Immediate Market Applications of a Cheap-Launch Technology

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Various schemes have been proposed for reducing the cost to access space; however, few have identified a path to successfully bring such a technology to market. The value proposition of cheap-launch to the current geosynchronous Earth orbit (GEO) communications satellite paradigm is not high—here it is operational costs and not capital costs that dominate. Operators of low Earth orbit (LEO) systems, however, may find that their continued survival dependent on reduced launch costs. Lower launch costs allows for utilization of less reliable and hence less expensive satellite systems. By developing a satellite cost model utilizing a build methodology that takes advantage of cheap-launch, an almost 50% cost reduction can be demonstrated in a LEO constellation's recurring capital expenses. In this case, it will be shown that a cheap-launch LEO system is in fact cheaper to build and deploy than current GEO systems, potentially triggering a shift from GEO to LEO as the dominant satellite communications paradigm.

Introduction

There are several technologies that hold the promise to decrease the cost of placing payloads into Earth orbit by orders of magnitude. Chief amongst these are impulsive launch technologies such as light gas guns, railguns, and ram accelerators, as well as the various forms of space-elevator and tether concepts. These technologies are all high-risk, meaning they require (to varying degrees) large up-front capital expenditures with no guarantee of eventual technical success. While the long-term benefits of using these kinds of concepts to reduce launch costs could yield such wondrous things as permanent large-scale human habitation beyond the confines of Earth, in the near term there needs to be a large tangible benefit to offset the risk incurred if any of these "cheap-launch" technologies is to be developed in the private sector.

Normally, a cheap-launch technology is an ideal development project for a large government agency to develop—its revenue flow is by and large assured, and a technology development failure does not endanger the agency's continued survival. Nevertheless, government agencies prefer doling out small amounts of money to a wide range of high-risk projects in the hopes that one will pan out. Rarely is a concentrated injection of capital spent in one place. In contrast, wealthy individuals like Elon Musk, Jeff Bezos, and Sir Richard Branson seem quite willing to spend large amounts of capital on high-risk aerospace projects. For these reasons, it seems more likely that cheap-launch will be embraced by the private sector. Eventual success and widespread adoption of a cheap-launch technology then depends on its profitable performance in the market place. Thus, we wish to examine the markets and business opportunities for any cheap-launch concept.

The analysis herein includes the effect cheap-launch on overall space system cost, including a cost study that compares a satellite constellation launched with a cheap-launcher to the current conventionally launched "big LEO" and "little LEO" satellite systems. Ultimately we will see that cheap-launched low Earth orbit (LEO) systems cost less than GEO satellite systems, which raises the possibility of LEO systems becoming dominant in the satellite communications market.

Methodology & Assumptions

Basic Assumptions

1. The cheap-launch system used in this analysis is a ram accelerator. Reusable launch vehicles may never be feasible, and it seems that only marginal cost reductions are possible with future rocket technologies (as opposed to orders of magnitude reductions). Radical reduction of launch costs implies non-rocket technologies. We have chosen impulsive-launch systems over tether/elevator concepts because they are more technologically mature. More importantly, impulsive launchers require lower capital expenditures to build by orders of magnitude. A space elevator, for example, has been estimated to cost up to $6.2B[1]. In contrast light-gas gun system for space launch has been estimated to cost $300M[2], and a ram accelerator less than $50M[3].

2. It is assumed that any cheap-launch system will not generate revenues strictly as a launching business. First, the satellite communications market, at $16B by 2012, is larger and growing much faster than the launch market[4]. Second, all impulsive cheap-launch concepts require satellite systems tolerant of high accelerations. In order to access the launch market, one is required to convince satellite operators to throw out decades of hardware heritage and adopt new system elements designed for the rigors of impulsive launch, a difficult task to accomplish.

3. Launch costs for GEO system are relatively minor when compared to hardware costs and operating costs[5]. The same is not true for LEO systems which will experience the most benefit from a cheap-launch system. Thus, we are only considering LEO constellation architectures with cheap-launch systems.

Overview of Cheap Launch Benefits To Satellite Communications

Obviously, cheap-launch reduces launch costs. How much launch costs are reduced depends primarily on the launcher's muzzle velocity and the cost of the upper stage apogee kick motor. A higher muzzle velocity means less upper stage delta-V, which in turn means a higher payload fraction. For small to mid sized projectiles (300kg - 2000kg) and reasonable muzzle velocities (6km/s), the cost of the upper stage motor is an order of magnitude greater than ram accelerator-related consumables[6]. Since the marginal cost increase of a larger propulsion system is small, a larger projectile will have a lower cost per kilogram delivered to LEO.

Less obviously, cheap-launch reduces space hardware costs. When launch is expensive, satellites must operate for a long time to pay off this initial expenditure. Long-lived (i.e. space-rated) components are expensive, further increasing system costs. With cheap-launch, inexpensive commercial off-the-shelf (COTS) components can be used, especially in LEO where the radiation environment is relatively benign. When hardware fails, a new satellite can be launched and deployed immediately. The reader may be skeptical in regards to hardware that can survive gun launch, but past efforts have shown that it is relatively easy to harden COTS electronics to survive well over 2000G of acceleration. For a full discussion of high-acceleration tolerant hardware, please see the companion paper "Ram Accelerator as an Impulsive Space Launcher: Assessment of Technical Risks" presented at the 2007 International Space Development Conference.

Cheap-launch allows scalability. Using short-lived spacecraft with inexpensive hardware, the time between satellite system generations would potentially drop from 10-15 years to as few as 1-3 years. Because of this, the satellite system size can be tailored to fit the rise and fall of subscriber demand. There would be no wasted satellite capacity, and the satellite hardware would always be of the most modern. All of this translates to a lower space system cost and reduced financial risk[7].

Costing Heuristics

The current design methodology was developed to create feasibility estimates for ram-launched constellations. Our basic costing philosophy is to be able to demonstrate cheap space hardware from historical satellite data. The core of the design analysis is a set of relationships and historical data gathered from Wertz[8], and implemented in a spreadsheet to enable some degree of exploration. The analysis is a zero-order sizing of the satellite, in a manually iterated design cycle:

1. The design cycle typically begins by choosing a target projectile mass.
2. The power subsystem and the receiving antenna are then sized based on a desired uplink/downlink capability for the system, using the Friis link equation[9].
3. Propulsion requirements are typically regarded as fixed in terms of Isp and delta-V, so these scale automatically within the spreadsheet.
4. The structural contribution to mass is then analyzed, and finally the other support subsystems are sized according to historical averages for mass fraction.
5. At this point, the communications capabilities are re-sized in response to the amount of surplus or deficient mass available from the target projectile specification, and iteration continues.
6. If the communications bandwidths are found to be woefully insufficient or excessive, the projectile mass is then incremented.
7. After a physical satellite design is closed, the single satellite cost is then estimated, including hardware, testing, and design costs.
8. The satellite system cost is then extrapolated on a learning curve with a learning rate of 90%, which is conservative for aerospace systems[10].

Since we will be developing satellites based on low-cost methodologies, the best historical database for us to use in costing is the Aerospace Corporation’s Small Satellite Cost Model[11] (SSCM), which contains a database of more than 50 satellites. A majority of these are science and defense satellites, and specialized systems engineering, instruments and support are often required. This results in a wide variation of subsystem costs—typical subsystem cost standard deviation is between 20% and 50%.

It should be noted that the average satellite cost per unit mass with the SSCM is lower than what is found in the more often used NASA/Air Force Cost Model (NAFCOM) database. Small satellites achieved their cost savings primarily through the use of commercial and off-the-shelf hardware and reduced testing regimes. Also, there are fewer reviews and traceability requirements levied on small satellites due to a general consensus that there are classes of space systems that are now well-understood.

The results obtained from the SSCM are further augmented utilizing a series of assumptions based on the fact that cheap-launch hardware can be of significantly lower reliability without detriment to total constellation reliability. These assumptions are levied as a cost modifier on a subsystem by subsystem basis. The majority of cost savings are actually yielded from IA&T and labor savings. Again, we emphasize here that hardware is space-rated.

Category/Subsystem	**Assumption**
Attitude Determination & Control System	Availability of COTS flight software and low cost hardware.
Power	Availability of low-cost switching and power distribution
Command and Data Handling (C&DH)	Limited radiation testing
Structure	Assembly line fabrication
Integration, Assembly, and Test (IA&T)	Integration test only (as opposed to individual component testing) and plug and play hardware.
Project Management / Systems Engineering (Labor)	Assembly line fabrication

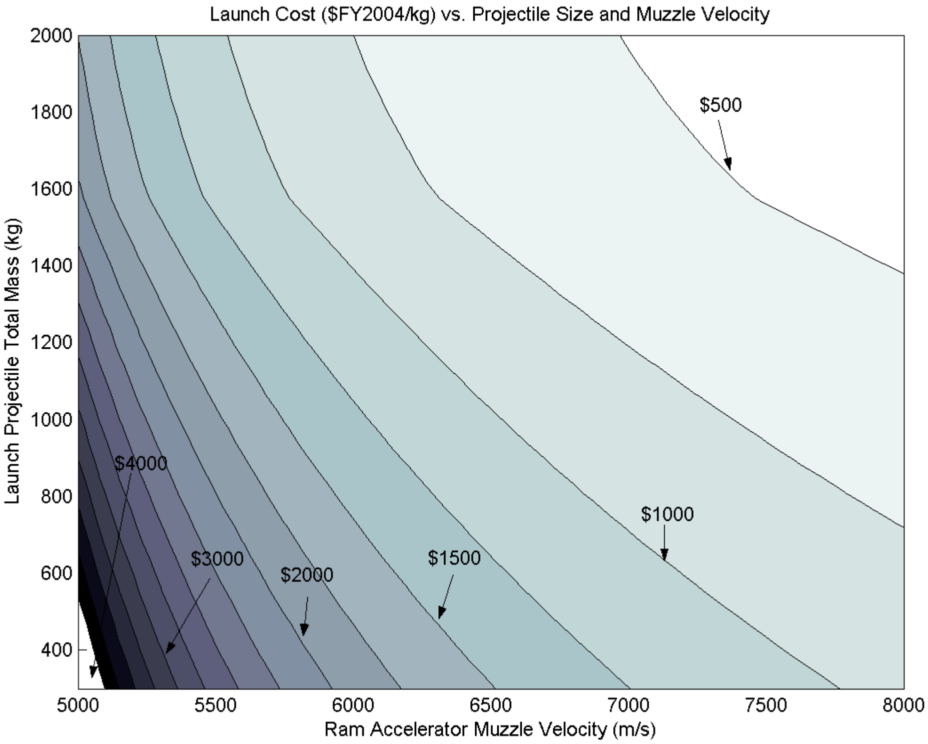
It is assumed that the operating lifetime of these ram-launched satellites is 3 years due to lower component reliability. Operational costs are assumed to be identical to the satellite constellation that is being compared. Determination of launch costs will be explained below, but it is assumed that launch costs will be $500/kg to an 800km circular orbit.

Launch Cost Determination

Scalability and hardware costs are dependent on the subscriber demand the size and capability of the satellites in question. These factors will be determined for each of the case studies found later in the paper. Launch costs, though, can be determined through launch simulations to determine upper stage delta-V. From the delta-V, motor size and cost can be estimated, and from there launch costs can be calculated. The major assumptions made in the dynamics and cost model are given in the table below.

Launch Dynamics Assumptions	**Cost Model Assumptions**
• Three layer atmosphere[12] • Aerodynamic drag coefficient is 0.0347 • Launch altitude is 200m • Launch angle is 22 degrees • Impulsive apogee kick • Apogee kick has Isp of 325 seconds • Target orbit is circular 800km altitude • Payload delivered is determined by rocket equation	• Launch costs due to upper stage motor • Model neglects ram fuel costs • Upper stage motor is solid rocket • Motor cost from NAFCOM • Neglects solid motor casing mass • Production run of 50 motors • Experience curve at 87%

The results of the cost and dynamics model are plotted below for a range of ram accelerator payload sizes muzzle velocities:



Case Studies

Big LEO

To date there are two big LEO systems in existence: Globalstar's and Iridium's satellite network. Big LEO is characterized by many satellites in low-Earth orbit providing voice and low data rate (10Kbps) services to mobile customers, i.e. customers with omni directional radios (mobile terminals). Globalstar currently offers a flat $49.99 per month for unlimited access with decreasing prices for additional years of service, but it requires a 4 year contract. Iridium's service costs approximately $0.99 per minute, and according to Frost and Sullivan Iridium's service has a much higher quality of service. All told, Globalstar's initial capital outlay was $3.3B while Iridium's constellation cost $5.5B[13]. Service is purchased directly from the satellite operators.

Globalstar and Iridium were enormous business failures to their initial investors. Nevertheless, both constellations are still in operation, albeit under different owners. Both are generating significant revenues from the mobile satellite services market. Despite this, Globalstar and Iridium customers should be alarmed as both constellations' satellites reach their service lifetimes. Industry analysts expect Globalstar's re-launch to cost approximately $1.2B[14], and Iridium's to be over $2B[15]. In the case of Globalstar, receiving $1.2B of investment is within the realm of possibility, but unlikely. A straight linear regression of Globalstar's revenues and expense yields a good model fit for the past 3 years. Extrapolating this forwards 10 years, taking into account its present equity[16], and discounting future revenues by 5% gives us a net present value of $900M. It is doubtful that Globalstar will be able to get a loan for more than this amount. In Iridium's case, it is the authors' opinion that a miracle will be required.

In the event that one of these constellations fails to re-launch, the slack will undoubtedly be taken up by GEO satellite operators like Inmarsat, Intelsat, and Thuraya. Currently Thuraya is the only satellite operator that offers service to mobile terminals, and charges $1.25 per minute[17]; however, the stranded customers would require to re-purchase satellite terminals.

The opportunity for the cheap-launch paradigm is to re-launch either Iridium or Globalstar. We consider this case to be the least risk case for cheap-launch technology. Here, the risk incurred is entirely technical risk, with little or no business risk since Iridium and Globalstar already operate with an existing customer base. Additionally, Globalstar and particularly Iridium may be less skeptical of cheap-launch technology—contemplating a radical new launch technology and satellite equipment suddenly becomes much more palatable when survival is on the line.

Below, we present the cost analysis for a cheap-launch satellite constellation and the savings it can bring to current LEO operators.

Big LEO SSCM Results Summary

- 50 satellites
- First satellite cost $7M
- Average satellite cost $3.9M
- Individual satellite mass of 500kg
- Launch cost at $12.5M for entire constellation

Table 1: Big LEO SSCM Results Comparison

	Globalstar	**Iridium**	**Cheap-Launch**
Capital Costs:	$1,200M	$2,000M	$206M
System Lifetime:	8 years	15 years	3 years
Avg. Capital Spending:	$150M/year	$133M/year	$69M/year
Avg. System Operating Cost:	$28M/year[18]	$28M/year	$28M/year
Savings Fraction:	54%	60%	100%

**All values given in 2006 dollars*

Cheap-launch essentially halves Globalstar's recurring capital expenses. Including the cost of building the ram accelerator itself, the new constellation could be paid for by taking loans against existing equity. The conclusion that we can reach is that a cheap-launch technology would ultimately allow Globalstar's and Iridium's business model to survive.

Little LEO

Orbcomm is the only little LEO system in existence. Little LEO is characterized by a number of small satellites that provide narrowband services such as asset-tracking and relaying data from remote sensors via short burst messages. This market is sometimes referred to as the telematics market. A typical Orbcomm terminal boasts of 2400bps uplink and 4800bps downlink. Orbcomm's satellites are small, massing only 22kg. In comparison, Globalstar's satellites mass 450kg, and Iridium's mass over 650kg. Furthermore, Orbcomm employs only 30 active satellites. As one could guess, at around $500M Orbcomm's initial system price tag was significantly lower than the big LEO constellations.

Orbcomm sells its service indirectly through its value-added resellers, which in turn provide a service to their particular market niches. Ultimately, the cost of wireless airtime is passed to the re-sellers' customers. Service price varies on usage, but estimates around $5.50[19] per subscriber per month are typical. Orbcomm is not unique in offering this narrowband service; Globalstar, Iridium, and some GEO satellite operators also offer similar services. Orbcomm, however, is the only constellation providing *only* narrowband service as its sole source revenue from its satellite system.

Orbcomm, like its big LEO brethren, also filed for bankruptcy shortly after launch. Unlike the big LEO constellations, Orbcomm should have enough cash and equity to re-launch as its satellites begin to fail in the 2007-2009 time frame. Re-launch costs are estimated at $6M per satellite[20], which includes satellite hardware and launch. In all, a complete re-launch will cost about $180M to replace 30 satellites. Orbcomm's recent and successful IPO will pay for the majority of this re-launch. All of this evidence indicates that the little LEO business model is sustainable.

Actually, it is quite possible that Orbcomm will do quite well in the coming years. Conventional wisdom states that satellite systems can never compete on price with a terrestrial communications network for mobile communications. For high data rate communications (i.e. voice) this is true. Higher data throughput means building costlier and more massive satellites. In contrast, the data rate requirements for narrowband communications are low because one only needs to orbit a certain minimum satellite payload size to handle the throughput. In the little LEO business model, it is a question of coverage area instead of satellite mass and data rates.

For Orbcomm to build and maintain a global network requires less than $300M every seven years. For cellular providers to just maintain a global network requires many tens of billions of dollars over the same time period. It is no wonder then that Orbcomm's price point of $5.50 per month is much lower than Cingular's, which is over $30 per month[21]. Here, the opportunity for cheap-launch is not to assist Orbcomm's constellation, but to compete with both satellite and terrestrial providers in the context of a cheap-launch startup.

SSCM Summary

- 30 satellites
- First satellite cost is $2.5M
- Average satellite cost $1.5M
- Individual satellite mass of 22kg
- Launch cost at $0.33M for entire constellation

Table 2: Little LEO SSCM Results Comparison

	Orbcomm	**Cheap-Launch**
Capital Costs:	$180M	$45M
System Lifetime:	7 years	3 years
Avg. Capital Spending:	$25M/year	$15M/year
Avg. System Operating Cost:	$6M/year[22]	$6M/year
Savings Fraction:	66%	100%

**(all dollar values given in 2006 dollars)*

Based on the results of the SSCM analysis, cheap launch allows an overall 33% savings over Orbcomm's system. In terms of a business opportunity, the conclusion we can reach is that cheap launch allows the possibility an Orbcomm competitor with startup costs of under $100M and a decisive competitive advantage in service cost.

GEO vs. Cheap-Launched LEO

Geostationary Earth orbit (GEO) is the current satellite communications paradigm with over 278 GEO satellites launched since 1995[23]. GEO satellite operators consistently operate at a profit and with high margins, between 30% for communications service providers and as high as 83% for satellite TV[24]. Previously, it was seen that a cheap-launched big LEO constellation costs approximately half that of a conventionally launched system. How does this compare to the cost of a GEO system?

The prevailing view is that LEO systems, in particular big LEO systems, are much costlier to build and launch than a comparable GEO system. The main question is to what degree are LEO systems more expensive? There are studies available that address this issue. One study in particular, "Comparison of LEO and GEO Satellite Systems to Provide Broadband Services[25]," directly addresses this question.

The results from this paper are fairly clear-cut: For a global LEO system of 80 satellites with the same data throughput as a global GEO system of 6 satellites, both satellite systems providing a 2-way broadband service (as opposed to 1-way broadcast) the LEO system is 1.6 times costlier than the GEO system. If the comparison was accomplished with a cheap-launched LEO system, we would find the results to be more equitable: A cheap-launched LEO system would have recurring capital expenses roughly 80% the cost of the GEO system.

The consequences of this should not be understated. It would now be more profitable to operate a mobile satellite communications platform at LEO, and cheap-launch would have found its niche.

Conclusion

Cheap-launch reduces space system cost. This happens through direct reduction of launch costs, but it also reduces space system hardware and fabrication costs because individual satellite component reliability is less critical. By utilizing historical database of satellite build costs and applying a set of assumptions based on an expectation of much lower satellite reliability, a comparison between a cheap-launched satellite constellation and a conventionally launched satellite constellation was drawn.

The results of this comparison are intriguing:

1. Cheap-launch can save the big LEO business model by allowing Globalstar and Iridium to re-launch their constellations.
2. Cheap-launch allows a competitive little LEO satellite constellation to be launched for under $100M. The little LEO business model is sustainable and likely competitive against terrestrial networks, and cheap-launch would allow a considerable competitive advantage over other satellite operators.
3. Cheap-launch ultimately makes doing business at LEO competitive with GEO. A LEO system with similar throughput to a GEO system would cost 20% less.

Optimistically, cheap-launch may confer an even greater cost savings than what was presented here. This analysis was conservative, and in all cases the system costs were dominated not by launch costs, but by satellite hardware costs. In theory, one should be able to launch LEO satellites made entirely of *non space –rated* COTS components as long as the satellite operates below the radiation belts (lower than 1000km[26]). Cisco Systems, for example, successfully demonstrated one of its routers on-orbit with almost no modification[27]. Using non space-rated COTS components would yield an order of magnitude of hardware cost reduction.

Finally, the authors would like to stress the ideal nature of the ram accelerator as a cheap-launcher. Every piece of experimental evidence to-date has shown that impulsive-launch systems can place useful satellite payloads into orbit. The ram accelerator technology has demonstrated the required performance to reach orbital velocities. Most importantly, the ram accelerator is an extremely simple device to build: The cost to build a ram accelerator is by far the most inexpensive of any cheap-launcher ever proposed.

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