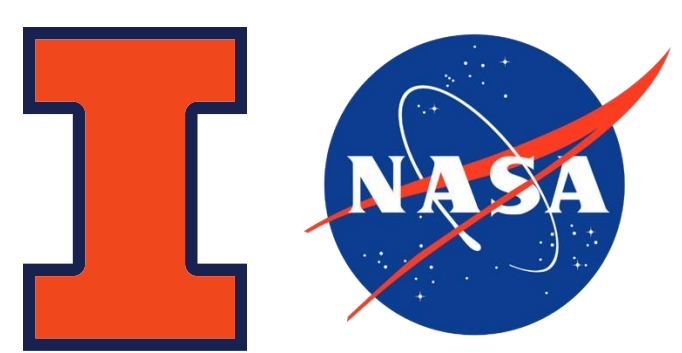




Alpha-Beta Steering for Mars Entries

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Introduction

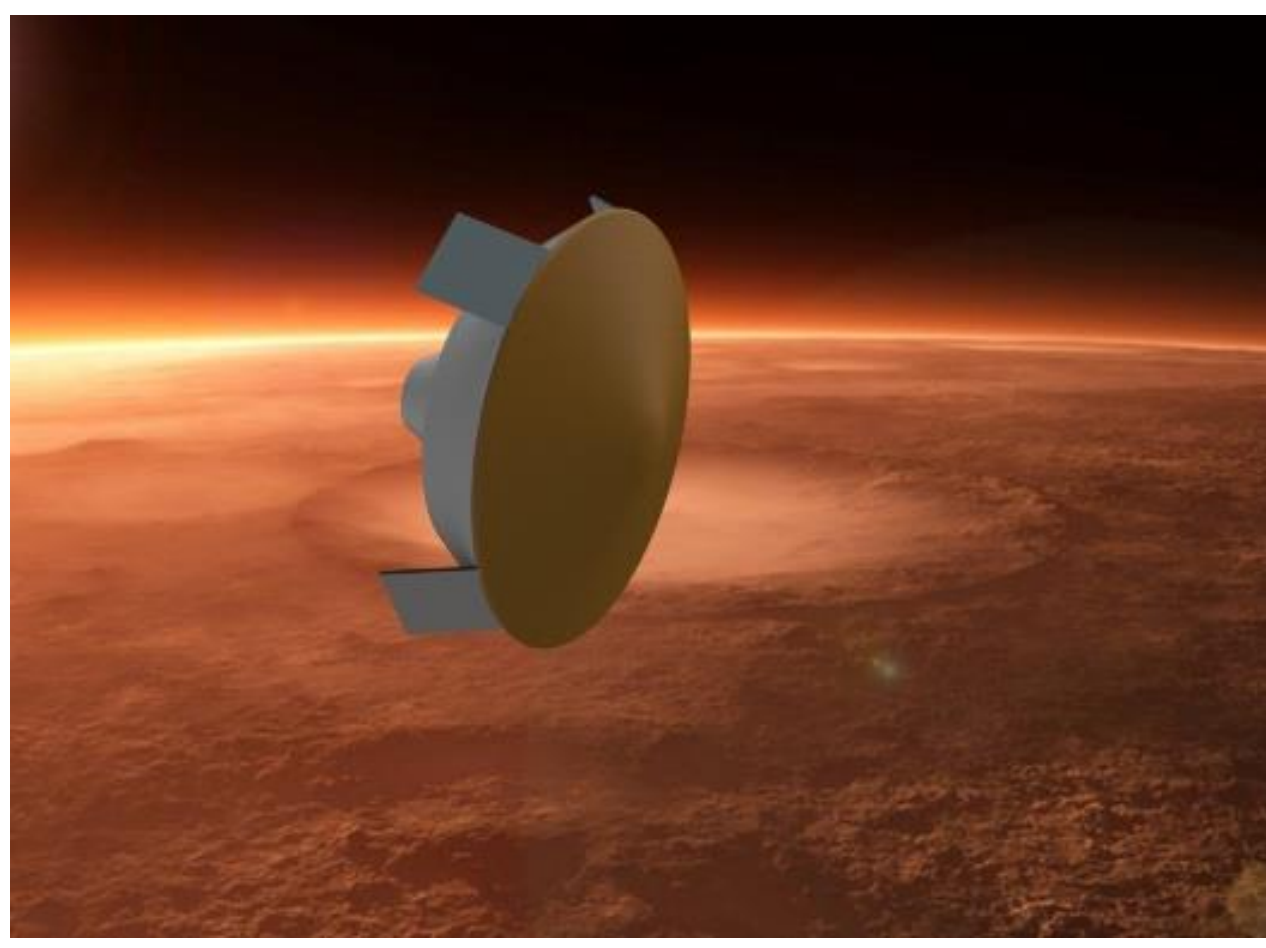


Fig. 1. Concept of Mars Entry Vehicle with Flaps

All guided entries of blunt-body entry vehicles have utilized bank-angle steering for hypersonic trajectory control. While bank-angle steering has been successful on Mars entry missions so far, such as the Mars Science Laboratory [1] and Mars 2020 missions [2], control over the longitudinal and lateral motion are highly coupled for this steering option. An alternative hypersonic steering scheme involves modulating the vehicle's angle of attack (α) and sideslip angle (β) to steer the vehicle, i.e. α - β steering. Also called direct force control (DFC), α - β steering has been recently studied in the literature for both entry and aerocapture missions at several planetary bodies, including Mars [3], Venus [4], Titan [5], and the ice giants [6]. α - β steering provides more decoupled control over the trajectory than bank-angle steering by primarily using α to control the longitudinal motion β to control the lateral motion [6]. Studies have shown that α - β steering may provide increased robustness to atmospheric dispersions [7], higher precision in landed accuracy, a lower propellant usage for powered descent, and a larger payload mass, relative to bank-angle steering [3], but the magnitude of flight performance differences are not fully explored. This study further investigates α - β steering and flap-based implementations [8] and compares performance to bank-angle steering.

Models

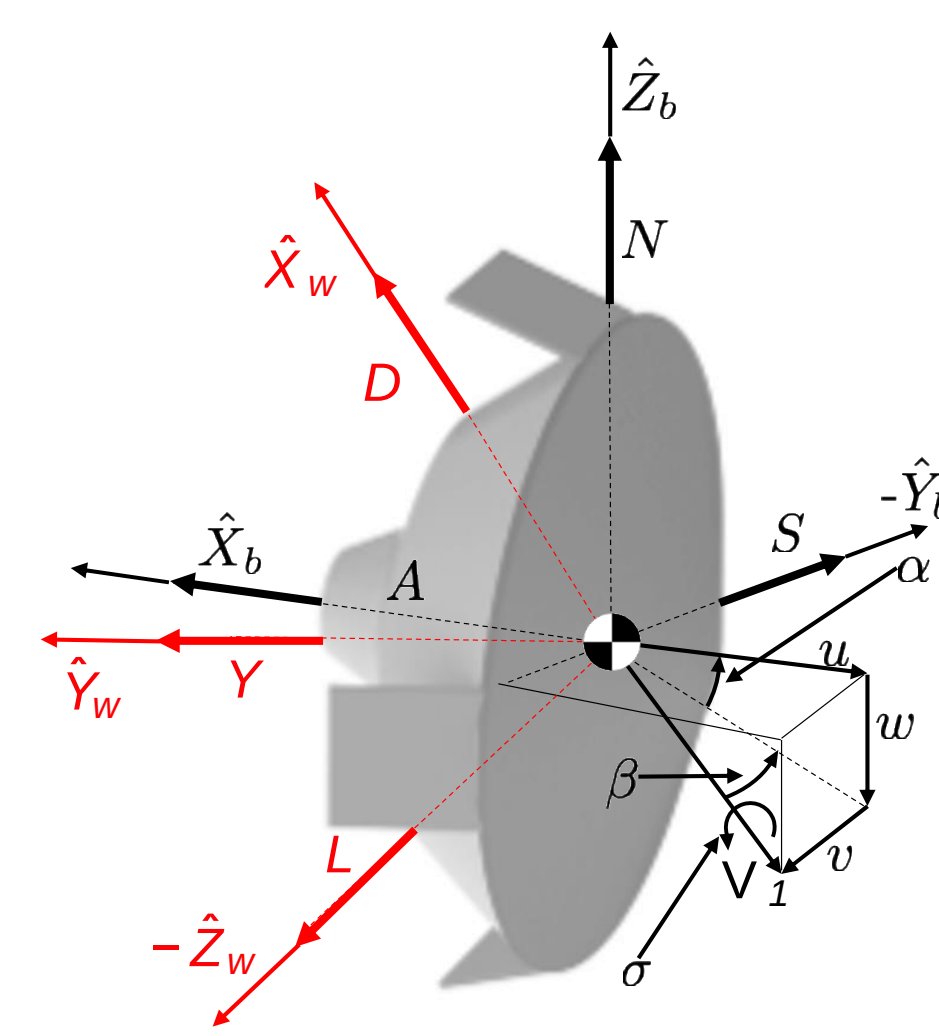


Fig. 2. α - β steering vehicle

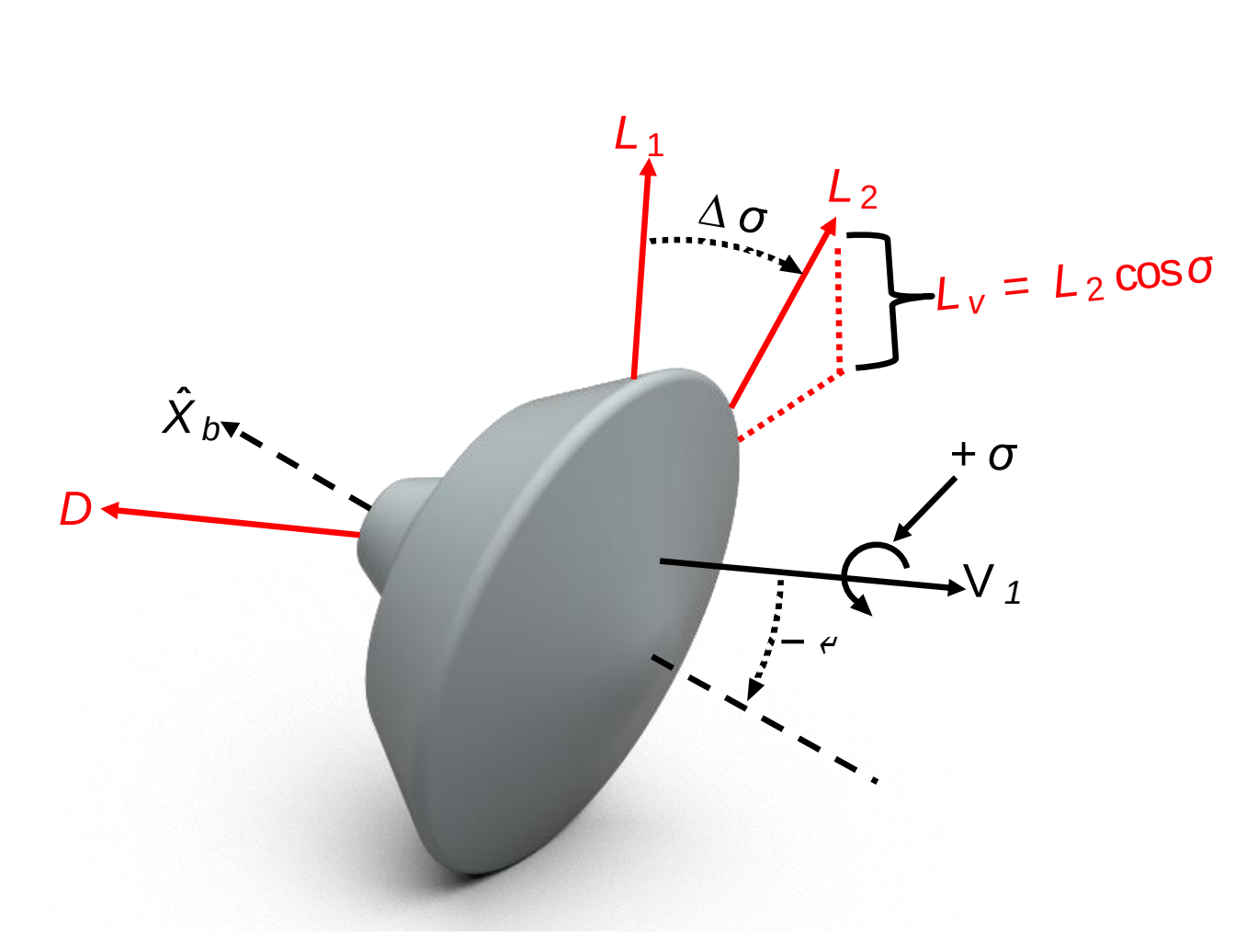


Fig. 3. Bank-angle steering vehicle

Baseline entry vehicles

- Mars Science Laboratory (MSL)
- Sample Retrieval Lander (SRL)

Vehicle aerodynamics

- Forebody: MSL aerodatabase (or fits to aerodatabase)
- Flaps: modified Newtonian

Atmosphere models

- Mars-GRAM
- Exponential atmosphere (for optimal control problems)

Optimal Control Problems

Several optimal control problems are formulated and solved to obtain an unbiased comparison of deterministic entry performance for α - β and bank-angle steering. These optimal control problems all consider the three-degree-of-freedom (3DOF) translational motion of an entry vehicle over a spherical, non-rotating Mars.

Problems under consideration

- Maximum terminal altitude
- Minimum propellant
- Minimum terminal error
- Minimum control effort
- Minimum heat load
- Minimum peak heat rate
- Minimum peak dynamic pressure
- Minimum peak aerodynamic load
- Maximum downrange
- Maximum crossrange

α - β steering offers improved performance over bank-angle steering due to its lower coupling, improved response time, and ability to modulate drag.

Table 1: Maximum terminal altitude results

Case	Terminal Altitude, km
σ : 20 deg/s	18.33
α - β : 20 deg/s	18.81
σ : 5 deg/s	17.70
α - β : 5 deg/s	18.80
σ : 2.5 deg/s	15.99
α - β : 2.5 deg/s	18.63

Table 2: Minimum heat load results

Case	Heat Load, kJ/cm ²
σ : unconstrained	3.17
α - β : unconstrained	3.07
σ : $\theta_f = 10$ deg	3.30
α - β : $\theta_f = 10$ deg	3.16
σ : $\theta_f = 12$ deg	3.48
α - β : $\theta_f = 12$ deg	3.37
σ : $\theta_f = 14$ deg	3.69
α - β : $\theta_f = 14$ deg	3.62

Control Performance

The 3DOF attitude dynamics of an entry vehicle with flaps are assessed in the presence of uncertainty to test flap performance for tracking α - β commands. Both a successive-linearization model predictive controller (MPC) and a linear-quadratic regulator (LQR) are utilized to bound controller performance in terms of algorithm complexity and onboard computational resource requirements.

Using the MPC generally provides improved performance but requires more computational resources.

LQR control law

$$\mathbf{u} = -\mathbf{K}\mathbf{x}_c + \mathbf{u}_e$$

MPC optimization problem

$$\begin{aligned} \min_{\mathbf{z}} \quad & J_{MPC} = \mathbf{z}^T \mathbf{H} \mathbf{z} + \mathbf{f}^T \mathbf{z} \\ \text{s.t.} \quad & \mathbf{A}_{eq} \mathbf{z} = \mathbf{b}_{eq} \\ & \mathbf{P} \mathbf{z} \leq \mathbf{h} \end{aligned}$$

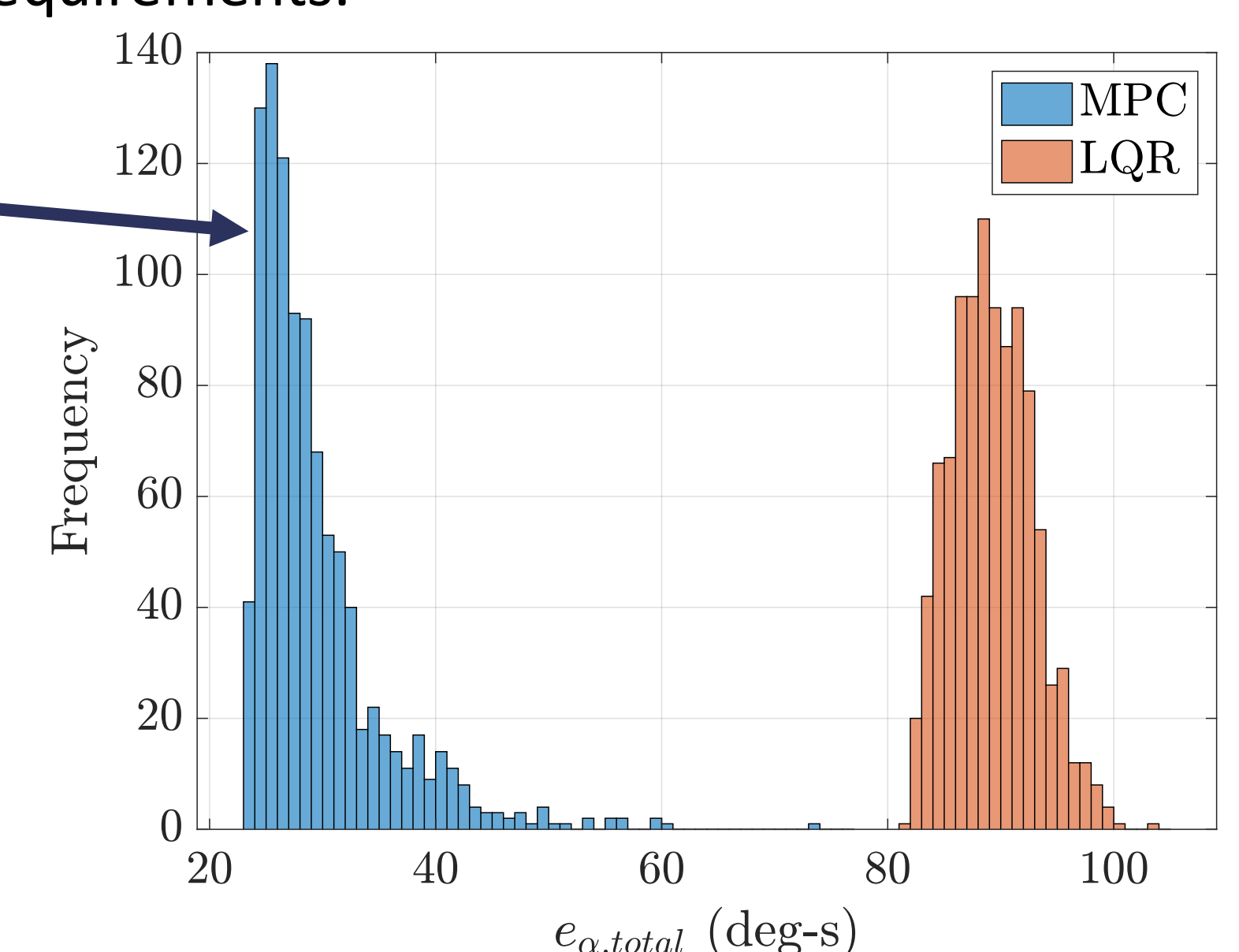


Fig. 6. MPC and LQR Monte Carlo performance

Closed-Loop Flight Performance

The robustness of the two steering options to dispersions is assessed using closed-loop steering commands from both the Apollo final phase guidance algorithm and optimal control solutions. This shows how the translational motion of the two steering options compare in the presence of uncertainty, depending on the class of entry guidance algorithm utilized.

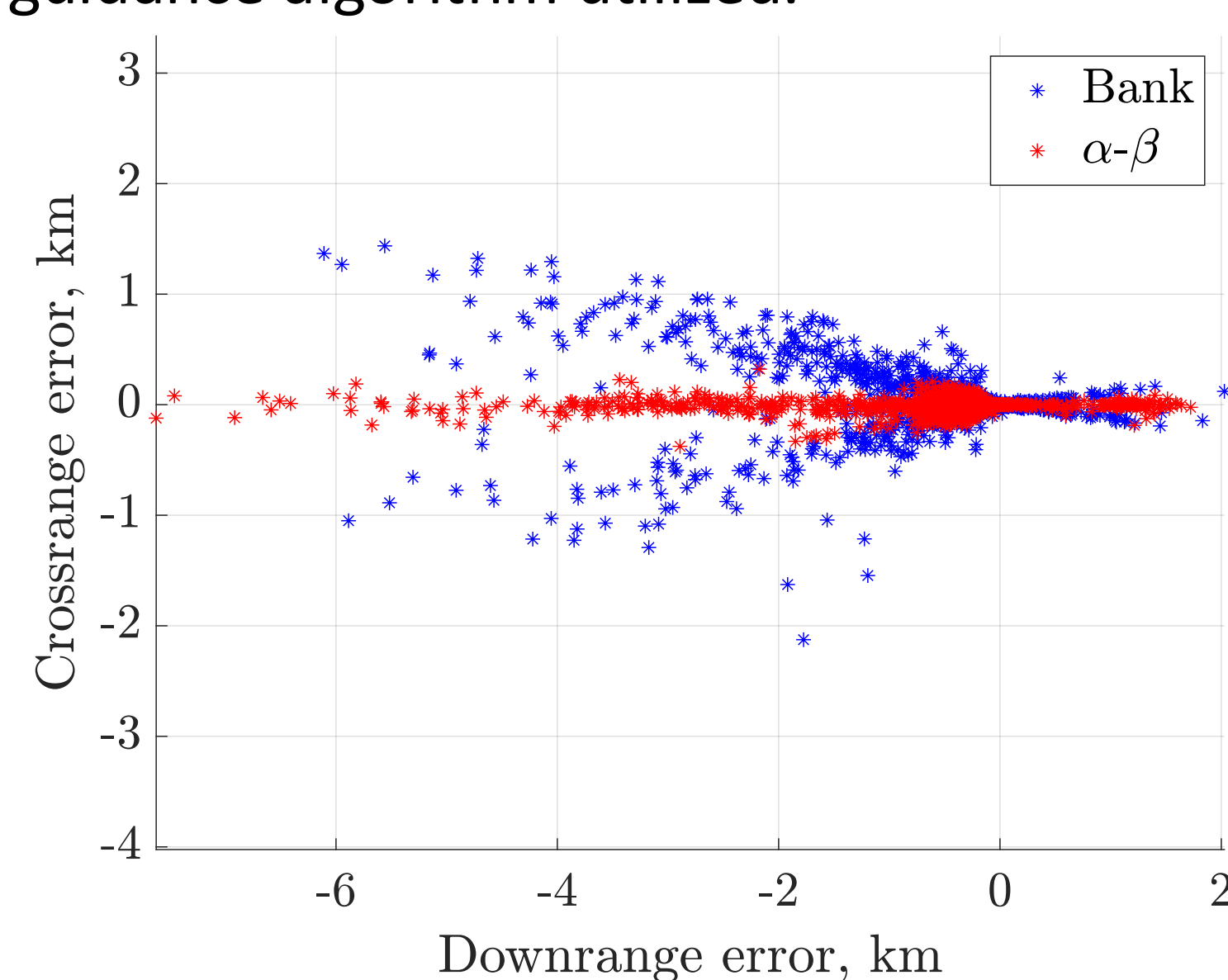


Fig. 7. Terminal position: optimal control

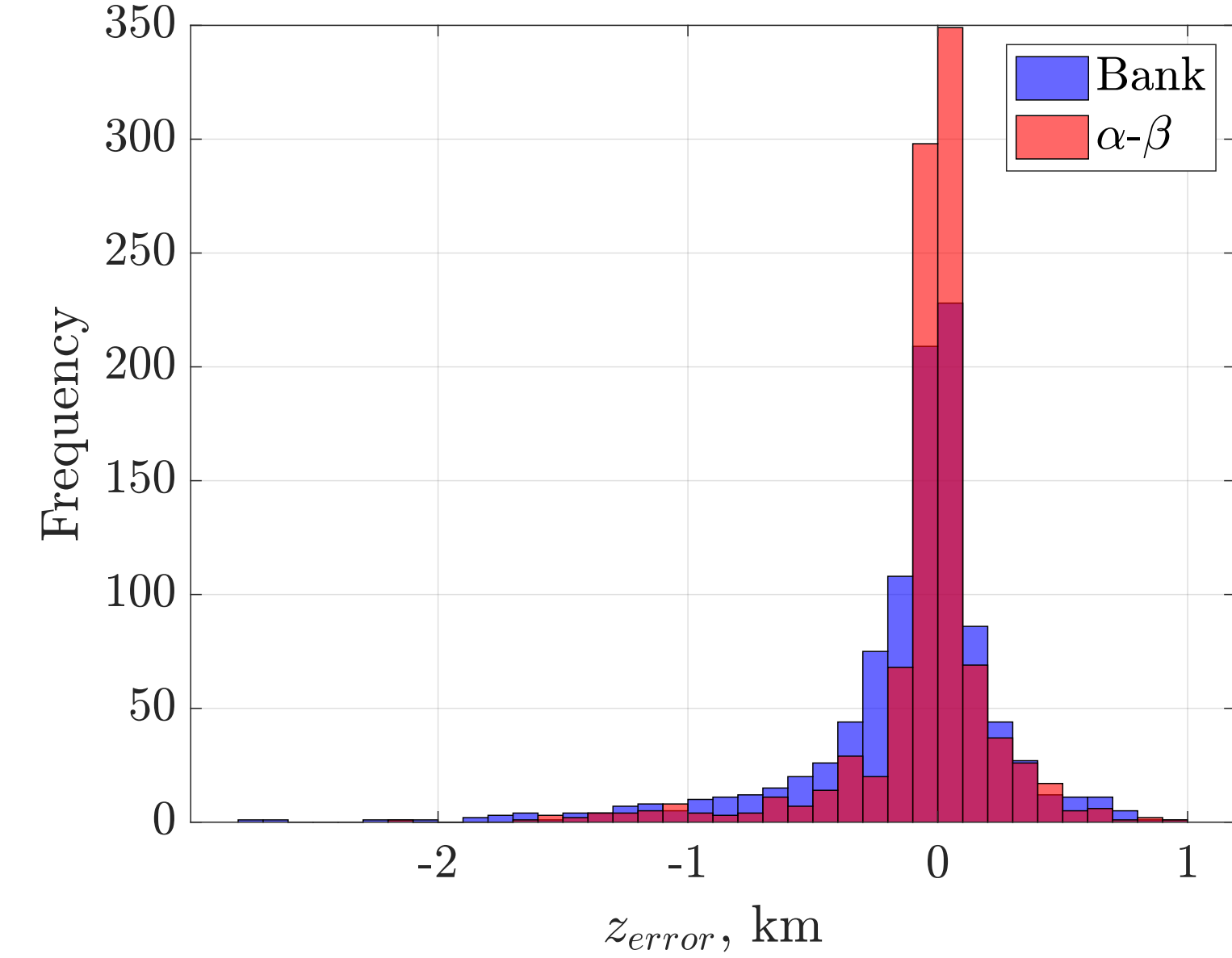


Fig. 8. Altitude histogram: optimal control

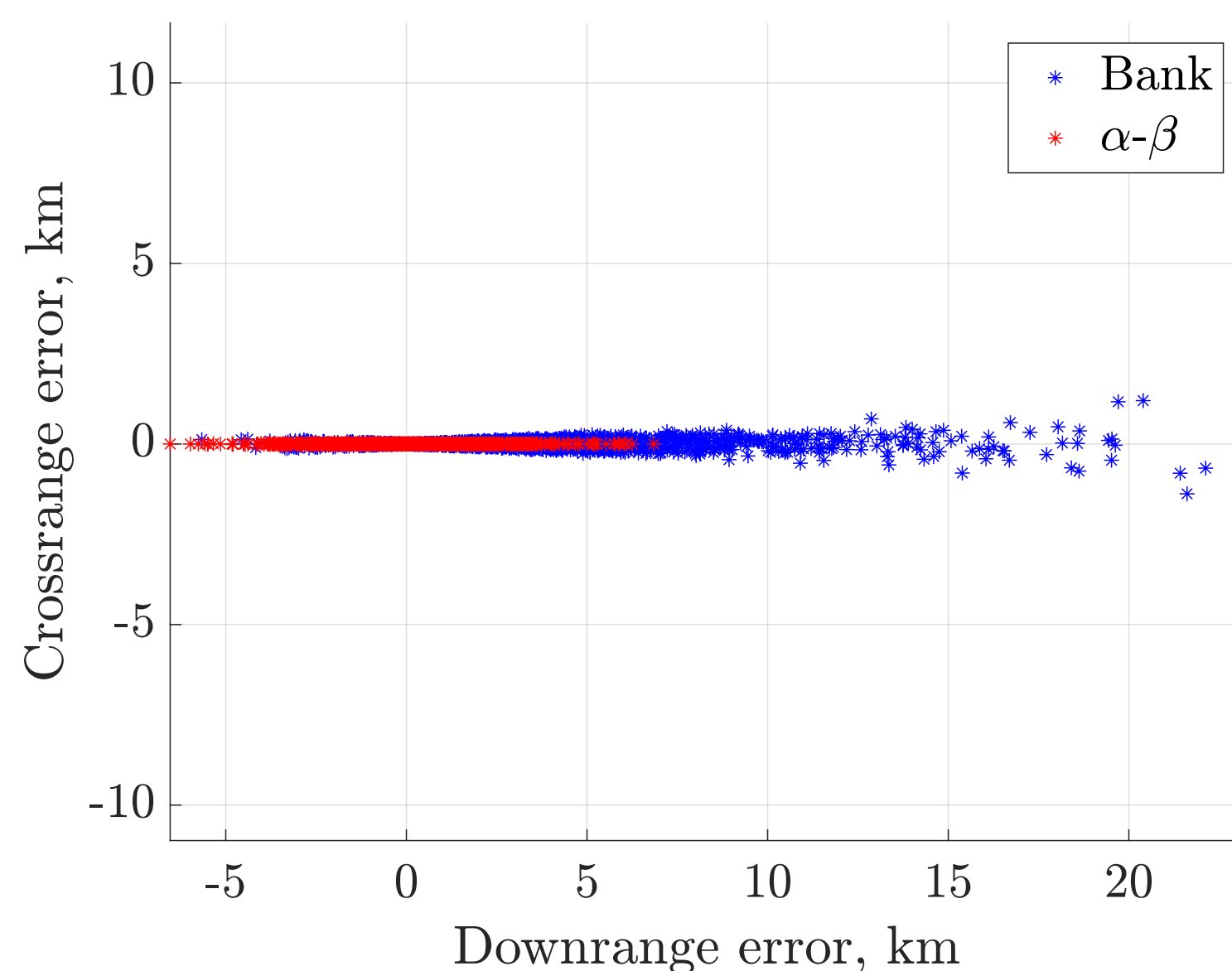


Fig. 9. Terminal position: Apollo guidance

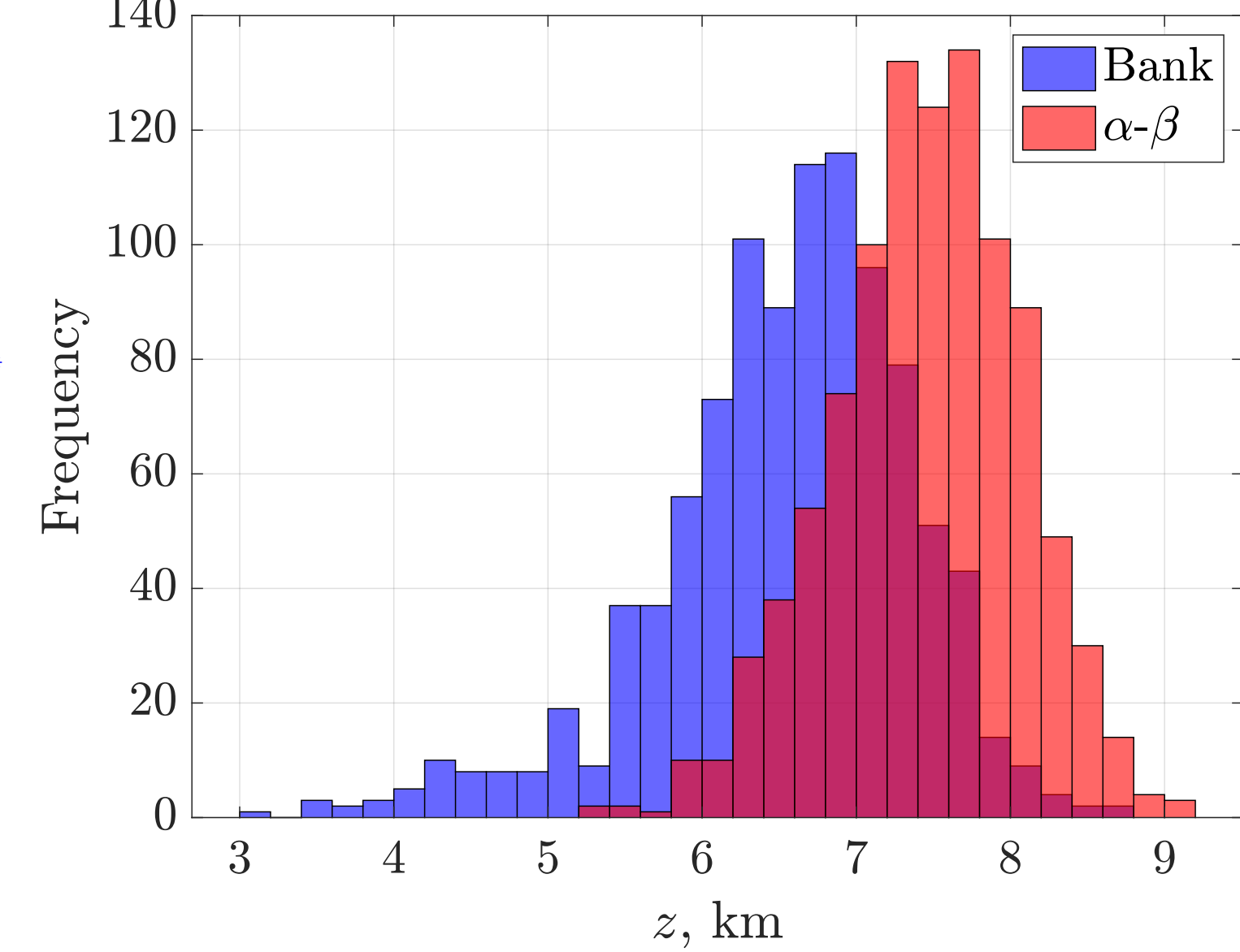


Fig. 10. Altitude histogram: Apollo guidance

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