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RELAXED MASS LIMITS: A NEW OPTION FOR REDUCING SPACECRAFT COSTS

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ABSTRACT

Changes in the economics of launch provide an opportunity for dramatic cost-savings in the design and manufacture of medium to heavy spacecraft. These changes provide an opportunity for spacecraft design engineers to buy heavier launches and relax their mass limits. They can then trade spacecraft mass growth for cost reduction, as opposed to spending large amounts of time and money reducing mass to stay on the smallest possible launcher. Avoiding these expenses and associated design compromises could yield dramatic cost-savings and other benefits derived from expanding the engineering trade space.

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SOMETIMES QUANTITY HAS A QUALITY ALL ITS OWN

Changes in the economics of launch provide an opportunity for dramatic cost-savings in the design and manufacture of spacecraft. Over the last decade, the United Launch Alliance (ULA) has offered relatively low-cost performance upgrades within its Evolved Expendable Launch Vehicle (EELV) launcher families, making it affordable to greatly increase the mass allowable for many spacecraft. The Space Exploration Technologies Corporation (SpaceX) is introducing launch vehicles that can launch medium, intermediate and heavy spacecraft at much lower prices than were previously available, and the Orbital Sciences Corporation may soon offer reduced prices for medium launches on their new Antares launcher.

The advent of these offerings provides an opportunity for spacecraft design engineers to trade spacecraft mass growth for cost reduction, as opposed to spending large amounts of time and money reducing mass to stay on the smallest possible launcher. Avoiding these expenses could yield dramatic cost-savings in the design and manufacture of spacecraft.

The reduced cost of launching heavier spacecraft will permit engineers to greatly increase their mass margins by choosing larger launch vehicles. Mass margin is the difference between the maximum possible mass permitted by the launch vehicle and the maximum expected mass under the current design, including all allowances for expected mass growth. Mass margins typically range from around five percent for well-known hardware to around 25 percent for new systems.

If mass margins can be increased significantly above the requirement (30 percent would cover most cases), the excess margin can then be spent to allow heavier spacecraft designs. Costs can be saved both by forgoing expensive mass-reduction efforts and by replacing high-cost designs with lower-cost designs that were too heavy to be considered under previous mass limits. Designers can start by holding spacecraft performance constant and using higher spacecraft mass limits to cut the total mission cost. This is a shift from past relationships between spacecraft mass and cost, where increased mass has usually been associated with increased costs.

This approach may remind some of stories about the Russian space industry practicing low-cost brute-force design. In this new era, the paradigm of gaining cost savings from relaxed mass limits is a matter of choice and opportunity, seeking to make best use of both higher-tech and lower-tech options.

In considering these opportunities, it would be wise for designers to conduct thorough cost-saving analyses of current design efforts before considering increases in spacecraft performance. Expanded systems engineering frameworks and more flexible cost models could provide crucial assistance to these analyses.

OPPORTUNITIES TO REDUCE SPACECRAFT COSTS

Space Mission Engineering: The New SMAD notes that "no one sets out to design a space mission that costs too much and takes too long, yet fixing this problem has proven remarkably elusive." The author highlights as an example that the top 10 DoD space programs in 2007 ran over budget by $32 billion.

Space Mission Engineering lists large margins and devaluing optimization as two closely linked systems engineering approaches to reducing mission cost. It asserts that "optimizing the design by driving margins as small as possible is one of the principal reasons that standardization has been dramatically unsuccessful." It notes that "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;
- Fewer 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".

The advent of new launchers provides an unprecedented instance where large margin increases can come with immediate cost savings.

LAUNCH VEHICLE DEVELOPMENTS

Table 1 below shows the currently active U.S. domestic launch vehicles in the medium, intermediate, and heavy classes. All the vehicles have at least six launches except:

- The new medium launcher, the Orbital Sciences Antares, has three successes in three flights and does not yet have a published price for a single launch.
- The new heavy launcher, the Falcon Heavy, is scheduled to have its maiden flight in 2015.

The ULA Atlas V and Delta IV launchers comprise the EELV family of vehicles. Delta II launchers are being phased out and very few remain in inventory.

Vehicle	Class	LEO kg	LEO Polar kg	GTO kg	Published prices in millions*	Year of price data
Antares	Medium	4,500-6,120				
Delta II	Medium	5,089		1,818	$65-137	2012

* These representative price numbers should be regarded as approximate, since none of them is likely to include all components of the total launch cost. For example, they may omit some additional launch processing or infrastructure costs.

Vehicle	Class	LEO kg	LEO Polar kg	GTO kg	Published prices in millions*	Year of price data
Atlas V	Intermediate	8,210-18,850	6,770-15,760	3,780-8,900	$187-223	2009-2013
Delta IV	Intermediate	9,190-13,730	7,690-11,600	4,210-6,890	$100-180	2009
Delta IV Heavy	Heavy	28,370	23,560	13,810	$370-435	2011
Falcon 9 v1.1	Intermediate	13,150		4,850	$82-97	2012
Falcon Heavy	Heavy	53,000		21,200	$165	2012

Table 1: Performance and Prices for Medium to Heavy U.S. Launch Vehicles†

Both the Atlas V and Delta IV offer low-cost upgrades to their smallest variants. As many as five strap-on solid rocket boosters (SRBs) can be added to the Atlas V. Either two or four solid rocket boosters can be added in pairs to the Delta IV. Each SRB is priced at an estimated $10 million, producing launcher performance upgrades as illustrated by the following examples. Each example includes a column showing the comparable Falcon 9 performance. The first example (Table 2) shows the additional performance expected for an Atlas V launching to a standard circular low Earth orbit (LEO) reference orbit of 200 km at 28.7 degrees using a five-meter payload fairing.

LEO REFERENCE	ATLAS V 511	ATLAS V 521	ATLAS V 531	ATLAS V 541	ATLAS V 551	FALCON 9 V1.1
Atlas V 501	34%	64%	89%	112%	130%	60%
Atlas V 511		23%	41%	58%	71%	20%
Atlas V 521			15%	29%	40%	
Atlas V 531				12%	21%	
Atlas V 541					8%	
# OF SRBS	1	2	3	4	5	APPROX. $40-140M SAVINGS
	$10 MILLION PRICE PER SRB					

Table 2: LEO Performance Increases for Variants of the Atlas V with a 5-Meter Fairing (percents)

The above performance improvements are in addition to pre-existing spacecraft mass margins. Since mass margins are based on the estimated spacecraft mass rather maximum launcher performance, the spacecraft mass margin increase is larger than the sum of the mass margin and the launcher performance increase due to using a smaller denominator. For example, a spacecraft scheduled to launch on an Atlas V 501 with a 10% mass margin would increase to a 49% margin on an Atlas V 511 at a cost of about $10 million.

† The Falcon 9, the Antares and both EELV families represent a new paradigm for launch vehicles in that all were developed as commercial programs under Other Transaction Authority (OTA) contracts, rather than under Federal Acquisition Regulation (FAR) cost-reimbursement contracts. In addition to changing launch economics, note that in 82 total launches as of April 30, 2014, none of the OTA-developed vehicles has had a catastrophic failure.

The second example (Table 3) shows performance to a standard Geosynchronous Transfer Orbit (GTO) orbit at 27 degrees using a five-meter payload fairing. A spacecraft going to GTO with a 10% mass margin on an Atlas V 501 would increase to a 54% margin on an Atlas V 511.

GTO	ATLAS V 511	ATLAS V 521	ATLAS V 531	ATLAS V 541	ATLAS V 551	FALCON 9 V1.1
Atlas V 501	39%	71%	97%	119%	135%	28%
Atlas V 511		23%	42%	58%	70%	20%
Atlas V 521			15%	28%	37%	
Atlas V 531				11%	19%	
Atlas V 541					7%	
# OF SRBS	1	2	3	4	5	APPROX. $40-140M SAVINGS
	$10 MILLION PRICE PER SRB					

Table 3: GTO Performance Increases for Variants of the Atlas V with a 5-Meter Fairing (percents)

These examples show that spacecraft designers have many opportunities to dramatically increase their mass margins at modest expense within the Atlas family and some opportunities to increase mass margins while saving launch costs by switching to a Falcon 9. The same pattern repeats for each combination of EELV and destination orbit.

For LEO spacecraft missions with expected masses up to about 13,000 kg and down to perhaps as low as 2,000 kg, there is an immediate opportunity to investigate the potential benefits and challenges of the new paradigm. The same is true for polar LEO missions up to about 11,000 kg and GTO missions up to about 6,400 kg. In the current budget environment, it should be regarded as imperative to identify where the greatest cost savings are likely to be found and to identify what barriers and limits must be addressed to realize the savings.

FUTURE LAUNCHER DEVELOPMENTS

SpaceX is currently developing the Falcon Heavy to launch spacecraft as heavy as 53,000 kg to LEO, about 86% more than the comparable Delta IV Heavy. Based on flight data from the first Falcon 9 V1.1 flight using the new Merlin 1D engine, they upgraded their estimated GTO payload for the Falcon Heavy to 21,200 kg, about 53% more than the Delta IV Heavy. If the Falcon Heavy is successful, SpaceX will be able to offer both cost and performance advantages for any spacecraft heavier than about 6,000 kg, and many lighter spacecraft as well.

Since the Falcon Heavy is currently priced at or below the cost of many Atlas V and Delta IV launchers, many intermediate spacecraft with mass higher than the maximum payload of the Falcon 9 could be considered for the Falcon Heavy and derive savings both in spacecraft costs and in launch costs.

The Falcon Heavy currently has three flights scheduled in the next few years, an initial test flight in 2015 followed by flights contracted for the U.S. Air Force and Intelsat. Designers of heavy spacecraft that have not yet begun their design phases should begin considering the new cost paradigm for their spacecraft and develop contingency plans to enable rapid adoption in the event that the Falcon Heavy proves reliable.

Medium-weight spacecraft may face a complex choice regarding which launcher and which paradigm to employ. The low cost of the Falcon 9 may cause the break-even point to fall somewhat below 4,000 kg to LEO. If the new Orbital Sciences Antares medium-class launcher (rated at over 6,000 kg to LEO) is priced significantly lower than the Falcon 9, it may extend the relaxed-mass-limit paradigm to even smaller spacecraft. In the meantime, some medium-weight spacecraft are being forced onto intermediate launchers, including small EELVs, by the current unavailability of certified medium launchers. These spacecraft will inherit huge mass margins and are prime candidates to benefit from relaxed mass limits.

COST-SAVING OPPORTUNITIES

Changes in the economics of launch open several opportunities for spacecraft and mission designers, as outlined above. Their first impulses, however, are likely to include increasing performance by adding more instruments, designing more powerful instruments, or adding secondary payloads. Each of these options could increase mission cost, risk and complexity. The opportunity to use relaxed mass limits to reduce costs is less traditional, but more responsive to the current budgetary environment. Designers could start by holding performance constant while using higher spacecraft mass limits to reduce the total mission cost as well as the risk of cost growth or schedule slips.

High and growing launch costs have created historical incentives for designers to launch spacecraft on the smallest possible launchers. The universal practice has been to invest in designs, materials and technologies that are more expensive, but enable decreases in spacecraft mass. Access to low-cost increases in launch performance allows spacecraft designers to forgo most, if not all, of these expensive investments. Many programs may be able to save money by purchasing commercial-grade systems and instruments that would otherwise have required alteration or substitution due to mass limits. Savings such as these may comprise a significant portion of total program costs.

Forgoing mass reduction investments and using off-the-shelf systems could bring additional benefits, such as shortening project schedules for additional time-related savings and putting satellites into service earlier. It might enable more rapid mission tempo for recurring missions. Enabling greater use of off-the-shelf systems could also make it easier to adopt a distributed architecture strategy or use commercial satellite buses, as discussed by Pawlikowski, et al. in the Spring 2012 edition of Strategic Studies Quarterly.

Low-cost launches would also enable current design features to be reconsidered for potential cost savings. For example, designers might:

- Use heavier, cheaper materials;
- Reduce machining of parts to reduce mass;
- Add heavier shielding against radiation to reduce electronics costs;
- Cut back on mass management processes.

Many of these cost-saving design changes could also produce spacecraft that are more robust and reliable, in turn reducing project risk.

In considering these opportunities, it would be wise for designers to make a thorough cost-saving analysis of current design efforts before considering increased performance. After the initial mass-related cost savings have been identified, budgets may also allow for relatively low-cost performance improvements, such as:

- Adding more fuel for longer satellite life or better mission performance;
- Adding larger solar arrays and batteries to power systems;

- Adding larger thermal control systems;
- Increasing the bandwidth of the communications system, enabled by increased power and mass.

These improvements could also enable a cascade of additional savings. Increased fuel loads could increase life-cycle benefits by extending spacecraft lifetimes. Adding more power production could eliminate the need for some expensive investments to reduce power consumption, for example, and increased bandwidth could reduce the need for expensive onboard data processing. Broad relaxation of limits on power, in addition to mass, could further ease the challenge of inserting new technologies.

The cost-saving benefits could cascade from mass to power and thermal control and then to mission systems. The cumulative effect is likely to improve the benefits and decrease the costs of using modularized or standardized systems. Higher mass margins could also make it easier to insert new technologies that have not yet been optimized to reduce their mass. The design space for spacecraft will expand in many dimensions. Adding more expensive design features could still be considered as a final step, budgets permitting, but only after the sum of the earlier efforts have defined a new cost floor.

EXPANDED SYSTEMS ENGINEERING TRADE SPACES

The new engineering paradigm created by these cost-saving opportunities will create two trade domains with very different dynamics. A "tight-mass-limit" domain will continue for smaller spacecraft, which will still benefit from traditional mass-control practices in order to use small launchers. A "relaxed-mass-limit" domain will be appropriate for many larger payloads, which will be able to pursue aggressive cost reduction strategies. For future super-heavy missions, such as NASA human spaceflight missions to the Moon or Mars, the "tight-mass-limit" paradigm will again be appropriate. Many spacecraft engineering organizations will need to develop an ability to toggle back and forth between the two paradigms. Aerospace engineers will need to develop and maintain an ability to operate in either paradigm.

In addition, the trend toward lower-mass and lower-power engineering in the broad global marketplace will continue. Aerospace engineering can and should continue to benefit from engineering investments made by others, especially if low mass and power consumption in one part of a design supports the relaxed-mass-limit paradigm in others.

CHALLENGES AND PITFALLS

Seizing this opportunity will go against one of the central traditions of our aerospace engineering culture. Most aerospace engineers have been trained by their education and career experience to optimize mass as a matter of course. As a result, they may find the new paradigm counterintuitive. Some engineers may resist low-cost low-tech designs simply because they are not high-tech and therefore not interesting.

This reaction will be compounded wherever engineering practice focuses exclusively on requirements without consideration of opportunities. All established requirements are predicated on often unspoken assumptions about what is possible and will therefore tend to be unresponsive to opportunities created by changing circumstances. In addition, the aerospace industry has a bad habit of accepting large cost risks and tolerating cost overruns that will be hard to break even with the best intentions. Some in the aerospace industry do not believe that significant cost reductions are possible without compromising performance or reliability, and will therefore refuse to make the attempt.

There will be practical limits and challenges in addition to cultural resistance. Some companies will have lost the skills or facilities needed to implement lower-tech solutions. It may be necessary to go beyond the aerospace vendor community to find needed capabilities. In some cases, the cost of engineering a new design will be greater than the potential savings in manufacturing costs. Volume constraints may replace mass constraints for some spacecraft.

Processes to manage a cost-reduction strategy that is independent of mass constraints may need to be developed. In particular, many engineering organizations may not have the ability to do the type of cost trade off analysis needed to take advantage of opportunities in an expanded trade space. Most of all, new paradigms always suffer from start-up errors as some people learn how to apply them while others resist or fumble the change.

The cost models employed by cost estimators will require major modifications and expansions. Many mass-based cost estimating relationships will become obsolete under the new paradigm and will need to be re-estimated or replaced. The cost per pound for some components will reverse their historical upward trends and drop suddenly to much lower levels. Cost estimators may end up needing either a separate set of methods for each paradigm or substantially different methods that are flexible enough to cover both.

Systems engineering and integration is likely to be more challenging under the new paradigm. As the new paradigm is accepted, some may be tempted to relax or abandon engineering discipline. In fact, adopting the new paradigm will require more discipline, especially to resist the temptation to fill higher mass limits with costly new features.

As the engineering trade space grows and adds new dimensions, it will also grow more complex. The risk of design errors early in the design phase may actually increase. Choosing the wrong paradigm at the beginning of a program is likely to have significant negative consequences. Rigorous systems engineering at the beginning of every program will therefore be essential.

The reward for getting the design paradigm right from the beginning is likely to be significantly increased performance at greatly reduced cost. Minimizing the cost of spacecraft structures and utilities could create budgetary space for insertion of new technologies or improvement of current technologies. If the new paradigm also enables more standardized core systems and interfaces, it could also allow for insertion of new technologies later in the design process. All if these should have high value to spacecraft buyers who are confronting unprecedented budget constraints.

SUPPORTING DEVELOPMENTS

Pioneering efforts to explore the relaxed-mass-limit paradigm will have great value to the aerospace industry. There is an immediate need for studies to explore structure and dynamics of the new paradigm. Case studies could be conducted on experiences of spacecraft design programs that launched on vehicles much larger than they needed or that were forced to spend large sums to meet artificially low mass limits. Analytic studies should be conducted to support any new spacecraft development that might benefit from the new paradigm. Opportunities may also be found to test the new paradigm on a smaller scale by significantly increasing the mass margins on only a subset of a spacecraft's systems.

One way to get early indications of the nature and extent of the relaxed-mass-limit paradigm would be to use it as a source of class projects in universities. Here are two scenarios that might prove interesting and valuable:

- A near 5,500 kg spacecraft can fly on an Antares with savings in launch costs and a tight mass margin or fly on a Falcon 9 with more than 100% mass margin and save on spacecraft costs.
- An 8,000 kg spacecraft can fly on a Falcon 9 and save money by using the 5,000 kg mass margin or cut launch costs by taking on a secondary payload.

In each case, which choice provides greater advantages?

TASC is exploring the relaxed-mass-limit paradigm with a view to providing systems engineering frameworks to help spacecraft developers exploit the new paradigm while avoiding the inevitable pitfalls. In particular, TASC is exploring what modifications and expansions current cost estimating methods will need to remain relevant to the new engineering practices that will develop out of the relaxed-mass-limit paradigm and other major innovations.

CONCLUSION

Changes in the economics of launch offer opportunities to spacecraft designers for three distinct kinds of cost savings.

- Savings from forgoing expensive mass-reduction and power-reduction investments;
- Savings from replacing current design features with lower-cost, higher-mass alternatives; and
- Savings in the cost of the launch itself.

They also offer opportunities for performance improvements that are currently prohibited by mass constraints and that may, in turn, enable further cost savings.

Regardless of what engineering trade space designers find themselves in, efforts to exploit these opportunities demand that a complete set of cost/performance relationships be developed as part of a cost analysis that is directed not just at cost assessment, but actively at cost reduction.

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