PRACTICAL MICROSAT LAUNCH SYSTEMS: ECONOMICS AND TECHNOLOGY

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ABSTRACT. The problem of an affordable, responsive, and reliable microsat launch system (MLS) has bedeviled the small-satellite community, especially in the United States, for decades. Rides on dedicated vehicles may cost $15M or more, while shared space is hard to find and harder to fit with the schedules of microsat operators.

Several efforts to build an MLS, generally focusing on cheap expendable launch vehicles (ELVs), have failed, as did the government's much-touted Bantam launch vehicle effort in the 1990s. Today, there are several options, both reusable and expendable, in development, as government agencies and corporations respond to the growing interest in microsats by trying once again to solve the problem.

In pursuing these efforts, it is instructive to consider why the problem was not solved long ago. A reliable and relatively affordable MLS, the NASA-developed Scout, was built over four decades ago. Since then, technological advances should have made duplicating its success a relatively minor problem. Why has this not been so?

The answers range from the volatile microsat launch market to the fixed costs involved in launch ranges and safety standards, to the technology itself. This paper examines MLS development efforts past and present, analyzes the technical and economic factors retarding their success, and offers prescriptions for the organizations now attacking the MLS problem.

Introduction

The desire for an affordable, responsive, and reliable microsatellite (microsat) launch system (MLS) is nothing new. Today, developers of microsatellites, especially in the U.S. where export controls make launching on foreign vehicles difficult, face a complex and often impossible situation. Rides on dedicated vehicles cost $15M or more, while shared space is hard to find and harder to fit with the schedules of microsat operators.

What is a microsat launcher? The definition used by the National Aeronautics and Space Administration (NASA) for its Bantam Low-Cost Boost Technology program (to be described later) was a capability to lift 150 kilograms (kg) into polar low Earth orbit (LEO).[1] This capability would cover most research microsats, clusters of nanosats, and many military and commercial satellites, like Orbital's 46-kg Orbcomm and the 28-kg XSS-10 inspection satellite built for the U.S. Air Force (USAF).

Accordingly, this paper uses the Bantam capability as a starting point. Since few launcher designs are aimed at exactly this capacity, somewhat larger vehicles, if they promise to cut launch costs, and smaller microsat launchers are examined as well.

Recent efforts to replace the MLS-type vehicles of the early Space Age with a cheap expendable launcher have failed. As several companies and government organizations pursue the elusive goal of the ideal MLS, it is vital to understand why the problem has resisted solution. This paper examines MLS development efforts past and present, analyzes the technical, economic, and organizational factors retarding their success, and offers prescriptions for those now engaged in the MLS field.

This paper focuses on the most difficult part of the microsat launch problem - development of a dedicated U.S. vehicle that will lower costs sufficiently to bring about expanded use of microsats and remove launch as a constraint. (Unless otherwise noted, all costs presented in this paper are in FY04$M.)

Background

The first U.S. launch vehicles were all microsat launchers. The Vanguard and Jupiter C were very inefficient, measured by the common standard of the cost per kilogram placed in orbit. They had payload capabilities under 30 kg to LEO and success records of only 50 percent.[2] Ballistic missiles and the space launchers derived from them were generally designed along aerospace industry principles emphasizing low weight and maximum payload, a formula not conductive to low cost for an expendable machine built in relatively small quantities.[3] NASA replaced the first launchers with the all-solid-propellant Scout, which served from 1960 to 1994. The final version, the Scout G, could put 210 kg into LEO for about $13.3 million (M)[4] [or $.063 million per kilogram (M/kg)].

The microsat market became less important in the U.S. as satellites grew larger. By the 1980s, when new technology expanded the capabilities of microsats, the Scout was nearing the end of its career. The Defense Advanced Research Projects Agency (DARPA) took the lead in buying a new rocket. The option the agency chose was the Pegasus, being developed by Orbital Sciences Corporation. The air-launched Pegasus has proven a reliable design, but predictions of flights costing $8-10M proved optimistic.[5] The current Pegasus XL, able to put over 280 kg into polar LEO, costs at $20M or more: beyond the reach of most academic institutions, and even of many government programs.[6] So Pegasus, while a success, is not the MLS solution.

The Situation

Microsat builders outside the U.S. have a variety of options, mainly using launchers developed in the nations of the former Soviet Union. For American companies, the high costs of domestic launchers, coupled with launch costs and export controls and the legal requirements for U.S. government-sponsored payloads to use American vehicles as much as possible, make launch a serious constraint hampering the long-predicted explosion of microsat development.[7]

The largest U.S. developer in terms of numbers has been Orbital Sciences Corporation (OSC), whose 34 Orbcomm communications microsats have been launched in groups of up to eight on the company's Pegasus vehicles. This success, though, does not carry over to most microsat development. Many science satellites need specific orbits, making it difficult to share space on Pegasus or larger launch vehicles. Rides on the Space Shuttle are now rarely available. Secondary opportunities on larger launchers do not always save money, and many payloads are bumped several times before funding, the right launch opportunity, and the readiness of the payload come together. (The XSS-10, launched in January 2003 after many delays, was an example.) It is costly and sometimes impossible to keep a microsat program alive while waiting years, in some cases, for an appropriate launch opportunity. Robert Sackheim, Assistant Director of Marshall Space Flight Center, went so far as to say the main problem with secondary launches is, "You hope to live long enough for your payload to be launched."[8]

It is the authors' contention that the full exploitation of microsats will require an American MLS that meets critical needs for a dedicated ride at low cost, on a reasonable timeline. Other measures have gone as far as they can to address the problem. The authors were unable to locate anyone in the microsat development community – government, academic, or private – who is satisfied with the current launch situation.

The Demand

It is impossible to put an exact figure on the number of microsats NOT built because of the launch problem. That the evidence is imprecise, though, does not make it less compelling.

The Space Test Program of the Department of Defense (DoD) can afford to launch only 20 percent of the payloads approved by its Space Experiments Review Board.[9] Many of these are microsats or experiments suitable for microsats. The USAF' s PICOSat and XSS-10 microsats were delayed for years by launch opportunities and its TechSat-21 constellation has been canceled, due in part to the costs imposed by dragging a program out for years while searching for an affordable launch.[10] The 10-satellite DoD-University Nanosatellite initiative, originally planned for a single launch in 2001, has decomposed into three missions with no firm launch dates.[11] The University of New Hampshire's CATSAT and the student-built Starshine II are sitting in storage with an uncertain future. NASA's University-class Explorers program was suspended in large part due to high launch costs.[12] Many proposals for other microsats, including commercial ventures such as KitComm, have evaporated or are stalled short of the hardware stage, due in part to the difficulties associated with securing a launch platform.[13]

The 2003 ASCENT study of space markets, performed for NASA by Futron, found the size of the small payload market was much more strongly affected by launch costs than were the larger payload markets. The study found that "science payloads funded through universities," many of which are microsats, "are likely to increase in number due to a relatively modest drop in launch prices" and that a 75 percent decline in the cost of launching small payloads would trigger more than a 200 percent increase in such flights through 2021.[14]

Lessons from Recent History

Over the past 20 years, there have been several efforts to build smaller, cheaper U.S. launchers. An examination of these efforts is important in identifying lessons to apply.

In 1981, a startup called Space Services Inc. (SSI) began work on the Percheron, a liquid-fueled modular launcher built of identical components 12 meters (m) high and 1.3 m in diameter. The first vehicle exploded during a static test. A second vehicle was never built because the company failed to obtain the customers or retain the investors needed.[15]

SSI changed its design to solid-fuel systems and, in 1982, flew a single-stage suborbital test vehicle based on the Aerojet M56-A1 used as the second stage in Minuteman ICBMs. In 1990, SSI was purchased by EER Systems, which switched to commercially available Thiokol solid motors. When the first Conestoga 1620 (with a capacity of 880 kg to LEO) was flown, it suffered a control failure and was destroyed. EER planned a second flight but was unable to raise funding.

Pacific American Launch Systems, founded in 1982 by Gary Hudson, planned the Liberty family of launchers. The Liberty I launcher was a two-stage, liquid-fuel design, with each stage having a single engine. Stage 1 used LOX/kerosene and stage 2 used the toxic N2O4/MMH. The vehicle would cost $2.5 million to place a 220-kg payload in polar LEO. Liberty had only reached the engine test stage when DARPA let the first contract for the Pegasus. The financial backers of Liberty dropped out, figuring Pegasus would capture the small-launch market. About $2 million had been invested before the company gave up in 1989.[16]

In 1988 came MicroSat Launch Systems, which partnered with Canada's Bristol Aerospace in a venture called Orbital Express. Bristol is a leading builder of sounding rockets, and the

Orbital Express was to use Bristol's proven solid fuel motors. By 1990, the partners had designed a launcher with a 140-kg capacity and a price tag of approximately $3.5M. Several further evolutions of this design took place to meet the needs of prospective customers, but firm deals proved elusive. In 1993, the only signed launch contract, with DoD, was canceled.[17]

AeroAstro, one of the first companies formed specifically to build microsats, explored entering the launch services market with its PA-X launcher. The PA-X was a two-stage, liquid-fuel design intended to cost about $6M per launch.[18] The engine was to be a simple pressure-fed type derived from TRW's Lunar Module Descent Engine. According to CEO Rick Fleeter, the company discovered it could lower the hardware costs for the launcher. But building a cheap microsat launcher proved difficult because overhead costs, such as range expenses, are not proportionate to the size of the rocket. As with other ventures of the early 1990s, the PA-X also had to compete against Pegasus, which had won government customers. PA-X never attracted sufficient funding or demonstrated economic feasibility, and the project ended in 1995.[19]

Many of the early U.S. launchers had their origin in components built for intercontinental ballistic missiles (ICBMs). The idea of converting surplus ICBMs directly to launchers has surfaced many times. In the 1990s, with the retirement of the solid-fuel, three-stage Minuteman II ICBM, the concept was reexamined. The Air Force funded design of small orbital launchers based on Minuteman, although the 1996 National Space Transportation Policy severely restricted when these could be used, a policy designed to protect private-sector launch companies. Several designs were produced by Lockheed-Martin under the Multi-Service Launch System (MSLS) contract, but the contract expired without any such vehicles having been ordered.

Its replacement, the Orbital/Suborbital Program (OSP) contract, was awarded to Orbital. The first two OSP vehicles were successfully launched in 2000. The idea of a relatively simple modified Minuteman morphed into something much larger, often called the Minotaur. The Minotaur uses the upper stages and payload fairing from the Pegasus XL, mated to the first two stages of a Minuteman II. The Minotaur can place over 400 kg in LEO but, with a total launch cost estimated as high as $19M, [$.0475M/kg], did not succeed in cutting launch costs for microsats.[20]

In 1997, NASA issued a request for studies to develop a new MLS called Bantam. The goal was a rocket with a 150-kg capacity to a 370km polar LEO and a cost of no more than $1.5M ($1.65 in FY04$M, equating to $.011M/kg) in "recurring marginal cost" per flight. (Placing 150 kg into this orbit equates to approximately 210 kg into low-inclination orbit from Cape Canaveral.) NASA provided study money to four companies. Unfortunately, according to NASA's analysis, none of the resulting designs appeared likely to cut costs below $3M. This would still have been a major improvement, but NASA opted to shelve the program.[21] Rocket Development Corporation, a partner on one team, even reported that a launcher the size of Bantam could not be operated commercially and therefore was not worth building, since the development costs could not be recouped by flying a small number of Government-sponsored payloads.[22]

Current Initiatives

There have been – and are – too many "paper rockets" to cover in detail. However, a comparison of the technology choices and cost projections offered by some of the current developers of MLS-type vehicles is in order.

Development of Microcosm's Sprite launcher has been partly funded through AFRL. The goal of the program is a clean-sheet modular design (the orbital launcher has seven identical propulsion "pods"), which would place 220 kg into polar LEO for a price estimated at $2.5M [$.011M/kg].[23] Microcosm has opted to go with a pressure-fed liquid-fuel rocket, using LOX and kerosene in high-pressure composite tanks. While a pressure-fed system allows designers to leave out expensive turbopumps, the tanks make some launch experts nervous because of the failure of a larger composite cryogenic tank during the NASA X-33 program. Microcosm engineers, though, believe smaller tanks can be built to high reliability, as the weight saved by a pressure-fed system allows for heavier tank construction.[24] The Sprite would be the largest pressure-fed rocket ever launched. Two suborbital vehicles have been flown, and four more are planned to prove the technology and concept of operations. The first orbital flight (assuming continued funding) could occur as early as 2006.[25]

The Air Force Research Laboratory's Space Vehicles directorate (AFRL/VS) has proposed a minimal vehicle which could be launched from an F-15E fighter. The launcher would be a three-stage solid-fuel design able to orbit up to 100 kg. An early estimate (1999) pegged development costs at $200M, with a $1 million recurring cost per booster [$.01M/kg].[26] That option included developing new high-performance motors. The laboratory is currently focusing on a version using off-the-shelf motors which would cost less to develop. Recurring costs are now estimated at about $5M [$.05M/kg].[27]

SpaceDev, a builder of small satellites, has proposed a launcher called Streaker with a capacity of 315 kg to polar LEO. The total price of a Streaker launch is expected to be under $10M [$.032M/kg].[28] SpaceDev has chosen a different technical direction from its competitors. Streaker would use a hybrid rocket motor, combining solid fuel with nitrous oxide as the liquid oxidizer. (SpaceDev purchased the assets of AMROC, a company which sought to develop a hybrid booster but collapsed after the first test article burned on the pad in 1989.) SpaceDev says its engineers have redesigned the hybrid motor (historically viewed as inefficient) to produce an efficient, low-cost engine burning HTPB (a common rubber compound) with nitrous oxide.[29]

Space Exploration Technologies (Space-X) has chosen a different approach for its Falcon small launcher (capacity about 350 kg to polar LEO). Space-X has benefited from a steady financing source, the private investment of CEO Elon Musk. (By contrast, Microcosm has had to slip its program by several years due to fluctuating funding.)[30]

Many companies look to minimize development difficulties and R&D costs by using as many off-the-shelf components as possible. The staff at Space-X has taken an opposing view: as company vice president Gwynne Gurevich puts it, "Legacy components equal legacy costs," and too much reliance on outside vendors creates a risk of uncontrollable cost increases. Space-X engineers have looked at existing technology but largely opted to build or subcontract their own designs, wanting to take maximum advantage of modern manufacturing and materials technology but avoiding the need for any breakthroughs.[31]

Space-X is offering a firm price of $6M [$.017M/kg] and has two customers signed. Musk predicts four or five launches a year can be sold at that price to DoD and NASA "when the government responds to the reality of a truly low-cost reusable launcher."[32]

The first-generation Falcon is a two-stage LOX-kerosene vehicle, with a pump-fed first stage engine and pressure-fed second stage. The first stage will be recovered by parachute for re-use, an idea never realized in practice on a large liquid-fuel rocket. First launch from a former Atlas pad at Vandenberg AFB is slated for December 2003.[33]

Several other private efforts – some now moribund, others still active – have emerged in the last few years. JP Aerospace, the High Altitude Research Corporation (HARC), and Starhunter Corporation are developing these three balloon-launched concepts. Other ground-launched systems were pursued by Rocket

Propulsion Engineering Company (RPe), whose Prospect LV-1 would carry over 200 kg to LEO, and Thurber Space Systems, which seeks to build a liquid-fuel booster in the same class.[34] The LV-1 would use a pump-fed system with composite tanks and H2O2 for the oxidizer. The LV-1's recurring cost is estimated at $2.3M, plus range and integration.[35]

DARPA is funding the Responsive Access Small Cargo Affordable Launch (RASCAL) project. RASCAL will use a custom-designed supersonic aircraft, a high-performance design with thrust-augmented jet engines and all-composite structure, as a reusable first stage. An expendable upper stage will be released at Mach 3. The idea is to orbit up to 110 kg for "$5,000 per pound or less" [$.011M/kg].[36] The development contract went to a small California firm, Space Launch Corporation (SLC), which will develop technology both for RASCAL and a private version, the SLC-1. A demonstrator flight by 2006 is hoped for. SLC's current planning assumes the SLC-1 version will be able to orbit a 50-kg payload for a total price of $1.5M [$.03M/kg][37].

A new factor in the development of the MLS is renewed DoD interest. In addition to the high-tech RASCAL effort, Air Force Space Command (AFSPC) and its development arm, the Air Force Space and Missile Systems Center (SMC), are joining DARPA in are acquiring a responsive, low-cost small launch vehicle (SLV) as part of the Operationally Responsive Spacelift (ORS) effort. The SLV will launch suborbital test vehicles for DAPRA's hypersonic technology effort and for global conventional strike as well as placing microsats in orbit.[38] The dual propose of the SLV offers the prospect of additional business for the launch contractor should a strike system be approved and developed for operational use.

The strike option puts a premium on responsiveness, a factor usually not crucial in space launch missions. Accordingly, companies building for the microsat market, which emphasizes low cost and reliability, must also pay attention to the speed with which their systems can be launched if they want to appeal to this potential additional DoD market. Responsiveness has, in recent years, led the military to prefer solid fuels for its long-range suborbital missiles. However, suitably designed liquid-fuel systems can also be loaded and launched quickly.

The Two Pillars

The U.S. has no shortage of launch facilities suitable for MLS. Pads for small launchers at Cape Canaveral, Wallops Island, Vandenberg AFB, and Kodiak are all far underused, and air-launched systems will not need pads. Also, there is no lack of industrial capacity to build small launchers or microsats.

Accordingly, the two pillars undergirding a "right service/right price" solution to the MLS problem are technology and cost. To state these as questions:

1. What technology is most suitable for a practical MLS? Will the MLS solution(s) be modernized versions of proven designs, or will they be innovative or even radical solutions? Propulsion technology, usually the most expensive component of a rocket's hardware, is the key variable here.

2. At what price point would the microsat market be opened up, allowing the current microsat developers to launch their microsats and encouraging institutions not now building microsats to build and enter the market?

Of the two pillars, cost is the most complex. We know how to build rockets. Building them cheaply is the challenge.

Technology Factors

Every type of launch option for the MLS has either been investigated or tested – launch from fixed pads, aircraft, balloons, and barges, among others. Each has its advocates, but so far the workable small launch vehicles have, with the exception of Pegasus, been pad-launched. A pad launch offers the lowest infrastructure costs, with tradeoffs including the limited range of launch azimuths from any particular pad and some loss of vehicle efficiency compared to rockets launched from altitude.

Many different types of propulsion options have been investigated. The rocket propulsion efforts so far can be sorted into solid, liquid (cryogenic and non-cryogenic), and hybrid systems, with several variations of each. SSI and Microcosm investigated grouping several small propulsion "pods" into a type of horizontal staging. Other manufacturers have used more conventional vertical staging (usually with two or three stages) or have used an aircraft or balloon as the first stage.

Technology Lessons Learned

Looking at the historical record, launchers have both succeeded and failed using liquid and solid fuel. The only serious hybrid effort to date, AMROC's, failed. The many disagreements in the propulsion field – solid vs. liquid vs. hybrid, pressure-fed vs. pump-fed, composite tanks vs. aluminum, and clustering vs. single-system – are likely to continue for a long time. What matters most is that the decisions on these matters are made as part of an integrated approach to the whole vehicle that takes in cost, operability, manufacturing labor, etc.

There is not any single technology path, which guarantees success or failure. Despite the prominent position of propulsion in Dr. Elias' cost breakdown in Table 1, the decisions about which propulsion method to use or to stage or to launch the vehicle, appear less critical than the overall program execution.

Cost Factors

The authors obtained estimates for nine MLS vehicles: two flight-proven systems now in operation, and seven now in some stage of development (meaning some hardware work has been accomplished). The two flight-proven vehicles, Pegasus and Minotaur, are estimated at approximately \$20M and \$19M per flight, respectively.[39] Figure 1 (below) displays the relationship between Capacity to polar LEO and Cost (FY04\$M).

While cost is inextricably intertwined with technology, things other than technology also affect it: range costs, launch licensing, and use of a flight termination system (FTS) acceptable to range safety authorities, etc. Since these ancillary costs do not scale down proportionately with the size of the rocket, they place a floor (approximately in the \$1M range) under the launch price of any U.S.-launched MLS.[40]

Launch costs of existing vehicles have proven heavily dependent on the flight rate. This creates a classic chicken-and-egg dilemma – fewer flights mean higher costs meaning still fewer flights, and so on, as the fixed costs of maintaining a production line and launch infrastructure are spread over a small number of flights, driving up marginal costs. For a privately financed vehicle, there is also the need to earn back the R&D investment.

Dr. Antonio Elias of Orbital Sciences, designer of the Pegasus, offered this breakdown of the cost of a notional small launcher:

Small Launcher Cost Breakdown	
Item	**% of Launch Price**
Propulsion	25.7
Mission Support Labor	25
Amortization of DD&E	21.4
Assembly Labor	8.6
Avionics	8.6
Flight Termination System and Range	7.1
Structures	4.3

Table 1. Components of a Small Launcher's Price[41]

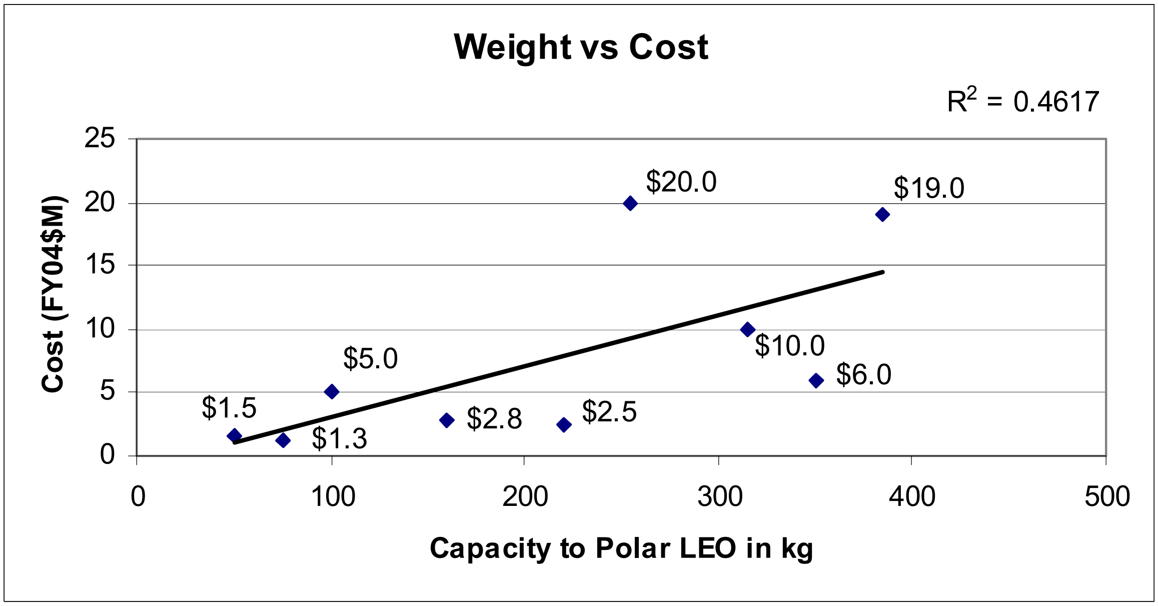

Figure 1. Weight vs Cost (Includes flight-proven systems)

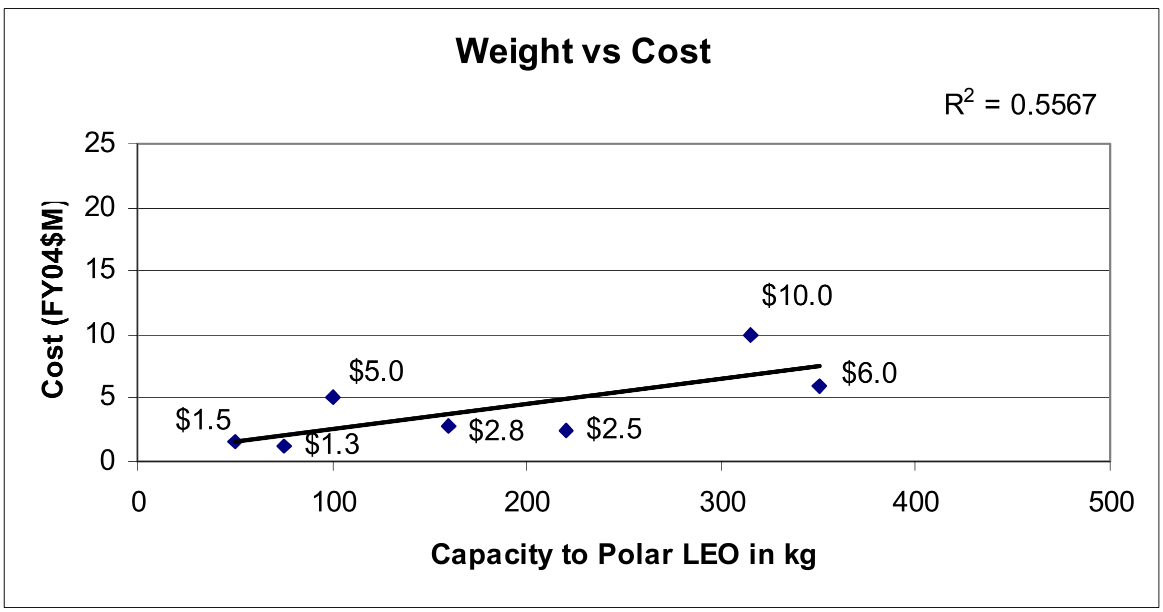

Figure 2. Weight vs Cost (Excludes flight-proven systems)

In evaluating cost for an MLS, it is important to remember that cost and efficiency are not the same thing, and the difference is stark with small launchers. The most efficient way to launch a satellite is to use a launcher appropriately sized for the payload. Measured in $/kg, a large launch vehicle appears cost effective but often is not so in reality, at least from the payload developers perspective. Microsat builders need low per-launch costs, which may involve a launcher that is, by the per-kg measure, very inefficient.

Another factor related to cost is risk. Increased R&D investment can cut risk by thorough testing, but investment funds are hard to find for most MLS developers. At the same time, most companies cannot afford a failure of their first launch vehicle. This creates a very difficult situation – made more difficult by the fact that the Holy Grail of the MLS business, low recurring cost, depends to some degree on how much money a company invests in designing its vehicle. Recurring and R&D costs are not opposites, but they are usually antagonists. For example, companies often cut R&D costs by buying off-the-shelf components, but such components are not necessarily good choices for low operating costs.

The authors began their study for this paper by focusing on per-mission cost. However, it became clear that efficiency and payload capacity also mattered, since microsats are so often launched in numbers larger than one, and this is likely to continue even in the presence of a low-cost MLS. That makes the correlation between weight (total payload capacity) and cost a factor of interest. Since the cost per kg is generally higher in the small-launcher market, so the comparison of interest is between MLS candidates rather than among all launch vehicles.

The correlation coefficient, R, measures both the strength and direction of the relationship between two variables measured from the same subject. The Coefficient of Determination, R^2, represents the proportion of variation in the dependent variable that has been explained or accounted for by the regression line[42], or as the proportion of variance in cost that is contained in weight. [Note: A trend line is most reliable when its Coefficient of Determination value is at or near one.]

For the nine pairs of data, the correlation coefficient is .68 and the Coefficient of Determination is .46. Hence, there is a medium positive correlation between weight and cost, in a linear sense, within the bounds of this data. Using the Coefficient of Determination, 46 percent of the variation in cost is explained by weight.

As this shows, the correlation between payload and cost is not perfectly linear ($R \neq 1$). Other factors that contribute to cost are terms of individual contracts (e.g. who pays for weather delays?), flight rate, variations in range pricing, the cost of integration between the payload and vehicle, etc. Interestingly enough, if the two flight-proven vehicles are removed [(255, 20) and (385, 19)], the graph takes a slightly different turn, as shown in Figure 2. The Coefficient of Determination is now .5567, indicating that this trend line is more reliable than the one computed using the flight-tested systems in the data set.

What does this tell us in practice? The fact that the weight vs. cost predictions of the MLS developers are closely related shows the analysis of this factor is consistent even when performed by different companies. This indicates the correlation is a valid one and is likely to be close to reality when new MLS systems are built.

Cost and Market

There is a market for a low-cost MLS, although it is very difficult to quantify. Estimates offered by payload developers of the cost per flight required to significantly expand the market range from $1M to $6M.[43] This translates to a range from $10K/kg to $33K/kg. Estimates of the recurring cost of a suitable launch vehicle that might emerge from current programs from

MLS developers range from $1.5M to $10M.[44] This translates to a range from $6K/kg to $50K/kg.

Figure 3 (below) displays the inputs from the Payload developers. Focusing on the Bantam-like weight of 150 kg, the authors received a variety of inputs: a range from $1.5M to $5M. (The outlier on this chart, $6M, is a figure Space-X offered based on its own market studies.) Depending on the value of the payload to the developer or perhaps the Return on Investment, the $5M may be an "affordable" figure compared to the flight-proven options.

Figure 4 (below) compares the estimates of MLS developers to the Payload developers' desired launch cost for the 150 kg range of satellites.

The data is not very firm, given that none of the vehicles involved have been flight-tested, but a picture does emerge of a tradespace in which technology and economics can meet. Space-X's Falcon estimate of $6M probably represents the high end of this zone of opportunity. Obviously, the lower costs can go the better. As to size, while we focused on the Bantam definition of a minimum launch capacity; the market is obviously greater if an MLS offers higher capacity while keeping the cost low.

This is a simplification, because some science and R&D satellites can share rides, and some commercial ideas call for launching in clusters. However, it is necessary to begin somewhere, and this overview at least provides a starting point for the more in-depth analysis not possible in a short paper. Again, the authors focused on the availability of a dedicated MLS because that is the element currently missing from a market, which does offer secondary slots and larger launch vehicles.

Finally, note the effect of development costs in Dr. Elias' breakdown (Table 1, above). Amortization of design, development and engineering (DD&E) expenses accounts for over 21 percent of cost. In Elias' example, this was $3.0M on a $14M vehicle. Elias feels $14M is the lowest practical price for a "minimum" launch vehicle.[45] (Not surprisingly, the other launch companies strongly dispute this point. The authors agree this estimate seems to be based too much on current practice without allowance for innovative cost-reducing ideas in either technology or operations.)

Whatever one's opinion on the proper numbers, Elias' breakdown shows the question of development funding is huge. A launcher which relies on investors who must be paid back is inescapably going to cost substantially more than one in which an independent source provides the development funding.

Interplay of Cost and Technology

Historically, with aerospace endeavors, new technology required has almost always been more difficult and costly to develop than proponents had forecast.[46] This does not mean new technology must be avoided. It does mean developers must expect that "pushing the envelope" is expensive (as was demonstrated with the X-15 and SR-71, two successes in breakthrough aerospace technology which went far over initial cost estimates), and challenging technology development requires funding reserves and commitment to be successful.

Developers also must recognize, expect and plan ways to mitigate cost, schedule, and technical risks when testing new technology. Builders of the NASA/OSC reusable X-34 demonstrator blamed their fatal cost overruns on NASA's insistence on reducing the risk of failure to nearly zero by requiring more oversight and redundant systems.[47] Risk is also increased by the understandable desire to keep budgets reasonable by making the leap to the final system in as few jumps as possible.

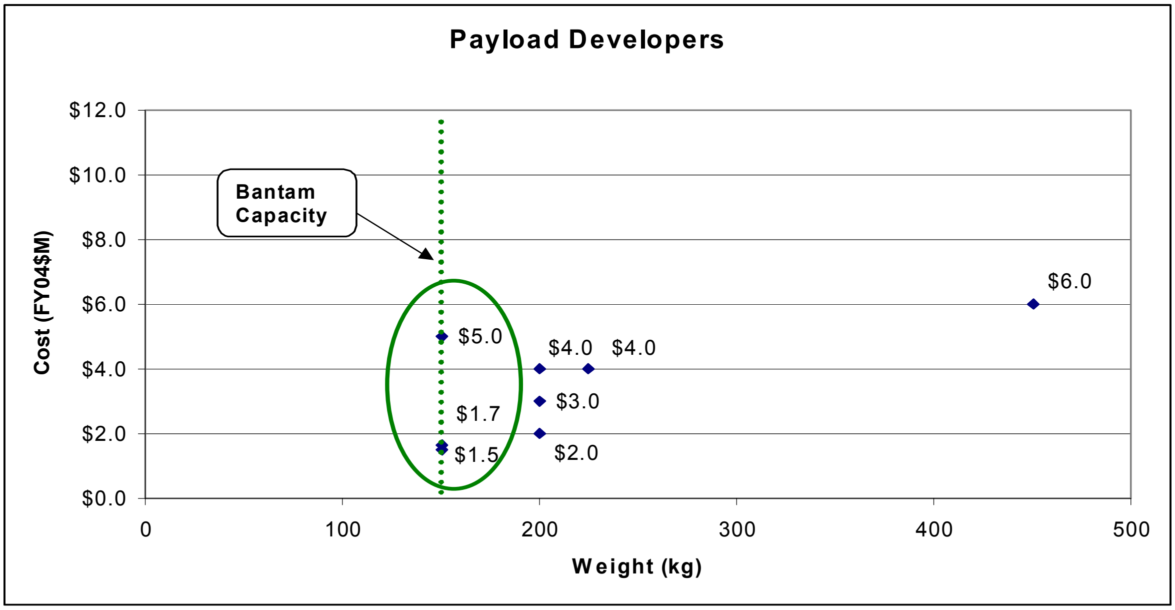

Figure 3. Payload Developer Inputs

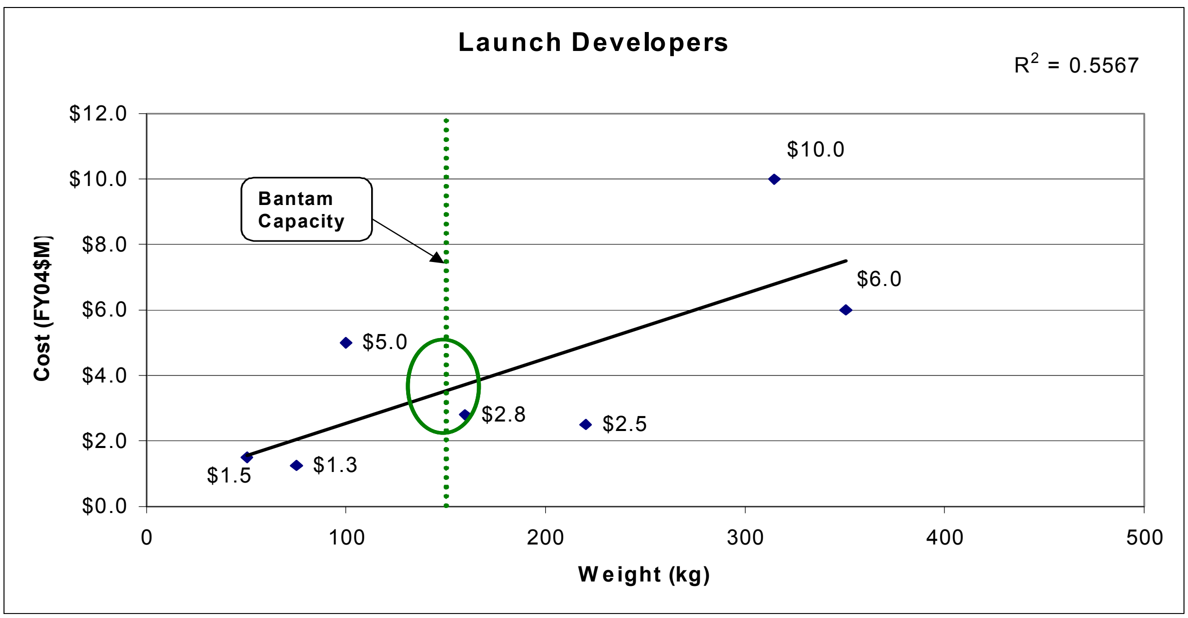

Figure 4. MLS Developer Estimates compared to Payload Developer Desire

Dr. Terry Bahill of the University of Arizona surveyed 20 development projects for his textbook *Metrics and Case Studies for Evaluating Engineering Designs*. He found that a breakthrough design approach may cost three times what a continuous improvement model does for the same performance.[48] As EER and SSI learned, an initial failure may mean the end of the enterprise, especially for a small company. Since the chance of such a failure is impossible to avoid entirely, this points to the need for a mix of risk reduction (with incremental rather than leap-ahead technology insertion) and proper funding. A company whose internal reserves or external contracts are inadequate for this contingency is at high risk no matter how its hardware is designed.

The Last Step: Execution

A program can have a superb design and excellent cost-cutting ideas, yet still fall prey to mistakes in execution. Loading a program with too many requirements and saddling it with a cumbersome and/or costly management structure are two of the ways past launch programs have been crippled.[49]

For a successful MLS, the requirements must not be stretched beyond the basics. As Henry Vanderbilt of the private Space Access Society put it, "Consider the pervasive tendency for any potential low-cost launch project to get latched onto by all the major government launch customers and end up stretched to gargantuan size and performance to meet all their requirements. Add in the tendency for multiple government R&D centers to lobby to have their pet technologies incorporated, and you have a recipe for repeated failure."[50]

Successful X-vehicles have traditionally been produced by organizations which have been kept as "lean" and collocated as the scope of the project allowed. (While the X-33 was promoted as a "Skunk Works" project, it was considerably more spread out through the newly merged Lockheed and Martin Marietta than Skunk Works successes like the SR-71 and F-117 had been when they were achieved with the key people under one roof.[51]

Wernher von Braun, whose revolutionary V-2 came out of such an "under one roof" shop at Peenemunde, insisted that his missile development efforts at Redstone Arsenal in the 1950s be organized along similar lines. Von Braun felt it was critical that everyone on the project be able to talk to each other face-to-face, and that the manager step out of his office and into the workshops.[52] While this is not practical for a gigantic project like the Space Shuttle (or von Braun's Apollo efforts), it is good advice for the MLS.

A development effort which is part of a large government entity is subject to covering its share of the overhead structure, as well as to having its budget "taxed" for headquarters activities and cut to fund "must-pay bills" which crop up elsewhere in the organization. This often-overlooked problem requires that the project be carried out, to the extent possible, in a small, dedicated organization, or that the budget be "fenced" by top-level directives. The alternative – development schedule stretchouts and higher costs – is acceptable in a program not aimed at lowest possible cost (for example, building a Stealth bomber), but is guaranteed to be lethal for an MLS effort where cost is #1.

Can We Build the MLS, and How?

There are classically three ways of building something at lower cost: Build more, build in a new way (i.e., using a new cost-saving design), or build more efficiently. While all these will probably need to be combined for a successful MLS, building in quantity will have to wait until the market develops in response to a proven vehicle. (A pod or cluster design like Microcosm's is a form of effort to build in quantity, although it necessarily has some tradeoffs in the mass fraction devoted to structures and thus the vehicle's efficiency.) Most of the MLS concepts now under development include at least some new ideas or emerging technology, from Space-X's recoverable first stage to SpaceDev's large hybrid motor. Building and operating with as small a team as possible is a nearly universal theme, an understandable one given the large role labor plays in small-launcher costs (see Table 1).

Some recommendations for a workable MLS program emerging from this study include:

- Development based on venture capital or other private investment from outside the launch vehicle company is not practical.

The proven market is not there to attract investors. Even if it were, the need to pay back the investors would minimize the new vehicle's potential to cut launch costs.

- Practical financing sources are thus limited to government contracts (e.g., Microcosm) or internal investment (e.g., Space-X). Accordingly, the role of the government in deciding to invest to break the chicken-and-egg cycle looms large.

- New technology, or a new design approach, may be important for drastically lowering costs in the absence of an established market. However, the degree of new technology must be carefully balanced against the risks involved.

- A design which maximizes operability (even at the expense of increased R&D funding), and uses modern technology without requiring a breakthrough has the best chance of success.

- A lean, dedicated organization (be it corporate, government, or a hybrid) whose budget is not subject to constant raiding for other priorities is essential.

- Design to cost (including operability cost) is more important than maximizing performance (common with launch vehicles) or designing for mass production (common with aircraft).

- The developer must have sufficient resources (internal or external) to survive an early failure.

Conclusions

A practical, affordable MLS is not outside the reach of American technological expertise. If we accept that it will take time for the market to expand, then the keys lie in intelligent design and management to maximize the cost reductions. As illustrated by the estimates of cost and capacity for the in-development MLS systems considered above, the cost numbers are somewhat clustered together and there is some competition for this niche, which will also help stimulate cost savings. The most important finding of this paper is simply that MLS development is possible within a cost range appealing to the Payload developers' expectations.

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Robyn Kane is Senior Econ/Business Analyst for The MITRE Corp. in Colorado Springs. Her degrees include a Master's in Mathematics/ Statistics and a B.S. in Mathematics/ Spanish. Robyn has published 9 articles and papers on space history and technology. She led cost analysis for a variety of Analysis of Alternatives (AoAs) and estimated a 20-year Life Cycle Cost for a Tactical Launch System using Minuteman II stages coupled with commercial boosters. She is a member of the Military Operations Research Society (MORS) and is the founder and President of the Pikes Peak Chapter of the Society of Cost Estimating and Analysis (SCEA).

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