AIAA Atmospheric Flight Mechanics Conference and Exhibit
5-8 August 2002, Monterey, California

AIAA 2002-4502

Guidance Design for Mars Smart Landers Using The Entry Terminal Point Controller

By
Gavin F. Mendeck
Aerospace Engineer, Ascent/Descent Dynamics Branch, Flight Design and Dynamics Division
NASA Johnson Space Center, Houston, Texas

Gilbert L. Carman
Aerospace Engineer, Ascent/Descent Dynamics Branch, Flight Design and Dynamics Division
NASA Johnson Space Center, Houston, Texas

Abstract
Outfitted with a lifting-body aeroshell, the Mars Smart Lander may use an Apollo-derived Entry Terminal Point Controller guidance algorithm to successfully achieve a parachute deployment within 5 km of the intended target. The guidance modulates the bank angle to control range based on deviations in range, altitude rate, and drag from a reference trajectory. An overview of the reference trajectory design process with a bank profile is presented. Sensitivity due to vehicle configuration and atmospheric conditions is discussed.

I. Introduction
The Mars Smart Lander (MSL) will demonstrate precision landing using active onboard guidance in support of the landing accuracy requirements for future robotic and subsequent manned missions. The preliminary mission design delivers a rover payload to the surface, using a direct-entry trajectory and a trimmed entry vehicle lift-to-drag ratio of 0.24. The goal of the MSL precision landing demonstration is to achieve parachute deployment within a 5 km horizontal radius of the nominal deployment target. Terminal phase deceleration will be accomplished by the parachutes, followed by powered descent to a soft landing using a propulsion system and landing radar or lidar.

The Entry Terminal Point Controller (ETPC) is derived from the Apollo command module entry guidance. This algorithm was competitively selected for use with the cancelled Mars 2001 lander.[1] The Apollo guidance has been man-rated and successfully flight proven with the 0.3 L/D command module on entries from Earth orbit as well as direct lunar returns. A detailed development of all phases of the Apollo guidance algorithm and their application to Apollo Earth entry trajectories is presented in Reference 2. The objective of this paper is to present the modifications which have been made to adapt the ETPC algorithm from the Mars 2001 lander for use with MSL. The processes for optimizing the entry guidance and trajectory for the best performance are discussed.

II. Guidance Overview
The original Apollo guidance design was for lunar return; however, sufficient mission flexibility was required to accommodate the large variations in entry conditions, including those of Earth orbit test flights and all types of lunar mission aborts. To satisfy redesignation requirements for a weather alternate landing area, an upper altitude controlled skip entry capability was included. For the direct Mars entry application the skip control phases are not used and only the final entry phase is incorporated. The final phase algorithm controls to a terminal range and velocity target using pre-derived influence coefficients with respect to errors about a nominal reference trajectory. This reference trajectory is defined by range-to-go, drag acceleration, and altitude rate as a function of relative velocity. A constant initial pre-bank attitude is maintained until a sensed atmospheric drag acceleration of approximately 0.1 Earth g's, when closed loop guidance bank commands are initiated.

The predicted range-to-go (R_p) is calculated as a function of drag (D) and altitude rate (r-dot) errors with respect to the nominal reference trajectory profile, using equation 1.

$$R_p = R_{ref} + \frac{\partial R}{\partial D}\left(D - D_{ref}\right) - \frac{\partial R}{\partial \dot{r}}\left(\dot{r} - \dot{r}_{ref}\right) \qquad (1)$$

The desired vertical component of the lift-to-drag (L/D) ratio is calculated as a function of the difference between the actual and predicted range-to-go.

$$\left(\frac{L}{D}\right)_C = \left(\frac{L}{D}\right)_{ref} + \frac{K_3\left(R - R_p\right)}{\partial R/\partial\left(L/D\right)} \tag{2}$$

The commanded bank angle (Φ_C) is then calculated as

$$\Phi_C = \cos^{-1}\left(\frac{L/D_C}{L/D}\right) * K2ROLL \tag{3}$$

The partial derivatives of predicted range in equations 1 and 2 are the controller gains, which are derived using linear perturbation theory with the nominal reference trajectory by reverse integration of the differential equations adjoint to the linearized equations of motion. Optimized control gains for converging the dispersed trajectory to the nominal reference at final velocity are implemented in the guidance as tabular functions of relative velocity. Because of slow system and trajectory responses to guidance commands, performance is empirically enhanced by the use of the over-control gain K_3 in equation 2 to improve range convergence behavior.

The sensed drag acceleration and lift-to-drag ratio (*D* in equation 1 and *L/D* in equation 3) are derived from accelerometer measurements and smoothed by first order filters. The term *K2ROLL* in equation 3 is the bank directional control (±1), which is reversed each time the target crossrange out of plane central angle exceeds the reversal criterion, which is a quadratic function of relative velocity.

III. Reference Profile Design

The primary objective of the guidance design is to achieve the best horizontal position accuracy possible with respect to the desired parachute deploy target while remaining within the constraining criteria of deployment altitude, Mach number, and dynamic pressure. Since the mission is still in preliminary design and the landing site has not been selected, the guidance is also designed to achieve the highest deployment altitude for a given vehicle configuration, entry interface, and atmosphere conditions. The reference profile design process uses optimal bank shaping to achieve these requirements.

Deployment Constraints

Constraints on the parachute deployment conditions directly affect the guidance design in order to ensure adequate margins for the dispersed trajectories to meet performance requirements.

Deployment Altitude. The preliminary lander configurations use a propulsive descent system to perform a soft landing after parachute deceleration. There is a minimum chute deployment altitude relative to the surface, below which the chute and propulsive system cannot decelerate the lander in time for a soft landing. The minimum altitude is a function of propulsive acceleration, the greatest expected altitude rate at chute deployment, and the chute drag acceleration. For the MSL preliminary design, the minimum deployment altitude above the site has been determined to be 3.5 km.

Mach Number. The Mach number at chute deployment has two effects on the chute: aeroheating and inflation dynamics. If the Mach number is too high, the chute may fail due to excessive heating at the stagnation point or experience a violent inflation that excessively loads the chute. Inflation at transonic speeds is also usually an area of concern. For the MSL preliminary design, the selected Mach limits are 1.4 to 2.2.

Dynamic Pressure. Sufficient dynamic pressure at chute deployment is critical to ensuring inflation. If the dynamic pressure is too low, the chute may have difficulty inflating properly. If the dynamic pressure is too great, the resulting peak loads may cause the chute to fail. For the MSL preliminary design, the selected dynamic pressure limits are 400 to 850 Pa.

The deployment logic employed by the guidance achieves the least possible range to the target while remaining within the deployment constraints. The logic places a priority on ensuring that the minimum deploy altitude is not violated. If the altitude determined by navigation decreases below the altitude limit, a forced deployment will occur no matter the range to the target or the Mach and dynamic pressure conditions. This results in an early deployment or an ‘undershoot’ relative to the target. An early deployment also occurs if the minimum Mach or dynamic pressure constraints are encountered prior to overflight of the target. If the target is reached and the Mach or dynamic pressure is too high, deployment will be delayed until the vehicle slows or hits the altitude limit. This results in a late deployment or an ‘overshoot’.

Profile Shaping

The shaping of the nominal reference profile for the MSL preliminary design must meet three requirements. It must minimize the horizontal range error at chute deployment with the 3-sigma dispersed runs deploying within 5 km of the target latitude and longitude. The vehicle must reach the target site while within the deployment constraints in order to ensure a successful deployment on target. Otherwise the deployment constraints may force an early or late deployment, negatively impacting the range error. Designing the nominal profile to perform acceptably in dispersed cases is of prime importance. Finally, as the MSL is in a preliminary design phase with no selected landing site, the chute deployment altitude capability must be maximized in order to permit landings over much of the surface of Mars.

Since ETPC guidance controls within a corridor about the reference profile to converge the terminal range, it is desirable to design this profile to provide as much margin as possible from the vehicle maneuver capability limits to accommodate dispersions. This means that bank angles of the nominal reference trajectory should allow sufficient margin so that, in a dispersed simulation, the guidance and vehicle is able to retain sufficient capability to converge the range without bank angle saturation. Experience has shown that the nominal bank limits can be reasonably estimated from the atmospheric density and C_d percentage dispersions using equation 4.

$$\Phi_{\min nom} = \cos^{-1}\left(100\% - \rho_{\%} - C_{d\%}\right) \qquad (4)$$

With typical atmospheric density dispersions of 25% and C_d dispersions of 10%, the initial minimum allowable bank angle is approximately 49°. The maximum allowable bank angle is 49° less than 180°, or 131°. These bank limits usually apply to any phase in the nominal entry trajectory. If the nominal profile cannot adequately perform within the bank angle constraints, the vehicle configuration may require an increase in L/D or a decrease in the ballistic coefficient.

The shaping of the reference profile is initially done in an open-loop simulation with a constant bank angle. If no constant bank is able to meet the performance requirements of range accuracy and deployment constraints, a variable bank profile design is used to achieve additional margins.

Constant Bank Profiles. The original Apollo guidance, from which ETPC is derived, assumed a constant bank reference profile. Due in part to this and its resilience to dispersions, a constant bank profile provides the best performance in dispersed cases. Such a profile is also simple to optimize if the vehicle configuration, atmosphere, and site elevation allow for acceptable performance. The open-loop shaping of the profile is easily examined with a parametric study over a range of bank angles. Quantities that are important in selecting the best constant bank angle are the margins in Mach and dynamic pressure and the deployment altitude above the site. The MSL preliminary design studies have shown that the nominal deployment should occur near Mach 2.0 and between dynamic pressures of 550 and 650 Pa so that the dispersed cases meet these deployment constraints. The deployment altitude of dispersed cases are typically ±4.5 km relative to the nominal deployment, which means the nominal deployment must be 4.5 km above the minimum deployment altitude of 3.5 km.

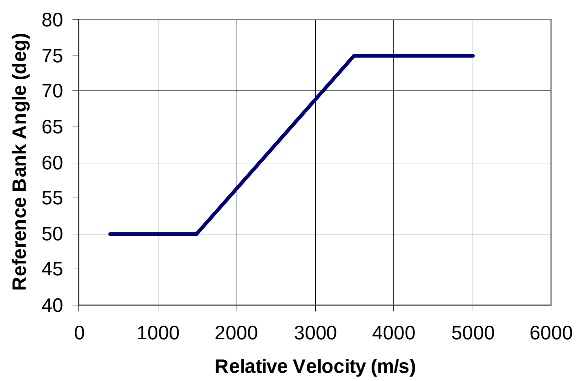


Figure 1: Sample Open-LoopVariable Bank.

Variable Bank Profiles. In some of the MSL studies, a change in the vehicle configuration (larger ballistic coefficient) or the arrival date (low-density atmospheric conditions) has degraded the constant-bank profile performance below acceptable levels. In situations such as this, employing a variable bank profile may recover some or all of the performance by reducing the bank angle at slower speeds to prolong the time spent in the lower, more dense atmosphere. Optimizing the variable bank profile is more involved than for the constant bank profile because there are several variables to manipulate. A simple variable bank profile that has performed well is a linear ramp between two constant values, such as shown in Figure 1. Investigation has shown that most acceptable variable bank profiles begin with a low-vertical lift bank angle, usually between 70° and 80°. The

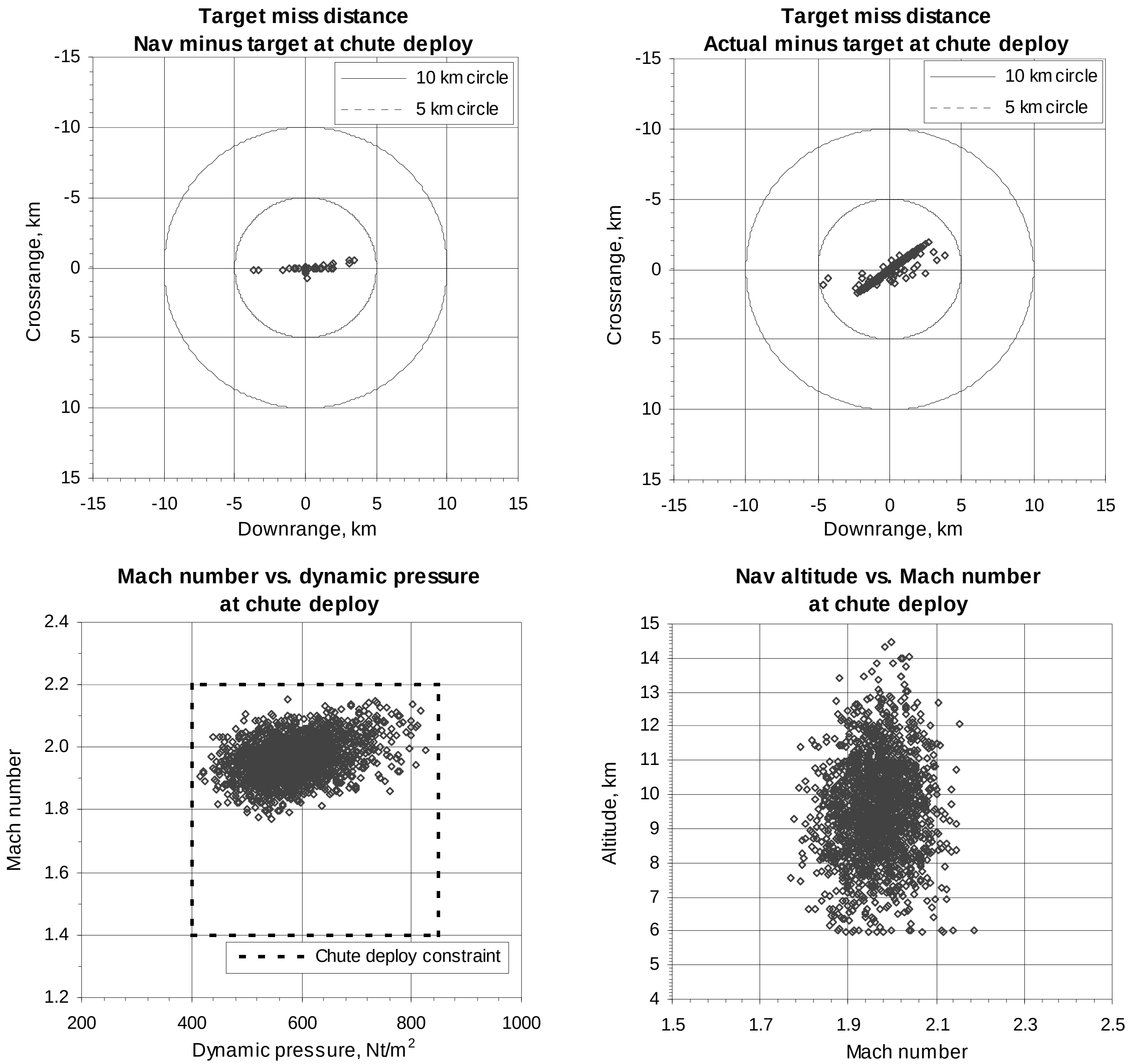


Figure 2: Sample of 2000 dispersed cases using an optimized reference profile.

nominal bank angle then decreases to the minimum bank angle found in Equation 4, typically close to 50°. The variable bank profile requires deployment constraint margins that are similar to those of the constant bank profile. Often a variable bank profile that results in a maximum altitude rate closest to zero has a good balance between the deployment margins and maximizing the altitude.

When an acceptable bank profile is found, controller gains are then derived from the resulting reference trajectory. The closed loop performance of the nominal and dispersed trajectories is assessed to determine if another iteration of optimizing the bank profile is required. Changes to the guidance gains and lateral control logic may also provide enhanced performance. Figure 2 is an example of dispersed performance for an optimized reference profile for a landing site at 2.5 km elevation. The robustness of the guidance is demonstrated as all of the dispersed deployments occurred within 5 km of the target, within the deployment constraints.

IV. Guidance & Entry Tuning

In addition to varying the reference profile, the performance of the entry guidance may be improved by the adjustment of the drag and lateral corridor and control gains. The conditions at entry interface, primarily the flight path angle, also affect the performance. These parameters can be easily optimized for a particular entry date to a targeted site, often with little or no impact to the mission or vehicle design.

Guidance Drag Control

Atmospheric density dispersion is a principal factor that degrades the guidance ability to converge to a fixed drag versus velocity profile. In order to compensate for off-nominal density dispersions, the geometric altitude must vary in an attempt to maintain nominal density altitudes. The purpose of the altitude rate error term in the ranging equation is to provide control damping to prevent excessive overshoot and oscillation in drag error convergence response characteristics. The altitude rate gain decreases to zero at final velocity, so drag error is the principal contributor to target miss.

Guidance Lateral Control

The initial bank command at guidance start is in the direction of the target position with respect to the relative trajectory plane. Bank reversals are triggered when the magnitude of the target crossrange out of plane central angle exceeds the reversal criterion, which is a quadratic function of relative velocity. Dispersions in atmospheric density can result in bank angle commands which remain saturated at maximum or minimum limits for a significant length of time, slowing the convergence of crossrange error.

The original Apollo guidance utilized only a single crossrange corridor. However, as a result of the larger atmospheric density variations of Mars, a tighter crossrange corridor was added prior to the first bank reversal, which provides improved performance by minimizing the peak crossrange overshoot that occurs after the first reversal. The corridor width is increased to the second level when the first reversal is initiated as shown in figure 3. Minimum bank angle command limits (maximum cosine limits) are implemented to maintain adequate crossrange control capability when the vertical L/D commands are large. The minimum bank limit is normally 15, which preserves adequate crossrange control in dispersed cases.

When the relative velocity becomes less than approximately 900 m/s, the effectiveness of bank angle modulation in controlling downtrack range becomes significantly diminished. At this point the bank commands are switched to a heading alignment controller instead, which aligns the vehicle velocity heading with the target, nulling the crosstrack position error when the target is reached.

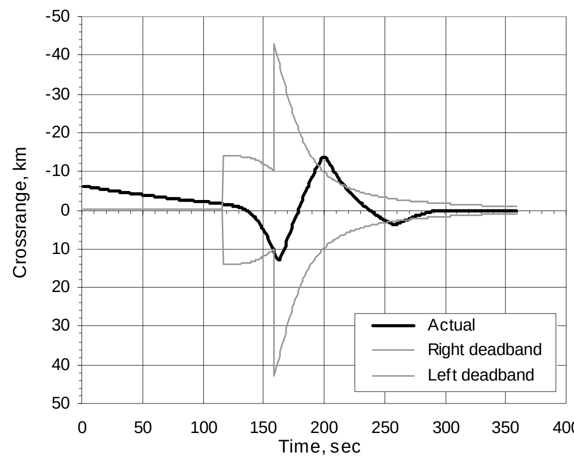


Figure 3: Sample bank reversal corridors.

Entry Flight Path Angle

Varying the flight path angle at entry interface can have a significant effect on the shaping of the reference profile as well as the ability to consistently meet the deployment constraints. The ideal flight path angle depends on a number of factors such as the given lift-to-drag ratio of the vehicle, the local atmosphere and the other entry interface conditions including the dispersion around the nominal flight path angle. A new reference profile must be generated for a new entry flight path angle. A few iterations are often necessary because the entry conditions and dispersions fluctuate depending on the flight path angle.

A study was conducted to determine the effect of the nominal entry flight path angle on the MSL preliminary performance. Constant bank angle was assumed and optimized for flight path angles between –12 and –16 degrees. A comparison with a zero-lift ballistic vehicle configuration was also done.

The charts in figure 4 illustrate the difference in performance of open-loop trajectories of ballistic and lifting bodies as the flight path angle changes between –12° and –16°. The difference in deployment altitudes at the lowest velocity is representative of the advantage a lifting entry vehicle always has over a

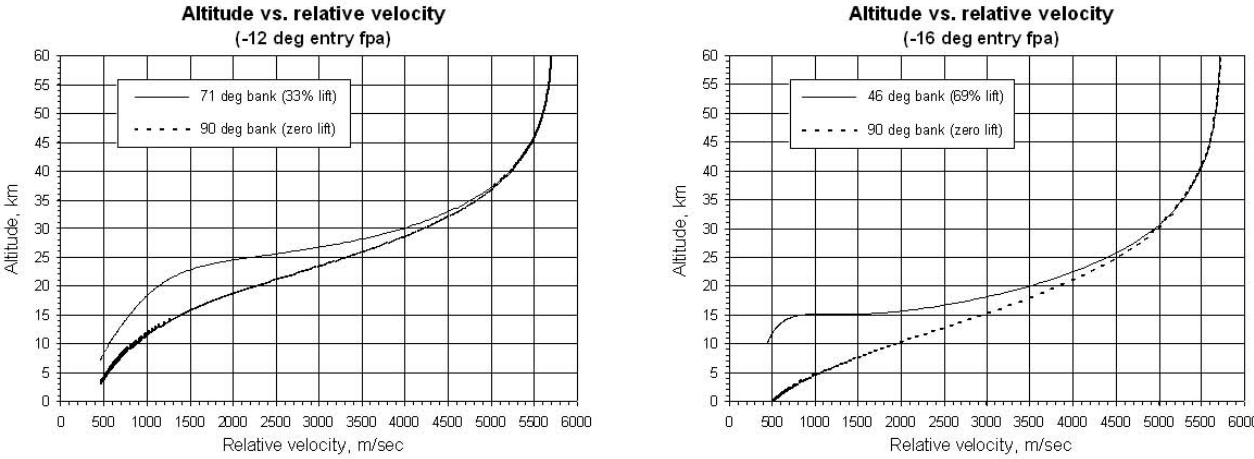


Figure 4: Comparison between ballistic and lifting body performance with various entry flight path angles.

ballistic vehicle in delivering the lander to higher landing sites.

For ballistic vehicles, a shallow flight path angle will result in the highest altitude for a particular Mach number. The range errors will be much greater, but this is inconsequential because a ballistic vehicle is not concerned with precision landing. The vehicle loads will be reduced and the dynamic pressure will be lower than for a steeper entry. The shallow flight path angle must still protect against skip-out. For the preliminary ’09 arrival conditions for MSL, the optimum flight path angle was –12° for a ballistic configuration, resulting in a maximum nominal load factor between 6 and 7g.

For lifting vehicles, a steeper flight path angle will result in smaller range errors as well as greater vehicle loads and less flight time to converge the range errors. The greater vehicle loading provides more control capability to converge the range errors, but must be balanced with vehicle structural and thermal limits. A steeper flight path angle allows for a deployment at a higher altitude for a given Mach number. One consequence is a lower dynamic pressure at deployment. For the preliminary ’09 arrival conditions for the MSL using a L/D vehicle of 0.24 and a ballistic coefficient close to 120 kg/m^2, a optimal flight path angle was around –14.5° with a maximum nominal load of 9g.

V. Configuration and Mission Design

It is possible, for a particular vehicle configuration in a given atmosphere defined by time and location, that the dispersed entry performance will not be acceptable for any combination of bank profile or guidance tuning. Such a situation usually leads to reassessment of the deployment constraints, the vehicle configuration (particularly ballistic coefficient), and selecting a date or site with more favorable atmospheric conditions.

Vehicle Configuration

Two parameters of the vehicle configuration play an important role in the design and performance of the entry guidance. Reference 3 discusses some approximate relationships between deployment conditions and vehicle configurations.

Ballistic Coefficient. The maximum acceptable ballistic coefficient of a vehicle configuration is dependent on the atmospheric conditions near the landing site. The greater the ballistic coefficient, the less drag acceleration experienced prior to chute deployment. If the ballistic coefficient is too great, the vehicle will not be able to decelerate in time to meet the chute or altitude deployment constraints. Lowering the ballistic coefficient allows a higher density altitude deployment at the cost of a lower dynamic pressure and higher Mach numbers due to the lower atmosphere density and temperatures. Figure 5 shows how the deployment conditions in Mach, dynamic pressure, and altitude can vary as a function of ballistic coefficient for constant-bank open-loop trajectories optimized to maximize the nominal deployment altitude using a 0.24 L/D configuration. The atmosphere data was generated by MarsGRAM 2001 for a late winter arrival in the southern hemisphere[4].

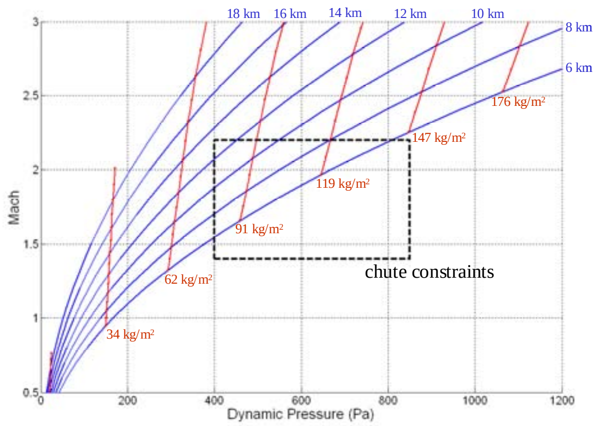


Figure 5: Sample optimized, constant-bank reference trajectories of different ballistic coefficients.

Lift-to-Drag Ratio. The minimum required L/D of a vehicle configuration is dependent on the desired deployment altitude as well as dispersions and uncertainties of the atmosphere, aerodynamic properties, and entry flight path angle. The greater the flight path angle dispersions are, the greater the possible delivery range error that the guidance must correct for. A greater L/D configuration is then required to 'fly out' larger delivery range errors. However, a greater L/D also has the undesirable effect of diverging the range error during bank reversals – too much L/D will diverge the range error during a reversal beyond recovery.

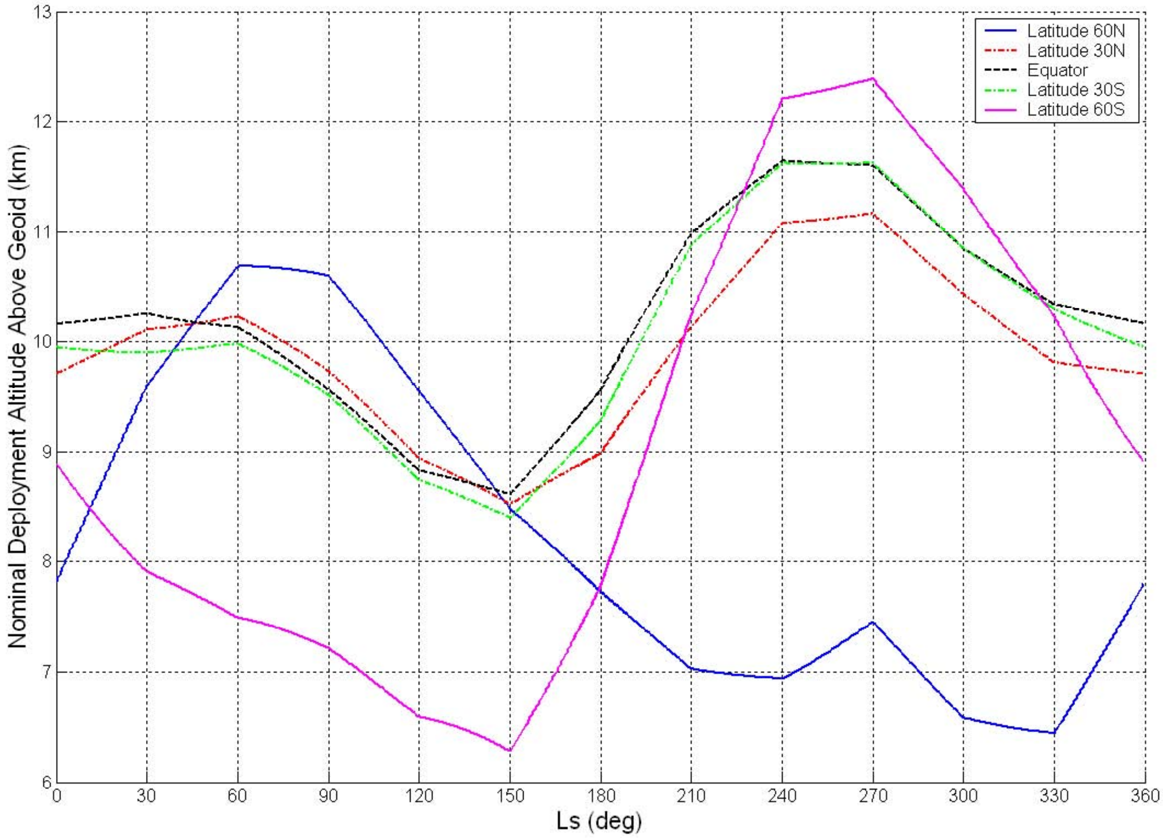
Atmospheric Conditions

The performance of the vehicle is heavily dependent on the atmosphere conditions of Mars, which vary in time and surface location. The chute deployment constraints of dynamic pressure and Mach number are directly related to the densities and speeds of sound in a given atmosphere profile. Due to this relationship, it is possible to determine the altitude and relative velocity for a particular Mach number and dynamic pressure in an atmosphere profile. By selecting a nominal chute deployment Mach and dynamic pressure it is possible to compare deployment altitudes between different atmosphere profiles. Since minimum deployment altitude is another constraint, the nominal deployment altitude is a useful figure of merit in estimating 'when' and 'where' the best opportunities for landing on Mars may be. This assumes the vehicle configuration allows the desired deployment conditions to be achieved.

Entry Date. The atmosphere of Mars varies greatly over the Martian year due to trends in the atmosphere related to the hemisphere seasons, distance from the sun, and the subliming and freezing of the atmosphere at the polar ice caps[5]. Solar longitude (L_s) is used as a standard of defining periods and seasons in the year. An L_s of 0° is the equinox of the northern hemisphere and an L_s of 90° is the summer solstice of the northern hemisphere. The average dust tau, a measure of the opacity in the atmosphere, also varies depending on the L_s and contributes to variations in atmospheric profiles.

Landing Site. The seasonal effects on the atmosphere are more pronounced for sites at higher latitudes. Some atmospheric models of Mars also take into account terrain effects which can vary the atmosphere properties as a function of longitude.

Figure 6 illustrates how the nominal deployment altitudes above the geoid can vary depending on the L_s and latitude, using the atmospheric model MarsGRAM 2001[4]. The nominal deployment conditions were selected to be Mach 2.0 and a dynamic pressure of 600 Pa. These preliminary results indicate that the higher latitudes are best reached during their spring and summer seasons. The low latitude sites are most accessible when Mars is near its perihelion (L_s of 250°). Missions to high elevation sites may be inhibited by entry date due to the atmospheric conditions and chute constraints that the vehicle can simply not perform acceptably within. This will also limit lander missions that do not perform precision landing.



Northern	Spring	Summer	Autumn	Winter
Southern	Autumn	Winter	Spring	Summer

Figure 6: Sample nominal deployment altitudes for different latitudes over the Martian year.

VI. <u>Future Work</u>

As the Mars Smart Lander mission continues to evolve in objectives, configuration, and mission design, the entry guidance will by necessity mature with it. Although the processes described herein are still under refinement, ETPC has been demonstrated to perform robustly within the uncertain Mars atmosphere.

The impact of mission design on the guidance performance will be studied further. Optimized results will be integrated into mission design and published.

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