Reinventing Space:
Low-Cost, Responsive Space Missions
USC ASTE 523, Spring 2021

Supplement 10

Summary of Methods for Reducing Cost

METHODS FOR REDUCING SPACE MISSION COST

For convenience, we have divided the major methods for reducing space mission cost into two broad categories and nine sub-categories:

Process and Programmatic

– Attitude	A
– Personnel	PI
– Programmatic	Prgm
– Government/Customer	Gov
– Contracting Methods	CTR
– Cost Sharing and Income Generation	CS/In

Technology and Systems

– Systems Engineering	SE
– Mission	M
– Launch	L
– Spacecraft Technology	Sp
– Ground System Communication	GS/C
– Manufacturing	Mnf
– Reliability and Risk Management	R&R
– Operations	Ops
– Software	S/W

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ATTITUDE APPROACHES FOR REDUCING COST

A T T I T U D E

Reducing Space Mission Cost—Attitude (A)		
Technique or Action	**Mechanism**	**Comment** © 2021, Microcosm, Inc.
A1. 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."
A2. 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, highly capable, low-cost space missions.
A3. 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.
A4. Recognize that low cost is NOT low reliability	Eliminates major argument of wanting only "high reliability"	a) Low cost, small spacecraft are equally or more reliable than high cost spacecraft. [NASA, 2008] 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 (See R&R 1)
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 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.

On this and subsequent charts, yellow highlights are methods that are particularly important.

ATTITUDE APPROACHES FOR REDUCING COST (CONT.)

A T T I T U D E

Reducing Space Mission Cost—Attitude (A)		
Technique or Action	**Mechanism**	**Comment** © 2021, Microcosm, Inc.
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 discussed can drive cost up if not implemented appropriately. This should not be used as an excuse for not doing them.
A8. Find a balance	Puts emphasis on achieving the broad goals of the end user at minimum cost and risk	Don't want performance at any cost because there is a high probability you will get 0 performance (R&R 1) or will be forced to sacrifice other important systems to achieve it. Also don't want lowest cost system with minimal performance. We want high utility at low cost and risk, but that requires balance to achieve.
A9. Look for and reward innovation	Reinforces the idea that low cost is important and provides additional motivation	If innovation is rewarded, it demonstrates in real terms that management regards innovation oriented toward reducing cost or improving performance as important. This helps reverse the culture of "Faster, Better, Cheaper — Pick any Two."
A10. Support other people and organizations that are trying to reduce cost	Begins the process of creating coalitions of people that support lower cost missions. Increases odds of success.	Changing the culture is dramatically hard. Creating a coalition of people who are mutually supportive is a major step in the right direction. This both reinforces the need and the idea that dramatically lower cost missions are possible in essentially all areas.

PERSONNEL RELATED METHODS TO REDUCE COST

PERSONNEL

Reducing Space Mission Cost—Personnel (PI)		
Technique or Action	**Mechanism**	**Comment © 2021, Microcosm, Inc.**
PI1. Make it somebody's job to find ways to dramatically reduce cost	Make low cost a part of the discussion at all times.	Who the job is assigned to shows the level of importance given by management. If it isn't somebody's job and there isn't any training in how to do it, dramatic cost reduction won't happen.
PI2. Create a small team to reduce cost	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. (See Prgm 1.) Teams can be for either of 2 purposes: 1. Find ways to drive down cost for the whole organization 2. Develop a specific mission at low cost
PI3. Empowered project team	Rapid decision-making; strong sense of person-al responsibility; allows "sensible" decisions	Eliminates a major function of the large, formal management structure. Encourages personal "ownership" of issues, often expressed as "I own that problem."
PI4. 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.
PI5. Provide training specifically in reducing cost	Provides a mechanism to actually get the intended results	Reducing cost is hard and takes skill and preparation. The implementation will be different in each program and organization, but skills can be, and should be, taught.
PI6. 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 smaller budget next year. Instead they should keep their budget and have half the savings put into an end-of-year bonus or party fund. (Rewards don't need to be monetary.)
PI7. 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.
PI8. Attend conferences and meetings on low-cost space systems	Generates ideas, shows what is possible (and what you don't want), and creates coalitions.	The 2013 Sequester cut off attendance at essentially all conferences and training programs at the time that these were most needed to dramatically drive down cost. Two regular conferences of value are the USU/AIAA SmallSat Conference and the AIAA Reinventing Space Conference.
PI9. Trust people more than procedures	It's people that get the work done and ultimately make it happen	Some level of procedures and formal processes are critical, but we need to find a reasonable balance and, in the end, trust those people who know how to get the job done.

PROGRAMMATIC METHODS FOR REDUCING COST

P R O G R A M M A T I C

Reducing Space Mission Cost—Programmatic Methods (Prgm)		
Technique or Action	**Mechanism**	**Comment © 2021, Microcosm, Inc.**
Prgm 1. Use 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.
Prgm 2. Use 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.
Prgm 3. Buy multiple spacecraft	Lowers cost due to both learning curve and continuity of production line	Makes use of both learning curve and continuity of production line. Maintaining a production line is critical for containing cost for all other types of vehicles—cars, trucks, ships, and airplanes. This is also true for spacecraft.
Prgm 4. Build to inventory	Reduces mission risk and permits higher system risk	1) 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. 2) Creates options for low-cost, rapid test missions and rapid insertion of new technology.
Prgm 5. 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. Examples: development of Soviet launch vehicles or early history of airplanes or UAVs.
Prgm 6. 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.
Prgm 7. Provide continuous, stable funding (i.e., avoid programs stops and starts)	Does not reduce cost per se, 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) Keep programs funded while decisions are being made

PROGRAMMATIC METHODS FOR REDUCING COST (CONT.)

PROGRAMMATIC

Reducing Space Mission Cost—Programmatic Methods (Prgm)		
Technique or Action	**Mechanism**	**Comment** **© 2021, Microcosm, Inc.**
Prgm 8. 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.
Prgm 9. Minimize formal documentation and reviews	Reduces program-matic 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 the as-built design.
Prgm 10. Use small business effectively	Small businesses are a major source of cost reduction technology and processes	Typically small businesses are not used for many space programs, both because of the contracting difficulties and the perception that small businesses don't understand the "real world" of space missions; but small businesses have created most of the small, low-cost space missions.

GOVERNMENT/CUSTOMER APPROACHES FOR REDUCING COST

GOVERNMENT

Reducing Space Mission Cost—Government / Customer Methods (Gov)		
Technique or Action	**Mechanism**	**Comment** © 2021, Microcosm, Inc.
Gov 1. Implement actions specifically to reduce cost	Demonstrates a real interest in reducing cost and willingness to take action to achieve it	Among those actions in other sections that can be done directly by the government or major customer: a) Foster an attitude of wanting and rewarding cost reduction (Att 1 to Att 10) b) Force trading on requirements (Sys 1) c) Reward low cost and innovation (Att 9 and Psnl 6) d) Reduce the cost of failure (Prgm 5) e) Provide funding continuity (Prgm 7) f) Make cost data available (Prgm 8) g) Sponsor training in reducing cost (Psnl 5) h) Develop a low-cost small launch vehicle (Lnch X) i) Create low-cost smallsat programs for both test and operations (Prgm 1 and Prgm 2)
Gov 2. Decentralize space system procurement	Allows innovation and options that would not be allowed under a centralized procurement approach	Innovation, particularly in reducing cost, often comes from “secondary” organizations within the government. These should be encouraged as a way of providing positive and valuable “competition of ideas” within the government and user community (See C-PA 1)
Gov 3. Sponsor R&D specifically 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.”
Gov 4. Sponsor knowledge preservation and dissemination	Actually using lessons learned rarely occurs, but is important to reducing cost	Space technology has far fewer books, commercial software, or university programs than any other comparable discipline. Knowledge is being lost at an exceptionally rapid rate.
Gov 5. Revise SBIR objectives to focus on cost reduction	An excellent source of innovative ideas for reducing cost	Currently, less than 4% of SBIR topics are directed specifically toward reducing cost. (50% would be better.) Can provide both innovative solutions and simpler, faster contracting mechanism with Phase IIIs.
Gov 6. Revise SBIR objectives to look at low-cost missions	Allows small business innovations to extend to mission definition	Most SBIR topics tend to be narrowly focused on specific technologies. This change would allow innovative systems and missions which is the best way to significantly reduce overall mission cost.

GOVERNMENT/CUSTOMER APPROACHES FOR REDUCING COST (CONT.)

GOVERNMENT

Reducing Space Mission Cost—Government / Customer Methods (Gov)		
Technique or Action	**Mechanism**	**Comment** © 2021, Microcosm, Inc.
Gov 7. Use SBIR Phase III	Sole-Source contract dramatically shortens schedule and cost	Sole-source contract mandated by law. Can shorten schedule by a year or more. Contracting process short and simple. Helps maintain funding continuity and, reduces cost. (See CTR 2.)
Gov 8. 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. (See Psnl 6 and 7.)
Gov 9. 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.
Gov 10. If a SmallSat program is successful, fund more, and do it soon.	Keeps low cost programs alive and encourages others to create low-cost programs	To reduce cost in the near term and long term, it's important to encourage and maintain successful low-cost programs. Killing off successful, low-cost programs sends the wrong message to the community.
Gov 11. Create an environment that fosters and rewards low cost	Gives emphasis and importance to cost reduction	Should extend to all levels—i.e., reward government personnel and organizations and contractor personnel and organizations for reducing cost and creating low-cost programs and systems.
Gov 12. Search for balance between cost and performance	Best way to achieve end user needs at minimum cost and risk	Very much like buying a car, the goal is to achieve a reasonable balance between what we want and what we can afford. (See Att 10 and SE 1-4.)

CONTRACTING METHODS FOR REDUCING COST

CONTRACTING

Reducing Space Mission Cost—Contracting Methods (CTR)		
Technique or Action	**Mechanism**	**Comment** © 2021, Microcosm, Inc.
CTR 1. Simpler contract process for small contracts	Could resolve problem of extended contracting delays for small problems	May be difficult to implement within current rules. Finding an acceptable contract vehicle for short programs is a major problem area--often equally or more difficult that finding funds.
CTR 2. Use SBIR Phase III	Sole-Source contract dramatically shortens schedule	Sole-source contract mandated by law. Contracting process short and simple. Can shorten schedule by a year or more. Consistent with objectives of small, low-cost, rapid program. (See Gov 7.)
CTR 3. Pay for work accomplished (i.e., avoid equal payments) on R&D programs	Equal payments can cause both schedule and cost growth	Spending on R&D programs can often be heavy at the front end to purchase or build test equipment, supplies, or software. Equal payments can force unexpected delays.
CTR 4. Advance payments to small businesses	Allows contractor to move more quickly and maintain or beat schedule	Cash flow is a major problem for small businesses, which can force decisions that are more expensive in the long run.
CTR 5. Avoid program gaps	Prevents unwanted cost growth and increased risk	Funding delays, particularly for small companies, means either layoffs or transfer of personnel to other programs from which they may not return. This increases cost, risk, and schedule. (See also Prgm 7.)
CTR 6. Allow contractor margin on R&D	Allows more honest budget process and greater budget control	With current practice, margin must be "hidden" in programmatic estimate, such that it's difficult for anyone to judge what the margin is. This makes it hard to manage and hard to control cost
CTR 7. Allow aggressive goals without penalty for missing them	Allows greater potential for dramatic cost reduction by not penalizing failure to fully achieve it	A key problem for setting aggressive cost goals is that the contractor is typically penalized for missing them, even if what they achieved is well below traditional cost projections. Need to find a way to reward success and not penalize small failures to meet aggressive targets.
CTR 8. Create a team	Allows everyone to work together toward common goals	Today's contract process creates teams by threatening keelhauling and walking the plank, neither of which create the desired effect. Building a strong team requires a balance between supporting team members and always demanding the best performance. This is very hard to do in formal contracting.

COST SHARING AND INCOME GENERATION APPROACHES FOR REDUCING COST

COST SHARING

Reducing Space Mission Cost—Cost Sharing and Income Generation (Cs/In)		
Technique or Action	**Mechanism**	**Comment © 2021, Microcosm, Inc.**
CS/In 1. Look for ways to generate income	Any income generated can be used to directly offset costs	A. License system use. Example: license GPS receiver manufacturers B. Sell data. Example: Sell images to new organizations C. Sell services when not in use. Example: Sell FireSat fire detection and monitoring to other countries D. Sell the satellite when you're done with it. Example: GEO comm satellites are routinely sold and moved
CS/In 2. Interagency cost sharing	Reduces cost for each organization involved, relative to each organization building a separate system	Likely to increase the total system cost to potentially conflicting requirements. Main problem to overcome is that each organization must be willing to compromise and that can prove difficult. Historically, multi-agency programs have often been canceled due to excessive cost created by conflicting requirements.
CS/In 3. International cost sharing	Similar to CS/In 2, but with international, rather that interagency partners	Works best by having each national partner provide an element of the system—i.e., payload from one country, spacecraft bus from another, and launch provided by a third country
CS/In 4. Buy data, rather than spacecraft	Reduces cost to the extent that the cost of the data is less than the cost of the system	Only works if there are other commercial customers for the data, such that system cost is spread over multiple customers. Could work, for example, with Earth imaging data or weather data.
CS/I 5. Use data from other space or terrestrial programs	Reduces the amount that has to be funded by the current program	Introduces complexities of coordination and incorporating data from a different source with likely different formats; goal is to make the source of the data transparent to the end user.

SYSTEM ENGINEERING
APPROACHES TO REDUCING COST

S Y S T E M S   E N G

Reducing Space Mission Cost—Systems Engineering (SE)		
Technique or Action	**Mechanism**	**Comment** © 2021, Microcosm, Inc.
SE 1. Trading on Requirements	Allows a balance between cost and benefit. Can dramatically reduce cost or avoid program cancelation if requirements are excessively challenging	*Trading on requirements* refers to adjusting the requirements to find the best balance between cost, risk, schedule and performance, much the same way individuals buy a car. Makes traditional competition difficult, but allows the government to become an "intelligent consumer." Example: defining required mission lifetime.
SE 2. Trading among requirements	Allows better performance in one area at the potential expense in other areas. Allows finding the best balance to meeting the end user needs	*Trading among requirements* means accepting less in one area in order to do better in other areas. Example: flying at a low altitude improves resolution, but reduces coverage and possibly mission lifetime.
SE 3. Create tiered requirements	Allows better performance at lower cost.	This refers to creating two or more tiers of requirements to allow optimizing multiple criteria, such as coverage and resolution. Example: multi-tier resolution requirement to prove good resolution when looking straight down and frequent coverage with lower resolution at lower elevation angles.
SE 4. Design capabilities driven system rather than requirements driven system	Allows maximizing performance at low cost (not necessarily minimum cost). May be the best approach to meeting end user needs	Extends concept of "trading on requirements" to minimize or eliminate requirements and concentrate on broad objectives. Allows design to be based on what exists or can be achieved at low cost. Example: building the system around an existing or "easy to invent" set of capabilities.
SE 5. Set functional rather than technical requirements and give reasons for them.	Allows the various requirements trading processes to work	Typically requirements documents specify what is to be done, but not why. Need the "why" in order to be able to conduct requirements trades.
SE6. Allow simultaneous development of critical mission elements	Reduces cost, schedule and mission implementation risk (See also SE 6.)	Classic example is the Apollo program simultaneous development of the Saturn V and the Moon landing elements and mission profile. If systems are to work together efficiently and effectively, they need to be developed in parallel, not in series. (See R&R 4 for addressing problem of added risk.)
SE 7. Concurrent Engineering	Allows schedule compression; increases feedback between groups	Potentially high non-recurring cost. Can achieve "local optimization," but reduces willingness to consider truly different approaches. Typically concurrent engineering refers to components or subsystems, whereas simultaneous development (SE 5) refers to larger elements of the mission.

SYSTEM ENGINEERING
APPROACHES TO REDUCING COST (CONT.)

SYSTEMS ENG

Reducing Space Mission Cost—Systems Engineering (SE)		
Technique or Action	**Mechanism**	**Comment © 2021, Microcosm, Inc.**
SE 8. Design-to-Cost	Adjusts requirements and approach until cost goal has been achieved	Has rarely been used. Arbitrary cost goals are unlikely to be successful.
SE 9. 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.
SE 10. Fly new component plus same component flown on last mission	Allows use of newer technology with higher capability without the associated risk.	Particularly useful for computer technology. Allows use of newest computer technology—both lower cost and more capability with very low risk. Can be used for other hardware as well.
SE 11. 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.
SE 12. Used Market-Based System approach for resource allocation	Allows the best possible end result within specific cost and resource constraints	Applicable to missions with multiple payloads. Sets up a market-based system to allow various PIs to trade power, mass, and cost or commodities in limited supply. (See Wessen and Porter [1998].)
SE 13. Use the existing knowledge base	Reduces cost, schedule, and risk by making use of the existing knowledge base Can see what has worked and not worked in prior programs Shortens the "learning curve" for finding approaches that work for your specific program	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, training programs, and conferences c. Commercial software tools d. Become a part of the low-cost community e. Take advantage of the knowledge of others
SE 14. Use a constellation of SmallSats	Reduces the impact of launch & spacecraft failures, allowing much lower cost approaches	Requires very low-cost SmallSats. Provides better persistence
SE 15. Use shorter mission lifetime	Allows more rapid system evolution with newer technology	Must compensate for shorter lifetime. Can have near continuous technology evolution

MISSION

Reducing Space Mission Cost—Mission Design (M)		
Technique or Action	**Mechanism**	**Comment** © 2021, Microcosm, Inc.
M1. 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.
M2. Use Repeat Coverage Orbit	Much more coverage with fewer satellites 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 in the latitude band of interest.
M3. 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 100 NMi due east from the launch site to the payload available in a given operational orbit.
M4. Reduce the minimum working elevation angle	Provides greater coverage and may reduce the number of spacecraft required	Coverage is very sensitive to the minimum working elevation angle. (Most of the land viewed from a mountaintop is at low elevations angles near the horizon.) Classic example is Iridium which made a very small reduction in the minimum elevation angle and reduced the number of spacecraft in the constellation from 77 to 66.
M5. Short mission design life	Reduces redundancy requirements and complexity	Most missions live much longer than their design life. Also allows introduction of newer technology on a regular basis. For "continuous" missions, we need to save enough money to make the shorter lifetime worthwhile.
M6. Use "localized," rather than global mission design (in time, region, function, or all 3)	Reduces the number of satellites and improves the utility of those that are used	Traditionally, we use a small number of very large spacecraft to cover all the world, all the time, with all of the sensors we might want to use. If launch-on-demand is available, we can local our coverage in time, location, and sensor choice by launching what sensors are needed into a Repeat Coverage Orbit (MisD 2 above) in response to world events.

MISSION DESIGN (CONT.)

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Reducing Space Mission Cost—Mission Design (M)		
Technique or Action	**Mechanism**	**Comment** © 2021, Microcosm, Inc.
M7. Use launch-on-demand to respond to immediate or short-term problems	Can dramatically reduce the number and complexity of the satellites needed on orbit	A short-term problem, such as the tsunami that hit Japan, can be addressed by launching one or a few very small satellites to help communications and location of those in need of rescue or assistance. Allows us to concentrate resources on times and locations where it is most needed
M8. Use Mission Diversity (See also R&R 2)	Reduces both cost and risk by using a mix of satellites	*Mission Diversity* refers to a mix of small satellites and more traditional large satellites, rather like having both aircraft carriers and PT boats in a naval fleet. It reduces cost and risk and improves both responsiveness and utility.
M9. Disaggregation	Allows multiple, much lower cost smallsats to replace one or a few larger satellites	*Disaggregation* is splitting up the multiple functions of a traditional large satellite into smaller pieces that can be done by much smaller, lower cost satellites. The smallsats must be much lower cost to allow the mission to be more economical.
M10. Look for other sources of data	Reduces the demand and complexity of the space system	May be able to use data from space in conjunction with other data to meet the needs of the end user at dramatically lower cost and risk.
M11. Use more on-board processing to reduce comm bandwidth	Lowering the bandwidth reduces cost, power, and complexity of the spacecraft	There is a continuous demand for more bandwidth (more channels, higher frame rate, greater definition). Could, for example, improve performance and reduce cost of FireSat by processing on board and sending down only the location and severity of the fire.

LAUNCH

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Reducing Space Mission Cost—Launch (L)		
Technique or Action	**Mechanism**	**Comment © 2021, Microcosm, Inc.**
L1. Use alternatives to orbital missions	Dramatically reduces "launch" cost	Use balloons, drop towers, parabolic flights, or suborbital flights as low-cost testing alternatives. (See separate table.)
L2. Use ASAP or ESPA rings	Significantly lower cost than dedicated launch	Does not allow selection of orbit or launch time. Not applicable for operational missions. Typically puts constraints on the spacecraft, such as no propellant or equipment that could be hazardous to the primary payload.
L3. Use Rideshare	Shares launch cost	Only works if systems have compatible orbits and schedules.
L4. 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. Less chance of failing to meet user needs.
L5. Develop lower-cost launch systems	Perhaps the single most important component of dramatically reducing space mission cost	Two distinct, separate goals: A. Low mission cost (small launch) B. Low cost/lb to orbit (larger launch) Four broad approaches to achieving it (See separate table): A. Reusable systems B. Air launch C. Other assisted launch (gun, rail, lasers, or other approaches) D. Big (or little) Dumb Booster
L6. Create 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.
L7. 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. Allows rapid testing of new technology.
L8. Develop Launch-on-Demand	Dramatically reduces mission risk. Allows responsive systems which reduce the need to cover all the world all the time.	Russians/Soviets have had launch-on-demand for over 30 years. During the 73-day Falklands war in 1982, the Soviets launched 29 payloads in direct response to the war. (The war was in southern South America where there was very little satellite coverage.)

SPACECRAFT TECHNOLOGY

S P A C E C R A F T

Reducing Space Mission Cost—Spacecraft Technology (Sp)		
Technique or Action	**Mechanism**	**Comment © 2021, Microcosm, Inc.**
Sp1. 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. In many cases, the hardware must be qualified for spaceflight. However, the principal potential problem areas are well known and can typically be anticipated.
Sp2. 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. More high quality CubeSat hardware is being developed and cost is being reduced.
Sp 3. Use more micro-electronics	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. Solutions appear to be emerging for rad hard problem.
Sp4. 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.
Sp5. Make 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.
Sp6. Use COTS software	Immediately available; dramatically lower cost; tested through use	May need modification and thorough testing. Typically not optimal for the application. Updated at little or no cost to the program.
Sp7. Use 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.

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SPACECRAFT TECHNOLOGY (CONT.)

SPACECRAFT

Reducing Space Mission Cost—Spacecraft Technology (Sp)		
Technique or Action	**Mechanism**	**Comment © 2021, Microcosm, Inc.**
Sp8. Use Plug-and-Play technology	Dramatically reduces cost and schedule for I&T	Has not been used much to date because it isn't optimal. Substantial work currently ongoing.
Sp9. 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).
Sp 10. Avoid large engines for in-space applications	Reduces cost, mass, and need for additional control components	Large engines in space often require entirely separate control system and may represent the largest single danger to the spacecraft once it is on orbit. Small thrusters can be controlled by spacecraft control system and recovery from errors may be possible. Longer thrusting times make little or no practical difference.
Sp11. Use low-cost testing	Reduces the time and cost for space qualification	Extensive, low-cost testing is good. Low cost and COTS products can undergo destructive testing and then be discarded. Low-cost substitutes for orbital testing are discussed in Sec. 5.3.
Sp12. Use 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.
Sp13. Build small spacecraft to inventory	Lowers manufacturing cost. Allows more rapid, lower cost testing and more responsive missions.	Lowers cost by allowing a production line approach to spacecraft manufacturing. Allowing rapid test missions lowers cost and risk on the development and insertion of new technology. (Requires that the spacecraft bus be versatile with reasonably large margins in key areas.) Creating small observation satellites to inventory allows responsive missions.

GROUND SYSTEM

Reducing Space Mission Cost—Ground System and Communications (GS/C)		
Technique or Action	**Mechanism**	**Comment © 2021, Microcosm, Inc.**
GS/C 1. Use service-provided ground systems	Much lower cost with little or no non-recurring	Substantial redundancy and large area of coverage. Disadvantage is that your mission may have to share priority with others. Can be as low cost as several hundred dollars per pass. (USN is largest provider.)
GS/C 2. Use transportable ground terminal	Low cost and movable to meet changing needs	GATR is major supplier. Should be used in conjunction with other approaches (such as user-provided systems) in case the terminal isn't available.
GS/C 3. 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.
GS/C 4. Use an Iridium or GlobalStar modem	Very low cost, continuous communications link	Low data rate, but nearly continuous coverage. Only applicable to LEO.
GS/C 5. Use Internet for data transfer	Essentially eliminates cost of data transfer	Internet data transfer is continuously being made more capable and more redundant with greater bandwidth available. Can use encryption for data security, if needed.
GS/C 6. Use AMSAT resources for science data return	Lower cost by having an unpaid network	Has worked successfully in astronomy for decades. Can both reduce cost and provide high reliability by having multiply redundant ground segments.

MANUFACTURING (MNF)

MANUFACTURING

Reducing Space Mission Cost—Manufacturing (Mnf)		
Technique or Action	**Mechanism**	**Comment © 2021, Microcosm, Inc.**
Mnf 1. Design to a cost goal	Trades must favor cost and flow, not performance optimization and zero defects standards. A type certification quality approach is required.	Such approaches are known in high volume consumer or industrial goods manufacturing.
Mnf 2. Throughput orientation approach	All activities must be designed to facilitate uninterrupted product flow through the factory. It requires changing the orientation from "performance optimized" to "throughput optimized".	Common practice in industrial engineering / factory design (process flow diagrams).
Mnf 3. Design for process	Design must consider downstream cost impacting factors such as design use of existing process capabilities, avoidance of unneeded surface finish requirements, design for operator error-proof assembly, design for parts orientation and handling, design for efficient joining and fastening, design for modularity, design for automated production.	This term is more commonly known in chemical engineering. It denotes design for very particular desired product properties—in this case the design for cost reduction enabling features.
Mnf 4. Design for manufacturing (DFM)	Component features are designed for ease of manufacturing. Material type, form, shape and tolerances are chosen for enhanced producibility.	Known practice in high volume manufacturing. Most effective when applied early in the process
Mnf 5. Design for assembly (DFA)	Component features are designed for ease of assembly. Parts are provided with features to make them easier to grasp, move, orient and insert, which will also reduce assembly time and assembly costs.	Known practice for assembly plant centered environments. Most effective when applied early in the process
Mnf 6. Standard catalogue materials	Selection criteria must favor universally available materials. Avoids scarce materials with risky dependencies. Reduces supply risks.	Down-select criteria must be availability driven.
Mnf 7. Elimination of special treatments	Selection criteria must favor common material properties. Avoids exotic processes that mandate single sourcing. Reduces supply risks.	Down select criteria must favor materials that do not require secondary or post manufacturing treatments.

MANUFACTURING (CONT.)

M A N U F A C T U R I N G

Reducing Space Mission Cost—Manufacturing (Mnf)		
Technique or Action	**Mechanism**	**Comment © 2021, Microcosm, Inc.**
Mnf 8. Best industrial practices, type certification	Best industrial practices based on self-assessment or benchmarking applied to maintain the right quality in place of mandatory legislated or traditional standards. Breaking loose from conventions and assumptions and challenges assumptions in order to add value.	Break from traditional aerospace quality standards to enable drastic cost reductions.
Mnf 9. Multiple sourcing mandate	Purchasing of individual items used to create a product from different, multiple providers in order to keep production on track in the event of a failure to produce at one particular source. Reduces production disruption risk and enables competitive bidding.	Lack of this mandate has a well-documented history of catastrophic production failures in the automotive and consumer electronics field.
Mnf 10. Stable product definition	Mandates a "released for production" Bill of Materials. Allows changes in product definition only in approved blocks.	Only deviations or deficiencies that have critical human safety impact are allowed to disrupt production.
Mnf 11. Modular design for repetitive production	Mandates early definition of common interface configurations. Makes parts and tools interchangeable. Allows vendors to finalize design and tooling early.	
Mnf 12. Low parts count design	Simplify sub-assembly design. The reduction of the number of parts in an assembly has the added benefit of generally reducing the total cost of parts in the assembly.	Massive impact on cost.
Mnf 13. High parts commonality	Create a corporate "parts bin" like the automotive industry does to use/re-use the maximum count of identical parts.	Additional benefit: Reduces operator error.
Mnf 14. Low process interdependence	Design for plug-and-play. Increase off-line independent production activities. Accelerates factory throughput. Allows more and larger sub-assemblies to be built independently.	Common practice in automobile production.

RELIABILITY AND RISK MANAGEMENT (R&R)

R E L I A B I L I T Y

Reducing Space Mission Cost—Reliability and Risk Management (R&R)		
Technique or Action	**Mechanism**	**Comment** © 2021, Microcosm, Inc.
R&R 1. Embrace dramatically lower cost, shorter schedule missions as a means to lower both cost and risk	Allows back-ups, which, in turn, allow the potential for much lower cost missions without the burden of excessive mission assurance	Focuses on the broader issue of mission risk, rather than simply parts or spacecraft reliability. Strongly related to the issue of Design to a Reliability of Zero, raised by Hurley and Purdy (See Att 4)
R&R 2. Use mission diversity to reduce cost and risk (See also MisD 8)	Reduces the demand that the system "not be allowed to fail"	A mix of larger, traditional assets and smaller, lower cost assets provide greater resilience and robustness. Reduces the demand for perfection and allows more rapid augmentation and replacement in case of failure or enemy attack.
R&R 3. Embrace implementation risk to reduce mission risk and cost	Allows system to take advantage of newer, lower-cost, more capable technologies	A major problem area is to use only components which have previously flown in space. This restricts the use of new technology which can reduce cost, reduce parts count, and improve the performance of small systems. (See R&R 4.)
R&R 4. Fly both an old (previously flown) component and a new one	Both provides back-up in case of failure and mitigates risk of using a new, unproven component	A way around the implementation risk of R&R 3 is to fly a component flown on the last mission plus a newer component. This allows the system to both take advantage of new technology, while providing back-up and good reliability of flight-proven components.
R&R 5. Accept implementation risk in more than 1 area	Allows elements to be developed that can work together to drive down mission cost and risk	Key problem is the potential added risk. Requires careful planning and back-up approaches available to manage risk. If adequate back-ups are available, may be able to optimize performance and reduce cost at little or no increased risk. (See SE 5 Apollo example.)
R&R 6. Use a constellation of SmallSats	Allows mission success in spite of launch & system failures	SmallSats need to be very low cost. Failures found on first units can potentially be fixed on subsequent ones. (See Sec 2B for example)

OPERATIONS (OPS)

OPERATIONS

Reducing Space Mission Cost—Operations (O)		
Technique or Action	**Mechanism**	**Comment © 2021, Microcosm, Inc.**
O1. 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. Much lower cost, simpler constellation management.
O2. Use 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.
O3. 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.
O4. 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.
O5. Co-locate operations and system design teams	Drives down operations cost by ensuring that operations are taken into account during system design	High operations costs come from two major sources: 1. Operations cost not taken into account during spacecraft design 2. Problems pushed downstream due to lack of adequate funding during system development
O6. Operate as a local asset	Avoids major cost of bureaucracy and decision-making	Trades reduced spacecraft efficiency for increased people and operations efficiency. (Similar to the use of PCs vs. large mainframe computers.) Think of the cost and problems if all of the trucks used by the government were controlled, maintained, and scheduled by a Federal Bureau of Trucking.
O7. Use large margins on the spacecraft (i.e., avoid optimization)	Reduces required level of monitoring; may allow 1-shift monitoring	Many small, low-cost spacecraft are designed to work successfully (or at least not fail) in essentially any orbit and any attitude, such that they can be left unattended for extended periods. May want subsystem experts to be on-call, if needed.
O8. Use single shift operations	Reduces personnel, management, and communications cost	24 hour, 7 days/week monitoring requires 4 or 5 shifts plus all of the management and communications overhead. Use a single shift requires that the spacecraft be able to survive unattended and call for help if it needs it.
O9. 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. (See GS/C 1, 2.)

SOFTWARE (S/W)

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Reducing Space Mission Cost—Software (S/W)		
Technique or Action	**Mechanism**	**Comment** © 2021, Microcosm, Inc.
S/W 1. Robust Ontology	Facilitates the development of standardized interfaces, well-defined electronic data sheets, and reusable software.	Modern software development approaches can reduce both the time and risk of software development.
S/W 2. Use Standardized interfaces for primary hardware/software functions	Allow interoperability of hardware and software components without changing the ground and/or flight software	Also reduces the volume of network traffic because interface definitions need not be transmitted during runtime.
S/W 3. Provide electronic data sheets for all interfaces,	Allows some automated code development and interface verification — both cheaper and more reliable	Electronic data sheets allow for machine parsing and searching for data elements required by core algorithms and software (ground and flight) as well as allowing for automated interface verification and data availability.
S/W 4. Create Reusable Flight Software	Allows major cost reduction in subsequent applications	Reusable flight software comes with an initial cost for development but facilitates large reduction in recurring costs in the future. Reusable flight software is best accomplished by partitioning the applications into the smallest possible functional elements (which may be process intensive) and then grouping them together as needed to meet throughput requirements.
S/W 5. Identify Configurable database elements for items that require tuning on-orbit	Reduces time for assembly and configuration of software	Tunable configuration items that can be identified prior to integration of flight software, along with a mechanism to access the configuration items as part of a database tool allows for tuning of algorithms as the integration task reveals necessary alignment (and other) information. It also allows for rapid assembly and configuration of hardware and software if mounting locations and hardware performance parameters can be inserted as the vehicle is configured.
S/W 6. Use Common Simulation / Modeling routines for all disciplines	Reduces the amount of code to be developed and tested	Develop baseline hardware and vehicle simulation models that can have incrementally increased fidelity but are based on core functionality to be used during analysis, software integration and test, and vehicle performance verification