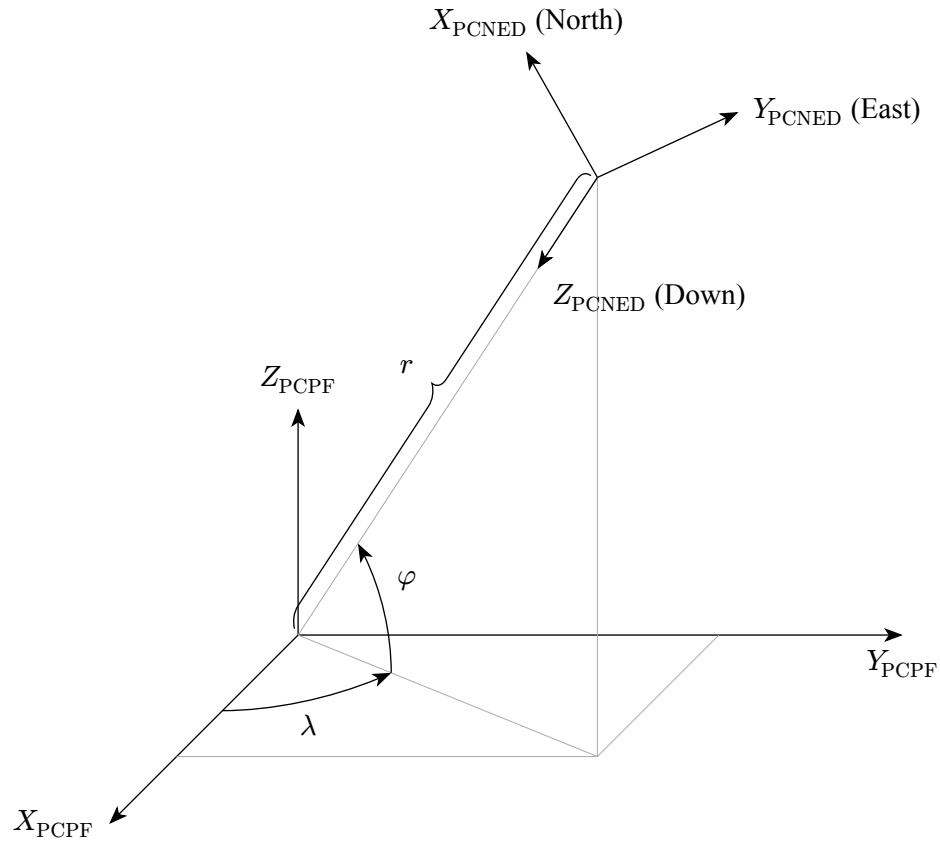


Fig. 38 State vector position components. The azimuth and flight path angle are positive as shown.

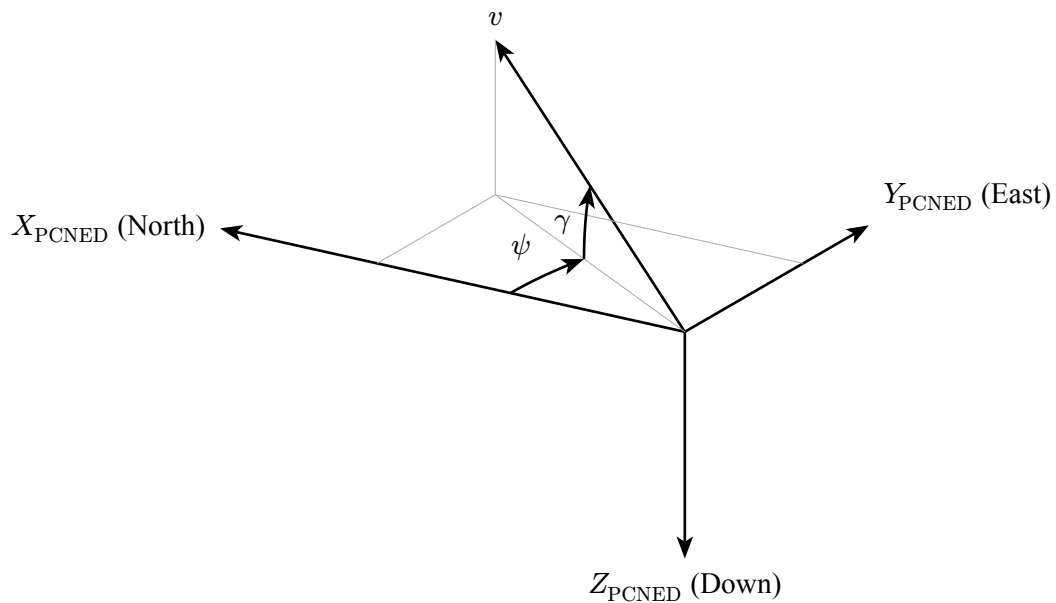


Fig. 39 State vector velocity components. The azimuth and flight path angle are positive as shown.

References

- [1] Lockwood, M. K., Edquist, K. T., and Starr, B. R., "Aerocapture Systems Analysis for a Neptune Mission," technical report NASA/TM-2006-214300, Washington, DC, 2006.

- [2] Rymer, A., Clyde, B., and Runyon, K., "Neptune Odyssey: Mission to the Neptune-Triton System," Technical Report, Washington, DC, 2020.
- [3] Simon, A., Nimmo, F., and Anderson, R., "Uranus Orbiter and Probe: Journey to an Ice Giants System," Technical Report, Washington, DC, 2021.
- [4] Dutta, S., Davis, W., Deshmukh, R., Gomez-Delrio, A., Lugo, R., Scoggins, J., Shellabarger, E., Chadavada, P., Garland, J., Williams, J., Morgan, J., Mages, D., Restrepo, R., Johnson, B., Matz, D., and Sandoval, S., "Aerocapture Solutions for Flagship-Class Uranus Orbiter and Probe," 2025.
- [5] Deshmukh, R., Dutta, S., and Chadavada, P., "6-DOF Uranus Aerocapture Trajectory Analysis," 2025.
- [6] Giriya, A., "A Flagship-Class Uranus Orbiter and Probe Mission Concept Using Aerocapture," *Acta Astronautica*, Vol. 202, 2022, pp. 104–118.. <https://doi.org/10.1016/j.actaastro.2022.10.005>
- [7] National Academies of Sciences, Engineering, and Medicine, "Origins, Worlds, And Life: A Decadal Strategy for Planetary Science and Astrobiology 2023–2032," The National Academies Press, Washington, DC, 2022.. <https://doi.org/10.17226/26522>
- [8] Dutta, S., Deshmukh, R. G., Scoggins, J. B., Shellabarger, E. R., Shafner, J. A., Trombetta, D. R., Corliss, J. M., Qu, M., Roelke, E., Pensado, A., Vitullo, N. A., Williams, J. D., Morgan, J. D., White, T., Briden, J. M., Matz, D. A., and Sandoval, S., "Aerocapture Earth Demonstration Design to Support Future Planetary Mission Needs," 2026.
- [9] Lu, P., Cerimele, C. J., Tigges, M. A., and Matz, D. A., "Optimal Aerocapture Guidance," *Journal of Guidance, Control, and Dynamics*, Vol. 38, No. 4, 2015, pp. 553–565.. <https://doi.org/10.2514/1.G000713>
- [10] Rea, J., and Putnam, Z., "A Comparison of Two Orion Skip Entry Guidance Algorithms," 2007.. <https://doi.org/10.2514/6.2007-6424>
- [11] Mendeck, G. F., and McGrew, L. C., "Entry Guidance Design and Postflight Performance for 2011 Mars Science Laboratory Mission," *Journal of Spacecraft and Rockets*, Vol. 51, No. 4, 2014, pp. 1094–1105.. <https://doi.org/10.2514/1.A32737>
- [12] Smith, K. M., "Predictive Lateral Logic for Numerical Entry Guidance Algorithms," 2016.
- [13] "Genesis Flight Mechanics Simulation and Trajectory Design Tool," 2021.. <https://software.nasa.gov/software/MS-27061-1>
- [14] Bezanson, J., Edelman, A., Karpinski, S., and Shah, V. B., "Julia: A Fresh Approach to Numerical Computing," *SIAM Review*, Vol. 59, No. 1, 2017, pp. 65–98.. <https://doi.org/10.1137/141000671>
- [15] Roelke, E., Pensado, A., Qu, M., Briden, J., Matz, D., Deshmukh, R., Shellabarger, E., Shafner, J., and Dutta, S., "Comparison of Earth Small-Sat Aerocapture Demonstration Trajectory Opportunities," 2026.
- [16] Starr, B. R., Westhelle, C. H., and Masciarelli, J. P., "Aerocapture Performance Analysis for a Neptune-Triton Exploration Mission," 2004.
- [17] Matz, D. A., Cerimele, C., and Sostaric, R. R., "Comparison of Aerocapture Performance Using Bank Control and Direct Force Control with Two Human-Scale Vehicles at Mars," 2020.