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FUNDING THE TRIAD

Wanting nuclear upgrades is easy — paying the bill is harder *page 28*

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A Delta 4-Heavy lifts off
from Vandenberg Air Force Base.

U.S. Air Force

With the advent of lower cost launchers, satellite designers should rethink some of their traditional assumptions about how to control costs. Gary Oleson, a senior engineer at TASC, explains how to thrive in today's dynamic launch vehicle market.

Advice to satellite designers:

"Carpe

VIEWPOINT

By Gary Oleson

The changing economics of launching satellites is creating dramatic cost-saving opportunities for designers and manufacturers of spacecraft. Over the last decade, the United Launch Alliance has offered performance upgrades within its Delta 4 and Atlas 5 launcher series. Customers have the option of adding strap-on solid rocket boosters at a cost of about $10 million each. This makes it affordable for mission planners to greatly increase the mass allowable for many spacecraft. Meanwhile, SpaceX is introducing launch vehicles that can launch medium, intermediate and heavy spacecraft at much lower prices than were previously available, and Orbital Sciences Corporation may soon offer lower prices for smaller vehicles through its new Antares launcher.

These lower cost offerings should change the launch cost calculations of customers in important ways. Design engineers no longer need to spend large amounts of time and money figuring out how to reduce mass to stay on the smallest possible launch vehicle. They can allow spacecraft mass to grow while taking pressure off their budgets. This, in effect, is a new cost reduction strategy, at least for the U.S.

Design engineers typically work within a rigid mass margin, which is the difference between the maximum possible mass permitted by the launch vehicle and the maximum expected mass of the satellite under the current design. Mass margin ensures, for example, that if the mass of a part increases during development, the satellite can still be launched on the same rocket. Mass margins typically range from around 5 percent for well-known hardware to around 25 percent for new systems, according to “Space Mission Engineering: The New SMAD,” a reworked version of the “Spacecraft Mission Analysis and Design” manual used by many design engineers. Engineers traditionally work hard to stay within mass limits, so they don’t break into the margin unnecessarily.

Now, however, shifting to a more powerful rocket of about the same cost as the planned rocket allows engineers to relax a satellite’s mass limit while keeping the margin the same or even increasing it. If a spacecraft with a mass margin of 25 percent was planned for a launcher that can put 5,000 kg in orbit, then the mass limit for the spacecraft would be 4,000 kg. But if the customer could afford a 6,000-kg launch capability, either by changing launchers or adding a strap-on booster, the mass margin would jump to 50 percent. The mass limit of the satellite could be relaxed to 4,800 kg without exceeding the original 25 percent margin. Lower-cost components could be incorporated that were too heavy to be considered under the previous mass limit. For example, a spacecraft with a 10 percent mass margin launching to LEO — low Earth orbit — on an Atlas 5 501, rated at 8,210 kg, could increase its margin to 47 percent by upgrading at a cost of about $10 million to an Atlas 5 511 rated at 11,000 kg.

This is just one part of the new paradigm that’s being opened by changes in the launch market.

diem”

REDUCING SPACECRAFT COSTS

The new paradigm promises to reduce the cost to satellite designers and mission planners in three ways:

- 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.

Designers planning to launch on an Atlas 5, for example, should investigate the potential benefits for LEO missions with expected masses of up to about 14,000 kg; for polar LEO missions up to about 11,000 kg; and for geostationary transfer orbit missions up to 6,600 kg, in which payloads are put into elliptical orbits preceding their final geostationary orbits at 36,000 kilometers.

In fact, in the current budget environment, it should be regarded as an imperative to assess changes in the launch market, identify where the greatest cost savings are likely to be found, and 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 of up to 53,000 kg to LEO, which would be about 86 percent more capacity than the comparable Delta 4 Heavy. Based on flight data from the first Falcon 9 V1.1 flight using the new Merlin 1D engine, SpaceX upgraded its estimated geostationary transfer orbit capacity for the Falcon Heavy to 21,200 kg, about 53 percent more than the Delta 4 Heavy. If the Falcon Heavy is successful, SpaceX will be able to offer both cost and performance advantages for any spacecraft heavier than about 5,500 kg, and many lighter spacecraft as well.

Since the Falcon Heavy is currently priced at or below the cost of many Atlas 5 and Delta 4 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 has three flights scheduled in the next few years: an initial test flight in 2015 followed by flights contracted for the Air Force and Intelsat. De-

Market maker: A Falcon 9 in a hangar at Cape Canaveral, Fla.

SpaceX

signers of heavy spacecraft who have not begun their work 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.

Designers of medium-weight spacecraft designers 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 cost point to fall somewhat below 4,000 kg to LEO. If the new Orbital Sciences Antares medium-class launcher (rated at over 5,000 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, the current unavailability of certified medium launchers is forcing some medium-weight satellites onto intermediate launchers, including the lowest capacity versions of Delta 4 and Atlas 5. These satellites will inherit huge mass margins and are prime candidates to benefit from relaxed mass limits.

COST-SAVING OPPORTUNITIES

The dynamic economics of the launch market are opening important opportunities for satellite designers, but those designers should guard against the impulse to increase 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. The new launch market enables 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.

NASA

Flawless so far: An Orbital Sciences Corporation Antares rocket at NASA's Wallops Flight Facility.

Forgoing mass reduction investments and using off-the-shelf systems could bring added benefits, such as shortening project schedules for additional time-related savings, and putting satellites into service earlier. More rapid mission tempos might be enabled 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 Air Force Lt. Gen. Ellen Pawlikowski and her co-authors 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.

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. Greater 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,

Dynamic marketplace

Vehicle	Class	LowEarth orbit (kg)	Low Earth orbit polar (kg)	Geostationary transfer orbit (kg)	Prices ($ millions)	Year
Antares	Medium	4,500-5,500		1,400	unavailable	
Delta 2	Medium	5,089		1,818	$65-137	2012
Atlas 5	Intermediate	8,210-18,850	6,770-15,760	3,780-8,900	$187-223	2009-2013
Delta 4	Intermediate	9,190-13,730	7,690-11,600	4,210-6,890	$100-180	2009
Delta 4 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

Two newcomers could soon shake up a U.S. launch vehicle market that was already dynamic: The Falcon Heavy is expected to make its first flight – a demo – from Vandenberg Air Force Base, Calif., later this year or in 2015. Orbital Sciences' Antares has launched twice with good performance reviews.

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. Relaxed mass limits could 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 has defined a new cost floor.

EXPANDED SYSTEMS ENGINEERING OPTIONS

The new engineering paradigm created by these cost-saving opportunities will create two tradeoff 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 missions to the moon or Mars, the tight-mass-limit paradigm may 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.

CULTURAL CHALLENGES

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 counter-intuitive. 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. This habit 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 for managing a cost-reduction strategy that is independent of mass constraints may have to be developed. In particular, many engineering organizations may not have the ability to do the type of cost tradeoff 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 increase. Choosing the wrong paradigm at the beginning of a program could 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 achieving the required 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 of these should have high value to spacecraft buyers who are facing unprecedented budget constraints.

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 student projects in universities. Students could be challenged to look at trade study scenarios and articulate which choices in each scenario would provide the greater advantage and why. The following scenarios present two possible trades:

- 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 percent 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?

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 the structure and dynamics of the new paradigm. Case studies could be conducted on experiences of spacecraft design programs that launched spacecraft 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 relaxing mass limits on only a subset of a spacecraft's systems.

TASC is exploring the relaxed-mass-limit paradigm with a view toward providing systems engineering frameworks to help spacecraft developers exploit the new paradigm while avoiding the inevitable pitfalls. In particular, TASC is studying 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.

Efforts to exploit these opportunities demand that a new 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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