

# GUIDANCE PERFORMANCE OF BANK-ANGLE AND ALPHA-BETA STEERING FOR A LARGE ROBOTIC MARS ENTRY VEHICLE

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Entry performance using Apollo-based entry guidance is assessed with a future entry system for a large robotic payload. Both a traditional bank-angle steering system and an innovative alpha-beta steering concept are considered to compare flight performance. Results indicate alpha-beta steering provides an order of magnitude improvement in crossrange error and mean altitudes up to 1 km higher than bank-angle steering. Results also show alpha-beta steering provides downrange errors with a spread half of that of bank-angle steering. Lastly, alpha-beta steering is found to provide a narrower spread of terminal altitude, Mach number, and dynamic pressure, indicating safer parachute deploy conditions.

## INTRODUCTION

Recent Mars entry systems have performed hypersonic steering with lift to more accurately target the landing site. These bank-angle steering systems, utilized for the Mars Science Laboratory (MSL)<sup>1</sup> and Mars 2020<sup>2</sup> missions, steer by modulating the bank angle to vary the in-plane component of the lift. Performing bank maneuvers, however places the lift in an out-of-plane direction, resulting in significant coupling in the control over the longitudinal and lateral motion. Bank-angle steering systems so far have relied upon open-loop bank reversals to manage the lateral error from bank maneuvers. While successful for past Mars entry missions, open-loop bank reversals generate perturbations in the trajectory and errors in the guidance.<sup>3</sup> Reliance on more sophisticated guidance algorithms, such as those utilizing optimal control to generate steering commands, may be able to eliminate open-loop bank reversals and reduce the performance losses.<sup>4,5</sup> However, implementation of such algorithms on a flight computer may also require a paradigm shift in onboard computing capability.

Future Mars entry systems for increasingly ambitious robotic payloads, such as the planned Mars Sample Return Sample Retrieval Lander (SRL),<sup>6</sup> may result in a significantly more challenging and aggressive entry as a result of high entry velocities and a larger vehicle ballistic coefficient. Obtaining sufficient landed accuracy, descent timeline, and parachute deploy conditions on these missions will likely be more challenging than on previous missions. Alpha-beta ( $\alpha$ - $\beta$ ) steering, also known as direct force control, is a novel proposed alternative hypersonic steering option, which may provide performance enhancements over bank-angle steering on future Mars entry systems. Instead of modulating the bank angle, these systems change the angle of attack  $\alpha$  and sideslip angle  $\beta$  to directly modulate the aerodynamic forces on the vehicle.<sup>7</sup> This results

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in a much more decoupled control of the longitudinal and lateral motion on the vehicle, with the angle of attack mostly controlling the longitudinal motion and the sideslip angle mostly controlling the lateral motion (although the motion in the two directions still impact each other a small amount<sup>8</sup>).

Several implementations have been considered to achieve  $\alpha$ - $\beta$  steering on an entry vehicle, including a morphing vehicle structure,<sup>3</sup> a center-of-gravity movement system,<sup>9</sup> and aerodynamic flaps.<sup>10</sup> This steering option has also been considered for a combination of entry, aerocapture, or aerogravity assist missions at Venus,<sup>11</sup> Earth,<sup>10</sup> Mars,<sup>12,13</sup> Titan,<sup>14</sup> and Neptune.<sup>15</sup> Comparisons to bank-angle steering have shown  $\alpha$ - $\beta$  steering has the potential to improve landed accuracy and propellant usage for powered-descent on human Mars missions<sup>16</sup> and may also be more robust to atmospheric dispersions,<sup>12</sup> relative to a bank-angle steering system. The solutions to optimal control problems have shown  $\alpha$ - $\beta$  steering provides altitude advantages over bank-angle steering, especially as vehicle maneuverability is lowered, and also results in reduced heat loads and peak heat rates.<sup>17</sup> Optimal control has also been utilized closed-loop for providing steering commands, in order to compare performance of bank-angle and  $\alpha$ - $\beta$  steering when sophisticated steering commands, not reliant on bank reversals, are utilized. While  $\alpha$ - $\beta$  steering generally provided improved lateral and altitude targeting over bank-angle steering, vehicle performance, assuming sufficient maneuverability available, was similar.<sup>4</sup> Due to the reliance of current and future guided Mars entry vehicles on analytical guidance algorithms, such as those based on the Apollo entry guidance algorithm,<sup>18,19</sup> it is important to consider the relative performance of bank-angle steering and  $\alpha$ - $\beta$  steering when this more simple class of guidance algorithm is utilized. These performance differences using conventional entry guidance algorithms can then be contrasted with those using optimal control to determine how bank-angle and  $\alpha$ - $\beta$  steering compare, depending on the sophistication of the entry guidance algorithm. Nearly all studies related to Apollo guidance have considered bank-angle steering. While Apollo-based entry guidance was adapted for  $\alpha$ - $\beta$  steering in two past studies,<sup>9,20</sup> no known studies have compared performance to bank-angle steering or have assessed dispersed performance when using this entry guidance algorithm with  $\alpha$ - $\beta$  steering. In this study, the dispersed performance of a future large robotic Mars entry system is compared between a baseline vehicle using a bank-angle steering system and another vehicle utilizing an  $\alpha$ - $\beta$  steering system. Both steering options use Apollo-based guidance algorithms to show how the two steering options compare, without making any major advancements or changes in the guidance.

## METHODOLOGY

### Equations of Motion and Models

Entry guidance performance is assessed by simulating the translational motion of the entry vehicle over an oblate, rotating Mars. The equations of motion (1)-(6)<sup>21</sup> describe this entry flight, where  $r$  is the radial distance of the entry vehicle from the center of Mars,  $\theta$  is the longitude,  $\phi$  is the latitude,  $V$  is the Mars-relative velocity magnitude,  $\gamma$  is the Mars-relative flight-path angle,  $\psi$  is the Mars-relative azimuth angle, and  $\Omega$  is the rotation rate of Mars.

$$\dot{r} = V \sin \gamma \quad (1)$$

$$\dot{\theta} = \frac{V \cos \gamma \sin \psi}{r \cos \phi} \quad (2)$$

$$\dot{\phi} = \frac{V \cos \gamma \cos \psi}{r} \quad (3)$$

$$\dot{V} = -D - g_r \sin \gamma - g_\phi \cos \gamma \cos \psi + \Omega^2 r \cos \phi (\sin \gamma \cos \phi - \cos \gamma \sin \phi \cos \psi) \quad (4)$$

$$\begin{aligned} \dot{\gamma} = \frac{1}{V} \left[ L \cos \sigma - Y \sin \sigma + \left( \frac{V^2}{r} - g_r \right) \cos \gamma + g_\phi \sin \gamma \cos \psi + 2\Omega V \cos \phi \sin \psi \right. \\ \left. + \Omega^2 r \cos \phi (\cos \gamma \cos \phi + \sin \gamma \cos \psi \sin \phi) \right] \quad (5) \end{aligned}$$

$$\dot{\psi} = \frac{1}{V} \left[ \frac{Y \cos \sigma + L \sin \sigma}{\cos \gamma} + \frac{V^2}{r} \cos \gamma \sin \psi \tan \phi + g_\phi \frac{\sin \psi}{\cos \gamma} - 2\Omega V (\tan \gamma \cos \psi \cos \phi - \sin \phi) + \frac{\Omega^2 r}{\cos \gamma} \sin \psi \sin \phi \cos \phi \right] \quad (6)$$

Here,  $g_r$  and  $g_\phi$  are the components of the acceleration due to gravity, including  $J_2$  effects:<sup>21</sup>

$$g_r = \frac{\mu}{r^2} \left[ 1 + J_2 \left( \frac{R_m}{r} \right)^2 (1.5 - 4.5 \sin^2 \phi) \right] \quad (7)$$

$$g_\phi = \frac{\mu}{r^2} \left[ J_2 \left( \frac{R_m}{r} \right)^2 (3 \sin \phi \cos \phi) \right] \quad (8)$$

In these expressions,  $\mu$  is the gravitational parameter, and  $R_m$  is the radius of Mars.  $D$ ,  $L$ , and  $Y$  are the aerodynamic drag, lift, and side force accelerations given by the following, where  $m$  is the mass,  $q_\infty$  is the freestream dynamic pressure, and  $S_{ref}$  is the aerodynamic reference area of the entry vehicle.

$$D = \frac{q_\infty S_{ref} C_D}{m} \quad (9)$$

$$L = \frac{q_\infty S_{ref} C_L}{m} \quad (10)$$

$$Y = \frac{q_\infty S_{ref} C_Y}{m} \quad (11)$$

The MSL aerodynamics database<sup>22,23</sup> is utilized to compute the drag, lift, and side-force coefficients  $C_D$ ,  $C_L$ , and  $C_Y$ , respectively, and the Mars Global Reference Atmosphere Model (Mars-GRAM) is utilized to compute atmospheric properties.<sup>24</sup> The geometric altitude  $z$  is computed using  $z = r - R_m$ . Initial conditions for the entry state are provided in Table 1.

**Table 1:** Entry Initial Conditions

| Parameter | Value   |
|-----------|---------|
| $z$       | 135 km  |
| $\theta$  | 0 deg   |
| $\phi$    | 0 deg   |
| $V$       | 8 km/s  |
| $\gamma$  | -13 deg |
| $\psi$    | 90 deg  |

The entry vehicle under consideration is a state-of-the-art blunt-body 70 deg sphere-cone vehicle, using either bank-angle or  $\alpha$ - $\beta$  steering. To assess implications of bank-angle steering and  $\alpha$ - $\beta$  steering on large and aggressive future Mars entry systems, the vehicle model is based on concepts for SRL.<sup>6,25</sup> Such a system is representative of a heavy robotic entry system as a precursor to human Mars missions. Entry vehicle properties for both steering options are shown in Table 2. The baseline vehicle uses a bank-angle steering system to steer during entry and flies at a hypersonic trim angle of attack  $\alpha_{bank} = -19$  deg, providing a hypersonic lift-to-drag ratio ( $L/D$ ) of 0.29. A diagram showing the aerodynamic forces on the bank-angle steering vehicle is shown in Figure 1a. Here, a positive bank angle is defined as a turn to the right. The vehicle using  $\alpha$ - $\beta$  steering flies at a variable angle of attack and sideslip angle, where  $-\alpha_{total,max} \leq \alpha \leq \alpha_{total,max}$  and  $-\alpha_{total,max} \leq \beta \leq \alpha_{total,max}$ . Furthermore, the total angle of attack  $\alpha_{total}$  is constrained such that  $\alpha_{total} = \cos^{-1}(\cos \alpha \cos \beta) \leq \alpha_{total,max}$ . These constraints on the allowable  $\alpha$  or  $\beta$  values commanded from the guidance ensure the control authority of the  $\alpha$ - $\beta$  steering vehicle does not exceed that of the bank-angle steering vehicle, ensuring a fair comparison. Figure 1b shows  $\alpha$  and  $\beta$  on the entry vehicle, where a

positive sideslip angle is defined as a positive rotation of the vehicle from the wind-relative velocity vector about the z-axis, and a positive angle of attack is defined as a subsequent positive rotation about the y-axis. Entry simulations for both steering options assume finite rate and acceleration limits, and the magnitudes of these values are also provided in Table 2.

**Table 2:** Entry Vehicle Properties

| Parameter             | Value                   |
|-----------------------|-------------------------|
| m                     | 5900 kg                 |
| Base radius           | 2.36 m                  |
| $\alpha_{total,max}$  | 19 deg                  |
| $\alpha_{bank}$       | -19 deg                 |
| $\dot{\sigma}_{max}$  | 20 deg/s                |
| $\dot{\alpha}_{max}$  | 20 deg/s                |
| $\dot{\beta}_{max}$   | 20 deg/s                |
| $\ddot{\sigma}_{max}$ | 2.75 deg/s <sup>2</sup> |
| $\ddot{\alpha}_{max}$ | 2.75 deg/s <sup>2</sup> |
| $\ddot{\beta}_{max}$  | 2.75 deg/s <sup>2</sup> |

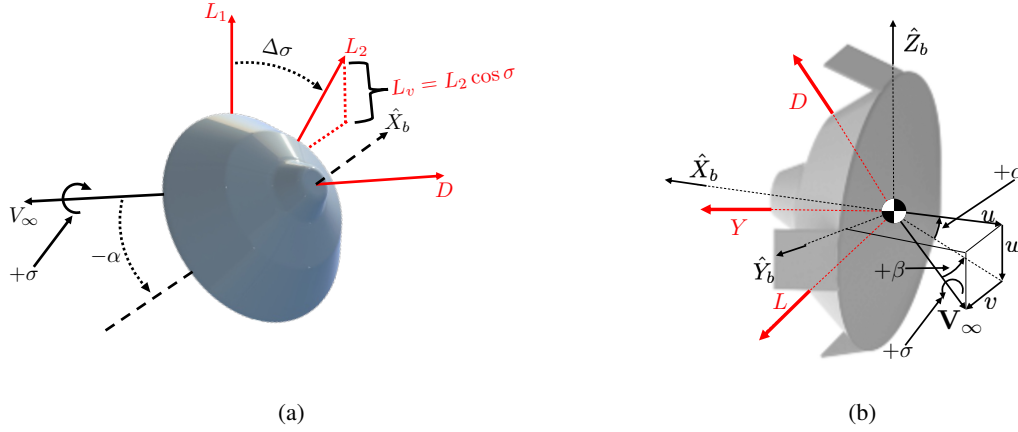


**Figure 1:** Steering option diagrams: (a) bank-angle steering and (b)  $\alpha$ - $\beta$  steering.

## Guidance Algorithms

Past guided Mars entry missions have used a variation of the Apollo entry guidance algorithm<sup>18</sup> to obtain bank commands during entry. This guidance algorithm is the baseline for SRL and is representative of a simpler, analytical guidance algorithm that is the current state-of-practice for Mars entries, compared to more computationally heavy numerical predictor-corrector algorithms<sup>7,26</sup> or optimal control schemes.<sup>4</sup> The Entry Terminal Point Controller<sup>19,27,28</sup> utilized for MSL and Mars 2020 is split into three phases: constant bank, range control, and heading alignment. Range control is the primary phase of flight and is based on the final phase of the Apollo Command Module entry guidance algorithm. During range control, the vehicle modulates its bank angle in response to drag acceleration and altitude rate errors in order to reach the desired downrange position at the terminal velocity. Implementation of this guidance algorithm requires an offline reference trajectory generation. This is achieved by simulating the open-loop, planar flight of the vehicle with a desired reference bank profile, providing the reference drag acceleration  $D_{ref}$ , reference altitude rate  $\dot{z}_{ref}$ , reference range-to-go  $R_{ref}$ , and reference lift-to-drag ratio  $L/D_{ref}$ . Using data from the reference trajectory, a backwards integration of the equations adjoint to the Jacobian of the planar entry equations of

motion yields the gains  $F_1$ ,  $F_2$ , and  $F_3$ , which are used to converge the vehicle to the target downrange at the terminal velocity.

The reference trajectory and gains are then implemented in the guidance as follows. The vehicle begins entry flying a constant bank angle, corresponding to the initial bank angle from the reference trajectory. At a drag acceleration of 0.2 g, range control begins. Drag acceleration and altitude rate data, along with the reference range-to-go, are used to predict the current range-to-go  $R_p$ , as shown in Eq. (12).

$$R_p = R_{ref} + F_1 (D - D_{ref}) + F_2 (\dot{z} - \dot{z}_{ref}) \quad (12)$$

The reference lift-to-drag ratio and the difference between the actual range-to-go  $R$  and  $R_p$  are used to compute a vertical lift-to-drag ratio command  $L/D_v$ . Here,  $K = 4$  is the overcontrol gain, a constant gain which is used to set the sensitivity of the guidance to drag and altitude rate errors.

$$L/D_v = L/D_{ref} + \frac{K}{F_3} (R - R_p) \quad (13)$$

$L/D_v$  is then translated to a bank angle magnitude command  $\sigma_{mag}$  by taking the inverse cosine of  $L/D_v$  divided by the nominal lift-to-drag ratio  $L/D_{nom}$ .

$$\sigma_{mag} = \cos^{-1} \left( \frac{L/D_v}{L/D_{nom}} \right) \quad (14)$$

These bank angle commands allow the vehicle to steer to the desired downrange, however any bank angles other than 0 or 180 deg result in out-of-plane motion. To manage the crossrange error and mitigate this out-of-plane motion, the sign of the bank angle is changed through open-loop bank reversals when the vehicle exceeds pre-designed deadbands of the lateral angle  $\lambda$  from the target as a function of velocity.  $\lambda$  is defined as the angle between the plane formed the velocity plane, containing the current inertial position and velocity vectors of the entry vehicle, and the target plane containing the current inertial position vectors of the vehicle and the guidance target.  $\lambda$  is calculated using the following expression, assuming the small angle approximation.<sup>29</sup>

$$\lambda = -\mathbf{U}_{tgt} \cdot \mathbf{U}_{norm} \quad (15)$$

Here,  $\mathbf{U}_{tgt}$  is the current inertial position unit vector of the guidance target, and  $\mathbf{U}_{norm}$  is the unit vector normal to the velocity plane. The lateral deadbands used to determine when the vehicle performs a bank reversal are quadratic functions of velocity and take the following form.

$$\lambda_{db,1}(V) = \frac{L/D_{nom}}{db1} \left( \frac{V}{V_{circ}} \right)^2 + \frac{db1,min}{R_m} \quad (16)$$

$$\lambda_{db,2}(V) = \frac{L/D_{nom}}{db2} \left( \frac{V}{V_{circ}} \right)^2 + \frac{db2,min}{R_m} \quad (17)$$

The two reversal deadbands,  $\lambda_{db,1}(V)$  and  $\lambda_{db,2}(V)$ , describe the lateral deadbands before and after the first bank reversal, respectively; previous Mars entries have used narrower deadbands for the first bank reversal to force an early bank reversal. The quadratic parameters db1 and db2 are most important and describe the overall shape of the two deadbands. The larger db1 or db2, the narrower the deadband. db1,min and db2,min are the constant terms describing the allowable lateral error at the end of the trajectory, and  $V_{circ}$  is a normalization velocity equal to the circular orbital velocity at the equatorial radius of Mars. The bank reversals in this study are all performed over-the-top, where the bank angle passes through a lift-up orientation/zero deg during the reversal.

Once the vehicle passes through a velocity of 1400 m/s, it transitions into the heading alignment portion of flight. The vehicle stops controlling its downrange to the target and instead flies mostly lift-up with a saturation bank angle of  $\pm 30$  deg, while nulling its remaining lateral error by flying straight to the target

laterally, as shown in Eq. (18). Here,  $\theta_{to-go}$  is the current great-circle angular distance to the target site, and  $K_{HA} = 100$  is a constant gain for heading alignment.

$$\sigma_{HA} = K_{HA} \tan^{-1} \left( \frac{\lambda}{\theta_{to-go}} \right) \quad (18)$$

While the Entry Terminal Point Controller was originally designed for bank-angle steering, it can also be adapted for  $\alpha$ - $\beta$  steering to compare the two hypersonic steering options with a similar Apollo-based guidance algorithm. Two past studies adapted Apollo-based entry guidance for  $\alpha$ - $\beta$  steering;<sup>9,20</sup> here an independently developed method is used to provide angle of attack commands, and a method for providing sideslip angle commands is taken from Ref 9. Similar to bank-angle steering, the  $\alpha$ - $\beta$  steering implementation for the guidance begins with a constant angle of attack phase (sideslip angle is held at zero deg). At 0.2 g drag acceleration, the vehicle begins range control. Range control for  $\alpha$ - $\beta$  steering still uses equations (12) and (13) to compute vertical lift-to-drag ratio commands. However, these commands are mapped to  $\alpha$ - $\beta$  commands instead of bank commands. Furthermore, due to the low coupling in the control over the longitudinal and lateral motion on vehicles using  $\alpha$ - $\beta$  steering, a command for  $L/D_v$  can be mapped directly to a commanded  $\alpha$ . This is accomplished in this study by querying the MSL aerodynamics database offline over several Mach numbers and angle of attack values. The data is then interpolated in flight with the current Mach number and commanded  $L/D_v$  to obtain the angle of attack command. While the angle of attack is used to target the downrange position during range control, the sideslip angle is used to null any lateral error. This is accomplished, as suggested in Ref. 9, by selecting  $\beta$  such that the vehicle flies straight toward the target laterally. With a certain desired velocity vector  $\mathbf{V}_{des}$ , the vehicle can be made to fly towards the target.  $\mathbf{V}_{des}$  is computed in the body frame as shown in Eq. (19) using the vector  $\mathbf{r}_{ct}$ , which points from the vehicle to the target, and the rotation matrix  $\mathcal{R}$ , which converts from a planet-centered inertial frame to the vehicle body frame.

$$\mathbf{V}_{des} = [u \quad v \quad w]^T = V\mathcal{R} \frac{\mathbf{r}_{ct}}{|\mathbf{r}_{ct}|} \quad (19)$$

The sideslip angle is defined is the inverse sin of the ratio between the lateral component  $v$  of the velocity vector in the body frame divided by the velocity magnitude. Hence, the commanded sideslip angle  $\beta_{cmd}$  to fly towards the target can be computed by Eq. (20). A gain  $K_\beta = 0.7$  is used to prevent the guidance from overcorrecting.

$$\beta_{cmd} = K_\beta \sin^{-1} \left( \frac{v}{|\mathbf{V}_{des}|} \right) \quad (20)$$

It is possible the commanded  $\alpha$ - $\beta$  values may beyond that achievable by the vehicle. If the steering commands yield a total angle of attack above  $\alpha_{total,max}$ ,  $\alpha$ - $\beta$  commands are reduced to provide values achievable by the vehicle. In these scenarios, the angle of attack is given priority over the sideslip angle if it is the sideslip angle causing the total angle of attack to saturate.

Due to the low coupling of the control over the longitudinal and lateral motion on vehicles using  $\alpha$ - $\beta$  steering, no heading alignment phase is needed to fly out lateral errors (the sideslip angle has been correcting these during range control). The vehicle could stay in range control until terminal descent initiation, however staying in range control this long may sacrifice altitude performance. As a compromise, the vehicle is chosen to stay in range control until it passes through a velocity of 1000 m/s, providing additional time in range control over bank-angle steering. Below this velocity, the vehicle flies full lift-up at  $\alpha = -19$  deg and at  $\beta = 0$  deg to raise the terminal altitude. Guided entry, as well as the simulation in this study, end at terminal descent initiation (TDI)/Straighten-Up and Fly Right (SUFR) when the vehicle begins to prepare for parachute deploy. This is initiated either by a velocity trigger at a velocity of 540 m/s or with a range trigger, when the range-to-go calculated by the guidance passes through zero. Perfect navigation is assumed in these guidance/trajectory simulations.

Tuning for the various guidance parameters and lateral deadbands was done using a combination of heuristic tuning of nominal and dispersed cases, as well as the values used for past Mars entries and those baselined for SRL. Both steering options utilize the same reference  $L/D$  profile, although the individual reference trajectories and gains for the two steering options are different. The reference trajectory generation for both

steering options use the bank profile shown in Figure 2 ( $\alpha$ - $\beta$  steering uses the  $L/D$  profile corresponding to this bank angle profile for its reference trajectory generation). The utilized reference bank profile is helpful for providing sufficient altitude for parachute deploy.

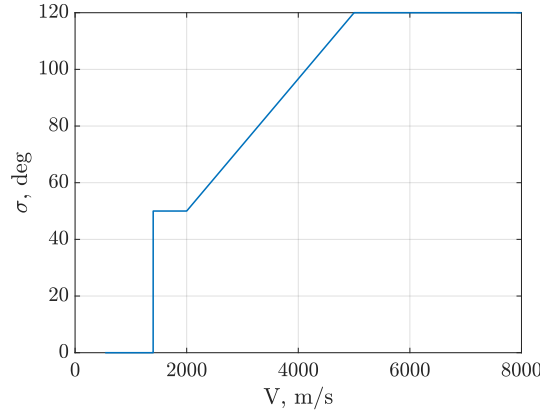


**Figure 2:** Reference bank angle profile.

## RESULTS

### Nominal Performance

The guidance performance of the two hypersonic steering options is first assessed in nominal cases. A target longitude and latitude of 19.87 deg and 0 deg are utilized, respectively, and the guidance for each steering option is tuned to closely hit the target in the nominal case. Lateral deadbands for bank-angle steering have a strong impact on vehicle behavior and needed to be modified to hit the target accurately in the nominal case while also having a desired three bank reversals. Both steering options closely hit the target in the nominal case, with bank-angle steering and  $\alpha$ - $\beta$  steering having downrange errors of 100.80 m and -136.30 m, respectively. The crossrange errors for the two steering options are nearly zero in these nominal cases.

Trajectory results for the nominal case are shown in Figure 3. In the nominal case, the vehicle using  $\alpha$ - $\beta$  steering has no out-of-plane motion, a contrast to bank-angle steering which has significant out-of-plane motion as a result of its high coupling of the control over the longitudinal and lateral motion. Hence, results for  $\alpha$ - $\beta$  steering are also shown for a case where the vehicle begins flight at a latitude of 0.5 deg; this case is perhaps more interesting, as it results in out-of-plane motion by the vehicle and requires the sideslip angle to be used to reach the desired latitude. The plot of altitude versus velocity in Figure 3a show the vehicle using  $\alpha$ - $\beta$  steering generally decelerates at a higher altitude than bank-angle steering. Much of this behavior is a result of the  $\alpha$ - $\beta$  steering vehicle flying at an angle of attack magnitude lower than  $\alpha_{bank}$ . This increases drag, reducing the ballistic coefficient and results in a deceleration at a higher altitude. The open loop bank reversals also typically (but not always) reduce altitude performance over the course of the trajectory, although they may provide a short term positive altitude perturbation. This is seen near 6 km/s and 3 km/s, for example, as a result of the first two bank reversals, where the altitude versus velocity profile for bank-angle steering moves close to or above the profile for  $\alpha$ - $\beta$  steering. Also as a consequence of flying with higher drag, the reference trajectory for  $\alpha$ - $\beta$  steering has a shorter angular distance flown, relative to bank-angle steering. To keep the same target longitude, the  $\alpha$ - $\beta$  steering vehicle enters at a longitude of 0.74 deg (the difference between the angular distances flown by the two steering options in their reference trajectories). This is shown in Figure 3b, where both cases of  $\alpha$ - $\beta$  steering have a non-zero initial longitude.

The bank profile for the bank-angle steering vehicle is shown in Figure 4a. Flight begins with a slew to a constant bank angle of 120 deg, and the vehicle then begins range control at about 50 s. Three bank reversals

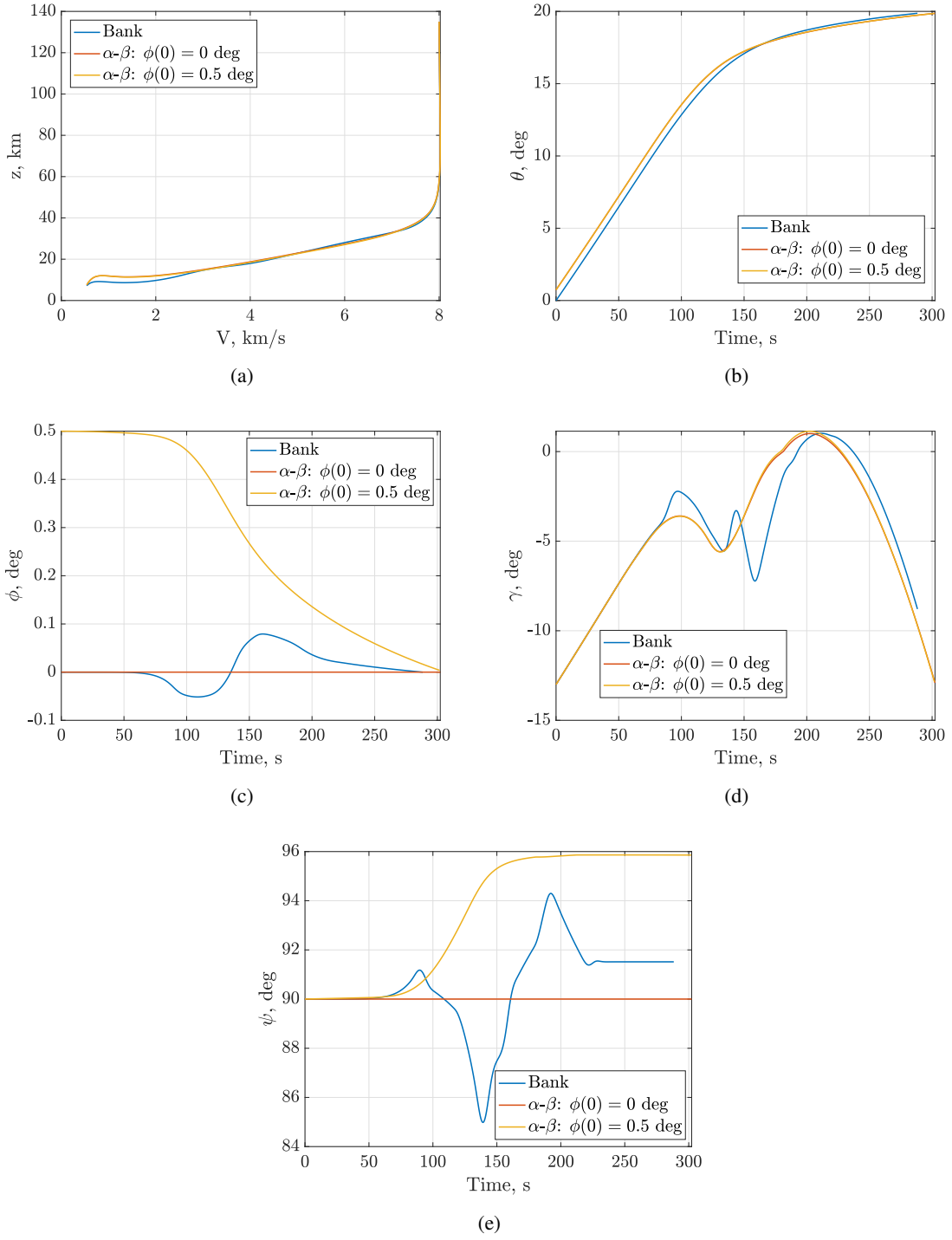


**Figure 3:** Trajectory results: (a) altitude versus velocity, (b) longitude versus time, (c) latitude versus time, (d) flight-path angle versus time, and (e) azimuth angle versus time.

are performed during range control. The bank reversals are all performed over-the-top, and the lateral motion (plotted in blue) and lateral deadbands (plotted in red) are shown in Figure 4b. At about 190 s, the guidance

enters heading alignment, where the bank angle saturates at the -30 deg heading alignment limit for about 20 s. After this, nearly all lateral error has been flown out, and the vehicle flies full lift-up for the remainder of the flight.

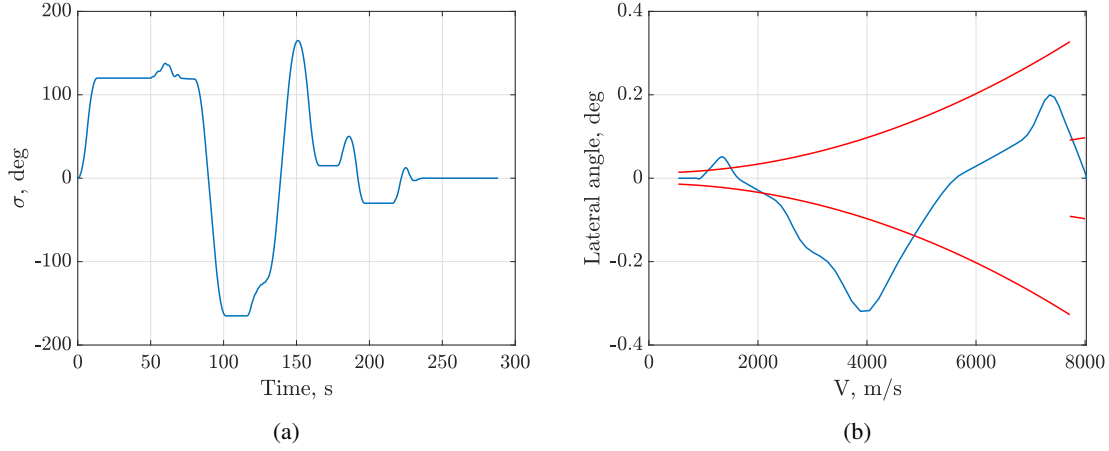


**Figure 4:** Nominal bank-angle steering results: (a) bank angle profile and (b) lateral motion.

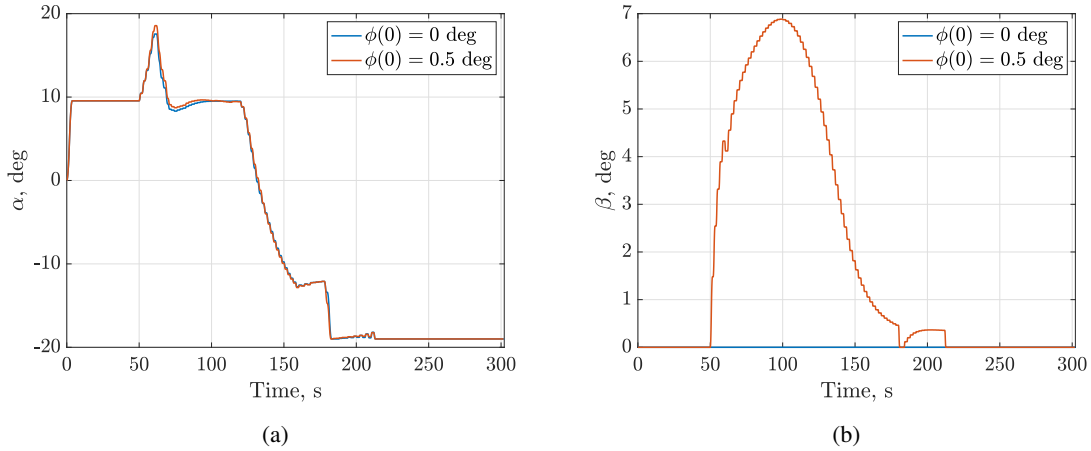


**Figure 5:** Nominal  $\alpha$ - $\beta$  steering results: (a) angle of attack profile and (b) sideslip angle profile.

Nominal control profiles for the vehicle using  $\alpha$ - $\beta$  steering are shown in Figure 5. The angle of attack profile in Figure 5a show the vehicle does an initial slew to a constant angle of attack of 9.55 deg. Range control begins around 50 s, with both negative and positive lift utilized during flight. As the control over the longitudinal and lateral motion is mostly decoupled for  $\alpha$ - $\beta$  steering, no control reversals are utilized. Once the vehicle passes through a velocity of 1000 m/s at 213 s, it flies full lift-up for the remainder of flight. The sideslip angle profile is shown in Figure 5b. When the vehicle begins flight at a latitude of zero deg, no sideslip is needed in flight, as the vehicle is already laterally aligned with the target. With a large initial latitude error, however, the vehicle uses up to 6.88 deg of sideslip to fly out this error.

### Dispersed Performance

Monte Carlo simulations are used to stress the guidance algorithms and test the robustness of the two steering options to dispersions. 1000 samples are used in each Monte Carlo simulation, and the dispersions

in the entry state, atmosphere model, aerodynamic coefficients, and mass are shown in Table 3.<sup>30</sup> Here  $C_A$  and  $C_N$  are the axial and normal force coefficients, respectively, and are used to calculate  $C_D$ ,  $C_L$ , and  $C_Y$ . Results are first considered using a velocity trigger. Statistics for the downrange error (DR), crossrange error (CR), and terminal altitude are provided in Table 4, and results are also presented graphically in Figure 6. With a velocity trigger, the bank-angle steering vehicle has a 28.82 km  $\times$  3.44 km ellipse at TDI, compared to the  $\alpha$ - $\beta$  steering vehicle, which has a 13.39 km  $\times$  28.50 m ellipse.  $\alpha$ - $\beta$  steering has a noticeably improved downrange targeting over bank-angle steering, where the standard deviation and length of the downrange diameter for  $\alpha$ - $\beta$  steering are about half as large as that of bank-angle steering. While the mean downrange error is only on the order of a hundred meters for  $\alpha$ - $\beta$  steering, the mean downrange error is about 4 km for bank-angle steering. The larger mean and standard deviations for the bank-angle steering downrange errors are due to poorly timed, large bank reversals in the top 20 percentile of cases, which result in the vehicle significantly overshooting the target. While further tuning and adjustments may be able to improve some of these individual cases, it is unlikely to be able to resolve all of the cases. The presence of these issues associated with bank reversals show a major disadvantage of bank-angle steering.

**Table 3:** Monte Carlo Dispersions

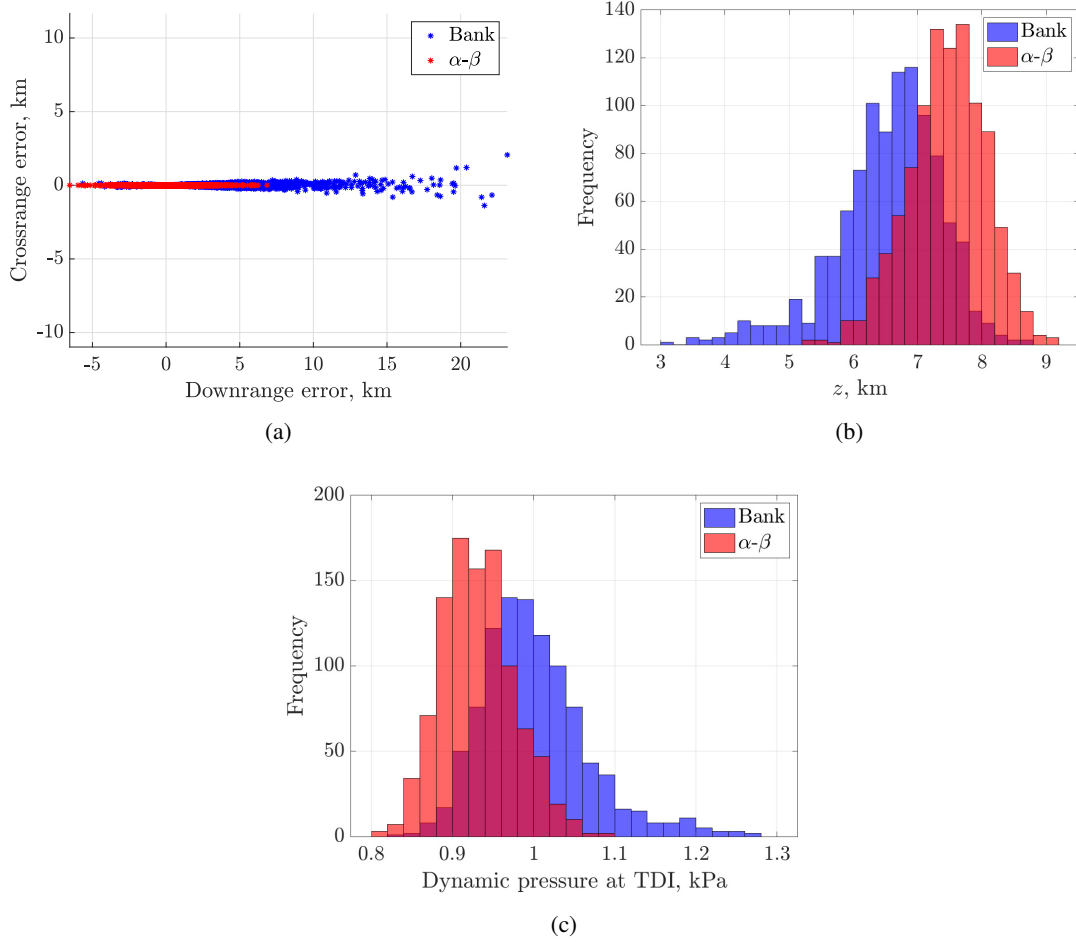
| Variable                  | Dispersion                 | Distribution |
|---------------------------|----------------------------|--------------|
| Initial altitude          | $\pm 2.8$ km $3\sigma$     | Gaussian     |
| Initial longitude         | $\pm 0.017$ deg $3\sigma$  | Gaussian     |
| Initial latitude          | $\pm 0.013$ deg $3\sigma$  | Gaussian     |
| Initial velocity          | $\pm 2$ m/s $3\sigma$      | Gaussian     |
| Initial flight-path angle | $\pm 0.2$ deg $3\sigma$    | Gaussian     |
| Initial azimuth           | $\pm 0.006$ deg $3\sigma$  | Gaussian     |
| Atmosphere profile        | 1000 Mars-GRAM atmospheres | -            |
| Hypersonic $C_A$          | $\pm 3\%$ $3\sigma$        | Gaussian     |
| Hypersonic $C_N$          | $\pm 5\%$ $3\sigma$        | Gaussian     |
| Supersonic $C_A$          | $\pm 10\%$ $3\sigma$       | Gaussian     |
| Supersonic $C_N$          | $\pm 8\%$ $3\sigma$        | Gaussian     |
| Mass                      | $\pm 2$ kg $3\sigma$       | Gaussian     |

$\alpha$ - $\beta$  steering also has significantly improved crossrange performance over bank-angle steering, with worst case crossrange errors on the order of tens of meters, compared to the 2 km crossrange errors possible on the bank-angle steering system. The improved crossrange error for the  $\alpha$ - $\beta$  steering vehicle is a result of their significantly lower coupling in the control over the longitudinal and lateral motion, the lack of any open-loop control reversals, and the ability to directly null out crossrange errors. This contrasts with bank-angle steering, which can have off-nominal cases where the bank reversals result in the vehicle getting stuck outside of the lateral deadbands during flight, causing large crossrange errors. Results also show  $\alpha$ - $\beta$  steering provides mean terminal altitudes about 0.9 km higher than bank-angle steering, indicating improved margin in the descent timeline. The standard deviation for altitude is about 27% lower for  $\alpha$ - $\beta$  steering as well. The guidance is not doing anything to try to raise the altitude, rather the deceleration at a higher altitude associated with  $\alpha$ - $\beta$  steering and the lack of open-loop bank reversals result in these higher altitudes. Just as with the downrange and crossrange, poorly timed bank reversals decrease the altitude performance in certain cases for bank-angle steering, resulting in terminal altitudes between 3 km and 5 km, not seen for  $\alpha$ - $\beta$  steering. The improved altitude performance of  $\alpha$ - $\beta$  steering over bank-angle steering also provides improved terminal dynamic pressure performance, as shown in Figure 6c. The standard deviation for terminal dynamic pressure for bank-angle steering is 0.07 kPa, compared to 0.05 kPa associated with  $\alpha$ - $\beta$  steering. This lower standard deviation for dynamic pressure indicates a narrower range of conditions needed to be tolerable for parachute deployment and a potential improvement in mission safety.

To illustrate the impact of the coupling in the control on the bank-angle steering system, an additional Monte Carlo simulation was performed for bank-angle steering with the out-of-plane motion turned off so

**Table 4:** Velocity Trigger Monte Carlo Results

| Parameter | DR: $\sigma$ , km | DR: $\alpha\text{-}\beta$ , km | CR: $\sigma$ , km     | CR: $\alpha\text{-}\beta$ , km | $z$ : $\sigma$ , km | $z$ : $\alpha\text{-}\beta$ , km |
|-----------|-------------------|--------------------------------|-----------------------|--------------------------------|---------------------|----------------------------------|
| Mean      | 4.18              | 0.13                           | $6.97 \times 10^{-3}$ | $-1.40 \times 10^{-5}$         | 6.56                | 7.45                             |
| SD        | 4.53              | 1.97                           | 0.17                  | $2.80 \times 10^{-3}$          | 0.83                | 0.61                             |
| 0.1%      | -5.66             | -6.54                          | -1.38                 | $-1.30 \times 10^{-2}$         | 3.06                | 5.29                             |
| 1%        | -3.16             | -4.81                          | -0.45                 | $-7.96 \times 10^{-3}$         | 4.03                | 5.94                             |
| 10%       | -0.77             | -2.50                          | -0.15                 | $-2.97 \times 10^{-3}$         | 5.55                | 6.64                             |
| 50%       | 3.37              | 0.13                           | $8.88 \times 10^{-3}$ | $-2.80 \times 10^{-5}$         | 6.66                | 7.48                             |
| 90%       | 10.37             | 2.49                           | 0.15                  | $2.91 \times 10^{-3}$          | 7.48                | 8.20                             |
| 99%       | 19.04             | 5.25                           | 0.37                  | $8.98 \times 10^{-3}$          | 8.17                | 8.74                             |
| 99.9%     | 23.16             | 6.85                           | 2.06                  | $1.55 \times 10^{-2}$          | 8.82                | 9.32                             |

**Figure 6:** Dispersed performance with velocity trigger: (a) terminal crossrange versus downrange, (b) terminal altitude histogram, and (c) terminal dynamic pressure histogram.

that the vehicle only performed a planar entry. In this case, no open-loop bank reversals are performed, and the vehicle just modulates the bank angle magnitude to fly to the target longitude. The data in Table 5 show the resulting performance and also provides the baseline bank-angle steering and  $\alpha\text{-}\beta$  steering results obtained

earlier. These results show the lack of bank reversals in the planar case significantly improves performance over the baseline bank-angle steering case. The mean and standard deviation for the downrange errors are both nearly cut in half, and the mean altitude increases by about 0.8 km. Comparison of bank-angle steering with only the planar motion to  $\alpha$ - $\beta$  steering show  $\alpha$ - $\beta$  steering still retains performance improvements, although the gap is much smaller than when the bank-angle steering vehicle utilized bank reversals. For example, the planar bank-angle steering case only has about a 30% larger standard deviation for the downrange error, and the terminal altitude is only about 0.1 km lower than the  $\alpha$ - $\beta$  steering system. Hence, much of the performance gap between the two steering options is a result of the open-loop bank reversals. Even without the bank reversals,  $\alpha$ - $\beta$  steering still provides improved performance, which may be attributed to its improved response time; the vehicle can directly change lift/drag by quickly changing its angle of attack, as opposed to the longer bank maneuvers needed on the bank-angle steering system.

**Table 5:** Monte Carlo Results Showing Impact of Turning Off Out-of-Plane Motion

| Parameter                      | DR, km | CR, km                 | $z$ , km |
|--------------------------------|--------|------------------------|----------|
| Mean: $\sigma$                 | 4.18   | $6.97 \times 10^{-3}$  | 6.56     |
| SD: $\sigma$                   | 4.53   | 0.17                   | 0.83     |
| Mean: $\sigma$ , planar motion | -2.53  | 0.0                    | 7.34     |
| SD: $\sigma$ , planar motion   | 2.57   | 0.0                    | 0.67     |
| Mean: $\alpha$ - $\beta$       | 0.13   | $-1.40 \times 10^{-5}$ | 7.45     |
| SD: $\alpha$ - $\beta$         | 1.97   | $2.80 \times 10^{-3}$  | 0.61     |

The impact of bank reversals are further explored by analyzing the worst-case overshoot case for bank-angle steering from the Monte Carlo simulations using a velocity trigger. Figure 7 shows this maximum overshoot case with the lateral motion, as well as the same case with only the planar motion considered. Both vehicles have the same profile up to 92 s when a large bank reversal is initiated for the case considering the out-of-plane motion. As this reversal and all others in this study are performed over-the-top, the additional lift-up flight provides a significant perturbation in the trajectory, which is visible in both the altitude versus velocity and flight-path angle profile in Figure 7. This perturbation creates range errors, which the guidance is ultimately unable to fly out. To try to counter this upwards perturbation, the vehicle saturates flying full-lift down, a contrast to the planar case. While this helps reduce the effect of the large bank reversal, the vehicle still majorly overflies the target, and the lift-down flight between 114 and 143 s as well as the loft in the trajectory, result in the vehicle losing significant altitude (about 2.6 km), relative to the case with planar motion. Poorly timed bank reversals like these cause a significant performance reduction in many cases, resulting in the improved performance in the hypothetical case where the lateral motion is turned off to avoid bank reversals.

Monte Carlo simulations are also performed using a range trigger. These results are tabulated in Table 6 and are shown graphically in Figure 8. Both steering options have similarly sized ellipses with the range trigger. The significantly improved and similar downrange performance, with both steering options having standard deviations of downrange error on the order of 30-40 m, is a result of the range trigger forcing the vehicle to enter TDI/SUFR when overflying the longitude target. Both steering options have low crossrange error on the order of fractions of a meter for alpha-beta steering, up to tens of meters for bank-angle steering. While this is an order of magnitude difference, these differences are small and would likely be eclipsed by navigation errors. Results also show  $\alpha$ - $\beta$  steering again provides an altitude advantage over bank-angle steering when using the range trigger.  $\alpha$ - $\beta$  steering has a mean altitude about 0.17 km higher than bank-angle steering, and  $\alpha$ - $\beta$  steering also has a terminal altitude standard deviation about half that of bank-angle steering. Similar to the velocity trigger, the significantly tighter clustering of the terminal altitude for  $\alpha$ - $\beta$  steering is a result of this system not using open-loop bank reversals. While the downrange performance is very similar for these two systems (because they are essentially being forced into TDI when they overfly the longitude target), the bank-angle steering system still suffers from poorly timed bank reversals, which result in a deviation in the relationship between range and velocity. Combined with the larger altitude variance on these systems, bank-

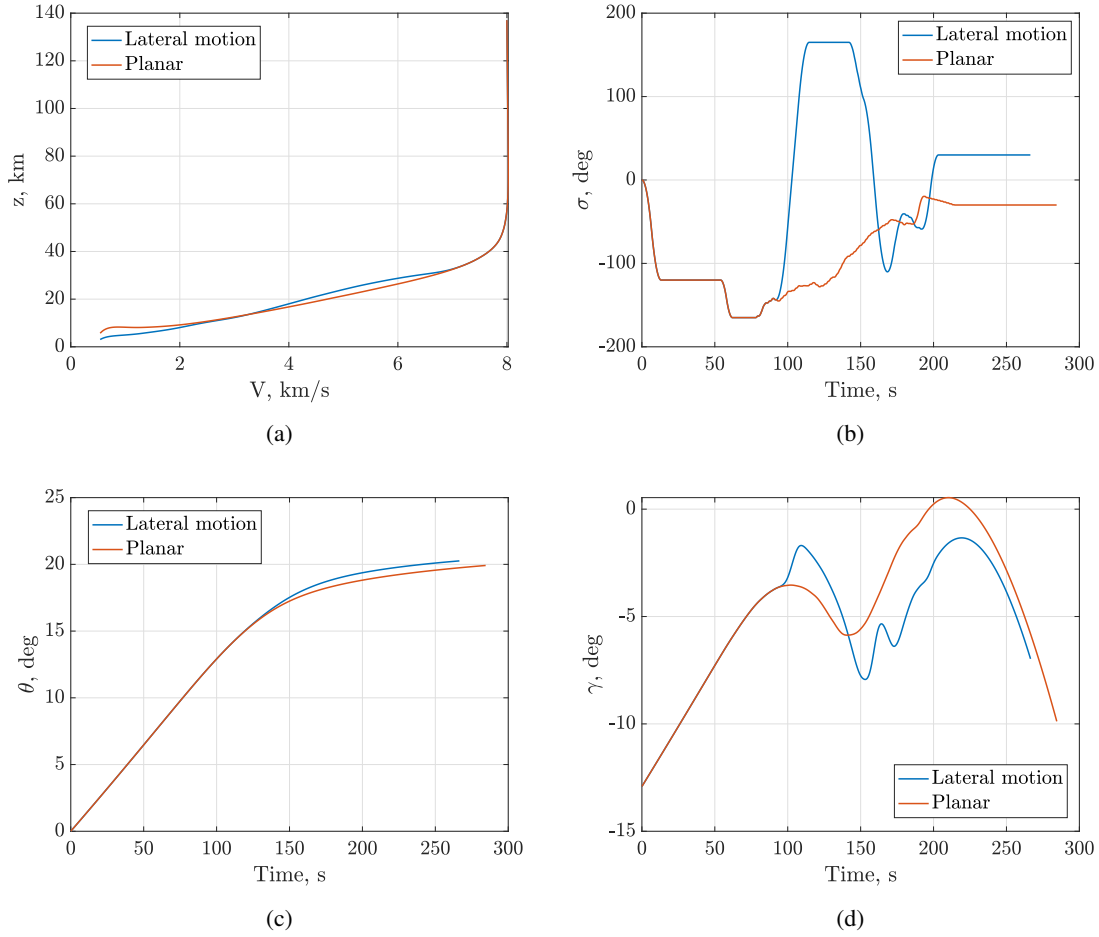
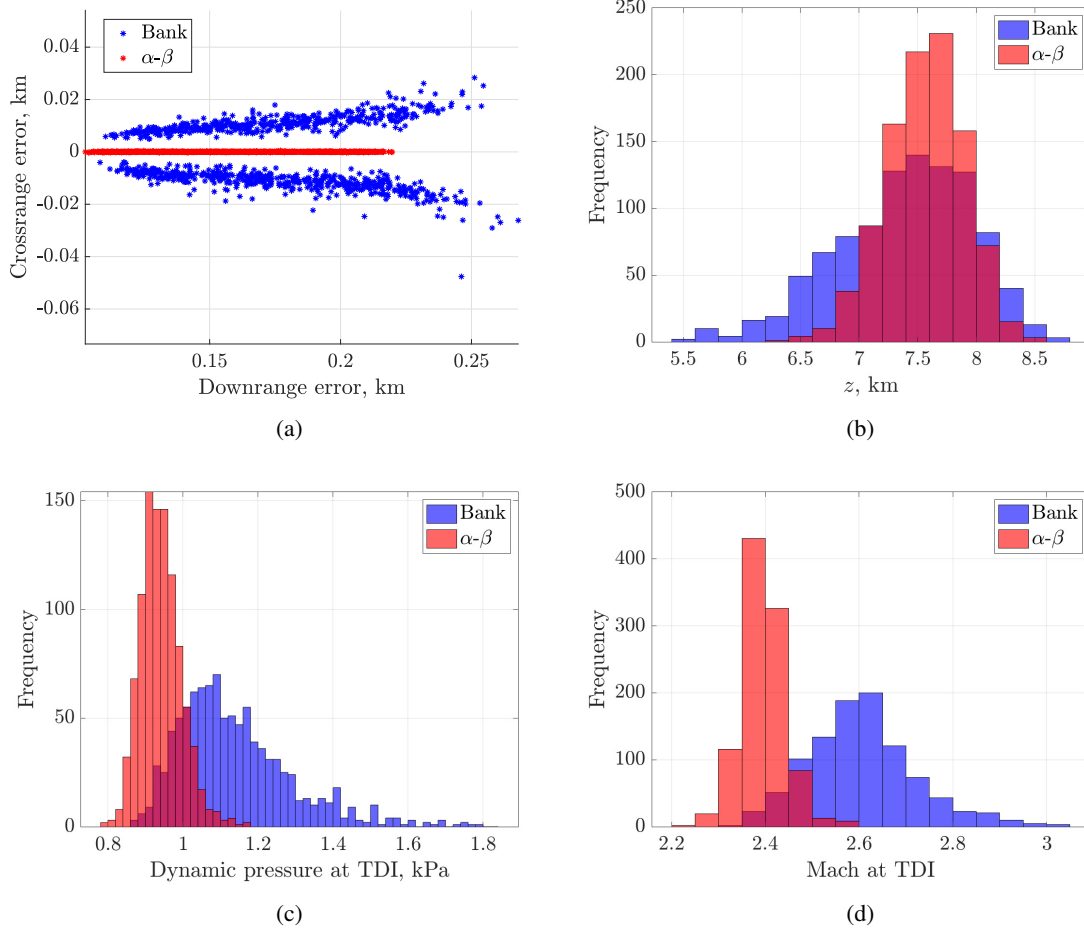


**Figure 7:** Maximum overshoot case for bank-angle steering, with and without out-of-plane motion: (a) altitude versus velocity, (b) bank angle profile, (c) longitude versus time, and (d) flight-path angle versus time.

angle steering has a much larger spread of Mach number and dynamic pressure at TDI. This is shown in Figures 8c and 8d, where bank-angle steering has standard deviations of 0.15 kPa and 0.12 for the terminal dynamic pressure and Mach number, respectively. These contrast with the much smaller standard deviations of 0.05 kPa and 0.05 for the dynamic pressure and Mach number, respectively, on the  $\alpha$ - $\beta$  steering system. Not only are these standard deviations smaller, indicating a narrower range of deployment conditions and a decreased chance of mission failure, but the vehicle using  $\alpha$ - $\beta$  steering also has its mean terminal dynamic pressures and Mach numbers at the low end of the spread of bank-angle steering values. This indicates more benign parachute deploy conditions when using  $\alpha$ - $\beta$  steering.

**Table 6: Range Trigger Monte Carlo Results**

| Parameter | DR: $\sigma$ , km | DR: $\alpha\text{-}\beta$ , km | CR: $\sigma$ , km      | CR: $\alpha\text{-}\beta$ , km | $z$ : $\sigma$ , km | $z$ : $\alpha\text{-}\beta$ , km |
|-----------|-------------------|--------------------------------|------------------------|--------------------------------|---------------------|----------------------------------|
| Mean      | 0.18              | 0.16                           | $-8.47 \times 10^{-4}$ | $1.00 \times 10^{-6}$          | 7.40                | 7.57                             |
| SD        | 0.04              | 0.03                           | 0.01                   | $6.60 \times 10^{-5}$          | 0.58                | 0.34                             |
| 0.1%      | 0.11              | 0.10                           | -0.05                  | $-3.30 \times 10^{-4}$         | 5.52                | 6.32                             |
| 1%        | 0.12              | 0.11                           | -0.02                  | $-2.21 \times 10^{-4}$         | 5.75                | 6.73                             |
| 10%       | 0.13              | 0.12                           | -0.01                  | $-5.80 \times 10^{-5}$         | 6.60                | 7.14                             |
| 50%       | 0.17              | 0.16                           | $-6.67 \times 10^{-3}$ | 0.00                           | 7.48                | 7.58                             |
| 90%       | 0.22              | 0.20                           | 0.01                   | $5.60 \times 10^{-5}$          | 8.09                | 7.99                             |
| 99%       | 0.25              | 0.22                           | 0.02                   | $2.20 \times 10^{-4}$          | 8.51                | 8.28                             |
| 99.9%     | 0.27              | 0.22                           | 0.03                   | $5.06 \times 10^{-4}$          | 8.90                | 8.61                             |

**Figure 8:** Dispersed performance with range trigger: (a) terminal crossrange versus downrange, (b) terminal altitude histogram, (c) terminal dynamic pressure histogram, and (d) terminal Mach number histogram.

### Performance Comparison with Increased Dispersions

Increased dispersions were considered to further stress the two guidance algorithms and understand how the vehicles perform for different uncertainties. Firstly, a Monte Carlo simulation with larger dispersions in the

entry state is considered. Here, the initial condition dispersions in Table 3 and doubled (with the exception of the flight-path angle which is multiplied by a value of 1.75), and the  $3\sigma$  values are changed to be the bounds of a uniform distribution. Monte Carlo results are shown in Table 7 and show the larger dispersions significantly reduce the performance of both steering options, relative to the baseline velocity trigger Monte Carlo simulation. Among the dispersions in the entry state, the dispersions in the initial altitude and flight-path angle have the greatest impacts on the resulting performance. Despite the performance reduction with larger initial conditions,  $\alpha$ - $\beta$  steering still retains similar advantages over bank-angle steering. The mean and standard deviations for the downrange error are more than half of that of bank-angle steering, the crossrange errors for  $\alpha$ - $\beta$  steering are orders of magnitude lower than that of bank-angle steering, and  $\alpha$ - $\beta$  steering retains its nearly 1 km mean altitude advantage. These performance advantages indicate  $\alpha$ - $\beta$  steering both provides improved targeting and robustness, relative to bank-angle steering, in the presence of large dispersions in the entry state.

**Table 7:** Monte Carlo Results with Increased Entry State Dispersions

| Parameter | DR: $\sigma$ , km | DR: $\alpha$ - $\beta$ , km | CR: $\sigma$ , km | CR: $\alpha$ - $\beta$ , km | $z$ : $\sigma$ , km | $z$ : $\alpha$ - $\beta$ , km |
|-----------|-------------------|-----------------------------|-------------------|-----------------------------|---------------------|-------------------------------|
| Mean      | 26.10             | 12.24                       | -0.16             | -0.02                       | 5.65                | 6.50                          |
| SD        | 84.18             | 36.83                       | 6.55              | 0.50                        | 2.15                | 1.64                          |

Monte Carlo results with larger dispersions in the vehicle aerodynamics are shown in Table 8. Here the dispersions in  $C_A$  and  $C_N$  are changed to be a uniformly distributed multiplier between 0.75 and 1.25 applied to the values interpolated in the aerodynamics database. These results show the similar orders of magnitude crossrange advantages of  $\alpha$ - $\beta$  steering seen earlier in this study. While  $\alpha$ - $\beta$  steering has over a 1 km altitude advantage over bank-angle steering, and the mean downrange error is two orders of magnitude lower for  $\alpha$ - $\beta$  steering, both steering options have similar standard deviations for the crossrange error and terminal altitude. The larger mean downrange error for bank-angle steering is again to poorly timed bank reversals which extend the range flown. The roughly equal standard deviations can be attributed to large aerodynamic dispersions occurring after range control when the vehicles can no longer fly out errors in the trajectory. This impacts both steering options similarly and dominate over other dispersions that can be flown out, resulting in the two steering options having similar standard deviations for the downrange error and altitude. Hence, while  $\alpha$ - $\beta$  steering has improved overall targeting over bank-angle steering, both options have similar robustness to large atmospheric dispersions.

**Table 8:** Monte Carlo Results with Increased Aerodynamic Dispersions

| Parameter | DR: $\sigma$ , km | DR: $\alpha$ - $\beta$ , km | CR: $\sigma$ , km | CR: $\alpha$ - $\beta$ , km | $z$ : $\sigma$ , km | $z$ : $\alpha$ - $\beta$ , km |
|-----------|-------------------|-----------------------------|-------------------|-----------------------------|---------------------|-------------------------------|
| Mean      | 7.79              | 0.04                        | -0.02             | $3.50 \times 10^{-5}$       | 5.49                | 6.55                          |
| SD        | 11.18             | 10.43                       | 0.74              | 0.01                        | 2.36                | 2.34                          |

Table 9 shows Monte Carlo results with increased dispersions in the density profile. These larger dispersions are obtained by multiplying a given density profile by a uniformly distributed random scalar value in between 0.5 and 1.5. The larger dispersions in the atmosphere result in a significant performance loss for both steering options that is generally more severe than for the larger aerodynamic dispersions but is less severe than the large entry state dispersions.  $\alpha$ - $\beta$  steering again has mean and standard deviations for the downrange error which are several times lower than the corresponding values for bank-angle steering.  $\alpha$ - $\beta$  steering also remains having means and standard deviations for the crossrange error, which are orders of magnitude lower than the values for bank-angle steering. The mean altitude for  $\alpha$ - $\beta$  steering is not about 1.2 km higher than bank-angle steering and the standard deviation for altitude is over 1 km lower. Similar to the larger dispersions in the entry state, these results indicate  $\alpha$ - $\beta$  steering provides improved targeting and robustness in the presence of dispersions in the atmosphere.

**Table 9:** Monte Carlo Results with Increased Atmospheric Dispersions

| Parameter | DR: $\sigma$ , km | DR: $\alpha$ - $\beta$ , km | CR: $\sigma$ , km | CR: $\alpha$ - $\beta$ , km | z: $\sigma$ , km | z: $\alpha$ - $\beta$ , km |
|-----------|-------------------|-----------------------------|-------------------|-----------------------------|------------------|----------------------------|
| Mean      | 14.39             | 5.74                        | -0.04             | $-2.48 \times 10^{-3}$      | 4.54             | 5.71                       |
| SD        | 22.77             | 11.56                       | 3.25              | 0.09                        | 5.98             | 4.90                       |

### Impact of Tuning Parameters

The comparisons of bank-angle and  $\alpha$ - $\beta$  steering in this study are dependent on the tuning of the entry guidance algorithms. As mentioned earlier, guidance parameters were tuned heuristically based on both nominal and dispersed cases; the impacts of these tuning parameters are discussed in this section. The most influential parameters for bank-angle steering are the quadratic parameters db1 and db2 describing the lateral deadbands before and after the first bank reversal. Monte Carlo simulations were swept across various values of db1 and db2, and various trajectory metrics are plotted in Figure 9 as functions of db1 and db2. Each dot

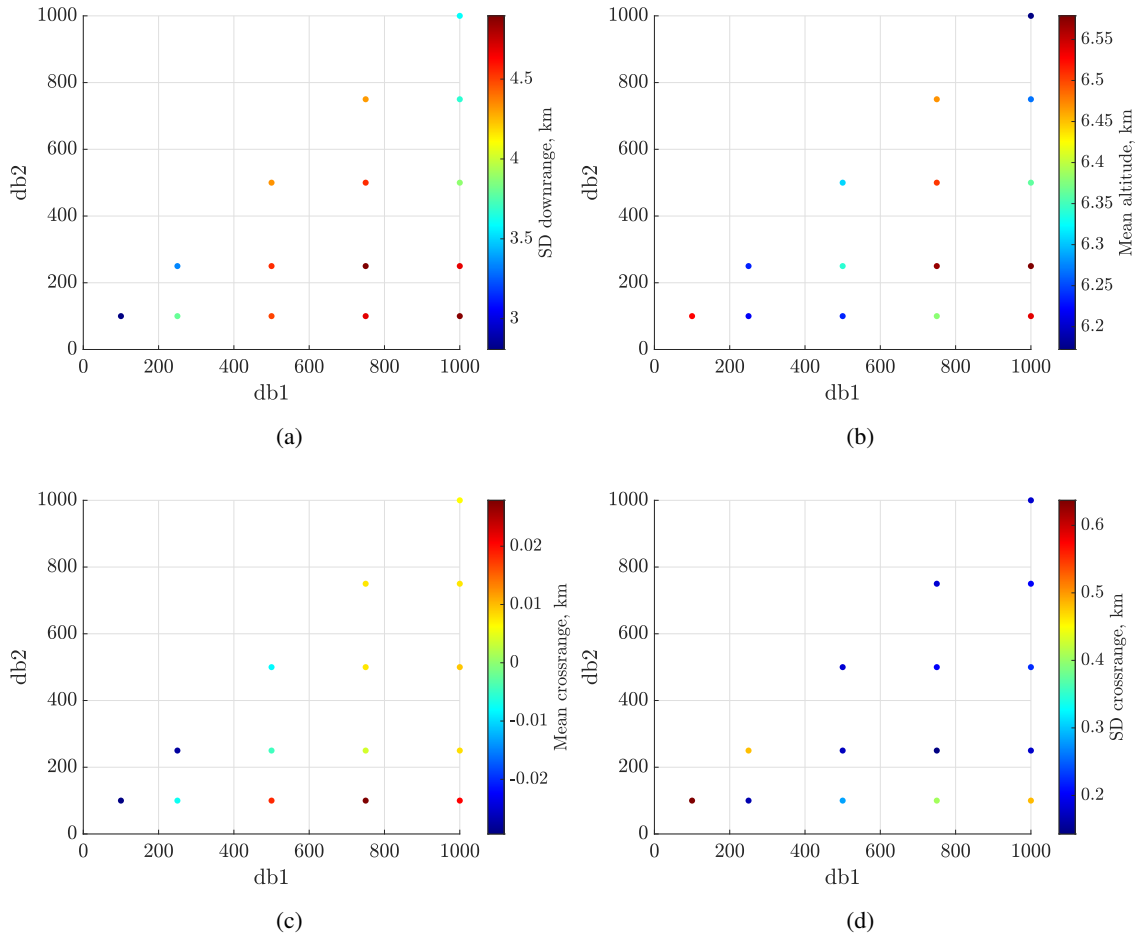


**Figure 9:** Trajectory metrics as a function of lateral deadband tuning parameters: (a) downrange standard deviation, (b) mean altitude, (c) mean crossrange, and (d) crossrange standard deviation.

represents the results of a Monte Carlo simulation. Only cases with  $db1 \geq db2$  are considered, as typical design of lateral deadbands has the deadband before the first bank reversal the same width or narrower than the

subsequent deadband. With bank-angle steering there is often a trade off in performance with a given tuning of  $db1$  and  $db2$  working well for certain parameters but poorly for others. For example,  $db1=100$ ,  $db2=100$  leads to the lowest standard deviation in downrange error among the cases considered, but this tuning also leads to relatively large mean crossrange errors and the highest standard deviation in crossrange error among the considered cases. This tuning also results in undesirable performance where 772 of the Monte Carlo cases only have one bank reversal, and the remaining 228 cases have just two bank reversals. In contrast, the tuning  $db1=1000$ ,  $db2=250$  has worse downrange performance with a standard deviation about 1.5 km higher, but the mean and standard deviation for the crossrange error are significantly improved. Additionally, the mean terminal altitude is improved for this tuning, and a more desirable behavior is obtained for the number of bank reversals. Here, 11 cases have two bank reversals, 667 cases have the nominal three reversals, and 322 cases have four bank reversals. Hence, there is a range of performance achievable with bank-angle steering depending on which trajectory objectives are prioritized, but results indicate it is challenging to have great performance across conflicting trajectory metrics, e.g. downrange and crossrange. An overall objective across various trajectory metrics, with the metrics scaled to be between 0 and 1, calculated to determine a sense of overall performance across the different tuning options:

$$\text{objective} = \text{mean DR} + \text{DR SD} + \text{mean CR} + \text{CR SD} - \text{mean } z + z \text{ SD} + \text{mean } q_{\infty} + q_{\infty} \text{ SD} \quad (21)$$

Results for this overall objective are shown in Figure 10, which show the chosen tuning of  $db1=1000$ ,  $db2=250$  provides among the best performance of the considered options, especially when considering the undesirable number of bank reversals associated with  $db1=100$ ,  $db2=100$ .

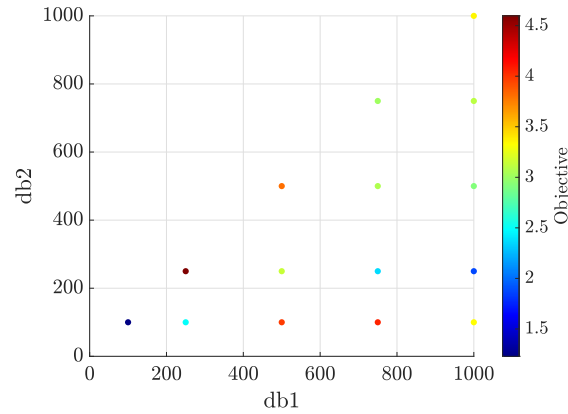


**Figure 10:** Overall objective of trajectory metrics as a function of lateral deadband tuning parameters.

Tuning for  $\alpha$ - $\beta$  steering is also considered, and this tuning is more straightforward due to the lack of the lateral deadbands and significantly lower coupling in the control. Figure 11 sweeps Monte Carlo performance across different values of  $K_{\beta}$ , showing how the mean and standard deviation of the terminal crossrange change. Due to the more decoupled nature of  $\alpha$ - $\beta$  steering, varying  $K_{\beta}$  has only a very small influence over any trajectory metrics other than the crossrange. A value of 0.7 was therefore chosen for  $K_{\beta}$  as it provides a very low mean and standard deviation for the terminal crossrange error. The impact of changing the velocity  $V_{HA}$  in which the  $\alpha$ - $\beta$  steering vehicle switches to flying full lift-up is swept in Figure 12. Despite the more decoupled nature of  $\alpha$ - $\beta$  steering for control over the longitudinal and lateral motion, varying  $V_{HA}$  impacts the mean and standard deviation for the downrange and altitude in different ways. Higher values of  $V_{HA}$ , when the vehicle starts flying lift-up earlier, lead to a higher mean altitude and lower standard deviation for the terminal altitude but also increase the standard deviation for the downrange error. Alternatively, smaller values of  $V_{HA}$ , where the vehicle starts flying lift-up later, reduce the standard deviation for the downrange error but provide worse altitude performance. A compromise with  $V_{HA} = 1000$  m/s provides moderate performance for the standard deviation of downrange and the mean and standard deviation for altitude, while also providing nearly the best performance for the mean downrange error. Although there is

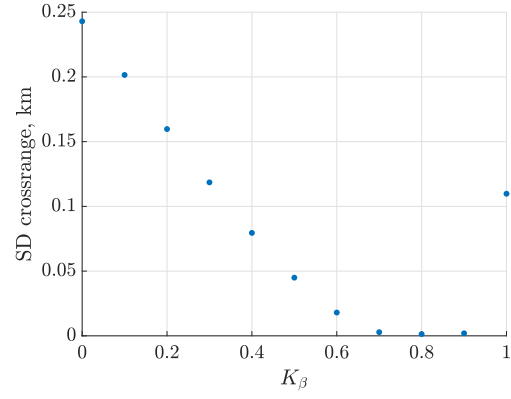
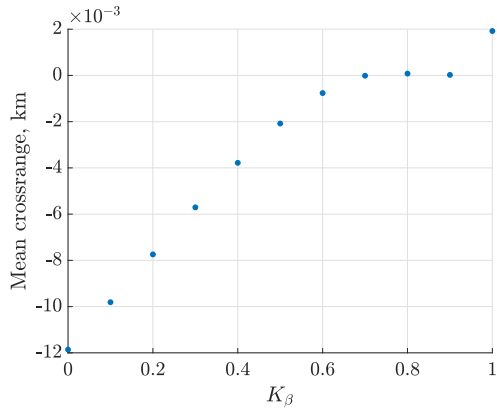


**Figure 11:** Crossrange performance for  $\alpha$ - $\beta$  steering as a function of  $K_\beta$ : (a) mean crossrange and (b) standard deviation of crossrange.

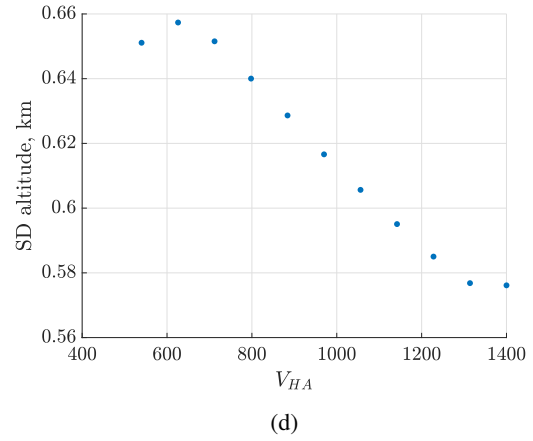
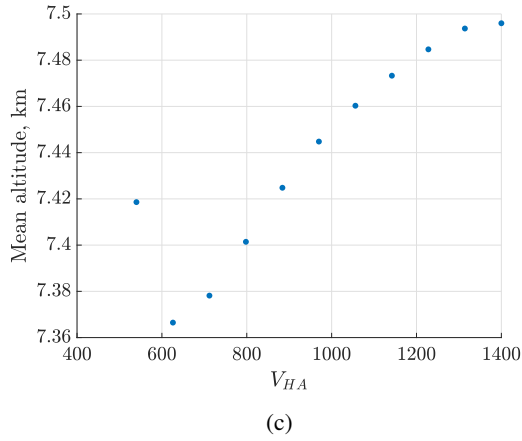
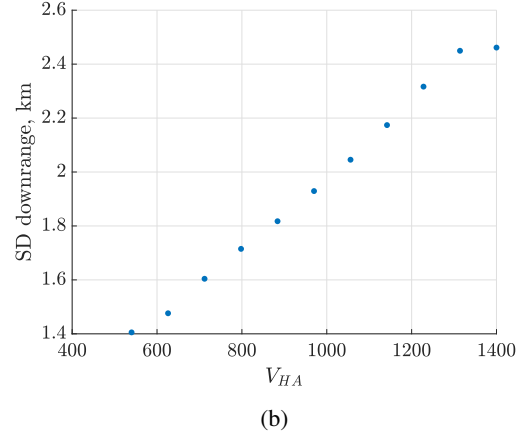
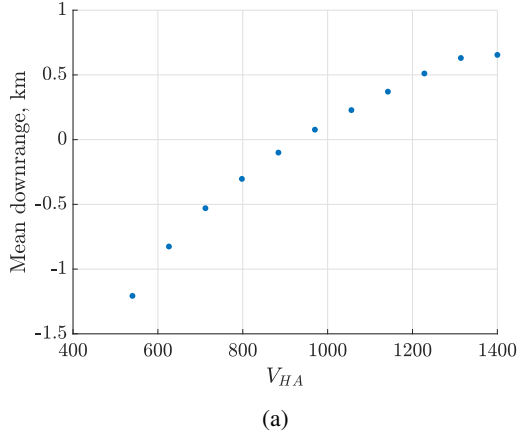


**Figure 12:** Trajectory metrics for  $\alpha$ - $\beta$  steering as a function of  $V_{HA}$ : (a) mean downrange, (b) standard deviation of downrange, (c) mean altitude, and (d) standard deviation of altitude.

a range of performance here for  $\alpha$ - $\beta$  steering when changing  $V_{HA}$ , for any considered value of  $V_{HA}$ ,  $\alpha$ - $\beta$  steering provides improved performance over all bank-angle steering cases in Figure 9, for all the considered performance metrics. Hence,  $\alpha$ - $\beta$  steering provides better performance across the board, and the performance can be adjusted individually, depending on which objectives are most important. A similar tuning procedure was performed for both steering options when using a range trigger.

### Impact of Vehicle Angle of Attack

So far the vehicle using  $\alpha$ - $\beta$  steering has flown with  $\alpha_{total,max} = 19$ , equivalent to the magnitude of the constant angle of attack on the bank-angle steering system. Here,  $\alpha_{total,max}$  is decreased for  $\alpha$ - $\beta$  steering to assess how performance changes and compares to the original bank-angle steering results (flight at  $\alpha_{bank} = -19$  deg). Separate Monte Carlo simulations are performed for  $\alpha_{total,max}$  values of 16 deg, 15 deg, 13 deg, and 11 deg, and results are provided in Table 10. For each new angle of attack, a new reference trajectory is generated from the bank profile in Figure 2, but the trim angle of attack utilized for the reference trajectory generation is now different. Hence, the reference  $L/D$  profile varies across these cases. This is therefore no longer as equal of a comparison as before, where the reference  $L/D$  profile was the same for both steering options. Across all of the cases,  $\alpha$ - $\beta$  steering retains superior downrange and crossrange performance over bank-angle steering, similar to before. Not only does  $\alpha$ - $\beta$  steering have downrange and crossrange advantages at these lower maximum total angles of attack, but the downrange advantage over bank-angle steering grows slightly as  $\alpha_{total,max}$  is lowered. For example, the length of the downrange ellipse decreases from about 13 to 11 km, for  $\alpha_{total,max} = 15$  deg and  $\alpha_{total,max} = 11$  deg, respectively. The shorter downrange ellipse length when the control authority is lower may be due to the smaller angle of attack values providing less sensitivity to off nominal conditions. For example, the increased amount of lift-down flight at a larger positive angle of attack, where the density is high, may create larger errors to be flown out than on a vehicle with a smaller angle of attack magnitude.

**Table 10:** Monte Carlo Results with Lower Maximum Angle of Attack for  $\alpha$ - $\beta$  Steering

| Parameter                                                | DR, km | CR, km                 | z, km |
|----------------------------------------------------------|--------|------------------------|-------|
| Mean: $\sigma$                                           | 4.18   | $6.97 \times 10^{-3}$  | 6.56  |
| SD: $\sigma$                                             | 4.53   | 0.17                   | 0.83  |
| Mean: $\alpha$ - $\beta$ , $\alpha_{total,max} = 16$ deg | -1.51  | $-1.02 \times 10^{-4}$ | 6.43  |
| SD: $\alpha$ - $\beta$ , $\alpha_{total,max} = 16$ deg   | 2.05   | $4.62 \times 10^{-3}$  | 0.58  |
| Mean: $\alpha$ - $\beta$ , $\alpha_{total,max} = 15$ deg | -1.43  | $-1.02 \times 10^{-4}$ | 6.00  |
| SD: $\alpha$ - $\beta$ , $\alpha_{total,max} = 15$ deg   | 1.97   | $4.65 \times 10^{-3}$  | 0.57  |
| Mean: $\alpha$ - $\beta$ , $\alpha_{total,max} = 13$ deg | -1.26  | $-1.60 \times 10^{-4}$ | 5.09  |
| SD: $\alpha$ - $\beta$ , $\alpha_{total,max} = 13$ deg   | 1.84   | $4.72 \times 10^{-3}$  | 0.56  |
| Mean: $\alpha$ - $\beta$ , $\alpha_{total,max} = 11$ deg | 0.46   | $-7.60 \times 10^{-5}$ | 4.16  |
| SD: $\alpha$ - $\beta$ , $\alpha_{total,max} = 11$ deg   | 1.67   | $3.71 \times 10^{-3}$  | 0.58  |

While the lower maximum total angles of attack still offer good downrange and crossrange performance on the  $\alpha$ - $\beta$  steering system, the lower maximum total angle of attack significantly impacts terminal altitude performance. Across all of these cases for  $\alpha$ - $\beta$  steering, the mean terminal altitude is worse than bank-angle steering, although the standard deviations are smaller for  $\alpha$ - $\beta$  steering. With  $\alpha_{total,max} = 16$  deg, the mean altitude performance of  $\alpha$ - $\beta$  steering is nearly the same as bank-angle steering, indicating an  $\alpha$ - $\beta$  steering vehicle with a reduced maximum total angle of attack of 16 deg can nearly outperform a bank-angle steering vehicle with a trim angle of attack of -19 deg. Although the mean altitude performance continues to drop, with  $\alpha_{total,max} = 15$  deg, for example, the 0.1 and 1 percentile cases are better than that of bank-angle steering. Hence, if terminal altitude performance is needed, the trim angle of attack may be reduced by about 3-4 deg for  $\alpha$ - $\beta$  steering, while still getting equivalent or better performance than the bank-angle steering system at  $\alpha_{bank} = -19$  deg. If only downrange and crossrange performance is needed, the trim angle of attack may be reduced by over 8 deg and still provide better performance than bank-angle steering. Reducing the total

angle of attack during entry is potentially advantageous as it would decrease the mass of the actuation system needed to obtain those angles of attack and also reduce flow impingement on the back of the vehicle.

## CONCLUSIONS

Entry performance is assessed in this study for a future Mars entry vehicle for large robotic missions. Vehicles using both an existing state-of-the-art bank-angle steering system and a future alpha-beta steering concept are considered and compared to each other. The Apollo-based Entry Terminal Point Controller algorithm is used for the bank-angle steering vehicle and is adapted for alpha-beta steering. Flight performance comparisons show alpha-beta steering has noticeable advantages over bank-angle steering. When using a velocity trigger, these advantages manifest as a significantly smaller spread of downrange errors, however these advantages also manifest as a smaller spread of Mach number and dynamic pressure at terminal descent initiation when using a range trigger. Both trigger options also show alpha-beta steering has altitude advantages over bank-angle steering, and crossrange advantages occur when using a velocity trigger. Alpha-beta steering retains improved performance over bank-angle steering over a variety of tuning parameters and for larger dispersions in the entry state, aerodynamics, and atmosphere. Improved downrange and crossrange performance over bank-angle steering for lower total angles of attack on the alpha-beta steering system, but altitude performance may suffer at these lower angles of attack.

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