ΔV Requirements for a Gun Assisted Launch to Circular Orbit

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Introduction and Assumptions

An earth-based gun can be used to send a projectile into space, but the trajectory will eventually bring the projectile back to the surface. Any practical orbit requires an additional change in velocity, presumably using traditional on-board rocket propulsion, in order to achieve a useful orbit. For the purposes of the study, it is assumed that the desired final orbit should be circular at a specified altitude. In this study, we address the preferred strategy for reaching a specified orbit in terms of the total rocket-burns change in velocity and the gun launch parameters. The design goal is to maximize the payload fraction of the projectile, which equates to minimizing the change in velocity that must be imparted by the on-board rocket. Implicitly, we assume that the gun can achieve any desired exit velocity (up to earth escape velocity).

Many of the same issues have been addressed in earlier papers [1-3]. Each of these papers discusses the aerobraking maneuver to apply one of the impulses needed to reach the desired orbit, as well as the single impulse and double impulse approaches discussed below. The findings in the present paper are somewhat different in that the one-burn (single-impulse) method appears to be preferable to aerobraking over a wide range of final orbits. The exact differences in the assumptions that lead to this difference in results have not be examined.

All the calculations assume that the gun is placed at the equator and the goal is an equatorial orbit. Changing the orbital plane would be an additional rocket burn. The earth's rotational speed has been included in the calculations.

The gun trajectory calculations do not account for aerodynamic losses. A separate study is being performed to look at losses and other aerodynamic effects. It is more accurate to think of the gun exit velocity and angle as the parameters taken from the gun trajectory at the edge of the sensible atmosphere. The velocity loss in the atmosphere would be an additional velocity increment that would be supplied by the gun. By ignoring the aerodynamic contributions, the trajectory calculations can be performed with closed-form equations and simple numerical searches. This allows for rapid studies over a wide range of parameters.

One-Burn Strategy

The one-burn strategy assumes that the gun trajectory reaches an apogee equal to the desired altitude of the circular orbit. A single burn is then used to circularize the orbit. The strategy requires that the gun have a variable exit velocity. It is assumed that the gun launch angle is fixed. This approach would seem to be easier to construct in practice for a large earth-based accelerator, although the gun described in reference 4 uses an ocean-based design that allows for an adjustable gun angle.

Figure 1 shows the relative performance of this strategy. The parameter ΔVrel is the rocket propulsion change in velocity needed for the projectile to reach the final orbit divided by the change in velocity needed for a pure (no gun) trajectory to orbit. The pure rocket trajectory is computed by starting with an elliptical orbit with the perigee at the earth's surface and apogee at the desired altitude, followed by a circularization burn. Aerodynamic and gravity losses (for a finite burn time) are not taken into account. The plot shows a the required velocity change is small compared to a pure rocket, with a corresponding large increase in the payload mass fraction for the projectile. A near horizontal gun launch angle is preferred, but there will be some compromise to account for aerodynamic losses. A vertical gun makes little sense using this strategy.

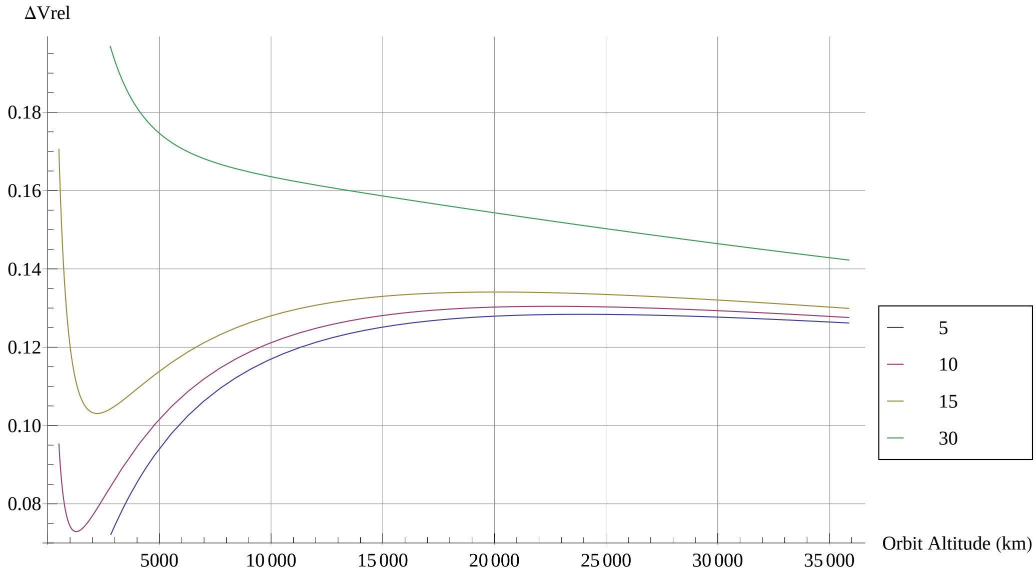

Figure 1. ΔV Required to reach circular orbit, relative to velocity change for pure rocket trajectory versus final orbit altitude. Curves are for various gun launch angles.

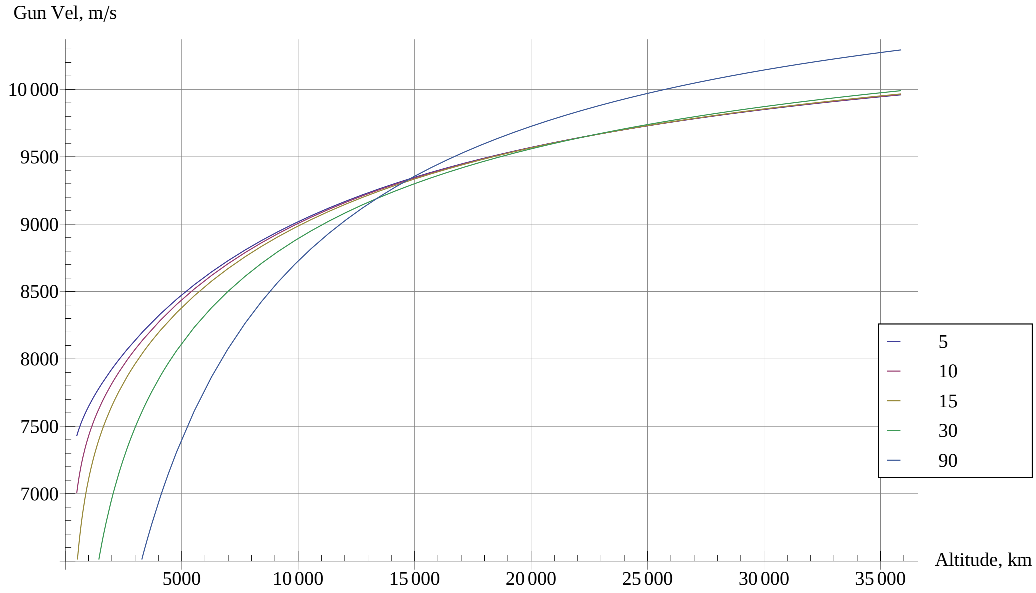

Figure 2. Gun exit velocity required to reach a specified altitude. Curves are for various gun launch angles.

Figure 3 is an interactive display of the gun trajectory and the final orbit (dashed line). The major axis for the gun trajectory ellipse is always horizontal, therefore as the gun launch angle is varied, the position on the globe moves. If this is viewed as a CDF (computable document format) file, then the sliders should be functional.

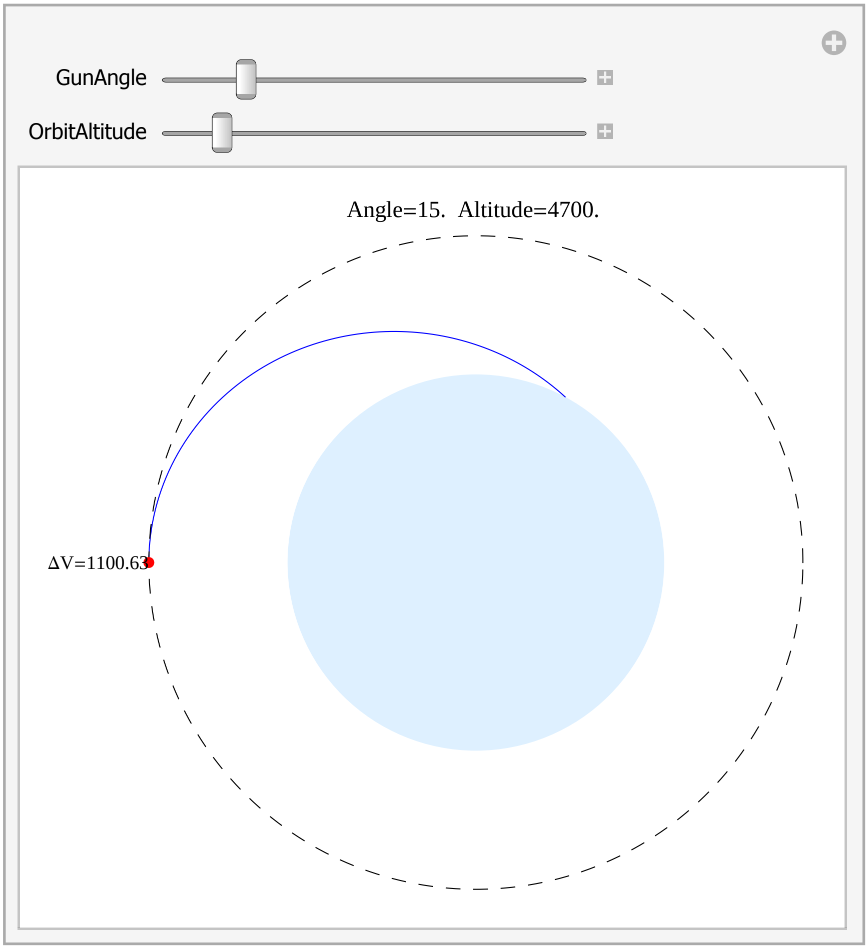

Figure 3. Interactive display of single-burn trajectory. Dashed circle is the target orbit. The GunAngle slider has the range 0-90°, and the OrbitAltitude slider goes from 0-45000 km above the surface.

Two-Burn Strategy

In the two-burn strategy, the gun angle and exit velocity can be fixed. There is an impulse at the top of the gun trajectory such that the perigee of the resulting orbit is at the desired altitude. At perigee, there is a second impulse to circularize. The strategy also can work if the can trajectory does not reach the desired altitude. Figure 4 shows a typical sequence. The figure is to relative scale. Figure 5 shows the efficiency parameter ΔVrel as a function of gun exit velocity and angle. For the shallow angles, there is a gun velocity that gives a minimum ΔV requirement. For high gun velocities (10 km/sec), all of the gun angle curves converge. For these cases, the apogee burn occurs so far from earth that the launch angle is not important. A similar plot is shown for a geosynchronous orbit altitude. The discontinuous slopes in the curves comes from the difference between the gun under-shooting the orbit altitude versus over-shooting. Note that for a high gun velocity (10 km/sec), the ΔV requirement to reach geosynchronous is lower than that required to reach low earth orbit.

Figure 7 is an interactive display of the gun trajectory (blue), transfer orbit (green) and the final orbit (dashed line).

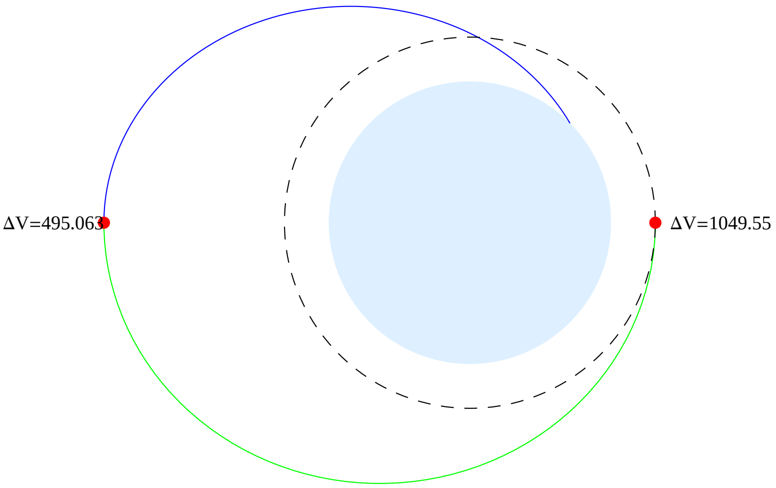

Figure 4. Example trajectory for two-burn strategy. 9 km/sec gun velocity, at 15° to horizontal. Target altitude is 1500 km.

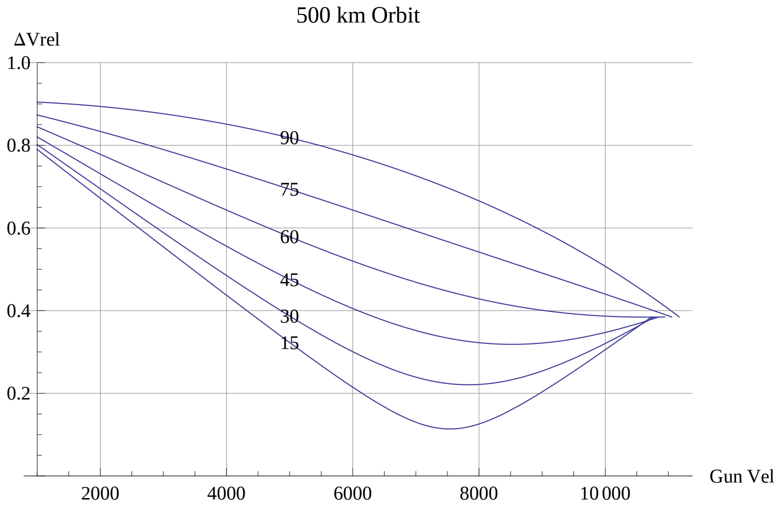

Figure 5. Relative rocket velocity change needed to achieve a 500 km orbit for a range of gun velocities and launch angles.

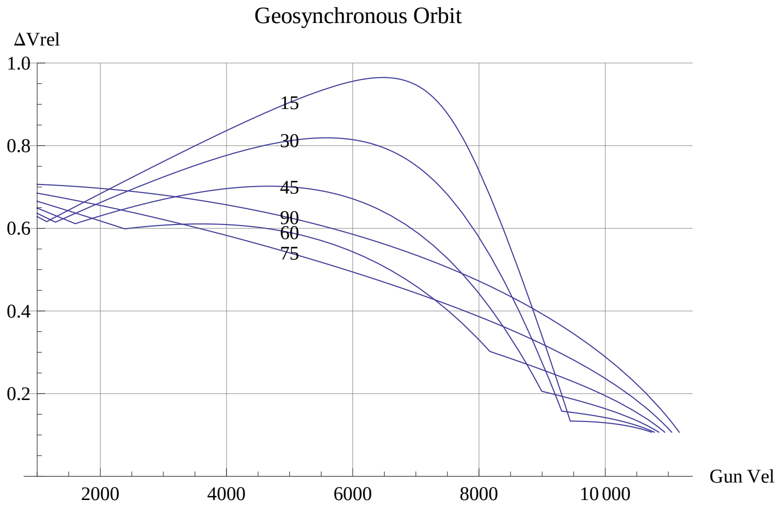

Figure 6. Relative rocket velocity change needed to achieve a 1000 km orbit for a range of gun velocities and launch angles.

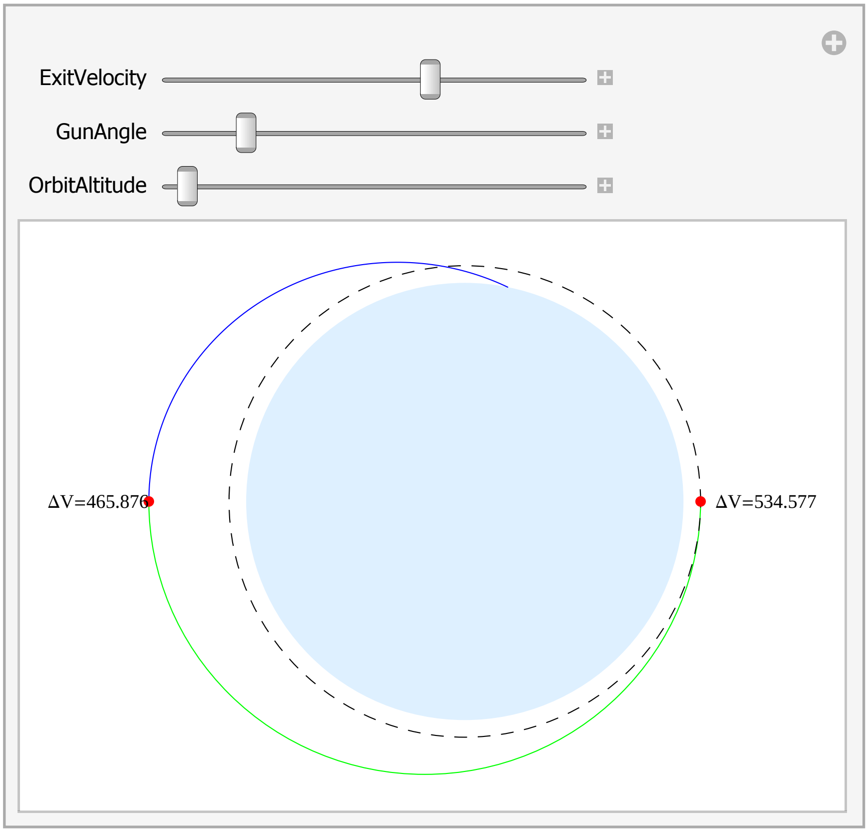

Figure 7. Interactive display of two-burn trajectory. Dashed circle is the target orbit, the blue curve is the initial gun trajectory, and the green curve is the transfer ellipse. The ExitVelocity slider has a range of 500-12000 m/sec, GunAngle goes from 0-90°, and orbit altitude goes from 0-45000 km above the surface.

Aerobraking Strategy

The aerobraking strategy requires three impulses; two are provided by the on-board rocket, and the third is provided by a pass through the earth’s atmosphere to slow the projective. Figure 8 shows a typical scenario. The gun trajectory (blue) must to above the desired orbit for the maneuver to work. At the apogee, a rocket impulse changes the ellipse so that the new perigee skims the atmosphere at a height appropriate to slow the projectile. The aerobraking brings the path such that the apogee now reaches the desired final altitude. A final rocket impulse circularizes the orbit.

The present analysis assumes that the aerobraking occurs instantly, just as we assume for the rocket burns. In reality, the aerobraking maneuver will have to occur over a broad angle. However, the crude assumption should not affect the rocket impulse requirements significantly. For the present purposes, we specify an altitude for the minimum altitude for the aerobrake maneuver. In the results shown below, a minimum altitude of 50 km is used.

The aerobrake maneuver should be essentially “free”. The aerodynamic loads and heat transfer are likely to be much smaller than occur at the gun exit, so no additional heat shield mass is needed.

Figure 9 shows the efficiency parameter ΔVrel for this strategy. For a low earth orbit and a high gun velocity, the rocket impulse requirement is nearly zero. The strategy does not work well for high altitude orbits. The plot for geosynchronous orbit is shown in Figure 10.

Figure 11 is an interactive display of the complete trajectory.

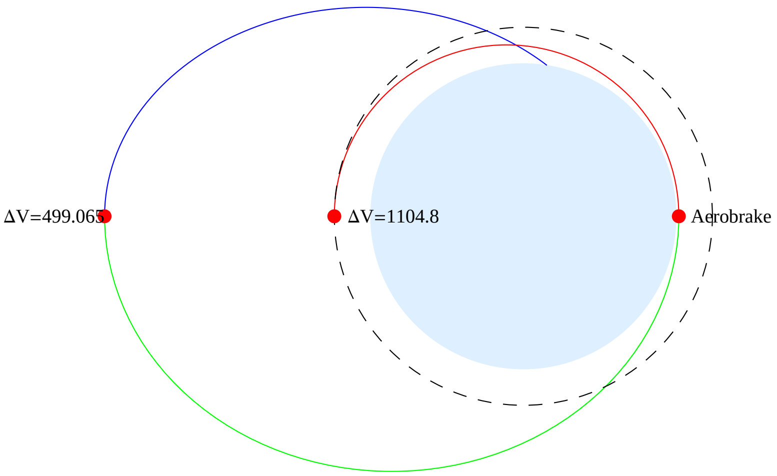

Figure 8. Example trajectory for aerobraking maneuver. 9 km/sec gun velocity with a launch angle of 30°. Target orbit at 1500 km.

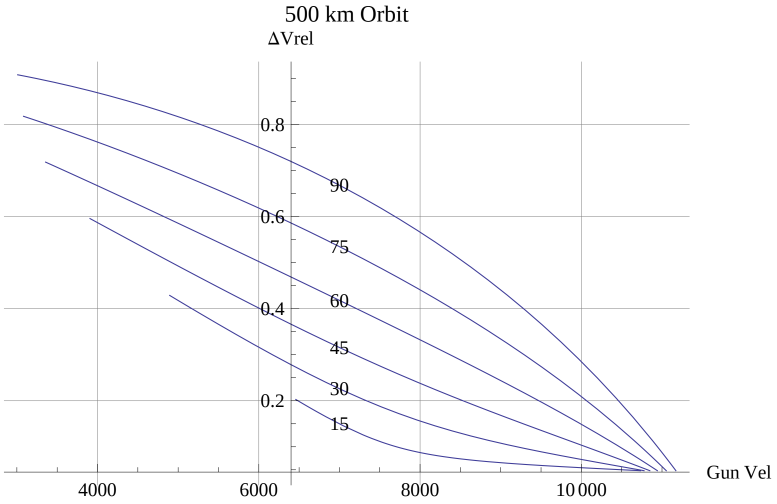

Figure 9. Relative rocket velocity change needed to achieve a 500 km orbit for a range of gun velocities and launch angles with aerobraking maneuver.

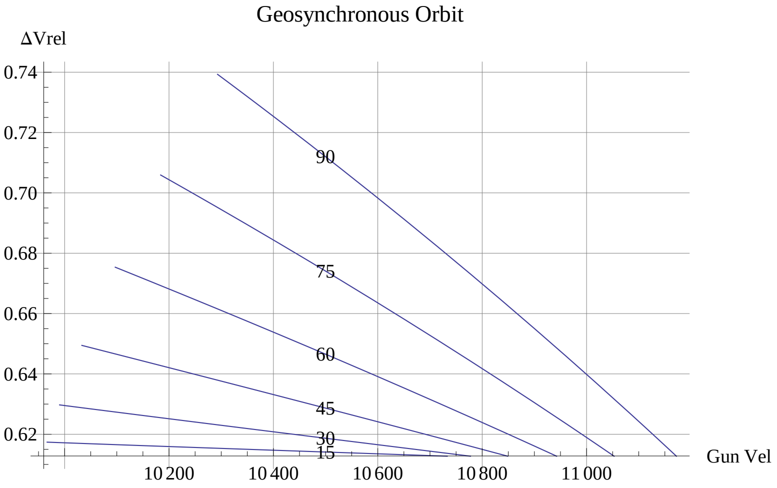

Figure 10. Relative rocket velocity change needed to achieve a geosynchronous orbit for a range of gun velocities and launch angles with aerobraking maneuver.

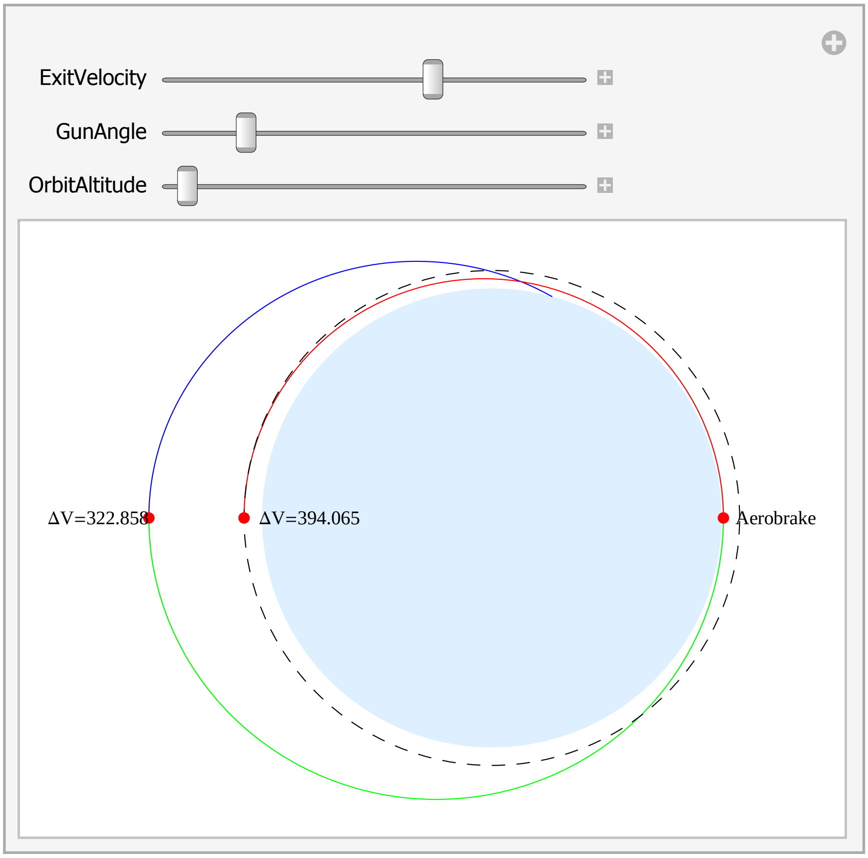

Figure 11. Interactive display of trajectory with aerobraking. The ExitVelocity slider has a range of 500-12000 m/sec, GunAngle goes from 0-90°, and orbit altitude goes from 0-45000 km above the surface. The minimum altitude at the aerobrake maneuver is 50 km.

Conclusions

Figure 12 shows a comparison between the different strategies considered. In order to simplify the plot, we have picked a single gun angle (10°) and gun velocity (10 km/sec). For the assumptions used in this study, the single-burn strategy is the most efficient over a wide range of orbit altitudes. For very low orbits, the aerobrake maneuver gives a slight advantage, but at significant additional complication to the projectile design and flight guidance requirements.

The original goal of using a gun and these maneuvers is to increase the final mass to orbit of the projective. Figure 13 makes the straightforward conversion from the ΔV requirement and the mass fraction for an assumed rocket specific impulse of 300 sec. For comparison, the mass fraction for a pure rocket is also shown. The large mass fraction should equate to dramatically lower cost-to-orbit.

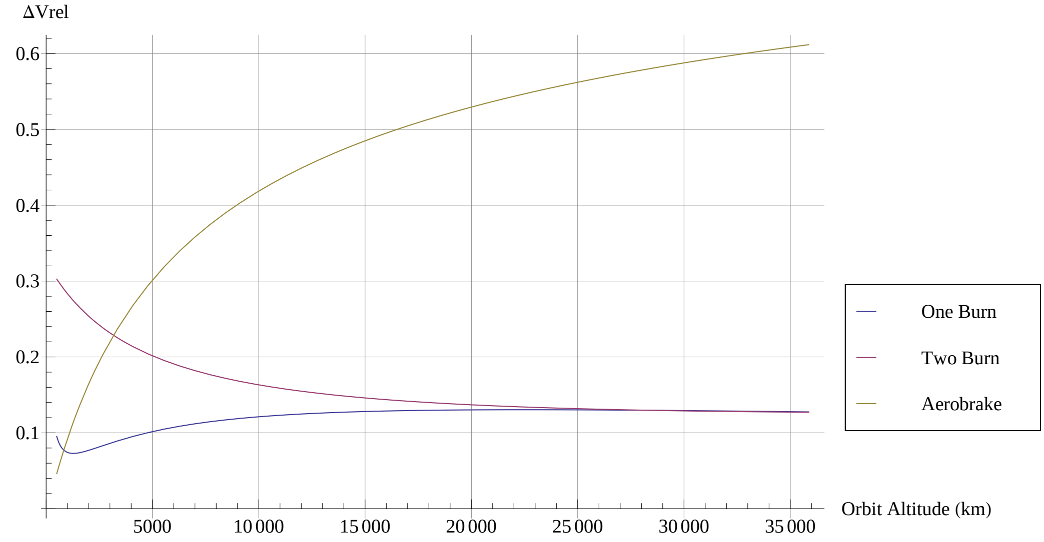

Figure 12. Relative velocity change required versus target orbit altitude for each of the proposed strategies. All three curves assume a 10° gun launch angle. Two-burn and aerobrake maneuvers assume a 10 km/sec gun exit velocity.

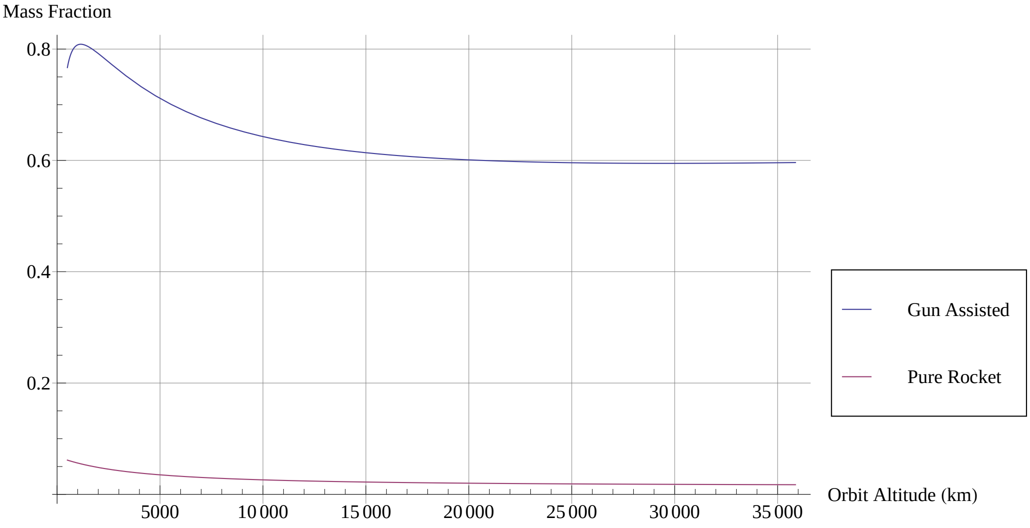

Figure 13. Mass fraction (final mass/initial mass) for projectile using single-burn strategy and same parameters as in Figure 12. Assumes ISP of 300 sec.

References

1. A.P. Bruckner and A. Hertzberg, “Ram Accelerator Direct Launch System for Space Cargo”, presented at 38th Congress of the International Astronautical Federation, October 1987, IAF-87-211.
2. P. Kaloupis and A.P. Bruckner, “The Ram Accelerator: A Chemically Driven Mass Launcher”, AIAA-88-2968.
3. David Bogdanoff, “Ram Accelerator Direct Space Launch System: New Concepts”, J. of Propulsion and Power, Vol. 8, No. 2, March-April 1992, pp 481-490.
4. John Hunterm Harry Cartland, Rick Twogood, “Cannons to the Planets”, GoogleTechTalk, Dec 2009.