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Abstract

The methods, processes, and technologies currently in use for major space programs are based on 50 years of lessons learned in the exploration of space. They draw on a large number of both successes and failures in space and represent our collective wisdom on how to do these programs efficiently and with a high probability of success. Nonetheless, it is clear that, collectively, they have also gotten us to a space program that we cannot afford, that is fragile and vulnerable to both enemy attack and uncontrollable failures (such as collisions with debris or other spacecraft), and that is not as responsive to meeting the needs of the end user as we would like it to be or as responsive as other nations have been for decades.

Fortunately, both technology and our understanding of space mission engineering is advancing rapidly. There are many past, current, and potential future programs that are demonstrating that dramatic cost and schedule reduction are possible while still maintaining good performance and high reliability. The lessons learned from these systems can reduce cost, risk, fragility, system vulnerability to attack or random failures, and, perhaps most important, create a robust and healthy space program that provides high utility, exciting challenges for engineers and scientists, and customers and users delighted with the end results.

Microcosm has been both studying and applying approaches developed throughout the world for over 15 years. This paper presents a summary of some of the most useful of roughly 100 methods, processes, technologies, and programs for achieving dramatic reductions in space mission cost. For convenience of discussion, we break these down into 9 broad categories -- Attitude, Personnel, Programmatic, Government/Customer, Systems Engineering, Mission, Launch, Spacecraft Technology, and Operations.

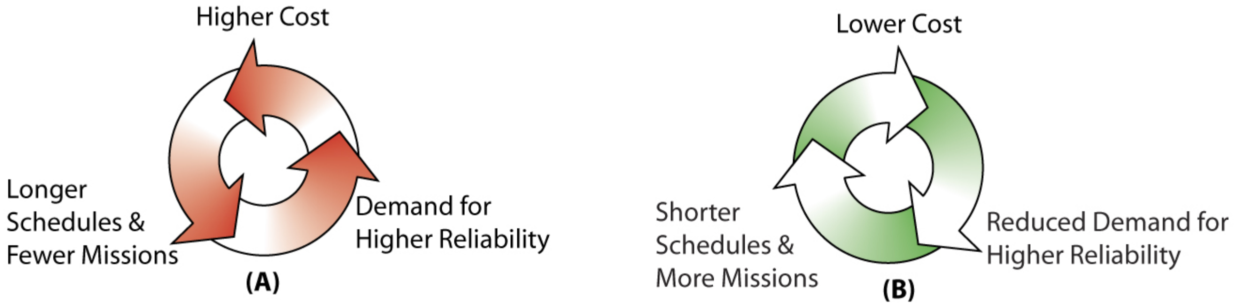
For a great many missions, we should be able to reduce cost by a factor of 5 to 10, while maintaining high reliability and reducing fragility and vulnerability. If, instead, we continue with business as usual, we simply don't have enough money to do the things that we need to do and want to do in space.

KEYWORDS: [Space system cost reduction]

1. **BACKGROUND**

As shown in Fig. 1, our goal is to find ways to reverse the Space Spiral of ever increasing cost, fewer missions, longer schedules, and demand for higher reliability. Essentially any process that breaks that cycle and begins to reverse it—i.e., that lowers cost, shortens schedules, increases the number of missions, or reduces the demand for higher reliability—will help the process. However, it's clear that breaking through the barriers of inertia and culture requires that we take moderately large steps

Figure 1. Our objective is to find ways to reverse the Space Spiral in (A). As shown in (B) any actions that reduce cost, shorten schedules, increase the number of missions, or reduce the demand for higher reliability will do this.



that make a significant and visible change. Also, as discussed in detail by Hurley and Purdy [2010] the "reliability" of Fig. 1 is largely parts reliability and numerical reliability computations. Actual ***mission reliability***, i.e., whether the end user will have the data they need it when they need it, is increased by lower cost, shorter schedules, and more missions because the system becomes much less sensitive to individual failures, delays, or program cancellations.

The sections below discuss some of the major steps that can be taken to drive down cost and schedule. However, two broad caveats apply to most of these items. First, because reducing cost and schedule is hard, it is unlikely that any single step will have a large enough effect to make a major change. While even small steps help, really turning the Space Spiral around and beginning to make large reductions in cost and schedule will require a concerted effort and combing multiple elements to have an effect large enough to be truly helpful to a program or to the space community more broadly. Second, it is clear that almost any step can have either positive or negative effects (and possibly both) depending on how it is implemented. For example, it is hard to overemphasize the value of strong up-front mission engineering. This is a critical part of reducing both cost and schedule. Nonetheless, a blanket rule that requires a 2-year up-front mission engineering phase before anything can be implemented would be counter-productive by preventing new technologies from coming on board quickly, generally slowing down small, quick turn-around programs, and likely increasing their cost. Each of the recommendations must be implemented with some sense of balance to achieve the desired results.

2. SPECIFIC APPROCHES TO DRAMATIC COST REDUCTION

2.1 Attitude

Large organizations would prefer to depend on processes and rules to reduce cost, but, as in most human activities, attitude and having the right people are critical to being successful. Table 1 summarizes the truly critical "attitude adjustments" that are needed to significantly reduce space mission cost and schedule. (People issues are discussed in Sec. 2.2.)

The largest single impediment to dramatically reducing cost and schedule is an attitude throughout the community most often expressed as "faster, better, cheaper—pick any two." [Wertz, 2011a, Sec. 13.2] This expresses the idea that we've done as well as we can do. In order to do better in one or two areas, we must do worse elsewhere, even though in virtually every other area of technology forward progress is real and moves at a much more rapid pace than in astronautics. The fact that technology advances and we have learned how to do things better over time should not be taken as a criticism of prior programs or prior management. Even though the space processes and technology that we have today have been created by some of the most capable and hard working engineers and managers in the world, this does not mean that we can't do better as time goes on.

Perhaps equally challenging is the idea that, so long as it works in the end, cost and schedule don't really matter. This is addressed quite well with the discussion of managing to a "reliability of zero" by Hurley [2010]. It doesn't matter that it was a

Table 1. Summary of Attitude-Related Approaches to Reducing Mission Cost and Schedule. The right attitude and personnel (Sec. 2.2) are truly critical for any of the other approaches to succeed. In this and the subsequent tables, what will typically be the most important or productive approaches are shaded. In this table, all of them are important.

Reducing Space Mission Cost—Attitude		© 2010, Microcosm, Inc.
Technique or Action	**Mechanism**	**Comment**
A1. Recognize that it's Possible and Achievable	Eliminates major impediment of being unwilling to attempt to reduce cost	Biggest single impediment to reducing cost is the view expressed by "Faster, Better, Cheaper—Pick any Two." There are a great many successful, reliable, responsive, highly capable, low-cost space missions.
A2. Recognize that Low Cost is NOT Low Reliability	Eliminates major argument of wanting only "high reliability"	a) Low cost spacecraft are equally or more reliable than high cost spacecraft. b) Lower cost can dramatically improve reliability for the end user by: allowing multiple spacecraft on orbit, shortening the schedule, and reducing the probability the program will be cancelled.
A3. Recognize that Low Cost is Important	Assigns importance to low-cost and keeps it from being the last thing on the list of goals	Reducing cost has to be a high priority such that we are willing to give up something to achieve it. "We may want to explore Mars at a resolution of 10 m. But exploring Mars at a resolution of 20 m may be better than not exploring Mars at all."
A4. Recognize that Change is Critical to Reducing Cost	Reduces the opposition to "new ways of doing business"	We cannot buy or build the same spacecraft as last time with the same rules and processes and expect it to cost less.
A5. Recognize that Reducing Cost is Hard Work and Takes Real Engineering	Allows the allocation of resources and effort that are needed to achieve cost objectives	Like anything else of value, reducing cost is hard work and takes dedication, real engineering, and time, money, and attention devoted to it. There's a price to achieving low cost.
A6. Recognize that the Need to Change is Not a Criticism of Prior Programs or Practices	Reduces resistance to cost reduction programs	The Space Shuttle was a remarkable engineering achievement built by some of the best engineers in the world, but it didn't satisfy its end objective of greatly reducing launch cost. We have processes and rules in place for very good reasons, but collectively they have created a space program that we cannot afford.
A7. Recognize that Virtually Any Technique Can Either Increase or Decrease Cost	Forces thinking about and evaluating changes within the context of individual programs—critical for successfully reducing cost	Cost reduction approaches must be implemented wisely with common sense. Virtually any of the techniques below can drive cost up if not implemented appropriately but this should not be used as an excuse for not doing them.

remarkably capable system when it was finally launched (or would have been a great system when it was cancelled) to the soldier that was killed because the system wasn't there.

In order to reduce cost and schedule, these have to be important to the system engineers, the program management, and the procuring organization. Finally, if you believe that something can't be done, or shouldn't be done, or isn't worth giving up something else to achieve, then it is likely that you won't be able to achieve it. Reducing cost and schedule is hard work and takes real effort and real engineering. **Reducing cost has a price.**

2.2 Personnel

Table 2 summarizes the second major pillar of reinventing space—personnel. Both the government and large organizations would much prefer to depend on rules, regulations, and processes, but the reality is that wars are won, inventions made, new businesses created, and creative ways to change how we do business in space are developed by motivated individuals who are out to get the job done. This

Table 2. Summary of Personnel-Related Approaches to Reducing Mission Cost and Schedule. Ultimately, it is people, not rules that reduce cost and schedule. (For a more extended discussion, see Wertz and Larson [1996].)

Reducing Space Mission Cost—Personnel		**© 2010, Microcosm, Inc.**
Technique or Action	**Mechanism**	**Comment**
PI1. Improved Interpersonal Communications	Dramatically reduces errors and omissions. Conveys understanding as well as data.	Large programs use formal, structured communications through specified channels. Small programs use personal communications by creating close working relationships and personal responsibility.
PI2. Small Team	Clear, nearly instantaneous communications; strong sense of personal responsibility	Can be a problem if a key person drops out, but in practice this rarely happens.
PI3. Co-Located Team	Improves communications; reduces sense of “we vs. them”	Best communications are face-to-face, but AMSAT and some others don’t seem to need it.
PI4. Empowered Project Team	Rapid decision-making; strong sense of personal responsibility; can make “sensible” decisions	Eliminates a major function of the large, formal management structure. Encourages personal “ownership” of problems and issues, often expressed as “I own that problem.”
PI5. Reward Low Cost (both people and organizations)	Provides positive incentive to both people and organizations	Traditionally if organizations spend less, they are rewarded by a reduced budget next year. Instead they should get a larger budget next year or have half the savings put into an end-of-year bonus or party fund. (Rewards don’t need to be monetary.)

means that individuals and small teams must be empowered to get things done and must be motivated to do them. Personnel and groups must be rewarded for major reductions in cost and schedule. For example, the reward for not spending all of your department’s computer budget by the end of the year is typically having a smaller computer budget next year. Amazingly, in most departments, the computer budget is always spent by the end of the year. A much better approach would be to split the savings between the organization, to reduce the overall budget, and the department end-of-year party fund.

Rewards don’t need to be money. Give whoever came up with the idea for significantly reducing cost or schedule the parking space next to the door and let the department manager park in the back lot. (Actually, it would probably be best to give the department manager a bit of a reward as well. In the end, you want both the individuals and their managers to be pleased with the result.) Many small satellite builders take great pride in building high quality, low-cost satellites in a very short time. It is something they have learned how to do that much bigger, better-funded organizations do not know how to do. Recognizing this excellence can be a reward in itself. **The real secret to reducing space mission cost is to empower individuals and small teams, motivate them to reduce cost, reward them for achieving it, and then get out of their way.**

2.3 Programmatic

Table 3 show the primary programmatic approaches for driving down space mission cost. Traditionally, operational systems are very large with limited potential for changes to reduce cost or schedule, but these systems are both expensive and “fragile.” As discussed by Wertz [2010, 2011a], smallsats can help overcome this problem in multiple ways in the near term and a mix of small satellites and traditional satellites can provide a robust capability with better performance, more flexibility, and greater mission assurance, at much lower cost.

Table 3. Summary of Programmatic Approaches to Reducing Mission Cost and Schedule. There are a large number of programmatic approaches that can help the problem. (See also Wertz and Larson [1996].)

Reducing Space Mission Cost—Programmatic **©2010, Microcosm, Inc.**

Technique or Action	Mechanism	Comment
Pg1. Operational SmallSats	Allows low-cost operational satellites	Smaller, much lower cost spacecraft are becoming more competent and can do far more in the future. Can dramatically reduce mission risk by allowing satellite replacement and multiple satellites on orbit.
Pg2. Low Cost, Rapid Test Missions	Greater potential for breakthroughs and more rapid technology insertion	Allows genuine tests (i.e., possibility of failure), instead of just on-orbit demonstrations. Creates potential for major, near-term breakthroughs.
Pg3. Use Small Business Effectively	Small businesses are a major source of cost reduction technology and processes	Typically small businesses are not used for creative processes, both because of the contracting difficulties and the perception that small businesses don't understand the "real world" of space missions.
Pg4. Buy Multiple Spacecraft	Uses both learning curve and continuity of production line	Much like buys of aircraft or ground vehicles.
Pg5. Provide Continuous, Stable Funding (i.e., avoid programs stops and starts)	Does not reduce cost, but avoids cost and schedule overruns	Stopping and restarting a program dramatically drives up cost and increases schedule well beyond the length of the schedule break. Typically not recognized by the program office. 3 key steps: a) Make major decisions away from funding boundaries b) If possible, provide multi-year funding c) Key programs funded while decisions are being made
Pg6. Make Cost Data Known	Drives more competitive cost proposals	It is very hard to reduce cost when cost data is known, and virtually impossible when it's not.
Pg7. Reduce the 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 or in early mission trials. Example: development of Soviet launch vehicles.
Pg8. Build to Inventory	Reduces mission risk and permits higher system risk	Can dramatically reduce mission risk by allowing satellite replacement. Less of a target for enemy attack. Mission becomes less susceptible to system failures or orbital debris.
Pg9. Minimize Formal Documentation	Reduces programmatic overhead for creating, reviewing, and maintaining documents	Critical to document reasons for key decisions and as-built design. Minimizing documentation also allows documents to be given importance and maintained. AMSAT uses redlined schematics to document as-built design.
Pg10. Compress the Schedule	Less overhead costs and less time to spend money	Must be done with care—requires (a) reducing the amount of work required and (b) providing expedited decision making.

Another key programmatic approach is reducing the cost of failure. If we build a test engine that is so expensive, it can't be allowed to fail, we will never really learn what the failure mechanisms are. A major advantage of smallsats is that failures in test or early in the program are less of a problem than with traditional large satellites. The very reliable Soviet launch systems had multiple failures in early launches. These failures were used to improve the design and essentially eliminate nearly all failure modes. The demerit of this approach is that, unfortunately, failures early in a program tend to jeopardize funding for later phases or later missions. This is an example of the culture that we have all created preventing us from doing things that we all understand are important to reducing cost.

Making cost data known is also key to reducing long term cost.* Often it is the government that most

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* Note that here we use cost and price interchangeably. Making the profit (= price − cost) known may be counterproductive by keeping some suppliers out of the market and focusing attention on a relatively small budget element that has little potential for adjustment and won't

strongly resists this step. For example, although we had the strong support of senior Aerospace Corp. personnel, we were not allowed to publish the current version of their Small Satellite Cost Model, SSCM, in the new *Space Mission Engineering* volume.

Buying multiple spacecraft simultaneously and launching from inventory is one of the major mechanisms to drive down cost, schedule, **and** mission risk. Here it is important that we understand the meaning of "schedule" in terms of the end user. When buying a car, we don't really care how long it takes to build that car. We only care about how long it takes to get one after we have made the decision to purchase it. While buying from inventory is certainly not the same as building something quickly, this distinction is somewhat lost on the end user that simply needs to get their mission data as soon as they can. Similarly, if we want our new car to have a new class of radio that just became available, we aren't concerned whether that radio was built into the car at the original assembly line, or was added by the dealer at some later stage in the process. What the end user wants is rapid functionality.

Buying multiple spacecraft, or at least one off of an assembly line allows us to take advantage of the learning curve to reduce cost per unit, often by a great deal. This involves not only learning, but tooling, spares, and production equipment. It also allows us to maintain a more-or-less steady manufacturing flow in an environment where use rates can change greatly. Inventory is effectively a buffer to draw from when launches or systems fail, are attacked by an enemy, or simply are in greater demand.

When using an assembly line, we aren't forced into a mode where everything has to work perfectly the first time. In addition, it means that we have people available (engineers, technicians, and supply chain managers) that understand the system, how it's built, and what the major problem areas are. We can fix problems that arise in early production (i.e., the Soviet approach) and can insert new technology as it becomes available. The use of an assembly line is a standard approach for aircraft, ships, and ground vehicles of all kinds. A key issue in nearly all other areas of government procurement is that once a manufacturing line is closed down, it is very expensive to start it up again. In traditional space systems, we effectively restart the assembly line with nearly every procurement.

Finally, the lack of funding continuity is one of the most damaging elements for a program and a major source of cost overruns [Wertz, 2011a, Sec. 13.6]. In large part, this is a management problem and not a funding problem. Basically, it requires rapid decisions in conjunction with planning ahead. Apparently, from the perspective of the program manager, it's worse to try and explain why you spent money on the early phases of a program that was later canceled than to stop the program and then explain cost and schedule overruns that can be blamed on the contractor or other outside factors. There is no doubt that some vacillation will be unavoidable, but much of it can be controlled.

2.4 Government/Customer

Table 4 shows the government (or other large customer) approaches to reducing cost and schedule. Of course one of the principal actions the government can take is to foster and encourage the other approaches described throughout this section. By making cost and schedule reduction a priority, being willing to allow some new ways of doing business to accomplish it, and devoting time and resources to creating lower-cost, much more rapid systems, a great deal can be accomplished.

Perhaps one of the more counter-intuitive approaches that the government can use to reduce cost and schedule is to decentralize space system procurement (item G2). On a fairly regular basis, calls for government reform point out "waste and inefficiency" presumably created by having multiple organizations working on a problem. Thus, there are regular calls for a "launch czar" or a "spacecraft czar" to reduce inefficiency by consolidating all of one activity into a single person or organization. In fact, this is likely to drive up cost, increase schedule, and be counterproductive relative to what we would like to achieve. We all recognize the value of competition in industry. With competition, multiple approaches are tested and we pick the ones that are best for our particular circumstances. But this same idea works within the government. If one person is in charge of launch, we will quickly eliminate all secondary programs in the name of efficiency, concentrate all of the work in a few large contracts (probably with the major primes), and, of course, make reliability the most important feature since if we have fewer systems it is more important that they work every time.

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bring about the large cost changes that are needed. Basically, beating on companies to minimize profit is not a good long-term substitute for finding ways to actually getting things done more economically.

Table 4. Summary of Government or Customer Approaches to Reducing Mission Cost and Schedule. Many of these involve implementing approaches described elsewhere in this section. (Notes in parentheses in the rightmost box of the first row refer to methods from other tables, i.e., Pg5 refers to Programmatic method 5.)

Reducing Space Mission Cost—Government / Customer		© 2010, Microcosm, Inc.
Technique or Action	**Mechanism**	**Comment**
G1. Implement Actions Specifically to Reduce Cost	Demonstrates a real interest in reducing cost and willingness to take action to achieve it	Among those listed elsewhere that can be done directly by the government or major customer: a) Foster an attitude of wanting and rewarding cost reduction (A1 to A7) b) Force trading on requirements (SE1) c) Reward low cost (Pl5) d) Provide funding continuity (Pg5) e) Make cost data available (Pg6) f) Reduce the cost of failure (Pg7) g) Develop a low-cost small launch vehicle (L5) h) Create low-cost smallsat programs for both test and operations (Pg 1 and Pg2)
G2. Decentralize Space System Procurement	Allows innovation and options that would not be allowed under a centralized procurement approach	Innovation often comes from small businesses and "secondary" organizations within the government. These should be encouraged as a way of providing positive and valuable "competition of ideas" within the government.
G3. Sponsor R&D to Reduce Cost	Main mechanism for finding lower cost solutions	Need to make reducing cost an alternative and acceptable objective for R&D, without demanding that it simultaneously "advance technology."
G4. Sponsor Knowledge Preservation and Dissemination	Actually using lessons learned rarely occurs, but is important to reducing cost	Space technology has dramatically fewer books, commercial software, or university programs than any other comparable major discipline. Knowledge is being lost at a rapid rate.
G5. Revise SBIR Objectives	An excellent source of innovative ideas for reducing cost	Currently, less than 4% of SBIR topics are directed specifically toward reducing cost. Can provide both innovative solutions and simpler, faster contracting mechanism via Phase IIIs.
G6. Use SBIR Phase III	Sole-source contract	Sole-source contract mandated by law. Can shorten schedule by a year or more. Contracting process short and simple.
G7. Assign the Task of Reducing Cost to an Individual or Organization	Allows cost reduction to be a part of the official hierarchy of organizational objectives	Typically, reducing cost is not in anyone's "job jar," which means that it is a secondary priority in a system where not all first priority tasks get done.
G8. Create a Program Intended Specifically to Reduce Cost	Allows cost reduction to be a part of the official hierarchy of organizational objectives	Similar to item above, but allows contractor participation. Can create specific objectives with a near-term schedule that can impact both near-term and longer-term, larger missions.

This is a prescription for feeding the Space Spiral that we discussed at the beginning of the section. If, instead of a single launch czar, there are programs for small, responsive launch systems from the Army, Navy, Air Force, NASA, and MDA (and perhaps even separate ones from Marshall Space Flight Center and NASA Ames), then we have the roots of a competitive environment in which low cost and fast response become what it takes to make your program proceed. If we need a launch vehicle that can put 10,000 kg into LEO, we could start designing that from the outset or we could start with multiple agencies working on ideas for putting 500 kg into LEO, select the most promising 3 or 4 of those to work on 2,000 kg to LEO vehicles, and so on. This approach gets us multiple small launchers that provide competition to hold down cost and develops and tests in flight alternate technologies that can be used to drive down cost on larger vehicles. Rather like airplanes or ships or computers, it doesn't necessarily make sense to have one supplier working with one government agency to solve the diverse needs of the space community.

The government controls most of the R&D spending in space technology. Unfortunately, there is a strong bias within the R&D community toward challenging new technology and away from practical systems capable of being implemented and able to reduce cost or schedule or both. For example, the *Small Business Innovative Research* (SBIR) program would be an excellent vehicle for small companies, for which a major strength is finding innovative approaches to reducing cost or doing things more quickly. Microcosm undertook a survey of both DoD and NASA space-related SBIR topics in 1996 for the book *Reducing Space Mission Cost* [Wertz and Larson, 1996] and again in 2010 for this volume. The rather discouraging results are shown in Table 5. It is likely that much more rapid advances in reducing cost and schedule would be possible if the government chose to sponsor more R&D oriented toward reducing cost, without demanding that it advance technology at the same time.

Another SBIR approach is to make more extensive use of SBIR Phase IIIs (G6). By law, the SBIR Phase III meets all of the competition in contracting requirements, is strongly encouraged by Congress, and has been endorsed within DoD [Finley, 2008]. This means that ideas developed under the SBIR program can go directly to being funded and built via a sole-source contract without another round of studies and competition, which can save more than a year and a large amount of funding and time in the competition and contracting process. Unfortunately, this isn't a popular law within the government bureaucracy because it eliminates another round of competition and contracting, and, therefore, is often ignored.

Table 5. Survey of the Principal Objectives of space-related Small Business Innovative Research (SBIR) topics in 1996 and again in 2010. (Study done by Microcosm in 1996 for Wertz and Larson [1996] and again in 2010 for Wertz [2011a].)

Principal Objective	**1996**		**2010**	
	No. of Topics	**Percentage**	**No. of Topics**	**Percentage**
New Software	33	15%	38	22%
Improvements to existing software or technology	67	30%	20	12%
New Technology	113	51%	108	63%
Reduce Cost	**8**	**4%**	**6**	**3%**
Total	221	100%	172	100%

Perhaps the most important thing that the government can do to reduce cost is either assign the task of reducing cost to an individual or organization (G7) or create a program intended specifically to reduce cost and schedule and fund some small programs to do that (G8). In both cases this allows reducing cost and schedule to become a part of the official hierarchy of organizational objectives, to be reported on at meetings, to get some assigned budget, and to flow regular status reviews up the management chain. All of this makes it clear that this is something the organization genuinely wants to accomplish and will be judged on how well it is being achieved.

2.5 Systems Engineering

Systems engineering approaches to reducing cost and schedule are summarized in Table 6. Perhaps the most fundamental of these is trading on requirements (SE1), an approach that has proven exceptionally successful in low-cost programs. [Wertz and Larson, 1996]. (See Wertz [2011a, Sec. 13.5.5] for a discussion on how to do this.) The critical issue is to find areas where there is increased performance available at increased cost and then balance need vs. cost. In many respects, this is equivalent to the process of an individual buying a car. We don't write out a set of specifications and send them around to car dealers to find out who can give us this car at the best price. Instead, we look in our wallet and typically find that there is bit less budget available than we would prefer. We then go around to various dealers and find out what is available at what price, knowing that there will be a certain amount of negotiation later on. Ultimately, we try to find a reasonable compromise between what we want and what we can afford. Our goal in space is the same—we would like to make the government into an intelligent consumer that can balance cost, schedule, performance, and risk.

Table 6. Summary of Systems Engineering Approaches to Reducing Mission Cost and Schedule. These approaches have proven to be extremely successful on many past and current low-cost, high-reliability missions.

Reducing Space Mission Cost—Systems Engineering		**© 2010, Microcosm, Inc.**
Technique or Action	**Mechanism**	**Comment**
SE1. Trading on Requirements	Allows a balance between cost and benefit	Makes are traditional competition difficult. Allows the government to become an "intelligent consumer."
SE2. Concurrent Engineering	Allows schedule compression; increases feedback between groups	High non-recurring cost. Can achieve "local optimization," but reduces willingness to consider truly different approaches.
SE3. Design-to-Cost	Adjusts requirements and approach until cost goal has been achieved	Has rarely been used. but not often (Discovery, New Frontiers). Arbitrary cost goals are unlikely to be successful.
SE4. Large Margins	Reduces testing; better flexibility; reduces cost of engineering, manufacturing, and operations	Margins traditionally kept small to maximize performance. Requires balanced implementation—forcing large margins in all components may drive up cost.
SE5. Fly New Computer Plus Same Computer Flown on Last Mission	Allows use of newer technology with higher capability without the associated risk.	Allows use of newest computer technology—both lower cost and more capability with very low risk. Can be used for other hardware as well. Approach used by SSTL.
SE6. Avoid "Design for a Reliability of 0"	Places much greater emphasis on cost and schedule as critical	Recognize that from a user perspective, every day that the system is late, it has a reliability of 0. A program that is cancelled due to cost or schedule overruns has a reliability of 0 to the end user.
SE7. Devalue Optimization	Allows multiple cost reduction methods	"Optimized solutions" prevent standardization and use of non-space equipment or processes and require that everything be uniquely designed for each specific application.
SE8. Use the Existing Knowledge Base	Reduces cost, schedule, and risk	Reinventing the wheel is rarely economical. According to John Mather, "6 months in the laboratory can save you a week in the library." Specific approaches to building on existing knowledge: a. Books and literature b. Courses and conferences c. Commercial software tools d. Become a part of the low-cost community e. Take advantage of the knowledge of others

This is an excellent example of the problem of culture and the difficulties it raises in trying to do business economically. The government wants to give an impression of being fair to all of the contractors. Assume they evaluate multiple proposals and select contractor A to build the next Mars lander. They work through the detailed design, trading on requirements as they go to get the most effective product at the best price. But when they're done the lander doesn't look very much like their original requirements and now contractor B comes back and says "if we had known that was what you wanted, we could have done it much cheaper," and, of course, that may be true. While we want to find ways around cultural (or legal) impediments, we also want to be sure that we understand why they exist so that we can find the right balance.

Trading on requirements typically demands other changes in the way we do business in space:

- Setting functional, rather than technical requirements (i.e., stating <u>what</u> we want done, not <u>how</u>)

- Documenting the source of requirements, so we know why they are needed
- Trading explicitly on the principal driving requirements
- Being willing to give up some level of performance in order to reduce cost or schedule

These are all things that we would do in normal buying decisions, but are much harder to do in a formal, rule-based system.

Another approach often used in low-cost systems is to use larger design margins (SE4). Traditional space systems are typically optimized for performance and, therefore, minimize margins. Everything is made as light and as thin and as small as possible, largely because space systems cost $10,000 kg to get to orbit and every fraction of a kg matters if we want to squeeze out as much performance as possible. But the net effect can be a system that is nearly impossible to build or change. Returning to our car analogy, assume we find the car we want, but we would like to put in a better radio because we will be making many long trips and the better radio gets more stations in remote areas. No problem. The radio is an extra $300. Of course, the new radio is heavier, so we will have to redesign the dashboard to be able to hold it. It also uses more power, so we'll need a larger generator. And then there's the heavier wiring for the rear speakers. And because everything has gotten heavier we can't meet our acceleration performance spec, so we will need a new engine. Fortunately, in the real world, cars are designed with lots of margin. For our spacecraft, large margins reduce cost, and the potential for cost and schedule overruns in quite a few ways:

- Less testing required
- Normal manufacturing tolerances acceptable
- Fewer rejects and reworks
- Less failures in both test and operations
- More robust design means less redesign
- Potential for standardized components
- Higher level of component and design reuse
- Can use more commercial grade components
- Can accept less certainty about the environment
- Reduces operations cost for planning and analysis

Most high quality products use large design margins to overcome the vicissitudes of the environment. In space, optimizing the design by driving margins as small as possible is one of the principal reasons that standardization has been dramatically unsuccessful. (In most cases, standardization means flying more capability and more mass than you actually need. Therefore, in space systems we tend to want the standard product, but with 3 of the 5 features removed to save mass and optimize performance.) Of course, this problem is made worse by the logic that says we must optimize performance so as to get the most bits (or whatever else it is we're buying) per spacecraft dollar. This leads not only to building Ferraris for every mission, but to customizing each individual Ferrari for the particular mission at hand. It results in a remarkably expensive way to observe, communicate, or predict the weather.

Finally, a key element of reducing cost is to make use of the knowledge base of what people have learned before. Low-cost, high-reliability missions have been around since the beginning of the space program and are getting more competent very rapidly with modern advances in mircroelectronics, processors, and composite materials. There is very little value in trying to reinvent what has been done before. It is important to learn what has worked and what hasn't worked in terms of reducing cost and schedule in prior programs and why. This means taking advantage of the knowledge of others, becoming a part of the low-cost, responsive space community, and making use of conferences, courses, and the existing literature base. In addition, a specific "Bibliography of Reducing Space Mission Cost" is available. (See Sec. 4.) This does not imply that every mission will want to follow every process developed for other missions. In many respects, each mission and organization is unique and will tailor what has been learned to their particular circumstances. But reinventing those processes is not the right approach.

2.6 Mission

Table 7 provides a summary of mission-related approaches to reducing mission cost and schedule. One of the most important elements of reducing mission cost is considering the possibility of alternative orbits. Traditional Earth surveillance missions want to last for a decade or more and, therefore, need to blanket the entire Earth with every sensor that will be needed in the future. (Because the spacecraft themselves are individually very expensive and effectively irreplaceable, the system as a whole tends to cost many billions.) If we are able instead to respond directly to world events, this cost can be dramatically reduced by both reducing the amount of coverage that is needed, but also by doing things,

Table 7. Summary of Mission-Related Approaches to Reducing Cost and Schedule. Cost reduction starts with the preliminary mission definition and design that largely determines many of the system costs.

Reducing Space Mission Cost—Mission		© 2010, Microcosm, Inc.
Technique or Action	**Mechanism**	**Comment**
M1. Change the CONOPS to Use Existing Data Communications	Much lower cost. Systems are maintained at little or no cost to end user	Make the satellite simply another node on the Internet. Use commercial providers to get the data to and from the spacecraft.
M2. Fly Low	Low altitude is a dramatically lower cost substitute for large aperture for observations or high power for active payloads	a) Resolution is proportional to distance/aperture (small numbers are better). b) For SAR or lidar, power required is proportional to R^4 c) Also avoids the orbit debris problem. Requires propellant for drag make-up.
M3. Use Repeat Coverage Orbit	Much better coverage for a pre-defined location than SSO	Gives up global coverage for much better coverage of a specific latitude range. Coverage is tuned to provide 4 to 6 successive orbits of coverage at the latitude of interest.
M4. Use Orbit Cost Function as a Measure of Orbit Cost	Allows cost vs. benefit trade on the orbit selection	Orbit Cost Function is the ratio of the payload available at 185 km due east from the launch site to the payload available in a given operational orbit.
M5. Short Mission Design Life	Reduces redundancy and complexity	Most missions live much longer than their design life. Also short design life allows introduction of newer technology on a regular basis.

such as flying low, that can provide excellent performance at reduced cost with systems that are not intended to last for decades. This also lets us introduce new technology as it becomes available and employ that technology in those specific circumstances where it's needed. Similar considerations can apply to other missions as well. The orbit for science missions is often chosen as the best orbit for that mission irrespective of cost, in part because the "cost" of an orbit tends to be intangible. This is the reason for introducing the *orbit cost function* [Wertz, 2011a] which is the ratio of the mass required in low Earth orbit (LEO), due east from the launch site to the total spacecraft mass needed in any given operational orbit. For example, going to GEO requires putting into LEO about 5 times the mass required in GEO. Going to the surface of the Moon requires about 8 times the mass in LEO that will ultimately end up on the surface of the Moon. This implies an orbit cost function of about 5 for GEO and 8 for the surface of the Moon. It may be that GEO or one of the Lagrange points is the ideal place for a scientific instrument due to excessive interference from the Earth. However, if we could get the same effect in LEO by tripling the mass of the spacecraft by adding shielding of baffling equal to the twice the spacecraft mass, we could potentially be much better off. We would still be launching only a bit more than half the mass of the more traditional mission, shielding or baffling are typically much lower cost than most other spacecraft components, we're in a very benign radiation environment and more uniform thermal environment, and we're in a regime where it is at least possible to get at the spacecraft in the future if something goes wrong. I don't want to imply that all scientific spacecraft should be in LEO, but that option should be a part of the cost reduction trade for many missions.

Finally, we should consider the use of "service provided" systems (i.e., existing, commercial ground stations) to reduce the overall mission cost, as discussed in Sec. 2.9 below. This typically provides better coverage, lower operating cost, and little or no up-front ground system development cost. The central issue here is that reducing mission cost and schedule is not just a low-cost payload, spacecraft bus, and operations, but starts with the entire mission design.

2.7 Launch

Although launch is typically not the largest element of cost in most missions, it nonetheless drives mission cost. It simply isn't worth launching a $2 million spacecraft on a $10 or $20 million launch vehicle. In addition, the lack of launch-on-demand, which the Soviets/Russians have had for decades and the Chinese are developing, prevents us from creating responsive, low-cost systems that would be capable of taking some of the work load off large, very expensive satellites and could prevent them from having to cover all the world all the time.

The major approaches to reducing launch cost are shown in Table 8. The single most effective approach to reducing both cost and schedule is not to launch to orbit at all. Depending on the goals of the experiment, test, or mission, there are multiple alternatives to a dedicated orbital launch [Wertz and Larson, 1996; Wertz, 2011a]. Balloon flights can provide hours or days at high altitude at very low cost. If 0-g is important, drop towers and drop tubes can provide excellent 0-g conditions for 5–10 sec by dropping a payload of up to 1,000 kg inside a vacuum tube. The data and payload are available essentially immediately and the experiment can typically be repeated twice per day. Periods of 0-g up to about 20-25 seconds (and even longer periods of lunar gravity or Mars gravity) are available from aircraft parabolic flights. Up to 40 parabolas a day can be flown, but perhaps the major benefit is that the experimenter and a few others can fly along, watch what happens, and make adjustments and corrections in real time.

The next step up from parabolic flights are suborbital flights on a sounding rocket. These can provide up to 12 minutes of excellent 0-g and an altitude of up to 1,200 km. This means you can get to LEO altitudes and above with vacuum and a full view of the Earth and space, just as you would in LEO. The only thing missing is the orbital velocity and a large chunk of the price tag.

For going all the way to obit at lower cost for small payloads, the principal options are rides as secondary payloads or shared launches. The ASAP (*Ariane Structure for Auxiliary Payloads*) Ring on the Ariane V provides accommodations for up to 6 payloads of 100 kg each and multiple slots can be used. the ASAP ring has been in use for many years and has provided the ride to orbit for many low-cost satellites. More recently, the ESPA (*EELV Secondary Payload Adapter*) ring has been developed which provides similar services for the Atlas and Delta vehicles. Depending on the specific mission needs, there are quite a few alternatives to a dedicated launch to orbit. Of course, each approach has both strengths and limitations, but all of them can provide potentially large reductions in both cost and schedule.

For larger spacecraft there are fewer options for reducing cost and schedule, although the use of some of the alternatives above for testing elements of the system may be able to find problems early in the program and, therefore, avoid more expensive fixes later.

Table 8. Summary of Approaches to Reducing Launch Cost and Schedule. While launch is typically not the principal element of space mission cost, it largely drives the mission cost. (For a more extended discussion of launch costs, see London [1996]. The Reinventing Space website [2011] also includes multiple papers on this topic.)

Reducing Space Mission Cost—Launch		© 2010, Microcosm, Inc.
Technique or Action	**Mechanism**	**Comment**
L1. Use Alternatives to Orbital Missions	Dramatically reduces "launch" cost	Use balloons, drop towers, parabolic flights, or suborbital flights as low-cost testing alternatives.
L2. Design for Multiple Launch Vehicles	Increases competition; reduces schedule risk	Used by all of the commercial constellations. Serves to protect schedule as well as reduce cost.
L3. Use ASAP or ESPA Rings	Significantly lower cost	Does not allow selection of orbit or launch time. Not applicable for operational missions.
L4. Rideshare	Shares launch cost	Only works if systems have compatible orbits and schedules.
L5. Low-Cost Small Launch	Allows operational smallsats plus tests of technology for larger missions	Low-cost small launchers (several sizes) are critical to a long-term cost reduction program. Payloads are getting smaller and launchers are getting bigger.
L6. Build Small Launchers to Inventory	Reduces mission risk and permits higher system risk	Can dramatically reduce mission risk by allowing satellite replacement. Less of a target for enemy attack. Mission becomes less susceptible to system failures or orbital debris.

Perhaps the best option for reducing both cost and schedule, or at least helping to prevent overruns, is to design the spacecraft for multiple launch vehicles. The cost of launch is typically negotiated between whoever is buying the launch and the launch provider. Clearly, there is more potential for negotiation if more than one launch provider is possible. Designing for multiple launch vehicles is usually not hard or expensive because the payload environments of all of the launch vehicles are typically similar, except for the Minotaur that provides up to 13 g's of axial acceleration because it is made from decommissioned ICBMs for which the loads were not a principal design consideration.

An equally important reason for designing for multiple launch vehicles is to protect the schedule. Recall that launch systems have approximately a 90% success rate. When a launch failure occurs, there is a significant downtime until the next launch of that system. In addition, if your payload was the next in line at the time of the failure, it may have been moved further back by higher priority launches when the launch system resumes operations. For this reason, nearly all of the constellation builders use multiple launch providers. This also provides a continuing negotiating position. Thus, if a constellation needs to launch 50 satellites, they may choose Launch Provider A for 15, Launch Provider B for 15, and reserve the last 20, depending on the performance of the first ones. Note that constellations may also use launch vehicles of different sizes by launching multiple satellites on a larger launcher. This can work out well or badly. Iridium launched its entire constellation without a launch failure. Unfortunately, GlobalStar lost 12 satellites on a single Zenit 2 launch failure [Harland and Lorenz, 2005].

A key to reducing both cost and schedule for systems of all sizes is the development of a low-cost, small, responsive launch vehicle. (For a detailed discussion, see Wertz [2010].) This is needed for both operational smallsats and for rapid testing of both technology and processes applicable to larger systems. It also provides for the rapid introduction of new technology, which is evolving particularly quickly in small spacecraft. Building launch vehicles to inventory, as needed for launch-on-demand, is primarily an issue of whether it is worth the interest cost on the money required to build the vehicle for the time period from when it is completed until it is launched. Thus, at 10% interest, holding the vehicle in inventory for 6 months would increase the build cost by 5% and the total launch cost by less than that, say 4%, plus an incremental cost for storage and maintenance.

The design and development of launch systems is beyond the scope of this summary. However, London [1994] provides an excellent overview of why launch system cost as much as they do and ways to reduce launch system cost. Wertz [2000] provides a cost model intended to compare reusable vs. expendable launch vehicles, which has been updated to model the added cost of launch-on-demand systems [Wertz, 2004]. A number of papers on low-cost launch systems are available at the Reinventing Space website [Reinventing Space, 2011].

2.8 Spacecraft Technology

As shown in Table 9, reducing the cost of spacecraft is largely a matter of finding lower cost, lighter, or more competent components. One of the better ways to do this is to have the spacecraft do more of the functions in software and less in hardware. This has multiple advantages, such as:

- Lower mass
- Lower recurring cost
- Much higher functionality
- Can be changed, upgraded, and fixed on orbit and also disadvantages:
- High non-recurring development cost
- Development process is difficult to manage
- Subsystem interfaces that are all in the spacecraft computer are difficult to control

The ability to fix the software on orbit is a key consideration for reducing cost and increasing reliability. This implies the need to ensure that mission operations has procedures and processes in place to change out the on-orbit software. Doing more in software also suggests that there is a major advantage to being able to fly the latest computer available. (Item SE5 above.) In effect, the spacecraft becomes a general purpose processor with most of the work being done in software. Because both software and on-board processors are evolving very rapidly, this also implies a large advantage to lower cost, short-lived spacecraft. It is likely that you have much more processing capability in your cell phone than many traditional on-orbit spacecraft. This means that newer spacecraft will typically be more competent than older spacecraft, such that the value of an on-orbit asset continues to decline. Some of the features that we can reasonably expect from future software controlled spacecraft, include:

Table 9. Summary of Approaches for Reducing Spacecraft Cost and Schedule. Note that all of the systems engineering approaches of Sec. 2.5 are key to reducing spacecraft cost as well. The Reinventing Space website [2011] also has many papers on this topic. For a detailed discussion of building low-cost communications satellites, see Davidoff [1998, now out of print] or Ford [2009].)

Reducing Space Mission Cost—Spacecraft Technology		**© 2010, Microcosm, Inc.**
Technique or Action	**Mechanism**	**Comment**
Sp1. Use Plug-and-Play Technology	Dramatically reduces cost and schedule for I&T	Has not been used much to date because it isn't minimum mass. Substantial work currently ongoing.
Sp2. More Extensive Use of Software	Minimizes mass and often allows use of a general -purpose processor	Can update and revise on-orbit as needed. Allows spacecraft to become a general purpose unit with specialized functions implemented in software.
Sp3. Use COTS Software	Immediately available; dramatically lower cost; tested through use	Possible drawbacks: May need modification and thorough testing. Typically not optimal for the application.
Sp4. Use COTS Hardware	Immediately available; dramatically lower cost; tested through use; less need for spares	Reduces both cost and risk when combined with large margins.
Sp5. Use CubeSat Hardware	All of the above plus built for space use	A specific example of COTS hardware for space applications. Most CubeSat hardware is in stock and available for immediate delivery.
Sp6. More Microelectronics	Lighter weight and lower cost than either mechanical parts or analog electronics	Takes advantage of dramatic recent growth in microelectronics. Key issue will be radiation tolerance—not a problem for low Earth orbit, but could be for higher orbits.
Sp7. Use Commercial Battery Technology	Both much lower cost and higher power density	Takes advantage of continuing advances in battery technology due to widespread use personal electronics of all sorts.
Sp8. Use More Composite Materials	Can be lighter, stronger, and lower cost	Can build much lighter, stronger structures with shorter schedules than metal tanks and structures. Potential problems include low thermal conductivity and near-zero coefficient of thermal expansion—very different than metals.
Sp9. Use Non-space Equipment	Takes advantage of existing designs, testing through use, and mass production	Typically not optimal. Often must be space qualified or put through major test program. Takes advantage of advances in design and extensive testing through use. Example: Carpenter tape antennas and hinges.
Sp10. Standardized Components and Interfaces	Reduces both cost and schedule. Avoids reinventing the wheel.	Has been remarkably unsuccessful in older space applications because it is sub-optimal in terms of weight and power. May be able to use these more in the future.
Sp11. Avoid Large Engines for In-Space Applications	Reduces cost, mass, and need for additional control components	Large engines in space often require separate control system and represent largest threat to the on-orbit spacecraft. Small thrusters can be controlled by spacecraft control system and recovery from errors may be possible.
Sp12. Hosted Payloads	Shares spacecraft bus and launch	Potential to increase cost and delay schedule if added payload creates conflicting requirements or forces a larger launch vehicle.

- Software-defined radio
- Pre-processing of images such that only the needed information is sent to the ground
- More responsive systems, such that the spacecraft can send more detailed data if and when it is requested by the end user
- Autonomous on-board control of both orbit and attitude such that the spacecraft always knows where it is and where it's looking
- Precise control of spacecraft motion based on dynamic analysis such that all motions are both rapid and nearly jitter free

These features don't reduce cost directly, but rather allow low-cost small spacecraft to be much more capable, such that they can do the job of older, larger, much more expensive systems.

Another processor-related function intended specifically to reduce cost is the use of more plug-and-play electronics. Here the goal is to make an interface between the various spacecraft components and subsystems that will be essentially similar the USB port on your computer in which multiple different items can be plugged in and begin to function immediately. This greatly reduces the time and cost associated with spacecraft integration and test. In addition, this allows the potential, for example, of a new more capable or more relevant payload to be put into a spacecraft that is in storage waiting for a need to be launched.

Using CubeSat hardware components, even if the satellite itself is not a CubeSat, is also a good way to drive down both cost and schedule. The two main advantages here are that CubeSat components are very low-cost and are maintained in stock and bought off-the-shelf, such that you can have them available with days. This not only reduces the cost and schedule of the component themselves, but also effectively eliminates, or greatly reduces, the need for spares because components can be obtained from inventory at any time. CubeSat components also make use of more modern technology, such as lithium-ion batteries, and that technology is tested on orbit much more rapidly because CubeSats themselves are launched more often and more quickly than traditional satellites.

Note that essentially all of the systems engineering approaches discussed in Sec. 2.5 serve to drive down the spacecraft bus cost. In addition, the effect of these processes is often multiplied when they are used together. For example, assume there is an existing optical instrument that is light weight and low cost. If we can use an existing instrument, it can drive down cost, risk, and schedule by a large amount. Of course, this instrument may or may not meet all of the mission requirements when flown in a traditional spacecraft. However, we can use a combination of trading on requirements (Item SE1); mission approaches, such as flying low (Item M2); and spacecraft approaches, such as the use of CubeSat components (Sp5) to create very capable, but also very low-cost space systems. This is the approach used for developing NanoEye, which can provide high-resolution imagery in a spacecraft with a projected recurring cost of less than $2 million [Van Allen, et al., 2011]. Typically, reducing the cost of a single component, i.e., buying lower cost reaction wheels, will have only a very small effect on the cost of the spacecraft and even less effect on the cost of the mission. Significantly reducing the cost and schedule of the mission as a whole typically requires that we use multiple, synergistic approaches to create a system that can meet our end objectives at very low cost and risk in a short period of time. For a much more extensive discussion of reducing spacecraft cost and schedule see Wertz and Larson [1996]. A large number of papers on this topic are also available on the Reinventing Space website [Reinventing Space, 2011].

There is at least one area in which low-cost spacecraft builders and traditional manufacturers would agree—test as much as possible and, if possible, test it like it flies. Testing is critical to finding both integration flaws and design flaws, often associated with the interaction between various components. Low cost satellite manufacturers will try to find low-cost ways to conduct testing and will orient the testing toward specific questions that must be answered—i.e., will the spacecraft survive the launch loads, will it overheat in the vacuum environment, will it work in the radiation environment? As much as possible, low cost tests will be designed to verify these characteristics. Traditional systems will tend to use a more formal approach and have a "required" series of tests. (Note that thermal vacuum testing has the merit of driving out gasses that have been trapped in the material such that the test article will outgas less on orbit.) Testing is an important part of the regime for both low-cost and high-cost systems.

2.9 Operations

Traditionally, mission operations have been an expensive and complex activity run from a mission operations center requiring multiple people and 24 hour coverage, 7 days a week. This, in turn, implies either 4 or 5 operations teams and, of course, the management and communications needed to make them work smoothly together. As summarized in Table 10, there are a number of approaches to greatly reduce this cost.

Table 10. Summary of Approaches for Reducing Mission Operations Cost and Schedule. Multiple approaches are now available for reducing the cost of mission operations. (For a more extended discussion, see Marshall, et al. [1996] and many papers from the Reinventing Space website [2011].)

Reducing Space Mission Cost—Operations	© 2010, Microcosm, Inc.	
Technique or Action	**Mechanism**	**Comment**
O1. Use Service-Provided Ground Systems	Lower cost with little or no non-recurring cost	Substantial redundancy and large area of coverage. Disadvantage is that your mission may have to share priority with others.
O2. Share Ground System Across Programs	Shares cost among two or more user organizations	Critical to compromise on requirements rather than simply combine all requirements from multiple programs.
O3. Use Iridium or GlobalStar Modem	Very low cost, continuous communications link	Low data rate, but nearly continuous coverage. Only applicable to LEO.
O4. Use Autonomous Orbit Control	Reduces personnel requirement on the ground	Also reduces propellant cost and provides precise timing for future coverage. Allows planned coverage with precision.
O5. Fully Autonomous Systems, On-board and in Operations	May allow one-shift coverage and less-frequent commanding	Autonomous systems may allow ground operations by a single shift or even one person maintaining the ground system, computers, and software. May increase non-recurring cost.
O6. Fly the Spacecraft Over the Internet	Simplifies operations by making spacecraft just another Internet site	Can use secure Internet or encrypted data to protect data and commanding. Means spacecraft can be controlled from virtually anywhere.
O7. Use AMSAT Resources for Science Data Return	Lower cost by having an unpaid network	Has worked successfully in astronomy for decades. Can reduce both cost and provide high reliability by having multiply redundant ground segments.
O8. Common Software for Test and Operations	Reduces both cost and schedule. Avoids reinventing the wheel	May be less efficient and less user friendly than the operations group would prefer.

The most direct approach to reducing operations costs is to reduce the operations crew to a single shift of 40 hours/week. This reduces the number of people, overhead, management, and communications costs. It also requires that the spacecraft be capable of "taking care of itself" for an extended period, including probably long weekends. Ordinarily this is much easier with small spacecraft that have large design margins and are capable of at least maintaining themselves in nearly any orientation. Many small spacecraft are operated by one person on a very part-time basis. [Marshall, et al., 1996.]

Another approach for reducing operations cost is the use of service-provided ground stations. Here we are making use of existing ground stations located around the world that are both manned and maintained in order to communicate with multiple spacecraft. This also provides a high level of redundancy and excess coverage. The main disadvantage is that you have to share priority with others. However, this can be overcome by complementing the service-provided system with dedicated remote antennas built specifically for your system. When used in conjunction with a service-provided system, these remote sites are not required to have near-100% reliability, because the other ground stations provide back-up and coverage in areas beyond the reach of 1 or a few dedicated remote antennas. Generally, the cost of the service-provided system is in the range of several hundred dollars per data pass, which is usually a great deal less than maintaining a dedicated ground system.

In conjunction with service-provided systems, there is the potential for simply flying the spacecraft over the Internet. This is done by using the service-provided system for communications between the satellite and the ground. The ground station then puts the data on the Internet, which is then downloaded by as many end users as need it. (A variety of encryption techniques are available that keep the data secure, if needed.) Commands are sent to the spacecraft via the same process and, again, can be encrypted to avoid others intentionally or inadvertently taking over the spacecraft. In this way, the spacecraft becomes effectively just another node on the Internet that you can talk to, get data from, and control from any location where Internet access is available.

One of the more cumbersome and critical ground station functions is maintaining the spacecraft orbit, particularly in low LEO where atmospheric drag is high. This can be accommodated by using a GPS receiver on board for navigation and autonomous on-board orbit control. [Conger, Gurevich, and Wertz, 2002; Plam, et al., 2008; Wertz, 2003**]** A secondary advantage of this approach is that you will know in advance (years in advance, if desired) just where your spacecraft is located at any given time to about 1 km in-track and more precisely in cross-track and radial.

Finally, another approach is to use AMSAT resources for science data return. This approach of making use of the amateur community has worked in astronomy for decades as amateur astronomers make most of the observations of variable stars for which it is simply too expensive to tie up the manpower and resources of professional astronomers. This would not only provide data return at much lower cost, it would also create a high level of interest in multiple communities where amateurs were collecting useful science data and genuinely helping in the exploration of space.

3. SUMMARY

In summary, there are several broad lessons from looking at the multiple approaches for dramatically reducing space mission cost and schedule:

- Significantly reducing overall mission cost and schedule typically requires using multiple techniques that complement each other. Unless there is a single large cost or schedule driver, making a change in only one approach or one part of the system is unlikely to have a major impact on the system as a whole.

- Reducing cost and schedule is not just a matter of finding a low-cost spacecraft bus or payload. It is a mission problem involving the full range of mission engineering issues in order to provide the end user the data they need, when they need it, at low cost and with high reliability.

- Truly reducing overall space mission cost significantly will require at least some investment in, and development of, both low-cost small spacecraft and low-cost, small, responsive launch systems.

- The greatest impact comes from mission diversity in which small spacecraft are used for some operational activities and also as a test-bed to rapidly and economically develop both processes and technology for reducing cost, schedule, and workload for larger missions.

The issue of mission diversity is important. Using a naval analogy, having even a few less battleships and a lot more PT boats changes the nature of the game. Diversity will allow us to do things we simply couldn't do before with a flexibility and responsiveness that isn't possible today in space. The right combination of assets will make us much less susceptible to enemy attack or the vagaries of launch failures, system failures, or collisions with orbital debris. It also makes the overall space mission enterprise much lower cost which gives us the potential of undertaking projects that today we simply cannot afford to undertake.

Our ultimate objective is to find ways to reverse the Space Spiral as shown in Fig. 1. What we would like to do is make use of the vast knowledge and experience base on reducing mission cost from throughout the world to begin to create much lower cost missions which will allow both shorter schedules and more missions, which will allow a reduced demand for 0 failures (that was unrealistic in the first place), which will allow further reductions in mission cost, and so on. In a real sense, we want to reinvent space—to return to the drive and excitement of the early space program, but with the advantages of modern technology and the experience base that 50 years of space exploration have brought.

4. SOURCES OF ADDITIONAL INFORMATION

The cost reduction methods summarized here are taken from the forthcoming text and reference, *Space Mission Engineering—the New SMAD*, which provides additional details on these methods and associated topics such as the use of small satellites to reduce cost, the impact of reliability considerations, and counterproductive approaches to reducing cost [Wertz, 2011a]. These are discussed in even more detail in the USC graduate course, "Reinventing Space—the Design of Low-Cost Space Missions," which is offered biannually [Wertz, 2011b]. A discussion of the utility of and market for small satellites and specific examples of low-cost, high utility smallsats was presented at last year's responsive space conference [Wertz, 2010]. Another current example is given by Van Allen, et al. [2011]. The standard reference works in this field are Wertz and Larson [1996], Sarsfield [1998], London [1994], Helvajian and Janson [2009], and Davidoff [1998], which is now out of print and has been replaced by Ford [2009]. Finally, Microcosm maintains a relatively complete annotated bibliography of Reducing Space Mission Cost, which is updated from time-to-time. For a current copy or to suggest updates to the tables here or entries in the bibliography, send an E-mail to Pam Esquinca at bookstore@smad.com. We would appreciate hearing your comments, recommendations, suggestions, and additions.

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