Rocket Performance Analysis Using Electrodynamic Launch Assist

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This work examines performance advantages, such as gain in altitude, payload and range, which might be provided to a variety of rockets and missiles through the use of magnetically levitated launch assist systems. Using subsonic launch speeds at Mach 0.8, it was found that rocket payloads to orbit can be increased by up to 35 percent and dynamic pressure loads reduced relative to traditional launch. Performance improves continually with increasing launch speed. The relative importance of projectile aerodynamics was assessed through a range of drag configurations and was found to have a significant impact on performance of vehicles launched with initial speed. Optimum propulsion ignition delay times were found to exist for projectiles characterized by high launch velocity or high drag. Finally, take-off angles for a given missile and launch speed are optimized resulting in increased range of up to 42 percent at Mach 0.8.

Nomenclature

A_{CS}	=	rocket cross-sectional area, m^2
C_D	=	rocket drag coefficient
LEO	=	Low Earth Orbit taken at 500 km
g	=	local acceleration of gravity, m/s^2
$GLOW$	=	Gross Lift-Off Weight, kg
I_{sp}	=	vacuum specific impulse, s
l_0	=	track length, m
M_0	=	launch Mach number
m	=	exhaust mass flow rate (fuel mass over burn time), kg/s
q	=	dynamic pressure $\frac{1}{2}\rho V^2$, Pa or kPa
t_b	=	burn time, s
T	=	rocket thrust, N or kN
U_e	=	rocket exhaust velocity, m/s
V	=	flight velocity, m/s
α_0	=	launch angle with respect to horizontal direction, ° or rad
θ	=	flight path angle with respect to vertical direction, ° or rad

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ε = rocket structural coefficient, defined as structure mass over structure plus propellant mass
λ = rocket payload ratio, defined as payload mass over initial mass
ρ = atmospheric density, kg/m^3
Δt = computational time step, s

I. Introduction

THE idea of using electromagnetic forces to assist in launching projectiles to orbit is not new[1-8] and is motivated by the high inefficiency of rocket propulsion within the Earth's atmosphere. Magnetic levitation launch-assist systems act as a cost-effective, reusable first stage to propel a vehicle to an initial speed to alleviate on-board propulsion requirements. Such systems are projected to dramatically reduce the cost of space exploration since the vehicle's first stage would be powered by electricity and remain on the ground unlike conventional rockets which suffer performance penalties from carrying fuel through the ascent. A multitude of applications, ranging from massive subsonic launchers to hypersonic launch of ordinance have been proposed, and the capacity to launch projectiles under short notice and rapid turn time is highly attractive for both military and commercial applications. Although such concepts have been under development for several decades, issues associated with high energy storage and discharge, rail degradation, and vehicle stability (launch accuracy) remain unsolved[8]. To resolve these issues closed-loop electrodynamic levitation suspension (EDS) systems are being investigated[9].

Electrodynamic levitation systems are inherently more robust and permit larger air-gaps than electromagnetic (EMS) systems, which translates to both simpler and less expensive construction. Although in theory EDS is stable, in reality the systems' near-zero damping implies that any induced vibration substantially affects performance. Some passive and hybrid systems have been described to attenuate vibrations in EDS open-loop suspensions, but no system is totally satisfactory and all passive or hybrid systems eventually become unstable at high speeds. The first proof of concept multiple degree-of-freedom trajectory control of an EDS vehicle has been demonstrated at NASA's subscale track located at the Florida Institute of Technology[9,10]. A study of real-time control of EDS levitation based on eddy currents induced in a solid rail is currently under development for heavy lift applications. Direct feedback control may be the final ingredient in realizing the tremendous potential associated with magnetic launch assist.

In light of recent developments on feedback control to resolve challenges in launcher technology, this work examines the potential performance gains that EDS might impart on contemporary rockets, ranging from relatively small sounding rockets to large payload capacity Earth-to-orbit systems. Although some references[††] indicate roughly a 20% reduction in fuel required to reach LEO for a launch speed of Mach 0.8, they do not indicate if performance continually increases with increasing launch speed, when and if diminishing returns occur, if an optimal launch speed exists, how much added orbital altitude may be gained for the same rocket or how drag impacts potential improvements. The goal of this study is to systematically examine a more complete set of parameters such as allowable accelerations, dynamic pressure limits, optimization of launch angles and propulsion ignition delay times in order to develop an understanding of various system optima and sensitivities. Additionally, systems that can handle higher dynamic pressure loads and accelerations are investigated. Finally the use of EDS for missile applications is studied as a means to increase range, paying particular attention to the effect of launch angle.

II. Governing System and Performance Parameters for EDS Launch Assist Systems

The main parameters that govern performance and limitations of the launch system and projectile are the average acceleration, $\bar{a}$, vehicle dynamic pressure, q, and the minimum force, F, energy, E, and power, P, which must be supplied to accelerate the vehicle. Given the projectile's average acceleration along the track, $\bar{a}$, the required track length, l_0, to reach launch velocity V_0 (or launch Mach number M_0) is given by $l_0=V_0^2/(2\,\bar{a})$. In order to launch at Mach 0.8 with an acceleration of 3 gee's 1,302 m of track are needed (taking 9.4 s for the vehicle to reach the end of the track). To launch at $M_0 = 1.5$, with 3 gee's of allowable acceleration, the track must be 4,577 m long (17.6 s). With a larger acceleration of 10 gee's, M_0 = 0.8 can be reached after 391 m (2.8 s), and Mach 1.5 after 1,373 m (5.3 s).[‡‡] Allowable accelerations for modern payloads are typically below 5 gee's and therefore track length may be a concern for launch Mach numbers above 0.8 and sensitive payloads. Moreover, rockets are also structurally restricted by the permissible dynamic pressure, $q=\frac{1}{2}\rho V^2$. Even though accelerations may be kept low with the use of a sufficiently long track, the dynamic pressure continually increases with launch speed. For rockets that are launched with a large enough

[††] "Maglev: Launching Rockets Using a Magnet", URL: http://liftoff.msfc.nasa.gov/News/1999/News-MagLev.asp [cited on 3 Nov 2004]

[‡‡] For comparison, Washington Dulles International Airport (IAD) has a 3,505 m long runaway and the Shuttle Landing Facility at Kennedy Space Center measures 4,572 m.

velocity, the maximum dynamic pressure occurs at the end of the track, rather than at some point along the trajectory. Such vehicles will be limited by both acceleration and dynamic pressure constraints. Unlike rockets, certain types of ordinance has the capability to withstand very high accelerations (up to 65,000 gee's[11]) and thus larger launch Mach numbers ($M_0 \sim 40$) are possible[6,7,12]. Their launch speed is restricted by the force, energy, and power limitations of the launcher rather than limits associated with projectile payload or structure.

The minimum force that must be supplied to the launch system is obtained by neglecting drag (aerodynamic and magnetic) during transit on the launch track. Whereas high acceleration or large mass implies very large forces, the energy required does not depend on track length. For example, it takes the same amount of energy (29 MJ) to launch a 5 kg shell using a 10 m track at Mach 10 as a 1,000 kg rocket at Mach 0.7 using a 600 m long track. However, the force required for either case depends on the track length, and the results are 5.9 MN for the 5 kg shell (at 60,000 gee's) and 49 kN for the 1,000 kg rocket (at 5 gee's). Lastly, the power required may be estimated by the discharge time of the energy requirement, or simply the energy required divided by the transit time, which results in 5 GW and 6MW for the shell and rocket, respectively.

III. Methodology

This section reviews the equations, assumptions, and computational procedure used to assess performance enhancement with launch assist. The velocity of the vehicle is calculated from the rocket equation[13],

$$V(t) = V_0 + U_e \ln\left(\frac{m_0}{m(t)}\right) - \int_0^t \frac{D(t)}{m(t)}dt - \int_0^t g\left(h(t)\right)\cos(\theta(t))dt \tag{1}$$

where $V(t)$ and $m(t)$ are velocity and mass, respectively, at any given instant t, m_0 is the initial mass (GLOW for a single stage), and V_0 is the initial velocity provided by the launch system. The exhaust velocity, U_e, and the instantaneous mass fraction determine the increase in velocity supplied by the rocket engines. The third and fourth terms on the right hand side account for drag and gravity loss, respectively. A numerical procedure with a forward-marching time-step is used to predict the flight profile (altitude, range, speed, etc.). A sensitivity study showed that a 10 ms time step is adequate to provide results accurate to less than 1% of the values obtained for time steps of less than 0.1 ms. A standard atmosphere model is used[13,14]. The vehicle and its control surfaces create no lift and the vehicle's axis and exhaust velocity are aligned with the flight path, except when an ascent trajectory is introduced in Section IV C.

Aerodynamic drag on the vehicle is calculated using a drag coefficient, C_D, taken to vary with the flight Mach number. To generalize the results, the basic shape of the drag curve is derived from Refs. 13, 15, and 16, and a scaling factor is used to characterize the amplitude. Figure 1 shows the drag curves for three different vehicles. The low drag coefficient corresponds to the drag curve in Ref. 13. The medium drag coefficient is comparable to Ref. 15 and corresponds to a scaling factor 2 (equal to twice the low drag coefficient at any Mach number). A factor of 3 results in the high drag curve, which may characterize rockets with more complex fin geometries such as those found in Ref. 16. These drag coefficients may be correlated to a cone half angle: the low drag case could represent a cone with half angle of 7°, and the medium and high drag cases result from cones of 12° and 18°, respectively. To help ascertain the relative importance of vehicle drag, each rocket type was examined using these three drag profiles.

Given the vehicle parameters (thrust, GLOW, fuel mass, mass flow rate) and the launch speed and launch angle the program generates the trajectory and predicts maximum altitude and range. When investigating the potential enhancement of payload mass with launch assist, the total initial mass of the rocket is held fixed whereas the amount of fuel is varied until the target performance is reached (orbit altitude or range). The difference between initial mass and fuel required gives the mass of payload and structure.

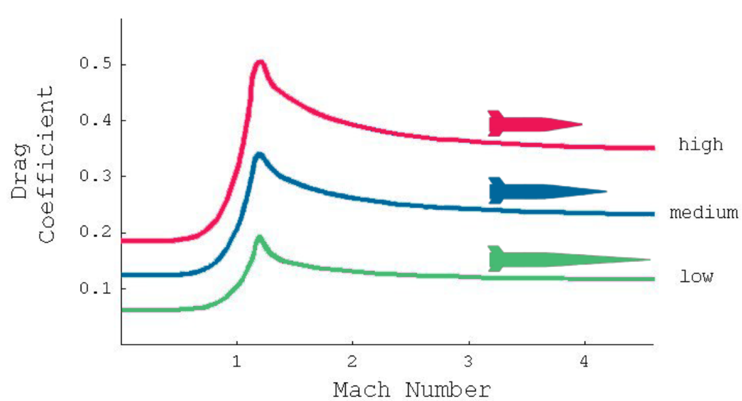

Figure 1. Drag coefficient curves and their corresponding nose cone shapes.

Table 1. **Summary of Rocket Systems Considered. * indicates a varying parameter in the computations.**

Parameter	Units	Rocket 1	Rocket 2		Rocket 3	
Rocket Type (General Description)	-	Nano-Satellite[17]	Athena I Booster[18]		Delta IV M Booster[18]	
Staging Description	-	Single-Stage	Stage 1	Stage 2	Stage 1	Stage 2
Fuel Type	-	solid	HTPB	HTPB	LH_2/LOX	LH_2/LOX
GLOW	kg	1,000	64,100	12,000	246,500	30,000
Fuel Mass *	kg	900	47,400	10,200	197,000	20,000
Empty Mass *	kg	100	16,700	1,800	49,500	10,000
Approximate Payload Mass	kg	10	-	800	-	8,000
Structural coefficient (stage) ε_i	-	0.090	0.090	0.089	0.090	0.091
Payload Ratio (stage) λ_i	-	0.010	0.187	0.067	0.122	0.267
Overall Payload Ratio (rocket) λ	-	0.010	0.012		0.032	
Rocket Cross-Sectional Area A_{CS}	m^2	0.3	4.15	4.15	20.4	12.6
Thrust T	kN	20	1,600	190	3,300	110
Vacuum Specific Impulse I_{sp}	s	204	286	284	427	448
Burn Time t_b	s	90	83	150	250	800

IV. Rocket Performance

In order to asses the capabilities of a launch assist system for different rocket applications, three broad rocket categories were considered: a nano-satellite launch vehicle (henceforth called Rocket 1), a rocket comparable to an Athena booster stage (Rocket 2), and a rocket comparable to a Delta IV M booster stage (Rocket 3). Although contemporary rockets would have to be modified (to sustain new horizontal accelerations, structural loading, etc.), the purpose here is to broadly explore the potential performance gains and relative impacts of acceleration, drag, dynamic pressure, etc. Table 1 summarizes the parameters for each rocket category.

A. Vertical Launch of Single Stage Sounding Rockets

Preliminary insight into performance gains using launch assist systems may be obtained through the analysis of vertically launched sounding rockets. Although a long vertical launching track is not practical, this simplified analysis exhibits some relevant trends and may be easily compared with conventional rocket performance without the complexity of trajectory optimization, which is addressed in Section C. Furthermore, launch assist systems mounted on the side of a mountain[4,6] or with a bend in the track may approach this limiting case, and would provide a useful experimental platform.

Figure 2 shows the maximum altitude achieved versus launch Mach number for Rocket 1, medium drag. A traditionally launched rocket (M_0 = 0) would achieve a maximum altitude of 771 km, whereas if launched at Mach 0.8 or Mach 2, it would reach 948 km (23% gain) and 1,179 km (53% gain), respectively. Given the low electricity costs associated with EDS, this increase may translate into a significant drop in launch cost.

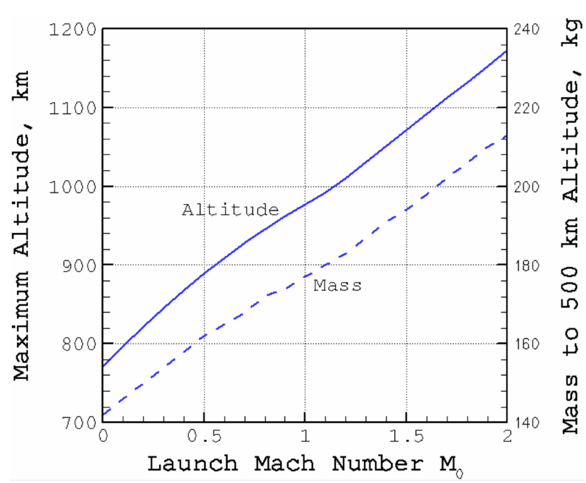

Figure 2. Maximum altitude and mass to 500 km altitude, versus launch Mach number, for vertical launch of Rocket 1, medium drag coefficient.

Performance gains may also be assessed based on how much more payload can be brought to a given altitude using the same amount of propellant (and hence same fuel cost). The target altitude is taken as 500 km to compare with data from Refs. 2, 17, and 19. Figure 2 shows a quasi-linear increase in payload capacity with launch Mach number, again for Rocket 1 with medium drag.

Table 2: Summary of improvement in performance, for vertical launch, single-stage rockets, for low drag (L), medium drag (M), and high drag (H) coefficients; Rockets 2(a) and 3(a) are the first stages of Rockets 2 and 3, respectively, and carry the second stage as a payload.

Rocket	% Altitude Improvement						% Mass to 500 km Improvement					
	at $M_0 = 0.8$			at $M_0 = 1.5$			at $M_0 = 0.8$			at $M_0 = 1.5$		
Drag Level	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**	**L**	**M**	**H**
Rocket 1	21	23	25	38	37	40	20	21	23	38	37	37
Rocket 2(a)	23	23	23	45	45	45	14	14	13	26	26	26
Rocket 3(a)	20	20	20	40	40	40	13	13	13	25	25	25

Note that payload here means payload mass plus structural mass. This simplification reflects an actual potential increase in payload since the structural mass varies only slightly for the same rocket carrying the same amount of fuel. Whereas a traditional rocket could only carry 142 kg to a 500 km altitude, if launched at Mach 0.8 it would carry 172 kg (21% gain), and if launched at Mach 2 it would carry 194 kg (37% gain). Similar gains are obtained for the other two rocket categories and are summarized in Table 2. All percentages are with respect to the same rocket launched with no initial speed.

To further assess the impact of vehicle drag, the variation in maximum altitude for various drag coefficients was calculated. Table 3 summarizes the increase/reduction in altitude with a low/high drag profile relative to the medium case, which is on the order of ±8% for launch Mach numbers from 0 to 1.5. However, to reach the same altitude as the medium rocket, the required launch Mach number changes significantly, reducing the force, energy, and power requirements. For instance, a low drag rocket may be launched at $M_0 = 0.46$ and reach the same altitude as a medium drag rocket launched at $M_0 = 0.8$, which represents a 42% reduction in launch speed and power, and a 67% reduction in required energy.

The maximum acceleration that a rocket can endure is a key driver in determining minimum track length. However, even if launched from a suitably long track the rocket may encounter limits associated with dynamic pressure. Since dynamic pressure is proportional to air density and to flight velocity squared, it may seem that launch assisted rockets will always experience maximum dynamic pressure at the launch point, similar to an un-powered projectile. However, this is not always the case with powered projectiles accelerating through their flight trajectory. As a result of the exponential decrease in density with altitude, the same rocket may actually experience lower maximum dynamic pressure with launch assist than with traditional launch. This can occur when the launch assisted rocket reaches a given altitude sooner than a traditional one. Thus in spite of the initial launch speed, it would be traveling less fast at that same altitude because it has not yet burned as much propellant, such that the product of density and velocity square is actually lower.

Figures 3 and 4 show the maximum dynamic pressure experienced by the rocket along its ascent for each category and the three drag levels for Rocket 1, respectively. For all three categories considered, the dynamic pressure is a minimum when the launch Mach number is around 0.3. The least massive vehicle, Rocket 1, accelerates the fastest and for launch Mach numbers larger than about 0.7 starts to experience increases in maximum dynamic pressure relative to a zero velocity launch. Figure 4 suggests that with no structural reinforcement Rocket 1 could be launched at around Mach 0.8 and carry 20% more payload. The lower the thrust-to-weight ratio, the slower the vehicle will be traveling through the denser portions of the atmosphere, and Rocket 3 may be launched at around Mach 1 before experiencing higher dynamic pressure loads. For launch Mach numbers larger than about 1.3, the three lines collapse because the maximum dynamic pressure now occurs at the end of the track. At higher launch speeds the rocket will always have changes in V^2 larger than the exponential decrease of density with altitude. The value of the maximum dynamic pressure for an actual Athena I rocket[18] is 140 kPa, and for a Delta II rocket[18] it is 58.9kPa, and the maximum dynamic pressure for a military airframe[19] is on the order of 140

Table 3. Effect of drag on maximum altitude, for sounding Rocket 1. Percents are relative to the medium drag coefficient values.

	Maximum Altitude, km			Required M_0		
Drag	**L**	**M**	**H**	**L**	**M**	**H**
$M_0 = 0$	840 + 9 %	771	707 - 8 %	-	$M_0 = 0$ 771 km	$M_0 = 0.24$
$M_0 = 0.8$	1,016 + 7 %	946	883 - 7 %	$M_0 = 0.46$ - 42 %	$M_0 = 0.8$ 946 km	$M_0 = 1.24$ + 55 %
$M_0 = 1.5$	1,162 + 8 %	1,072	991 - 8 %	$M_0 = 1.09$ - 27 %	$M_0 = 1.5$ 1,072 km	$M_0 = 1.94$ + 29 %

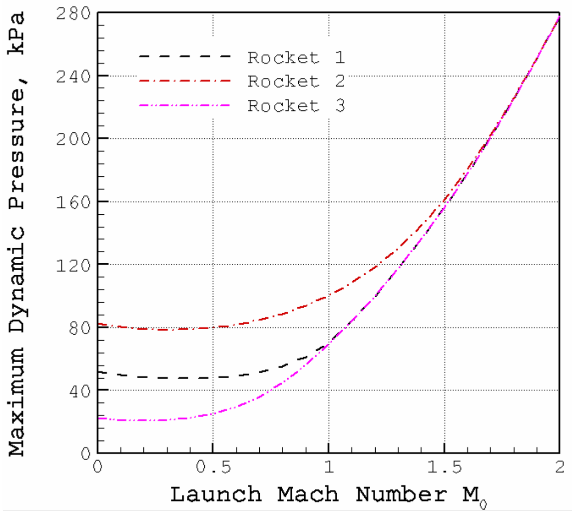

Figure 3. Maximum dynamic pressure versus launch Mach number for a medium drag coefficient, and different rocket categories.

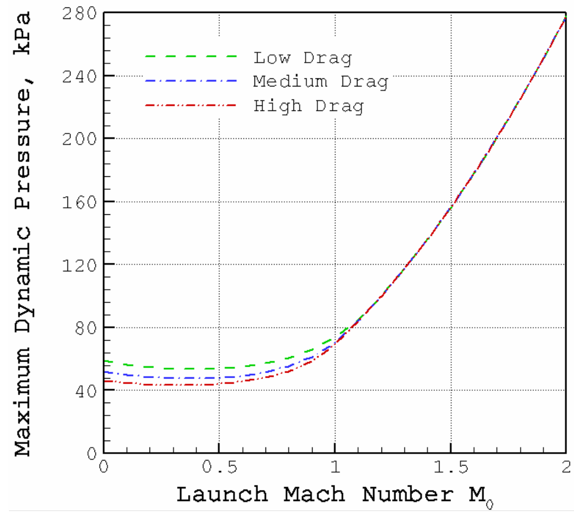

Figure 4. Maximum dynamic pressure versus launch Mach number for Rocket 1, and varying drag coefficients.

kPa. The values obtained here are larger because Rockets 2 and 3 are based on the Athena I and Delta IV M powerful *booster* stages.

Figure 4 examines Rocket 1 with low, medium, and high drag and shows that higher drag results in lower maximum dynamic pressure since speeds at low altitudes are reduced. However, these results are rather insensitive between the drag profiles considered (less than 10% difference with respect to medium drag at $M_0 = 0$). These studies indicate that launch assist is advantageous and the maximum dynamic pressure can actually be decreased if a suitable launch Mach number is chosen.

In the cases discussed so far, the engines were ignited at the end of the launch track. However, for certain rockets an ignition delay (i.e. a delay between the rocket leaving the track and ignition of the engines) may result in a performance improvement. If there were no drag, the best performance would always be obtained by igniting the engines immediately at the end of the track, thus expelling as much mass as soon as possible to decrease gravity losses. Conversely, if the drag and/or the launch speed are large, the losses rapidly increase because of the combined effect of high velocity, high drag coefficient, and large atmospheric density. For instance, it is better to ignite Rocket 1 after a short delay (about 2 s) if it is launched at Mach 5 and if it has a medium drag coefficient, or if it is launched at Mach 1 and has a very large drag coefficient (twice the medium drag coefficient, delay of about 8 s). Thus, an ignition delay seems to be advantageous only for extreme cases that would not actually be realistic for a rocket – a large launch Mach number would require too much power, and a very large drag profile is unlikely. However, other rocket configurations with medium drag may benefit from an ignition delay even at low launch Mach numbers, and this possibility should be further investigated.

B. Vertical Launch of Multiple Stage Sounding Rockets

To increase efficiency and payload to orbit, most rockets employ multiple stages. This section examines the benefits that launch assist may provide to multi-stage rockets, using Rockets 2 and 3. As before, the study of a vertically launched sounding rocket is useful to asses trends associated with performance advantages. Immediately after the first stage burns out, the structural mass of the first stage is dropped (4,700 kg for Rocket 2, and 19,500 kg for Rocket 3), and the second stage is ignited. Table 4 shows the performance improvements obtained using launch Mach numbers of 0.8 and 1.5, relative to a traditional launch ($M_0 = 0$).

Table 4: Summary of improvements in maximum altitude for multistage sounding rockets.

Rocket	% Altitude Improvement					
	at $M_0 = 0.8$			at $M_0 = 1.5$		
Drag Level	L	M	H	L	M	H
Rocket 2	18	18	18	37	36	36
Rocket 3	45	43	42	116	106	98

Whereas the performance of single-stage rockets using launch assist yield similar percentage improvements at the same launch

Mach number for different rocket categories and drag characteristics, the performance gains using multi-stage rockets depend strongly on rocket configuration. Alternatively, the gain in performance of a specific multi-stage rocket is strongly dependent on the launch speed. This suggests that the rocket configuration (mass of each stage, structural coefficient, payload coefficient, etc.) should be optimized for a given launch Mach number. Even though a launch assisted vehicle will always benefit in terms of maximum altitude and payload mass, it may lose some of its potential due to a poor design.

Some authors have suggested that an electrodynamic (or electromagnetic) launch assist system may be used to replace the first stage of a multi-stage rocket[2]. In order to asses the viability of this concept, computations have been carried out to determine what would be the required launch speed necessary to reach the same altitude as a two-stage rocket if only the second stage is used with the launch assist. It turns out that the second stage of Rocket 2 and of Rocket 3 need to be launched at $M_0 = 13.6$ and $M_0 = 29.3$, respectively. Such launch velocities would require extremely high power and result in dynamic pressures of 12.8 MPa and of 59.6 MPa for Rockets 2 and 3, respectively. These difficulties arise in replacing the powerful first stage of an existing rocket with a launch assist system. A more powerful second stage equivalent would be required to reach these altitudes using one stage with a reasonable launch assist. Alternatively, it may be possible for a launch assist system to replace a smaller and less powerful first stage, with reasonable launch speeds.

C. Orbital Insertion Using Launch Assist

The discussion of the previous two sections was concerned with sounding rockets so that the influence of important launch assist parameters could be examined. However, the aim for most applications is to deliver a payload into a circular or elliptical orbit around the Earth. Traditional rockets are launched vertically and then, depending on configuration, tilt toward the horizontal for orbital insertion. Only this component in the direction parallel to the Earth's surface leads to the circularization velocity necessary to achieve orbit. Furthermore, a more likely launcher orientation would be near horizontal. The purpose of this section is to examine some simplified rocket trajectories and compare results between traditional and launch assisted rockets. The computations assume a launch due East from Kennedy Space Center latitude of 28.5 degrees.

A basic trajectory optimization code was written both for the traditional rocket and for the launch assist rocket. The optimization is based on a typical Earth-launch trajectory as described by Turner[20], which includes: a vertical segment, a portion where the flight path continuously changes from vertical to non-vertical in anticipation for the gravity turn (turn at constant rate), a gravity turn portion, a constant pitch section, and finally the orbital insertion at the desired altitude. It is interesting to note that the single-stage rockets that are considered here have a short burn time, and hence at the time when flying at constant pitch could be beneficial the propulsion system is off. The constant pitch angle section is equivalent to a gravity turn for this case.

Having set the segments for the ascent trajectory, the method is to vary the flight time spent on each one, the rate of turn after the vertical section, and the flight angle at the start of the gravity turn. The trajectory that reached the desired altitude, i.e. LEO at 500 km, with the maximum tangential (parallel to the Earth's surface) speed is taken to be the optimized trajectory. The optimized trajectory for Rocket 1 launched traditionally is shown in Fig. 5. The rocket spends 50 seconds in a vertical path, then turns at a constant rate for 20 seconds, and starts the gravity turn with an angle of 55.7° so that it reaches LEO at the apogee of the gravity turn parabola with an absolute horizontal speed of 2,525 m/s.

The optimization of the trajectory for the launch assisted rocket is similar, except that the rocket is launched horizontally from the launch-assist track and hence makes first an upward turn and keeps an inclined flight path (not necessarily vertical) before starting the gravity turn. Moreover, a penalty in drag is introduced for the initial turn that the rocket needs to perform in order to change its flight angle as it leaves the horizontal track. This penalty is taken to be equal to the induced drag that a wing would produce when generating the necessary lift for the turn. Whereas this may not be the method that would be used to make such a turn, it has the advantage of reflecting the effect of the steepness of the turn and provides an estimate for the ΔV penalty. For Rocket 1 launched at Mach 0.8, the optimized trajectory turns the

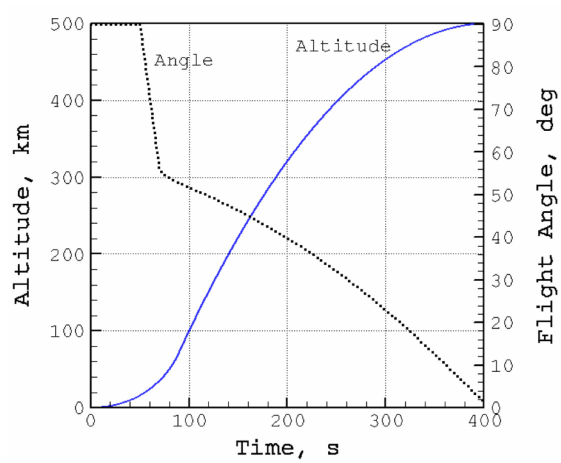

Figure 5. Optimized trajectory for traditional launch of Rocket 1, medium drag coefficient.

Table 5. Summary of optimized trajectory and corresponding performance, for Rocket 1, medium drag.

Launch		**Traditional**	**launch-assist at $M_0 = 0.8$**	**launch-assist at $M_0 = 1.5$**
Trajectory Parameters	**ascent sections**	50s vertical 20s turning	5s turning 10s constant angle	5s turning 0s constant angle
	angle before gravity turn	55.7°	69.3°	68.4°
Tangential speed at LEO altitude		2,525 m/s	3,108 m/s + 23.1 %	3,427 m/s + 35.7 %
Payload to LEO circular orbit		7.8 kg	10.5 kg + 34.6 %	12.3 kg + 57.7 %
Maximum Dynamic Pressure		52 kPa	66 kPa	164 kPa
Maximum Acceleration		19.60 gee's	19.69 gee's	19.74 gee's

rocket from horizontal to a flight angle of 69.3° before the gravity turn starts, and reaches LEO with a horizontal speed of 3,108 m/s. Compared to the traditionally launched rocket, this corresponds to a 23% improvement in horizontal velocity before orbital circularization. For a launch at Mach 1.5, the horizontal velocity at LEO is 3,427 m/s, and is reached by turning the rocket from horizontal to 68.4°. This trajectory is similar to that for a launch Mach number of 0.8, and corresponds to a 36% improvement in horizontal velocity at LEO.

At LEO altitude of 500 km, the velocity needed to circularize the orbit is 7,618 m/s. For orbital insertion, the traditional rocket needs a further increase in velocity of 5,093 m/s, requiring a fuel mass of 92.2 kg (to be taken from the 100 kg reaching LEO). The rocket launched at Mach 0.8 will need 89.5 kg of fuel for circularization, and the one launched at Mach 1.5 will require 87.7 kg of fuel. Starting with a GLOW of 1,000 kg, the traditional rocket is able to put 7.8 kg of payload into circular orbit, whereas the assisted rocket launched at Mach 0.8 can put 10.5 kg (35% gain), and 12.3 kg (58% gain) if launched at Mach 1.5. Table 5 summarizes these results.

During the ascent, the traditionally launched rocket undergoes a maximum dynamic pressure, q_{max}, of 52.0 kPa and a maximum acceleration of 19.60 gee's (19.59 gee's of maximum tangential acceleration and only 0.59 gee's of maximum centripetal acceleration during the turns). For the launch-assisted rocket at Mach 0.8, q_{max} is 66.4 kPa and the maximum acceleration is 19.69 gee's. If launched at Mach 1.5, q_{max} is 164.3 kPa and the maximum acceleration is 19.74 gee's. The acceleration of launch assisted rockets is similar to that of a traditional launch, and is mainly the result of thrust, which is a maximum when the rocket is still burning but has expended most of its fuel. Acceleration could be reduced for hybrid and liquid rockets by throttling the engines. Calculations for rockets which are throttled to a permissible acceleration of 5 gee's yield comparable penalties for both launch methods, thus maintaining the same relative advantage of launch assisted rockets over traditional launch. However, the dynamic pressure increases considerably when the rocket is launched at Mach 1.5. The only way to significantly reduce the maximum dynamic pressure that a launch assisted rocket undergoes is to decrease the launch speed.

V. Ballistic Missile Trajectories

In addition to orbital applications, launch assist systems have been shown to significantly increase the range of un-powered projectiles and ordinance[7,13]. This section examines potential range and payload gains for powered missile applications. As in the study of rockets, three general single stage missile categories are considered, called Missile 1, Missile 2, and Missile 3, and are defined by the parameters in Table 6. All the trajectories in this section are ballistic.

A. Range and Payload

Figure 6 shows typical trajectories for Missile 1 with medium drag launched at 60° with respect to the horizontal, versus launch Mach numbers. The number next to each curve indicates the time required to reach the target. Although the range continually increases with launch speed there is an optimal combination of launch speed and angle which is most efficient. Alternatively, launch assist can be used to increase the mass delivered to a target. The increase in range with launch Mach number is also shown in Fig. 7. Because this missile has insufficient thrust-to-weight to be launched at 60 degrees without initial speed the curves start at about Mach 0.4, which is the minimum launch speed at which Missile 1 is able to remain aloft until burnout.

Table 6. Summary of Missile Systems Considered. * indicates a varying parameter in the computations.

Parameter	Units	Missile 1	Missile 2	Missile 3
Missile Type (General Description)	-	-	-	Jupiter IRBM[§§]
Fuel Type	-	solid	solid	LOX/RP-1
GLOW	kg	1,000	10,000	50,000
Fuel Mass *	kg	860	8,700	43,500
Empty Mass *	kg	140	1,300	6,500
Approximate Warhead Mass	kg	50	500	2,400
Structural Coefficient ε	-	0.095	0.084	0.086
Payload Ratio λ	-	0.050	0.050	0.048
Rocket Cross-Sectional Area A_{CS}	m^2	0.3	1.77	5.7
Thrust (vacuum) Th	kN	20	250	760
Vacuum Specific Impulse I_{sp}	s	204	255	267
Burn Time t_b	s	86	87	150

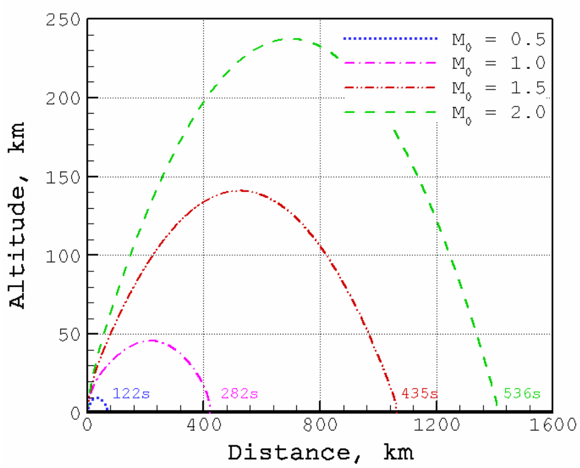

Figure 6. Altitude versus distance for different launch Mach numbers, for a launch at 60°, Missile 1, medium drag coefficient. The numbers next to each curve give the time to the target (burn time is 86 s).

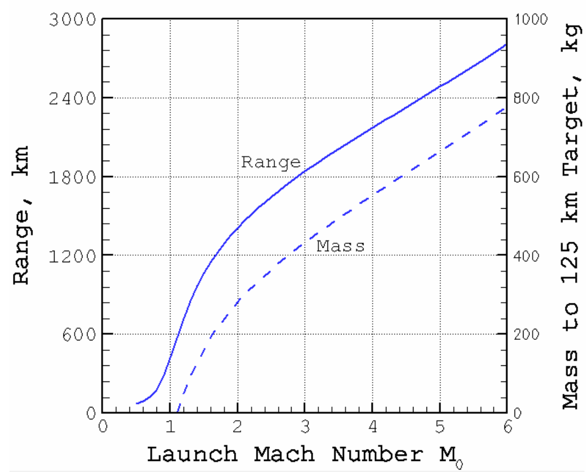

Figure 7. Range and mass to a target 125 km away, versus launch Mach number for a launch at 60°, Missile 1, medium drag coefficient.

Contrary to the variation in altitude achieved by the vertical sounding rockets, the change in range with launch Mach number is not linear. There are two reasons for this behavior. First, given the rocket's initial mass, there is an optimum launch angle for each launch speed that maximizes range. For Missile 1 the use of a 60° angle is not appropriate for low launch Mach numbers; the identification of an optimum launch angle will be described in Section C. Second, launching at speeds which result in the vehicle traveling near Mach 1, where the drag coefficient is very large, in the dense lower atmosphere induces large drag penalties. In spite of this behavior, using a launch assist system considerably increases the range of a missile using the same structure, engine and amount of fuel.

Figure 7 also shows the mass that can be delivered to a target 125 km away as a function of launch Mach number using again a ballistic trajectory and launch angle of 60 degrees. The curve intercepts the abscissa axis at approximately Mach 1.1 because for lower launch speeds a range of 125 km cannot be achieved. Its shape is similar to the range curve and can be described by the same interpretation. Table 7 summarizes the range achieved for the three categories of missiles when launched at the angle for maximum range. As discussed in the following section, this angle may not be the same as the one that maximizes the mass delivered to the target.

[§§] Adapted from Wikipedia "Jupiter ICBM", URL: http://en.wikipedia.org/wiki/Jupiter_IRBM [cited 3 Nov 2004]

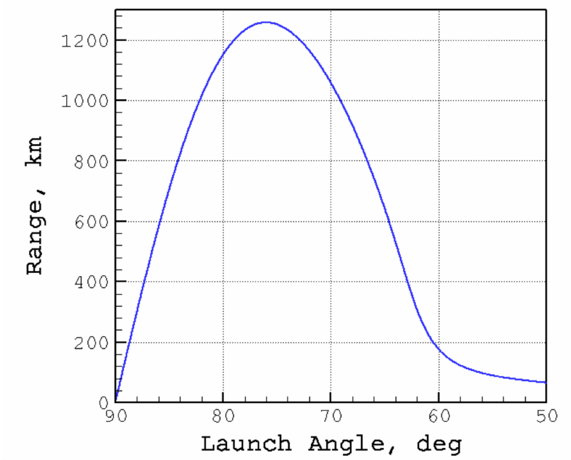

Figure 8. Range verus launch angle for launch at Mach 0.8 of Missile 1, medium drag.

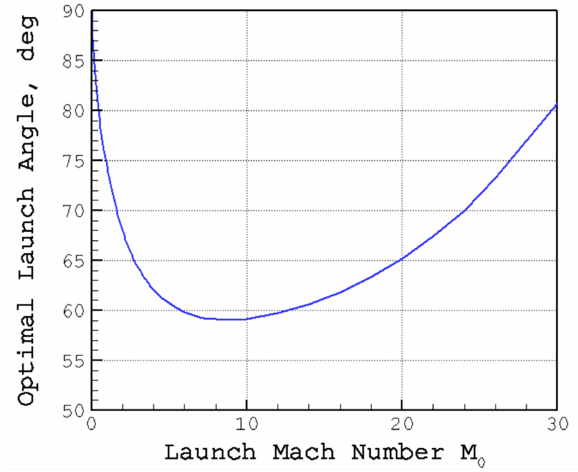

Figure 9. Optimal launch angle for maximum range versus launch Mach number, for Missile 1, medium drag.

B. Optimal Launch Angle

In the previous section the improvements using launch assist were shown for a missile launched at a 60° angle. However, the performance of the system depends on more than the launch Mach number. In particular, for each launch Mach number and mass (GLOW) there is an optimum launch angle that maximizes the range, and a detailed optimization needs to be done in order to take maximum advantage of the launch system.

A typical variation of range with launch angle is shown in Fig. 8 for Missile 1 launched at Mach 0.8. This demonstrates the existence of an optimal launch angle to maximize range. The slope of the range curve is relatively steep around the optimum, indicating that a small variation near the optimal angle may result in a large change in range. Consider for instance Missile 1 launched at Mach 0.8. The optimal launch angle is 76.0° corresponding to a range of 1,258 km. If, however, Missile 1 is launched at 72.0°, it would only reach 1,166 km, which is 7.3% less (8.4% less if launched at 80°).

The variation in optimal launch angle versus launch Mach number results from a balance between the tendency toward smaller launch angles to increase range and the tendency to large angles to alleviate drag losses associated with traveling through the lower atmosphere. As shown in Fig. 9, the launch angle decreases with launch Mach number up to about Mach 9, and then increases in order to minimize drag losses because of the very high speed. rocket. This high speed behavior is far more relevant for structurally robust un-powered ordinance[6,12], whereas the decrease in launch angle at lower speeds is more relevant for the class of missiles considered in this work.

The range curve in Fig. 10 shows again a quasi-linear increase in maximum range versus launch Mach number when the Missile 1 is launched at the optimal angle for range. With launch at Mach 0.8 or Mach 1.5, range can be increased by 42% and 65%, respectively. Table 7 shows a comparison of range achieved when launching at the optimum angle for range and when at 60 degrees. The significant differences come from the fact that 60° may deviate more or less from the optimal launch angle for each Missile and each launch Mach number

The maximum acceleration that the missile experiences during its trajectory occurs just before burnout, when the mass is a minimum and the thrust but virtually no drag are acting on the projectile. Hence, a missile launched at high speeds does not endure a maximum acceleration significantly greater than the same missile launched slower. However, the maximum

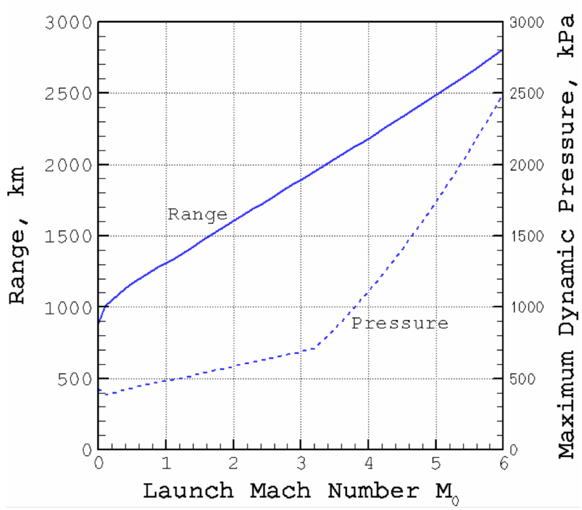

Figure 10. Range and maximum dynamic pressure versus launch Mach number, at angle for maximum range, for Missile 1, medium drag.

Table 7. Comparison of achievable range at the optimum launch angle, and range at a constant launch angle of 60°. The number in parenthesis gives the corresponding optimum angle.

Missile	Range at $M_0 = 0.8$		Range at $M_0 = 1.5$		Range at $M_0 = 3.0$	
	$\alpha_0 = 60°$	optimum launch angle	$\alpha_0 = 60°$	optimum launch angle	$\alpha_0 = 60°$	optimum launch angle
Missile 1	177 km	1,258 km $\alpha_0 = 76.0°$	1,064 km	1,456 km $\alpha_0 = 70.8°$	1,841 km	1,856 km $\alpha_0 = 60.7°$
Missile 2	1,652 km	2,556 km $\alpha_0 = 72.7°$	2,572 km	2,876 km $\alpha_0 = 68.0°$	3,557 km	3,600 km $\alpha_0 = 63.1°$
Missile 3	170 km at 63.9°	2,493 km $\alpha_0 = 82.5°$	964 km	2,832 km $\alpha_0 = 77.2°$	3,085 km	3,651 km $\alpha_0 = 69.8°$

dynamic pressure does become a concern at large launch Mach numbers as can be seen in Fig. 10. For launch Mach numbers below 3.2 the maximum dynamic pressure occurs as the missile is descending, shortly before impacting the target. For launch Mach numbers above 3.2 the maximum dynamic pressure occurs at the end of the track which results in a steep increase in the curve in Fig. 10.

VI. Summary and Conclusions

The performance of both rockets and missiles can be significantly improved through the use of an electrodynamic launch assist system. Launching with EDS at subsonic speeds has major advantages: it requires a relatively short track, acceptable levels of energy and power, does not cause significant noise concerns, and promises a considerable decrease in cost relative to traditional systems. For a subsonic launch at Mach 0.8, altitude can be expected to improve by at least 20%, payload to orbit by up to 35%, and range by up to 42% (37%, 58%, 65% respectively for supersonic launch at Mach 1.5).

From the investigation of the effect of drag, the advantages of the aerodynamic shape of the vehicle were shown to be significant. Whereas the reachable altitude or range could be improved by around 8% with a low drag profile, the launch speed required to reach that same location could be decreased by more than 40%, thus resulting in a significant reduction in track length, energy, power, and costs.

Specific ascent trajectories can be devised to deliver a payload to orbit by means of a rocket launched from a horizontal EDS track. A single stage rocket can be designed for launch at different speeds and with different payloads. The optimized ascent trajectory would be similar to that of traditionally launched rockets, except for the initial section (horizontal instead of vertical launch), and make use of the same means of reducing acceleration, dynamic pressure, and aerothermal heating.

A rocket launched with an EDS may experience a lower maximum dynamic pressure compared with traditional rocket. If the launch speed is correctly chosen and assuming that the structural requirements for an initially horizontal orientation of the vehicle are not significant, the structural mass of the vehicle could actually be reduced. If the EDS track can be configured to any required angle for the launch of small and medium missiles, it is very important to vary the angle properly to maximize range for a variety of launch configurations.

With the technology available today, the high reliability, responsiveness and cost-effectiveness of an EDS could be exploited for the terrestrial launch of rockets, missiles, ordinances, and even ramjets, scramjets and rocket-based combined cycle applications. Current investigations include the use of air-breathing engines through the preliminary launch trajectory, improved modeling of trajectory optimization, and data for specific launch vehicles including drag profiles. Additionally, the possibility of implementing an EDS for launch from the moon where drag and gravity losses are reduced is being assessed.

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