IMPLICATIONS OF GUN LAUNCH TO SPACE FOR NANOSATELLITE ARCHITECTURES

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Abstract

Engineering and economic scaling factors for Gun Launch to Space (GLTS) systems are compared to conventional rocket launch systems. It is argued that GLTS might reduce the cost of small satellite development and launch in the mid to far term, thereby inducing a shift away from large centralized geosynchronous communications satellite systems to small proliferated low earth orbit systems.

INTRODUCTION

The present space launch industry is oriented toward large geosynchronous satellites due to favorable scaling of rocket launch and satellite costs with size. The technical and economic factors behind this scaling will be explored and contrasted to the potential scaling of GLTS systems. It will be shown that GLTS systems appear to yield a maximum return on investment for 100-1000 kg satellite payloads.

The microprocessor induced a shift in the computer industry from mainframes to small computers by enabling small computers to become cost effective. Because it enables small payloads to become cost effective, GLTS might induce such a shift in communications satellite architectures.

ECONOMICS OF PRESENT LAUNCH SYSTEMS

The commercial space launch industry is oriented toward ever larger geosynchronous satellites (Agrawal 1986). The reason for this is shown in the return on investment model data of Figure 1, which shows that economic payoffs increase strongly with satellite size (Agrawal 1986). This trend derives from the fact that both launch and satellite prices per kilogram decline steeply with satellite size. Since revenues are almost linear with satellite mass, the return on investment increases strongly with satellite mass.

For Figure 1, launch costs are assumed as \$550,000$M^{-.45}$ per kg and satellite costs are assumed as \$10 million for design plus \$840,000$M^{-.25}$ per kg. Revenues are assumed to be \$15,000 per kg of satellite per year excluding 50 kg of satellite weight for parasitic mass. Revenues are calculated as a simple fraction of initial investment costs for the satellite and launch. M is the satellite or payload mass in kg.

Historical launch prices per kg to LEO are plotted in Figure 2 versus payload size (Isakowitz 1991). Although there is a great deal of scatter due to differences in accounting methods and government subsidies, there is clearly a strong downward trend. Nonlinear regression analysis indicate that the best geometric fit to this data is for a launch price per kg proportional to the -0.45 power of mass with a launch cost at one kilogram of \$540,000.

Satellite prices show a similar behavior as illustrated in the data of Figure 3 derived from an Aerospace Corporation cost model (Lenard, 1990). A major basis for both these trends is that many of the same functions are necessary when designing, fabricating, launching, and operating launch vehicles and satellites, semi-independent of their size. The larger the satellite or launch vehicle, the better these costs are amortized. Most of these costs are also better amortized with higher launch rates.

Another factor which strongly influences launch prices is useful payload fraction. Larger vehicles such as the space shuttle or a Titan-4 have larger payload fractions to orbit that small vehicles such as the Scout (Isakowitz 1991). A vehicle which launches more payload for a given vehicle size should be able to deliver that payload at a lower price since the vehicle cost component of the price would be lower.

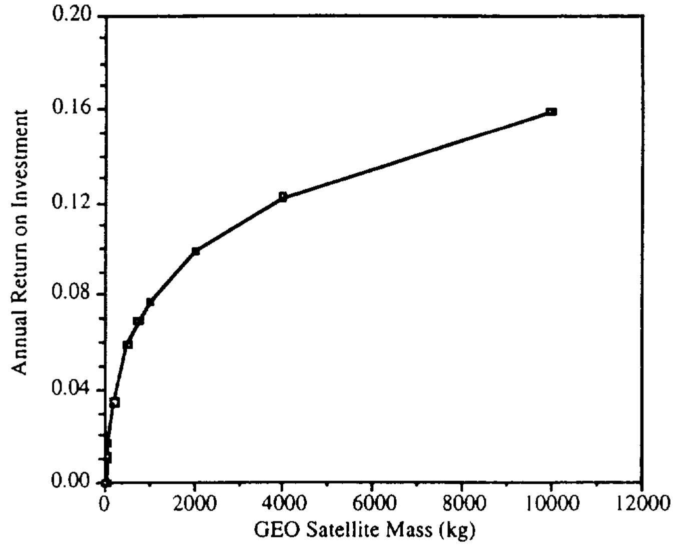

FIGURE 1. Return on Investment Model for Present Satellite Communications Systems

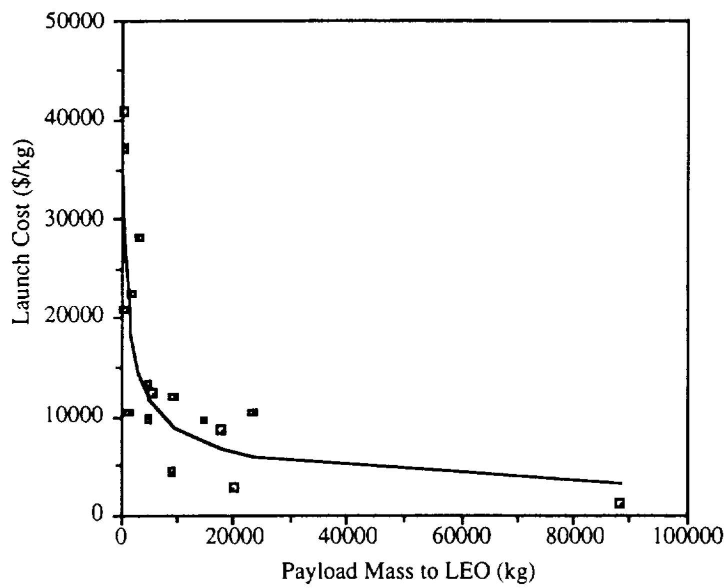

FIGURE 2. Historical Launch Costs versus Payload Mass (Isakowitz, 1991)

The effect of vehicle size on payload fraction is most easily seen in performance models for single stage to orbit (SSTO) vehicles (Hampsten 1994). Figure 4 shows a predicted payload fraction for a SSTO as a function of vehicle size. Even quite large SSTO vehicles (1000-2000 tons) have payload fractions well below the 3-5% typical for large multistage vehicles (Isakowitz 1991). A SSTO vehicle must be quite large to be cost effective, since payload fractions much below 1% would probably not be cost competitive in operation (Hampsten 1994).

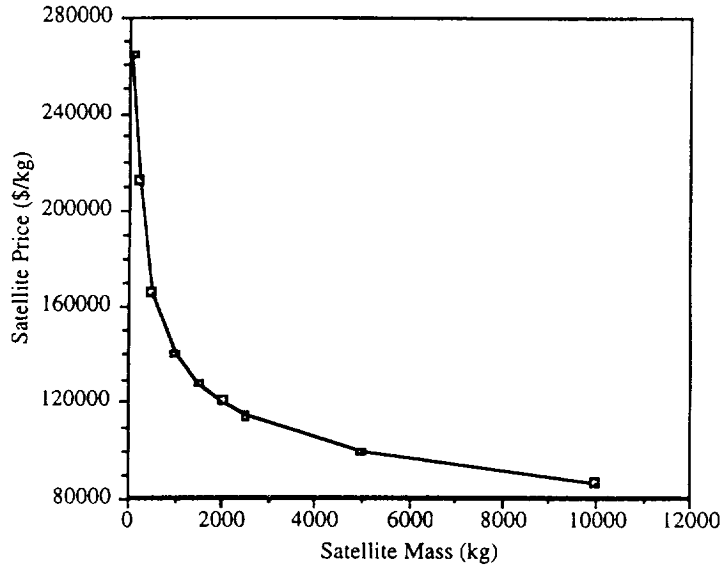

FIGURE 3. Model for Dependence of Satellite Prices on Mass

Development of such large vehicles is very expensive. Development costs for a 1000 ton class SSTO have been estimated at $6B-$37B (Aviation Week 1994) (Space News,1994). Such large investments are difficult to motivate in either the government or commercial sectors.

Development of much smaller, less costly vehicles would be much easier to initiate, but cost ineffective and technically difficult due to the vanishingly low payload fractions achievable with very small vehicles. Resorting to a totally new technological approach such as gun launch to space has the potential to resolve this dilemma.

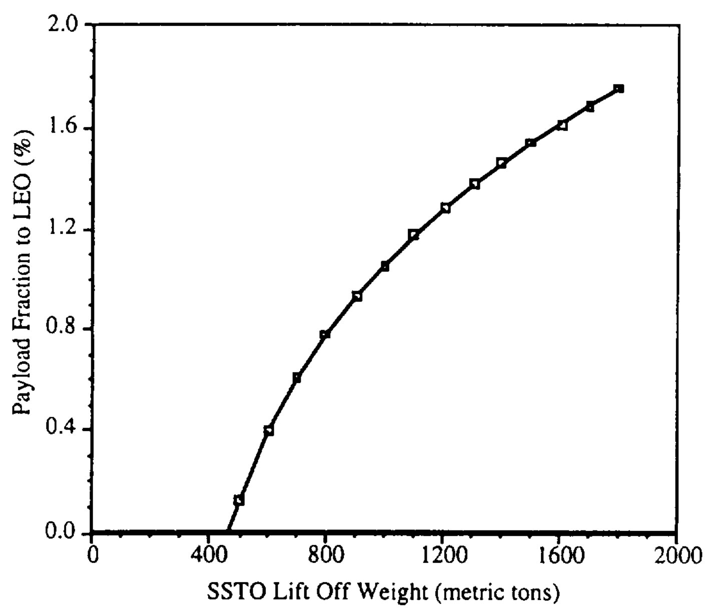

FIGURE 4. Effect of Rocket Launch Vehicle Scale Size on Payload Fraction.

Small launch vehicles have small payload fractions for two reason. First, the proportion of parasitic masses such as valves, tanks, etc., grows as vehicle size diminishes. Second, aerodynamic losses and total velocity increment to orbit grow rapidly with the vehicle surface area to volume ratio.

ECONOMICS OF GUN LAUNCH SYSTEMS

Gun launch systems largely avoid both these problems since the propulsion system parasitic mass and fuel are mostly not accelerated with the payload, remaining in the rest frame of the launcher. Since the propulsion system and fuel are not accelerated, the gun can achieve high effective payload fractions even for tiny payloads. Since bulky fuel is not carried with the payload, the payload is physically much smaller, and aerodynamic losses are greatly reduced.

A gun launched payload does have significant parasitic masses for sabot, armature, structural reinforcement, and thermal shielding. These parasitic masses cannot be determined precisely without rigorous engineering, but estimates of 10-40% have been made (Castle, 1990). If the gun provides almost the entire velocity increment necessary to achieve orbit, this translates to payload fractions to orbit of 60-90%.

A good means of comparing the payload fraction achieved with guns with that of rockets is to calculate an effective specific impulse for gun launch analogous to that for a rocket stage (1). This allows direct comparison of the payload mass fraction obtainable from a gun to that obtainable from a rocket.

Gun effective specific impulse = $I_{SPe} = -V/g_0 \mathrm{Log}_e (M_P/M_L)$ (1)

V = gun launch velocity
g_0 = acceleration of gravity
M_P = payload mass = M_L - parasitic masses
M_L = gun launch accelerated mass (does not include gun propellant)
λ = mass efficiency ratio = M_P/M_L

Figure 5 shows effective specific impulse as a function of gun velocity for several ratios of payload to total launch mass. Conventional military powder guns launching standard shells at 800-1800 m/sec attain mass efficiency ratios, λ, of 0.7-0.9. These guns demonstrate effective specific impulses in the 500-2000 second range, yielding much higher mass efficiency ratios than could be obtained with rockets.

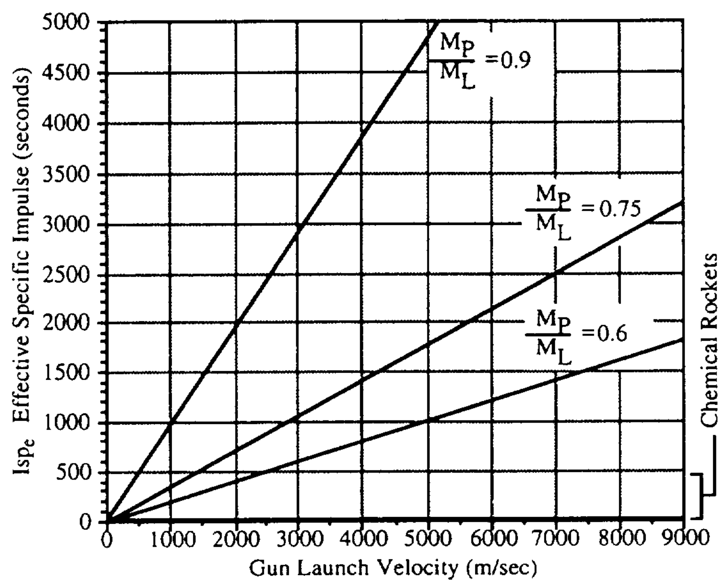

FIGURE 5. Effective Specific Impulses Achievable with Gun Launch Systems

Unfortunately, conventional powder guns cannot efficiently produce velocities over about 2000 m/sec. Launch to orbit requires much higher velocities, at least 7900 m/sec orbital velocity, plus another 500-2000 m/sec for aerodynamic losses, plus small gravity losses.

Research and development has been conducted on many gun technologies over the years. Figure 6 shows a taxonomy of the various gun types which have been explored (Palmer, 1991).

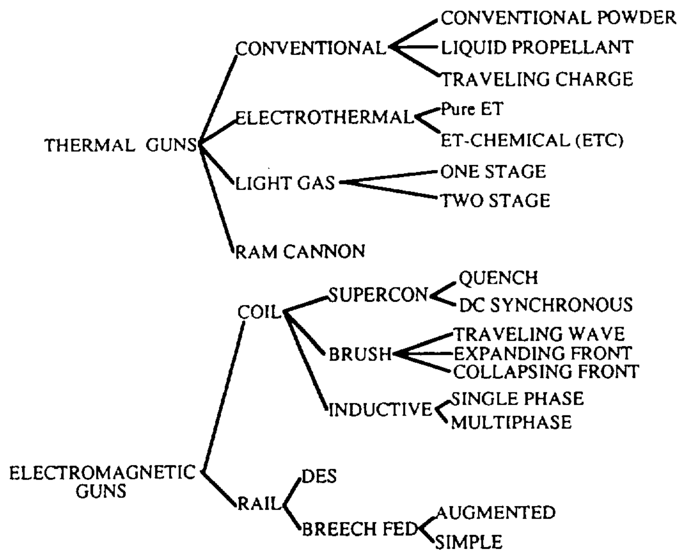

FIGURE 6. Taxonomy of Guns Types

Thermal guns are relatively low in cost to develop, but have thus far had practical upper velocity limits of 2000-4000 m/sec. Such a gun would require an additional 4500-8000 m/sec rocket boost to achieve orbit, and the booster would have to be designed to withstand high accelerations. At the 4500 m/sec end of this range, such a rocket might achieve orbit with a single stage less expensively than conventional small rockets, which require three or four stages.

Electromagnetic guns have been much less well developed due to the very high cost of the electrical power supplies necessary to drive them. If the satellite payload mass is assumed to be 50% of the gun launched mass, and the electromagnetic launcher is assumed to be 30% efficient at a launch velocity of 9000 m/sec, an electromagnetic launcher to propel a 1000 kg payload into orbit might require a capacitor power supply costing over $12B. Capacitor costs are assumed at a $0.63/Joule first unit cost with a learning curve cost factor exponent of 0.9.

Velocities over 7 km/sec have been achieved with electromagnetic railguns. However, these velocities have been obtained for very small masses at impractically low efficiencies. Development of higher efficiency launchers and lower cost power supplies will be necessary to achieve practical GLTS. Steady progress has been achieved in both areas in the last several years.

Assuming that an electromagnetic launcher could be developed with 30% efficiency at 9000 m/sec, and that power supply energy storage costs could be reduced to $0.001 per joule, a highly cost effective launch system would result. Such a system could launch many payloads at low cost and, over time, eliminate present high cost satellite design and construction practices.

Assuming that satellites would eventually be designed and constructed at prices similar to those for tactical missiles, the economics of satellite communications would be revolutionized. Figure 7 shows model data for the return on investment as a function of satellite size in such a scenario.

For Figure 7, a 100,000 kg total on orbit mass is assumed for the satellites. The number of satellites would then equal 100,000 divided by the satellite mass. Satellite costs are assumed as $10M for design plus $840,000$M^{-.25}$ per kg for the first satellite plus $10,000$M^{-.15}$ for all additional satellites. Revenues are assumed as $15,000 per kg of useful satellite mass per year with the useful mass fraction calculated as 0.3M^{-1}. Launcher construction costs are assumed as $8,000,000$M^{-.3}$ per kg of launched mass. Launcher operations costs are estimated at 25% of launcher construction cost plus $100,000 per launch. Revenues are calculated as a simple fraction of initial investment costs of satellite and launcher. M is the satellite or payload mass in kg.

The returns on investment would be very high at current spaceborne communications prices, probably resulting in a dramatic reduction in space communications prices world wide. At some point, space communications could become lower in price than terrestrial wireless or even land line communications.

An important feature of Figure 7 is that return on investment is optimal for satellites in the range of 100-1000 kg. This is due to the low functional mass fraction of very small satellites and the high cost of very large gun launch systems. This feature of GLTS could greatly reduce initial investment costs and incentivize development of small launchers capably of cheaply launching small, mass produced communication satellites.

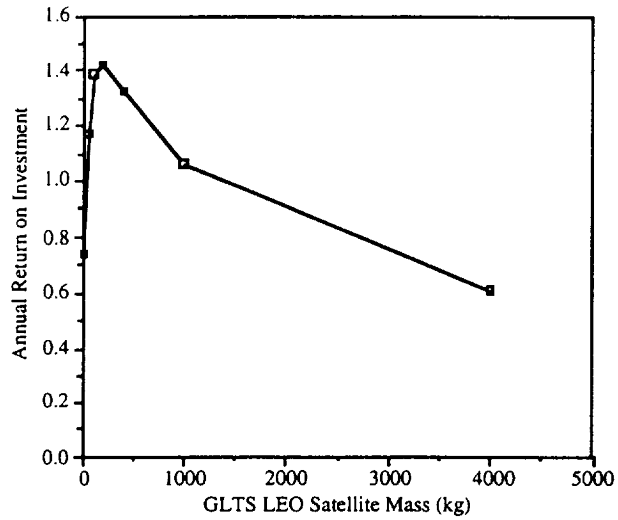

FIGURE 7. Return on Investment for Gun Launched Low Earth Orbit Satellite Systems

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