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What's the Price of Low Cost?†

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Abstract

Many programs presented at prior USU meetings have been exceptionally successful at reducing the cost of space missions. Typically this is done by a variety of mechanisms that change fundamental characteristics of how business is done in space. (The missions flown do not literally reproduce their more expensive predecessors, or they would have not have been able to significantly reduce cost.) Thus, a critical question arises – What is the price of low cost? What do we give up in order to achieve the advantage of dramatically lower cost?

This paper examines the 10 case study space missions presented in the new book, *Reducing Space Mission Cost*. Relative to the projections of traditional cost models (our best estimate of "should have cost"), these missions reduced total program cost by 50% to more than 90%.

Cost reductions have come about in all mission segments—the spacecraft bus, payload, launch, ground segment, and mission operations. This paper summarizes the cost reduction methods employed by these missions to provide a first answer to the title question.

Background

Microcosm has recently completed work on a three year project for the U.S. Air Force Academy to examine and document methods for reducing the cost of space missions. The result of this activity is the book *Reducing Space Mission Cost (RSMC)** [1] which contains ten detailed case studies of both past and ongoing missions that have been successful in reducing cost relative to more traditional programs. The missions themselves are very diverse, falling into three broad categories:

AMSATs:

AO-13	Amateur radio
AO-16	Amateur radio

Other LEO:

Ørsted	Danish mag. field mission
Freja	Swedish magnetosph. sat
SAMPEX	First SMEX small explorer
HETE	High-energy science mission
RADCAL	Radar Calibration satellite
ORBCOMM	Comm. system test
PoSat-1	Portuguese tech. transfer

Interplanetary:

Clementine	Lunar / asteroid test satellite
Pluto Exp.	Fast mission to Pluto

Because of the book development process, much of the material was written in parallel. Many of the case studies were among the last items to be finished and, although the discussion of the technology

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methods draws heavily on the case studies, there was no opportunity in the book itself to summarize the results of the fully completed case study work. Thus, a principal purpose of this paper is to review the complete set of case studies and to summarize and evaluate the methods used by these missions to reduce cost.

This work should be viewed as the beginning of a long-term work in progress. For many years, people have brought anecdotal data to the Utah State Conference and other meetings to describe specific methods, philosophies, technology and management approaches for reducing mission cost. What is needed is to begin the process of critically examining what low cost really means and how to go about achieving it. We need to look at what has worked in the community as a whole, what is working, and what new methods people are proposing. We also need to try and understand the real processes at work. The fact that a particular organization can significantly reduce cost does not necessarily mean that they understand fully what was responsible for that success. Building a space mission is a remarkably complex process. In the end, each mission achieves a level of results at a specific cost. But it may not be at all clear, even to those who have done it, how this result differs from more traditional space missions, or what specific techniques contributed most to achieving the cost objective.

Before looking at the results, we need to point out the importance of what the case study authors have accomplished, and the difficulty of the task which they undertook. Many of us write professional papers about the technology we have developed and the merits of our particular approach. In contrast, we have asked the case study authors to reveal significant cost data associated with their program and to examine carefully both what works and what doesn't work in reducing cost. Clearly, these issues are sensitive and get at some of the most critical features which distinguish one contractor from another. Nonetheless, the case study authors have recognized the importance of making this information available to the community. We sincerely hope that these assessments will encourage others to do the same so that our community as a whole can look carefully at what works and what doesn't work and make technical judgments based on real cost data rather than qualitative generalities. Ultimately, reducing mission cost requires that we look at real cost, just as reducing mass requires that we start with a real mass budget.

What is Low Cost?

The Utah State University conference is compelling evidence that large cost reductions are possible. Many of the reports at this conference are on programs that are dramatically lower cost than more traditional approaches achieving comparable results. We believe most of the individuals at the USU conference would concur with these statements. However, a fundamental problem arises when we ask what does this really mean? What is low cost, lower cost, reduced cost? What qualifies a program, other than unverifiable claims, to say that it is truly reduced cost?

One key to this question is to recognize that no one starts out to create a high cost program. In our experience, waste and fraud are not rampant in the space industry. Good decisions are made in virtually all space programs with the fundamental objective of achieving the most cost-effective solution possible to the requirements that have been established.

A large fraction of space products are bought on competitive bids and the contract is awarded to the company that can achieve the stated objectives at minimum cost. Consequently, "low-cost" clearly means something different than simply buying the same product for less money. Almost by definition, a “Low-Cost Space Telescope” will not be the same instrument or the same spacecraft as the "real" Space Telescope. There is no compelling evidence that Space Telescope itself could have been built for significantly less than the actual amounts expended. One could, of course, always be a bit more efficient, or beat a bit more profit out of the various contractors, or require more uncompensated overtime from the engineers. But clearly this process will have only a minor impact on cost. It will not create the dramatic changes that we are seeking or that we believe have occurred in low-cost missions.

If low-cost does not mean buying the same spacecraft or ground system for less money, then there are clearly a series of key questions to address:

- What does low cost really mean?
- Which organizations or groups are achieving it?
- How do they do it?
- What is the price of low cost?
- What can the government do to avoid screwing the process up?

To begin, we need to establish what we mean by traditional and low-cost missions. This is done using *cost models* which have historically been used to provide purely empirical estimates of what it costs to build and fly spacecraft. Cost models ignore the subtleties of how things are built in order to try and answer the fundamental question of what a new mission will cost if we know relatively little about it except perhaps its mass, orbit, and basic mission parameters. A large number of cost models are available. For our purposes, we will use the one defined in Chapter 20 of *Space Mission Analysis and Design*, 2nd edition, (SMAD) [2] because it is widely available and easy to use and apply. We define a *traditional space mission* as one which approximately follows the design rules and cost estimates presented in SMAD.

In contrast to the traditional mission, we define a *reduced cost mission* as one for which the life cycle cost is substantially lower than that predicted by traditional cost models for that mission. Thus, Pluto Express, at an estimated cost of $150 million, might be regarded as expensive, but qualifies as a reduced cost mission by the standards of traditional interplanetary missions.

Finally, we define a *low-cost mission* as one for which the life cycle cost is substantially less than the average cost of a space mission of that type. This, of course, means that we must have in mind some idea of what we mean by average cost. This will depend on the type of mission, how the spacecraft is built, and the time frame in which it is built. For concreteness, Table 1 provides a working definition of what we mean by low-cost space missions in the RSMC context.

With these definitions, we can begin to understand "low-cost" in more concrete terms. The next two tables, also from RSMC, summarize the actual costs of the 10 case study missions (Table 2) and their costs relative to the SMAD cost model (Table 3). All of the values have been inflated to constant FY95 dollars. It is important to recognize that this approach makes no claim to cost effectiveness or what a spacecraft should cost for what it does. The SMAD model is simply the best empirical data on what a mission spacecraft would cost if built by traditional means. Consequently, Table 3 is our best estimate of what the actual costs are relative to a traditional space program. The conclusion is that the case study missions have reduced total mission cost by 50% to more than 90% with respect to projections by traditional cost models.

Class	Typical Cost [1]	Low Cost	Typical Mission	Low Cost Mission
Low-Earth orbit	$150M to $2,000+M	<$50M	DMSP, GRO	Alexis, Freja
Geosynchronous	$250M to $2,500+M	<$75M	Intelsat, TDRS	Ball GEO comsat [2]
Interplanetary	$1,500M to $3,000+M	<$500M	Galileo, Casini	Clementine

[1] Life-cycle cost including development, spacecraft, launch, and operations
[2] Proposed, but not built

TABLE 1. Empirical definition of a low-cost mission. As a working definition we refer to a mission as "low-cost" if it is 3 or more times less expensive than typical missions in that class. (from RSMC [1]).

It is also important to recognize that Tables 2 and 3 are not meant to provide a comparison between the specific low-cost missions. Each mission was developed under unique rules, regulations, and guidelines which define what can be achieved and how it must be done. The mission payloads were dramatically different and their performance in terms of scientific and technical return have been different as well. Thus, we cannot legitimately use this table to say that one mission is better than another. However, we can use it to say that the approaches used by the organizations that developed the case study missions are capable of reducing cost substantially relative to more traditional missions.

How Do They Do It?

Given that the organizations represented in the case study missions can achieve results at dramatically lower cost than traditional programs, how do they do it? Perhaps the most important conclusion is that there is no single common solution among the organizations. There is no one method or process which is common to all of the organizations that substantially reduce cost and no way to fit them into a common mold. Some organizations will prefer to buy rather than build to avoid reinventing what has already been developed. Others will build if they possibly can, on the grounds that they can control the cost, schedule, and performance and have the equipment available to meet specific spacecraft needs. In addition, answers need to be interpreted in the context of individual programs and organizations. In a very real sense, the only common denominator among the organizations is that they all put substantial importance on and real effort into the process of reducing cost.

The broad methods of reducing cost used by the case study organizations are given in Table 4 and their use on the case study missions are summarized in Table 5. Specific elements of design philosophy are summarized in Table 6. These tables are intended to provide an overview of what is done within the case study organizations. Nonetheless, it is important to recognize that it is the implementation of these rules within the context of each organization that really matters. For example, nearly all of the organizations emphasize minimizing documentation. This responds to the general perception that there is excessive documentation within most space programs. Nonetheless, it is equally clear that all of the organizations recognize the importance of having good documentation that records what has actually occurred. AMSAT, for example, has a continuous running log containing essentially all of the documentation for all of the components. This set of ringbinders becomes a complete description of the as-built spacecraft, such that any problems which arise on orbit can be immediately addressed in terms of the equipment which is, in fact, on board.

As one would expect, many of the cost reduction issues revolve around people and staffing. It is people, and not processes, policy, or regulations that ultimately make spacecraft work and reduce mission cost. One of the important methods that we had left out of our summary in the book itself was the empowerment of mission teams to make decisions. The authors reminded us of this several times and frequently pointed out that the empowerment of teams was a key issue.

On the other hand, we had thought that a key issue would be creating incentives—that is, finding ways to incentivize the staff to successfully reduce cost. None of the organizations identified this as one of the techniques which they used. Nonetheless, one of the most apparent characteristics of the organizations that create small low-cost satellites relative to the more traditional organization is the high level of motivation of the individuals involved. The individuals are motivated, committed, and want to make the project occur and see it succeed at low cost. To us, this implies that the organizations have provided substantial incentives. It is simply that these incentives are not bonuses or monetary rewards but much more strongly linked to psychological benefits, such as individual responsibility, pride, motivation to see something accomplished, and the desire to be part of a team that has achieved something which others have not.

While the summaries in these tables are important, it is also clear that it is the method by which they are applied that is most important. In order to make these approaches work within your organization, it is important to understand what has been done and how it has been done in order to achieve appropriate results. There is no single “right” method, but simply a variety of approaches, each of which can be made to work within the circumstances in which they are applied. For each space mission that we have studied, multiple methods and approaches are used, and in the end methods are chosen which work within the context of that organization.

What is the Price of Low Cost?

The section above summarizes the methods that organizations have used to substantially reduce space mission cost. The net result of this process is a mission which is cheaper, but which is also different than a traditional mission. Fundamentally, there is a price to reducing cost. To make dramatic reductions in cost people and organizations have to behave differently. There has to be less emphasis on rules and processes and in bidding against fixed requirements, and more emphasis on working with people to achieve results and ensure higher reliability. This begins to suggest a part of the difficulty associated with either government programs or large commercial bureaucracies in which the emphasis is on procedures and regulations to maintain quality or reduce cost. As the AMSAT case study has clearly proven, contracts, regulations, and policies are simply nowhere near as effective as motivated people.

The distinction between “low cost” and “cost effective” is important but also potentially misleading. “Cost effective-ness,” while a worthwhile goal, all too often serves as a euphemism for business as usual. Being “cost effective” is sometimes what we do if we don’t want to undertake the hard work of genuinely reducing cost.

Keeping the above danger in mind, we can distinguish between a low-cost program and one which is cost effective with Figure 1, which shows performance measured in some quantitative fashion on the vertical axis versus cost on the horizontal axis. The only assumption for this curve is that there is a non-zero cost associated with putting anything in orbit, and that beyond that the cost of improving performance is

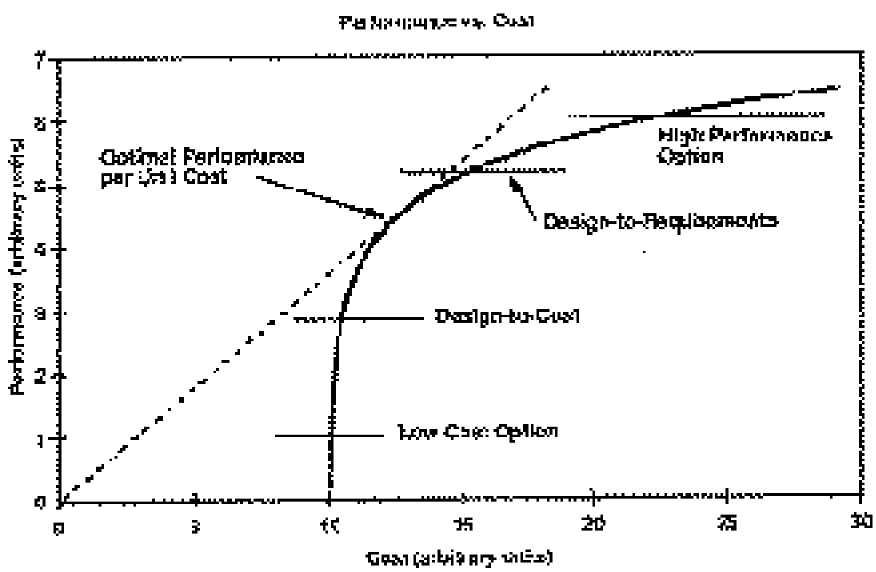

Fig. 1 The Range of Cost Options. For the underlying curve, we assume that there is a minimum cost to launch anything into orbit. Beyond that, the cost of additional performance is proportional to the performance already achieved. See text for discussion.

proportional to the level of performance we already have. This results in a decaying exponential in which the performance of very low-cost programs can be improved by adding relatively small amounts of money and the performance of high-cost programs can be improved only by large cost increases. By definition, the most cost effective program is the one with the greatest performance per unit cost. This is the program represented by the tangent to the curve which passes through the origin. This gives us the maximum performance per unit cost. Programs significantly below this are “low cost” and are less than optimal in the short run.

Low-cost programs which are less than optimal in the short run may still be the most efficient in the long run. If essentially all of the satellites retain their utility throughout their entire design life, then designing to the tangent point in Figure 1 makes sense. However, if many satellites are lost due to obsolescence, operational errors, failures, launch mishaps, or other factors unrelated to the spacecraft itself, then it may be that a series of lower cost spacecraft, in which the cost of the losses are minimized, will be more efficient than the inherently more expensive, cost-effective spacecraft. In the extreme, let's assume that we know that there will be a 15% launch failure rate. Using a series of low-cost, less-efficient satellites, we can accommodate the failure rate by building 15% more satellites or, to be exceptionally conservative, 30% more. If, instead, we build a single, efficient, cost-effective large satellite, we now have a 15% probability that the entire capability will be lost.

What is the real price of low-cost? What do we give up to achieve a low-cost mission? The first order evidence is as follows:

Reliability is Not Sacrificed

Both low-cost spacecraft and high-cost spacecraft experience failures, some of which are recoverable and some of which are not. Although there is no good statistical evidence, the anecdotal evidence suggests the failure rates are approximately the same between the two categories, with a slight advantage in reliability to the very low-cost missions. We believe that this comes about because the low-cost missions are smaller, simpler, have far fewer parts, larger margins, and fewer failure modes. All things being equal, we would expect a smaller number of failures from such spacecraft. In addition, the designers are not pushed to optimize performance and, therefore, will opt instead to provide "excessive" margins in order to ensure successful performance.

Getting Exactly What You Want is Sacrificed

Buying a low-cost spacecraft is comparable to buying a family car. We don't write down detailed specifications and then asking who can build such a car. We look at our approximate budget, evaluate what is available on the market, and select a car which is some compromise between what we want and what we can afford. It is exactly this process that goes into buying low-cost spacecraft or other mission components. The result is that we meet most of our objectives at far lower cost, but we do so in part by giving up the ability to demand specific performance levels.

Optimal Performance is Sacrificed

On the whole, small and low-cost spacecraft will be less efficient than larger ones, because the design is less than optimal. The attitude control system, for example, will be a larger percentage of the spacecraft mass for a less accurate system than will be the case in a large spacecraft. The same applies for other subsystems. The net result is that the spacecraft bus is a larger percentage of the spacecraft than it would be on a more traditional mission. Consequently, the mass remaining for the payload is smaller. Reducing the spacecraft bus cost has forced us to reduce even more the spacecraft resources available to the payload and, consequently, the overall mission performance.

Control and Accountability are Sacrificed

The government is often interested not so much in low cost as in cost accountability. What the government wants is frequently ironclad contracts with cost guarantees and performance penalties. However, this is not the type of contract that genuinely produces low-cost systems. Low-cost is more likely to be achieved by giving organizations and individuals a significant level of freedom, challenging them to minimize cost, and being willing to accept or work with the results. Thus, a key question for any program interested in reducing cost is, do you truly want to achieve low cost or are you more interested in having control, accountability, and someone to hang if there is an overrun?

Cost Effectiveness is Sacrificed-in the Short Run

In the short run, it is likely that the most cost effective way to do university research would be to give all of the research dollars available to MIT, Cal Tech, and Stanford. These are strong organizations with creative individuals that will use the research dollars to produce results. Nonetheless, while this can work in the short run, it is unlikely that it will provide the best results for the nation in the long run. It is the competition among ideas, and the ability of the innovator, small entrepreneur, or individual researcher to challenge the existing paradigm that produces breakthroughs and dramatic results. These breakthroughs and new ways of thinking are critical to success. Nonetheless, they rarely occur in the most mainstream programs or most widely accepted approaches to working problems.

How Can the Government Avoid Damaging the Process?

Making dramatic reductions in space mission cost is essentially a creative or inventive process. “Labor-saving gadgets” are the cliché for what people invent in their garage. As can be seen from the case studies, creative spacecraft engineers ask themselves “how can I get this done with limited resources and not much time?” As with almost all inventions, the solution may, or may not, work as intended every time. Nonetheless, the record of the SmallSat community is extremely good, which indicates that in most cases this creative process is alive and well, and functioning nicely.

Unfortunately, most of the elements which nurture the inventive and creative process are hard to find in large organizations and government. It is extremely difficult to manage creativity or to write a task order to invent a new way of doing something in sixty man hours and by the end of next week. The bottom line is that policy and regulation can do an enormous amount to screw up the process and prevent it from moving forward, but can do relatively little to advance it.

An excellent example of this dichotomy comes from recent Microcosm experience in the area of space launch, a major cost element for small, low-cost satellites. We believe we have an excellent approach to dramatically reducing small satellite launch cost. (Whether our approach is actually a good one and will work in the long run is immaterial to the policy issues involved. We certainly believe it is a strong approach.) In early 1996, NASA administrator Dan Goldin expressed frustration with the launch community and announced the need for near-term development of what he termed a Bantam Lift Vehicle, capable of putting 200 lbs into LEO for less than $1 million. Microcosm believes that we can do this. For a non-recurring development cost on the order of $6 million (depending, of course, on specific requirements and contractual issues), we believe we can develop such a vehicle in approximately 24 months.

Unfortunately, in a broad sense, no one is interested. NASA is willing to invest several tens of millions of dollars in technology so that industry can get there, but by policy NASA is not permitted to develop a vehicle, unless it is reusable. Expendable vehicles are the province of DoD. Unfortunately, DoD does not have a requirement for light lift, but only medium lift and heavy lift. DoD believes their needs will be met by the Evolved

Expendable Launch Vehicle (EELV). They have no interest in looking at light lift.

In addition, there is also an unwritten policy that industry should do near-term vehicle development on its own and that government should be spending its resources looking at long-term solutions and developing technology. The net result of this space policy is remarkably frustrating. Microcosm wastes scarce marketing resources; groups that want to launch small spacecraft are frustrated by dramatically high costs; and the government is spending millions of dollars trying to invent technology to do something which we believe can already be done. Irrespective of the technical merits or demerits, the policy is a mess.

Unfortunately, we believe this example is not an isolated incident, but is indicative of a broad problem with space policy approaches. Many of the most common approaches used by the government have the potential of being counterproductive in that they are more likely to drive costs up rather than reduce them. Table 7 is a summary of these potentially counter-productive approaches and the basic reasons for the problem.

What is required, in our view, is for the government to create an environment that allows cost reduction to occur and to be rewarded, and then allow that environment to work. There is ample evidence that individuals and organizations be creative in reducing space mission cost, and can find ways to do business differently, if they are given a reasonable opportunity to do so. Table 8 summarizes actions which the government can take to create an environment that reduces cost. On the whole, these are not easy steps for the government, in large part because there are many things which are ultimately more important than reducing cost. For example, the government needs to preserve a very strong image of fairness in its contracting process. In many respects, organizational accountability is much more important than low-cost or achieving results. Avoiding the appearance of duplication and wastefulness is more important than fostering a diversity of opinion in looking for creative solutions to problems.

We believe that the policy problems associated with reducing space mission costs are very real. In the end, the public perception of what the government is doing is equally or more important than obtaining specific results. Within the government process, rewards go to very conservative approaches which minimize risk rather than to approaches which may produce spectacular results or spectacular failures.

Summary: Implement a Proactive Program

Reducing cost is hard work. It takes a skilled and competent team which is knowledgeable in the engineering of the systems involved; it requires inventing things; it requires management judgment; and some level of faith in the people who are actually doing the work. It is hard, if not impossible, to fully manage or orchestrate the process of reducing cost.

The strongest approach to reducing cost is rather like the Nike television commercial, “Just do it!” To reduce cost, an organization should create a proactive program that consciously looks at specific ways to reduce cost. It should be set aside from the main program in order to avoid hindering rather than helping. At the same time it must have the support and attention of the program manager and lead system engineer. They must buy into the process, or it cannot succeed because the approaches will never be implemented.

At the government level, the previous section lists items to avoid and suggestions for positive approaches. Basically, the key elements for government are to foster research aimed specifically at cost; to spend some portion of program resources on looking at ways to reduce cost; and to devote approximately 20% of new initiative dollars on alternative approaches and technologies that might not be successful, but offer potential cost breakthroughs.

Lastly, and perhaps most important, we strongly recommend that all of us try and learn from others, and how they have done it. Reducing space mission cost is not a new activity or something that has never been done. There are many organizations in the United States, Europe, and elsewhere that have been doing this for years. One piece of advice provided at every SMAD tutorial over the last five years still holds: if you are interested in low-cost solutions, attend the AIAA/Utah State University SmallSat Conference. Listen, read the papers, and talk to people in the corridors. It remains the best advice.

References

1. J. R. Wertz and W. J. Larson, ed., *Reducing Space Mission Cost* Microcosm Press and Kluwer Academic Publishers, 1996.
2. J. R. Wertz and W. J. Larson, ed., *Space Mission Analysis and Design*, 2nd edition, Microcosm Press and Kluwer Academic Publishers, 1992.
3. J. R. Wertz and S. Dawson, *Microcosm Directory of Space Technology Data Sources,* Microcosm Press, 1996.

TABLE 2. Cost Summary for Reducing Space Mission Cost Case Study Missions. Because of strong differences in performance, requirements, and infrastructure, costs are not comparable between missions. However, the overall table allows an estimate of what can be achieved in terms of reducing mission cost. SSCM refers to the Small Satellite Cost Model which is intended to provide a more realistic estimate of the cost of small satellites [1] Note: For cost/kg in last 2 rows, $1/g = $1K/kg.

Mission Data							Est. Bus Cost		Actual Cost (FY95$M)					
Name	*Prime contractor*	*Funding Organ.*	*Mission*	*Mass (kg)*	*Launch Date*	*Page Ref.*	*SMAD*	*SSCM*	*Spc. Bus*	*Payload*	*Launch*	*Grnd Seg.*	*Ops.*	*Total*
Ørsted	CRI	Denmark	Mag. field	60	(1997)	353	$28M	$3.8M	$8.8M	$5.7M [1]	$2.0M	$1.1M	$0.8M	$18.4M [1]
Freja	Swedish Space C.	Sweden	Magneto sphere	214	1992	375	$44M	$12.8M	$12.5M	$6.0M	$4.8M	$0.8M	$0.4M	$24.5M
SAMPEX	GSFC	NASA	Science	161	1992	397	$39M	$9.4M	$31.9M	$11.7M	$15.6M	$7.5M	$6.0M	$72.6M [2]
HETE	MIT/Aero-Astro	NASA	Gamma rays	125	(1996)	411	$34M	$7.0M	$5.6M	$15.8M [3]	$7.0M	$1.7M	in P/L	$30.1M
Clementine	NRL	BMDO	Test/ explor	232	1994	427	$59M	$22.7M [4]	$52.0M	$4.8M	$21.3M	$1.5M	$5.3M	$85.0M
Pluto Express	JPL	NASA	Explo-ration	103	(2003)	449	$1140M	$12.1M [4]	$226M	$9M	$43M	in spc.	$6M	$284M [5]
RADCAL	DSI	USAF	Radar Cal.	92	1993	475	$36M	$7.8M	$4.4M	in spc	$12.2M	in spc.	n/a	$16.6M [6]
Orbcomm	Orbcomm	OSC	Comm.	33	1995	487	$25M	$2.7M	$10.7M	in spc	$3.0M	$0.7 [7] M	$1.3M	$15.7M
AO-13	NA	AMSAT	Am. radio	84	1988	507	$34M	$7.0M	$0.96M	in spc	$0.28M	N/A	N/A	$1.24M [8]
AO-16	NA	AMSAT	Am. radio	9	1990	507	$20M	$1.1M	$0.18M	in spc	$0.03M	N/A	N/A	$0.20M [8]
PoSAT-1	SSTL	Portugal	Test/ Obser	49	1993	551	$26M	$3.2M	$1.15M	$0.38M	$0.27M	$0.20M	$0.10M	$2.10M
Average cost/g for LEO Missions, excluding AMSAT ($1/g = $1K/kg)							$496/g	$84/g	$148/g	$168/g	$58/g			$259/g
Average cost/g for Pluto Express and Clementine							$4400/g	$95/g	$958/g	$954/g	$129/g			$1187/g

1. The Ørsted payload cost includes $3.2M of pre-launch and post-launch science support that would not be a part of traditional mission budgets. 2. SAMPEX was initiated under more traditional costing rules and practices and changed to a "low cost" mission late in the procurement process. 3. HETE payload cost includes estimate of foreign contributions, initial ops and maintenance cost, substantial technical software integration costs that are usually included in the spacecraft bus cost. 4. The SSCM cost estimate is not applicable to interplanetary spacecraft. Values listed are intended only for comparison. 5. Costs given are for the Pluto Express, FY'95 configuration. (See case study for discussion) To facilitate system trades, the program intentionally avoided traditional categories and broke the cost into mission development (spacecraft + grnd seg), launch system, and mission operations and data analysis. Here mission development is in "spc bus" and the payload has been separately costed. 6. For RADCAL, the $4.4M spacecraft included the payload and 2 ground stations. The military provided operations at an unknown cost. Total cost is $16.6M + Operations and Maintenance. 7. For ORBCOMM, ground segment cost is for spacecraft control center only. Network Control Center and Gateway Earth Station costs are excluded. 8. Most of the AMSAT labor provided at no cost. Paid labor would raise cost by approximately a factor of 10.

Table 3 Ratios of Actual Cost to Projected Cost for Reducing Space Mission Cost Case Study Missions. Because of strong differences in performance, requirements, and infrastructure, costs are not comparable between missions. However, the overall table allows an estimate of what can be achieved in terms of reducing mission cost. Projected costs are based on the cost model for traditional programs given by Wong in Chap. 20 of *SMAD [2].* When payload is included in spacecraft bus cost, then space segment cost (= bus + payload) provides a better representation of the cost ratio.

	Bus	Payload	Space Seg.	Launch	Grnd Seg	Ops + Main	Total Prog
AMSAT							
AO-13	2.8%	in spcraft	1.8%	0.4%	N/A	N/A	1.0%
AO-16	0.9%	in spcraft	0.5%	0.2%	N/A	N/A	0.3%
Average	1.8%	inspcraft	1.1%	0.3%	N/A	N/A	0.7%
Other LEO							
Ørsted	31.8%	27.1%	29.8%	12.1%	4.2%	33.9%	19.6%
Freja	28.2%	18.5%	24.1%	7.2%	0.7%	4.1%	9.0%
SAMPEX	82.2%	41.1%	64.7%	93.9%	14.2%	109.2%	51.1%
HETE	16.3%	59.4%	35.1%	42.2%	1.4%	in payload	14.4%
RADCAL	12.3%	in spcraft	8.2%	73.3%	in spcraft	N/A	14.7%
ORBCOMM	42.7%	in spcraft	24.9%	18.1%	0.2%	6.1%	4.2%
PoSAT-1	4.4%	1.9%	3.3%	1.6%	0.7%	4.2%	2.2%
Average	31.1%	28.9%	26.9%	35.5%	3.6%	31.5%	16.5%
Interplanetary							
Clementine	88.5%	24.0%	72.2%	32.1%	1.9%	54.1%	36.3%
Pluto Express	19.8%	18.0%	19.7%	7.6%	in spcraft	14.0%	15.8%
Average	54.2%	21.0%	46.0%	19.9%	1.9%	34.0%	26.1%
Avg - All exc. AO	36.3%	27.1%	31.3%	32.0%	3.3%	32.2%	18.6%
Avg - All Missions	30.0%	27.1%	25.8%	26.2%	3.3%	32.2%	15.3%

Table 4. **Summary of Cost Reduction Methods.** How the rules are applied is the key to reducing cost. (Adapted from RSMC [1].)

Method	Mechanism	Comments
Programmatic		
Schedule Compression	Reduces overhead of standing army; forcing program to move rapidly does drive down cost	Often results in a poor design due to lack of up-front mission engineering; must reduce work required to be consistent with schedule
Reduce Cost of Failure	Allows both ambitious goals and calculated risk in order to make major progress	Fear of failure feeds cost-growth spiral; major breakthroughs require accepting the possibility of failure–particularly in test
Continuous, Stable Funding	Maintains program continuity; maintains team together	Program delay will be funding break + 2-4 months
Minimize Documentation	Reduces programmatic overhead for creating, reviewing, & maintaining	Critical to document reasons for key decisions and as-built design
Personnel		
Improved interpersonal communications	Dramatically reduces errors and omissions; conveys understanding as well as data	Large programs use formal, structured communications through specified channels
Small Team	Clear, nearly instantaneous communications; high morale; strong sense of personal responsibility	Problem if a key person drops out -- but in practice it rarely happens.
Co-located Team	Improves communications	Best communications are face-to-face, but AMSAT and others don't seem to need it
Empowered Project Team	Rapid decision making; strong sense of personal responsibility; can make "sensible" decisions	Eliminates a major function of the management structure
Systems Engineering		
Trading on Requirements	Eliminates non-critical requirements; permits use of low-cost technology	Makes traditional competition difficult
Concurrent Engineering	Allows schedule compression; reduces mistakes; increases feedback between engineering and manufacturing	High non-recurring cost relative to lowest cost programs; can achieve optimal design
Design-to-Cost	Adjusts requirements and approach until cost goal has been achieved; makes cost paramount	Spacecraft have rarely used it
Large Margins	Reduces testing; better flexibility; reduces cost of engineering, manufacturing, and operations	Margins traditionally kept small for best performance–drives up development cost
Technology		
Use COTS Software	Immediate availability; dramatically lower cost; tested through use	May need modification and thorough testing; typically not optimal for application
Use COTS Hardware	Same as software	Same as software
Use Existing Spares	Reduced cost; rapid availability; meant for space	Can only do this so long as spares exist -- not applicable for operational programs
Use of non-space equipment	Takes advantage of existing designs and potential for mass production	Typically not optimal; must be space qualified
Autonomous systems	Reduces operations costs	Can increase non-recurring cost
Standardized components and interfaces	Reduces cost and risk by reusing hardware; standardization is a major requirement for other types of manufacturing	Has been remarkably unsuccessful in space; sub-optimal in terms of weight and power
Extensive Use of Microprocessors	Minimizes weight; provides high capability in a small package; allows on-orbit reprogramming	Problem of single-event upsets; high cost of flight software; very difficult to manage and control software development
Common S/W for Test and Operations	Reduces both cost and schedule; avoids reinventing the wheel	May be less efficient, user-friendly than ops group would prefer

Table 5. Methods of Cost Reduction Applied by RSMC Case Study Missions. ✻ indicates methods regarded as being of particular importance for that mission. Data for the BremSat case study [3] has been added to that from RSMC. Other methods regarded as important by the authors include focused, limited objectives; strong, up-front systems engineering; use of experienced, skilled personnel; provide a strong technical challenge; and tight management control.

Method	Ør	Fj	Sx	He	Cl	PE	Ra	Or	Am	Po	Br
Programmatic											
Schedule Compression			•	•	✻	•	✻	•	•		
Reduce Cost of Failure			•	✻	•	•		•	•	•	•
Continuous, Stable Funding	•	•	•		•		•			•	
Minimize Documentation	•	•	•	•	•	•			•		
Personnel											
Improved interpersonal communications	•	•	•	•		•			✻	•	•
Small Team	•	•	✻	✻	✻	✻	•	•	•	•	•
Co-located Team			•		•	•	•			•	•
Empowered Project Team	•	✻		✻	✻	•		✻	•	•	✻
Systems Engineering											
Trading on Requirements				•	•	•	•		•	✻	•
Concurrent Engineering		•	✻			•	•		•		•
Design-to-Cost	•		•	•		•	✻		•	✻	•
Large Margins	•	•									•
Technology											
Use COTS Software	•	•						•	•	•	
Use COTS Hardware		•			•		•		•	•	•
Use Existing Spares						•			✻		
Use of non-space equipment									✻		•
Autonomous systems			•			•		•		•	•
Standardized components and interfaces		•	✻				•			•	•
Extensive Use of Microprocessors		•		✻	•	•		•		✻	•
Common S/W for Test and Operations	•							•			✻

Table 6. Construction and Design Philosophy for Case Study Missions. As in Table 5, the BremSat case study mission [3] has been added. Most authors stressed the importance of extensive testing as critical to a successful low-cost satellite program.

Design Approach	Ør	Fj	Sx	He	Cl	PE	Ra	Or	Am	Po	Br
1 = Build vs. 5 = Buy	3	3	1	1	2	1	1	3	1	1	2
1 = Best parts vs. 5 = Low cost parts	1	3	3	3	1	1	1	4	5	4	2
1 = Sys. level testing vs. 5 = all levels	5	5	5	3	5	5	5	1	3	2	4
1 = QA In-house vs. 5 = contractor	4	2	3	3	3	1	1	3	3	3	4
1 = High tech vs. 5 = low tech	3	3	1	1	1	1	3	3	5	3	3
1 = New each time vs. 5 = evolutionary	na	4	na	1	1	1	2	2	5	5	2
Design for multiple launch vehicles	Yes	No	No	No	No	No	Yes	No	Yes	Yes	No

TABLE 7 Potentially Counterproductive System Acquisition Approaches to Reducing Space Mission Cost. Each is intended to reduce cost, but has a high probability of increasing cost instead. (from RSMC [1].)

Approach	Potential Benefit	Disadvantages
1. Consolidated, centralized acquisition and engineering	Provides greater accountability; gives appearance of reducing waste	Likely to force out small organizations and innovative approaches; likely to lock in high-cost approaches
2. Contractor cost sharing of development costs	Reduces cost to the government if major customers are in the private sector (e.g., computer development)	Forces out the small player; investment economics drive acquisition—will require very large ROI, because the government is a high-risk customer
3. Contractor cost sharing in up-front studies	Reduces study cost	Forces out the small, innovative contractor; contractor costs will be recovered in higher indirect rates
4. Cost guarantee on R&D programs	Limits government cost commitment; good for achieving accountability but not for reducing cost	Forces out the small contractor and doesn't permit taking risks that could dramatically reduce cost
5. Doing work in-house	Eliminates subcontracting cost; can be effective if the group has experience with low-cost, efficient production	May drive up costs due to lack of efficiency and knowledge; may be largely an excuse to maintain a large infrastructure
6. Reducing the level of up-front systems engineering	Shortens program schedule and avoids over-engineering a strawman design	Ignorance is rarely of value in reducing cost or improving performance

TABLE 8. Actions the Government Can Take to Create an Environment That Reduces Cost. Direct government policies and actions are far more likely to increase cost rather than reduce cost. However, creating an environment in which inventive organizations and individuals can work effectively can foster cost reduction. (from RSMC [1]).

Action or Approach	Comment
1. Force trading on requirements	Make this a formal process by or with the performing organization or contractor
2. Require strong mission engineering	All programs should have strong, formal system trades, ongoing utility analysis, and up-front mission engineering
3. Provide continuous funding	Force decision making on subsequent phases in parallel with current phase
4. Reward low cost	Find mechanisms to reward (and not punish) all individuals and organizations which contribute to reducing cost
5. Reduce the cost of failure	Recognize the need to allow reasonable risk and failure rates in test and R&D activities
6. Make cost data available	Getting the lowest-cost solution is essentially impossible unless the engineers designing the system know what the costs are
7. Decentralize space system procurement	Innovation comes from small businesses and "secondary" organizations within the government. Work with them.
8. Sponsor R&D to reduce cost	Make reducing cost an alternative and acceptable objective for R&D, without demanding that it simultaneously "advance technology"
9. Sponsor knowledge preservation and dissemination	Space technology has dramatically fewer books, commercial software, or university programs than any other major discipline. Knowledge is disappearing very rapidly.
10. Revise the SBIR rules	Small companies are a major source of innovative approaches to cost reduction, but current rules discourage them