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# Powered Descent Trajectory Guidance and Some Considerations for Human Lunar Landing

Ronald R Sostaric

NASA Johnson Space Center

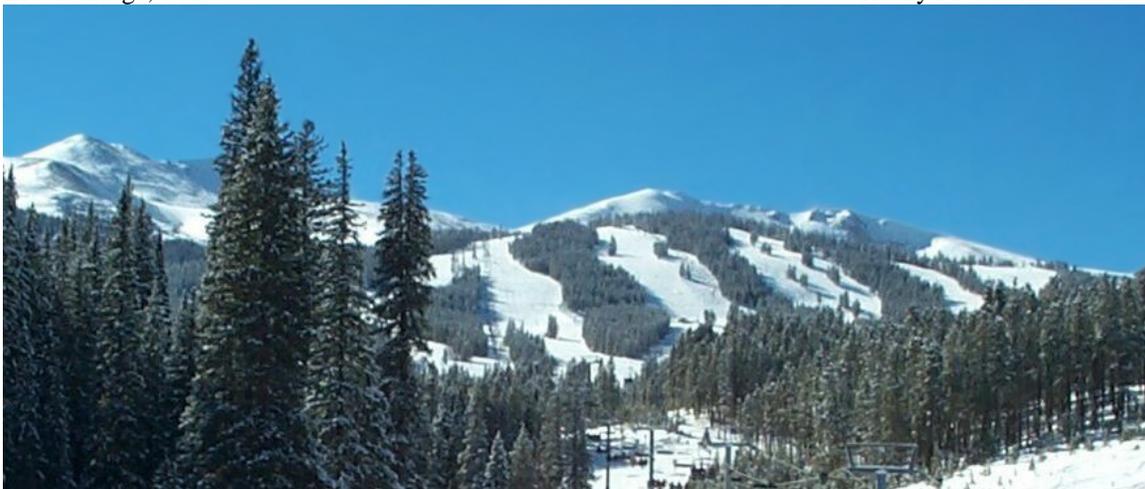
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# **POWERED DESCENT TRAJECTORY GUIDANCE AND SOME CONSIDERATIONS FOR HUMAN LUNAR LANDING**

**Ronald R. Sostaric**

The Autonomous Precision Landing and Hazard Detection and Avoidance Technology development (ALHAT) will enable an accurate (better than 100m) landing on the lunar surface. This technology will also permit autonomous (independent from ground) avoidance of hazards detected in real time. A preliminary trajectory guidance algorithm capable of supporting these tasks has been developed and demonstrated in simulations. Early results suggest that with expected improvements in sensor technology and lunar mapping, mission objectives are achievable.

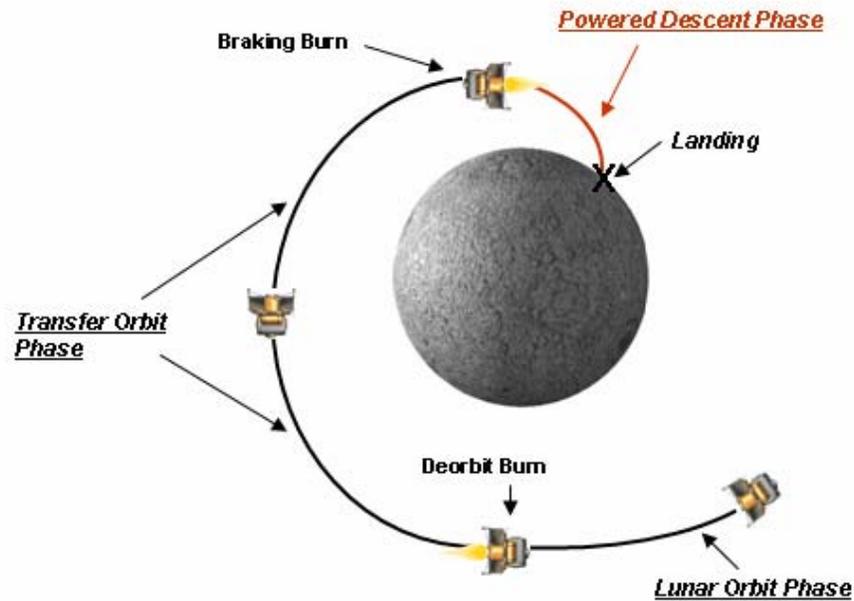
## **INTRODUCTION**

The Lunar Surface Access Module (LSAM) will land the next generation of lunar astronauts on the Moon. The vehicle must touch down softly and accurately on the lunar surface, while meeting constraints on the state variables during the descent. An accuracy of 100m or better will likely be required for Outpost class missions, in which pre-deployed mission assets are already in place on the Moon. This requires a significant increase in capability over the Apollo Lunar Module, particularly in navigation accuracy. Also desirable is the ability to detect and avoid surface hazards, such as rocks and craters. Advances in sensor capability allow for accurate detection of these surface features. The trajectory guidance must allow for dynamic retargeting to avoid the hazards detected by the sensing systems. The trajectory shape must take into account constraints for allowing the sensors to see the landing area, as well as time and altitude margin for adjusting the trajectory based on the information determined by the sensors. A propellant prediction algorithm is also useful for developing a cost function for landing site selection, as well as estimating the remaining horizontal translational distance capability of the vehicle. Some other trajectory guidance considerations include terrain clearance and possible abort back to orbit. Analysis results using the candidate algorithm and trade studies addressing these considerations are presented.

## **Flight Phases**

Figure 1 shows the phases of flight applicable to ALHAT. The ALHAT system becomes active during the circular lunar orbit, currently planned for 100 x 100 km. The de-orbit burn begins the sequence of maneuvers necessary to land on the lunar surface. The de-orbit is targeted for a 100 x 15.24 km transfer orbit. The periapse of 15.24 km (50,000 ft) is chosen to minimize propellant usage without exceeding safety margin needed in case of a failed Powered Descent Initiation (PDI) or for terrain clearance. This was the same periapse height used in Apollo.

Following the de-orbit burn is about a one hour coast to PDI.



**Figure 1 ALHAT Flight Phases**

The Powered Descent Phase is depicted in Fig 2. It begins at PDI and continues until touchdown on the lunar surface. The engine remains on throughout this phase. Powered Descent consists of 4 sub-phases:

*Braking Phase.* The objective of the braking burn is to steer the vehicle toward a soft landing at the landing site as efficiently as possible. The braking burn uses a version of Powered Explicit Guidance (PEG). This is a mode of the Shuttle Ascent Guidance that has been shown to be essentially optimal for exo-atmospheric flight. During braking, the engine throttle remains at a high and relatively constant setting.

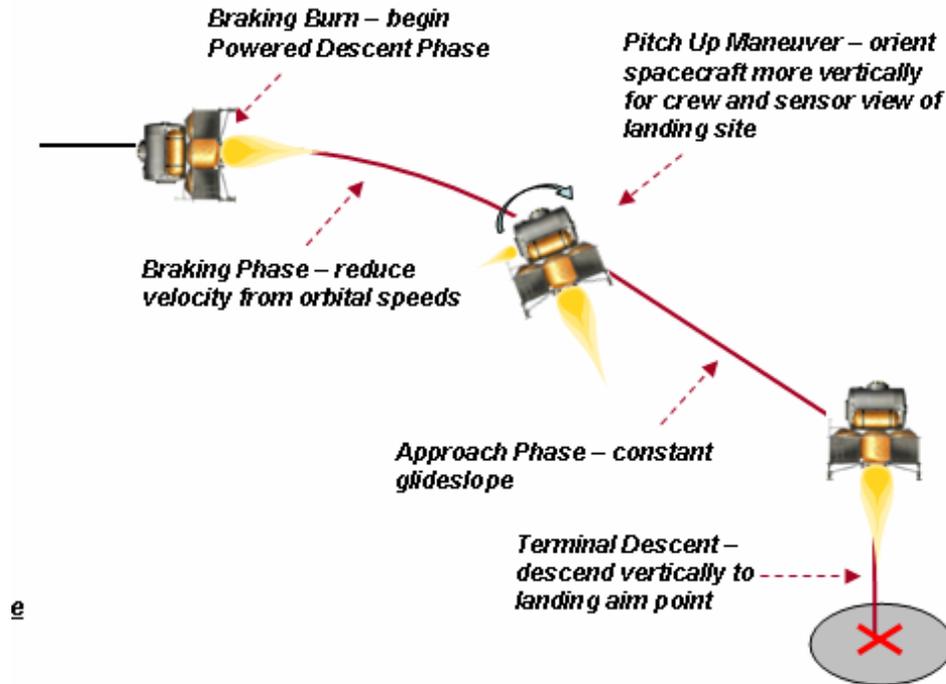
*Pitch-up.* Following the Braking phase, it may be desirable to maneuver to an attitude that permits crew to have a view of the landing area. At the same time, sensors can scan the landing point and surrounding area.

Since the Braking Phase will require the vehicle to generally be horizontal, and the attitude necessary for viewing is relatively vertical by comparison, an intermediate pitch-up maneuver is required. This is a rate limited maneuver that adjusts the vehicle attitude from the angle at the end of the Braking Phase to the orientation required for the start of Approach Phase.

*Approach Phase.* During Approach, the vehicle maintains a relatively constant attitude with a relatively low throttle setting. The guidance scheme for this phase is similar to that used during Apollo and is discussed in greater detail in the following section.

*Final (or Terminal) Phase.* The objective of the final phase is to descend slowly to the landing site in a near vertical orientation, staying above the landing aim point and nulling out any remaining horizontal velocity.

### Powered Descent Phase



**Figure 2 Powered Descent Sub-Phases**

## **GUIDANCE SCHEME**

### **Braking Phase Guidance**

The braking phase uses a version of Shuttle Ascent PEG that has been shown to be optimal for exo-atmospheric flight. There are documents available that cover this scheme<sup>1-3</sup>, so it will not be discussed in detail in this document. Future ALHAT results will utilize a modified version of PEG that was created by Tom Fill of Charles Stark Draper Laboratory (CSDL). Results presented here were generated using the unmodified version.

As a side note, unlike ALHAT, the Apollo LM Guidance used a Braking Phase scheme that was the same as the Approach Phase<sup>4</sup>. This scheme was similar to the analytical scheme presented below. ALHAT has chosen a PEG-like approach for the Braking Phase since it has demonstrated increased performance in simulations. It also has the added advantage of assuming a constant throttle as part of the solution, whereas the Apollo guidance commanded a variable throttle throughout the Braking Phase, and had to be augmented by a throttle routine due to an engine instability at certain throttle settings.

### **Analytic Guidance for Pitch-up and Approach Phase**

An analytic guidance scheme is currently being applied to the Pitch-up and Approach Phases. It assumes a quadratic profile in acceleration (or quartic in position) during the phase. The trajectory is shaped by selecting a set of boundary conditions, which are used to solve for the coefficients of the guidance equations.

Develop equations for Approach. Update material from AIAA paper<sup>5</sup>. Clean up notation.

### **Final Descent Guidance**

The objective during the final phase is to vertically descend at a small, constant velocity to the landing site. This does not require a guidance algorithm in the same sense as the earlier phases. During Apollo, this phase, as well as some or most of Approach, was flown by the commander. However, since the ALHAT system is being designed to be applicable to crewed, cargo, and robotic missions, the guidance must include a reference algorithm for non-piloted final descent. Furthermore, even though the target at the end of the Approach Phase, is zero horizontal velocity at a vertical attitude, this target will not be met exactly. The horizontal position and velocity will also be affected by other perturbing forces such as fuel slosh, pointing error, etc. Thus, a guidance law with velocity feedback is desirable. Position feedback may also be beneficial. A basic guidance scheme has been developed. The guidance equations for this scheme follow a simple proportional error feedback law:

$$\begin{aligned}a_v &= a_{t,v} - K_{vv}(v_v - v_{t,v}) \\a_{h1} &= K_{vh1}v_{h1} - K_{rh1}(r_{h1} - r_{t,h1}) \\a_{h2} &= K_{vh2}v_{h2} - K_{rh2}(r_{h2} - r_{t,h2})\end{aligned}$$

For constant velocity targeting, the vertical acceleration target ( $a_{t,v}$ ) is set to one Lunar G. Also, note that if the vehicle is directly above the landing site with zero horizontal velocity, the commanded acceleration in the horizontal direction will be zero.

This scheme has undergone initial testing and works properly, but it has not yet tested with a control algorithm and realistic dynamics in the loop. It requires further study and may require modification once further testing has been completed.

### **TRAJECTORY DESIGN**

In general, a typical primary trajectory design objective is to minimize propellant. However, for many phases of flight there are competing objectives, thus making the job of the trajectory design engineer interesting. The lunar powered descent maneuver is fairly large in delta-V (on the order of 2000 m/s) and has a large multiplier (or “gear ratio”) to mass on the pad so even small reductions in delta-V during powered descent can make a significant difference in mass for the overall architecture.

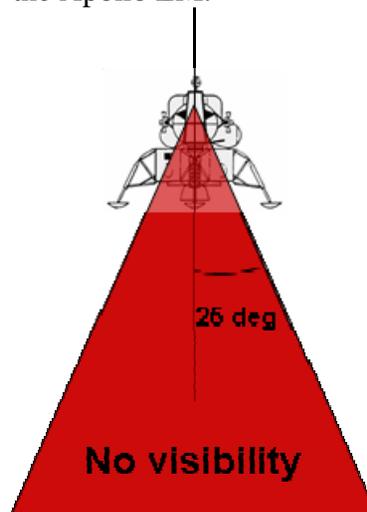
The trajectory guidance concept proposed here takes these concerns into account. The first and longest phase, called Braking, is designed to minimize propellant usage. However, as the vehicle begins to approach the lunar surface, some other concerns must be traded off with propellant usage. First, in order to successfully land to the desired

accuracy, there must be enough margin in the trajectory design to remove dispersions prior to landing. Secondly, enough time must be allotted for hazard detection sensing, crew interaction, and hazard avoidance. In addition, there may be other constraints on the trajectory path. For example, a crew window view may be required during the descent.

## NEAR SURFACE APPROACH

While it is expected that the LSAM will have a window for crew viewing, the exact role of the window during landing operations is unclear. During Apollo, the crew viewing of the lunar surface through the window was the primary method of hazard detection and landing site selection. ALHAT is developing sensor technologies that will provide the crew significantly more information that would be available to them via a window alone. The collection of sensors may include an optical camera, which could provide the same functionality as a window, though arguably at lower reliability. In addition, some of the landing sites currently under consideration have very poor lighting conditions for crew viewing. One example is the Shackleton Crater site, which stays lit for a significant majority of time, but the sun never rises more than a few degrees above the horizon. For these landings, the direct crew view will likely be used as merely a backup. However, it is possible that the window view may still be part of the primary operational scenario for missions with appropriate lighting, particularly for the first few missions, or the sortie-type missions. Thus, the direct crew window view impact on trajectory must be considered.

Requiring the direct window crew view of the landing site places some significant constraints on the descent trajectory. Though LSAM designs are only at a conceptual level at this time, it can be assumed that crew viewing directly below the vehicle will be blocked by the spacecraft engine and other structure. The Apollo LM had no visibility in a 25 deg cone<sup>6</sup>, measured from vertical, as shown in Figure 3. This forces the vehicle to approach the landing site with a look angle (measured between the vehicle vertical and the line of sight to the landing point) of greater than 25 deg, at least during the regime in which a view is desired. It can reasonably be assumed at this point that LSAM constraint would be somewhat similar to the Apollo LM.



### Figure 3 No Visibility Constraint

Figure 4 shows a series of reference approaches for achieving a crew window view, including the Apollo LM trajectory. The final condition for each case is zero horizontal velocity at height of 30 m, with a descent rate of -1 m/s. Each case represents the path flown while holding particular look angle during the approach, assuming a 1.2\*LunarG constant acceleration provided by the engine, which requires a near-minimum throttle setting. The blue, right-most line shows the limiting case, where the look angle is 25 deg. This would correspond to the case at which the landing site is at the edge of the window. At the opposite end of the spectrum shown in figure 4 is the Apollo LM path. Flying this approach causes a look angle of about 52 deg, which would well away from the edge of the window.

The ideal approach for sensing the landing area is vertical or near vertical descent. This minimizes the slant range which improves the returns to the sensor. It also allows a clearer view of hazards, with less obstruction and shadowing. On the other hand, the window view improves with a more horizontal approach.

The red, 35 deg look angle line was selected as a compromise between optimal crew viewing and sensor viewing. The path follows approximately a 45 deg depression angle (measured from horizontal to the trajectory path). The initial point of the red line (about 800 m altitude and range) represents a preliminary estimate of the location at which a HDA scan would begin. The scan must begin early enough such there is adequate time to complete the initial scan, allow for crew processing of the information and decision making, and still have enough margin for maneuvering to avoid any hazards. Current assumptions require the scan to begin at least 100 sec to touchdown. These assumptions are undergoing refinement.

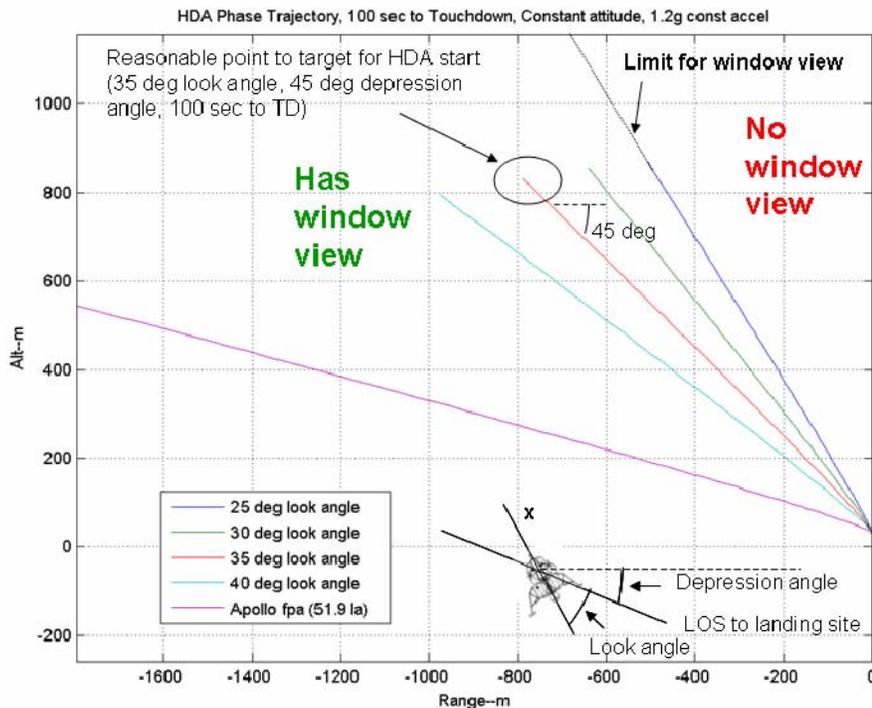
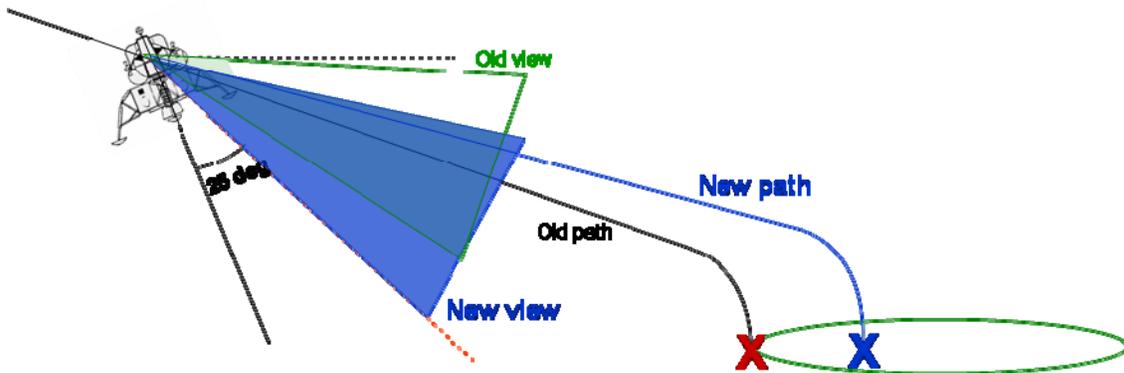


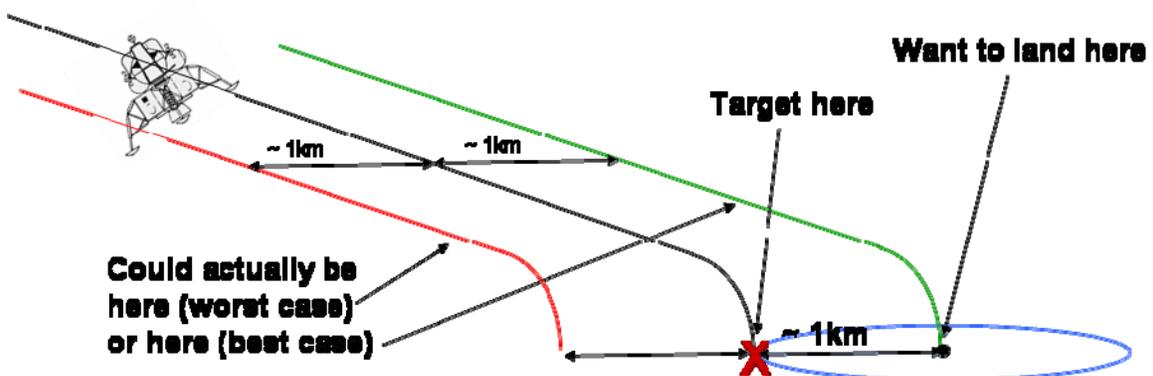
Figure 4 Reference Approaches to Landing Site

Another consideration for direct crew window viewing during the approach concerns landing site redesignation. In order to redesignate short, or up range, the vehicle would need to pitch more towards the horizontal in order to reduce the horizontal velocity more quickly. This would cause the landing site to move more towards the bottom edge of the window. On the other diverting long, or downrange, improves the window view, by rotating the vehicle attitude more toward the vertical, and increasing the look angle. This is shown in figure 5. In addition, diverting the same amount of distance in the up range or downrange direction has a greater delta-V cost for up range. This cost is increased for more horizontal approaches.



**Figure 5 Diverting Long Improves Window View**

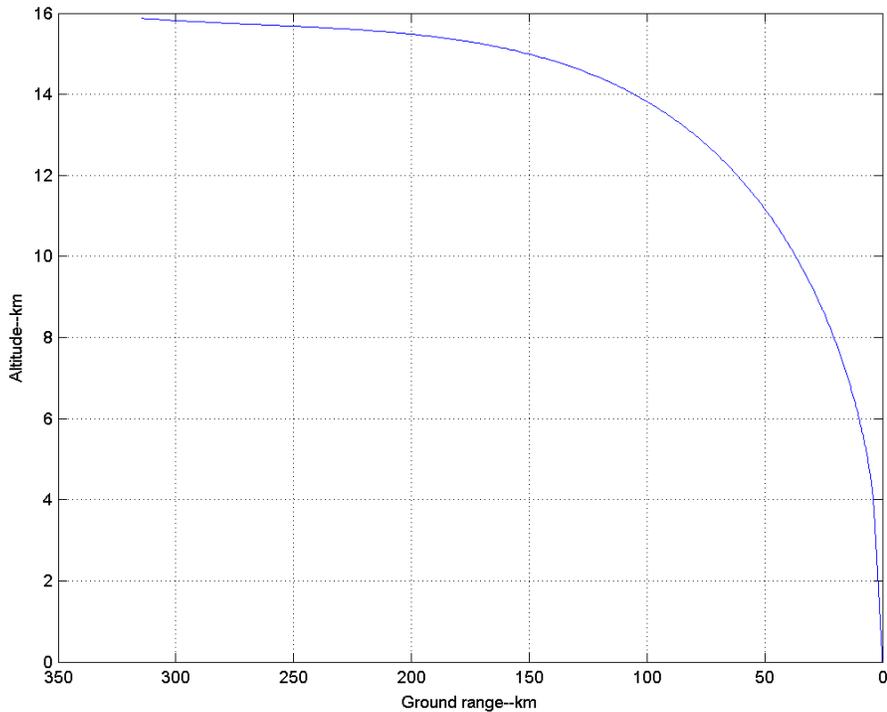
Apollo handled these concerns by only planning to perform downrange diverts. The 45 deg approach path proposed in figure 4 does not leave much margin for a crew view, and would not maintain the view for any significant up range divert. In order to preserve the crew view and achieve the 100 m accuracy, the LSAM would have to target up range of the landing site by the amount of the estimated worst case dispersions at the start of the approach. Rough early estimates show that the navigation error may be on the order of 1 km prior to the operation of the Terrain Relative Navigation system. Figure 6 shows how targeting up range by 1 km may result in a worst case divert downrange of 2 km.



**Figure 6 Targeting For Preserving a Direct Window View**

## NOMINAL TRAJECTORY

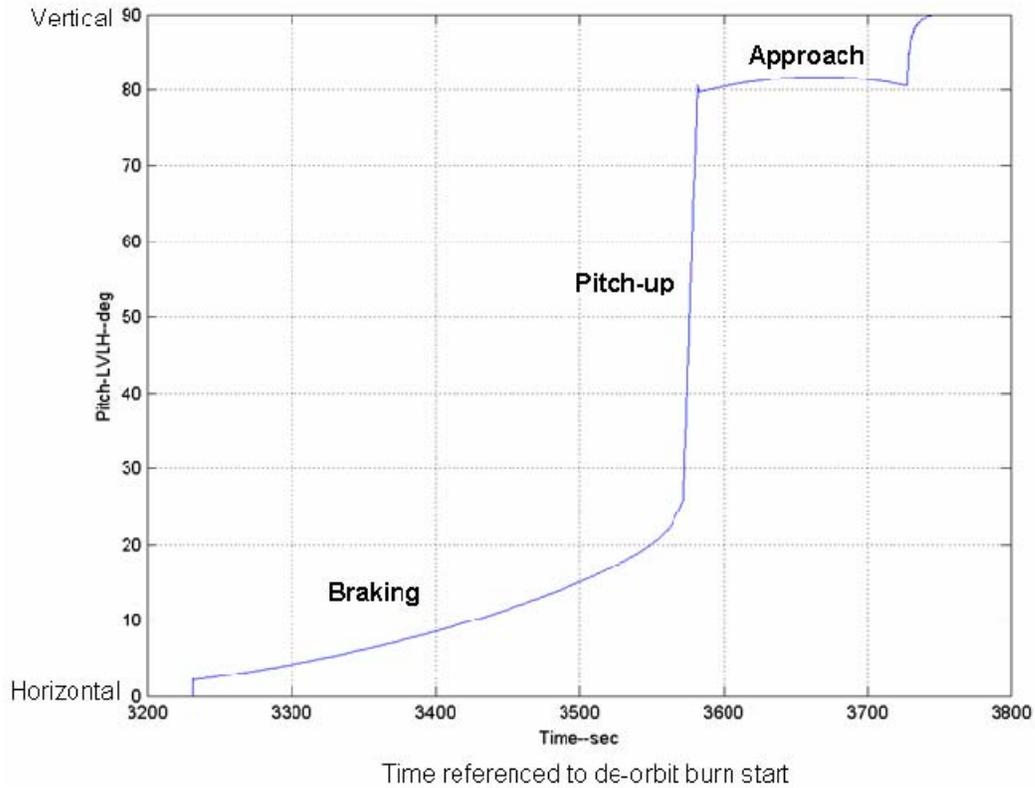
Figure 7 shows the altitude-range plot for the entire Powered Descent Phase for a nominal trajectory targeting a 45 deg depression angle during the Approach Phase. The vehicle travels over 300 km in range during the descent. Figure 8 shows the pitch attitude over time, as referenced to the start of the de-orbit burn. A pitch of 90 deg corresponds to vertical, and zero deg is horizontal. The sequence of phases can be seen clearly in figure 8. The entire powered descent lasts 527 sec (6 min 47 sec). The first 341 sec is the Braking Phase, during which the vehicle attitude is mostly horizontal. Towards the end of the Braking Phase, the vehicle begins to pitch a little more vertical as horizontal velocity is removed and the gravity increases the altitude rate. The Braking Phase is followed by a 10 sec pitch maneuver to the attitude required for the start of Approach Phase. During the Approach Phase, a relatively constant attitude is maintained. The Approach Phase lasts 146 sec for this trajectory. Following Approach is the Final Phase, at which the vehicle pitches to vertical for the final 30 sec and nulls any remain horizontal velocity while maintaining a constant 1 m/s altitude rate.



**Figure 7 Powered Descent Phase Altitude vs Range**

Figure 9 shows the thrust acceleration provided by the engine during the descent. The throttle setting remains constant at fairly high setting during the Braking Phase, but the decrease in propellant mass causes the acceleration to increase during the phase.

Notice that the maximum acceleration is only 6 m/s<sup>2</sup>, much less than one Earth G, so crew G effects will not be an issue.



**Figure 8 Powered Descent Phase LVLH Pitch vs Time**

During Pitch-up Phase, the engine is throttled back to the low setting desired for the Approach Phase. The Approach Phase is targeted for a relatively constant acceleration of about 1.2\*LunarG. This value, as well as the Approach phase length of 146 sec, was chosen based on previous analysis and has not yet been optimized for this descent profile. A low acceleration during Approach Phase allows the vehicle to be closer and slower to the landing site for improved viewing and sensing during the approach, but at the expense of fuel.

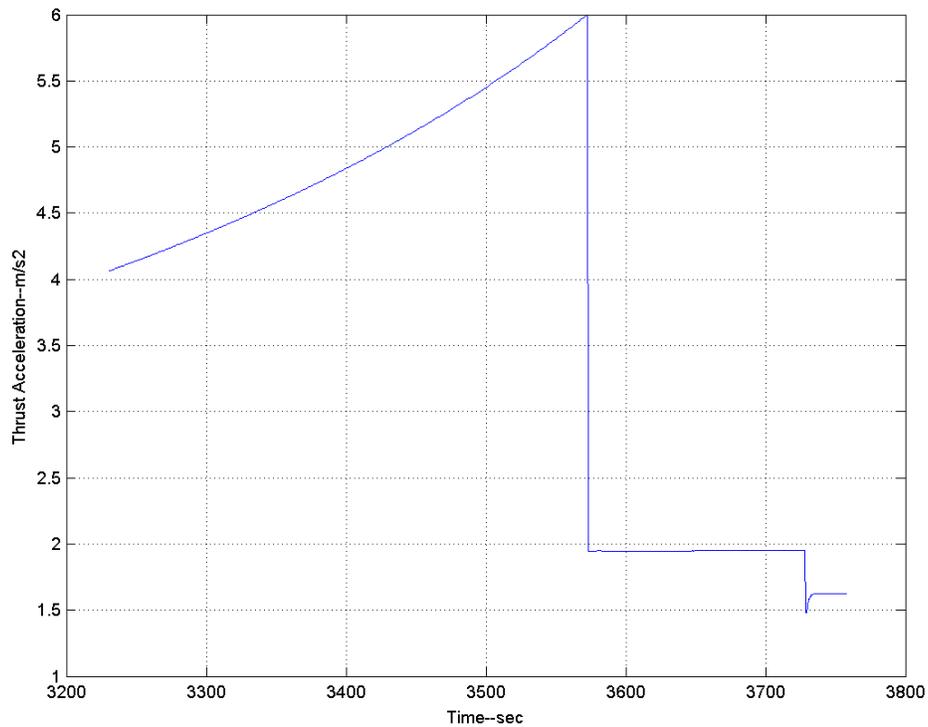
The final phase thrust acceleration is approximately equal to one LunarG, which allows the vehicle to maintain a constant velocity during the final descent of about 30 m.

Figure 10 shows the nominal trajectory path for the Approach Phase only, including reference elevation lines. The nominal trajectory follows close to the 45 deg elevation line. Also included on the plot are callouts (black circles) at various amounts of time remaining. Since a number of events will occur (see Figure 11) during the final approach and landing, it helps to look at the callouts to get a feel of where the vehicle will be at a given time. The 176 sec callout represents the start of Approach Phase, when the Pitch-up has been completed. The crew would get their first view of the landing site shortly following. Though small hazards are not likely to be visible at this time, the crew should be able to detect larger scale features associated with the desired landing area.

Also, it is envisioned that the TRN system will be active during this time. The remaining dispersions must be identified and removed quickly, as the cost to remove them increases rapidly in this phase.

At about 100 sec (current rough estimate), the ALHAT System transitions more to Hazard Detection and Avoidance mode (not necessarily turning off TRN yet, though). The range is now less than 1 km, and smaller scale hazards are identified by the sensors and sensing algorithms. Once a safe site has been identified, the vehicle must maneuver to land the new location, if it is different than the current target.

More plots of both the Powered Descent Phase and the Approach Sub-Phase are contained in Appendices A and B.



**Figure 9 Powered Descent Phase Thrust Acceleration vs Time**

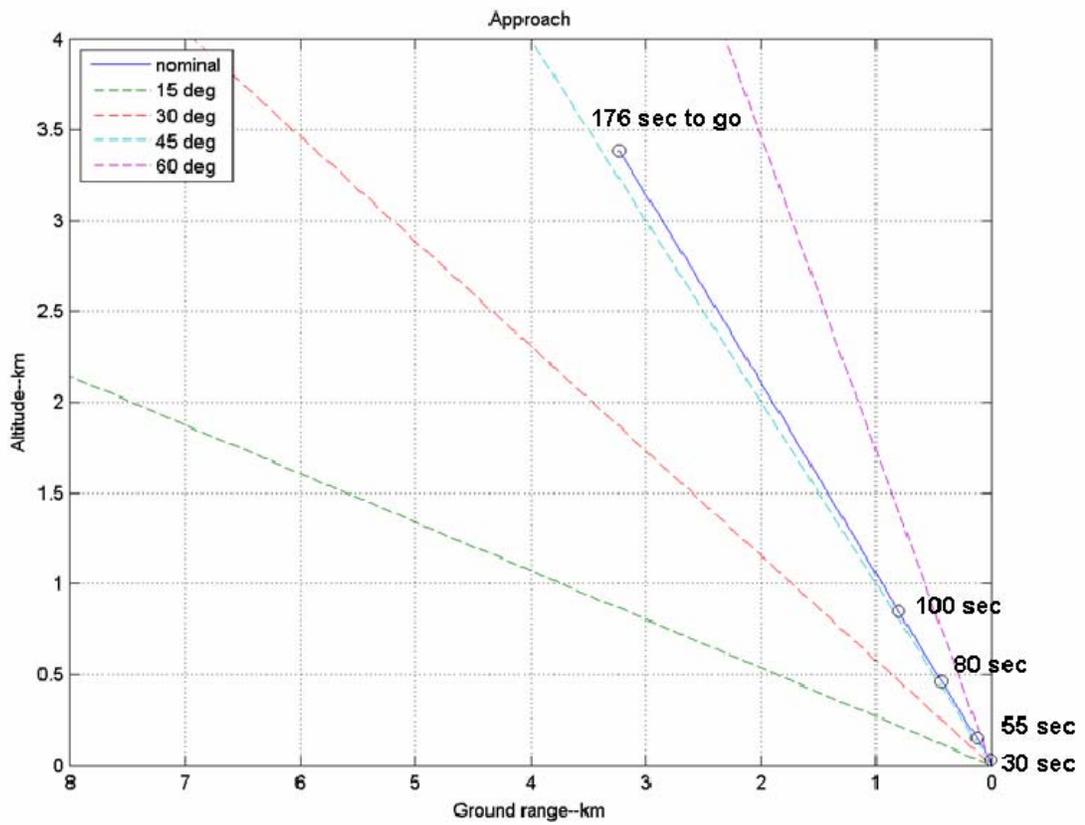


Figure 10 Approach Sub-Phase Altitude vs Range



Figure 11 Approach and Final Descent Events

## CONCLUSION

### ACKNOWLEDGMENT

Ron would like to acknowledge a few of the many who contributed in some way to this work, either through their support, technical work, or discussions. In particular, Tom Fill and Steve Paschall of Draper Labs have made significant contributions to ALHAT guidance and trajectory, and have helped shape this work. Also, from CSDL, are Laura Forest, Tye Brady, and Bobby Cohan. From JSC, Carlos Westhelle, Jerry Condon, Lee Bryant, Chris Cerimele, Chiold Epp, Tim Straube, Jeremy Rea, and Jennifer Gruber. Thank you very much to all.

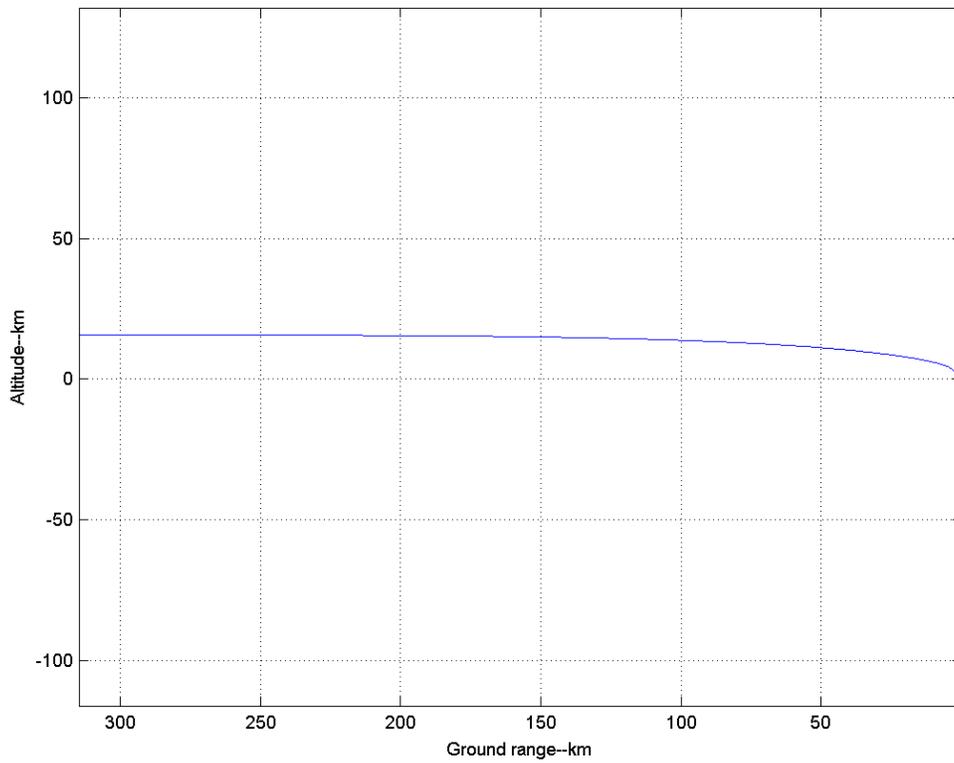
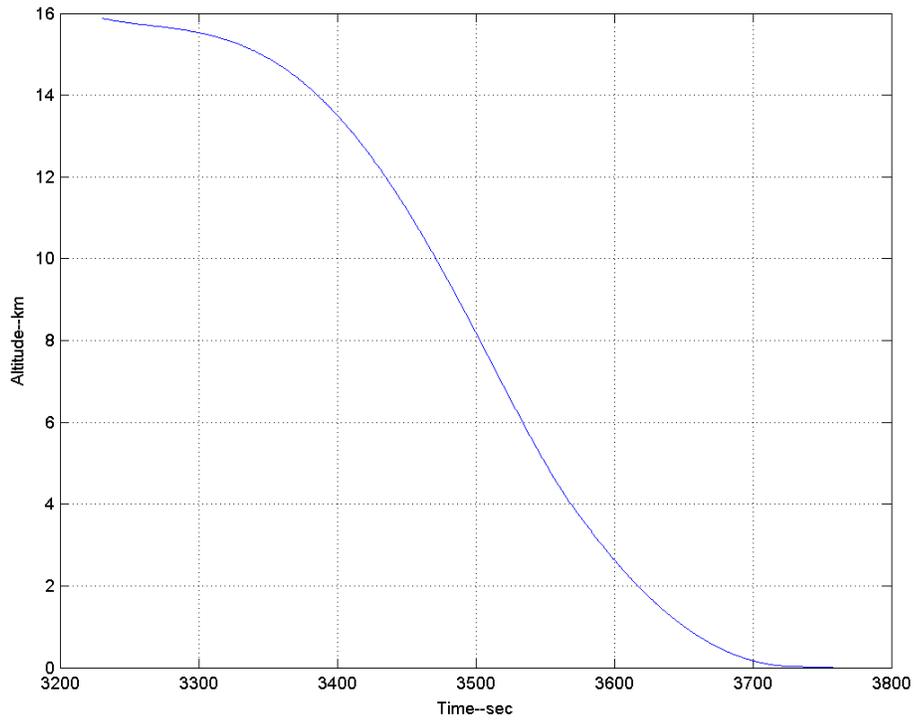
### NOTATION

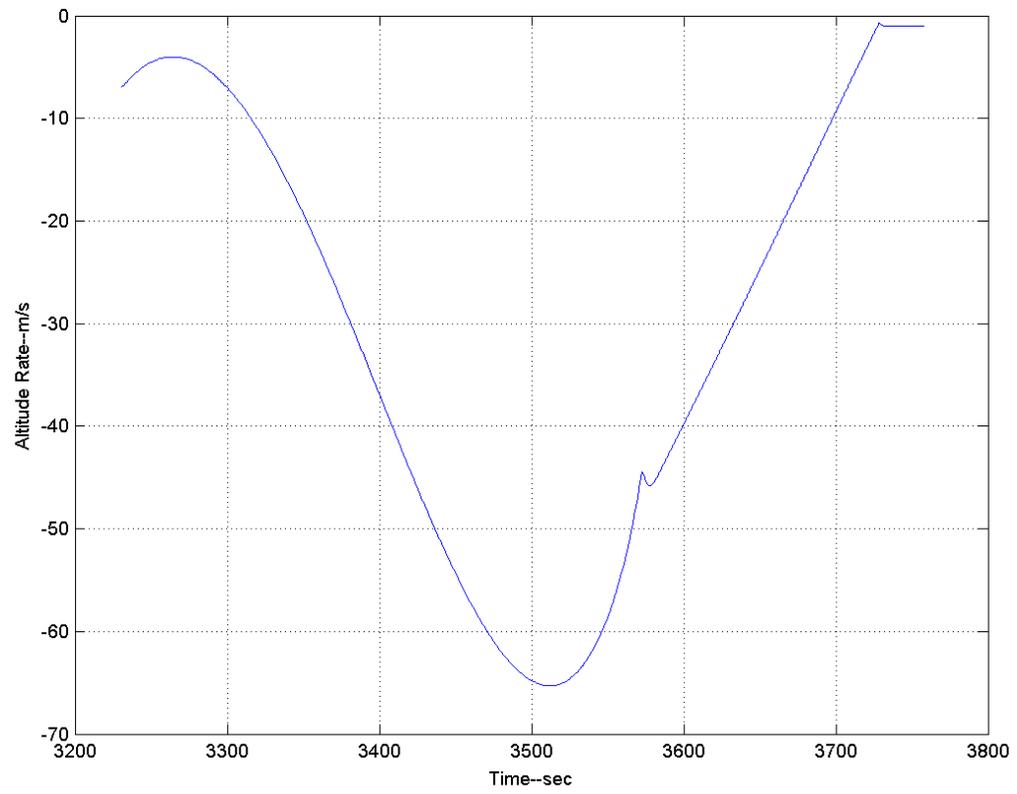
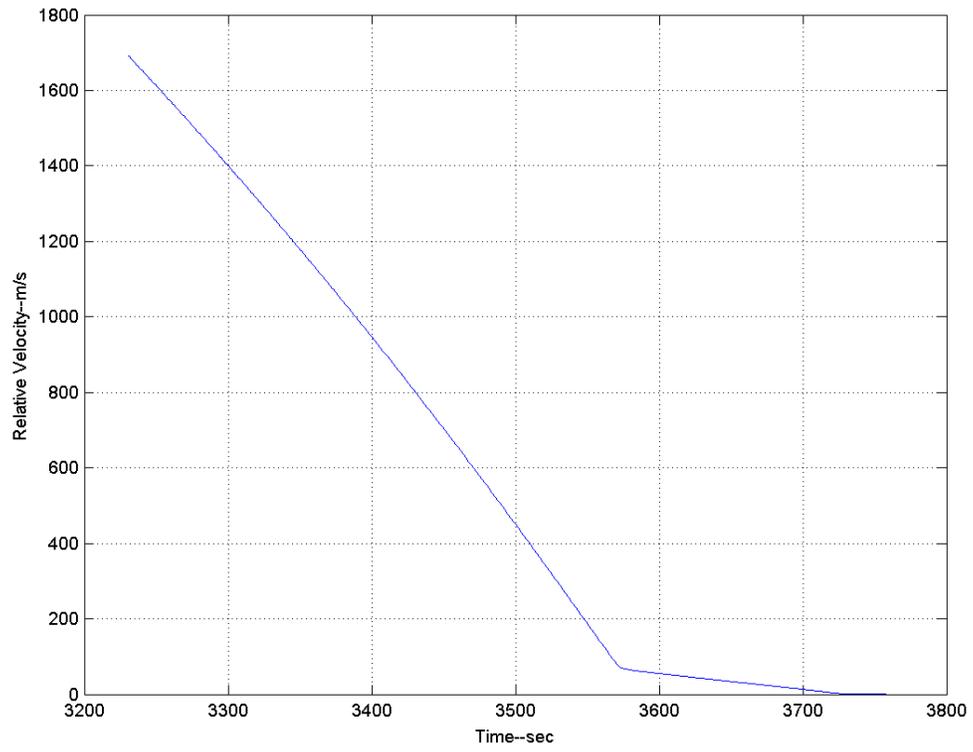
ALHAT	Autonomous Landing and Hazard Avoidance Technology
CSDL	Charles Stark Draper Laboratory
HDA	Hazard Detection and Avoidance
JSC	Johnson Space Center
LM	Lunar Module
LOS	Line of sight
LSAM	Lunar Surface Access Module
PDI	Powered Descent Initiation
PEG	Powered Explicit Guidance
TRN	Terrain Relative Navigation

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## APPENDIX A: POWERED DESCENT PHASE PLOTS





## APPENDIX B: APPROACH SUB-PHASE PLOTS

