

National Aeronautics and  
Space Administration



# Desensitized Aerocapture Guidance

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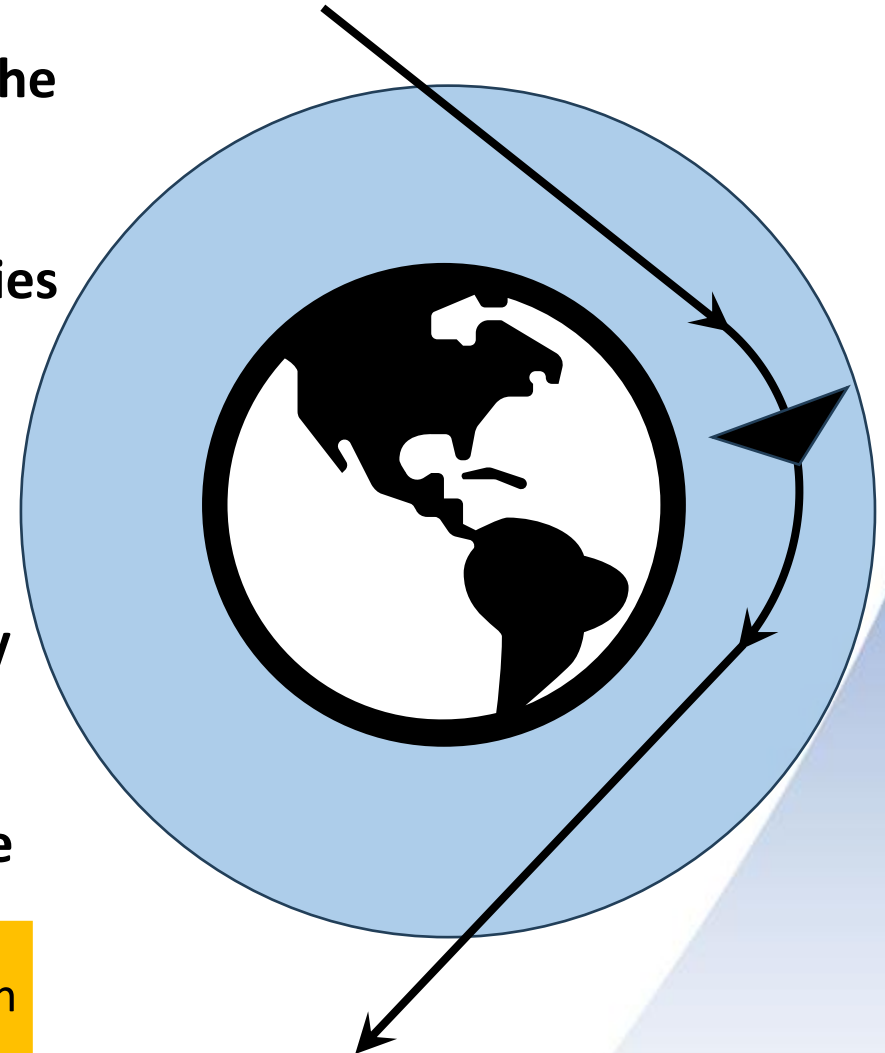
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*NASA Langley Research Center*

*2025 AIAA SciTech Forum*  
*Orlando, FL*  
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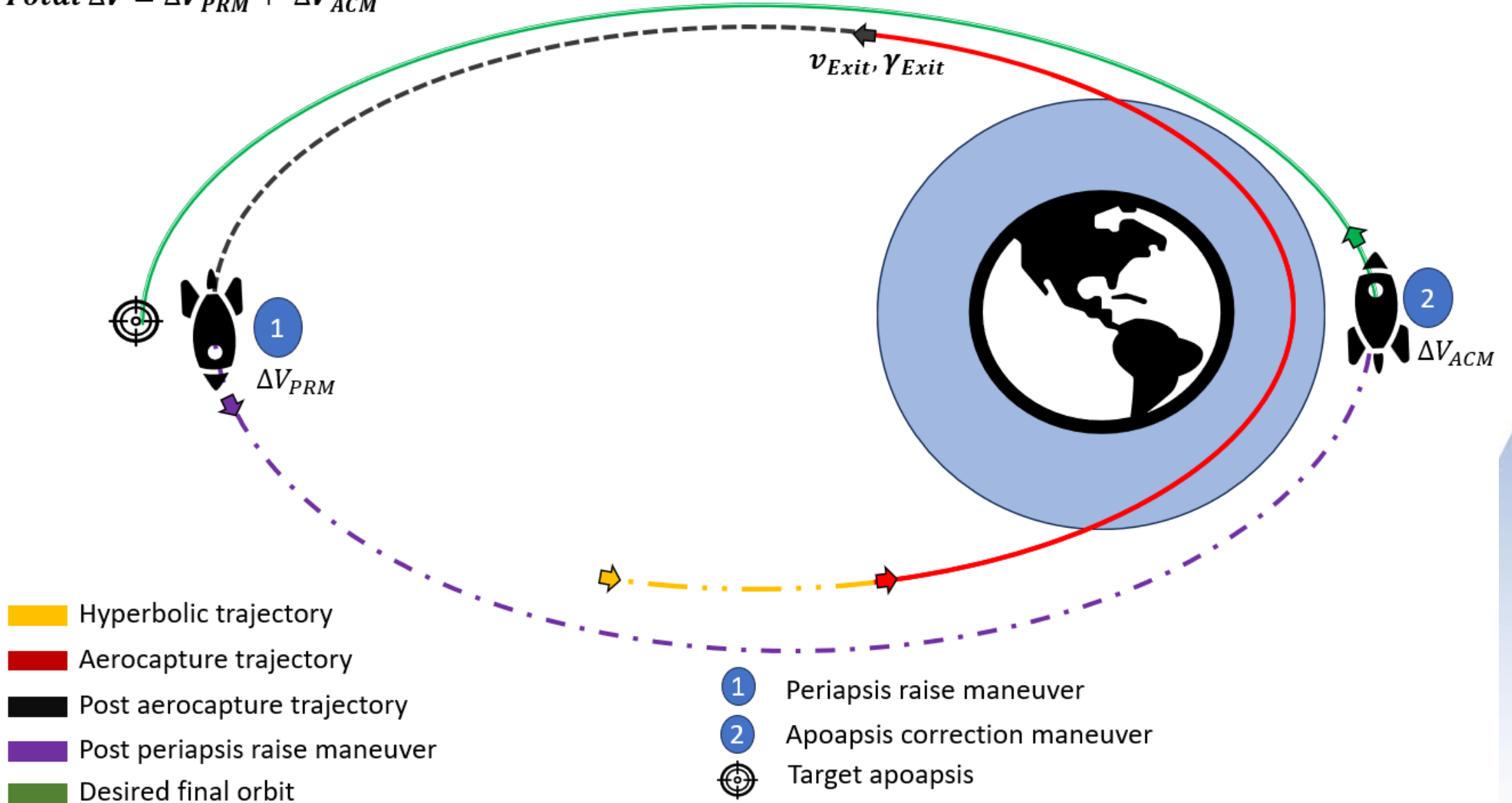
- **Aerocapture is a maneuver in which a spacecraft will dissipate its excess energy during a single pass through the planet's atmosphere to get captured into an orbit.**
- **Aerocapture can enable vehicles to have faster trajectories with larger payloads and capture into an orbit without increasing the fuel requirements**
  - Thermal protection
  - Guidance complexity
- **Aerocapture using bank modulation is gaining popularity especially for ice giants mission concepts**
- **Recent studies shows that aerocapture is sensitive to the uncertainties in the atmosphere**

This work focuses on determining desensitized aerocapture guidance using bank modulation that is robust to uncertainties in atmospheric density

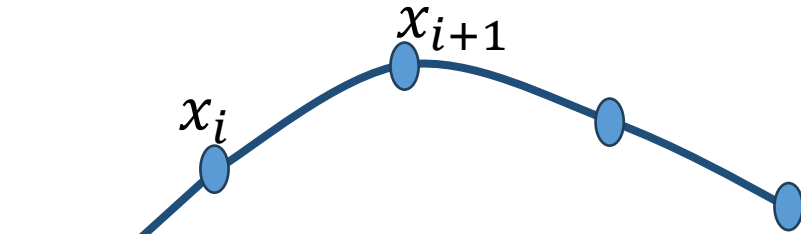


# Aerocapture CONOPS

$$Total \Delta V = \Delta V_{PRM} + \Delta V_{ACM}$$



- In this work, we use a direct optimization method to determine the aerocapture guidance using bank angle modulation
- Direct optimization methods transform the ordinary differential equations that represent the equations of motion into algebraic constraints and transform the problem into a parameter optimization problem
- The aerocapture guidance is determined using
  - Interior Point Optimizer
  - Automatic differentiation
  - Using Hermite Simpson collocation method



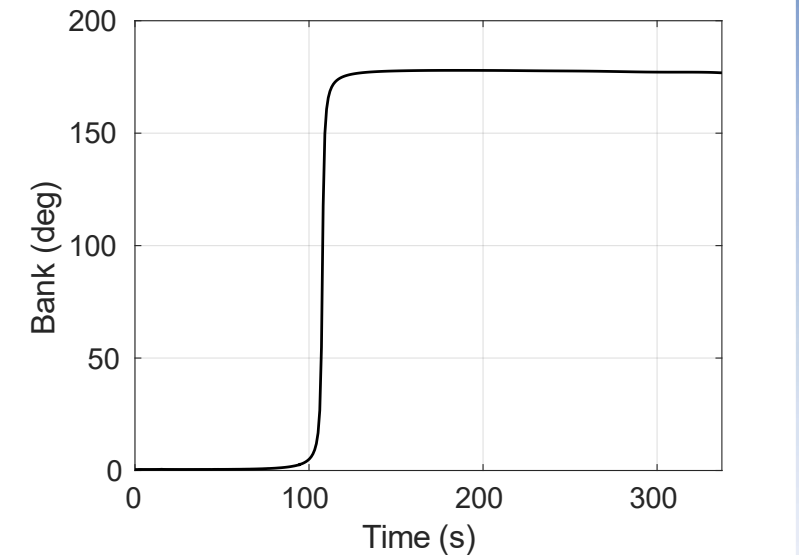
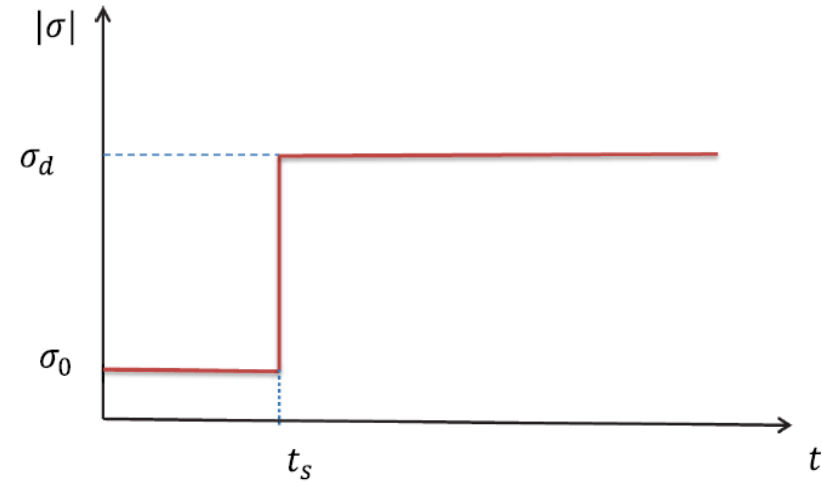
$$\dot{x} = -x + u, \quad x(0) = x_0$$



$$x_{i+1} = x_i + \Delta t(-x_i + u_i)$$

- $X$  = States
- $U$  = Controls
- $\Delta t$  = Time between two nodes
- $x_0$  = Initial state
- $i$  = Node index

- **Optimal Aerocapture Guidance minimizes the total  $\Delta V$  required post aerocapture to get captured into a desired orbit**
- **In literature ignoring the planet's rotation and J2 terms it is shown the optimal solution is bang-bang with a single switch [1]**
- **Our analysis show similar bank profile structure with planet's rotation and J2 terms**



Bank profile for optimal aerocapture



# Indirect Methods



➤ Indirect methods uses calculus of variations to determine the optimal control

➤  $J = \textit{Terminal Cost} + \textit{Running Cost}$

- function of final states and time
- function of states, control and time

➤  $\textit{Hamiltonian} (H) = \textit{Running Cost} + \lambda^T (\textit{EOMs})$

- $\lambda$  is Lagrangian multipliers (costates)
- EOM – Equations of Motion

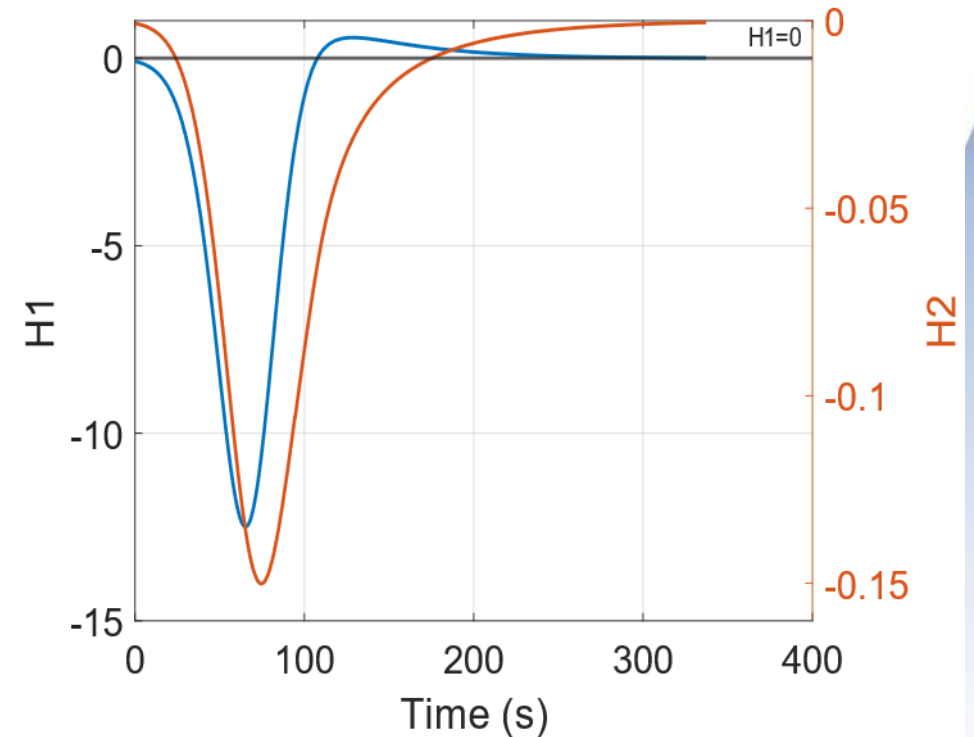
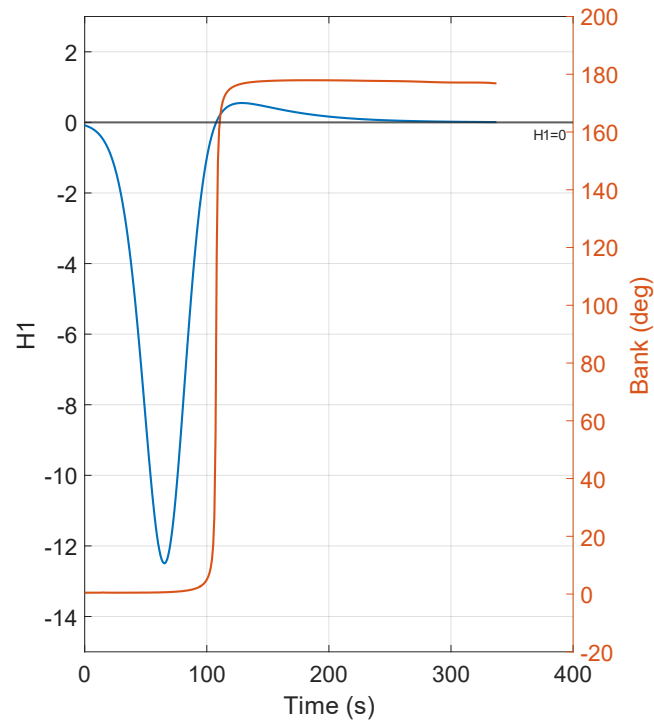
➤ Optimal control minimizes Hamiltonian

# Hamiltonian Analysis

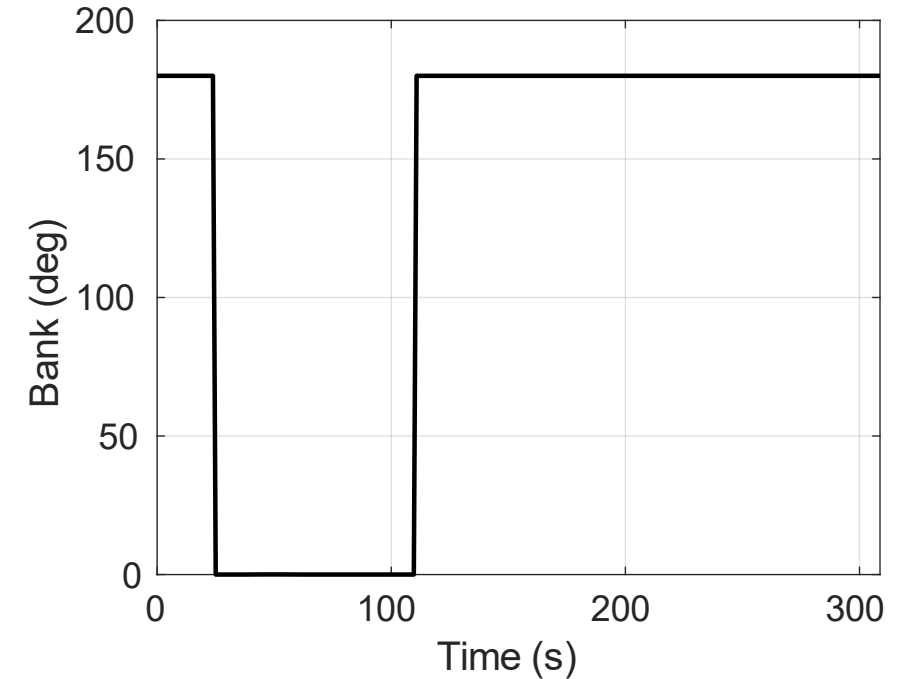
$$\mathcal{H}(x^*, \sigma^*, \lambda^*, p, t) \leq \mathcal{H}(x^*, \sigma, \lambda^*, p, t) \forall t \in [0, t_f]$$

$$\mathcal{H}(x, \sigma, \lambda, p, t) = H_0(x, \lambda, p, t) + H_1(x, \lambda, p, t) \cos \sigma + H_2(x, \lambda, p, t) \sin \sigma$$

- $\mathcal{H}$  = Hamiltonian function
- $x^*$  = Optimal states
- $\sigma^*$  = Optimal bank profile
- $\lambda^*$  = Optimal costates
- $p$  = Constant Parameters
- $t$  = Time
- $\sigma$  = Feasible bank profiles
- $t_f$  = Final time



- Recent studies have shown that uncertainty in the atmospheric density can significantly affect the aerocapture performance
- Desensitized Optimal Control (DOC) for aerocapture can reduce the sensitivity of the maneuver with respect to density uncertainties along the trajectory
- DOC targets the apoapsis altitude at the end of the aerocapture and augments the performance index that provides optimal aerocapture guidance with sensitivity terms to determine robust guidance



Bank profile for desensitized aerocapture

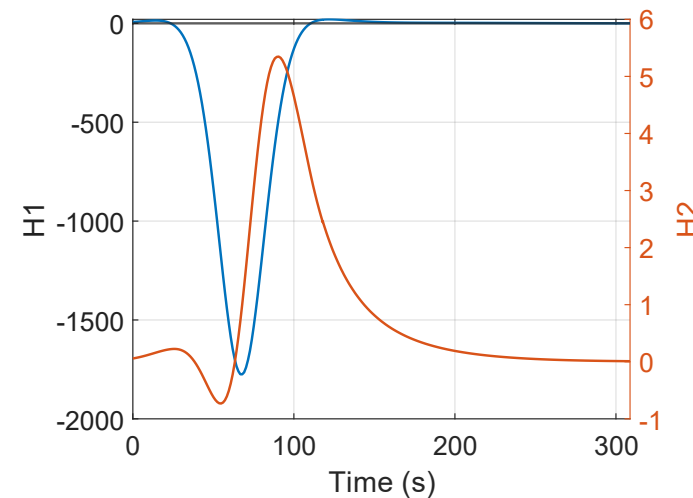
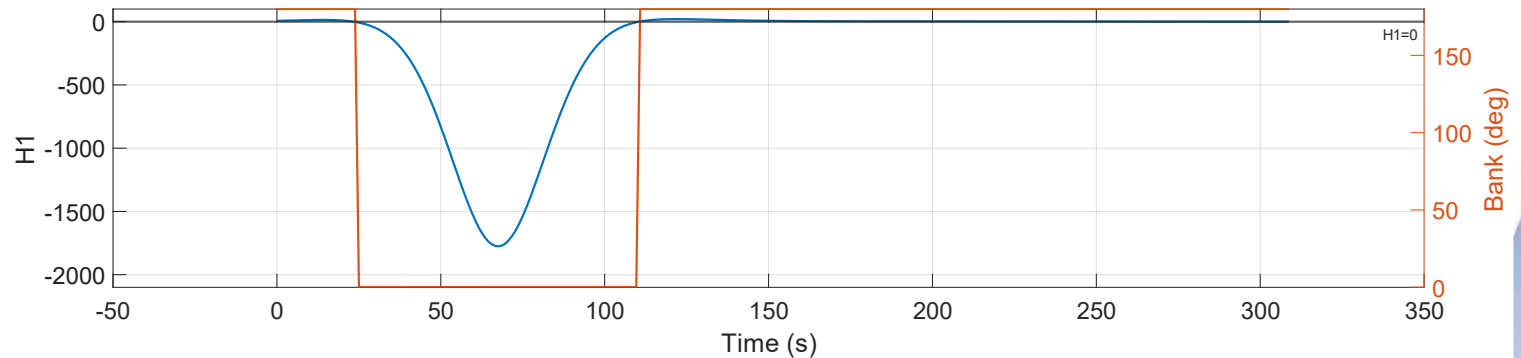
$$J = \Delta V + w_1 (\text{Sensitivity of } v_{exit} \text{ and } \gamma_{exit} \text{ to the uncertainty in } \rho_0)$$

- $\rho_0$  is the constant term in exponential density model

$$\mathcal{H}(x^*, \sigma^*, \lambda^*, \lambda_{\Lambda}^*, \Lambda^*, p, t) \leq \mathcal{H}(x^*, \sigma, \lambda^*, \lambda_{\Lambda}^*, \Lambda^*, p, t) \forall t \in [0, t_f]$$

$$\mathcal{H}(x, \sigma, \lambda, \lambda_{\Lambda}, \Lambda, p, t) = H_0(x, \lambda, \lambda_{\Lambda}, \Lambda, p, t) + H_1(x, \lambda, \lambda_{\Lambda}, \Lambda, p, t) \cos \sigma + H_2(x, \lambda, \lambda_{\Lambda}, \Lambda, p, t) \sin \sigma$$

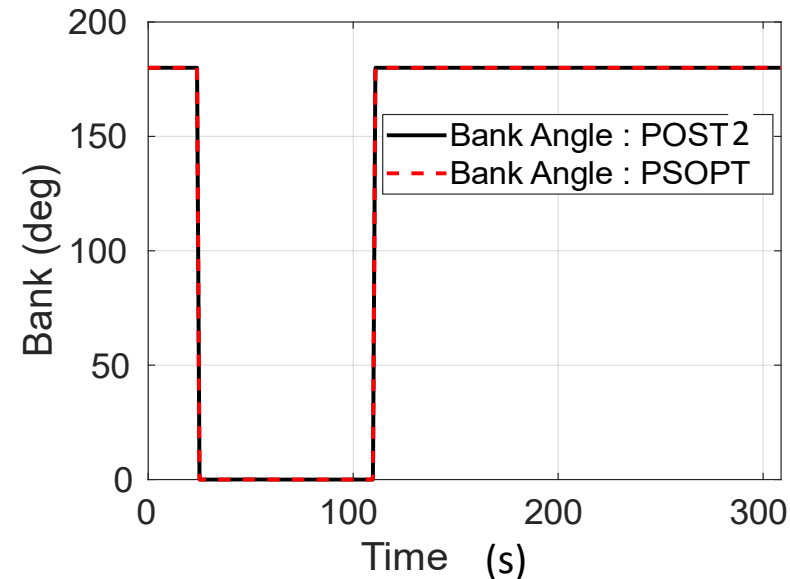
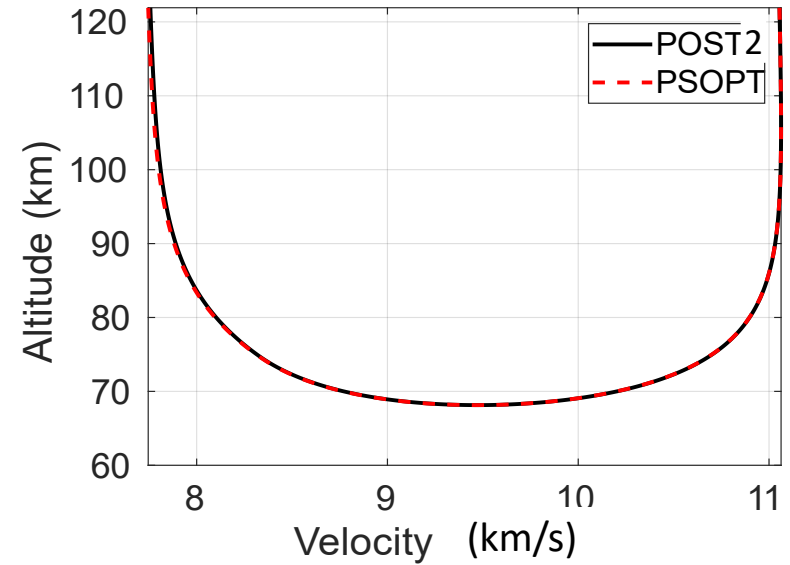
- $x^*$  = *Optimal states*
- $\Lambda^*$  = *Optimal sensitivity states*
- $\sigma^*$  = *Optimal bank profile*
- $\lambda^*$  = *Optimal costates*
- $\lambda_{\Lambda}^*$  = *Optimal sensitivity costates*
- $p$  = *Constant Parameters*
- $t$  = *Time*
- $\sigma$  = *Feasible bank profiles*
- $t_f$  = *Final time*



- The guidance is modeled in a flight mechanics simulation to see the performance results
- POST2: Program to Optimize Simulated Trajectories II
- The optimal bank profile from external optimizer in this case PSOPT is generated as a table with respect to time using linear interpolation
- POST2 configured to have same simulation settings as in PSOPT

	Apoapsis at exit	$\Delta V$ required
PSOPT	200.15 km	129.81 m/s
POST2	199.90 km	130.64 m/s

\*\* Target apoapsis at exit is 200 km



# Density Dispersions

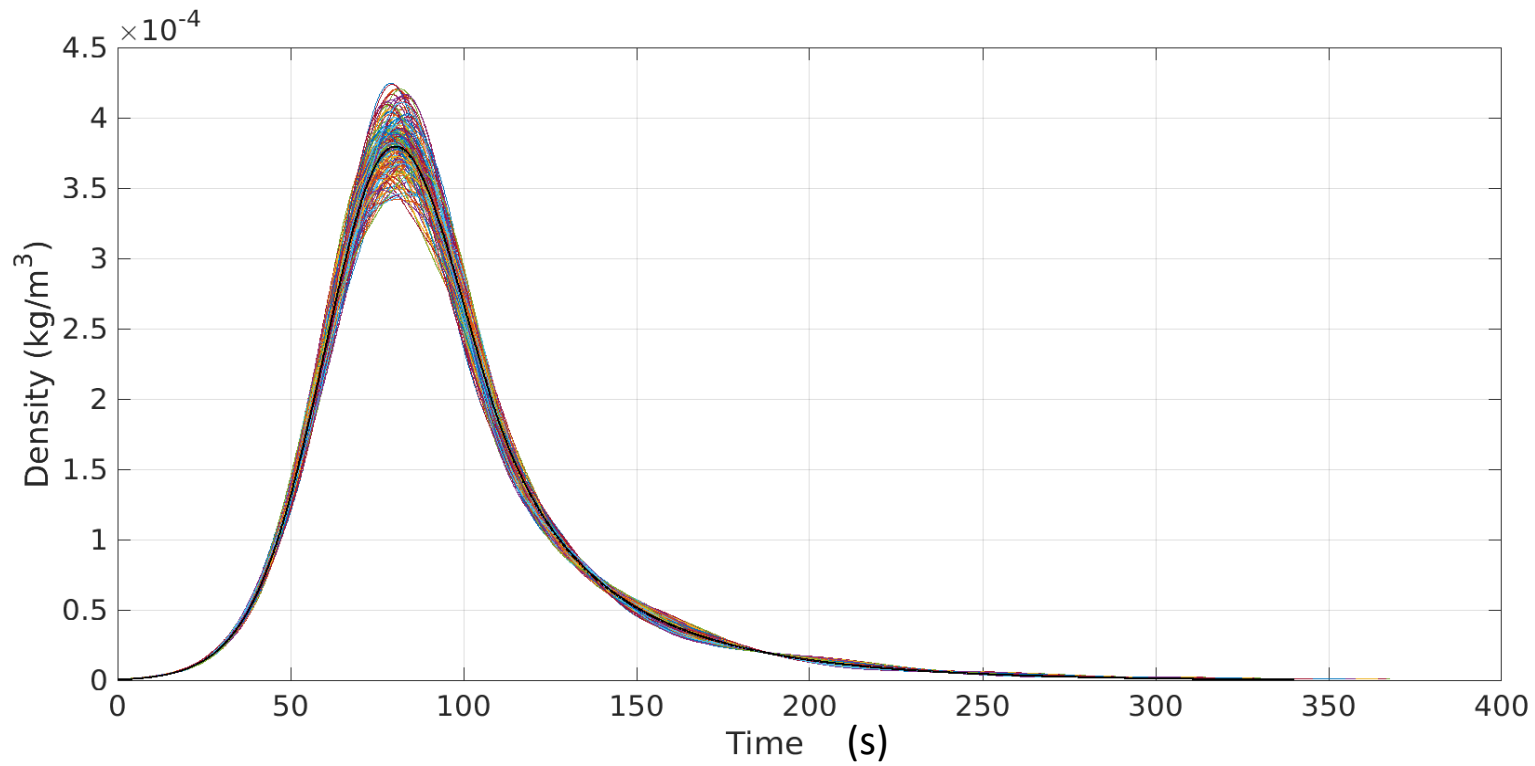
$$\rho_{0_{Disp}}(t) = \rho_0 + \hat{\rho} \sin(2\pi\mathcal{F}t + 2\pi\Phi)$$

Amplitude

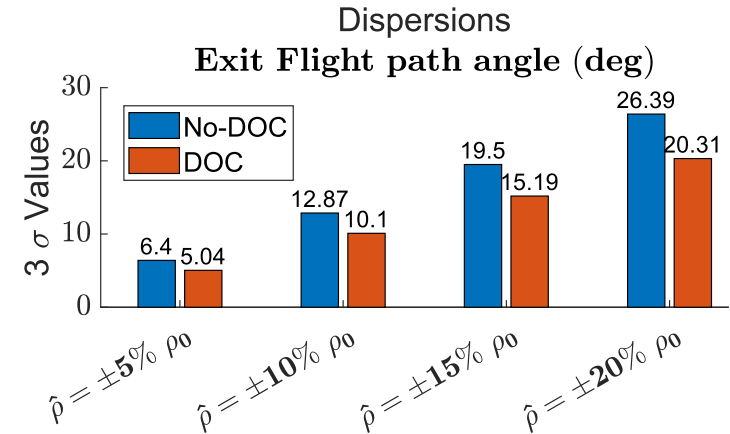
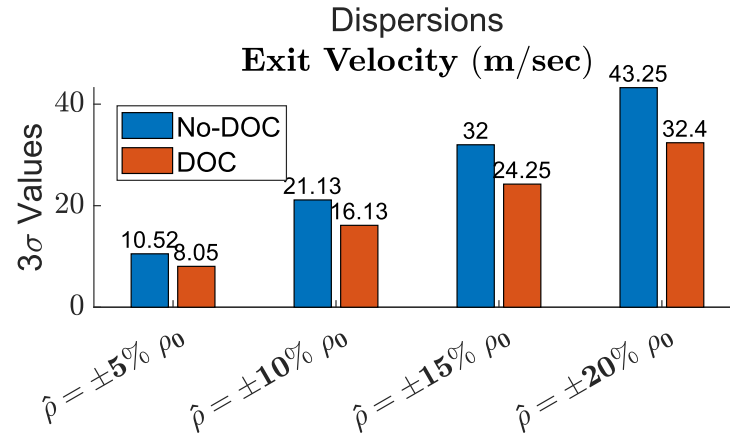
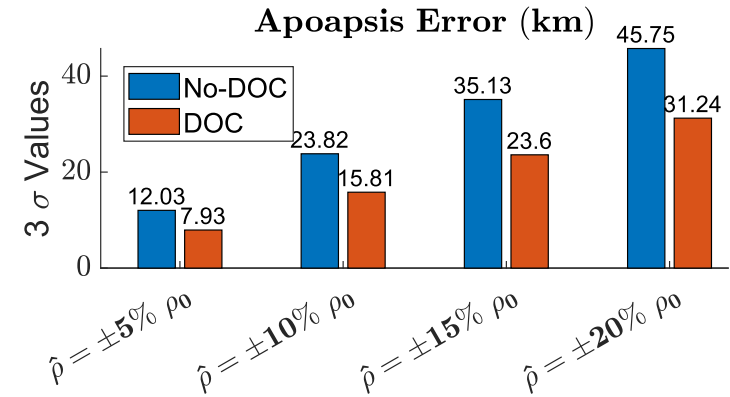
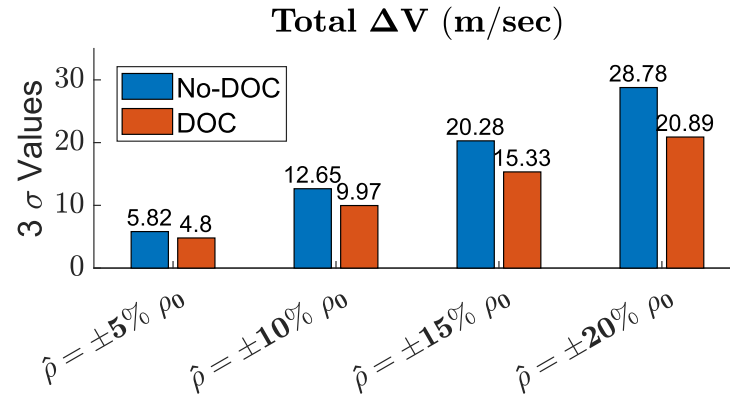
Frequency

Phase

➤  $\hat{\rho}$  and  $\Phi$  is dispersed uniformly with 50 sec time period sine signal

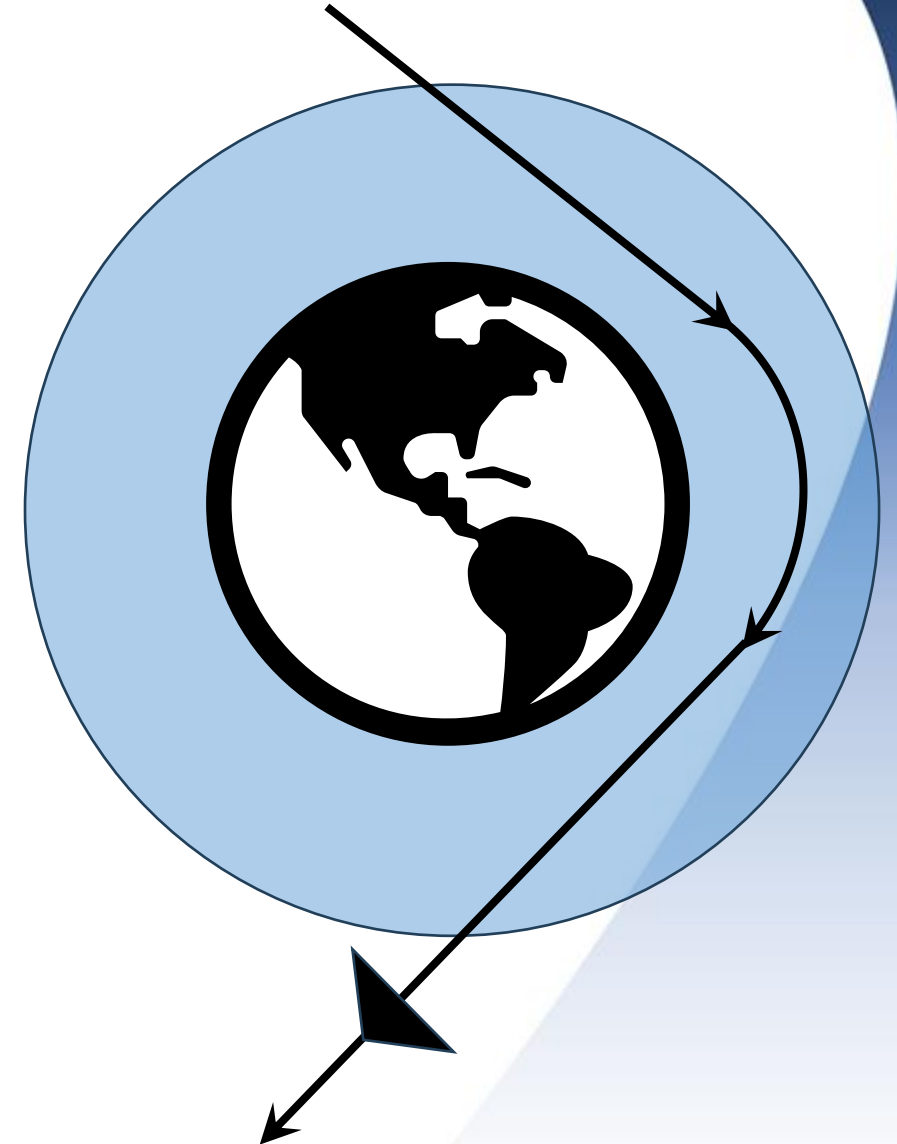


# 3 $\sigma$ Values from Monte Carlo Analysis



- I. DOC allows for tighter orbit insertion performance in the presence of growing density dispersions
- II. As the density dispersions increase the aerocapture performance between DOC and No-DOC become more apparent

- **Aerocapture can reduce the fuel requirements to get captured into an orbit around the planet**
  - The benefits of aerocapture becomes more apparent with the fast interplanetary trajectories enabled by new launch architectures
- **An open loop desensitized aerocapture guidance can provide aerocapture using bank modulation that is more robust to the uncertainties in the atmospheric density**
- **DOC solution is also a bang-bang profile like No-DOC solution but with two switches**
  - Future work will investigate if a Numerical Predictor-Corrector (NPC) guidance assuming the bank structure with two switches will provide more robust guidance.



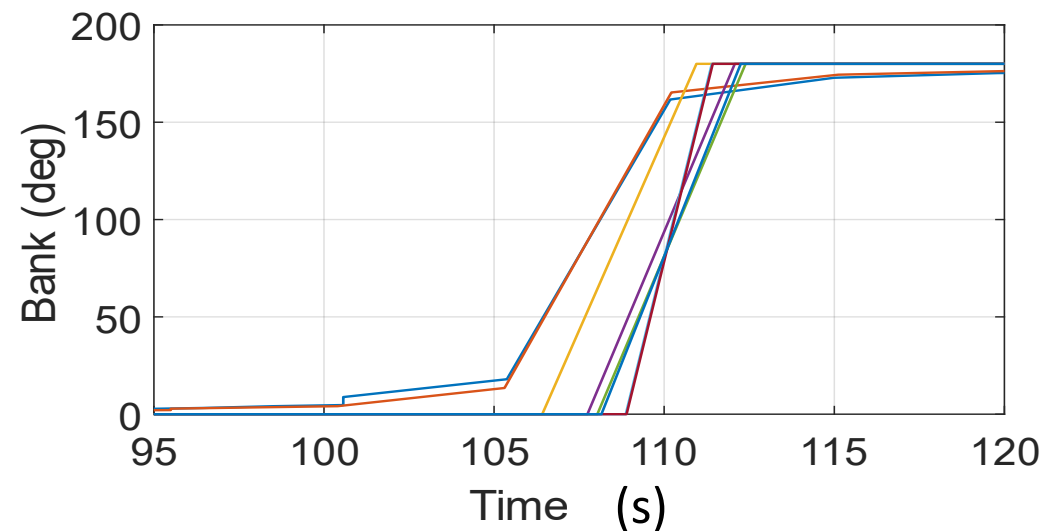
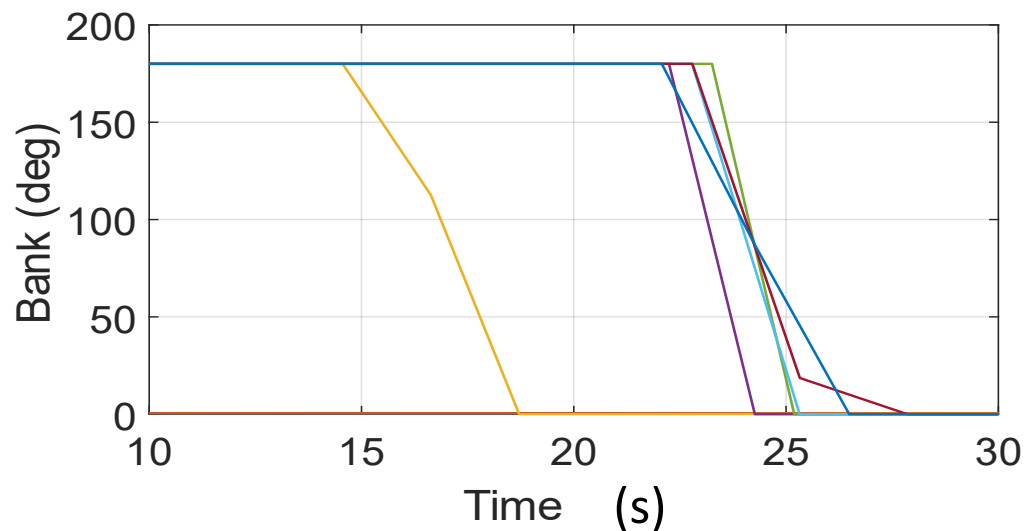
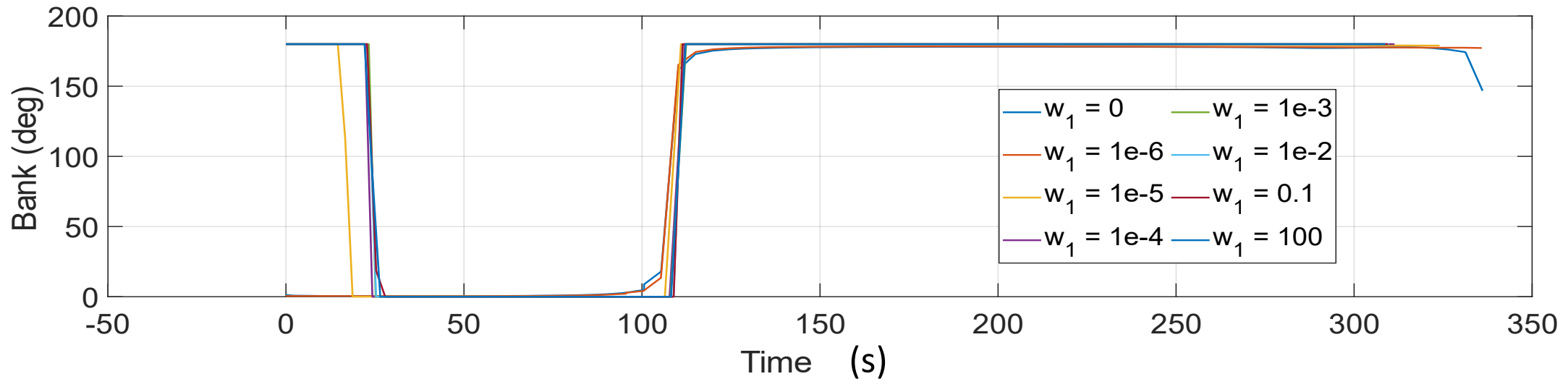


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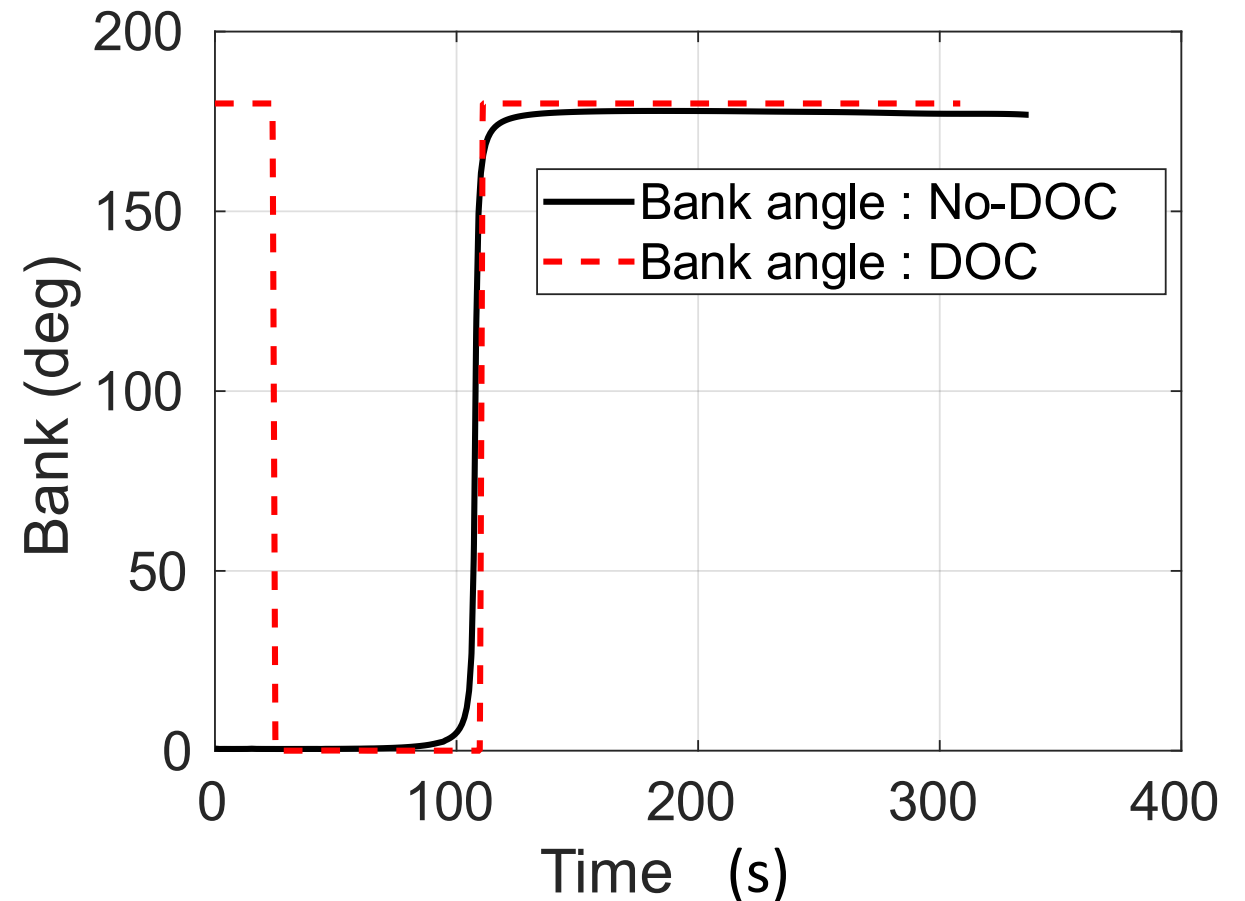
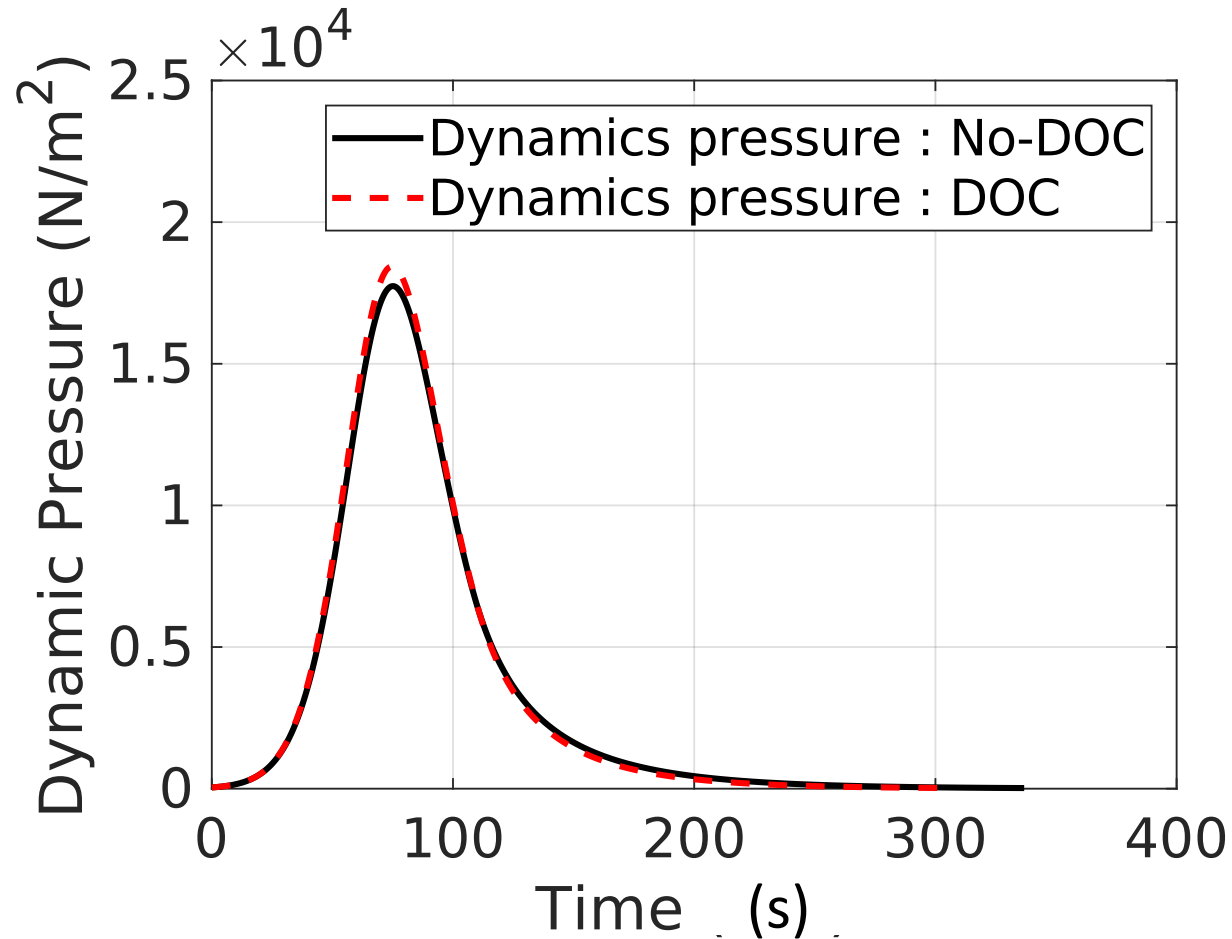
Thank You

# Bank Profiles for Different $w_1$ Values

➤ For the DOC solution, in this work, we consider  $w_1$  as  $1e-3$



- The DOC and No-DOC solution look similar except for the two switches instead of one switch



- **New launch architectures such as Starship will allow one to design fast interplanetary trajectories**
- **However, the spacecraft must dissipate its excessive energy to get capture into an orbit around the destination planet.**
- **Using a fully propulsive system can be cost prohibitive or even lead to an infeasible mission design.**

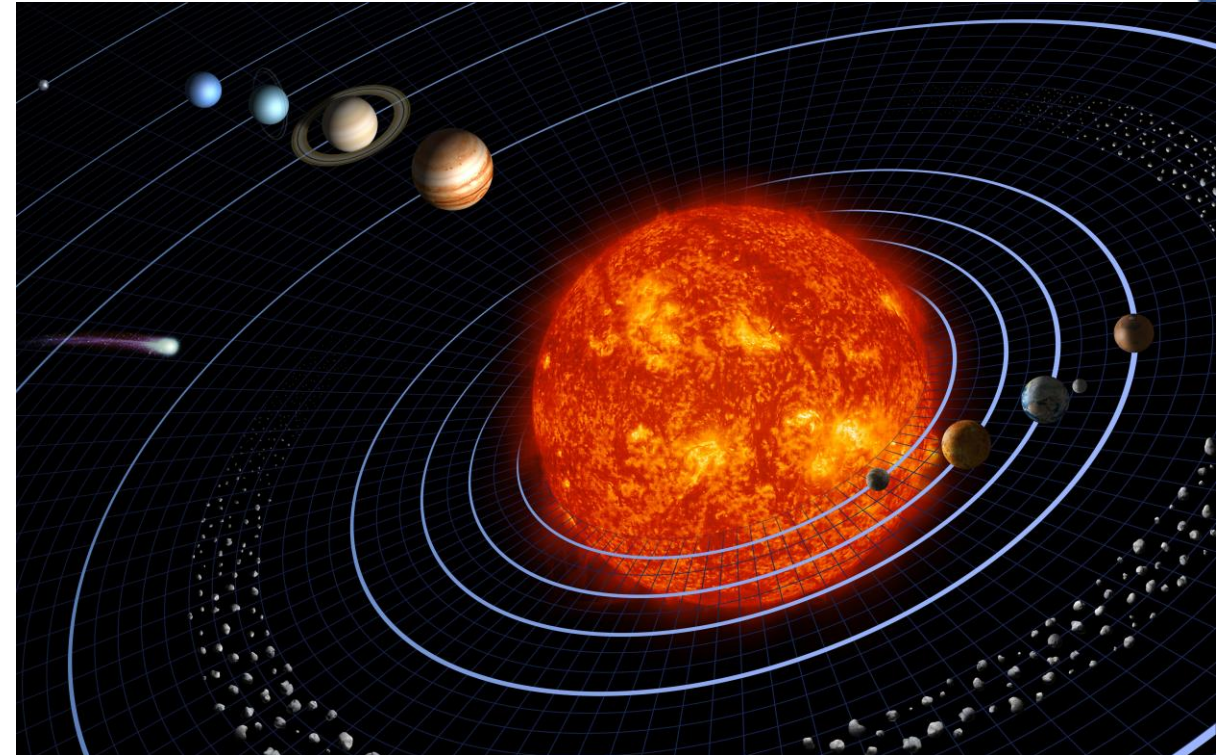


Image Credit : NASA

# Total $\Delta V$ and Apoapsis Error Distributions

